Millimeter Wave Coherent Synchrotron Radiation in a Compact Electron Storage Ring

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ABSTRACT

Installation of a 2856 MHz RF system into the XLS compact electron storage ring would allow the generation of millimeter wave coherent synchrotron radiation. Operating at 150 MeV, one could produce bunches containing on the order of 2×10^7 electrons with a bunch length $\sigma_{L0} = 0.3$ mm, resulting in coherent emission at wavelengths above 0.8 mm. The characteristics of the source and the emitted radiation are discussed. In the case of 100 mrad horizontal collection angle, the average power radiated in the wavelength band 1 mm $\le \lambda \le$ 2 mm is 0.3 mW for single bunch operation and 24 mW for 80 bunch operation. The peak power in a single pulse of a few picosecond duration is on the order of one watt. By reducing the momentum compaction, the bunch length could be reduced to σ_{L0} = 0.15 mm, resulting in coherent synchrotron radiation down to 500 μm.

I. INTRODUCTION

Synchrotron radiation in an electron storage ring is a result of incoherent spontaneous emission. The radiated power is directly proportional to the number of electrons in the ring, N. However, if the electrons can be packed into a "small bunch" it is possible to obtain coherent synchrotron radiation proportional to N^2 for wavelengths that are larger than the bunch length ($\lambda \ge \pi \sigma_{L0}$). Numerous authors have discussed the theory of coherent synchrotron radiation including emission from electrons in a storage ring (see reference [1] and the references therein). Experimentally, coherent synchrotron radiation (CSR) has only been observed from linac beams coupled to a bending magnet, it has not been observed in a storage ring.

There is potential for producing short electron bunches in the existing XLS ring at BNL to study coherent synchrotron radiation in a storage ring. A summary of the main parameters of the compact, racetrack style XLS ring is given in Table 1.

Energy, E [MeV]	200
Circumference, C [m]	8.5
Dipole Bending Radius, ρ [m]	0.604
Betatron Tunes, ν_x, ν_y	1.41,0.41
Momentum Compaction, α	0.322
Energy Loss per Turn, U_0 [KeV]	0.234
Longitudinal Damping Time, τ_e [ms]	19
Natural Emittance, ε_0 [nm-rad]	59.2

Table 1: Main Parameters of XLS Storage Ring

According to the theory of electron storage rings, the equilibrium electron bunch length, σ_{L0}, scales as [2],

$$\sigma_{L0} \propto \left(\alpha E^3 / \omega_{rf} V_{rf}\right)^{1/2}. \quad (1)$$

So, to make short bunches implies: 1.) reducing the energy of the ring (E), 2.) increasing the RF voltage (V_{RF}), 3.) increasing the RF frequency (ω_{RF}), and/or 4.) reducing the momentum compaction (α).

In this paper we will discuss the potential for short bunches in the XLS ring using a combination of the first three techniques in the above list. We consider a 2856 MHz RF system with a large RF voltage (V_{RF} = 1.5 MV) at low energy (E = 100-200 MeV) to produce submillimeter electron bunches. In Table 2 the "zero current" bunch length, σ_{L0}, is listed as a function of energy for this RF system. Bunches of 0.2-0.5 millimeters are possible if there are no other deleterious effects to lengthen the bunch. The reduction of the momentum compaction can be used in a second phase of the project to further reduce the bunch length.

Ring Energy [MeV]	σ_{L0} [mm]
100	0.17
150	0.32
200	0.5

Table 2: Bunch Length versus Ring Energy

II. ELECTRON BEAM PROPERTIES

The preceding discussion did not take into account any electron beam intensity dependent effects. It was implicitly assumed that the peak current ($I_p \equiv Nec/\sqrt{2\pi}\sigma_L$) in the electron bunch is below the so called microwave instability threshold as given by the following formula [3],

$$I_p^{th}[A] \le \frac{2\pi\alpha\sigma_E^2 E[eV]}{(Z_L / n)[\Omega]}, \quad (2)$$

where Z_L / n is the broad band longitudinal coupling impedance of the ring divided by the mode number $n = \omega / \omega_0$. Exactly what the value of Z_L / n should be for short bunches is difficult to answer as this is a subject of active research. In order to proceed we will assume a very conservative value of $Z_L / n = 10\ \Omega$.

Requiring the electron bunch lengths to be those given by the value for the 2856 MHz RF system with V_{RF} = 1.5 MV, the threshold peak currents are calculated and listed in Table 3 along with the equivalent average currents or number of electrons per bunch. The large value of the momentum compaction in the XLS ring (α = 0.322) is advantageous for increasing the threshold current for low energy operation.

E [MeV]	σ_{L0} [mm]	σ_{E0} [10^{-4}]	I_p^{th} [A]	I_{ave}^{th} [μA]	N^{th} [10^7]
100	0.17	1.0	0.20	10	0.18
150	0.32	1.5	0.66	62	1.1
200	0.49	2.0	1.62	234	4.1

Table 3: Microwave Instability Thresholds for the XLS Storage Ring with $Z_L / n = 10\ \Omega$

The computer code ZAP [4] was used to determine the equilibrium parameters of the XLS electron beam including the effects of intrabeam scattering (IBS). The final properties of the electron beam, accounting for the microwave instability threshold and IBS are listed in Table 4. For energies below 150 MeV, IBS increases even the longitudinal dimensions of the beam. For this reason we focus our attention on energies in the range of 150-200 MeV where bunches with $\sigma_L \approx$ 0.3-0.5 mm and 1-4x10^7 electrons should be possible. The lifetime of the electron beam has been estimated to be ≈ 1.5 hours [1]. This lifetime is more than adequate. In addition, the ring will be injected with a full energy linac, allowing operation in "top off" mode with very little decay in the electron beam current.

E [MeV]	N [10^7]	σ_L [mm]	σ_x [mm]	σ_y [mm]	σ_E [10^{-4}]
100	0.18	0.32	0.34	0.20	2.1
150	1.1	0.32	0.31	0.19	1.5
200	4.1	0.49	0.32	0.19	2.0

Table 4: Final Parameters of the Electron Beam in the XLS Storage Ring

III. 2856 MHZ RF SYSTEM

The key to achieving sub millimeter bunches is the use of a high frequency RF system. Although to date most storage rings have RF systems with frequencies at or below 500 MHz, the MIT-Bates South Hall Ring makes use of a single cell, normal conducting, 3 GHz CW linac structure as its RF system [5]. For a normal conducting cavity, the average accelerating gradient that can be achieved is 2 MV/meter. This limit is set by the ability to remove heat from the copper cavity before excessive distortion detunes the cavity. There would need to be 3 accelerating sections, each having five cells, which is too large to fit in the ring.

To achieve higher gradients and to lower the overall power requirements we propose using a superconducting RF cavity. The present thinking is to stretch the circumference of the ring to 9.6 m to provide more space for the cavity and diagnostics. The properties of the 2856 MHz superconducting RF system to be used in the XLS ring are given in Table 5. A more complete discussion of the RF cavity can be found in reference [6].

Frequency [MHz]	2856
Peak Voltage, V_{rf} [MV]	1.5
Effective Gradient [MeV/m]	5.8
N_{cell}	5
R_{sh} / Q [Ω]	240
Unloaded Q_0	10^9
L_{tot} [m]	0.8

Table 5: Superconducting 2856 MHz RF System

IV. SYNCHROTRON RADIATION

Before discussing coherent emission of synchrotron radiation we briefly outline incoherent emission where the intensity of radiation is proportional to the number of electrons in a bunch. The radiation emitted by a relativistic electron moving in a magnetic field is called synchrotron radiation. The spectrum of the radiation is very broad band but it is usually characterized by a so called "critical wavelength" given by [7],

$$\lambda_c\,[\text{Å}] = \frac{18.64}{B_0\,[\text{T}]\,E^2\,[\text{GeV}]}. \tag{3}$$

Thus for the energies of E = 150 & 200 MeV in the XLS ring the critical wavelengths are λ_c = 1004 Å & 423 Å respectively. The incoherent power (P_{coh}) per milliradian of horizontal arc (θ) and integrated over all vertical angles is proportional to the number of electrons and is given by [7],

$$P_{inc}(\lambda)\left[\frac{\text{watts}}{\text{mrad }\theta-\text{mm}}\right] = \frac{8.42\times10^{-8}\cdot\rho^{1/3}[\text{m}]\cdot I[\text{Amp}]}{\lambda^{7/3}[\text{mm}]}\cdot, \tag{4}$$

for $\lambda >> \lambda_c$ which is the regime of interest for the present discussion of coherent emission. In this wavelength regime the power is independent of the energy of the ring and depends only weakly on the ring parameters, i.e., $\rho^{1/3}$. As such, for a fixed current, one ring is as good as the next.

V. ESTIMATE OF COHERENT RADIATION

The above discussion of synchrotron radiation ignored any coherence effects that may be present when electrons are packed into small bunches. The qualitative argument for the enhancement of radiation due to coherence effects is as follows. When electrons are bunched into a region with a dimension significantly less than the wavelength of the radiation being emitted, all the charges radiate in phase like one macroparticle and the radiation output is proportional to N^2. Numerous authors have done quantitative analyses of the coherence effects for electrons in a Gaussian bunch of dimensions, $\sigma_x, \sigma_y\ \&\ \sigma_L$, the results will simply be reviewed here [8]. The coherent power, P_{coh}, is given in terms of the incoherent power P_{inc} by,

$$P_{coh}(\lambda,\sigma_L) = [1+(N-1)\cdot H(\lambda,\sigma_L)]\cdot P_{inc}(\lambda) \tag{5}$$

where $H(\lambda, \sigma_L) = \exp\left[-(2\pi\sigma_L)^2/\lambda^2\right]$ for a Gaussian electron beam. For wavelengths short compared to the electron bunch length the incoherent spectrum is unaffected, but for wavelengths on the order of the bunch length and longer, the radiation output is enhanced by up to a factor of N. For wavelengths larger than a few centimeters the radiation will be suppressed because these wavelengths are below the cutoff of the storage ring vacuum chamber which has a full aperture vertical dimension of 35 mm.

In Figure 1 we plot the coherent spectral power for the wavelength range of 0.1 mm ≤ λ ≤ 10 mm for the electron beam parameters given in Table 4. For comparison the maximum incoherent power assuming a circulating current of one ampere is also plotted in Figure 1. It can be seen that for wavelengths λ > 0.8 mm there is an enhancement of the radiation output beyond what is available on the XLS ring or any other ring for that matter.

To determine how much coherent power is in a given wavelength range we integrated equation (5) over several ranges of wavelength for the two bunch lengths, σ_L = 0.3 & 0.5 mm, and tabulated the results in Table 6.

$\sigma_L = 0.32$ mm, $I = 62\ \mu A$			
$\lambda_1 [mm] \rightarrow \lambda_2 [mm]$	0.8→1.0	1→2	2→10
$\int_{\lambda_1}^{\lambda_2} P_{coh}(\lambda,\sigma)\, d\lambda$ [μw / mrad θ]	9×10^{-3}	2.8	8.4
$\sigma_L = 0.5$ mm, $I = 234\ \mu A$			
$\lambda_1 [mm] \rightarrow \lambda_2 [mm]$	0.8→1.0	1→2	2→10
$\int_{\lambda_1}^{\lambda_2} P_{coh}(\lambda,\sigma)\, d\lambda$ [μw / mrad θ]	1.7×10^{-3}	4.2	73

Table 6: Coherent Power for Various Wavelength Ranges and Two Electron Bunch Lengths

VI. CLOSING REMARKS

The infrared beamline IR4 on the VUV ring at the NSLS collects radiation from about 100 mrad of horizontal arc. For the racetrack design of the XLS, one could consider collecting radiation from the entire dipole, π radians, if optics of the proper design and reflectivity were available [9].

When a 2856 MHz cavity is used in the XLS ring there can be 81 equally spaced bunches. In this case there exists the possibility of an additional coherence between the various bunches. In practice the stability of multiple bunches in the XLS storage ring against such deleterious effects as ion trapping and multibunch instabilities requires further analysis.

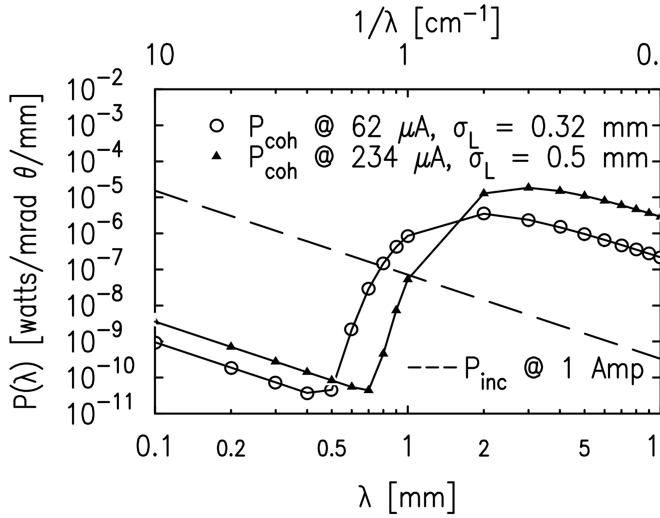

Figure 1: Comparison of Incoherent & Coherent Power versus Radiation Wavelength for the XLS Ring. For incoherent emission, I = 1 ampere, and for coherent emission the currents are taken from Table 4.

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