X-ray Characterization of a Table Top Synchrotron Light Source

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The need for advanced light sources is well documented by the creation of new facilities such as SOLEIL, DIAMOND, MAX IV and the upgrades of older facilities.

The applications of light sources encompass all aspects of sciences spanning the fields of physics, chemistry, biology, material science, electronics and medicine.

An option to provide “more light” to this community is to develop small laboratory sources beyond the standard and rotating anodes.

Recently, several “small scale synchrotron” sources were proposed, whereby the most advanced system is the Mirrorcle© developed by Prof. Yamada (Japan) with three functioning systems.
Mirrorcle© could have four output ports,
1. FIR port,
2. soft X-rays port,
3. hard X-rays
4. full spectrum port
Ferrara unit activity in LABSYNC project:

characterization of Mirrorcle as X-ray source for imaging application

Bremsstrahlung X rays from thin target

wire target $\approx 0.1$ mm
Mo, Rh, W

20 MeV System

Monochromatic X rays
PXR

Crystal: Si – graphite - diamond

Discussed in poster section
X ray flux from bremsstrahlung X rays

MIRRORCLE

target
X ray flux from bremsstrahlung X rays

MC simulation of MIRRORCLE x-ray spectra

Mo, Rh and W targets

Wire diameter from 5 to 125 μm

Added filtration (diagnostic spectra): Mo, Rh, Al
Energy dependence of bremsstrahlung X rays

W x-ray spectra 4 – 6 -20 MeV
@ 75 cm from target 100 μm kapton window
X-ray spectra for energy-band monochromatization
40 cm from target 1mm Be window filtration

Tungsten, $E_0 = 6$ MeV

Tungsten, $E_0 = 20$ MeV
X ray flux from bremsstrahlung X rays

Mo and Rh x-ray spectra
40 cm from target 1mm Be window filtration
X ray flux from bremsstrahlung X rays

### OUTPUT COMPARISON

#### forward

<table>
<thead>
<tr>
<th>filtration</th>
<th>target</th>
<th>4 MeV</th>
<th>6 MeV</th>
<th>20 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>kapton 100 µm</td>
<td>125 µm W</td>
<td>7.9 E+2</td>
<td>2.4 E+3</td>
<td>6.9 E+4</td>
</tr>
<tr>
<td>kapton 100 µm</td>
<td>120 µm Rh</td>
<td>6.4 E+2</td>
<td>1.9 E+3</td>
<td>5.5 E+4</td>
</tr>
<tr>
<td>kapton 100 µm</td>
<td>125 µm Mo</td>
<td>6.0 E+2</td>
<td>1.8 E+3</td>
<td>5.1 E+4</td>
</tr>
</tbody>
</table>

#### X RAY TUBE output 0.75 m from target W

<table>
<thead>
<tr>
<th>filtration</th>
<th>80 kVp</th>
<th>110 kVp</th>
<th>140 kVp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Be 1 mm</td>
<td>2.86</td>
<td>2.28</td>
<td>1.79</td>
</tr>
<tr>
<td>Al 2.5 mm</td>
<td>1.6 E-1</td>
<td>2.7 E-1</td>
<td>4.0 E-1</td>
</tr>
</tbody>
</table>
Mo: $K_\alpha = 17.4$ keV; $K_\beta = 19.6$ keV
Rh: $K_\alpha = 20.2$ KeV; $K_\beta = 22.7$ keV
X-ray flux from bremsstrahlung X rays

### OUTPUT COMPARISON FOR $K_{\alpha}$ line MONOCHROMATIZATION forward

<table>
<thead>
<tr>
<th>Target</th>
<th>Energy band $\Delta E = 1$ keV</th>
<th>X-ray TUBE 50 kVp - Be 1 mm</th>
<th>MIRROCLE 4MeV kapton win.</th>
<th>MIRROCLE 6MeV kapton win.</th>
<th>MIRROCLE 20MeV kapton win.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>Mo $K_{\alpha}$ (17.4 keV)</td>
<td>1.5E+6</td>
<td>2.67E+7</td>
<td>4.06E+7</td>
<td>2.82E+8</td>
</tr>
<tr>
<td>Rh</td>
<td>Rh $K_{\alpha}$ (20.2 keV)</td>
<td>6.3E+5</td>
<td>2.73E+7</td>
<td>4.15E+7</td>
<td>2.74E+8</td>
</tr>
</tbody>
</table>
X ray flux from bremsstrahlung X rays

**W x-ray spectra for energy-band monochromatization**

40 cm from target 1mm Be window filtration

![Graphs showing x-ray spectra](image)

Tungsten, $E_0 = 6$ MeV

Tungsten, $E_0 = 20$ MeV
### OUTPUT COMPARISON FOR MONOCHROMATIZATION

**forward**

| Energy band | X-Ray TUBE  
80 kVp - Be 1 mm | MIRROCLE 4MeV | MIRROCLE 6MeV | MIRROCLE 20MeV |
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>20 (19 - 21)</td>
<td>3.24E+5</td>
<td>2.93E+6</td>
<td>5.99E+6</td>
<td>5.82E+7</td>
</tr>
<tr>
<td>30 (28.5 – 31.5)</td>
<td>4.48E+5</td>
<td>1.12E+7</td>
<td>2.31E+7</td>
<td>2.23E+8</td>
</tr>
<tr>
<td>40 (38 – 42)</td>
<td>4.60E+5</td>
<td>2.82E+7</td>
<td>5.81E+7</td>
<td>5.58E+8</td>
</tr>
</tbody>
</table>

**OUTPUT @ 75 cm from the target (W wire 0.125 mm)**

Photons mA⁻¹ s⁻¹ mm⁻²
Optimization for mammography application

Bremsstrhalung radiation and fluorescence emission

\[ E_0 > m_0c^2 \]

\[ \theta \approx \frac{m_0c^2}{E_0} \]

180°

E_0

90°

X ray fluorescence emission

Bremsstrhalung radiation

0°
Optimization for mammography application

Considering a different point of view ...
Backward emission
Optimization for mammography application

**X-ray imaging simulation for mammography**

Flat panel detector

20 μm-thick Al disk in 4.5 cm plexiglass bulk

5x10⁹ incident photons

<table>
<thead>
<tr>
<th>Spectrum</th>
<th>Contrast</th>
<th>Dose (mGy)</th>
<th>SNR</th>
<th>SNR²/Dose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo 30 kVp, 0.8 mm Be, 30 μm Mo, 13°</td>
<td>2.08%</td>
<td>3.35E-01</td>
<td>8.18</td>
<td>2.00E+02</td>
</tr>
<tr>
<td>Rh 32 kVp, 0.8 mm Be, 25 μm Rh, 13°</td>
<td>1.55%</td>
<td>3.38E-01</td>
<td>8.42</td>
<td>2.10E+02</td>
</tr>
<tr>
<td>6 MeV e⁻, 100 μm Mo target, 0.8 mm Be, 30 μm Mo, 90°</td>
<td>1.76%</td>
<td>3.51E-01</td>
<td>8.05</td>
<td>1.84E+02</td>
</tr>
<tr>
<td>6 MeV e⁻, 100 μm Mo target, 0.8 mm Be, 30 μm Mo, 180°</td>
<td>1.89%</td>
<td>3.50E-01</td>
<td>8.26</td>
<td>1.95E+02</td>
</tr>
<tr>
<td>20 MeV e⁻, 100 μm Mo target, 0.8 mm Be, 30 μm Mo, 180°</td>
<td>1.97%</td>
<td>3.51E-01</td>
<td>8.69</td>
<td>2.15E+02</td>
</tr>
<tr>
<td>20 MeV e⁻, 10 μm Mo target, 0.8 mm Be, 30 μm Mo, 180°</td>
<td>2.49%</td>
<td>3.55E-01</td>
<td>9.18</td>
<td>2.37E+02</td>
</tr>
<tr>
<td>6 MeV, 0°</td>
<td>0.15%</td>
<td>6.09E-01</td>
<td>2.06</td>
<td>6.93E+00</td>
</tr>
</tbody>
</table>
Optimization for mammography application

**OUTPUT COMPARISON backward**

Output 0.75 cm from target  
mGy/mAs

<table>
<thead>
<tr>
<th>Mirrorcle</th>
<th>X ray tube</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MeV</td>
<td>20 MeV</td>
</tr>
<tr>
<td>W</td>
<td>Rh</td>
</tr>
<tr>
<td>0°</td>
<td>2160</td>
</tr>
<tr>
<td>90°</td>
<td>1.33</td>
</tr>
<tr>
<td>180°</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Anodic current

<table>
<thead>
<tr>
<th>80 mA</th>
<th>100 mA</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6 mA</td>
<td>7.3 mA</td>
</tr>
<tr>
<td>4.9 mA</td>
<td>6.3 mA</td>
</tr>
</tbody>
</table>

Equivalent impact current backward (180°)
X ray flux from bremsstrahlung X rays

OUTPUT MEASUREMENT and IMPACT CURRENT EVALUATION

shielding wall

40 cm  76 cm

148 cm

265 cm

monitor chamber

Imaging detectors position RadEye2

detectors position for calibration TLDs -chamber

mirrocle

40 cm  76 cm

148 cm

265 cm
WP4: X ray flux from bremsstrahlung X rays

TLDs exposed at the Department of Experimental Radiotherapy, Katholieke Universiteit of Leuven, Belgium.

Reading of TLDs  PPL
Exposure time 300 s

14.8 mGy @ 2.65 m

0.616 mGy/s @ .75 m (MIRRORCLE 6 MeV)

37.0 mGy/min
EVALUATION OF THE IMPACT CURRENT IN MIRRORCLE 6 MeV

1) Digital detector signal (energy absorbed in digital detector)
2) Monitor Chamber measurement
3) Direct TLD comparison (Leuven exposure vs PPL exposure)
4) Monitor chamber distance scaled

<table>
<thead>
<tr>
<th>target</th>
<th>filtration</th>
<th>TLD</th>
<th>chamber</th>
</tr>
</thead>
<tbody>
<tr>
<td>125 μm W</td>
<td>kapton 100 μm</td>
<td>0.616</td>
<td>0.707</td>
</tr>
</tbody>
</table>

X-ray flux from bremsstrahlung X rays

<table>
<thead>
<tr>
<th>RadEye2 signal</th>
<th>monitor chamber</th>
<th>Direct TLD compar.</th>
<th>monitor chamber imaging</th>
</tr>
</thead>
<tbody>
<tr>
<td>target</td>
<td>i (μA)</td>
<td>i (μA)</td>
<td>i (μA)</td>
</tr>
<tr>
<td>W (125 um)</td>
<td>6.8 · 10⁻¹</td>
<td>9.7 · 10⁻¹</td>
<td>8.4 · 10⁻¹</td>
</tr>
<tr>
<td>Mo (125 um)</td>
<td>5.4 · 10⁻¹</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Rh (120 um)</td>
<td>4.6 · 10⁻¹</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>
Imaging performance MIRRORCLE 6 MeV

- shielding wall
- mirrocle
- monitor chamber
- Imaging detectors position RadEye2
- Test object
- 40 cm
- 76 cm
- 148 cm
MIRRORCLE produces very wide X-ray spectra

**TARGET**

- **Mo wire** ≈ 0.7 mm² Impact area (0.125 mm) x (5.8 mm)
- **Rh wire** ≈ 0.7 mm² Impact area (0.120 mm) x (5.8 mm)
- **W wire** ≈ 0.7 mm² Impact area (0.125 mm) x (5.8 mm)
- **Pb sphere** ≈ 0.8 mm² Impact area (Φ = 1.0 mm)

Imaging performance MIRRORCLE 6 MeV
RadEye2™ C-MOS detector for digital radiography

Electrons collected (arbitrary normalization) per fluence unit of a monochromatic photon beam vs energy E (keV) of the incident monochromatic beam. In red electrons collected on photodiode coming from scintillation of gadox screen, in black electrons produced by direct interaction of radiation in the collection area of photodiode.
Imaging performance MIRRORCLE 6 MeV

**RadEye2™ C-MOS detector for digital radiography**

![Graph showing imaging performance](image)
Spatial resolution analysis

Lead Star pattern image obtained with MIRROCLE 6 MeV

Rh target
RadEye 2 C-MOS detector
Imaging performance MIRORCLE 6 MeV

CONTRAST OF 0.02 mm Pb embedded in PMMA
Imaging performance MIRRORCLE 6 MeV

Comparison of spatial frequency response of the digital detector in terms of SWRF ($MTF$) between Diagnostic X-ray beam and MIRRORCLE X-ray Beam

SWRF normalized to zero frequency
Focal spot measurement MIRRORCLE 6 MeV

- Shielding wall
- MIRRORCLE
- Monitor chamber
- Imaging detectors position RadEye2
- Ring test objec
- 40 cm
- 76 cm
- 148 cm
- 33 cm
Focal spot measurement MIRRORCLE 6 MeV

Target wire
Φ = 0.125 mm

<table>
<thead>
<tr>
<th>b (mm)</th>
<th>o (mm)</th>
<th>i (mm)</th>
<th>M</th>
<th>a (m)</th>
<th>p (mm)</th>
<th>l (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>326.0±0.5</td>
<td>11.7±0.1</td>
<td>15.0±0.1</td>
<td>1.28±0.01</td>
<td>1.1±0.01</td>
<td>1.6±0.1</td>
<td>5.8±0.2</td>
</tr>
</tbody>
</table>

length of the impact area

penumbra profile

profile of the impact area
X ray imaging with very wide X-ray spectrum (10 keV - 6 MeV)

0.1 mm Al disk

**Edge enhancement** in radiographic image of a 0.1 mm-thick Al disk in contact with detector surface

**Electrons collected** (arbitrary normalization) per fluence unit of a monochromatic photon beam vs energy $E$ (keV) of incident monochromatic beam, *in air* (blue) and passing *through 0.1 mm of Al* (red).
Edge enhancement model

Absorption image due to low energy part of spectrum ($E < 150$ keV)

Emission image due to high energy part of spectrum ($E > 1$ MeV)

Edge enhancement as a result of sum of absorption and emission images.
Conclusions

MC simulations have demonstrated that x-ray beams generated by the interaction of MeV electrons with target materials of diagnostic interest are far more intense than those generated by conventional x-ray tubes.

Significant improvement in x-ray beam monochromaticity can be achieved by viewing the x-ray emission from a direction orthogonal or antiparallel to that of the incident electron beam.

X-ray imaging performance of the current MIRRORCLE system allows one to obtain radiographs of test object with experimental conditions similar to clinical systems.

To take advantage of the better efficiency of the compact synchrotron in terms of the number of x-ray photons produced per electron impinging on the target, an optimization of electron current and/or injection rate is desirable.