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Stray light simulation in device for gas pressure/density measurement through Rayleigh scattering

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I.N.RI.M. TECHNICAL REPORT

Summary

Abstract

This technical report is aimed to give some insights on the estimation of stray light impact occurring in the realisation of a compact device for gas density/pressure measurements based on Rayleigh scattering. The performed optical simulations fit into the context of the framework of WP2 of JRP "18SIB04 QuantumPascal": the purpose of this work package ('*Alternative non Fabry Pérot based approaches for the realisation of absolute and partial pressure standards*') is to evaluate the metrological performance of several innovative non-FP based methods and techniques for the realisation of absolute and partial pressure standards; in particular, in coherence with Task 2.1 of this WP a novel system for gas/density pressure measurements (in the range 10 ÷ 1 MPa) was developed. Stray light phenomenon is one of the main factors affecting the performance and limiting the resolution of any device based on Rayleigh scattering, because of the spurious light scattered by particles which are different by the working gas; this results in an unwanted contribution in the intensity collected by the detector, so, identifying the stray light sources, properly designing the geometry of the device and taking care of the arrangement of mechanical countermeasures for breaking down its influence is key to improve the overall accuracy and sensitivity of the system: the density and the pressure of the gas species are the quantities to be inferred from the direct measurement of the light scattering.

To fulfill such objectives, the monolithic chamber with the features shown in FiguresFigure 1 andFigure 2 was designed and realised.

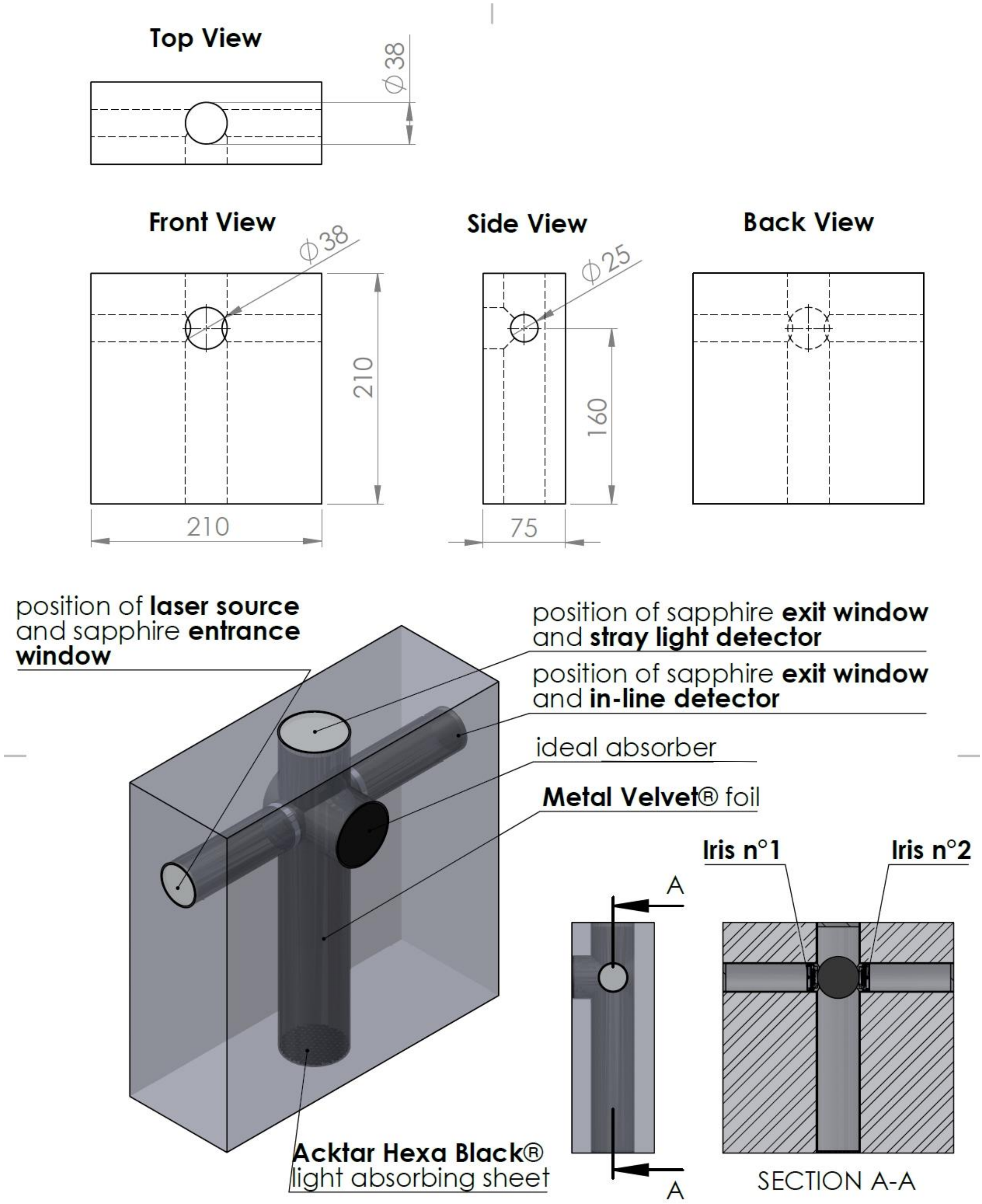

Figure 1: schematic mechanical scheme of the chamber, with main dimensions and positions of principal opto-mechanical components, as conceptually implemented in the simulations

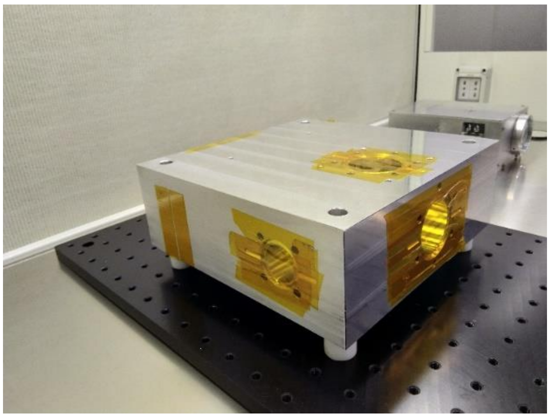

Figure 2: real picture of machined aluminum chamber

Optical set up in Zemax software

The aim of this technical report is to present some results of optical simulations performed through Zemax Optic Studio software in order to estimate the amount of stray light generated by a monochromatic and nearly collimated gaussian laser source (λ = 445 nm, r_{1/e^2} = 2 mm, beam divergence = 2.5 mrad[1], initially fixed output power = 600 mW); the same beam propagates inside the channels of a machined monolithic aluminum chamber, undergoing scattering phenomena after the interaction with the mounted sapphire viewports and the internal walls of the chamber itself.

Simulation results in non-sequential mode

The physical dimension under investigation is the **total power**[2] of the optical signal collected by the lateral stray light (service) detector; in particular, the power ratios with respect to the input light were calculated in two different situations:

1. **two iris diaphragms installed inside the chamber, but no coatings applied**;
2. **coated channels and iris diaphragms inside the chamber**

compared to the **reference condition** of **no coating and no baffles/iris diaphragms** inside the chamber. In this specific situation, some physical parameters of the optical elements were tuned in order to fix some constraints that remained unchanged during the simulations; empirically, it was observed that the power of stray light -as measured by its detector- is in the ratio of about 1:1000 with respect to the input power (corresponding to a ~ 30 dB power reduction): starting from this assumption, the -originally unknown-scattering properties of the sapphire windows were arbitrarily selected in the relative fields, in the program layout.

[1] Position of a gaussian source and divergence angle θ, in Zemax, are linked by this formula: $Position = beam\ size/tan\left(\frac{\theta}{2}\right)$

[2] The most coherent choice to qualitatively investigate the behaviour of the signal subject of investigation when some physical parameters are changed is to estimate, by simulation, the *integral of the irradiance over the entire beam*, in the absence of any suitable physical model.

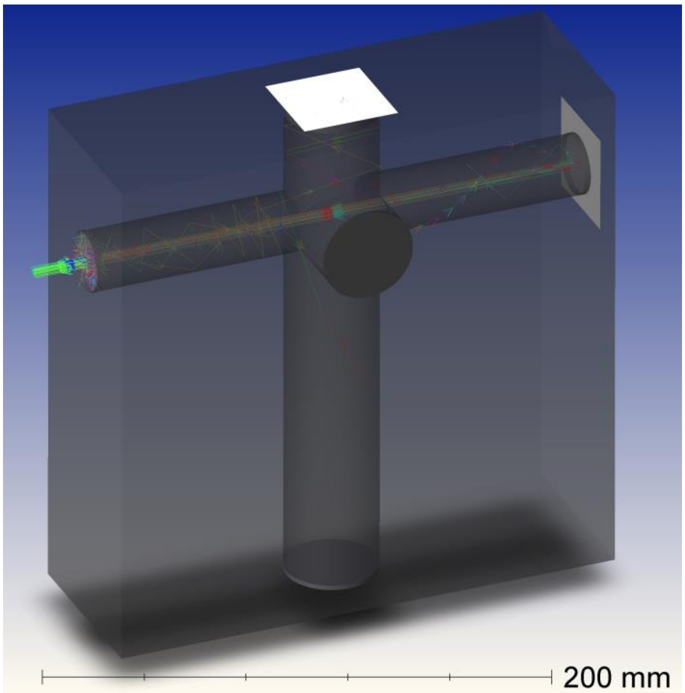

Figure 3: Zemax shaded model of rays propagating inside the chamber and finally hitting the two detectors

More specifically, the scattering properties of the three sapphire windows (modelled in Zemax as simple "Cylinder Volume" objects, made of sapphire -SF9- glass) were set according to the following prescriptions:

- **Bulk** (volume) **scattering**: volume physics model = "*Rayleigh.dll*";
- **Surface scattering** from front and back AR coated plane faces: "*K-correlation.DLL*" [1].

No other scatterers were considered in the simulations, apart from the coating contribution (lambertian) when needed.

For what concerns the coatings applied to the internal channels and the absorbers, the specifications of the materials chosen for the purpose are listed below:

- Sheet of **Hexa-Black Light Trap Material**;

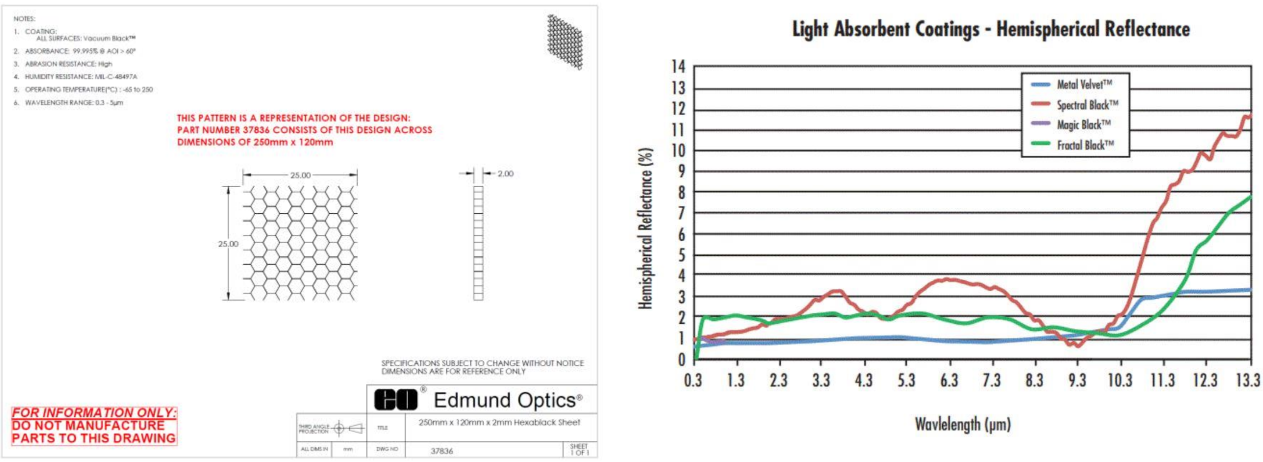

Figure 4: specifications of Hexa-Black Light Trap Material, from Edmund Optics e-commerce website

- Sheet of **Metal Velvet Foil**;

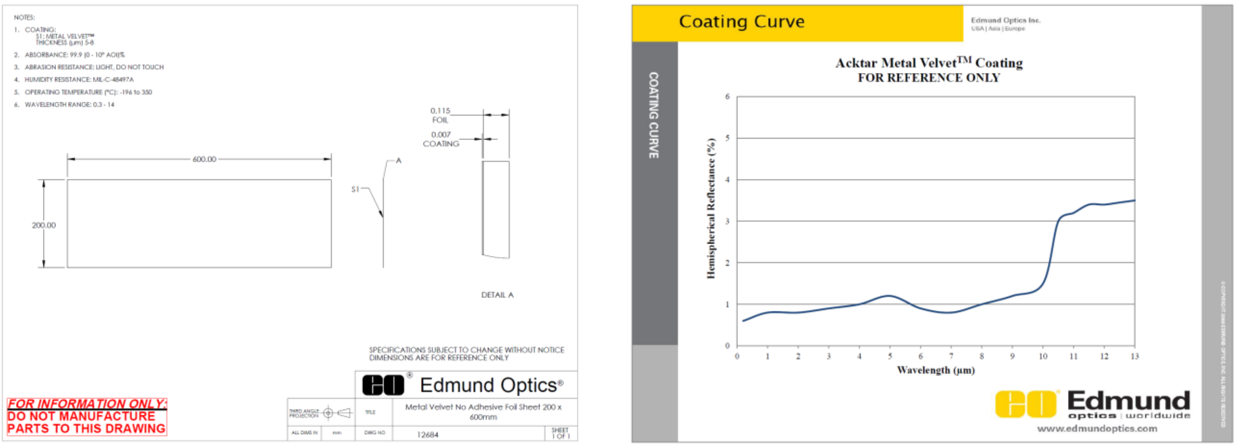

Figure 5: specifications of Metal Velvet Foil, from Edmund Optics e-commerce website

Operationally, after the choice of the materials and the scattering properties of the viewports, the first set of simulations in the "reference" condition were carried on to estimate the statistical error to be attributed to the total power collected by the two detectors, always using one million rays: the measured standard deviation of the power on the in-line detector - where the most part of the photons collide (total hits = ~ 956000) - amounts to ~ 0.02 % of the input signal, while the standard deviation relative to the variability of the power of the stray photons impinging on the lateral detector is around the 1.6 % of the average stray signal (total hits ~ 13500); this is a significant datum to be taken into consideration, since the standard deviation of the stray light signal showed a tendency to increase together with the progressive decrease in the apertures of the iris diaphragm and the application of a coating inside the chamber walls: less light travelling inside the chamber and scattering phenomena due to the nature of the surfaces, asks for more accuracy in ray tracing; that means the necessity of using more rays (more intersections and more segments per ray) in non-sequential ray tracing, significantly impacting on the elaboration time and demanding high specifications requirements of the hardware used for the simulations.

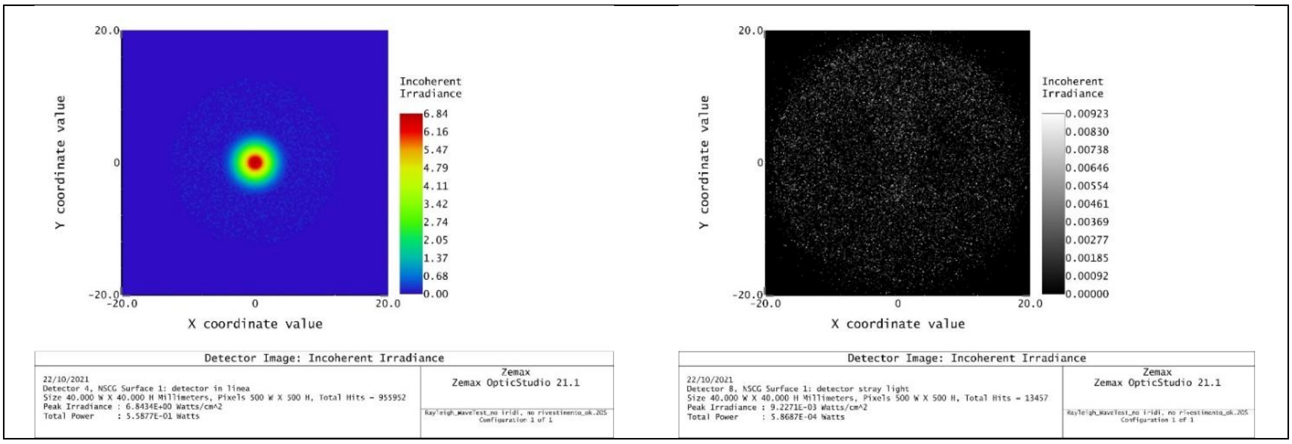

Figure 6: irradiance plot of the spot visualized on the in-line detector (on the left) and stray light signal in the "reference" condition of no iris diaphragms and no coatings and absorbers installed inside the chamber

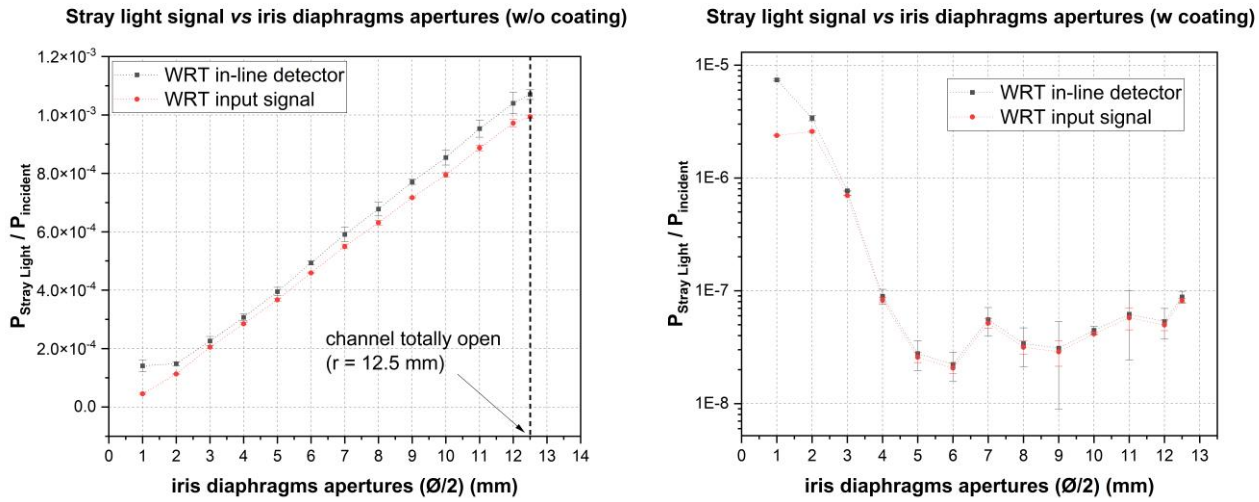

Figure 7: plots of the irradiance ratios of the signals with respect to the apertures of the iris diaphragms, without (on the left) and with 99.5 % absorbance coating applied (on the right)

The simulations performed suggest that the application of a 99.5% absorbance coating (with lambertian scattering model overimposed) seems to be capable of breaking down the disturbance of the stray light of more than 40 dB, comparing both of the plots in Figure 7 in the regions where any iris diaphragm is present in the channel. The nearly constant offset between the curves in the left plot of Figure 7 is related to the reflectance and scattering properties of the entrance window, while the progressive decrease in the *P* ratios in the right plot for both of the curves seems to suggest some diffraction phenomena (multiplying the stray photons impinging on the detector) occurring when the aperture of the iris diaphragms is kept small or comparable to the beam size (in particular where Ø/2 < 6 mm) – an effect that is masked in the previous plot, because of its small magnitude –. The reason for assigning the coating an absorption coefficient of 99.5 % originates from the necessity of having a sufficient number of photons to be traced in their path to the detector, without exaggerating the hardware requirements for an accurate ray tracing.

The variability of the power of the stray photons detected with respect to the power of the source is the last aspect investigated, and the results were inserted in the plot in Figure 8.Figure 8

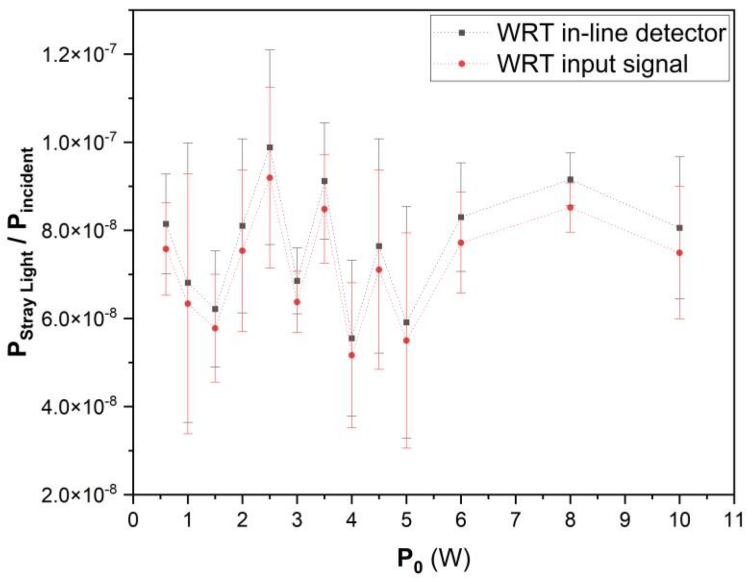

Figure 8: plot showing how the stray photons change their power as the power of the light source varies in the range (0.6 ÷ 10) W; each point averages the results of three consecutive simulations

This time, 99.5 % absorbance coating was applied to the internal channels of the chamber but no iris diaphgrams were considered in the optical set up (to allow a sufficient number of photons propagating inside the chamber, in order to keep the simulation more stable and repeatable at its best). According to the plot, no significant trend emerged from the simulations, with the considered power ratios randomly ranging from $(5.2 \pm 1.7) \times 10^{-8}$ to $(9.2 \pm 2.1) \times 10^{-8}$; this suggests that, in the considered range of power of the source (0.6 ÷ 10) W, the power ratio of stray photons impinging on the stray detector is mostly unaffected by the strength of the source, in this specific layout design.

Conclusions

From the simulations described in the previous paragraphs, the following conclusions can be drawn:

1. The use of a couple of variable-apertures iris diaphgrams inside the aluminum chamber without applying any coating to the internal walls is capable of cutting down the stray light influence of about one order of magnitude at maximum, with the power ratios changing from 10^{-3} (iris diaphgrams completely open) to 10^{-4} (with the signal passing through 2 mm aperture – same size as its input diameter); decent linearity between power ratios and iris apertures is identifiable.
2. The application of a 99.5 % (slightly smaller than its true value, as declared by the producer) absorbance coating to the channels dramatically breaks down the power ratios of several orders of magnitude (up to 10^{-9}), independently from the iris apertures (apart from an unclear behaviour occurring when $Ø/2 < 6$ mm).
3. Considering the same coating and removing the iris diaphgrams from the optical layout, the power ratios between stray light and input light source in the designed set up seem to be independent from the power of the source in the range explored (0.6 ÷ 10) W: with the increase in the power source, the stray photons impinging on the lateral detector show more power, but they don't see their number increased (the number of impacts is preserved).

References

[1] *How to model surface scattering via the K-correlation distribution*, Sanjay Gangadhara, OpticStudio Knowledge Base, March 31, 2021