Laser beam used to measure and highlight the transparency changes in gamma irradiated borosilicate glass

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The optical windows are the bridges of connection between the laser systems and the real environment and therefore are often subjected to hostile conditions which they can affect the optical and mechanical performances. The purpose of this paper is that by applying special diagnostic techniques through a low laser power to be able to investigate the transparency changes of the glass made optical windows, caused by exposure to indirectly ionizing radiation (e.g. X, gamma radiation). Basically, we investigated the changes due to the colour centres or other defects produced by irradiating borosilicate glass with ^{60}Co, as a source of gamma radiation. In principle, we can expect to changes in the transmittance properties of these glasses and for larger-size induced defects even to an increase in their scattering properties, or a change in the spatial profile of the laser beam used as a test beam. In addition, we used optical anisotropy (linear dichroism) as a technique for highlighting the changes in the structure or in the interactions between the constituent components of the samples. Several Schott BK-7 glass samples were irradiated using the IFIN-HH - gamma irradiation facility, at a dose rate of about 0.163KGy/h ±7% produced by gamma energies of 1.332MeV and 1.173MeV. Energetic and spatial beam characterizations (according to ISO 11554 and ISO 11146-1 standards) and linear dichroism highlighting, were performed on a low power He-Ne laser beam (linearly polarized), before and after passing the beam through each irradiated glass sample. According to the changes in the glass transmittance, were evaluated: dichroism induced by gamma radiation (the magnitude of linear dichroism and the mean factor of the sample transmission), the evolution of power energy and the laser beam propagation test. Spatial beam characterization was performed to see whether or not there are changes in the internal structure of glass samples, shown by the varied values of the beam propagation factor M^2. In our case, the experimental set-up has highlighted a relative decrease of the initial laser beam power of 53% on the entire range of absorbed doses (0÷27KGy). At the same time we showed a relative increase in the coefficient of propagation (M^2) of 7.76% and 8.1% (two fitting methods). The measurements were made with different experimental set-ups containing the following elements: He-Ne laser type 25-LHP-151-230 (Melles Griot, USA), power-meter type PowerMax-USB UV-VIS (Coherent, USA) and a beam profiler type GRAS20 with dedicated software BeamGage (Ophir Optronics, USA) [13, 14. 15].

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1. Introduction. Experimental procedure

In general, glass is a material with specific optical and mechanical properties and it is almost optical homogeneous (refractive index, absorption or transmission, dispersion). However, the optical and (or) mechanical proprieties can be changed by varying the glass composition. There are also external factors, such as nuclear radiation, which may change, increase or decrease optical properties [1, 2]. It is therefore important to know how the degree of impairment of optical glasses set their usability when they serve as protection between the laser beam and such a hostile environment. Optical BK-7 glass is a transparent material in the range of visible because the band gap of BK-7 glass is greater than 4.4eV [3]. He-Ne laser photons energy (1.96eV) is less than 4.4eV and cannot excite carriers. Therefore the optical glass does not absorb the corresponding light wavelengths (633nm) and it not affects our investigations. On the other hand, gamma radiation creates defects (colour centres) that impose new energy levels in the band gap, allowing greater carrier excitation and light absorption. This phenomenon is called darkening of the transparent glasses under gamma radiations. An irradiated glass window attenuates visible light as it passes through it, requiring a more powerful lighting source and therefore, requiring the knowledge of all the parameters of a laser beam. Any sample that will be gamma-irradiated is initially isotropic, as all glasses are. Gamma irradiation causes induced anisotropy in the sample as a function of absorbed doses. Measurement of the gamma-induced anisotropy involves observing the absorption of two orthogonal polarization directions as a function of absorbed doses. However, the experiment involves measuring the amount of light that has passed through the sample. We measure the power of the transmitted beam at each total accumulated dose. Therefore, we have a parallel component and a perpendicular one (versus polarization plan) to the transmitted power after the laser beam traverses different irradiated glass samples. Linear anisotropy and linear dichroism are essentially two metrics of same quantity. Anisotropy is usually defined by the ratio: $r = (\tau_0-\tau_{90})/(\tau_0+\tau_{90})*0.5$. (Eq.1) [4] and linear dichroism (in terms of transmission) is defined as: $\Delta\tau=\tau_0-\tau_{90}$ (Eq.2) [5], where, $\tau_0=P_0/P_i$, $\tau_{90}=P_{90}/P_i$. P_0, P_{90} is the power measured when the analyzer is parallel to the direction of polarization, and respectively perpendicular to it, and P_i is the initial power of the laser. A laser beam can be characterized by measuring its spatial intensity profile at perpendicular points to its propagation direction. (Fig. 1)- Spatial beam intensity distribution at waist location $z=Z_0$).

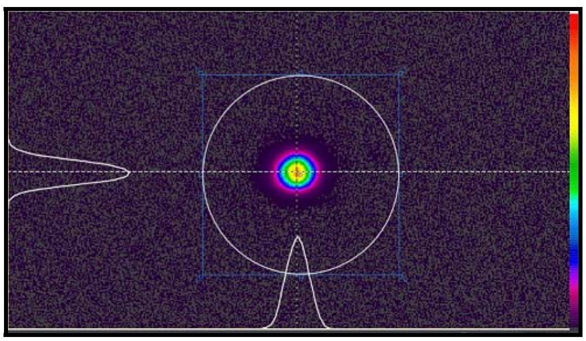

Fig. 1.a. Shows the spatial profile at z_0=326mm (in free space).

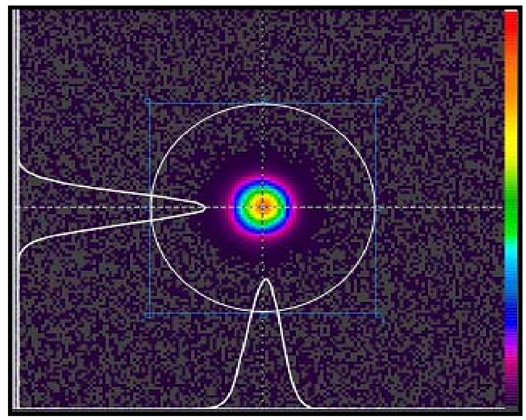

Fig. 1.b. Shows the spatial profile at z_0=326.8mm (0KGy).

The spatial intensity profile is the variation of intensity as a function of distance from the center of the beam, in a plane perpendicular to its propagation direction. Such a wave propagating along the z-axis will have its electric field uniformly distributed in the x-y plane. This implies that the spatial intensity profile of such a light source will be uniform as well. However, a light beam does not extend to infinity. In this experiment, we investigated the spatial profile of a Gaussian laser beam.

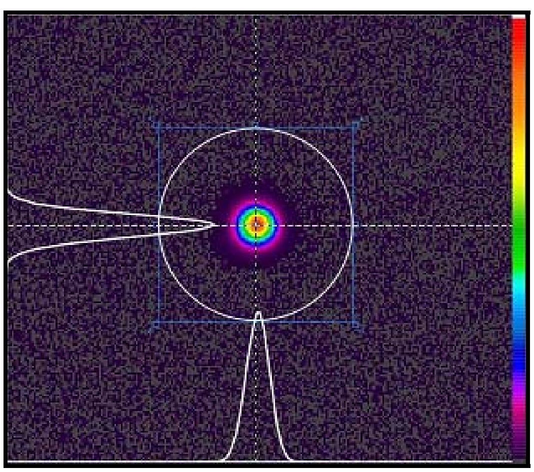

Fig. 1.c. Shows the spatial profile at z_0=326.6mm (5.6KGy).

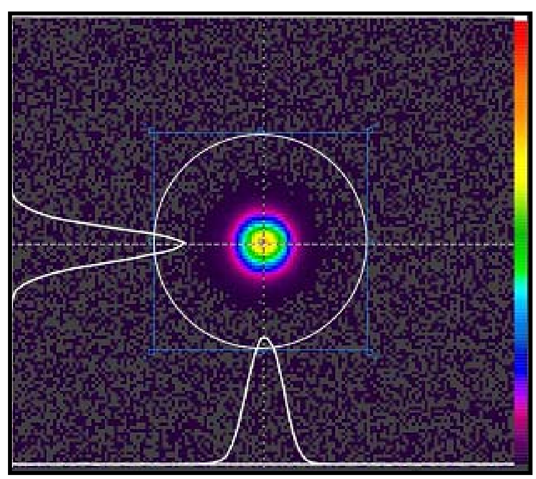

Fig. 1.d Shows the spatial profile at z_0=325.8mm (27.1KGy).

A Gaussian profile is characteristic of most lasers. We will discuss some properties of such Gaussian beams. In particular, we will concentrate on the fact that a Gaussian beam has a non-uniform intensity profile. Furthermore, by studying the profile of a laser beam, we are able to extract a characteristic radius of the Gaussian beam, known as the spot size, at a particular location along the direction of propagation of the beam. Our experiment consists of two parts. In the first part, we will verify optical anisotropy (linear dichroism) as techniques for studying the changes induced by the formed colour centres in irradiated optical glasses. In the second part of the experiment, we will verify that the laser beam maintaining its Gaussian intensity profile. We will use this profile to extract a value for the spot size, divergence angle, propagation factor (M^2), etc. A property of Gaussian beams is that they remain Gaussian as they propagate through any combination of optical elements such as lenses and mirrors. Therefore, we wanted to test whether the degree of change in the parameters of a laser beam after its passage through our gamma ray irradiated optical glass samples which are designed optical transmission windows affect or not their usability. In generally, the damage in transparent optical windows does not exhibit a sudden threshold, but rather the sensitivity to gamma irradiation and laser damage is characterized by curves representing the damage as a function of gamma doses and laser beam intensity. Although data on the sensitivity of different materials to gamma and laser exist separately, the effect of both cumulated is almost unknown.

As we known, the beam is diverging, as if is diffracting from the minimum spot size d_0. This imposes a limitation on our ability to focus a laser beam. It is not possible to focus laser light to a single point because its diffraction is limited by very fact that an ideal Gaussian does not exist in reality. In practice, the quality factor M^2 has been defined to describe the deviation of the laser beam from a theoretical Gaussian. For a theoretical Gaussian beam $M^2=1$, but for a real laser beam $M^2>1$. In all cases, the M^2 factor, which varies significantly, affects the characteristics of a laser beam and cannot be neglected in optical studies. Based on the theory of second order intensity moment, some laser parameters for He-Ne Gaussian laser beam passing through BK-7 gamma irradiated glass are studied numerically. The basic techniques for these laser measurements are documented in ISO 11146 and 11554 standards (Fig.2).

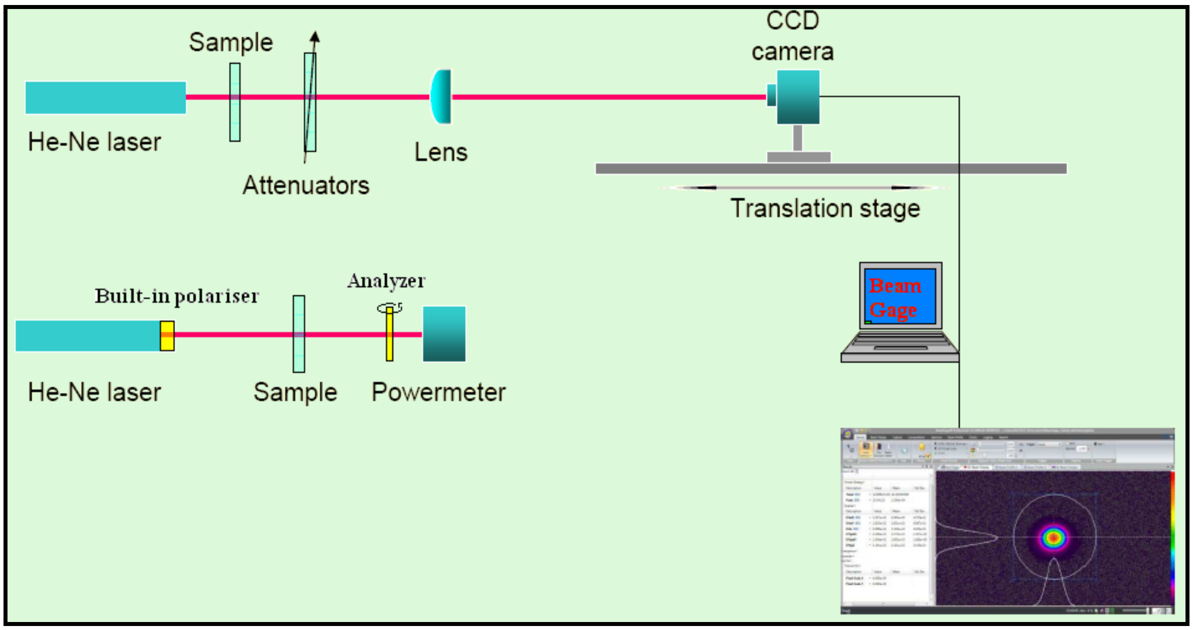

Fig. 2. Shows the schematic experimental set-up.

2. Gamma irradiation process and test samples

To simulate the operating conditions in the field of gamma rays, a $^{60}Co_{27}$ source was used to produce an absorbed dose rate of 0.163KGy/h/25cm in sample. Irradiation was performed at room temperature, using a gamma irradiation chamber and a source of $^{60}Co_{27}$ located in the DRMR-IFIN-HH, Bucharest. A $^{60}Co_{27}$ source emits two gamma quanta with energy 1.173MeV (99.85%) or 1.332MeV (99.98%) and an energy beta radiation of 0.31MeV (99.88%) and of 1.49MeV (0.12%) [ANNEX][12]. The effects of beta radiations are completely eliminated due to their strong attenuation in air (25 cm) and 0.5 mm thick polyethylene that coated our samples. Total absorbed doses (Gy) of gamma radiation accumulated in our samples were estimated by calculation, keeping in mind: the activity of the source (Bq), Co^{60} decay scheme, radiation energy (MeV), their relative abundance (%), attenuation mass in the sample (cm^2/g), the square of the distance between the sample and the source (cm^2) and the irradiation time (s).

Absorbed dose values that were achieved for BK-7 glass cylinders are: 0.095; 0.179; 1.5; 2.8; 5.6 and 27KGy. The dimensions of our Schott BK-7 glass cylinders were 25mm diameter and 10mm thickness. In Table.1 are the real values of the seven samples used in the experiment. The average thickness for our samples is 9.9mm±2.3%, value that had been used in calculations. The dispersion of these thickness values will be found in the final results. Samples have relatively large thickness because of the low absorption, in the visible region of the spectrum, for doses below 10KGy. At the average energy of 1.25MeV of a gamma radiation ^{60}Co source, there is no danger of radioactive activation of any chemical elements contain by our glass samples. In terms of radioactive contamination the glass samples were coated in protective film with the purpose that the measurements can be performed shortly after the end of irradiation.

Table 1. Real thickness distribution of our samples.

Sample, BK-7 Φ=25mm	Standard thickness [mm]	10						
Mean thickness 9.91mm±2.3%	Real thickness [mm]	9.82±1.8%	9.74±2.1%	9.83±1.8%	10.37±3.5%	9.87±1.4%	9.86±1.4%	9.89±1.2%

3. Measuring the power of the laser beam after passing through the sample.

The most important method of testing the performance of a laser system is to measure its power output [6, 7]. Output power directly affects laser's ability to perform a certain process after passing through an irradiated glass. Results were obtained with a powermeter type PowerMax-USB UV-VIS. Measuring this parameter is very important from the time a laser is manufactured and to the final end customer who will be using the laser system in nuclear applications. Figure 3 shows the measurement of laser's power after passing through irradiated glasses.

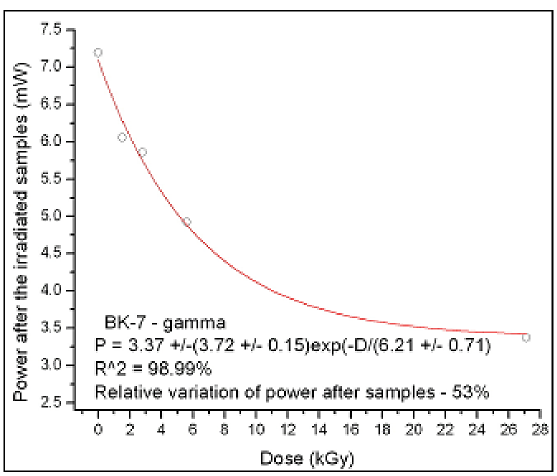

Fig. 3. Shows the variation of laser power after passing through irradiated glasses.

These types of measurement systems are composed by a sensor that is placed into the laser beam after passing through samples and provides a signal proportional to the initial laser output and a meter attached to it, which is an analyzer that will display and interpret the signal from the sensor. The power of a laser is measured in Watts and often reported in terms of mW. This is referring to the optical power output of continuous wave (CW) lasers. From the data obtained, we determined the variation of the absorption coefficient in measured samples as we can see in Fig.4.

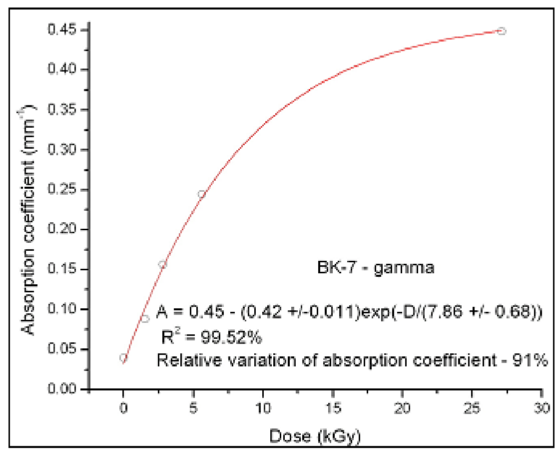

Fig. 4. Shows the absorption coefficient after passing through irradiated glasses.

These data indicate an increase in the absorption coefficient of about 91% compared to non-irradiated sample. Moreover, the relation (1) and (2), anisotropy and dichroism induced by gamma radiation was evaluated by the parameter $\Delta\tau$, like the difference between the transmission coefficients of the probing radiation for perpendicular and parallel orientations of the polarization plane (relative to the direction of the gamma rays at irradiation) as well as by the parameter r, representing induced anisotropy. Measurements were made using one type of laser He-Ne - 633nm - red - type 25-LHP-151-230 (Melles Griot, USA). The variation of these two parameters representative for highlighting the degree of degradation of samples during irradiation is presented according to the dose range considered in the experiment (0÷27KGy) and it is represented in Fig. 5 and Fig. 6.

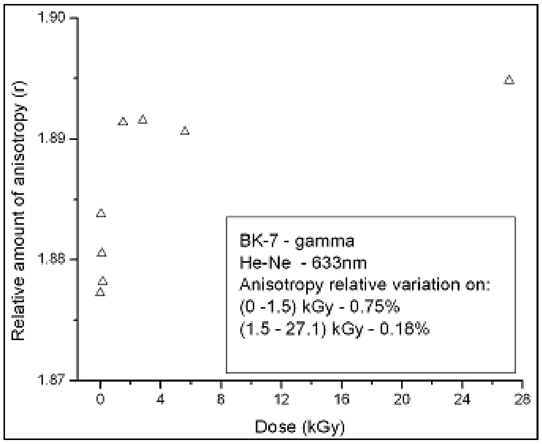

Fig. 5. Shows the dichroism induced by gamma radiation.

It shows a relative variation induced dichroism, the whole dose range, approximately 54.35%. The relative amount of anisotropy versus absorbed dose it is shows in Fig. 6.

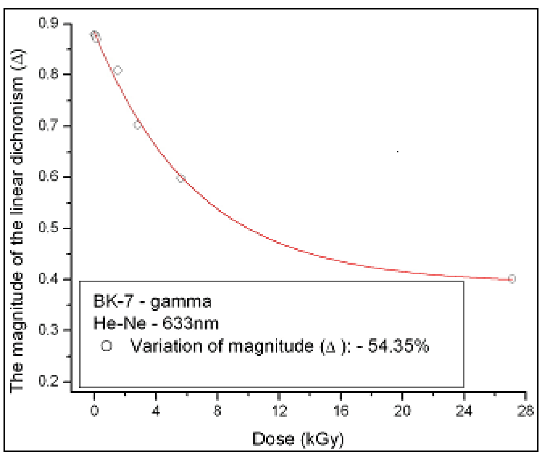

Fig. 6. Shows the induced anisotropy (in terms of transmission) by gamma radiation variation.

It shows a relative variation induced anisotropy, the whole dose range, approximately 0.93%**.** Fig.6 shows the amount of gamma radiation-induced anisotropy versus absorbed dose for the laser wavelengths 633 nm. The graphic representations highlight the relative variation of the parameter (0.75%), depending on the dose (0÷1.5KGy), and a smaller decrease (0.18%) for dose range (1.5÷27.1KGy).

4. Measuring the propagation parameters of the laser beam after passing through the samples

From laser beam propagation theory, the second moment or 4σ width definition is found to be of fundamental significance [8, 9, 10]. It is defined as 4 times the standard deviation of the energy distribution evaluated separately in the x and y transverse directions over the beam intensity profile. According to ISO 11146 standard, the propagation factor (M^2) measurement of beam quality works as well for He-Ne laser as it does for well collimated lasers. ISO 11146 provides the measurement procedures to characterize the propagation properties of laser beams. In this standard, the beam diameters are defined by second order moments of the power density distribution, which can be measured with a CCD camera. However, the measurement of the energy density distribution of a Ne-Ne laser is critical because of the high value of the beam propagation factor that results in a high divergence angle compared with a nearly diffraction limited beam. The 4σ method is most sensitive to noise, and if your camera or beam noise content is high, you might want to use a better averaging or statistical analysis to obtain accurate results. A big advantage of this method is that it is not influenced by multi mode content. The propagation properties of any stigmatic beam are fully described by the beam waist d_0, the distance from the waist z_R and the divergence angle θ. The product of divergence angle θ_0 and the beam waist d_0 of a fundamental laser beam (TEM_{00}) it is constant and depends only on the wavelength (λ): $\theta_0 d_0=1.27\lambda$. The phenomenon of optical diffraction dictates that this constant is the smallest product of divergence and beam waist. A fundamental laser beam also is called diffraction limited. The laser beam propagation factor M^2 is defined as the ratio of the products of divergence angle and beam waist of the measured beam to the product of the fundamental beam: $M^2=(0.785/\lambda)d_0\theta_0$. The propagation of a simple astigmatic beam can be expressed by two analogous expressions to equation (4), which describe the propagation along the two principal axes of the beam Fig. 7-b, Fig. 7-c. Therefore, six parameters are needed to characterize a simple astigmatic beam (d_{0x}, d_{0y}, θ_x, θ_y, $z_{0,x}$, $z_{0,y}$). The combined determination of all beam propagation parameters according to ISO 11146 has to be performed by recording the spatial propagation of the beam diameters after passing through the irradiated samples. The beam parameters are then obtained from a hyperbolic fit to the measured data. Because the accuracy of the beam parameters strongly depends on the number and positions of the measurement planes with respect to the beam waist, ISO 11146 gives detailed provisions. Figure7 to show the power density distributions of the He-Ne laser after passing through irradiated glass, these beam profiles were captured, at one Rayleigh length before and after the waist. (Fig. 1). At least six measurement planes should be near the beam waist (within one Rayleigh range) for accurately determining the waist diameter. At least six additional measurement planes in a distance more than two Rayleigh lengths away from the beam waist are necessary for accurate determination of divergence angle and waist position. If the measurement planes are arranged nearly symmetrically around the beam waist, the accuracies can be further increased. The laser beam passing through the irradiated sample was attenuated to levels below the saturation power of the CCD camera by placing of neutral or color filters (gray, red) associated with CCD camera. Because the fact that He-Ne laser light used has a linear polarized, the laser beam power is virtually halved. This leads to the use of a smaller number of intermediate filters and hence a reduction in errors introduced to the laser beam passing through.

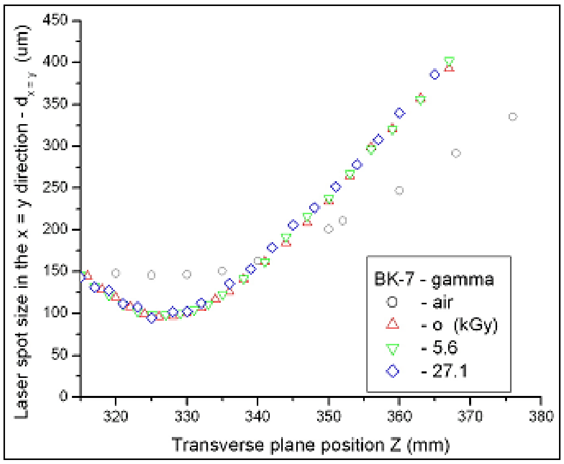

Fig. 7.a. Shows illustration of the measured beam diameters of the laser beam (stigmatic) on the dose range (0÷27.1KGy) as a function of propagation distance Z.

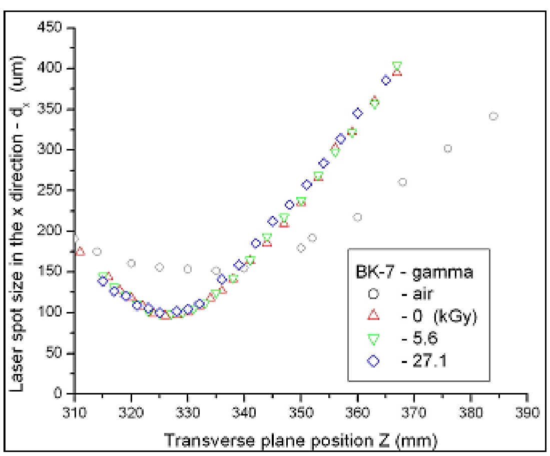

Fig. 7.b. Shows *illustration of the measured beam diameters of the laser beam (simple astigmatic) on the dose range (0÷27.1KGy) as a function of propagation distance Z (x direction).*

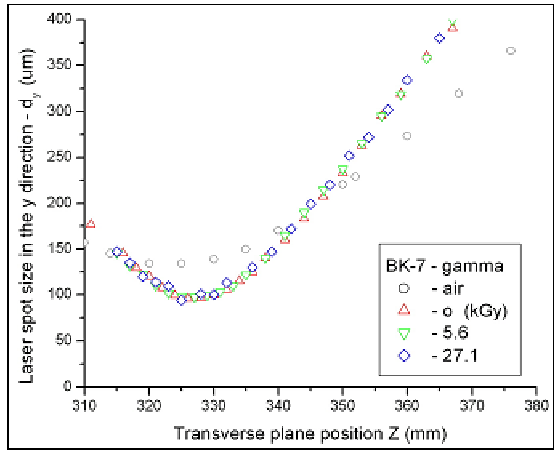

Fig. 7.c. Shows illustration of the measured beam diameters of the laser beam (simple astigmatic) on the dose range (0÷27.1KGy) as a function of propagation distance Z (x direction).

In this illustration of the measured beam diameters of the He-Ne laser, the Fig.7-b shows the X axis of the beam and the Fig.7-c, the Y axis. A 14-bit CCD camera was used to capture the power-density distributions of a simple astigmatic beam (Figure 7-b, c). An almost circular and smooth power-density distribution was measured at the beam waist. At distances of about one Rayleigh length away from the waist, the beam profile is almost rectangular. The relative deviation of the measured beam diameters to the fitted parabola is less than 5% (Table 2).

The M^2 beam-propagation factors of the two principal axes, calculated directly from these data, are xx and yy. It has been clearly demonstrated that ISO 11146 can be applied not only to “simple” laser beams. Using this characterization technique, it is therefore possible to describe the complete beam propagation behavior and the focusing of such beams in an elegant and unambiguous way. This has been demonstrated in this experiment, and this He-Ne laser is a good example of the standard’s application. The M^2 factor and divergence angle could be easily obtained from performing a hyperbolic fit to the measure beam diameters along the beam propagation axis: $d_i^2=a+bz_i+cz_i^2$, (3), where d_i is the beam diameter at the location z_i, a, b, c are the hyperbola parameters (Tab.3). This relationship is equivalent to the equation: $d_i^2=d_{0i}^2+[d_{0i}^2\,(z_i-z_0)/Z_R]^2$, (4), which is true relative to the laser beam propagation. Then the beam propagation factor can be calculated using simple equations: $Z_{0,2}=-b/2c$, $d_{0,2}=[(4ac-b^2)/4c]^{0.5}$, $\theta_2=c^{0.5}$, $Z_{R2}=[(4ac-b^2)/4c^2]^{0.5}$, $M^2=\pi[(4ac-b^2)]^{0.5}/8\lambda$, f=281.81mm (Eq.5). The disadvantage of this method is that we have to do lots of measurements and some adjustment is needed every time we move CCD. This procedure might take a long time. Moreover sometimes it is not necessary to know the exact value of M^2, only estimation of M^2 is just needed.

Table 2. Shows the propagation coefficients obtained by two fitting methods (eq.4, 5).

Dose (KGy)	Z_{01}	Z_{02}	d_{01}	d_{02}	θ_1	θ_2	Z_{R1}	Z_{R2}	M^2_1	M^2_2
Air	326.16 ±0.38%	326.2 ±0.5%	142.8 ±0.5%	143.06 ±0.5%	6.07 ±0.6%	6.06 ±1%	23.4 ±0.66%	23.62 ±0.5%	1.069 ±0.7%	1.07 ±1%
0	326.87 ±1.27%	326.9 ±1.3%	92.29 ±1.8%	94.88 ±1.5%	9.53 ±1.5%	9.55 ±2%	9.92 ±1.9%	9.96 ±1.5%	1.09 ±1.8%	1.12 ±2%
5.6	326.66 ±1.07%	326.6 ±0.2%	93.69 ±0.99%	95.49 ±1%	9.52 ±0.25%	9.5 ±1.5%	9.84 ±3.01%	10.06 ±1%	1.11 ±1.98%	1.13 ±2%
27.1	325.81 ±1.27%	326.0 ±1.1%	99.24 ±1.7%	99.22 ±1.5%	9.38 ±0.45%	9.39 ±2.5%	10.58 ±1.7%	10.56 ±2%	1.155 ±2.7%	1.16 ±3.5%
Relative variation (%)	0.32 ±2.2%	0.18 ±2.14%	35.37 ±1.93%	33.68 ±1.66%	36.31 ±2.38%	36.5 ±2.2%	58.03 ±3.14%	57.83 ±2.96%	8.04 ±5.45%	7.76 ±5.15%

Table 3. Shows the hyperbolic fitting equation parameters from eq.3.

Dose (KGy)	Air	0	5.6	27.1
a ($\times 10^6$)	3.94 ±0.32%	9.7 ±0.21%	9.67 ±0.58%	9.35 ±0.89%
b ($\times 10^3$)	24.03 ±0.31%	59.39 ±1.32%	59.2 ±0.59%	57.36 ±0.9%
c	36.83 ±0.35%	90.85 ±1.1%	90.64 ±0.58%	88.02 ±0.89%

5. Results and discussion

The measured diameters data at various positions along the lens created waist for irradiated glass are given in Table 2. These data were taken directly from the BeamGage display for the beam after each measurement. The diameter measurements and their relative positions with respect to the waist creating lens were then used in predicting the laser beam characteristics. Numerical values for the beam quality factor M^2 were obtained by fitting method as defined in the proposed ISO standard and also fitting the entire data set to the theoretical relation given in Eq.5. The results of these calculations are given in Table2. As can be seen, the value for M^2 generally has a relative variation over the range of doses of (0÷27KGy). (The results of the fitting routine for different dose level are shown in Fig.8).

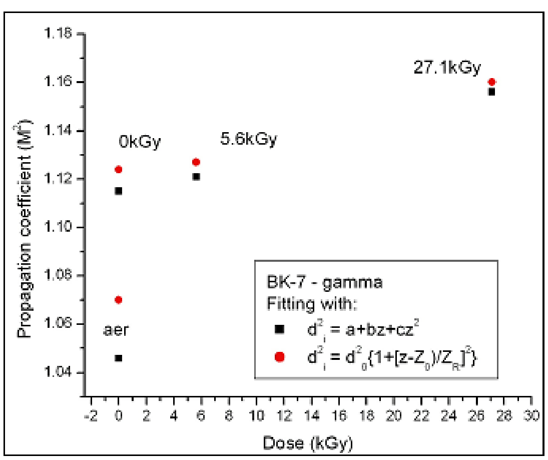

Fig. 8. Shows the beam quality factor M^2 were obtained by fitting method.

The numerical values for the beam parameters obtained from the curve fit routine are shown in the Table 2. Introducing the parameters obtained by fitting routine (a, b, c) in relations (5), we obtain the propagation parameters of the laser beam (after focusing). These are presented in Table 2. As illustrated, the data set for the beam diameter measurement, at the conditions of the absorbed dose, fits well to the real beam propagation model. In fact, this difference in fit goodness between the curves fit with equation (3) versus the equation (4) is shown by the difference in M^2 values, as it is indicated by the little difference in M^2 values at the all dose levels. The data sets fit the theoretical model as well for all dose levels. Sets of data, characterizing the propagation of a laser beam, were taken at all the dose levels where the fit match to the theory, with consistent results obtained each time. In addition to the results for the M^2 values, the results for others beam parameters calculations are also given in Table.2. There is no obvious difference between the two analysis techniques between the calculated values for the beam Rayleigh range, for minimum waist diameter or for the beam divergence angle. The values obtained for the beam waist diameter at the exit lens of focusing are consistent with expected values. However, by both fitting methods, there is a variation of the propagation parameters. The beam waist is reduced by 34.53%, the beam divergence angles increase by 36.41% and the Reyleigh decreases by 57.93%. The beam waist locations have a very small variation of 0.5%.

6. Conclusions

We conducted a series of tests measuring the spatial propagation parameters on a continuous wave laser beam. Tests were performed on a He-Ne laser type in accordance with ISO 11146-1-2005. Beam propagation parameters investigated after passing the irradiated samples range were obtained by fitting hyperbolic (two types of curves) of the experimental data. The analysis of the experimental data provided by these tests showed relative error variation below 5% for both fitting procedures. The propagation factor M^2 (quality) has reported variation of the beam propagation for absorbed dose (glass samples) in each case of about 8%, related to free space. Reduction by about 35% of the waist is a possible auto-focus phenomenon in the sample thickness (10mm). A reduction is observed also at the focus distance (Reyleigh) by about 58%, and an increase of about 36% of the divergence angle. An insignificant variation it is observed at the beam waist locating distance. A more significant variation (decrease) is in the power of the laser beam after crossing the irradiated sample thickness. Our tests showed that ISO procedures in effect have relevance in the analysis of laser beam propagation through optical hostile environments, which may affect their optical and mechanical properties during operation. We will extend the analysis procedures in the case of a powerfully laser pulse and its decrease after passing thru different types of samples exposed at different strengths nuclear radiations. This way we will take into account both the radiation environmental and the laser effects to some samples placed in the focal area of the laser beam [11].

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APENDIX

(^{60}Co decay scheme)[12]: