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POTENTIAL APPLICATION OF THE LOS ALAMOS FREE-ELECTRON LASER: HIGH-TEMPERATURE SUPERCONDUCTORS

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ABSTRACT

An improved understanding of High-Temperature Superconductors (HTSC's) should result from the direct investigation of the energy gap associated with the superconducting state. An adaptation of the classic transmission experiments using a broadly tunable Free-Electron Laser (FEL) to irradiate the HTSC single crystals or thin films as a function of photon energy and sample temperature is described. In particular, the Los Alamos FEL has a projected tuning range of 9-160 μ m (140-8 meV). In addition, its 10 to 20-ps micropulse structure, linear polarization, coherence, monochromaticity, focusability and peak power features should make it a unique research tool for probing HTSC's with critical temperature (T_c) from $\sim$ -30 to $\sim$ 400 K (depending on the energy gaps involved).

1. INTRODUCTION

Realizing the tremendous potential for the development and application of the new High Temperature Superconductors (HTSC's) requires an improved understanding of the fundamental mechanisms that are involved in these unusual mixed oxide materials [1,2]. One of the most significant questions involves the nature of the energy gap that evidently develops as the sample temperature is reduced below the critical temperature (T_c). Characterization of the magnitude of this gap and its behavior under a variety of parameter changes could be a key to developing these materials further.

It is proposed that this issue can be investigated by the adaptation of the classic microwave transmission experiments on low temperature superconductors of Biondi and Gartunkel [3]. However, in this case, one would use a pulsed, tunable, monochromatic, coherent, and linearly polarized source of mid infrared (MIR) and far infrared (FIR) radiation, i.e., the Los Alamos Free Electron Laser (FEL). A projected extension of its previously demonstrated tuning range of 9.3 μ m to 9.160 μ m [4] would allow the scanning of any HTSC gaps whose magnitudes are from 8-140 meV. This range spans the present theoretical estimates [5,6] and/or preliminary reported measurements in materials with T_c 's from about 30-400 K.

II. EXPERIMENTAL CONSIDERATIONS

A. Free-Electron Laser Properties

The Los Alamos FEL is an RF-Linac driven oscillator that has been operated nominally at about $10.6\mu\text{m}$ since 1983 [7,8]. The optical pulse format is dictated by the e-beam pulse structure that consists of a $100\text{-}\mu\text{s}$ long macropulse involving about 2000 micropulses of 10 to 20-ps duration separated by 46 ns.

The FEL's operation is schematically represented in Fig. 1 of Ref. [8], and the actual beamline is shown here in Fig. 1. An rf-linac generates the 21-MeV relativistic electron beam with pulse format as above. A 60-degree achromatic triplet aligns the e-beam on the oscillator axis. The beam is then transported through the permanent magnetic wiggler which is composed of a linear array of SmCo_5 magnets with an alternating magnetic pole arrangement. This provides a static magnetic field (directed up and down along the length) of the wiggler) for the e-beam that produces small transverse oscillations in the e-beam trajectory as it traverses the wiggler. As a result spontaneous radiation is emitted by the electrons which then transits the resonator cavity in the same time interval ($\sim 16\text{ns}$) that the next e-beam micropulse enters the wiggler region. Subsequent superpositions of optical micropulses provide sufficient fields for stimulated emission to occur after which the optical power grows by about nine orders of magnitude (peak intracavity power ~ 1000 MW) in several microseconds.

The resonance condition in the oscillator for the generated laser wavelength (λ_L) with relativistic effects included is approximately:

$$\lambda_L = \frac{\lambda_w}{2\gamma^2} \left(1 + \frac{1}{2}(A_w)^2 \right)^{-1}, \quad (1)$$

where λ_w is the wiggler period, γ is the e-beam Lorentz factor, and A_w is the wiggler field parameter. This relationship shows that the wavelength can be tuned by varying λ_w , A_w , or γ^2 . We have basically fixed λ_w and A_w and used the $\frac{1}{\gamma^2}$ dependence. Using the nominal values of $\gamma = 12$, $\lambda_w = 2.73$ cm (fixed), and $A_w = 0.76$ one obtains $\lambda_L = 10.4\mu\text{m}$. From this set of conditions, one can project the tuning range of this FEL to $\sim 160\mu\text{m}$ based on our recorded transport of beam energies as low as 5 MeV to the electron spectrometer positioned after the wiggler in our beamline. One expects to be able to transport even lower energy beams as discussed below. Of course, appropriate windows and mirrors are needed for the oscillator cavity.

Figure 2 shows a reproduction of the tuning done previously (from Ref. 7) with ZnSe windows and copper mirrors and using a 1.8 mm diam axial hole to couple out the radiation. In this earlier case the tuning was from $9\text{--}35\mu\text{m}$, and the evidence for lasing beyond $16\mu\text{m}$ was in the observation of the second or third optical harmonics and the observed effects in the electron beam spectra. A more recent demonstration of tuning out to $45\mu\text{m}$ is described in Ref. 4. The extended range of Fig. 2 indicates the projected long-wavelength tuning based on only running accelerator A at lower energies with accelerator B turned off. Alternatively, because our two accelerator tanks are driven by independent klystrons and rf amplifiers, we can easily change the rf phase of accelerator B vs accelerator A (see Fig. 1). Operations would be extended by having B run in a decelerating mode (180° out of phase) so that even lower e-beam energies would result while still operating the accelerators at the field levels for which they were designed. Modifications to the electron beam transport system (beamline optics) might be needed to effectively operate for energies less than 6 MeV (which in principal might be as low as 1.2 MeV).

Table I summarizes the approximate wavelength regimes that could be addressed for various ranges of e-beam energy. This estimate is based only on our present wiggler parameters. The actual implementation of lasing on the fundamental at longer wavelengths may require increasing the gap between the magnet arrays (decreasing the effective field in the gap) to accommodate the larger optical modes or changing the wiggler period. As an example of the latter case, one could use every other magnet slot in the wiggler frame and double λ_w . It is noted that the first extension beyond the $9\text{--}35\mu\text{m}$ regime is not limited by e-beam transport since we have demonstrated the 6.3 MeV case. Case 3 could provide coverage of most HTSC's and Cases 4 and 5 might provide tests of low temperature superconductors (such as Nb compounds) with $T_c < 10\text{--}20\text{K}$. The long wavelength limit of the latter two cases is somewhat speculative without supporting simulations to see if major modifications to the resonator cavity, wiggler, or e-beam are needed.

B. Radiation Outcoupling and Infrared Detection

Although the radiation may be generated in the oscillator cavity, it still needs to be coupled outside the cavity. The windows at the ends of the oscillator cavity have been generally ZnSe whose transmission drops rapidly after about $20\mu\text{m}$. There is a straightforward change to Halide materials such as CsI and $\text{Te}(\text{Br},\text{I})$. These may allow reasonable transmission out to $70\mu\text{m}$

Ultimately an ideal broadband window appears to be diamond which transmits wavelengths out to $200\mu\text{m}$ and beyond. Appropriate anti-reflection coatings may be needed and this would mean limited bands for any one coating. The copper mirrors from the $9\text{-}35\mu\text{m}$ work with $1\text{-}2\text{ mm}$ diam axial holes for outcoupling should be directly applicable for the entire tuning range.

Our present infrared detector capability which is designed for the $9\text{-}11\mu\text{m}$ regime would have to be supplemented in some cases. The liquid-He cooled Hg:Ge photodetectors have very little sensitivity beyond $16\mu\text{m}$, while Zn:Ge photodetectors are useful to about $40\text{-}50\mu\text{m}$. We would anticipate that our pyroelectric devices would continue to provide useful data over the expected wavelength range at our power levels. The grating in the spectrometer would be changed to match the wavelength bands of interest.

III. SUPERCONDUCTIVITY AND THE PROPOSED INITIAL EXPERIMENTS

A. Background

The critical temperature for the low-temperature superconductor is generally a few degrees Kelvin and the gap associated with such states has been a few meV. Some early studies of such features were accomplished measuring the transmission of microwave [3] or very far infrared radiation through the samples [10]. The change in transmission was often characterized as a change in surface resistance to the radiation. Examples of surface resistance ratios for superconducting and normal states are given in Biondi and Garfunkel's work on aluminum [3]. They observed an abrupt increase in this parameter for photon frequencies corresponding to about $3.3\hbar\omega/kT_c$ (the gap factor for aluminum) at $T = T_c$. Isotherms of surface resistance also indicated a change in the effective gap as the sample temperature increased towards T_c . The gap magnitude and its temperature dependence was generally explained by standard Bardeen, Cooper, and Schrieffer (BCS) theory [11].

In the case of High Temperature Superconductors, their very existence is a challenge to the theorists. A number of models are being developed that do not rely on phonons mediating the pairing of electrons in the superconducting state. As one example, Bedall, et al., [6] have analyzed the Y-Ba-Cu-O case and provide an energy gap estimate of $E_g = 3.16\text{ kT}_c$. For $T_c = 95\text{ K}$ this implies a gap energy of about 26 meV. Table II shows a series of estimated gaps in energy, wavelength and wave number for several representative T_c 's. The estimated e-beam energy for the FEL in all cases seems quite attainable. Such tuning would allow a rather complete coverage of anticipated HTSC samples. Of particular interest is the region for T_c

100K since this may involve wavelengths that are readily attainable from the FEL (40-11 μ m).

B. Proposed Initial Experiments

It is proposed to probe the HTSC's by scanning in energy (wavelength) across the energy gap with the tunable FEL radiation. One would measure the variation of transmission and reflection by the thin HTSC sample as a function of laser wavelength, power, and sample temperature. Figure 3a shows a schematic of the initial experimental setup. The FEL source, sample, and detectors are indicated. One of the key issues will be to use irradiation powers that match the sample's thermal capability and the detector's sensitivities. The relatively high peak power FEL beam will be split to allow a sampling of beam properties (power, wavelength, spatial size, spatial alignment) for normalization information during a scan.

Transmission should remain relatively constant for photon energies less than the gap, and then decrease abruptly when the photon energies exceed the gap energy. As schematically illustrated in Fig. 3b the plot of transmission vs $h\omega/kT_c$ should indicate the gap factor (in BCS theory this is about 3_2^1). One should be able to directly measure this value of the gap factor for $T = T_c$. The variation of the parameter with temperature should provide useful data to HTSC modeling efforts. Alternative techniques that use a broadband source to irradiate the sample (Fourier Transform Spectrometer) and selectively evaluate transmitted radiation at a number of wavelengths may not be as sensitive to the gap parameter as the tuned monochromatic irradiation experiments. Also, the linear polarization of the laser probe might be useful in revealing anisotropic effects in single crystal samples [5]. In addition, reflection measurements at a few angles could provide sufficient information to determine the complex conductivity by taking advantage of the FEL's coherence, linear polarization, and monochromatic features [12].

A second phase of experiments could be implemented using the micropulse (10 to 20 ps duration) structure of the FEL. This is schematically illustrated in Fig. 4. If sufficient numbers of electrons are promoted across the gap to the normal conducting states in 10's of picoseconds, would the sample behave as a normal conductor to an rf current for a short time and then relax back to the superconducting state? The nature of this response would be particularly interesting in the context of switching the sample's state of conductivity.

IV. CONCLUSIONS

It appears that the Los Alamos FEL can be modified to provide a significant, new research tool for the investigation of HTSC samples. The proposed Mid Infrared Adjustable Coherent

Light Experiment (MIRACLE) Facility [4] should provide a probe of gap energies from about 8-140 meV which may include samples whose critical temperatures are from 30 K to room temperature, (depending on the gap factor). Sample preparation availability remains a key issue for the technique's widespread use, but a new physical measurement data base could result that is directly related to the pairing mechanisms involved. This information would complement the new material systems approach (HTSC without rare earths, as an example [13,14]). Details of the facility operation in the extended tuning mode and results of the planned, initial experiments will be reported at a later time as available.

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FIGURE CAPTIONS

Fig. 1 The beamline configuration for the Los Alamos FEL oscillator experiment. Either mirror could be used as the out-coupler of the infrared radiation.

Fig. 2 Continuous wavelength tuning range for the FEL as a function of e-beam energy. The region from 9-35 μm was demonstrated in Ref. 7. The extended range is based on the FEL resonance equations and probable low-energy e-beam transport. Reference 4 provides an update for the tuning capability to 45 μm .

Fig. 3 Figure 3a is a schematic representation of the simple transmission experiment for the FEL radiation through the HTSC sample. Reflected signals would also be monitored simultaneously. Figure 3b is a schematic representation of the transmission (surface resistance) of radiation as a function of $\hbar\omega/kT_c$. In this example the gap factor is about three.

Fig. 4 A schematic representation of the possible HTSC sample relaxation time effects. The laser micropulse probe has a full width at half maximum (FWHM) of 15 ps. The observed radiofrequency resistance may change when electrons are promoted to the normal state and then relax back to the superconducting state.

TABLE I

Potential broadband tuning ranges for the Los Alamos FEL and the electron beam energies required.

<u>Case No.</u>	<u>Wavelength (μm)</u>	<u>Photon Energy (meV)</u>	<u>Electron Beam Energy (MeV)</u>
1	9 - 35	138.0 - 35.4	23.0 $\rightarrow$ 11.5
2	9 - 70	138.0 - 17.7	23.0 $\rightarrow$ 8.0
3	9 - 160	138.0 - 7.7	23.0 $\rightarrow$ 5.0*
4	100 - 400	12.4 - 3.1	6.4 $\rightarrow$ 3.0*
5	100 - 800	12.4 - 1.6	6.4 $\rightarrow$ 1.9*

* Use accelerator B as a decelerator and assume the present wiggler period. Transport below 5.0 MeV has not been demonstrated yet.

TABLE II

Estimated wavelengths of interest for the FEL probe of a high-temperature superconductor energy gap.

Approximate T_c (K)	Estimated Gap ^a			Los Alamos FEL e-beam (MeV) ^c
	meV ^b	μm	cm^{-1}	
25	7	177.1	56	4.7
50	14	88.6	113	6.9
100	28	45.9	217	9.8
200	55	22.5	444	14.1
300	83	14.9	669	17.3
400	110	11.3	887	19.9

^a Approximate energy gap $E_g(0) = 3.2 (k_B T_c)$.

^b 1 eV = 1.24 μm = 8066 cm^{-1} ; 1 meV associated with 11.605 K

^c Assumed 10.4 μm at 21 MeV for Los Alamos FEL Oscillator

Fig. 1

Fig. 2

FIG. 3

FIG. 4