“Energy Systems” manuscript No.
(will be inserted by the editor)

Space Weather Influence on Power Systems: Prediction, Risk Analysis, and Modeling

Vitaliy Yatsenko · Nikita Boyko ·
Steffen Rebennack · Panos M Pardalos

Received: date / Accepted: date

Abstract This paper concentrates on dynamic probabilistic risk analysis of optical elements with complex characterizations for damages using a physical model of solid state lasers and a predictable level of ionizing radiation and space weather. This article focuses mainly on a solid-state laser model, mathematical models for dynamic probabilistic risk assessment and software for the modeling and prediction of ionizing radiation. The probabilistic risk assessment method for solid-state lasers is presented considering some deterministic and stochastic factors. Probabilistic risk assessment is a comprehensive, structured, and logical analysis method aimed at identifying and assessing risks in solid-state lasers in order to cost-effectively improve their safety and performance. This method is based on the Conditional Value-at-Risk (CVaR) and on the expected loss exceeding Value-at-Risk (VaR). We propose a new dynamical-information approach for the radiation damage risk assessment of laser elements affected by space

---

Vitaliy Yatsenko
Space Research Institute of NASU and NSAU,
Prospect Glushkova 40, 03022 Kiev, Ukraine
Tel.: +38 050 384 29 67
Fax: +380-44-526 41 24
E-mail: vyatsenko@gmail.com

Nikita Boyko
Department of Industrial and Systems Engineering
University of Florida
E-mail: nikita@ufl.edu

Steffen Rebennack
Department of Industrial and Systems Engineering
University of Florida
E-mail: steffen@ufl.edu

Panos M Pardalos
Center for Applied Optimization
Department of Industrial and Systems Engineering
University of Florida
303 Weil Hall, P.O.
Box 116595 Gainesville, FL 32611-6595 USA
Tel.: +1 352 392 9011
Fax: +1 352 392 3537
E-mail: pardalos@ufl.edu

radiation. Our approach includes the following steps: laser modeling, modeling ionizing radiation influences on laser elements, probabilistic risk assessment methods, and risk minimization techniques. Black-box models of space ionizing radiation influences on laser elements are developed for risk assessment in laser safety analysis. The mathematical model's inputs are the radiation influences on laser systems and the output parameters are dynamic characteristics of the solid laser.

Keywords risk analysis, power systems, laser elements, ionizing radiation, damage, global optimization, prediction, black-box modeling, dynamical-information approach

1 Introduction

Risk assessment is widely used in economics, ecology, and the environmental sciences. The term generally refers to the analysis of the relative risk of injury from exposure to a potentially hazardous physical or chemical agent [1]. It is distinguished from hazard analysis or hazard evaluation by comparing statistically the computed risk to either a known risk or an absolute chance of a final oucome or event. Hazard analysis or hazard evaluation is simply the process of determining the potential hazards from operation or activity [2].

The fundamental purpose of risk assessment is to answer the question, "How safe is safe?" This question must be answered in order to derive the accessible exposure limits; *i.e.*, the exposure of radiation to lasers.

Some researchers argue that these limits should imply zero risk, and under no theoretical exposure conditions (regardless of how unrealistic) should exposure be possible above the Maximum Permissible Exposure (MPE) limit. A related argument is whether the MPEs are inherently safe under all conceivable conditions. Other scientists argue for a reasonable worst-case approach, where risk analysis is applied to the derivation of each hazard class. The latter approach has generally prevailed, however, and so the research continues. A more detailed discussion on this topic can be found, for instance, in [3,4].

One of the sources of hazard is the activity of the Sun. The solar wind causes storms that threaten stable work of electronic and elecrical systems and therefore are a subject of active research. The solar wind is a stream of charged particles – a plasma – ejected from the upper atmosphere of the Sun. It consists mostly of electron and proton streams with energies of about 1 keV. Thus, severe space weather perturbations occurring during solar cycles have the potential to cause a large-scale electricity systems blackout (see [5]). The geomanetic storms are especially hazardous in the outer space where the devices are not protected by the Earth magnetosphere and atmosphere.

Quantitative models for addressing risks associated with space weather should be considered of crucial importance. In particular, state-of-the-art analysis of ionizing radiation influence on laser systems has been conducted by Biedilov [6] and Rose [7]. Their research concentrates on estimating the predictable level of space radiation – and other radiation field environmental influences – on optical materials, laser elements, and solid state lasers. They analyzed the following models:

(a) solar flare influence on laser systems,
(b) forecasting the ionizing radiation influences, and
(c) risk assessment in laser safety analysis .

Furthermore, the possibility of using statistical probability risk assessment and nonlinear forecasting models of laser dynamics under ionizing radiation influences is analyzed. This is a “black box” or “input-output” model, which seeks only to reproduce the behavior of the system’s output in response to changes in its setpoint or input. The model’s inputs is the radiation influence on lasers while the output parameters are indexes (integral characteristics) of laser elements.

There are several different approaches to risk assessment [8]. The most common are

(a) risk analysis in the derivation of MPEs,
(b) risk analysis in the development of hazard classes and the derivation of AELs, and
(c) risk analysis in the determination of control measures.

Three approaches appear to be most typical: the “judgement call” approach, the “probabilistic approach”, and the use of “weighting factors” [8]. All of these approaches are open to interpretation. For example, some official or committee must answer the tricky question: “What is an acceptable risk in this case?” A common solution is bootstrapping.

The idea is to make use of other already understood hazards that are socially acceptable, and use the comparative risk to determine the acceptable risk for the new hazard. By making a judgement call, we refer to the weighing of conflicting evidence and research results from different laboratories, and placing more weight upon sources of data with a proven track record and upon evidence that fits with our current knowledge. The probabilistic approach is generally applied to foreseeable and predictable accidents [8].

2 A Novel Approach to Risk Analysis

We analyzed state-of-the-art approaches to measure effects of the ionizing radiation influence on optical materials, laser elements, and solid lasers. The bottom line of our research is that the basic tenets of risk assessment have always been applied to laser safety using statistical methods. However, risk analysis must also consider aspects of human behaviors. Hence we propose the following choice of methods for risks assessment:

(a) statistical methods,
(b) reliability measures,
(c) optimization techniques,
(d) acceleration modeling of laser functioning, and
(e) nonlinear mathematical models.

The research of radiation effects on space devices is becoming an increasingly important nascent field. It has long been known that electrical systems are susceptible to radiation. Recent research has raised the possibility that mechanical devices may also be prone to radiation-induced damage [9]. Especially sensitive to radiation are devices with mechanical motion governed by electric fields across insulators; *i.e.*, electrostatically positioned cantilever beams. Since insulators can fail under a single event of dielectric rupture, there is a distinct possibility that these devices will have decreased performance in the space environment. A further complication is the fact that radiation can cause bulk lattice damage and can materials more susceptible to fracture.

In spite of the long history of solid state lasers – in particular neodymium lasers – the study of influence of ionizing radiation on the lasers' parameters is still an important task. This problem is repeatedly coming into researchers' focus, both throught their aspirations to understand the fundamental processes ("What is going on in this system?") and through the importance of providing reliable, practical systems during their space missions [10,11].

We define risk as the probability of future loss. This definition can be applied consistently to laser elements and it is highly useful for prospective risk assessment, although it is not a universally accepted definition. In contrast, retrospective risk assessment concepts and definitions combining loss probability and loss sevirity are not covered in this paper.

In order to analyze risk, we propose to use a method called *deviation measurement*. Therefore, let us introduce a state space $\mathit{\Omega}$, where the elements $w \in \mathit{\Omega}$ represent the laser's states. Furthermore, let P be a probability measure of $\mathit{\Omega}$. Now, consider the functions $X : \mathit{\Omega} \mapsto \Re$, interpreted as random variables, belonging to the linear space $\mathcal{L}^2$; *i.e.*, functions for which the mean $\mu(X)$ and the variance $\sigma^2(X)$ exist. Such a function X may describe the quality of the plant. When referring to the expectation-bounded risk measure of a device on $\mathcal{L}^2$, we mean some functional $\mathit{\Gamma} : \mathcal{L}^2 \to \mathbb{R}$ satisfying (partially or completely) the following set of conditions.

a) $\mathit{\Gamma}(X + C) = \mathit{\Gamma}(X) - C$ for all X and constants C,
b) positive homogeneity,
c) subadditivity,
d) an expectation-boundedness, and
e) monotonicity.

The function that satisfies all five conditions is called a *coherent risk measure.*

In physical applications, decision should be taken to minimize risk within the available circumstances. Let us simply contemplate a subset X of L. Suppose that $\mathit{\Pi}$ is nonempty, compact, closed and convex. Then, we are interested in the solution of the problem

$$\min\{\mathit{\Gamma}(X) \mid \text{ over all } X \in \mathit{\Pi}\} \tag{1}$$

This approach makes it possible to use radiation damage risk assessment methods to gauge space radiation damage to laser components. A functional model of risk analysis is shown in Fig. 1.

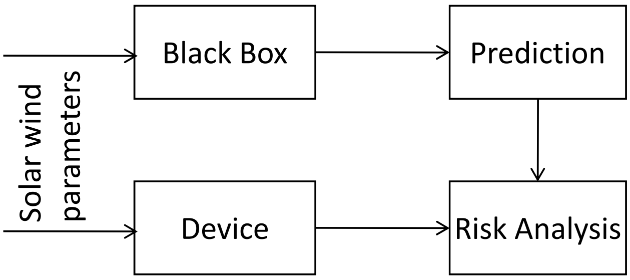

Fig. 1 Functional model of risk analysis.

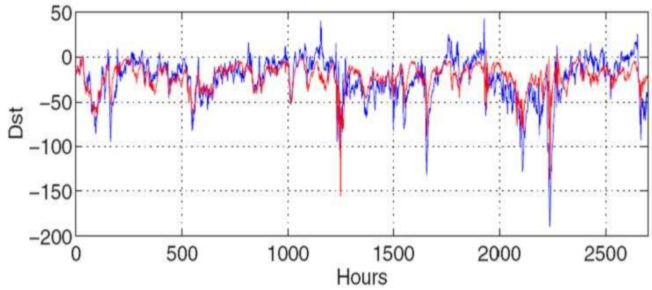

Fig. 2 Prediction of Dst index

3 Optimization Approach to Risk Prediction

The optimization approach is based on the optimization model for space weather prediction [12]. It uses the black-box model to describe magnetospheric dynamics and global optimization techniques to reconstruct of the the dynamical systems.

The "black-box" model aims to reveal the information and dynamic features causing the event, or preceding its occurrence. Discrete recursive (nonlinear autoregressive moving average models with exogenous input) models are also considered. This is an "input-output" model, which seeks only to reproduce the behavior of the system's output in response to changes in its setpoint or inputs. One of the most important features of our model is that the model terms are physically interpretable. For example, discrete and continuous time models of the evolution of the *Dst*-index can be derived using dynamic-information methodology.

Assuming that magnetospheric plasma is weakly turbulent, we propose a nonlinear black-box model to forecast its state. We also assume that this weakly turbulent state is caused by the influence of solar wind velocity and southern component of the Interplanetary Magnetic Field (IMF). This state can be described in terms of local Lyapunov exponents [13], which characterize the sensitivity of plasma dynamics with respect to geomagnetic disturbances. Using the decomposition of nonlinear disturbances into a series of correlation functions, we propose nonlinear discrete dynamic models of magnetospheric plasma state. These nonlinear dynamical models provide forecasting tools for space weather. Our approach to the reconstruction of the dynamical model is based upon the application of multiobjective learning algorithms to identify the model's structure and parameters. A forecasting algorithm based on Lyapunov exponents is also proposed. For their effective use, we suggest two methods for the structure and parameter identification:

(a) genetic optimization and
(b) nonlinear, constrained optimization.

The observational time series data have been extensively used to analyze the magnetospheric dynamics by using optimization techniques of phase space reconstruction. An example of a *Dst* index prediction is shown in Fig. 2.

The simulation results show that the proposed techniques provide an efficient method to get the optimal difference equation model of a chaotic system. Our approach allows forecasting the *Dst*-index 9 hours ahead in the absence of abnormalities in the solar wind. The linear correlation of the predicted value of the first local Lya-

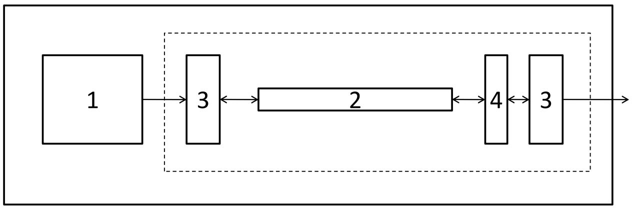

Fig. 3 Flow diagram of diode pumped solid state laser: pump laser diode 1, solid state laser, consisting of laser crystal 2, optical resonator with mirrors 3 and a laser radiation controls device 4

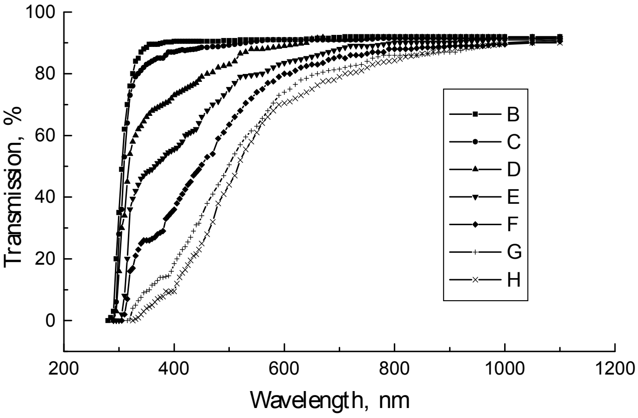

Fig. 4 Transmission of glass plate (K8 glass) a thickness 1 mm on a γ- radiation dose. The doses of irradiation in Roentgens corresponds to B – 0, C – 10^4, D – $6 \cdot 10^4$, E – $1.1 \cdot 10^5$, F – $3.1 \cdot 10^5$, G – $7.1 \cdot 10^5$, and H – $1.71 \cdot 10^6$.

punov exponent with the measured one is about 99 for a 1-hour prediction. It is possible to achieve a prediction up to 100 hours ahead.

4 Optimization Problem with Constraints on Risk

Let $z = f(v, u)$ be a loss function of a device depending upon the control vector v and a random vector u. The control vector v belongs to a feasible set V, satisfying imposed requirements. We assume that the random vector u has a probability density $p(u)$. Now, consider the function

$$\Phi_\alpha(v, \zeta) = \zeta + (1-\alpha)^{-1} \int_{f(u,v)>\zeta} (f(v, u)) - \zeta) p(u) du, \tag{2}$$

where α is the CVaR confidence level and ζ is nonnegative.

This enables us to include CVaR in the constraints and replace them by the function $\Phi_\alpha(v, \zeta)$. For instance, let us consider the problem of minimizing the mean loss $\mu(v) =$

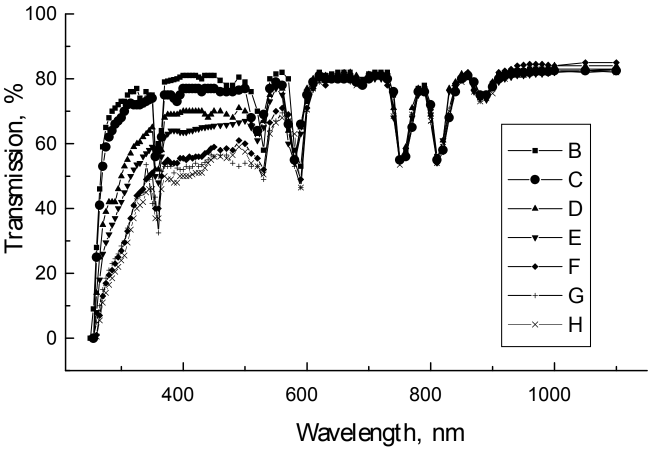

Fig. 5 Transmission of of Nd:YAG crystal plate irradiated by γ-radiation. The doses of irradiation in Roentgens corresponds to $B - 0$, $C - 10^4$, $D - 6 \cdot 10^4$, $E - 1.1 \cdot 10^5$, $F - 3.1 \cdot 10^5$, $G - 7.1 \cdot 10^5$, and $H - 1.71 \cdot 10^6$.

$\mathbb{E}(-f(v,u))$ subject to some balance constraints $v \in V$, and two CVaR constraints with confidence levels β and γ. Let us bound the two CVaR levels of interest with constants C_β and C_γ. In this case, the optimization problem can be stated as follows

$$\min \mu(v) \tag{3}$$

$$\text{s.t. } v \in V, \Phi_\beta(x,\zeta) \leq C_\beta, \Phi_\gamma(x,\eta) \leq C_\gamma, \tag{4}$$

$$\zeta, \eta \geq 0. \tag{5}$$

5 The Algorithms for Model Reconstruction and Numerical Experiments

This section introduces an innovative approach to model reconstruction and describes the obtained numerical results of the computational experiments [12]. Unlike previously developed approaches, we reduce the problems with the structure and nonlinear model parameters reconstruction to mathematical programming. The optimization model allows us not only to predict Dst-index dynamics for time steps forward, but it also accounts for some nonlinear effects in the magnetosphere.

The dynamic model of the black box can be set by the discrete equation with single input and output as

$$y(k) = F[y(k-1), \ldots, y(k-n_y), \ldots, u(k-1), \ldots, u(k-n_u), \xi(k), \ldots, \xi(k-n_\xi)], \tag{6}$$

where $F[\cdot]$ is a polynom in the variables $u(k)$, $y(k)$, and $\xi(k)$, $u(k)$ corresponds to the input, $y(k)$ is an output, and $\xi(k)$ is a variable modeling a possible noise at the time point k.

Let us briefly describe the problem of unknown polynomial parameters estimating under the assumption that the structure of the polynom is known. Let $\hat{\theta}$ denote the unknown parameters of the polynom and row vector ψ contains variables $u(k)$, $y(k)$ and their possible combinations up to l-th order and $k-1$ time point. Then, the equation (6) can be written as

$$y(k) = \psi^{\top}(k-1)\hat{\theta} + \xi(k). \tag{7}$$

The prediction error is represented by

$$J(k) = (y - \psi(k))^{\top}(y - \psi(k)), \tag{8}$$

where y equals the Dst-index value at time k. It is easy to notice that equation (8) appears to be a quadratic error. Thus, we have reduced the parameter reconstruction problem to a problem of minimizing $J(\theta)$ subject to several constraints; *i.e.*,

$$\min J(\theta) \tag{9}$$

$$\text{s.t. } \theta \in D, \tag{10}$$

where D is a multidimensional subset corresponding to the physical constraints of the model. The mathematical model (9) - (10) can be easily implemented with standard mathematic packages and it enables reliable prediction.

5.1 Solution Method

We propose two algorithms to tackle the optimization problem (9) - (10). The first algorithm uses the standard constraint optimization approaches. The second one is a genetic algorithm for finding (optimal) parameters of the model. The following prediction error $J(\theta)$ was taken for solving the reconstruction problem

$$J(\theta) = \sqrt{\frac{(\hat{y}(k) - y(k))^2}{\sum (y(k) - \bar{y}(k))^2}}, \tag{11}$$

where $\hat{y}(k)$ is a predicted value of the output, $y(k)$ is a measured value of the output, $\bar{y}(k)$ is the expectation of $y(k)$.

The results of the computations via the identification algorithm demonstrate that the following equation provides the most precise Dst-index prediction for model

$$\begin{aligned} y(i) = & x_1 \cdot y(i-1) - x_2 \cdot u(i-1) - x_3 \cdot y(i-2) \cdot u(i-1) \\ & - x_4 \cdot y(i-4) - x_5 \cdot u(i-4) \cdot u(i-6) - x_6 \cdot y(i-2) \\ & + x_7 \cdot y(i-3) + x_8 \cdot y(i-3) \cdot u(i-1 + x_9 \cdot y(i-5) \\ & + x_{10} \cdot u(i-1) \cdot u(i-7) + x_{11} \cdot u(i-2) \\ & + x_{12} \cdot y(i-3) \cdot u(i-2) + x_{13} \cdot u(i-2) \cdot u(i-5) \\ & - x_{14} \cdot u(i-5) + x_{15} \cdot u(i-7) \cdot u(i-12), \end{aligned} \tag{12}$$

where x_1 to x_{15} are unknown parameters of the model. $u(i)$ is a product of solar wind speed by a southern component of magnetic field vector at the time point i; $y(i)$ is a Dst-index value at time point i.

Correlation-based adequacy tests applied to model (12) show the absence of significant statistical connection between the input and prediction error. This result indicates that the reconstructed model adequately represents the Dst-index.

The numerical solution to the optimization problem (8) accounts for constraints on possible parameters and leads to the following discrete recursive model

$$\begin{aligned}\hat{y}(i) =& 1.36 \cdot y(i-1) - 4.98 \cdot u(i-1) - 0.18 \cdot y(i-2) \cdot u(i-1)\\ &- 0.56 \cdot y(i-4) - 1.42 \cdot u(i-4) \cdot u(i-6) - 0.76 \cdot y(i-2)\\ &+ 0.53 y(i-3) + 0.11 \cdot y(i-3) \cdot u(i-1) + 0.36 \cdot y(i-5)\\ &+ 0.91 \cdot u(i-1) \cdot u(i-7) + 2.72 \cdot u(i-2)\\ &+ 0.08 \cdot y(i-3) \cdot u(i-2) + 0.79 \cdot u(i-2) \cdot u(i-5)\\ &- 0.92 \cdot u(i-5) + 0.24 \cdot u(i-7) \cdot u(i-12).\end{aligned} \tag{13}$$

The numerical experiments confirm that the Dst index behaves similarly to a linear oscillator under the external perturbing force. Therefore, the studied system has the following two major properties. First, the external force is a nonlinear function of solar wind parameters. Second, the eigenfrequency of the magnetosphere's eigenmodes must be very small compared to the characteristics of the perturbing force volatility. The process of energy pumping leads to transferring system energy to eigenmodes of the magnetosphere.

The developed mathematical programs and the proposed solution techniques allow us to reliably predict the Dst-index for several steps ahead. This indicates that this method can be implemented for practical purposes. The accuracy of the prediction is expected to improve using real time parameter adaptation algorithms [12].

6 Experimental Results

The flow diagram of a diode pumped solid state laser is shown in a Fig. 3. The elements of the chart are: pump laser diode (1), solid state laser (consisting of a laser crystal) (2), optical resonator with mirrors (3) and a laser radiation controls device (4) (Q-switch, nonlinear optical crystal etc.) Each element of the laser is characterized by parameters taken into account when determining the laser radiation parameters - output power or energy, spectral composition of the laser beam radiation spatial structure, temporal characteristics, and polarization.

The diode pumped laser output functional dependence on the main pumping parameters and on the characteristics of basic laser elements is well known for the basic modes of generation. Features of major types of lasers, such as Nd:YAG lasers, are sufficiantly accounted for in the literature (see, for instance, [14]). In connection, for the development of a model estimating the influence of ionizing radiation on a laser, experimental information is needed about the influence of radiation on absorption and scattering of light in optical elements, the change of reflectivity of multi-layered dielectric mirrors, the change of transmission and absorption of the laser crystal on a wavelengths of pumping and a lasing.

We obtained the gamma radiation effects' experimental dependencies on the characteristics of optical glasses from a cobalt-60 source (crown glass, uviols, glasses K108L) which contains a cerium and laser elements. Examples of this are laser Nd:YAG crystals with a neodymium concentration of 1%, neodymium doped laser glasses, and passive laser Q-switches on the basis of dye doped polymers [15]. For an illustration, see Fig. 4 and Fig. 5. The doses of irradiation in Roentgens corresponds to B – 0, C – 10^4, D – $6 \cdot 10^4$, E – $1.1 \cdot 10^5$, F – $3.1 \cdot 10^5$, G – $7.1 \cdot 10^5$, and H – $1.71 \cdot 10^6$.

The influence of gamma irradiation of laser crystal on the laser output (at wavelength of the second harmonic) of the diode pumped Nd:YAG laser is shown in Fig. 6. The laser kit of LASKIT@500 of ALPHALAS GmbH(Germany) was used for the measurements. The considerable decline of the laser slope efficiency with the growth of the dose of the irradiation is clearly visible.

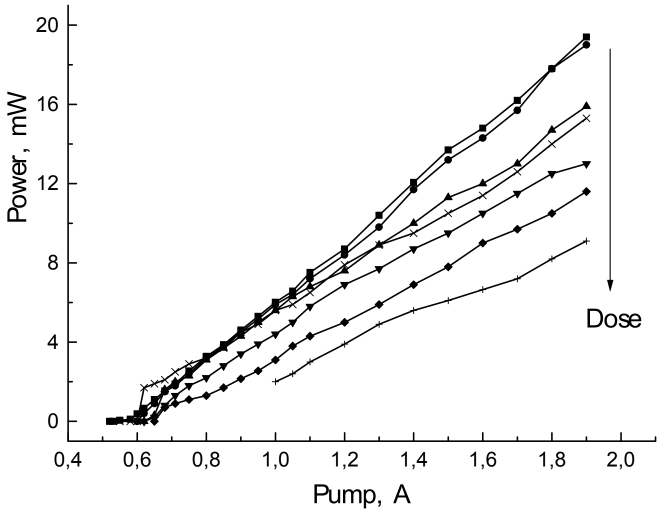

Fig. 6 Output of the diode pumped Nd:YAG laser (second harmonic wavelength) after irradiation of laser crystal by gamma radiation.

7 Conclusions

We developed a new approach for radiation damage risk assessment for laser elements through space radiation. This approach is based on laser dynamics modeling, prediction of space radiation, Conditional Value-at-Risk measurement, and the expected loss exceeding Value-at-Risk.

The following models have been proposed:

1. solar flare influences on laser systems,
2. forecasting of ionizing radiation influences, and
3. risk assessment in laser safety analysis.

The possibility of using statistical probability risk assessment and nonlinear forecasting models of laser dynamics under ionizing radiation influences has been analyzed. This is a “black-box” or “input-output” model seeking only to reproduce the behavior of the system’s output in response to changes in its setpoint or inputs.

Nonlinear mathematical models of space radiation and magnetic storms are used to study their effect on laser systems has been elaborated. A space radiation simulation study has been conducted, as well as as an analysis of the forecasting level of ionizing fields in space using Dst-index.

Algorithms and software for optimal structure and parameters of forecasting mathematical models of ionizing radiation were considered. Forecasting mathematical models of ionizing radiation by numerical methods have been tested.

References

1. [FEMA: HAZUS-MH, Technical Manual], Federal Emergency Management Agency, Washington DC (2003).
2. Douglas, J., "Physical vulnerability modelling in natural hazard risk assessment," Nat. Hazards Earth Syst. Sci. **7**, 283–288 (2007).
3. Byrd, M. and Cothern, R., [Introduction to Risk Analysis], Government Institutes (2000).
4. Todinov, M., [Risk-Based Reliability Analysis and Generic Principles for Risk Reduction], Elsevier Science Ltd. (2006).
5. Grigsby, L. L., [Electric Power Generation, Transmission, and Distribution], CRC Press (2007).
6. Biedilov, M., Bejsembaeva, H., and Saidov, R., "Influence of ionizing radiation on performance of lasers," Ukr. Phys. J. **26**, 1981–1986 (1981).
7. Rose, T., Hopkins, M., and Fields, R., "Characterization and control of gamma and proton radiation effects on the performance of nd:yag and nd:ylf lasers," IEEE journal of quantum electronics **31(9)**, 1593–1602 (1995).
8. Knopov, P. and Pardalos, P., [Simulation and Optimization Methods in Risk and Reliability Theory], Nova Science Publishers Inc. (2009).
9. Lee, C., Johnston, A., Tang, C., and J., L., "Total dose effects on microelectromechanical systems (mems): Accelerometers," Trans. Nuc. Sci. **43**, 3127–3134 (1996).
10. Sun, D., Zhang, Q., Zh.Xiao, J., and et.al., "Influence of gamma-ray irradiation on absorption and fluorescent spectra of nd:yag and yb:yag laser crystals," Chinese Physics Letters **25(6)**, 2081–2084 (1999).
11. Kaczmarek, S., "Influence of ionizing radiation on performance of nd: Yag lasers," Cryst. Res. Technol. **34(9)**, 1183–1190 (1999).
12. Cheremnykhnnn, O., Yatsenko, V., Semeniv, O., and Shatokhina, I., "Nonlinear dynamical model for space weather prediction," Ukr. Phys. J. **53**, 502–505 (2008).
13. Pardalos, P. and Yatsenko, V., "Optimization approach to the estimation and control of lyapunov exponents," Optimization Theory and its Applications **128(1)**, 29–48 (2006).
14. Zverev, G., Golaev, Y., Shalaev, E., and Shokin, A., "Lasers on yttrium aluminum garnet with neodymium," Radio i svyaz **144** (1985).
15. Brodin, M., Negriyko, A., and Yatsenko, V., "Risk analysis of laser elements for complex characterization of damages by space radiation," SPIE Conference "Optics and Optoelectronics," Prague Congress Centre, Prague, Czech Republic Damage to VUV, EUV, and X-ray Optics II (XDam2) **7361** (1985).