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# The TPLUS project : a table-top tunable parametric UV radiation source

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**Abstract.** We present the project of a parametric radiation source, the Tunable Parametric Laboratory Ultraviolet Source (TPLUS). We aim at building a prototype of such a source with an electron gun of moderate energy, 100 keV, interacting with a periodic multilayer within a high vacuum experiment chamber. The objective of this table-top facility is to provide users with a cost-effective, simple-handling mean to provide a tunable and intense radiation source in the extreme UV and soft x-ray ranges.

## 1. Introduction

The objective of the TPLUS (Tunable Parametric Laboratory Ultraviolet Source or T+) project is to prove that it is possible to build, at a relatively low cost, a laboratory tunable extreme UV (EUV) source based on the emission of parametric radiation (PR) by a periodic multilayer, working in continuous mode operation, which can be easily implemented in academic and industrial centres for various purposes: characterization of optics, detectors and spectrometers for the EUV, chemical analysis, source of EUV radiation for physical chemistry studies, ... Currently, no EUV source using non-relativistic electrons interaction with multilayer targets and exploiting the transition (TR) or parametric radiation has been reported in the literature. Nevertheless several successful experiments have been carried out in the soft x-ray domain using relativistic electron beams supplied by LINAC or storage rings by a Japanese team [1] or a US-Russian collaboration [2].

In the hard x-ray domain, some PR sources using crystal targets and relativistic electrons supplied by medium energy LINAC have been developed and used for scientific applications especially in Germany and Japan [3]. It is worth mentioning the PR-based source [4] in operation in Japan at the Nihon University. It produces x-rays around 15-20 keV and is dedicated to perform phase contrast imaging. It is based on a 100 MeV pulsed LINAC whose electrons interact with a silicon crystal. By rotating the crystal it is possible to change the emitted wavelength. This source works in pulsed mode (2 Hz) that induces long acquisition times.

Different EUV sources have been developed in the context of the EUV lithography [5]. They are mostly based on laser-produced plasma using liquid target or discharges in gas. They can offer an important power but their emission is limited to a narrow spectral range around 13.5 nm. A drawback for metrology application is the uneven “shape” of their spectrum and their relative lack of pulse-to-pulse stability.

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Another system for EUV lithography is the “pocket synchrotron” Mirrorcle developed in Japan [6,7][6]. In these 1 to 2 m large apparatus, the electrons are accelerated up to 4 or 20 MeV and produce mainly infrared (IR) radiations. EUV radiation can be obtained by inserting a thin foil in the storage ring, giving rise to an intense TR emission. Let us also note the CEMOX (Centrale d’Elaboration et de Métrologie des Optiques X) instrument working with a plasma source and used to characterize new multilayer coatings [8]. However it presents two main limitations: the available spectral range is limited due to region just near absorption edge of available filters and the pulsed operation (at 1 Hz) induces limited signal-to-noise ratio.

Except the synchrotron radiation or the free electron lasers, only available in large facilities, there is at present no tunable source of EUV radiation. Its use is quickly developing, mainly because of the implementation of the EUV lithography dedicated to the manufacturing of the next generation of electronic chips [9], of research in solar and extra-solar imaging from spatial telescopes [10] and of “attosecond” physics [11]. In addition, most of the private or institutional laboratories elaborating EUV optical components generally characterize their products by means of x-ray diffractometers operated in the hard x-ray range and complete their measurements using synchrotron radiation at the wavelength of application. The availability of a laboratory tunable EUV source would be invaluable for such purposes.

## 2. Physical principle

Our EUV source is based on the PR emission in the case of Bragg resonant transition radiation, occurring when fast electrons propagate through a periodic medium (crystal, multilayer interferential mirror) close to the Bragg conditions. It can be seen as TR undergoing Bragg diffraction in a periodic lattice, as shown in Figure 1. When electrons impinge a stratified structure of period  $d$  at a glancing incidence  $\theta$ , radiation of wavelength  $\lambda$  is produced in the direction close to  $2\theta$  with respect to the incident electron beam direction, as given in first approximation by the Bragg law. By the coherent superposition of diffracted waves, this radiation is monochromatic, intense and directional.

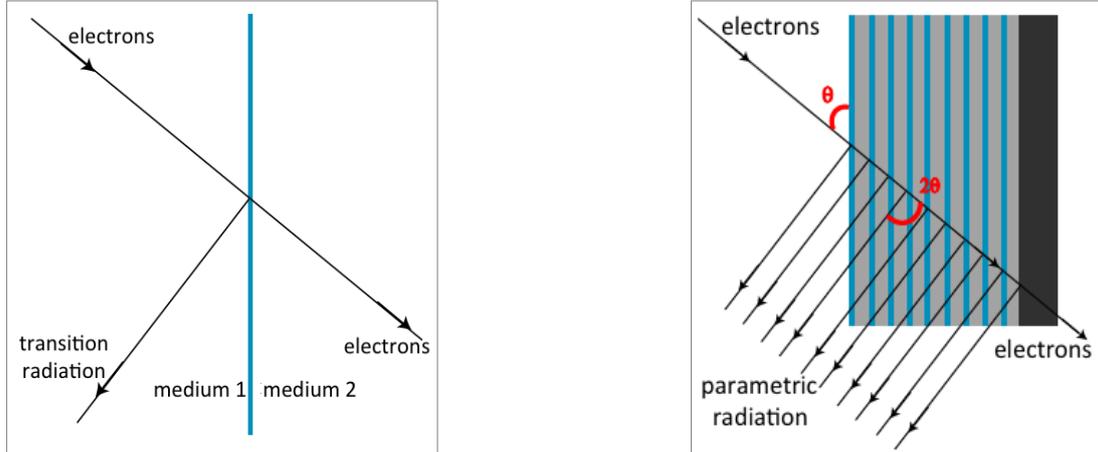


Figure 1 : Principle of the transition (left) and parametric (right) radiations.

When high-energy electrons of velocity  $v$  are bombarding the periodic multilayer under a glancing angle equal to  $\theta$ , PR is emitted close to the Bragg conditions. The  $n^{\text{th}}$  order PR frequency is given by the following relation in which  $\gamma$  is the Lorentz factor of the relativistic electrons [12]:

$$\omega^{PR} = \frac{2\pi mc}{2d \sin q} \left( 1 - \frac{1}{2g^2 \sin^2 q} \right) \quad \text{with} \quad g = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} .$$

The frequency is related to the diffraction of virtual photons associated with the Coulomb field of a fast electron. In the case of ultra-relativistic electrons impinging on the periodic multilayer structure under a  $\theta$  glancing angle, the previous expression of the  $n^{\text{th}}$  order PR frequency is simplified and given by:

$$W^{PR} = \frac{2\pi n c}{2d \sin \theta} .$$

The radiation is collimated within an emission angle of about  $1/\gamma$  with respect to the specular direction of electron trajectory, that is to say, the emission is very anisotropic: the intensity decreases very rapidly when one gets away from this well defined direction.

In the non-relativistic case the spatial distribution of the PR is more complicated. The general expression of the intensity and yield of the radiated energy is developed into details in reference [13–15] in the PARAMETRIX calculation code working within the framework of the classical theory of electromagnetism in continuous media. Nasonov *et al.* have published recently theoretical calculations of the PR spectral and angular distributions emitted from a multilayer irradiated by 100 keV electrons [16]. Upon a  $45^\circ$  incidence angle, photons of 23.5 nm wavelength are emitted in the case of Si/Nb multilayer target having a 10 nm period. Their calculations demonstrate the feasibility of such a monochromatic source with an efficiency that is large enough for practical applications. They predict a yield of approximately  $10^5$  photon per electron with 100 keV impinging electrons the multilayer. In this case, with an electron gun providing 1 mA current, we can predict an order of magnitude estimate intensity of about  $5.10^9$  photons. $eV^{-1}.s^{-1}.sr^{-1}$  at the energy of 100 eV considering a spectral width of 1 eV. This value is lower than the  $10^{15}$  photons. $s^{-1}.sr^{-1}$  for both He I (58.4 nm) and He II (30.4 nm) lines supplied by a He-plasma, generated with the electron cyclotron resonance technique. Nevertheless this He source can emit only a few intense lines.

### 3. Proposed apparatus

The device under construction consists in the source by itself plus the characterization tools of the electron and PR beams. The scheme of the system is shown in figure 2. The main components of our apparatus are :

- a 100 keV Kimball Physics electron gun, which will deliver electrons under 1 mA current, focused on a 1 mm diameter spot on the surface of multilayer;
- a multilayer target, *i.e.* a periodic stack of nanometric layers deposited on a very thin silicon nitride membrane, and its four axes sample holder (3 translations, 1 rotation);

as elements of the source, and

- a Roper back-illuminated CCD camera whose pixel size is  $20 \mu m \times 20 \mu m$  for the diagnosis of the EUV radiation
- a YAG scintillator coupled with a visible camera, and Bergoz wire vibrating monitors for the diagnosis of the electron beam.

The layers of the target will be made of light materials, to minimize the *Bremsstrahlung* radiation yield, proportional to the square of the atomic number, and preserve the spectral purity of the source. The materials have to resist to the electron beam and to an eventual heating. Monte Carlo simulations have shown that if the thickness of the stack and the membrane does not exceed 600 nm, then less than 5% of the incident beam energy will be deposited in the target. The option to produce a self-standing multilayer will also be considered.

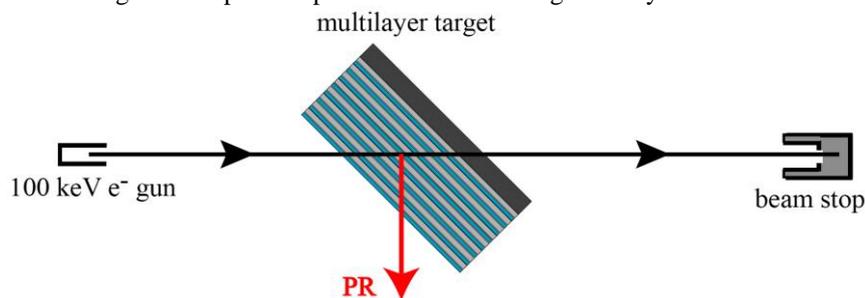
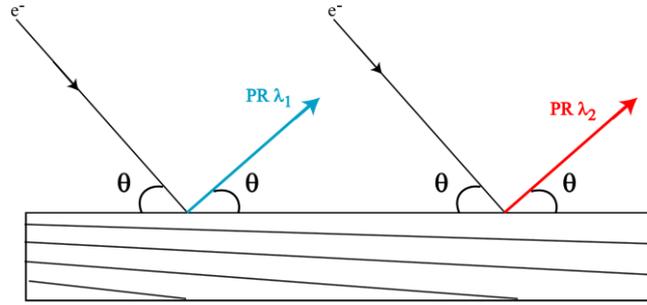


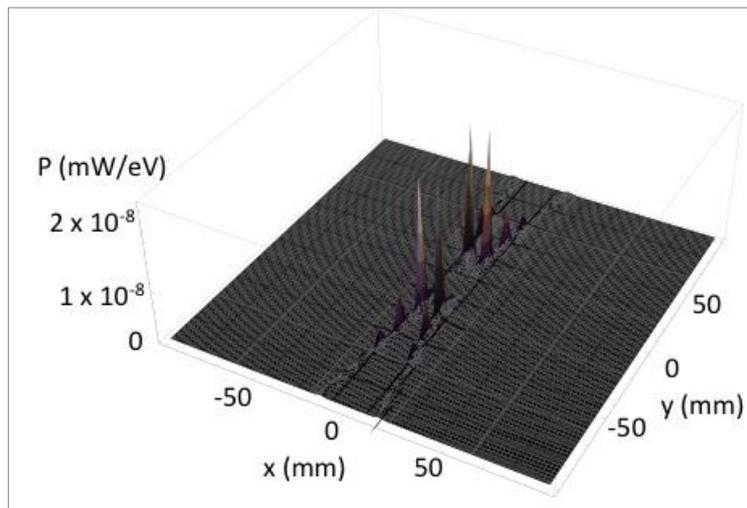
Figure 2: Scheme of the T+ apparatus. The PR will be detected by a CCD camera.

The energy of the emitted PR can be tuned either by changing the glancing angle or the period of the multilayer. However, it is preferable to obtain a source with a fixed exit. Indeed, the fixed exit of the source is a valuable feature because it makes easy its implementation for most of its uses. So we plan to use laterally d-graded multilayer targets [17]. These particular multilayers present a lateral gradient of period, see figure 3. Then, by translating the target under the electron beam, the multilayer period changes and so the PR energy.



*Figure 3: Wavelength tunability with the laterally d-graded multilayer target.*

We first plan to use the well-known Mo/Si multilayer to obtain a PR source at 92 eV (13.5 nm) in the following conditions. The multilayer is designed with 50 bilayers, with 4 nm-thick Mo layers and 6 nm-thick Si layers. The PARAMETRIX code is used considering 100 keV electrons impinging the target at incidence of  $45^\circ$  and with a current of 1 mA, and a square 100 mm x 100 mm plane detector located at 40 mm from the centroid source point. The result of this simulation giving the spectral power density is shown in figure 4.



*Figure 4 : Spectral power density of PR emitted by a Mo/Si multilayer irradiated at  $45^\circ$  by 100 keV, 1 mA electrons and measured on a square 100 mm x 100 mm plane detector located at 40 mm from the source point.*

The scale of intensity of emitted radiation is given in  $\text{mW}\cdot\text{eV}^{-1}$ , which corresponds to the power in 1 eV spectral bandwidth. Given the power value of about  $10^{-8} \text{ mW}\cdot\text{eV}^{-1}$  at the energy of 92 eV, this leads to about  $10^5 \text{ photons}\cdot\text{s}^{-1}\cdot\text{eV}^{-1}\cdot\text{sr}^{-1}$ . This is in agreement with the value predicted by Nasonov *et al.* [16]. It is observed that the spatial distribution of the emitted PR is complicated and presents some intense and narrow symmetric peaks. We expect that the experimentally observed distribution will result from the convolution of the simulated distribution by the spatial, energy and angular distributions of the electron beam impinging the target.

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