Cathodoluminescence of Rare Earth Ions in Semiconductors and Insulators

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For the curious:

Q: Are rare earth elements rare?

A: Not particularly – they are all significantly more abundant than gold.

Q: Are rare earth elements "earth"?

A: No, "earth" is an archaic word for oxide.

Applications

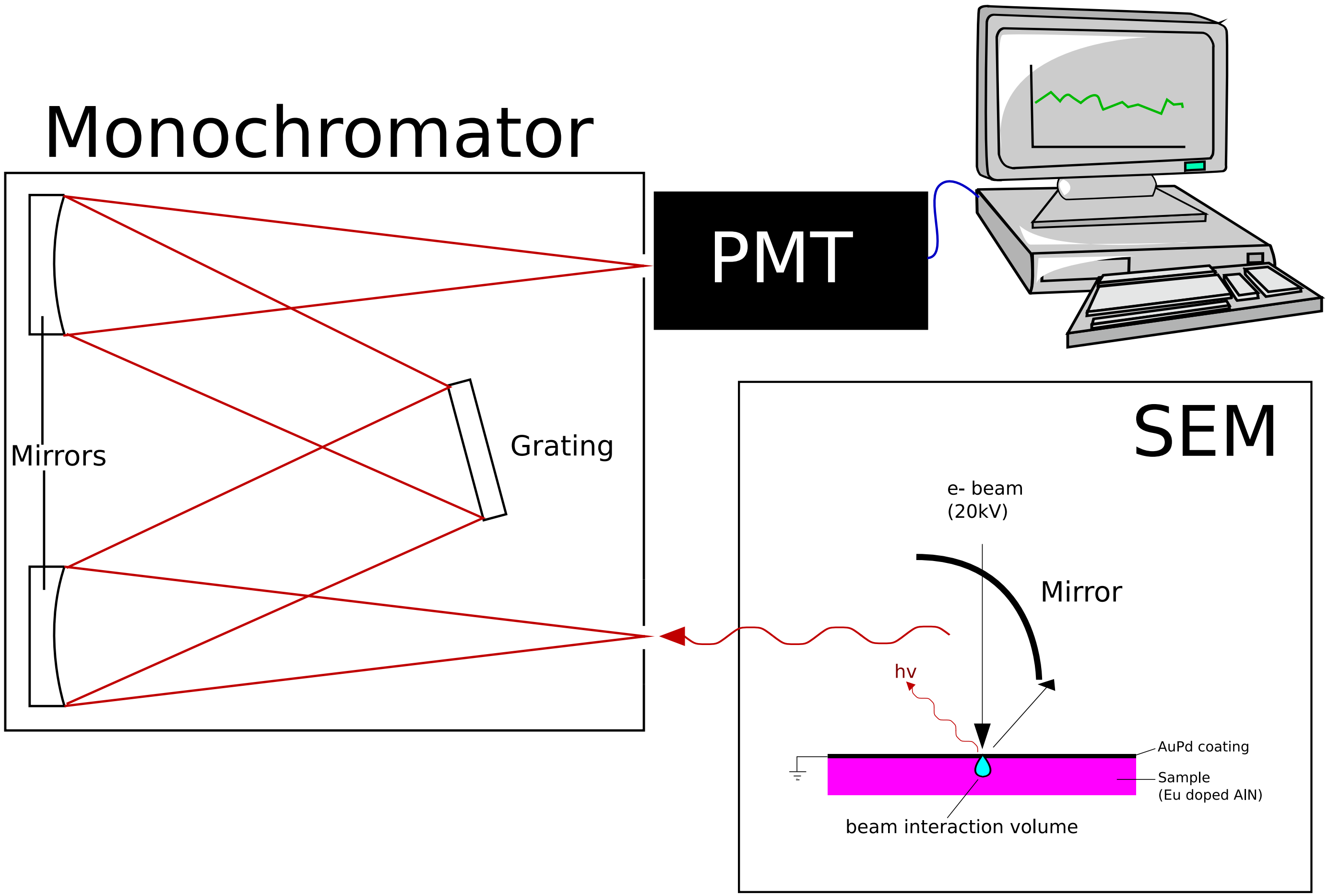
Electrically pumped lasers, light sources, and light amplifiers

- REIs are already used in optically pumped lasers
- REIs have consistent emissions in the visible spectrum independent of host material
- create a display from different REIs in same host

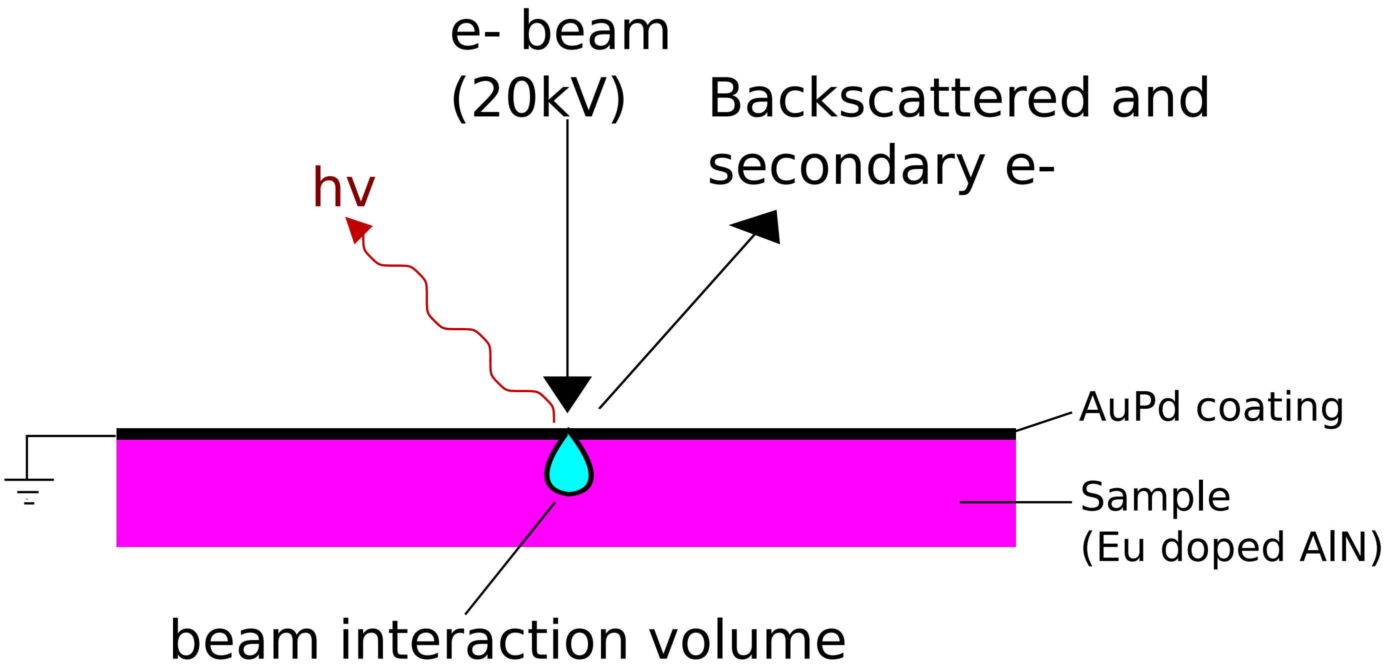
Wide Bandgap Semiconductors

- Transparent to visible light
- Efficient REI emission – Ions can be electrically excited
- Can use semiconductor tricks – can make PN junctions to inject electrons

Experimental Setup



Interaction with the beam



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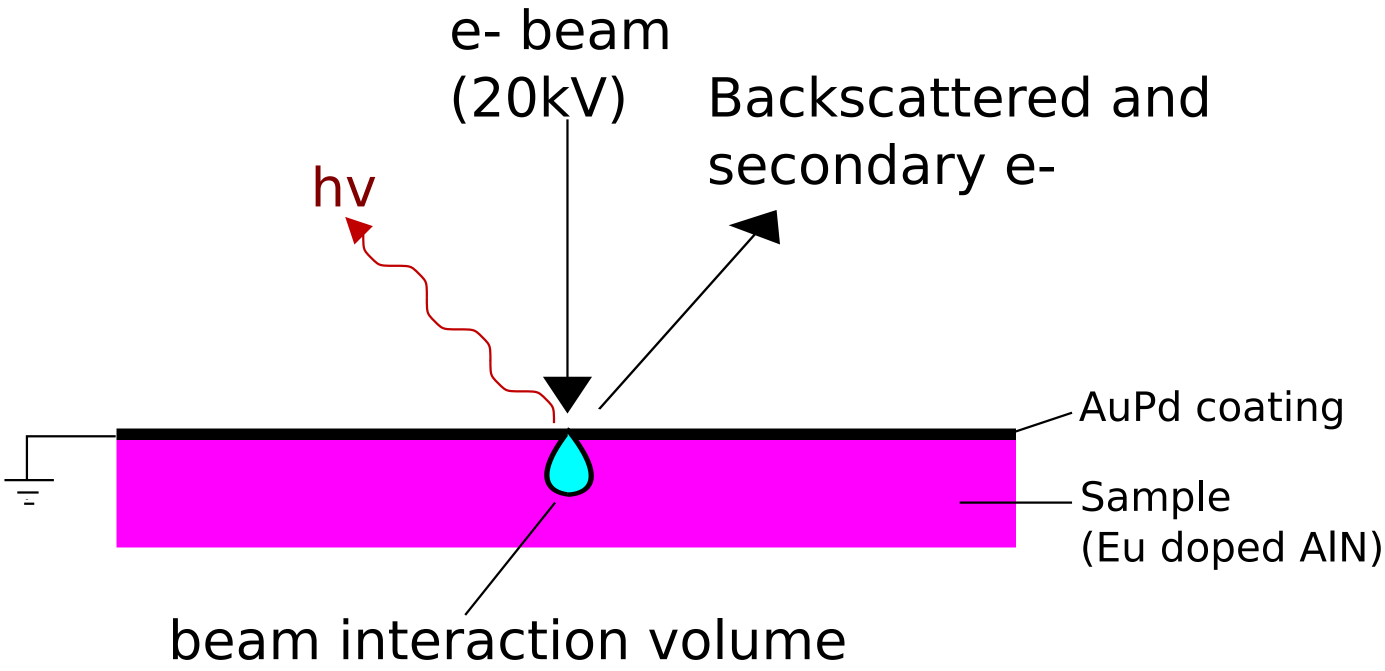
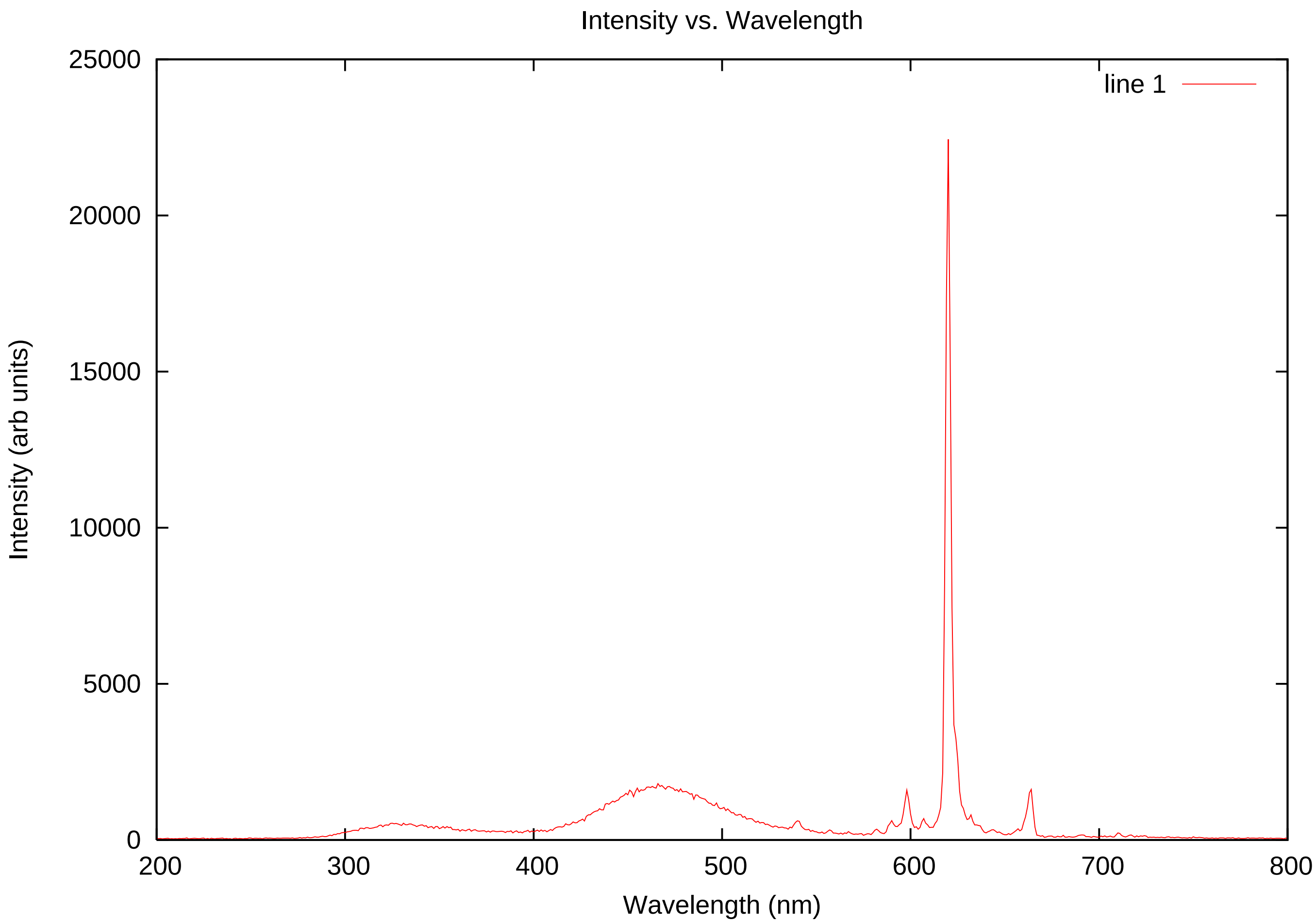


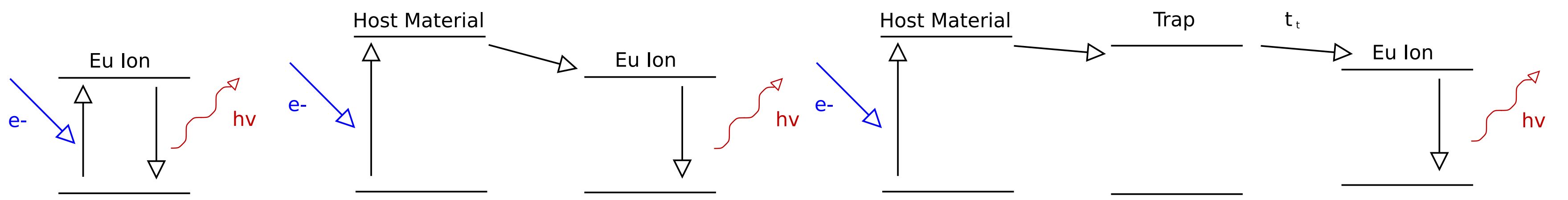
- Collisions create electron hole pairs
- Electron Energy $= 20$KeV
- 620nm Photon Energy ≈ 2eV

What do we see?



Questions

- Is the process efficient? What is the limiting factor?
- How do the REIs become excited?
  - Directly by beam electrons hitting the REIs?
  - Electron hole pairs transferred from the base material?
  - Is there an intermediate trap?



The Model

- 2 Energy Level System
- N total Ions, N_e excited, and N_g in the ground state
- p pump rate, k decay rate, $\tau = \frac{1}{k}$ decay time constant

$$\frac{d}{dt}N_e = pN_e - kN_g = pN_e + kN_e - kN$$

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Solutions:

$$N_e = \frac{pN}{p+k}\left(1 - e^{-(p+k)t}\right)$$

$$N_e = \frac{pN}{p+k}e^{-kt}$$

The Model and Spot Mode

In spot mode, the beam just dwells on one spot. If we wait a moment:

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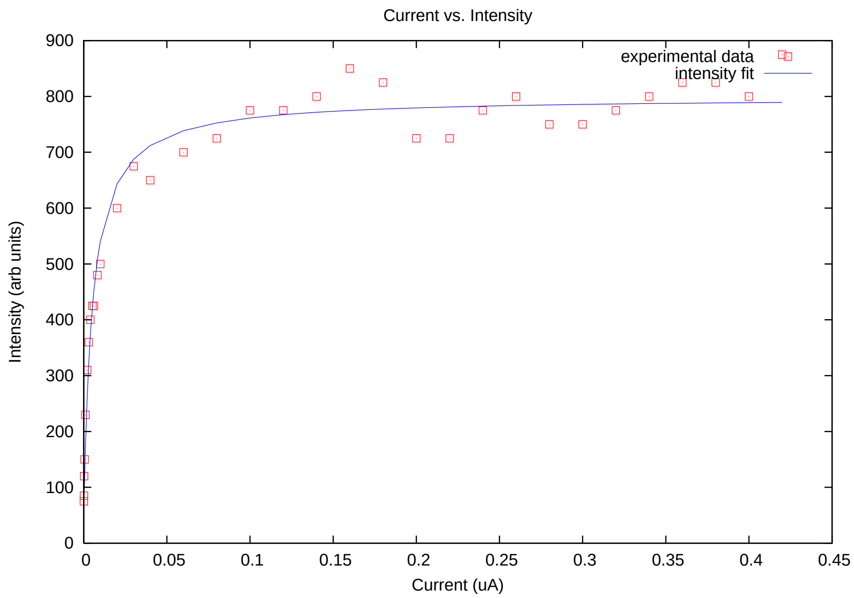
However, this only really tells us about the ratio $\frac{k}{p}$.

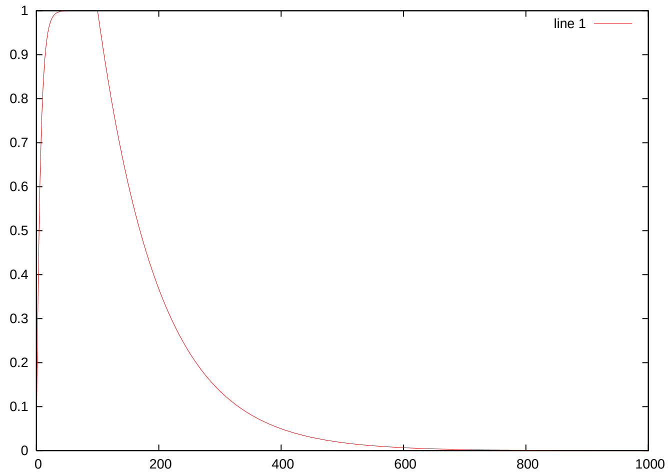
$$N_e \approx \frac{pN}{p+k} = \frac{N}{1+\frac{k}{p}}$$

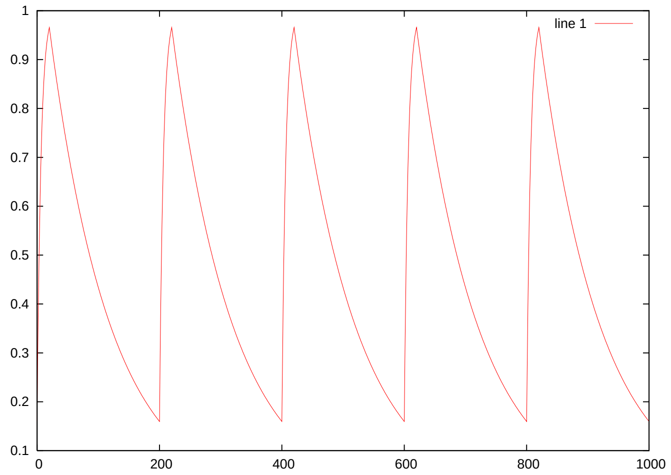
Spot Mode and Saturation



- Output saturates – efficiency is not the limiting factor
- Intensity is less than for photoluminescence (PL) – fewer REIs are being excited
- That rules out direct excitation and direct host transfer

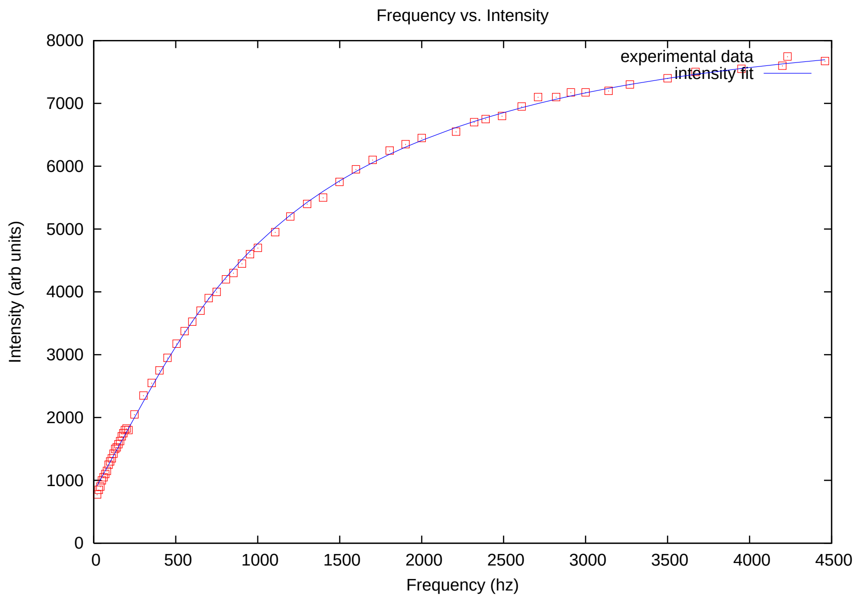
The Model and Line Mode





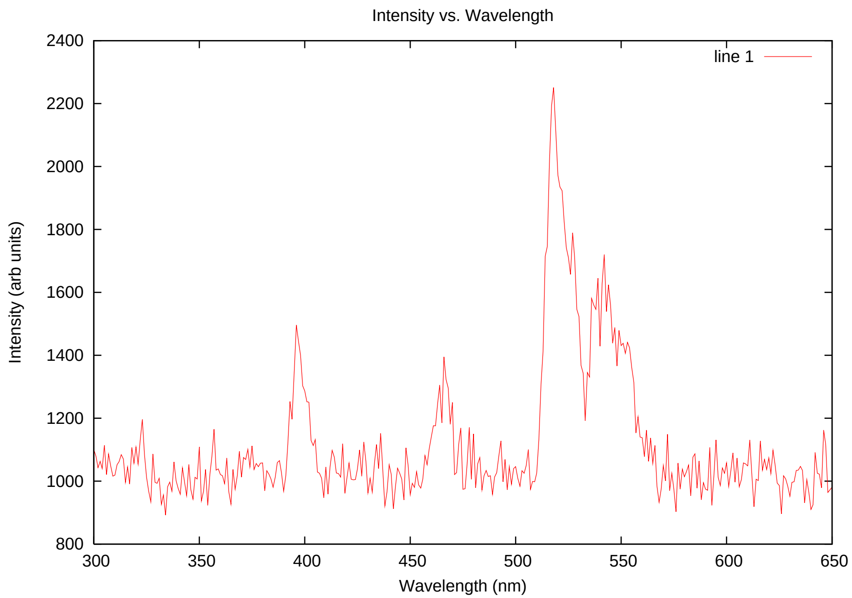
- The beam only shines on a spot part of the time.
- Finding the steady state is done numerically.
- The frequency of the scan is varied.
- The time average is fit to the data, determining k.

Does The Model Work?



- $k = 1.46 * 10^6$ $p = 1.60 * 10^7$
- $\tau = 6.82 * 10^{-5}$ seconds is similar to the relaxation time of Eu
- This does not show evidence for a trap

REIs in Insulator – Er in Glass



- Shows a drop compared to Er in semiconductors.
- Indicates that direct excitation is not the mechanism at work.
- We're still investigating this material.

Conclusion and Summary

- Difference in intensity between CL and PL, and dependence on host material, suggests direct excitation is not at work.
- However, the measured time constant is similar to that of Eu, meaning that if there is a trap, it is faster.
- Still, something besides the number of REIs and the efficiency must be the limiting factor – traps are likely to be it.
- More measurements are needed – taking data is slow with the current setup.