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Electron Transport and Transient Conductivity of Irradiated Insulators

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Irradiation of an insulator by an intense electron beam causes a large transient increase in the conductivity, due to ionization. In this talk, the development of a theory of this effect and comparison with experiments are described. Predictions of the scaling of transient conductivity over a wide range of beam current are made on the basis of present understanding, and issues for future work are presented.

A detailed treatment of ionization and excitation leads to an electron energy distribution in the irradiated medium, Fig. (1), from source energy down to about 10 eV. This calculation is for NaCl. A treatment of electrons at lower energies requires consideration of the band structure of the medium, for which we use the model shown in Fig. (2). In it, the conduction electrons behave as free electrons. Note that electron energy is measured from the bottom of the conduction band.

Electrons with energy below the gap energy, E_g, lose energy by interaction with phonons only. The rates of energy loss to longitudinal optical phonons (by Frölich's model) and to longitudinal acoustical phonons (by the deformation potential interaction) are shown in Fig. (3) as functions of electron energy. These models contain an upper limit (the Brillouin zone radius) on the change in electron wave number in electron-phonon scattering. This affects the scattering for energies $\gtrsim$ 2 eV, leading to the discontinuity in slope shown in the figure.

The Langevin theory of recombination is used to describe the rate at which electrons disappear from the conduction band.

Using the rates of ionization, energy loss, and recombination described above, one calculates the steady-state energy distribution. This is shown in Fig. (4) for a 4.5 MeV beam of 1 kA/cm^2 current density. Note that the distribution divides itself into two groups, the thermal and the epithermal electrons. The electron densities of these two classes of electrons separately, as well as the combined density, are shown as functions of beam intensity in Fig. (5).

The models discussed above for electron-phonon scattering lead to collision frequencies which are given as functions of electron energy in Fig. (6). The three curves are for scattering by optical and by acoustical modes, and for the total rate. At energies $\lesssim$ 0.1 eV, the total rate has been reduced by a saturation correction so that the mean free path does not exceed the lattice constant.

The predicted steady state conductivity of irradiated NaCl is shown in Fig. (7) as a function of beam current density. Also shown are the separate contributions of the thermal and epithermal groups of electrons. Vaisburd and coworkers found a 0.4 power law in the conductivity vs beam current (Fig. 8), in the range of 1 to 10^3 A/cm^2, while the present theory gives a 0.5 power dependence in the same regime. It is unclear what the experimental accuracy is, and this difference might well be within experimental error.

The predicted evolution of the conductivity with time is illustrated in Figs. (9) and (10). In the former, where a 0.1 ns beam pulse is assumed, the response time of the conductivity is seen to be on the order of 10 ps (assuming a 1 kA/cm^2 4.5 MeV beam) which is consistent with the observations of Vaisburd et al. We must point out, however, that the decay of the conductivity is not exponential, and has a long tail, so the concept of response time should be treated with caution. Another important point is that the response time decreases with increasing beam current density. This is because the density of holes goes up, thereby decreasing the lifetime of thermal electrons. This is why the conductivity response time discussed here is so much shorter than the ones observed in classical (low-current) photoconductivity measurements.

The conductivity during and after a 20 ns beam pulse is shown in Fig. (10). On this time scale, the conductivity is predicted to decrease somewhat over the duration of the pulse, due to heating of the medium.

We conclude that the theory is consistent with experiments, and explains the nonlinear dependence with beam current density, and the fast response. Many important issues remain for future work. Several of them are listed in Fig. (11).

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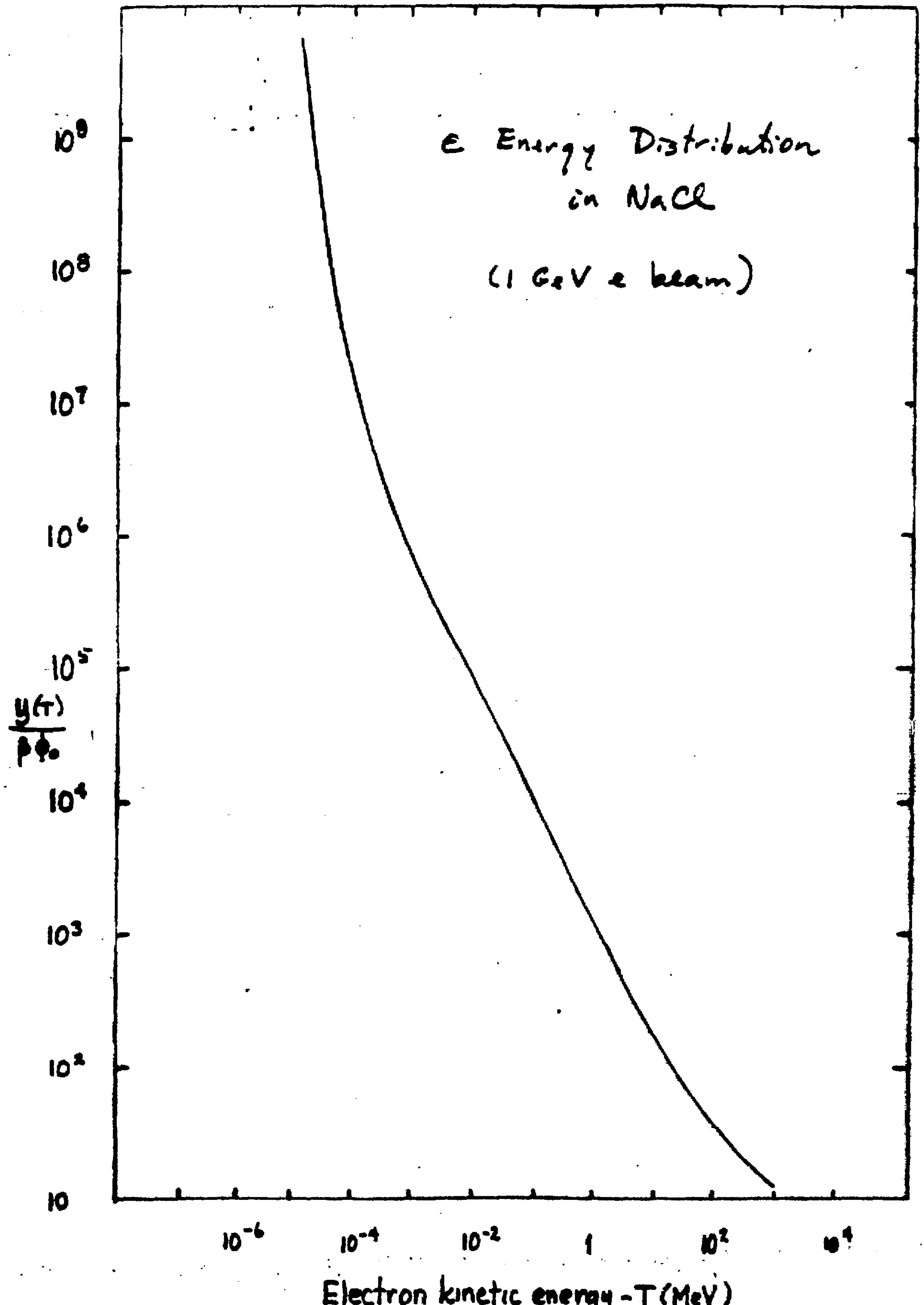
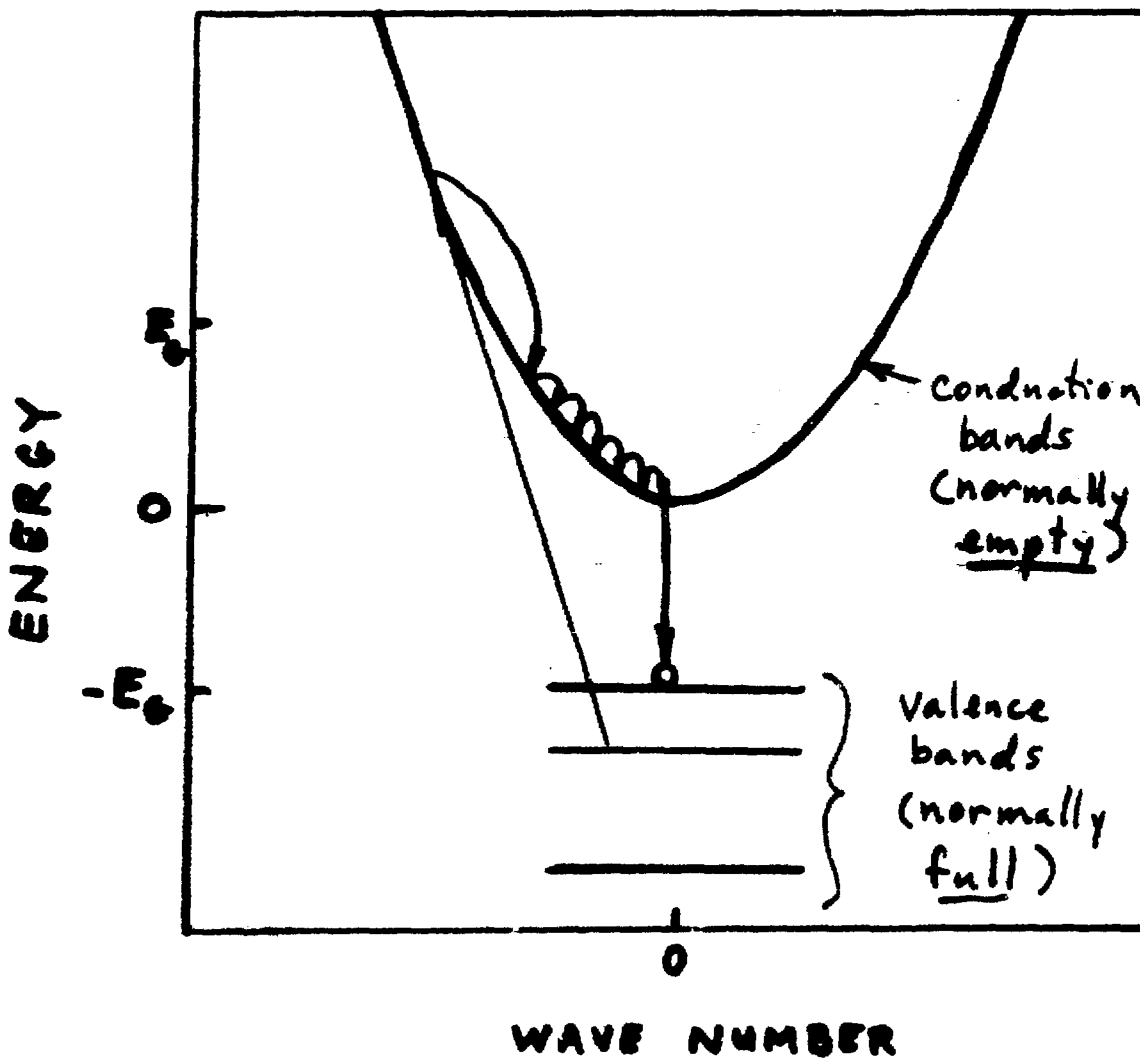
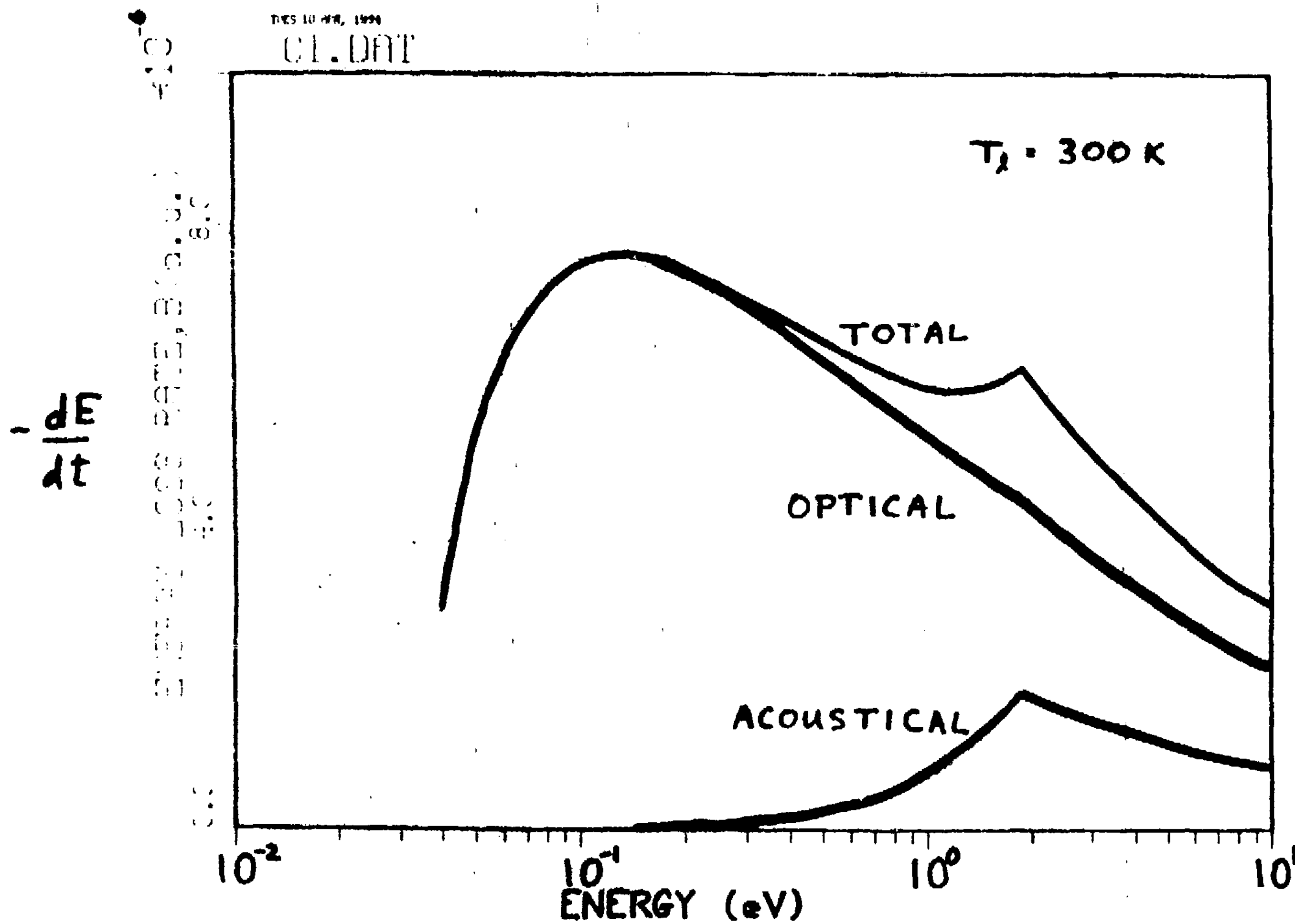


e Energy Distribution
in NaCl
(1 GeV e beam)
10
10^2
10^3
10^4
10^5
10^6
10^7
10^8
10^9
$\frac{y(T)}{p\phi_o}$
10^{-6}
10^{-4}
10^{-2}
1
10^2
10^4
Electron kinetic energy - T (MeV)

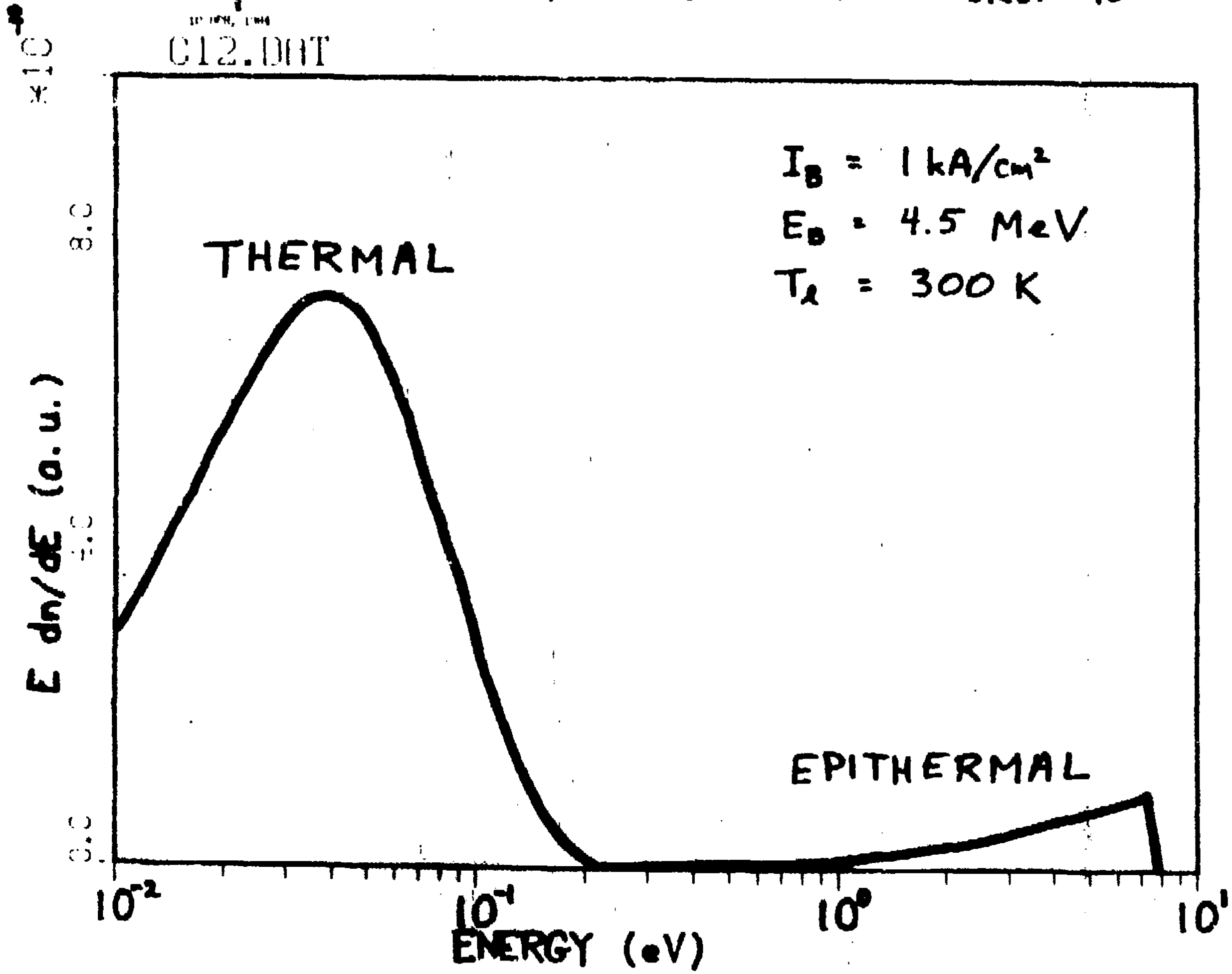
Band Structure of Alkali Halide (Schematic)

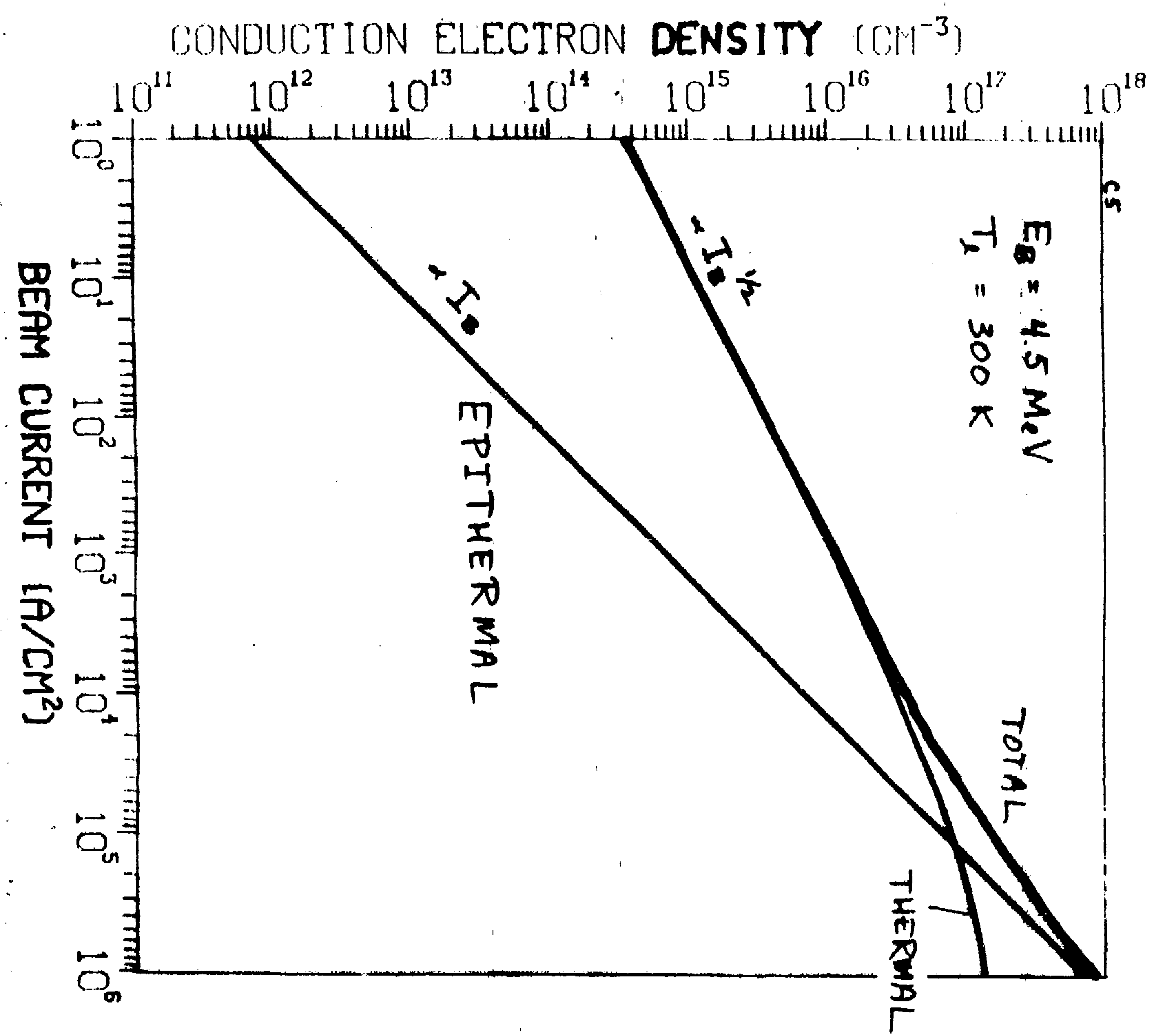


RATE OF ENERGY LOSS TO PHONONS



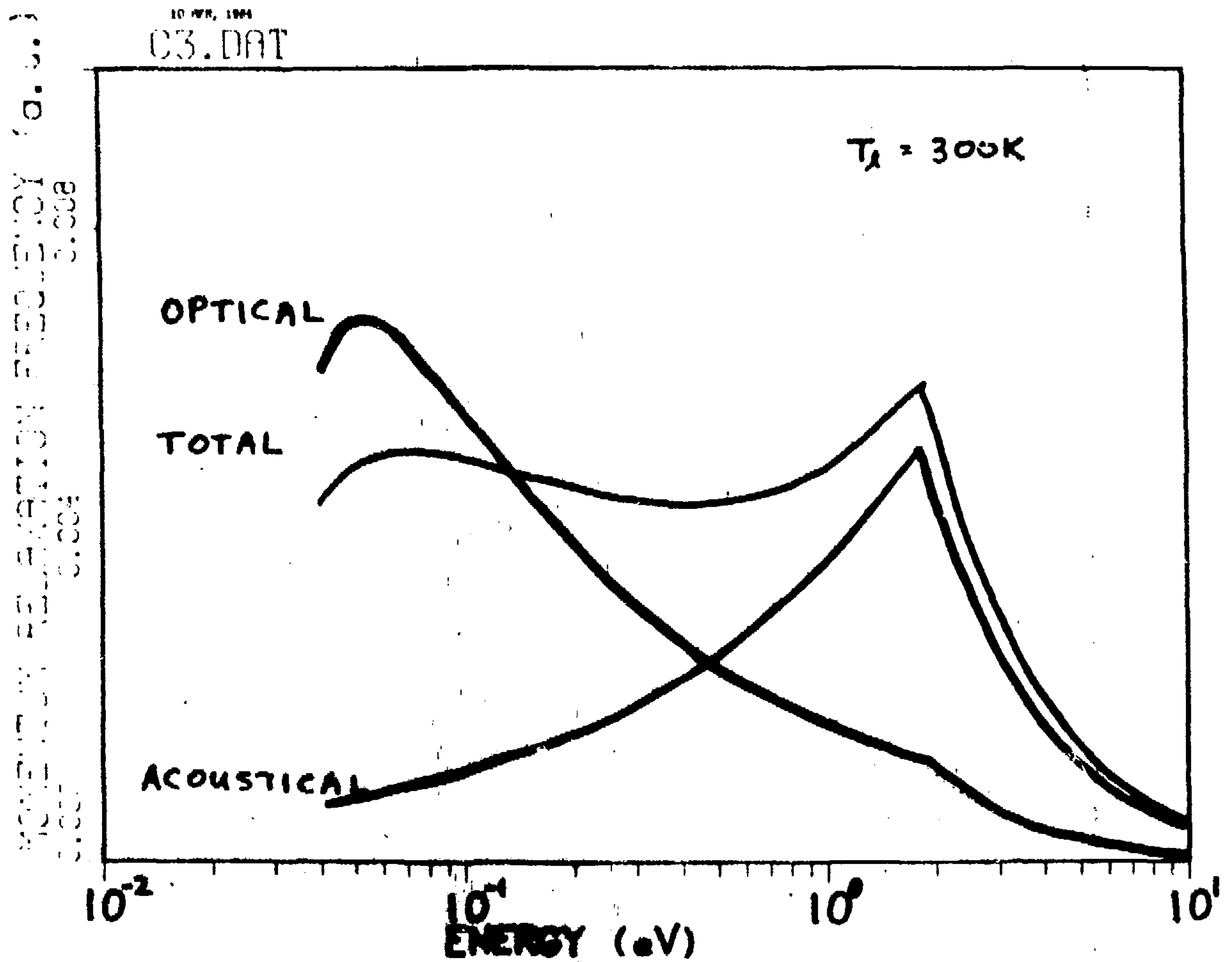
Steady-state distribution of conduction electrons

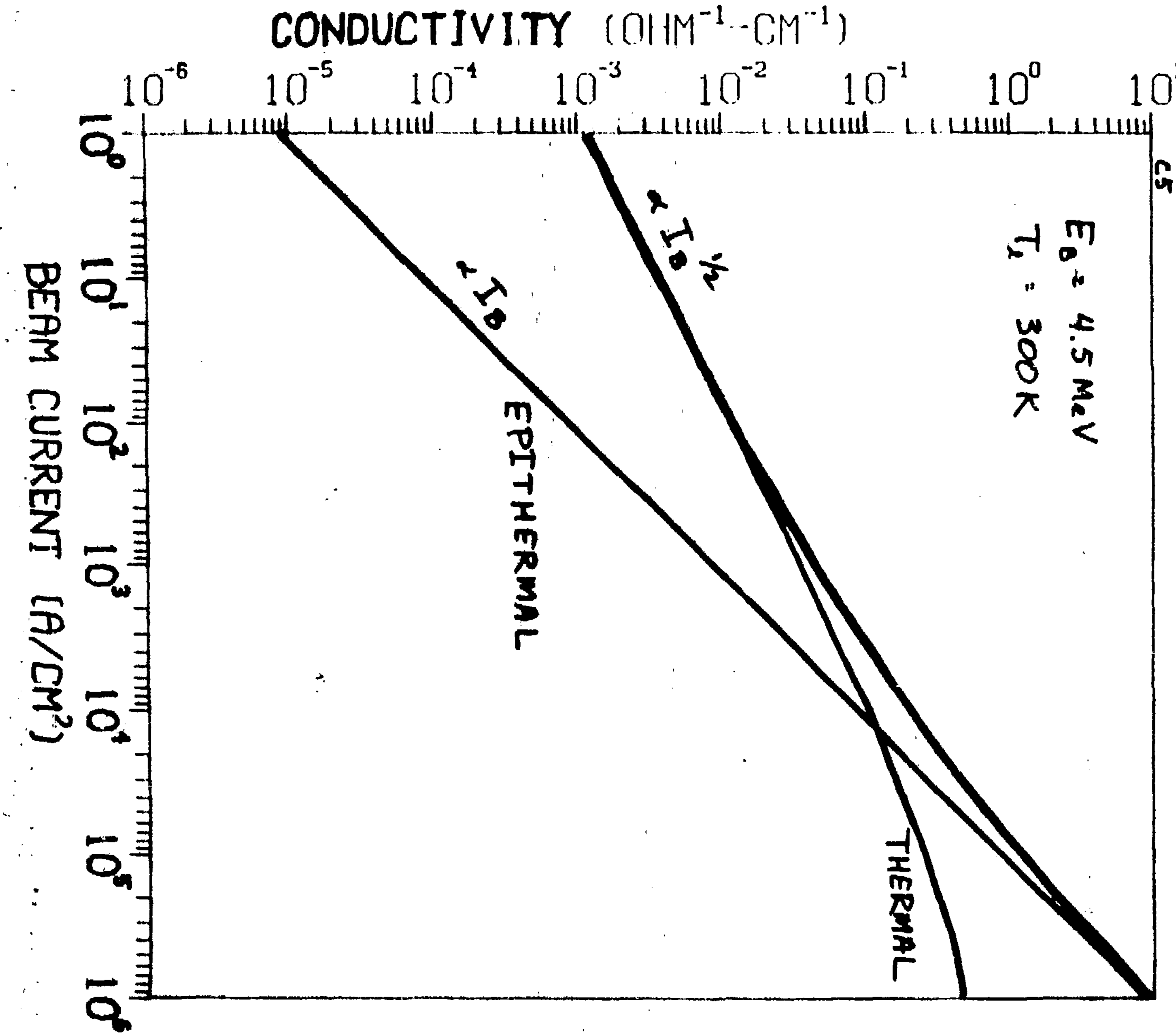




CONDUCTION ELECTRON DENSITY (CM^{-3})
10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16} 10^{17} 10^{18}
BEAM CURRENT (A/CM^2)
10^0 10^1 10^2 10^3 10^4 10^5 10^6
E_B = 4.5 MeV
T_ℓ = 300 K
$\propto I_B$
$\propto I_B^{1/2}$
EPITHERMAL
TOTAL
THERMAL

ELECTRON - PHONON COLLISION FREQUENCIES




CONDUCTIVITY (OHM^{-1}-CM^{-1})
10^{-6} 10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1}
BEAM CURRENT (A/CM^2)
10^{0} 10^{1} 10^{2} 10^{3} 10^{4} 10^{5} 10^{6}
$E_B = 4.5$ MeV
$T_\ell = 300$ K
$\propto I_B^{1/2}$
$\propto I_B$
EPITHERMAL
THERMAL
C5

Experiments – Conductivity of bombarded alkali halides. Vaisburd et al

For $I_B = (0.001 - 1)\ kA/cm^2$,
$\sigma = (0.8 - 2.8) \times 10^{-3}\ ohm^{-1}\ cm^{-1}$

$$\sigma \propto (I_B)^{0.4}$$

Response time ≤ 0.1 nsec
(possibly greater when $T > 300°K$)

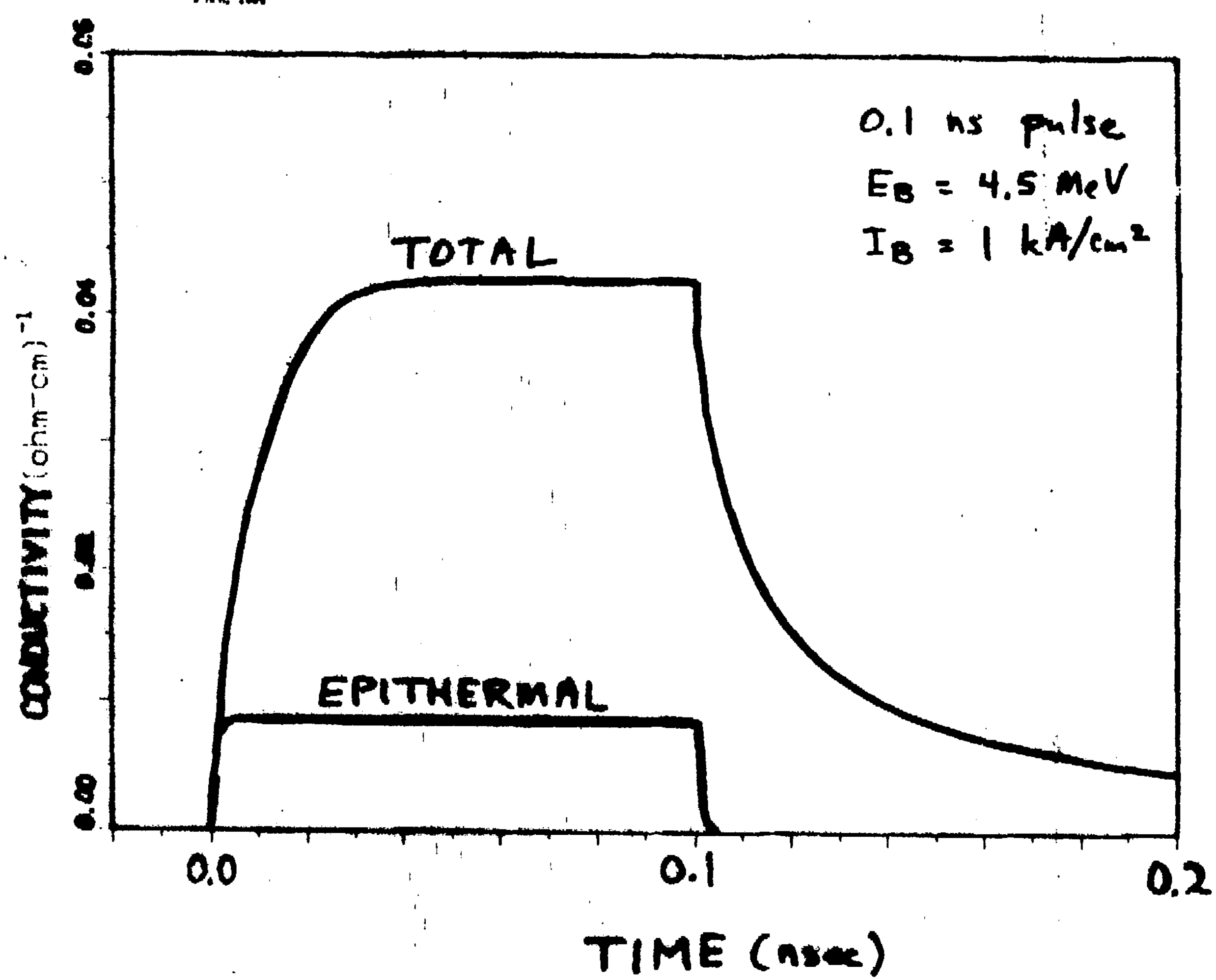
Issues for Theory

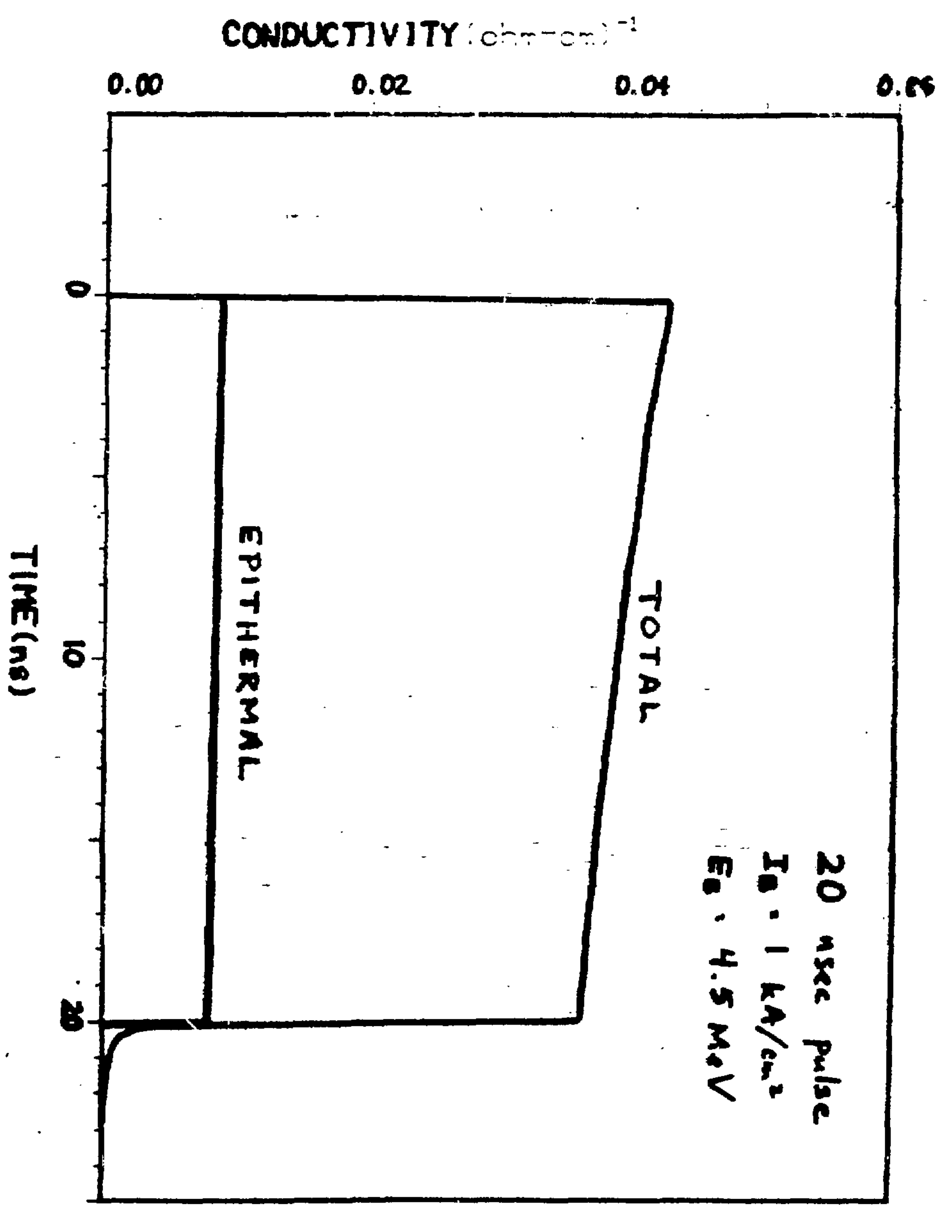
What are the important processes?

What is the origin of the 0.4 power law?
Does this scaling apply at higher I_B?

Why is the response so fast?
(conventionally $> 10^{-8}$ sec)

Time-dependent conductivity





CONDUCTIVITY (ohm-cm)^-1
0.00
0.02
0.04
0.06
TIME (ns)
0
10
20
TOTAL
EPITHERMAL
20 nsec pulse
I_B = 1 kA/cm²
E_B = 4.5 MeV

Issues for Future Work

- How are the predictions affected by the following, at intensities > 1 kA/cm^2?
  - interaction between conduction electrons (screening, plasmon effects, Auger recombination, nonlinear Boltzmann equation)
  - additional mechanisms for e-phonon scattering, above 2eV
  - overlap of recombination radii of holes
- What ionization and conductivity behavior are expected for other classes of insulators?
  - SiO_2, organic
- Do the transient ionization and conductivity appreciably affect the energy deposition rate for CPBs in solids? How, and by how much?