VACUUM WINDOW DESIGN FOR HIGH-POWER LASERS

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Abstract

One of the problems in the high-power lasers design is in outcoupling of a powerful laser beam out of a vacuum volume into atmosphere. Usually the laser device is located inside a vacuum tank. The laser radiation is transported to the outside world through the transparent vacuum window. While considered transparent, some of the light passing through the glass is absorbed and converted to heat. For most applications, these properties are academic curiosities; however, in multi-kilowatt lasers, the heat becomes significant and can lead to a failure. The absorbed power can result in thermal stress, reduction of light transmission and, consequently, window damage. Modern optical technology has developed different types of glass (Silica, BK7, diamond, etc.) that have high thermal conductivity and damage threshold. However, for kilo- and megawatt lasers the issue still remains open. In this paper we present a solution that may relieve the heat load on the output window. We discuss advantages and issues of this particular window design.

INTRODUCTION

Conventional laser technology provides with a variety of optics for high-power laser applications. Modern high-power CO_2 lasers reach 50 kW level of power [1]. At this power level the laser optics must be transparent in a large range (for tuneable lasers) and have high damage threshold ([2]).

In this paper we assume (as an example) 100 kW cw IR laser beam passing through a window with 20 cm diameter. Distribution of the power per unit area is given in the next figure (Fig. 1).

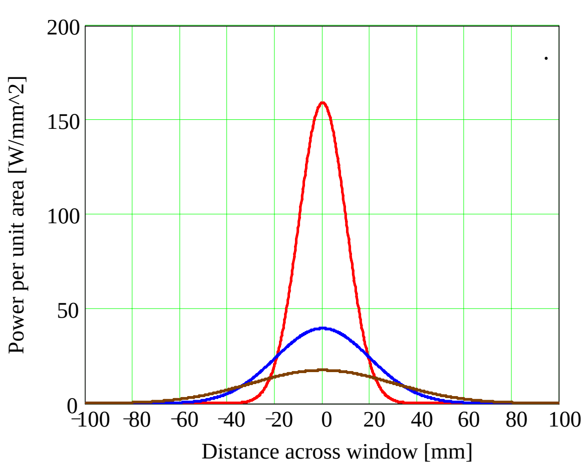

Figure 1: Power [W/mm^2] for three beam sizes of 1, 2 and 3 cm RMS.

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These power levels (~100 W/mm^2) may be dangerous for the laser optics. Vacuum window is one of the main concerns, since its damage may cause vacuum leak and, in turn, failure of a laser performance.

In this note we discuss an approach for reducing heat load on unit surface for a vacuum window of a high-power laser. First, we review a vacuum foil design in industrial accelerators. In the following we discuss similar approach in high-power laser case. Next we suggest certain design and estimate it's thermal and optical properties. In conclusion we review a future work.

A SCHEME FOR LASER VACUUM WINDOW

The problem of extraction of the powerful beams from the vacuum to the atmosphere is not new. For instance, industrial accelerators provide with a few MW power electron beams. Special extraction device (BINP, Russia) is being used in order to separate vacuum volume and atmosphere [3]. In this device a thin foil is attached to the flange of a vacuum tank. Two magnetic trims, located before the foil, scan the electron beam across it reducing the heat load per unit area.

We suggest the following laser window design that is close to the BINP design above (Fig. 2). Moving stock, driven by a motor, synchronously rotates two laser mirrors back and forth. This causes laser beam to scan across vacuum window, distributing heat load over a larger area. Vacuum window in this case should be made of rectangular shape.

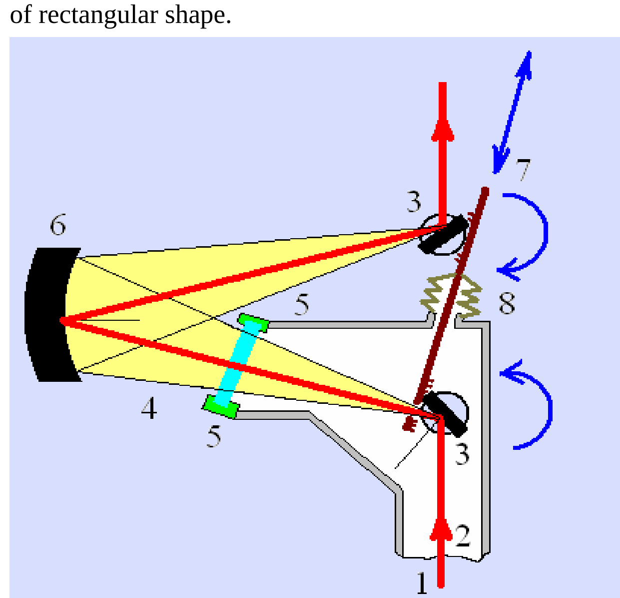

Figure 2: 1 – incoming laser beam, 2 – vacuum tank, 3 – mirrors on rotating support, 4 – vacuum window, 5 – window holder, 6 – curved mirror, 7 – moving stock, 8 – bellow.

Some advantages of this scheme are:

- Less heat per unit area on the window
- Flexibility: rotation can be switched on and off depending on the laser wavelength and power
  Main disadvantage of this scheme is:
- Moving parts in vacuum (bellow's lifetime)

Thermal properties

The benefit of the suggested scheme is in distribution of the absorbed heat over a large area. As shown in Fig. 3, the area covered by the moving spot is much larger than the beam size.

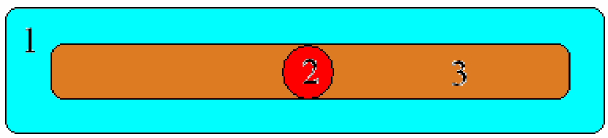

Figure 3: Front view: 1 – window, 2 – beam profile, 3 – area occupied by the laser light when mirrors are rotated.

Thus, the power load per unit area will be decreased:

$$\frac{P_3}{P_2} \approx \frac{A_2}{A_3},$$

where P stands for the power per unit area, and A is the area.

Simpler solution is in defocusing of the radiation beam to a larger size [4]. Let us compare the “swiping” scheme with the “defocusing” one. We assume normal distribution of power as shown in Fig. 1. For a “defocusing mirror” scheme the power per unit surface is:

$$P(x,y) = \frac{P_0}{2\pi\sigma_X\sigma_y}\exp\left(-\frac{x^2}{2\sigma_x^2}\right)\exp\left(-\frac{y^2}{2\sigma_y^2}\right),$$

where σ_X, σ_y are horizontal and vertical beam sizes respectively.

For the “swiping” scheme the power distribution is given by the following expression:

$$P(x,y) = \frac{P_0}{2\pi\sigma_x\sigma_y 2L}\int_{-L}^{L}\exp\left(-\frac{(x-t)^2}{2\sigma_x^2}\right)dt\cdot\exp\left(-\frac{y^2}{2\sigma_y^2}\right),$$

where $2L$ is the swiping range.

In the following we assume that 100 kW beam is defocused along horizontal dimension only (rectangular window is used). For the “defocusing” scheme we take $\sigma_X=30$ *mm*, $\sigma_Y=10$ *mm* (beam size is increased three times horizontally). For the “swiping” scheme we take a beam with $\sigma_X=\sigma_Y=10$ *mm* and swiping range $L=76$ *mm*. Figure 4 shows the power distributions (power is integrated along the vertical axis).

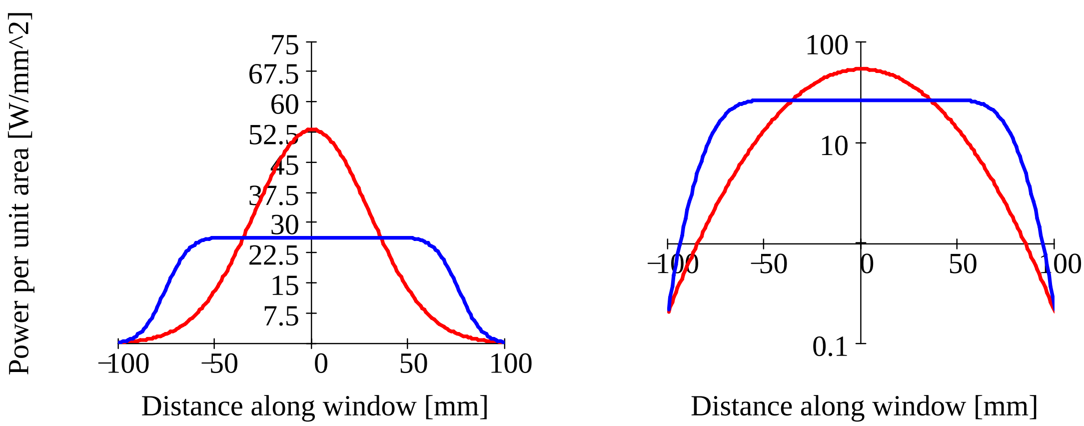

Figure 4: Power distributions for the “defocusing” (red) and “swiping” (blue) schemes. Left plot is the same as the right one but in log scale.

From the left plot we may conclude that the power per unit area is twice as smaller for the “swiping” scheme than for the “defocusing” scheme. Note that we made the amounts of power to be the same at the edges of the window for both schemes (right plot).

Next we make a coarse estimate for the swiping speed of the system. We assume that the radiation power in the spot with the radius of 1 cm is 100 kW. The radiation passes through ZnSe vacuum window (bulk material absorption is 10^{-3} at 10.6 um [5]) with the thickness of 1 cm and the horizontal dimension of 20 cm. For 1 second the temperature change of the material inside the spot is:

$$\Delta T = \frac{P\cdot A\cdot \Delta t}{\rho\cdot \pi\sigma^2\cdot h\cdot c} \approx 18K,$$

The ZnSe material properties are taken from [6]. The temperature change of 18 degrees does not seem large (however, the steady-state temperature of the window material should be estimated). For the swiping speed we assume that in one second the radiation spot travels across the window on the distance equal to one spot size. Then the radiation spot will move across the whole window (20 cm) during ~20 seconds.

We note, however, that in this “order-of-magnitude” estimate no cooling was taken into account. The realistic analysis of the temperature dependence must include cooling and heat transfer, smooth distribution of power in the radiation spot, relaxation of the temperature between cycles, start-up regime, etc.

Optical properties

Since the central mirror is convex, it provides focusing of the beam horizontally that is desirable to compensate. The straightforward way of doing it is to make the other two mirrors defocusing. We write the horizontal transport matrix for the system as:

$$M_S = \begin{vmatrix} 1 & 0 \\ 2/R_1 & 1 \end{vmatrix} \cdot \begin{vmatrix} 1 & S \\ 0 & 1 \end{vmatrix} \cdot \begin{vmatrix} 1 & 0 \\ -2/R_0 & 1 \end{vmatrix} \cdot \begin{vmatrix} 1 & S \\ 0 & 1 \end{vmatrix} \cdot \begin{vmatrix} 1 & 0 \\ 2/R_1 & 1 \end{vmatrix},$$

where R is the radius of curvature and S is the distance between the mirrors.

Choosing $R_1=2R_0=2S$, we obtain a focusing-free optical system. Thus the 1st and the 3nd mirrors have to be made concaved. The vertical transport matrix (drift of the length 2S) differs from the horizontal one, which induces some ellipticity into transverse radiation profile. This can be corrected by making the mirrors equally concaved vertically.

However, for some of the high-power lasers the output radiation Raleigh range may be significantly larger than the optical path length along the swiping system. In this case the ellipticity of the output radiation transverse profile is a minor effect.

FUTURE WORK AND CONCLUSION

In the following we discuss some comments and directions of future work on this scheme.

1. The scheme includes three mirrors. Reflection losses on the mirrors must be analysed. We note, however, that in any case laser system may require several mirrors for the output beam alignment.
2. The incidence angle and effective glass thickness are changing while beam is being swiped across the window. This may cause heat load to be greater to the edges of the window. It may not be a serious problem; in general, the change of angle should be small.
3. Speed of rotation should be estimated. The speed is determined by thermal conductivity of the window material, cooling and heat transfer.
4. Long mirror deformation under the heat should be calculated and corrected. It can be corrected with a temperature stabilization circuit.
5. Rectangular window might be preferable as compared with a large round window. In the first case thickness of the window can be chosen to be less, having the same mechanical rigidity against atmospheric pressure. In turn, this will cause smaller absorption losses in the window material.

There is a number of FEL projects and proposals, which consider the output laser power in a sub-MW to MW range [7-10]. The problem of radiation transport through the vacuum window may become a serious issue at this level of power. The scheme, discussed in this note, can provide with an effective solution of this problem.

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