A study of charge collection processes on polycrystalline diamond detectors

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on Large Scale Applications
and Radiation Hardness
of Semiconductor Detectors

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Introduction

During this presentation the following topics will be covered:

Diamond as a radiation detector: its working principle

Investigation of the effect of light on deep trap levels by charge collection measurements

A study on optimisation of charge collection enhancement (pumping) by means of β irradiation

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Polycrystalline CVD diamond properties

☺
- Radiation hardness, up to: 10^{15} hadrons cm^{-2}
- Fast response: ~ 1 ns
- Very low leakage current: ~ 1 pA cm^{-2}
- Low dielectric constant: 5.6 ε_0
- Large wafers: ~ 20 cm Ø
- Working at room temperature

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- Signal/Noise lower than silicon: ~ 10
- Low charge collection efficiency
- Defects, mainly due to the polycrystalline nature of CVD diamond, originate trap levels in the bandgap

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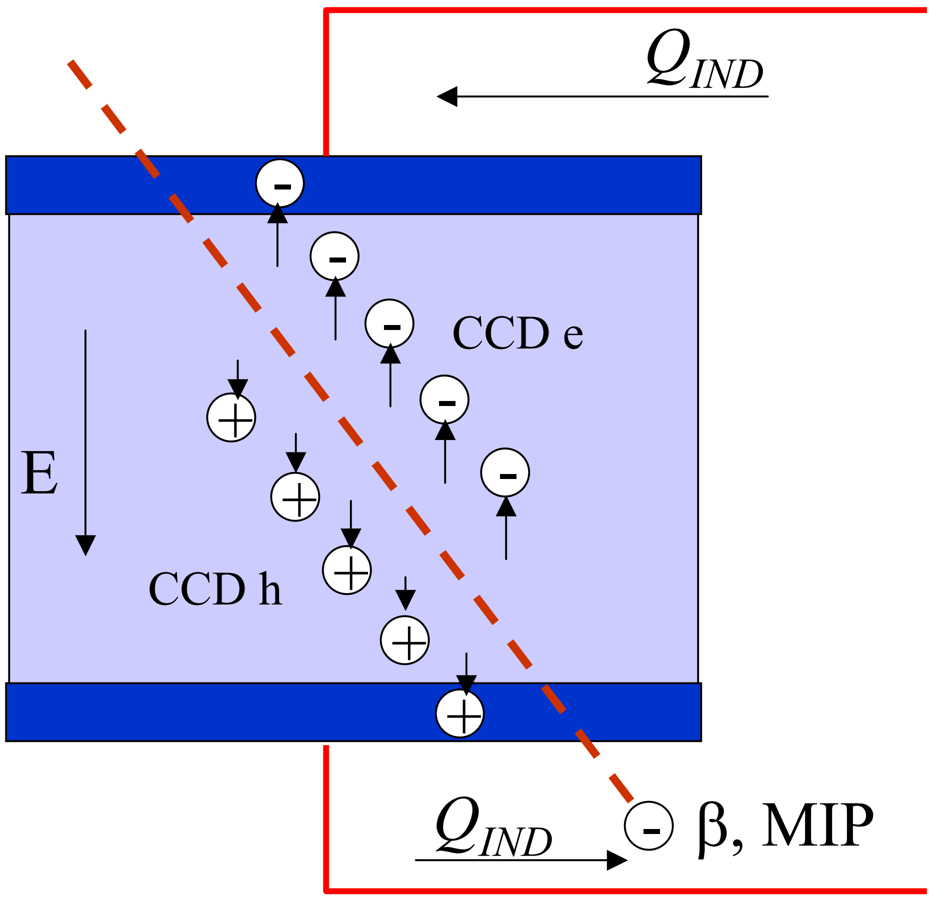
Homoepitaxial growth is also presently being studied…

Charge Collection Distance (λ)



$$Q_{IND} = Q_{ION} \cdot \frac{\lambda}{t}$$

$$\lambda = \lambda_e + \lambda_h$$

$$Q_{ION}/t \approx 36.3 \frac{e^-}{\mu m}$$

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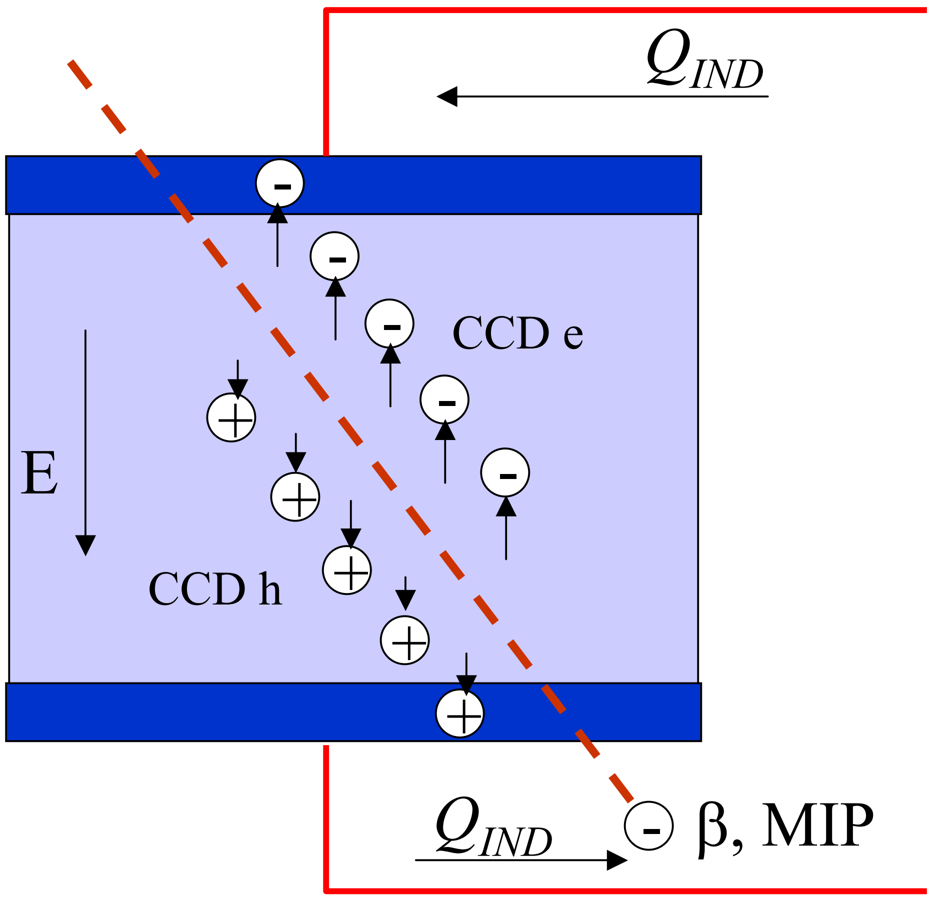

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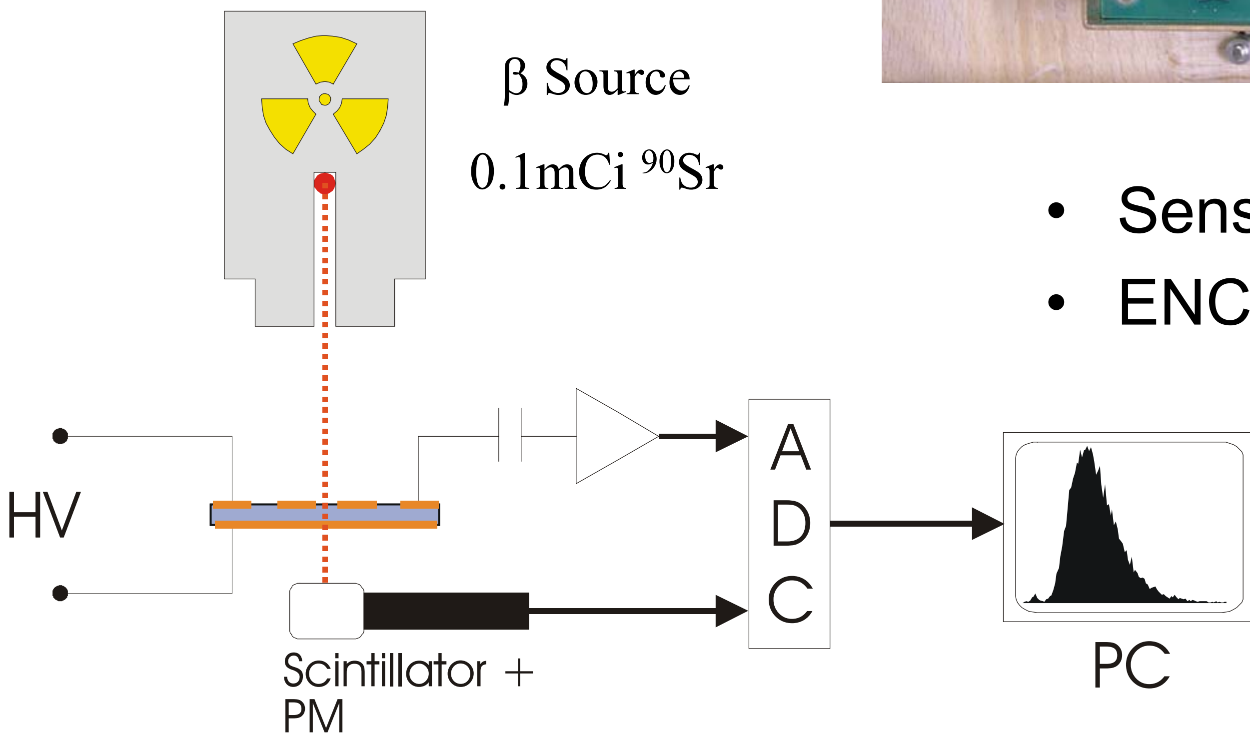
In most recent diamonds ($\lambda \sim t$) CCD is also limited by bulk width

Experimental setup

Reproduction of the original setup by dr. Fred Hartjes from NIKHEF, Amsterdam

- Sensitivity ≈ 220 e⁻/mV
- ENC ≈ 350 e⁻



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β Source

0.1mCi ^{90}Sr

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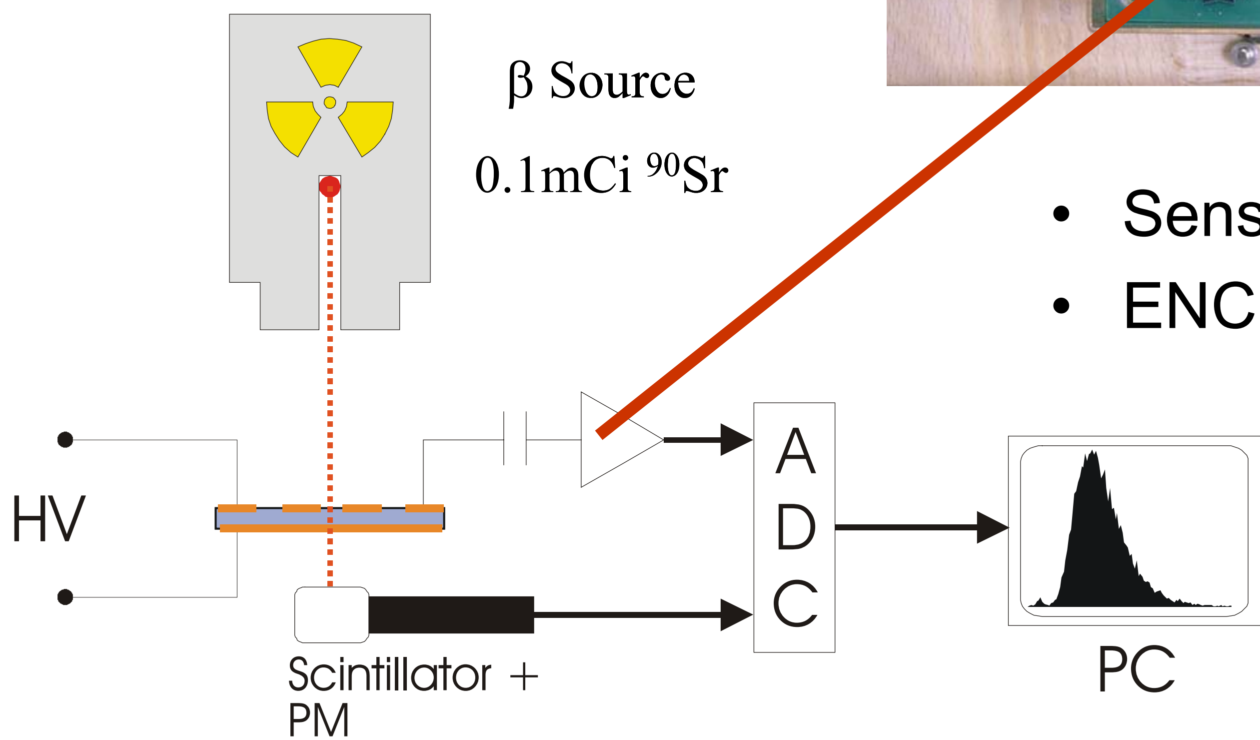

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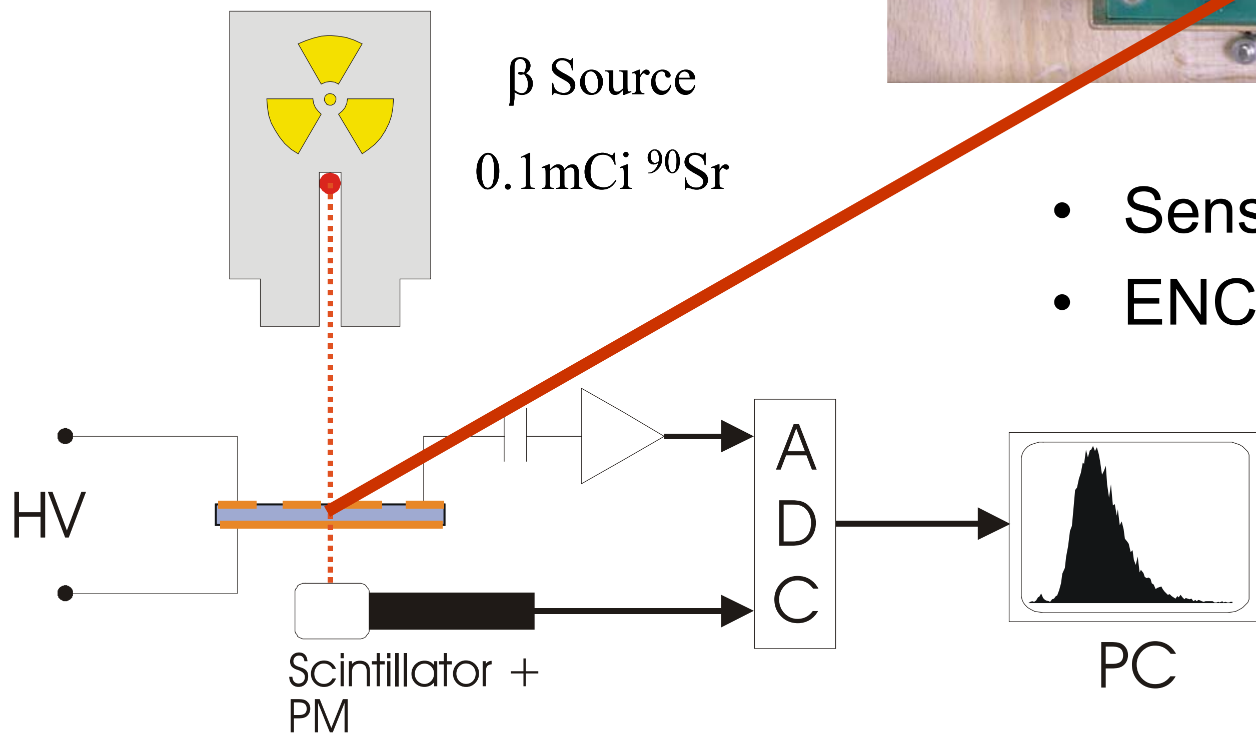

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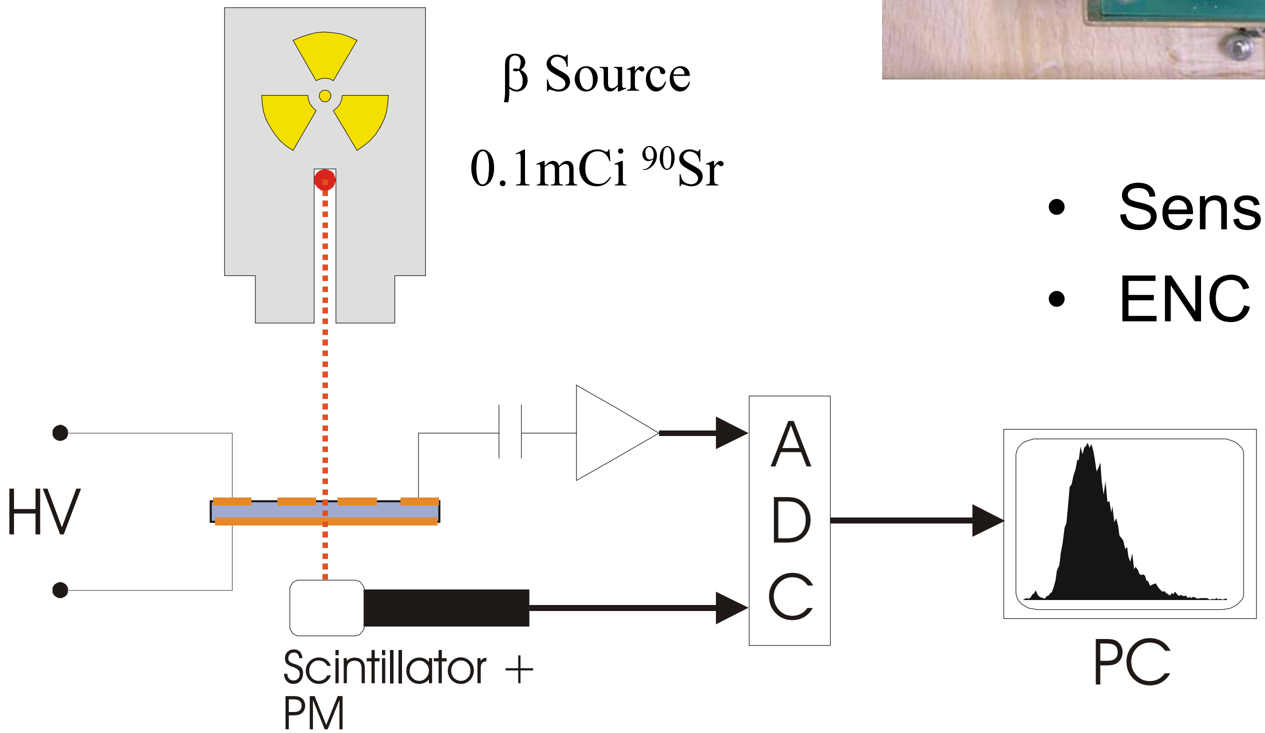

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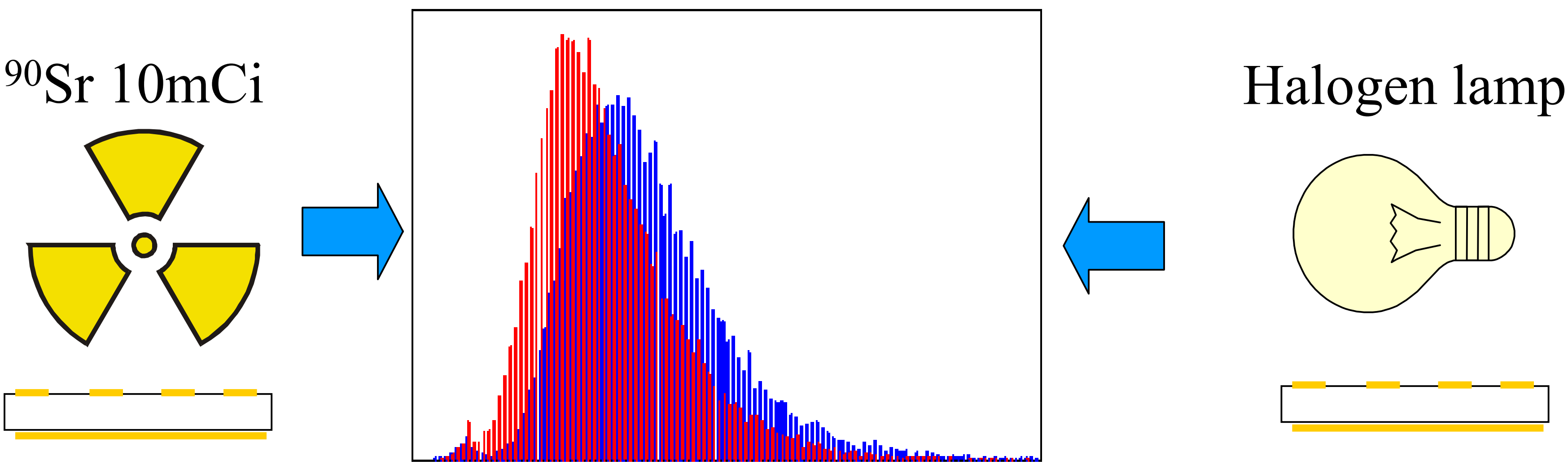
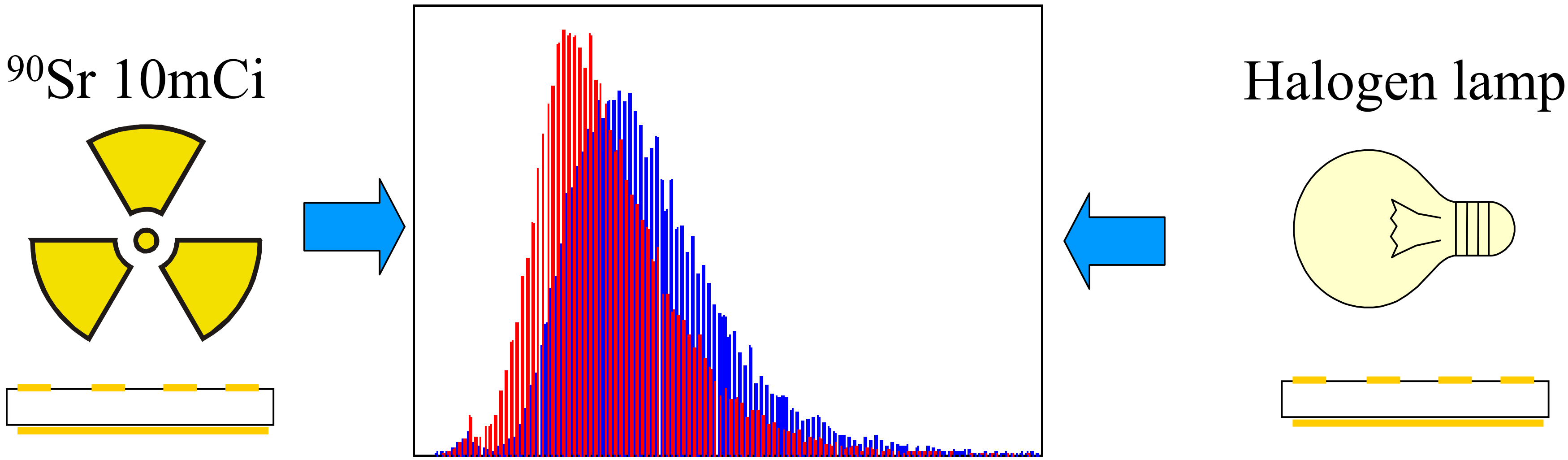
The 'pumping' effect



The 'pumping' effect

Measurement β source: 0.1 mCi ^{90}Sr



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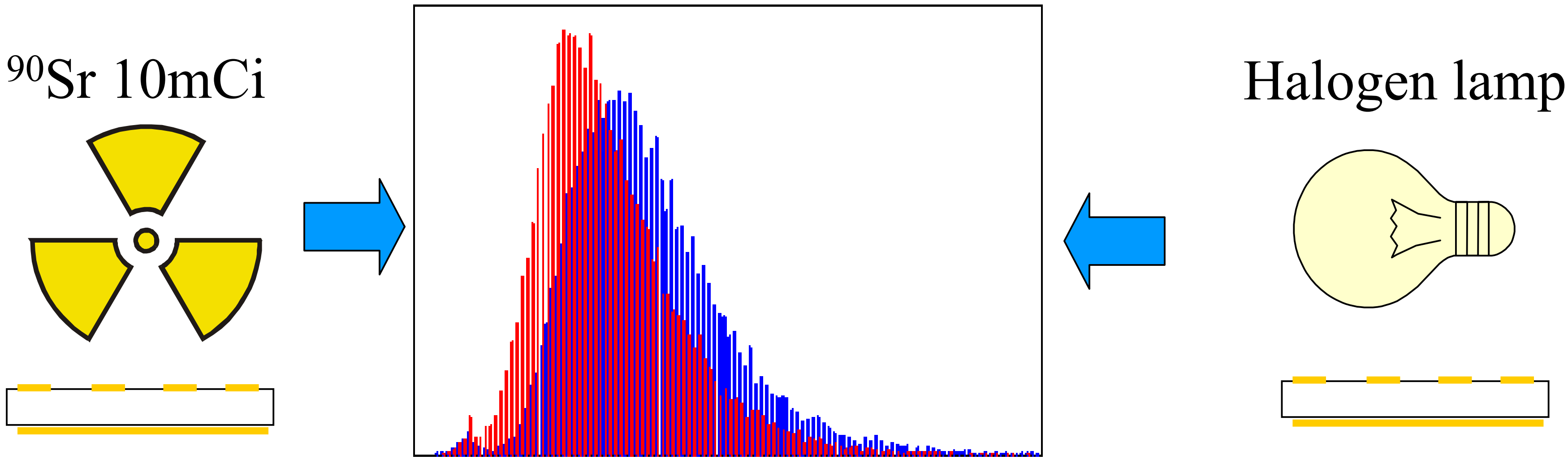
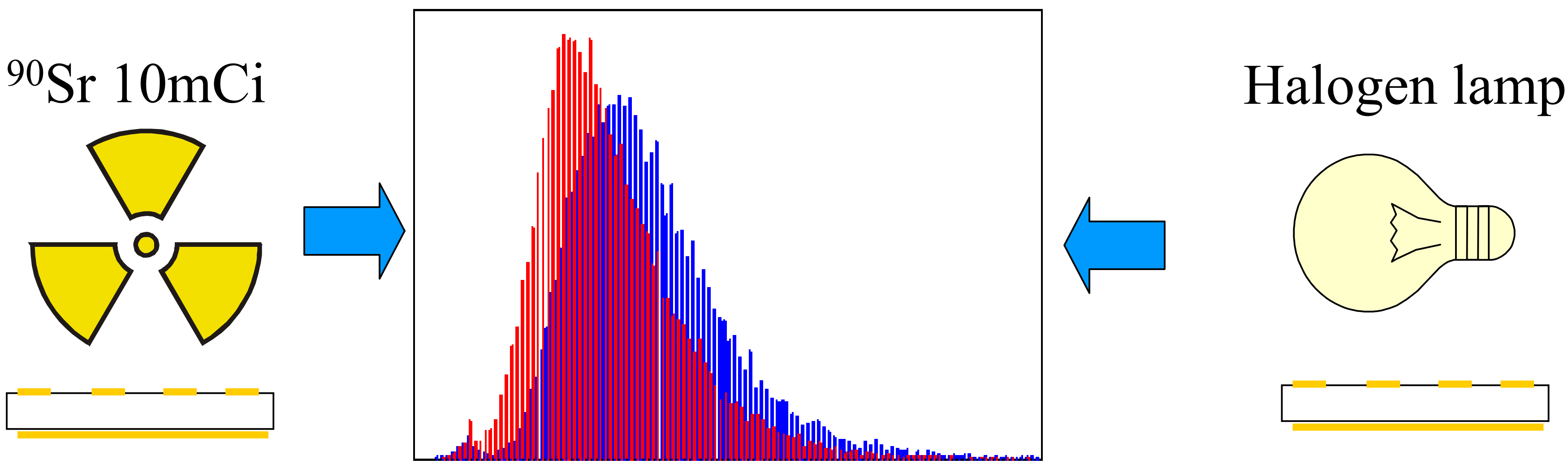


The 'pumping' effect

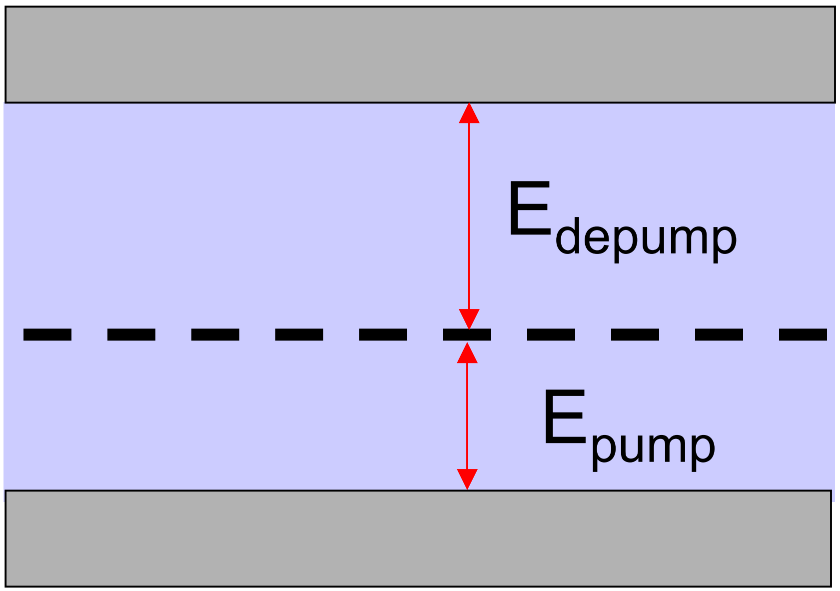
- Measurement β source: 0.1 mCi ^{90}Sr
- But if diamond is exposed to intense radiation, its signal is increased
- This *pumping* effect is permanent, until diamond is exposed to light (or heated ~600K)



T *Investigation of the effect of light on deep trap levels by CCD measurements*

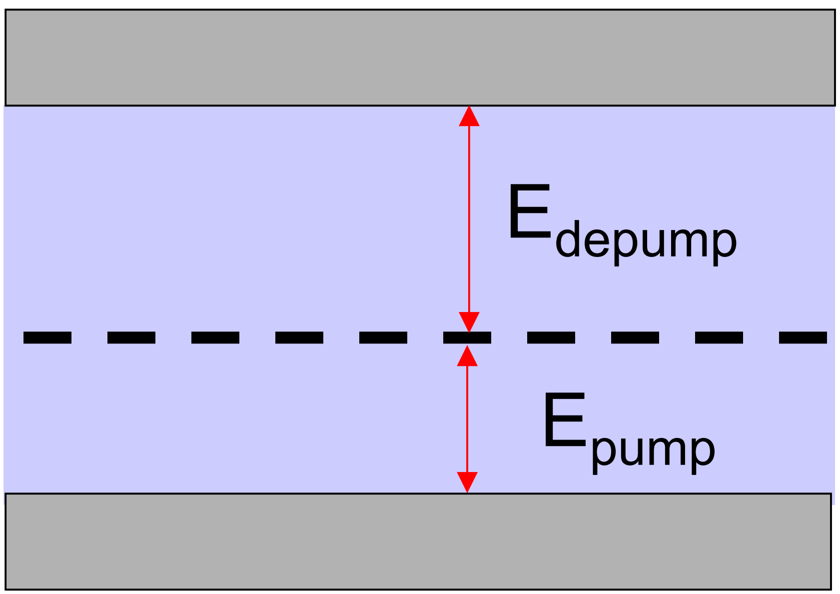
- Interpretation of pumping effect as the passivation of deep trap levels inside diamond bandgap
- Investigation of this effect by means of CCD measurement after sample illumination with monochromatic light
- Model refinement with two trap level bands

Our interpretation of pumping



Our interpretation of pumping

Carriers' mean life enhancement is due to traps passivation



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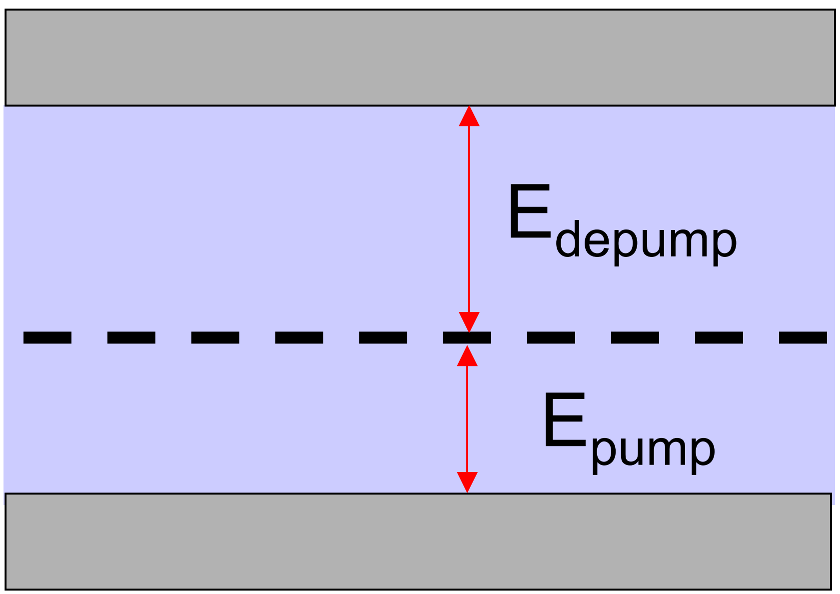

Emission by charged centers (e.g.positive) pumps diamond lowering the capture cross section of states

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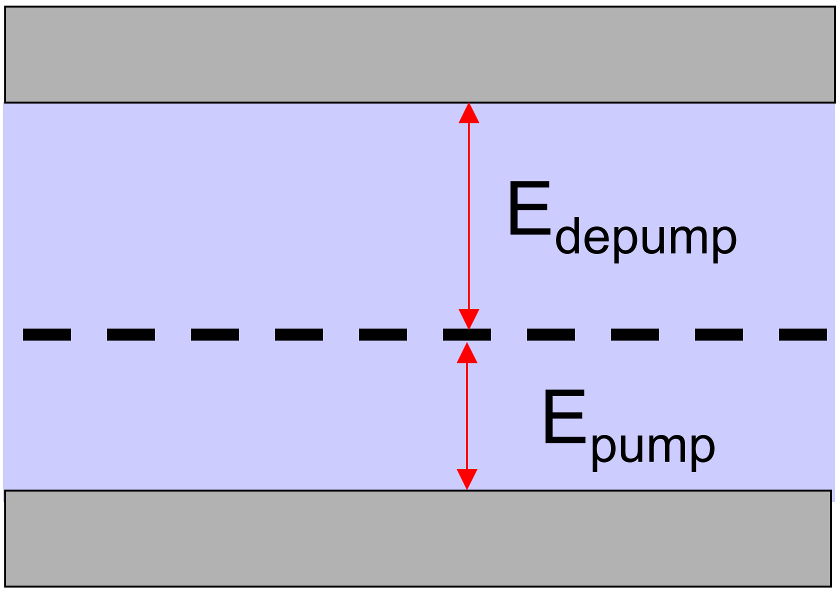

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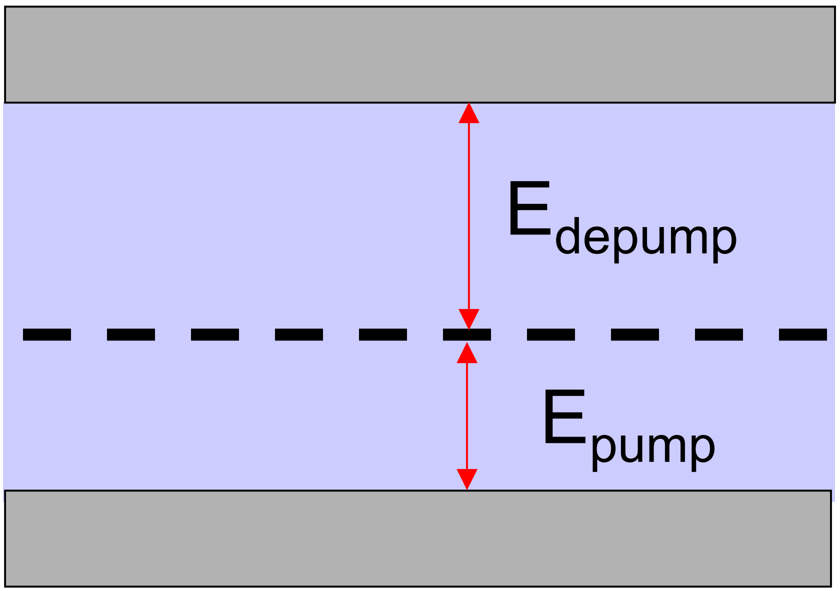

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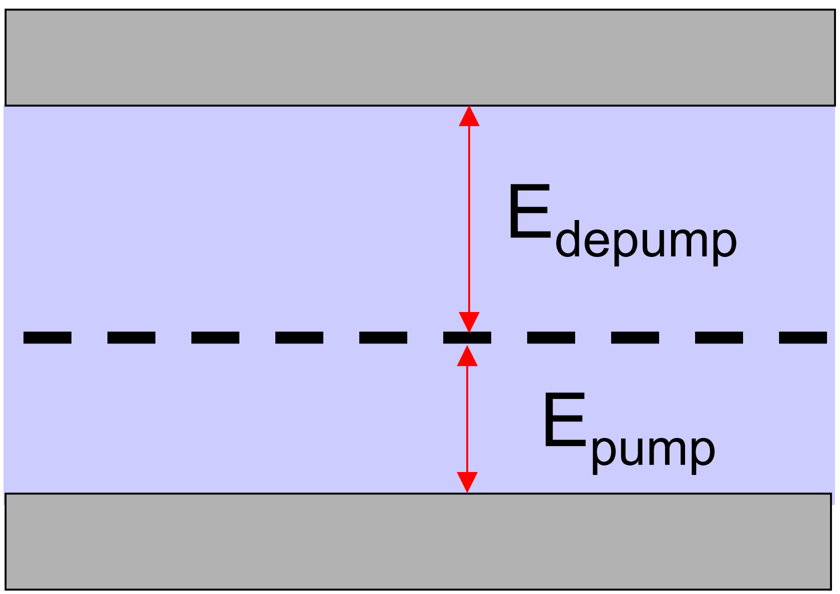

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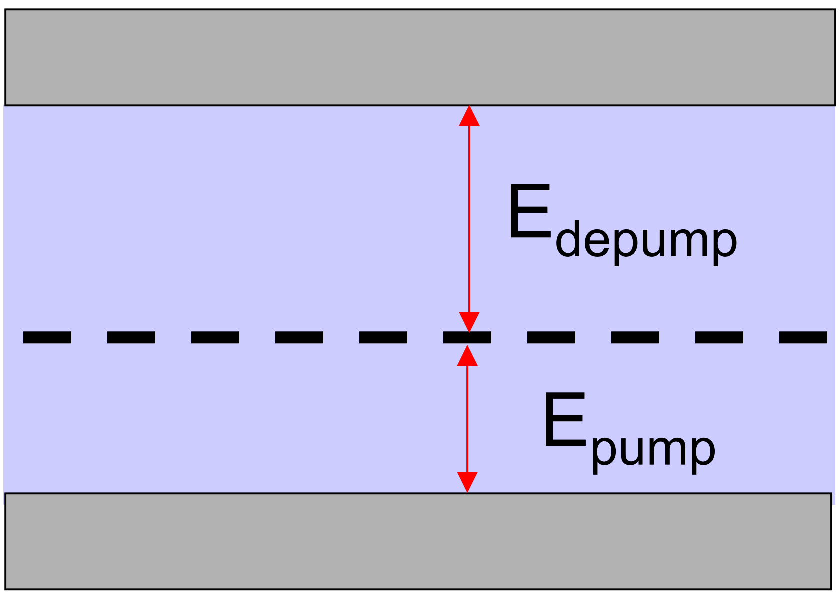


$$E_{depump}+E_{pump}=E_{gap}$$

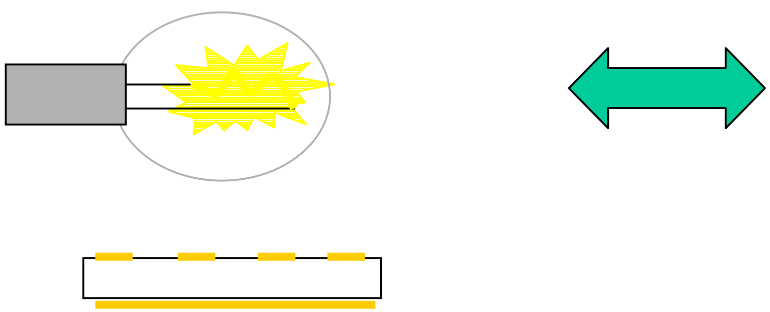
Pumping-depumping energies are thus complementary

Investigation of deep trap levels

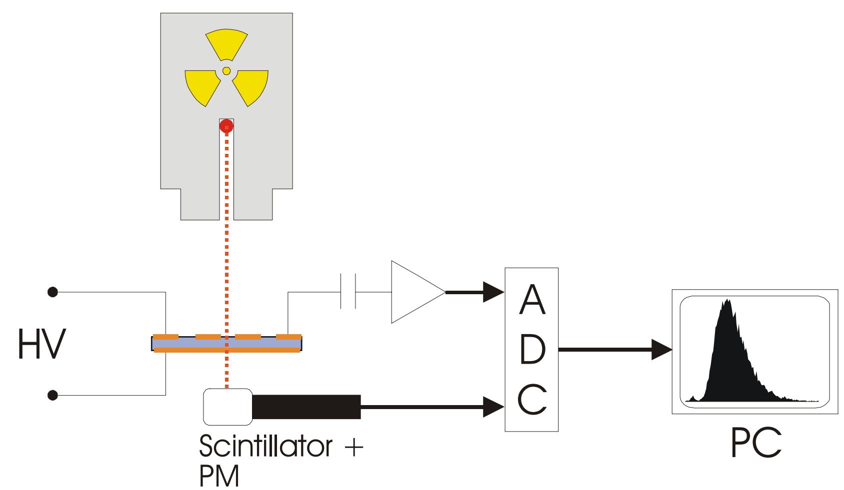
Study of deep trap passivation effect by light radiation

- Exposure to radiation (220-1000 nm)
- Photocurrent measurement
- CCD measurement

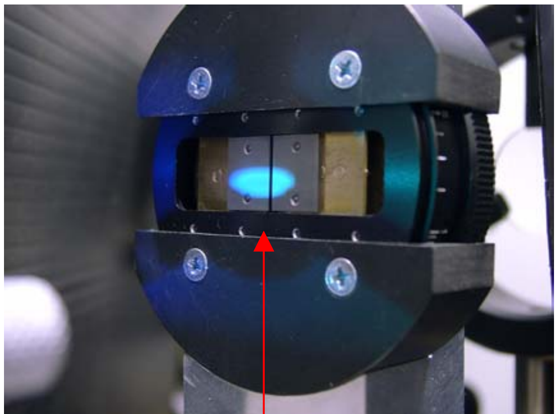
Selected wavelength light source

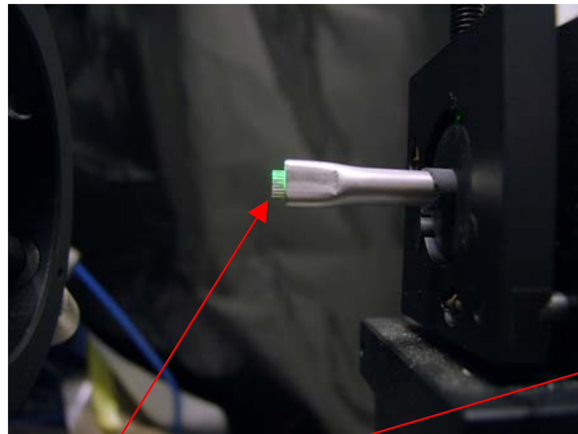


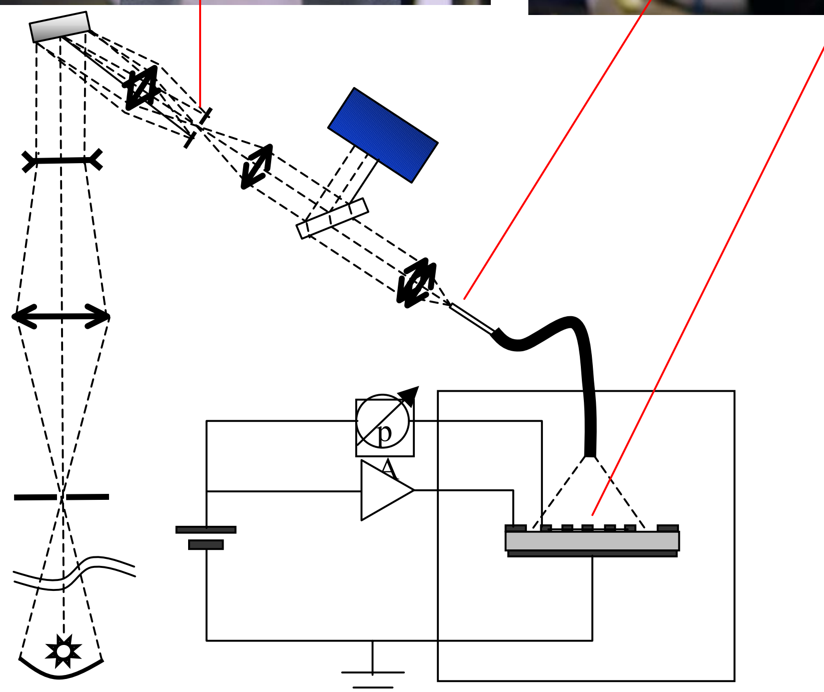
β source



Monochromator







- Photoconductivity measurement system
- Single monochromator
- Range: 180-1000 nm
- Resolution: 2.5 nm

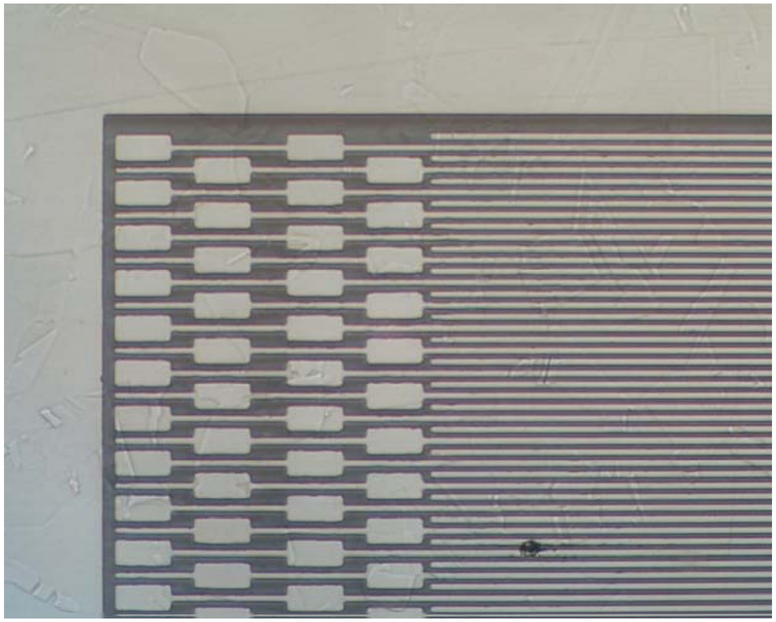
Device under test

Polycrystalline CVD diamond DEBID
(CERN RD42 collaboration)

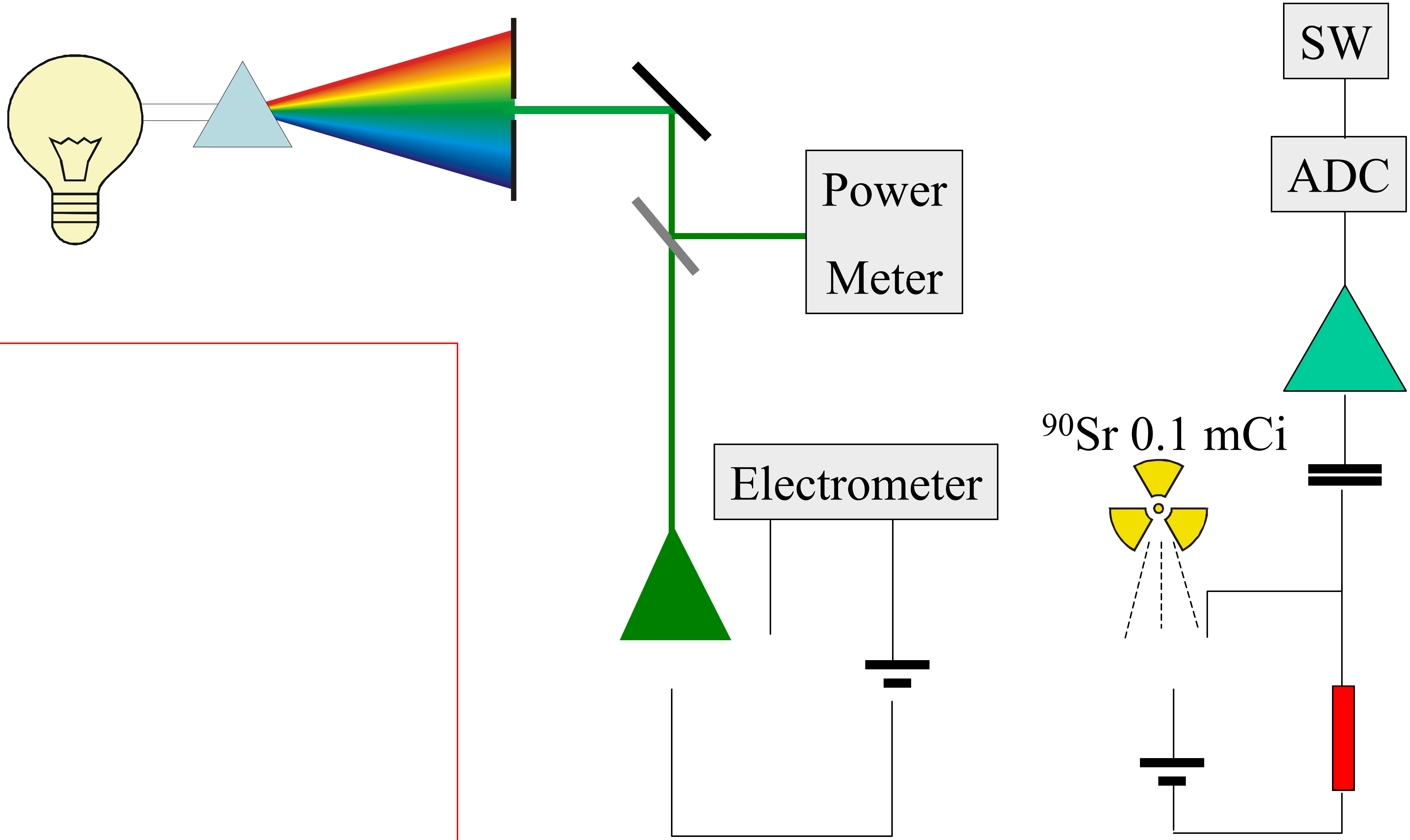
Tracking device prototype

[Sung Han for the RD42 Collaboration, “Diamond Beam Telescope for Charged Particle Tracking”, *IEEE Transactions on Nuclear Science*, 49 (4), p.1857]

- Width: 470mm
- Al metallized area: 25mm^2
- Pitch: 50mm
- Microstrips shorted



Measurement details



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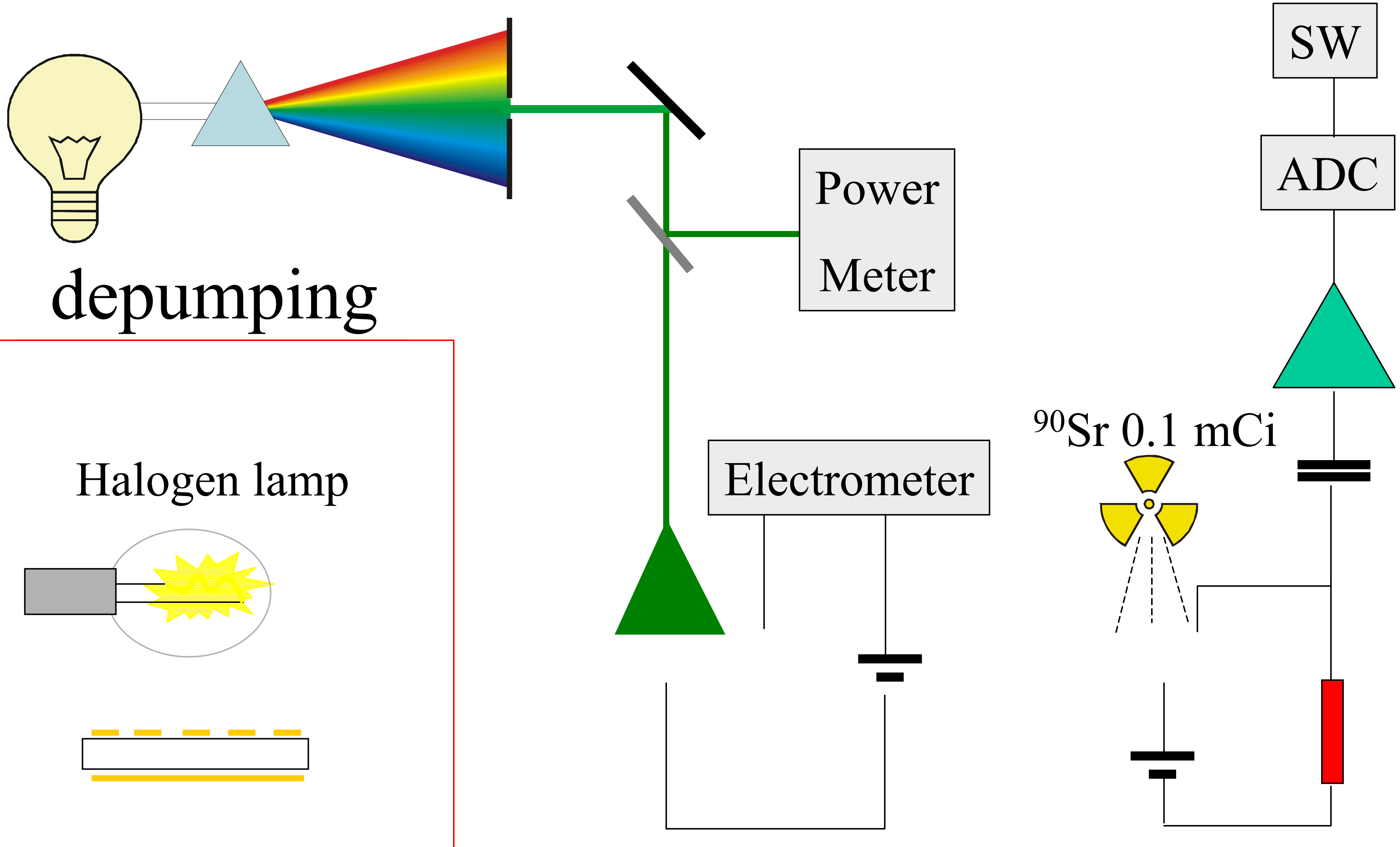

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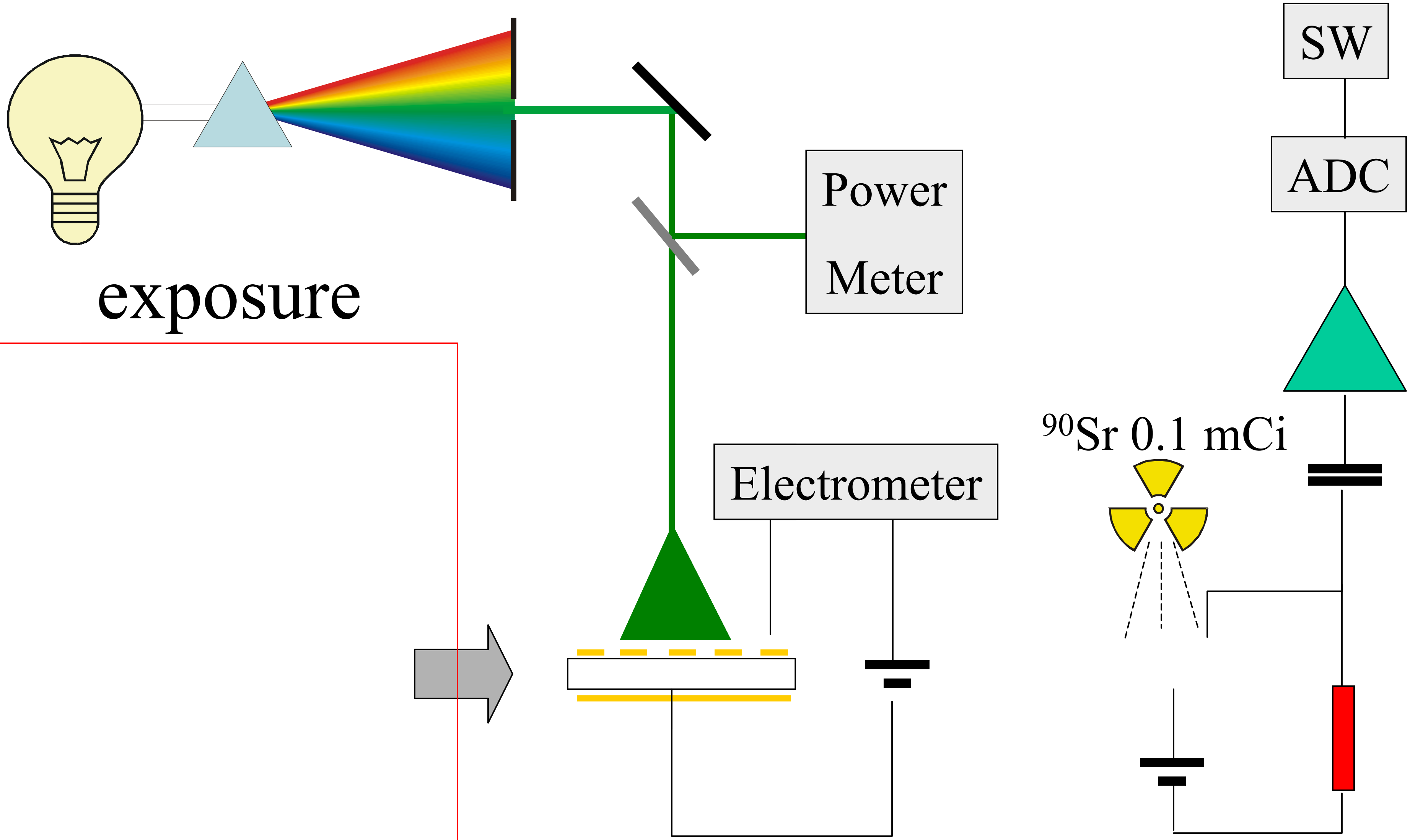

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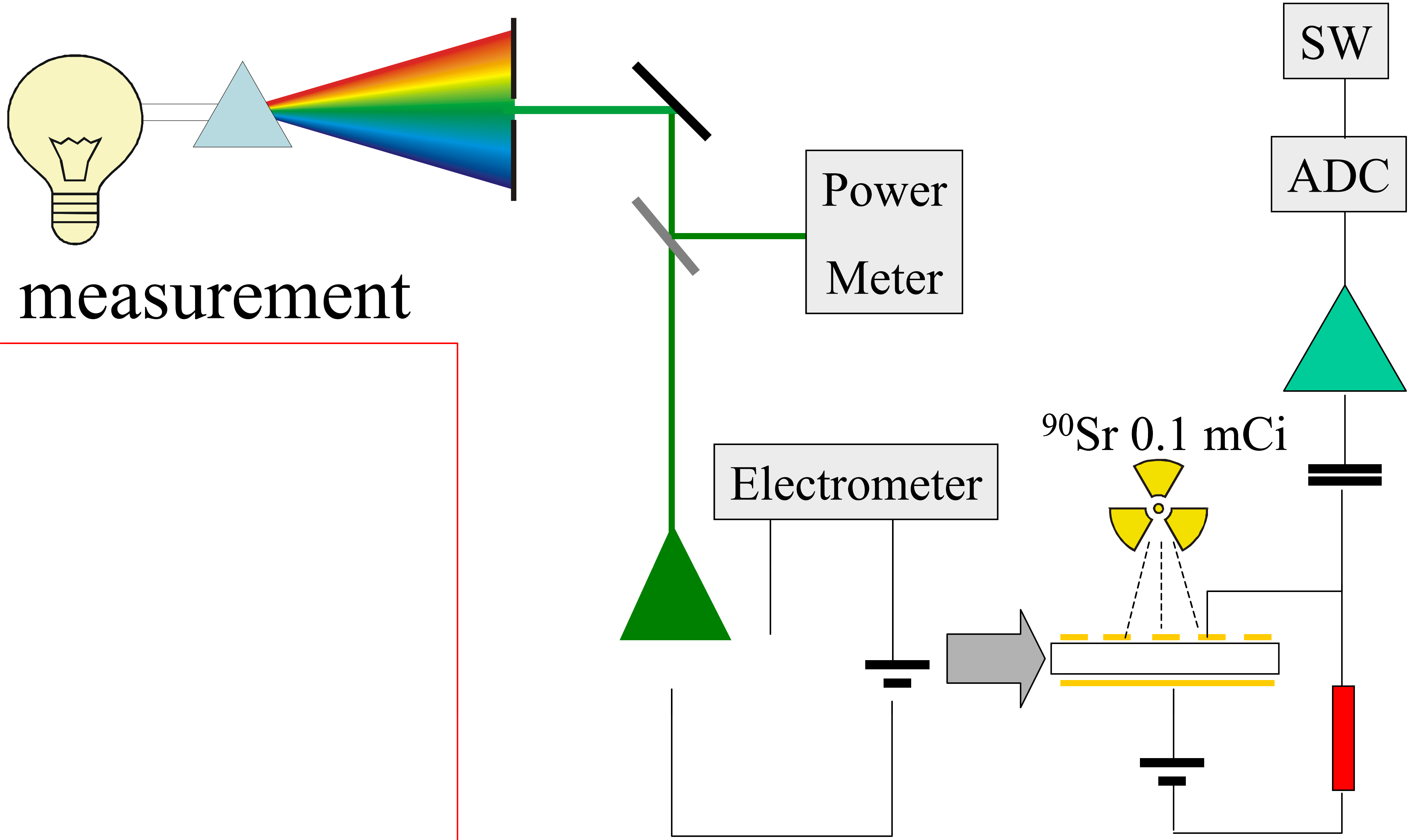

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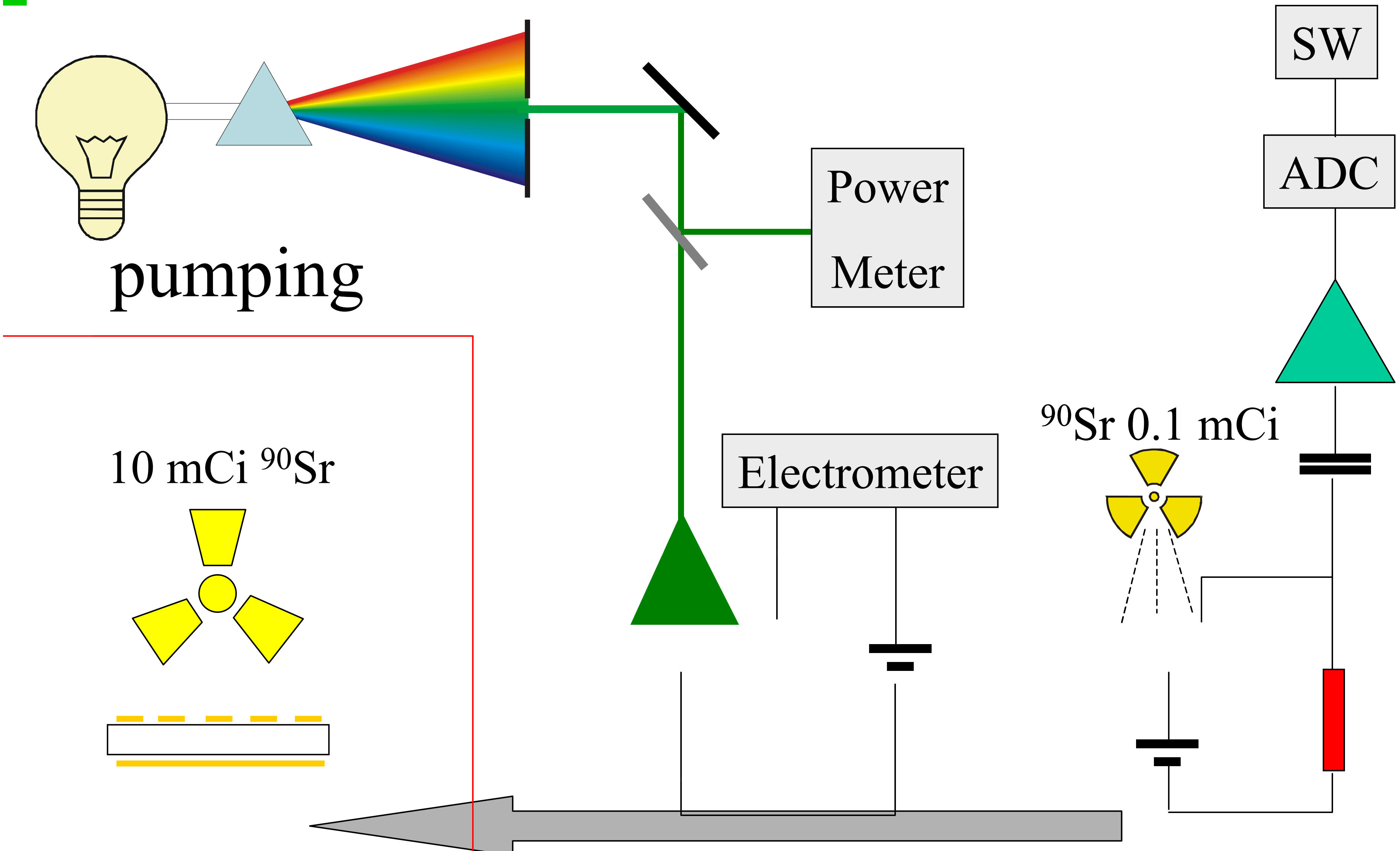

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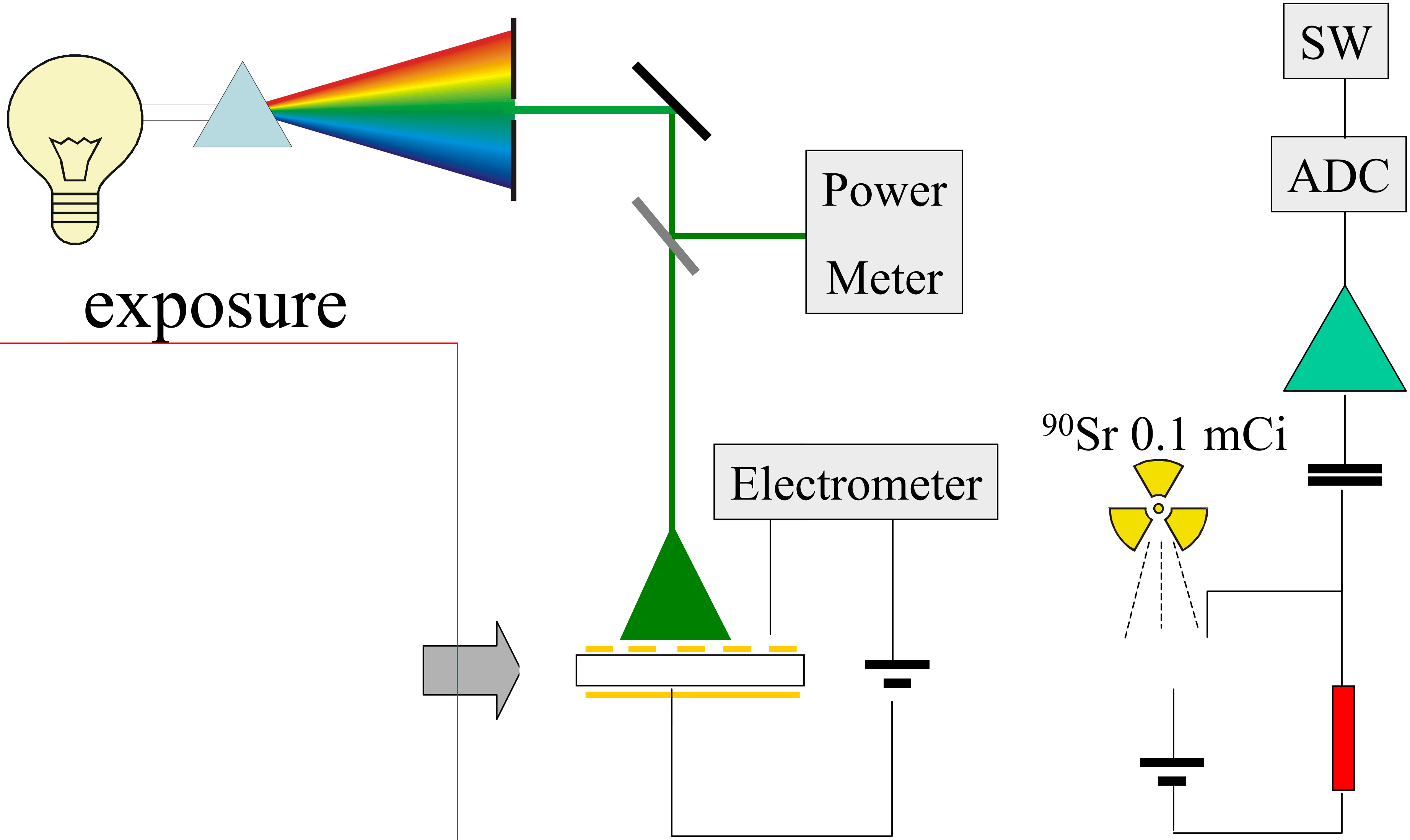

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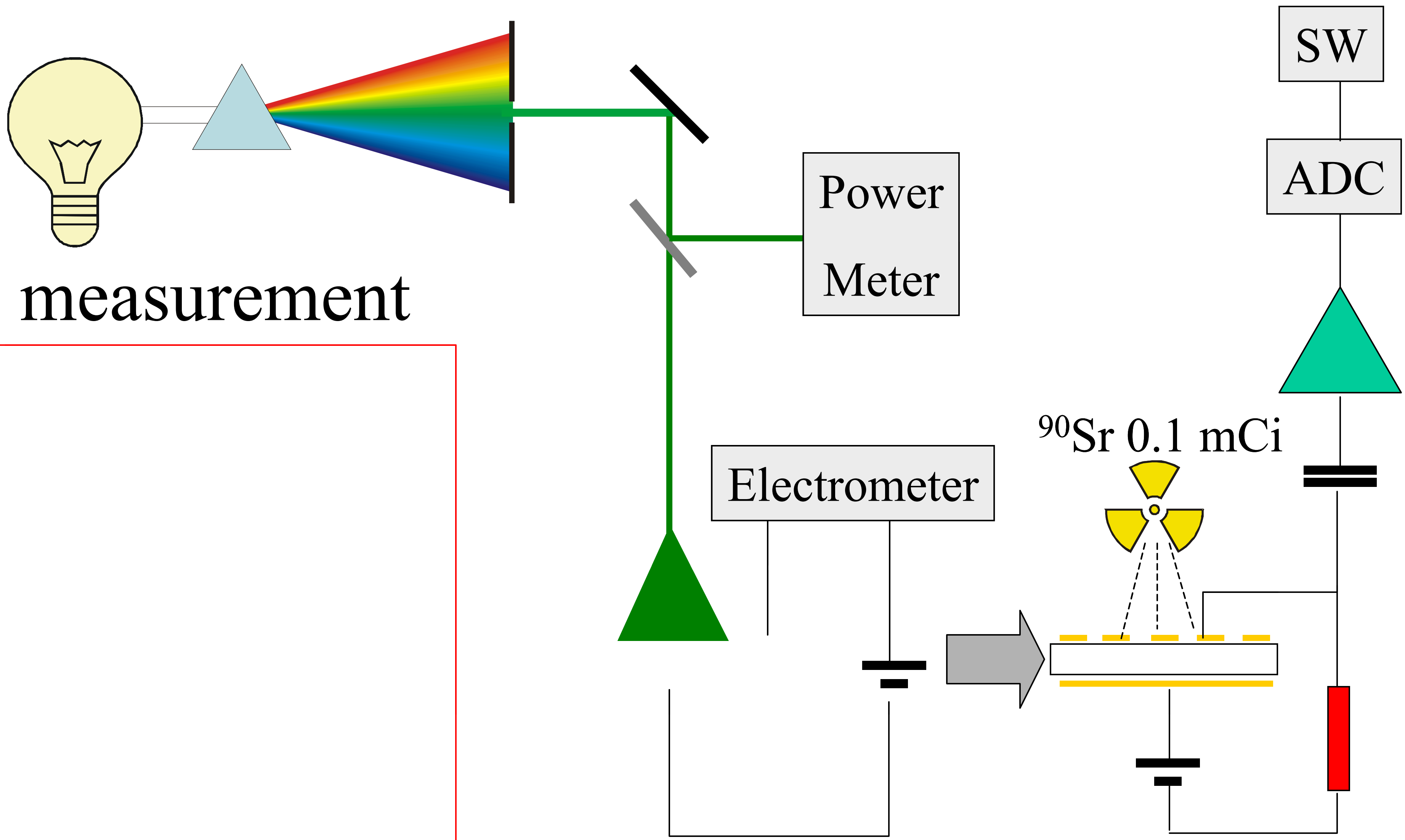

measurement

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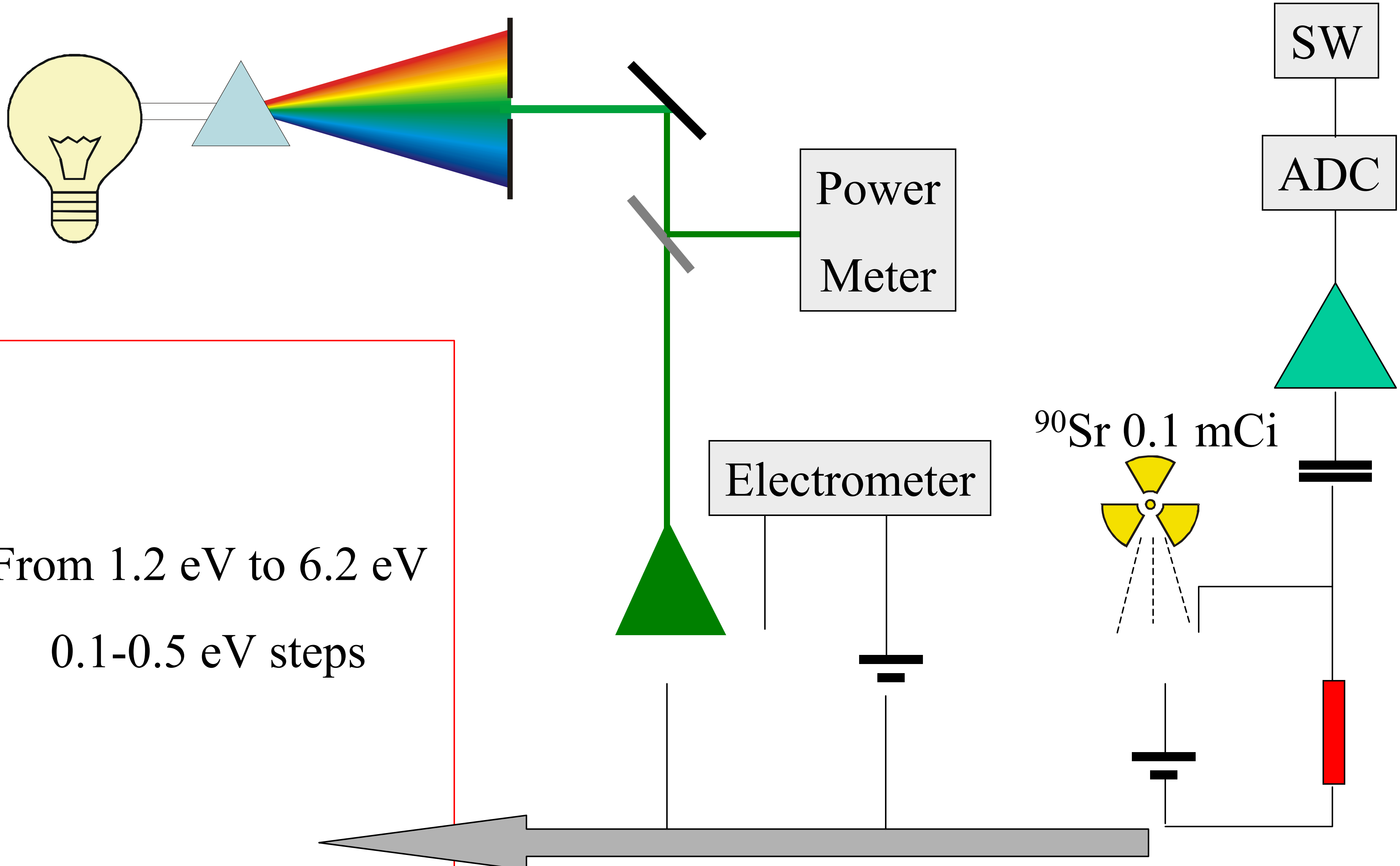
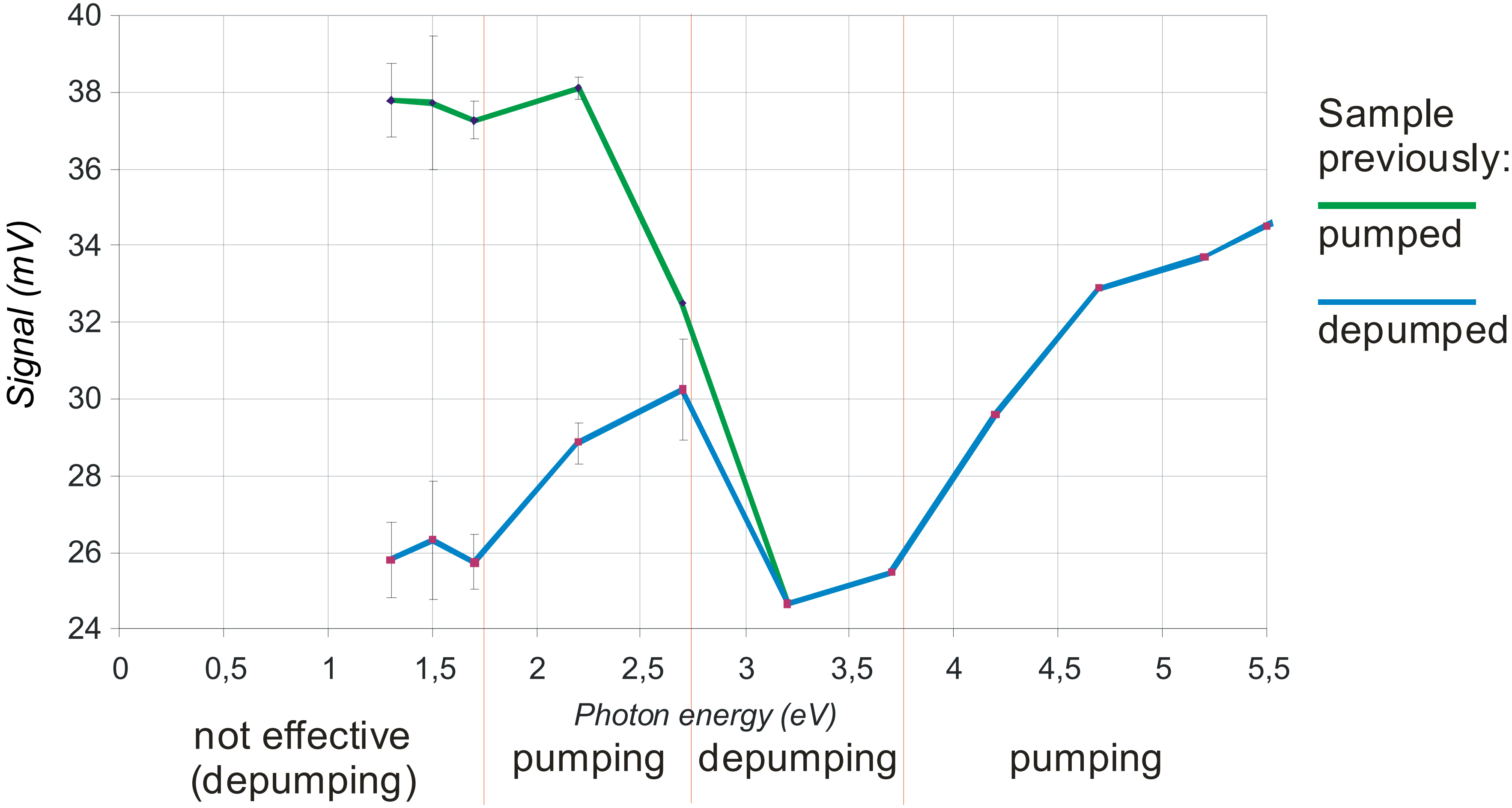


From 1.2 eV to 6.2 eV

0.1-0.5 eV steps

Charge collection distance spectrum



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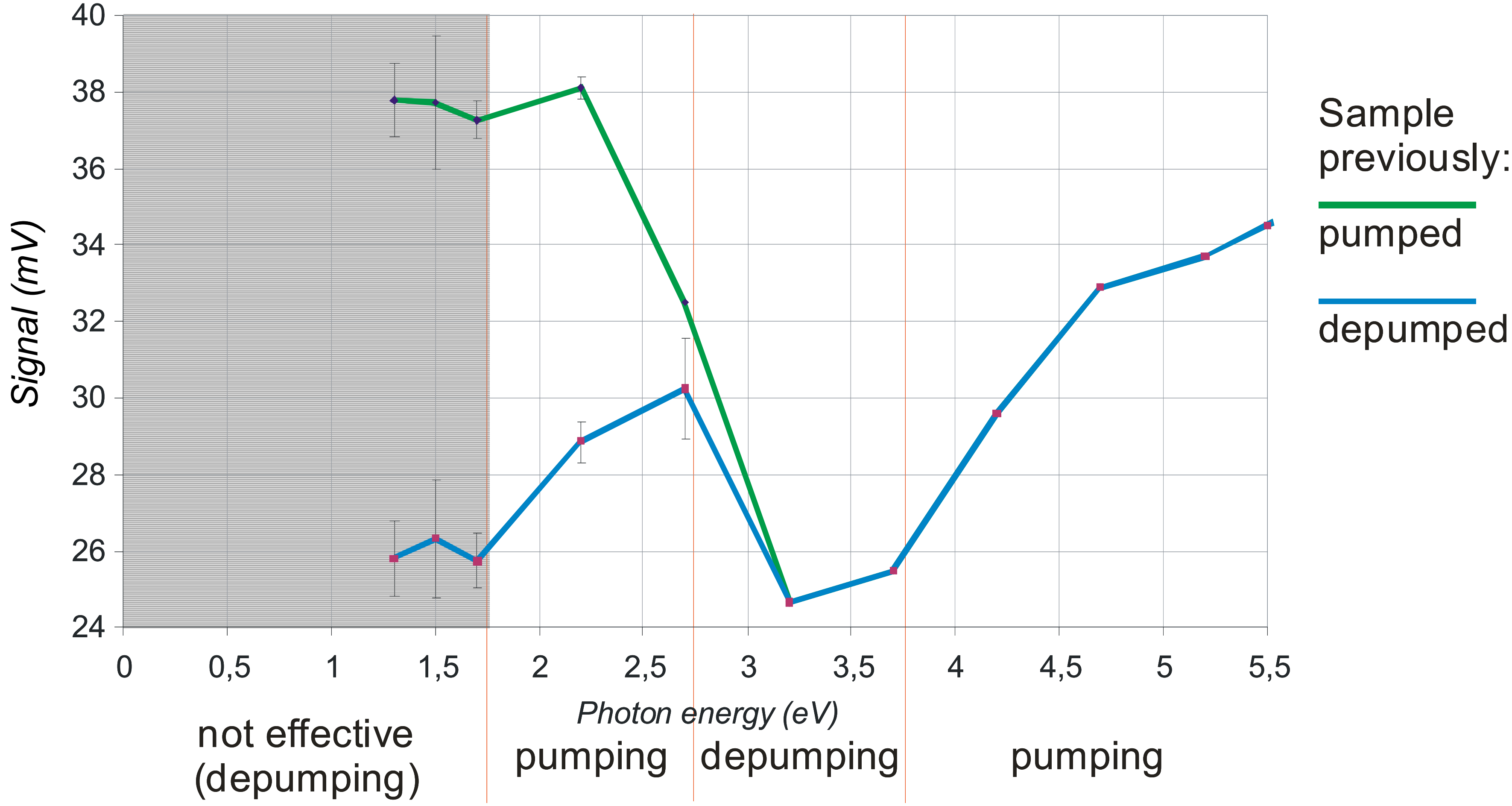
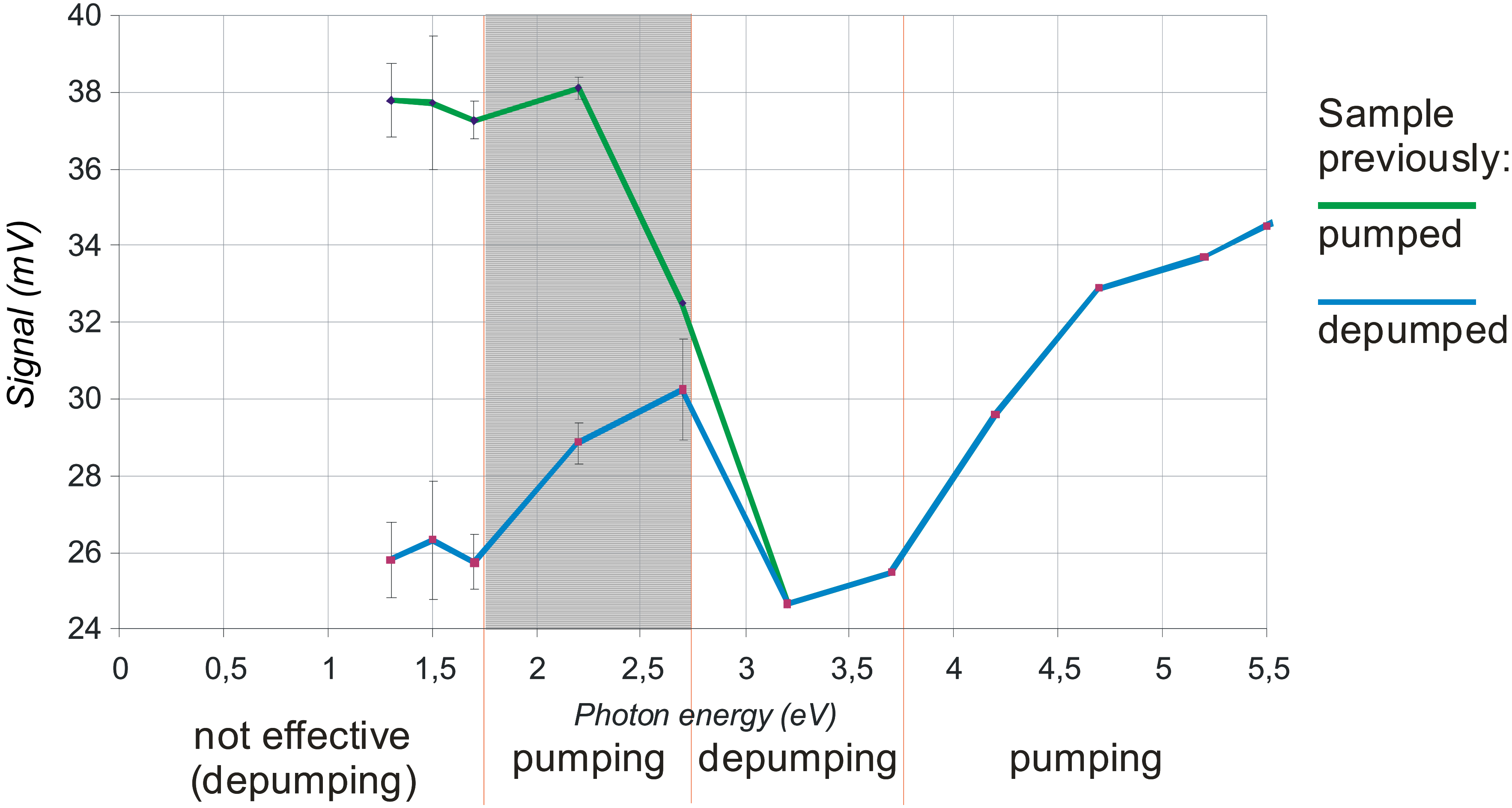


Not relevant energies, probably due to extremely low efficiency.

Thermal annealing suggests that these are depumping energies

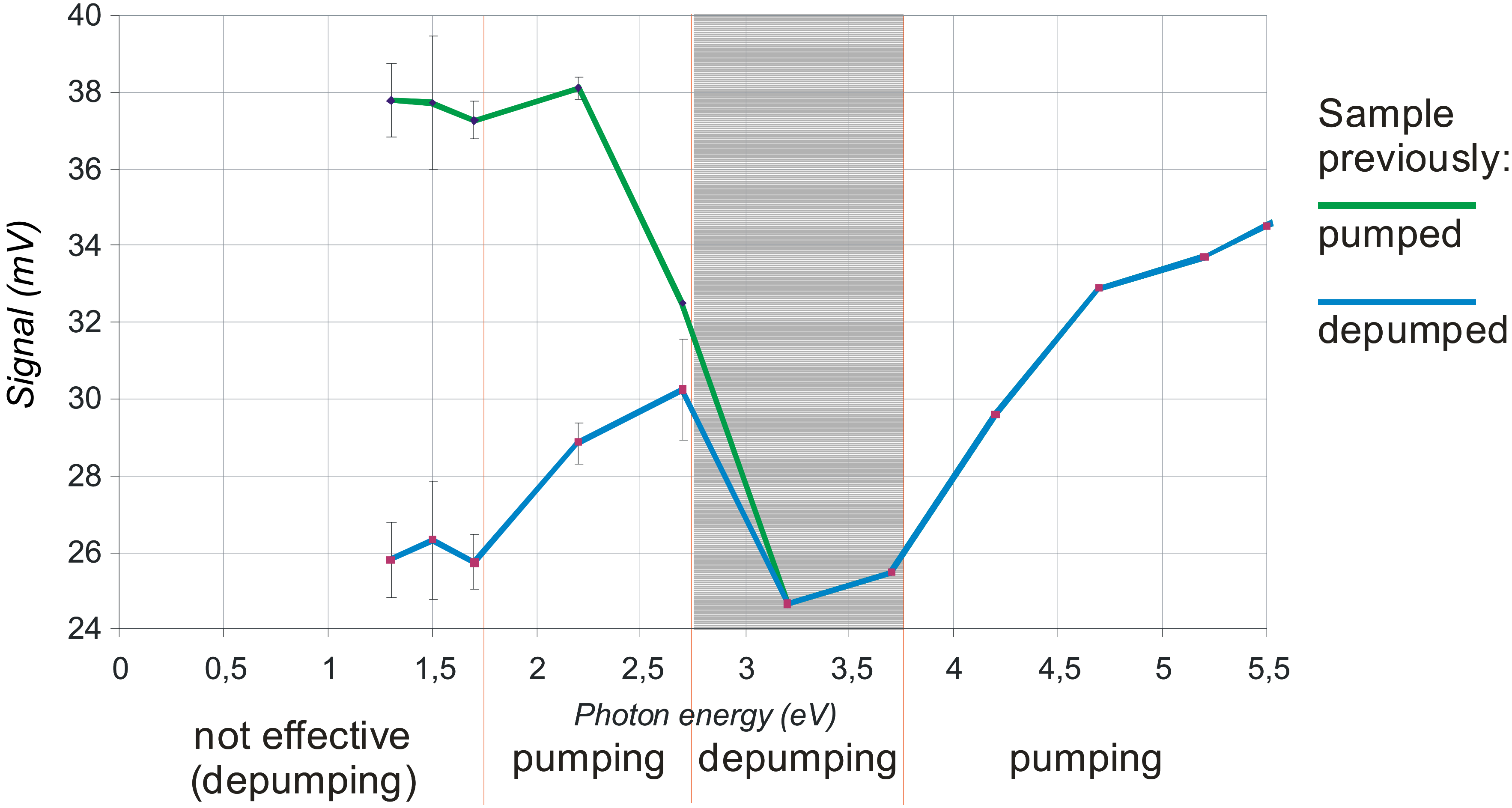
Charge collection distance spectrum



Partially pumping energies:

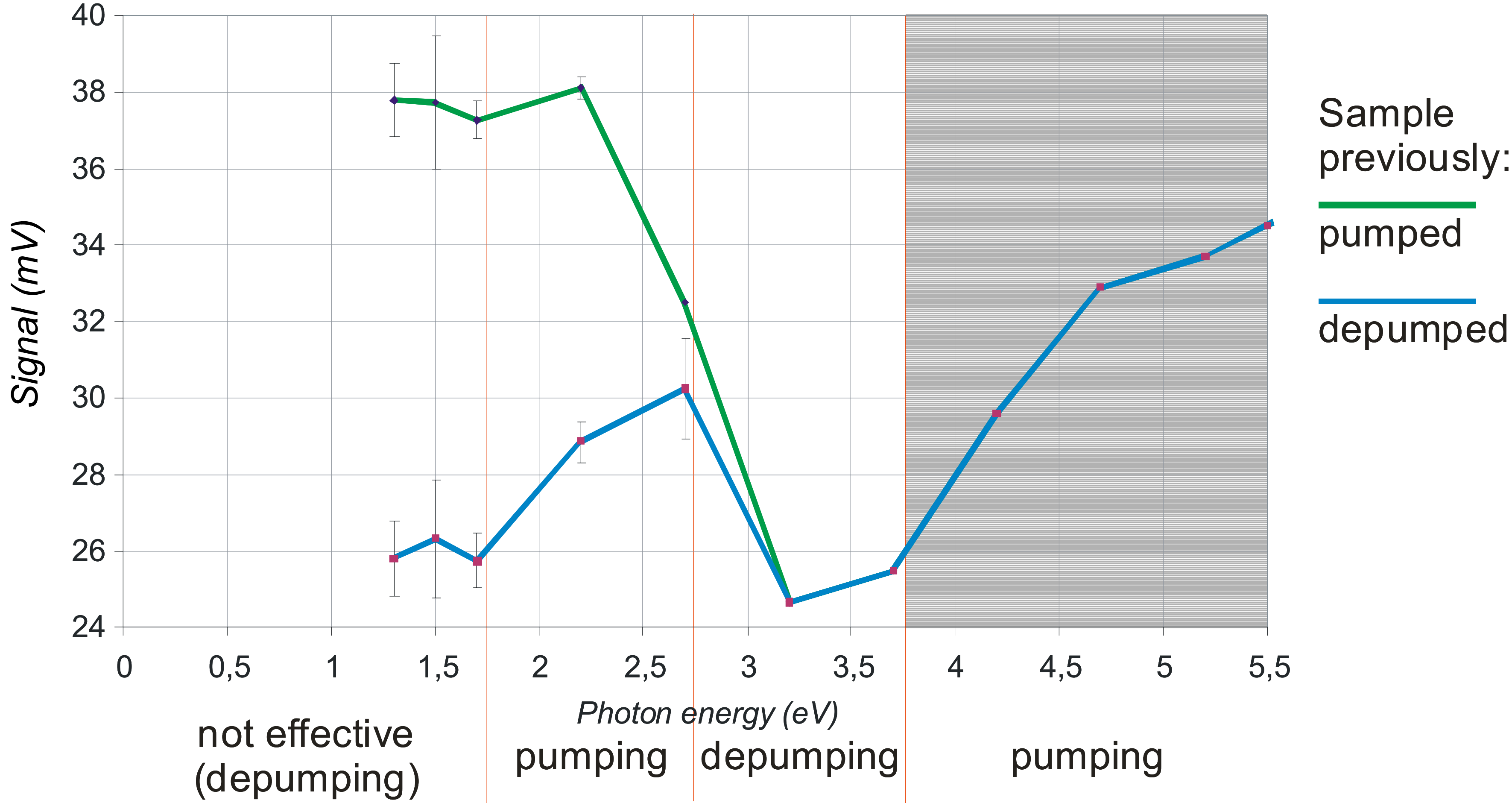
CCD tends to settle on an intermediate value

Charge collection distance spectrum



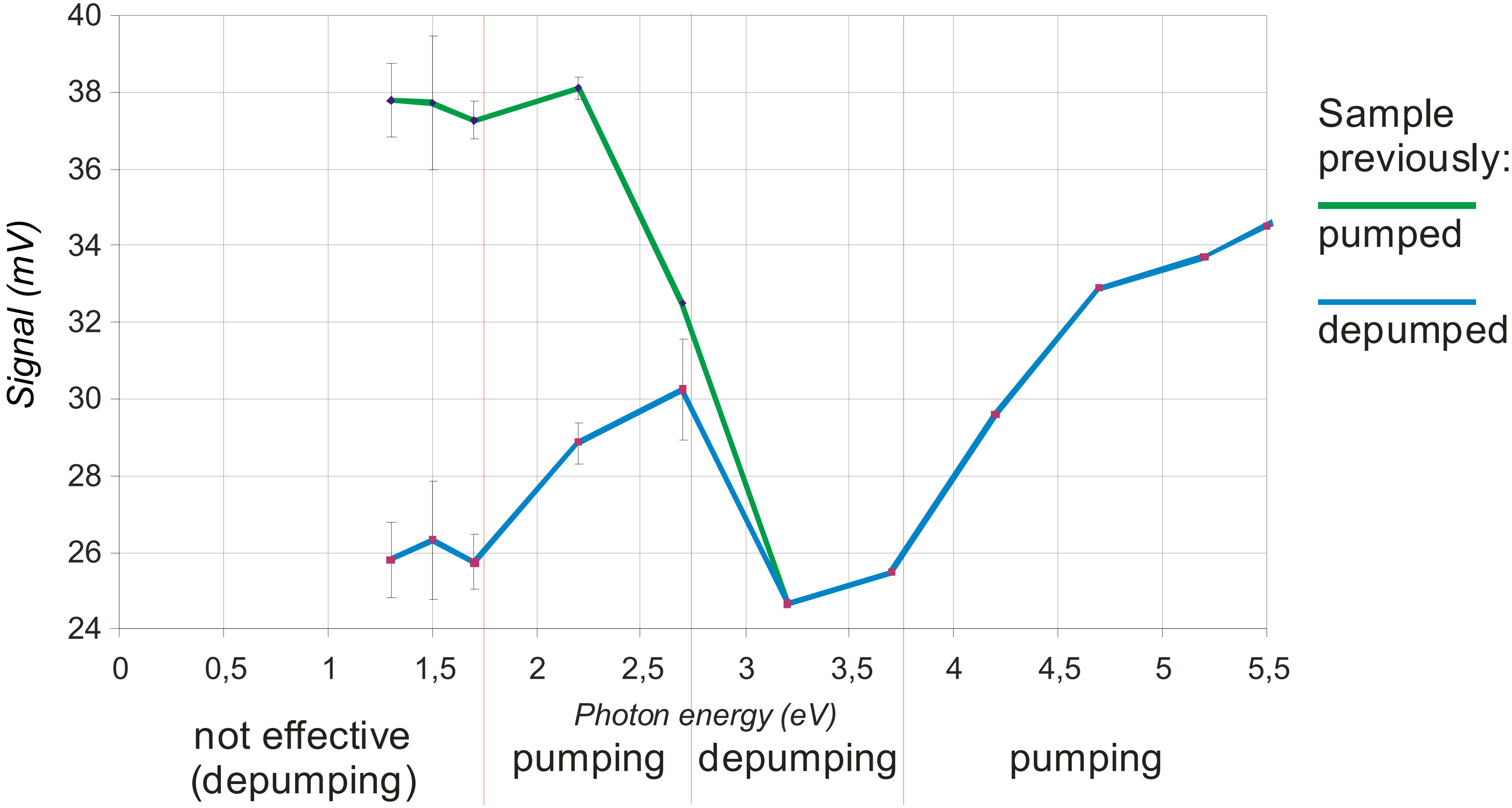
Depumping energies

Charge collection distance spectrum



Pumping energies

Charge collection distance spectrum

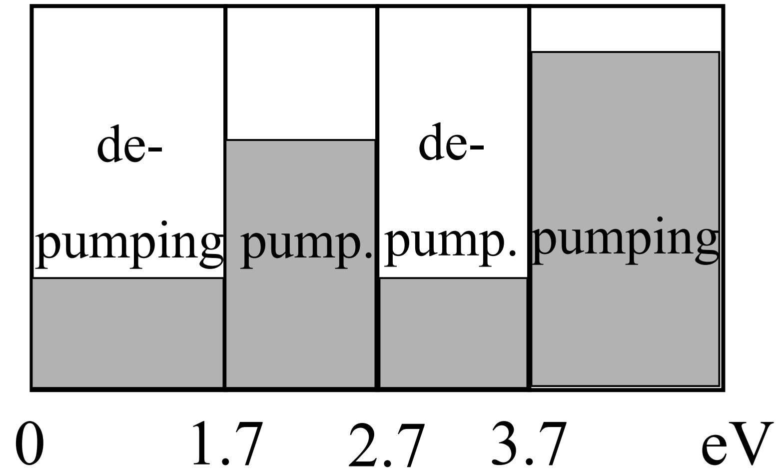


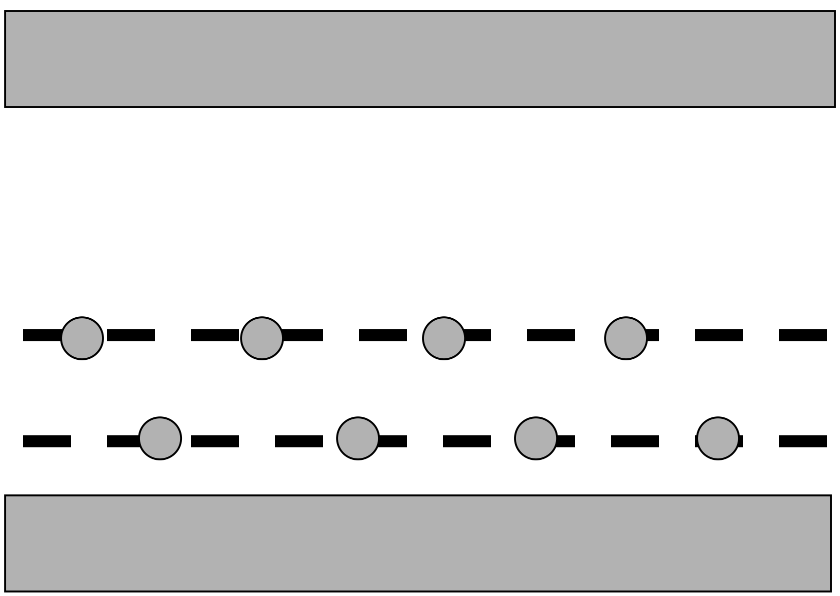
The energy range is divided in complementary intervals:

if E pumps the sample, $E' = E_{gap} - E$ depumps it

Principle of interpretation

Twofold pumping-depumping energy ranges prove the existence of two kind of centers involved in the pumping process





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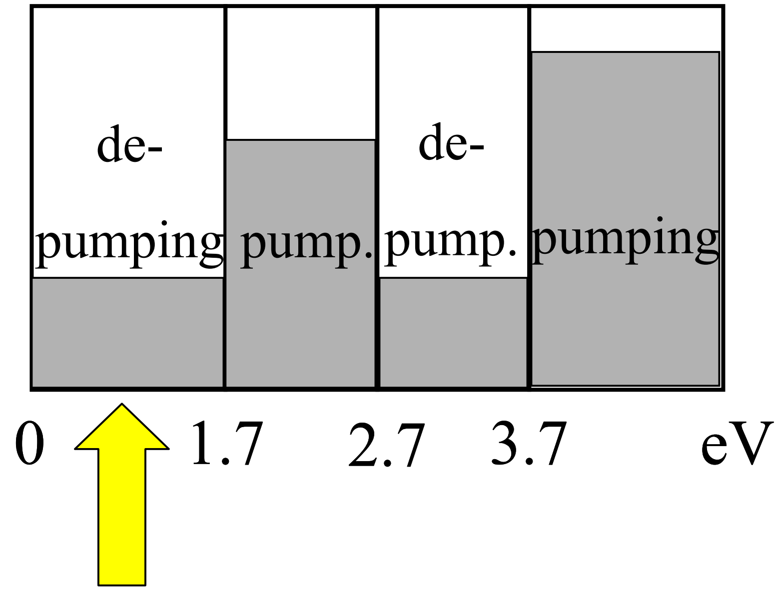
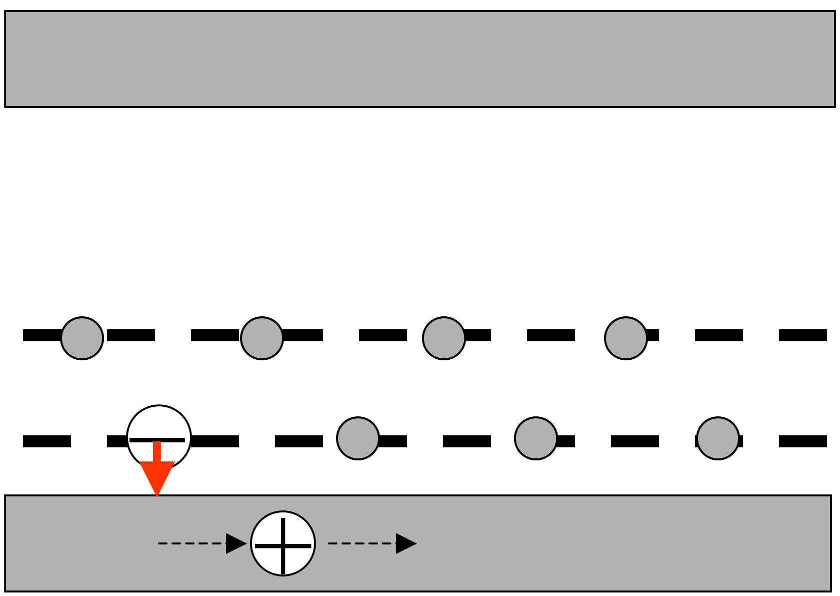


First depumping process:
emission



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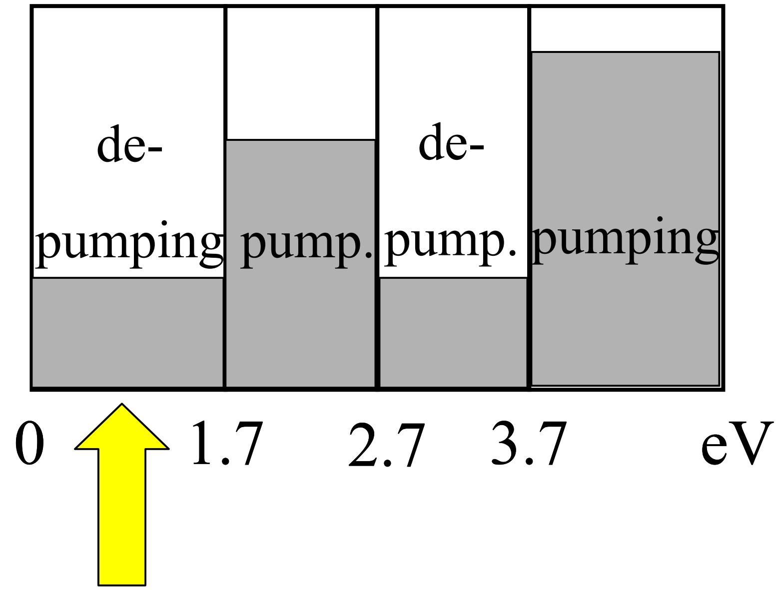
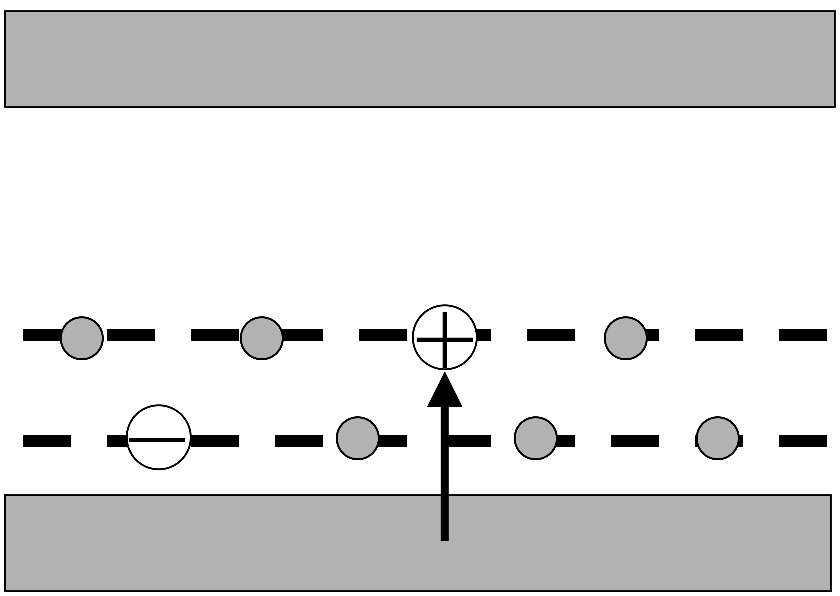


First depumping process:
recombination



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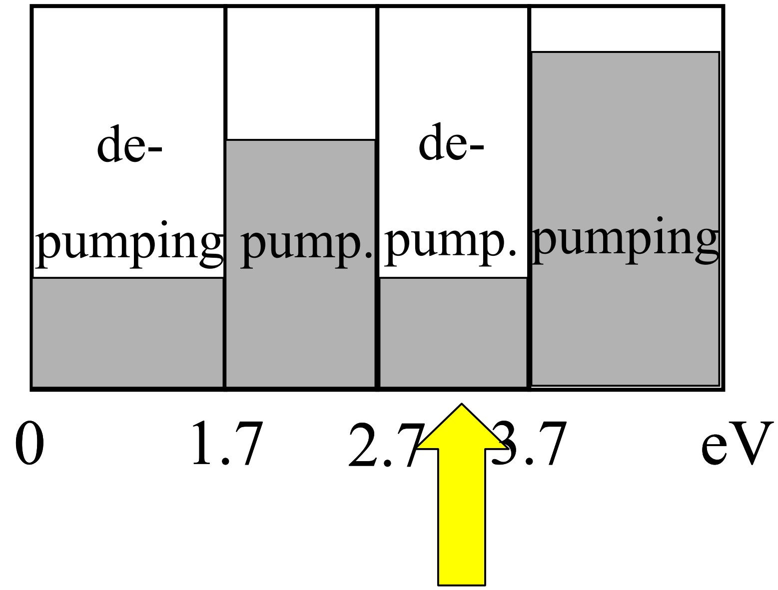

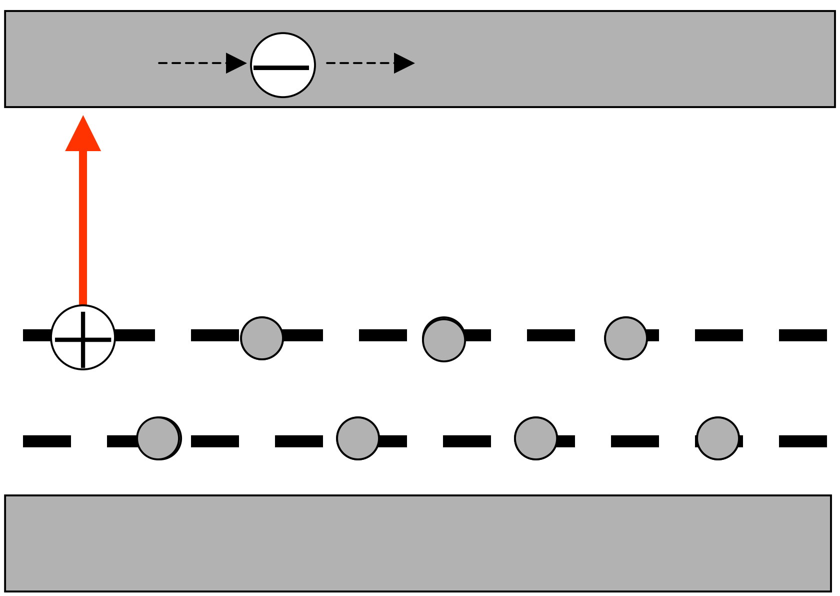

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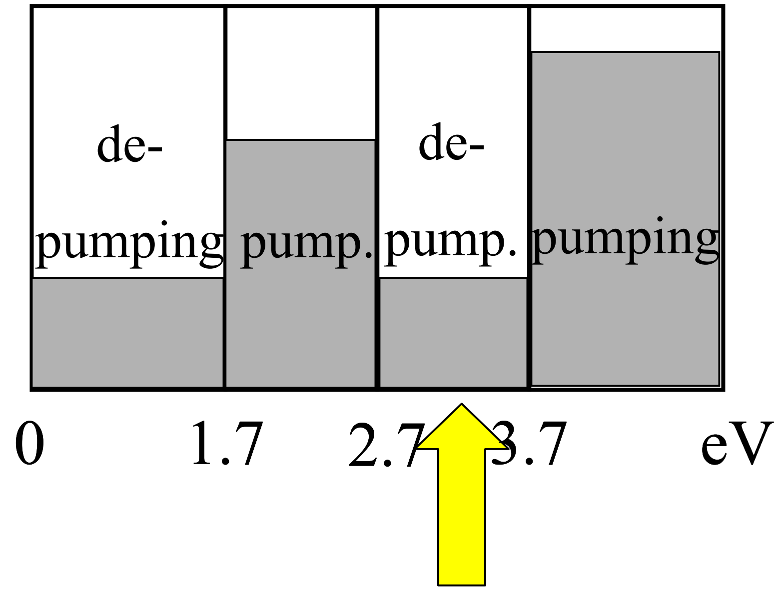

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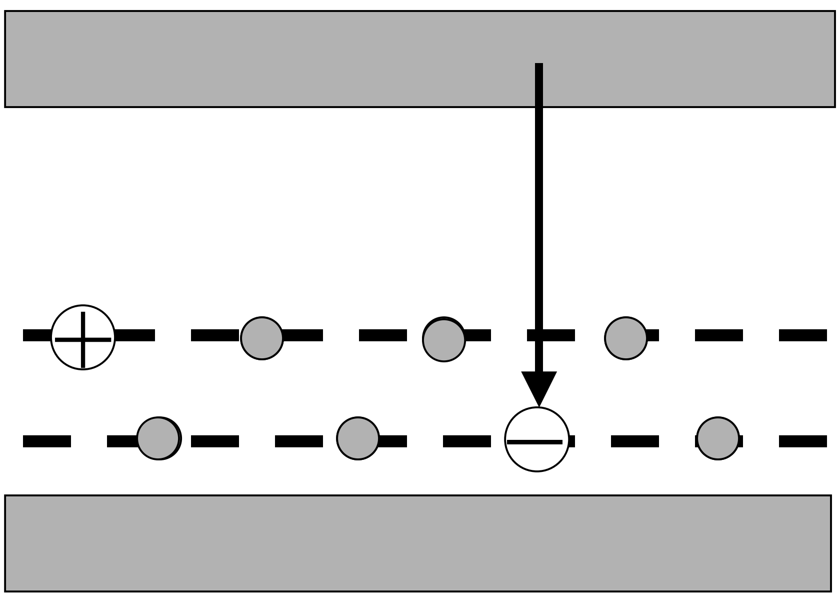

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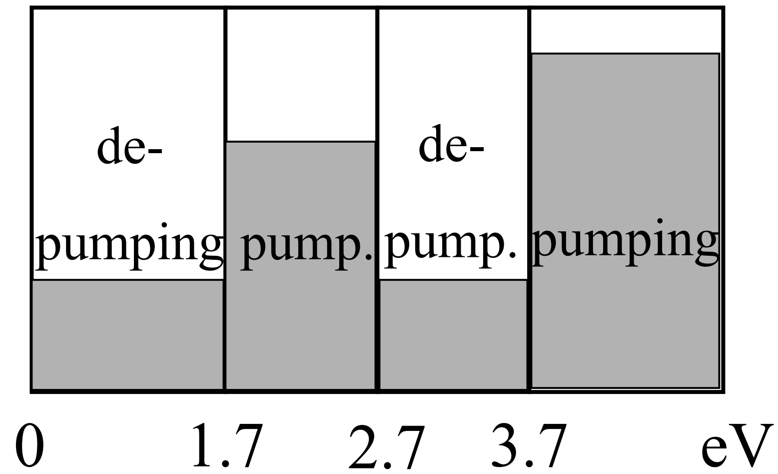

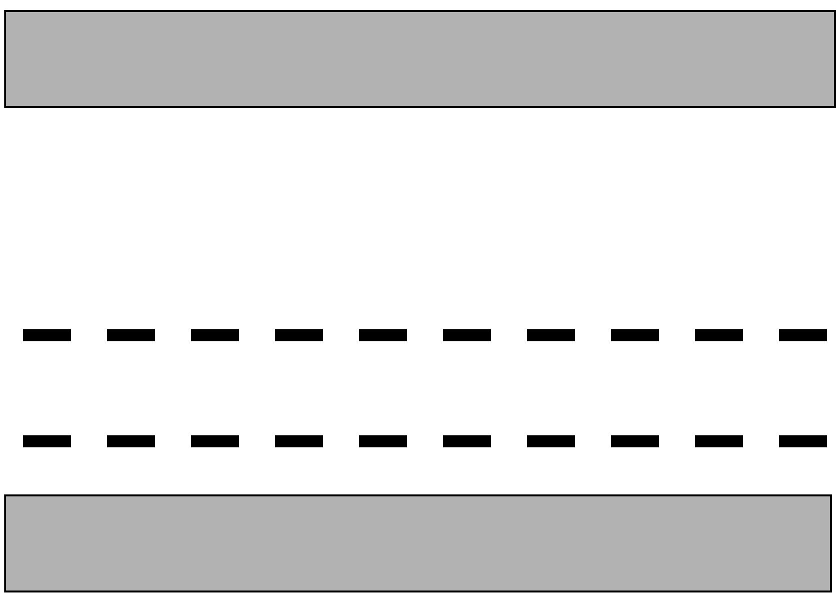

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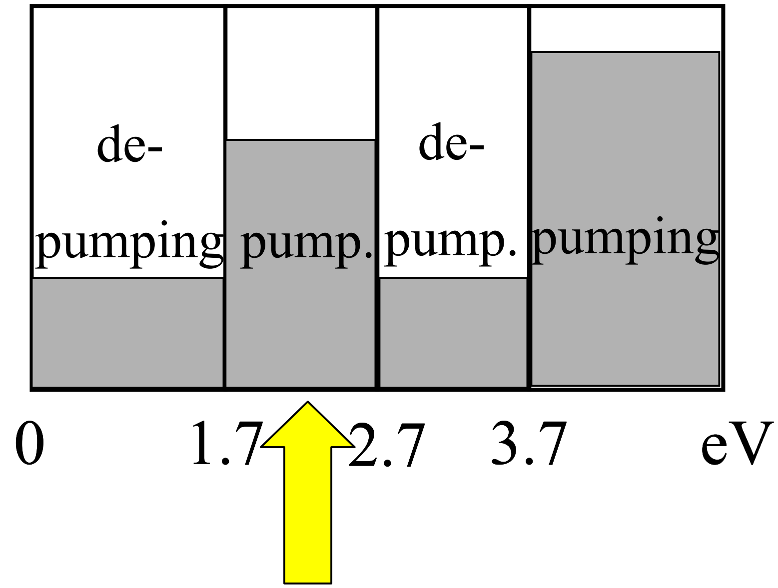

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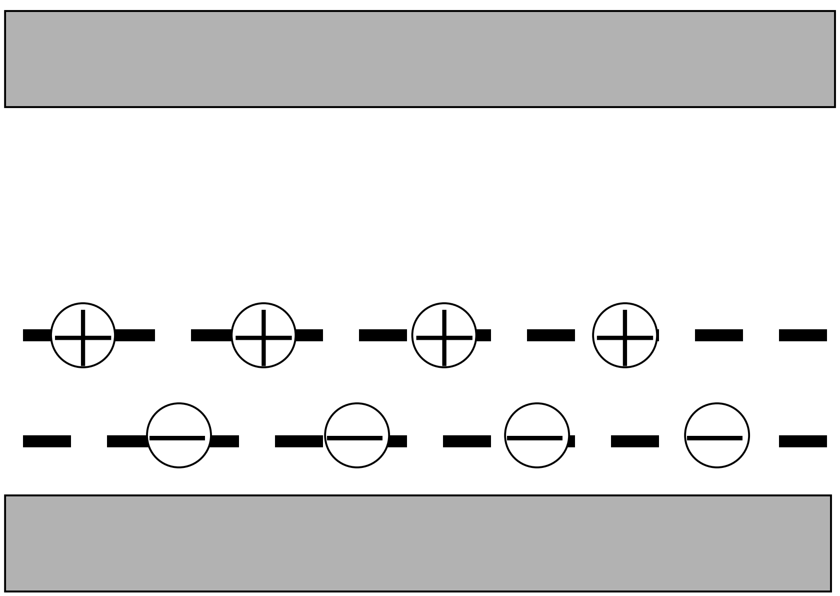

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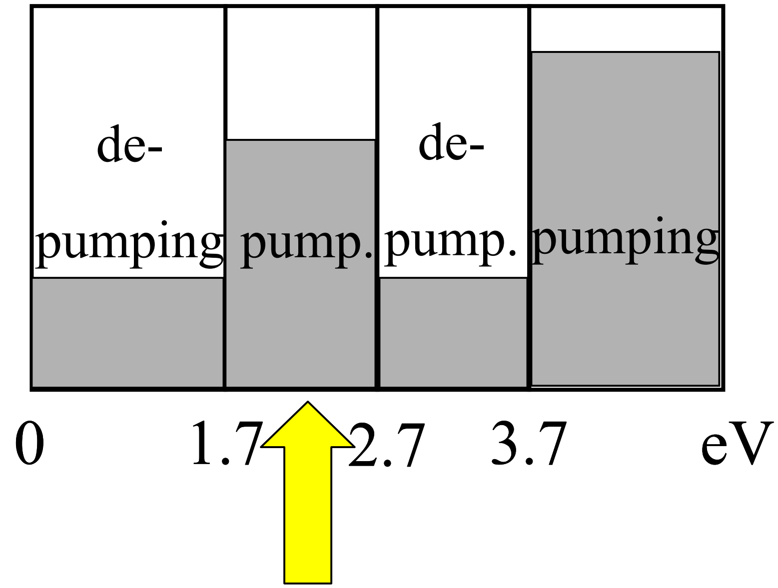

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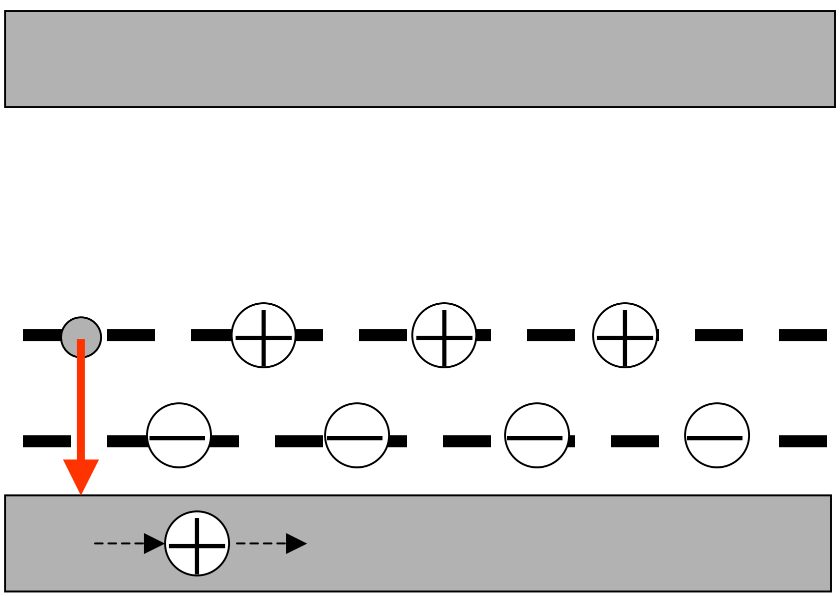

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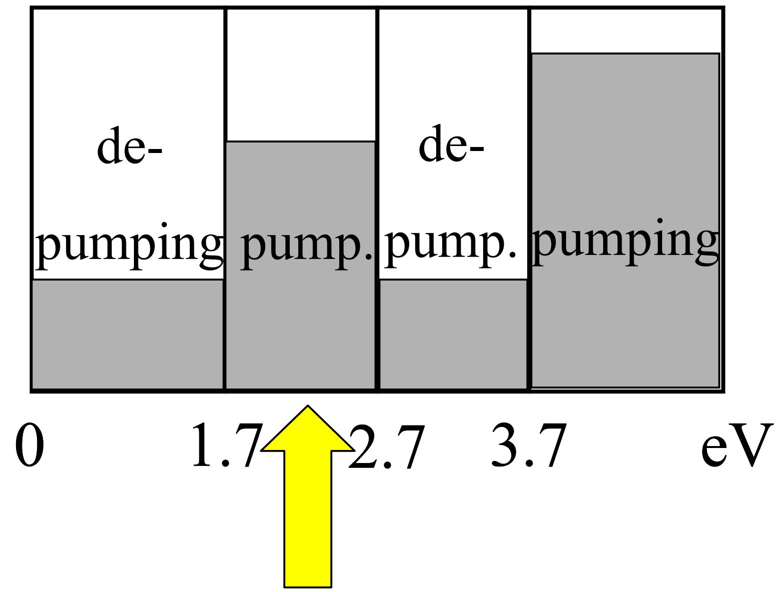

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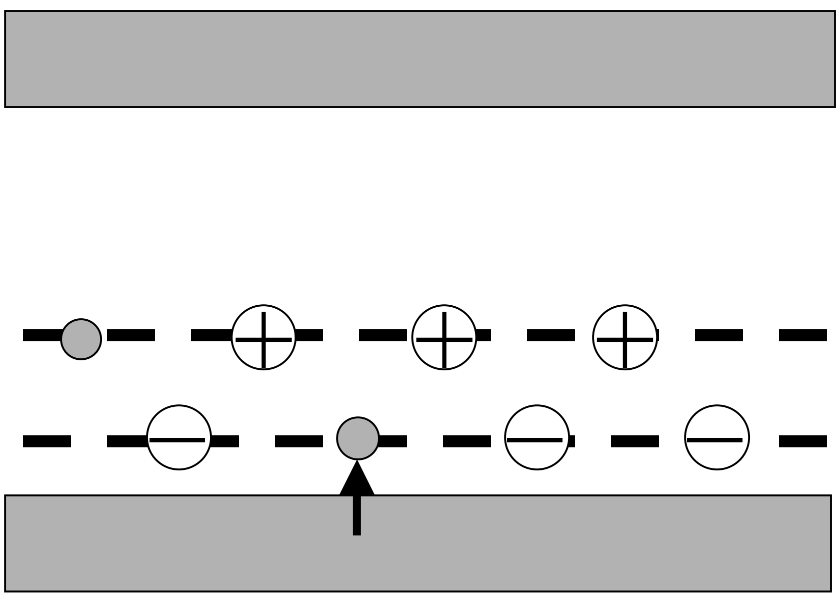

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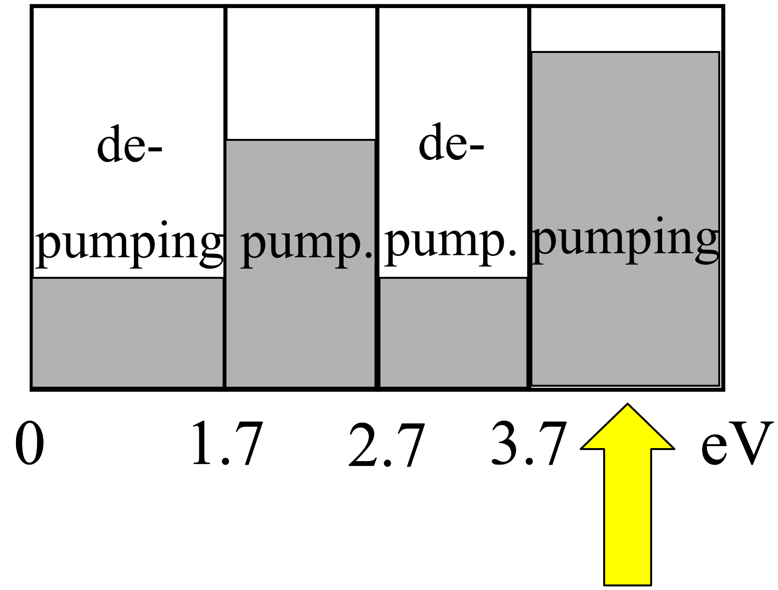
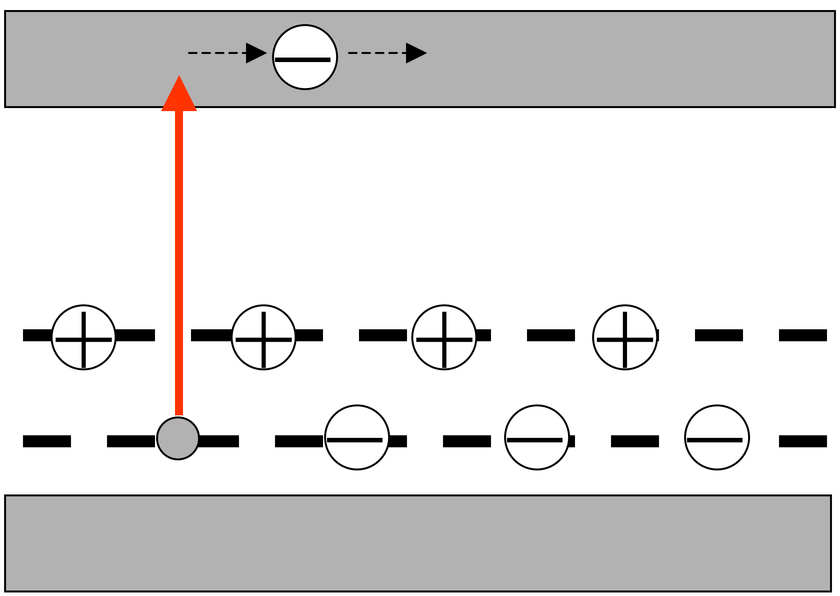
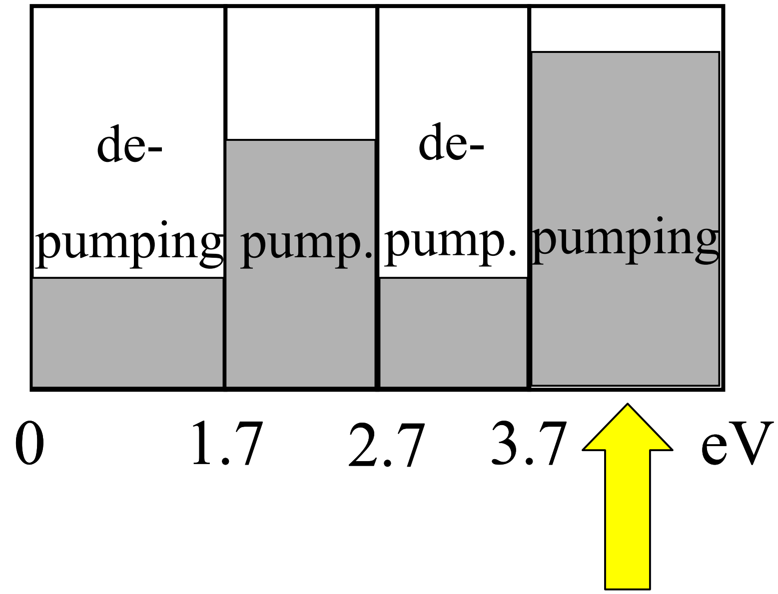


Second pumping process:
emission

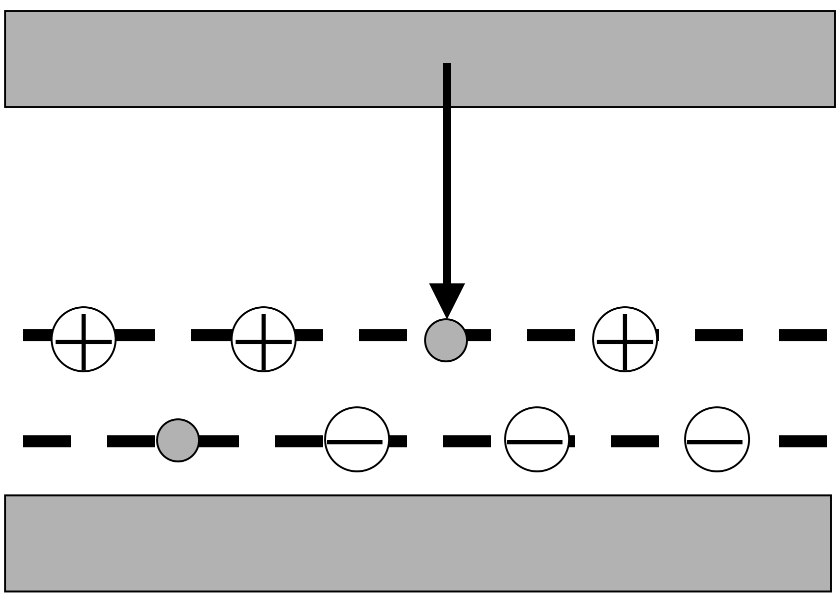


Principle of interpretation

Twofold pumping-depumping energy ranges prove the existence of two kind of centers involved in the pumping process



Second pumping process:
recombination



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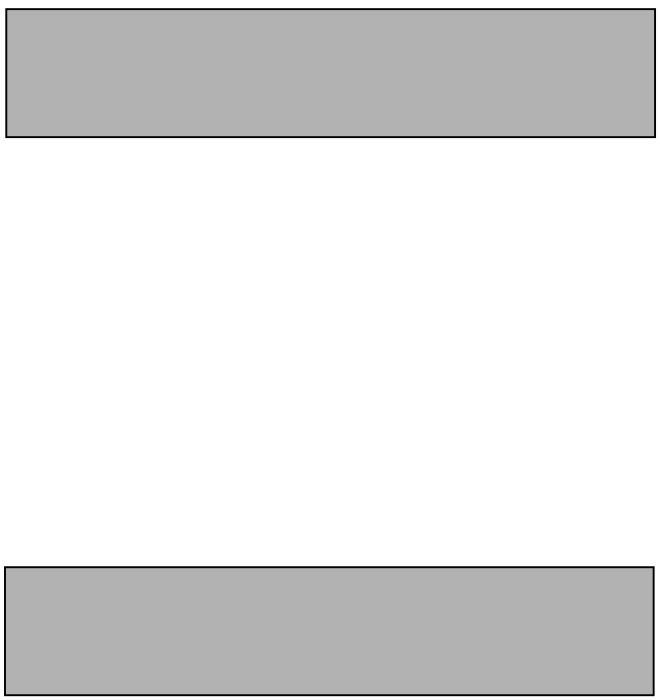
Observations indicate, for the CVD diamond sample under examination, the following structure



- Two bands of level in the low half bandgap
- Low band negative and high band positive in the depumped state, both neutral in pumped state
- Lower band begins at about 1 eV and ends at about 1.7 eV, higher band begins at 1.7 eV and ends at about 2.7 eV
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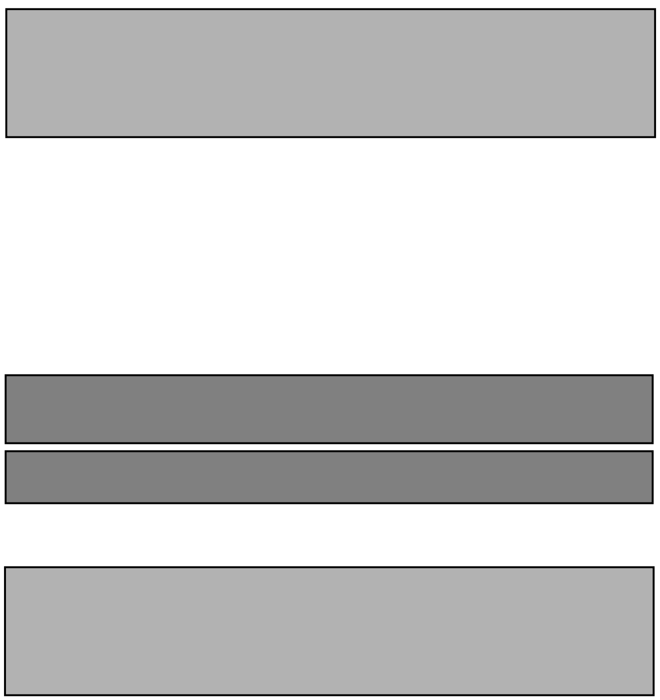

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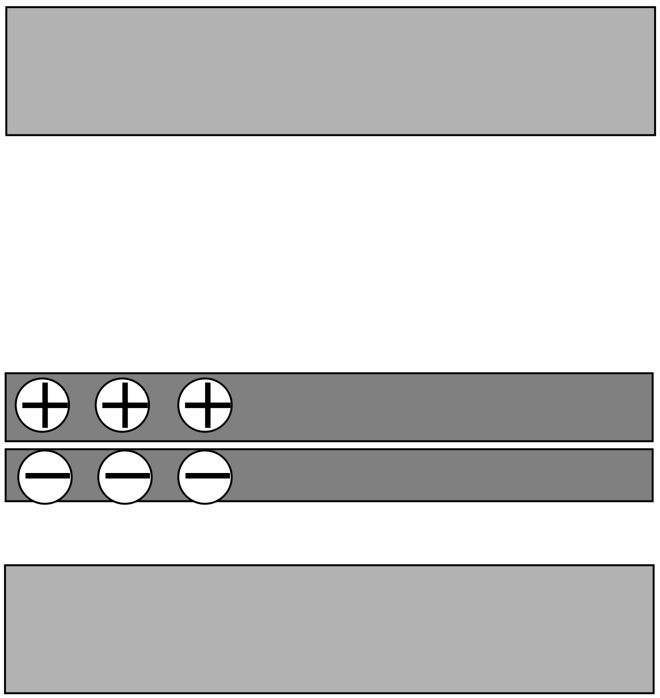

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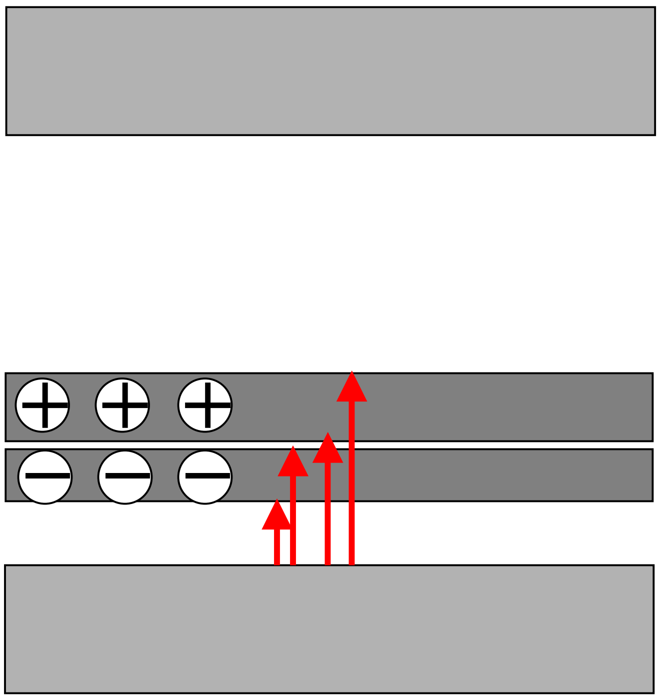

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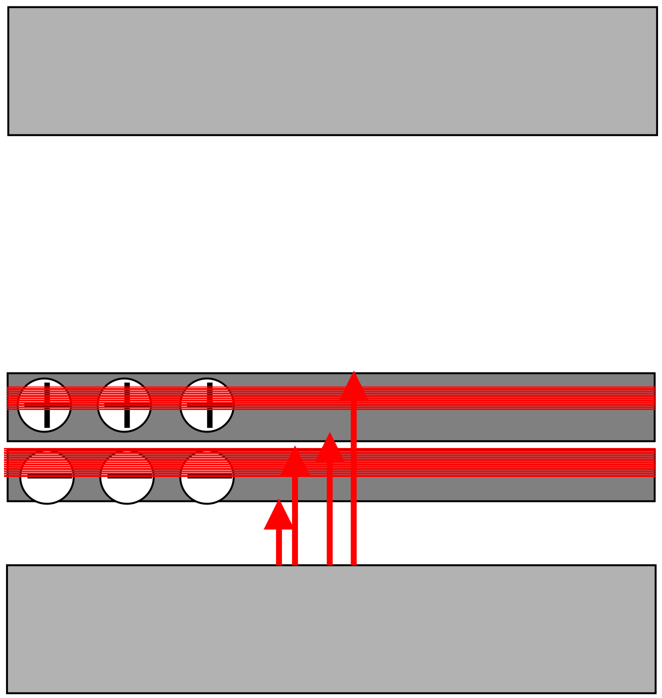

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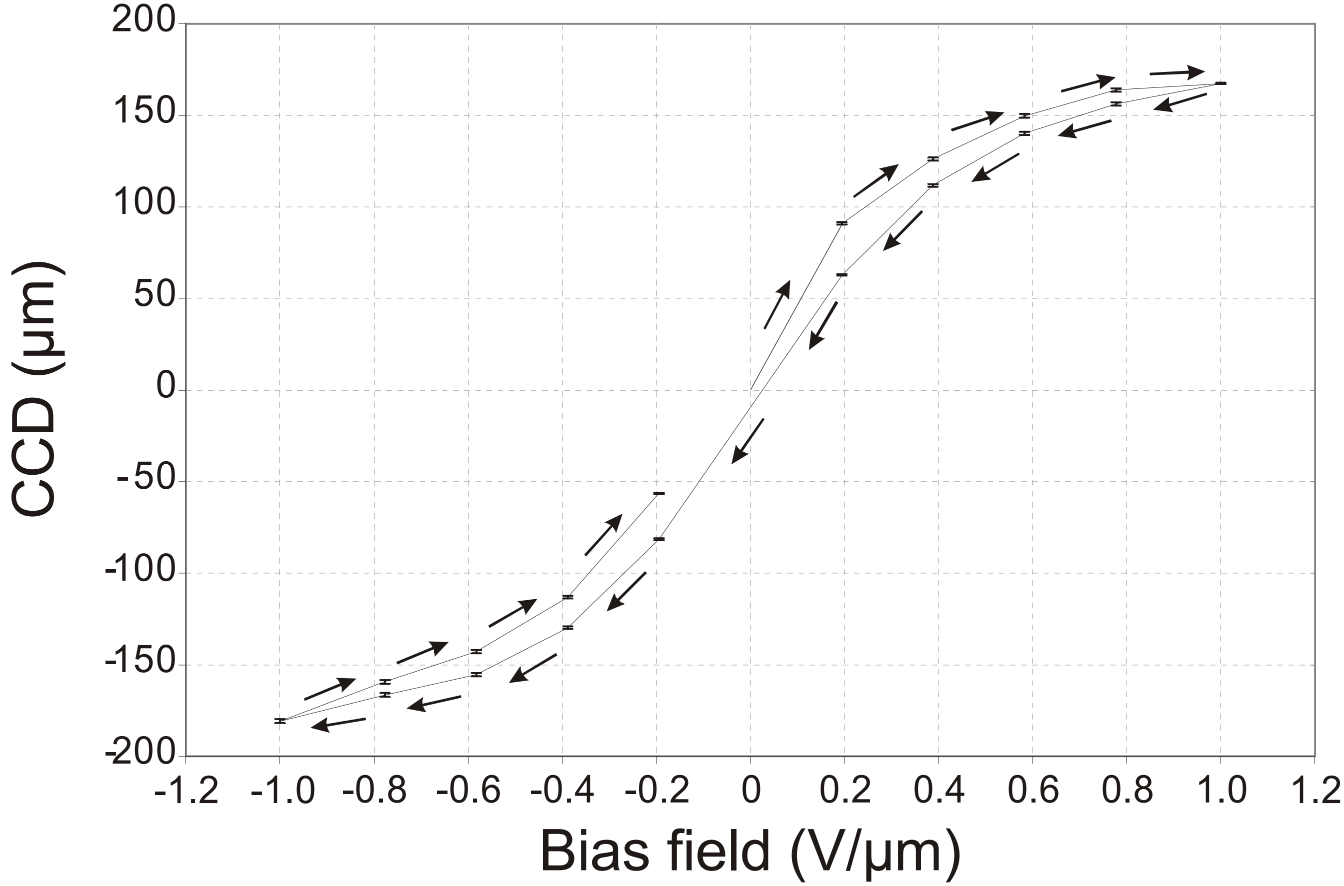
A detailed study on pumping

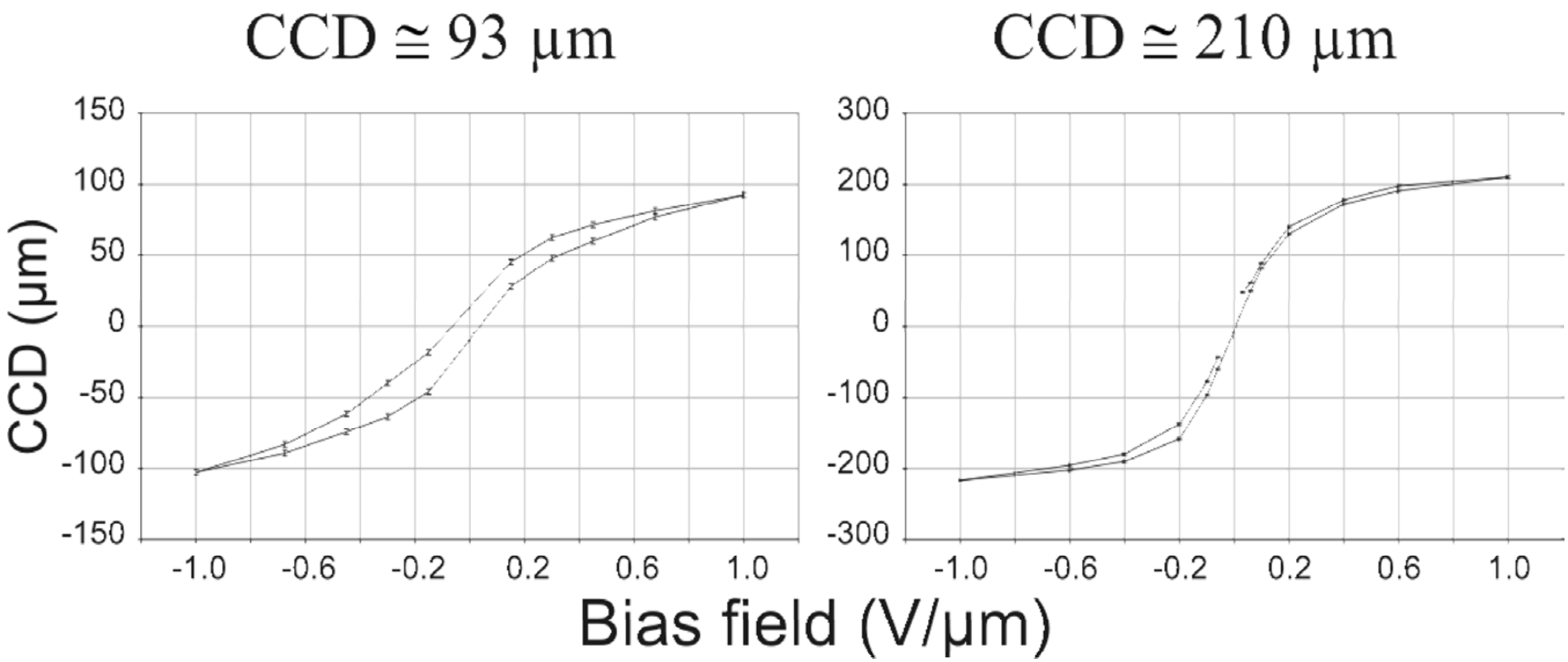
- Correlation of polarization effect with respect to CCD in various diamonds
- Correlation of pumping efficiency with respect to CCD
- Study of bias voltage influence on pumping dynamics

Hysteresis effect



This effect is known in CVD diamonds

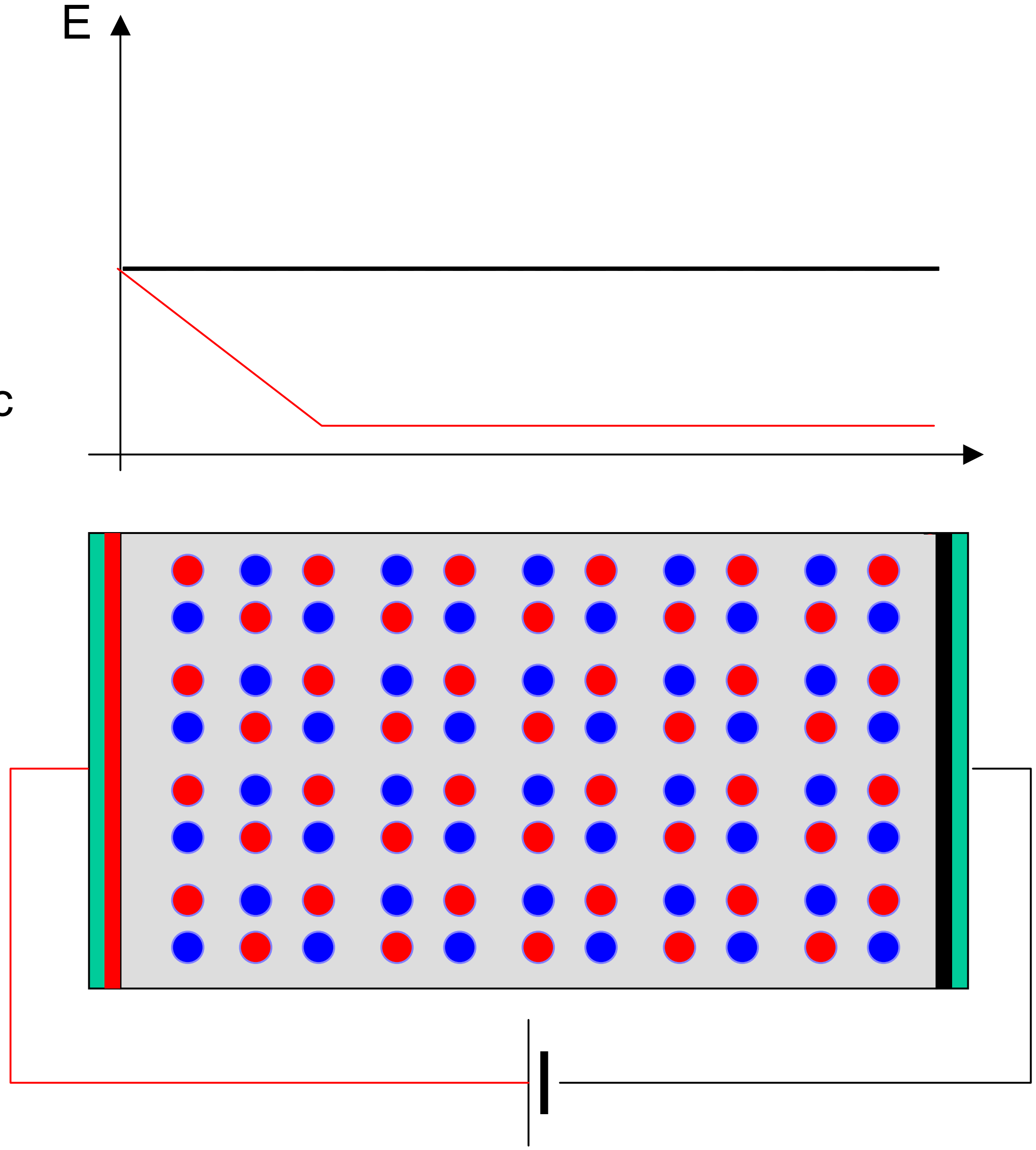
Hysteresis vs. CCD

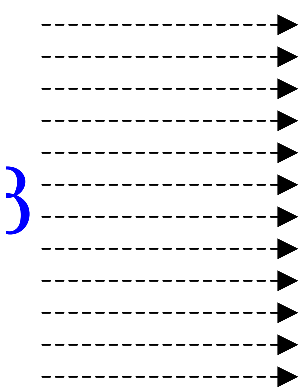


- Hysteresis is anticorrelated to CCD

Polarization effect

Beta irradiation
Charge displacement,
Local charge neutrality,
One carrier model
Uniform electric field
Polarization





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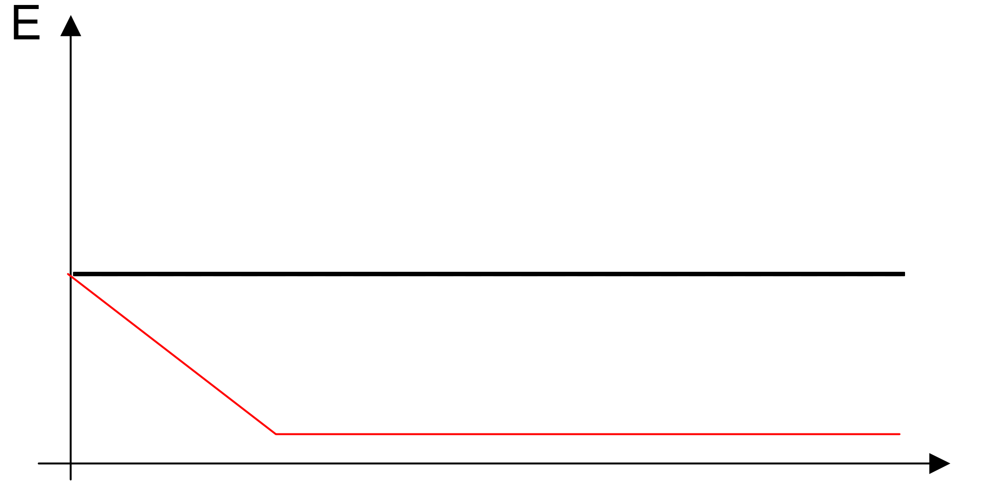

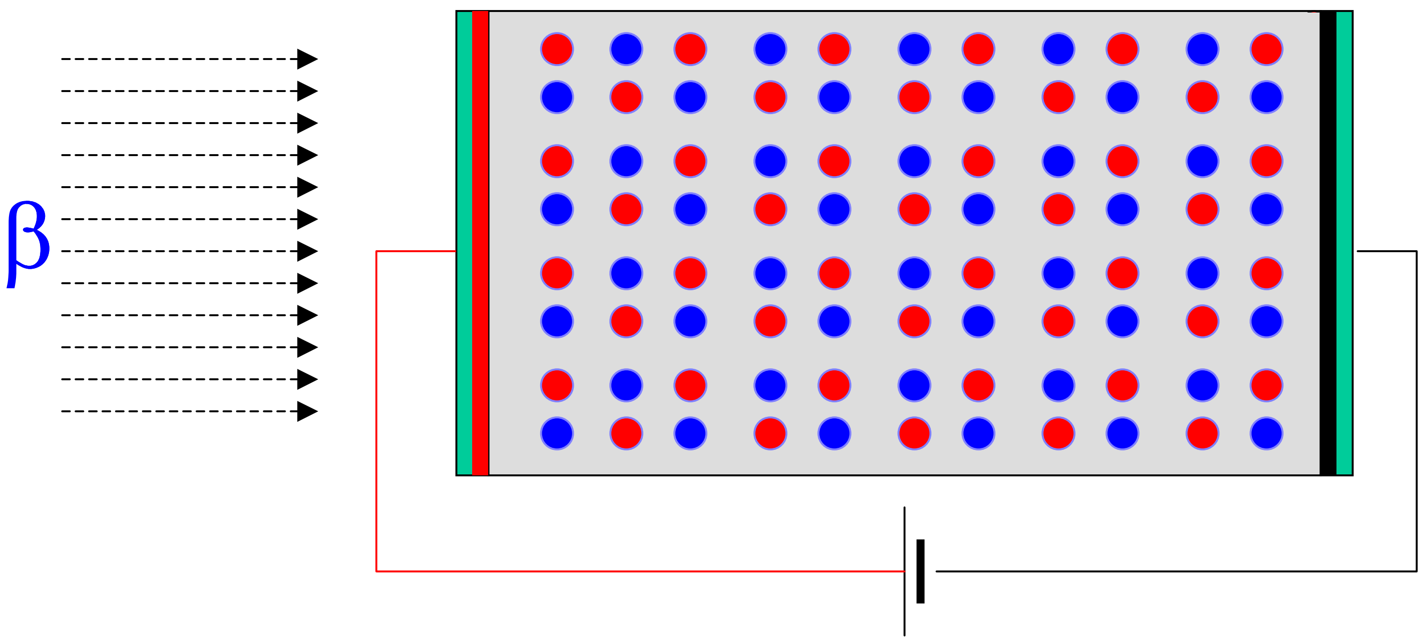

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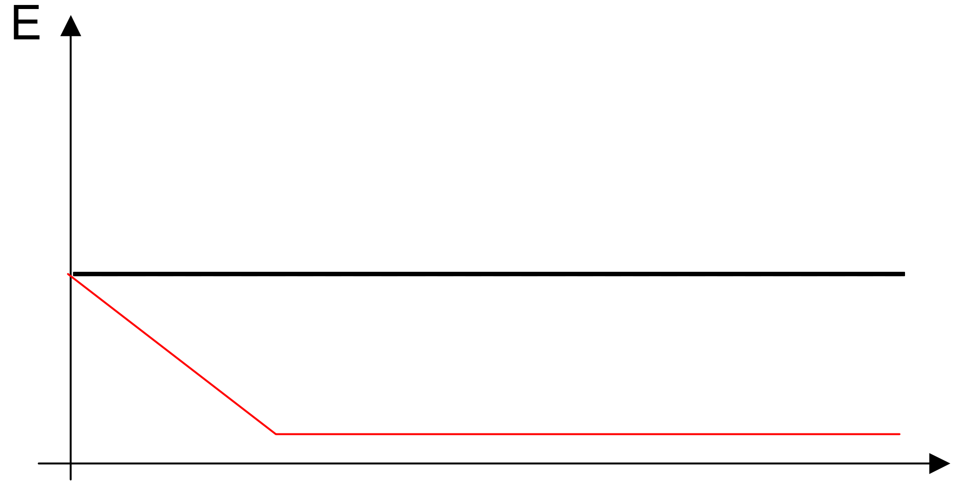

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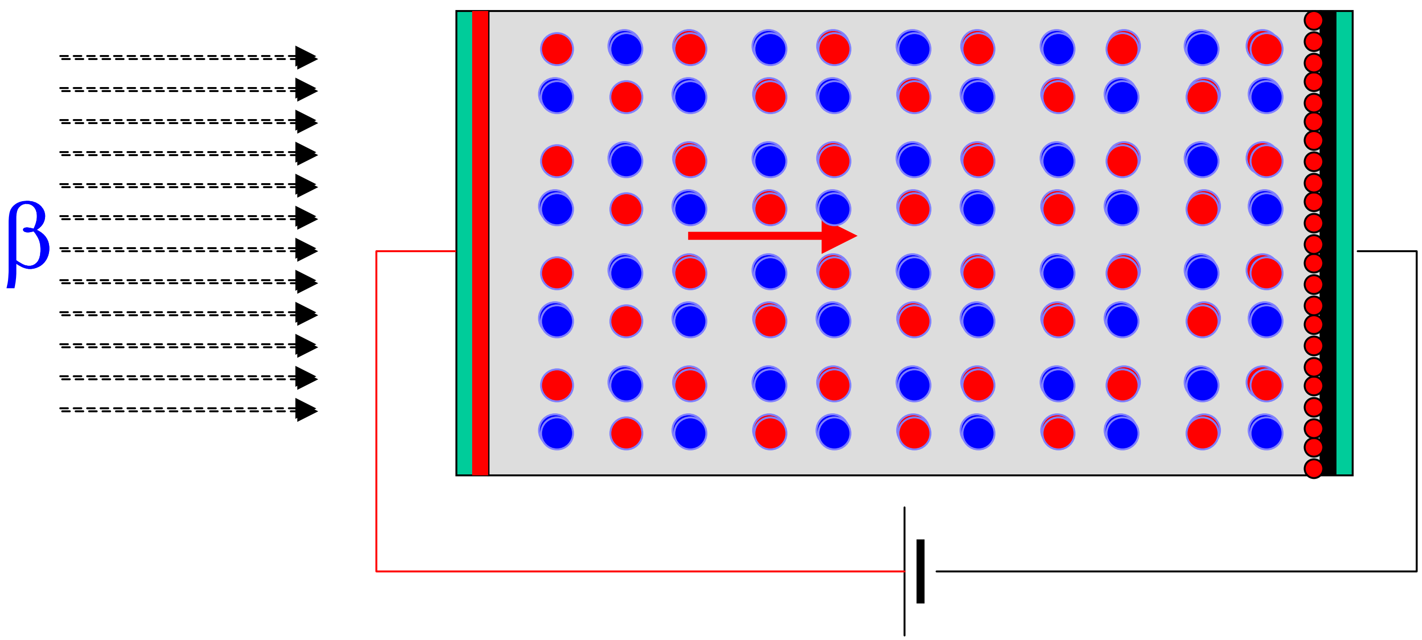

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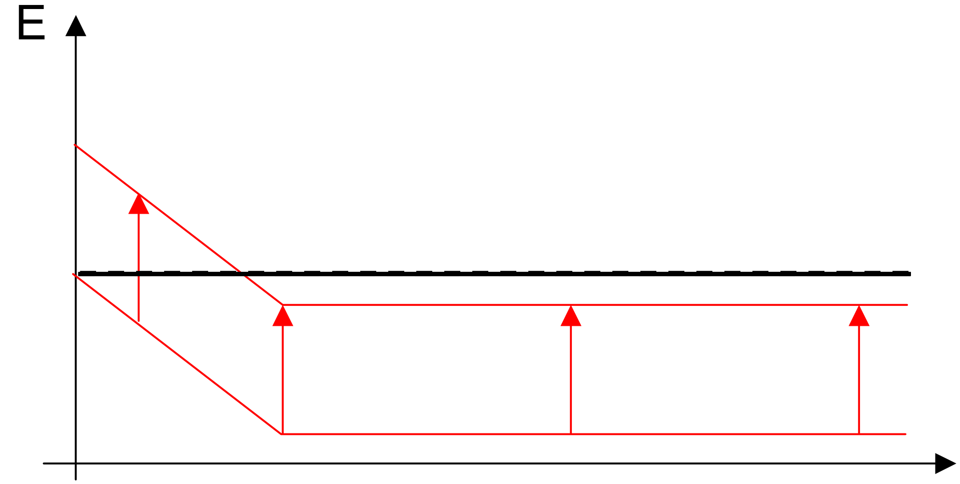


Constant bias voltage, Constant mean field

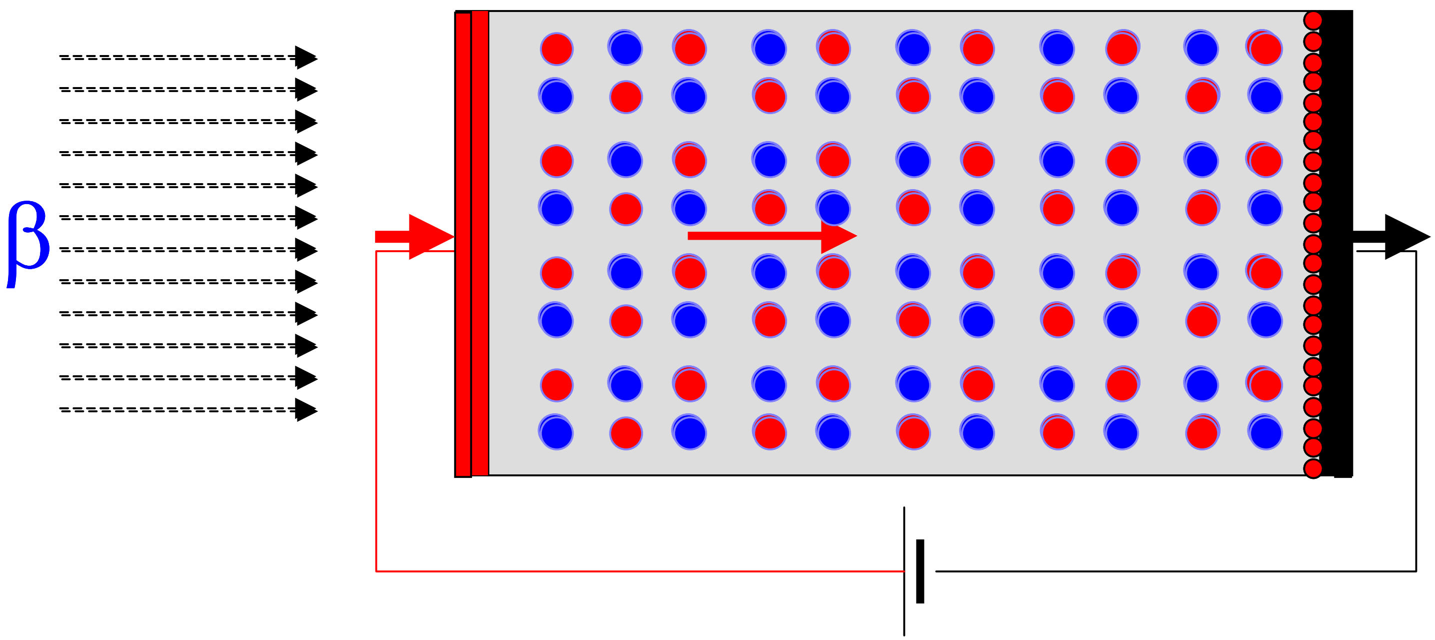
Beta irradiation

Charge displacement, One carrier model

Local charge neutrality

Uniform electric field

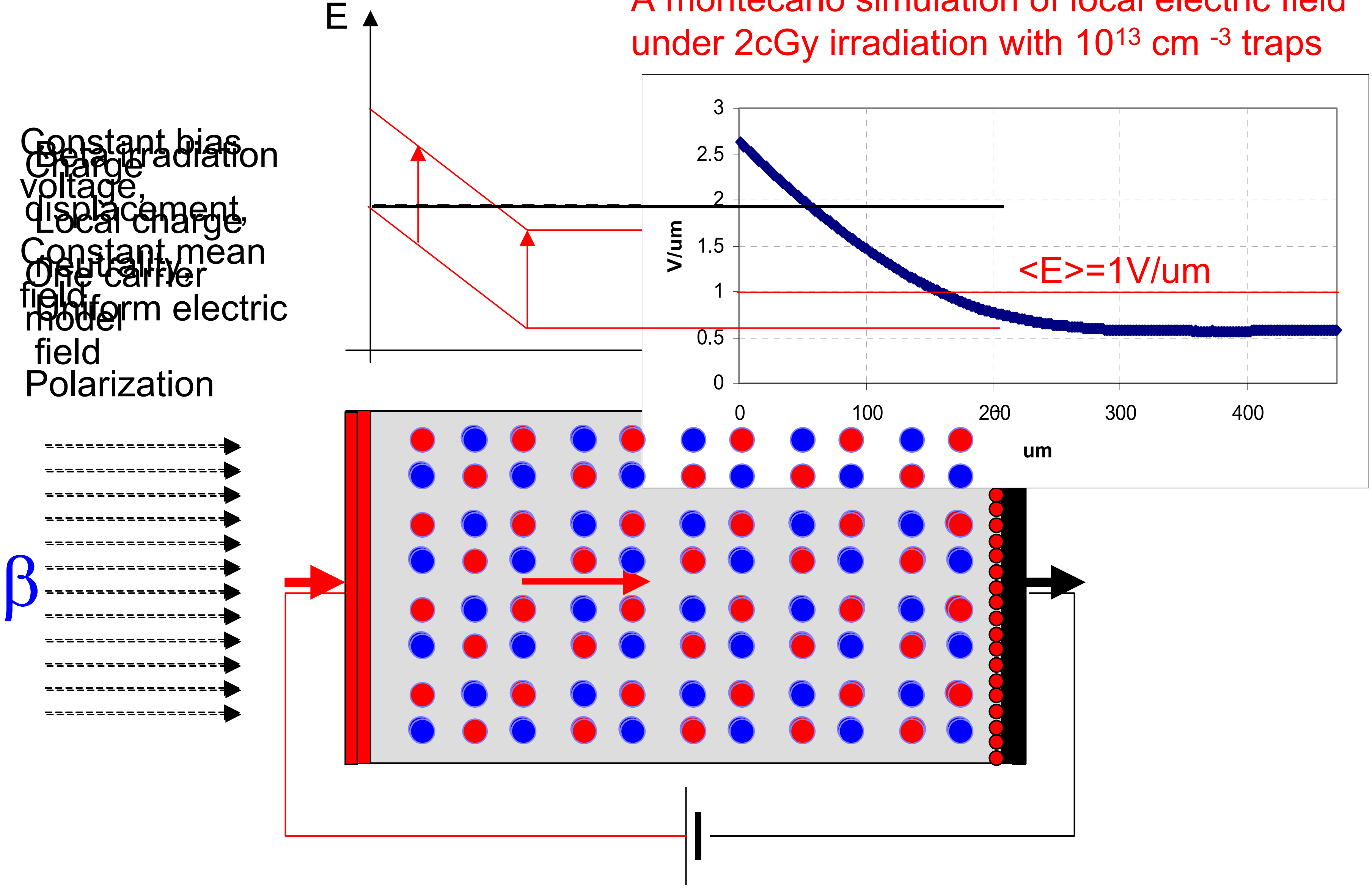
Polarization



Polarization effect

A montecarlo simulation of local electric field under 2cGy irradiation with 10^{13} cm $^{-3}$ traps

Constant bias voltage,
Constant mean field
Beta irradiation
Charge displacement,
One carrier model
Local charge neutrality
Uniform electric field
Polarization



Pumping vs. CCD

- CCD measurements of several samples both in pumped and depumped state

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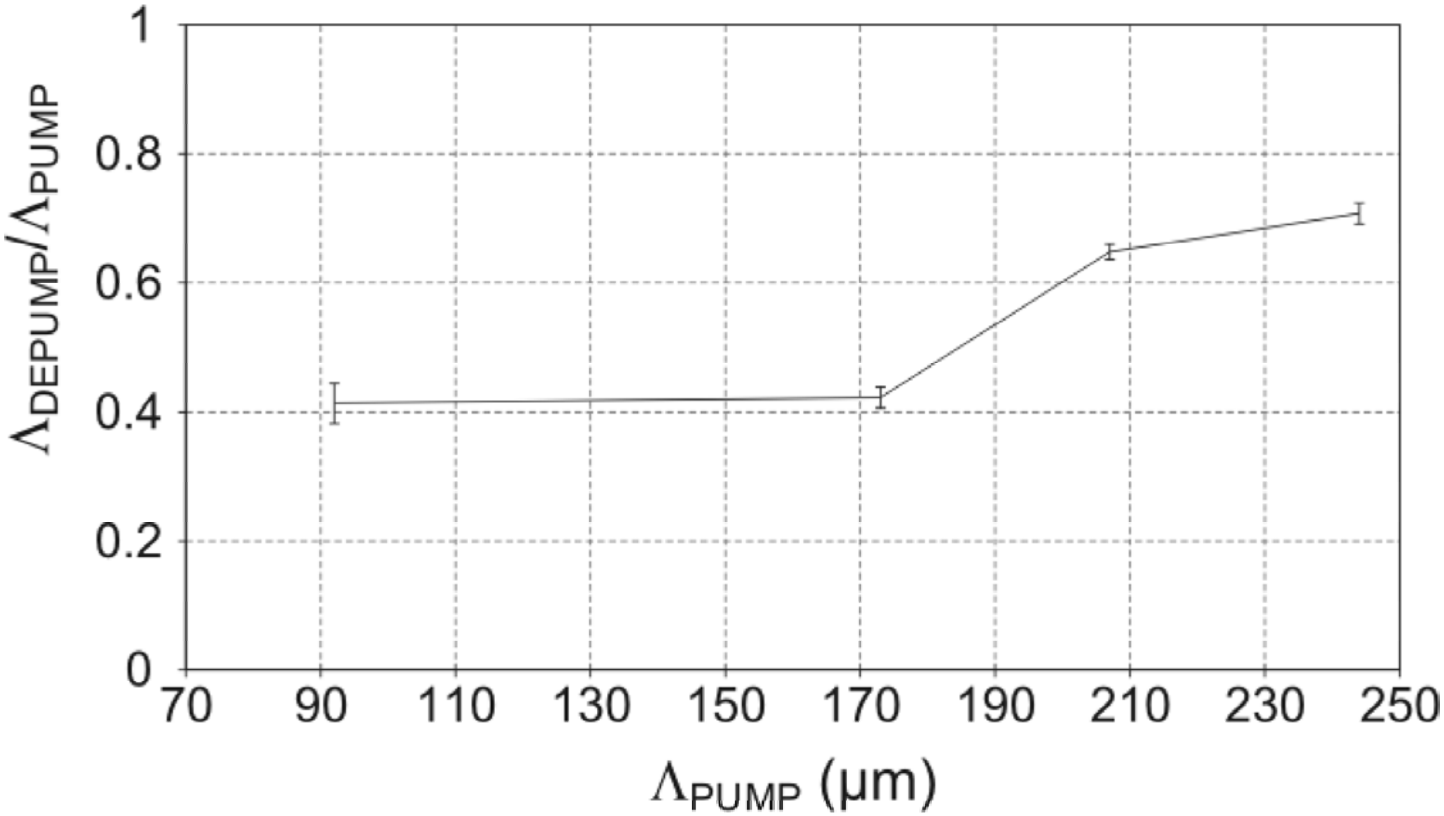

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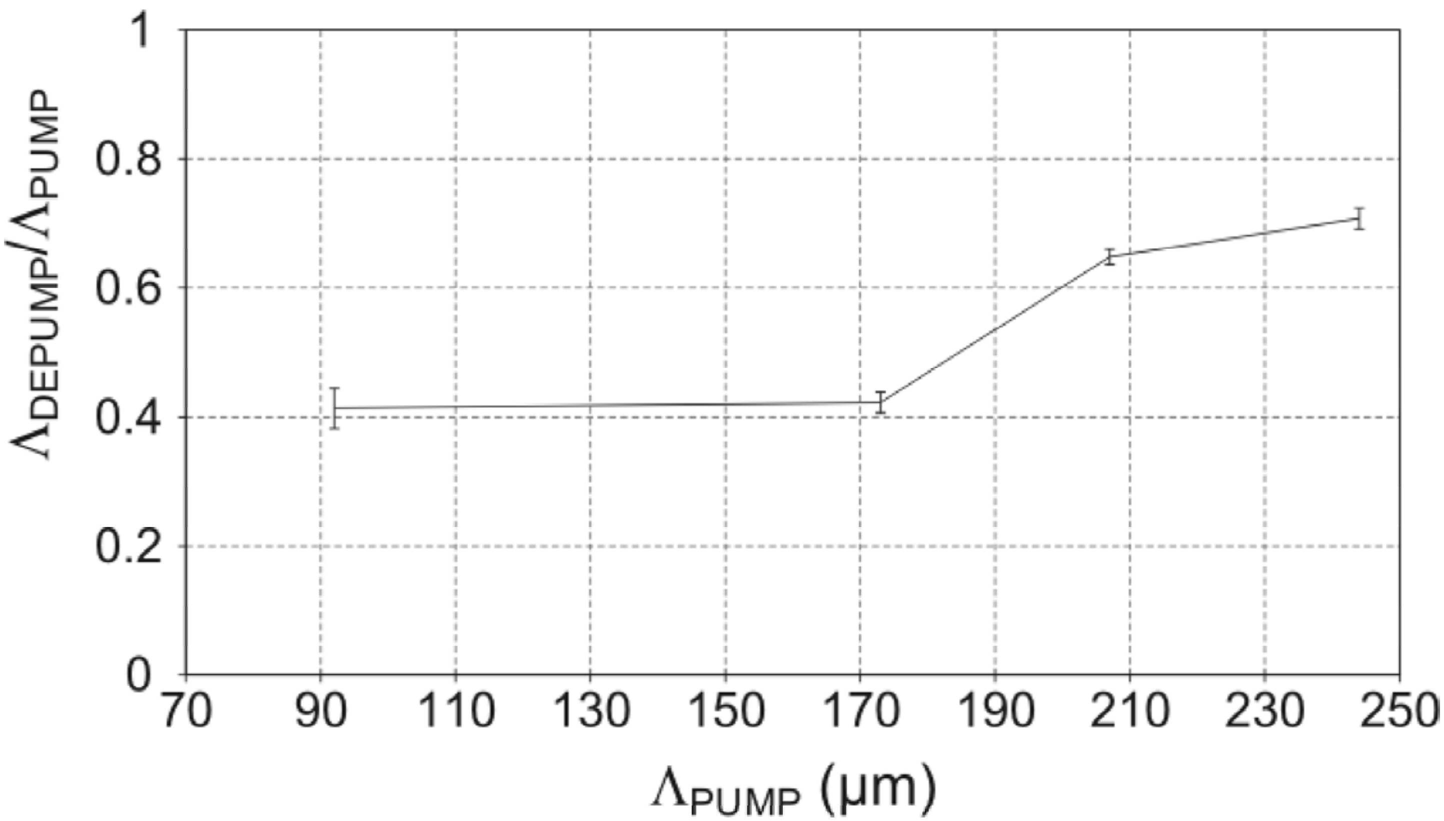

- Pumping is correlated to defects in crystal lattice

Bias field and pumping dynamics

Bias field and pumping dynamics

Model: $$\Lambda(\Phi) = \frac{\Lambda(\infty)}{1 + \alpha \exp\left[-\gamma\Phi\right]}$$

α: passivable traps/not passivable traps ratio

γ: traps filling constant

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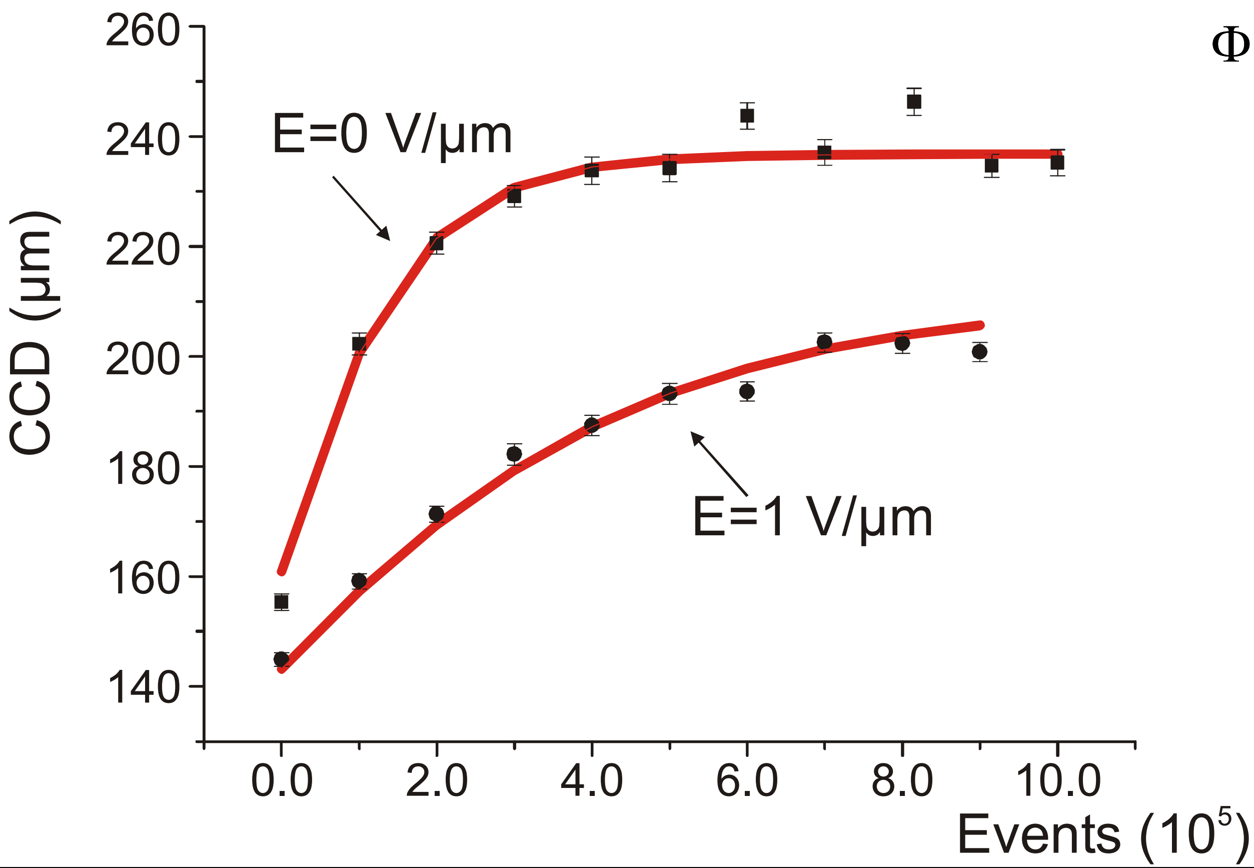

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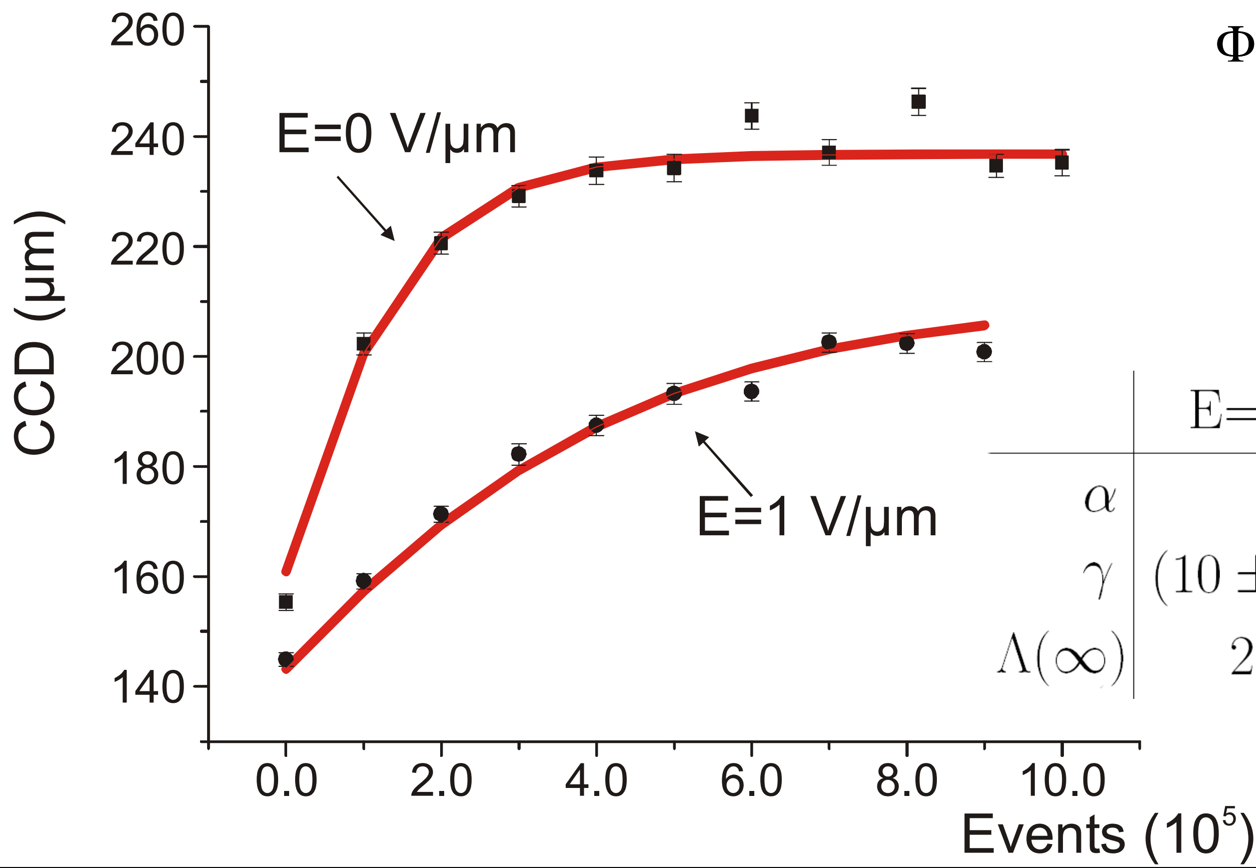
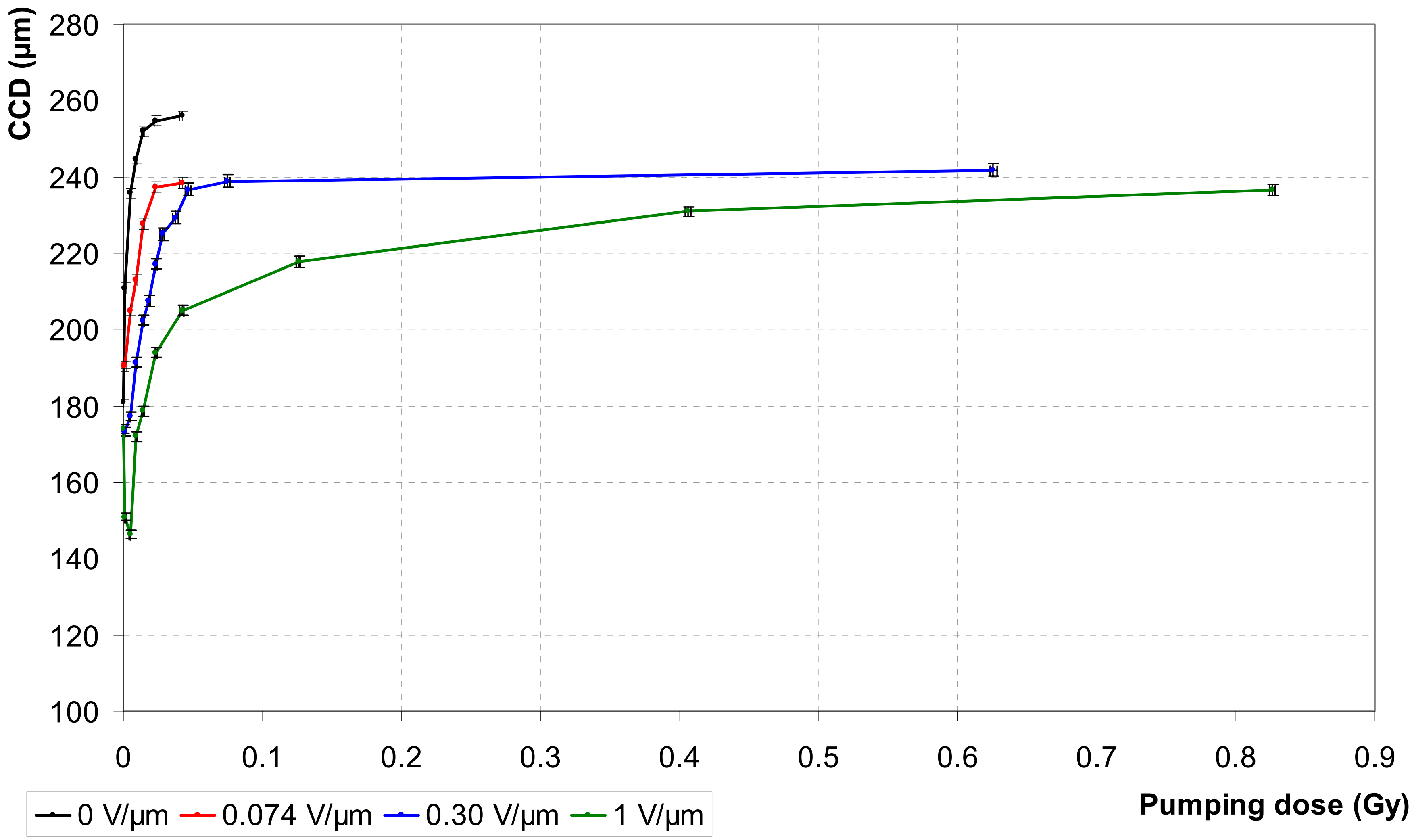


	E=0 V/µm	E=1 V/µm
α	0.47 ± 0.02	
γ	$(10 \pm 1) \cdot 10^{-6}$	$(3.3 \pm 0.5) \cdot 10^{-6}$
$\Lambda(\infty)$	236 ± 2	210 ± 4

Pumping and bias: a further study



Conclusions

A diamond tracking prototype was illuminated with various wavelengths, after being previously fully pumped and depumped. This study brought to the conclusion that there are at least two deep bands of trap levels inside diamond’s band gap, the lower one negative and the higher one positive in the depumped state, both neutral in pumped state.

Lower band:	*1 eV - 1.7 eV*
Higher band:	*1.7 eV - 2.7 eV*

A further study with tighter band gap scanning is needed in order to better locate trap levels

A study on pumping proved the correlation between pumping and lattice defects.
Some bulk polarization effect was also shown and correlated with the presence of trap levels.
A study on pumping dynamics confirmed the presence of a polarization effect and provided a recipe for pumping optimization

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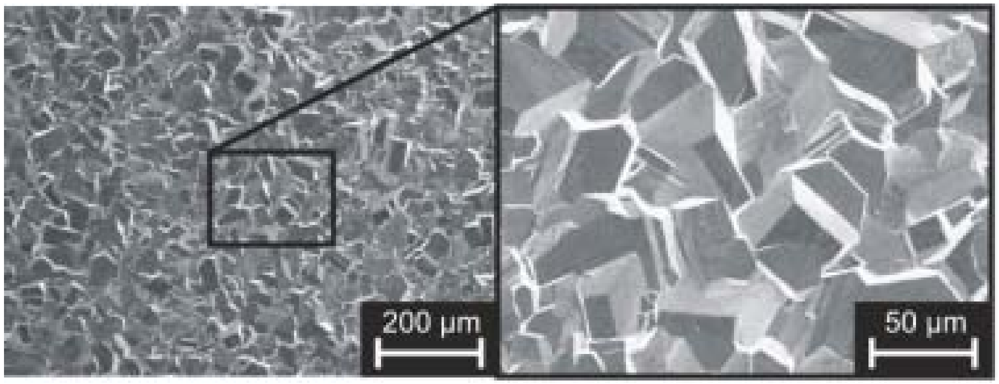
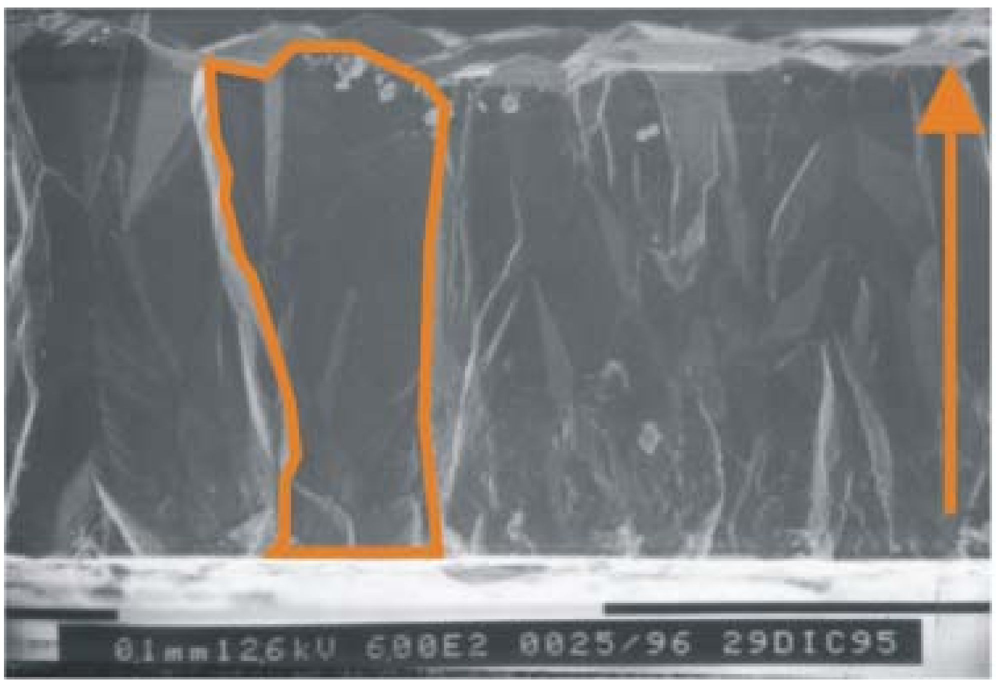
CVD diamond structure



Polycrystalline structure

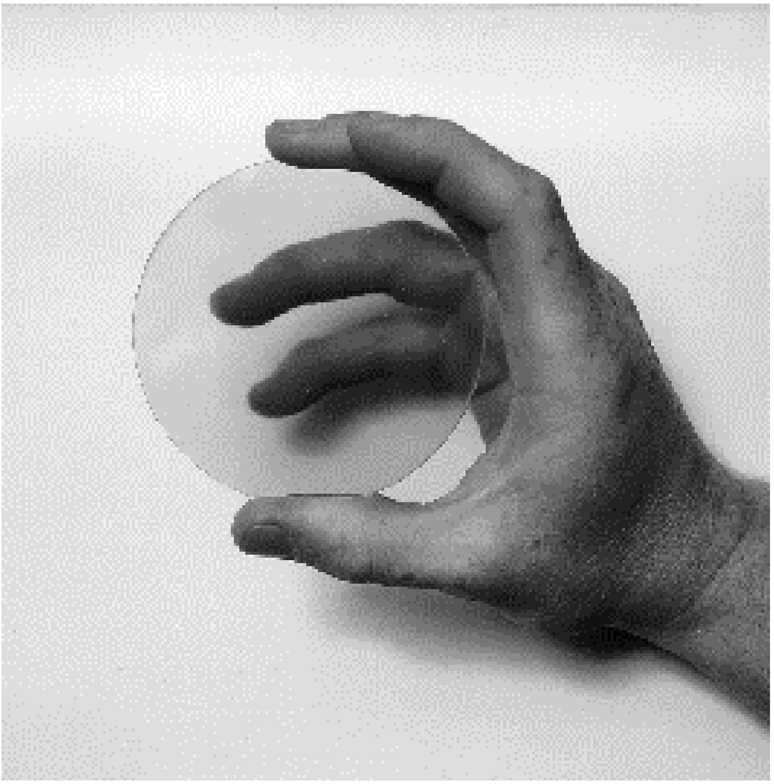


growth side

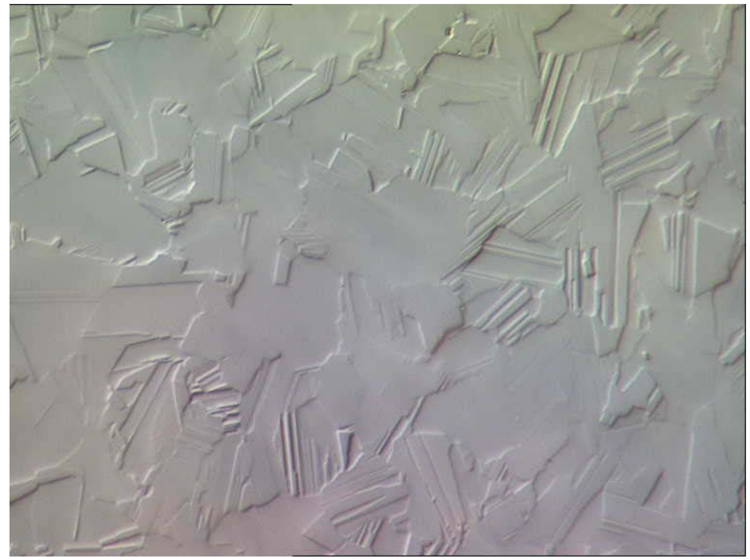
Grains enlarge during growth

substrate side

Diamond wafer



courtesy De Beers Industrial Diamonds



Lapped diamond surface

CVD diamond properties

- Single grains' quality is not uniform
  $\Rightarrow$ signal is not uniform
- Defects concentrated on grain boundaries
- Quality improves with thickness
- It is possible to remove defective material (standard procedure for CERN RD42 samples)

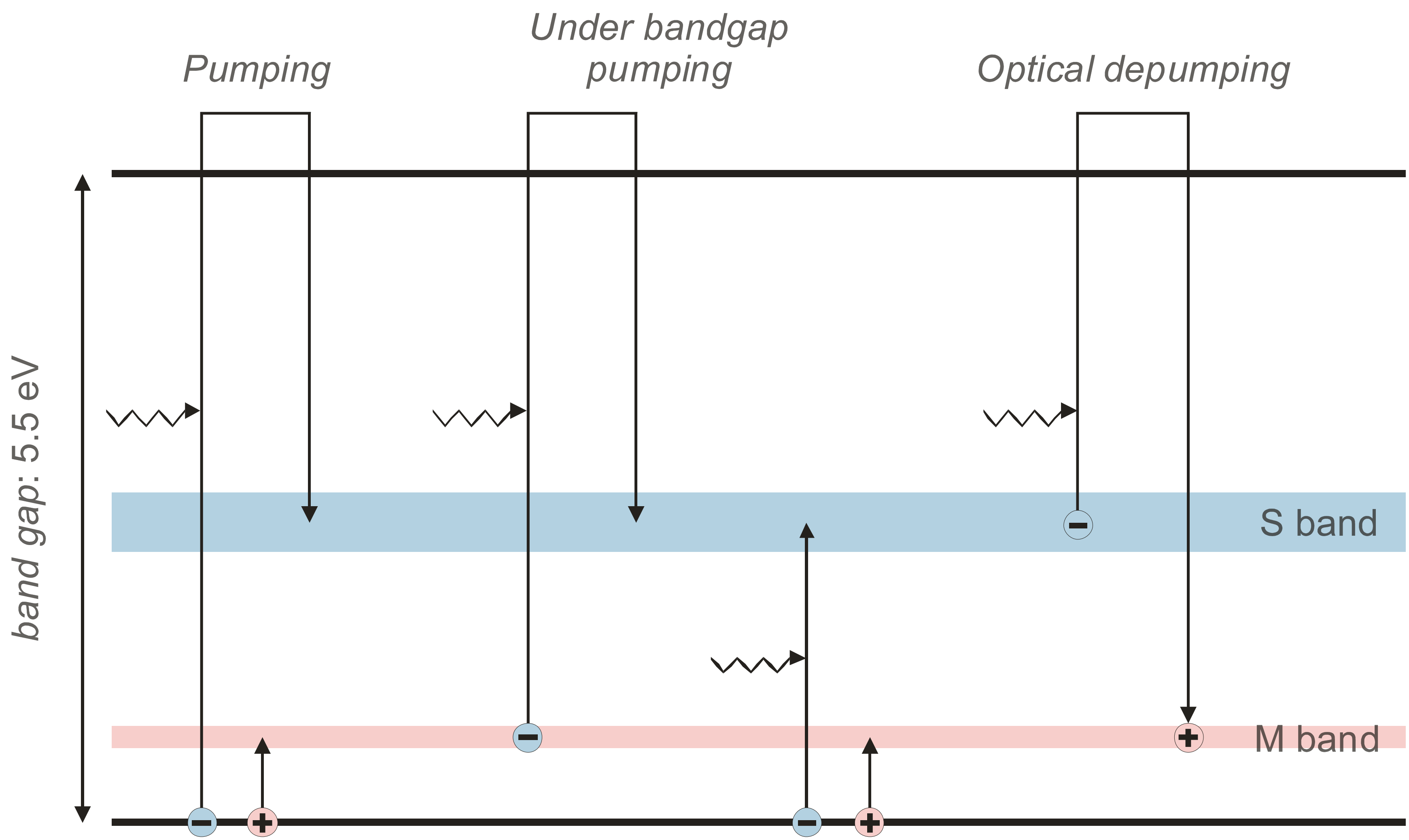
Diamond vs. silicon

Property	Di	Si	Pros	Cons
E_{bond} (eV)	7.37	4.63	Radiation damage hardness	
ε_r	5.70	11.9	C low	
E_G (eV)	5.5	1.12	Low dark current(200 pA/cm^2) $T_{OP} > 20\,^\circ$ C	
$\lvert\vec{E}_{\text{OPER.}}\rvert$ (V/μm)	1-4	0.1	Fast signal	
$\mu_{e,l}$ (cm^2 V^{-1} s^{-1})	1800-1200	1350-480		
Intrinsic			No doping No depletion Both polarities	
E_{couple} (eV/coup.)	13	3.6		Low signal

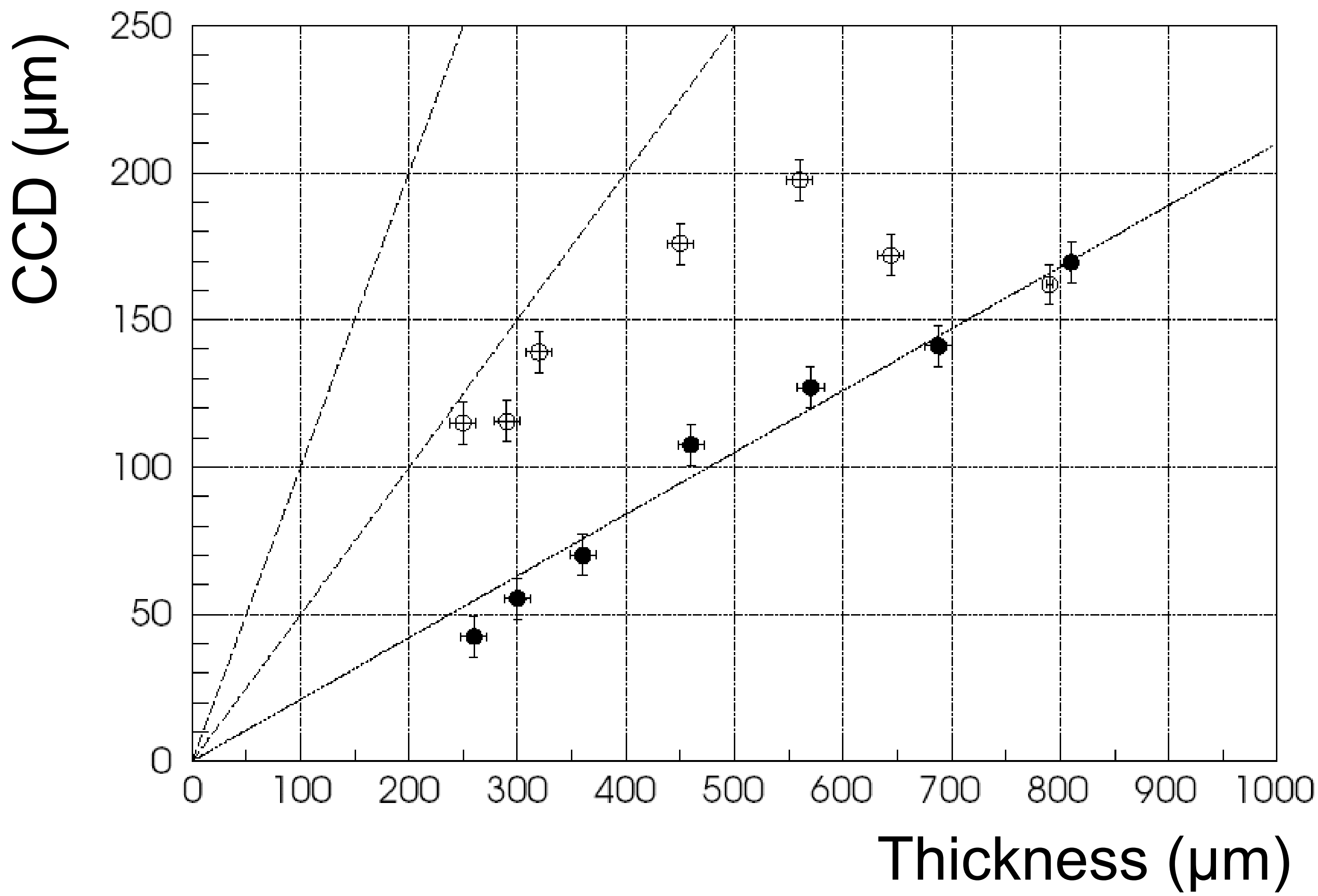
Signal/noise ratio with fast electronics (25 ns) on Minimun Ionizing Particles

Present: 10 $\rightarrow$ Objective: 15

Pumping and depumping scheme



Material removal (by Harris Kagan, OSU)

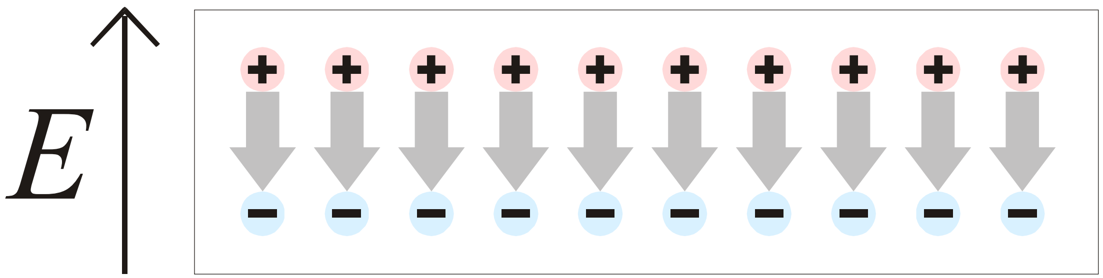


Hysteresis vs. CCD

Hysteresis vs. CCD

- Charges are pulled apart by externally applied electric field

Hysteresis vs. CCD



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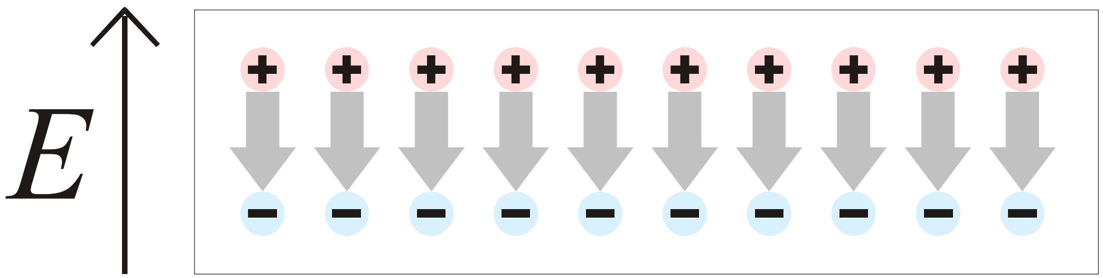

- Charges are pulled apart by externally applied electric field
- Charges are trapped and generate an opposite internal field

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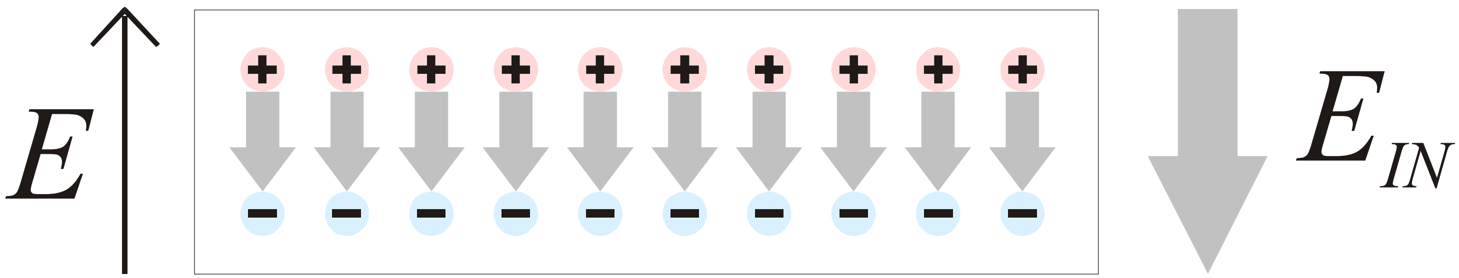

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