COHERENT TERAHERTZ RADIATION EMITTED BY SUB-PICOSECOND ELECTRON BUNCHES IN A MAGNETIC CHICANE

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Abstract

Coherent radiation emitted by relativistic electron bunches traversing the edge regions of dipole magnets in a chicane bunch compressor was extracted and transported for measurement, using a dedicated terahertz beamline at the Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL). Measurements include frequency spectrum and polarization of the radiation. The measurements are compared to predictions from QUINDI, a new simulation code developed at UCLA to model radiation emitted by charged particles in bending systems. Simulations and measurements indicate that because of interference of radiation from the two magnet edges, the edge radiation is suppressed at long wavelengths. In addition to being a source of broadband terahertz radiation, the system is also used as a non-invasive, single-shot, relative bunch length diagnostic to monitor compression in the chicane.

INTRODUCTION/MOTIVATIONS

Advanced accelerators, such as high power FELs, require electron beams with low emittance, low energy spread, and high peak current [1]. To obtain the high peak current, electron bunches must be compressed longitudinally. Currently, the most common method of bunch compression is to use a magnetic chicane. Radiation is emitted when electrons bend in the magnetic fields of the chicane; the radiation is coherent for wavelengths longer than the bunch length.

The coherent radiation is beneficial, in that it can be used as a longitudinal bunch diagnostic or as a dedicated terahertz radiation source. But the radiation is also destructive: the emission of coherent radiation by the beam leads to self-interactions which distort the longitudinal phase space, which can limit compression and cause an increase in the transverse emittance [2]. Previous measurements at the ATF indicate that the electron bunch length can be compressed to below 150 fs with a peak current exceeding 1.5 kA, but that under full compression, the energy spectrum and current profile are strongly fragmented [3].

This experiment characterized the coherent radiation emitted by sub-picosecond electron bunches traveling through the downstream edge of the 3rd and the upstream edge of the 4th chicane magnets. An attempt was made to distinguish between synchrotron radiation (SR) [4] emitted during bending in the constant dipole fields, and edge radiation (ER) [5, 6, 7] emitted during motion through the dipole fringe fields. ER has been shown to be a useful source of terahertz radiation which has different properties than standard SR, including higher intensity at long wavelengths and nearly radial polarization.

EXPERIMENT DESCRIPTION

As shown in Fig. 1, the ATF features a 1.6 cell S-band photoinjector of the BNL/SLAC/UCLA type [8], matched to an emittance compensation solenoid. The beam is accelerated to 61 MeV by two SLAC-type linac sections and focused with a quadrupole triplet before entering the chicane. The chicane is a four dipole symmetric type with an integrated radiation port, which is specifically designed to collect radiation from magnet edges 3b and 4a (see Fig. 2). Due to the angular acceptance of the port, the chicane radiation is a superposition of radiation from two edges and two bending regions. The radiation exits the port through a z-cut quartz vacuum window, travels down the radiation transport line, and is focused by a *picarin* (a plastic, also called *tsurupica*) lens to achieve a point-to-parallel transport. The radiation enters the diagnostic area, which contains a Michelson interferometer, wire-grid polarizer, and a silicon/diamond cryogenically-cooled bolometer. The entire transport line (about 6 m long) and diagnostic area can be enclosed and flushed with dry nitrogen to eliminate absorption by airborne water molecules. Relevant operating parameters for this experiment are listed in Table 1.

Table 1: Typical Operating Parameters

Parameter	Value
Electron energy	61 MeV
Electron bunch charge	300 pC
RMS bunch length, before chicane	600 μm
RMS bunch length, after chicane	40 μm
Peak current, before chicane	60 A
Peak current, after chicane	2 kA
Chicane B-field, nominal	0.17 T
Chicane bend radius	1.2 m
Chicane R_{56}	-8.6 cm

BACKGROUND

Radiation exiting the chicane is a superposition of both SR and ER. The characteristics of SR are well known and can be calculated analytically. In general, ER must

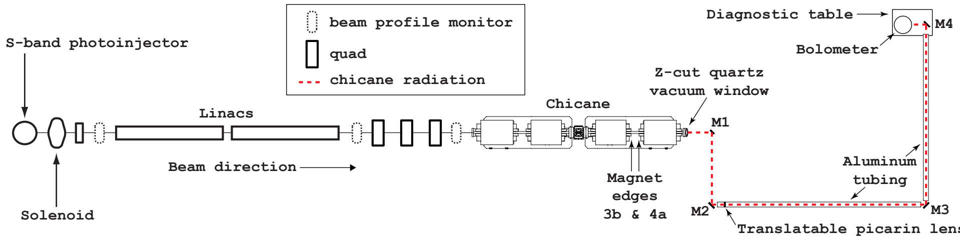

Figure 1: Diagram of the relevant beamline section and chicane radiation transport.

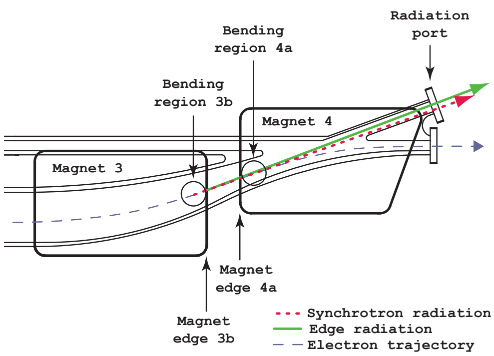

Figure 2: Diagram of the last two magnets of the chicane, showing sources of the radiation that was collected.

be calculated numerically, because the exact form of the dipole fringe fields is not known. However, certain approximate models have been formulated [5, 6], which allow predictions of the characteristics of ER for certain spectral regimes. In these models ER is similar to transition radiation, with a flat spectral response up to a characteristic frequency, nearly radial polarization, and an angular distribution peaked at $1/\gamma$, where γ is the relativistic factor.

For a given emission process, the spectral-angular distribution of radiation from a bunch of N electrons can be expressed as

$$\frac{d^2 I}{d\omega\, d\Omega} = [N + N(N-1)f(\omega)]\frac{d^2 I_0}{d\omega\, d\Omega}, \qquad (1)$$

where $\frac{d^2 I_0}{d\omega\, d\Omega}$ is the single electron spectral-angular distribution. Here $f(\omega)$ is the bunch form factor, which describes the spectral distribution of the bunch. For wavelengths longer than the bunch length (for our case $\sim 40\ \mu$m), the second term in Eq. 1 dominates, and each type of radiation is coherently enhanced by a factor of N (typically $\sim 10^9$) over the incoherent radiation.

The radiation from two edges of opposite sign (entering/exiting) can be expressed as

$$\frac{d^2 I_{tot}}{d\omega\, d\Omega} = \frac{d^2 I}{d\omega\, d\Omega}\, 4\sin^2\left[\frac{\pi L}{2\lambda\gamma^2}(1+\gamma^2\theta^2)\right], \qquad (2)$$

where L is the distance between edges, λ is the radiation wavelength, and θ is the observation angle. Thus ER from adjacent edges is predicted to interfere for wavelengths long compared to L/γ^2.

The total energy-per-pulse of the chicane radiation scales approximately inversely with the bunch length, making it useful as a non-invasive, single-shot, relative bunch length monitor. During this experiment, the coherent radiation was used to optimize chicane compression.

SIMULATIONS

CSR/CER Simulations

QUINDI [9, 10] simulations were run for single-magnet and two-magnet geometries (as in the last two magnets of the chicane) to examine the effect of interference between coherent synchrotron radiation (CSR) and coherent edge radiation (CER). A zero-emittance, zero-energy spread Gaussian bunch with bunch length $\sigma_t = 130$ fs and transverse beam size $\sigma_r = 300\ \mu\text{m}$ was used. The spectra are shown in Fig. 3. Due to interference of radiation from the two magnet edges, CER is strongly suppressed at long wavelengths; CSR shows no large scale interference effects.

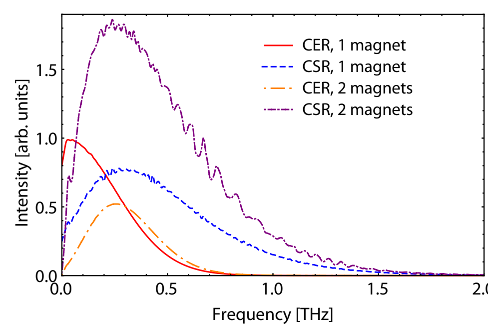

Figure 3: QUINDI simulations of single- and two-magnet CER and CSR.

Start-to-end Simulations

Start-to-end simulations were performed with PARMELA [11] for beam dynamics in the photoinjector and linacs, elegant [12] for beam transport, and QUINDI for radiation simulations. In addition, the optical design software ZEMAX was used to model the terahertz radiation transport. Simulations of the chicane radiation are compared to measurements in the following section.

MEASUREMENTS

Spectrum

The chicane radiation spectrum was measured before and after improvements were made to the transport line, as shown in Fig. 4. The improvements included enclosing the transport line and flushing with dry nitrogen, and replacement of the fused silica radiation port vacuum window with a z-cut quartz window.

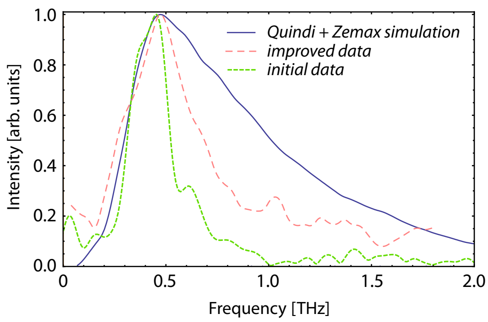

Figure 4: Measurements of the chicane radiation spectrum before and after transport line improvements were made, compared to start-to-end simulations. The simulated spectrum is broader due to the fact that QUINDI does not model self-fields, which increase the energy spread and result in a longer bunch and thus a broader spectrum.

Polarization

A linear polarizer measurement is an effective way of distinguishing between SR, which is linearly polarized, and ER, which is nearly radially polarized. The chicane radiation polarization was measured with a wire-grid linear polarizer (tungsten wire, wire diameter 10 μm, spacing 30 μm) by rotating the polarizer and measuring the transmitted intensity with the bolometer. The result is shown in Fig. 5, along with QUINDI simulations of the chicane radiation and single magnet CER and CSR. The measurement indicates that the CER has been suppressed due to interference, hence the collected radiation is mostly CSR.

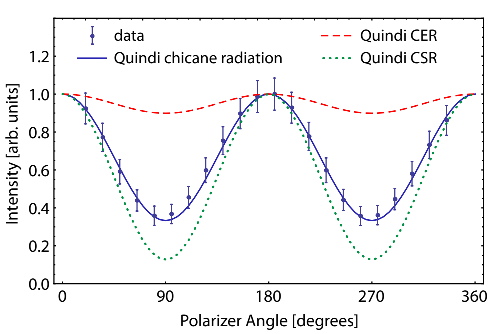

Figure 5: Chicane radiation polarization from measurement and QUINDI simulation; also shown are QUINDI simulations of single magnet CER and CSR.

CONCLUSION/OUTLOOK

The spectrum and polarization of the coherent terahertz radiation emitted by sub-200 fs electron bunches traversing the region of the downstream edge of the 3rd and the upstream edge of the 4th dipole magnets in a chicane was simulated and measured. Simulations agree with measurements and show that the edge radiation from two magnet edges of opposite sign interferes destructively for wavelengths long compared to L/γ^2. Experiments involving single magnet terahertz CER are currently underway at the Neptune beamline at UCLA.

The experimental setup proved to be useful as a non-invasive, single-shot, relative bunch length monitor to optimize chicane compression; however the radiation is thought to be the main source of longitudinal phase space distortions during compression, leading to fragmentation of the energy spectrum and current profile. The inclusion of self-fields to QUINDI is planned so that a complete study of longitudinal phase space distortions in the chicane can be performed.

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