

Quantum Well Saturable Absorber Dynamics: Physical Processes and Modelling.

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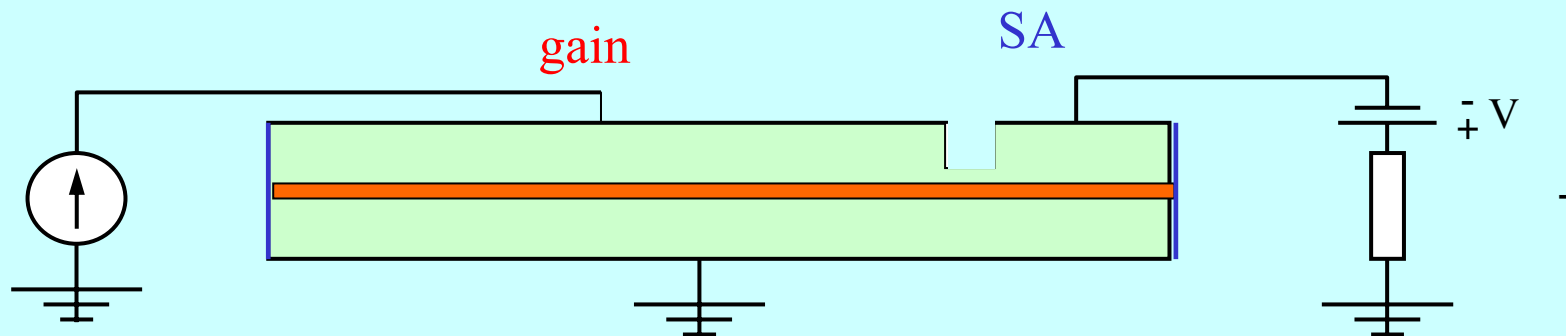
Outline:

- Background
- The physical effects and their modelling
- Full and reduced models
- Conclusions and future work

Devices with saturable absorbers :

1. Light sources: mode-locked and Q-switched lasers

- Applications include: OTDM sources, all-optical clock recovery, microwave over fibre, WDM comb generation, etc [E.A. Avrutin *et al.*, *IEE Proc.- Optoelectron.*, **147**, 251 (2000)]

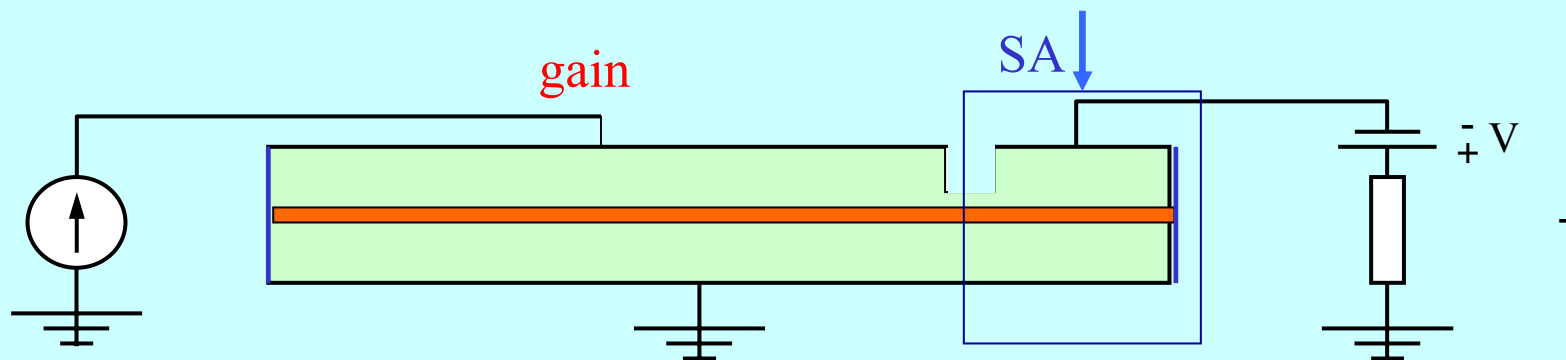


Forward-biased **gain** section + Reverse-biased **saturable absorber (SA)** section.
Carriers removed (swept out) from the SA by electric field

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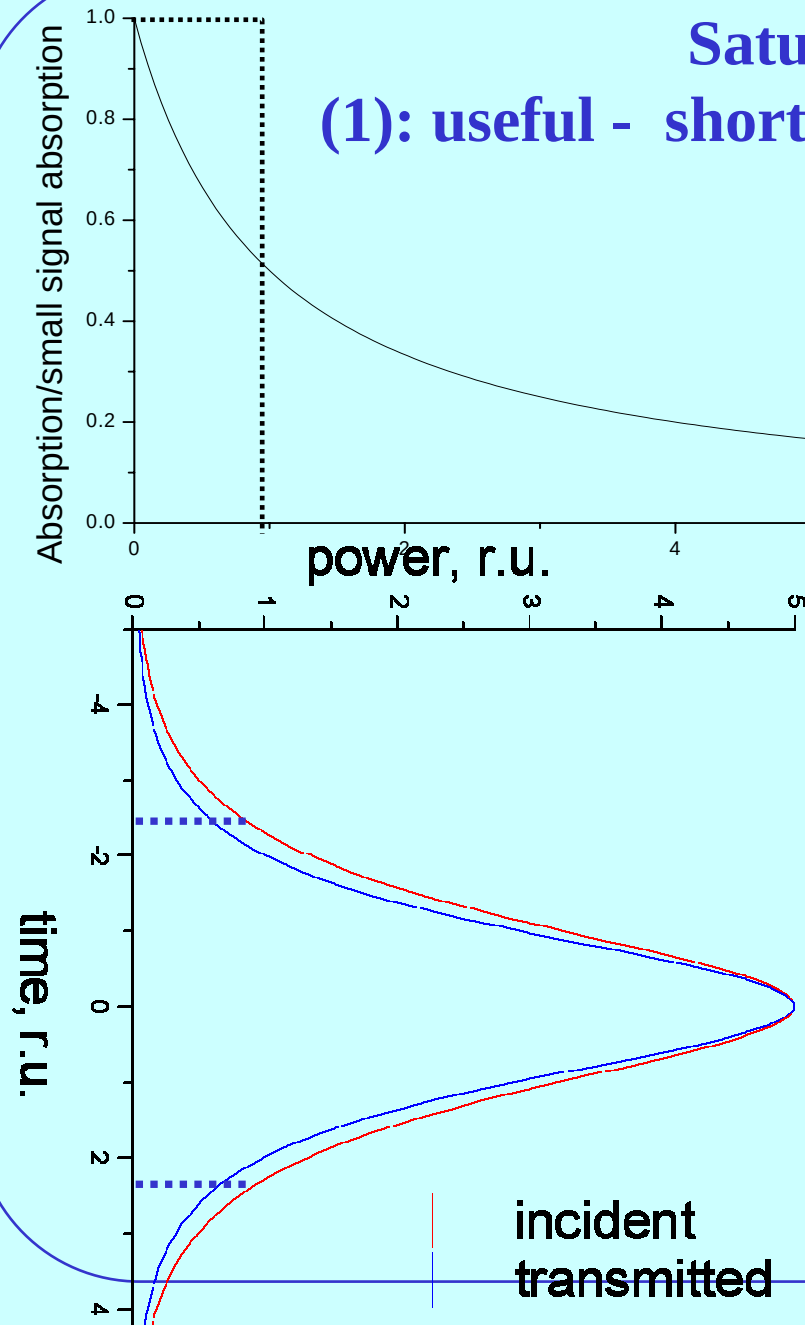
2. Signal processing devices

- OTDM demux, 2R, 3R, noise suppression [e.g. Mørk *et al.* *IEEE JQE* 2004].
- transmission or reflection mode, tandem geometry or free-standing absorber

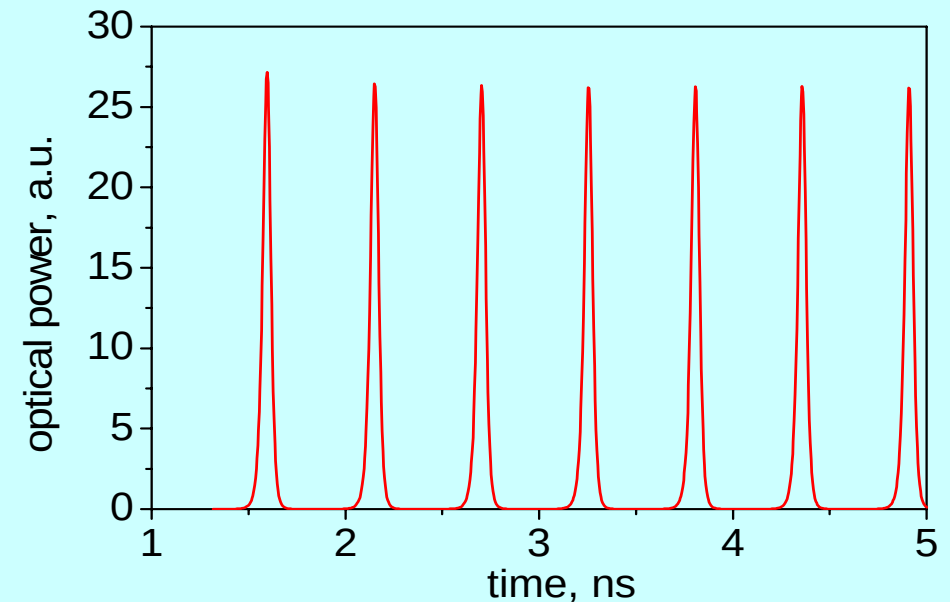
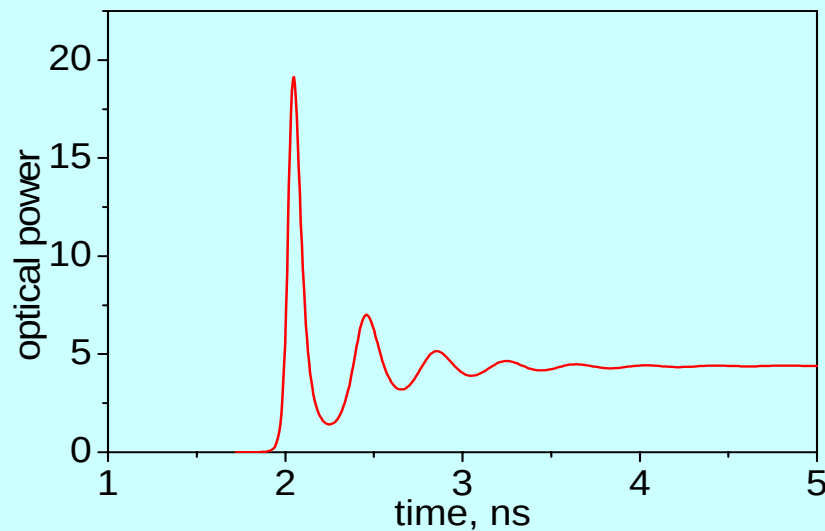
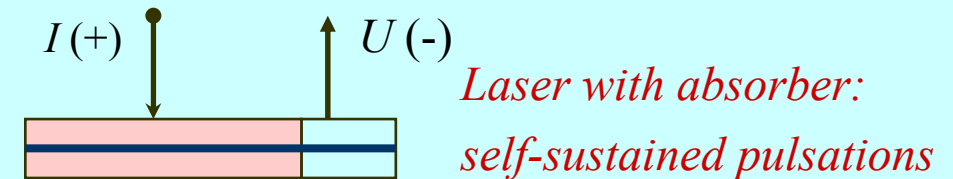
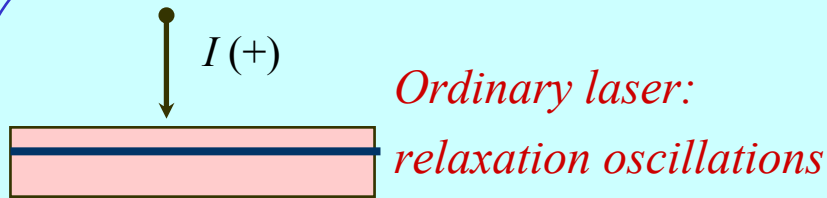
Saturable absorber action: (1): useful - shortening pulses, enabling mode locking

- Centre of pulse: high power $\Rightarrow$ transmitted
- Pulse wings: low power $\Rightarrow$ absorbed

Leads to mode locking



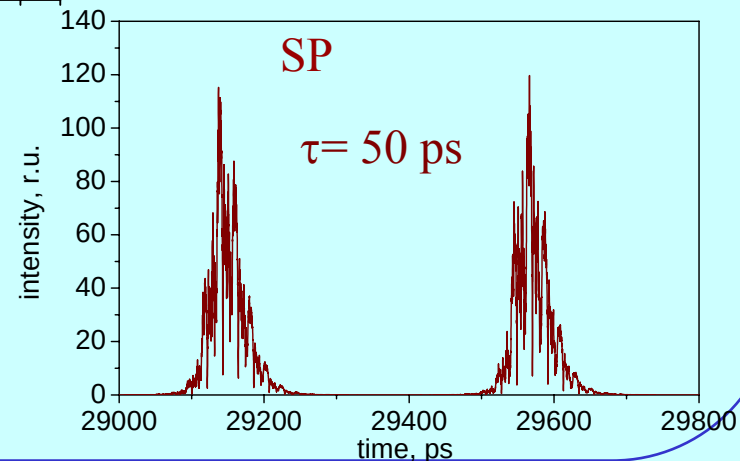
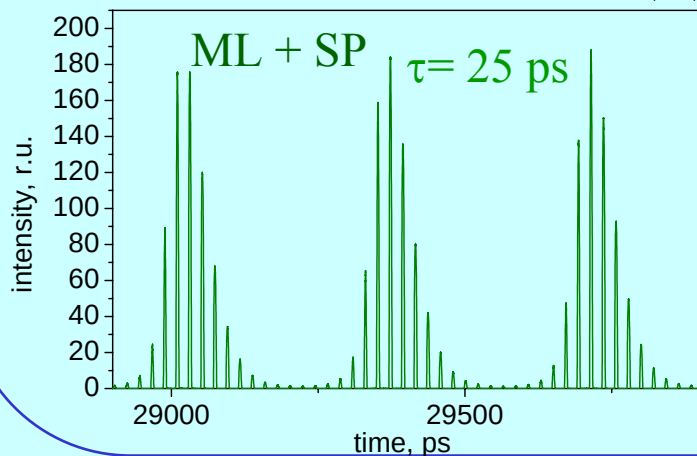
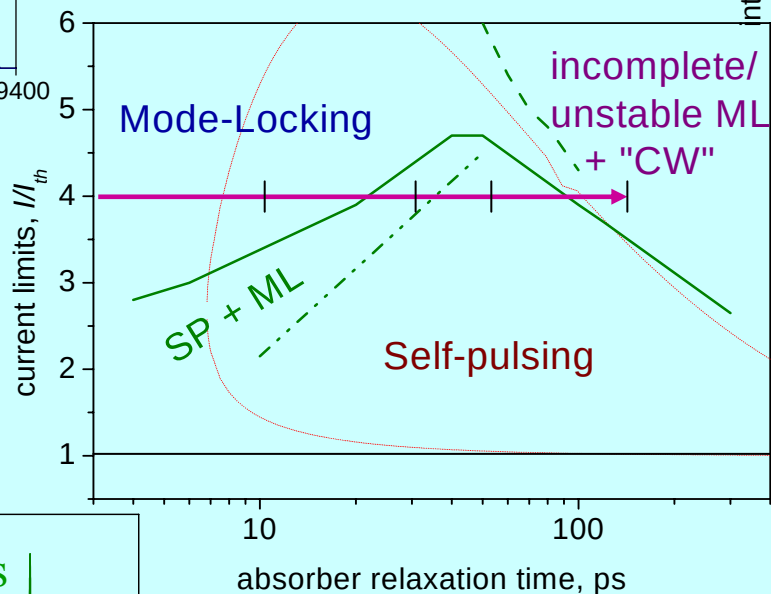
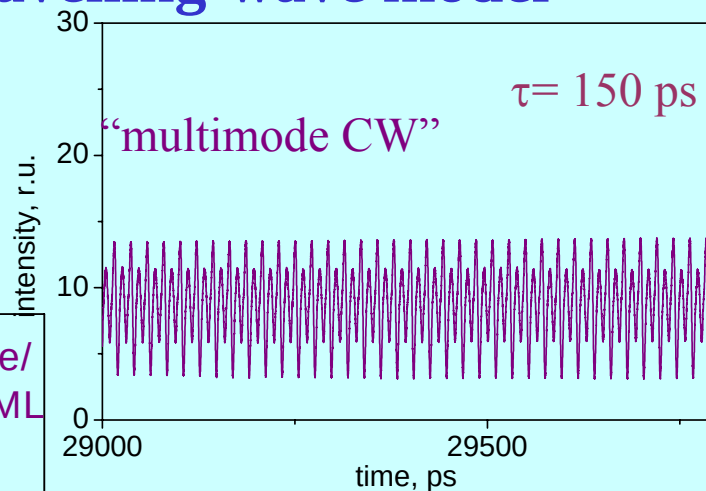
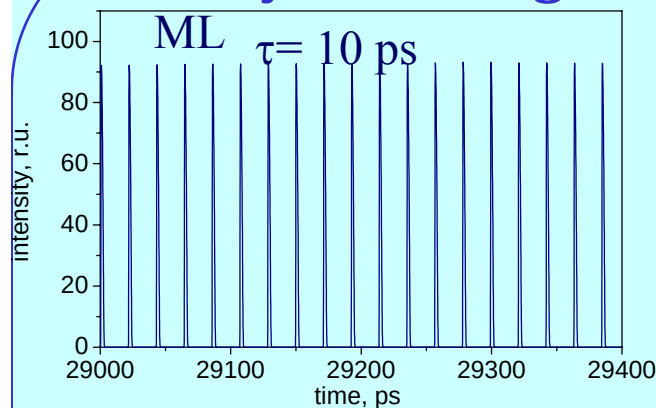
Saturable absorber action (II): parasitic: self-pulsing



- self-sustained-pulsations (SSP) = passive Q-switching.
Relaxation oscillations made self-sustained by **positive feedback** in the laser provided by the **saturable absorber**
Frequency $F \sim 1\text{-}10$ GHz (approximately $\propto I - I_{th}$); duration $\tau \sim 5\text{-}50$ ps

Often appear as envelope on mode-locking train

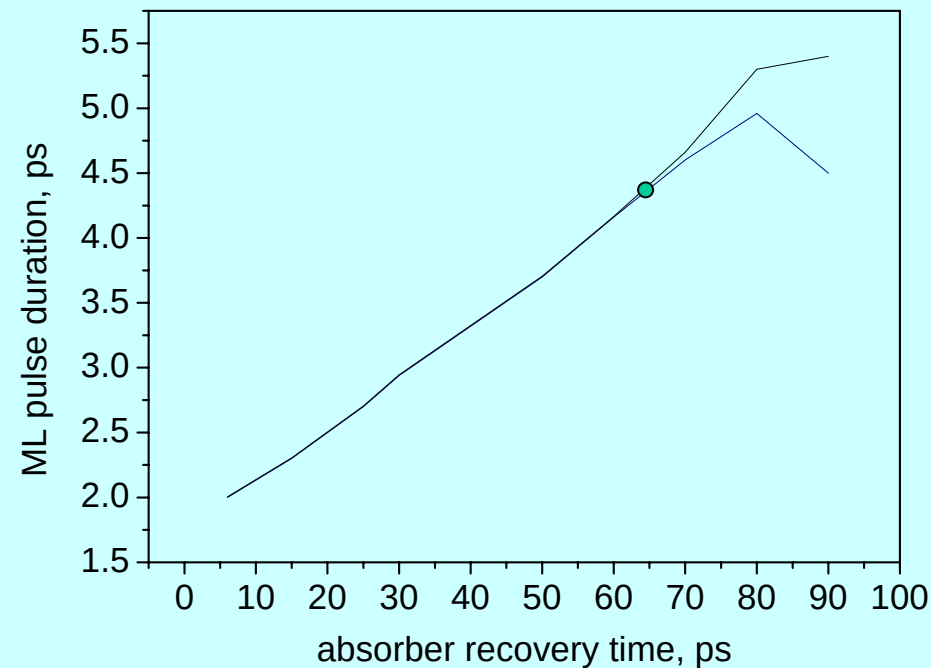
Dynamic regimes in a tandem laser by travelling-wave model



Travelling wave model

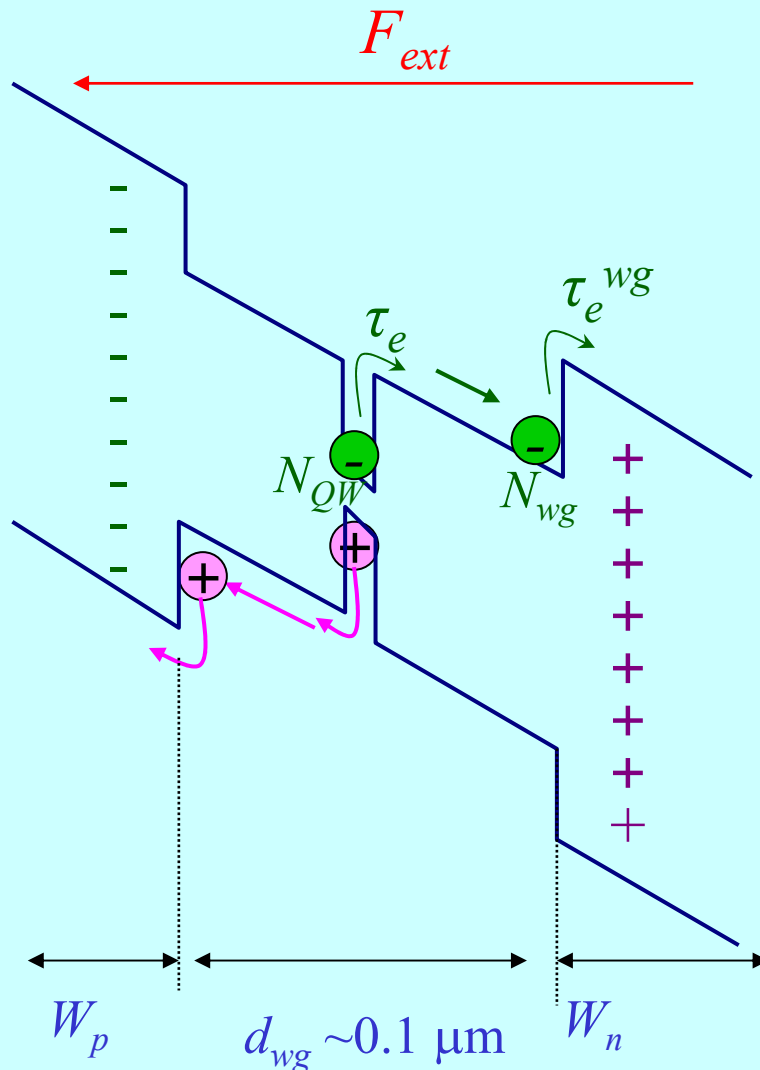
Rate equation model (can only predict self-pulsing or not)

Effect of absorber relaxation time on ML pulse duration



- $I/I_{th} = 5.2$ – no self-pulsing
- Bifurcation due to onset of imperfect/unstable (envelope-modulated) ML
- Need short absorber times for good quality ML

Recovery process and recovery time in a reverse-biased absorber



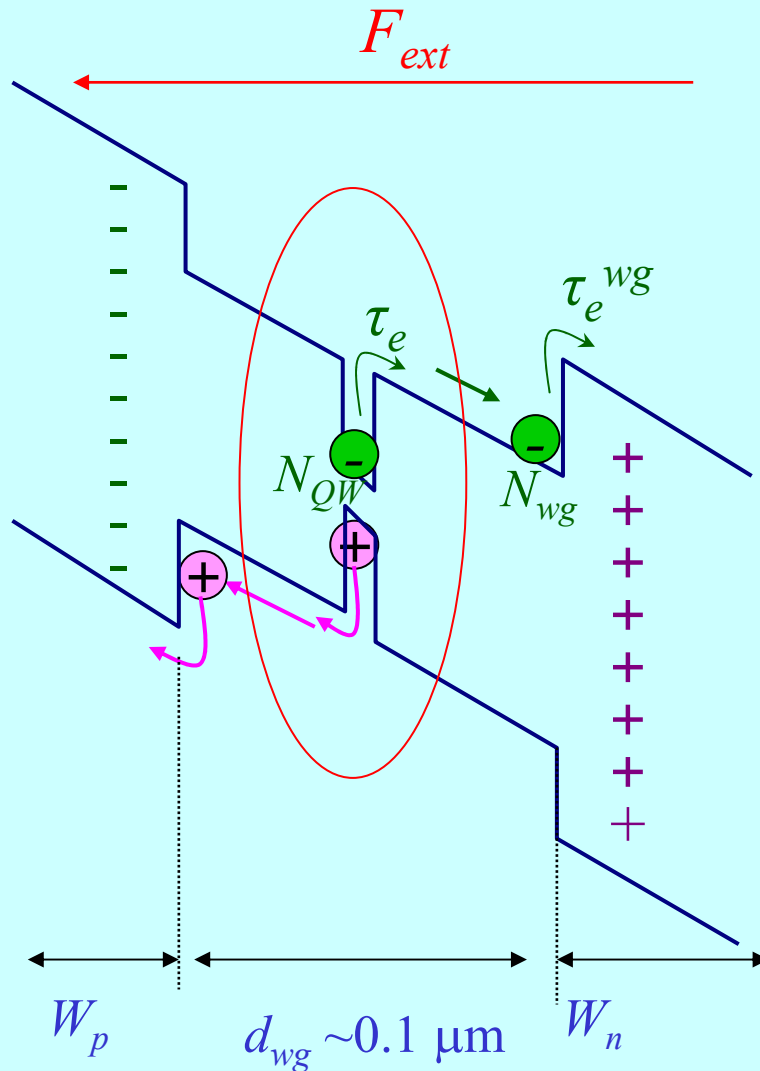
Quantum well embedded in the waveguide layer;
field F_{ext} applied to contacts

Carriers escape by field sweepout:
QW $\rightarrow$ waveguide $\rightarrow$ claddings $\rightarrow$ bias circuit .

$$\frac{dN_{QW}}{dt} = v_g \alpha(N_{QW}, F_{QW}, S) S - \frac{N_{QW}}{\tau_e(F_{QW})}$$

Main approach so far: an approximate one
predicting $\tau_{QW}^h = \tau_{QW}^{h(0)} \exp(-F_{QW}^h / F_{scale})$

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Our theory

[V.V.Nikolaev and E.A. Avrutin, *IEEE JQE*, **39**, 1653 (2003)]

- Carrier escape time τ = (carrier density n) / (escape flux density J/e):

$$\frac{1}{\tau} = \frac{J}{en} = \frac{1}{n} \int_{E_0}^{\infty} j_E(E_z) dE_z.$$

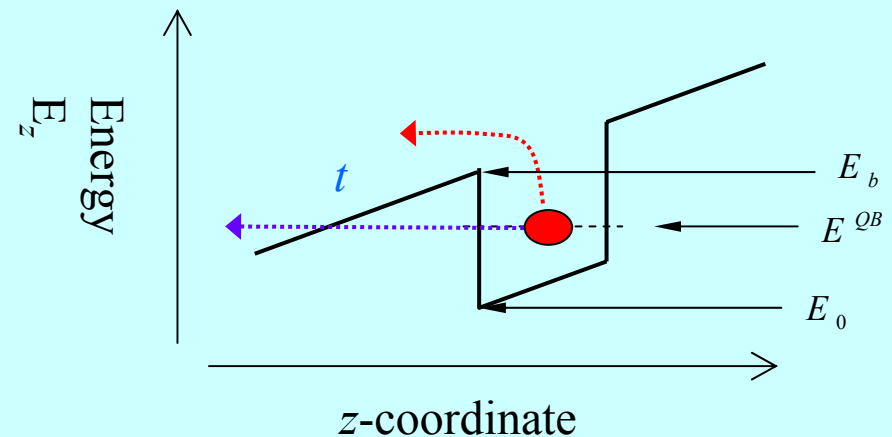
density of the escape particle flux (per E_z)

occupation function
contains Fermi statistics

$$j_E(E_z) = \frac{1}{2\hbar\pi} \frac{P(E_z)}{|1 - r_+ r_-(E_z)|^2} |t(E_z)|^4$$

Modification of 3D DoS by
QW: quasibound levels below
barrier, peaks/troughs above

Barrier
transmittance

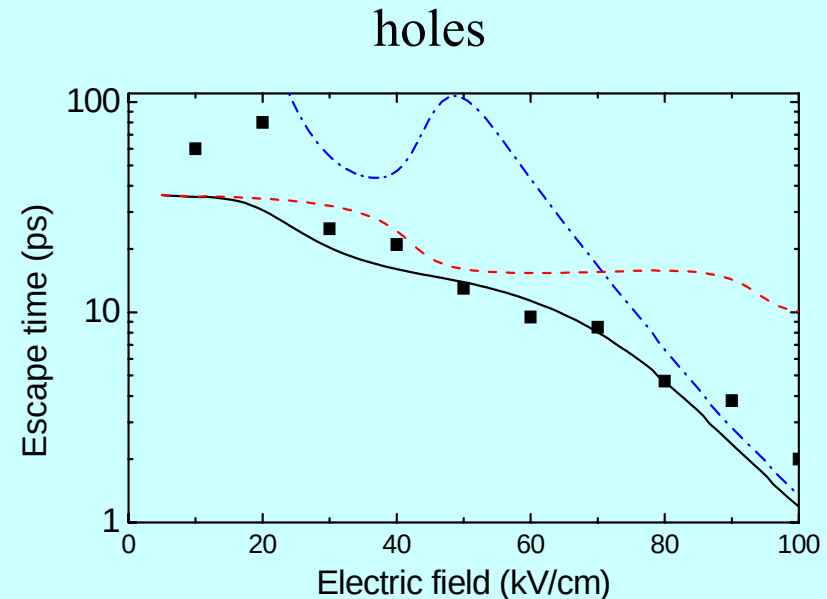
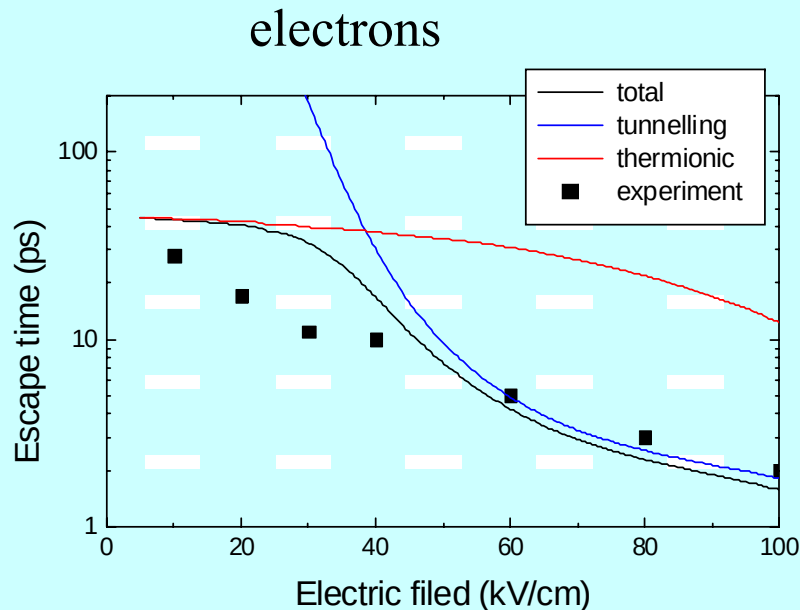


- Exact solution of the problem in 1-particle approach
- Tunnelling and thermal activation treated on the same footing. No quasi-3D or purely-2D.
- Quasi-analytical calculation in terms of Airy functions

Comparison between theory and experiment

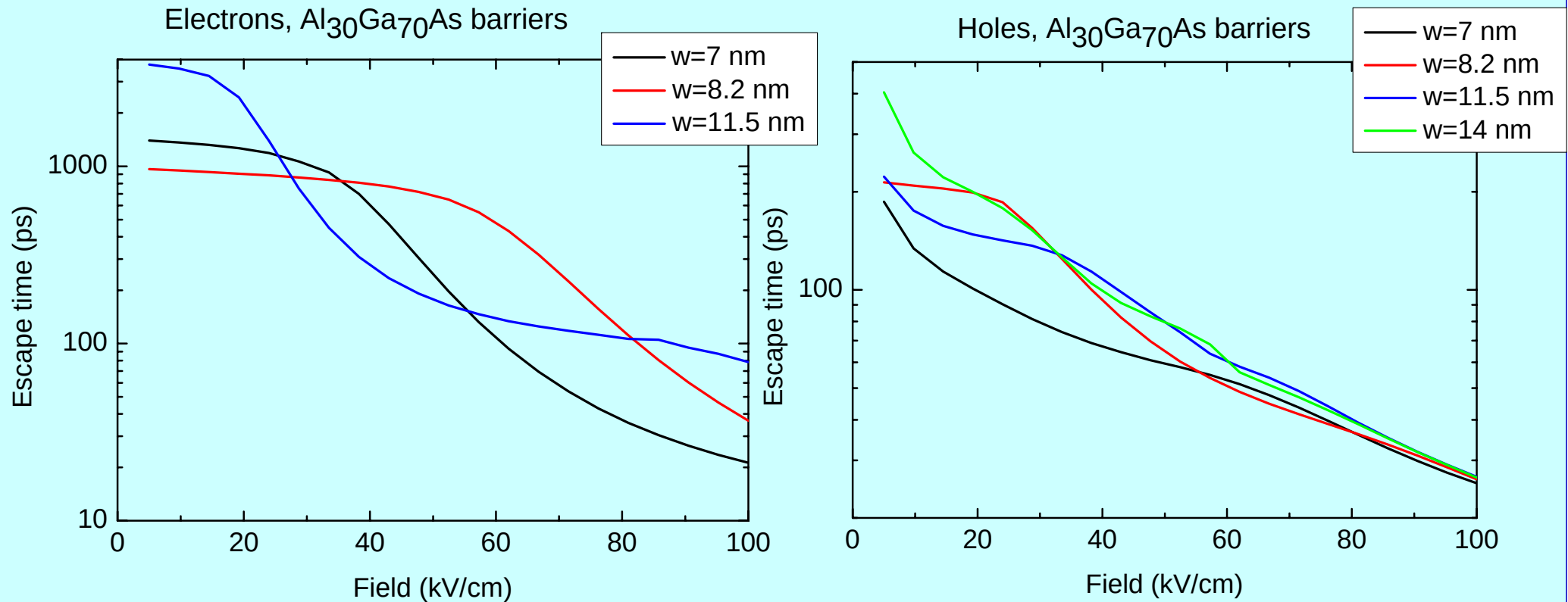
The experimental points are taken from [J. A. Cavailles *et al.*, *IEEE JQE*, **28**, 2486 (1992)] .

The structure contains a **single QW** with asymmetric barriers



- Good agreement between theory and experiment.
- For low electric fields, thermionic component dominant; for higher field, in this structure, tunneling dominant.
- In this structure, electron and hole escape time comparable.

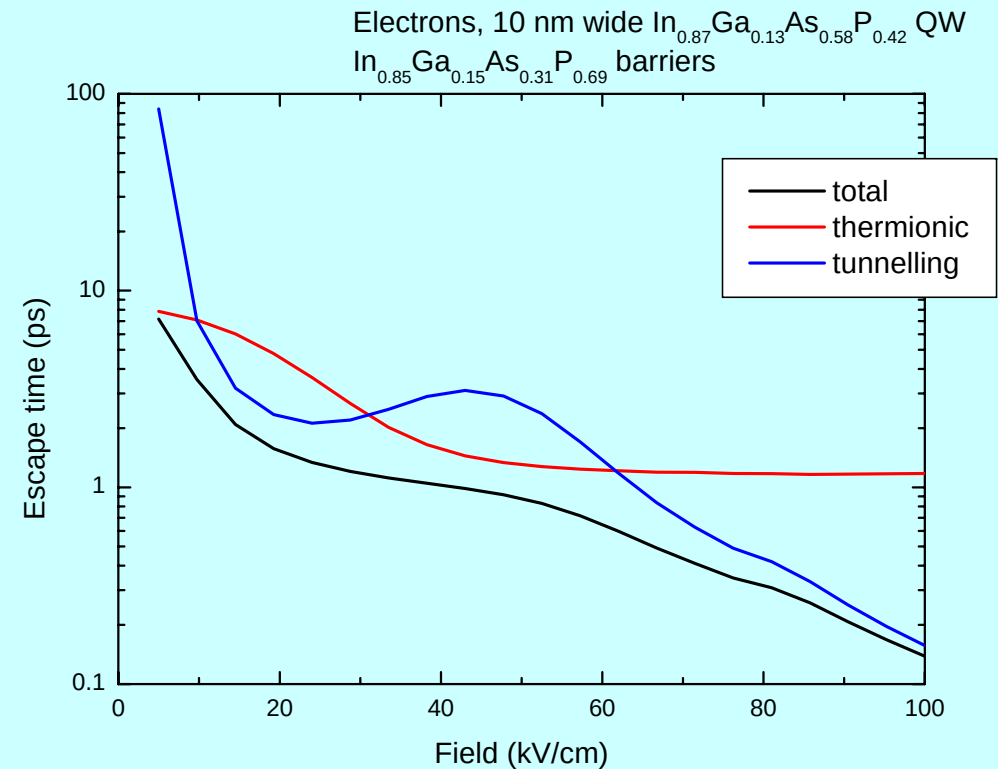
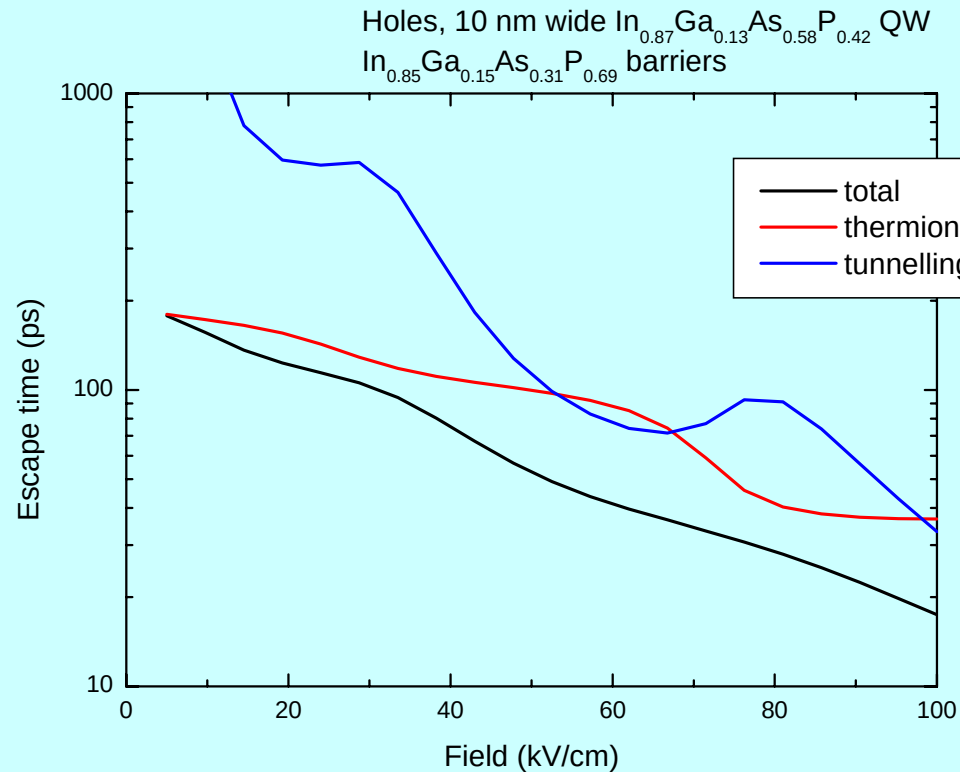
Field dependence of escape time for various barrier compositions (hence well depths) and well widths. AlGaAs



Electron and hole times similar

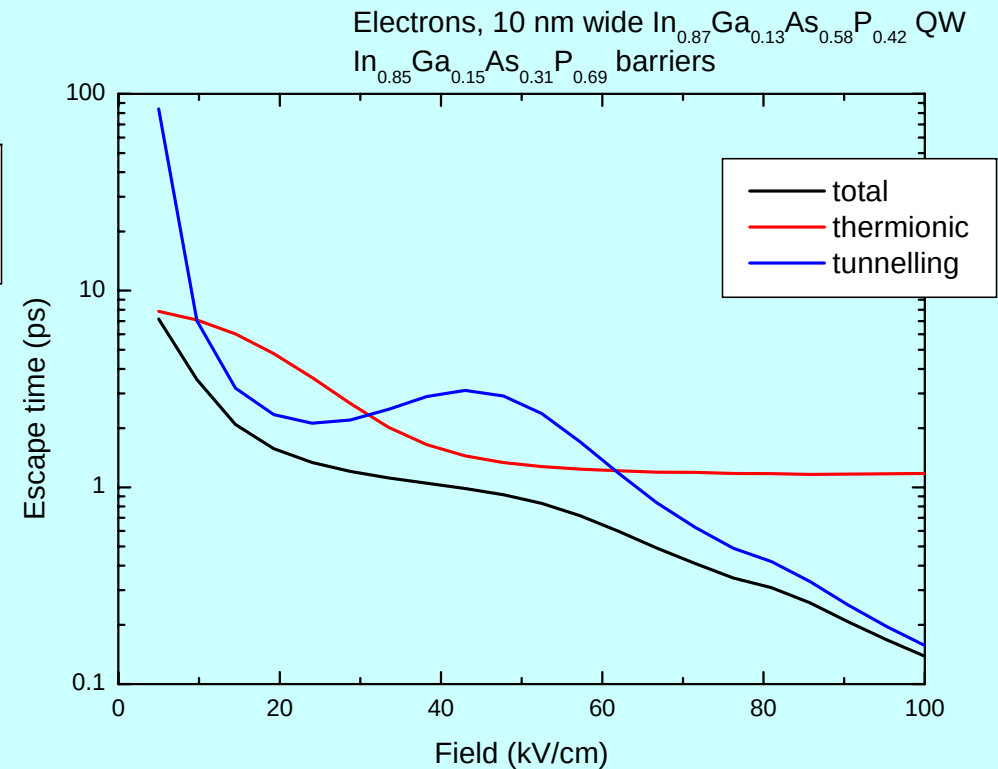
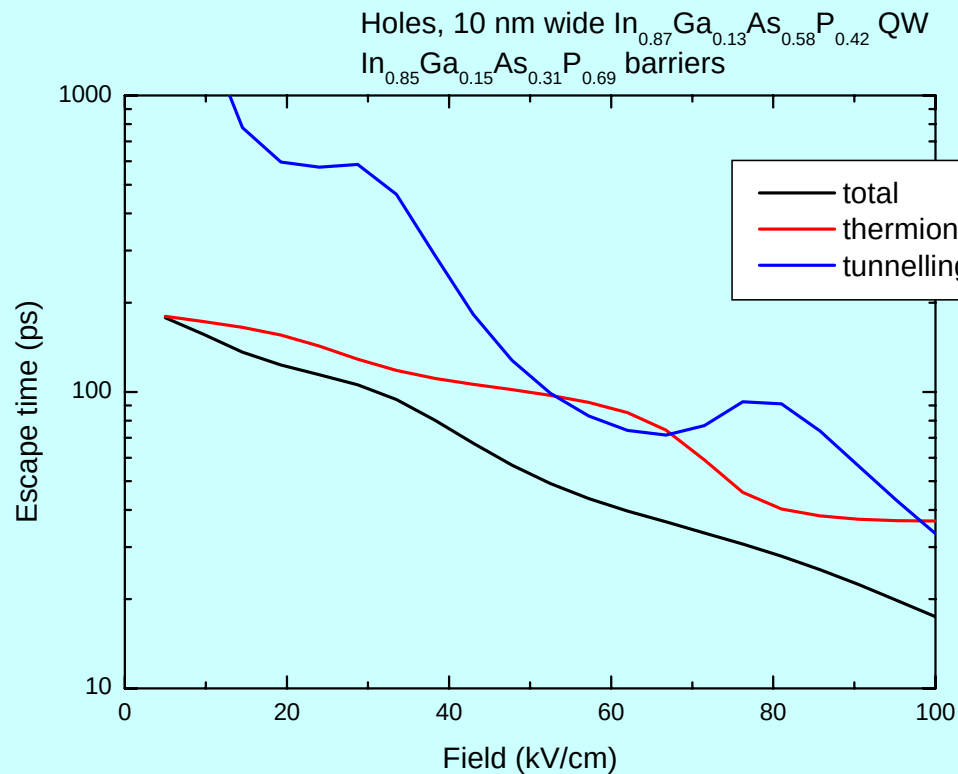
Strongly non-exponential behaviour for electrons (resonant emission from quasibound levels)

InGaAsP results



- Hole escape slower than electrons – likely to determine overall dynamics
- Closer to exponential than GaAs/AlGaAs

InGaAsP results

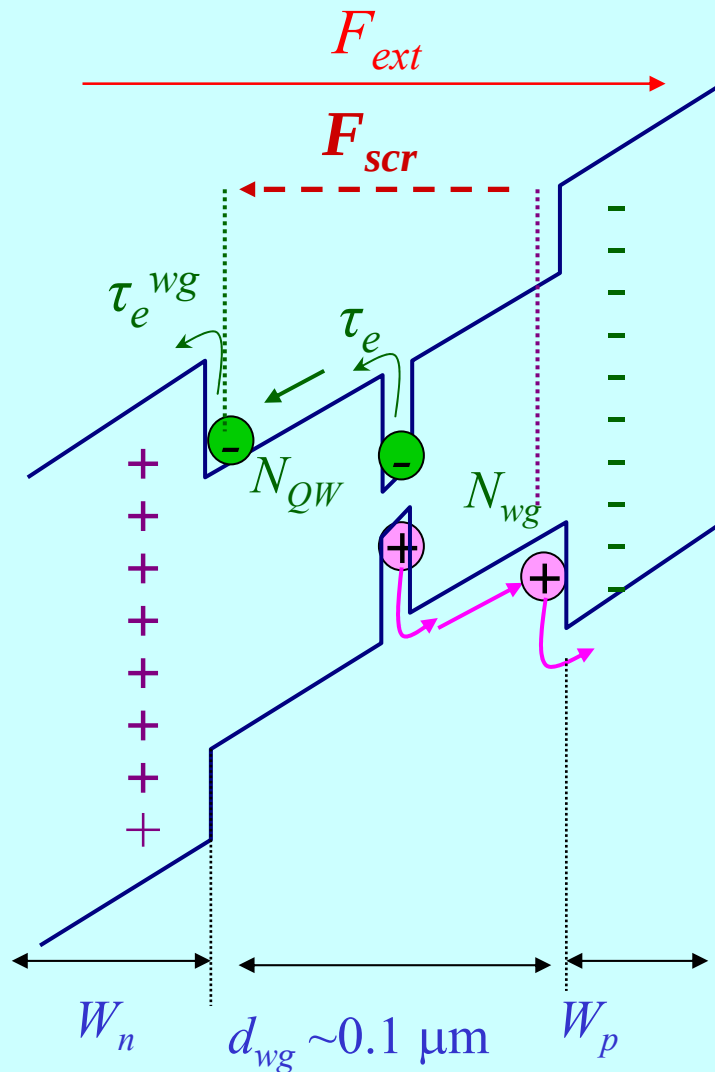


- Hole escape slower than electrons – likely to determine overall dynamics
- Field dependence of hole escape slower to exponential than GaAs/AlGaAs

Can describe escape from QW in a realistic structure. But is this the end of story?



Recovery process and recovery time in a reverse-biased absorber



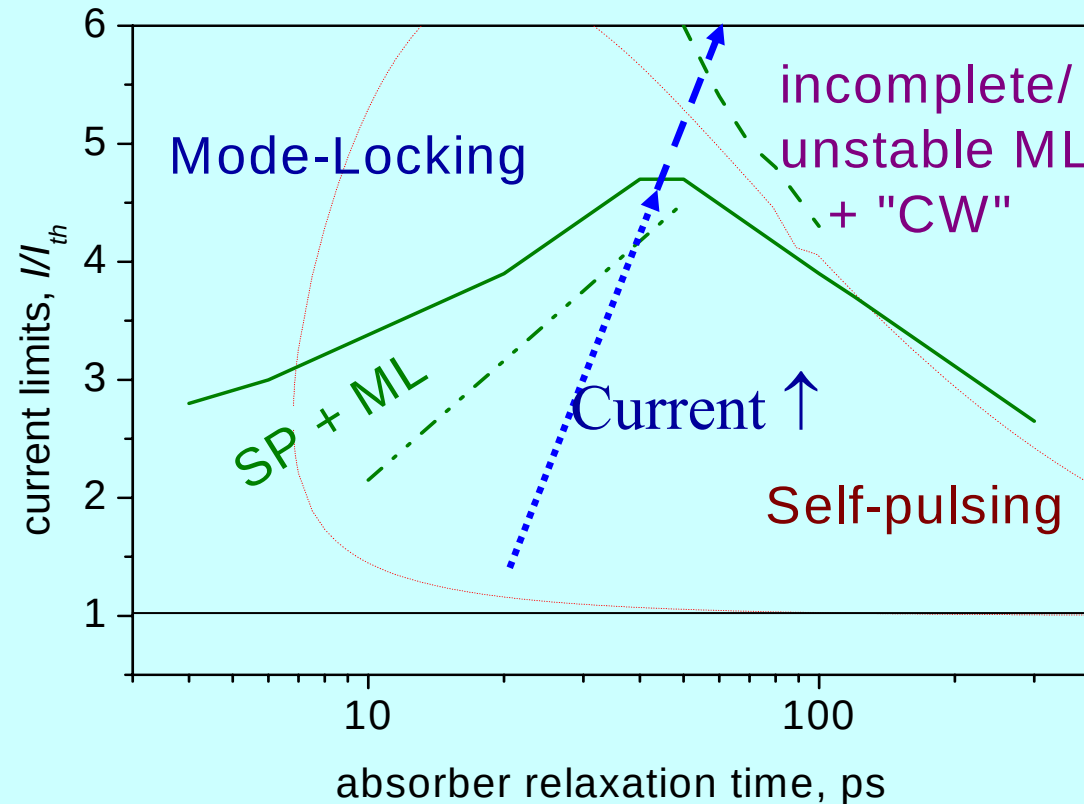
QW embedded in the waveguide layer;
field F_{ext} applied to contacts

Carriers escape by field sweepout:
QW → waveguide → claddings → bias circuit .

Escaped carriers create screening field F_{scr}

$$P \uparrow \Rightarrow N_{QW} \uparrow \Rightarrow N_{wg} \uparrow \Rightarrow F_{scr} \uparrow \Rightarrow F \downarrow \Rightarrow \tau_e \uparrow$$

Recovery time including screening and escape kinetics



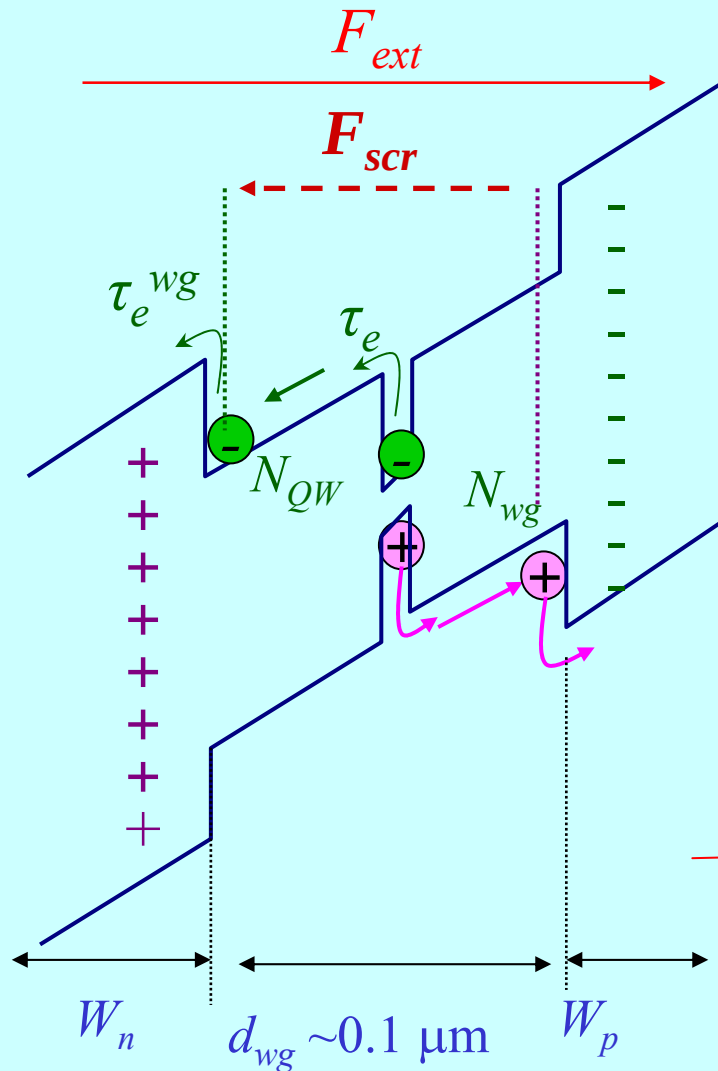
$\tau_e(P) \gg \tau_e(0)$ @ given bias voltage

Threatens mode-locking range:

- need to take care with design
- more accurate modelling of absorber necessary



Recovery process and recovery time in a reverse-biased absorber



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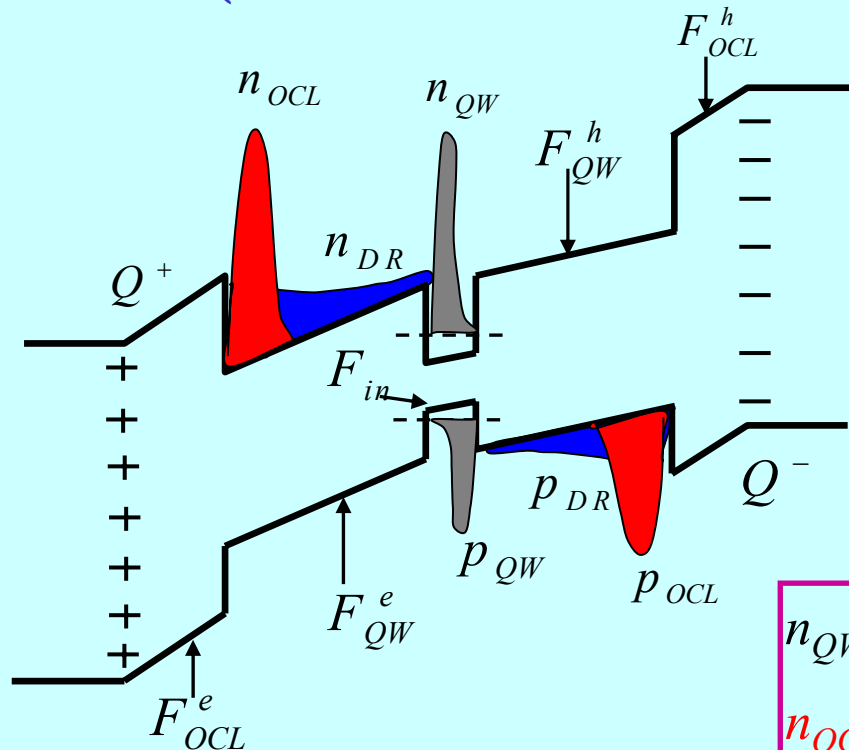
$I \uparrow \Rightarrow P \uparrow \Rightarrow N_{QW} \uparrow \Rightarrow N_{wg} \uparrow \Rightarrow F_{scr} \uparrow \Rightarrow F \downarrow$
 $\Rightarrow \tau_e \uparrow$

~~Escape theory - drift-diffusion model +~~
~~Schroedinger-Poisson solver for QW?~~

Too slow for dynamic calculations.
Need something faster.

Delay-differential model (DDM) for absorber dynamics

(after: E.A.Avrutin and V.V. Nikolaev, NUSOD'2004, Santa Barbara, Aug 2004) :



Diffusion neglected.

12 (+) Dynamic variables, 12 (+) main equations

6 Ordinary Differential Equations (ODE) +

6 Delay-Differential Equations (DDE)

(contain term delayed by drift time)

DDM

light
 $P(t)$

$n_{QW}(t), p_{QW}(t)$ (ODE)

$n_{OCL}(t), p_{OCL}(t)$ (DDE)

$n_{DR}(t), p_{DR}(t)$ - DDE

$Z^{e,h}(t) \rightarrow \tau_{dr(e,h)}$ (ODE)

Q^+, Q^- (ODE)

$\phi_{scr e,h}$ (DDE+algebra)

$\tau_{QW,OCL}^{e,h}$

$F_{QW,OCL}^{e,h}(t) \rightarrow F_{in}^{e,h}(t) \rightarrow \alpha(t)$

Treatment of the fields outside and inside the QW:

- Outside: flat capacitor approximation

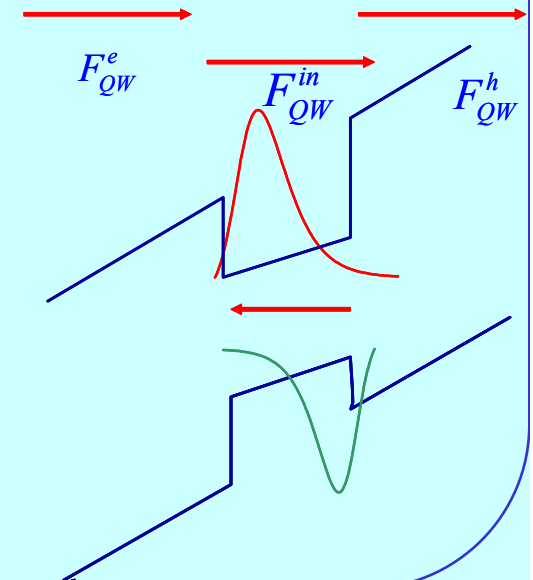
$$F_{QW}^{e/h} = \frac{2\pi e}{\varepsilon} [\text{positive charge to the left} + \text{negative charge to the right}]$$

$$\text{e.g. } F_{QW}^{e/h} = \frac{2\pi e}{\varepsilon} \left[\frac{Q^+ - Q^-}{e} - (n_{OCL} + n_{DR} + p_{OCL} + p_{DR}) \pm (n_{QW} - p_{QW}) \right]$$

- Inside: an approximate Schroedinger-Poisson procedure. Assume homogeneous field across the QW:

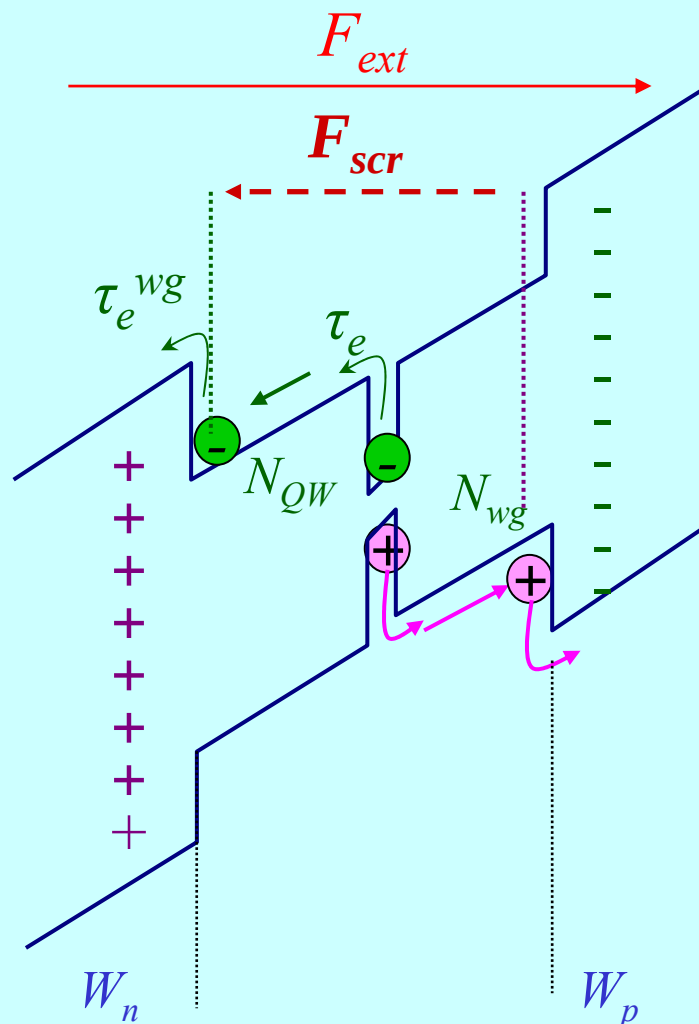
$$F_{QW}^{in} = \frac{F_{QW}^e + F_{QW}^h}{2} - \frac{2\pi e}{\varepsilon} \int_{QW} dz \left| p_{QW} \psi_h^2(F_{QW}^{in}) - n_{QW} \psi_e^2(F_{QW}^{in}) \right|$$

- The wave functions $\psi_{e,h}$ expressed in terms Airy functions $\Rightarrow F_{QW}^{in}$ a relatively straightforward transcendental equation for the field



Further modification: inclusion of carrier heating

Are we overestimating screening – include heating of drifting carriers by field ?



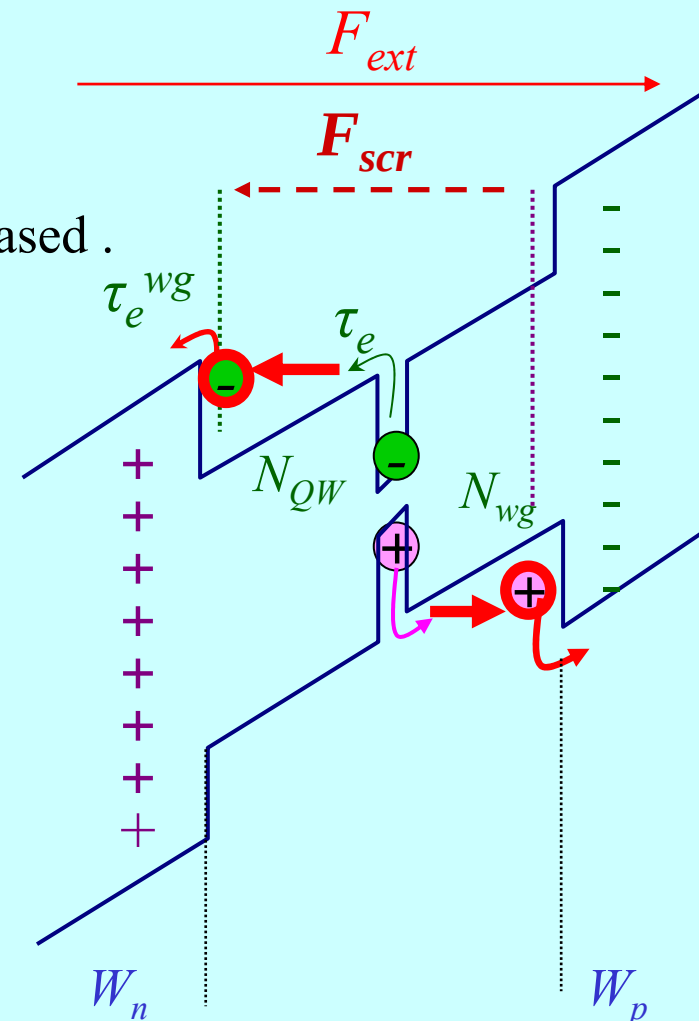
Carrier temperature in the OCL: why?

Are we exxagerating screening – include heating of drifting carriers by field ?

OCL carriers heated by field

(in the QW, no movement in field $\Rightarrow T=\text{const}$)

⇒ OCL-contact barrier penetration greatly eased .



Carrier temperature in the OCL: how?

OCL carriers heated by field (in the QW, no movement in field $\Rightarrow T=\text{const}$) $\Rightarrow$
 $\Rightarrow$ OCL-contact barriers effectively reduced. Need an equation for energy per volume:

$$\frac{d}{dt}U_e = \boxed{en_{DR} |v_{dr}^e| F_{QW}^e} - J_{engOCL}^e + J_{engQW}^e - \frac{U_e - \bar{U}_e}{\tau_u}$$

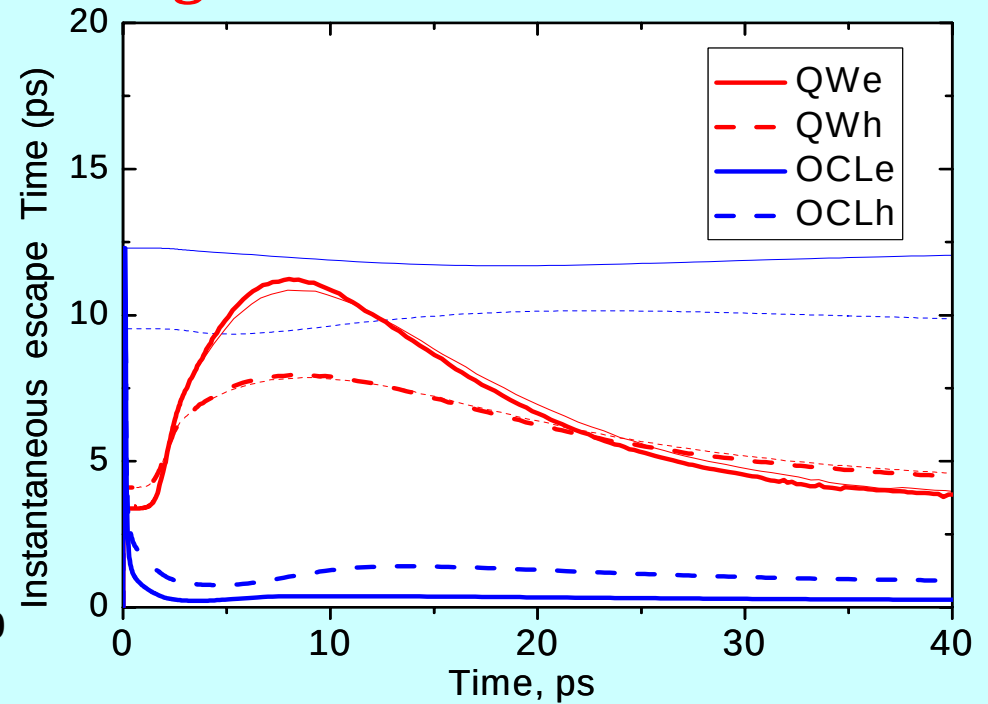
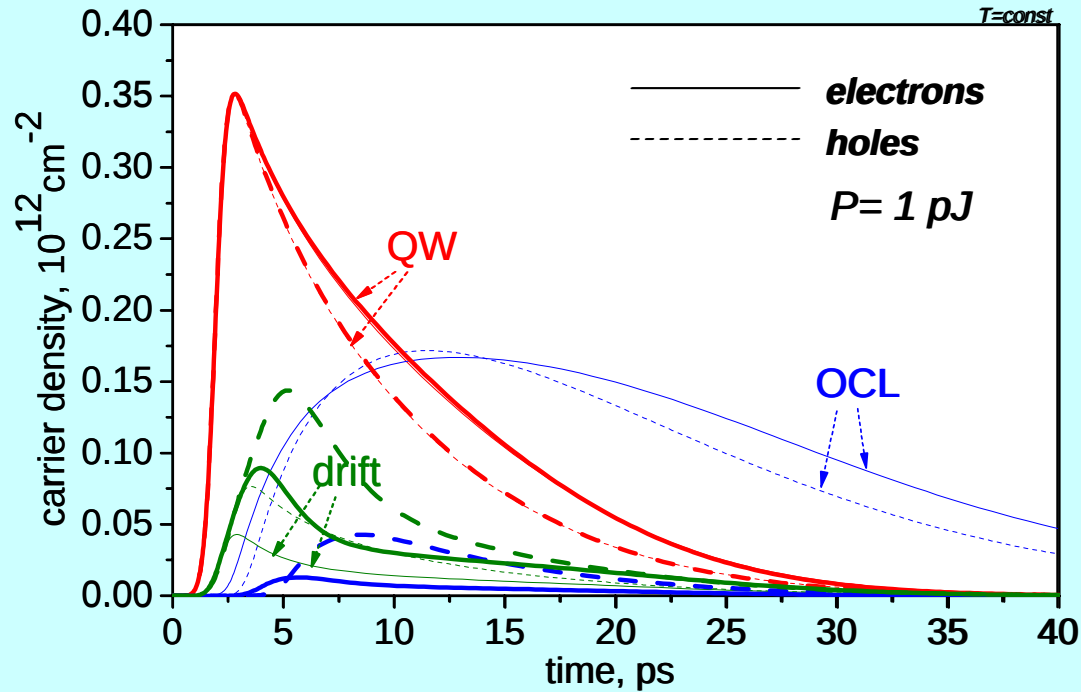
$$J_{engOCL}^e = \frac{1}{2\pi\hbar} \int_0^\infty (E + kT) \theta_B^2(E) P_{OCL}^e(E) dE \quad \text{energy drain into the barriers}$$

$$J_{engQW}^e = \frac{1}{2\pi\hbar} \int_{\Delta E_{QW} - kT}^\infty (E - \Delta E_{QW} + kT) \frac{|\theta(E)|^4}{|1 - r_+ r_-(E)|^2} P_{QW}^e(E) dE \quad \text{energy supply from the QW}$$

- The energy is recalculated into temperature $U_e = \frac{3}{2} k_B T_e (n_{DR} + n_{OCL})$
- recovery with a time $\tau_u = 1$ ps, to $\bar{U}_e = \frac{3}{2} k_B T_{lattice} (n_{DR} + n_{OCL})$

12 equations $\rightarrow$ 14 equations: $U_{e,h}$

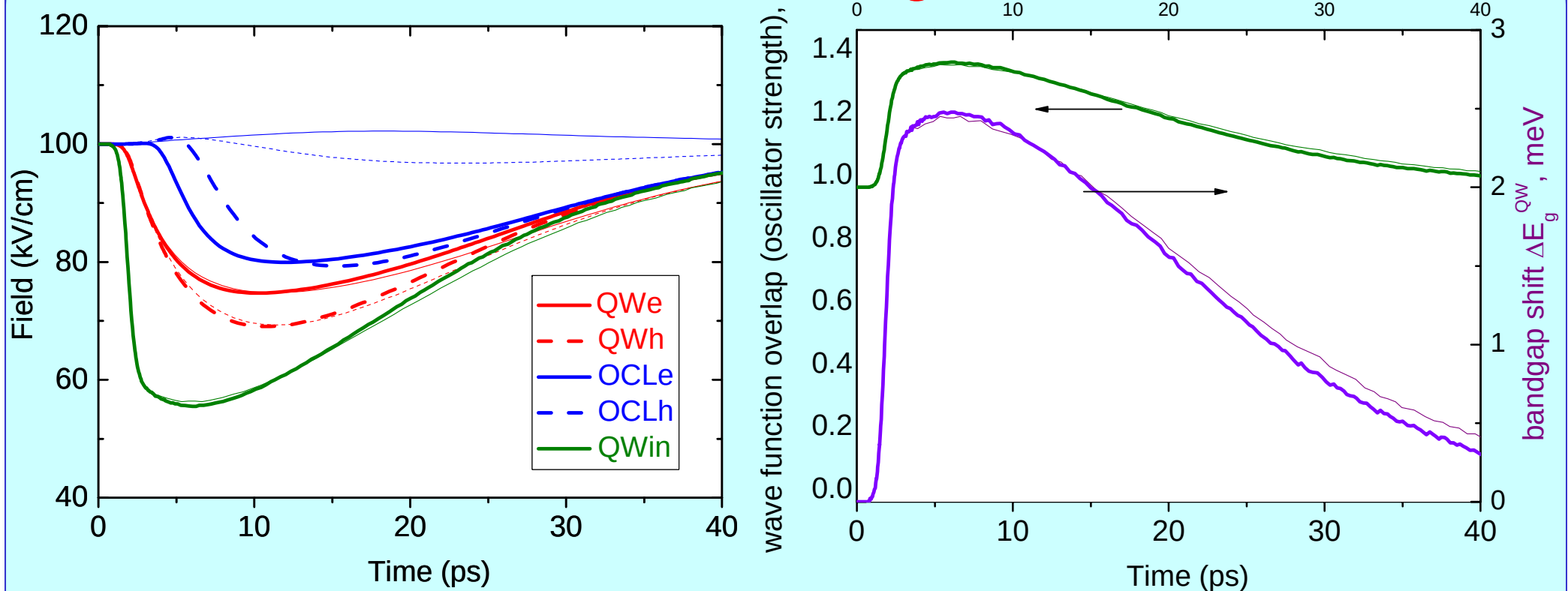
Dynamics of parameters: carrier densities and recombination times with heating



- Non-exponential dynamics
- OCL carrier density strongly decreased by the reduced OCL-contact barrier
- Drift slows down $\Rightarrow$ larger drifting density
- QW carrier density and field virtually the same!

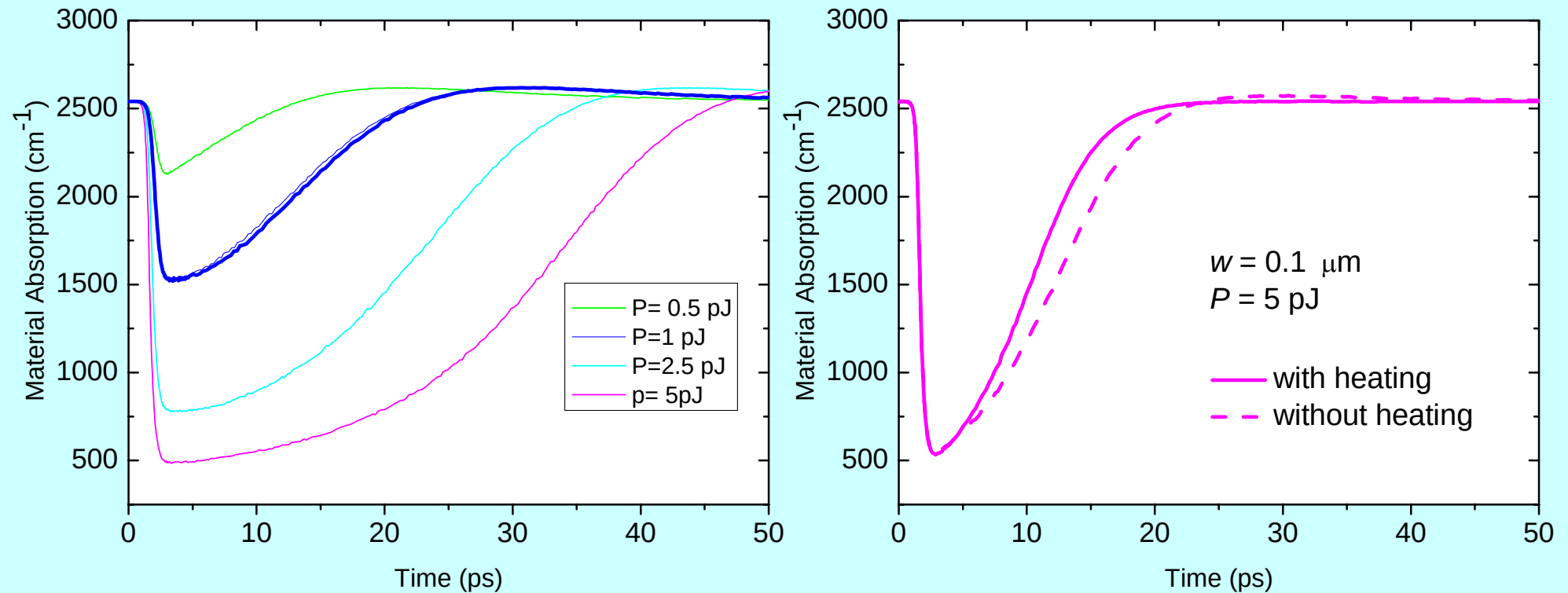
$$\text{Al}_x\text{Ga}_{1-x}\text{As: } x_{\text{barrier}}=0.5, x_{\text{OCL}}=0.25, x_{\text{QW}}=0$$

Dynamics of parameters: fields and electro-absorption with heating



- Strong screening seen by QW fields
- QW fields (internal and external) almost unchanged by inclusion of T $\Rightarrow$ little change in the electroabsorption

Absorption recovery dynamics **with heating**

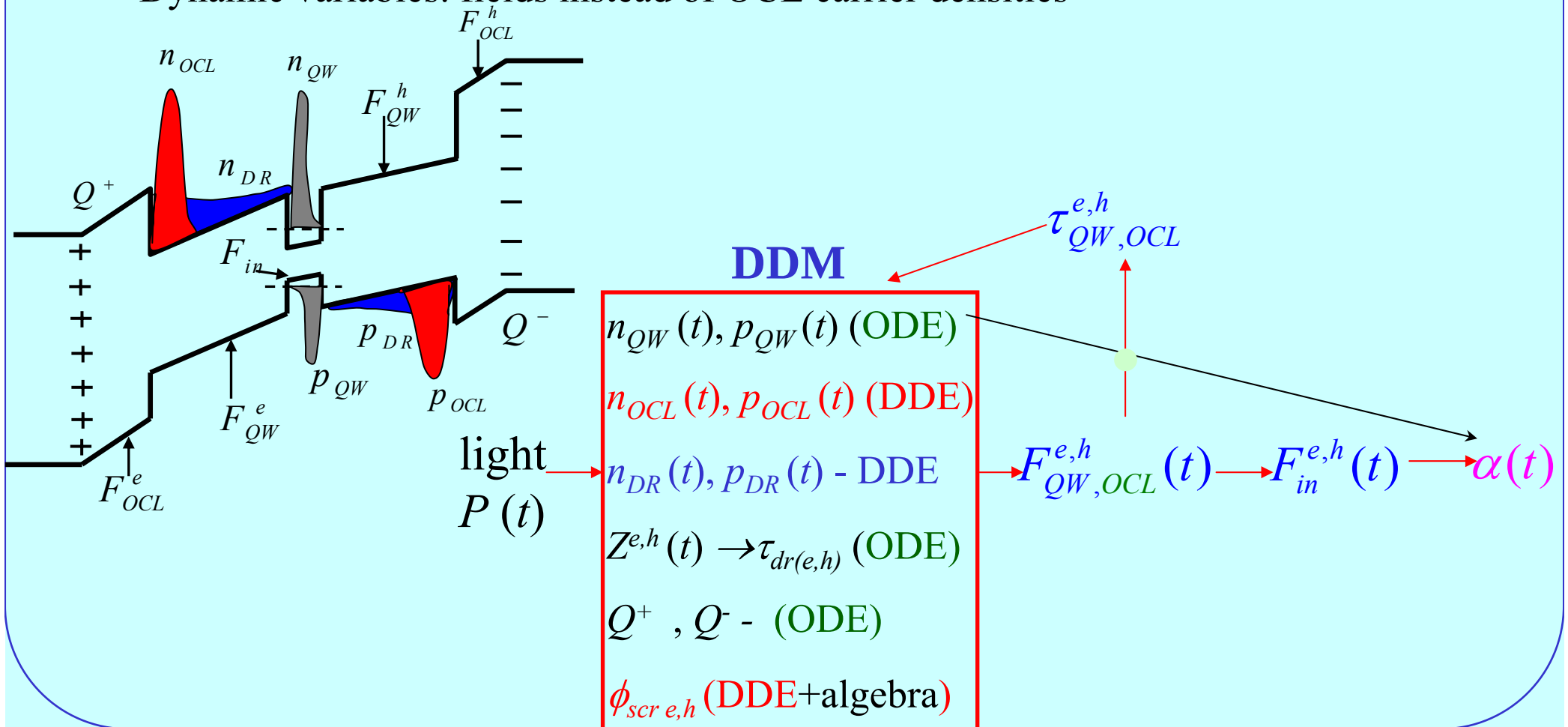


- Recovery increasingly non-exponential as input power increases
- Little change with heating included, particularly at smaller power

Redistribution of carriers within groups is not too important –
it's mainly the total charge that matters!

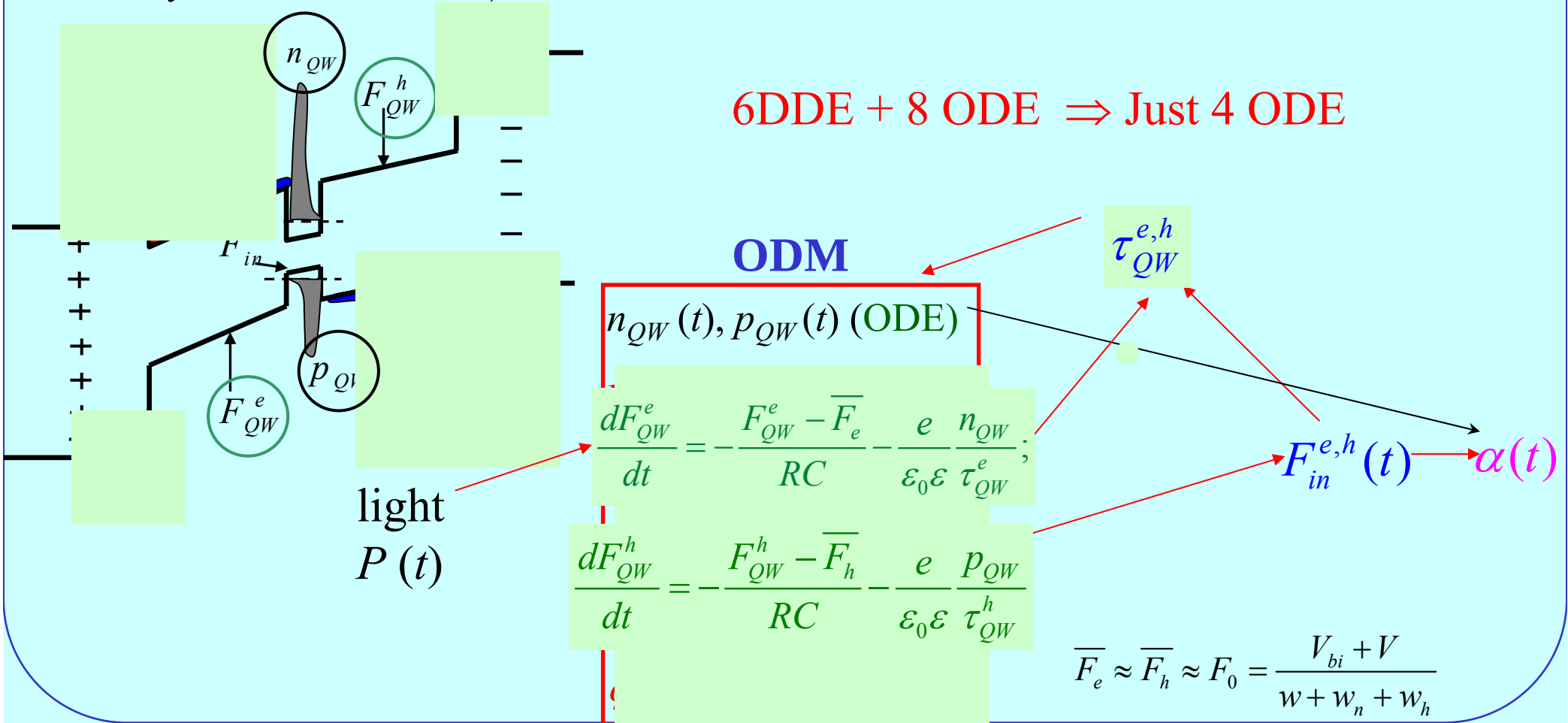
Simplified model

- Valid for:
 - Broad waveguide (wider than the depleted regions)
 - Modest screening (hence modest power)
- Dynamic variables: fields instead of OCL carrier densities

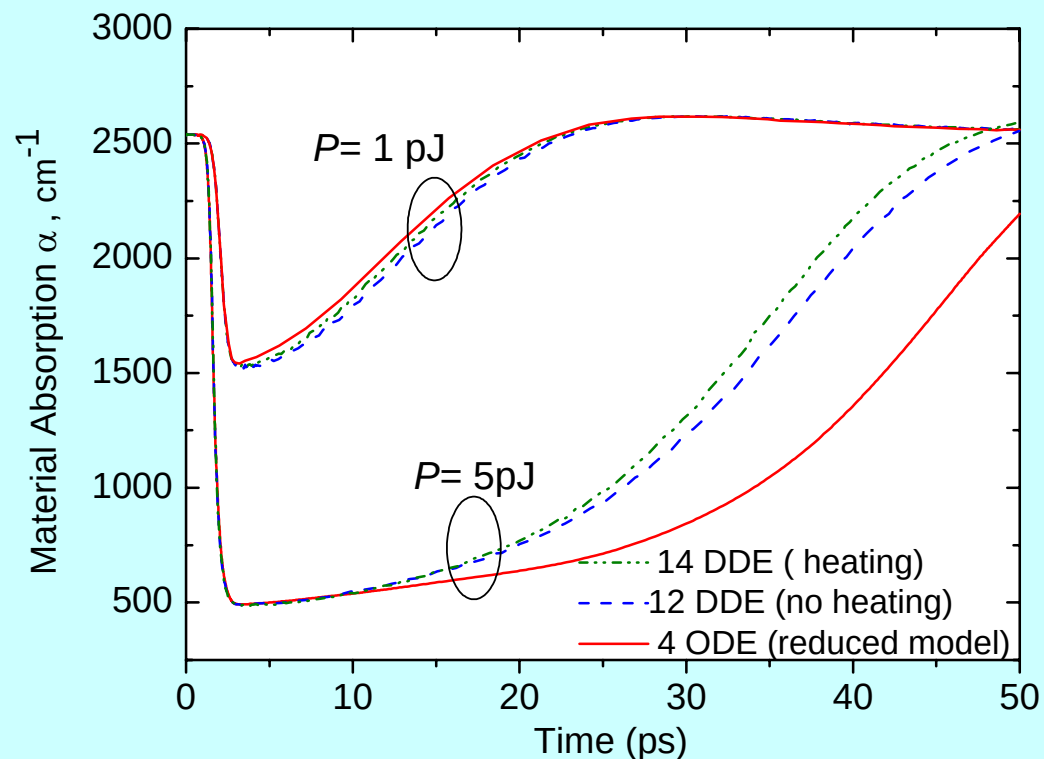


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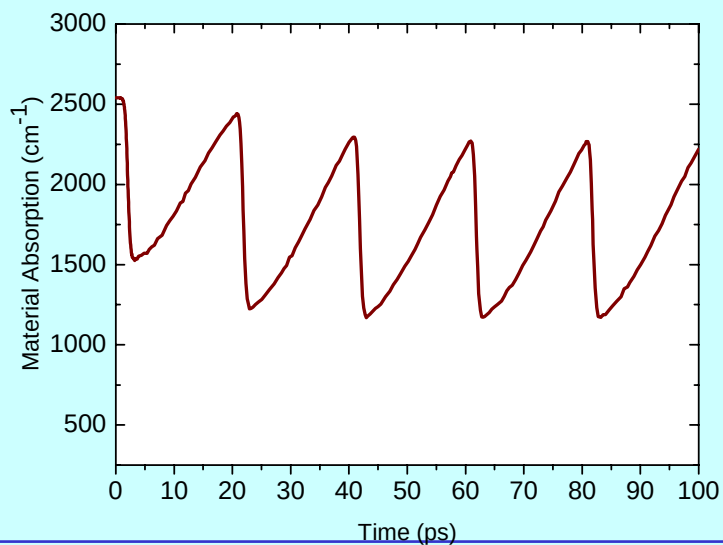
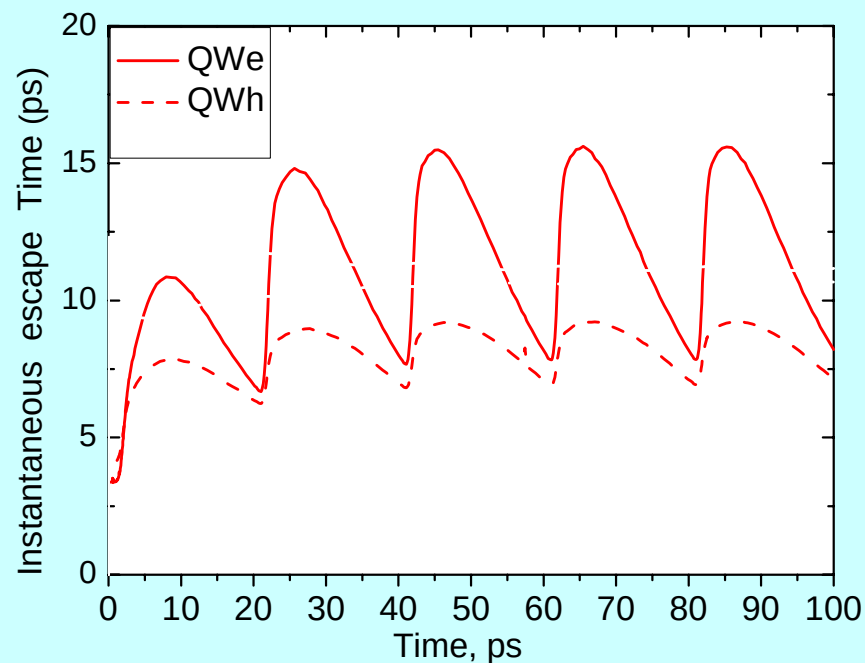
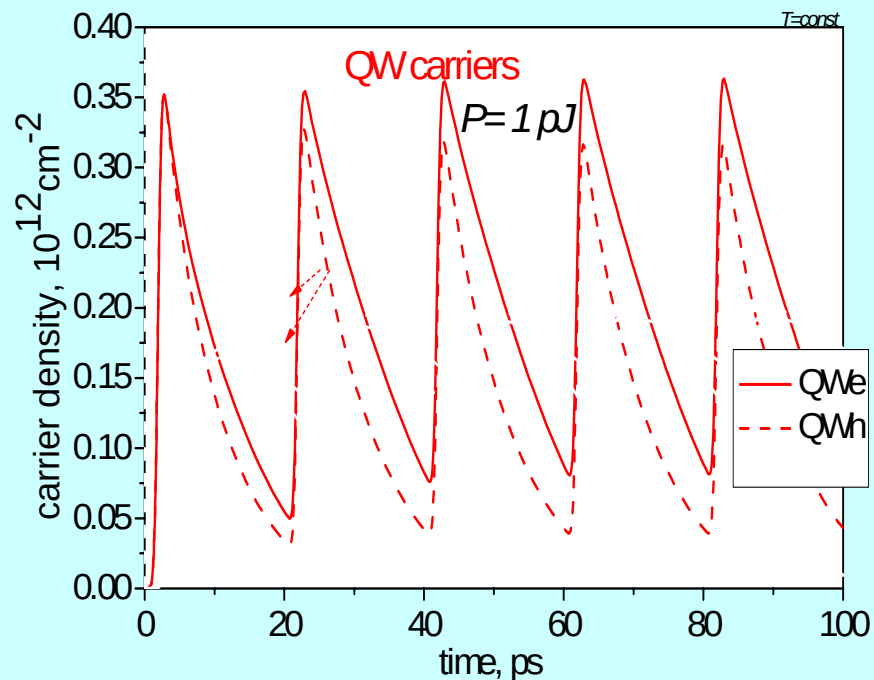


Simplified vs. full model



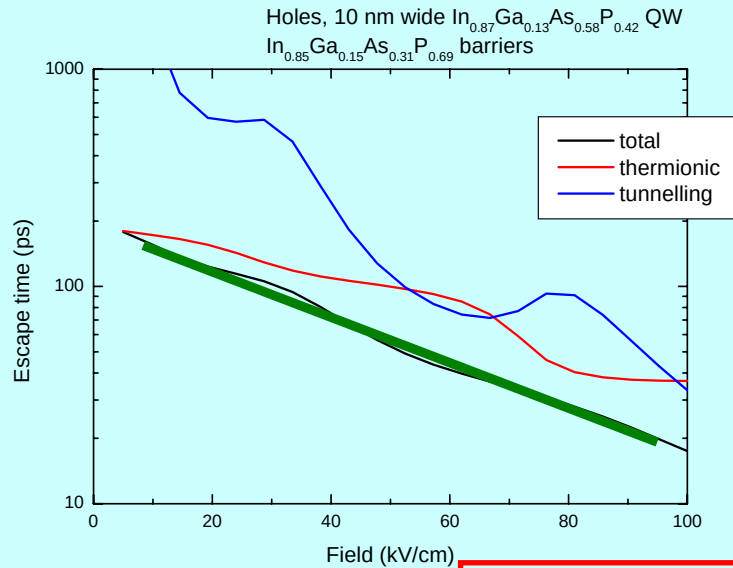
- Excellent agreement at modest power
- For very high power pulses, full model still preferable

Absorber operation under repetitive stream of pulses





A phenomenological approach retaining the main physics



$$\rightarrow \tau_{QW}^h = \tau_{QW}^{h(0)} \exp(-F_{QW}^h / F_{scale})$$

$$F_{QW}^{e,h}(t) \approx F_{QW}^{in}$$

+ phenomenological/extracted $\alpha(n, p_{QW}, F_{QW}^i)$

light
 $P(t)$

$$\frac{dn, p_{QW}}{dt} = G(t) - \frac{n, p_{QW}}{\tau_{e,h}^{QW}}$$

$$\frac{dF_{QW}^h}{dt} = -\frac{F_{QW}^h - \overline{F}_h}{RC} - \frac{e}{\epsilon_0 \epsilon} \frac{p_{QW}}{\tau_{QW}^h}$$

$$\frac{dF_{QW}^e}{dt} = -\frac{F_{QW}^e - \overline{F}_e}{RC} - \frac{e}{\epsilon_0 \epsilon} \frac{n_{QW}}{\tau_{QW}^e};$$

$$\tau_{QW}^{e,h}$$

$$\alpha(t)$$

$$\overline{F}_e \approx \overline{F}_h \approx F_0 = \frac{V_{bi} + V}{w + w_n + w_h}$$

Conclusions

- Short absorber relaxation time needed for operation of many devices – an important parameter
- Processes involved are carrier escape from the QW and carrier kinetics in the OCL
- Simple efficient theory of carrier escape inc. tunnelling and thermionic escape.
- Carrier kinetics in OCL studied by delay-differential model
 - Carrier accumulation in OCL and screening important for pulses with $P > \sim 0.1$ pJ;
 - carrier heating by field is only of modest importance
- Simplified model including only differential equations works well for moderate pulse powers (of the sort typically encountered in mode-locking)