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# Targets emitting transition radiation for performing X-ray lithography by the tabletop synchrotron MIRRORCLE-20SX

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## Abstract

The tabletop storage ring synchrotron (SRS) MIRRORCLE-20SX is a powerful source of soft X-rays emitted from transition radiation (TR) targets. SRS can be used as a source for performing X-ray lithography (XRL) when it emits TR power $P_{\mathrm{XRL}} \geqslant 50$–$100\,\mathrm{mW}$ of photons having energy in the range 490–1860 eV. One-foil targets in SRS can emit a high TR power, and the electron beam geometry of MIRRORCLE-20SX requires using TR strip targets with a width $\cong 3\,\mathrm{mm}$. $P_{\mathrm{XRL}}$ emitted by one-foil strip TR targets is estimated for several foil materials, and varying foil thickness $d$. These results show that a target containing one C foil with $d \cong 260\,\mathrm{nm}$ can be used for performing XRL. Target made of one collodion foil with $d \cong 290\,\mathrm{nm}$, and target of one Al foil with $d \cong 200\,\mathrm{nm}$ emit less, but could also be used for XRL. We manufactured such targets by depositing layers of these materials on slide glass, using Teepol as a releasing agent, and subsequently floating them on a water surface. The C layer is prepared by a horizontal resistance thermal evaporation, and supported by a 270–300 nm thick collodion layer, formed onto the Teepol film. The Al layer is thermally evaporated.

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## 1. Introduction

Transition radiation (TR) is emitted when a relativistic particle passes through the interface between two media [1]. The emission has a conical shape with a maximum intensity at an angle $\theta \cong 1/\gamma$, with respect to the direction of the incident particle, and half-intensity angle of $\Delta\theta \cong \theta \cong 1/\gamma$, where $\gamma = (1 - v^2/c^2)^{-1/2}$ is the relativistic factor [2]. Main sources of TR are synchrotrons producing relativistic electrons. For such synchrotrons, most power is emitted from TR targets consisting of foils with sub-micron thickness [3,4]. In linear accelerators, the injected electrons pass only once through the target [5]. Storage ring synchrotrons (SRS) emit more TR power, because their injected electrons recycle many times through the target [6].

XRL represents an important tool for micro-machining of components with minimum features of the order of 70 nm [7]. SRS can be used for performing X-ray lithography (XRL) if it can emit TR power $P_{\mathrm{XRL}} \geqslant$ 50–100 mW [8] of photons with energies in the range 490–1860 eV [9].

H. Yamada and Photon Production Laboratory Ltd. (http://www.ppl-X-ray.com) developed MIRRORCLE-20SX, which produces 20 MeV electrons, and is the smallest tabletop SRS in the world, and can be used as a source for XRL [10,11]. MIRRORCLE-20SX is characterized by a very long lifetime $\tau$ of the electrons injected in the storage ring, which allows operation with beam currents of more than 1 A [12,13].

Development of a theory for emission of TR by low-energy SRS [9] clarified that one-foil TR targets can emit a high power, because $\tau$ is inversely proportional to the thickness of the target. Therefore, here we discuss and deal only with one-foil TR targets. The electron beam of

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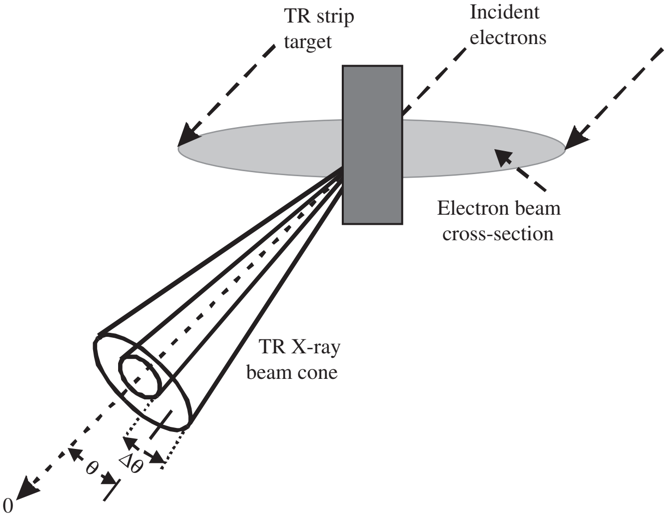

Fig. 1. Emission of transition radiation from a foil strip TR target in MIRRORCLE-20SX.

MIRRORCLE-20SX has a width of 20 mm, and a height of 3 mm [14]. To achieve emission of TR from a square area, our TR targets represent a vertical strip of a foil with a width of 3 mm. A schematic diagram of the emission of TR from such a foil strip TR target in MIRRORCLE-20SX is shown in Fig. 1.

In this paper is estimated the emitted power $P_{\mathrm{XRL}}$ by one-foil strip TR targets for performing XRL by MIRRORCLE-20SX. It is discussed what kind of foils are most suitable for this purpose. Such one-foil TR targets are manufactured, and details of their preparation are discussed.

## 2. Design of one-foil strip TR targets for performing XRL

The power emitted from a one-foil strip TR target is determined by the lifetime $\tau$ of the electrons injected in the storage ring, and the energy spectrum $\Delta E(E)$ emitted from the target, for one pass of one electron through it. Yamada has proposed a method for calculation of $\tau$, which is limited by elastic Coulomb scattering from nuclei of the target material, inelastic scattering related to emission of bremsstrahlung by the target, and scattering from the residual gas in the storage ring [15]. The knowledge of $\tau$, gives the number of passes $N_{\mathrm{P}}$ of one injected electron through the target, before this electron's dissipation. $\Delta E(E)$ is calculated using the theory for emission of TR by low-energy SRS [9]. The TR power $P_{\mathrm{XRL}}$ emitted by photons with energies $E$ in the range 490–1860 eV is

$$P_{\mathrm{XRL}} = C_{\mathrm{c}} N_{\mathrm{el/s}} N_{\mathrm{p}} \int_{490\,\mathrm{eV}}^{1860\,\mathrm{eV}} \Delta E \,\mathrm{d}E, \tag{1}$$

where $N_{\mathrm{el/s}}$ is the number of electrons injected in the storage ring for 1 s, and $C_{\mathrm{c}}$ is a calibration constant obtained by a comparison between our experimental data, and calculated results. $N_{\mathrm{el/s}}$ is evaluated at full operational power of MIRRORCLE-20SX, namely a peak injected current 100 mA, injection pulse time 150 ns, and a pulse repetition rate 400 Hz. Notably, we expect to double the operational power of MIRRORCLE-20SX, within one year, which would double both $N_{\mathrm{el/s}}$, and $P_{\mathrm{XRL}}$.

$P_{\mathrm{XRL}}$ is estimated for several foil materials as a function of the foil thickness $d$ of the one-foil target, and the results are presented in Fig. 2. The following material densities $\rho$ (g/cm$^3$) are used: $\rho_{\mathrm{Be}} = 1.85$, $\rho_{\mathrm{C}} = 1.8$, $\rho_{\mathrm{collodion}} = 1.35$, $\rho_{\mathrm{Al}} = 2.695$, $\rho_{\mathrm{Ti}} = 4.54$, and $\rho_{\mathrm{Au}} = 19.32$. We choose collodion (cellulose nitrate), because it is very light, contains relatively small amount of hydrogen compared to other plastics (collodion could decompose partially in a powerful beam of relativistic electrons as a result of a loss of some hydrogen atoms), and can form nanometer-scale layers reproducibly. It is seen that Be, C, collodion, and Al targets can emit $P_{\mathrm{XRL}} > 50$ mW which means that such targets could be used for performing XRL.

Apparently, targets made of materials with lowest possible atomic number $Z$ emit most TR power $P_{\mathrm{XRL}}$. Literature check of the lowest possible $Z$ thin foils, offered by foils producers [ACF Metals, http://www.techexpo.com/WWW/acf-metals/page1.html, Lebow Company, http://www.lebowcompany.com/foils_list.htm, Goodfellow Company, http://www.goodfellow.com/csp/active/gfResults.csp], shows that there are no Li ($Z = 3$) sub-micron foils, and

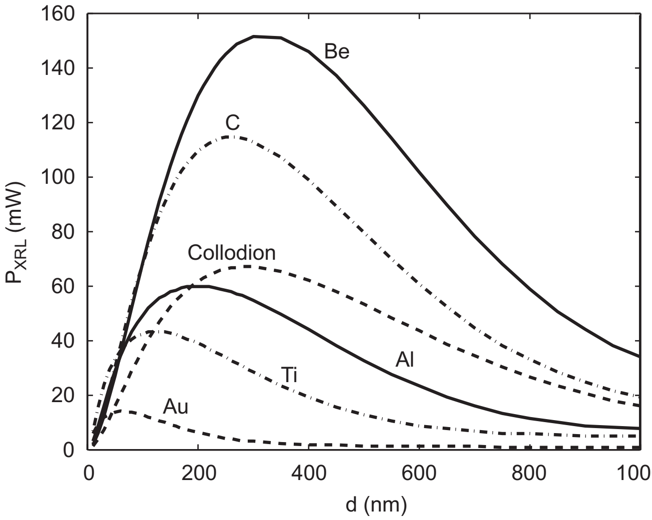

Fig. 2. Estimated emitted power $P_{\mathrm{XRL}}$ from one-foil strip TR target in MIRRORCLE-20SX, as a function of the foil thickness $d$. Results for several foil materials are provided. Only targets emitting $P_{\mathrm{XRL}} \geqslant$ 50–100 mW can be used for performing XRL.

Table 1
Optimal foil thickness $d_{\mathrm{opt}}$ of one-foil strip TR target, and maximal emitted power $P_{\mathrm{XRL}}^{\max}$ by such a target in MIRRORCLE-20SX

| $E$ (eV) | | Collodion | Be | C | Al | Ti | Au |
|---|---|---|---|---|---|---|---|
| [490, 1860] | $d_{\mathrm{opt}}$ (nm) | 290 | 300 | 260 | 200 | 120 | 60 |
| | $P_{\mathrm{XRL}}^{\max}$ (mW) | 67.1 | 151.5 | 114.6 | 60.0 | 43.3 | 14.1 |

These data are extracted from Fig. 2.

B ($Z=5$) foils are catastrophically damaged even for low electron beam currents [16].

The dependence $P_{\mathrm{XRL}}(d)$ has a maximum at $d=d_{\mathrm{opt}}$, and $d_{\mathrm{opt}}$ is different for different foil materials (Fig. 2). For thinner foils ($d<d_{\mathrm{opt}}$), the emitting region is too thin, and for thicker foils ($d>d_{\mathrm{opt}}$) there is too strong scattering of the electrons injected in the storage ring. The data from Fig. 2 for the optimal foil thickness $d_{\mathrm{opt}}$, and the maximal emitted power $P_{\mathrm{XRL}}^{\max}=\max[P_{\mathrm{XRL}}(d)]$ are shown in Table 1, for all of the investigated foil materials. Be TR target offers a largest $P_{\mathrm{XRL}}$, but since Be is regarded as carcinogenic we do not use it. Therefore, the best one-foil TR target for XRL contains one C foil with $d\cong d_{\mathrm{opt}}=260$ nm, which provides $P_{\mathrm{XRL}}>100$ mW. TR target containing one collodion foil with $d\cong 290$ nm, as well as TR target containing one Al foil with $d\cong 200$ nm, give $P_{\mathrm{XRL}}>50$ mW, and could also be also used for XRL. Based on the results from Section 2, we committed ourselves to preparing sub-micron foils of C, collodion, and Al, and manufactured one-foil strip TR targets for performing XRL by MIRRORCLE-20SX.

## 3. Preparation of one-foil strip TR targets for MIRRORCLE-20SX

The one-foil strip is attached to an open frame non-magnetic stainless steel holder. Two small tips screwed close to the open side of the frame limit the free-standing length of the strip to either 8 mm, or 5 mm. The width of the strip is 3 mm.

Slide glass is used as a substrate, and a film of hardened liquid Teepol is used as a releasing agent. After depositing the target layer, the front surface of the glass (without a target layer) is line scratched by a diamond cutter to shape a strip with a width of 3 mm, and a length of at least 16 mm. The glass is then broken, forming a glass strip, by pressing its fixed back surface along the line scratch. The target layer is floated on water and pulled out of it, to stand between the frame tips.

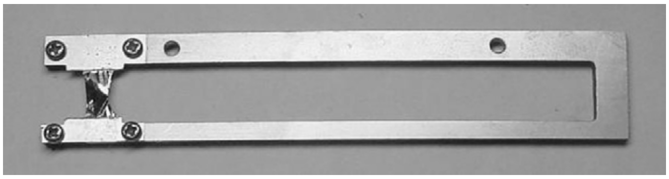

Fig. 3. Photo of TR target containing one Al foil strip with a thickness $d\cong 200$ nm.

Test pieces are prepared simultaneously on a slide glass with a narrow strip of a sticky tape on its surface, without using Teepol. After depositing the layer, and removing the tape, the layer thickness is measured by a film edge stepper DEKTAK. Since the layer is thicker close to the edge, its thickness is recorded away from the edge, where the layer has a relatively constant thickness.

### 3.1. Al target

Al is thermally evaporated from a tungsten boat with sizes $0.2\times 6\times 100$ mm in vacuum of $<1.10^{-5}$ Torr. One hundred and thirty milligram Al is loaded in the boat, the current is 65 A, and the distance boat-substrate is 90 mm. This results in evaporation of Al layer with a thickness $d\cong 200$ nm. A photo of one Al foil strip TR target prepared from this Al layer is shown in Fig. 3. The strip stays slack (not tight) on the frame.

### 3.2. Collodion target

Collodion layer (cellulose nitrate) is prepared from a 5% solution of collodion in isoamyl acetate. This solution is obtained by mixing two equal weights of commercial 10% solution of collodion in isoamyl acetate, and isoamyl acetate itself. The slide glass, containing a Teepol film, is pulled out of the solution, forming a collodion layer with a thickness $d\cong 270$–$300$ nm. A photo of one collodion foil strip TR target prepared from this layer is included in Fig. 4. The strip stays on the frame without a visible deformation.

### 3.3. C target

C layer is formed by a resistance thermal evaporation (RTE) [17,18]. Horizontal RTE instrument (Fig. 5), attached to a thermal evaporation system, is used for this purpose. C rod with a diameter $\Phi=3$ mm, and a length $l=25$ mm is utilized. Maximum current of 155 A can be passed through the rod in our system. We could not

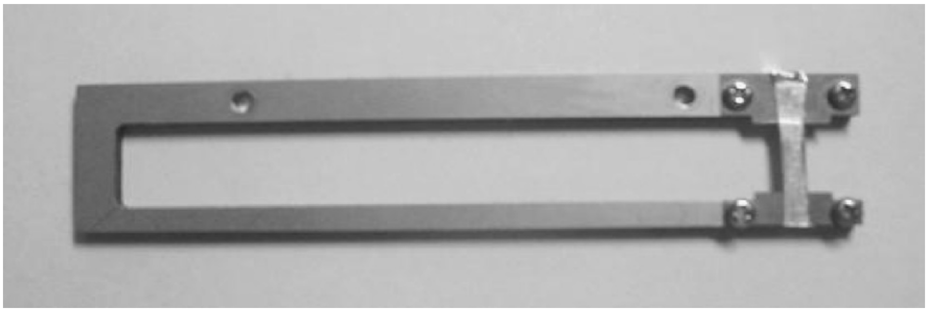

Fig. 4. TR target of one collodion foil strip with a thickness $d=270$–$300$ nm.

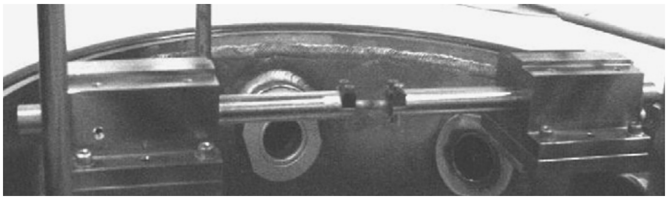

Fig. 5. Instrument for performing a resistance thermal evaporation (RTE) of C. C rod with a diameter $\Phi = 3\,\mathrm{mm}$, and a length $l = 25\,\mathrm{mm}$ is used. Maximum current of 155 A is passed through the rod.

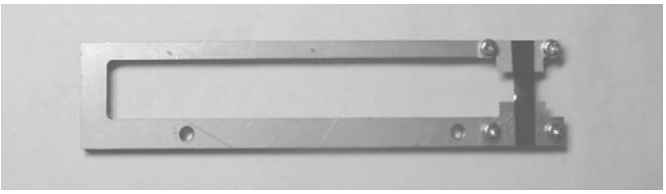

Fig. 6. TR target containing one C layer with a thickness $d = 265$–$310\,\mathrm{nm}$, onto one collodion layer with a thickness 270–300 nm.

evaporate such spectrographic C rods from the Japanese Company NILACO. But experiments with spectrographic C rods of the French Company Carbone–Lorraine were successful.

RTE was performed in vacuum $<2.10^{-5}$ Torr, at a current 155 A, a distance C rod-substrate 70 mm, and evaporation time 280 s (till the C rod broke down). These conditions produced a C layer with a thickness $d \cong 265$–$310\,\mathrm{nm}$. Unfortunately, C strips made of this layer folded into wires while pulling them out of the water.

To support the C strips, we used a collodion layer with a thickness 270–300 nm, whose preparation was discussed in Section 3.2. When C layer is evaporated onto the Teepol film though, its surface is torn by numerous flakes developed as a result of a thermal deterioration of the Teepol. When the collodion layer covers the Teepol film, the surface of the evaporated next C layer is quite flat. A photo of one C/collodion foil strip TR target prepared from this two-layer structure is shown in Fig. 6. At present, we are working on removing the collodion-supporting layer by reactive oxygen-plasma etching, following the process described in Ref. [19].

## 4. Conclusions

We designed optimal one-foil strip TR targets for performing XRL by our SRS MIRRORCLE-20SX. These results indicate that nanometer-scale foils of C, collodion, and Al are needed, and give the desired thickness of each of these foils. We prepared such foils, and manufactured one-foil strip TR targets, with a width 3 mm, for MIRRORCLE-20SX.

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