Fused silica glass is used in optical components in lithography equipment for microelectronics. Increasing component densities in modern electronics necessitate shorter wavelengths and higher energies for light sources in the lithography process. Studies have shown that prolonged exposure to UV radiation at usual operating levels can produce damage to the glass in the form of microchannel cracks. It is known that two-photon-absorption of radiation in materials yields changes in the index of refraction and material density of the glass. The goal for the workshop was to understand how microchannels might be produced by the UV exposure – currently the physical mechanism for this is not understood and may be dominated by electromagnetic effects (nonlinear wave propagation for the UV radiation) or solid mechanics (elasticity theory for the glass) or coupling for these aspects.

In the workshop, a core group of approximately sixteen participants (faculty and graduate students) focused on examining the electromagnetic model for UV wave propagation through the glass. This is motivated by the possibility that nonlinearities in the optics model can destabilize the primary beam intensity profile and re-focus the radiation into much smaller beams, called filamentation. Such filamentary beams could plausibly have the spot-size of microchannels and the intensity needed to burn microchannels in the silica. Figures from previous studies suggest that the microchannels can form with regular spacing around the nominal perimeter of a circular beam, as might be expected from an angular perturbation mode from the linear stability of an axisymmetric beam.

Most of the analysis and numerical simulations carried out in the workshop were applied to a paraxial wave model given by E.M. Wright et al (Applied Optics 1999) which included irreversible compaction (increase in the index of refraction) due to cumulative radiation dose. Using this model, we have the following equation for the slowly-varying amplitude $A$:

$$2i k^2 n_0^2 \left( \epsilon_z \frac{\partial A}{\partial z} + \epsilon_t \frac{\partial A}{\partial t} \right) = \frac{\partial^2 A}{\partial x^2} + \frac{\partial^2 A}{\partial y^2} + k^2 n_0^2 \left[ 2 \epsilon_z P^b + \epsilon_t^2 P^{2b} \right] A, \quad P = \int_0^t |A|^4 \, dt'. $$

Here $P$ represents the two-photon dose term, $n_0$ is the index of refraction initially, $k$ is the wavenumber for the carrier wave, and the small parameters $\epsilon$ measure the difference in scales between the carrier and slowly-varying waves.

Analytical efforts yielded a new formula for the phase of the uniform plane waves in this model. Using this as a base state, linear stability did provide a criterion suggesting that after a critical time there will be spatial linear instabilities yielding growth of intensity in the direction of propagation. Numerical simulations using finite difference methods produced results consistent with these predictions. Further analysis is needed for the case of Gaussian beams. Preliminary numerical studies for circular beams showed that maximum intensities on exiting the glass did occur in annular rings – further studies are needed to determine whether these rings are stable or some observed numerical instabilities (break-up into patterns of spots) are physically robust.

In addition to more careful analysis of the Wright model, other work carried out in the workshop included:

- More careful derivation of the paraxial wave equation from Maxwell’s equation to retain other terms stemming from spatial and temporal variation of the index of refraction (time-dependent heterogeneity of the glass). Preliminary analysis of this model yielded first-order transport equations for the amplitude and phase for plane-wave wave packets.

- Review of the research literature on development of laser-induced cracking of silica and formation of sub-scale nanogratings suggested that cumulative effects of low-intensity laser pulses could lead to growth of microchannels through stress concentrations formed at the edge of the imposed UV beam. Further work is needed to formulate an appropriate solid mechanics model forced on multiple time-scales by the UV-induced compaction.