Powerful X-ray source on the basis of CW 600-keV electron LINAC

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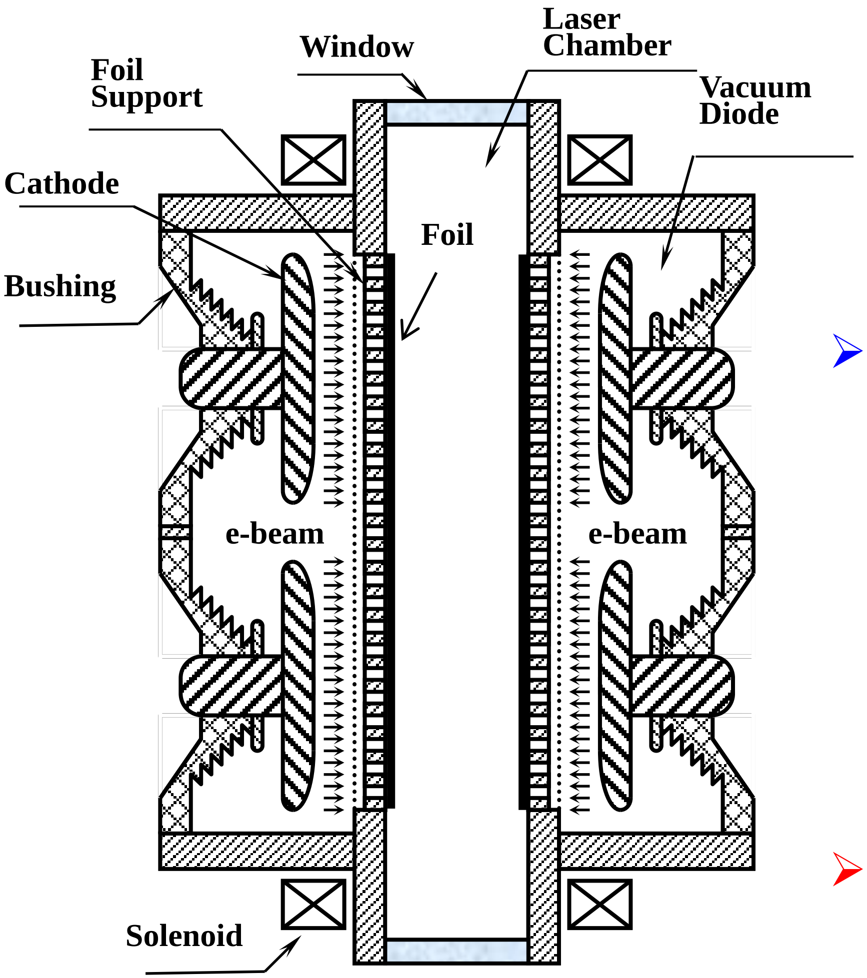
Motivation

Schematic of e-beam-pumped laser

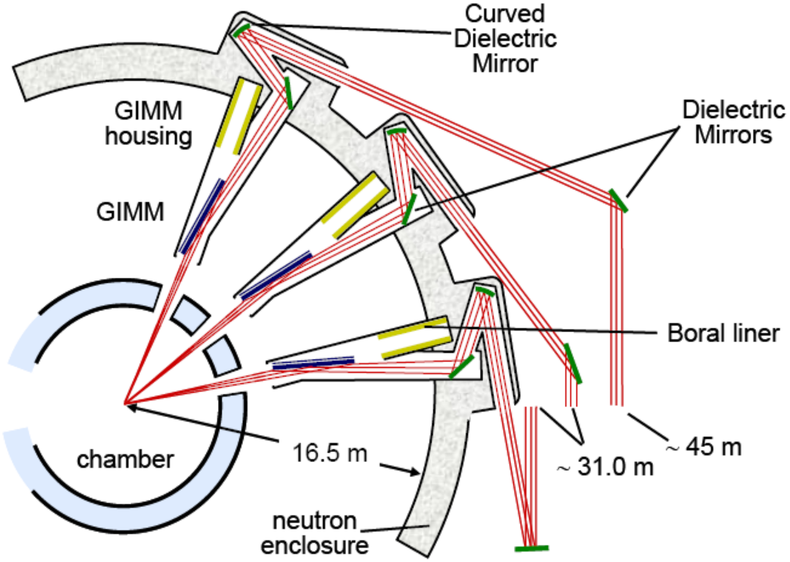


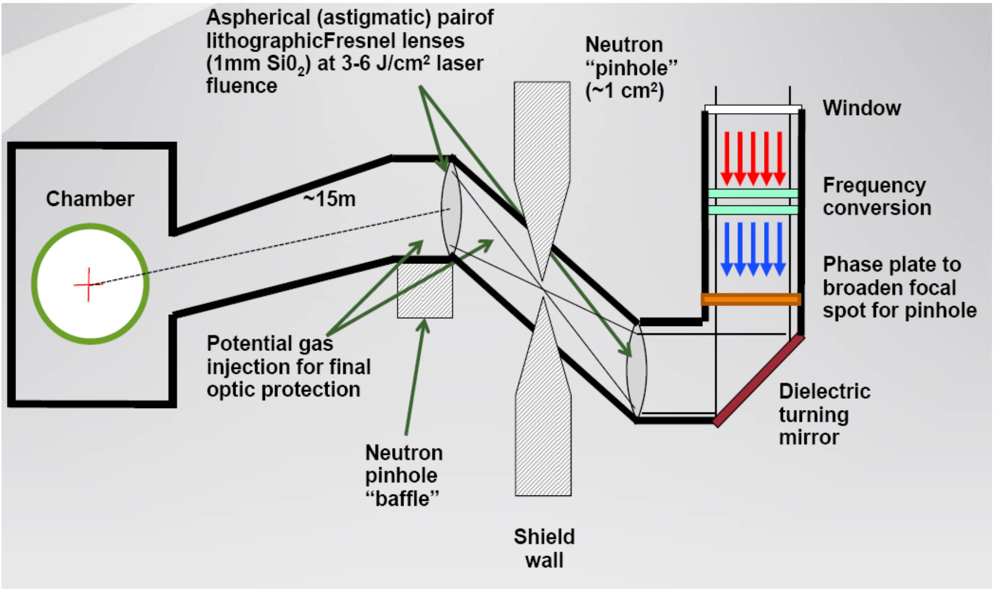
- **Laser driver for the Inertial Fusion Energy (IFE) power plant should operate at repetition rate of 5–10 Hz uninterruptedly for two years with pulse energy ~1 MJ, overall efficiency ~7%, producing totally $3*10^8$ pulses (I.N. Sviatoslavsky, *et al. Fusion Tech*, 1992, 21, 1470).**
- **E-beam-pumped KrF lasers can satisfy these severe conditions. High radiation stability is required for KrF laser windows irradiated by UV light, scattered electrons and bremsstrahlung X-rays . For instance, total absorbed X-ray doses ~1 MGy during the operation run might cause significant degradation of KrF laser window transmittance.**
- **Our goal was to develop a powerful hard X-ray source, which is capable to deliver over 1 MGy doses to samples of various optical materials within reasonable irradiation time ~ 10−100 hours.**

Motivation

KrF Fusion Test Facility design (NRL)

DPSSL LIFE design (LLNL)



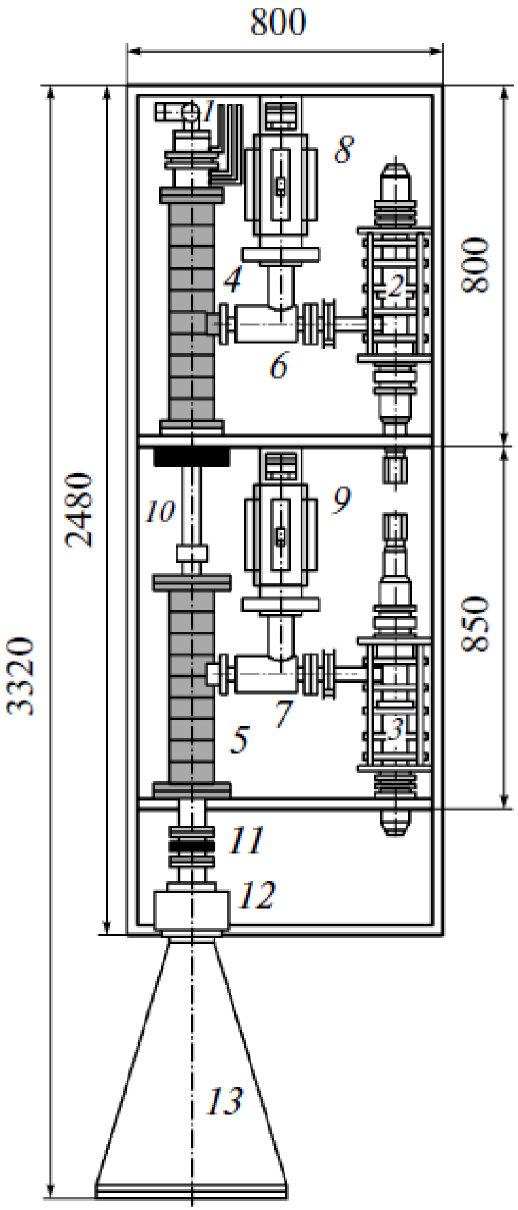


Ionizing-radiation-induced darkening caused by color centers formation is also one of the most serious problems for transmissive optics of the target chamber of the IFE plant suffering from different kinds of ionizing radiation: TN neutrons, gamma rays, x-rays, ions, and target debris.

Linear quasi-CW e-beam accelerator at Skobel’tsyn Institute of Nuclear Physics, Moscow State University

LINAC repetitively operates at 2450-MHz with pulse duration of ~20 ps.
Electrons energies 600 and 1200 keV with current 0÷50 mA are available (the maximum power ~60 kW) .

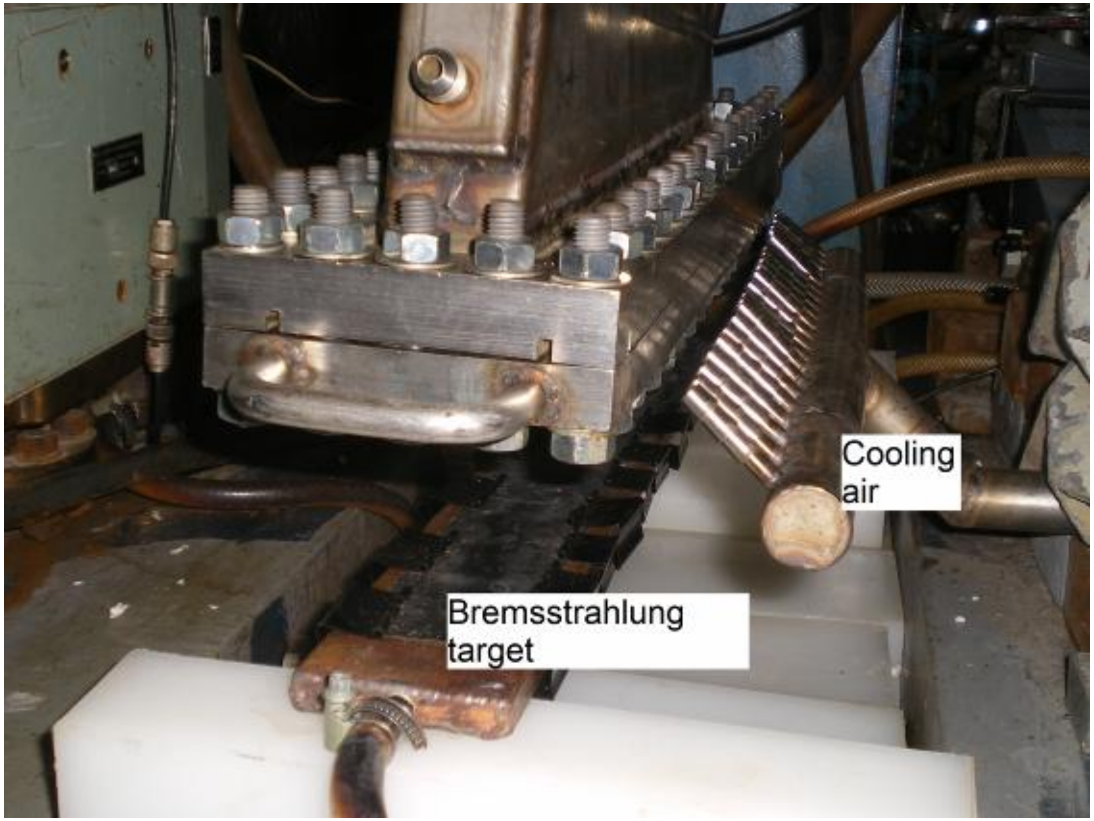
E-beam gun (1); klystrons (2, 3); 1st and 2nd accelerating sections (4, 5); feeding waveguides (6, 7); ion pumps (8, 9); intermediate drift space (10); transverse and longitudinal scanning magnets (11, 12); chamber for e-beam ejection into the atmosphere (13).



LINAC adjustment for X-ray generation

- In routine operation e-beam with a total current ≤ 1 mA is magnetically scanned over 40×5 = 200 cm^2 area and extracted to atmosphere through ~ 100 μm Ti foil.
- To obtain 600 keV e-beam the 2nd LINAC section was switched off. To minimize e-beam interaction with 2nd section structure, its resonance frequency was detuned of the 1st one.
- To realize the required X-ray power e-beam current was increased up to 20 mA (12 kW) with Ti foil cooling by air flow (30-50 m/s) and bremsstrahlung converter was designed with Ta plates (0.3 mm) set at water-cooled Cu tube of rectangular cross section.

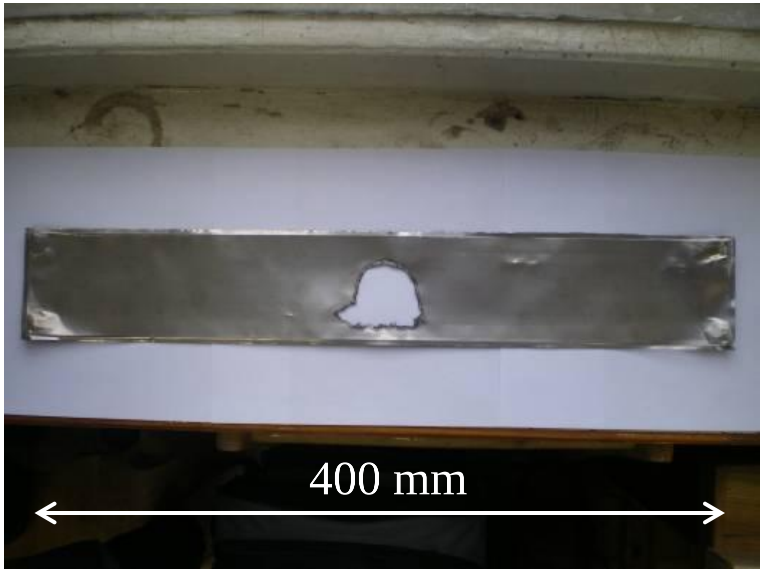
E-beam output horn



Design of bremsstrahlung e-beam converter

Large-area e-beam-scanning performance

- In the first experiments on generating bremsstrahlung radiation, e-beam transmission through the 2nd unpowered section was optimized and e-beam scanning amplitude was adjusted in two orthogonal directions at low beam current (below 0.1 mA). The magnitude of the injected beam current was regulated by voltage at the 1st gun anode. Injected e-beam dimensions for different currents were kept constant by appropriate adjustment of the 2nd anode voltage.
- After accelerator tuning we increased 1st anode voltage to get about 20-mA injected e-beam. To our regret, in this set of experiments because of e-beam scanning system failure the output Ti foil was burned out, and tungsten-impregnated cathode of our electron gun was poisoned by atmosphere air.

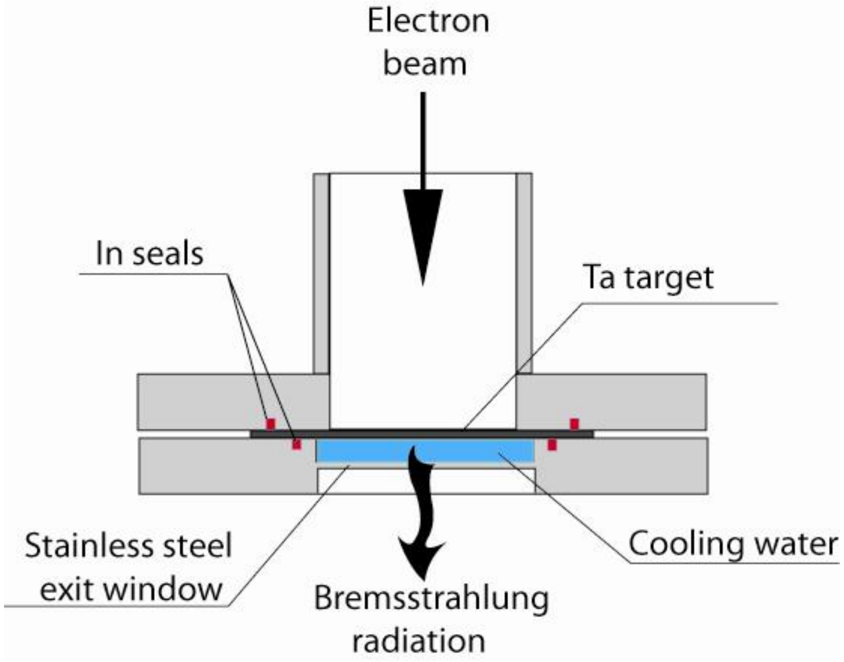


- Large-area magnetically-scanned performance of the X-ray source requires about 100 hours to produce ~1 MGy dose, while the critical issue for a long-time operation is thin Ti foil.

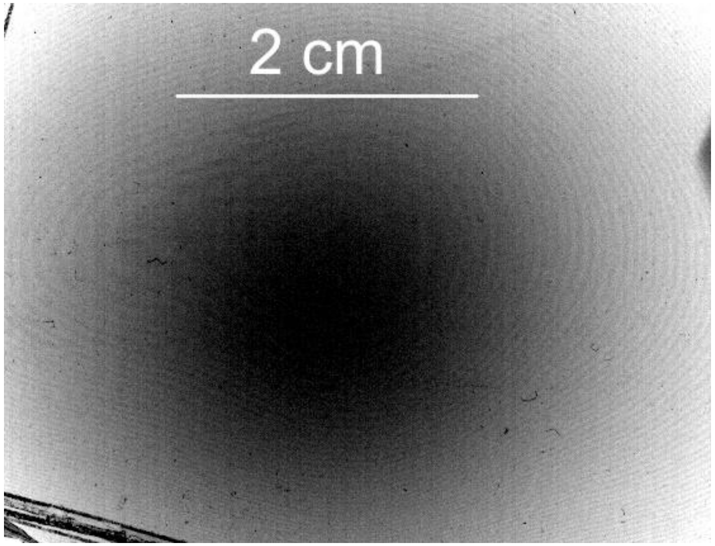
Ti foil burned out by e-beam current

Sealed performance of X-ray converter

- **Novel sealed design of the X-ray converter was implemented: instead of e-beam extracting to atmosphere through thin Ti foil, 0.3-mm thickness W target was used, being placed in vacuum downstream e-beam accelerated in the 1st stage of the LINAC, while the 2nd section was dissembled.**
- **It was expected to produce significantly higher X-ray flux with lower e-beam current of few mA in a small cross section diameter ~1 cm at the target .**

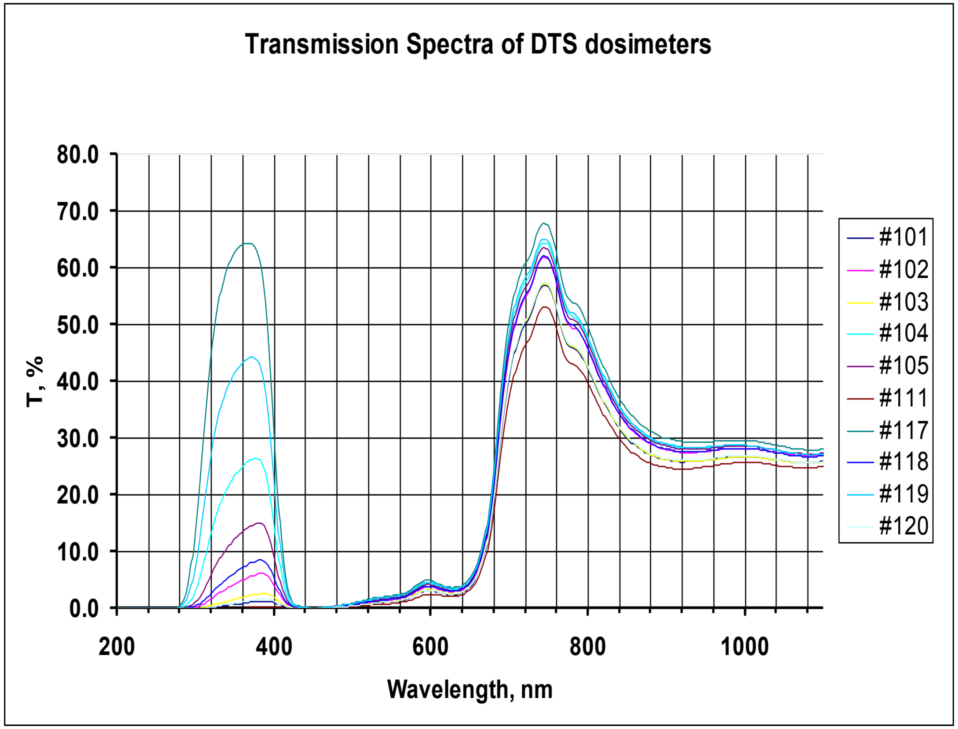


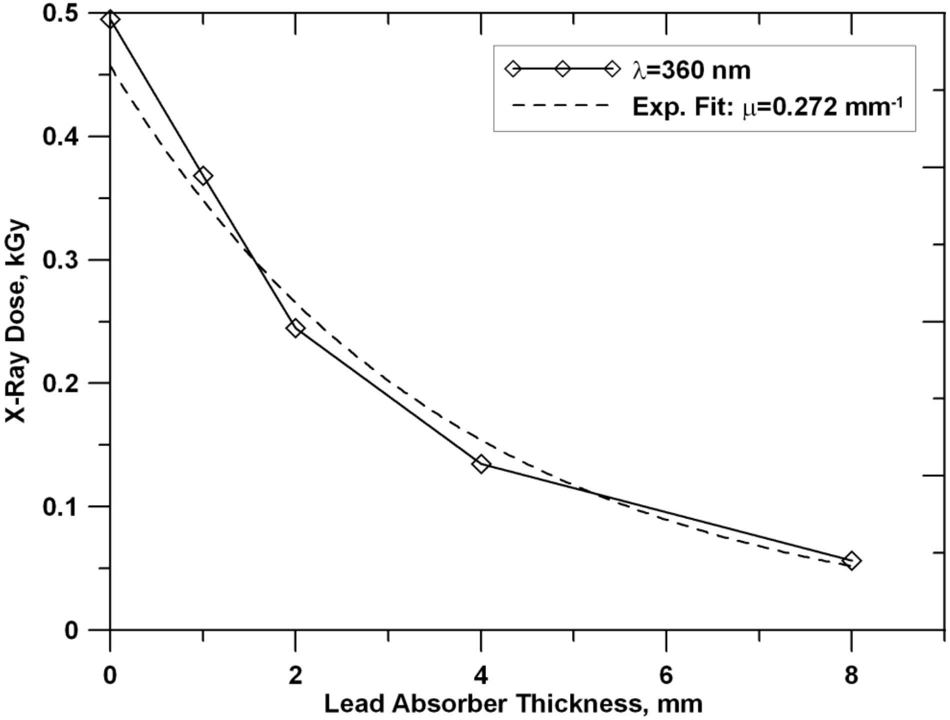
Sealed design of X-ray converter



Imprint of X-ray irradiation on the glass plate at 1.7-cm from the target

Characterization of Hard X-Ray Source





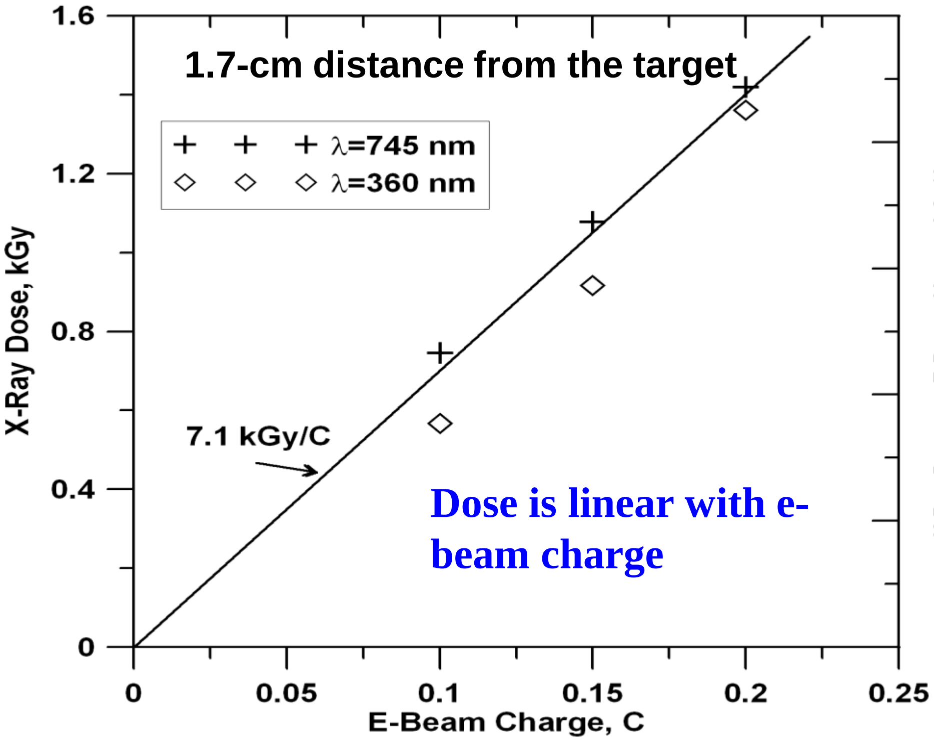
Calibrated nickel-activated silicon glass DTS–0.01/1 dosimeters were use for x-ray dose measurements.

$D = 28.2 \times A^{2.32}$ (kGy) at λ=745 nm

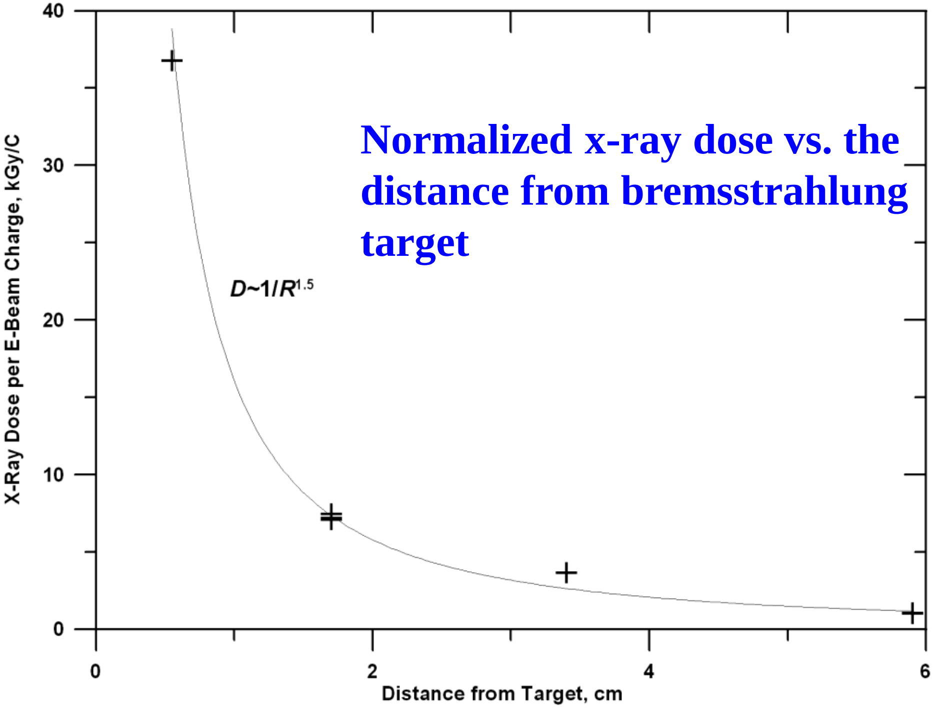
$D = 464.6 \times A - 33.1$ (kGy) at λ=360 nm

The best exponential fit to the experimental attenuation curve in the lead is achieved for absorption coefficient $\mu = 2.72\ \text{cm}^{-1}$ corresponding to the mean energy of x-ray quanta $h\nu \approx 400$ keV

Characterization of Hard X-Ray Source



Dose is linear with e-beam charge



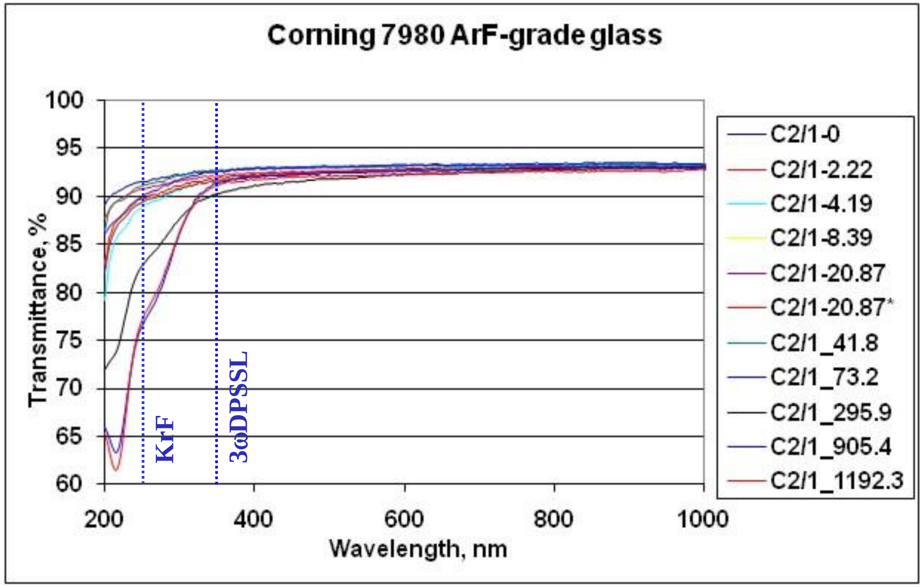
Normalized x-ray dose vs. the distance from bremsstrahlung target

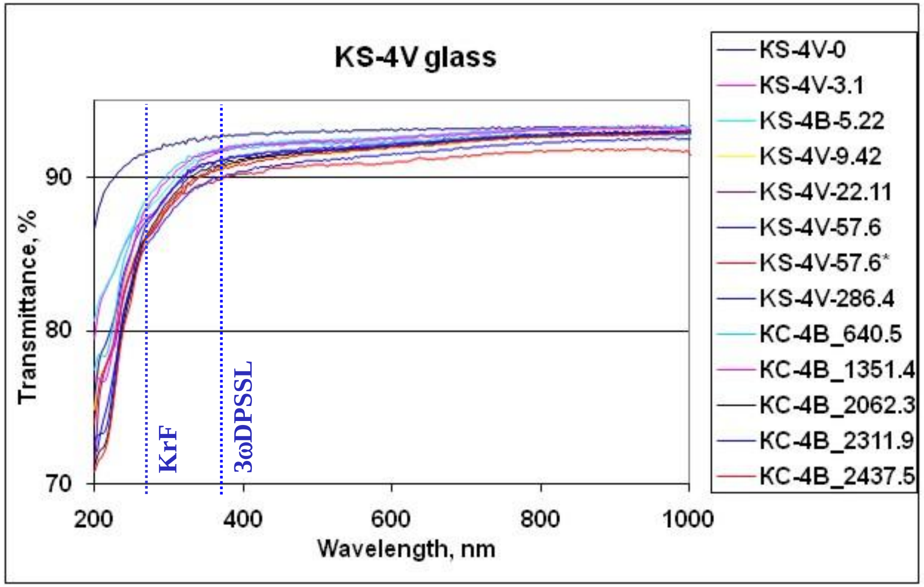
Dose rate of x-rays with average *hν* = 400 keV is up to 30 Gy/s at 5-mA e-beam current. Doses as high as 1 MGy are available for irradiation time less then 10 hours.

Optical samples under testing

- **Fused silica** is considered to be the material of choice for reactor chamber windows and final Fresnel lenses, as well as for KrF laser driver windows. Large-size (~1-m), high-quality thermomecanically and radiation-stable optical elements can be produced of different kinds of this glass.
  Russian KU-1 glass and analogues Corning 7980 have hydroxyl OH concentration ~1000 ppm, other impurities (mainly chlorine) are from ~200 ppm (KU-1) to 20 ppm (ArF- grade Corning 7980). The novel KS-4V glass from I.V. Grebenshchikov Institute of Silicate Chemistry has impurity concentration (of the main 15 elements) less than 0.5 ppm, OH less than 0.1 ppm, and chlorine less than 20 ppm.
- **Fluorite (CaF_2)** crystals although being less mechanically strength are well suitable for fluorine environment in UV and VUV domains as laser windows. The impurity concentration in CaF_2 from S.I. Vavilov State Optical Institute was ~15 ppm.
- **MgF_2** crystals and **leicosapphire Al_2O_3** being highly resistant to fluorine etching are common materials for multilayer AR and HR coatings of KrF laser windows and mirrors. High-purity MgF_2 samples from Corning, Kerth Cristalle were chosen for testing along with MgF_2 and Al_2O_3 samples from State Optical Institute.

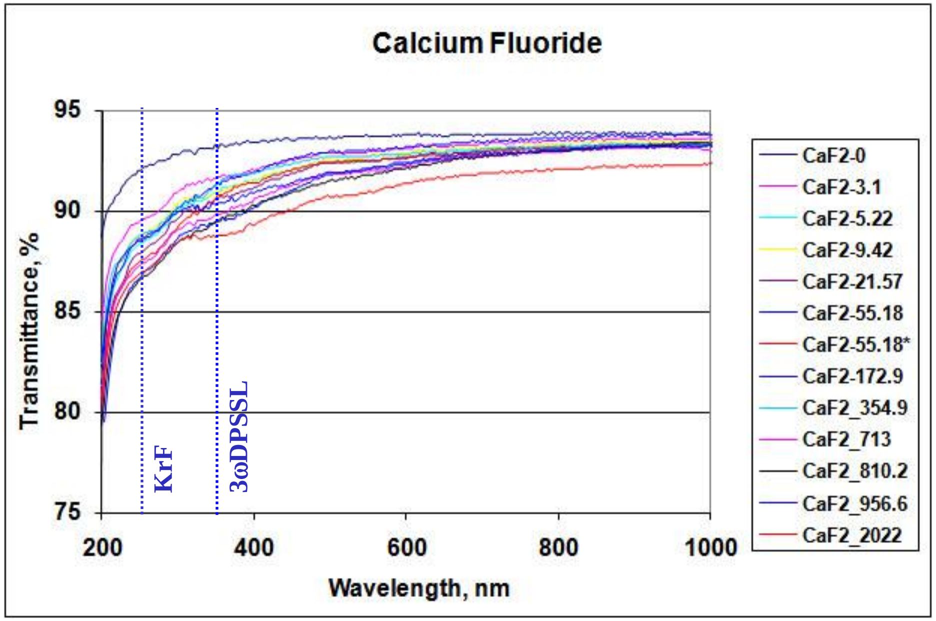
Degradation of Optical Materials under X-Ray Irradiation (Fused Silica)

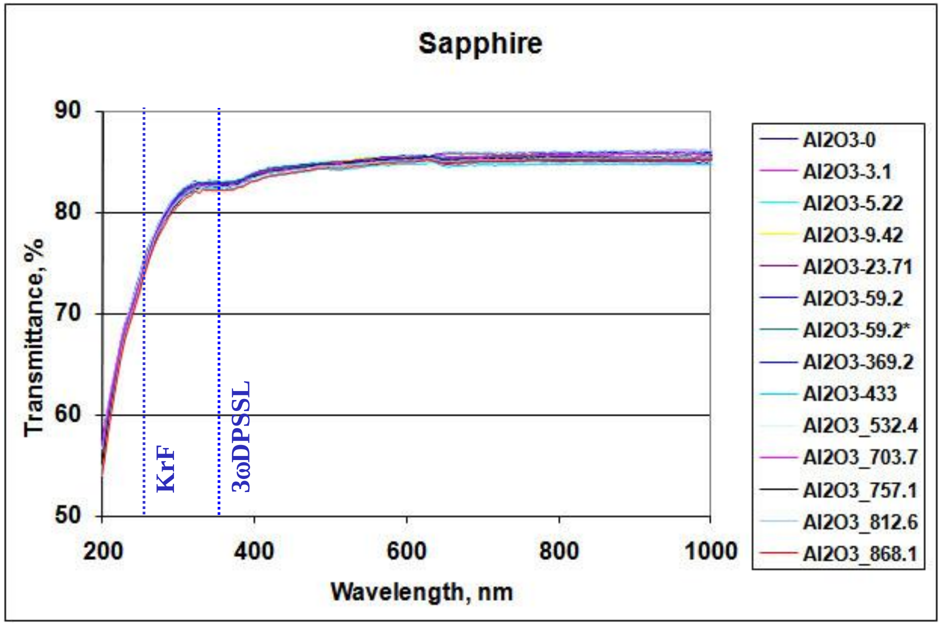




- **The most intensive absorption bands in X-ray irradiated fused silica are observed at 213 nm (E´ centers) and 260 nm (NBOHC);**
- **“Dry” KS-4V glass demonstrates better radiation stability in the UV spectral range than ArF-grade Corning 7980, which was the best among “wet” glasses;**
- **X-ray-induced absorption for 3ωDPSSL (λ=353 nm) is less than for KrF laser (λ=248 nm).**

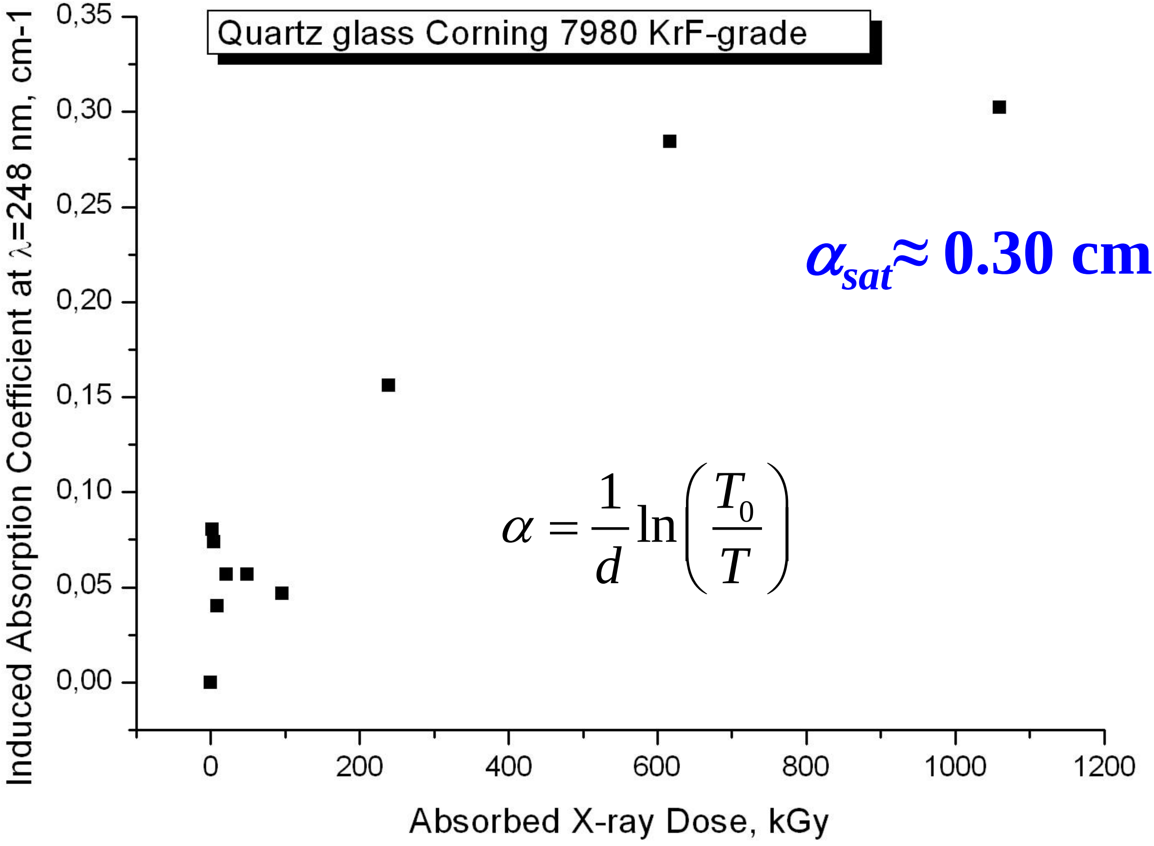
Degradation of Optical Materials under X-Ray Irradiation (CaF_2 & Al_2O_3)





- **CaF_2 and Al_2O_3 crystals are the most stable UV optical materials under X-ray irradiation;**
- **For tested materials SiO_2, CaF_2 Al_2O_3 (densities ρ =2.2, 3.2 and 4 g/cm^3) and energy of quanta $h\nu$ ~ 400 keV mass absorption coefficient is μ/ρ ~ 0.1 g/cm^2, and the X-ray range is $l_{X\text{-}ray} = 1/\mu$ ~ 2.5–5.0 cm. X-ray- induced absorption coefficient is appropriate to characterizes transmittance loss.**

Induced absorption coefficient (λ=248 nm) vs. absorbed x-ray dose

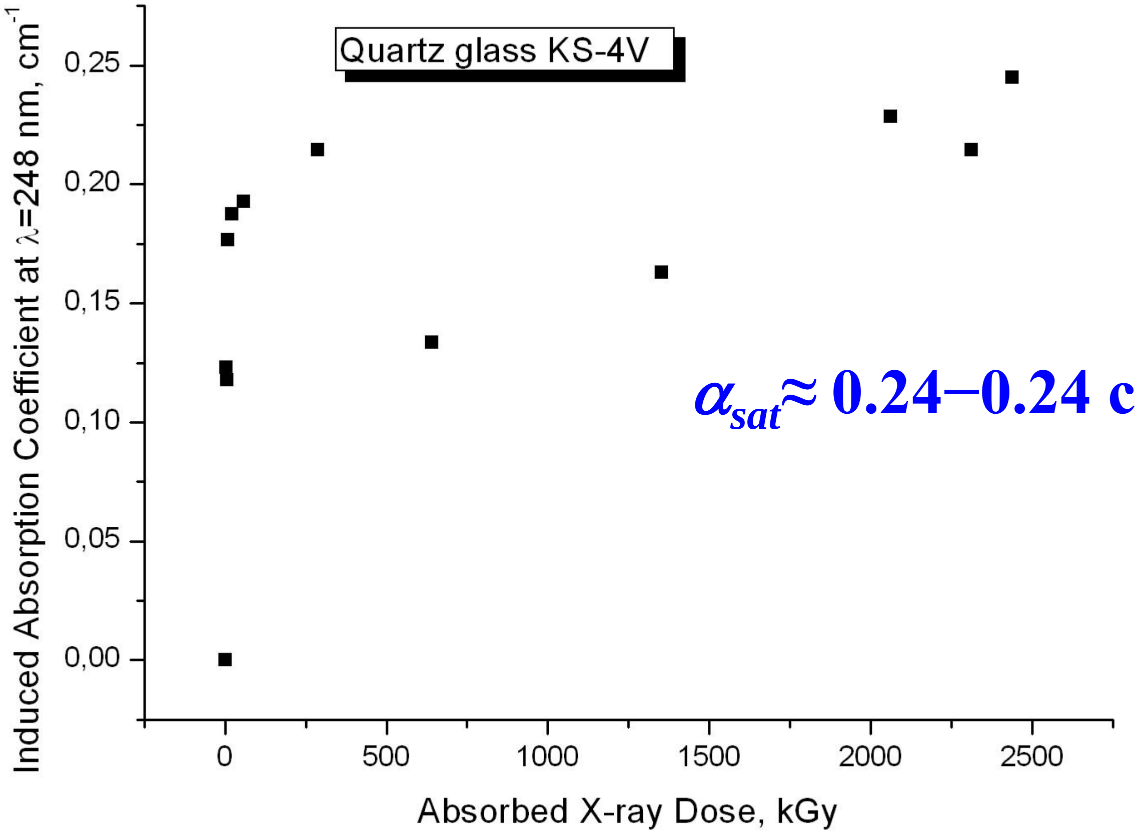


$\alpha_{sat} \approx 0.30\ \mathrm{cm}^{-1}$

$$\alpha = \frac{1}{d}\ln\left(\frac{T_0}{T}\right)$$

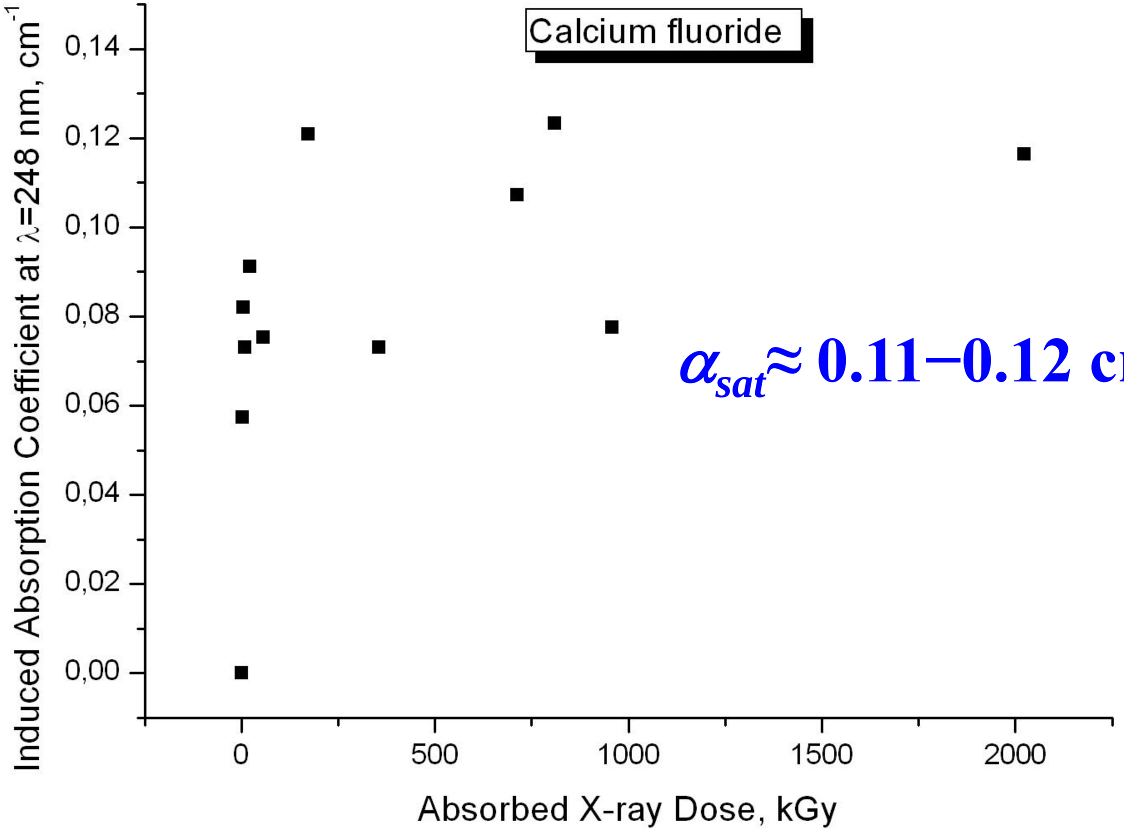
X-ray-induced absorption coefficient α gradually increases in dependence on cumulative absorbed X-ray dose with tendency to saturation though sometimes it is not strictly monotonic.

Induced absorption coefficient (λ=248 nm) vs. absorbed X-ray dose



$\alpha_{sat} \approx 0.24 - 0.24\ \mathrm{cm}^{-1}$

Induced absorption coefficient (λ=248 nm) vs. absorbed X-ray dose



$\alpha_{sat} \approx 0.11 - 0.12\ \mathrm{cm}^{-1}$

Conclusions

- LINAC-based powerful quasi-CW X-ray source with dose rate ~30 Gy/s and 400-keV quanta energy was developed and characterized for testing of radiation stability of the IFE optics.

- Optics response to hard X-ray photons was measured for fused silica, CaF_2 and Al_2O_3 crystals with total amassed doses in the samples as high as ~1–2 MGy.

- The obtained results show that X-ray-induced absorption for both KrF laser (248 nm) and 3ω DPSSL (353 nm) tends to saturate at rather high level resulting in transmission degradation especially for shorter laser wavelength.

- Temperature annealing and bleaching of color centers by UV (or X-ray) radiation may reduce darkening of the IFE reactor chamber and laser driver optics.