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FAR-IR/THz RADIATION FROM THE JEFFERSON LAB FEL ENERGY RECOVERED LINAC

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The Free Electron Laser at Jefferson Lab is the first of a new generation of light sources based on a photo-injected energy recovered linac. The present machine has a 40 MeV electron beam and an average current of 5 mA. The electron bunches are extremely short with FWHM values that are in the few hundred femtosecond regime. These electron bunches pass a chicane around the optical cavity, and therefore emit synchrotron radiation. In the far-IR region, the wavelength of the light being emitted, approaches that of the electron bunch length, giving rise to multiparticle coherent enhancement. The result is a broadband spectrum whose average brightness is more than 5 orders of magnitude higher than can be obtained from conventional incoherent synchrotron IR sources. We will discuss preliminary measurements of this radiation, and applications to spectroscopy and imaging.

1. Introduction

The infrared spectral region from 1cm to 1 micron wavelength covers an energy range that includes superconductivity band gaps, semiconductor band gaps, and intramolecular vibrational energies. In this region there is a need for very bright sources, because conventional thermal infrared sources are not bright enough to yield good signal to noise spectra, nor powerful enough to drive new phenomena.

During the past decade infrared synchrotron radiation has served the community well in providing about a microwatt/cm^{-1} into a diffraction limited area×angle product ($\sim\lambda^2$) compared with the nanowatt/cm^{-1} which is typically provided by thermal sources (globars). In the far-IR beyond 100 micrometers, synchrotron radiation is superior not just in brightness, but in terms of total power as well. However, there is always a need for brighter sources for both linear and non-linear spectroscopy. In this paper we calculate the infrared brightness emitted by a new accelerator [1] with extremely short (sub-picosecond) pulses. In this situation the electron bunch length is shorter than the wavelength of synchrotron light over much of the far-IR region, resulting in a multiparticle coherent enhancement [2] of the synchrotron radiation. In this case the brightness is given not by the beam current, or number of particles in a bunch, but by this quantity squared. Since there are 10^8 particles per bunch in the Jefferson Lab accelerator, the enhancement is 8 orders of magnitude over the conventional incoherent synchrotron radiation for average brightness or power. This advantage is somewhat reduced by the fact that the Jefferson Lab machine has an average current of only 5mA, which is 2 orders of magnitude smaller than typical storage rings, making the advantage 6 orders of magnitude over existing facilities. However, the peak brightness is additionally enhanced at Jefferson Lab compared with electron storage rings by 2-3 more orders of magnitude due to the shorter bunch length.

2. Theoretical

We first specify the parameters used in the calculations. Specifically, we calculate the spectral output from a dipole magnet in the energy recovery system of the Jefferson Laboratory Free Electron Laser1 (FEL) in the 1 – 10,000 cm-1 (1 micron to 1cm) range. We assume some typical parameters for the machine, namely that we have 100 pico-coulomb electron bunches at a 37.4 MHz repetition rate. We also assume that the electron beam has full width half maximum (fwhm) horizontal and vertical beam sizes of 200 microns. We take the electron beam energy to be 40 MeV, the bending radius to be 1m, and we assume that we extract 90 × 90 milliradians of light (approximately an f /11 beam).

The power emitted by an electron bunch as a function of frequency (ω) and solid angle (Ω), is derived by extending the classical electrodynamics [3] theory for a single electron, to a system of N electrons thus:

$$\frac{d^2 I}{d\omega d\Omega} = \left[N[1-f(\omega)] + N^2 f(\omega)\right] \times \underbrace{\frac{e^2\omega^2}{4p^2c}\left(\int_{-\infty}^{\infty} \hat{n}\times\left(\vec{\beta}\times\hat{n}\right)e^{i\omega\left(t-\frac{\hat{n}\cdot\vec{r}(t)}{c}\right)}dt\right)^2}_{\zeta} \quad [1]$$

where e is the charge on an electron, β is the ratio of the velocity of the particle bunch to the velocity of light, n is a unit vector, r(t) is the position of the center of the electron bunch, and N is the number of particles in the bunch. f(ω) is the longitudinal particle distribution within the bunch, which is assumed to be Gaussian, and thus of the form:

$$f(\omega) = e^{-\frac{4\pi^2\sigma^2}{\lambda^2}} \quad [2]$$

Where ω is the frequency of the light at wavelength λ and we have written the expression in this form to show how the enhancement is proportional to the wavelength. There are practical ways to solve this. Kim [4] has shown that the term ζ of Eq. 1 can be written in practical units to give the time-averaged photon flux, F, as:

$$F_v(\theta_v) = 1.325\times10^{16} E^2 \left(\frac{\lambda_c}{\lambda}\right)^2 \left(\left(\left(1+\gamma^2\theta_v^2\right)K_{\frac{2}{3}}(\xi)\right)^2 + \gamma^2\theta_v^2\left(1+\gamma^2\theta_v^2\right)K_{\frac{1}{3}}^2(\xi)\right) \quad [3]$$

in units of photons/sec/mrad.(horiz)/mrad.(vert)/amp/0.1%bw. In the above equation, γ is the ratio of the electron mass to the rest mass, which in practical units is given by:

$$\gamma = 1957 \times E(GeV) \quad [4]$$

λ_c is the critical wavelength which divides the output power in half and is given in practical units by:

$$\lambda_c(Angstroms) = \frac{5.59\rho(meters)}{E^3(GeV)} \qquad [5]$$

while the K terms are modified Bessel functions of fractional order, whose argument, ξ, is given by:

$$\xi = \left(\frac{\lambda_c}{2\lambda}\right)\left(1+\gamma^2\vartheta_v^2\right)^{\frac{3}{2}} \qquad [6]$$

The first term, in $K_{2/3}$, on the right represents light polarized parallel to the orbit plane (or horizontally polarized), while the second term involving $K_{1/3}$ corresponds to light polarized perpendicular to the orbit plane, (or vertically polarized). Clearly, we require the integral of $F_v(\theta_v)$ over θ_v in Eq. 3. Note that the expression is symmetrical about $\theta_v = 0$.

The limits of the integration are set by the smallest of the physical opening angle of the extraction optics, or the "natural opening angle" θ_{nat}, of the synchrotron radiation, whose full width half-maximum value can be approximated in the infrared spectral region [5] by:

$$\theta_{nat}(mrads) = 1.66\left(\frac{1000\times\lambda(\mu m)}{\rho(meters)}\right)^{\frac{1}{3}} \qquad [7]$$

Kostroun [6] has shown that the spherical Bessel functions $K_x(y)$, of fractional order x, can be readily evaluated using the following algorithm:

$$K_x(y) = 0.5\left(\frac{e^{-y}}{2} + \sum_{r=1}^{\infty} e^{-y\cosh(0.5r)}\cosh(0.5xr)\right) \qquad [8]$$

Power and Brightness Calculations

In Fig. 1 we present the results of this calculation in units of (average) watts/cm-1 over the range 1-10,000 cm^{-1}, or 1 centimeter to 1 micrometer. In the same figure we compare a 2000K thermal source and a synchrotron radiation source. The superiority of the JLab FEL in the THz range is clear.

Having calculated the total flux emitted into the optical beamline as a function of wavelength, we now address the brightness, which is defined as the flux per unit source area per unit solid opening angle. This is the quantity that is conserved by any optical system and which ultimately limits the performance of any experimental system.

In practical terms, we assume that the brightness is the flux divided by the opening angle θ, and the area of the source. The angle is the smaller of the natural opening angle, θ_{nat}, or the physical angle defined by the extraction optics. The area of the source is determined practically by summing in quadrature the physical size of the electron bunch and the size determined by diffraction which is set equal to λ/θ.

In Fig.2 we present the result of these calculations, again for average brightness not peak, and comparing the JLab FEL with both a thermal source and with the synchrotron radiation source at Brookhaven National Laboratory. Once again the superiority in the THz region is clear. It is also interesting to observe that the synchrotron radiation source is superior to the thermal source in brightness across the entire spectrum.

For completeness, in Fig. 3, we plot the peak brightness of the JLab FEL compared with the other 2 sources. For the NSLS we assume that the pulses are 1 nanosecond long and occur each 20 nanoseconds, so the multiplication factor for the data in Fig. 2 is 20. For the JLab FEL the pulses are 1 picosecond long and occur every 30 nanoseconds, so the factor is 30,000. This plot hints at an exciting new potential for this source, namely exciting non-linear phenomena.

Motivated by these calculations we installed a diamond window to extract dipole radiation immediately prior to the laser chicane. We then made preliminary measurements using a rapid-scan Nicolet Impact spectrometer with a Si beamsplitter and a pyro-electric detector. Using an Eltec 420M3 5mm diameter lithium-tantalate detector with no window or filter, set up in voltage mode and yielding 500 volts/Watt, we obtained the data shown in Fig. 4. While not yet quantitative, the data clearly demonstrates the multiparticle coherent enhancement. For comparison we also show the theoretical output expected for a 400 fsec fwhm Gaussian electron bunch. Note that the low frequencies are attenuated by the collection geometry and beamsplitter efficiency, and the structure is likely due to rotational bands of water vapor.

Conclusions

We have shown that the short bunches in the new generation of sub picosecond energy recovery systems yield broadband high brightness far-IR radiation with about 1 watt/cm^{-1} of power into the diffraction limit. The JLab machine is the first of a new generation of such machines, and already this accelerator is being upgraded to double this current. Eventually such machines may yield average currents of 100 mA, making them highly competitive with storage rings. However, one caveat remains, this being the question of stability. The beam positional stability is superior to storage rings by design – it is necessary for lasing to occur, but the pulse-to-pulse variations in the beam current may give rise to source fluctuations that swamp any measurements. Since energy recovery linac light sources are being considered for x-ray applications, it is important to measure the IR light as an indicator.

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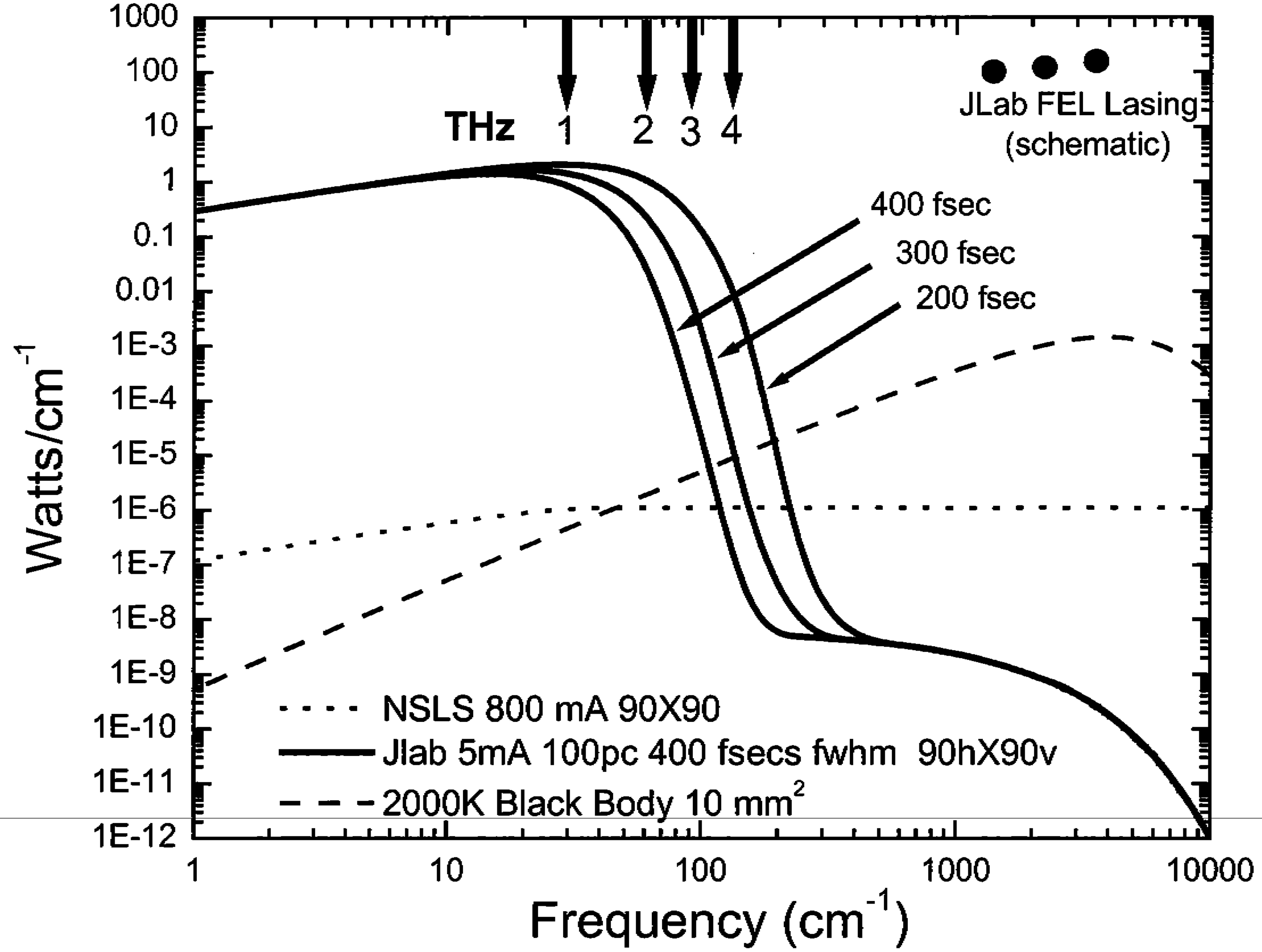
Figure Captions

Fig. 1. Total (average) power emitted by the JLab FEL for 3 electron bunch lengths, compared with the National Synchrotron Light Source, Brookhaven and a 2000K thermal source. Note that this is the time-averaged power, the peak power being $\sim 10^2$ times higher for the NSLS and $\sim 10^5$ times higher for the JLab FEL.

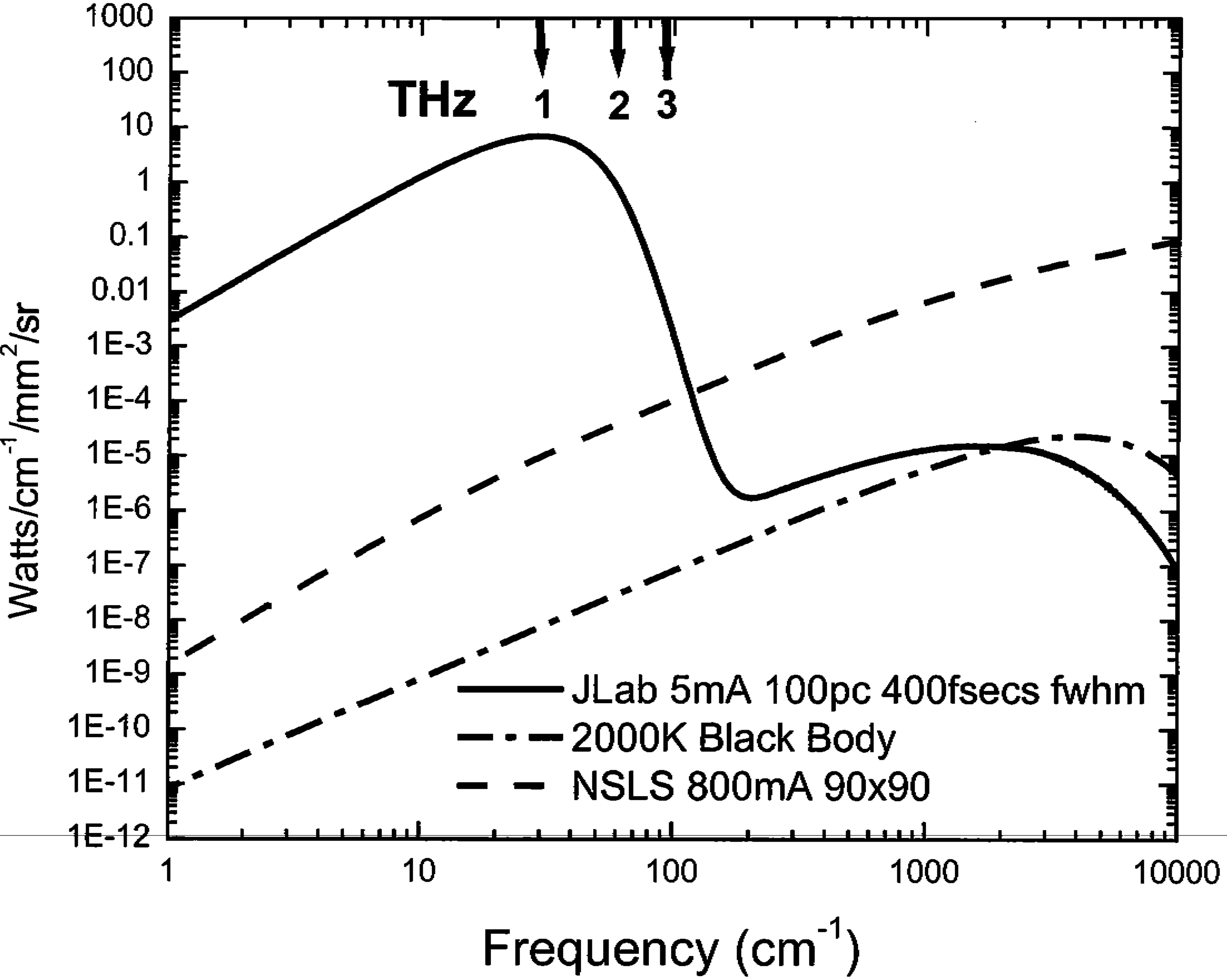
Fig. 2. The average brightness calculated for the JLab FEL, and compared with a 2000K black body and the synchrotron radiation source at Brookhaven National Laboratory.

Fig. 3. The peak brightness calculated for the JLab FEL, and compared with a 2000K black body and the synchrotron radiation source at Brookhaven National Laboratory.

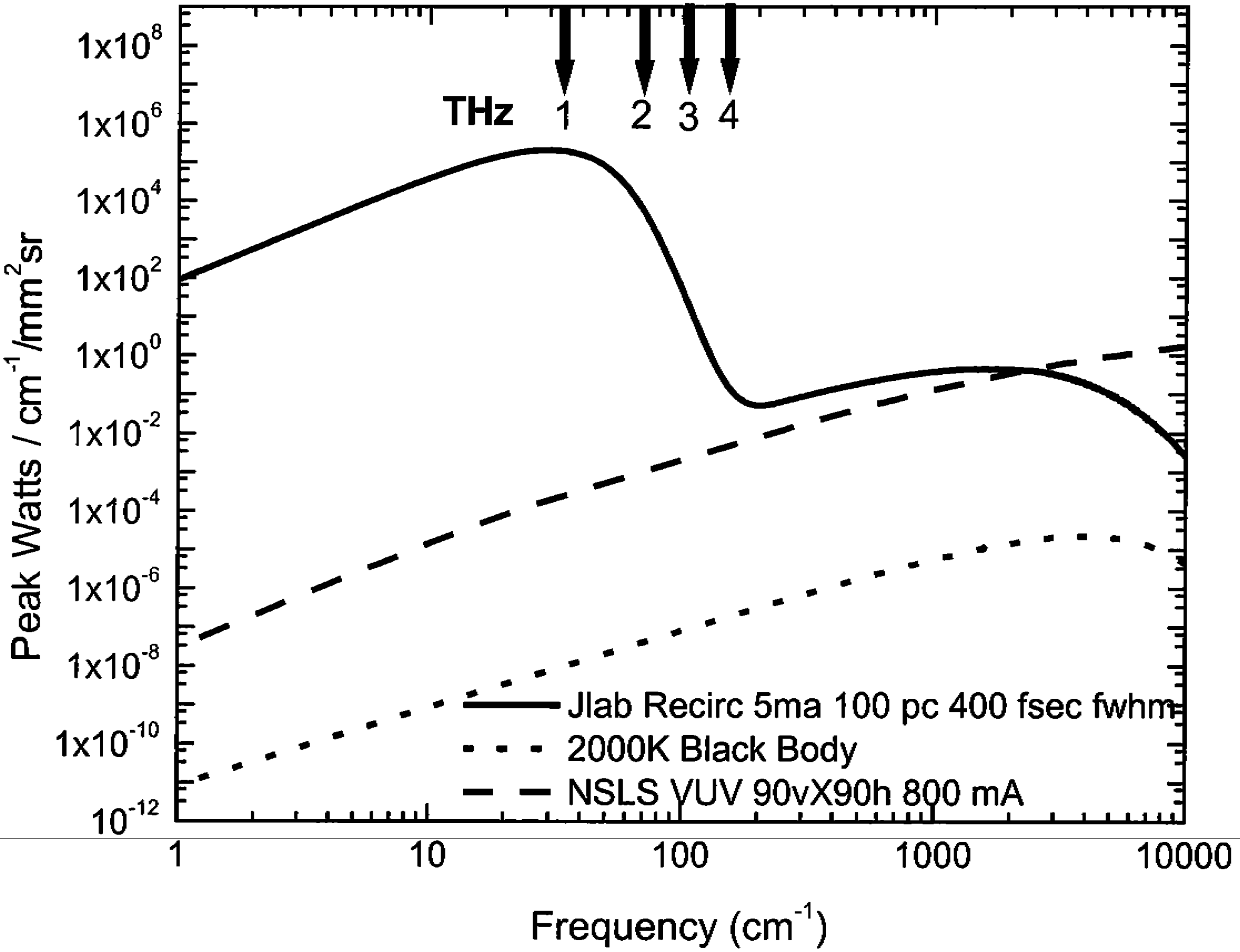
Fig. 4. The first data taken in the THz spectral region showing the multiparticle coherent enhancement. The data have not been quantified.



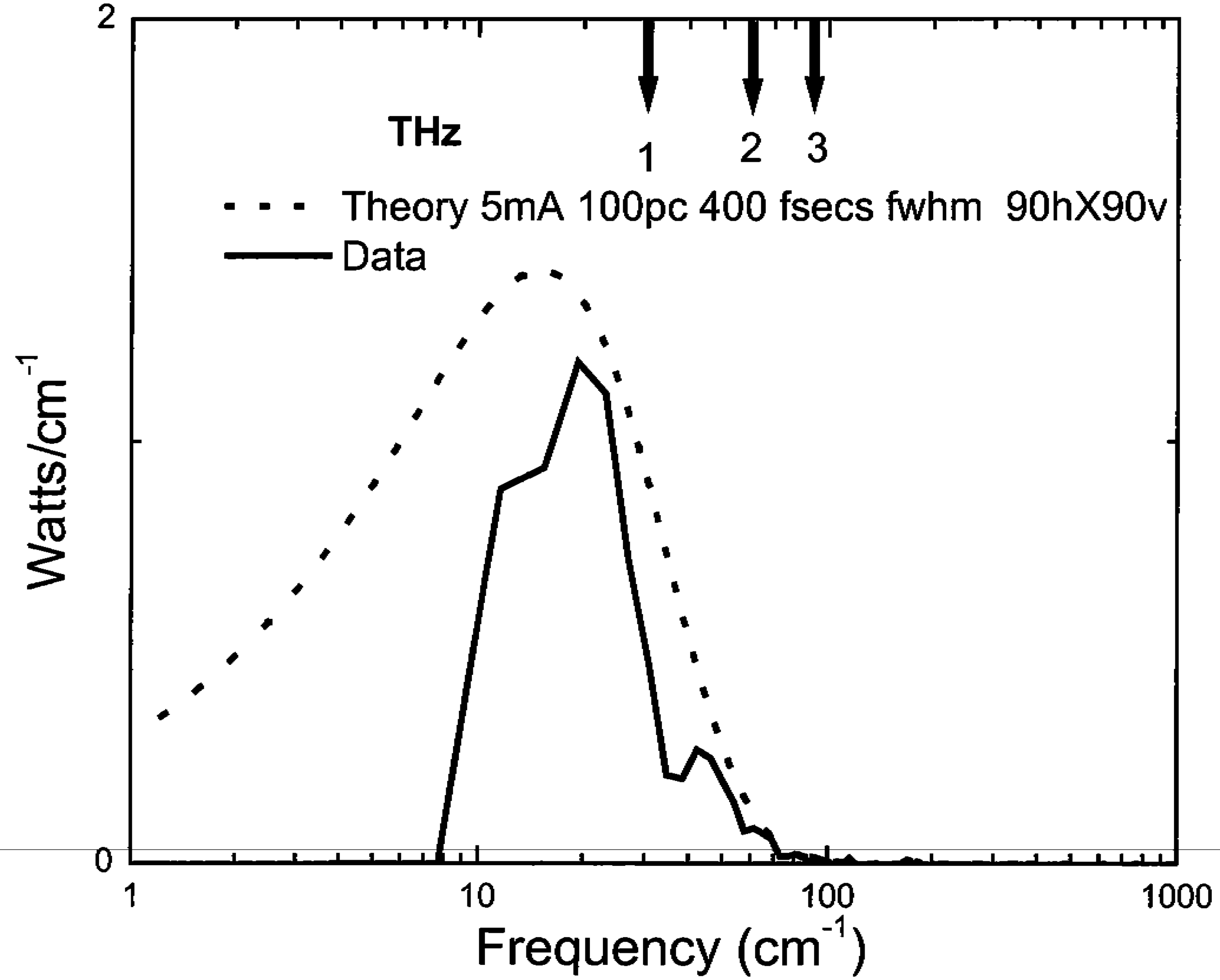
Williams Fig. 1



Williams Fig. 2



Williams Fig. 3



Williams Fig. 4