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Abstract. — We present VUV emission spectra taken on the ACO storage ring from the permanent magnet undulator NOEL (1), currently dedicated to free electron laser experiments, along with an overview at the properties of undulator radiation. The analysis of the spectra includes corrections for the emittance of the electron beam and a small mismatch between the direction of the measurement and the undulator axis. We conclude that this undulator represents a powerful source of VUV radiation in the spectral range 100-1 300 Å.

1. Introduction.

Synchrotron radiation has proven to be an extraordinarily useful source for spectroscopic studies in atomic, molecular and solid state physics in the last ten years. The impact has been very strong above 10 eV where the spectral brightness of synchrotron radiation is several orders of magnitude larger than that obtainable from other light sources [1].

However, for many experiments this is not sufficient and an ideal source will be a laser. A tunable laser between 2 000 Å and 50 Å will probably take some time to come out [2]. At the present time the best solution is to use undulators on storage rings and there is a good chance that the next generation of synchrotron radiation will be based primarily on undulator and multipole wiggler radiation (Super ACO, ALS...) as compared to the existing machines which use the radiation emitted by the electrons in the normal bending magnets of the ring.

A linear undulator, originally proposed by Motz [3] is a periodic transverse magnetic field structure with many periods (20 to 100 or more), intended to produce a synchrotron radiation spectrum of one or several narrow lines. These are due to interferences from electromagnetic fields emitted by the same electron at different points of the trajectory, though contributions from different electrons are incoherent. Narrow lines will be observed only if the angular spread of the particles in the beam is small.

In general, one uses a sinusoidal field given by:

\[ B(Z) = B_0 \sin \left(2\pi Z / \lambda_0 \right) \]  

where \( B_0 \) is the maximum field, \( \lambda_0 \) the period of the undulator and \( Z \) the axis coordinate.

Short period superconducting undulators have been built at Orsay [5] and Novosibirsk [6] but the more convenient and now classical technology is the permanent magnet arrangement introduced by Halbach [7] (Fig. 1).

The magnetic field produced along the undulator axis and the trajectory in the x-y transverse plane of an electron travelling along this axis, can each be easily calculated numerically. The results for a 17 period arrangement [8] are displayed on figure 2.
The permanent magnet undulator structure introduced by K. Halbach uses a configuration of magnets rotated by $\pi/2$ from one position to the following. The figure shows an undulator with 2 periods.

Fig. 1. — The permanent magnet undulator structure introduced by K. Halbach uses a configuration of magnets rotated by $\pi/2$ from one position to the following. The figure shows an undulator with 2 periods.

Fig. 2. — Numerical calculations for a 17 period permanent magnet arrangement [8] of:

a) Magnetic field.

b) Transverse speed.

c) Trajectory of the electrons in the $(xy)$ plane. The transverse average displacement of the trajectory $(200 \mu)$ is almost negligible compared to the field homogeneity [8].

The power emitted by high energy electrons passing through an undulator can be calculated by the Lienard-Wiechert formula [9] either numerically, by using a set of calculated or measured points of the intensity of the field along the axis [8], or analytically by using a given field distribution such as in (1) and developing the emitted power, in the approximation $N$ (number of undulator periods) $\gg 1$, into a series of discrete lines [4]. This last approach is the more widely used and leads to analytical formula which however must be computed numerically since they contain several sums of Bessel functions with various arguments. The most important aspects of the undulator theory are summarized in the next section.

Short period permanent magnet undulators have been built or are under construction in the various synchrotron radiation centres around the world [1]. The purpose of this paper is to present the first VUV radiation spectra obtained with a permanent magnet undulator on the ACO storage ring at Orsay. We show that the classical undulator theory fits well the results if one includes the effect of the emittance of the ring and that the undulator spectral brilliance exceeds by several orders of magnitude the one of a normal bending magnet.


2.1. — The emission from the linear undulator consists in a series of lines whose wavelengths are given by:

$$\lambda_i = \frac{\lambda_0}{2 \sqrt[4]{1 + K^2/2 + \gamma^2 \theta^2}}$$

where:

$\lambda_i$ = wavelength of the $i$th harmonic

$\lambda_0$ = undulator period

$\gamma = E/m_0 c^2 = E$ (MeV)/0.511 where $E$ is the electron energy

$\theta$ = angle between the direction of observation and the undulator axis

$K = 0.934 B_{\text{mag}}(T) \lambda_0 \text{ (cm)}$ : « deflection parameter » which characterizes the undulator.

Due to the high operating energy of electron storage rings ($\gamma > 300$ in practice) the undulator wavelength, $\lambda_0$, may be shifted easily toward the VUV spectral range. Also the observed wavelength depends very strongly on the observation angle, $\theta$.

2.2. — The emitted flux is spatially concentrated within a horizontal (undulator plane) half-angle of:

$$\theta_h \approx \frac{1 + K^2/2}{\gamma}$$

and vertical:

$$\theta_v \approx 1/\gamma$$

This concentration of the power into a narrow solid angle ($\theta_h, \theta_v \lesssim$ a few mrad) is due again to the relativistic Doppler effect.

2.3. — When observed in a narrow cone centred on the undulator ($\theta = 0$) axis, the spectral width (that we define here for convenience as $\lambda/\Delta \lambda$) of the $i$th harmonic is simply:

$$\lambda_i/\Delta \lambda_i \sim iN$$

where $N$ is the number of undulator periods. The observation cone aperture has to be smaller than a certain angle $\theta_m$ in order to avoid line broadening due to the effect of the variation of $\lambda_i$ with the observation angle. From (2) and (3) it comes:

$$\theta_m < \frac{1}{\gamma} \sqrt{\frac{1 + K^2/2}{iN}}$$
\( \sim 0.5 \text{ mrad} \) for the 1st harmonic for \( K = 2.3 \) at the nominal energy of ACO (536 MeV, \( \gamma = 1050 \)).

Within this angle the spectral shape function of the \( i \)th harmonic is given by (Fig. 3):

\[
\frac{dI(\lambda)}{d\lambda} \propto \frac{1}{\lambda^4} \left( \frac{\sin x_i}{x_i} \right)^2
\]

where

\[
x_i(\lambda) = \pi N \left( i \frac{\lambda_i}{\lambda} \right).
\]

Only odd harmonics are emitted along the axis.

2.4. — Off-axis the spectrum of high order harmonics cannot be anymore approximated by (5). They are broadened as \( \theta \) increases. The whole spectrum of the undulator (obtained by integrating over \( \theta \)) is, therefore, a broadband spectrum exhibiting sharp maxima corresponding to the location of the various harmonics at \( \theta = 0 \). Several cases have to be considered according to the order of magnitude of the « deflection parameter », \( K \), of the undulator.

\( K \ll 1 \) : only the fundamental line is emitted.

\( K \sim 1 \) : several harmonics are emitted and their intensity is comparable to the fundamental.

\( K \gg 1 \) : a great number of harmonics is present. The fundamental is shifted toward long wavelengths and the width of the high ranking harmonics is increased by the effect of angle dependence (Eq. (4)) for any practical aperture of the observation cone (further broadening effects will be discussed below).

Therefore, the spectrum is quasicontinuous and is just \( N \) times the synchrotron radiation spectrum of 1 undulator pole : this is the « wiggler » case.

In practice the case \( K \ll 1 \) is not interesting because not much power is emitted. The case \( K \sim 1 \) (undulator case) is useful to get more photons in the low energy tail of the synchrotron radiation spectrum (100-2 000 Å). This is the situation in which we are mostly interested in this paper. The case \( K \gg 1 \) (wiggler) is used to produce light in the high energy tail of the synchrotron radiation spectrum, for X-ray production.

2.5. — The total emitted power is:

\[
P_{\text{em}}(W) = 7.3 \ E^2(\text{GeV}), I(A), N K^2/\lambda_0(\text{cm})
\]

where \( I \) is the current stored in the ring.

The maximum central brightness of odd harmonics is:

\[
\frac{dI}{d\lambda \ d\Omega} = 1.74 \times 10^{12} \times
\]

\[
E^2(\text{GeV}) \ I(A) N^2 F_i(K) \; \text{photons/s/0.1 % band/ (0.1 mrad)^2}
\]

where:

\[
F_i(K) = \left[ \frac{J_{-1} \left( \frac{i K^2}{4 + 2 K^2} \right)}{J_{-1} \left( \frac{i K}{4 + 2 K^2} \right)} \right] \times
\]

\[
i^2 \ K^2 (1 + K^2/2)^2
\]

and \( 0 < F_i(K) < 0.5 \).

This brightness may be affected by various causes of broadening of the line : energy dispersion of the ring, trajectory distortions, finite size of the electron beam in the undulator, emittance of the beam (angular distribution of the speeds of the electrons). The corresponding broadenings can be estimated easily from formula (2). In practice, the most important rôle is played by the emittance. The additional broadening due to this effect is approximately given by:

\[
(\lambda_i/\Delta \lambda_i)_\theta = (1 + K^2/2)/\gamma^2 \bar{\theta}^2
\]

where \( \bar{\theta} \) is the half-width of the angle distribution. For example, \( \bar{\theta} \sim 0.3 \text{ mrad} \) at high energy (536 MeV) on the ACO storage ring, 0.45 mrad on DCI and is expected to be less than 0.1 mrad on Super-ACO (10).
Then for \( K = 2.3 \):

\[
(\bar{\lambda}/\Delta \bar{\lambda})_h \approx 37 \quad \text{ACO (536 MeV)}
\]

\[
250 \quad \text{ACO (200 MeV)}
\]

\[
2 \quad \text{DCI (1 700 MeV) (10)}
\]

\[
15 \quad \text{DCI (600 MeV)}
\]

\[
200 \quad \text{Super-ACO (800 MeV)}
\]

These numbers give the ultimate bandwidths that can be obtained independently of the harmonic number. Therefore the brilliance of high order harmonics is greatly influenced by this effect.

2.6. — The radiation emitted in any particular direction by the linear undulator is polarized linearly. Near axis the polarization is very close to the undulation plane. For large aperture cones of utilisation (\( \theta \approx 1/\gamma \)) the light is polarized at 80 to 90\% in the undulation plane, except in a small spectral region corresponding to the long wavelength tail of the second harmonic. For example, in our experiment, this would affect the 1 000-1 200 Å part of the recorded spectrum (see below).

3. Description of the experiments.

The permanent magnet undulator NOEL (« Nouvel Onduleur pour l’Etude du Laser ») has been previously designed [8] for the free electron laser experiments on the ACO storage ring working at low energy (150-240 MeV) [11]. However it will be also a useful tool for producing VUV radiation when the ring is working at its maximum energy (536 MeV). The undulator characteristics are listed in table I.

The undulator radiation characteristics on axis are listed on table II for the harmonic 1 to 9 for the undulator close to its minimum gap value (corresponding to \( K = 2.29 \)). More detailed tables and figures can be found in reference [12]. The effect of the emittance of the beam (cf. section 2) has been approximately taken into account and included in table II. It reduces the expected brilliance by a factor of 1 to 10 between 1 300 and 100 Å. However, the gain in brilliance with respect to the normal bending magnets synchrotron radiation [13] is noticeable, ranging from \( 10^3 \) to 10 in this spectral region.

The undulator emission for the conditions defined in table II has been measured with a 19° grazing incidence toroidal monochromator (Figs. 4 and 5). The entrance slit of the monochromator, 0.1 x 1 mm in size, was placed at 3.5 m from the center of the undulator. This corresponds to vertical and horizontal observations half-angles of 15 and 150 μrad respectively. Their effect on the observed spectrum is then almost negligible as compared to the beam emittance. A numerical fit has been made on the first harmonic including the emittance in the horizontal plane and a possible misalignment, by an angle \( \theta_0 \), of the monochromator with the undulator axis. The intensity,

Table I. — Characteristics of the permanent magnet undulator NOEL.

<table>
<thead>
<tr>
<th>Magnetic material</th>
<th>SmCo₅ (( B_r \simeq 0.85 ) T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full length</td>
<td>1.33 m</td>
</tr>
<tr>
<td>Number of periods</td>
<td>17</td>
</tr>
<tr>
<td>Period</td>
<td>78 mm</td>
</tr>
<tr>
<td>Transverse pole width</td>
<td>100 mm</td>
</tr>
<tr>
<td>Vacuum Chamber full gap</td>
<td>25 mm</td>
</tr>
<tr>
<td>Undulator minimum gap</td>
<td>33 mm</td>
</tr>
<tr>
<td>Undulator maximum field</td>
<td>0.31 T</td>
</tr>
<tr>
<td>Undulator K range</td>
<td>0.2-3</td>
</tr>
<tr>
<td>ACO electron energy range</td>
<td>150-536 MeV</td>
</tr>
</tbody>
</table>

Table II. — Central brilliance of the NOEL undulator at \( K = 2.29 \) on the ACO storage ring at 536 MeV (brilliance is expressed in number of photons/s/0.1 Å/0.1 % band/(0.1 mrad)^2). This brilliance is compared with the one of a normal bending magnet of ACO at the same electron energy. The expected effect of the emittance of the beam on the undulator performance is also displayed. The total emitted power is 2.5 W for the undulator and 700 W for the ring.

<table>
<thead>
<tr>
<th>Harmonic number</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (Å)</td>
<td>1 280</td>
<td>426</td>
<td>256</td>
<td>183</td>
<td>142</td>
</tr>
<tr>
<td>Theoretical line-width ((\bar{\lambda}/\Delta \bar{\lambda})_h)</td>
<td>18</td>
<td>54</td>
<td>90</td>
<td>126</td>
<td>162</td>
</tr>
<tr>
<td>Undulator theoretical brilliance/(10^{12})</td>
<td>3.6</td>
<td>5.8</td>
<td>6.3</td>
<td>6.0</td>
<td>5.6</td>
</tr>
<tr>
<td>Calculated bending magnet brilliance/(10^{10})</td>
<td>0.10</td>
<td>0.55</td>
<td>1.2</td>
<td>2.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Gain over bending magnet radiation brilliance</td>
<td>3 600</td>
<td>1 000</td>
<td>520</td>
<td>270</td>
<td>170</td>
</tr>
<tr>
<td>Gain over bending magnet including emittance</td>
<td>3 200</td>
<td>560</td>
<td>200</td>
<td>76</td>
<td>40</td>
</tr>
</tbody>
</table>
given by (5) and (6) has been integrated over the angles in the horizontal direction assuming a gaussian distribution:

\[ P(\theta) = \frac{1}{\sqrt{2 \pi} \sigma_\theta^2} \exp\left(-\frac{\theta^2}{2 \sigma_\theta^2}\right) \]  

where \( \sigma_\theta = \sigma_x/\beta_x \sim 0.25 \text{ mrad} \) and \( \beta_x \) is the betatron function in the undulator section \( (\sigma_x \sim 0.5 \text{ mm}, \beta_x \sim 2 \text{ m}) \). The best fit is obtained (Fig. 4) for a misalignment \( \theta_0 \sim 0.25 \text{ mrad} \). (The high energy tail is due to the 4th harmonic seen at the 3rd order of the grating).

The relative intensities of the higher order harmonics can also be understood by assuming a misalignment of \( \theta_0 = 0.25 \text{ mrad} \). Figure 6 shows the result of the numerical calculation of the undulator spectrum at the same angle. Although this calculation does not include the emittance one can see that the relative intensities are roughly the same as in the experimental spectrum of figure 5. In particular the even harmonics are as intense as the odd ones. The non-negligible electron beam emittance is responsible for the broadening and for the long tails of the peaks, as for the
harmonic 1. The higher the order, the broader is the curve, and the spectrum becomes almost continuous for $i > 4$. For $\lambda < 200 \, \text{Å}$ the response curve of the grating in the monochromator drops sharply (at 240 MeV harmonics as high as number 23 have been observed).

A quantitative comparison has been made with the synchrotron radiation emitted in a bending magnet by putting the same monochromator and detector on a synchrotron radiation beam line. After correction for the different solid angles used for the measurement with the undulator and the bending magnet, we found:

$$\frac{\text{Brilliance und.}}{\text{Brilliance synchr.}} (400 \, \text{Å}) \approx 650.$$ 

Given the uncertainties in this estimation (due to two successive adjustments of the measurement chain in two different places) this result is in very good agreement with the theoretical ratio listed in table II ($\times 560$).

Therefore we have demonstrated that the NOEL undulator on the ACO storage ring will constitute a very powerful source of VUV radiation in the spectral region 1 300-100 Å. In 1984, a new monochromator will be installed at the output of the undulator line. A focusing mirror will allow one to take full advantage of the unique properties of undulator radiation. With this mirror the use of an entrance slit sufficiently large (of the order of a few mm) in the vertical direction will allow one to mix up the emission angles and to obtain a quasi-continuous spectrum. Then a large range of wavelength (typically 100 to 500 Å) will be usable without having to modify the undulator gap (although this operation can be made easily).

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References


