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13. ABSTRACT *(Maximum 200 words)*
An analysis was performed to determine the best multilayer combination for initial experiments, consistent with available electron beam sources. A study was also performed as to the allowable tolerances for thickness variations of the multilayer. It was found that allowable variations were well within a controllable range. Initial issues with accelerator availability and x-ray detector noise were resolved, and experiments are set to begin in the near future to demonstrate the resonant transition radiation that is the goal of this effort.

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Transition radiation generated by MeV electrons in a multilayer solid target as an X-ray source for medical applications: proof-of-principle experiments

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Final
Report

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Proposed Research

Bi-chromatic X-ray contrast diagnostics, proposed two decades ago [1], was later on developed into a potentially useful medical tool [2]. The diagnostics utilizes a large difference in the absorption of X-ray photons with energies just below and just above the contrast material (e. g. Iodine). Despite apparent initial successes, the technology has not become widespread, in large part because it relies so far on synchrotron X-ray radiation, which is available only at major national facilities like Light Sources at BNL or LBL. More recently, R&D began on using X-ray transition radiation as a source for medical applications [3]; however, while a number of advances have been made, the technology still relies on a GeV electron accelerator.

Proposed R&D is based on the earlier publications of Prof. Alex Kaplan's group (of which Peter Shkolnikov is part), which theoretically demonstrated feasibility of generating intense narrow-band X-ray transition radiation by few-MeV electrons traversing solid multilayer structures (see e. g. [4]; the first experimental observations of X-ray TR in multilayer sub-micron nanostructures were reported in [5]). The most dramatic difference of those results from the main body of the previous work on X-ray transition radiation is the proposed possibility to use electron beams of 5-10 MeV energy to generate X-rays in the keV range, whereas the conventional technology based on foil stacks needs electron energy three orders of magnitude higher. As a result, widely available and relatively inexpensive industrial and medical electron accelerators may be used instead of electron synchrotrons of the national-facility kind. Another innovation is the utilization of resonances at inner-shell absorption edges of materials to narrow the bandwidth of the generated radiation. The proposed research aimed at providing experimental verification of this theoretical concept, thus making a critically important step toward practical applications.

The proposed specific experimental design was based on the following premises:

(i) The combination of a high-Z "radiator" and a low-Z "spacer," optimal for the X-ray photons ~1 keV, would remain optimal for an order of magnitude higher energy needed for medical applications;

(ii) The electron energy of 6-8 MeV would be available at a medical accelerator at Stony Brook Health Science Center; we actually have agreement with the relevant Department head for full cooperation, including engineering personnel;

(iii) A ready set of X-ray detectors would be available to the experiment through Dr. Zhong Zhong of BNL; and

(iv) An experienced accelerator scientist, Dr. Lefferts of Stony Brook Physics Dept., would be part of our team;

(v) Based on (i) and (ii), we expected to utilize Mo/Si multilayer targets readily available from many sources (including Columbia University and LBL); and

(vi) Based on (ii), we expected that Bremsstrahlung would be two orders of magnitude below the TR signal, so that we could limit ourselves to measuring TR output integrated over the angle.

Such design looked completely feasible in the time frame and on the scale of the support requested by us.

Results

Theory: substantially new theory developed for generating hard-X-ray transition radiation

The AFOSR award initiated intense theoretical development, led by Prof. Alex Kaplan of Johns Hopkins University [6-8]. It has been discovered that the need to generate 30-50 keV X-ray TR requires substantial changes in our theory developed for ~1 keV photons, because the dielectric constants in this higher energy range are significantly different. In particular, the choice of the materials for the multilayer target proposed in [4] is no longer applicable. Our original approach led to choosing the layer of heavy atoms as a "radiator" at its K-shell transition, and the layer of light atoms as a neutral "spacer". However, during our detailed calculations we realized that the above approach, good in the softer X-ray domain, does not produce desirable results in the hard X-ray domain. The major problem is that in the 20 -- 50 KeV X-ray domain the transition radiation spectrum with such pairs shows a spectral **dip** at the chosen K-shell, instead of spectral **peak**. The problem arose how to break through this obstacle by finding new approach to the proper choice of the pairs of "radiator" and "spacer".

The search through the elements in the Periodical Table and huge spectral date for each one of them resulted in locating a few candidates of spacers for any given "radiator" to produce strongly pronounced resonant peak of transition radiation with the contrast better than two orders of magnitude. Surprisingly enough, these new spacer candidates, as a rule, are heavier than the radiator. One of criteria/stipulations on these candidates is that they have to be technologically viable and accessible, which narrows down the field of candidates, but still leaves at lest two candidates for each radiator element. Thus, our initially proposed target (Mo/Si) was to be replaced by e. g. a Mo/Ag target, for which we expect a strong, 1% wide maximum of TR centered at 20 KeV (see Figs. 1 and 2). Another important result was that the expected TR conversion efficiency at the energies of interest is much smaller than that at sub-keV energy considered in previous work. In combination with the need to use a different accelerator (with higher electron energy) than initially proposed, this led to several dramatic changes in the experimental design.

Experiment: the development and implementation of the current, much more realistic and sophisticated, experimental design

As a result of theoretical progress described above, and in the course of our experimental work, **all the components** of the originally proposed experimental setup have had to be replaced, and the resulting eventual setup is much more sophisticated than the one initially proposed.

1. Target. When the prior theoretical work was revised for higher photon energy (see **Theory** above), it was discovered that the combination "high-Z radiator -- low-Z spacer" wouldn't work at 20 keV. Thus, Mo/Si multilayers were not useful anymore, and a new set of material pairs was proposed, in particular Mo/Ag. Combined with unexpectedly high electron energy we are now utilizing (please see below, **Accelerators**), which increased the optimal target period thickness to 0.22 μm, this development deprived us of both ready available targets and easily accessible material deposition technologies. After numerous fruitless negotiations with various commercial and non-commercial prospects, including initially proposed Columbia University group of Dr. David Wundt, we finally were able to convince a person who had prepared the analogous target for the Japanese experiments of 1999, to make the target for us. He started his work in April, and we received the first test targets (with 10 periods instead of optimal 200) on May 22, 2006. In the meanwhile, we work with a model target that consists of one Mo and one Ag layer, to develop and test the experimental setup.

2. Detector. The X-ray detectors on which we initially counted appeared not appropriate to the task, in particular because of too high x-ray background in the facility and the need for higher working energy range. Thus, a new **detector was found, purchased, incorporated into out setup, and tested**.

3. Personnel. Unfortunately, we were unable to use services of Dr. Lefferts (who declined to work with us shortly after the award was received) and Dr. Zhong (since his detectors appeared to be of no help to us). Instead, we involved, on a part-time basis, Dr. Kiyashko, an experienced physicist from former USSR. He left our team at the end of 2005. At this point, one of our research scientists, formerly of Kurchatov's Institute in Moscow, is helping Dr. Shabalov and me. A key role is played, of course, by ATF BNL personnel. Altogether, it seems to be sufficient to continue experiments.

3. Accelerator and overall setup. The medical accelerator at HSC, after several months of negotiations with manufacturers, proved to be inaccessible, as our experiments would take too much time away from its medical services. (It must be noticed, however, that the parameters of the Varian Clinac 2100 fit perfectly our proposed source, with the electron energy 6-20 MeV, electron beam cross section of 0.5 cm, and the beam current ~ 1 mA in microsecond high-repetition pulses, so that such accelerators seem to be a very good electron source for future applications of X-ray transition radiation with multilayer targets.) Subsequent search eventually led us to the linac at Accelerator Test Facility (ATF) of Brookhaven National Lab. It is an excellent facility, but its minimum energy (30 MeV) is much higher than the one envisioned in our proposal. In addition to changing the optimal target period thickness, this has two major consequences:

- the contrast between TR and the Bremsstrahlung drops sharply, to just the factor of 2 even at the optimal angle, which makes the angular measurements mandatory; and
- TR becomes much more collimated.

Subsequently, a **completely new setup has been developed and implemented**, which includes:

- electronically controlled high-precision positioning devices:
- a new optical device that would allow to precisely aim the detector; and
- a new, custom-made collimator.

Eventually, this led to the need for a **dedicated space** for our experiments on the ATF linac, including a new vacuum chamber and a new optical table, which was completed a few weeks ago after **almost 6 months** of work at ATF.

Summary

Under the AFOSR support, we have dramatically advanced all components of the initially proposed research, with the resulting better understanding of the physics of X-ray TR at multi-keV energies, as presented in new theoretical publications [6-8], and in the development and implementation of the totally new experimental set-up suitable for those energies. While the stated goals of the proposed research have not been attained yet, those results enable us to continue experiments to their completion.

It is important to note also that an additional promising result of our work under this AFOSR grant has been the development of close cooperation between BNL and Stony Brook University. In the course of it, a **new collaborative experimental project** has emerged, which is aimed at investigating prospects of using a unique **compact Terawatt CO_2 laser** developed recently at ATF [9] to drive a **novel, promising source of MeV protons and ions for medical and industrial applications.** The source will be based on high-field laser-plasma interaction. Such interaction was at the center of Shkolnikov's prior AFOSR- supported research back at Prof. Kaplan's group at Johns Hopkins; this fact is a key component of the new project, which is now in search for external support. The project was recently approved at ATF, and preparatory work began.

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[4] A. E. Kaplan, C. T. Law, and P. L. Shkolnikov, Phys. Rev. E**52**, 6795 (1995).

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New publications prepared in the course of the project

[6] A. E. Kaplan, A. L. Pokrovsky, and P. L. Shkolnikov, *"Transition radiation in metal-metal multi-layer nanostructures as a medical hard X-ray source,"* to be published in J. Applied Phys.

[7] P. L. Shkolnikov, A. L. Pokrovsky, and A. E. Kaplan, *"Metal-metal nanolayered structures for generation of hard x-ray radiation,"* APS March'06 Meeting in Baltimore, MD.

[8] A. E. Kaplan, A. L. Pokrovsky, and P. L. Shkolnikov, "*Transition radiation in multilayer nanostructures as a medical source of hard-X-ray radiation,*" to be presented at CLEO'06 in Long Beach, CA.

[9] Igor Pogorelsky, Markus Babzien, Igor Pavlishin, Daniil Stolyarov, Vitaly Yakimenko, Peter Shkolnikov, Alexander Pukhov, Alexei Zhidkov, Victor T. Platonenko, *"Terawatt CO2 laser: a new tool for strong-field research,"* High-Power Laser Ablation VI, May 7-12, 2006, Taos, NM.

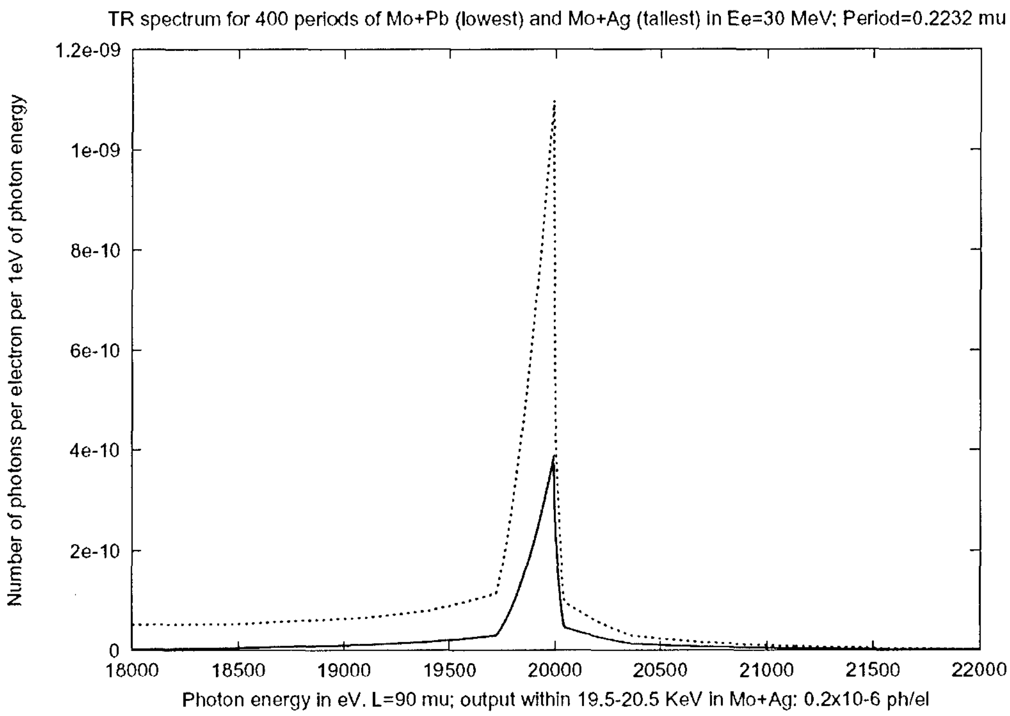

Fig. 1

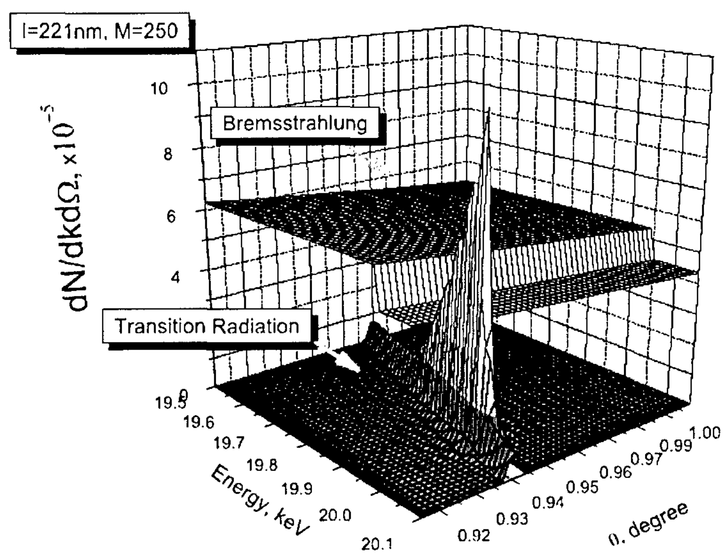

Fig. 2. The theoretical radiation spectrum of 250-period Ag/Mo nano-structure (total width $\approx$ 55μm).