Accelerator technologies for EUV or Soft X-ray Lithography

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Ritsumeikan University,
Tabletop Synchrotron Laboratory and
Photon Production Laboratory Ltd.
20 years experiences since development of superconducting synchrotron X-ray lithograph source AURORA
20 years experiences

AURORA was not adapted by lithography because,

I. 1W flux was not enough

II. If source is large and expensive, by the failure of 1 machine, whole process will be stopped!

III. Proximity projection is failed in mask correction technology.

IV. MTBF was not enough.

- 10W for proximity, 1 to 10 KW for projection is necessary
- Downsizing and cost down is necessary
- Shifted to Laser or e-beam plasma EUV
- Number of components should be reduced. SuperC technology is troublesome
I started working for normal conducting, low energy synchrotron technology 20 years ago.

These machines are completed and regularly used. CV4 is delivered to Hitachi for ultra fine resolution CT.
MIRRORCLE is a real storage ring

4A beam current is accumulated
10ms damping time, 1min lifetime is recorded

Immediate after the injection
During the damping
Fully damped

accumulation
Injection is stopped
Beam decay
By success in CW top-up injection we are able to obtain desired high power EUV or X-ray flux!

Synchrotron MIRRORCLE-CV4 HP model produced for HITACHI Ltd.

Provide 10μm space resolution CT!
In this talk we focus on:

- Introduction of Synchrotron-Cherenkov radiation for EUV and soft X lithography.
- 20 MeV tabletop synchrotron can generate 1KW EUV or soft X.
- 20 MeV synchrotron-Cherenkov Laser for 10KW.
- Comparison with other sources such as X FEL and ERL
How to generate EUV or X-ray by low energy synchrotron

> use target in the electron orbit

Important note!
Target last permanently. Deblis never happen because plasma is not generated.

CNT weave or yarn is used for EUV or soft X generation

40μ W or 10μ Cu sphere glued on 5.5μm CNT wire are used for hard X-ray generation
### SC radiation by 1 target with 20MeV ring

<table>
<thead>
<tr>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-3} \times 100 \times 0.1 \text{[A]} / 1.6 \times 10^{-19})</td>
<td>(6.25 \times 10^{16} / 50 \text{mrad}^2)</td>
</tr>
</tbody>
</table>

- Ring size: 1m
- Beam size at 1m distance is 50mmφ

### Undulator radiation by 300 MeV ERL

<table>
<thead>
<tr>
<th>Expression</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(10^{-5} \times 100 \times 0.1 \text{[A]} / 1.6 \times 10^{-19})</td>
<td>(6.3 \times 10^{14} / 1.3 \text{mrad}^2)</td>
</tr>
</tbody>
</table>

- Ring size: 10m
- Beam size at 10m distance is 13mm

#### Beam line

- Beam line can be 1m
- We can collect whole EUV radiation by mirror

- Beam line you need 10m due to thick concrete wall

#### Radiation yield

- Brems total radiation yield/1mm thick target/1 electron:
  - \(10^{-3} \text{photons/e, 0.1\% band, mm target}\)

- TR or Cherenkov gives 100 times more: \(> 10^{-1}\)

- Undulator gives 100 times more: \(> 10^{-3}\)

#### Average beam current

- Average beam current: 100mA
Either Cherenkov or TR radiation is the mechanism to be used

Cherenkov radiation occur when \( n = 1 + \Delta n > 1 \)

The radiation spread \( \theta: \quad 1/\gamma < \theta \sim 2\Delta n \) hollow cone

In EUV and X-ray region,
Spectrum is monochromatic.
It is coherent radiation

Transition radiation occurs at the boundary of two medium
The radiation spread: \( \theta \leq 1/\gamma \) hollow cone
Spectrum is continuous \( \gamma \cdot \hbar \omega_p \)
Cherenkov radiation under magnetic field

It is called Synchrotron-Cherenkov radiation.

It is neither Cherenkov nor Synchrotron
The angular distribution of synchrotron-Cerenkov radiation

T. M. Rynne, G. B. Baumgartner, and T. Erber

J. Appl. Phys. 49(4), April 1978, p. 2233

Given formalism is same for SR except the refraction index $n \neq 1$

\[ I(\omega, \theta) = \left( \frac{e \omega}{c} \right)^2 \chi_c \frac{E}{mc^2} \frac{H_{\text{ef}}}{H} \left[ \beta J'_\nu(\nu \beta n_r \sin \theta) \right]^2 + \left( \frac{\cot \theta}{n_r} J_\nu(\nu \beta n_r \sin \theta) \right)^2 \]

for $\Delta n \ll 1$ ($n=1+\Delta n$)

\[ \frac{d^2 N}{d(\hbar \omega) d\psi} = \frac{2 \alpha}{mc^2} \frac{L}{\chi_c} \left( \frac{2}{\nu} \right)^{1/3} \left\{ [A_i'(\xi)]^2 + \left[ \psi\left( \frac{\nu}{2} \right)^{1/3} \text{Ai}(\xi) \right]^2 \right\} \]

SR formalism is given for $\frac{(mc^2/E)^2 - 2\Delta n + \psi^2}{\psi} > 0$

\[ \frac{d^2 N^S}{d(\hbar \omega) d\psi} = \frac{\alpha}{3\pi^2} \frac{L}{\chi_c} \frac{mc^2}{E^2} \frac{H_{\text{ef}}}{H} \left[ 1 + \left( \frac{E}{mc^2} \psi \right)^2 \right]^2 \times \left( K_{2/3}^2(\xi^S) + \frac{(E\psi/mc^2)^2}{1 + (E\psi/mc^2)^2} K_{1/3}^1(\xi^S) \right) \]

SC formalism is given for $\frac{(mc^2/E)^2 - 2\Delta n + \psi^2}{\psi} < 0$

SC spectrum (1.13a) then exhibit an oscillatory behavior. It is convenient to introduce a new variable analogous to Eq. (2.1b),

\[ \xi = \frac{3}{2}(-\xi)^{3/2} \]

(2.7)

since the limit $H \to 0$ is linked with the limit $\xi \to \infty$, the spectral form (1.13a) can be replaced by the asymptotic estimate

\[ \frac{d^2 N}{d(\hbar \omega) d\psi} \approx \frac{2 \alpha}{\pi mc^2 \chi_c} \left\{ \left[ 2\Delta n - \left( \frac{mc^2}{E} \right)^2 - \psi^2 \right]^{1/2} \right. \]

\[ \left. - \left[ 2\Delta n - \left( \frac{mc^2}{E} \right)^2 - \psi^2 \right]^{1/2} \sin^2 \left( \xi + \frac{\pi}{4} \right) \right\} \]

$\xi \gg 1$. (2.8)
Oscillatory behavior appears beyond the SR regime $\psi > 1/\gamma$

The basic SC spectrum assumes a particularly simple form in case $\xi > 1$ [cf. Eqs. (1.13b), (2.4), and (2.14)]:

$$
\frac{d^2N}{d(\hbar\omega) d\psi} \approx \frac{\alpha L}{2\pi mc^2 \chi_c} \left\{ \frac{(mc^2/E)^2 - 2\Delta n + 2\psi^2}{[(mc^2/E)^2 - 2\Delta n + \psi^2]^{1/2}} \right\} \times \exp \left\{ -\frac{2\nu}{3} \left[ \frac{mc^2}{E} \right]^2 - 2\Delta n + \psi^2 \right\}^{3/2}.
$$

For appropriate choices of the index, such as $\Delta n \sim -\omega^{-2}$ [cf. Eq. (3.1a)], Eq. (2.18) displays the low-frequency damping which is characteristic of SC radiation. Clearly, the intensity decreases for larger opening angles:

In particular, the angle at which the intensity has diminished to one half the peak value is approximately given by

$$
\psi_{1/2}^2 \sim \frac{0.7(mc^2/\hbar\omega)(H/H_{cr})}{[1 - 2\Delta n(E/mc^2)^2]^{1/2}}.
$$

In the index-dominated regime (2.15), this estimate can be sharpened to

$$
\psi_{1/2}^2 \sim \frac{0.5}{(-\Delta n)^{1/2}} \frac{(mc^2)^2 H}{E \hbar \omega H_{cr}},
$$

which shows that increasing values of the index tend to reduce the angular dispersal of the radiation. Since index variations of this kind can be engendered by vacuum polarization, it is possible that novel focusing effects might be associated with pulsar emission.
Measurement of angular distribution of soft X-ray radiation from thin targets in the tabletop storage ring MIRRORCLE-20SX
Hironari Yamada et al.
Experimental set up

- Target is aligned parallel to the magnetic field
- The target-detector distance is 720 mm
- Applied magnetic field is 3300G
- Plastic scintillator
- Radiation from the target
- Radially positioning system
- The scintillator scans in the plane perpendicular to the median plane of the electron orbit
The EM radiation yield from 100nm thick CNT yarn must be very weak.

If thick target is used, soft X-ray is captured inside of target.

Electrons are hitting target every 1.5ns repeatedly in the storage ring.

Electron penetrate the thin target and re-circulate.

Gain 1KW energy by RF cavity

The beam current is 40A
Plastic scintillator (PS) is connected by plastic fiber to photo multiplier (PM).
- Read current from PM and CF converter is used.
- Mechanism moves the PS radially and rotate around the axis of radiation
- 8.5 μm thick NE102 plastic scintillator only detect EUV and soft X-rays up to 2keV, but no hard X-rays or UV’s are detected.
- Filter made of 385 nm thick Al foil select radiations higher than 400eV
Experimental results on 55nm thick DLC

(a) Without Al filter
Photon energy higher than 73eV is detected
2 peaks appear

(b) With Al filter
Photon energy higher than 400eV is detected
Hollow radiation having 3 ridges appears

(c) = (a)-(b)
Photon energy range 73eV<E<420eV
……… absorption edge of C 277eV is detected
Experimental results on 10μm thick CNT wire (yarn)

A) Measured by plastic Scint.

B) With 0.385μm Al filter

C) A-B 73eV<E<420eV

Median plane
Our results are consistent with Rinne theory

Hollow cone distributions are due to the TR, and directional distribution is due to the SCR

Mo

Absorption edges are 2.3 keV (L), and 17.5 keV (K)
Radiation spread ~ ±15 mrad hollow cone
no SCR is expected, so this is TR

Sn

Absorption edges are 3.4 keV (L), and 25 keV (K)
Radiation spread ~ ±20 mrad hollow cone
no SCR but TR

Al

Absorption edge: 1.5 keV (K)
SCR is within the detection range

C

Absorption edge is 277 eV (K)
Radiation spread ~ ±5 mrad directional
SCR is detected

Photon energy higher than 400 eV
Radiation spread ~ ±30 mrad hollow cone
Must be Transition
Comparison with Rynne theory

<table>
<thead>
<tr>
<th></th>
<th>Our case</th>
<th>theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$</td>
<td>20</td>
<td>50 MeV</td>
</tr>
<tr>
<td>magnetic field</td>
<td>3.3kG</td>
<td>5 kG</td>
</tr>
<tr>
<td>photon energy</td>
<td>277 eV</td>
<td>2.4 eV</td>
</tr>
<tr>
<td>Obs. or Cal. $\psi$</td>
<td>5 mrad</td>
<td>12 mrad</td>
</tr>
<tr>
<td>$\frac{H/E}{\hbar\omega}$</td>
<td>5.9E-4</td>
<td>0.04</td>
</tr>
<tr>
<td>$\psi^2 \propto A \frac{H/E}{\hbar\omega} / \sqrt{\Delta n}$</td>
<td>A=4500</td>
<td>A=4500</td>
</tr>
<tr>
<td>$\Delta n$</td>
<td>0.0011</td>
<td>1.56x10^{-4}</td>
</tr>
</tbody>
</table>

Higher electron energy, lower magnetic field, higher photon energy, higher $\Delta n$ reduces the radiation spread.
Measured EUV power from CNT

Radiated power from the CNT target is 19µA at repetition 70Hz.
Detector efficiency is 0.236[W/A] at the C k-edge energy 277eV.
Transmission rate by filter is 0.925.
Beam current 100mA,
The radiation power/pixel at 1000Hz repetition,
\[ P_{\text{max}} = \frac{19}{0.236/0.925 \cdot 1000/70} = 3897\mu\text{W/pixel} \]
Pixel solid angle \( \Omega_{\text{PS}} = \frac{(3\times3)}{(720\times720)} = 1.74\times10^{-5}\text{sr} \)
(detector is 720mm from the source)
Photon density at the peak \( P_{\text{max}}/\Omega_{\text{PS}} = 235\text{W/sr} \)
\[ = 1.29 \times 10^{13}\text{ photons/s, mrad}^2, 0.1\%\text{bw} \]
Focus size 3x0.01mm\(^2\) presents the Brilliance
\[ = 4.28 \times 10^{14}\text{ photons/s, mm}^2, \text{mrad}^2, 0.1\%\text{bw} \]
Average power over the radiation field is 98 mW
Summary of SC radiation

- SC radiation appears at the absorption edge of materials.
- Photon energy is 277 eV for C,
  
  (108 eV for Be targets)
- Radiation spread $\psi$ is $<1/\gamma$. Higher photon energy presents narrower angular spread.
- 20 MeV present 5 mrad.
- Radiation power over the radiation field is $98 \text{mW}/60 \text{mrad}^2$
  
  at the peak: 235 W/sr
- Radiation must be highly coherent.
20 MeV tabletop synchrotron can generate 1KW EUV or soft X by setting 1000 of strings and by CW continuous injection
1 kW EUV source is feasible

By setting 1000 of CNT target along the beam orbit
By using a magic mirror (quasi ellipsoidal mirror)

Be generates 108 eV photons
C 277 eV
Continuous CW beam injection scheme is our key technology.
Synchrotron-Cherenkov or Transition Radiation Laser

amplification is not required!

1. SC generates monochromatic, TR generate continuous wave.
2. Wave front and electron must have the same phase velocity
3. Number of target is 100

Photon power: \( P = P_o \text{number of targets} \)
EUV laser theory
(Quantum mechanical approach)

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Transition Radiation X-Ray Laser Based on Stimulated Processes at the Boundary Between Two Dielectric Media

Kenneth E. Okoye and Hironari Yamada

Abstract—This paper analyzes a model of a transition radiation laser based on stimulated emission induced by relativistic electrons crossing the boundary between two media of different dielectric properties. Interaction between the incident radiation and the electrons in this boundary region is taken into account. Phenomenological quantum electrodynamics is applied to derive analytical expressions for stimulated emission and absorption probabilities. Analogos of Einstein’s coefficients for the transition processes have also been derived and discussed. It is shown that stimulated emission is greater than absorption. The gain is then calculated.

Index Terms—Absorption, gain, laser, stimulated emission, transition radiation.

I. INTRODUCTION

The operation of classical laser (CL) is based on the occurrence of population inversion achieved by pumping [3], which is emitted when an electron crosses the boundary between two media of different dielectric constants. Resonance transition radiation (RTR) using a periodic multilayer foil or stack foils has been reported by many groups [4]. Use of micro bunched beam is also proposed to generate coherent interaction [5]–[8], but any gain is yet to be reported.

A novel laser scheme proposed by Yamada [9] combines FEL mechanism, Einstein’s forced radiation mechanism, and one out of the following: Bremsstrahlung, parametric radiation, or transition radiation. The mechanism which selects the wavelength is introduced in this novel scheme similar to SASE-FEL. One of the periodic interactions of the radiation scheme is shown in Fig. 1. Spontaneous radiation is generated at the first stage by thin targets (not shown). This radiation is then monochromatized by a crystal. When the target itself is made of a thin crystal, monochromatic...
Synchrotron-Cherenkov Laser is a classical laser but start with coherent radiation!

\[ S_i^\nu = \sigma Q_i \]

\[ F_i^\nu = N \frac{I_i^\nu}{4\pi c} B_{10} = N \frac{I_i^\nu}{4\pi c} \frac{c^3}{8\pi h \nu^3} A_{10} = S_i^\nu \frac{I_i^\nu c^2}{32\pi^2 h \nu^3} \]

\[ I_i^\nu = S_{i-1}^\nu + F_{i-1}^\nu \times \mu I_{i-1}^\nu \quad \kappa = c^2 / 32\pi^2 h \nu^3 \]

\[ I_i = \sigma \eta^{i-1} Q_0 + \sigma \eta^{i-1} Q_0 \times \kappa \mu I_{i-1}^2 \]

\[ \sigma \eta^{i-1} Q_0 \kappa \mu I_{i-1}^2 > I_{i-1} \]
Accelerator for SCL can be Energy Damping LINAC

5m long

100 CNT Insertion

20KW

20MeV LINAC

Note: Recovery of electron energy is not essential for only 20 MeV 20KW beam.
# EUV source Candidates

<table>
<thead>
<tr>
<th>Radiation mechanism</th>
<th>Accelerator</th>
<th>Ee</th>
<th>Size</th>
<th>Focal point size</th>
<th>Power</th>
<th>COST (MUS$)</th>
<th>comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>undulator</td>
<td>storage ring inserton</td>
<td>&gt;1 GeV</td>
<td>30m Dia.</td>
<td>20µm dia.</td>
<td>10 mW</td>
<td>25W</td>
<td>30</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1KW is not achievable</td>
</tr>
<tr>
<td>SASE FEL for X-ray</td>
<td>Normal C Linac</td>
<td>&gt;1 GeV</td>
<td>1km long</td>
<td>100 µm dia.</td>
<td>1J/ pulse</td>
<td>100J/ pulse</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Average power is low</td>
</tr>
<tr>
<td>SASE FEL for EUV but not for soft X</td>
<td>ERL with Super C LINAC</td>
<td>&gt;300 MeV</td>
<td>&gt;20m long</td>
<td>1mm dia.</td>
<td>10 KW</td>
<td>10 KW</td>
<td>300</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feasible but many to be studied</td>
</tr>
<tr>
<td>SCR or TR for EUV and soft X</td>
<td>Storage ring</td>
<td>&lt;20 MeV</td>
<td>1mx3m</td>
<td>10µm x 1mm</td>
<td>10 kW</td>
<td>1000 KW</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>ERL with Normal C</td>
<td></td>
<td>5mx5m</td>
<td></td>
<td></td>
<td></td>
<td>Feasible but many to be studied</td>
</tr>
</tbody>
</table>
conclusion

SCR or TR with tabletop storage ring for 1KW EUV is ready and
SCR with ERL is the way to 10KW EUV or soft X-ray laser