2.5 Optimizing ring-based CSR sources

J.M. Byrd, S. De Santis, Z. Hao, M. C. Martin, D.V. Munson, D. Li, H. Nishimura, D.S. Robin, F. Sannibale, R.D. Schlueter, R. Shoenlein, J.Y. Jung, M. Venturini, W. Wan, A. A. Zholents, M. Zolotorev, LBNL

JMByrd@lbl.gov

2.5.1 Introduction

Coherent synchrotron radiation (CSR) is a fascinating phenomenon recently observed in electron storage rings and shows tremendous promise as a high power source of radiation at terahertz frequencies. However, because of the properties of the radiation and the electron beams needed to produce it, there are a number of interesting features of the storage ring that can be optimized for CSR. Furthermore, CSR has been observed in three distinct forms: as steady pulses from short bunches, bursts from growth of spontaneous modulations in high current bunches, and from micro modulations imposed on a bunch from laser slicing. These processes have their relative merits as sources and can be improved via the ring design.

The terahertz (THz) and sub-THz region of the electromagnetic spectrum lies between the infrared and the microwave [1]. This boundary region is beyond the normal reach of optical and electronic measurement techniques and sources associated with these better-known neighbors. Recent research has demonstrated a relatively high power source of THz radiation from electron storage rings: coherent synchrotron radiation (CSR) [2]. Besides offering high power, CSR enables broadband optical techniques to be extended to nearly the microwave region [3], and has inherently sub-picosecond pulses. As a result, new opportunities for scientific research and applications are enabled across a diverse array of disciplines: condensed matter physics, medicine, manufacturing, and space and defense industries. CSR will have a strong impact on THz imaging, spectroscopy, femtosecond dynamics, and driving novel non-linear processes.

CSR is emitted by bunches of accelerated charged particles when the bunch length is shorter than the wavelength being emitted. When this criterion is met, all the particles emit in phase, and a single-cycle electromagnetic pulse results with an intensity proportional to the square of the number of particles in the bunch [4, 5]. It is this quadratic dependence that can produce colossal intensities even with fairly low beam currents [2]. Until recently CSR has not typically been observed in electron storage rings because the electron bunch lengths are longer than the waveguide cutoff imposed by the dimensions of the vacuum chamber, so full-bunch coherent emission is suppressed. The first observations of CSR from storage rings were of quasi-chaotic bursts of intensity caused by density modulations in unstable electron bunches [6-9], similar to the self-amplified spontaneous emission (SASE) used in the design of several proposed free electron lasers. While studies of this 'bursting' phenomenon have provided glimpses into the powers available with CSR, the unstable nature of the emission makes this a problematic THz source for scientific measurements. We have experimentally verified a model [10] predicting where this unstable bursting regime will occur [9] and have used this experience to design a new source where the bursting instability can be avoided.

Stable CSR has been produced during machine experiments at the BESSY-II storage ring [11, 12] and the first scientific measurements using this CSR source were recently reported [3]. This stable CSR emission is not driven by any instability, yet it extends to higher frequencies than predicted by a simple full-bunch coherence model [12]. This model is described in these proceedings and elsewhere [13]. The combination of the experimentally verified models for stable CSR as well as the threshold of which current levels will produce bursting instabilities allows us to fully design and optimize a new CSR source that will produce copious amounts of stable far-IR, THz and sub-THz, synchrotron radiation.

CSR has also been recently observed in storage rings as a result of laser slicing of the beams [19-21]. In this process, interaction of an electron beam with a femtosecond laser pulse co-propagating through a wiggler modulates the electron energies within a short slice of the electron bunch comparable with the duration of the laser pulse. Propagating around an electron storage ring, this bunch develops a longitudinal density perturbation due to the dispersion of electron trajectories. This perturbation emits short pulses of temporally and spatially coherent terahertz pulses that are inherently synchronized to the modulating laser. Although this technique was originally developed for producing ultrashort x-ray pulses, the CSR emission has interesting possibilities as a source.

In this paper, we present several of the concepts for optimizing a ring for producing both stable CSR and ultrashort terahertz pulses from laser sliced beams in the context of CIRCE (Coherent InfraRed CEnter), a ring we have proposed which incorporates many of these concepts. Many of these concepts were originally inspired by a compact CSR source described by Murphy et al. [15]. The first section of this paper presents several general considerations for an optimized CSR ring and is followed by details of CIRCE. We present the calculated CIRCE photon flux where a gain of 6 - 9 orders of magnitude is shown compared to existing far-IR sources. Additionally, the particular design of the dipole vacuum chamber has been optimized to allow an excellent transmission of these far-infrared wavelengths. We believe that a small storage ring optimized for CSR such as CIRCE can be constructed for a modest cost.

2.5.2   General Considerations

As discussed in [22], the wavelength range where CSR can be generated lies between the bunch length and the vacuum chamber cutoff and is given by

$$\frac{2\pi\sigma_z}{\sqrt{\ln(N)}} < \lambda < 2h\left(\frac{h}{\rho}\right)^{1/2} \tag{1}$$

where σ_z is the bunch length, N is the number of the electrons in the bunch. The cutoff wavelength of the vacuum chamber $2h\left(\frac{h}{\rho}\right)^{1/2}$ is determined by the chamber full height h, and the bending radius ρ. Note that this cutoff wavelength differs from the familiar waveguide cutoff of plane waves. This is due to the opening angle of the radiation. Although shorter wavelengths can be generated from shorter bunches, the threshold of the CSR microbunching instability strongly limits the bunch charge at shorter bunch lengths. From these considerations, we have determined that optimum natural bunch length for maximizing stable CSR emission from the bunch is in the range of a few psec.

The natural bunch length in an electron storage ring shows the following dependence

$$\sigma_z = \frac{\alpha c \sigma_e}{2\pi f_s} \propto \sqrt{\frac{\alpha E^3}{\rho \omega_{rf} V_{rf}}} \tag{2}$$

where σ_ε is the fractional energy spread, f_s is the synchrotron frequency, E is the beam energy, α the momentum compaction, and ω_{rf} and V_{rf} are the RF angular frequency and voltage. The bunch length can be lowered by reducing beam energy and momentum compaction, and increasing the RF frequency and voltage. Our ideas on achieving this within practical limits in a ring are described below.

The criteria for selecting the beam energy are quite different from a typical synchrotron light source. Because of the radiation wavelength is much longer than the critical wavelength (except for impractically low beam energies), the incoherent radiation intensity and spectrum are independent of wavelength. Rather, the energy is chosen from a weaker set constraints. Foremost is the effect on the bunch length via the energy spread (proportional to E) and longitudinal focusing (proportional to $E^{1/2}$). It is critical that the beam energy be chosen such that the energy spread doesn't increase due to instability or from intrabeam scattering. Furthermore, radiation damping decreases sharply with energy (proportional to E^3), increasing the sensitivity to instabilities which increase inversely proportional to energy. However, lower energy favors several aspects of the mechanical design such as magnets. It also significantly reduces the thermal loading on the first mirror in the beamline due to the radiation at the critical wavelength.

The requirements of the machine lattice are significantly different from those of third generation light sources. The transverse emittance does not need to be minimized because the relatively long wavelength radiation. In fact, it may be useful to increase the emittance in order to mitigate intrabeam scattering effects. Furthermore, there are no immediate advantages to small vertical emittance and thus it may be possible to run at an increased coupling. The primary constraint on the optics is the control of the momentum compaction. Because the primary mechanism for shortening the bunch length at a given beam energy is the momentum compaction, this capability must be

included in the optics as well as the ability to control higher order terms in the momentum compaction via additional sextupole and octupole families. We have found that a modified DBA lattice has all of the desired properties [18].

To shorten the bunch length, it is useful to maximize the RF voltage and frequency. This also increases the threshold for the microbunching instability. Following development of superconducting RF cavities for storage rings, we believe the optimum system available is a 1.5 GHz HOM-damped design which may be capable of reaching voltages of 1 MV. Two such systems have recently been designed and installed [16-17]. One interesting feature of this is that the beam loading at lower beam energy and beam current is extremely small, possibly allowing the cavity to operate at high loaded-Q. Furthermore, the total RF power needed to operate such a system could be below a few kW. Higher frequency RF systems are possible but require increasing smaller apertures to reach significant shunt impedances.

Although the ring size places no direct constraints on the physics of CSR emission, the following practical effects should be considered: adequate straight section space for injection and RF system, arc length sufficient for the modified DBA optics described above, and straight section for a wiggler to allowing laser manipulation of the beam.

There are two interesting considerations on the design of the vacuum system. The first is the difficulty in extracting terahertz synchrotron radiation. The vacuum chamber height must be large enough that the radiation over the desired wavelength range is not suppressed due to waveguide cutoff described above. For example, for ρ=1 m, h=1 cm, very little radiation is emitted for wavelengths longer than λ_{cutoff}=2 mm. It is not trivial to extract the CSR because of the relatively large opening angle of the radiation compared with that at the critical wavelength. The opening angle is given by

$$\theta_{rad} = \left(\frac{\lambda}{2\pi\rho}\right)^{1/3} \tag{3}$$

The beamline requires typically requires over 100 mrad vertical acceptance to extract most of the radiation at millimeter wavelengths. The second consideration is the geometric impedance of the vacuum chamber. Our studies indicate that the broadband component of this impedance is negligible compared to the radiation impedance. In other words, at bunch lengths short enough to generate CSR, the radiation impedance is dominant and other broadband impedances can be neglected. However, it is important to consider narrowband impedances if the ring is operated in multibunch mode.

### 2.5.3   Circe Ring Design & Beamline Extraction

We now want to design CIRCE, a ring-based source optimizing the emission and extraction of CSR. In the design of such a source one of the fundamental requirements is the stability of the CSR emission. We have therefore optimized the various machine parameters to maximize the CSR emission while keeping the beam current below the bursting threshold [9,13]. We maximize the CSR bandwidth by designing a vacuum chamber with a very low frequency cutoff to allow for transmission of wavelengths out to ~1 cm, and by tuning the ring parameters to increase the static distortion of the electron bunch profile as discussed in [13,22] to extend the CSR emission to shorter wavelengths. A double-bend achromat lattice was chosen to allow significant flexibility in getting to low momentum compaction, a key requirement to produce ~ 1 picosecond

bunch lengths. Lowering the energy of the electron beam to a moderate value of 600 MeV, helps shorten the bunches but is not so low that it becomes difficult to maintain the stability of the electron beam. A higher-frequency RF system (1.5 GHz superconducting) also aids in shortening the electron bunches. Additional families of magnets were added to allow fine control of higher order components of the momentum compaction.
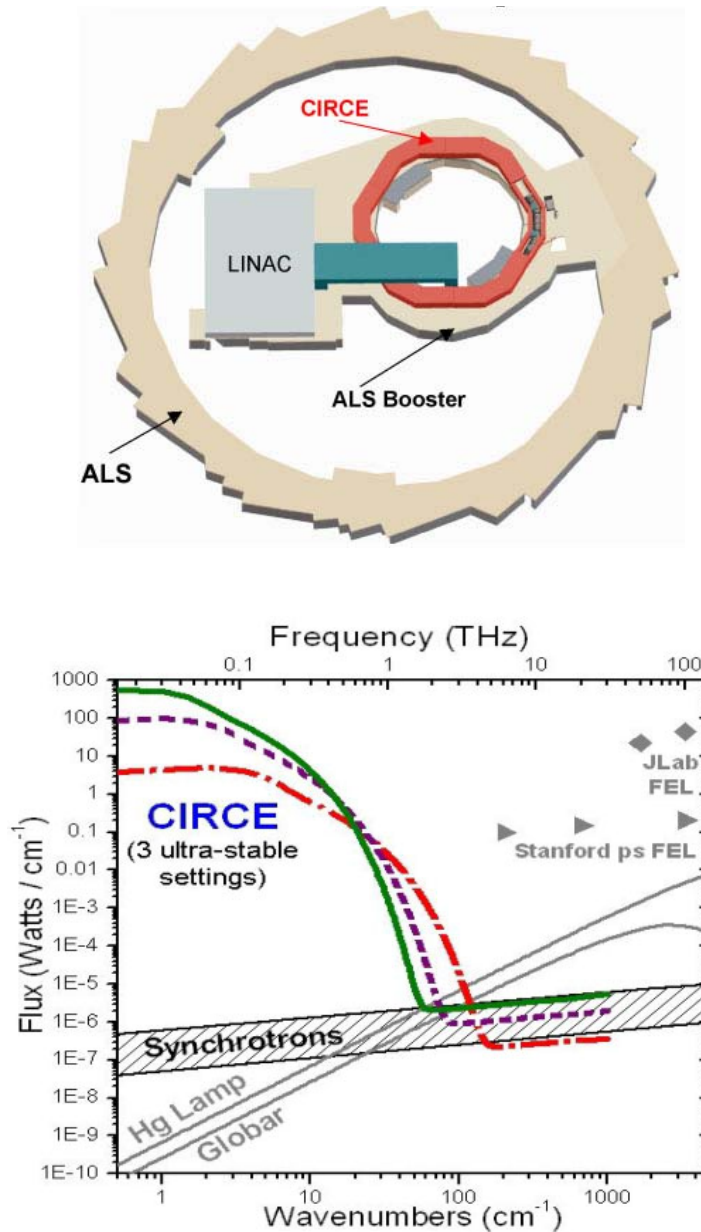
Figure 1. Top) Location of the CIRCE ring on top of the existing ALS booster sheilding. The ring design allows for numerous CSR beamlines located directly next to the shield walls and the parasitic use of the ALS injector for full-energy beam injection into CIRCE. Bottom) Flux calculations for CIRCE compared with conventional synchrotron and thermal far-IR sources, as well as two existing free electron lasers. The three CIRCE curves demonstrate how the CIRCE source can be tuned for high power, for extending coherent emission to shorter wavelengths, or somewhere in between.

The optimized size of a ring having all these parameters is almost the same size at the existing Advanced Light Source (ALS) booster ring, which allows an opportune use of available space at the ALS. We propose to build the CIRCE ring on top of the existing booster shielding and make use of the booster for full energy injection, as shown in a 3 dimensional computer aided design (CAD) drawing in Figure 1,top. The booster shielding tunnel is a single, poured in place, 1 meter thick concrete structure. As such it is quite stable with accelerometer measurements showing that the top surface is as stable as the main ALS experimental floor. We plan to build a compact shielding block system very close to the CIRCE ring to allow for the beamlines to fit on the same booster ring shielding surface. This proximity of the beamlines to the source points in the bending magnets gives another advantage for keeping the vibration pickup on the photon beam to a minimum. Initial studies of the ALS infrastructure have found no showstoppers for building the CIRCE ring on this location.
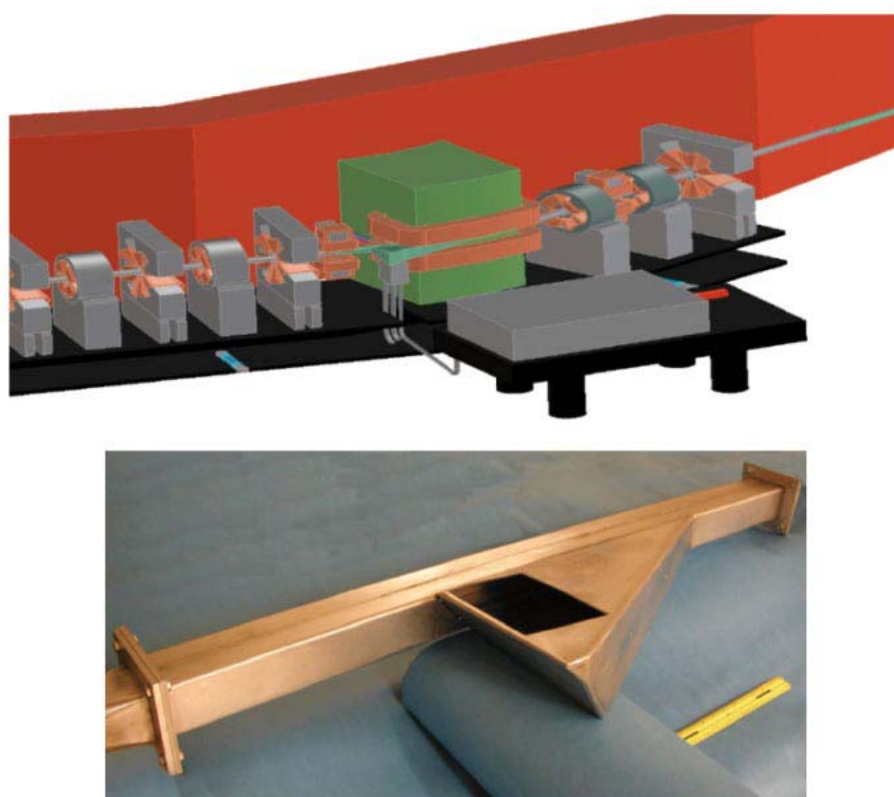
Figure 2. Top) Cutaway view of a dipole source with optical table. The experiment sits less than 1 m from the source of the radiation. Bottom) A photograph of a full-scale prototype chamber fabricated for RF testing. The chamber is designed to collect 300 mrad horizontally and 140 mrad vertically. This very large acceptance means that the first mirror collects 95% of the radiation at 1 mm wavelength, so the CSR extraction is very efficient.

Once the CSR is emitted by the electron bunches, it is important to efficiently collect this powerful THz light. We accomplish this by choosing short radius bending magnets which allow the placement of the first collecting mirror close to the source point, and by a uniquely designed vacuum chamber shown in the left panel of Figure 2. The opening of this vacuum chamber follows the photon beam profile allowing us to collect the light from a full 60% of the electron beam's trajectory within the bending

magnet. The first mirror located at the large end of this chamber will collect 300 mrad horizontally by 140 mrad vertically. This very large vertical collection angle captures 95% of the emitted synchrotron radiation at a 1 mm wavelength, and 100% collection of shorter wavelengths. The right panel of Figure 2 schematically shows how the first mirror will deflect the beam 90 degrees downward, and then will be followed by beamline optics to re-image the light into a spectrometer or other end station equipment located directly outside the shield walls.

The unusual design of the vacuum chamber means that we must concern ourselves with trapped electromagnetic field modes usually referred as high order modes (HOM), which could influence the stability of the electron beam. Accurate simulations of these fields in the chamber have shown only small couplings between these modes and the electron beam. Additionally, the large photon beam aperture after the first mirror allows the HOM to propagate outside the main chamber where they can be easily damped by RF absorbers. Bench measurements on a full-scale mock chamber (shown in the photograph in Figure 2) have completely confirmed the simulations results so that we are confident that HOM will not be an issue for the beam stability [14].

2.5.4 CIRCE Performance

Using the machine parameters for the CIRCE ring in our model for the CSR production from distorted electron bunches, we calculated the THz flux produced by the CIRCE ring. The results are plotted along with conventional synchrotron and thermal far-IR sources in Figure 1. The three different CIRCE curves represent three (of many) possible machine configurations. To maximize the CSR bandwidth toward the short wavelengths, we need to decrease the electron bunch length while keeping the distribution distortion to the maximum allowed by the model stability criterion for the bursting instability [13]. At shorter bunch lengths, the threshold for bursting goes down so the total number of electrons and therefore the total CSR power emitted is limited (red curve in Figure 1). To increase the total power emitted we can lengthen the bunch, while maintaining the maximum distortion. This means the CSR doesn't extend to as short of wavelengths, but it allows for increasing the number of electrons in the bunch (green curve). Since the intensity emitted goes like the number of electrons squared, the flux can be significantly increased in this method.

Table 1. List of performance parameters for the CSR emission of the designed CIRCE ring. Powers and energies are integrated from $1 - 100$ cm^{-1}. When two values are presented as a range, they correspond to the red and green curves in Figure 1.

| Source Parameter	Value	Ring Parameter	Value
Average Power	13 – 311 Watts	Electron beam energy	600 MeV
Peak Power	3.5 – 28 Kilowatts	Total beam current	20 – 225 mA
Pulse Length	≥ 300 femtoseconds (transform limited)	Momentum compaction	$1\text{-}8\times10^{-4}$
Repetition Rate	Up to 1.5 GHz	Electron pulse length	1-3 psec
Wavelength range	1 cm-200 micron	RF frequency	1.5 GHz
Energy/pulse	9-210 nJ	RF Voltage	0.6-1.5 MV

Comparing to existing synchrotron and thermal far-IR sources, Figure 1 shows that CIRCE will have between a 6 and 9 order of magnitude increase in average flux. A list of parameters for the CSR light generated by CIRCE is given in Table 1. The emitted

light will come in transform limited pulses with durations of ~ 300 femtoseconds at the shorter wavelengths, and at a repetition rate tunable between 4.5 MHz and 1.5 GHz (varied simply by choosing which electron bunches are filled). Since these pulses are single cycle, they should be coherent with each other, and therefore we are investigating a pulse-stacking resonator. This would allow particular beamlines to amplify the peak power of the pulses at the expense of repetition rate, and allow that user to select the timing of their pulses independent of the other beamlines and users at CIRCE.

2.5.5   Broadband Bursting mode

When the current per bunch exceeds the threshold for the CSR driven instability [3-6], quasi-random bursts of CSR in the terahertz frequency range appear. This instability is associated with the spontaneous generation of temporary microstructures in the bunch longitudinal distribution. These structures last for several turns, radiating CSR with strong fluctuating intensity but at higher frequencies than in the stable mode. This effect can be potentially exploited by experiments that require higher frequency photons but not a stable CSR flux.

Figure 3 shows the result of a simulation of the broadband bursting mode for the CIRCE case. The spectrum for a stable CSR emission below the burst threshold is shown as a dotted line, while the unstable situation above threshold, when bursting is present, is shown as a solid line. The "unstable" spectrum is averaged over several bursts. For wavenumbers from ~ 70 cm^{-1} to ~ 150 cm^{-1}, the unstable case shows about one order of magnitude higher flux. The simulation uses the SET 1 configuration of Table 2 with the current per bunch below and above the instability threshold.
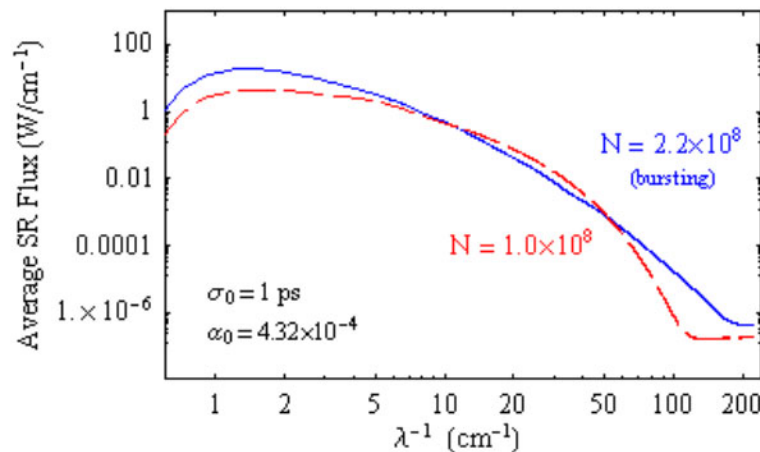
Figure 3: Simulated CSR spectrum for the broadband bursting mode of CIRCE. The roll-off to the left of the curves is due to the vacuum-chamber shielding.
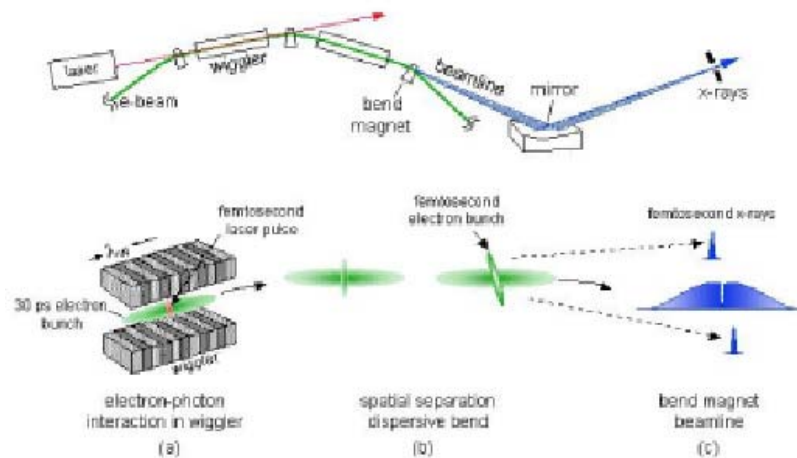
2.5.6   Laser slicing of beams

We are planning to include in one of the CIRCE straight sections a wiggler magnet for allowing femtosecond laser modulation of the electron beam [19]. The first beamline using such a technique, commonly referred also as "slicing", has been successfully operating at the ALS since 2001 for the production of femtosecond x-ray pulses [20]. In this scheme a short laser pulse is propagated together with the electron beam in a

wiggler for modulating the energy of a short slice (~ 100 fs) of the electron bunch. Due to the nonzero momentum compaction, a density modulation in the bunch longitudinal distribution is induced when the beam propagates along the storage ring. It has been predicted and experimentally confirmed at the ALS [21], that such density modulations radiate intense short pulses of CSR in the terahertz frequency. These CSR pulses are regularly used at the ALS as diagnostics for the fine tuning of the slicing experiment and could be potentially used as a terahertz source as well.

The interaction of a laser with a relativistic electron beam in a wiggler magnet is schematically illustrated in Fig. 4. A 100-fs optical pulse of moderate energy modulates the energy of an ultra-short (~30 μm) slice of a stored electron bunch as they co-propagate through a wiggler in a storage ring (Fig. 4a). The energy-modulated electron slice is spatially separated from the main bunch in a dispersive section of the storage ring (Fig. 4b) and is used to radiate fs x-rays at a bend-magnet or insertion-device (Fig. 4c). The energy modulation of electrons creates a small perturbation to the electron bunch longitudinal density consisting of a dip and two side bumps due to the dispersion of the electron trajectories, which causes the high and low energy electrons to move far away from their original positions while the electron bunch moves from the wiggler to the radiation source. This perturbation gives rise to an electron emission of a temporally and spatially coherent infrared light. The intensity of this radiation scales quadratically with the number of misplaced electrons. This scheme is referred to as laser slicing and has been implemented in the ALS as a source of femtosecond x-rays.

Figure 4 Schematic of laser slicing of an electron beam. The beam energy is modulated via interaction with a laser pulse in a wiggler. The energy modulation leaves a hole in the bunch via time-of-flight dispersion of the modulated beam. The "hole" can then radiate coherently.

Measurements of the infrared radiation at the ALS were performed at two bend magnet sources located one-half sector downstream from the wiggler at the beamline 5.3.1 (BL5.3.1), and 8 sectors downstream from the wiggler at the beamline 1.4 (BL1.4). Figures 5a and c show a calculated electron longitudinal distribution in two source locations and for two lattices assuming energy modulation of six times the natural energy spread and rms pulse length of 45 fsec. In all cases, electrons with $\Delta E < 0$ accumulate toward the head of the bunch while electrons with $\Delta E > 0$ accumulate toward the tail of the bunch, creating a dip in a distribution with two side bumps. The uncorrelated energy spread of electrons causes a smearing of the distributions which is

growing with the increased distance from the wiggler. A corresponding spectrum of the infrared signal for all four cases is shown in Figs. 5b and d.
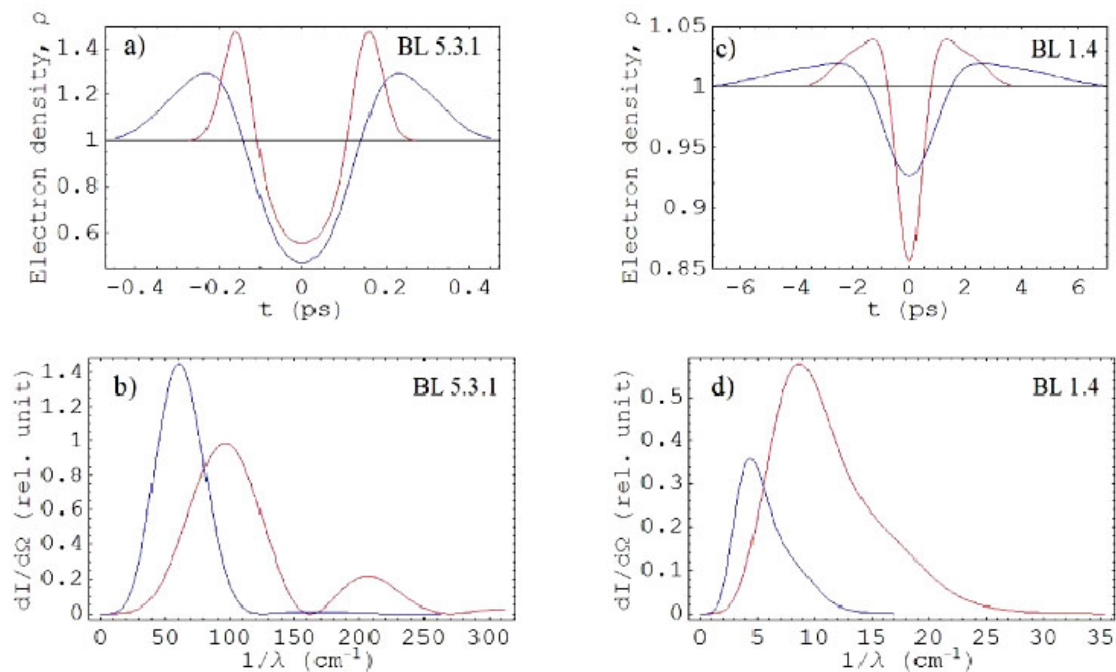

Figure 5: A predicted perturbation in the electron density distribution and a spectrum of the infrared radiation caused by this perturbation shown for BL5.3.1 and BL1.4 for the nominal lattice (red line) and for the experimental lattice with an increased momentum compaction factor (blue line). Plots a) and c) show the distribution and plots b) and d) show the corresponding spectrum.

Figure 6 (left) shows the oscilloscope trace of the infrared signal measured at the BL1.4 for the electron bunch current of about 1 mA, well below a threshold of the bursting instability observed previously. Figure 6 (right) shows the measured spectrum at two points in the ring. Nearer to the slicing (BL5.3.1), the pulse is still narrow and the spectrum peaks at higher frequencies. Farther from the slicing (BL1.4), the pulse has broadened considerable and the spectrum shifts to lower frequencies. The relative amplitude is due to the acceptance of the beamlines. The measured spectra illustrate the difficulties of extracting long wavelength radiation from a conventional light source. For example, the spectrum at BL1.4 appears shifted to higher frequencies than expected because of the low frequency cutoff of the vacuum chamber. The spectrum at 5.3.1 has significant structure due to reflections in the transport of the radiation and due to water vapor absorption.

Figure 7 shows the example of the calculated CSR spectrum for a possible slicing configuration of CIRCE. In this case the beam is modulated inside a wiggler in a straight section and the CSR is collected from a dipole magnet port 2.5 m downstream. The laser pulse, 50 fs FWHM, has the intensity necessary for an energy modulation of the electrons as large as six times the beam energy spread. The current per bunch is 10 mA and the integrated energy of the CSR pulse over 100 mrad horizontal acceptance is ~ 8.5 µJ. The maximum repetition rate is limited by the requirement on the laser power to 10-100 kHz.
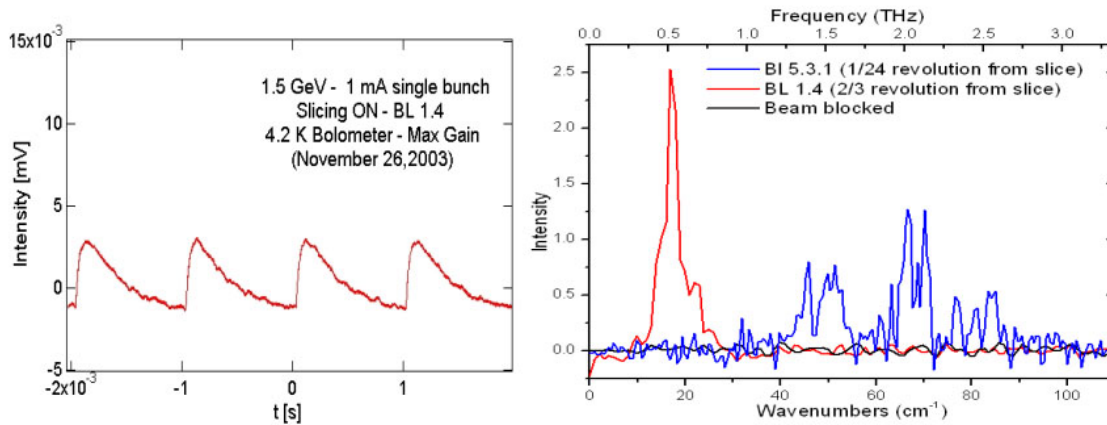
Figure 6: Left) The infrared signal measured with the nominal lattice at the BL1.4 with laser turned on and electron bunch current of ~1 mA. Right) Spectra measured at BL 5.3.1. and BL1.4. The structure on the measurement is due to reflections in the beam line and water vapor absorption.
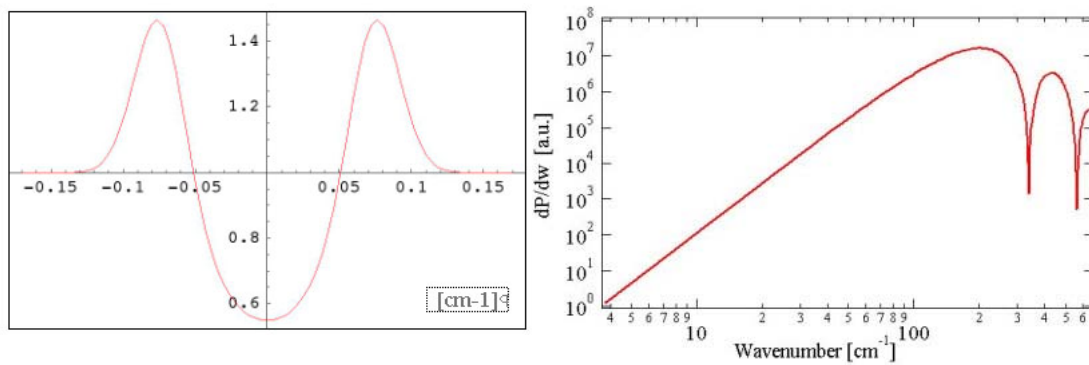
Figure 7: Calculated CSR spectrum for a possible configuration of the laser "slicing" mode in CIRCE.

Comparing the spectra in Figures 1 and 7 one can see how the slicing mode significantly extends the CIRCE capabilities towards higher frequencies. One of the tantalizing possibilities of this technique is the tailoring of the time domain terahertz pulse via appropriate shaping of the laser pulse. This would allow a unique capability in a synchrotron source.

2.5.7   Conclusion

CIRCE will be a *revolutionary* source for a traditionally difficult spectral region at the border between optics and electronics, namely the "THz-gap." We have explored the virtues of a small ring dedicated to the production of *coherent* far-infrared and THz radiation and have determined conclusively that such a machine will create a true leap forward for the field and is entirely feasible. The total estimated cost for building the ring, including the first several beamlines, is less than $20 million. Just as conventional synchrotron radiation has been a boon to x-ray science, coherent synchrotron radiation may lead to many new innovations and discoveries in terahertz science.

2.5.8 Acknowledgments

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