Main Characteristics of the Tabletop Synchrotron Light Sources MIRRORCLE

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Abstract - **Arguments are presented, indicating necessity for development of smaller synchrotron light sources (SLSs), for use by individual companies. Pioneer in developing tabletop SLSs (TSLSs) is the company Photon Production Laboratory (PPL) in Japan. They manufacture TSLSs of the brand MIRRORCLE, available in 4 models operating at electron energies between 1 MeV and 20 MeV. The main characteristics of these TSLSs are analyzed. Applicability of the 4 different models, for particular practical applications, is discussed. It is shown that MIRRORCLE TSLSs have significant advantages for X-ray imaging, compared to X-ray tubes and conventional SLSs.**

Keywords – **electron tabletop synchrotron light source (TSLS), MIRRORCLE TSLSs, main characteristics, X-ray imaging**

I. Introduction

Light interacts with matter by several mechanisms, as illustrated in Fig. 1 [1].

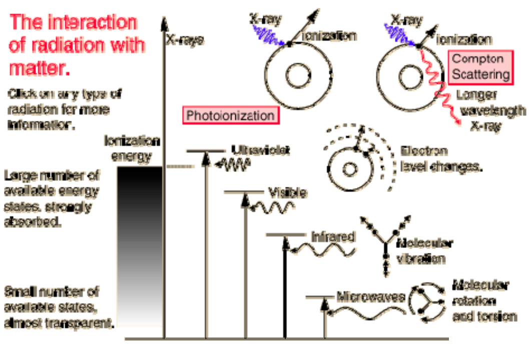

Fig. 1. Illustration of the most common mechanisms of interaction of light with matter

Light passing through matter can: rotate/vibrate atoms, excite atomic electrons, ionize atoms, and generate light with other energies. Since the strength of each of these phenomena depends individually on the photon energy, both the absorption of light and the ionization of the material can vary significantly with respect to the photon energy. The dependencies of the attenuation coefficient on the photon energy are presented in Fig. 2 for iron [2] and soft tissues [3], which are chosen as representatives of very dense solids and biological materials.

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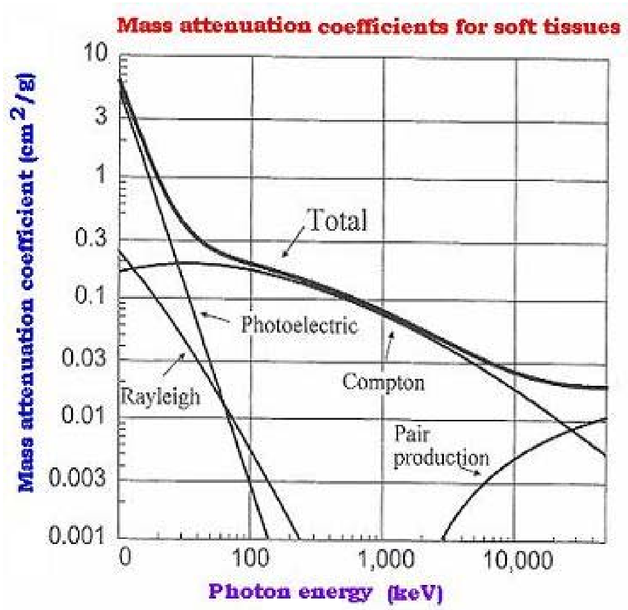
(a)



(b)

Fig. 2. Dependence of the attenuation coefficient on the photon energy, for light in: (a) iron, (b) soft tissues

These graphs indicate that both UV and X-ray light are absorbed less in matter and ionize matter more than visible light, its spectral region being from 1.65 to 3.10 eV. It can be estimated from these data that UV and X-ray light can be transmitted strongly even through thick metal bodies. The illustrated above strong dependence of both the absorption and the ionization of a given material on the photon energy, for solid, soft, and biological materials, determines the necessity for using different types of UV and X-ray light sources, capable of emitting light with spectral and intensity characteristics suitable for different practical applications.

The main types of UV and X-ray sources are: Emitting tubes, Lasers, Synchrotron light sources.

In emitting tubes, a cathode filament generates electrons, which irradiate the anode, whereat UV or X-ray light is emitted. Correspondingly, the emitted light has a low intensity and a relatively narrow spectrum.

Light emitted by Lasers has a relatively high intensity and a very narrow spectrum, regardless of the photon energy.

Conventional synchrotron light sources (SLS) usually contain two components: Linear accelerator (LINAC) and a storage ring. The LINAC accelerates electrons to a required relativistic energy, and injects them into the storage ring. Most often, the storage ring has a toroidal shape, whereat a magnetic field regulates each of the injected relativistic electrons to circulate many times through the housing of the toroid. The multiple circulation of each injected relativistic electron through the toroid leads to increasing the current density of the electron beam in the storage ring. Light is emitted as a result of the radial acceleration of the electrons, as well as inclusion of optional specialized devices called insertion devices. Such a light has quite high intensity and wide spectrum.

The unique characteristics of synchrotron light create a significant demand for using SLSs. Conventional SLSs are huge facilities, spread over areas of the order of km^2, which cost hundreds of millions of US dollars. Correspondingly, SLSs are owned by one or several governments, being located at areas remote from big cities, and their time for public access is often limited, imposing significant difficulties for external users.

Synchrotrons and storage rings are used most often for studies of materials, as well as for collisions of relativistic energy particles. Particle colliders operate with particles with energies of the order of tens of GeV.

According to the discussed above data, light with photon energy of at least 1 MeV can be transmitted strongly through and ionizes a vast majority of material samples. By a comparison, visible light is not transmitted through and does not ionize most such samples. It is known though that transmission of light through is required for performing non-destructive testing (NDT) of solid material samples. Furthermore, ionization is required for spectroscopic analysis of the structure of material samples. Conventional SLSs can be also used in the following applications [4]: structural analysis of crystalline and amorphous materials, energy dispersive X-ray diffraction, powder diffraction analysis, X-ray crystallography of proteins and other macromolecules, magnetic scattering, small angle X-ray scattering, inelastic X-ray scattering, tomography, X-ray imaging in phase contrast mode, X-ray standing wave experiments, photolithography for MEMS structures as part of the LIGA process, high pressure studies, residual stress analysis, and X-Ray Multiple Diffraction.

It might be possible however to use SLSs, with photon energies lower than those for conventional SLSs, for many of the above mentioned applications. Such a SLS would be smaller and less expensive than conventional SLSs, considering that 50 MeV SLS is already too expensive to be owned by an individual company, and too big to be positioned in one room of an ordinary building [5].

Based on all of the above, there is a significant interest in developing SLSs for materials studies which are emitting light with photon energies from ~0.5 to 20 MeV, being small enough and less expensive than conventional SLSs, and allowing ownership by individual companies.

A pioneer in development and manufacturing of electron tabletop synchrotron light sources (TSLS) is the company Photon Production Laboratory Ltd (PPL) in Japan, lead by Professor H. Yamada. They have designed [6], prepared, and studied the performance of TSLS from the brand MIRRORCLE, and offer such machineries operating at electron energies E_{el} = 1, 4, 6, and 20 MeV.

II. Design Essentials of Tabletop Synchrotron Light Sources MIRRORCLE

Each TSLS MIRRORCE contains two integrated units: a microtron and a storage ring. The microtron accelerates electrons to the required relativistic electron energy, and the storage ring increases the electron beam current [7].

In such a microtron, electrons are generated by an electron gun. Thereafter, these electrons circulate within the microtron, under the influence of a constant magnetic field. The kinetic energy of the electrons increases by a constant amount, after each revolution is completed, by passing them through the electric field of an RF cavity. Therefore, the diameter of each circular electron orbit is proportional to the number of the pass through the RF cavity. Once the electrons energy reach the operating energy for a particular microtron, corresponding to the largest orbit, the electrons enter an extraction channel and exit the microtron. The principle of functioning of the MIRRORCLE microtrons is illustrated in Fig. 3.

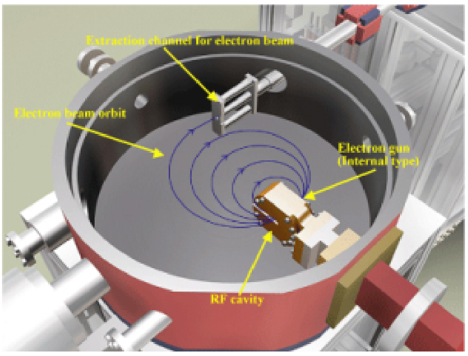


Fig. 3. Depicting generation and trajectories of electrons accelerated in a MIRRORCLE microtron, as well as extraction of electrons, reached the operating energy, from the microtron

As mentioned earlier, conventional SLSs employ usually LINACs for accelerating electrons, rather than microtrons. The MIRRORCLE microtrons however have the following advantages in comparison with the LINACs:

1. The microtrons provide better focused electron beam. This is a result of both inhomogeneity of the electric fields around the edges of the accelerating tubes and a significant length of LINACS.

2. The MIRRORCLE microtrons have an energy filtering function, due to same conditions for circulating, accelerating and extracting for all of the electrons.
3. The MIRRORCLE microtrons are relatively compact, lightweight, and moderately priced

After exiting the microtron, relativistic electrons, with the operating energy, enter the storage ring. It is a conventional storage ring, where these electrons pass many times along almost ideally circular orbits with an almost invariable diameter.

The light is radiated from a target positioned in the storage ring, whereat each of the circulating electrons passes many times through the target. The radiation mechanisms depend on the material and the dimensions of the target, and include:

- Bremsstrahlung, characterized by a wide spectrum including the hard X-ray region
- Transition radiation, with a narrow spectrum in the soft X-ray region
- Synchrotron-Cerenkov radiation, with a narrow spectrum in the EUV region [8]

III. Distinctions of the Four MIRRORCLE Models

As already mentioned, there are four MIRRORCLE models, offered by PPL, with operating electron energies E_{el} = 1, 4, 6, and 20 MeV.

Since the diameters of the largest electron orbits, in both the microtron and the storage ring, are proportional to the operating electron energy, the diameters of both the microtron and the storage ring, for a particular MIRRORCLE model, are proportional to its operating electron energy E_{el}. For example, the microtron with E_{el} = 20 MeV has 1.3m diameter, whilst the smaller microtron with E_{el} = 6 MeV has 0.65m diameter.

According to the PPL website [9]:
"- MIRRORCLE CV (with E_{el} = 1 MeV and 4 MeV) are the smallest in the brand and are suitable for X-ray imaging, XAFS fluorescence, and advanced materials analysis.
- MIRRORCLE-6FIR synchrotron radiation is possible to useas high-intensity THz light.
- MIRRORCLE-20 model is suitable for EUV light applications."

The spectral regions of emission, machinery photos, as well as respectively studied and recommended applications, for the models with E_{el} = 6, 20 and 4 MeV, are illustrated in Fig. 4 [9].

A photo of the 1 MeV TSLS MIRRORCLE-CV1 is shown in Fig. 5. More information about the TSLSs MIRRORCLE is presented in the PPL website [8].

IV. Example of MIRRORCLE Application. X-Ray Imaging

Main application of X-rays is for imaging objects interior, which can not be visualized by visible light.

Spectral dependencies of X-ray emitted from conventional SLSs, X-ray tube, and MIRRORCLE are presented in Fig. 6.

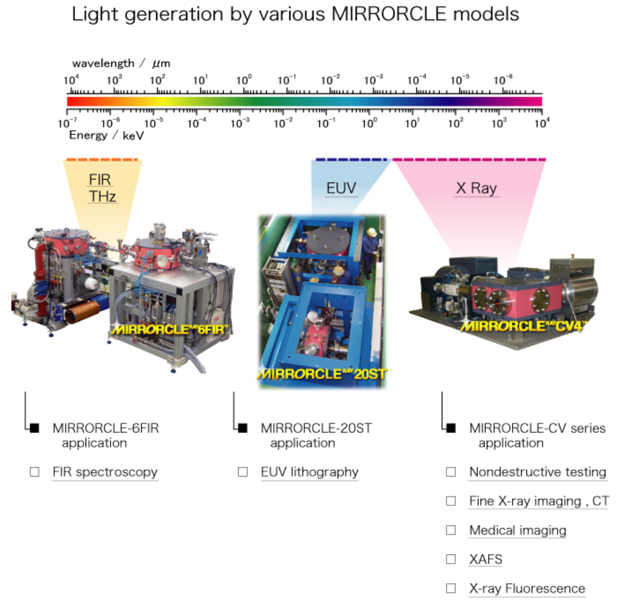


Fig. 4. Photos of 3 models of MIRRORCLE, spectral regions of their light emission, and PPL recommendations about their practical applications

Fig. 5. Photo of the smallest model of MIRRORCLE - for E_{el} = 1 MeV

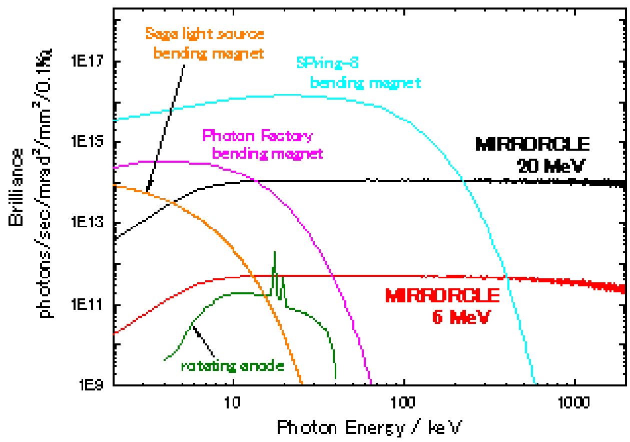


Fig. 6. Typical spectral dependencies of the brilliance of light emitted from a rotating anode X-ray tube, bending magnets of three Japanese SLSs, as well as from MIRRORCLE with E_{el} = 6 MeV, and E_{el} = 20 MeV

Advantages of X-ray imaging by MIRRORCLE, with respect to X-ray imaging by conventional SLSs and X-ray tubes, are illustrated in Fig. 7.

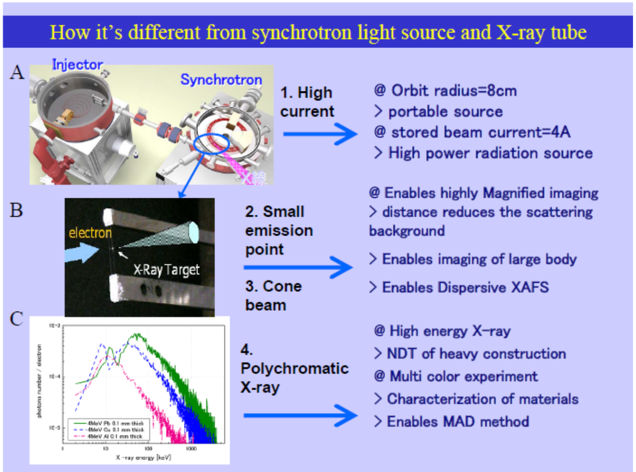


Fig. 7. Presentation of advantages of performing X-ray imaging by using light emitted from MIRRORCLE, with respect to X-ray imaging by conventional SLSs and X-ray tubes

X-ray images of a mechanical valve obtained by MIRRORCLE, LINAC, and X-ray tube are shown in Fig. 8.

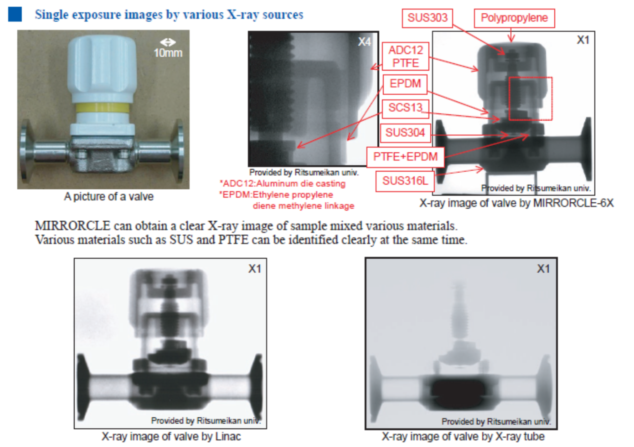


Fig. 8. X-ray images of a mechanic valve obtained by using light emitted: from MIRRORCLE TSLS - see the top line, from a LINAC – the left side of the bottom line, and from X-ray tube – the right side of the bottom line

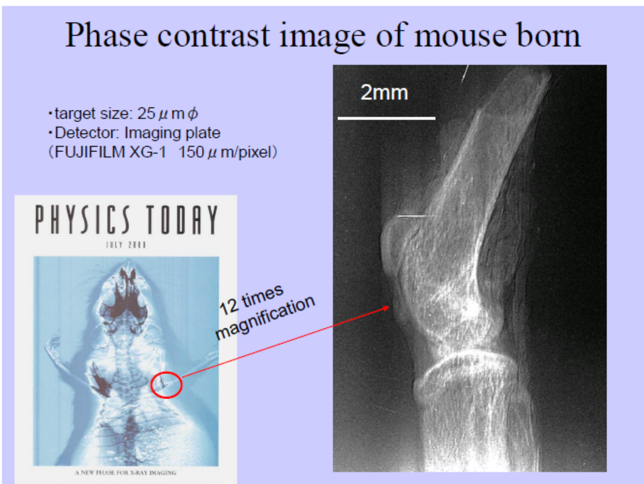


Fig. 9. X-ray images of a mouse, and its elbow bone

X-ray images of a mouse and its elbow bone are shown in Fig. 9.

V. Conclusion

There is an ongoing demand for SLSs of X-ray and EUV light, which are small enough and less expensive than conventional SLSs, to allow ownership by individual companies. Responding to this demand, the tabletop SLSs (TSLSs) MIRRORCLE have been produced by the Japanese company Photon Production Ltd (PPL). The brand MIRRORCLE includes 4 models for operating electron energy E_{el} = 1 MeV, 4 MeV, 6 MeV, and 20 MeV. In these machineries, relativistic electrons with the above E_{el} are generated and extracted from a microtron, and then injected into a storage ring. In the storage ring, each of these relativistic electrons passes many times through a target, which emits light with characteristics depending on the material and the design of the target. It turns out that light emitted from MIRRORCLE TSLS has some significant advantages with respect to light from conventional SLSs and emitting tubes. The different MIRRORCLE models are recommended for different practical applications by PPL.

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