Powerful X-ray source and numerical code for simulation of transmissive optics darkening in the course of KrF laser-driven IFE engine operation

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Motivation

- Only $3\omega$ (or $2\omega$) Diode Pumped Solid State Laser (DPSSL) and e-beam-pumped Krypton Fluoride (KrF) laser can interruptedly operate for a long time at a repetition rate of 5–10 Hz with high pulse energy $\sim 1\text{MJ}$ and overall efficiency $\sim 7\%$ to satisfy the requirements for the future IFE power plant laser driver (T.C. Sangster, R.L. McCrory, V.N. Goncharov et al., *Nucl. Fusion* 2007, 47, S686).

- Large-size, high laser strength and radiation resistant optics, which collects numerous laser beams on the TN capsule, is one of the critical issues for the IFE engine.

- Reactor chamber final optics suffers from TN neutrons, X-rays, ions, and target debris while e-beam-pumped KrF laser windows are illuminated by hard Bremsstrahlung and soft characteristic X-rays. Total absorbed X-ray doses $\sim 1\text{ MGy}$ during the operation run might cause significant degradation of KrF laser window transmittance.

- Our goal is to develop powerful X-ray sources for testing of commonly used optical materials and to elaborate an avalanche numerical code to simulate X-ray transport in the matter.
Motivation


Ionizing-radiation-induced darkening caused by color centers formation is the most serious problem for a transmissive optics.
E-beam-pumped GARPUN KrF laser as a test bench for Bremsstrahlung X-ray measurements

GARPUN laser arranged for X-ray measurements: 1- laser chamber of 19*22*140 cm$^3$ volume; 2- vacuum diode; 3- Ti foil; 4- foil support (hibachi); 5- anode grid; 6- solenoid; 7- cathode; 8- bushing; 9- output windows; 10- X-ray absorbers; 11- lead shielding; 12- NaI(Tl) scintillator; 13- neutral glass filters; 14- photomultiplier.
A stack of TLD dosimeters were used to measure X-ray energy fluence in the position of laser windows.
Attenuation curves measured for different X-ray absorbers

X-ray absorbers
thickness:
Al - 0.2–120 mm
Cu - 0.05–45 mm
Pb - 1–6 mm
Absolute measurements of X-ray emission were performed by means of 1-mm thickness Al₂O₃ TLDs calibrated at standard ¹³⁷Cs radioactive source. A stack of 25 detectors was placed inside an aluminum matrix and accumulated X-ray dozes at the position of output window (1) and at 80-cm from the window (2, 3). In cases (1, 2) laser chamber was filled with the gas, in (3) laser chamber was evacuated.

Energy fluence of X-rays irradiating laser windows is $\sim 1 \cdot 10^{-3}$ J/cm² per shot. For 100-kJ scale ICF KrF laser drivers X-ray fluence onto laser windows can be estimated as $\sim 10^{-2}$ J/cm² per shot.
Monte Carlo Algorithm was developed to calculate electron transport through the matter.

\[ \frac{d\vec{P}}{dt} = e \cdot \left[ \vec{v} \cdot \vec{B} \right] , \quad \vec{P} = \frac{m_e \vec{v}}{\sqrt{1 - v^2 / c^2}} . \]  

(1)

\[ \frac{d\vec{S}}{dt} = \vec{v} , \]

(2)

\[ \xi \in (0,1); Q = N\sigma , \]

Moliere expression for inelastic collisions of electrons with atoms:

\[ \frac{d\sigma_{\text{in}}}{d\varepsilon} = 2\pi r_e^2 \frac{Z}{\beta^2 T} \left[ \frac{1}{\varepsilon^2} - \frac{1}{\varepsilon(1-\varepsilon)} \cdot \frac{(2T+1)}{(T+1)^2} + \frac{1}{(1-\varepsilon)^2} \cdot \frac{T^2}{(T+1)^2} \right] . \]

(3)

Rutherford expression for elastic collisions of electrons:

\[ \frac{d\sigma_{\text{el}}}{d\Omega} = \frac{Z^2}{\beta^2 p_e^2} \frac{r_e^2}{(1 + 2\eta - \cos \theta)^2} . \]

(4)

\[ \eta = \left( \frac{Z^{1/3}}{137 \cdot 0.885} \right) \cdot \frac{1.13 + 3.76 \cdot (Z/137)^2 \cdot (T + 1)^2}{T(T + 2)} . \]

Bethe-Bloch equation for total electron energy loss per unit length:

\[ \frac{dT}{dS} = 0.3056 \cdot \frac{\rho Z}{A\beta^2} \cdot \left\{ \ln\left[ \frac{T^2}{2T^2} \right] + \frac{T^2 / 8 + 1 - (2T + 1) \ln 2}{(T + 1)^2} \right\} . \]

(5)
Monte Carlo code calculating e-beam pumping
Development of an avalanche numerical code for calculating bremsstrahlung X-ray radiation

- Monte-Carlo code for e-beam transport is elaborated to calculate bremsstrahlung X-ray emission yield from the laser cavity and to evaluate a lifetime of laser windows.
- The main purpose of the code under development is simultaneous calculation of e-beam pumping energy distribution in the gain volume and X-ray radiation flux incident on the chamber windows.
- The secondary electrons that appear as a result of photoelectric absorption process can in turn generate X-ray photons. Such electron-photon cascade is considered.
- X-ray interaction with the matter are taken from "Gamma Factor" code and modernized regarding efficiency of sampling of scattering processes and approximation of the relevant cross sections. XCOM: Photon Cross Section Data Base recommended by National Institute of Standards and Technology (NIST) are used as a basis for calculating the cross section data.
A new 3D Monte-Carlo code is under development to work out both e-beam and X-ray radiation transport in laser chamber with the goal to calculate e-beam pumping distribution in the gain volume and X-ray radiation flux incident on the laser windows and partaking in their degradation.
Bremsstrahlung and photo-absorption cross sections

Bremsstrahlung cross section for an electron with kinetic energy $T$ incident on an atom with atomic number $Z$ with respect to the photon energy $k$ (Koch & Motz, *Rev. Mod. Phys.*, 31, 920 (1959)):

$$ \frac{d\sigma_{br}(T, Z)}{dk} = A'(T, Z) \cdot \frac{r_0^2 \cdot \alpha \cdot Z \cdot (Z + \xi(Z))}{k} \cdot R(T, T', Z) , \text{ where} $$

$T, T'=T-k,$ and $k$ are in $m_e c^2$ units; $\alpha = 1/137$ is the fine structure constant; $r_0$ is the classical electron radius;

$$ R(T, T', Z) = (1 + \frac{(T'+1)^2}{(T+1)^2}) \left[ \Phi_1(\delta) - \frac{4}{3} \cdot \ln Z - 4 \cdot \tilde{f}_c(T, Z) \right] - \frac{2}{3} \frac{T'+1}{T+1} \left[ \Phi_2(\delta) - \frac{4}{3} \cdot \ln Z - 4 \cdot \tilde{f}_c(T, Z) \right] $$

$$ \delta = 136 \cdot Z^{-1/3} \cdot 2\Delta \ , \ \Delta = \frac{1}{2} \left( \frac{1}{T'+1} - \frac{1}{T+1} \right) = \frac{k}{2(T+1)(T'+1)} $$

$$ A'(T, Z) = \frac{\Sigma_1(T, Z, 0, T)}{\Sigma_1^{NIST}(T, Z, 0, T)} , \text{ where} $$

$$ \Sigma_m(T, Z, k_{min}, k_{max}) = \int_{k_{min}}^{k_{max}} dk \cdot \frac{d\sigma_{br}(T, Z)}{dk} $$

and $\Sigma_1^{NIST}(T, Z, 0, T)$ is defined from Seltzer & Berger, *Atomic Data and Nuclear Data Tables*, 35, 345 (1986).

$$ d\sigma_{br}(k, \theta) = \frac{4 \cdot r_0^2 \cdot \alpha \cdot Z^2 \cdot dk}{(y^2 + 1)^2} \cdot F(y) , \quad F(y) = \left\{ \frac{16y^2r}{(y^2 + 1)^2} - (1 + r)^2 - \left[ 1 + r^2 - \frac{4y^2r}{(y^2 + 1)^2} \right] \cdot \ln M(y) \right\} $$

$$ r = 1 - \frac{k}{T+1} , \quad M(y) = \Delta^2 + \left( \frac{Z^{1/3}}{111 \cdot (y^2 + 1)} \right)^2 , \quad y = (T+1) \cdot \theta \quad \text{for small scattering angles}; $$

$$ y^2 = \beta(1 + \beta)(T+1)^2 \cdot (1 - \cos \theta) \quad \text{for any angles}. $$

**Photo-absorption cross sections:**

$$ \sigma_{ph}(k) = \frac{A_K}{k} + \frac{B_K}{k^2} + \frac{C_K}{k^{7/2}} + \frac{D_K}{k^4} \quad \text{for } k > U_K \quad \text{(binding energy of K-shell, and)} $$

$$ \sigma_{ph}(k) = \exp[A_j + B_j \cdot t + C_j \cdot t^2 + D_j \cdot t^3] , \text{ where } t=\ln k \text{ and } k > U_j \quad \text{(for other shells)}. $$
Mathematical problem of X-ray spectrum reconstruction from transmission measurements

A relation between a photon number density distribution \( z(\varepsilon) \) and the radiation intensity behind the absorber \( u(x) \) is set by Fredholm integral equation:

\[
A z \equiv \int_{\varepsilon_0}^{\varepsilon_{\text{max}}} K(x, \varepsilon) z(\varepsilon) d\varepsilon = u(x)
\]  

(1)

where \( A \) is the linear operator; \( K(x, \varepsilon) \)- the core of the integral equation; \( \varepsilon_0 \) and \( \varepsilon_{\text{max}} \) are the boundaries of the radiation spectrum. A classical solution of Eq.(1) derived as \( z = A^{-1} u \), is not stable in respect to small variations of \( u(x) \) and \( A \). Tikhonov's regularization algorithm (A.N. Tikhonov, V.Ya. Arsenin, "The methods of solving of the incorrect problems", M.: Nauka, 1974) was applied to solve this incorrect inverse problem using a smoothing functional

\[
M^\alpha[z, u_\delta] = \| A_h z - u_\delta \|_{L_2}^2 + \alpha \Omega[z], \quad \text{where} \quad \Omega[z] = \| z \|_{W_2^1}^{\varepsilon_{\text{max}}} = \int_{\varepsilon_0}^{\varepsilon_{\text{max}}} \left( z^2(\varepsilon) + q [z'(\varepsilon)]^2 \right) d\varepsilon
\]

(2)

Minimization of functional (2) gives Euler equation for approximations \( A_h \) and \( u_\delta \)

\[
\alpha \left[ z_\alpha(t) - z_\alpha''(t) \right] + \int_{\varepsilon_0}^{\varepsilon_{\text{max}}} R(t, \varepsilon) z_\alpha'(\varepsilon) d\varepsilon = f(t), \quad \varepsilon_0 \leq t \leq \varepsilon_{\text{max}}
\]

(3)

where \( R(t, \varepsilon) = R(\varepsilon, t) = \int_{c}^{d} K_h(x, t) K_h(x, \varepsilon) dx, f(t) = \int_{c}^{d} K_h(x, t) u_\delta(x) dx, z_\alpha(\varepsilon_0) = z_\alpha(\varepsilon_{\text{max}}) = 0 \)
Calculation of build-up factor for X-ray radiation transfer through thick media

As geometry of experiments was strongly different from an ideal one for a narrow beam the core $K(x,\varepsilon)$ in Eq.1 was recounted for a real geometry using a build-up factor. The following processes were taken into account:

\[
\frac{\partial \sigma_{\text{coh}}}{\partial \Omega} = \frac{r_0^2}{2} (1 + \cos^2 \theta)[F(q,Z)]^2
\]

Elastic coherent Rayleigh photon scattering

where $\theta$ is the photon scattering angle; $q$, the impulse transferred by a photon to all atomic electrons without energy absorption, and $F(q,Z)$ is the form-factor [4].

Inelastic noncoherent Compton scattering on bound atom electrons

\[
\frac{\partial \sigma_{\text{inc}}}{\partial \Omega} = ZS(q,Z)\frac{\partial \sigma_{\text{RNT}}}{\partial \Omega}
\]

where $S(q, Z)$ is the function of noncoherent scattering [4], $q$, the impulse transferred by a photon to one of the atomic electrons, and

\[
\frac{\partial \sigma_{\text{RNT}}}{\partial \Omega} = \frac{r_0^2}{2} \left[ 1 + k \left( 1 - \cos \theta \right) \right]^{-2} \left[ 1 + \cos^2 \theta + \frac{k^2 \left( 1 - \cos \theta \right)^2}{1 + k \left( 1 - \cos \theta \right)} \right]
\]

is Klein-Nishina-Tamm cross-section, $k$ is the photon energy in the units of energy at rest for electron $m_e c^2$, and $r_0$ is the classical radius of an electron.

Cross-sections of the rest processes were used from [5], while electron-positron pair production was not taken into account as it has the threshold of more than 1 MeV.

Gamma Factor code calculating X-ray transport
Comparison of calculated albedo for normal beam incidence on Al with the experimental data of M. Berger and D. Raso, Radiation Res., 12, No. 20 (1960).

Approximation of build-up factors

Simulated data were approximated by

\[ B(\varepsilon, S) = 1 + C(\varepsilon) \times S \times \exp[D(\varepsilon) \times S] \]

where \( S = \mu d \) is the absorber thickness in "free run" lengths, \( \mu \) is absorption coefficient, \( C \) and \( D \) are found by the least square method in the form \( a + 1/(b + c \times \varepsilon) \).

A total error of the build-up factor approximation was about 2% within the range of energy (\( \varepsilon > 50 \) keV) and thickness (\( S < 6 \)) variation.

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<th>Table 1. Energy build-up factor for Al filter.</th>
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<td>( \mu d/\text{Al} )</td>
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<th>Table 2. Energy build-up factor for Cu filter.</th>
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Test reconstruction of the model X-ray spectrum with an exact attenuation curve

Regularization algorithm was applied for the test reconstruction of nonmonotonic model spectrum $z(e) = 1 - \cos[\omega (e - e_0)]$ and the core of the integral equation (1) in the form $K(x, \epsilon) = \exp(-\gamma x/\epsilon)$. At discretization we used a uniform energy netting $\epsilon$ (41 point) and a nonuniform netting by filter thickness $x$ (81 point).

The calculations with the exact right-hand part $u^0(x)$ in Eq.1 show that the minimum of $\alpha$, up to which the solution is stable, is close to 1.0E-14.
Test reconstruction of the model X-ray spectrum with a disturbed attenuation curve

Test calculations for the model spectrum were performed with random “measurement” errors on the attenuation curve introduced by a generator of pseudo-random numbers $u(x)=u^0(x)(1+\varepsilon \times \zeta)$, where $\zeta$ is the random number uniformly distributed over $[-1,1]$ and $\varepsilon$ is the relative accuracy of “measurements”.

The calculations with the disturbed right-hand part $u(x)$ ($\varepsilon=0.1$) in Eq.1 show that the optimal $\alpha_{opt} \leq 1.0E-10$. 
Reconstruction of the real spectra

In put d ata

Absorption curve

Cu

Pb

Al
Results of Bremsstrahlung spectra reconstruction

- The maximums of bremsstrahlung X-ray spectra being reconstructed from the measured attenuation curves with different absorbers (Al, Cu, Pb) lie in the range of photon energies $\varepsilon = 70$-100 keV.

- For mean electron energy of about $\varepsilon_e = 300$ keV this is in a good agreement with the mean photon energy $<\varepsilon> = \int_0^{\varepsilon_e} \varepsilon z(\varepsilon) d\varepsilon \approx 0.3\varepsilon_e$ calculated for photons distributions of S.J. Wyard (Nucleonics, 13, 44-45, 1955) $z(\varepsilon) = \frac{2}{\varepsilon_e^2}(\varepsilon_e - \varepsilon)$

  or R.D. Evans (The Atomic Nucleus, pp. 614-617, Mc Graw-Hill Book Company, New York, Toronto, London, 1955) $z(\varepsilon) = \frac{1}{\varepsilon_e} \left[ 3.2 \left( 1 - \frac{\varepsilon}{\varepsilon_e} \right) + 2.4 \left( \frac{\varepsilon}{\varepsilon_e} \right) ln \left( \frac{\varepsilon}{\varepsilon_e} \right) \right]$

- Although high-photon-energy peak observed at ~450 keV might be artificial it could indicate to the presence of high-energy electrons generated in a vacuum diodes due to cathode plasma instabilities (S.Friedman, et al., Appl. Phys. Lett. 77, 1053, 2000).
Transient absorption coefficients induced by X-ray irradiation (average quanta energy $h \nu \sim 100$ keV, energy fluence $F_{X-ray} \sim 10^{-3}$ J/cm$^2$, pulse duration $\sim 100$ ns) were measured to be $\alpha \approx 0.015$ cm$^{-1}$ in CaF$_2$ and $\alpha \approx 0.01$ cm$^{-1}$ in SiO$_2$ at wavelengths of probe radiation $\lambda = 248$ and 460 nm. Being rather small in current experiments transient absorption can affect under the IFE-scale conditions with expected $F_{X-ray} \sim 10^{-2}$ J/cm$^2$. 
Relaxation dynamics of transient absorption centers

Relaxation of transient induced absorption in KS-4V glass at the wavelengths of 260 nm (left) and 350 nm (right) after irradiation by e-beam pulse.

Transient e-beam-induced defects at room temperature tend to self-healing in nanosecond to hours interval after irradiation pulse. During their relaxation residual (long-lived) defects are formed.
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 \( \leq 1 \text{ mA} \) is magnetically scanned over \( 40 \times 5 = 200 \text{ cm}^2 \) area and extracted to atmosphere through \( \approx 100 \mu \text{m} \) Ti foil.
- To obtain 600 keV e-beam the 2\(^{nd}\) LINAC section was switched off. To minimize e-beam interaction with 2\(^{nd}\) section structure, its resonance frequency was detuned of the 1\(^{st}\) 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**
Sealed performance of X-ray converter

- The sealed design of the X-ray bremsstrahlung converter was a water-cooled Ta target of 0.3-mm thickness placed in the vacuum downstream e-beam;
- higher X-ray flux at lower e-beam current of few mA was generated by e-beam of 1-cm diameter cross section.

Sealed design of X-ray converter

Imprint of X-ray irradiation on the glass plate at 1.7-cm from the target
Calibrated nickel-activated silicon glass DTS–0.01/1 dosimeters were used for X-ray dose measurements.

\[ D = 28.2 \times A^{2.32} \text{ (kGy)} \] at \( \lambda = 745 \text{ nm} \)

\[ D = 464.6 \times A - 33.1 \text{ (kGy)} \] at \( \lambda = 360 \text{ nm} \)

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 \( h \nu \approx 400 \text{ keV} \)
Characterization of Hard X-Ray Source

Dose rate of x-rays with average $h\nu = 400$ keV is up to 30 Gy/s at 5-mA e-beam current. Doses as high as 1 MGy are available for irradiation time $\leq 10$ hours. Mass absorption coefficient for tested materials SiO$_2$, CaF$_2$, Al$_2$O$_3$ (densities $\rho = 2.2, 3.2$ and $4$ g/cm$^3$) is $\mu/\rho \sim 0.1$ g/cm$^2$, and the X-ray range $l_{X-ray} = 1/\mu \sim 2.5$–$5.0$ cm is comparable with windows thickness $d$. Then X-ray-induced absorption coefficient is a measure of the transmittance loss: $\alpha = \frac{1}{d} \ln \left( \frac{T_0}{T} \right)$.
Optical materials (OM) under testing

- **Fused silica (SiO$_2$)** 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 thermomechanically 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$_2$O$_3$, 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$_2$O$_3$ samples from State Optical Institute.
Mechanisms of color centers formation in SiO$_2$

- TN neutrons directly knock-out Si or O atoms in the SiO$_2$ lattice; electron-hole pairs and excitons are generated by intense UV laser light, soft x-ray and gamma-ray plasma emission, energetic Compton electrons. These primary defects are trapped by point structural defects pre-existing in the material. The latter are originating from manufacturing process. In fused silica obtained through oxidation of SiCl$_4$ oxygen-deficient centers (ODC), oxygen-excess centers, hydroxyl OH and Cl$_2$ species exist, whilst in fused quarts which is processed by melting of natural SiO$_2$ the main impurities are metals (Al, Ge).

- Opposite to the defects formation are processes of the decay and mutual defects relaxation, both being affected by temperature increase (annealing) or successive irradiation. Some radiation-induced defects are transient and tend to a self-healing after irradiation pulse, while the residual are long-living at room temperature.
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);
- X-ray-induced absorption for $3\omega$ DPSSL ($\lambda=353$ nm) is less than for KrF laser ($\lambda=248$ nm);
- X-ray-induced absorption coefficient $\alpha$ gradually increases in dependence on cumulative absorbed X-ray dose with tendency to saturation, though sometimes it is not monotonic.

$\lambda=248$ nm $\rightarrow \alpha_{\text{sat}} \approx 0.50$ cm$^{-1}$
Degradation of Optical Materials under X-Ray Irradiation (Fused Silica)

“Dry” KS-4V glass demonstrates better radiation stability in the UV spectral range than “wet” glasses

λ = 248 nm → $\alpha_{sat} \approx 0.24$ cm$^{-1}$
Degradation of Optical Materials under X-Ray Irradiation (CaF$_2$)

CaF$_2$ crystals are well stable under X-ray irradiation

$\lambda = 248 \text{ nm} \rightarrow \alpha_{sat} \approx 0.12 \text{ cm}^{-1}$
Degradation of Optical Materials under X-Ray Irradiation ($\text{Al}_2\text{O}_3$)

$\text{Al}_2\text{O}_3$ is the most stable UV optical material under X-ray irradiation
Repetitive-rate soft X-ray source

Rep-rate source based on low-pressure high-voltage discharge provides 50-Hz train of 1-µs x-ray pulses with average flux of 2÷3 mW/cm² (absorbed dose rate up to 5 Gy/s) in the range $h\nu=6.0÷20$ keV

Dose distribution in the TLD stack

$I(t)$

$U(t)$

$U_0$

Thyratron

TLDs

$h\nu=6.3$ keV

$h\nu=9.4$ keV

$h\nu=10.8$ keV

Dose, rel. units

Al absorber thickness, µm
Degradation of optics transmittance under soft x-rays

Accumulated irradiation fluence $F_{x-ray} = 60 \text{ J/cm}^2$ of soft X-rays ($h\nu = 6–20 \text{ keV}$) produced absorbed dose in the samples of $1.5*10^5 \text{ Gy}$
Conclusions

- Bremsstrahlung X-ray emission in a large-aperture GARPUN KrF laser pumped by double-sided 300-keV, 60-kA 100-ns e-beams was fully characterized by time-resolved scintillation technique and absolutely calibrated thermo-luminescence dosimeters (TLDs).
- Monte-Carlo code for e-beam transport is elaborated to calculate bremsstrahlung X-ray emission yield from the laser cavity and to evaluate a lifetime of laser windows.
- Regularization algorithm was developed to reconstruct the Bremsstrahlung X-ray spectra using experimental data on radiation transmission through different absorbers.
- A powerful linac-based quasi-CW hard X-ray source \( (h \nu \sim 400 \text{ keV}) \) was developed with a dose rate \( \sim 30 \text{ Gy/s} \) and total amassed doses in the test samples as high as \( \sim 1–2 \text{ MGy} \).
- A rep-rate soft X-ray source \( (h \nu = 6–20 \text{ keV}) \) based on high-voltage glow discharge (1-\( \mu \text{s}, \) 50-Hz) was demonstrated with a dose rate \( \sim 5 \text{ Gy/s} \) being absorbed in a thin surface layer \( \sim 0.1–1 \text{ mm} \).
- The obtained results show that X-ray-induced transient absorption at both 248 nm (KrF laser) and 353 nm (3w DPSSL) can hardly affect on optics transmission, while residual absorption results in rather high losses especially for UV laser light.
- Temperature annealing and bleaching of color centers by UV (or X-ray) radiation reduce darkening of the IFE reactor chamber and laser driver optics.