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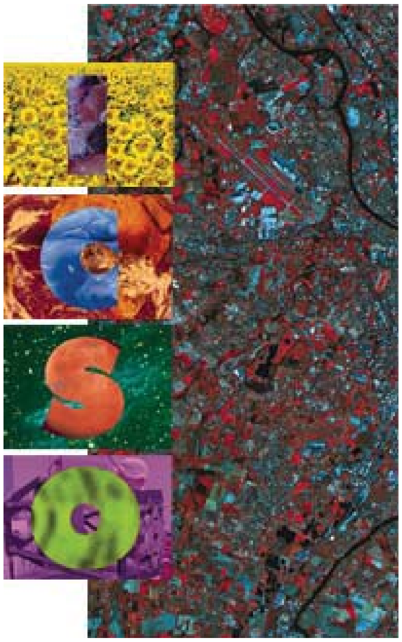

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RADIATION IMPACT ON THE CHARACTERISTICS OF OPTICAL GLASSES TEST RESULTS ON A SELECTED SET OF MATERIALS

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RÉSUMÉ - Il est bien connu dans la communauté de l'optique spatiale que les radiations peuvent significativement altérer la transmission des verres. Pour surmonter cet inconvénient, les verriers ont développés des équivalents dopés Cérium des verres classiques. La transmission de ces verres dopés est bien moins sensible aux radiations. Néanmoins, l'impact des radiations sur l'indice de réfraction est un phénomène moins connu qui peut affecter aussi bien les verres classiques que les équivalents dopés.

L'Agence Spatiale Européenne a initialisé un programme de R&D dans le but d'établir une banque de données regroupant les coefficients de sensibilité (ou coefficients de dose) pour l'ensemble des caractéristiques optiques des verres (transmission / indice de réfraction / compactification…) La première partie de cette étude, consistant à définir la méthodologie pour une telle banque de données, est réalisée par ASTRIUM SAS en coopération avec SCK CEN. Elle comprend des études théoriques associées à la mesure et à la caractérisation d'une sélection de verres classiques et dopés.

Les aspects théoriques de cette étude sont présentés ici, suivis par les résultats obtenus jusqu'à maintenant.

***ABSTRACT** - It is well known within the Space optics community that radiation may significantly affect transmittance of glasses. To overcome this drawback, glass manufacturers have developed Cerium doped counterparts of classical glasses. This doped glasses display much less transmittance sensitivity to radiation. Still, the impact of radiation on refractive index is less known and may affect indifferently classical or Cerium doped glasses.*

ESTEC has initialised an R&D program with the aim of establishing a comprehensive data base gathering radiation sensitivity data, called Dose coefficients, for all the glass optical parameters (transmittance / refractive index / compaction……). The first part of this study, to define the methodology for such a data base, is run by ASTRIUM SAS in co-operation with SCK CEN. This covers theoretical studies associated to testing of a selected set of classical and "radiation hardened" glasses.

It is proposed here to present first the theoretical backgrounds of this study and then to give results which have been obtained so far.

1. INTRODUCTION

The Space radiation environment is known for long to affect transmittance of space borne optics. Cerium doping of glasses is an efficient way to limit this effect and glass manufacturers have developed such glasses either specific e.g. for coverglasses of solar panels or equivalent to some catalog glasses for use in refractive optical components. Still, other glass characteristics, such as refractive index, may be affected by radiation.. Ce doping may appear ineffective or even detrimental to the minimization of these other effects, as shown hereafter. Compaction of glasses and glass ceramics under radiation may also be identified. This particularly affects reflective mirrors, by modifying their curvature by differential compaction of the front and rear sides of the substrate.

Still, there are only few reliable data on the glass characteristics sensitivity to radiation. To fill this gap, ESTEC has sponsored a study currently run by ASTRIUM in cooperation with SCK-CEN. Its major aim is to define the approach for the gathering of sensitivity coefficients (with the assumption of linearity) in a comprehensive data base. Experiments on a limited number of standard and Cerium doped glasses have been run in the frame of this study, to assess the validity of such an approach. First results are given and discussed hereafter.

2. THE SPACE ENVIRONMENT AND ITS POTENTIAL IMPACTS TO OPTICS

The near Earth environment is affected by a variety of energetic particles including transient components (protons and heavier ions from galactic cosmic rays and solar particles events), trapped components (electrons, protons and heavier ions) and atmospheric and terrestrial secondaries (neutrons). This environment is illustrated in figure 2/1 a.

Knowing the orbit characteristics of the spacecraft and the mission duration and expected launch time, the expected radiation characteristics which may reach the optical elements can be modeled. This has been run for 3 typical cases: Earth observation satellite on a polar orbit (800 km altitude) during 5 years, Constellation of communication satellites on a medium earth orbit (1000 to 3000 km) during 10 years, Geo communication satellites (36000 km) during 15 years. The following table (fig.2/1 b) summarizes the expected dose range for different locations within the spacecraft.

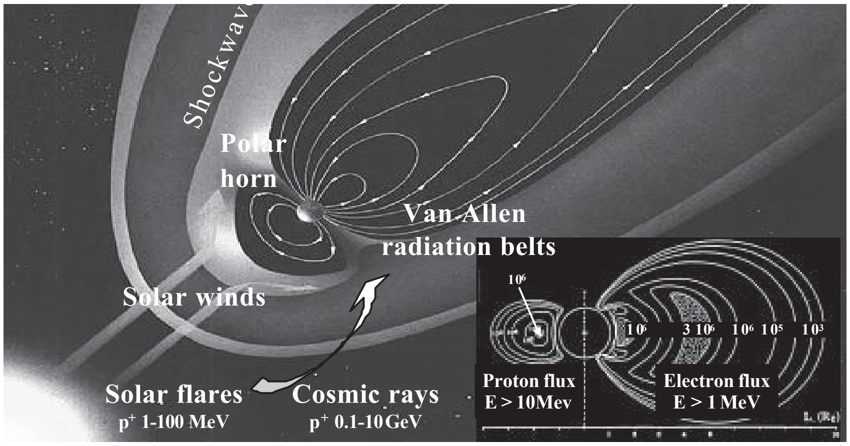


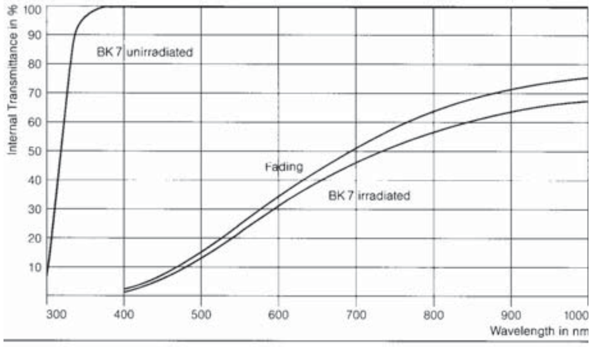
Figure 2/1 a *The near Earth protons and electons radiatin environment*

Spacecraft radiation environment is driven by the near Earth radiation belts.

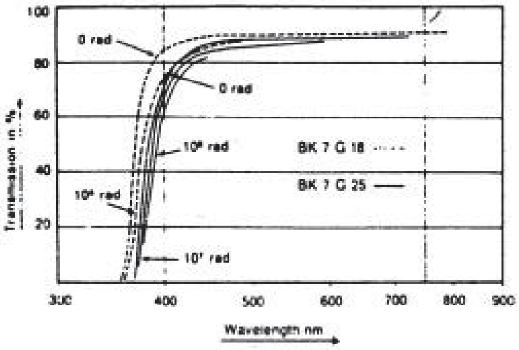
Orbit / mission type	Not exposed to Space	Exposed to Space
LEO type 1	1 to 5 krad (mainly protons)	1 Mrad
LEO type 2	10 to 100 krad (mainly protons)	18 Mrad
GEO	5 to 500 krad (mainly electrons)	180 Mrad

Figure 2/1 b *Cumulated doses on optical elements for the 3 types of mission. Depending on the location of the optical elements in the spacecraft and the mission type, cumulated doses may vary from 1 krad to about 200 Mrad.*

The impact of such an environment on the performances of spaceborne optics has early been considered and results reported in a number of publications. Data can be found by example in the Schott glass catalog for transmission losses.

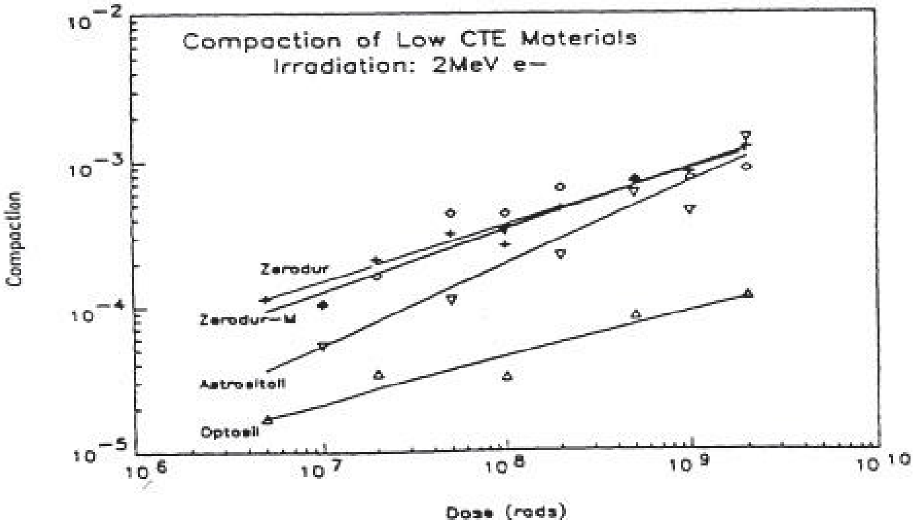


As shown here for Schott BK7glass, transmission losses in classical glasses may reach 90% after irradiation



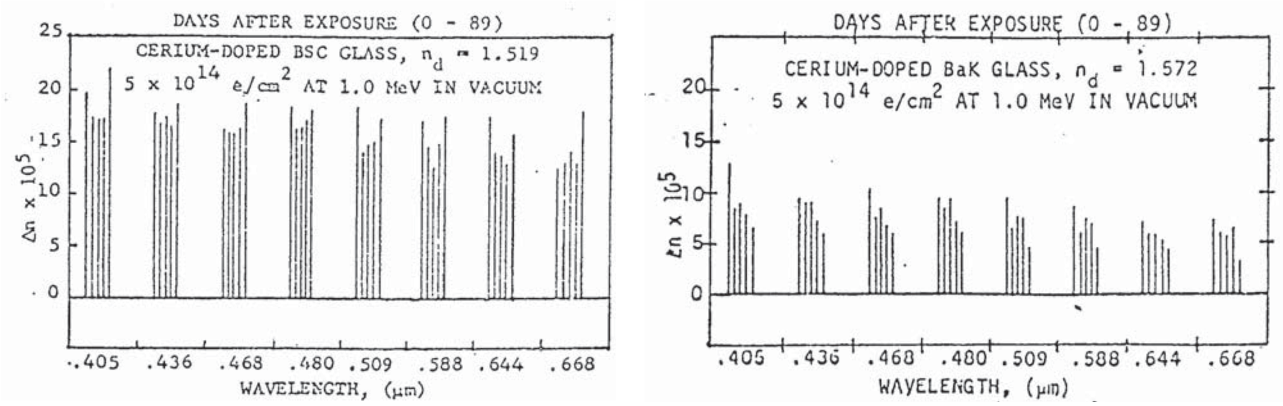
Ce doping of BK7 glass strongly limits transmission losses under irradiation, with the drawback of some yellowing

Publications from P.L.Highby and E.J. Friebele give valuable data on material compaction



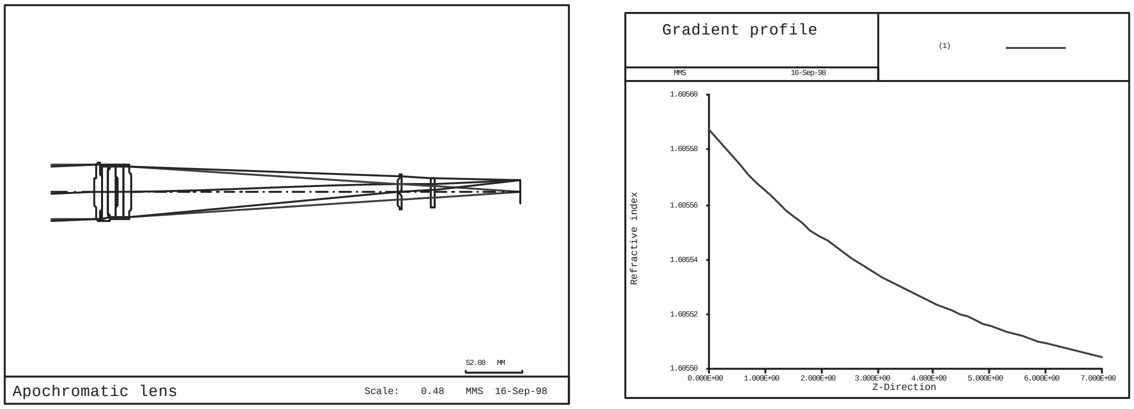
The compaction under radiation of low thermal expansion coefficient glasses and ceramics follows a non linear law versus dose when exposed to more than 1 Mrad

Data related refractive index changes under radiation can be found by example in publications from I.Malitson, as pictured hereafter.

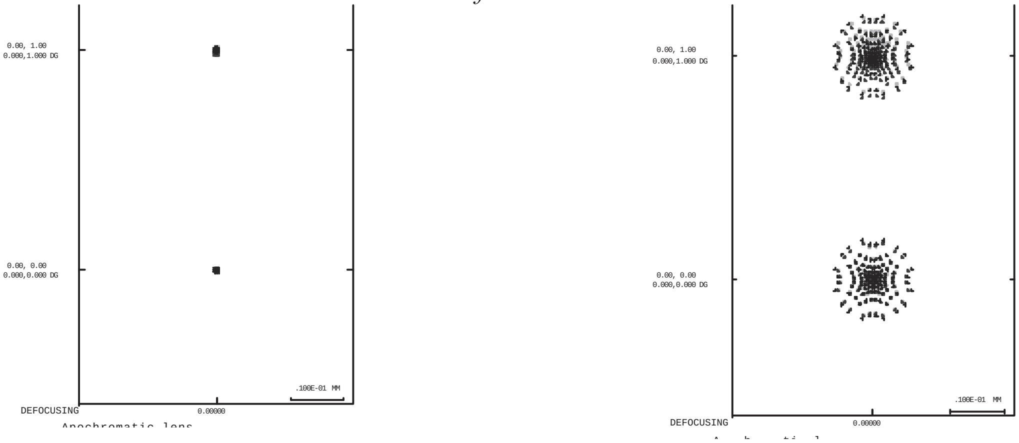


Variations of refractive index strongly depends on glass composition and may affect both Ce doped and classical glasses. RI changes of a few 10^{-4} have been measured for doses in the order of 1Mrad

Impact of such variations on the performances of spaceborne optics may be assessed through modeling. The in-flight behaviour of already flown optical instruments give an additional in-sight on these radiation impacts.



An apochromatic teleobjective has been simulated , with an exponential-type index gradient on the first lens.

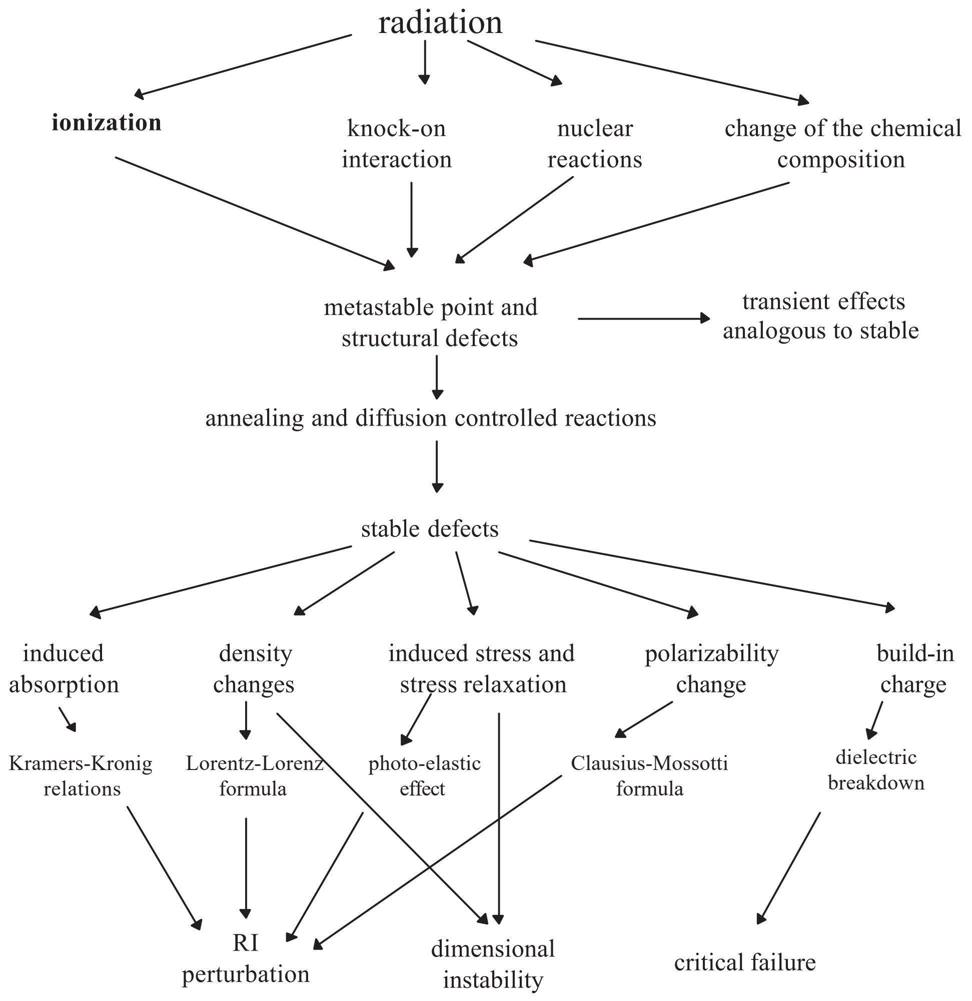


Polychromatic spot diagram before irradiation *Polychromatic spot diagram after irradiation*

The spot diagram , nearly perfect before irradiation, may exceed 70 µm after the simulated refractive index gradient.

3. THE UNDERLYING PHYSICAL PHENOMENA

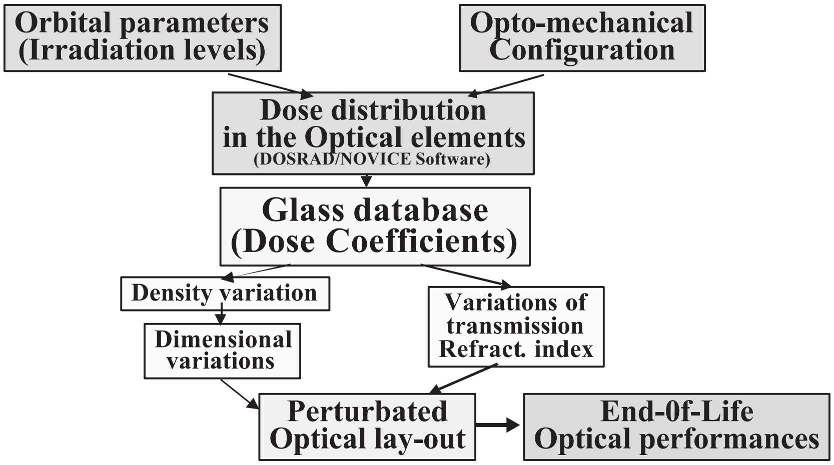
The basic radiation-matter interactions are summarized in the following sketch. Considering Space radiation characteristics, the only significant phenomena is ionization. In this case, it is expected that any type of radiation, either electrons, protons or gamma, be equivalent at the same dose level.



Basic radiation-matter interactions result in related changes of all the material optical properties. These changes are linked by theoretical relationships which may be used to correlate them (e.g. Kramers-Kronig relations between absorption and refractive index (RI) / Lorentz-Lorenz formula between density and refractive index).

4. THE DOSE COEFFICIENTS APPROACH

A data base giving linear Dose coefficients, say, the sensitivity of glass characteristics to radiation, associated to any optical design software will enable to analyze the performances of an optical system in Space radiation environment, as sketched hereafter.

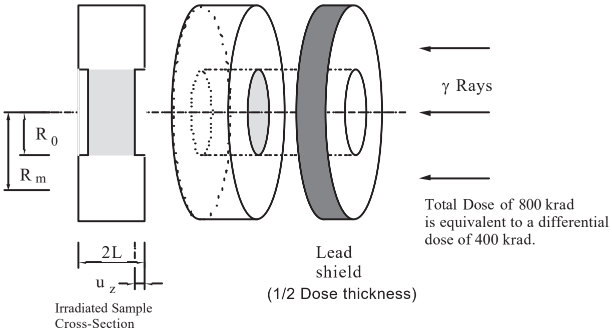


The study reported here aims at experimentally validate this approach. The validations which are reported here include protons and γ radiations testing on 4 mm thick samples from 50 krad up to 900 krad and measurements of related impacts on refractive index and transmission/absorption of 11 Schott glasses, either classical or Ce doped.

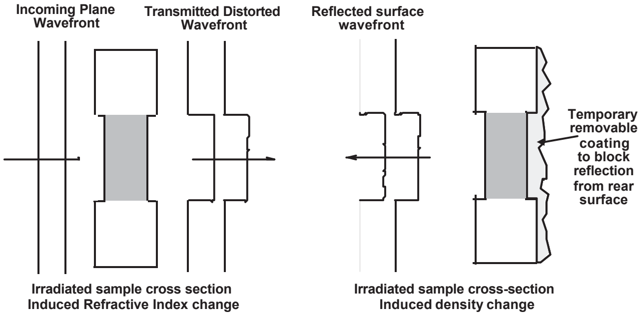
5. CHARACTERISATION OF GLASS RADIATION SENSITIVITY

5.1 The measurement approach

The impact on refractive index has been derived from measurements of transmitted wavefront steps of partially irradiated samples as shown in figure below. The measurement of the reflected wavefront steps also allow the determination of compaction/ density changes which occur in the glass material



A dose step annular profile is achieved by placing a ring lead shield in front of the sample, γ / p^+ radiation giving a constant dose over the full thickness of each area.

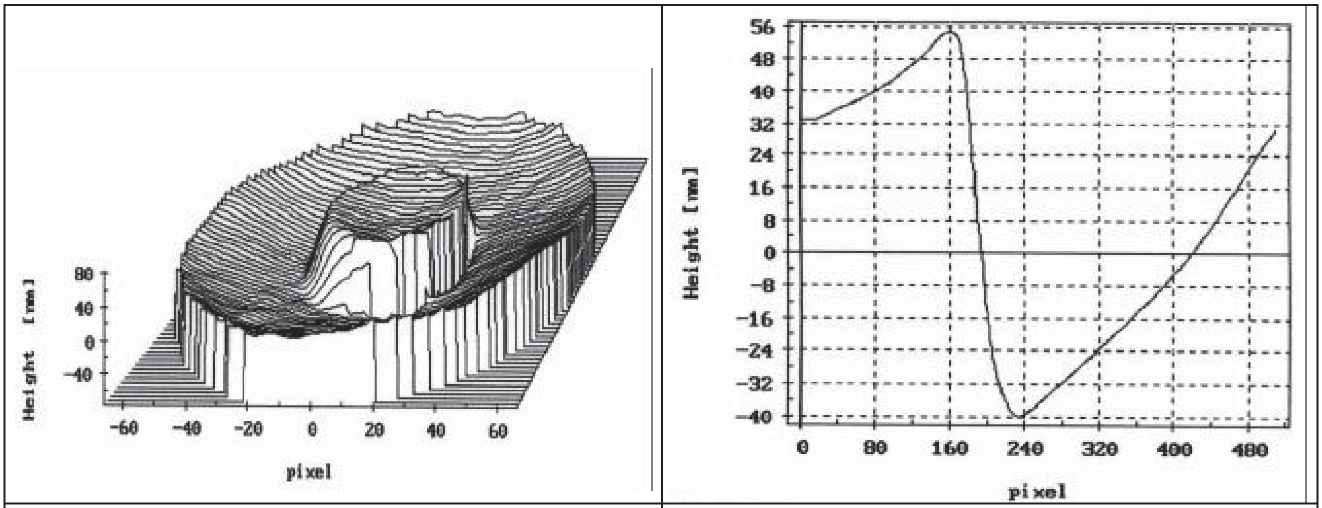


The interferometric testing of the transmitted and reflected wavefronts allows an accurate determination of the refractive index (RI) and density changes

The samples are exposed to full dose in the central unshielded area of 10 mm diameter. The periphery of the 30 mm diameter samples is exposed to half the dose with gamma and not subjected to radiation with protons.

WFE measurements have been run at 2 wavelengths, 543.6 nm and 633 nm, with the DIRECT 100® interferometer from Zeiss.

The achieved measurement accuracy of the induced wavefront steps depend on the sample intrinsic wavefront accuracy. With well polished samples in the λ/30 range, as long as the irradiation step is steep enough, the achieved measurement accuracy is around 10 nm with a minimum measurable step of about 10 nm. A typical wavefront profile is shown in figure 3.1/1.



The 3D wavefront profile clearly shows the impact of radiation on the transmitted wavefront (BK7 p^+ 900 krad)

The induced wavefront step is determined from the measured radial profile as shown here (BK 7 glass / protons 900 krad)

Figure 3.1/1: *Collimated protons radiation allows an almost perfect dose step to be obtained, thus authorising an accurate determination of the induced change in refractive index*

The impact on transmission has been measured from 200 nm to 1200 nm using a CARY 5E® spectrophotometer. Measurements of the transmission is done at the center and at the edge of the gamma irradiated samples, doubling the available measurements data.

5.2 The samples batch

As already mentioned, 11 types of Schott glasses have been submitted to either protons radiation (3 dose levels), either to low dose rate gamma radiation (Co60 source) with 2 different dose steps, thus allowing to measure transmission impact at 4 dose levels (50 / 100 / 200 and 400 krads).

An overview of the irradiated samples is shown in figure 5.2/1.

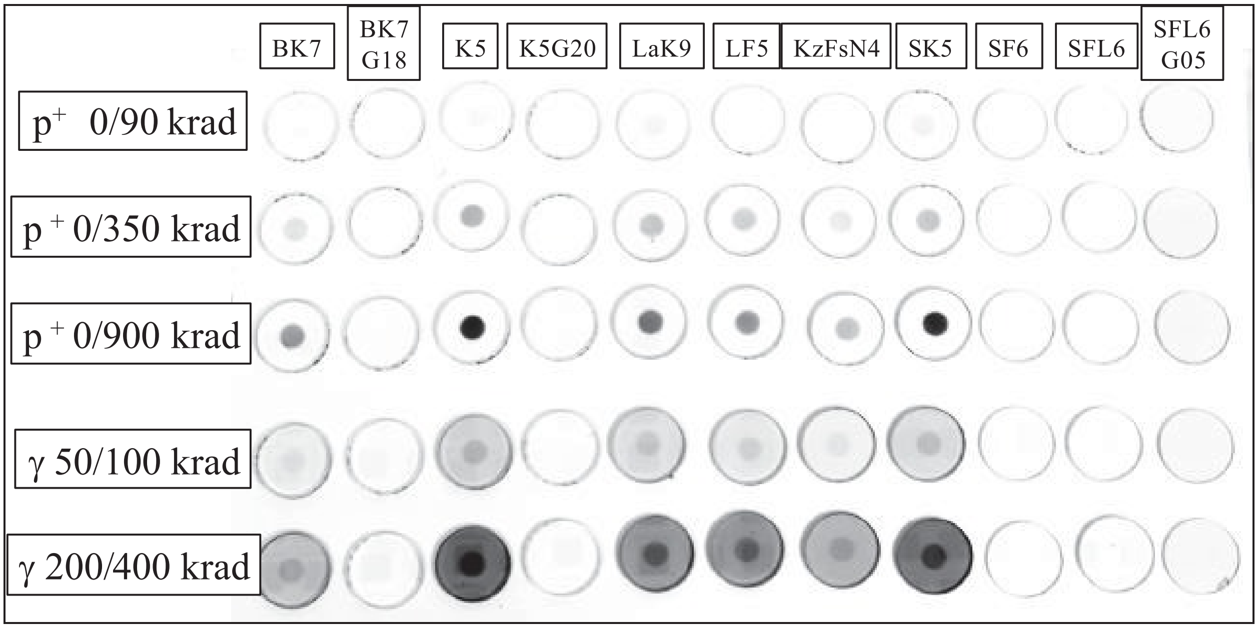
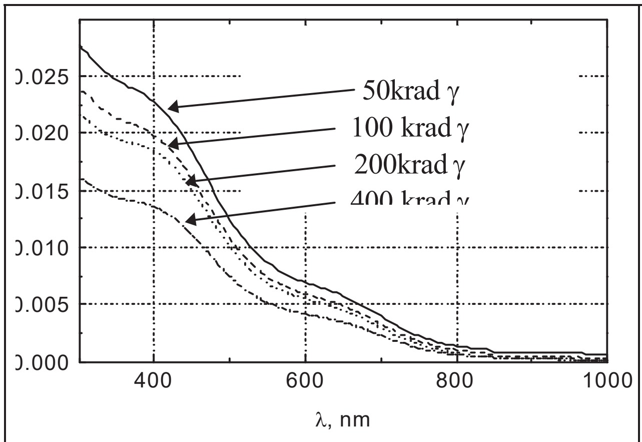


Figure 5.2/1: *Major differences in the behaviour of glasses can readily be identified here. Even some classical glasses, like SF6, show very low transmission sensitivity to radiation. Additionally, a different transmission behaviour between proton and gamma radiation can be already assessed.*

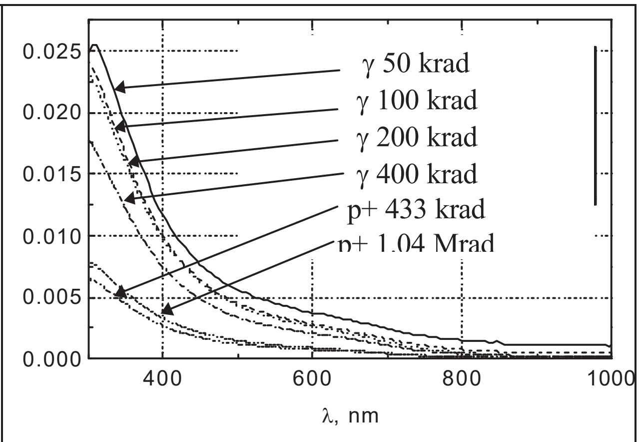
5.3 Measurements results and discussion

Figures 5.3/1 to 4 give measured induced absorption coefficients , normalized to the absorbed dose. The spectral curves for protons irradiated samples very well fit to a single curve. Differences between gamma and proton induced spectral absorption is somewhat unexpected. Fundamentally, for glassy materials, the predominant radiation damage mechanisms are ionization and radiolysis and at the atomic level within the solid both energetic photons and particles give rise to the same defects i.e. colour centres. Our results on the face of it appear therefore somewhat counter-intuitive and clearly require further careful and detailed study before any firm conclusions can be drawn. In particular, relaxation effects may affect the results, as dose rate differences between protons (Mrads/mn) and gamma (6 rads/mn) may play a significant role. Previous experiments show significant relaxation may happen within the first 10 days.



K5 induced absorption coef./dose (cm^{-1}/krad)

Fig. 5.3/1



BK7 induced absorption coef./ dose (cm^{-1}/krad)

Fig.5.3/2

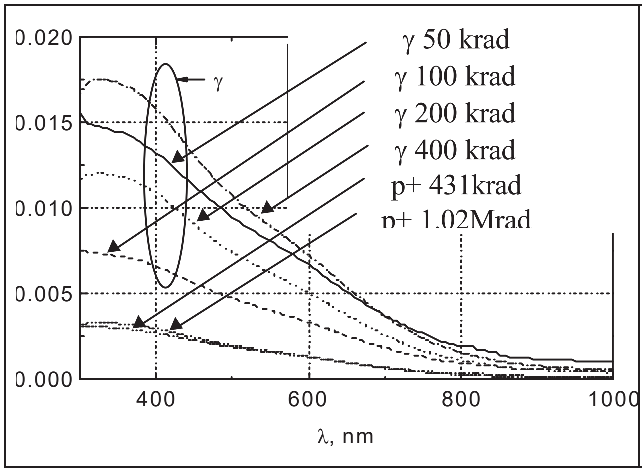
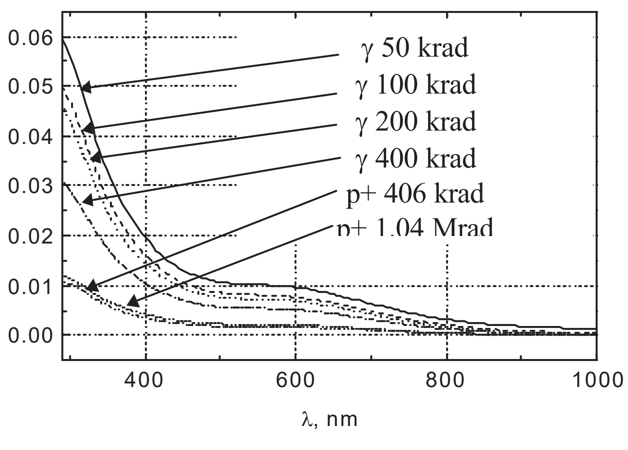
	
LaK9 induced absorption coef./dose (cm^{-1}/krad)	SK5 induced absorption coef./ dose (cm^{-1}/krad)

Fig. 5.3/3

Fig.5.3/4

. Figure 5.3/5 shows the amplitude of the wavefront steps for 2 types of glasses Although the number of data is too low here to make any definite conclusion, it shows quite a good linear and similar variation of refractive index with proton and gamma dose.

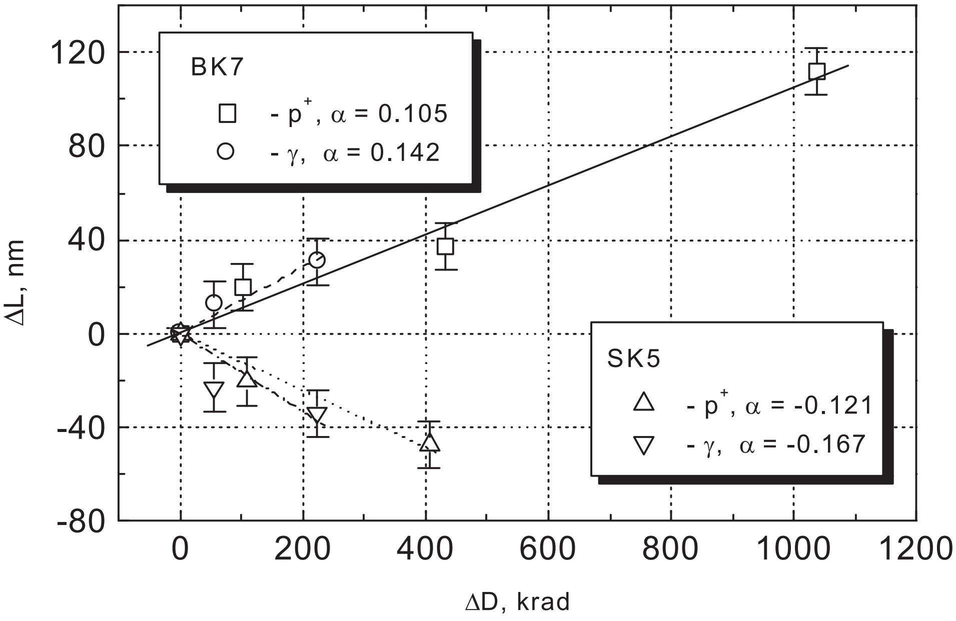


Figure 5.3/5: *The measured wavefront steps quite well fit with a linear behaviour of refractive index induced changes with dose. Sign is opposite for BK7 and SK5.*

The induced changes in refractive index are derived from the above measurements and are in the range of 10^{-5} / Mrad.

Index changes, which could potentially influence the performance characteristics of a diffraction-limited optical system, have to be larger than 10^{-5}, though in some cases even changes of 10^{-6} can play a role. For missions of common interest, the upper limit of the radiation dose is of the order of a few hundreds of krads for the GEO orbit and only of some krads for the LEO ones. Taking into account the estimated scale of the dose coefficients, we can conclude that the measured changes will be most often acceptable.

6. CONCLUSIONS AND FUTURE OUTLOOK

Future outlook will include:

- further measurements of transmission to better assess relaxation
-measurements of 0.2 mm thin samples aiming at verifying the Kramer's Kronig's relations
- improvement of the processing of induced wavefront steps measurements to gain in sensitivity
- investigation on the differences between gamma and protons influences on glasses

Still, the present work already allows to draw outstanding results and conclusions, including:

- characterisation of refractive index variations at 2 different wavelengths and confirmation of the linearity behaviour of refractive index variations versus dose
- identification of a potentially different behaviour of glasses versus gamma and protons radiation for absorption and confirmation of the linearity behaviour of the induced absorption coefficient versus dose at any wavelength

In final, thanks to the careful study of radiation effects on glass and the organisation of a large glass data base which can be widely used by the optical community, the evaluation of radiation impact on Space borne optics, based on the proposed “Dose Coefficients” approach, will be made easy and reliable.

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