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PROPOSAL FOR THE EXPERIMENTAL DEMONSTRATION OF THE COHERENT RADIATION*

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INTRODUCTION

It is of great importance to provide an experimental demonstration of the *coherence* of the radiation of electromagnetic waves from a short bunch of electrons performing oscillations in a direction transverse to the main direction of motion.

It is known that electrons circulating in a storage ring lose energy to *synchrotron radiation.*[1] Another method to stimulate radiation is to let an electron bunch travel through a *wiggler* or an *ondulator* device.[2] In either case the spectrum usually peaks in correspondence of wavelengths considerably smaller the length of the electron bunch; in this situation the power radiated is then linearly proportional to the number N of electrons in the bunch, as it is customarily observed.[3] Nevertheless, it may be possible conceiving a situation where the bunch length is considerably smaller or at least comparable to the wavelength of the peak of the radiation spectrum. If this is the case, it is then speculated[4] that the power radiated is proportional to the square N^2 of the number of particles in the bunch. This effect, which we can call a *coherent effect*, is of course very important since it would help to enhance the amount of the power radiated with a lower electron intensity.[5]

Unfortunately the *coherent effect* is difficult to observe since it is not easy to create beam and trajectory parameters which yield a bunch of length smaller than the radiation wavelength.[6,7] We thus propose here an experiment which has the two goals: (i) to generate an experimental situation where electrons in a bunch of length ℓ radiate electromagnetic power at a variable wavelength λ, and (ii) to observe with measurements the total amount of radiation versus λ and the beam intensity N. This experiment can be executed at the Accelerator Test Facility either at Brookhaven[8] or at Argonne National Laboratory[9].

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EXPERIMENTAL APPARATUS

The experimental apparatus is simple and shown schematically in Fig. 1. It takes at the start a short bunch of electrons at the relatively low energy of 4 MeV. It is important that the electron bunch is as short as possible. Beam intensity is not very crucial; actually a lower intensity is preferable to control easily both the bunch length and the transverse emittance. The experiment needs to make only relative measurements of the electromagnetic power being radiated and the beam intensity is to be large enough to allow easy detection of the radiation. We assume that the bunch length is 6 psec and the normalized transverse emittance is $4 \times 10^{-6}\pi$·mm·mrad. A beam intensity with a peak value of 0.1 n Coulomb may be required.

At the exit of the electron gun there is a conventional wiggler magnet with a field variable up to 1 kG and a period of 40 cm. The wiggler is 4 m long and thus is made of ten periods. The devices can be made of conventional magnets with quadrupoles included for focusing. A magnet gap of few cm is adequate for letting the beam through. Previous experiments[6,7] employed conventional bending magnets for the production of synchrotron radiation. The use of a wiggler, as proposed here, is more advantageous since it provides a better defined and controlled radiation wavelength.

Leaving the wiggler, the electron bunch enters a bending magnet which deflects the beam away toward a collector for energy recovery, or toward a dump underground. At the same time the radiation traveling in a straight line will leave the bending magnet and enter a radiation detector. The bending magnet has a field of 1.0 kG and a length of 0.2 m for a bending angle of 20^o. It may be useful that a data gathering is attached to the radiation detector for the collection of the experimental results and subsequent data analysis. At the same time it will be important to gather information on the bunch length, transverse dimensions and intensity. The electron beam energy and the wiggler field are also to be recorded.

THE ELECTROMAGNETIC RADIATION

The electrons going through the wiggler magnet perform transverse oscillations with a period given by the period of the wiggler $2\ell_w$ and an amplitude which depends on the wiggler field B_w and the magnetic rigidity $(B\rho)$ of the particles according to the following formula

$$a = \frac{(B\rho)}{B_w}\left[1 - \sqrt{1 - (\ell_w B_w/2B\rho)^2}\right] . \qquad (1)$$

With a field of 250 Gauss one derives an amplitude of oscillations of 8.4 mm.

In the limit each electron is performing an infinitely long sequence of oscillations, the spectrum of the radiation is monochromatic with a frequency corresponding to the wavelength

$$\lambda_r = \ell_w/\gamma^2 \qquad (2)$$

which, with the values of the parameters taken above, gives 2.6 mm. This is about the assumed bunch length $\ell_e = 2$ mm. The only way to increase the radiation wavelength is by increasing also the wiggler period or lowering the beam energy. But it is clear that there are conflicting requirements and that it is not indeed easy to fulfill the *coherence regime* obtained with $\ell_e \gg \lambda_r$.

Since the electrons are performing in the experimental set up only ten oscillations, the radiation will have a wider spectrum with a bandwidth around the critical frequency of about 10%. Moreover the radiation has spatial distribution with an angular aperture of about $1/\gamma \sim 100$ mrad.

The total energy radiated for the case the bunch is made of a single electron is given by

$$W_0 = (56.3 \text{ keV}) \frac{E^4}{(B\rho)} n B_w \arcsin\left[\frac{\ell_w B_w}{2(B\rho)}\right] \tag{3}$$

where $(B\rho)$ is the particle rigidity in Gauss·meter, E the kinetic energy in GeV, n the number of periods in the wiggler, $2\ell_w$ the period length in meter and B_w the wiggler field in Gauss.

In the approximation of a long bunch with N electrons the total energy radiated by the bunch is

$$W_L = N W_0 \tag{4}$$

whereas in the limit of a very short bunch, because of the *coherence effect* the total power radiated is

$$W_s = N^2 W_0 \tag{5}$$

As an example, let us take $B_w = 250$ Gauss and $N = 1 \times 10^9$ electrons, then

$$W_0 = 40 \ \mu\text{eV}$$
$$W_L = 40 \text{ keV}$$
$$W_s = 40 \text{ TeV}$$

At the repetition rate of 40 MHz the cw power for the short bunch case is 260 W, easily detectable. In the case of long bunches the power level is nine orders of magnitude lower and thus more difficult to measure.

MEASUREMENTS

It is thus conceived that our proposal in a "yes" or "no" experiment. If any radiation will be observed in significant amount it will be caused by *coherence effects*; if no radiation is measured the same effects can be questioned.

To perform a complete set of measurements to demonstrate further the enhancement due to *coherence effects* the following parameters will be varied:

a) The wiggler field B_w. This will vary the amplitude of the oscillation and the total power being radiated. According to Eq. (1) the amplitude is linearly proportional to B_w, and according to Eq. (3) the power radiated increases quadratically with B_w. Too large values of the field are not useful since the amplitude of the oscillation gets too large and it will make the source spot size of the radiation also too large to be detected.

b) The number N of electrons. Depending on whether the *coherence effects* are present, the power radiated will have either one of the two dependencies shown by Eqs. (4 and 5). Moreover, in the case the bunch length is just about equal to the radiation wavelength, one can expect a mixture of N and N^2 dependencies. A plot of measurements of power versus N is then very useful.

c) The beam energy. For a fixed length of the wiggler period, the only way to vary the wavelength of the radiation is to change the beam energy according to Eq. (2). By increasing the beam energy, the power radiated of course increases, but the wavelength will correspondingly decrease and the dependence with the number N of particles should become more linear.

In summary, it is important to have the possibility of varying and measuring the wiggler field B_w, the beam intensity N and the beam energy γ. It is assumed that the control and reading of the last two parameters is provided by the Accelerator Test Facility itself; the control and measurements of the wiggler field will be included in the design of the wiggler itself.

TRANSVERSE FOCUSING

An important requirement for this experiment is to keep the transverse beam bunch size to a dimension smaller or comparable to the radiation wavelength. At the energy of 4 MeV the betatron emittance is 0.4 πmm·mrad, and one will need a strong focusing system to keep the bunch size to around a millimeter. For this purpose, quadrupoles with alternating gradients (QF and QD) in a FODO cell arrangement are interplaced with the wiggler magnets. The quadrupoles have a 5 cm length and a maximum gradient of 100 G/cm and are separated by 0.4 m, the wiggler period. This focusing system provides a $\beta_{\rm max} \sim 1.3$ m at the center of each quadrupole.

Before entering the wiggler, the electron bunch will be sufficiently focused to match the transport in the wiggler itself. Care is taken to avoid introducing dispersion and other chromatic effects that may lead to a bunch length increase. Leaving the wiggler, the electron bunch is deflected by the dipole magnet which is then followed by a suitable focusing elements for the beam disposal.

THE RADIATION DETECTOR

The most important part of the experiment is the measurement of the radiation lost by the electrons. The radiation has a wavelength in the few millimeters range and it can first be transported by a waveguide attached to the end of the wiggler on one side of the magnet which deflects the electrons away. In order for the radiation to propagate freely through the waveguide this can be made of rectangular cross-section, 4 cm wide and 1 cm high, which will serve also as a filter to lower frequency noise radiation. The waveguide is 50 cm long and terminated at the receiving end with an adapter; if the adapter includes a resistive load, the square of the current flowing through the load is a direct measurement of the power being radiated. Other methods of measurement include directional couplers attached to the waveguide and followed by a frequency analyzer.

COMPONENTS AND COST

Table I gives a list of the components required for the execution of the experiment and the corresponding cost estimate. The total technical cost is 135 K$ to which the labor of the equivalent two scientific man/year is to be added at 65 K$ each; finally a 35 K$ is added for travel, computing and other administrative tasks. The total cost of the experiment is thus 300 K$. To this one should add overhead, contingency and escalation. In order to procure the several parts, one might to have wait two years for the completion of the experiment in which case the spending profile can be split in 200 K$ for the first year and 100 K$ for the second. Once in place, the experiment itself should take only about 10 weeks run of the Accelerator Test Facility in order to gather all the necessary data.

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Table I Components and Cost

Wiggler	20	Dipoles		
		length	20 cm	
		$B_{\max}$	1 kG	
		Aperture	8×2 cm^2 $(H \times V)$	50 K$
Focusing	11	Quadrupoles	(QF or QD)	
		length	5 cm	
		$G_{\max}$	100 G/cm	
		Bore Radius	4 cm	
	3	quadrupole triplet for matching		
		between RF gun and wiggler		20
	3	quads triplet after deflecting dipole		
Deflecting Dipole	1	length	0.2 m	2.5
		field	1 kG (similar to wiggler)	
Vacuum Chamber		stainless steel or aluminum		
		2 mm thick 8×2 cm^2 $(H \times V)$		
		length	6 m straight	2
Waveguide		0.5 m long copper 4×2 cm^2		0.5
		attached with flanges to v.c.		
Radiation Detectors				10
Vacuum Valves	2		}	10
Pumps	2	(10^{-7} torr)	}	
Power Supply for Dipoles				10
Quadrupoles				10
Data Gathering/Computer				20
				135 K$
2-One man year (scientific)				130
Travel, computing, etc.				35
				300 K$

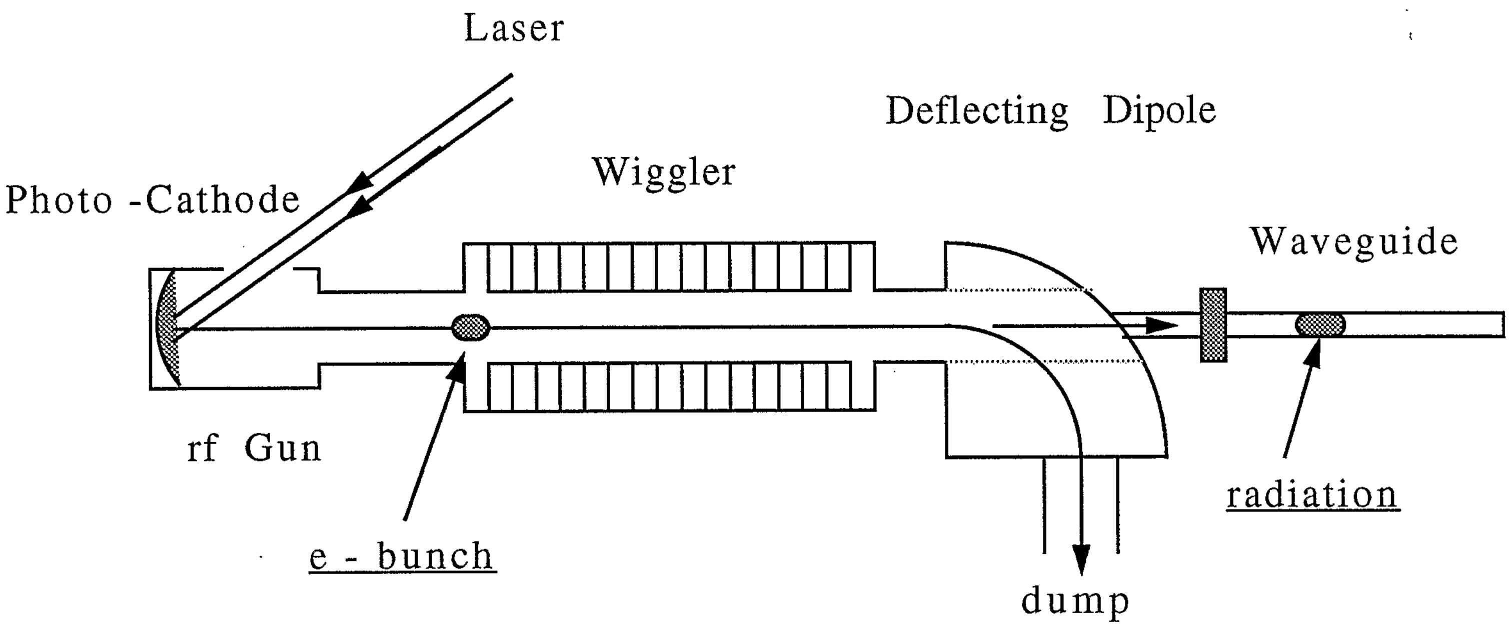

Fig. 1 Experimental Set - Up