Photodetachment Neutralizer Development - Laser Window Design Study

FINAL REPORT, VOL. I - SUMMARY

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1.0 INTRODUCTION AND SUMMARY

Photodetachment neutralization (PDN) has been proposed as a major improvement to the gas cell neutralization utilized on current neutral beam heating systems for magnetic containment fusion devices. A neutral beam must be created from an ion beam after the ions have been accelerated by electro-magnetic fields. Typical beam systems start with a negative ion beam of deuterium and use collisions between the beam ions and molecules in a neutral gas cloud to neutralize the charged ions. Gas cloud collisions have the deleterious side effect of scattering the ions in the beam as they are neutralized and therefore reduce the quality and usefulness of the resulting neutral beam. The PDN approach uses collisions with photons in a "cloud" of infrared laser light to detach electrons from the negative ions. Since the ions collide with low "mass" photons, the quality of the beam is left essentially unaffected. Therefore, if PDN can be shown to be both possible and practical it would become the method of choice where the best neutral beam quality possible is needed.

In the preceding PDN study¹, the characteristics and technology requirements were established for a practical PDN system which could be used with a wide range of neutral beam operating conditions. This system and its requirements are described in section 2. This system will use a Chemical Oxygen Iodine Laser (COIL) to produce a light beam with photons of a near optimal wavelength which can be reflected back and forth across the path of the ion beam to create the necessary high density light "cloud" required for the photodetachment process. In a fusion device the neutral beam goes directly into the process vacuum chamber and therefore the oxygen iodine gas mixture in the laser must be isolated by a window from the neutral beam channel without loss of too much light or leakage of miniscule quantities of laser gas. The aerodynamic windows that have traditionally been used with chemical lasers are viewed as undesirable for the fusion application where any contamination of the fusion vacuum chamber by laser gas would be a big problem. The previous study therefore evaluated the options for windows made of various solid materials and cooling configurations. That study concluded that a double disk window made of sapphire with a fluorocarbon coolant flowing between the disks could be made to meet the PDN system requirements. However, it was also concluded

that the technological issues were uncertain enough that a verification by designing, fabricating, and testing of a demonstration window would be required before feasibility of such a window could be considered certain.

The purpose of this study contract was to lay the ground work to make such a test demonstration possible. The statement of work defined for this study consisted of two tasks:

Task I Determination of the absorption characteristics of the proposed sapphire window material and the fluorocarbon coolant.

Task II Design and analysis of the proposed double disk heat exchanger window and demonstration test hardware.

The two tasks have been completed with the resulting design incorporating the results of the absorption characterizations and a few improvements that came to light during the course of the design. The window has been enlarged slightly to decrease the intensity of the incident light and make the design more conservative. The analysis of the expected window performance indicates that the PDN system requirements ought to be feasible and point to a successful test verification program when funds become available.

The design and analysis of this PDN laser window was performed by the staff of the Optical Components Department of the Applied Technology Division of the TRW Defense and Space Systems Group. The details of this work are reported in Volume II and summarized in Section 3 of Volume I.

2.0 PDN SYSTEM REQUIREMENTS

The photodetachment neutralizer concept requires a certain optical thickness in the "cloud" of 1.315 micron photons in the path of a negative deuterium ion in order that an electron is stripped and a neutral atom is produced. The neutral fraction obtained from a D^- beam passing through the PDN is a function of the ion beam energy, length of the neutralizer along the ion beam path, intercavity flux of the laser mode interacting with the ion beam and the laser wavelength. Details of this process are well described by J. Fink.^{2,3} The optical thickness needed to deliver a given neutral fraction as a function of the deuterium beam energy for a COIL laser (1.315 micron) are shown in Figure 2.1 (from Reference 2). Two major conclusions can be made based on these data:

1. The required optical thickness is large. In order to obtain a neutral fraction larger than 90%, the required thickness is on the order of 10 to 15 $MWcm^{-1}$, depending on the beam energy. Since the thickness is a product of the intercavity flux and the length of the neutralizer, a PDN designer can trade off the flux against the neutralizer length.
2. The PDN system design can be made "universal." The required optical thickness is independent of the beam power. For a given system design the stripping fraction is the same for any beam current, provided that the ion energy is given. This feature allows development of one generally applicable PDN system design. The same hardware can serve as a neutralizer for 1 Ampere beam which has been attained with the present D^- technology or for 100 Ampere beam which might be needed in the future fusion systems.

The required optical thickness can best be produced inside a closed and folded COIL laser resonator. A schematic of the folded resonator concept is shown in Figure 2.2. The ion beam passes only through the folded region of the resonator, which is separated from the lasing portion of the resonator by a window. As the number of folds is increased, the total optical thickness in the ion beam path increases. There is a limit, however, where more folds yield little benefit since each mirror introduces additional losses into the optical cavity for which the size of the laser must compensate.

Figure 2-1. The optical thickness of a photoneutralizer delivering a neutral fraction.

Figure 2-2. Folded Resonator Concept

The principal loss of the circulating intercavity light flux is due to the absorption and scattering at the mirrors and the window. The loss of photons due to neutralization is negligible (one photon per reaction, i.e., approximately 1 W per 1 A of neutralized current). In steady state the cavity loss has to be supported by the laser gain medium and in order to minimize the required laser power (i.e., the closed cavity power), the mirror and window losses should be minimized. The effective mirror reflectivity and the window transmissivity should therefore be as close to unity as possible. The previous study determined that silicon carbide mirrors with built-in heat exchangers could meet the PDN requirements. Such mirrors, with proper manufacture and coatings, can be built with scattering and absorptance losses of less than 5×10^{-4} (or reflectivity $R = 0.9995$).

PDN WINDOW REQUIREMENTS

The COIL laser gain medium (at a pressure 2 to 10 Torr) must be separated from the beam interaction region by a window since the ion beam requires a low pressure region (10^{-6} Torr) for its propagation, and the fusion chamber must be protected from contamination.

While the precise requirements for the window could be optimized in a system design trade study by varying the number of folds in the resonator, for the purposes of determining the capabilities of PDN window technology, the following representative maximum requirements were established for the material and thermal analysis:

- o Incident, one way flux 40 kW/cm^2
- o Input/output beam footprint $3 \times 10 \text{ cm}$
- o Wavelength 1.315 micron

We previously concluded through the material comparison analysis that the best material candidate is a clear sapphire (Al_2O_3). The thermal analysis had shown that only the double pane, liquid cooled concept is feasible and only if the incident beam footprint is expanded to approximately $10 \times 10 \text{ cm}$. The laser beam expansion can be done by a combination of expanding and focussing mirrors on both sides of the window. This introduces at least four additional mirrors into the optical resonator, but the beam shaping telescope reduces the one way flux to a

level which can be thermally handled by the window. The proposed coolant was a Fluorinert Electronic Fluid (FC-104).

Proposed Window Summary

Material	Al ₂ O ₃
Concept	Double pane liquid cooled
Coolant	FC-104 Fluorinert fluid
Irradiance	12 kW/cm ²
Footprint	10 x 10 cm
Expanding Telescope	Required

Double pane window transmissivity was considered an open question because the absorption of FC-104 coolant was not known accurately enough at this wavelength. The transmissivity of FC-104 would have to be measured at 1.315 microns in future phases of the PDN development. The window material is transparent and antireflection coatings are required to reduce the losses to about $2 \cdot 10^{-4}$ per pass per coating. Index matching concept for FC-104 would have to be verified.

The double pane window concept is shown in Figure 2.3. This was chosen so that a coolant can be introduced between the panes. Two types of cooling were considered: gas and fluid. The fluid has a larger heat transfer capability and there is an additional advantage that the indices of refraction between the windows and the coolant can be matched thus minimizing one source of loss. Several window thickness were chosen (1/4, 3/8, 1/2 inch) and several window spacings were considered as well as various coolants. The beam footprint that was considered was 10 x 3 cm. The incident flux density was 40 kW/cm² for total flux density of 80 kW/cm² passing through the window. While this is the best concept, it still cannot be cooled adequately at the full flux value. A beam shaping telescope concept was therefore developed as shown in Figure 2.4 in order to spread out the beam footprint thereby lowering the incident flux density. The expanded footprints considered were 10 x 10 cm and 15 x 15 cm, respectively.

Figure 2-3. Double Window

Figure 2-4. Beam Shaping Telescope

Technology Verification Requirements

The double pane window with fluid and index matching was seen as a feasible concept, but it required experimental verification of important issues such as:

- a) Coolant absorption measurement
- b) Proper choice of index matching constituents and the effect on absorption
- c) Deflection and associated beam degradation

It was recommended that a Proof of Principle Test be performed in order to verify and characterize the material window conceptual configuration. Such a test could best be accomplished using the existing COIL laser with the appropriate hardware modifications to install the window with its appropriate instrumentations. This Proof of Principle project would include the fabrication of the proposed window which would be instrumented to give experimental data on all signification parameters, i.e., coolant velocity, temperatures, deflection, etc. The results of this test would be used to characterize and to develop design and performance criteria for the conceptual design.

3.0 WINDOW DESIGN AND ANALYSIS

A double paned cooled window was proposed as the means of isolating the gain medium from the vacuum in which the photodetachment process is to take place. A single pass steady state cavity flux of 40 kW/cm^2 (a double pass flux of 80 kW/cm^2) through a $10 \times 3 \text{ cm}$ beam footprint was specified. In order to reduce the intensity through the window it was proposed that the beam be expanded through the window with a system of expanding/contracting telescopes. The maximum expansion of the beam is limited by the size of sapphire available. It was determined that 8-inch sapphire can be procured. The largest beam footprint which could be passed through this size window (allowing a sufficient rim around the outside for mounting) is $12.36 \times 12.36 \text{ cm}$. This was thus chosen as the size of the operational window to analyze for use in the PDN application. It is noted that expanding the $3 \times 10 \text{ cm}$ beam to $12.36 \times 12.36 \text{ cm}$ and contracting it back to $10 \times 3 \text{ cm}$ requires four toroidal mirrors. A demonstrator window for technology verification testing purposes was designed and analyzed for use with an outcoupled COIL beam (10 kW , $10 \times 3 \text{ cm}$ picture frame). The demonstrator is a double paned sapphire window cooled between the panes with a fluoroinert coolant.

In order to perform the analyses on the demonstrator and operational windows, absorption coefficients of sapphire samples and of fluoroinert coolants were measured. The measured values of absorption coefficient beta were 0.019 cm^{-1} and 0.0079 cm^{-1} for two sapphire samples and 0.017 cm^{-1} for the fluoroinert coolant. The difference in beta for the two sapphire samples led to an investigation which determined that there are several grades of optical quality sapphire with varying values of beta.

The measured values (which were both used in different analyses) are very conservative when compared to published data. It is recommended that similar measurements be done on premium quality sapphire. This could indicate increased safety factors and/or enable higher intensity power to be passed through the windows. It is anticipated that the absorption coefficient of premium grade sapphire will be low enough that expanding the beam to $10 \times 10 \text{ cm}$ rather than $12.36 \times 12.36 \text{ cm}$ will be sufficient. If this is found to be the case, the expanding/contracting telescoping system

will be simplified since four cylindrical rather than four toroidal mirrors can be used.

The demonstration window was designed for a 10 x 3 cm beam, and a coolant flow of 50 ft/sec, and coolant pressure at the window of 74 psi. The thickness of the sapphire window panes for the demonstrator was chosen to be 0.2 inches. This thickness was arrived at by minimizing the predicted combined thermal and pressure stresses. (A thicker window has higher thermal stresses while a thinner window has higher pressure stresses.) It was suspected before the analyses that this window would have a large operating safety factor. Analysis of this beam therefore was performed using a beta of sapphire of 0.019 cm^{-1} (the high measured value). The thermal/structural analysis showed a safety factor of 6.9. The resulting demonstration window design is shown in Figure 3.1.

Drawings of the operational window were not generated (they will be generated at the conclusion of the test phase). The operational window will however in principle be identical to the demonstrator except in size, and coolant gap. Analyses on the operational window assumed beta of sapphire of 0.008 cm^{-1} (the low measured value) with double pass flux of 15.71 kW/cm^2 through a 12.36 x 12.36 cm footprint. A safety factor of 3.32 was determined for this case.

The computer models predict that the proposed double pane heat exchanger (HEX) window will be capable of isolating the gain region from the photodetachment region. The proposed window will be able to withstand the high pressure stresses and thermal stresses involved in the PDN application.

Figure 3-1. Demonstration Window Design

4.0 RECOMMENDATIONS FOR FUTURE WORK

It is recommended that a technology verification follow-on program be instituted to substantiate this design and theoretical analysis utilizing the existing COIL laser and associated hardware (calorimeter and cavity box). The following recommendations are suggested to be included in this follow-on program to the PDN development project.

1. Generate detailed drawings of the shutter which was laid out as part of the current contract effort.
2. Perform absorption measurements on 8-inch diameter premium grade sapphire disc to determine if 10x10 cm beam size can be used.
3. Build the demonstrator double pane window designed in this current contract.
4. Build the shutter.
5. Interface the demonstrator window and the shutter to COIL cavity box and cone calorimeter.
6. Perform technology verification tests.
7. Compare experimental results to theoretical predictions and update the theoretical model as required.
8. Design and analyze an operational double pane window for a desired specific PDN system.

5.0 REFERENCES

1. Photodetachment Neutralizer Development - Laser Resonator Study, Final Report, by V. Vanek et. al. prepared for UC LLNL by TRW Inc., September 30, 1983. Contract W-7405-ENG-48 DOE, P.O. 1340105
2. J. H. Fink, UCRL-87301, 9/28/82, LLNL
3. J. H. Fink, UCID-19788, 6/22/83, LLNL