Analysis of coherent terahertz synchrotron radiation with a superconducting hot electron bolometer

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Outline

- Coherent synchrotron radiation at THz frequencies
- Superconducting hot electron bolometer (HEB)
- Single pulse detection with HEB
- Outlook
BESSY II

Revolution:
- 1.25 MHz, 0.8 µs, 240 m
- InSb hot electron bolometer ($\tau \approx 1$ µs)

Bunch separation:
- max. 400 bunches
- 500 MHz, 2 ns, 60 cm
- superconducting hot electron bolometer

Bunch length
- $>35$ ps, $>5$ mm (normal user optics)
- $<7$ ps, $<1$ mm (low alpha optics)
- autocorrelation
Coherent THz Radiation from a Synchrotron

Dedicated machine mode: “low $\alpha$“ optics

- Bunch shortening down to and below the mm-range
- Emission in the THz range is drastically enhanced

\[ P = N P_1 (1 + N f_{\lambda}) \]

$P_1$: power from a single electron

$N$: number of electrons

$f_{\lambda} = \exp[-(2\pi\sigma/\lambda)^2]$ (form factor)

$\sigma$: rms bunch length
Synchrotron Spectrum

N-times higher intensity (Gaussian bunch assumed)

Cut-off due to shielding effects

Powerful source emitting in the THz and sub-THz range

"THz gap"
Incoherent vs. Coherent SR

- Intensity extends to higher wavenumbers than expected for Gaussian bunch shape.
- Power increase of up to 100000 compared to the incoherent SR.

Applications of CSR

U. Schade et al., APL 84, 1422 (2004)

E.J. Singley et al., PRB 69, 092512 (2004)

H.-W. Hübers et al., SPIE 6275, 627505 (2006)

FIG. 1 (color online). Calculated equilibrium longitudinal distribution for different currents per bunch using the shielded SR wake. BESSY II case with a natural bunch length of 2.5 ps.

FIG. 2 (color online). CSR gain as a function of the wave number $1/\lambda$. The BESSY II data for two different currents per bunch are compared with the shielded SR calculation and with the curve for a Gaussian distribution of the same length.

F. Sannibale et al., PRL 93, 094801 (2004)
Bolometer

Heat transfer:
\[ C \frac{dT}{dt} = P(t) - G (T - T_0) \]
C: heat capacity
G: heat conductivity

Temperature modulation:
\[ \Delta T = \frac{\Delta P}{G \sqrt{1 + \omega^2 (C/G)^2}} \]

Responsivity:
\[ R(\omega) = \frac{\Delta V}{\Delta P} \propto \frac{1}{G \sqrt{1 + \omega^2 (C/G)^2}} \]

\[ \omega << 1/\tau : \quad R(\omega) \propto \frac{1}{G} \]

\[ \omega >> 1/\tau : \quad R(\omega) \propto \frac{1}{\omega C} \]

\( \tau = C/G \) : bolometer time constant

Absorber, C
Thermal coupling, G
Bolometer
Signal
P = P_0 + \Delta P \cos(\omega t)
External circuit
Thermistor
Heat sink
Superconducting Nanobridge

Radiation, dc & IF

Diffusion cooling

Phonon cooling

Dimensions:
L: 0.2 - 1.0 µm
w: 1 - 4 µm
d: 3.5 nm
Superconducting Hot-Electron Bolometer

- **Superconducting state**
- **Normal state**
- **Resistive transition region**
- **Operation point**

Graph showing resistance and temperature with current and voltage as parameters.
Response Time

Time constants:

\[ \tau \approx \tau_{e-ph} + \frac{c_{ph}}{c_e} \tau_{esc} \]
\[ \tau_{e-ph} \approx 10 \text{ ps for NbN (} T_c = 9 \text{ K)} \]
\[ \tau_{esc} = \frac{4d}{\alpha u} \approx 38 \text{ ps (} d = 3.5 \text{ nm)} \]

Fast device:
- material with small \( \tau_{e-ph} \), large \( u \)
- thin films, small \( d \)
- large phonon transmissivity \( \alpha \)

Velocity of domain walls controls the bandwidth.
Measurements of time constants

- electro-optic sampling
- $\lambda = 386$ nm
- analysis with 2T model

FIG. 1. Experimental (dots) and simulated (solid, dotted, and dotted–dashed lines) responses of a 3.5-nm-thick NbN HEP to a 100 fs excitation pulse. The main plot time resolution is 25 ps; the time-resolved rising part of the signal is shown in inset. Ambient temperature was 2.15 K.

FIG. 2. Time-resolved experimental (solid line) and simulated (dotted and dotted–dashed lines) responses of a 3.5-nm-thick NbN HEP to a 100 fs excitation pulse. Ambient temperature was 10.5 K.

Design

- NbN film: 3.5 nm thick (dc reactive magnetron sputtering)
- Transition temperature: 9 K, width: ≈ 0.5 K
- Si substrate: > 10 kΩ cm
- Two arm log-spiral antenna terminated by 50 Ω coplanar line

6 or 12 mm diameter extended hemispherical Si lens with Parylene AR coating.
Antenna Pattern

A. Semenov et al., accepted IEEE MTT 2006
Antenna Pattern

- Rel. Gain [dB]
- Angle [deg]
- FWHM [degrees]
- Wavelength [µm]

- 2.5 THz
- 4.3 THz

- 6 mm lens
- 12 mm lens
Spectral Response

![Graph showing spectral response for Twin-Slot and Log-Spiral antennas.](image)

- **Frequency [THz]**
- **Gain [rel. units]**
- **Wavelength [µm]**

- **Twin-Slot**
- **Log-Spiral**
Spectroscopy: Experimental Setup

- Dipole radiation from dipole 2.2
- NIR to FIR
- 60(h) x 40(v) mrad² acceptance
Experimental Setup

- about 9 m from source point to detector
- Bias-T: 0.1 - 18 GHz
- Amplifier: 0.1 - 12 GHz
- Sampling oscilloscope: 50 GHz
**Measurement with InSb Detector**

**Blade Signal (μA)**

- **τ_{rise} ≈ 200 ns, τ_{decay} ≈ 400 ns**

**InSb Detector Signal (mV)**

- **σ_{rms} < 1 mm**

**Single bunch CSR intensity and threshold at 1.25 MHz**

- **f_s = 2.15 kHz**
- **f_s = 5 kHz**
- **f_s = 3 kHz**
- **f_s = 7.2 kHz**

**Fill pattern:**
- 100 buckets filled (200 ns)
- 300 buckets empty (600 ns)

Beam Filling

- THz Signal
- X-Ray Signal

Bursting threshold

$\propto I^2$

Single Pulses Detected with a Superconducting HEB

BESSY II: tune 2.3 KHz, 9.2 mA
HEB: 8.0 K, 2.1 mV, 164.1 µA
**Single Pulse: Rise Time**

Measurement:
\[ \tau_{\text{rise}} \approx 50 \text{ ps} \]

Detector:
\[ \tau_{\text{e-ph}} \approx 10 \text{ ps} \]
\[ \tau_{\text{esc}} \approx 38 \text{ ps} \]
\[ \tau_{\text{electr}} \approx 35 \text{ ps} \]

Electron bunch:
\[ \tau_{\text{FWHW}} \approx 10 \text{ ps} \]
Single Pulse

Intensity vs. time: \( I(t) = I_0 R^N \)

Number of reflections: \( N = \frac{(L/D)}{\tan \phi} \)

\( \phi = \arccos \left( \frac{L}{(L+ct)} \right) \)

\( R = 0.9, D = 170\text{mm}, L = 9.1\text{m} \)

Stable and Bursting Pulses

\[ \alpha = 5.7 \times 10^{-5}, I_B = 80 \, \mu A \]

\[ \alpha = 4.4 \times 10^{-5}, I_B = 280 \, \mu A \]

\[ \alpha = 10.4 \times 10^{-5}, I_B = 260 \, \mu A \]
Interferograms measured with different detectors

- HEB
  - low $\alpha$ ($4 \times 10^{-5}$)
  - 40 mA

- Ge:Cu (10-30 $\mu$m)
  - low $\alpha$ ($4 \times 10^{-5}$)
  - 40 mA

- Ge:Ga
  - low $\alpha$ ($4 \times 10^{-5}$)
  - 40 mA
Spectrum of stable CSR

![Graph]

- Antenna cut-off
- CSR roll-off

Signal [a.u.]

Wavenumber [cm$^{-1}$]

Mirror displacement [cm]
Spectrum of CSR in bursting mode

- Antenna
- Atmosphere (H₂O)
- Decrease of CSR

**HEB**
- low $\alpha$ ($4 \times 10^{-5}$)
- 40 mA

**InSb**

**Signal [a.u.]**

**Wavenumber [cm⁻¹]**
1) Synchronization of UV/Vis and THz radiation

Array of HEBs with resonant antennas

2) Single pulse spectroscopy

Gain [rel. units]

Wavelength [µm]
3) Faster detector with YBCO

Fast non-bolometric response (<2 ps) but slow bolometric response (>2 ns).

4) Faster detector with electrothermal feedback

Constant voltage bias:

\[ T \xrightarrow{\uparrow} R \xrightarrow{\downarrow} P_{\text{BIAS}} \xrightarrow{\uparrow} T \xrightarrow{\downarrow} \]

\[ \tau_{\text{eff}} = \frac{\tau_0}{1 + \alpha T/n} \]

~10 times faster, but fast bias required

M. Lindgren et al., APL 74, 853 (1999)
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M. Abo-Bakr, J. Feikes, K. Holldack, U. Schade, G. Wüstefeld
Impurity ionization
- highest sensitivity: lightly compensated p-Ge
  \( N_D \approx 10^{12} - 10^{13}\text{cm}^{-3} \)
- large bandwidth: compensation required
  (life time \( \propto N_C^{-1} \))

Material
- Ge:Cu       cut-off @ 30 \( \mu \text{m} \)
- Ge:Be       cut-off @ 52 \( \mu \text{m} \)
- Ge:Ga       cut-off @ 115 \( \mu \text{m} \)
- stressed Ge:Ga  cut-off @ 210 \( \mu \text{m} \)
InSb-Detector: Basics

Detection mechanism:
Absorption of radiation by free electrons

Response time: \( \approx 200 \) nsec \( (\approx 1.5 \) MHz\)

\[ \alpha \propto \left(1+\omega^2 \tau_e^2\right)^{-1} \]
Photoionization Spectroscopy

- Identification of impurity atoms
- Determination of energies
- Determination of detector responsivity