Coherent THz Radiation Sources at the NSLS

G.L. Carr,¹ W.S. Graves,¹ E.D. Johnson,¹ R.P.S.M. Lobo,² L. Mihaly,³ J.B. Murphy,¹ B. Sheehy,¹ D. Talbayev³ and D.B. Tanner².

¹ National Synchrotron Light Source, Brookhaven National Laboratory
² Physics Dep’t - University of Florida
³ Physics Dep’t - Stony Brook University

email: carr@bnl.gov
Coherent synchrotron radiation is produced when relativistic electron bunches, having longitudinal density variations on a scale comparable to or smaller than the wavelength, are accelerated.

The intensity per spectral interval for a multiparticle system is:

\[
\frac{dI}{d\omega_{\text{multiparticle}}} = \left[N + N(N-1)f(\omega)\right] \frac{dI}{d\omega_{\text{one particle}}}
\]

where \( f(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega \hat{n} \cdot \hat{z} / c} S(z) \, dz \right|^2 \); \( S(z) \) being the longitudinal charge density.

\[ \Rightarrow \text{Coherent intensity enhancement } I \sim N^2 \text{ when } f(\omega) \neq 0. \]

Short bunches radiate coherently for \( \lambda > \sigma_L \), the bunch length.

\( dI/d\omega \) is also large since \( \text{Power} = \frac{2e^2a^2}{3c^3} \gamma^4 \) and \( \gamma \) is \( \sim 10 \) or more.
Sustaining very short (< 1 cm) electron bunches in a synchrotron storage ring is difficult, due to radiation damping. Coherent synchrotron radiation at such long wavelengths is not propagated by the storage ring’s metal vacuum chamber.

Linear accelerators do not “store” electrons, so short bunches can be created and maintained through the accelerator.

In analogy to the chirped pulse compression methods employed with pulses of light, electron bunches can also be compressed by inducing an energy “chirp” across the length of a long bunch, and then using the dispersion of dipole magnets to compress the bunch.

At the NSLS Source Development Lab (SDL) linac, overall bunch lengths (RMS) can be varied from 5 ps down to below 400 fs.
• Photocathode electron gun, \(~ 1\text{nC charge (nearly } 10^{10} \text{ electrons, large } N\).\

• 200 MeV S-band linac. Four linac sections, first two provide variable energy “chirp” on electron bunch.

• Bunch compression in dipole chicane between 2nd and 3rd linac sections.

• Coherent synchrotron emission as transition radiation (or from dipole).
- Intensity $\sim N^2$ is a signature of coherent emission.

- Problem: bunch shape (and spectral distribution) changes with Q. Broadband detector does not differentiate.

- Solution: Restrict detected spectral range to wavelengths of 5 mm and longer ($\lambda \gg$ bunch length for all conditions).

- Quadratic dependence confirms coherent character.
Polarizing-type (Martin-Pupplett) Michelson interferometer with f/2 optics, high-spectral resolution.

Lamellar grating interferometer with f/1.6 optics, lightpipe coupling.
Coherent THz pulses produced by SDL linac, measured with calibrated pyroelectric energy detector, are comparable to largest produced by non-accelerator methods.

~ 1 µJ Energy per Pulse (!)
Coherent THz spectral output can be used as a diagnostic of electron bunch density.

Under certain conditions, a bunch density modulation having a period of about ~ 50µm (150 fs) can be produced. This density modulation appears as additional structure around $\lambda = 50$ µm in the coherent emission.
Electron bunches in storage ring are normally not short enough to produce useful CSR. What controls bunch length in a synchrotron storage ring?

- RF accelerating cavity restores energy and bunches the beam.
- Emission of synchrotron radiation “damps” the beam, leading to an energy spread. Dispersion of ring converts energy spread into longitudinal spread.
- Electrons within bunch interact through charge, wakefield, perturbation on RF cavity fields, etc.

Solution?

- Increase $V_{RF}$ in cavity, lower ring energy (reduces emitted photons and lowers energy spread), reduce dispersion, spread out charge into more (smaller) bunches. But instabilities can (do) arise (e.g., bursting behavior).
- BESSY II has achieved stable CSR, but only for extremely low (< 40 µa) current. Estimate <3 ps duration bunches.
- NSLS - VUV ring can produce large coherent “bursts”. Can stable operation be achieved?
Bursts of CSR from NSLS VUV Ring

Coherent emission bursts observed when beam current exceeds stability threshold.

Coherent far-infrared emission observed SDL linac. Quadratic dependence on number of particles confirms coherent process.

Spectral content from interferometer is consistent with other measurements of the longitudinal bunch density.

Coherent intensity is HIGH. Single, sub-ps pulses with 1 µJ content measured.

Potential source for:

- Coherent THz spectroscopy, imaging.
- Non-linear spectroscopy.
- Pump-probe (including THz pump).

Special thanks to the NSLS/SDL staff without whose dedicated efforts this work would not have been completed: P. Marino, G. Nintzel, B. Singh, S. Pjerov, C. Stelmach