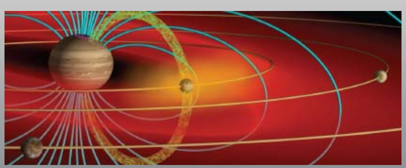
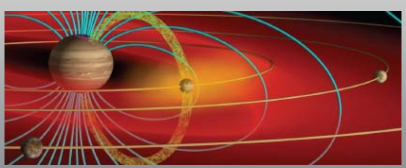


Radiation Hardness of Optical Materials

Dominic Doyle, ESA-ESTEC, Optics Section

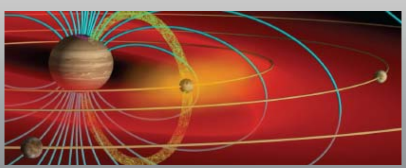
- Outline
  - Radiation effects physics of optical materials
  - Examples
  - Challenges for EJSM radiation environment
  - Approach to qualification & testing
  - The literature & data sources (Citations to get you started)
  - Conclusion and recommendations



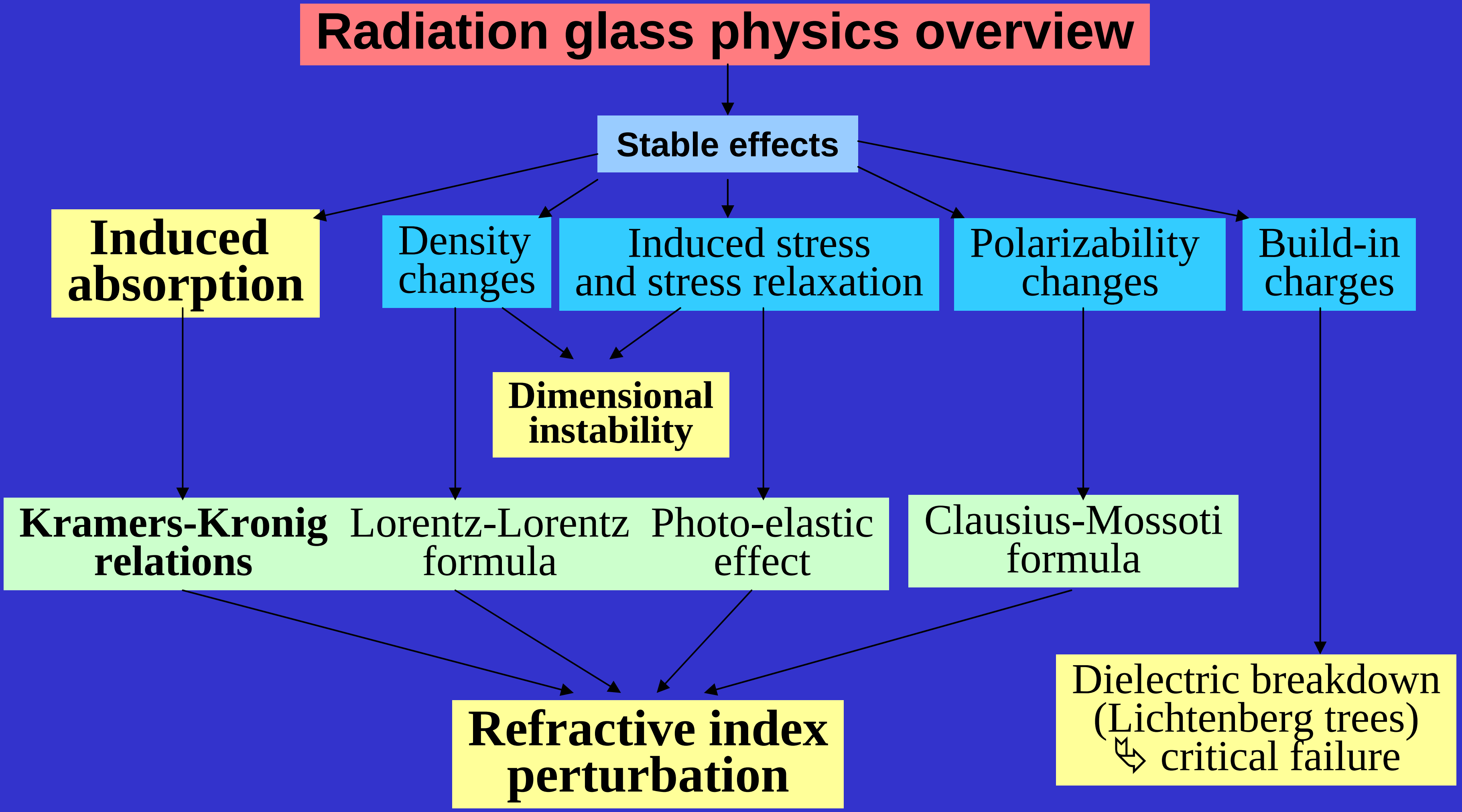
Radiation effects on Optics, Basic Phenomenology & Examples

- Radiation effects on optical glasses, crystals, coatings and (mirror) substrates may include:
  - Induced colour centres (spectral absorption impact => darkening)
  - Density changes => ref. index, & dilatation or compaction
  - Birefringence (Crystals)
  - Charging => Lichtenberg figures, fracture
  - Fluorescence, Luminescence and Scintillation
  - Dielectric breakdown

See also Willis presentation OPFM Workshop June 2008,
https://opfm.jpl.nasa.gov/europajupitersystemmissionejsm/tutorials/Tutorial_5/player.html



Overview of Glass Damage Physics



Radiation glass physics overview

Stable effects

Induced absorption

Density changes

Induced stress and stress relaxation

Polarizability changes

Build-in charges

Dimensional instability

Kramers-Kronig relations

Lorentz-Lorentz formula

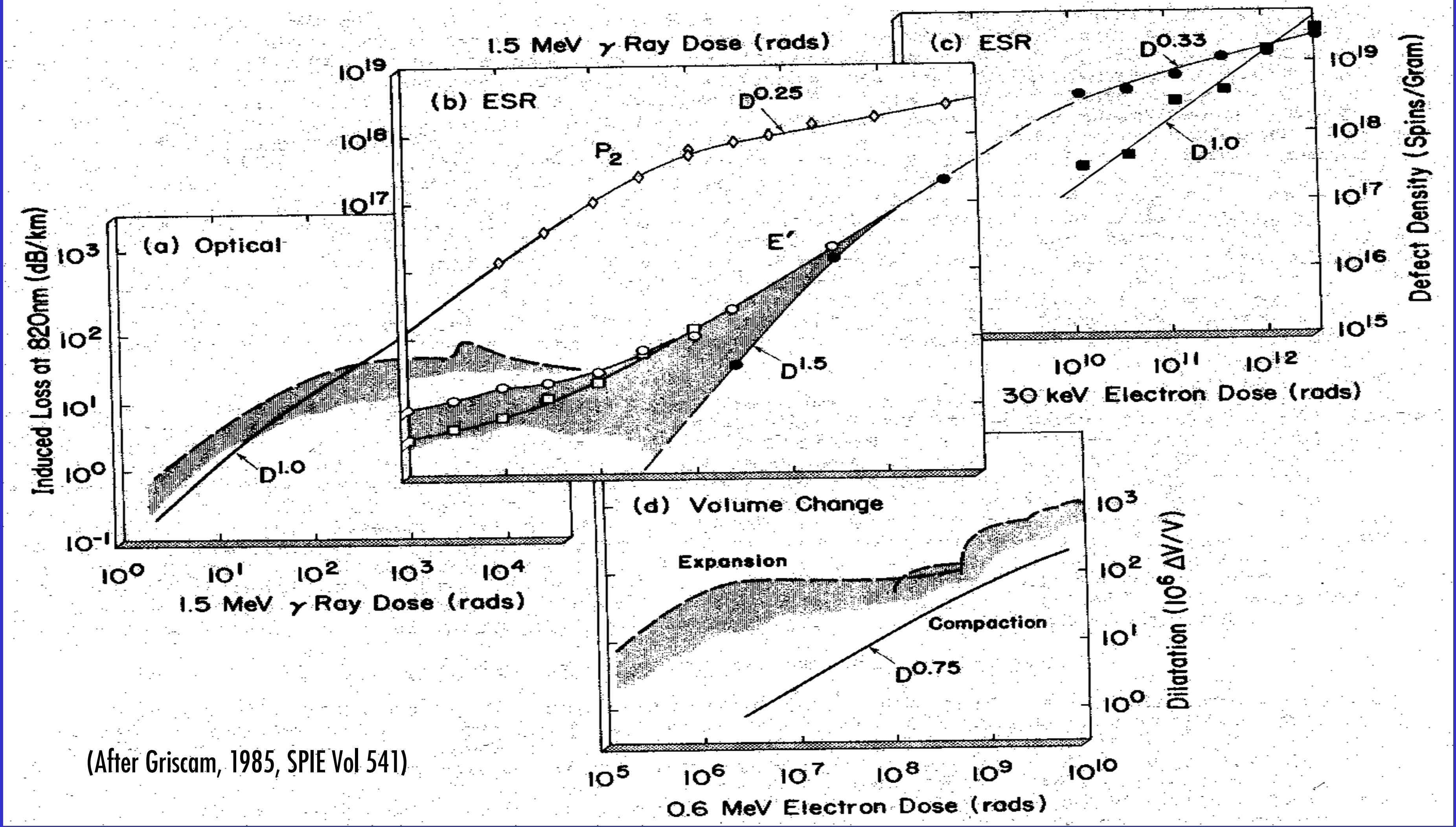
Photo-elastic effect

Clausius-Mossoti formula

Dielectric breakdown (Lichtenberg trees)
↳ critical failure

Refractive index perturbation

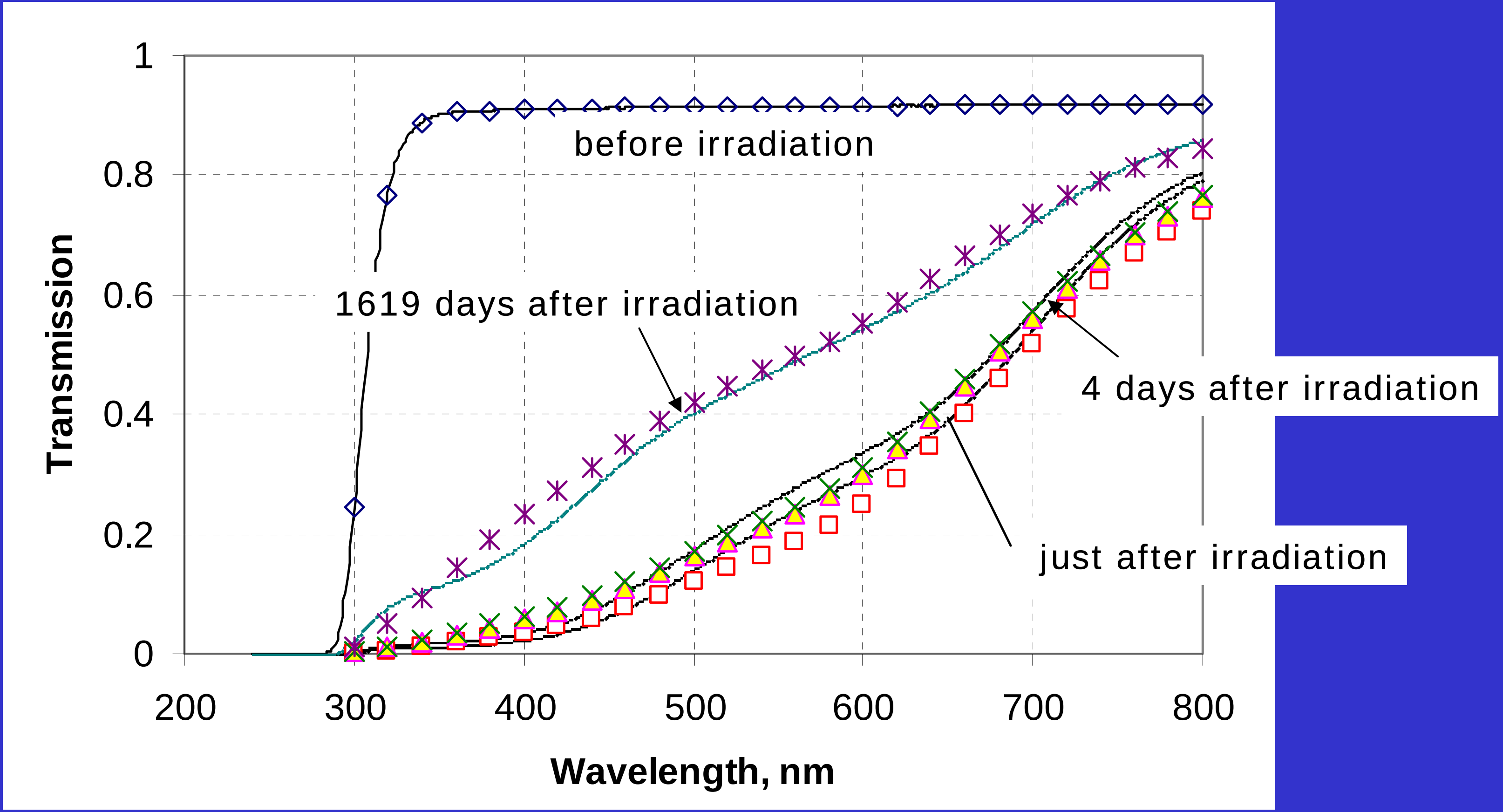
Radiation Damage is a Complex Phenomenon



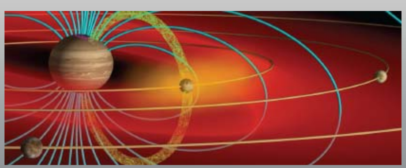
(After Griscam, 1985, SPIE Vol 541)

Induced Absorption

BK7



Simulated (symbols) and measured (curves) results obtained on a 5-mm thick BK7 glass sample. Gamma irradiation during 7 days up to a total dose of 800 krad.



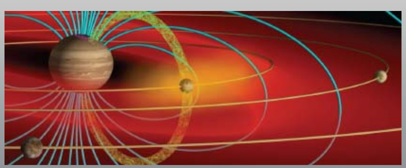
Induced Absorption

- Normalised parameterisation is very useful, e.g.

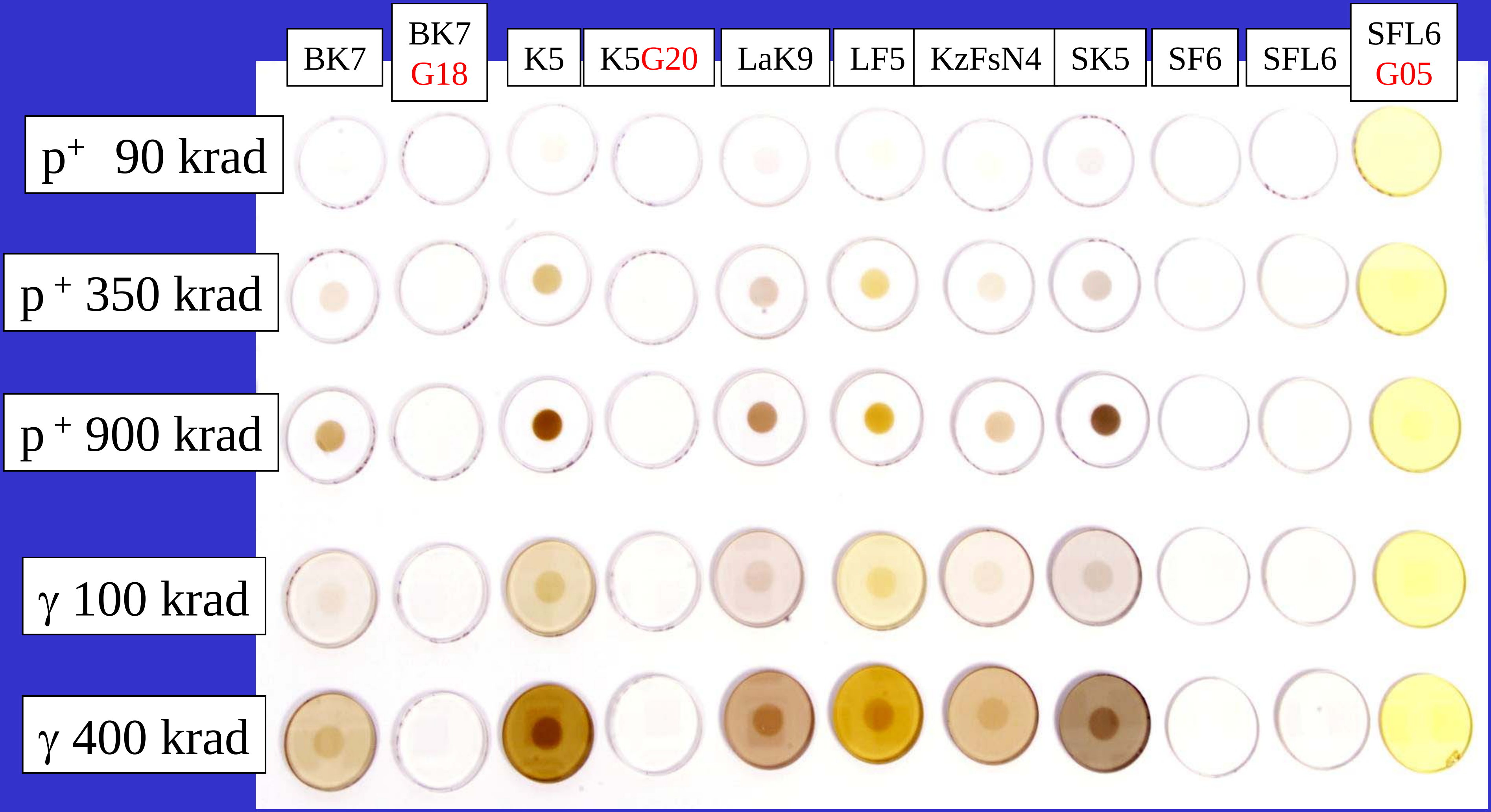
- The radiation Induced Absorption Spectrum (IAS) is defined from transmission spectra measured before (T_0) and after (T_1) irradiation

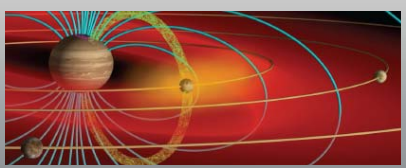
$\Delta\alpha = (1/L)\ \ln(T_0/T_1)$, L – sample thickness

European Space Agency

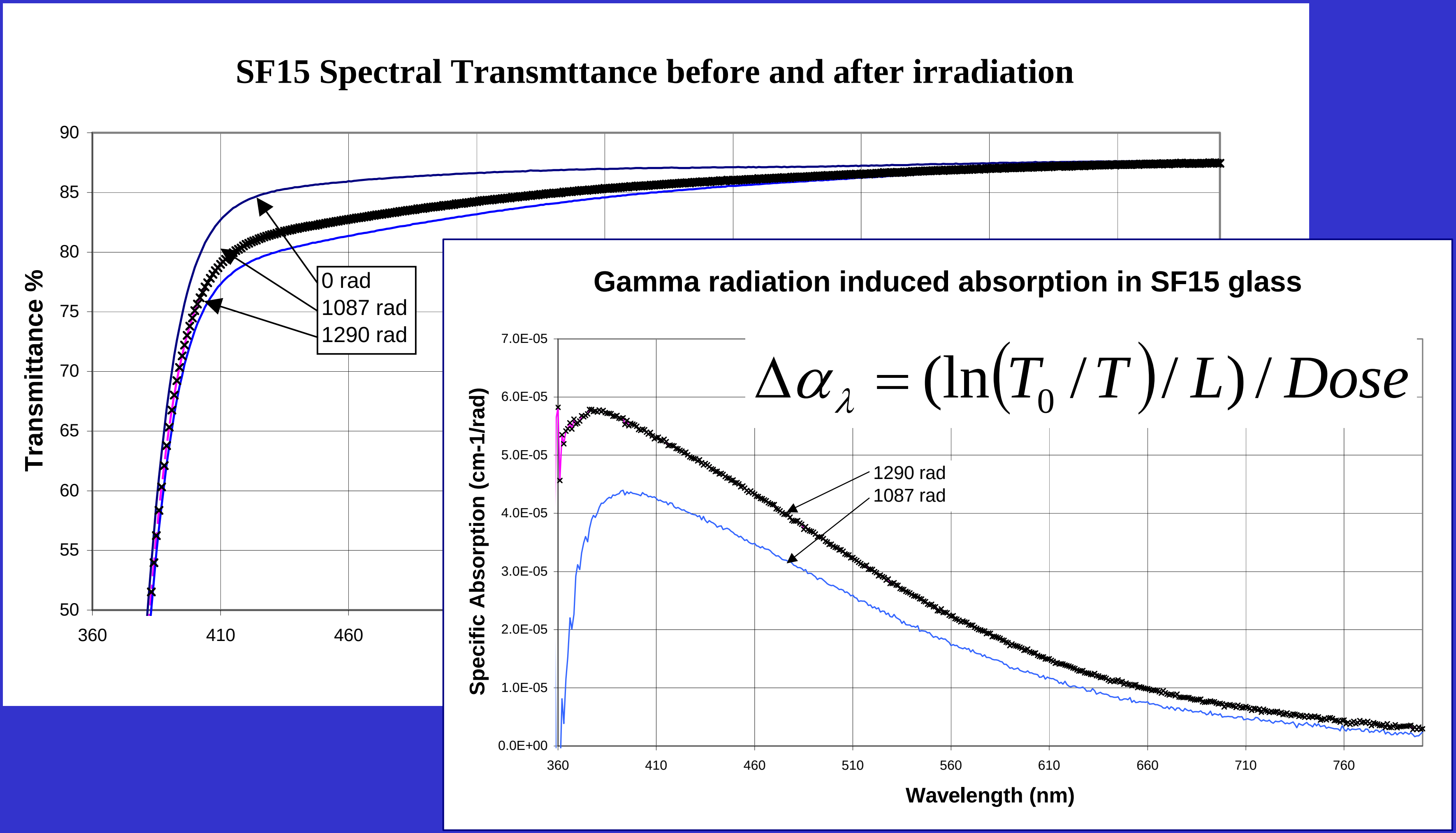


Induced Absorption

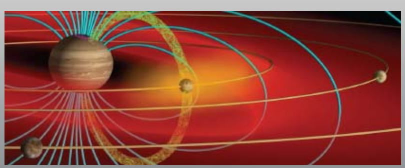




IAS Example



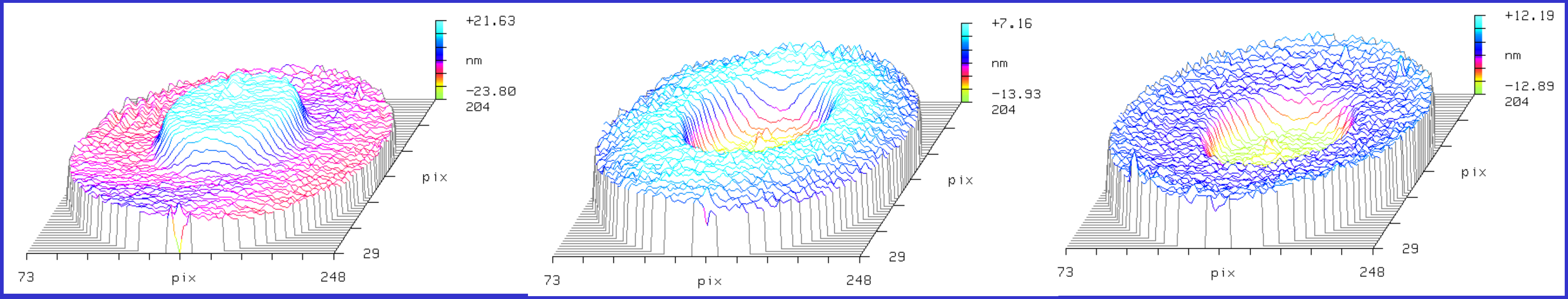
$$\Delta\alpha_\lambda = \left(\ln\left(T_0 / T\right) / L\right) / Dose$$



Refractive Index 1

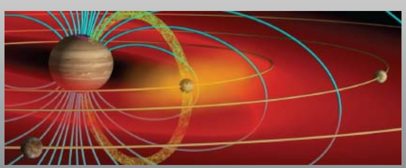
Bulk transmitted WF (Induced OPD Changes), 400 krad Gamma, BK7 Series

NB Rad-hard = resistant to Darkening ONLY!



ΔOPD (nm) = + 22 - 16 - 13

- Different behaviour for BK7 series, notably induced OPD sign change between normal and "rad-hard"

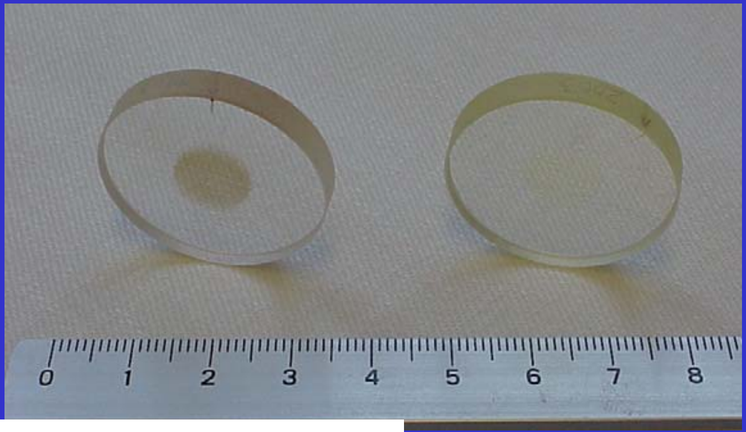


Refractive Index 2

Bulk WFE (Induced OPD Changes), p-600 krad, LaK9 series

Normal Glass:

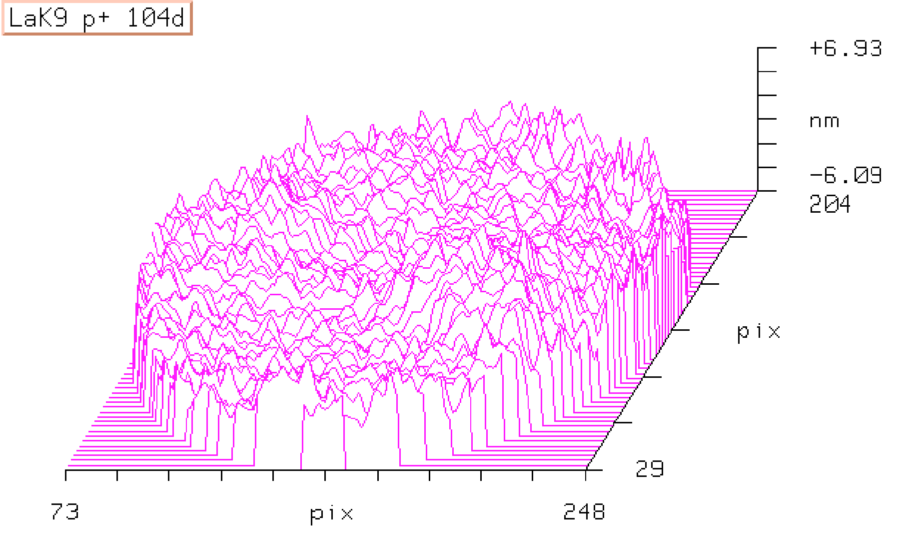
no RI damage detectable

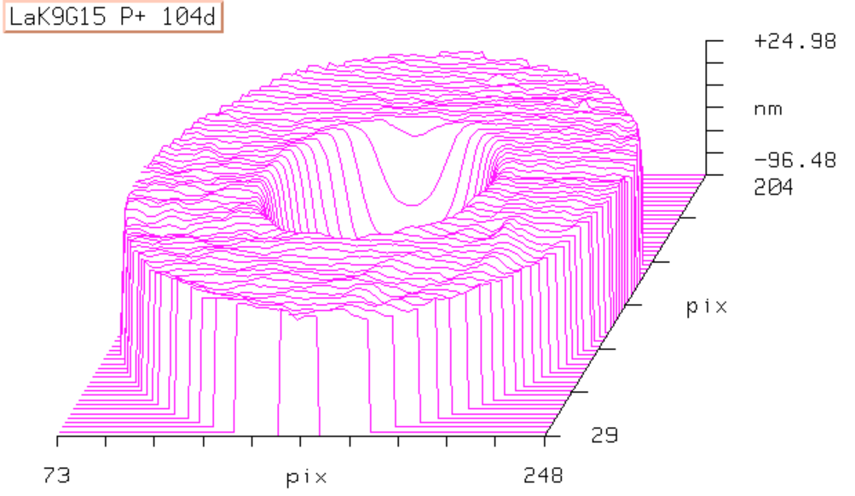


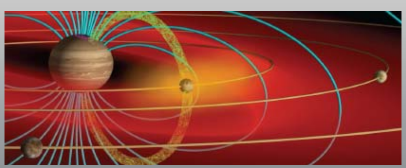
Rad-Hard Analogue

OPD = - 92 nm !

(Significant damage)







Refractive Index

Example of measured radiation induced Refractive Index changes

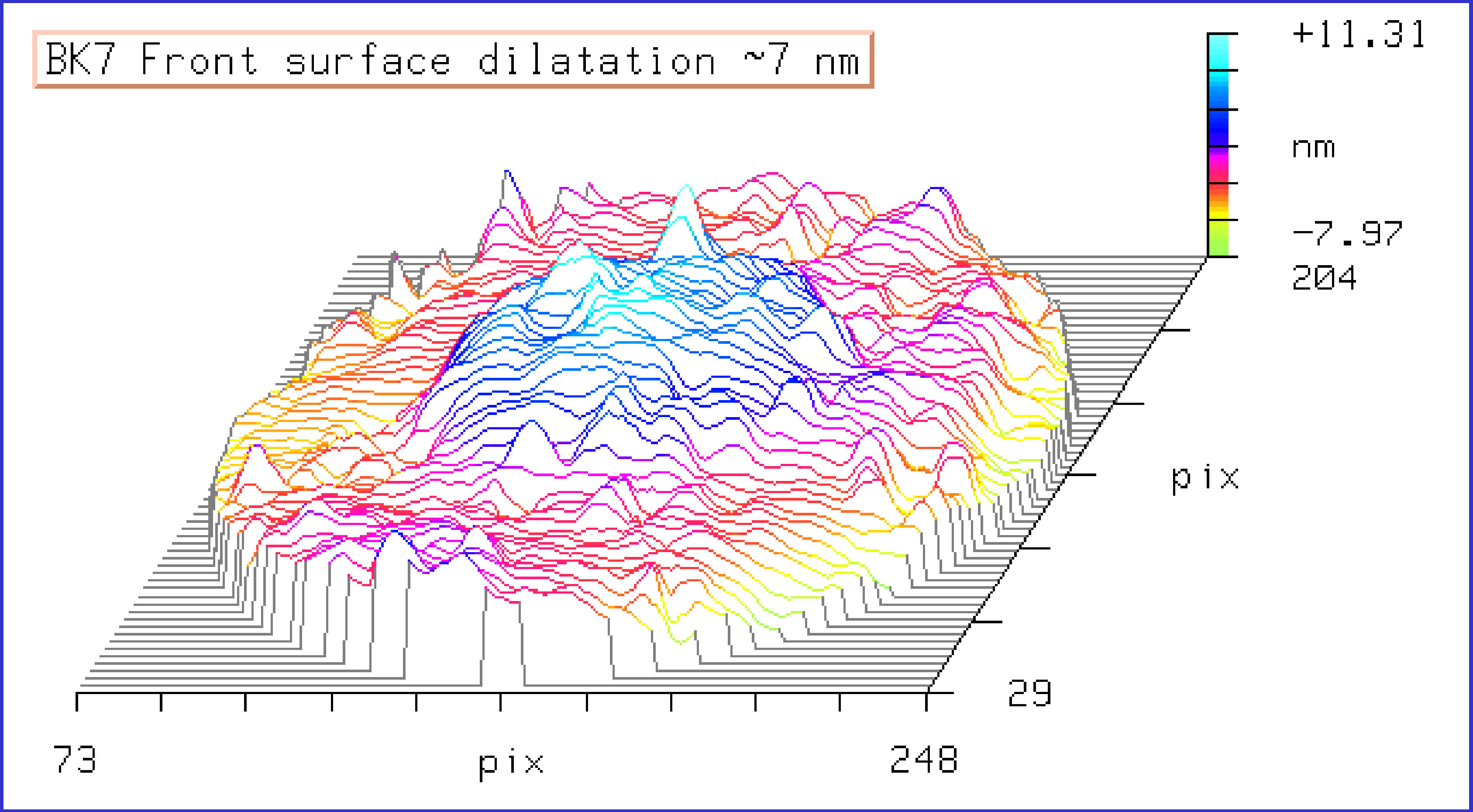
Glass	(Type)	OPD (nm)	RI change (@633 nm) (x10^{-5})	Predicted RI change (x10^{-5})	RI Dose Coeff. (x10^{-11} per rad)
LaK9	N	N.M.	< 0.1	1.1	< 0.15
LaK9G15	RH	-110	+2.20	4.0	**3.25**
BK7	N	+22	-0.45	3.0	- 0.74
BK7G18	RH	-16	+0.32		0.53
BK7G25	RH	-13	+0.26		0.43
Fused Silica		N.M.	< 0.1		< 0.15

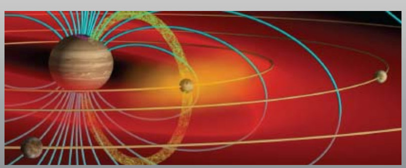
Is this important?

Depends on the refractive index tolerances in your optical design (transmissive optics).

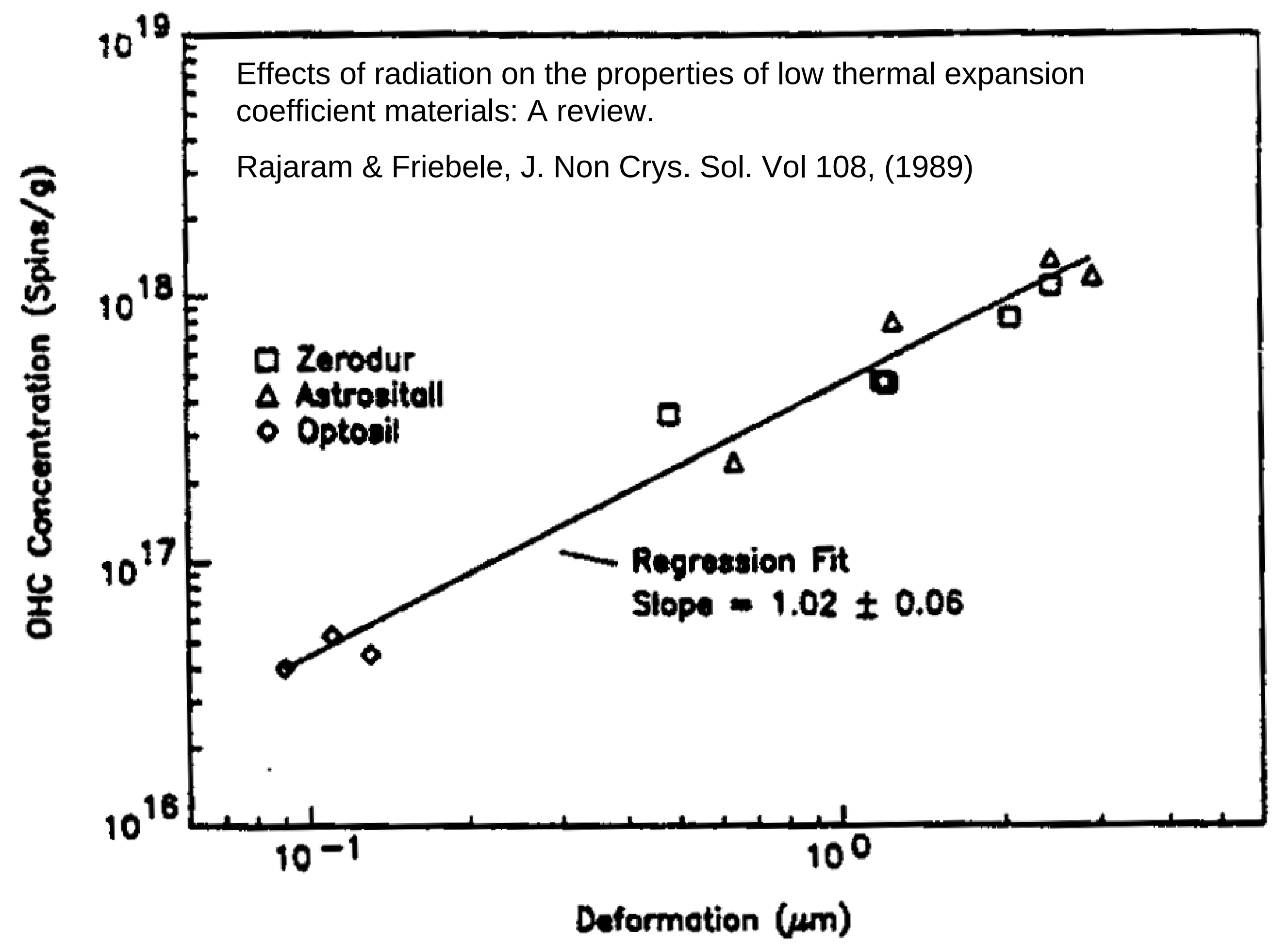
European Space Agency

Density - Dilatation





Density – Compaction of Glass Ceramics

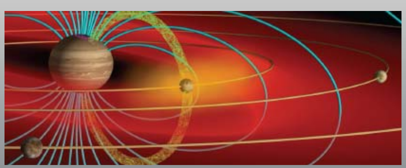


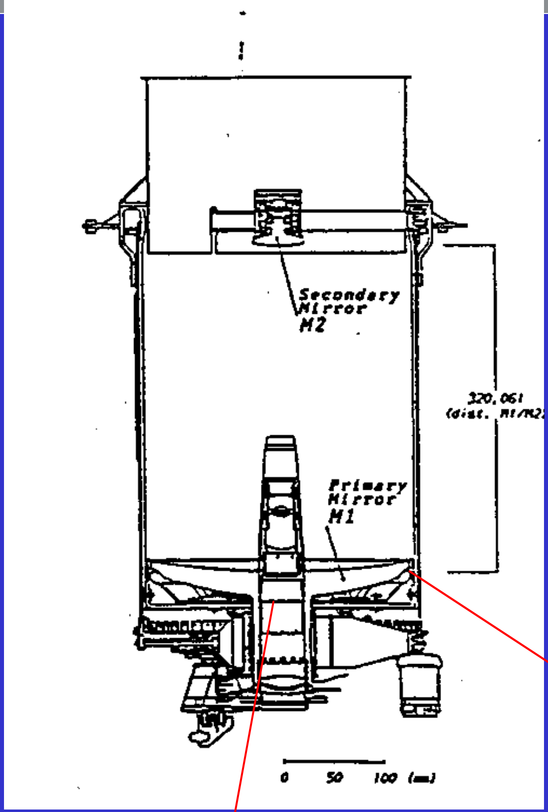
Effects of radiation on the properties of low thermal expansion coefficient materials: A review.

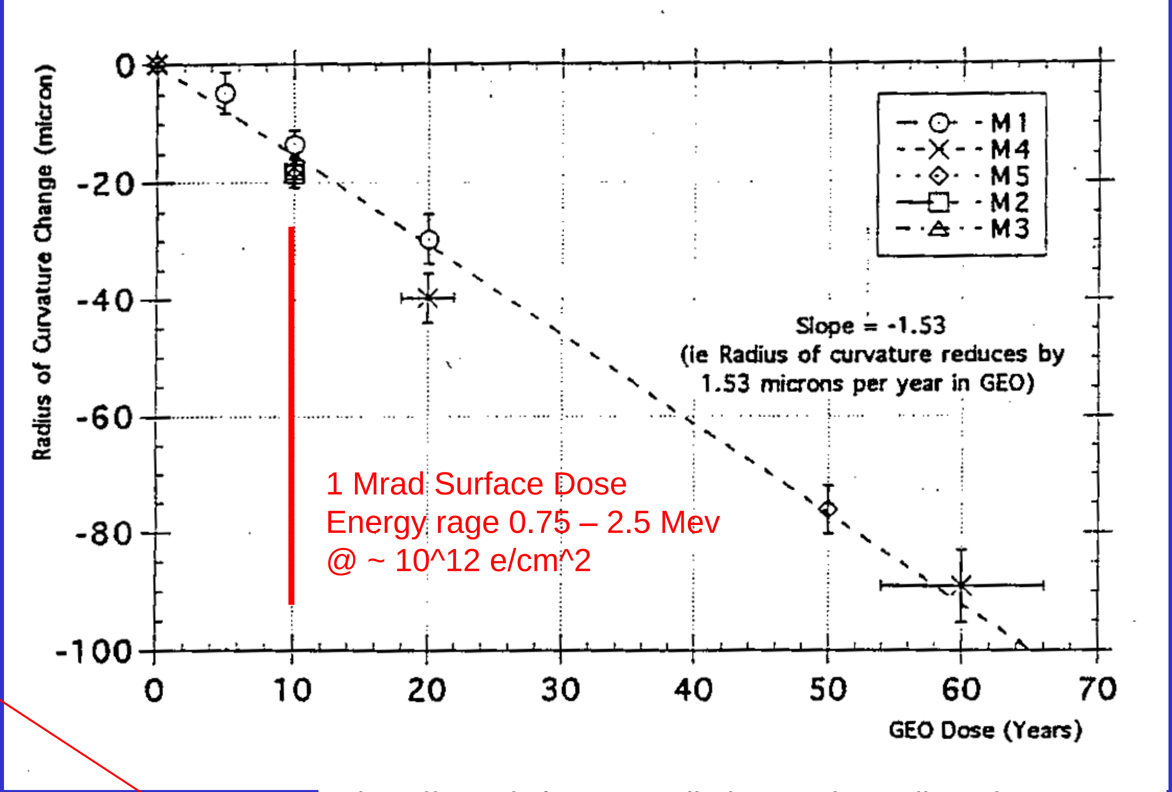
Rajaram & Friebele, J. Non Crys. Sol. Vol 108, (1989)

⇒ Compaction due to oxygen hole centers in single and multi-component glass and glass-ceramics

Zerodur – SILEX Example

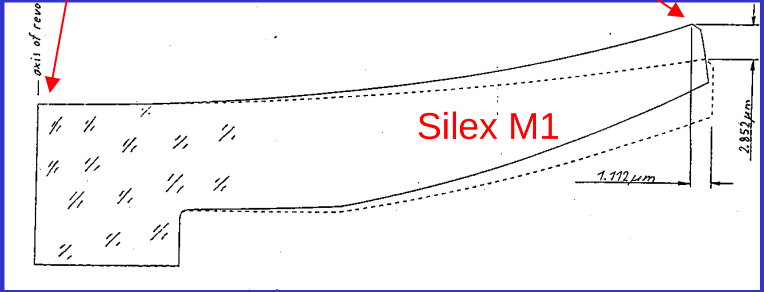






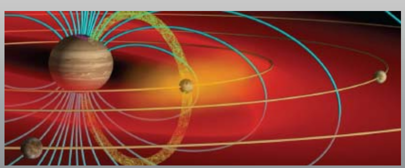
1 Mrad Surface Dose
Energy rage 0.75 – 2.5 Mev
@ ~ 10^12 e/cm^2

The effect of electron radiation on the radius of curvature of a Zerodur mirror. Doyle et al SPIE Vol. 2775, 1996



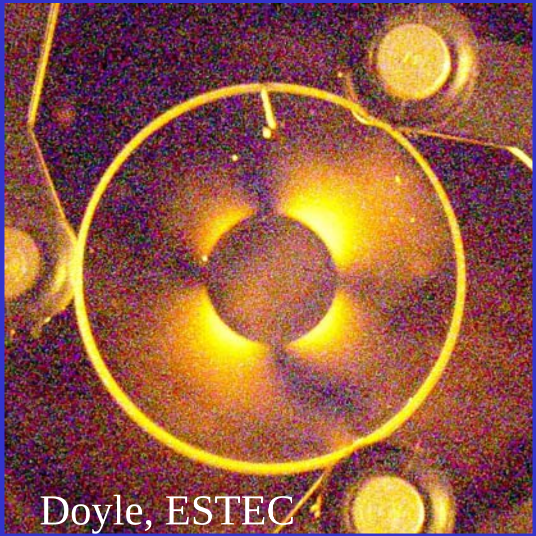
Silex M1

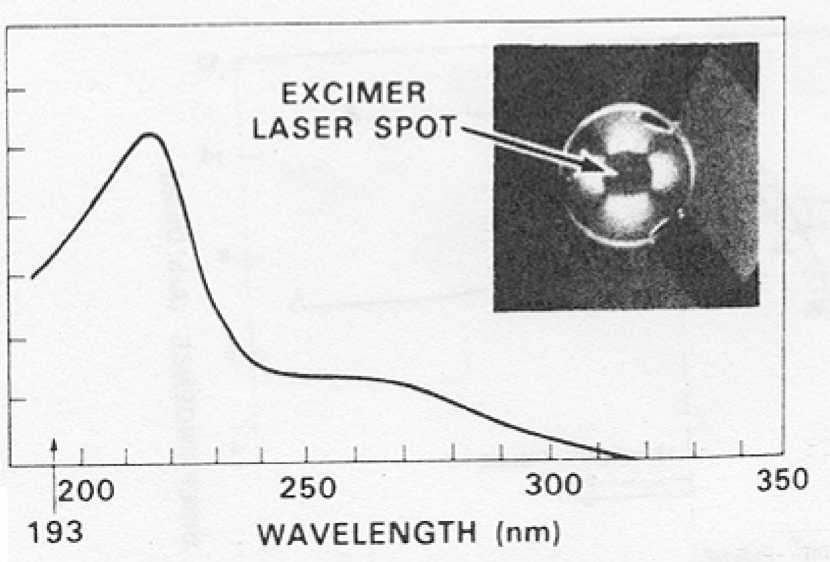
Radius of Curvature Reduction vs Electron Irradiation Dose in Geo

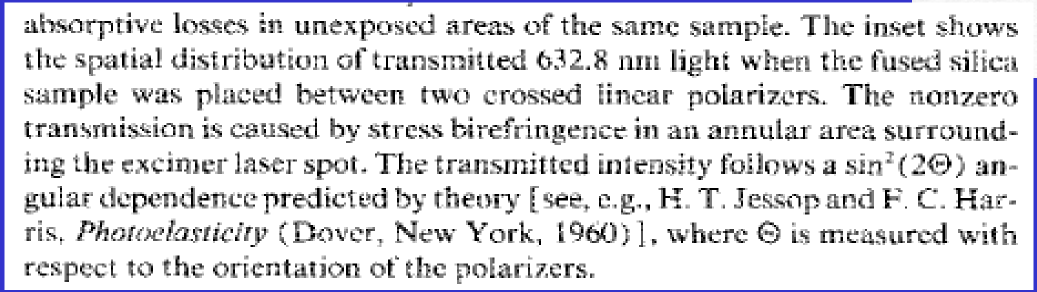


Birefringence

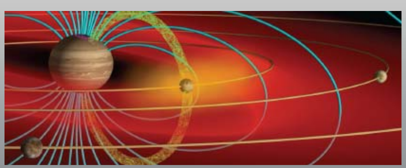
Radiation induced stress-birefringence due to Proton irradiation (non-uniform) of Cerium doped glass Lak9G15. Pictures show polarised light transmitted by the samples when placed between crossed polarisers under illumination with a Sodium d-line spectral lamp (589 nm). The characteristic cross shaped pattern is in accordance with theoretical predictions.


Doyle, ESTEC




absorptive losses in unexposed areas of the same sample. The inset shows the spatial distribution of transmitted 632.8 nm light when the fused silica sample was placed between two crossed linear polarizers. The nonzero transmission is caused by stress birefringence in an annular area surrounding the excimer laser spot. The transmitted intensity follows a $\sin^2(2\Theta)$ angular dependence predicted by theory [see, e.g., H. T. Jessop and F. C. Harris, *Photoelasticity* (Dover, New York, 1960)], where Θ is measured with respect to the orientation of the polarizers.

(After Rothschild et al,
App. Phys. Lett. 55, 1989)



CaF2 @ 10 Mrad

Space radiation testing of radiation resistant glasses and crystals

Tammy D. Henson and Geoffrey K. Torrington
Sandia National Laboratories, P.O Box 5800, Albuquerque, NM 87185-0972

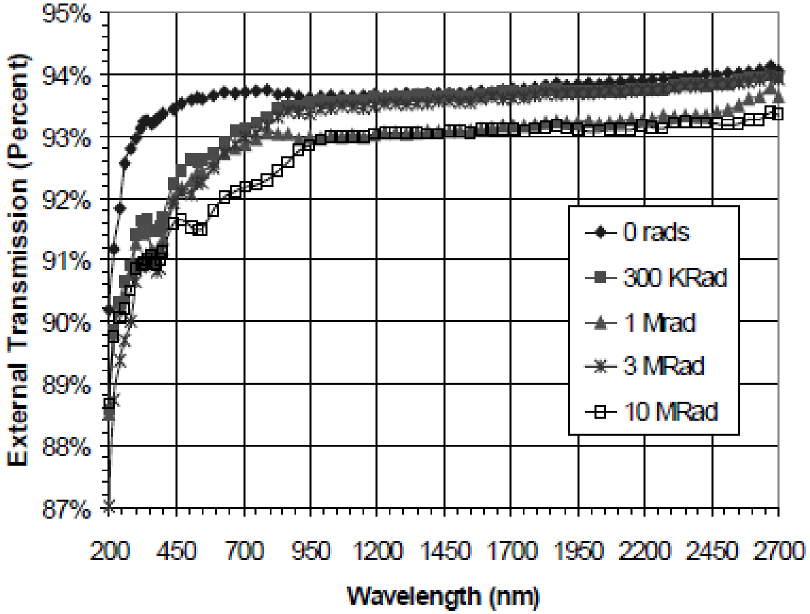
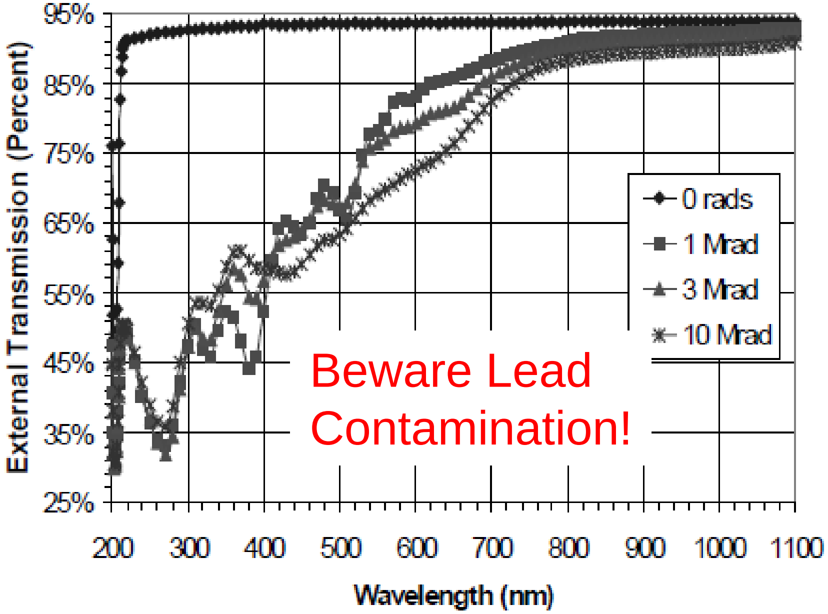


Figure 23. Transmission measurements of a Schott 157 nm eximer grade synthetic monocrystalline CaF$_2$ window after exposure to gamma radiation (t = 7.065 mm).



Beware Lead Contamination!

Figure 24. Transmission measurements of a Schott 193 nm eximer grade synthetic monocrystalline CaF$_2$ window after exposure to gamma radiation (t = 9.94 mm).

Inorganic Optical Materials III, Alexander J. Marker III, Mark J. Davis, Editors,
Proceedings of SPIE Vol. 4452 (2001) © 2001 SPIE · 0277-786X/01/$15.00

Fluorescence, Luminescence & Scintillation

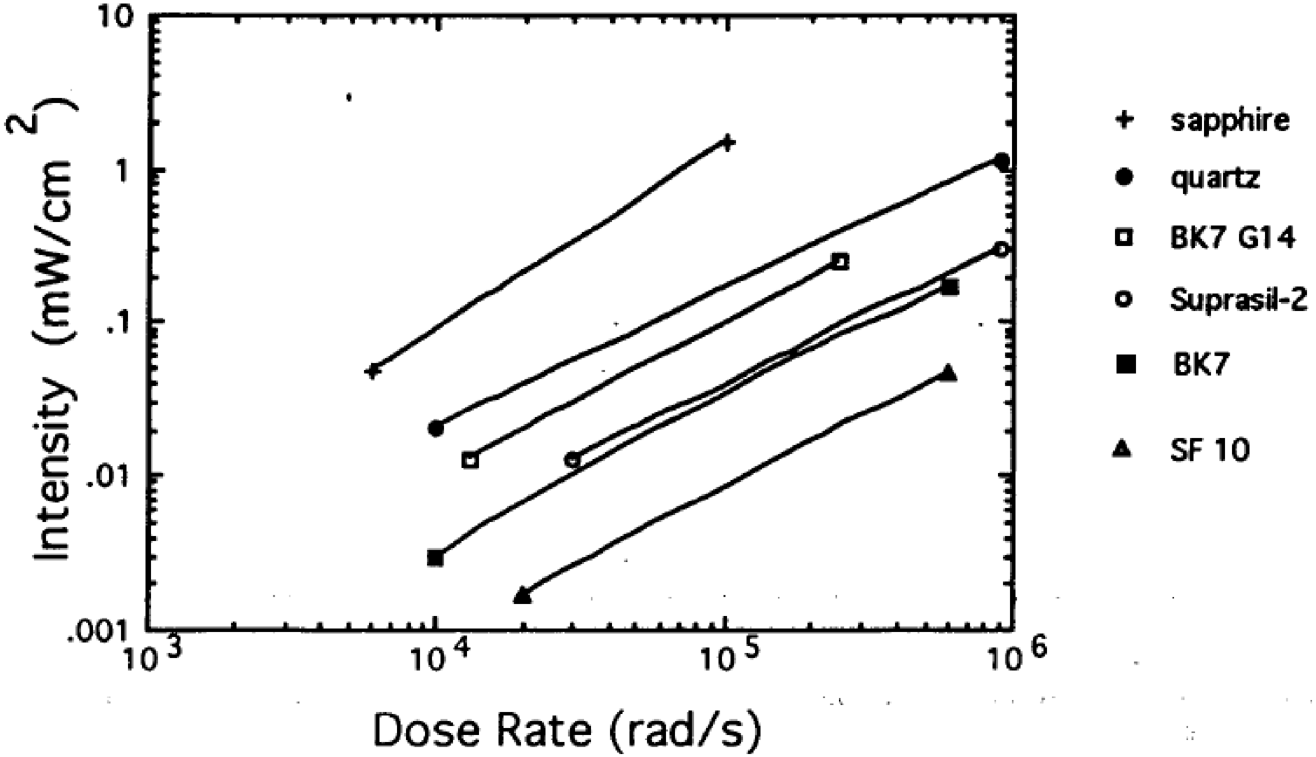
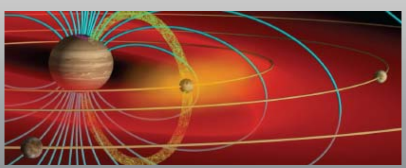


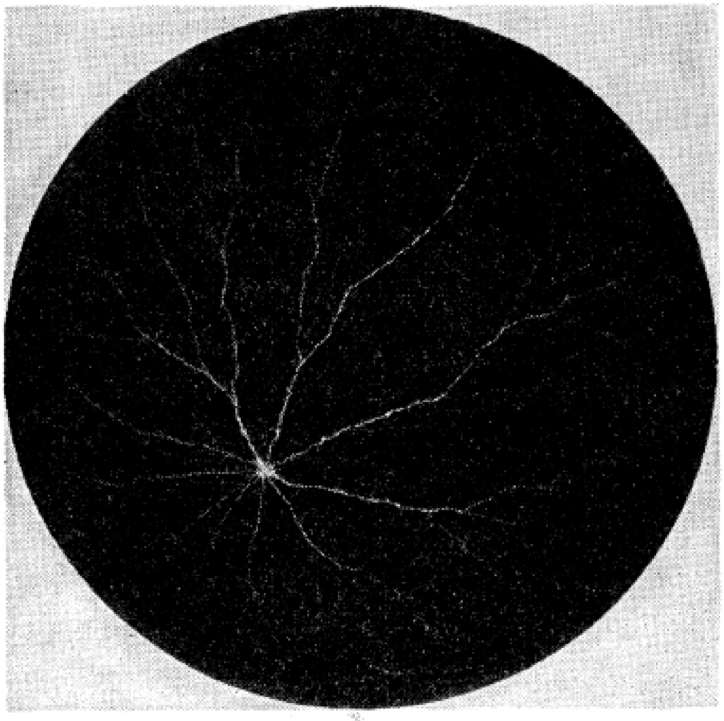
Fig. 3: Radiouluminsence intensity vs. dose rate for selected optical materials. [Treadaway (1975a)]

Treadaway (1975a) M.J. Treadaway, B.C. Passenheim and B.D. Kitterer "Transient Radiation Effects in Optical Materials" Intelcom Rad Tech Inc. Report No. SAMSO-TR-75-174. This is a very thorough and information packed report on a series of experiments that addressed particularly the study of the effects of radiation on optical materials of interest in connection with spacecraft.

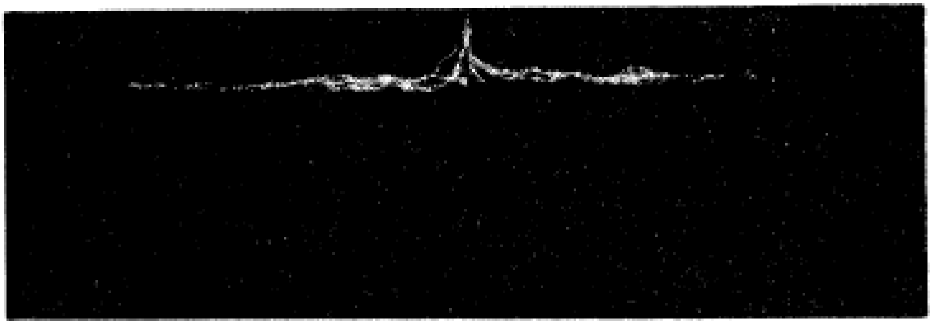


Dielectric Breakdown

Lichtenberg figures



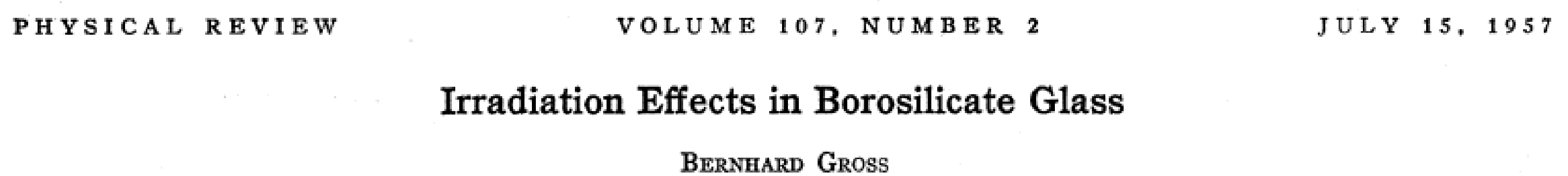
(a)



(b)

FIG. 1. (a) Top view of discharge figure in borosilicate sample. (b) Lateral view of discharge figure in borosilicate glass (for this photograph a lateral section of the sample was cut away, to avoid distortion of the picture by the curved lateral surfaces).

Known since 1957!



PHYSICAL REVIEW VOLUME 107, NUMBER 2 JULY 15, 1957

Irradiation Effects in Borosilicate Glass

BERNHARD GROSS

Filters & Coatings

Rosetta, OSIRIS Camera

468 H. U. KELLER ET AL.

SSR, 128, 2007

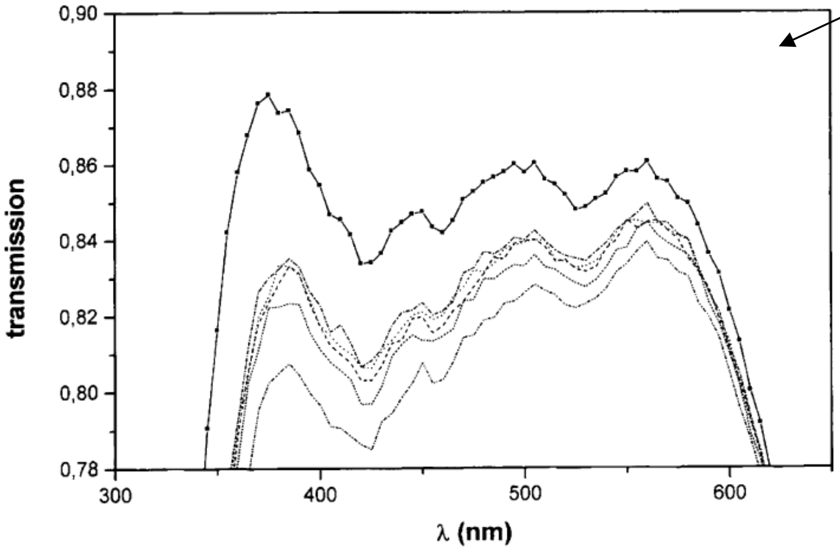


Figure 15. Transmission curves for KG3 glass. The bold curve provides the transmission prior to irradiation to a proton fluence of 10^{13} cm^{-2}. The dashed curves show the recovery of transmission with time at room temperature.

Colour Glass, with annealing recovery over days (at room temp)

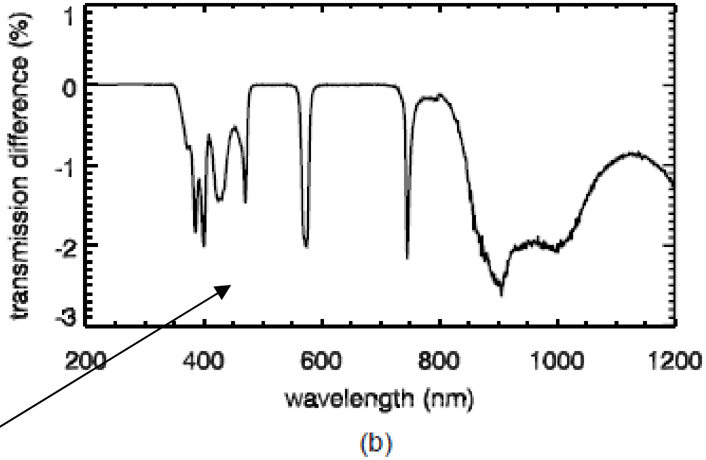
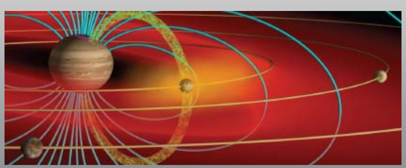


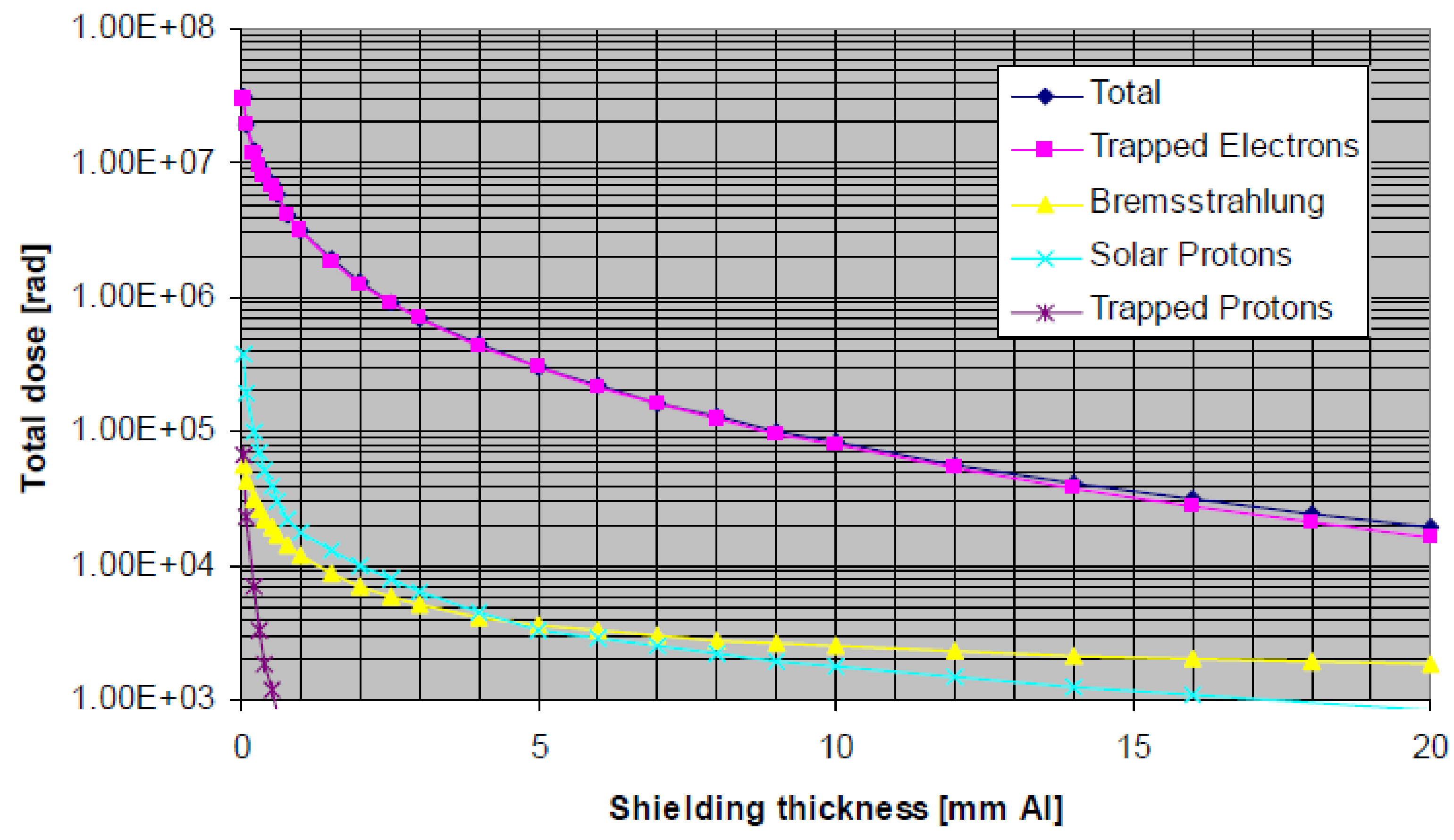
Fig. 3. (a) Measured transmission of the 572-nm interference filter as a function of wavelength. Continuous curve, non-irradiated filter; dashed 30-keV irradiated portion of the filter. (b) Difference between the non-irradiated portion of the filter and the irradiated portion.

Naletto et al App. Opt. 42, 2003

Interference Filter
Delta tx post p+ irradiation

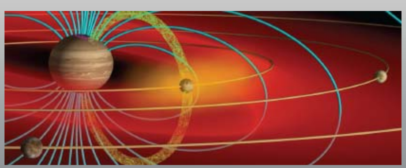


Peculiarities of the EJSM JGO Radiation Environment



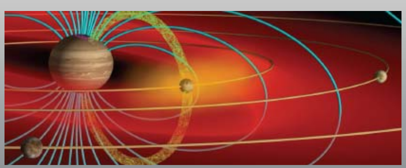
ESA Laplace Environment Spec, Iss. 2 Rev 0, JS-14-09

- Trapped electrons are the dominant ionising radiation component >50 MRad surface dose equivalent
- Dose rate estimate for Glass 30 mRad/s (for 10 mm Al equiv shielding)



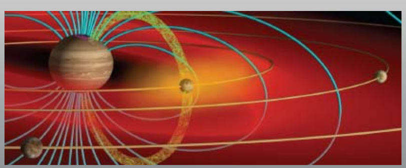
Approaches for Qualification and Testing

- Differential testing essential
  - – Baseline before irradiation
  - – Incremental dose accumulation
  - – Measure performance loss after each step
  - – Maintain unirradiated control sample(s)
- Test for annealing impact (long term)
- Temperature and environment (air/vacuum) may be important



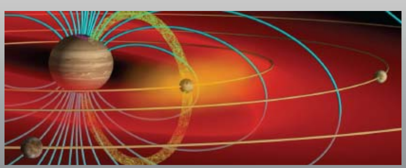
Literature, Sources

- Check complimentary reports from testing of materials in other domains e.g.
  - Plasma Fusion reactor programmes (e.g. ITER, where doses of >100s GRads are reached!)
  - Laser fusion programmes
  - X & EUV optics for lithography projectors
  - Particle accelerators e.g. LEP at CERN
  - Glass fiber radiation responses (V. long path lengths)



Some Data and Literature Resources

- ESA Radiation Effects Unit web site “ESCIES”
  - https://escies.org/ReadArticle?docId=227
- NASA Photonics web site “Miss Piggy at Goddard”
  - http://misspiggy.gsfc.nasa.gov/photonics/
- IEEE Radiation Effects Data Workshops
  - http://ieeexplore.ieee.org/xpl/RecentCon.jsp?punumber=7606
- SPIE Digital Library
  - Conference series on Photonics for Space & Radiation Environments (Ed. Taylor)
  - http://spie.org/x648.html?product_id=382659



Selected References 1

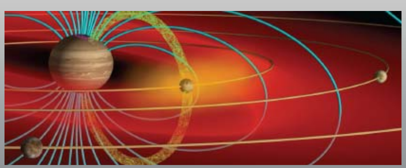
Optical design and technologies for space instrumentation
R.H. Czichy, SPIE Proceedings Vol 2210, 1994

Radiation-stable infrared optical components
Nicolai D. Savchenko, T. N. Shchurova, A. Kondrat, and N. I. Dovgoshej, Proc. SPIE Int. Soc. Opt. Eng. 3359, 523 (1998)

Radiation qualification and testing of a large number of optical glasses used in the ESA Fluid Science Laboratory onboard the Columbus Orbital Facility of the International Space Station
Dominic B. Doyle, Thierry M. Dewandre, Dirk Claessens, Ellen De Cock, Luc Vautmans, Olivier Dupont, and Andrei I. Gusarov, Proc. SPIE Int. Soc. Opt. Eng. 4823, 124 (2002)

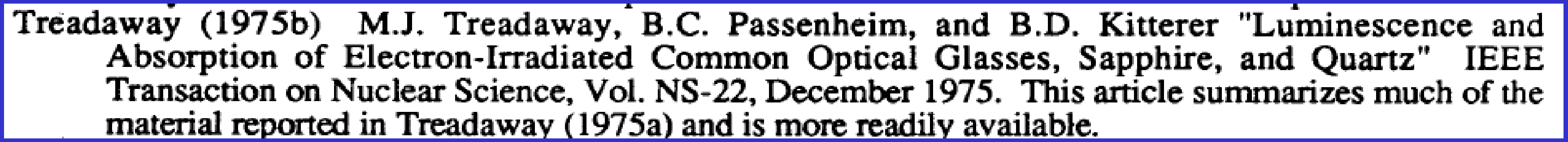
Measuring space radiation impact on the characteristics of optical glasses: measurement results and recommendations from testing a selected set of materials
Michel Fruit, Andrei I. Gusarov, and Dominic B. Doyle, Proc. SPIE Int. Soc. Opt. Eng. 4823, 132 (2002)

Space radiation testing of radiation-resistant glasses and crystals
Tammy D. Henson and Geoffrey K. Torrington, Proc. SPIE Int. Soc. Opt. Eng. 4452, 54 (2001)



Selected References 2

P.W.Levy: Overview of nuclear radiation damage processes: phenomenological features of radiation damage in crystals and glasses; *SPIE Proc.* 541 p.2 (1985)



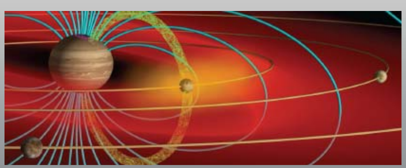
Treadaway (1975b) M.J. Treadaway, B.C. Passenheim, and B.D. Kitterer "Luminescence and Absorption of Electron-Irradiated Common Optical Glasses, Sapphire, and Quartz" IEEE Transaction on Nuclear Science, Vol. NS-22, December 1975. This article summarizes much of the material reported in Treadaway (1975a) and is more readily available.

Effects of ionising radiation on selected optical materials: An overview
Wirtenson, G.R. & White, R.H., Tech. Report LLNL, UCRL-ID-111453, 1992

Effects of radiation on the properties of low thermal expansion coefficient materials: A review
M. Rajaram & J.E Friebele, J. Non Cryst, Solids, Vol 108, 1989

Discharge phenomena in electron-irradiated glasses
A.I. Akishin, Yu.S. Goncharov, L.S. Novikov, Yu.I. Tyutrin and L.I. Tseplyayev
Radiation Physics & Chemistry, Vol 23, Iss. 3, 1984, (Special Issue Trapping Charge Phenomena in Irradiated Dielectrics)

Charging of mirror surfaces in space
S.T. Lai, J.Geophys.Res. Vol 110, 2005



Selected References 3 (Coatings & Filters)

***Effect of Gamma-ray irradiations on optical filter glass*.**

Appourchaux, Thierry; Gourmelon, George; Johlander, Bengt. Optical Engineering. 1994 May; 33(5): pp 1659-1668.

***Optical filters and mirrors//Chapter VI Analysis of filter and mirror performance*.**

Blue, M. D. Chapter V, Investigation of the effects of long duration space exposure on active optical system components. Langley, VG: NASA; 1994 Oct; NASA Contractor report 4632.

***Effect of Space Charged Particle Environment on Optical Components and Materials*.**

Bourrieau, J.; Romero, M. Proceedings of and ESA Symposium on Spacecraft Materials; 1979 Oct; ESTEC, The Netherlands. : ESA; 1979; ESA SP-145: 275-285.

***Vacuum Deposited Optical Coatings Experiment*.**

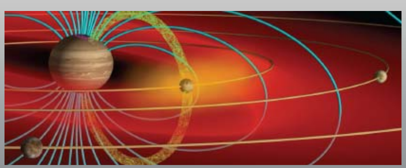
Charlier, Jean, Matra, Velizy. Levine, Arlene S. LDEF - 69 Months in Space, First Post-Retrieval Symposium; 1991 Jun; Kissimmee, Florida. Hampton, Virginia: NASA, Langley; 1991; NASA Conference Publication 3134: pp 1343-1360.

Synthesis of Broadband Anti-reflection Coatings for Spaceflight Infra-red Optics.

Cole, C.; Bowen, J. W., University of Reading, UK. Dewandre, Thierry M.; Schulte-in-den-Baumen, Joachim J.; Sein, Emmanuel. Space Optics 1994: Space Instrumentation and Spacecraft Optics; 1994 Apr; Garmisch-Partenkirchen, FRG. Bellingham, Washington: SPIE; 1994; 2210: pp 506-532. ISBN: 0-8194-15146.

Proton Radiation Damage in Optical Filter Glass.

Grillot, P. N.; Rosenberg, W. J. Applied Optics. 1989; 28(20): p. 4473.



Selected References 4
Compaction of Fused Silicas

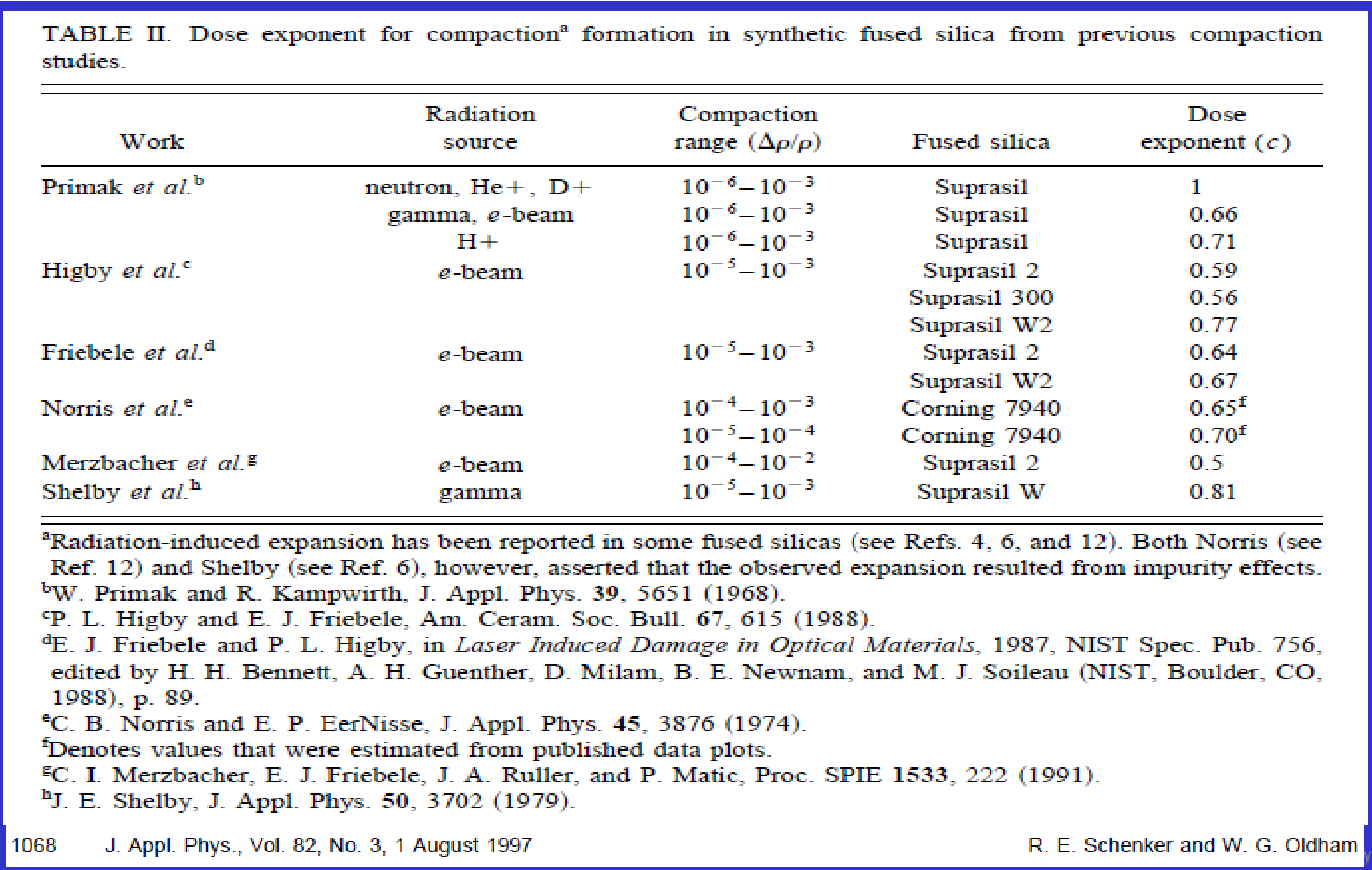


TABLE II. Dose exponent for compaction[a] formation in synthetic fused silica from previous compaction studies.

Work	Radiation source	Compaction range ($\Delta\rho/\rho$)	Fused silica	Dose exponent (c)
Primak *et al.*[b]	neutron, He+, D+	$10^{-6}-10^{-3}$	Suprasil	1
	gamma, *e*-beam	$10^{-6}-10^{-3}$	Suprasil	0.66
	H+	$10^{-6}-10^{-3}$	Suprasil	0.71
Higby *et al.*[c]	*e*-beam	$10^{-5}-10^{-3}$	Suprasil 2	0.59
			Suprasil 300	0.56
			Suprasil W2	0.77
Friebele *et al.*[d]	*e*-beam	$10^{-5}-10^{-3}$	Suprasil 2	0.64
			Suprasil W2	0.67
Norris *et al.*[e]	*e*-beam	$10^{-4}-10^{-3}$	Corning 7940	0.65[f]
		$10^{-5}-10^{-4}$	Corning 7940	0.70[f]
Merzbacher *et al.*[g]	*e*-beam	$10^{-4}-10^{-2}$	Suprasil 2	0.5
Shelby *et al.*[h]	gamma	$10^{-5}-10^{-3}$	Suprasil W	0.81

[a] Radiation-induced expansion has been reported in some fused silicas (see Refs. 4, 6, and 12). Both Norris (see Ref. 12) and Shelby (see Ref. 6), however, asserted that the observed expansion resulted from impurity effects.

[b] W. Primak and R. Kampwirth, J. Appl. Phys. **39**, 5651 (1968).

[c] P. L. Higby and E. J. Friebele, Am. Ceram. Soc. Bull. **67**, 615 (1988).

[d] E. J. Friebele and P. L. Higby, in *Laser Induced Damage in Optical Materials*, 1987, NIST Spec. Pub. 756, edited by H. H. Bennett, A. H. Guenther, D. Milam, B. E. Newnam, and M. J. Soileau (NIST, Boulder, CO, 1988), p. 89.

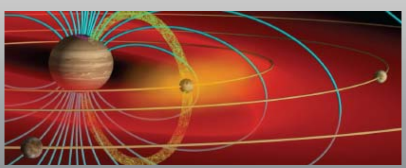
[e] C. B. Norris and E. P. EerNisse, J. Appl. Phys. **45**, 3876 (1974).

[f] Denotes values that were estimated from published data plots.

[g] C. I. Merzbacher, E. J. Friebele, J. A. Ruller, and P. Matic, Proc. SPIE **1533**, 222 (1991).

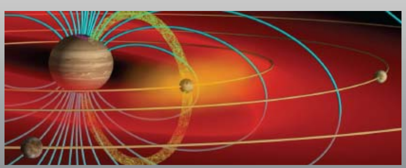
[h] J. E. Shelby, J. Appl. Phys. **50**, 3702 (1979).

1068 J. Appl. Phys., Vol. 82, No. 3, 1 August 1997 R. E. Schenker and W. G. Oldham



Conclusions & Recommendations

- Always carefully review the literature
- Leverage optics design lessons from previous (deep space) missions
- Design to be **RADIATION TOLERANT** vs performance requirements at EOL
- Select materials and alternatives (availability can be a problem)
- Design test campaign to qualify materials against TID requirement
  - Consider Dose rate, Annealing and Energy spectrum
  - Synergistic effects may also be important; temperature environment, thermal cycling, surface charging and dielectric breakdown, UV, molecular contamination, air-vacuum, etc
- Measure induced degradation of the **driving optical performance parameter** for each material
- Test early and often to secure results and evaluate thoroughly to convince QA



Thanks for your Attention

- Dominic Doyle

  - Optics Section ESTEC (TEC-MMO)
  - Room Dg002
  - Telephone +31 71 565 3634
  - Email: dominic.doyle@esa.int