PRELIMINARY CALCULATIONS ON THE DETERMINATION OF APS PARTICLE-BEAM PARAMETERS BASED ON UNDULATOR RADIATION*

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Abstract

The potential measurement of particle beam emittance at a third-generation synchrotron radiation facility such as the Advanced Photon Source (APS) by characterizing the observed undulator radiation from an insertion device is considered. The nominal APS particle beam parameters have been used in calculations for insertion devices with periods of λ=3.3 cm, λ=5.0 cm (in two configurations), and λ=1.8 cm. The US program, the MDK1F program, and analytical formulae were used. Sensitivity to variations of emittance by 20% from the nominal value are addressed.

I. INTRODUCTION

The commissioning of the third-generation synchrotron radiation facilities with low natural emittance carries with it the challenge to characterize and monitor the particle beams. One well-established, but somewhat complicated technique is based on the effects of non-ideal beam parameters such as finite transverse emittance and energy spread on the observed undulator radiation (UR). [1-7] The nominal APS parameters including 7-GeV energy, a natural emittance of 8 x 10^{-9} m rad, a relative energy spread of 0.1%, and a baseline vertical coupling of 10% have been used in evaluating these effects for insertion devices with λ=3.3 cm, λ=5.0 cm (in two configurations), and λ=1.8 cm. Specific calculations using the US program [8] for λ=3.3 and the MDK1F program [4] for λ=5.0 cm and 1.8 cm are briefly presented. These calculations were used as a guide to us for designing on-line emittance measurement techniques. Progress in this area has been reported in [6,7].

For the parameter space at APS, and after calculation of effects of particle beam parameters on the standard APS undulator A's radiation, we have developed a plan for a "diagnostic undulator." Some parameters are specifically optimized for the diagnostics tasks. Generally, the UR carries complete information about all first and second moments of particle phase space: beam position, beam direction, beam size, beam divergence, tilt of the emittance ellipse, and other coupling terms. [3-7] A single bending magnet (BM) source addresses beam position and size although the bend plane can introduce uncertainty from energy spread. An undulator should emit more photons than a BM so that faster phenomena (beam instabilities) might be detectable in the 100-ps timescale.

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II. APS BEAM PARAMETERS AND UNDULATOR CONSIDERATIONS

The nominal APS storage ring particle beam parameters are given in [9]. The natural emittance (8x10^{-9} m rad) and vertical coupling coefficient (10%), the energy (7.0 GeV) and energy spread (0.1%), and beam current (100 mA) are all critical in evaluating the undulator radiation and its strength compared to the nearby bending magnet radiation.

Although not necessarily in the order of priority, design criteria for an undulator have now been developed and for our case they are:

1. Photon energy 20-80 keV to provide phase space resolution of ~0.02-0.06 nm. This can even address the 1% vertical coupling operations regime.
2. Low magnetic field (≤0.2 T) to give low field errors and low trajectory errors.
3. Low undulator parameter, k<1.0 to provide directly calculable undulator properties.
4. Low x-ray power (100 W-400 W) to keep the thermal load of optics manageable.
5. Adequate flux to allow single bunch/single pass measurements. Should be above the BM background continuum by 100 fold.
6. Large aperture to make the system's presence transparent to the storage ring accelerator operations.

In practice, the basic question of what happens to the standard APS undulator A radiation when the finite particle beam emittance is included was previously addressed by a series of calculations using the SHADOW program. [1,2] The angular distribution of the harmonics were clearly changed from the zero- to the APS-emittance cases. An extension of this study was performed using the program US [8] to address the calculated effects for emittance changes of ±20% around the nominal APS value which are briefly reported in the next section. The fundamental problem of sensing the smaller vertical emittance changes with the given asymmetry of the horizontal and vertical emittance (with 10% vertical coupling) remains a challenge experimentally. Absolute intensity and spectral shape of the harmonics remain key features.

A separate question was approached in collaborations between the APS and Frascati groups. The use of interference effects in UR from two undulators separated by a drift space or dispersive section was considered. In addition, the desire to be transparent to the SR operations led us to consider initially a full storage ring vacuum chamber (SRVC) gap of 4 cm. We then chose a calculational regime of period, λ=5.0 cm, N=20, and ΔL=1.5 m. The MDK1F [4] program which is based on the Monte Carlo technique was used to address the effects of emittance and energy spread. In this case the formalism also addressed the problem through the standard Twiss parameter (α,β,γ) characterization of particle beams. Initial calculations were carried out on the IBM 3090 at Frascati Lab using APS-like particle-beam parameters. Calculations were again done at the nominal value and at ±20% of that value. Some of these results were presented at EPAC '94 [5], and a few examples are given in Section III. The code was transported to APS in October 1994, and preliminary studies were done on the SUN workstations.

After noting the difficulty in showing significant sensitivity to the small, but critical (to APS) vertical emittance, another tactic was pursued. As parameters were considered, we put more emphasis on making the UR cone angle noticeably smaller than the nominal 8.6 µrad of vertical divergence of the APS particle beam at 10% coupling. We focused on criteria to reach a few µrad divergence angles in a reasonable length (3-5 m). The APS straight sections are 5.2 m. We also accepted the fact that the APS would eventually have many smaller gap vacuum chambers, and at that point the diagnostics undulator with a comparable gap would still avoid being the limiting aperture. Parameters explored analytically were a combination of criteria 1-5 with #6 being viewed at a different point in the commissioning cycle. An undulator of 160 periods with λ=1.8 cm, and using the third harmonic keV photons gives a cone angle of about 1.7 µrad [9].

III. PRELIMINARY RESULTS AND DISCUSSIONS

In this section, a few examples of results from calculations using US, MDK1F, and analytical relationships are presented.

A. US Results

The fundamental question of the finite beam parameter effects on undulator radiation is illustrated in Fig. 1. Figure 1a shows the calculated spectrum from the λ=3.3 cm (K=0.37) case with zero emittance, E=7.0 GeV, and 100 mA stored beam current. Its peak brilliance is about 8×10^{21} at the fundamental energy of about 13.1 keV. In Fig. 1b, the nominal emittance is the solid line, and the dashed and dotted curves show the 1.20 times nominal and 0.80 times nominal vertical emittance cases (10% vertical coupling). The peak brilliance is reduced to about 4.4×10^{17} with the intensity at about 13.1 keV further modulated by ±10%. The effects are similar, but a little more pronounced for the second and third harmonics. The UR intensity was explored off axis and some minor effects are seen in the lobes at the 10^{11} brilliance level on the x=0 line as shown in Fig. 2. Vertical slices display some effects for the nominal vertical emittance value and variations of ±20% around it.

B. MDK1F Results

For a single undulator with λ=5.0 cm, N=34, and K=1.48, calculations with APS-like particle-beam parameters are

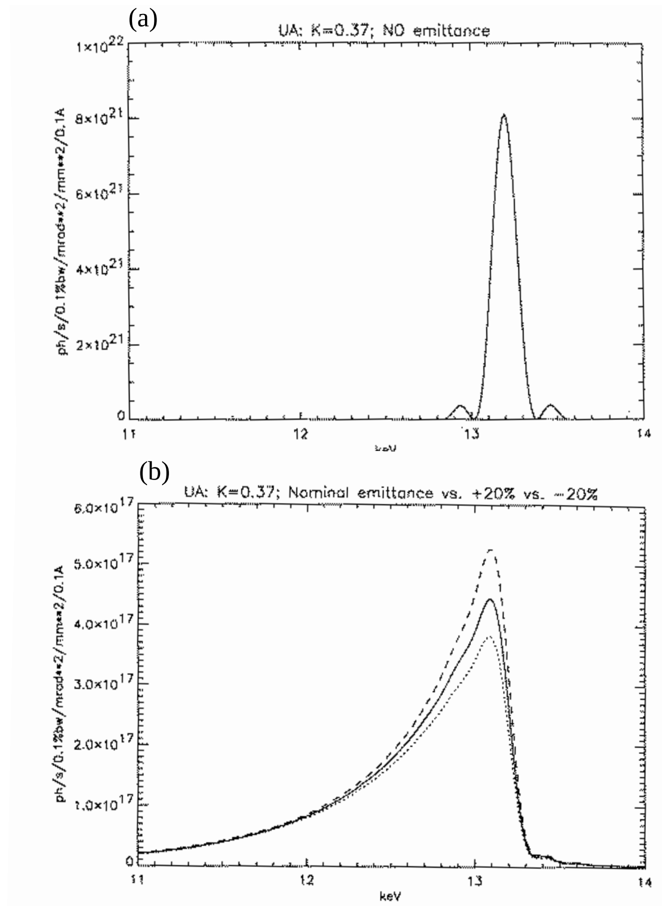

Figure 1: US calculation results for the undulator fundamental spectrum and with K=0.37: (a) zero emittance beam, and (b) an APS nominal emittance (solid line) and for ±20% around the vertical emittance value.

reported in Figs. 1-4 of [5]. It was noted there that the reliability of the analytic approximation decreases at higher harmonics compared to the numerical results in that study.

Another investigation involved the use of MDK1F to assess UR from two 1-meter (N=20) undulators separated by a 1.5-m drift section. The optical klystron configuration shows sensitivity to the energy spread of the particle beam, the larger horizontal emittance, and the small vertical emittance in descending order, respectively. Figure 3 shows the calculated effects of energy spread on the third harmonic spectral intensity plot. The solid curve is for one energy, and the dashed curve has the 0.1% energy spread. The modulation of intensity is visibly reduced. In Fig. 4, the on-axis brilliance is again addressed with an assumed $\beta_{x,y}$=18 m and $\alpha_{x,y}$=0. Here the solid curve includes the emittance and no energy spread, and the dashed curve has emittance and the 0.1% energy spread. In the first case, the emittance effect has almost completely obscured the interference patterns even before the energy spread is added. By considering Figs. 3 and 4, one has an idea of the dramatic effect of finite emittance. The test of varying the vertical emittance by 20% was not attempted.

As a follow-up study, the case of the λ=1.8 cm period undulator was begun using the MDK1F program ported to the APS computer network and implemented on a Sparc-10 SUN

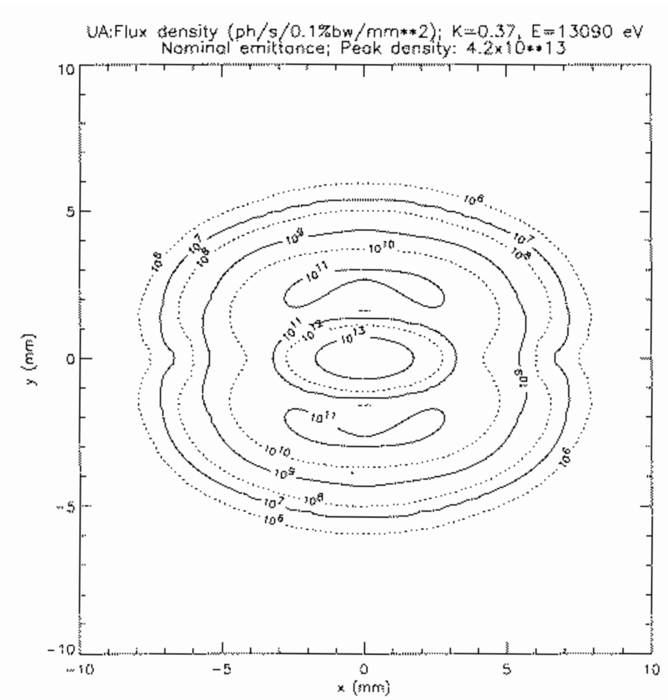

Figure 2: US calculation results in the undulator fundamental spectrum off axis in x and y. The intensity contours are indicated.

workstation. Calculational times in excess of 20 hours for a grid point proved to be impractical, and the code may be tested for calculational speed on the ANL IBM sometime in the future.

C. Other Results

An investigation of central cone flux for the undulator compared to the BM radiation continuum was performed using standard analytical formulae. The undulator fluxes for the first and third harmonic were calculated for periods from 1 to 7 cm

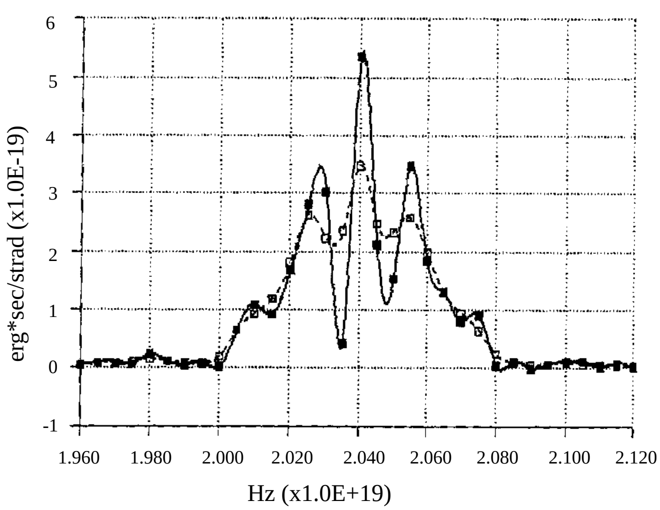

Figure 3: MDK1F results for an optical klystron configuration showing the calculated third harmonic spectral region without (solid) and with (dashed) 0.1% energy spread and no emittance.

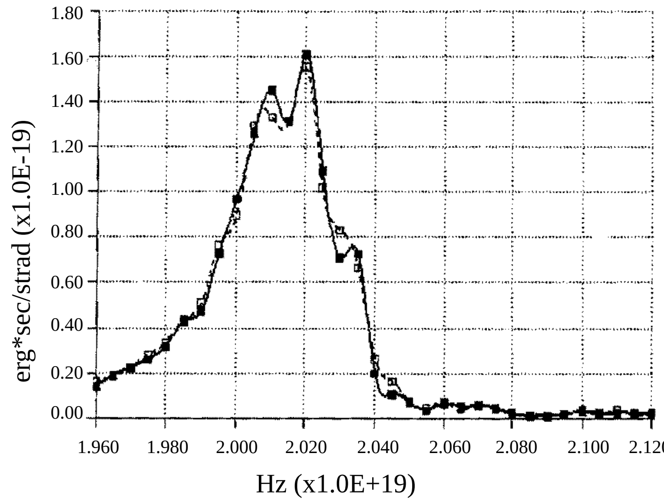

Figure 4: MDK1F results as in Fig. 3 with APS emittance effects added and with (solid) and without (dashed line) 0.1% energy spread.

in the energy range from 1 to 100 keV. We have settled on λ=1.8 cm, 160 periods, with a fundamental energy at about 25 keV as a good candidate for the undulator. As discussed in [9], the UR cone angle is small compared to the beam divergence, and thus the UR can be used as a sensitive probe.

IV. SUMMARY

In summary, calculations have been performed to assess the effects of APS particle beam parameters on UR. The sensitivities to variations around the nominal value have also been addressed, and these results have provided direction on diagnostics undulator concept designs. Further studies will focus on the λ=1.8 cm case and exploration of smaller vertical coupling of the APS particle beam.

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