CIRCE, THE COHERENT INFRARED CENTER AT THE ALS*

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Abstract

CIRCE (Coherent InfraRed CEnter) is a proposal for a new electron storage ring to be built at the Advanced Light Source (ALS) of the Lawrence Berkeley National Laboratory (LBNL). The ring design is optimized for the generation of coherent synchrotron radiation (CSR) in the terahertz frequency range. Among others, CIRCE operation includes three interesting CSR modes: ultra stable, femtosecond laser slicing and broadband bursting. CSR allows CIRCE to generate an extremely high flux in the terahertz frequency region. The many orders of magnitude increase in the intensity over that presently achievable by 'conventional' sources, has the potential to enable new science experiments. The characteristics of CIRCE and of the different modes of operation are described in this paper.

INTRODUCTION

The interest in science using radiation in the terahertz region is steadily increasing. Generating radiation of significant intensity in this frequency range, between microwaves and infrared (IR), is not straightforward and this region is often referred as the "terahertz gap". As a consequence there is a strong need for new more powerful terahertz sources.

In the last few years, there has been significant progress in the understanding of CSR in storage rings: i) for the first time stable CSR was produced in a storage ring [1] and a theoretical model explaining the observation was proposed [2], ii) a model accounting for the CSR terahertz bursts observed at several rings was also presented [3, 4] and experimentally verified [5, 6], iii) experiments at the LBNL showed the generation of intense terahertz CSR pulses by using the so called "slicing" technique, based on the energy modulation of a fraction of the electron beam by a femtosecond laser pulse [7].

At the LBNL we are proposing CIRCE, a ring based source completely optimized for the generation of coherent terahertz synchrotron radiation that exploits the full complement of the CSR production mechanisms mentioned above. The calculated photon flux for CIRCE exceeds by more than 8 orders of magnitude the terahertz flux of "conventional" sources.

CIRCE DESCRIPTION

Figure 1 shows a 3D layout of the CIRCE ring inside the ALS facility. CIRCE will be located on top of the ALS Booster shielding sharing the injector with the ALS storage ring. Table 1 shows the main parameters for CIRCE.

The lattice includes six Double Bend Achromat (DBA) cells with ~ 3.5 m straight sections between the arcs. Requirements on the emittance are quite relaxed because the source size is diffraction limited in the terahertz region. In the optimization of the CSR performance of a storage ring it is very important to have control of its non-linear dynamics. The CIRCE lattice includes several families of sextupole and octupole magnets for fulfilling to this requirement [8].

The vacuum chamber in the dipole magnets and the first in-vacuum mirror have been designed for a 140 mrad vertical acceptance for better matching with the large emission angle of the terahertz synchrotron radiation. Jointly with the 300 mrad horizontal acceptance, this configuration allows for three 100 mrad horizontal, 140 mrad vertical acceptance ports per dipole magnet with a potential of 36 total beamlines in CIRCE.

Additional technical specifications and design information can be found elsewhere [9], here in this paper we focus our attention on the description of some interesting modes of operation for CIRCE.

Table 1: CIRCE Ring main parameters

Energy [MeV]	600	Ring Length [m]	66
Natural Emittance [nm]	56.3	Relative Energy Spread (rms)	4.5×10^{-3}
RF freq. [GHz]	1.5	RF Voltage [MV] (supercond. system)	1.2
Harm. Number	330	Bend Radius [m]	1.33

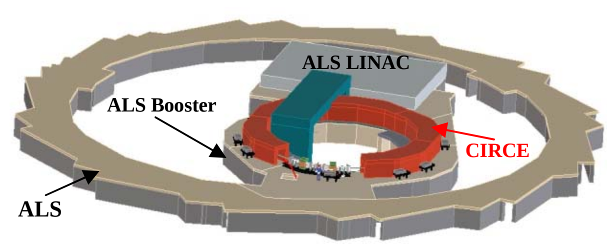

Figure 1: The CIRCE ring in the ALS complex.

ULTRA-STABLE CSR MODE

CIRCE's principal mode of operation is the ultra-stable CSR mode, as it allows for the simultaneous combination of high and stable power, features of extreme importance for most of the experiments using terahertz radiation.

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Figure 2 shows the impressive flux in the THz region, calculated for three sample ultra-stable settings of CIRCE, compared with that obtained from typical conventional sources.

In this ultra-stable case, the configuration used at BESSY II [1] for the first measurement of stable CSR is now fully optimized in CIRCE by maximizing the CSR production following the criteria specified in [2]. These also include avoiding the CSR induced THz bursts [3-6] by maintaining the current per bunch below the instability threshold, for a steady and stable flux of photons.

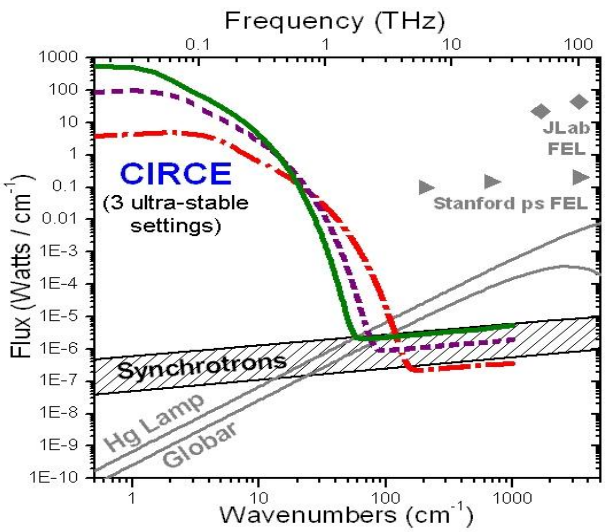

Figure 2: CIRCE photon flux in the ultra-stable mode. Single bending magnet port with 300 mrad horizontal acceptance.

The basic mechanism exploited in this ultra-stable mode of operation is the following. The field associated with the synchrotron radiation emitted by the electrons in the bend magnets, generates a stable distortion of the bunch longitudinal distribution, which assumes a sawtooth-like shape with a sharp leading edge. Such a distribution radiates CSR at frequencies much higher than for the case of a pure gaussian bunch with same rms length.

Table 2: CIRCE parameters for three different ultra-stable settings. Power and energy values are calculated for the bending magnet horizontal acceptance of 300 mrad and integrated from 1 to 200 cm^{-1}

	Nat. Bunch length [ps]	Mom. Comp.	Total stored current [mA]	Current per bunch [μA]	Total CSR power [W]	Pulse peak power [kW]	Energy per pulse [nJ]
SET 1	1.0	$4.3\ 10^{-4}$	29.4	90.0	30.0	~ 8	20.0
SET 2	2.0	$1.7\ 10^{-3}$	148	450	277	~ 37	185
SET 3	3.0	$3.9\ 10^{-3}$	381	1150	973	~ 86	649

Table 2 shows the CIRCE main parameters for the three different spectra shown in Fig. 2. In the ultra-stable setting SET 1, the momentum compaction is tuned to a lower value to have a shorter natural bunch length. This reduces the maximum stable current you can store per bunch, and thus the CSR intensity, but extends the CSR spectrum towards higher frequencies. In SET 3, a larger momentum compaction increases the threshold for the burst instability allowing for more current per bunch and more CSR power at the cost of a reduced bandwidth. Finally, SET 2 represents a situation in between the previous modes.

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 [1], radiating CSR with strong fluctuating intensity but at higher frequencies than in the stable mode. This effect can potentially be 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 dashed 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.

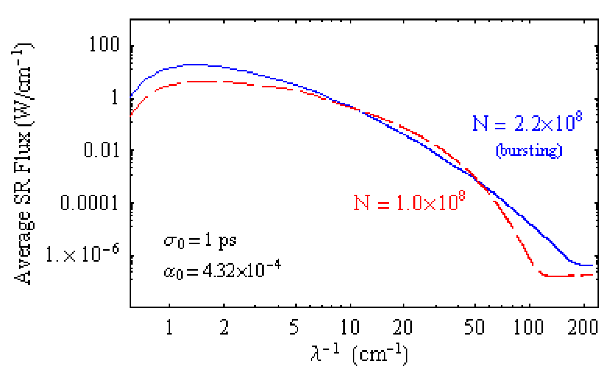

Figure 3: Simulated CSR spectrum for the broadband bursting mode of CIRCE. The roll-off to the left of the curves is due to the vacuum-chamber shielding (not present in Fig. 2).

FEMTOSECOND LASER SLICING CSR

In one of the CIRCE straight sections, we are planning to include a wiggler magnet to allow femtosecond laser modulation of the electron beam [10]. 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 [11]. In this scheme, a short laser pulse is propagated together with the electron beam in a wiggler and modulates 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 [12] and experimentally confirmed at the ALS [7], that such density modulations radiate intense short pulses of CSR at the terahertz frequencies. These CSR pulses are regularly used at the ALS as diagnostics for the fine tuning of the slicing experiment and could potentially be used as a terahertz source as well.

Figure 4 shows an 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 to 10-100 kHz by the requirement on the laser power.

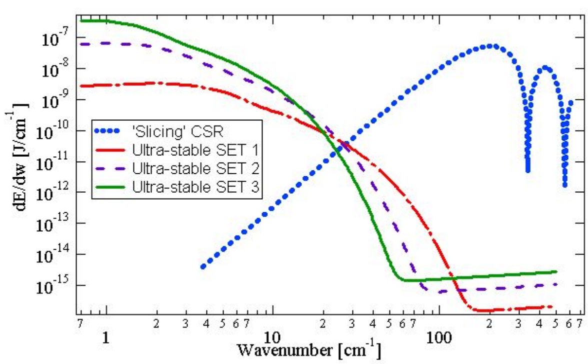

Figure 4: Calculated CSR spectrum for a possible configuration of the laser "slicing" mode in CIRCE.

Comparing in Figure 4 the ultra-stable and the slicing CSR spectra, one can see how the slicing mode significantly extends the capabilities of CIRCE towards higher frequencies.

CONCLUSIONS

We have presented CIRCE, an optimized CSR source in the terahertz frequency range. The scheme is based on a storage ring and shows the flexibility of such a solution, where several different modes of operation can easily be obtained. CIRCE capabilities cover most of the terahertz spectrum with a photon flux of more than 8 orders of magnitude larger than in the present conventional sources, including 3rd generation light sources.

At the present time, we have completed a detailed feasibility study on CIRCE that includes linear and nonlinear dynamics studies [8], magnetic design of all the magnets and design of the special high acceptance dipole vacuum chamber. Additionally, we have performed high order modes measurements on a dipole vacuum chamber prototype and investigated the compatibility of CIRCE with the ALS facility. No show stoppers have been identified. The cost for the CIRCE construction, including several beamline front ends, is estimated to be less than $ 20M.

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