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Laser emission at 830 and 960 GHz from quantum cascade structures

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Outline

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- Motivation and previous research on QCL's in B field
- Design for 1 THz laser: discussion
- Laser performance and transport analysis
- Design for 840 GHz: an unexpected laser?!
- Conclusions and perspectives

Motivation for magnetic field study

- Extend the wavelength limits of QCL's
- Study of systems with strong confinement
- Suitable system for fundamental studies:
  - Extremely reduced thresholds (1 A/cm^2)
  - Photonic confinement (favorable scale of dimensions with λ)
- Spectroscopy of active region

Literature survey

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Mid-Ir: Spectroscopy on existing devices, scattering analysis and design optimization, gain models

•D.Smirnov et al., *Phys. Rev. B*, **66,** 121305 (2002)

•A. Leuliet et al. *Phys. Rev. B*, **73**, 085331 (2006),

• A. Vasanelli et al., *Appl. Phys. Lett.,* **89**, 172120 (2006)

•I Savic et al., *Phys. Rev. B* **73**, 075321 (2006)

•M. Semtsiv, *Appl. Phys. Lett*. **89**, 171105 (2006)

•THz: magnetically assisted gain, spectroscopy on existing devices

•V. Tamosiunas et al., *Appl. Phys. Lett.,* **83**, 3873 (2003)

•J. Alton et al., *Phys. Rev. B*, **68**, 081303 (2003)

•G. Scalari et al., *Phys. Rev. Lett.,* **93**, 237403 (2004)

•N. Pére-Laperne et al., *Appl. Phys. Lett.,* **91**, 062102 (2007)

3D confinement on THz QC laser

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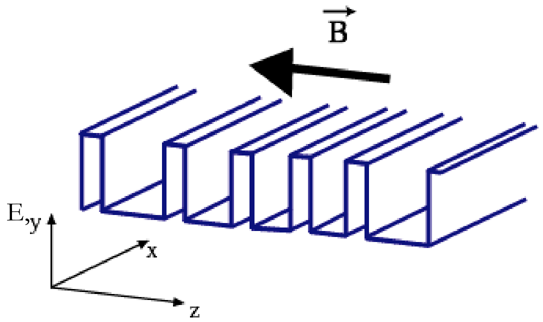
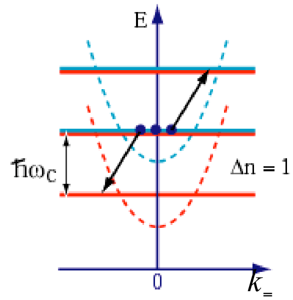
Perpendicular magnetic field on a MQW system

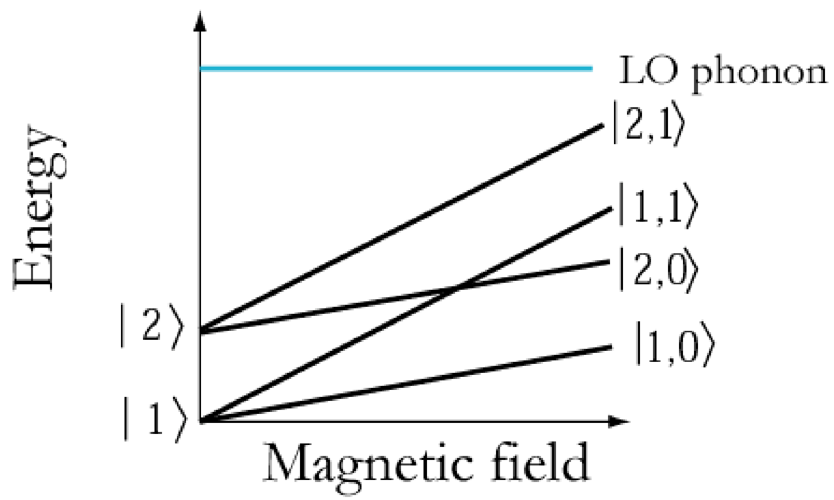
B≠0





$$E_n=(n+1/2)\ \hbar\omega_C+E_0$$

Subbands break into Landau ladders



The allowed energy changes:

$$\Delta E=\delta n\hbar\omega_C$$

Optical selection rules:

$\Delta N=0$ for TM polarization

$\Delta N=\pm1$ for TE polarization

Magnetic confinement: 2 regimes

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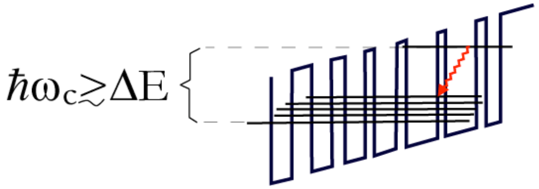
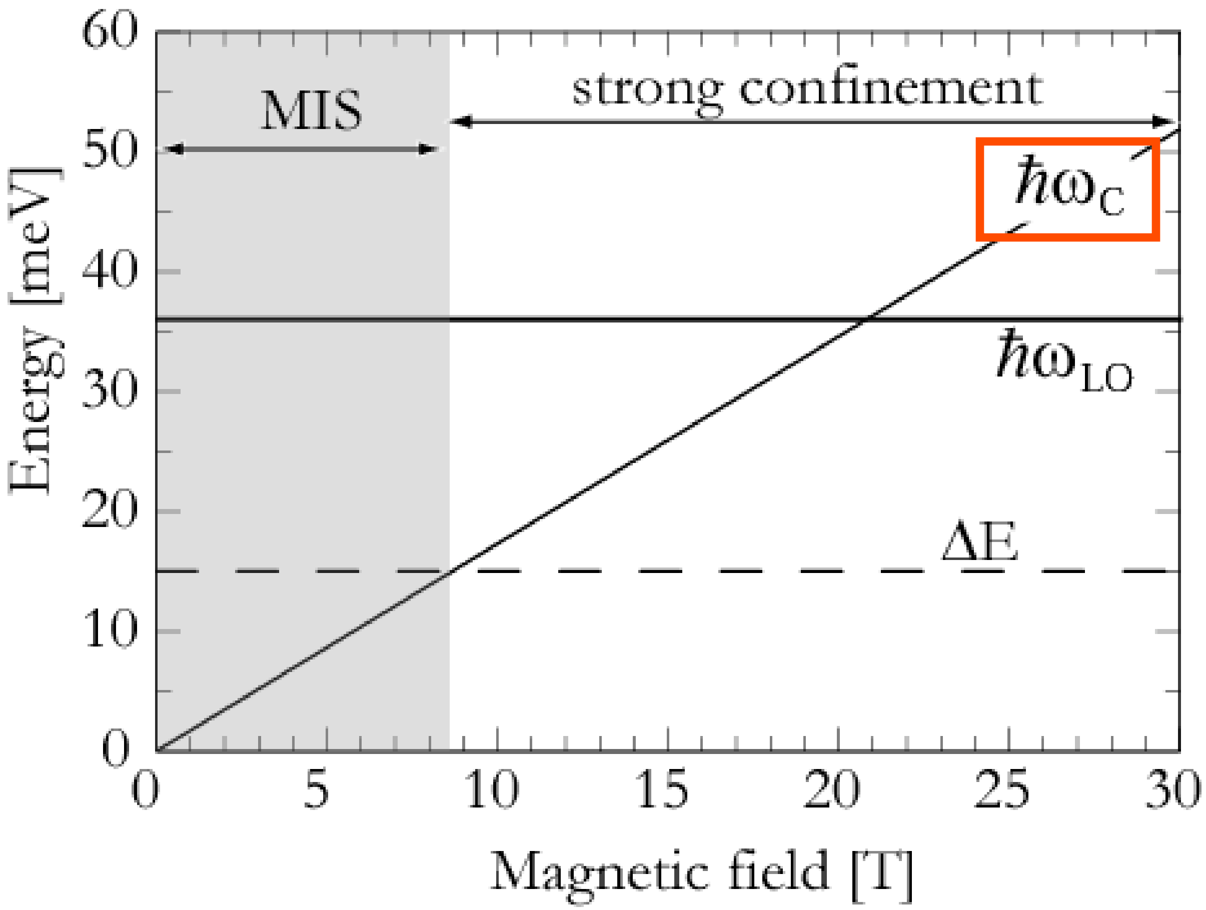




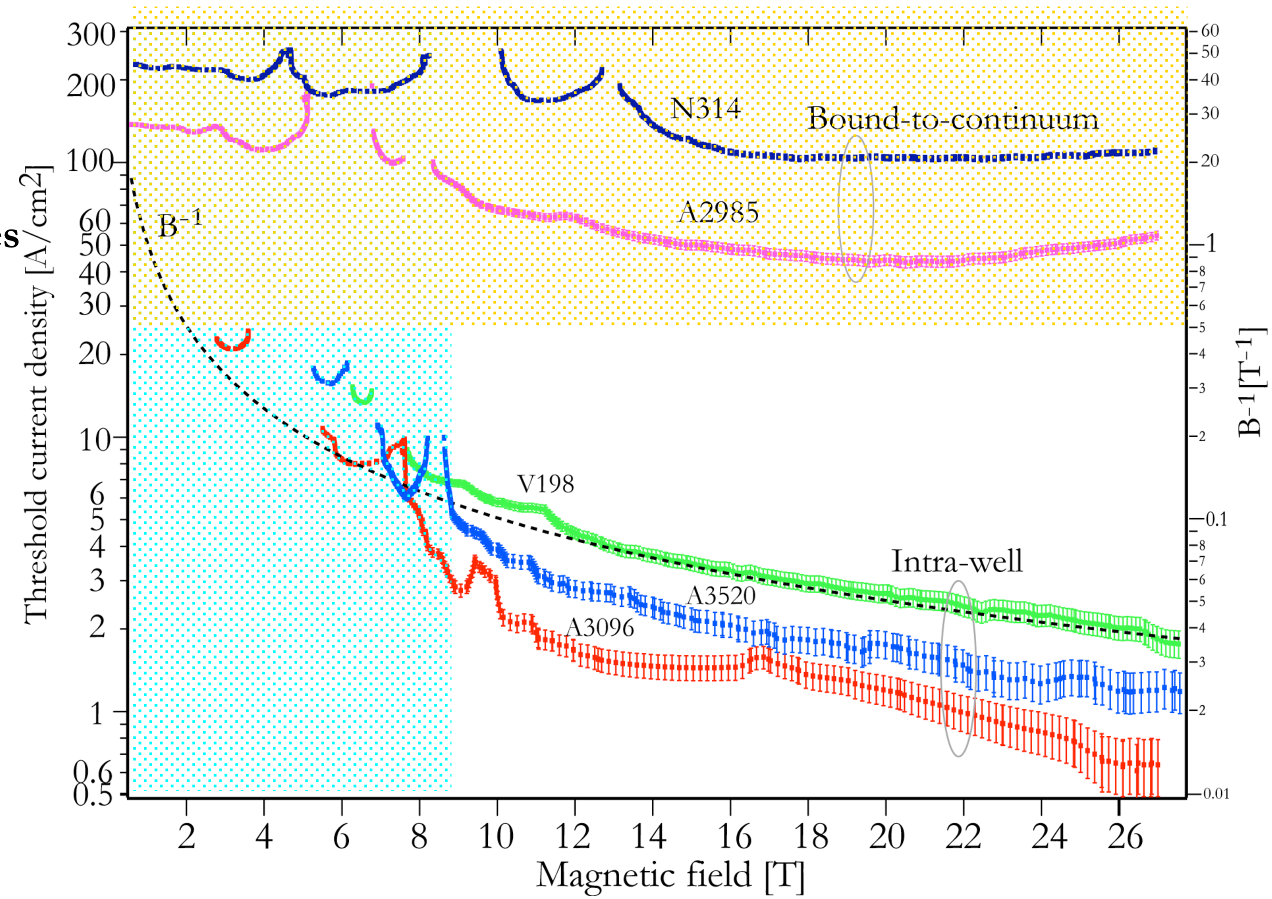
Intra-well Vs bound-to-continuum

Ultra-low threshold

accessible only to intra-well samples

Key role of IR scattering

And wavefunction delocalization



G. Scalari et al., Phys. Rev. B, 76, 115305(2007)

Magnetically assisted gain on "big wells"

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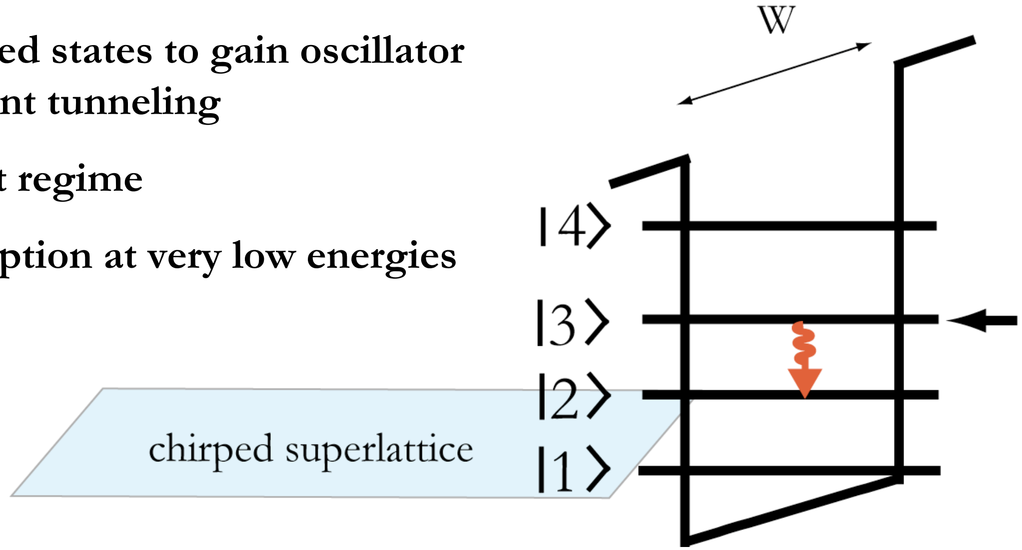
- A "big well" with a transition between excited states to gain oscillator strength and population inversion via resonant tunneling
- Relies on localization in strong confinement regime
- Chirped superlattice as injector: cross absorption at very low energies



Frequency (THz)	3.6	1.8	1.6	1.35
Big Well width (Å)	360	550	570	607

1 THz structure

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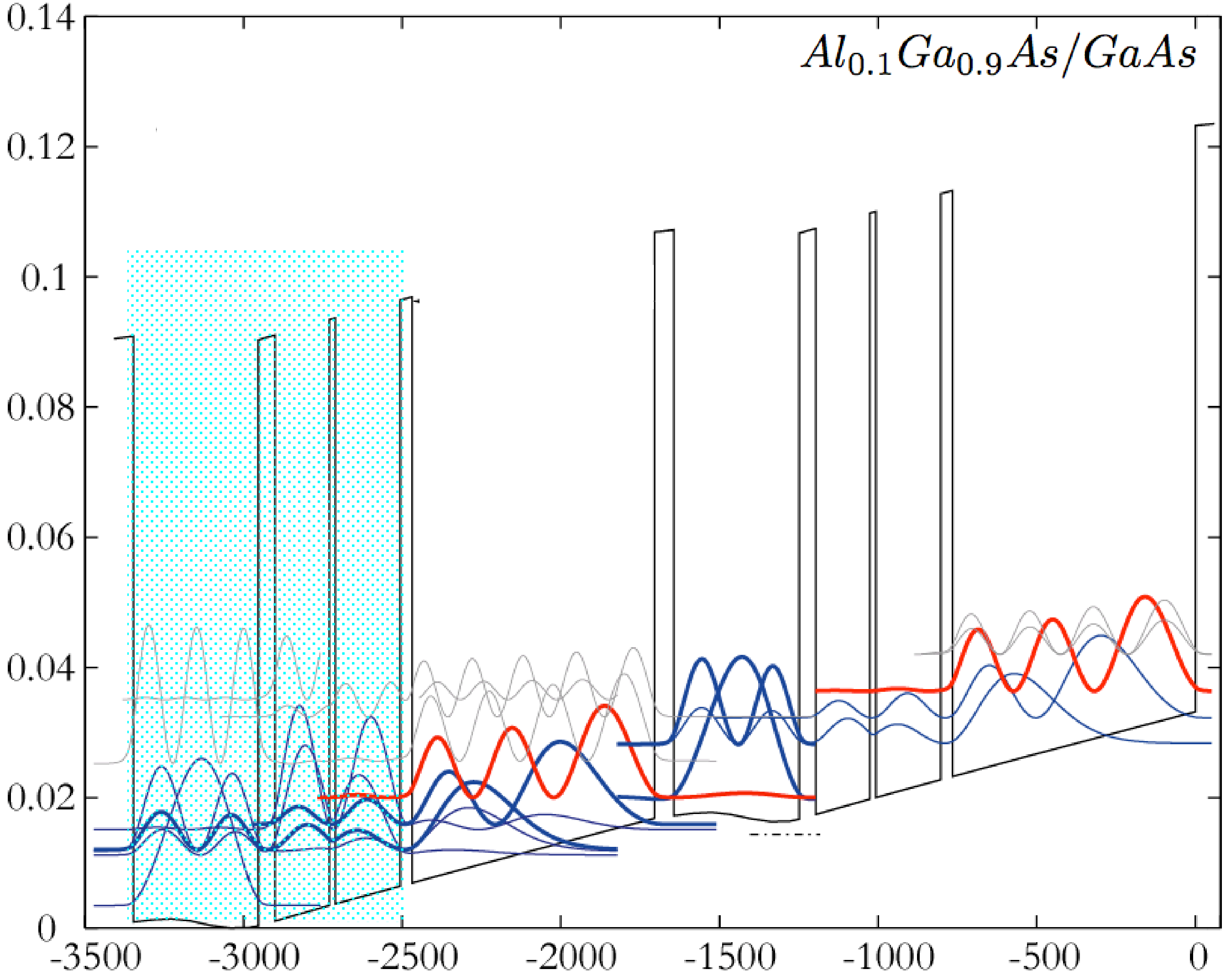
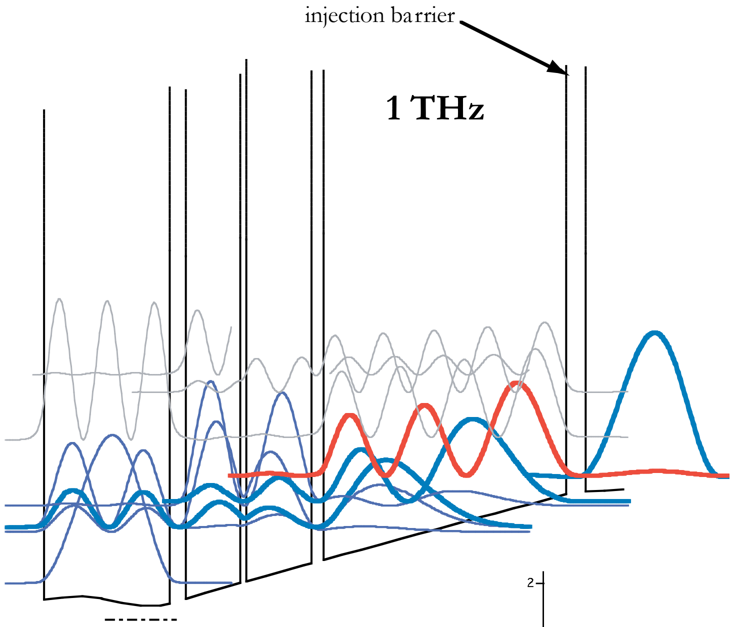
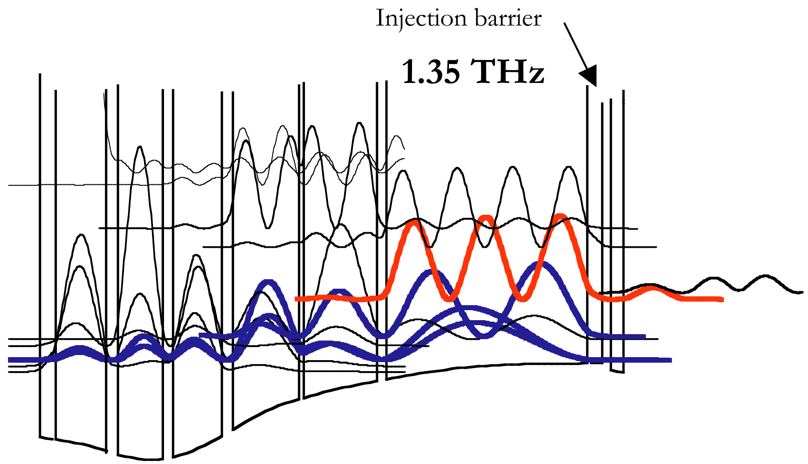
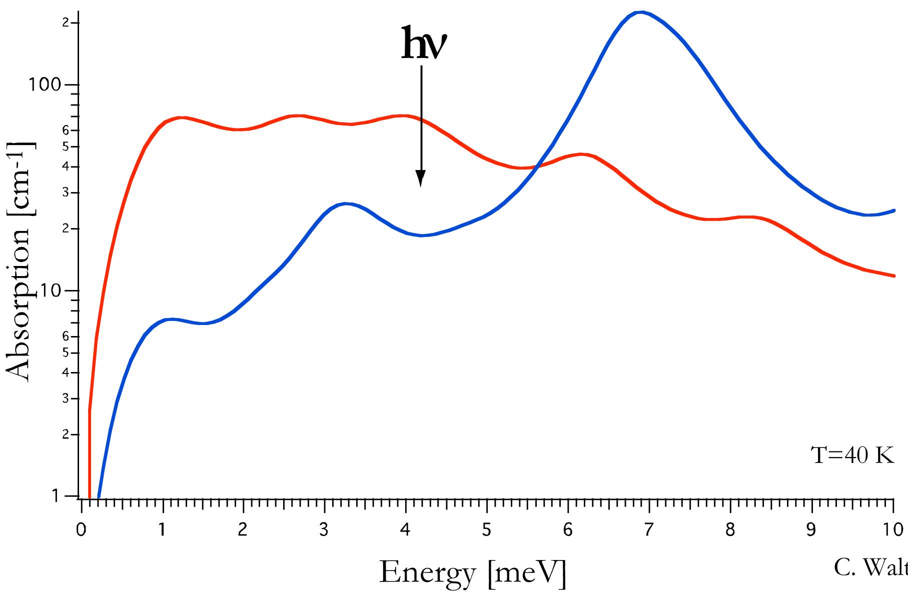


G. Scalari *et al*., unpublished (2007)

Designing the losses: absorption “gap” @ 4 meV







C. Walther *et al.*, Appl. Phys. Lett., **89**, 231121 (2006)

Active region: details & numbers

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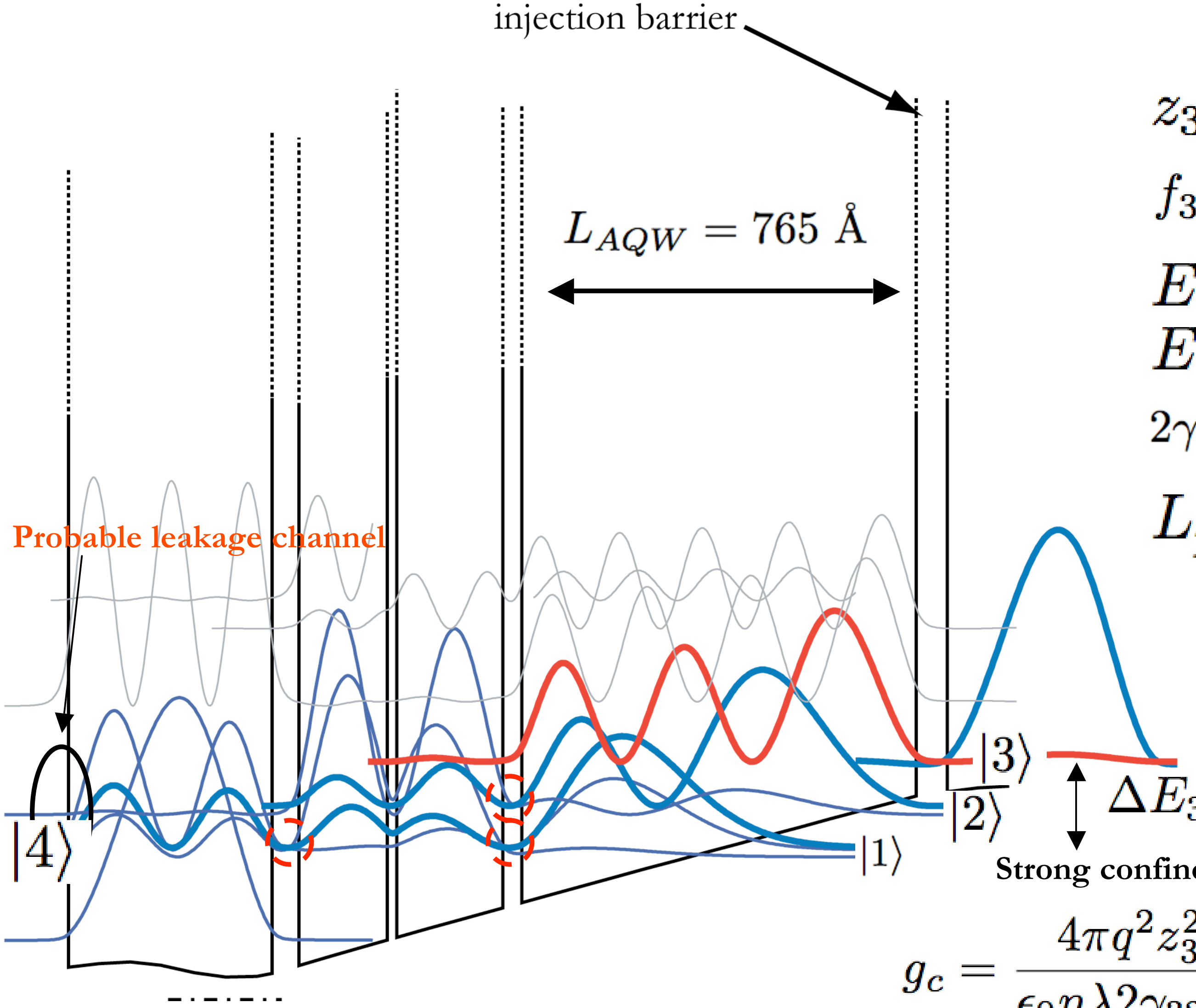

$$z_{32} = 154 \text{ Å}$$

$$f_{32} = 26$$

$$E_{32} = 4.14 \text{ meV}$$

$$E_{21} = 3.85 \text{ meV}$$

$$2\gamma_{32} \leq 0.4 \text{ meV ??}$$

$$L_p = 1704 \text{ Å}$$

Strong confinement regime starts @ 4.6 T

$$g_c = \frac{4\pi q^2 z_{32}^2}{\epsilon_0 n \lambda 2\gamma_{32} L_p} \simeq 2.8 \times 10^{-10} \text{ cm}$$

Transport at B=0 T

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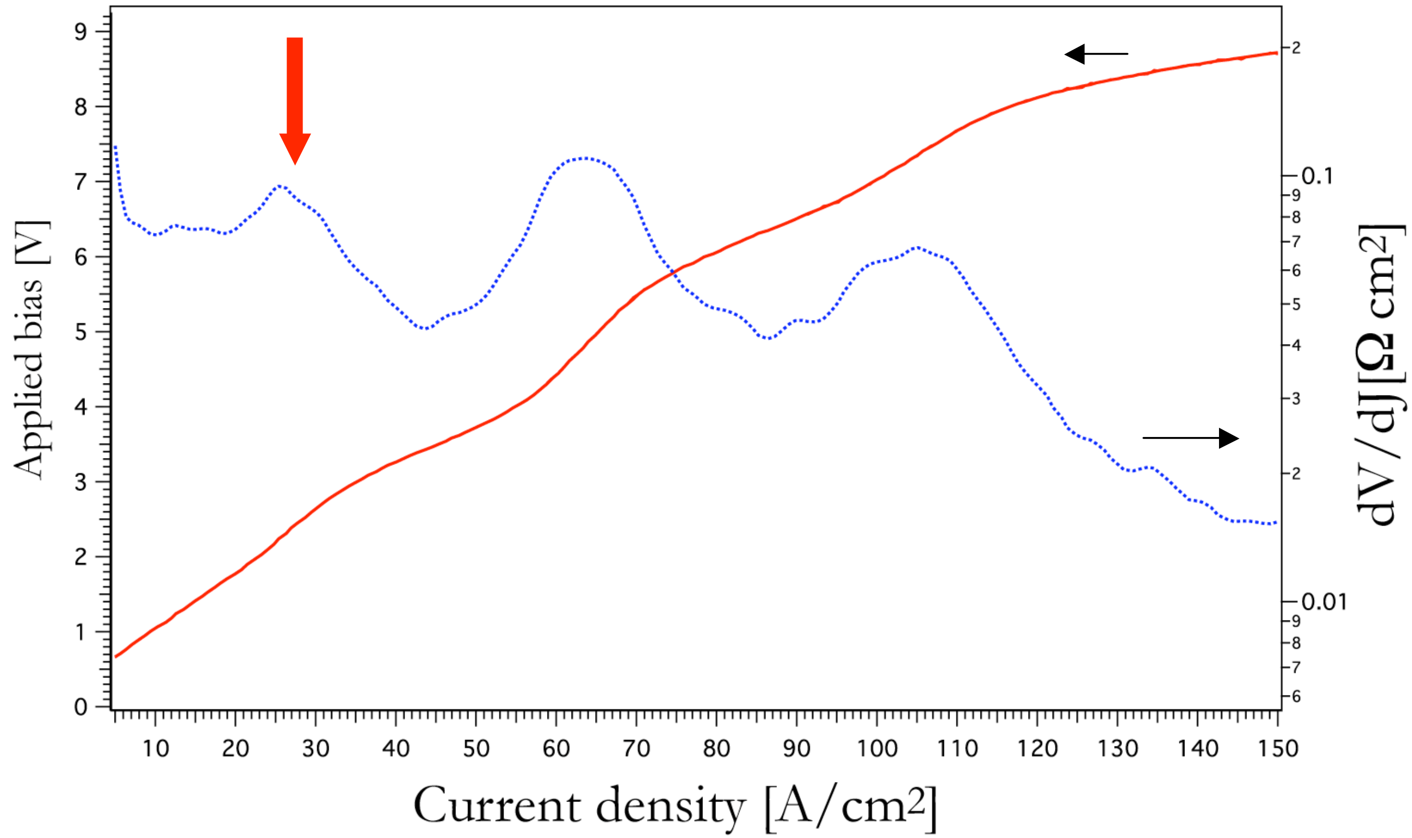

$$J_{max} \simeq 30A/cm^2$$

$$\tau_{\perp} \simeq 1 \text{ ps}$$

$$\tau_{up} = \frac{qn_s}{2J_{max}} - \frac{1}{4\Omega_{inj}^2 \tau_{\perp}} \simeq 100\text{ps}$$

950 GHz QCL

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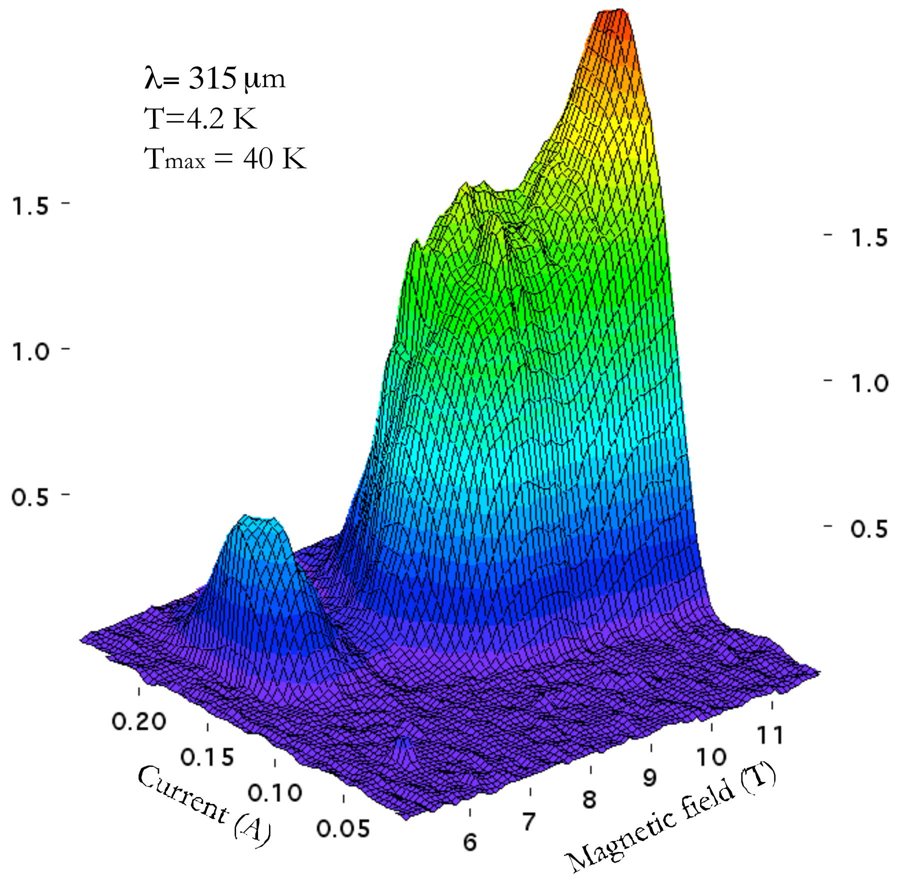
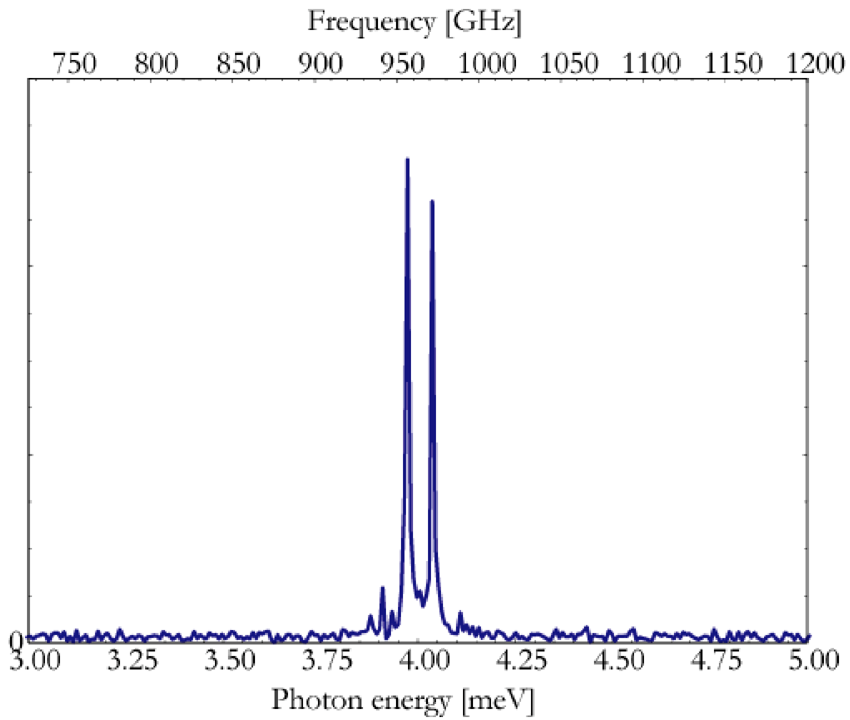


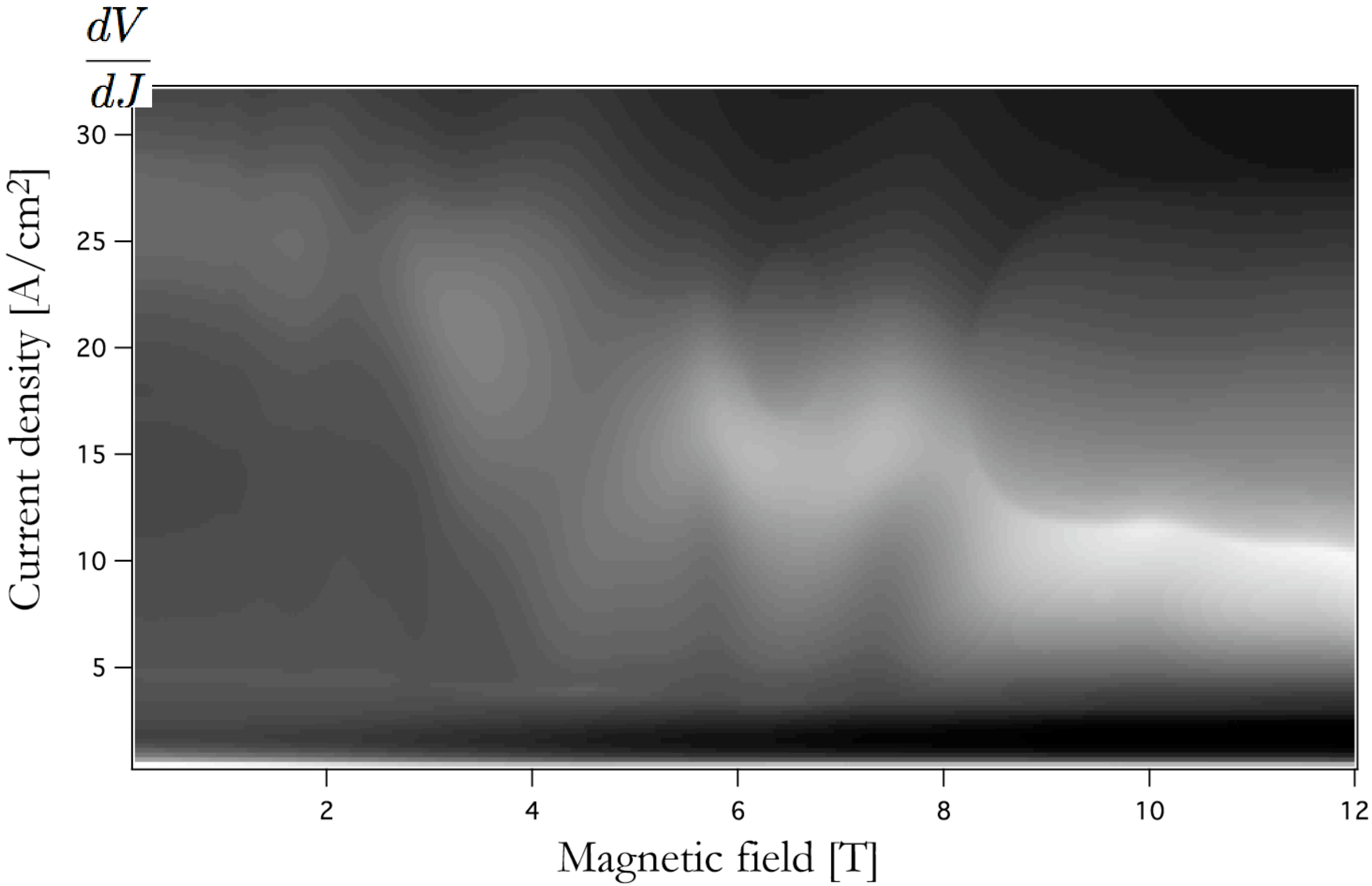


$$J_{thresh}(12\ \mathrm{T}) = 10\ \mathrm{A}/cm^2$$

1.5 mm long, 400 µm wide DM ridge

G. Scalari *et al.*, unpublished (2007)

Transport: differential analysis



Transport: lasing in small cavities

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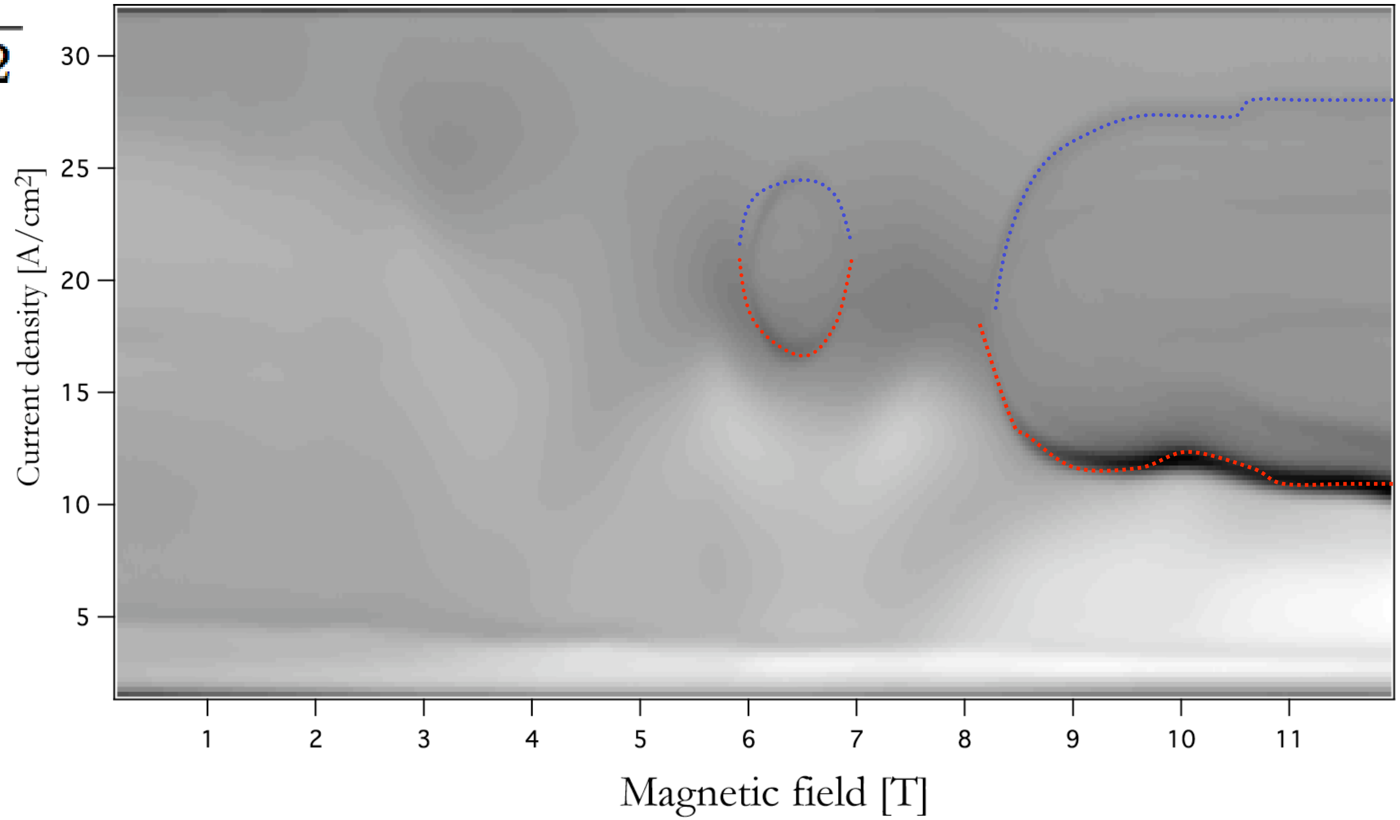
$$\frac{d^2V}{dJ^2}$$



Very small laser ridge 550 μm long 100 μm wide: no change in threshold

Magnetotransport (I)

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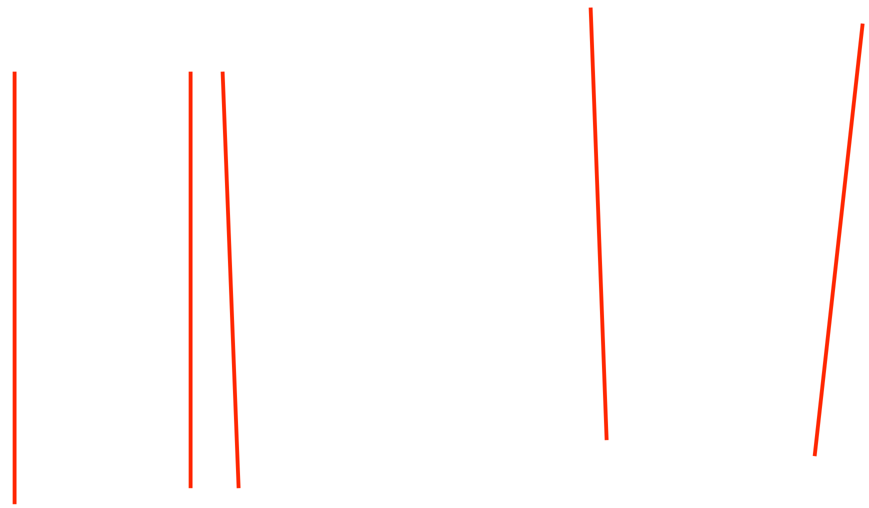
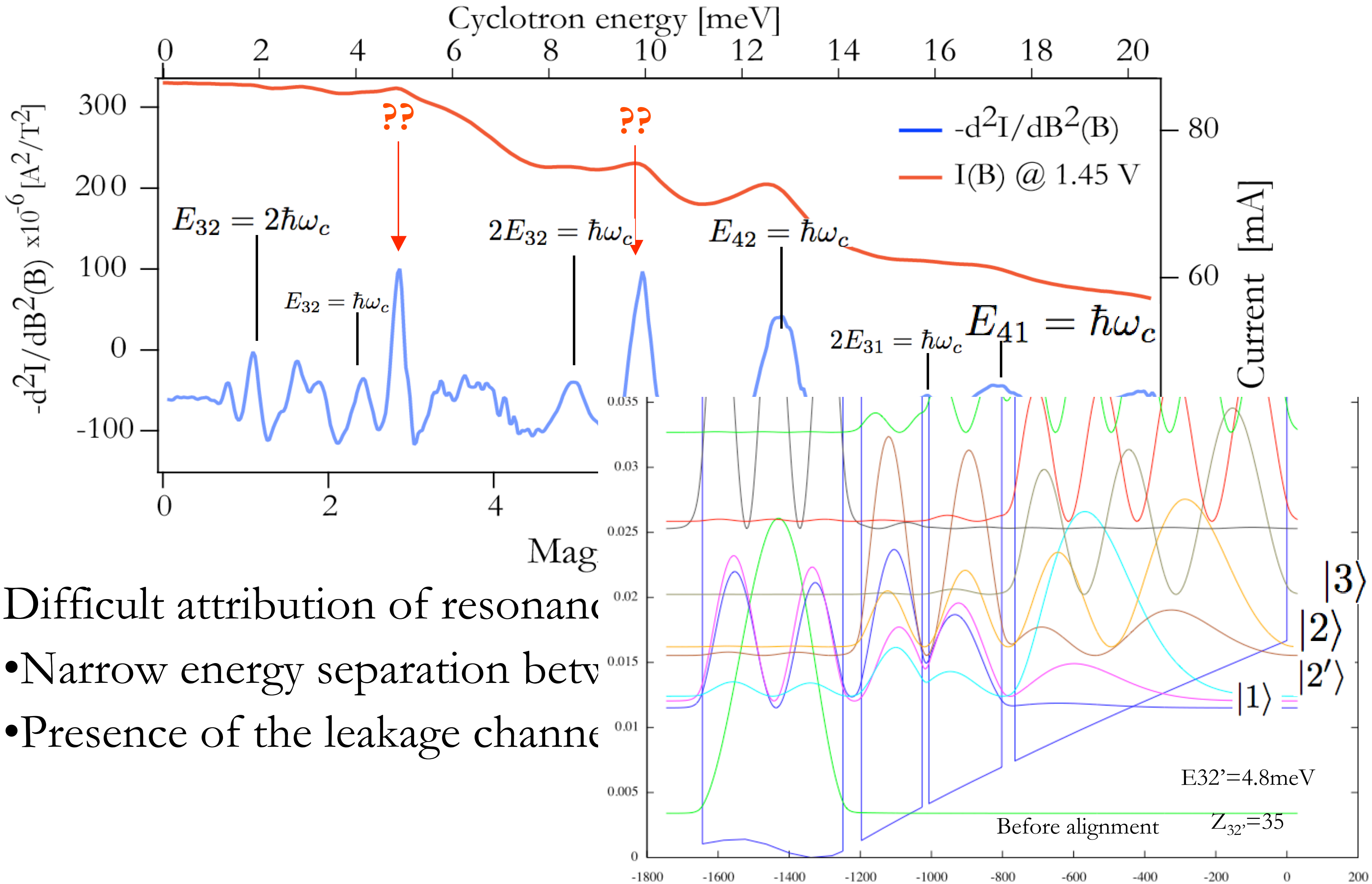
$$-\frac{d^2 J}{dB^2}$$

Applied bias [V]



Magnetic field [T]

Magnetotransport (II)



Difficult attribution of resonanc

•Narrow energy separation betw

•Presence of the leakage channe

Temperature dependence

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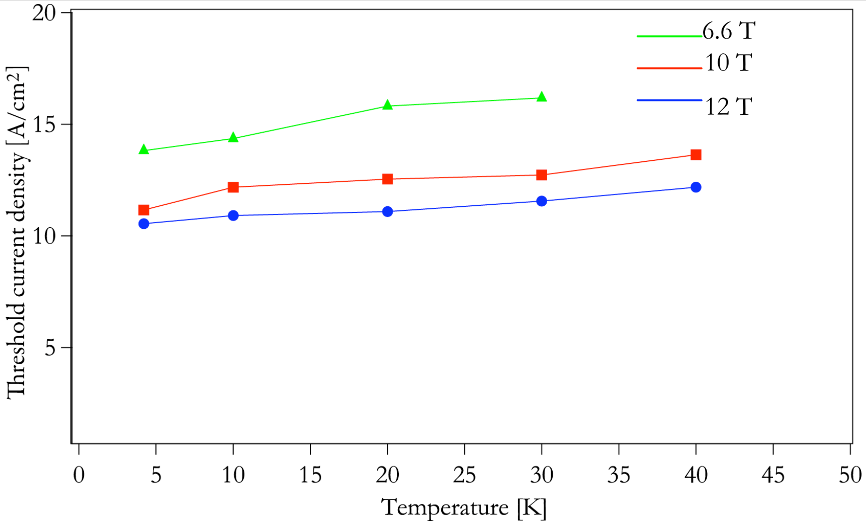
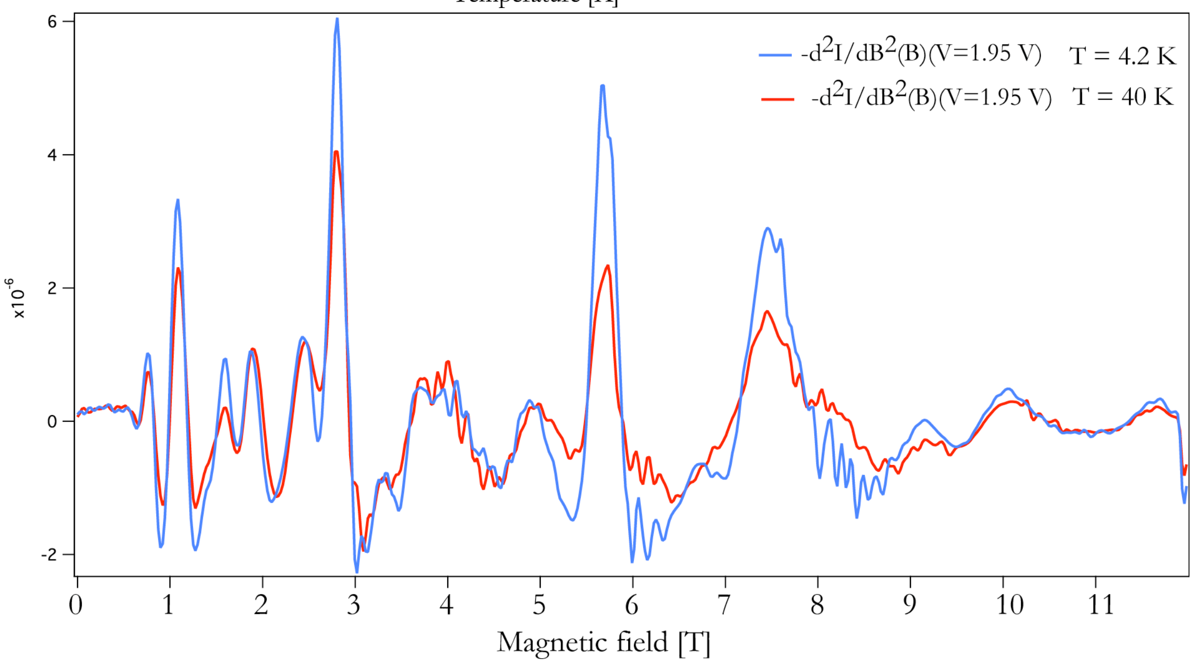


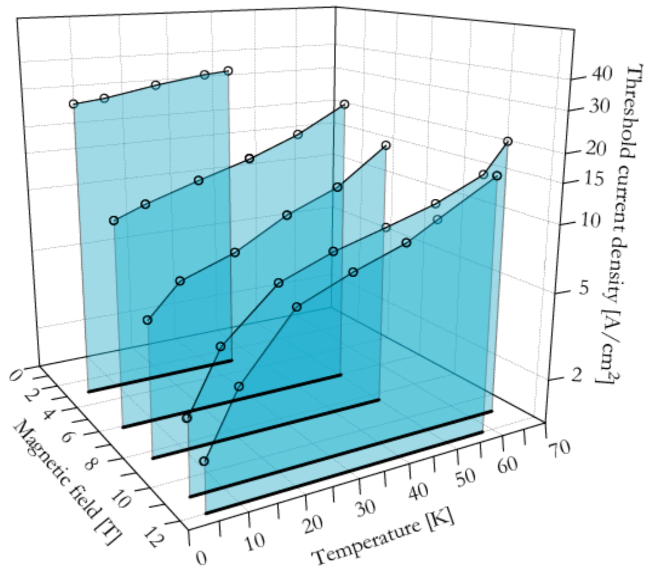
T max = 40 K

….limited by experiments…

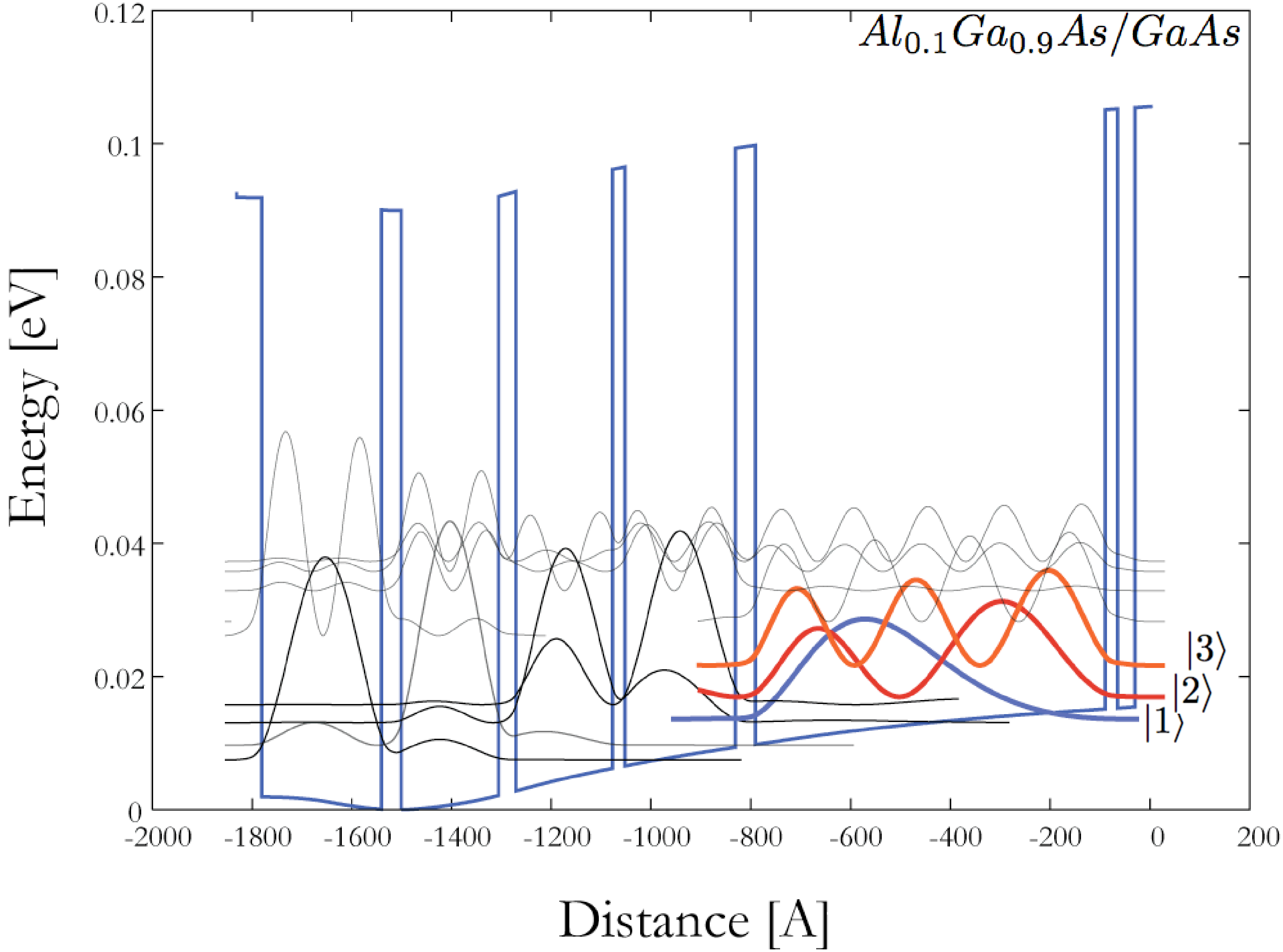
It does not follow usual "activated" trend

Leakage again or different physics?





Lasing at 860 GHz… unexpected!



$z_{32} = 147$ Å

$2\gamma_{32} \leq 0.5$ meV ??

$f_{32} = 27$

$E_{32} = 4.7$ meV

$L_p = 1786$ Å

$L_{AQW} = 701$ Å

Efield = 0.74 kV/cm

Transport at B=0 T…looks ok..

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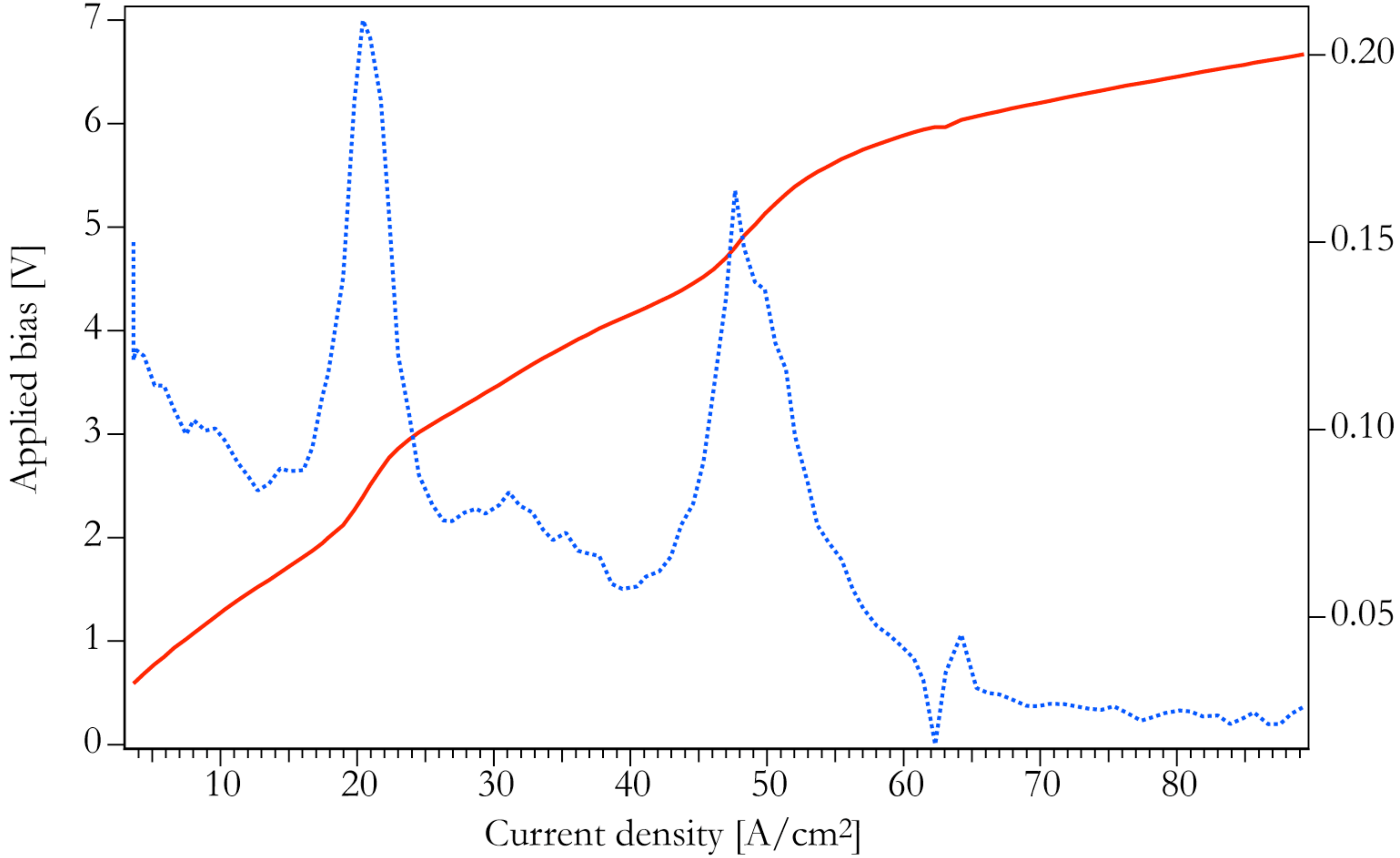
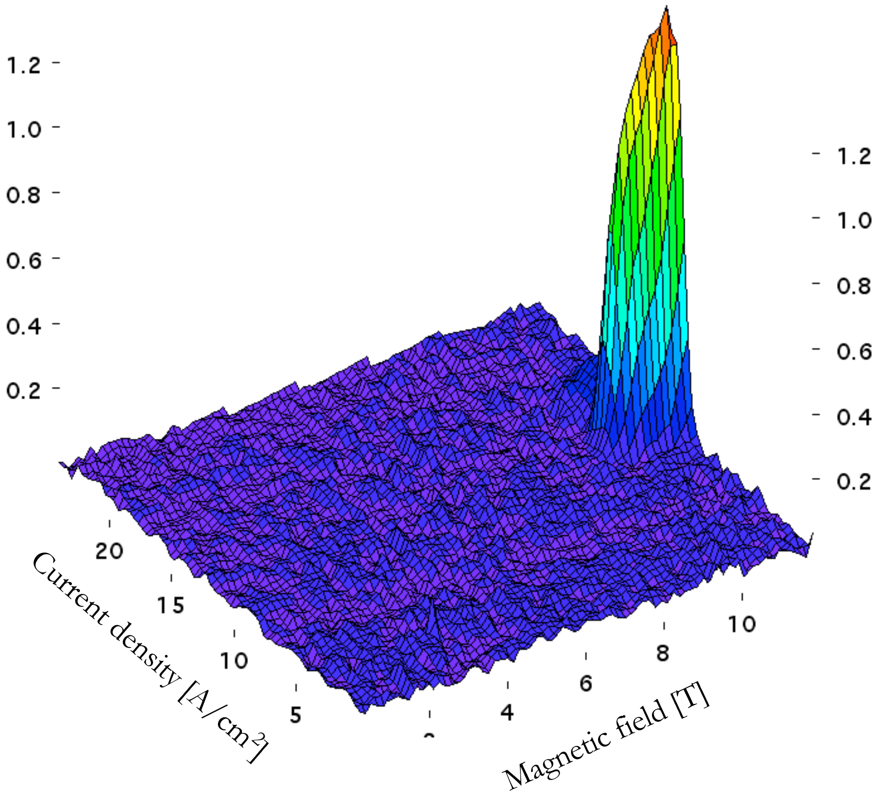


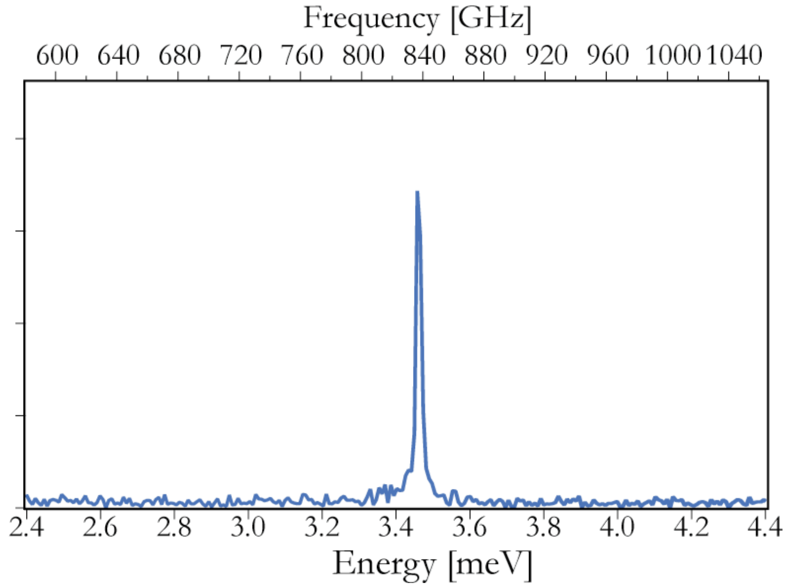
$$J_{max} \simeq 20A/cm^2$$

$$\tau_{\perp} \simeq 1 \text{ ps}$$

$$\tau_{up} = \frac{qn_s}{2J_{max}} - \frac{1}{4\Omega_{inj}^2 \tau_{\perp}} \simeq 150\text{ps}$$

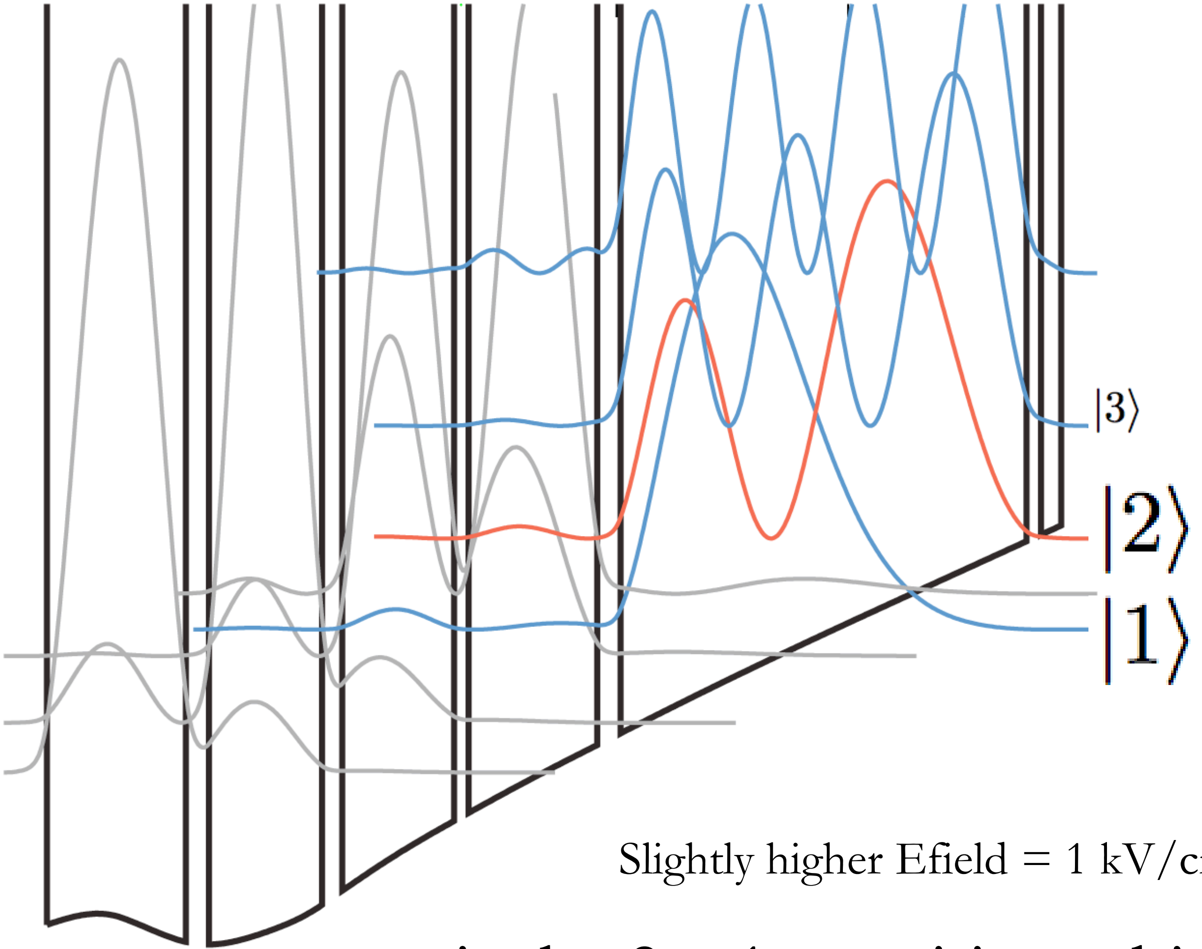
…but the spectrum is 840 GHz!





$$J_{thresh}(12\ \mathrm{T}) = 10\ \mathrm{A}/cm^2$$

…back to the structure…



$$f_{21} = 11$$

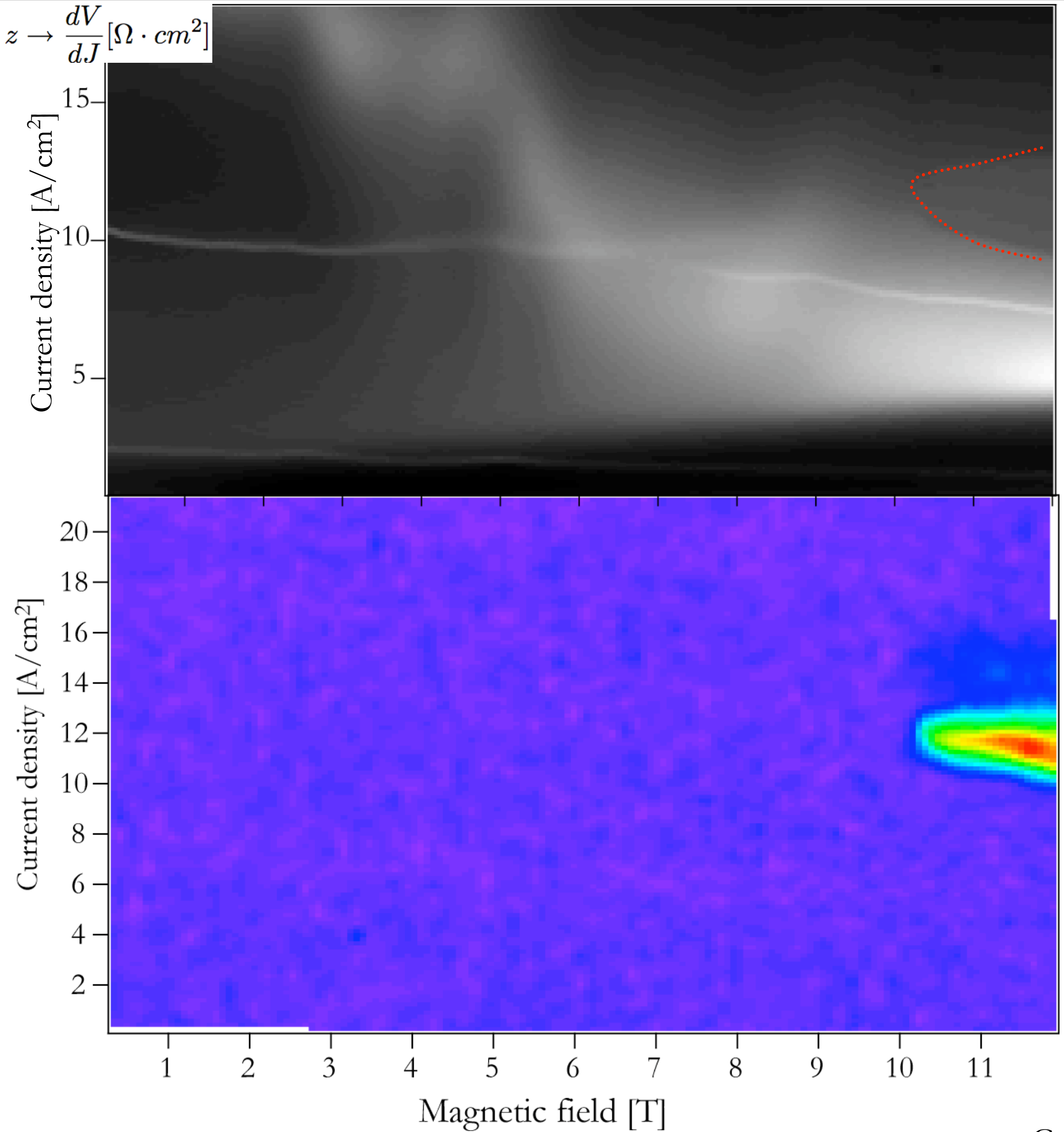
$$z_{21} = 105\ \text{Å}$$

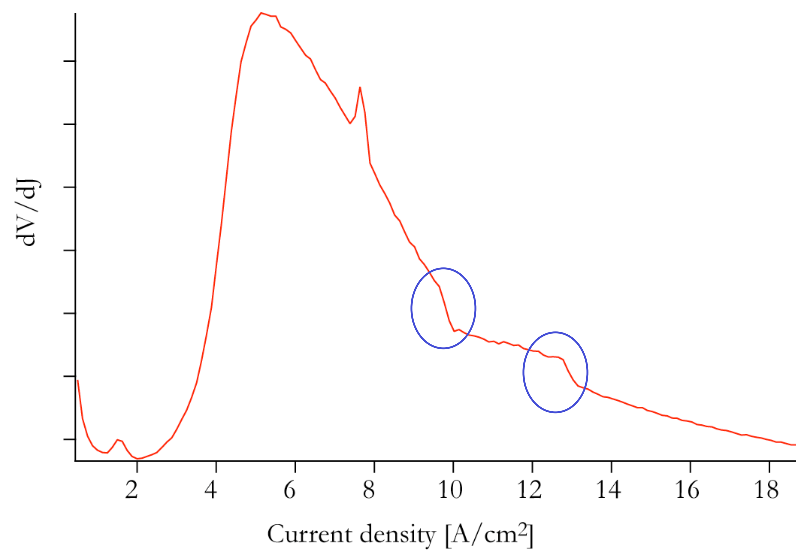
$$E_{21} = 3.6\ \text{meV}$$

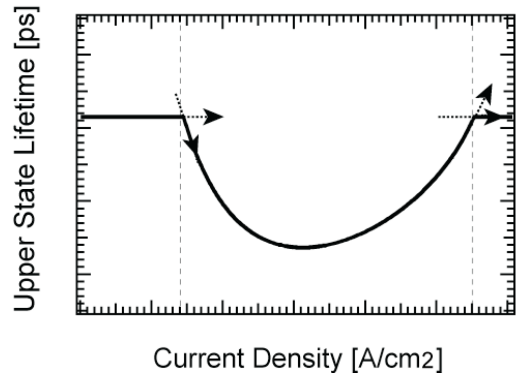
Slightly higher Efield = 1 kV/cm

….is the 2->1 transition which is lasing…

Lasing as a function of magnetic field







G. Scalari, R. Terazzi et al., Appl. Phys. Lett., 91, 032103 (2007)

Magnetotransport

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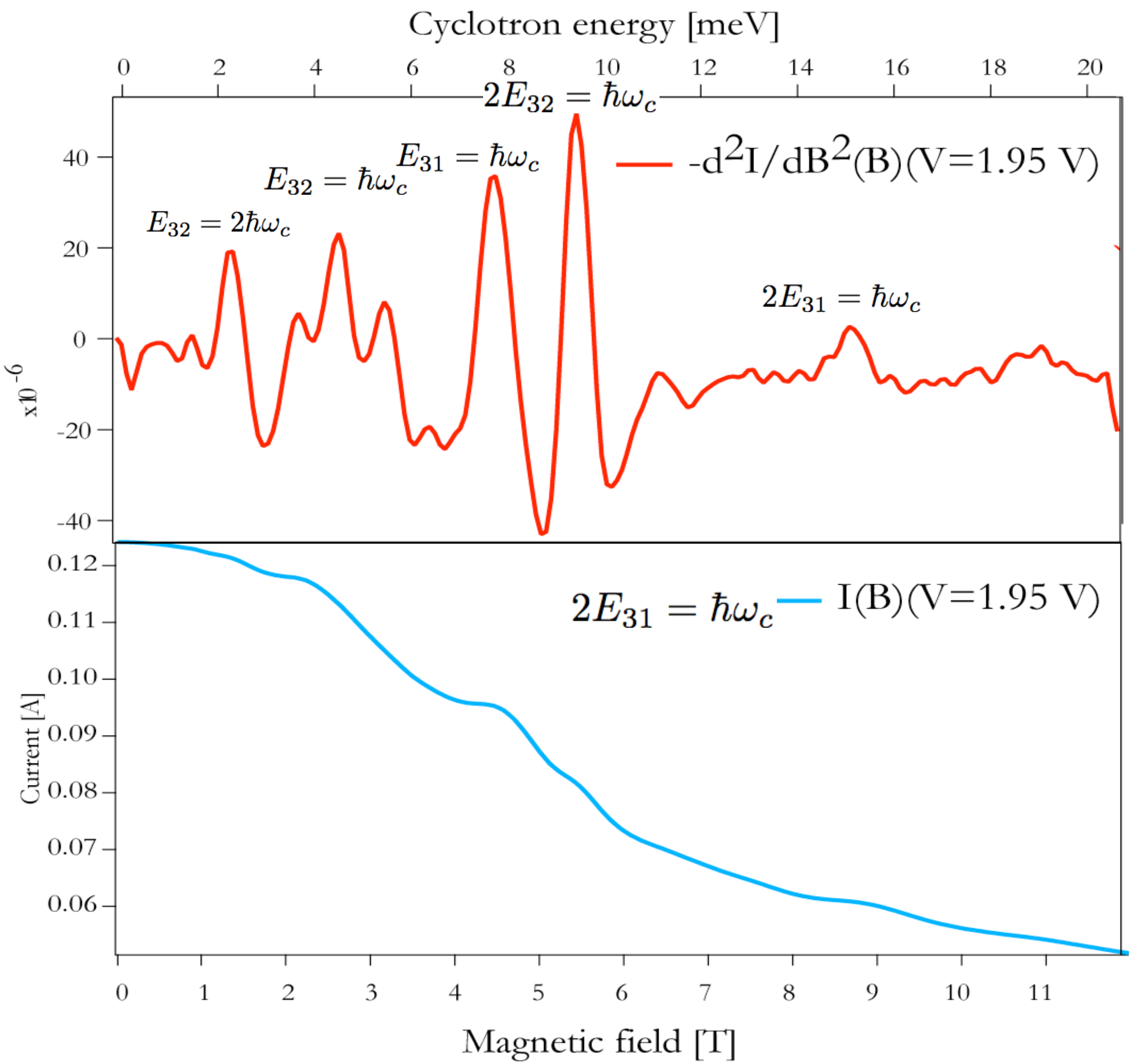

In this case resonances are well identified

THz QC wavelength coverage: extension to long wavelength

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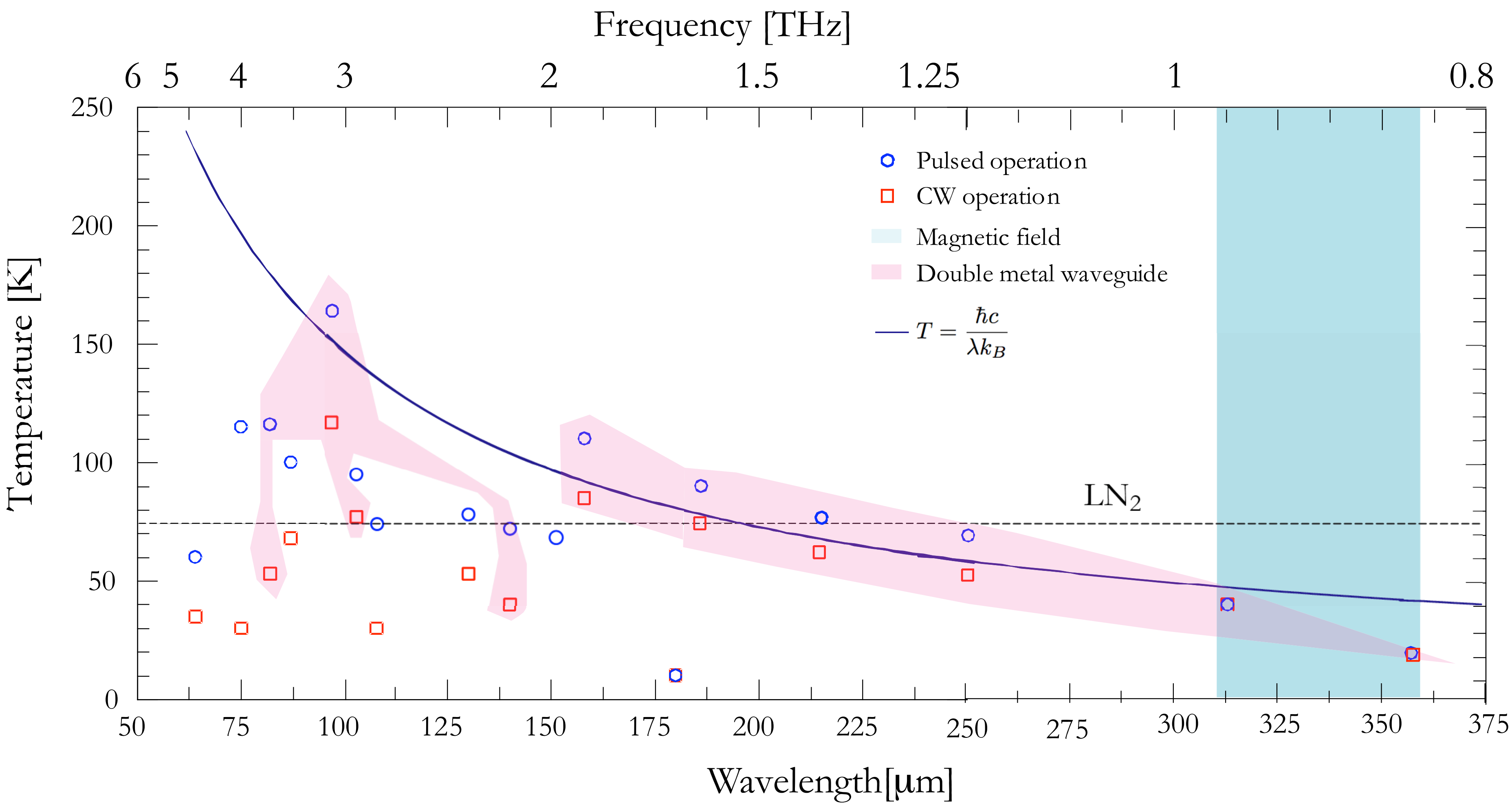

Conclusions and perspectives

•QCL wavelength coverage extended up to 355 μm :

now QCL technology spans more than two orders of magnitude!! (2.7-355 μm)

•Narrow energy spacing: tricky design and measurement interpretation. High resolution of magnetotransport

•Fundamental studies: interface roughness, intra-subband dephasing, lifetimes, resonant tunneling