Cyclotron Resonance of Multi-Layered Epitaxial Graphene under Very High Magnetic Field

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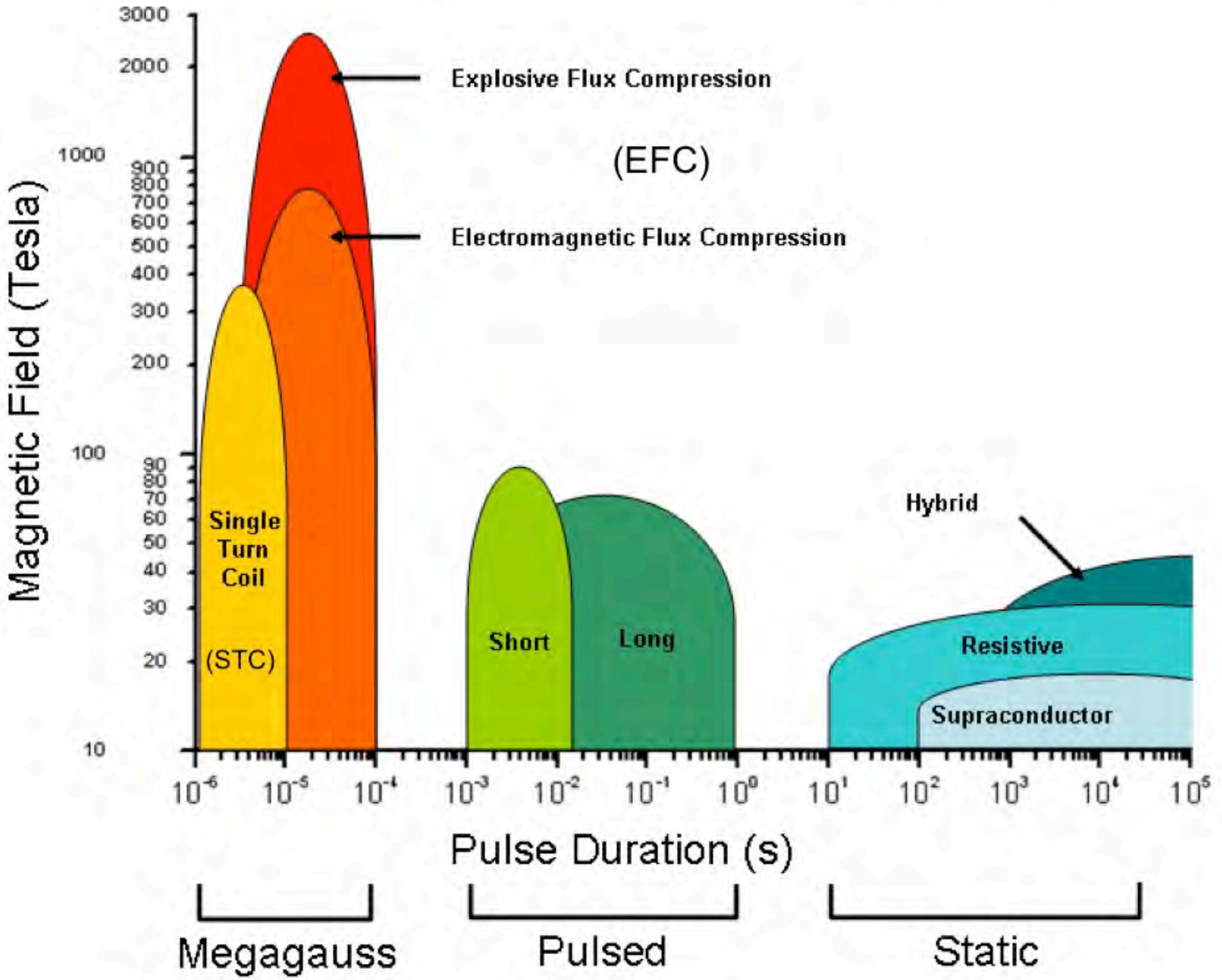
Outline

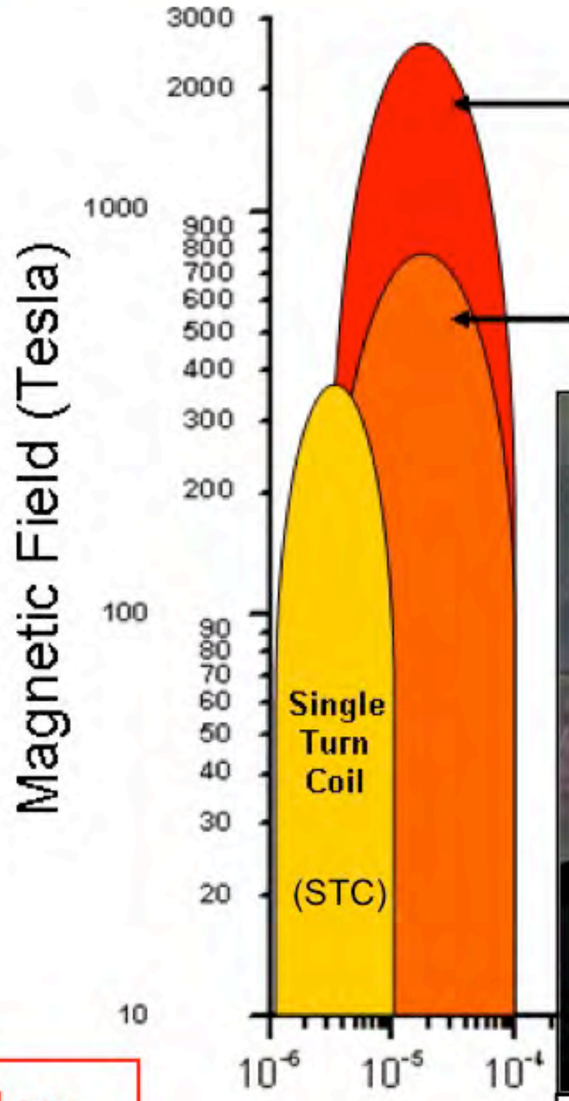
- MEGAGAUSS Generator
- Cyclotron Resonance of Graphene
- Conclusion

High Magnetic Field Production

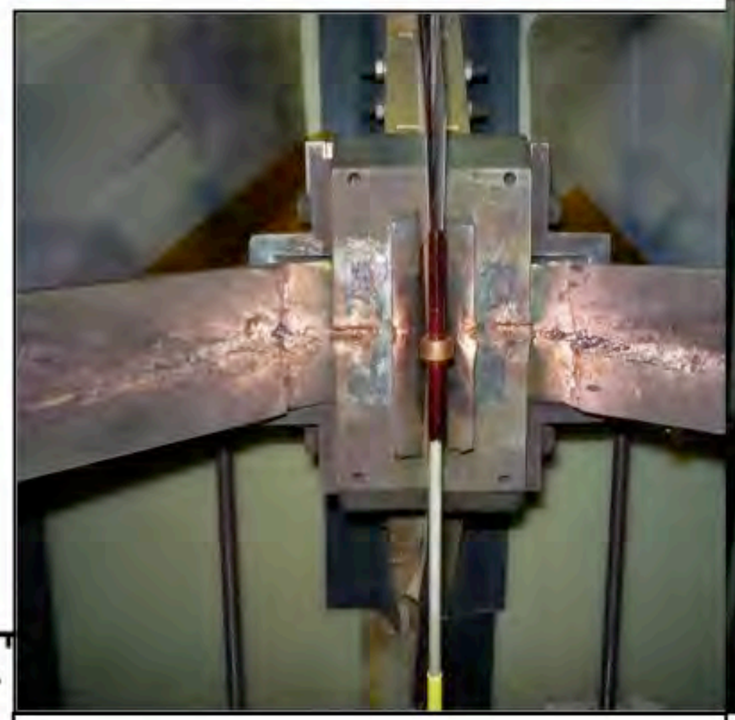


High Magnetic Field Production

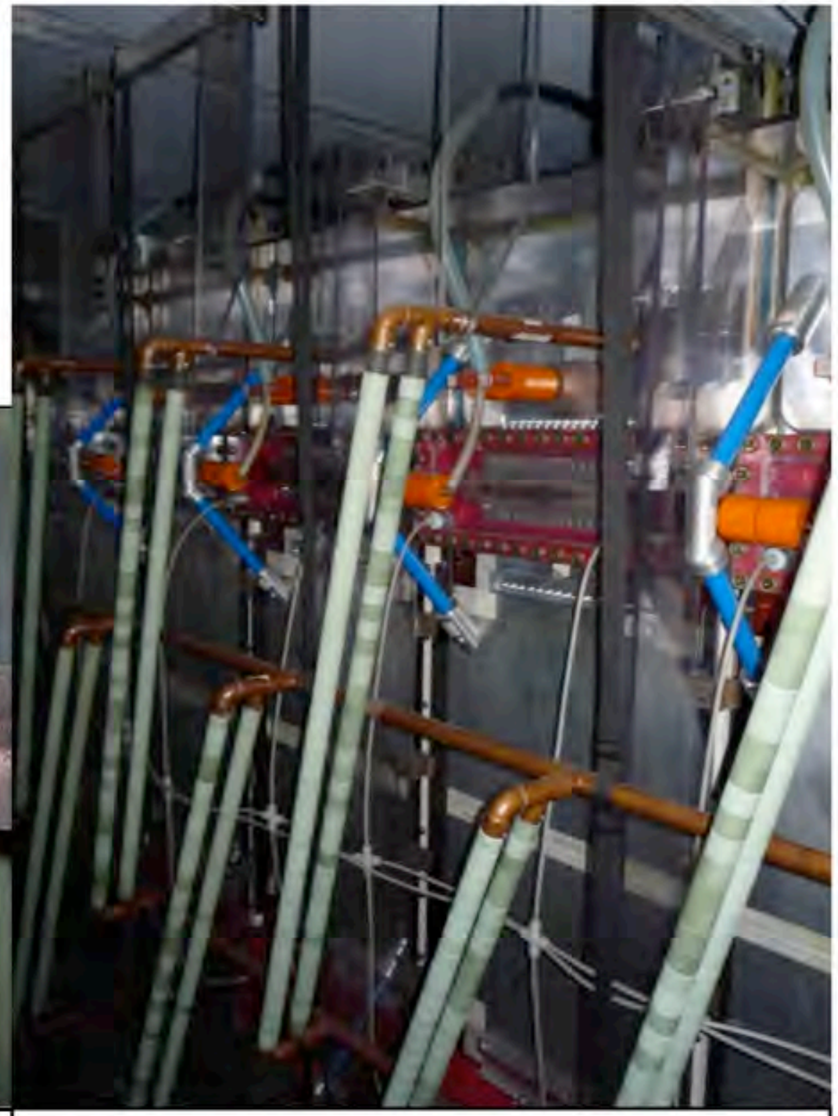
Limited by Velocity



350T STC Max
~2800T EFC Max

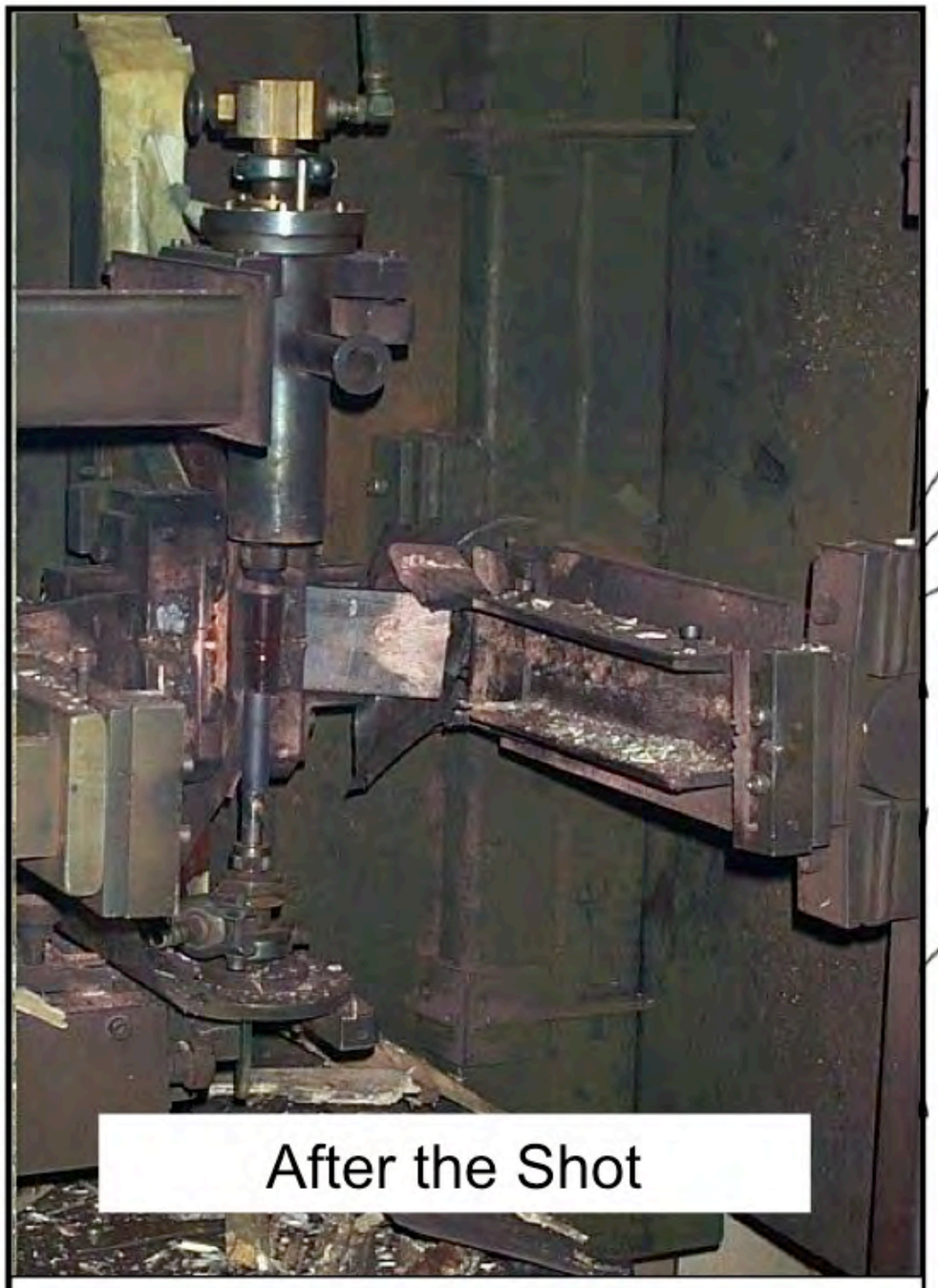


Single-Turn Coil
(LNCMI-Toulouse)



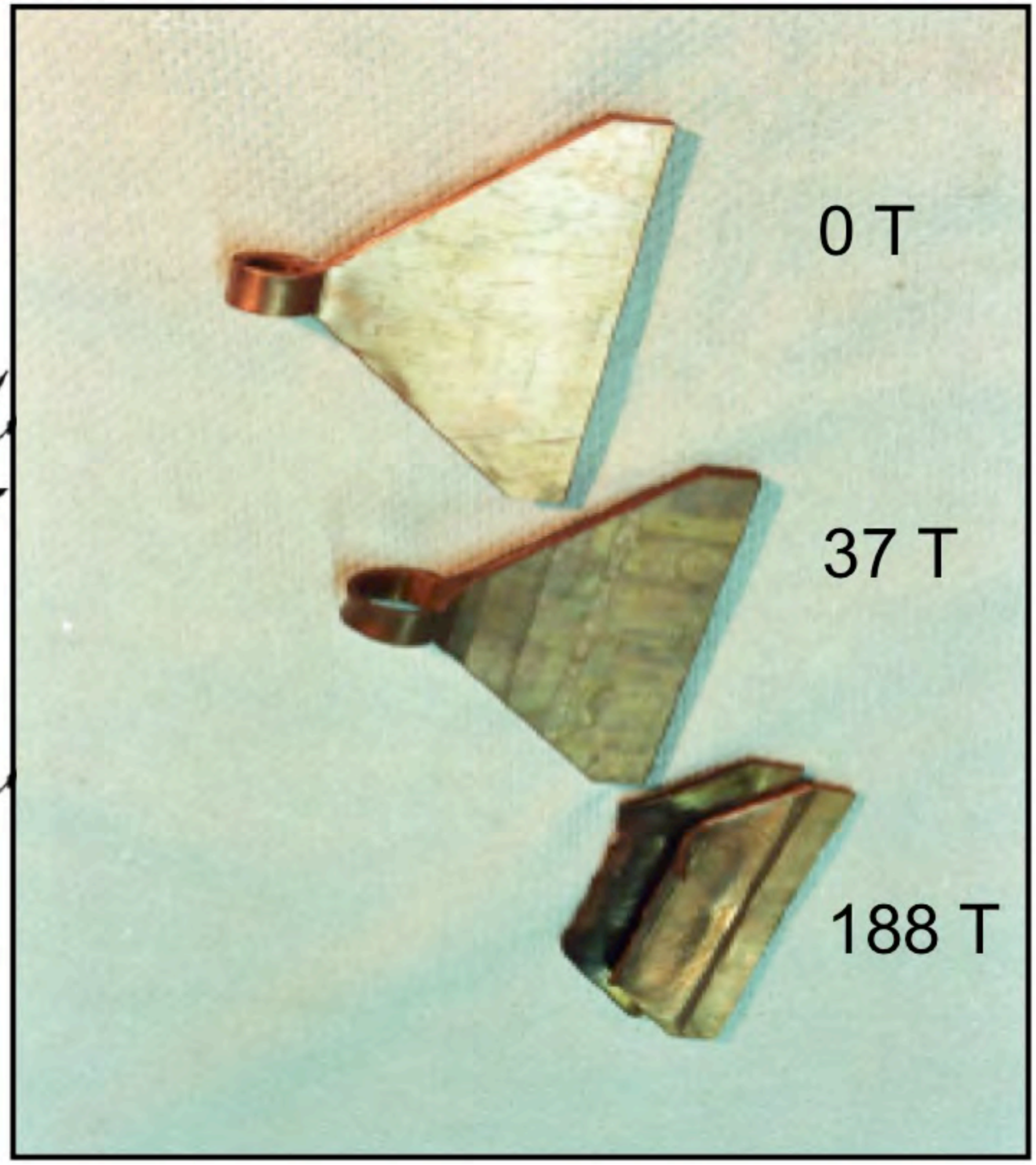
Megagauss Generator
(LNCMI-Toulouse)

Generator MEGAGAUSS : Principle

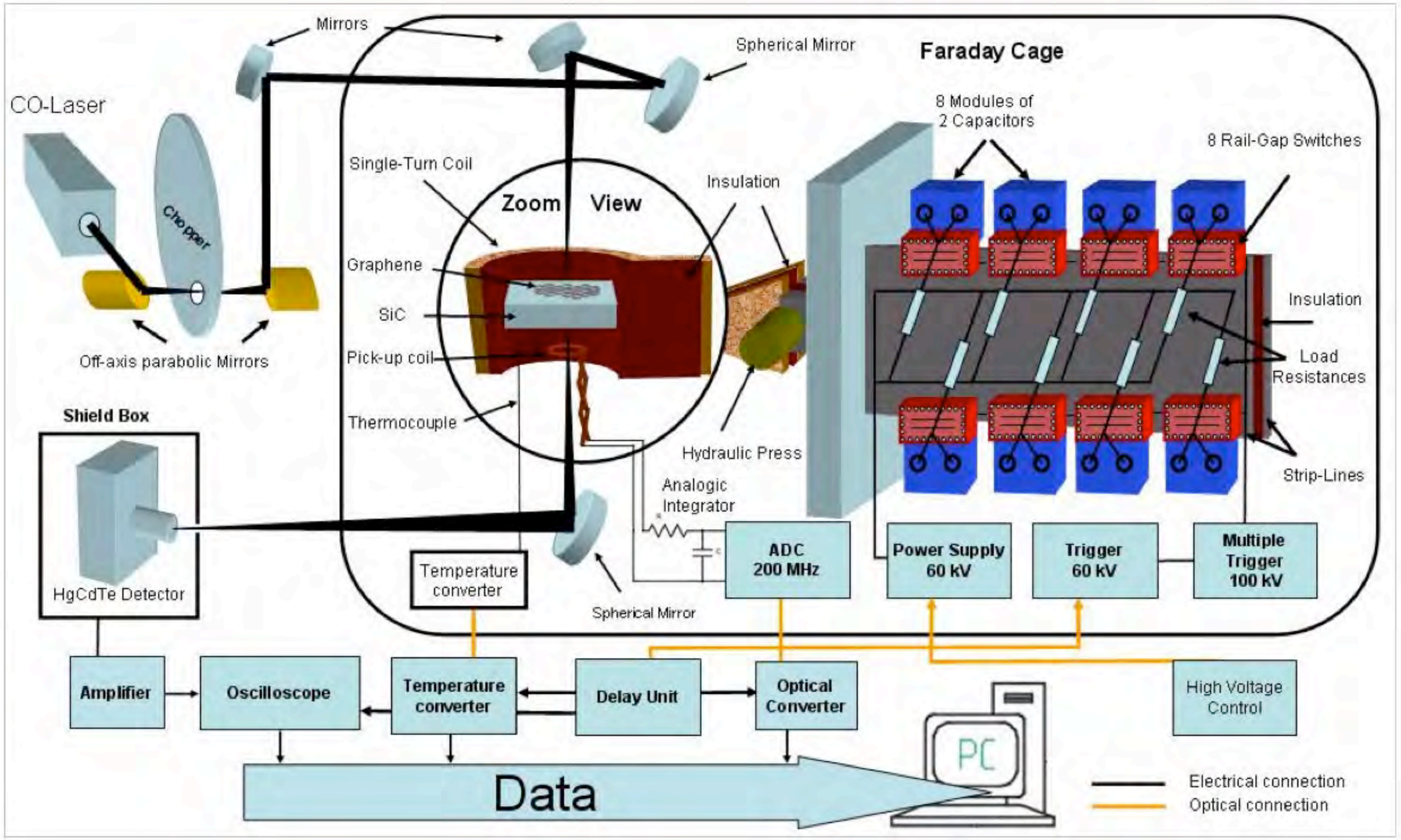


After the Shot

Sample OK



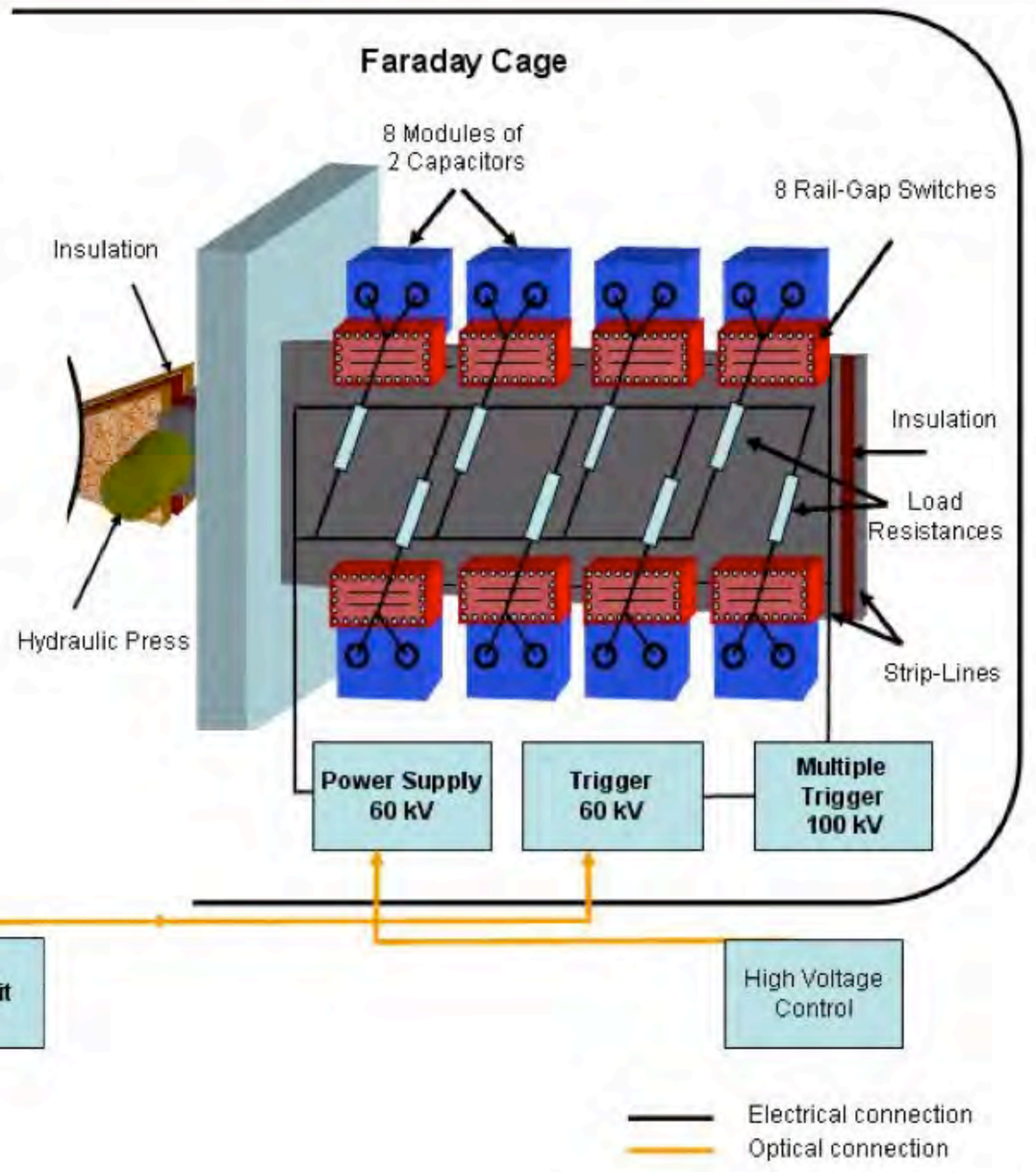
Cyclotron resonance : Setup



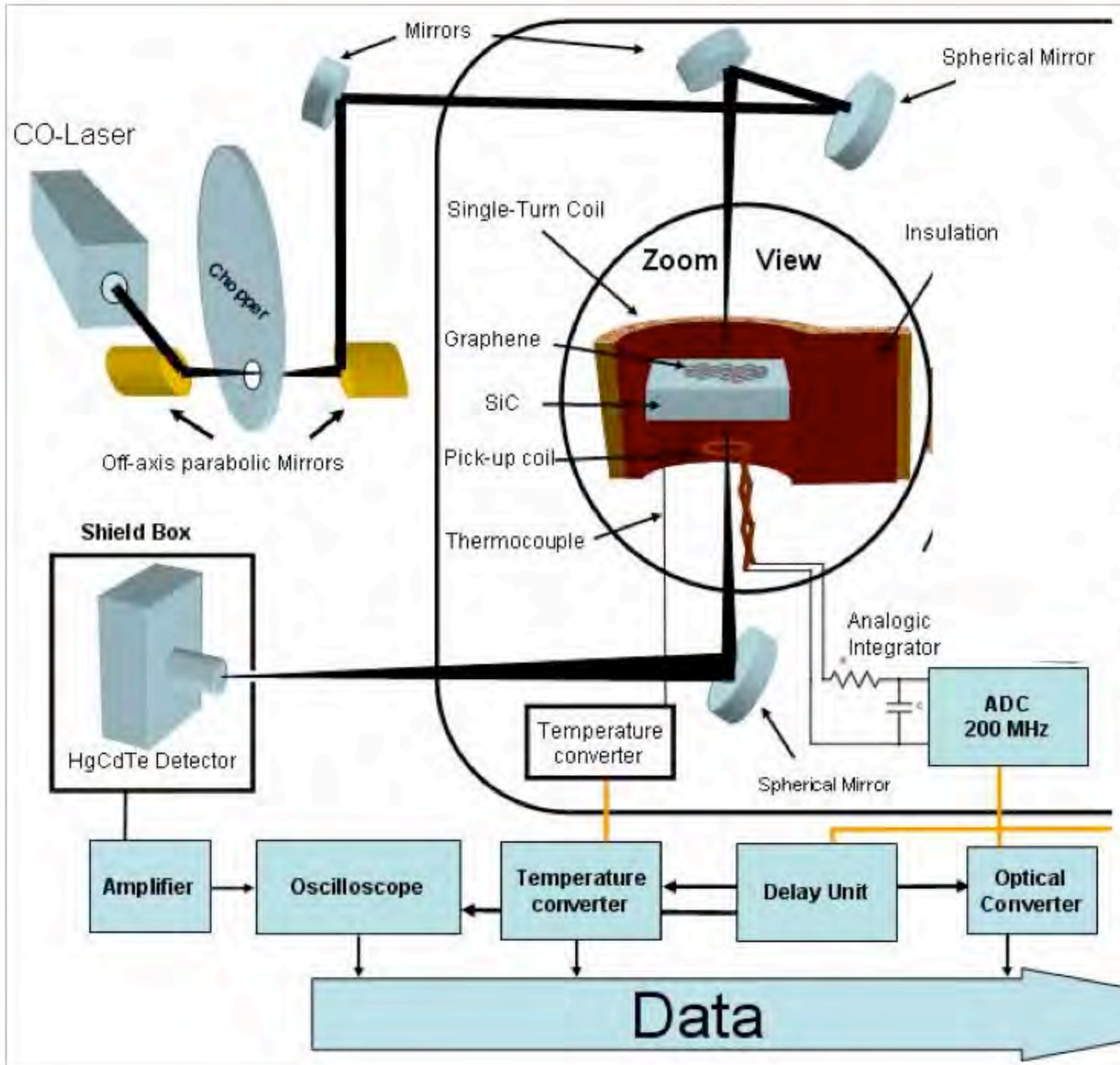
Cyclotron resonance : Setup

Generator part :

- 60 kV Charging Voltage
- Current ~ MA
- Copper coils (Ø 3 to 20 mm)
- Inductance ~ 20 nH
- Max Field ~ 331 T (Ø3 mm)



Cyclotron Resonance : Setup

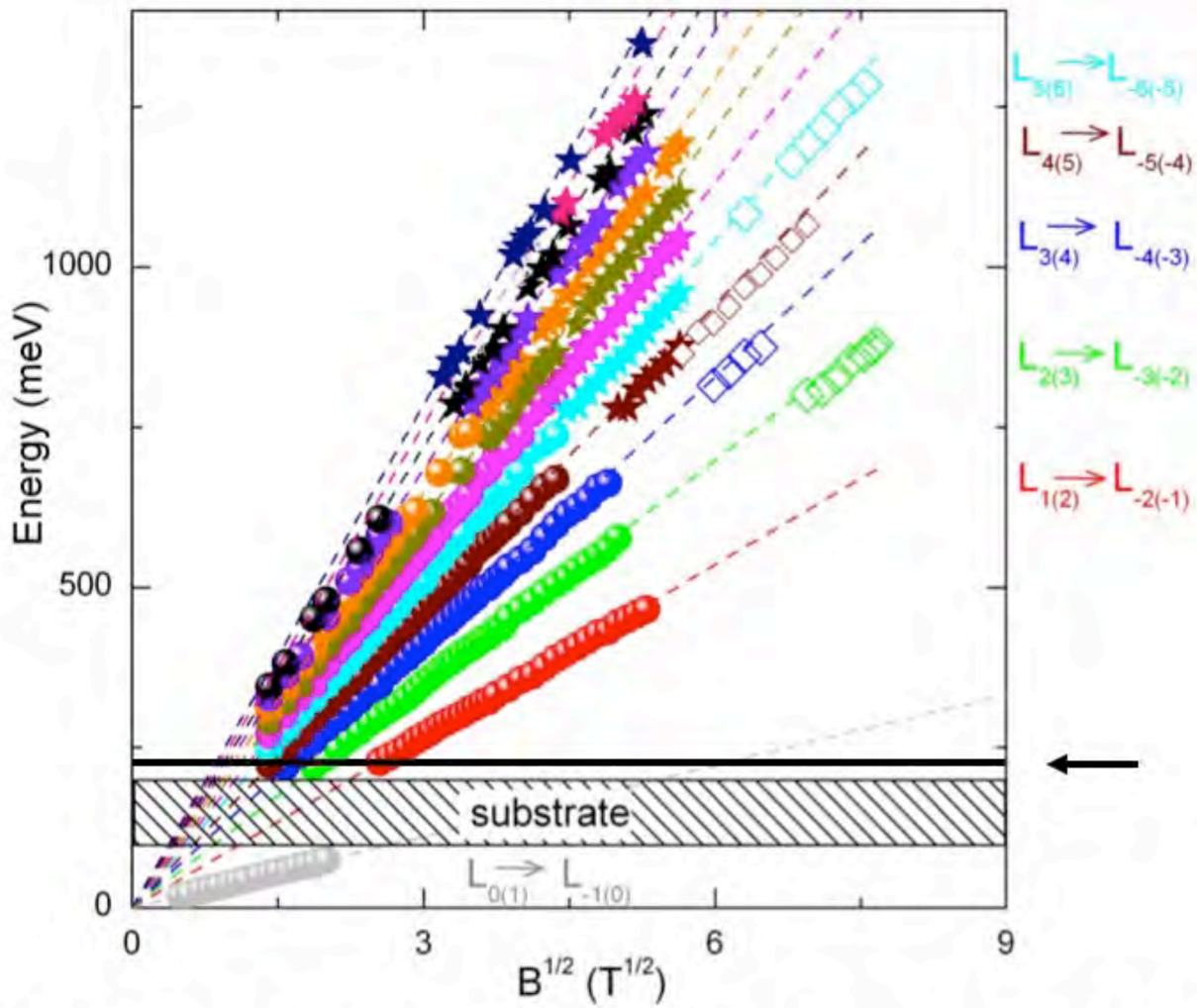


Optical & Acquisition Part

- CO laser (205-240 meV)
- 2W max power
- Chopper
- Parabolic Mirrors
- Spherical Mirrors
- Fast photodetector (HgCdTe photodiode)
- Pick-up Coil (integrator)
- Thermocouple

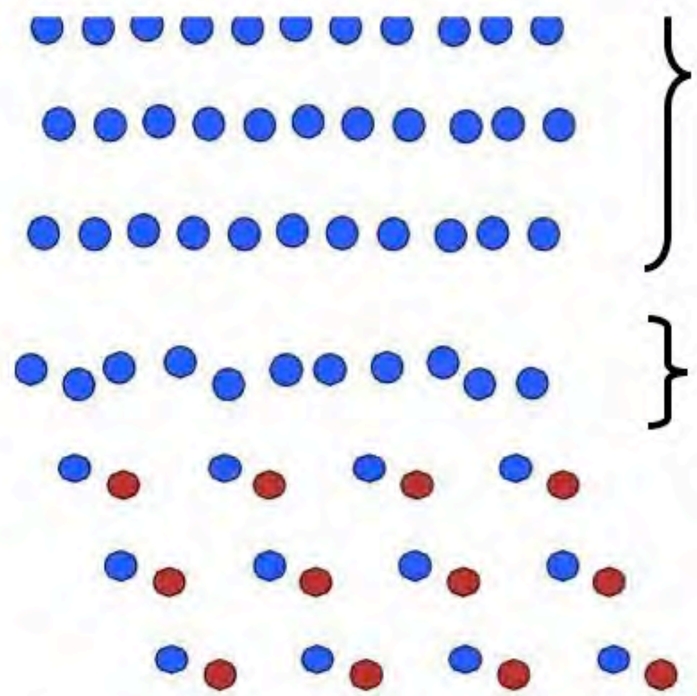
Cyclotron Resonance : Previous Results

Fan-Chart of Landau level transitions in multi-layered epitaxial graphene grown on SiC



P. Plochocka et al, PRL 100, 087401 (2008)
And N. Ubrig, Thesis (2011)

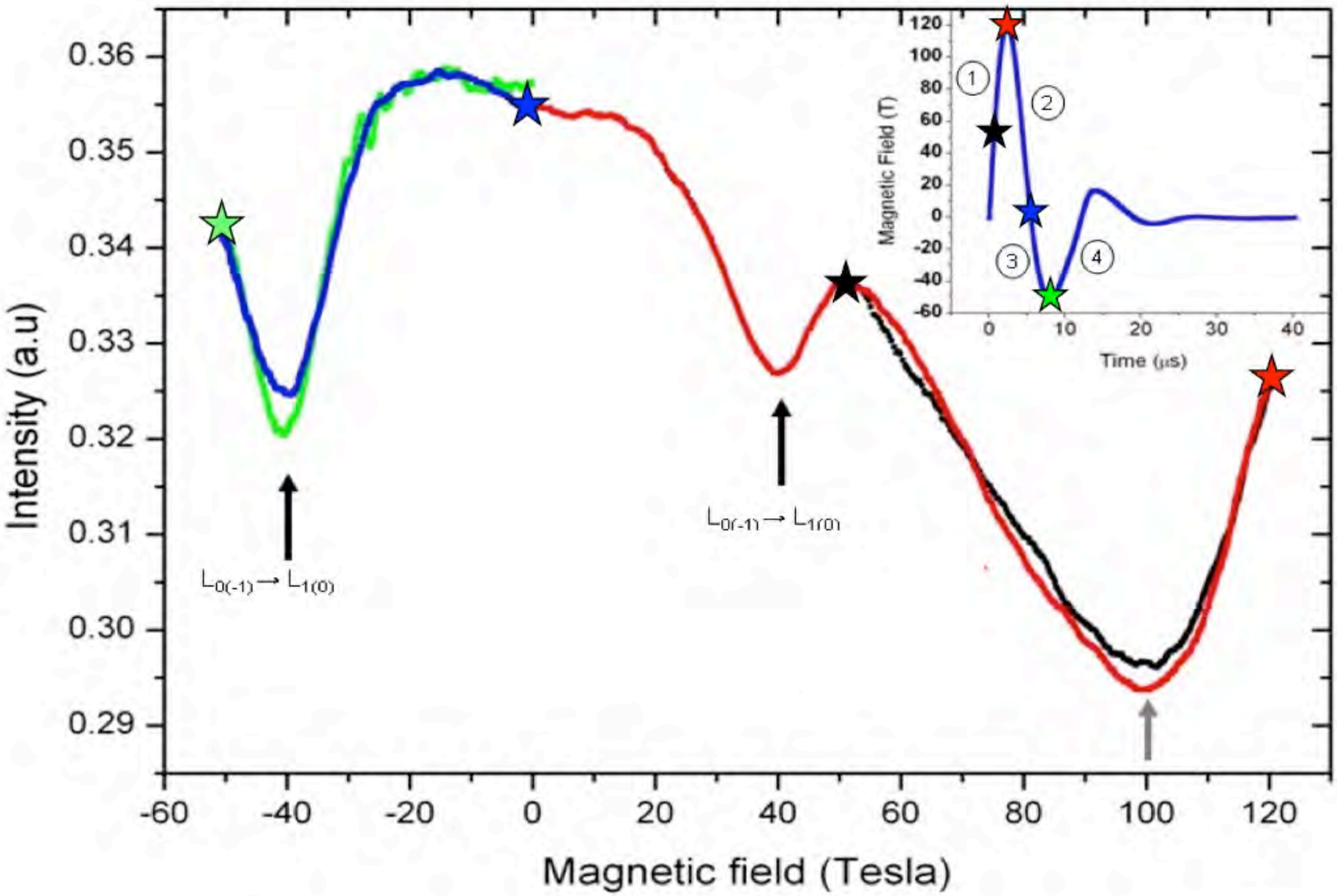
Multi-layered Epitaxial Graphene grown on SiC (C-face)



Varchon, Thesis (2008)

Cyclotron Resonance : Preliminary Results

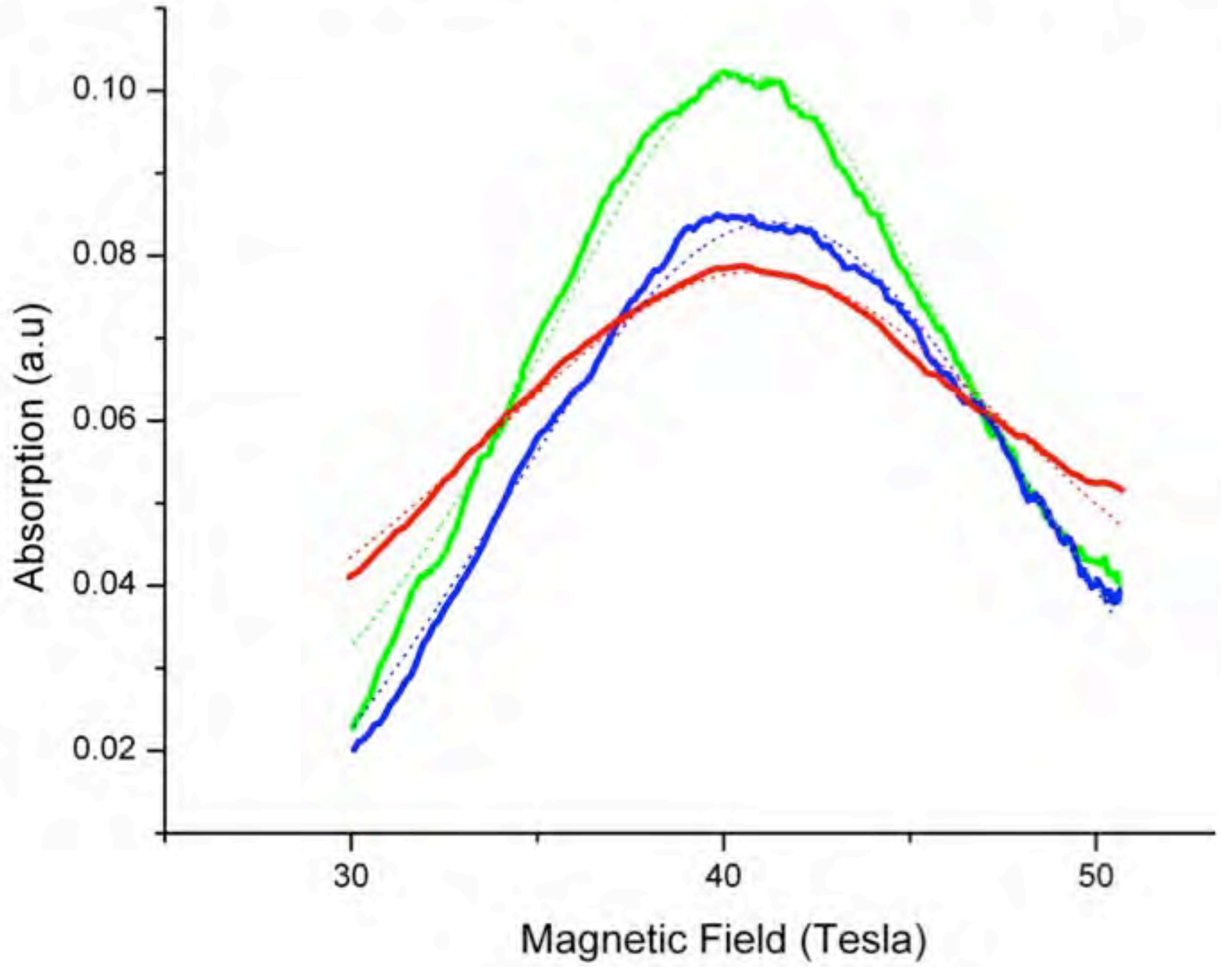
Transmission at 229 meV of Multi Layered Graphene at room temperature



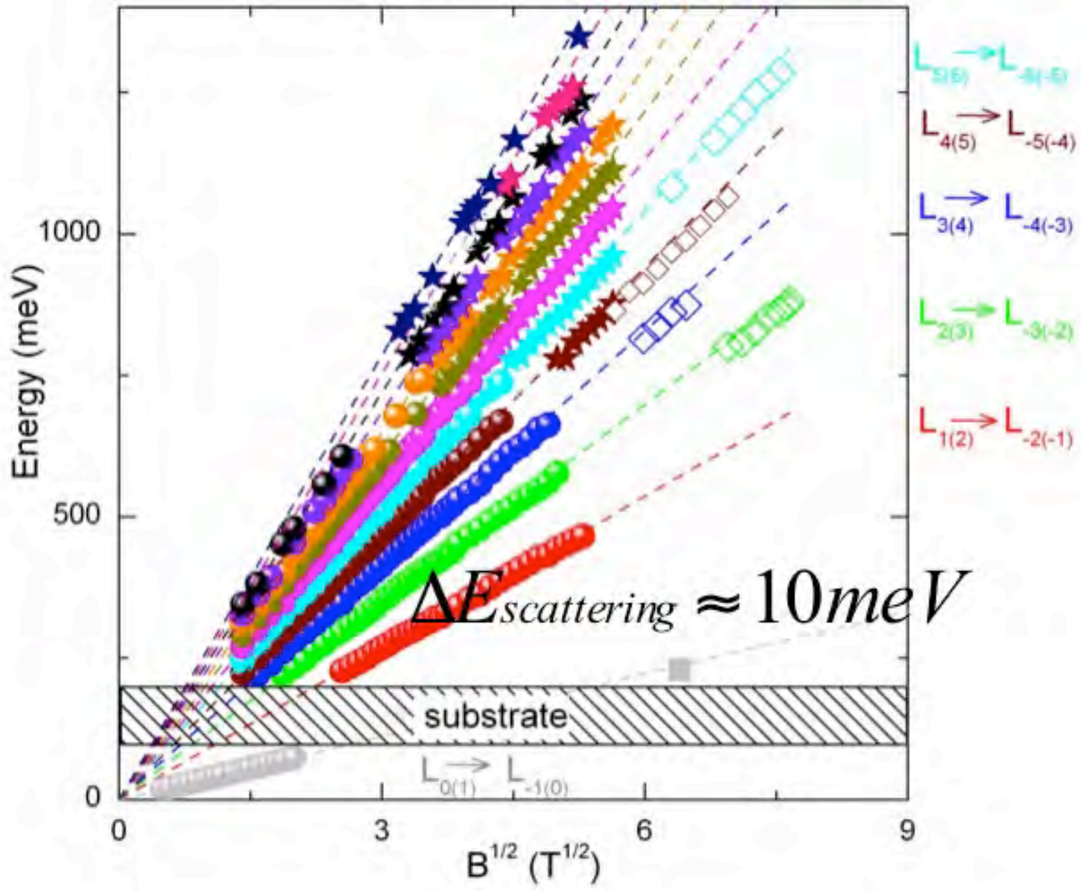
1. Upsweep (Positive field)
2. Down sweep (Positive field)
3. Upsweep (Negative field)
4. Down sweep (Negative field)

Cyclotron Resonance : $L_{-1(0)} \rightarrow L_{0(1)}$ transition

Fundamental Transition $L_{0(-1)\rightarrow 1(0)}$ of Graphene with 229 meV Laser at Room Temperature



Fan-Chart of Landau level transitions in multi-layered epitaxial graphene grown on SiC



$$E = \nu_F \sqrt{2\hbar |eB|}$$

Fermi velocity ≈ 1×10^6 m.s^{-1}

Cyclotron Resonance : $L_{-1(0)} \rightarrow L_{0(1)}$ transition

Very large broadening

- electron-phonon interaction,

with E_{2g} (~200 meV) and a new observed near 230-240 meV (optical?)

*Orlita et Al, PRL **103**, 186803 (2009)*
*Miller, Science **324**, 924 (2009)*
Pound et al, arxiv:1104.5169v1, (27 april 2011)

Hysteresis to be confirmed

- Temperature change during the shot
- Eddy Current correlation
- Phonon width modulation

$$\Delta T(r) = \frac{r^2}{4\rho_m c_p} \int_0^{\Delta t} \sigma_0 \left(\frac{d}{dt} \vec{B}_{ext} \right)^2 dt$$

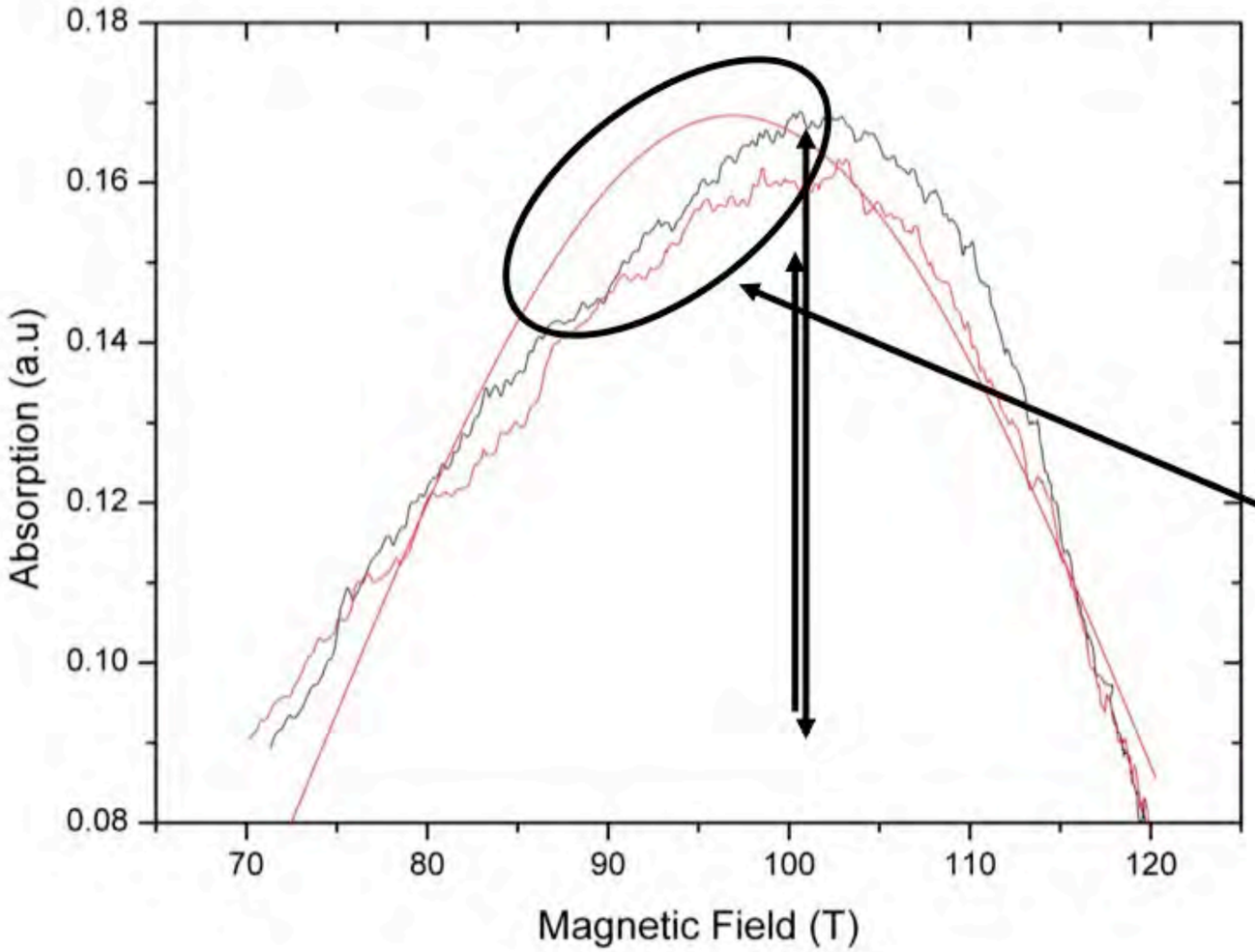
VS

Thermal Diffusion and phonon width

- more accurate (s/n ratio, synchronisation)
- more shots (statistic)
- temperature dependence (from RT to 4K)

Cyclotron Resonance : Other Absorption

Absorption near 100T



Peak Maximum

→ near 100 Tesla

Peak Amplitude

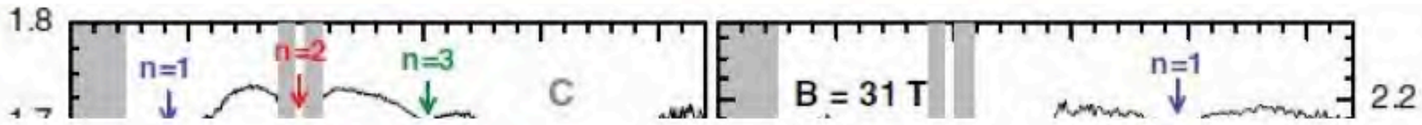
→ 2 times the fundamental

Assymetric Peak Shape

→ Not a simple Lorentzian

→ ?

Bilayer Contribution



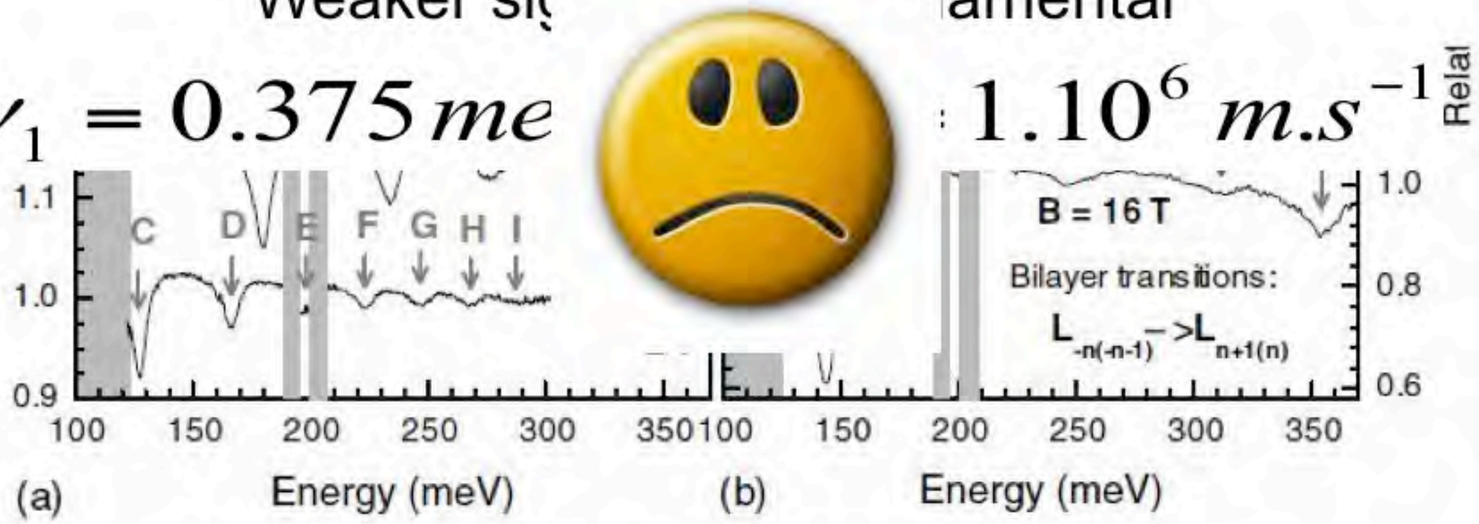
Standard four band model

(Koshino and Ando, PRB 77, 115313 (2008))

Transition expected at 75 T for 229 meV

Weaker sig amental

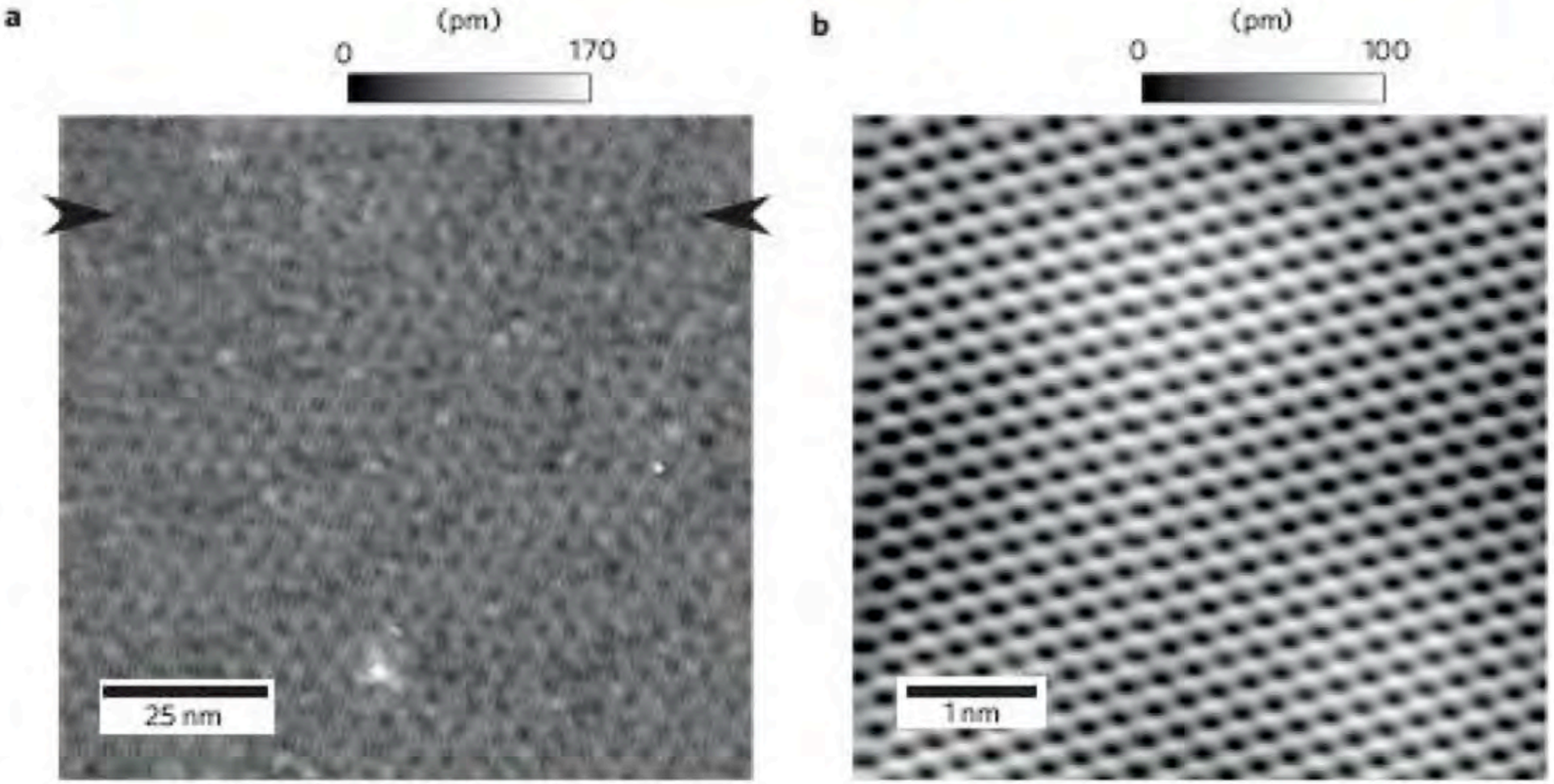
$\gamma_1 = 0.375 me$: $1.10^6\ m.s^{-1}$



Orlita et Al, PRB 83, 125302 (2011)

Bilayer inclusion(~20%) below 40 T

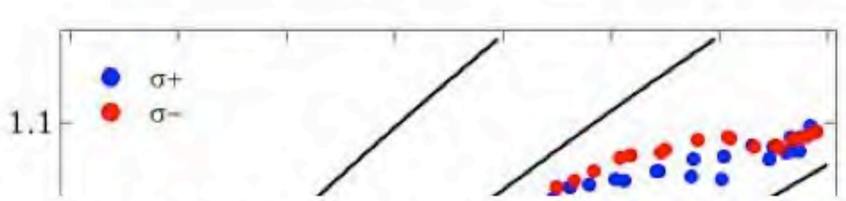
SuperLattice

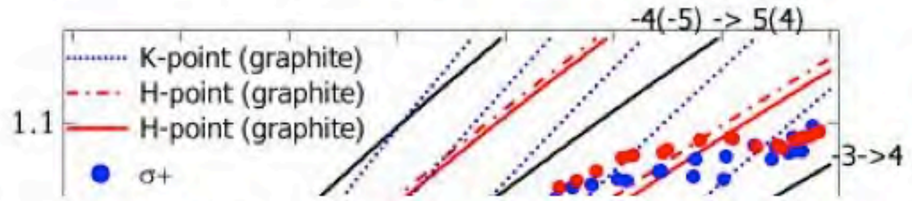


Topographic STM images of multi-layer graphene shows periodic height variations of L*= 4 nm period deduced from first/second layer moiré.
D.L Miller et Al, Nature Phys. ***6****, 811–817 (2010)*

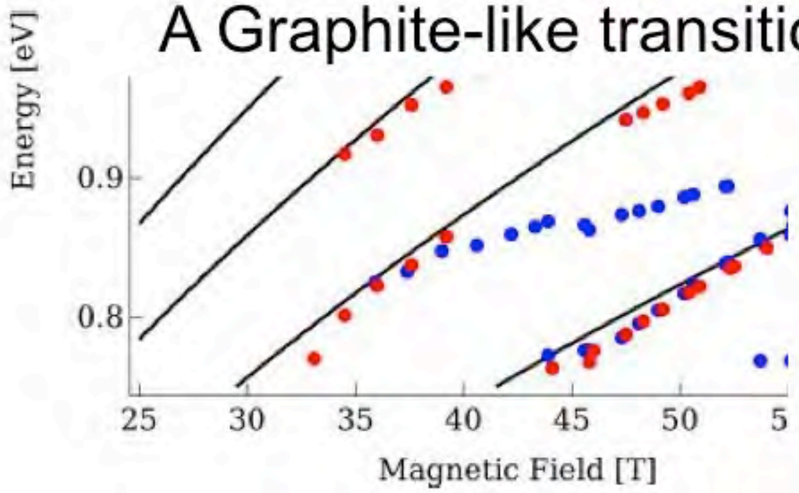
Multilayer Contribution, SuperLattice

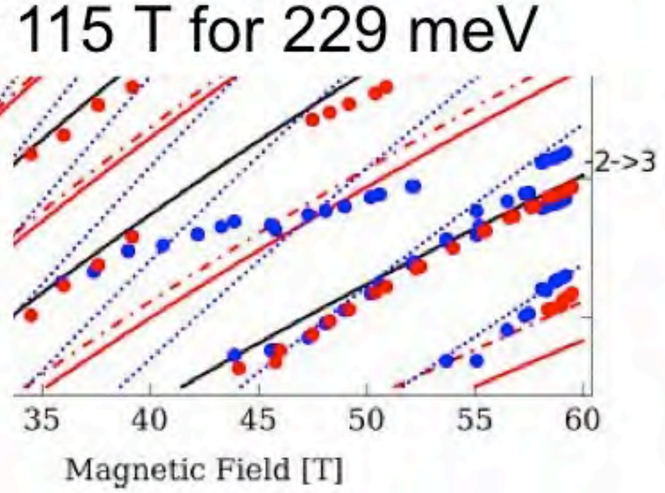
Some new features are expected when $l_b < L^*$ (B > 42 T)





A Graphite-like transition expected near 115 T for 229 meV





Special observed feature

Ubrig, Thesis (2011)

Other Absorption

Conclusion

Multi-layer transition and confinement to be confirmed
Some SuperLattice dependence indices

Some orders of magnitude @100 T :

- Zeeman splitting 10 meV
- Magnetic Length 2.5 nm
- Valley Splitting ~10 meV
- e-h assymetry in bilayer ~20 meV

Conclusion and Perspective

Summary

Fundamental transition

- First observation of fundamental transition above 35 T
- Large broadening and hysteresis to be studied (e- phonon)

Other transition

- New experimental observation
- Very high signal
- Probably SuperLattice dependent

Later

- Faraday rotation
- Spectroscopy above 100T

Thanks

Collaborators :

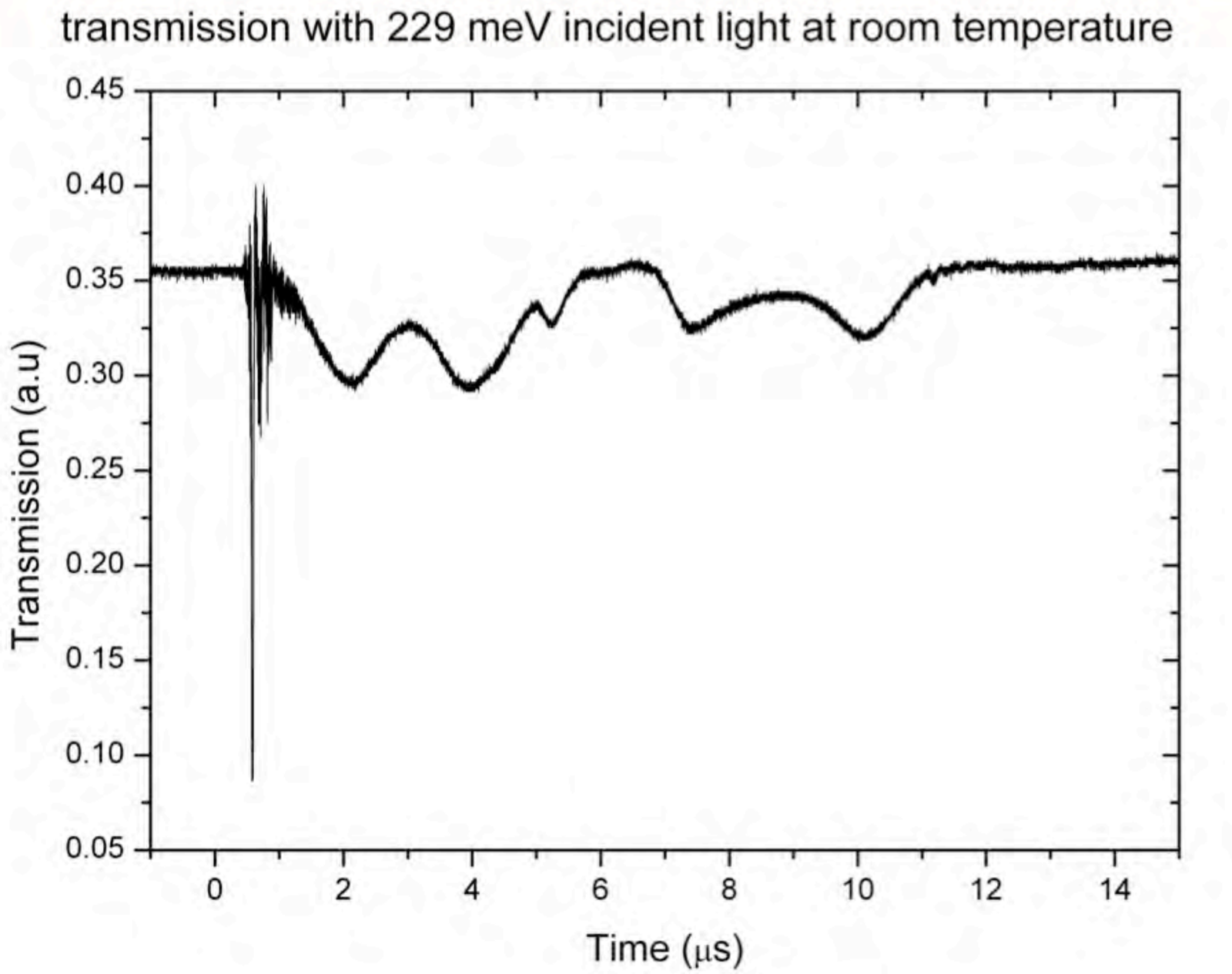
- W. De Heer, C. Berger.
- P. Plochocka. , M. Orlita, M. Potemski

LNCMI

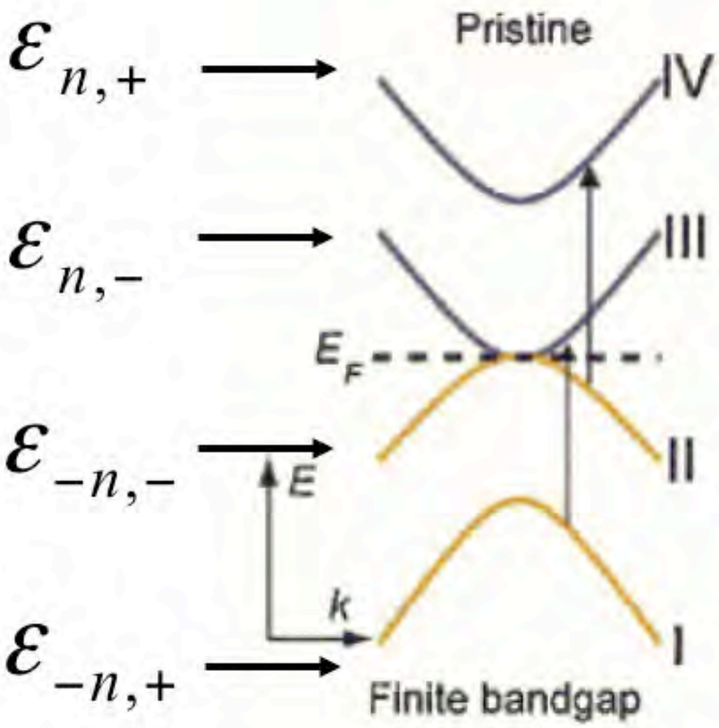
Tehnical Support at LNCMI

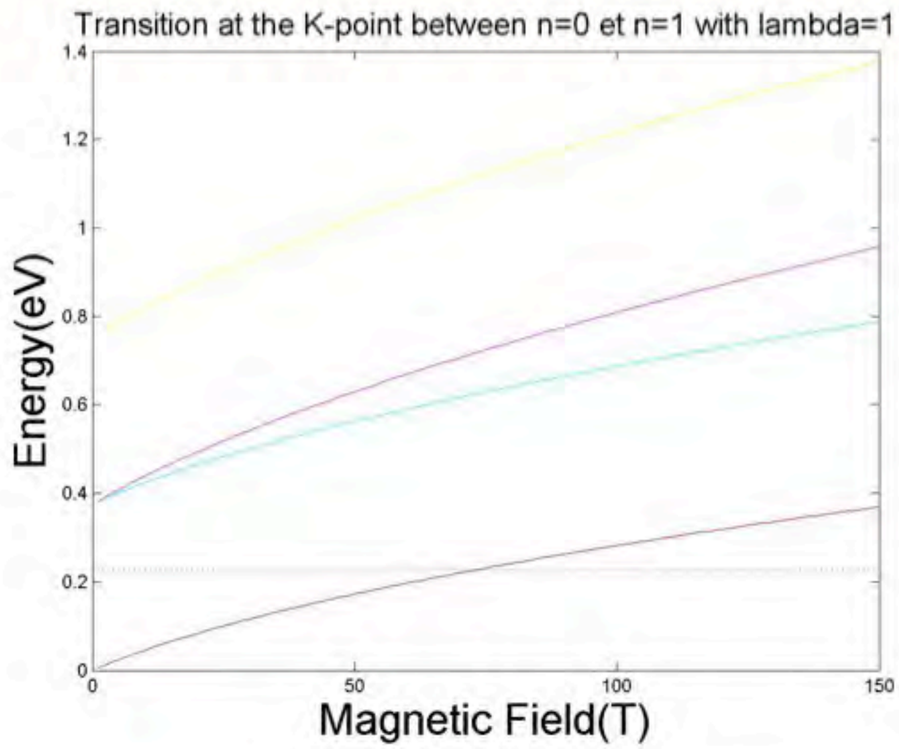
Thanks for your attention

Additionnal slide : Trigger noise



Additionnal slides : Multilayer ?



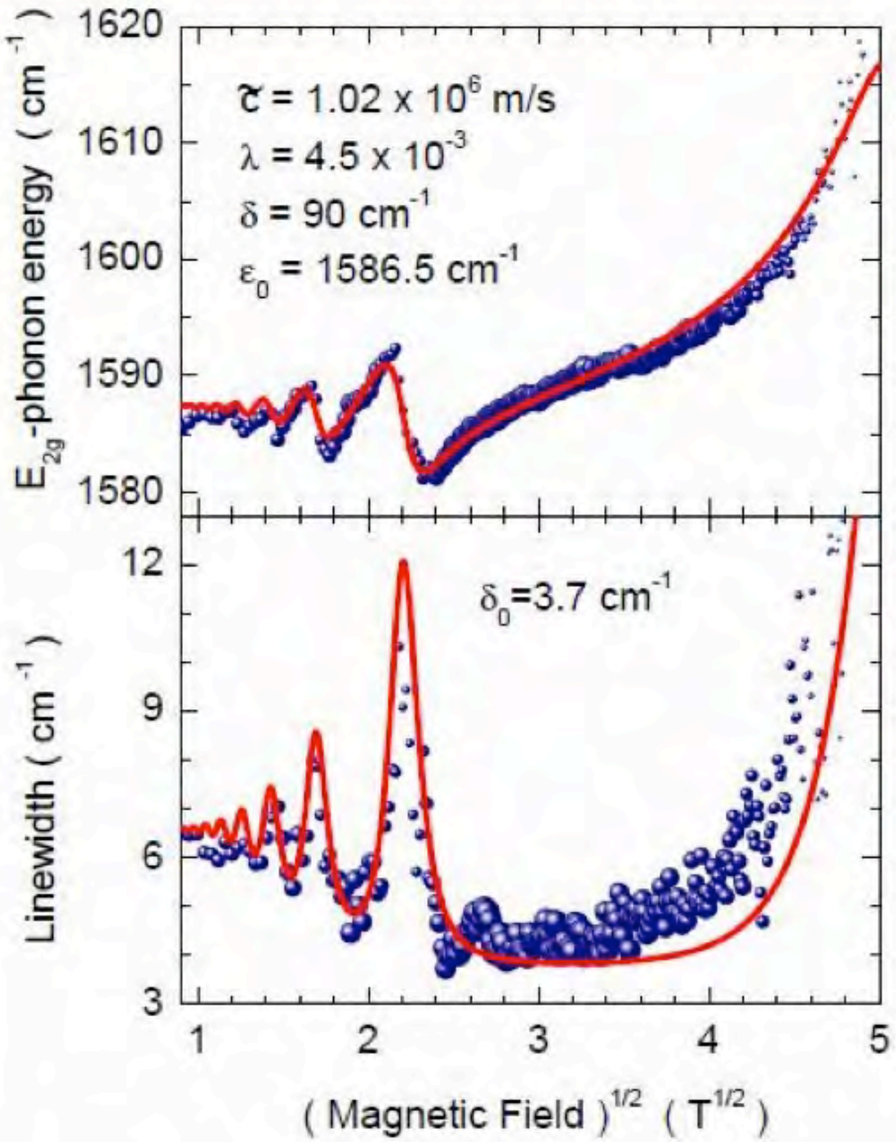


$$\varepsilon_{n,\mu} = sign(n)\frac{1}{\sqrt{2}}\left[\lambda^2\gamma_1^2 + (2|n|+1)E_1^2 + \mu\sqrt{\lambda^4\gamma_1^4 + 2(2|n|+1)E_1^2\lambda^2\gamma_1^2 + E_1^4}\right]^{\frac{1}{2}}$$

$$\gamma_1 = 375meV \qquad \gamma_0 = 3.15\,eV \qquad E_1 = v_F\sqrt{2\hbar|eB|}$$

M. Koshino and T. Ando, PRB, **77**, 115313 (2008)

Additionnal slides : E2g Phonon



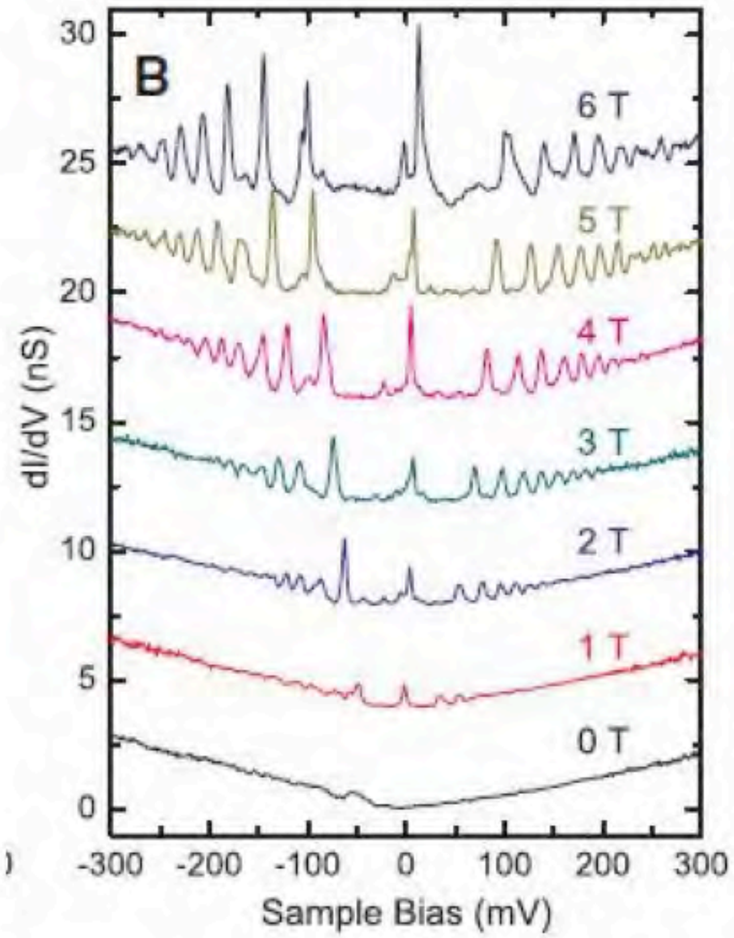
*Orlita et Al, PRL **103**, 186803 (2009)*

Cyclotron Resonance : 230meV phonon

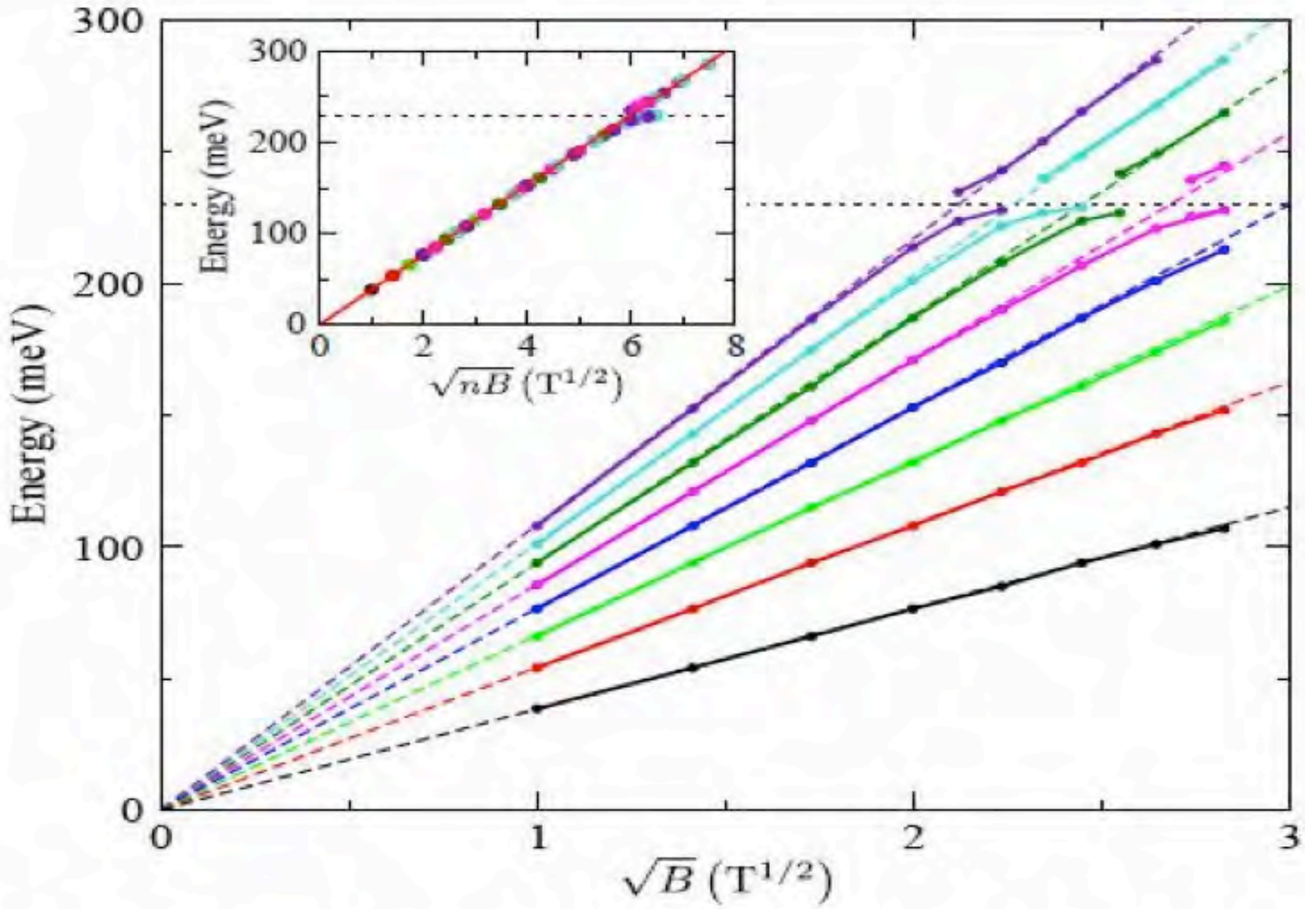
Large broadening

- electron-phonon interaction,

with E_{2g} (~200 meV) and a new observed near 230-240 meV (optical?)

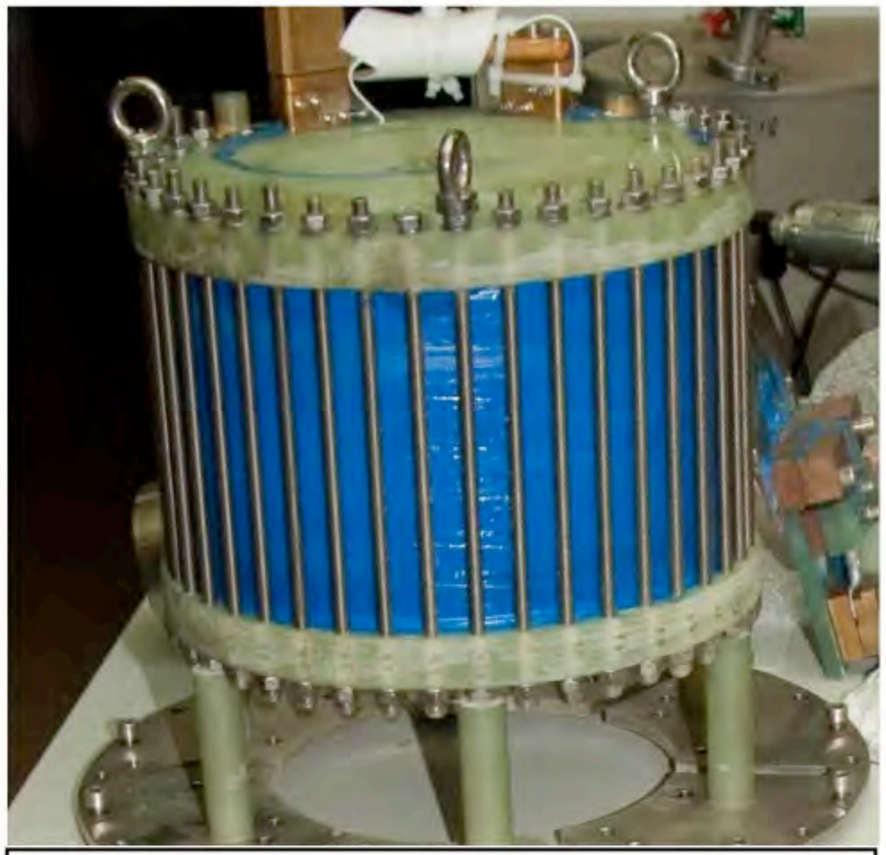


Miller, *Science* **324**, 924 (2009)



Pound et al, arxiv:1104.5169v1, (27 april 2011)

Additionnal slide :High Magnetic Field Production

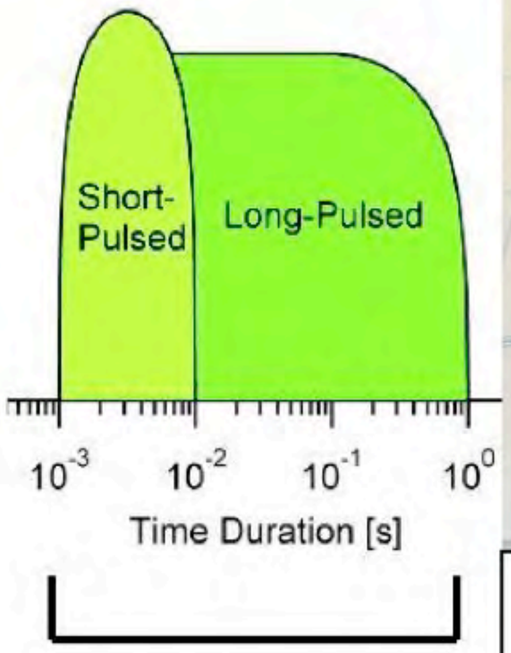


Standard 60 Tesla Coil

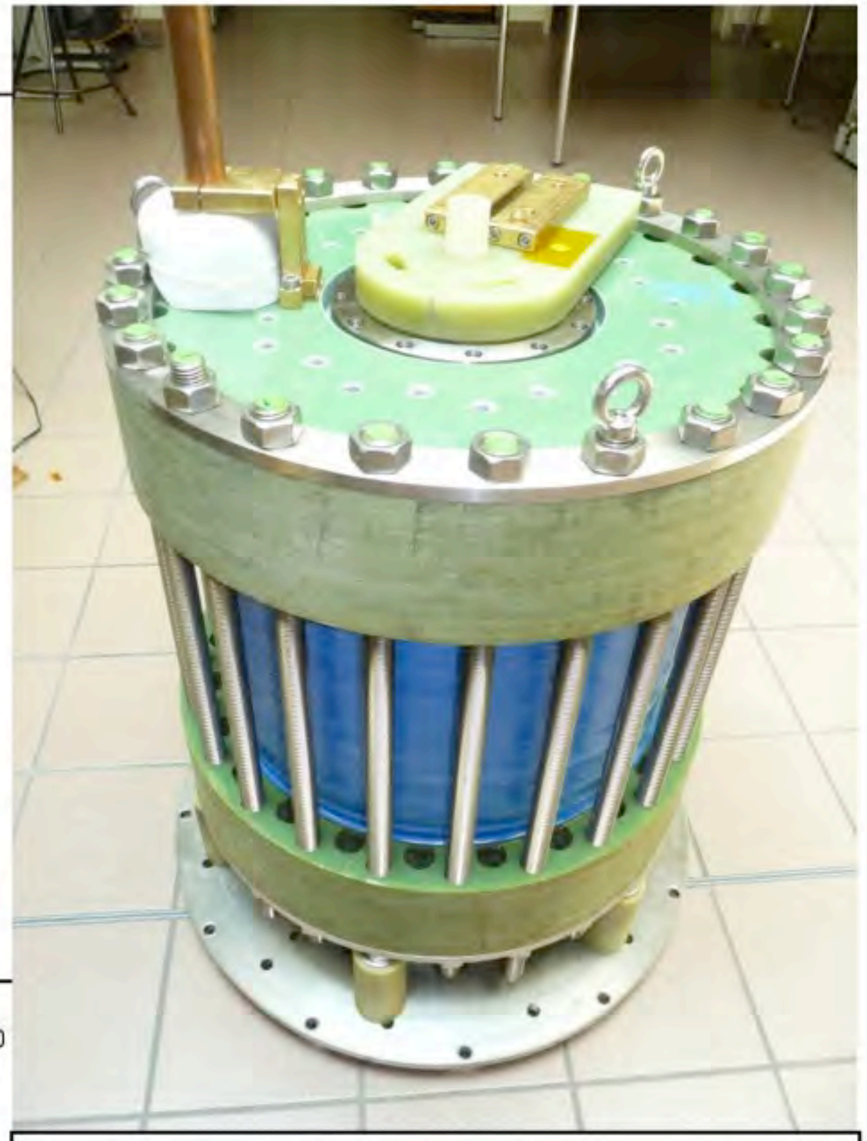
(LNCMI-Toulouse)

Limited by Pressure

89T Max



Pulsed

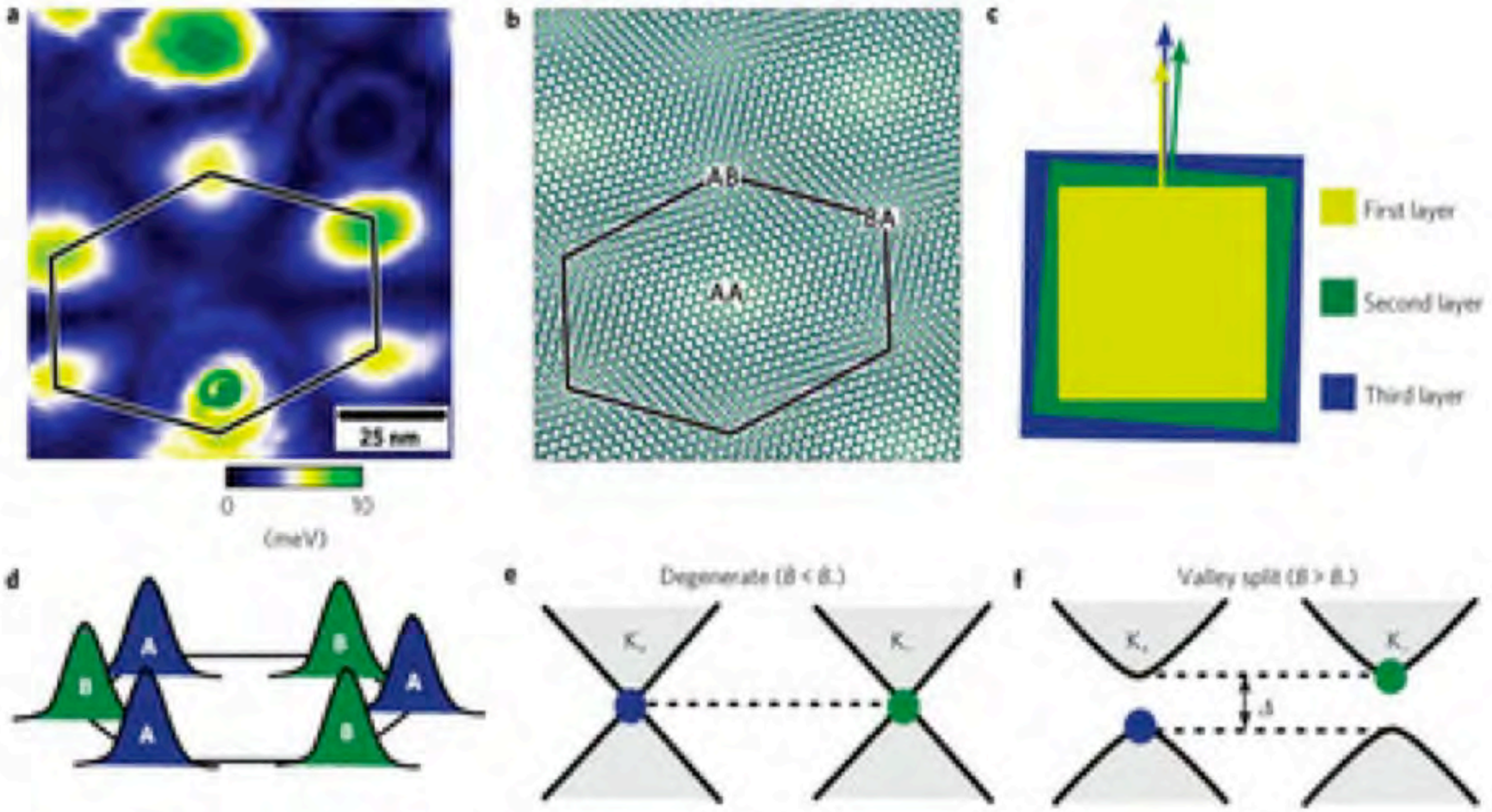


Coil-In-Ex 79 Tesla Coil

(LNCMI-Toulouse)

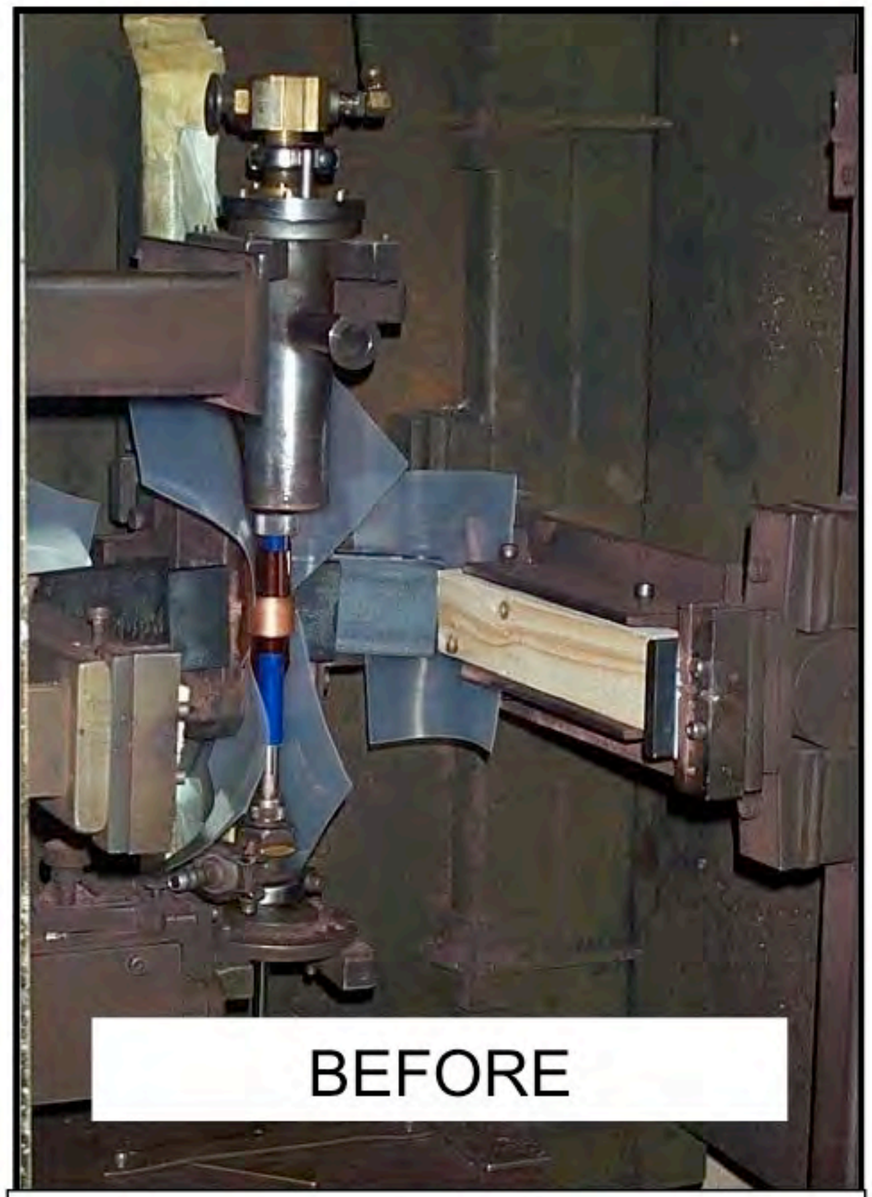
Multilayer Contribution, SuperLattice

Expected new features when $\ell < \ell^*$



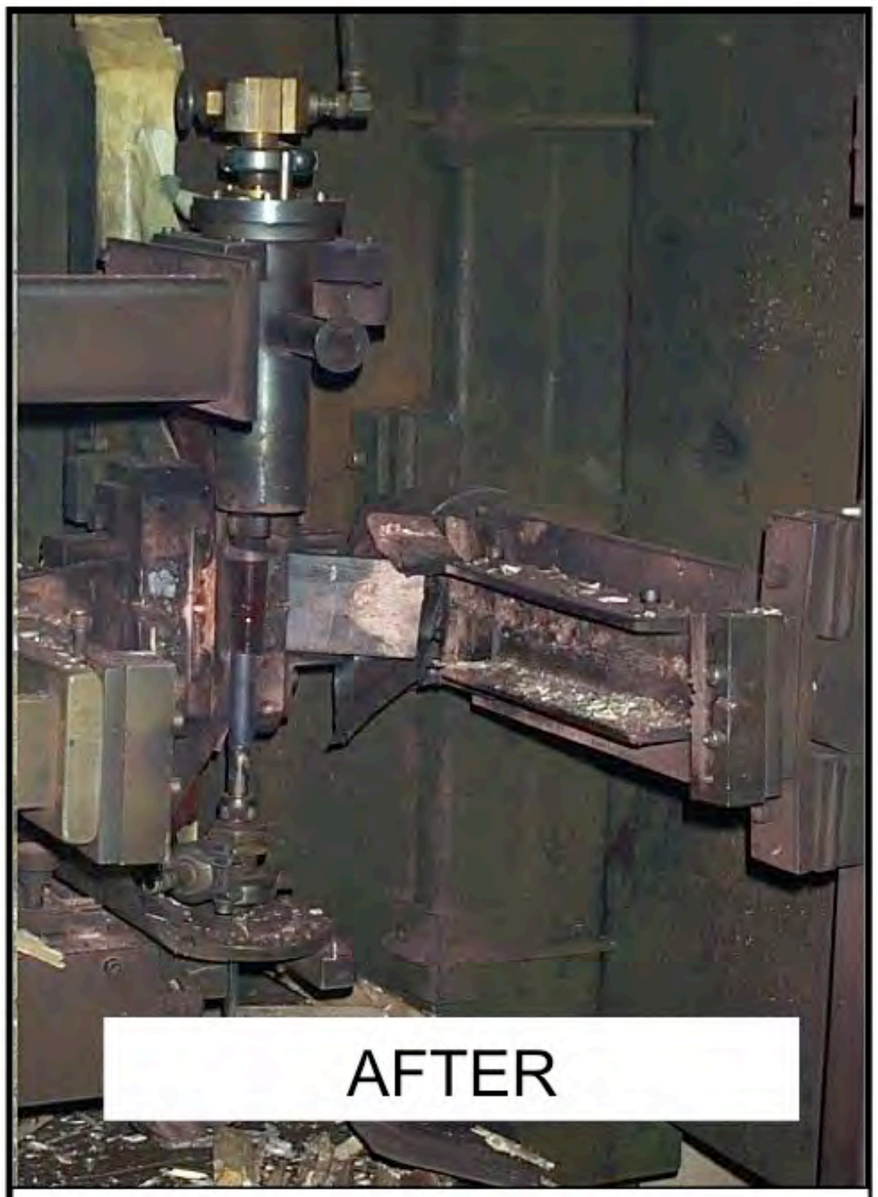
D.L Miller et Al, Nature Phys. 6, 811–817 (2010)

Additional slide : Principle



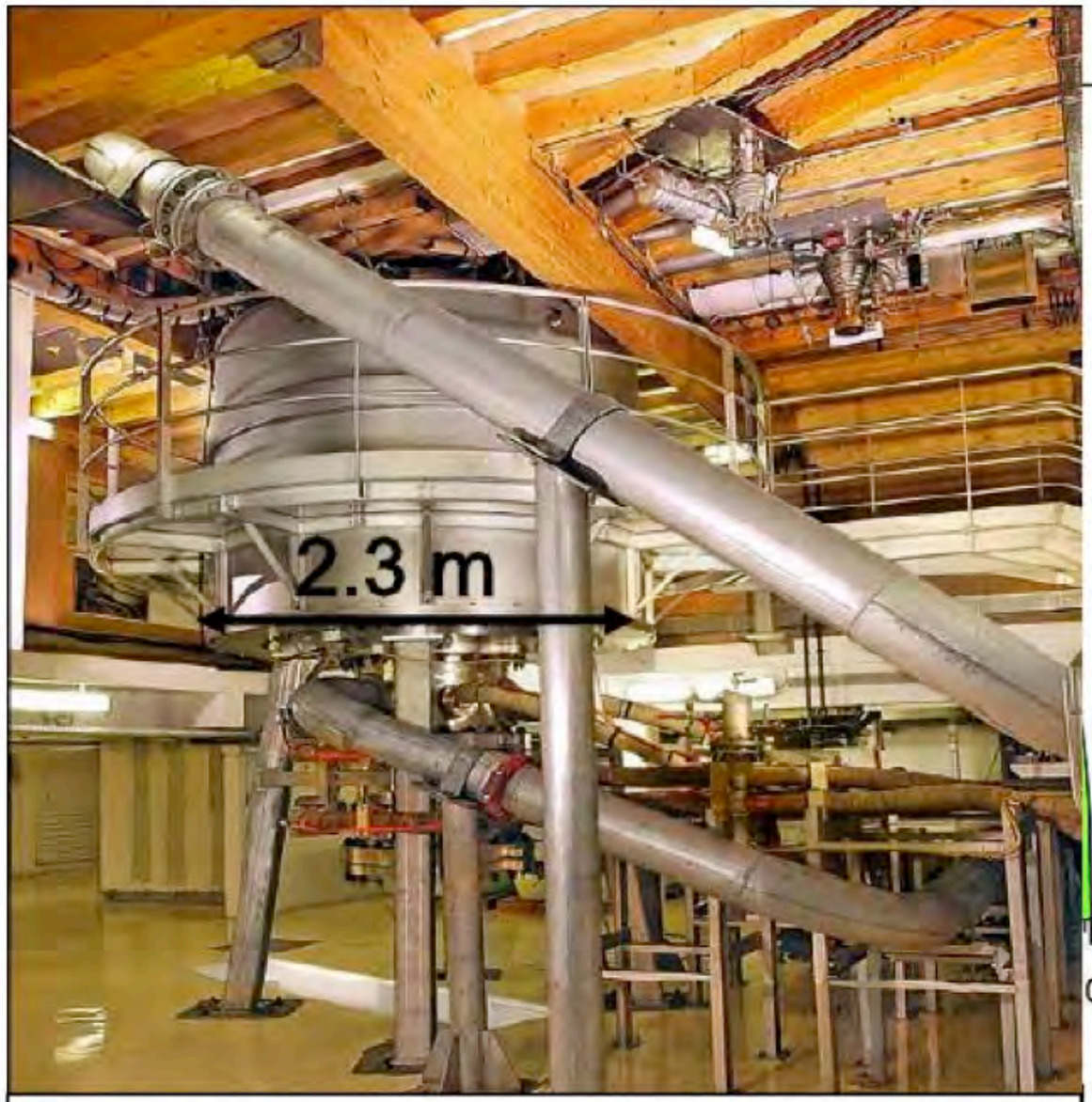
Sample + Coil

SHOT



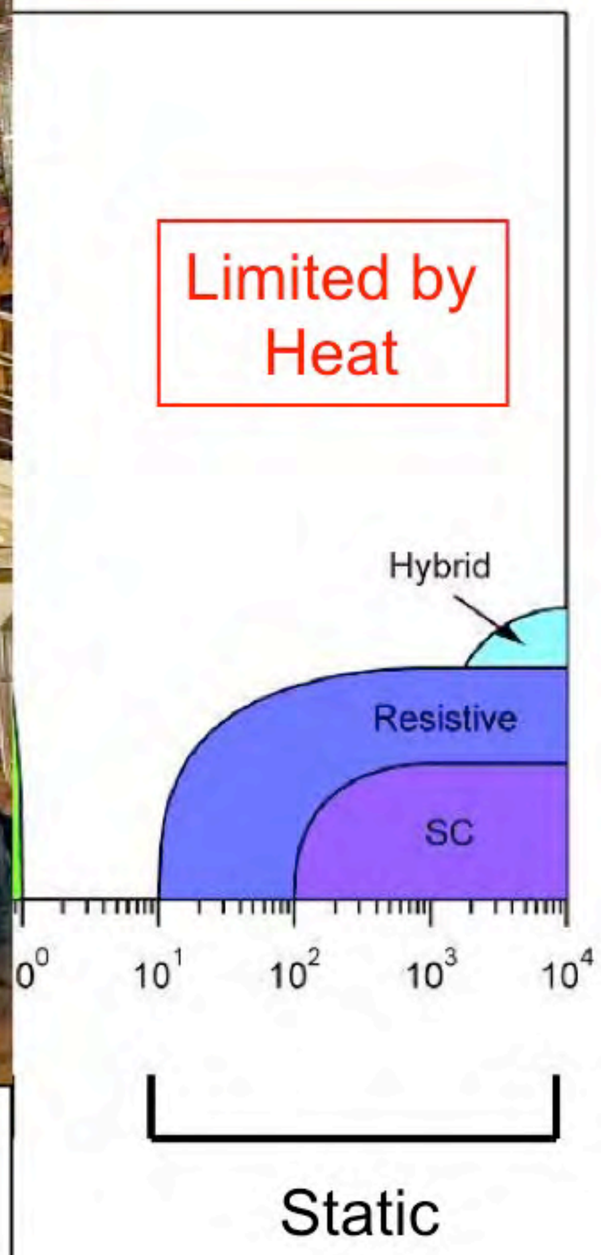
Sample OK

Additionnal slide :High Magnetic Field Production

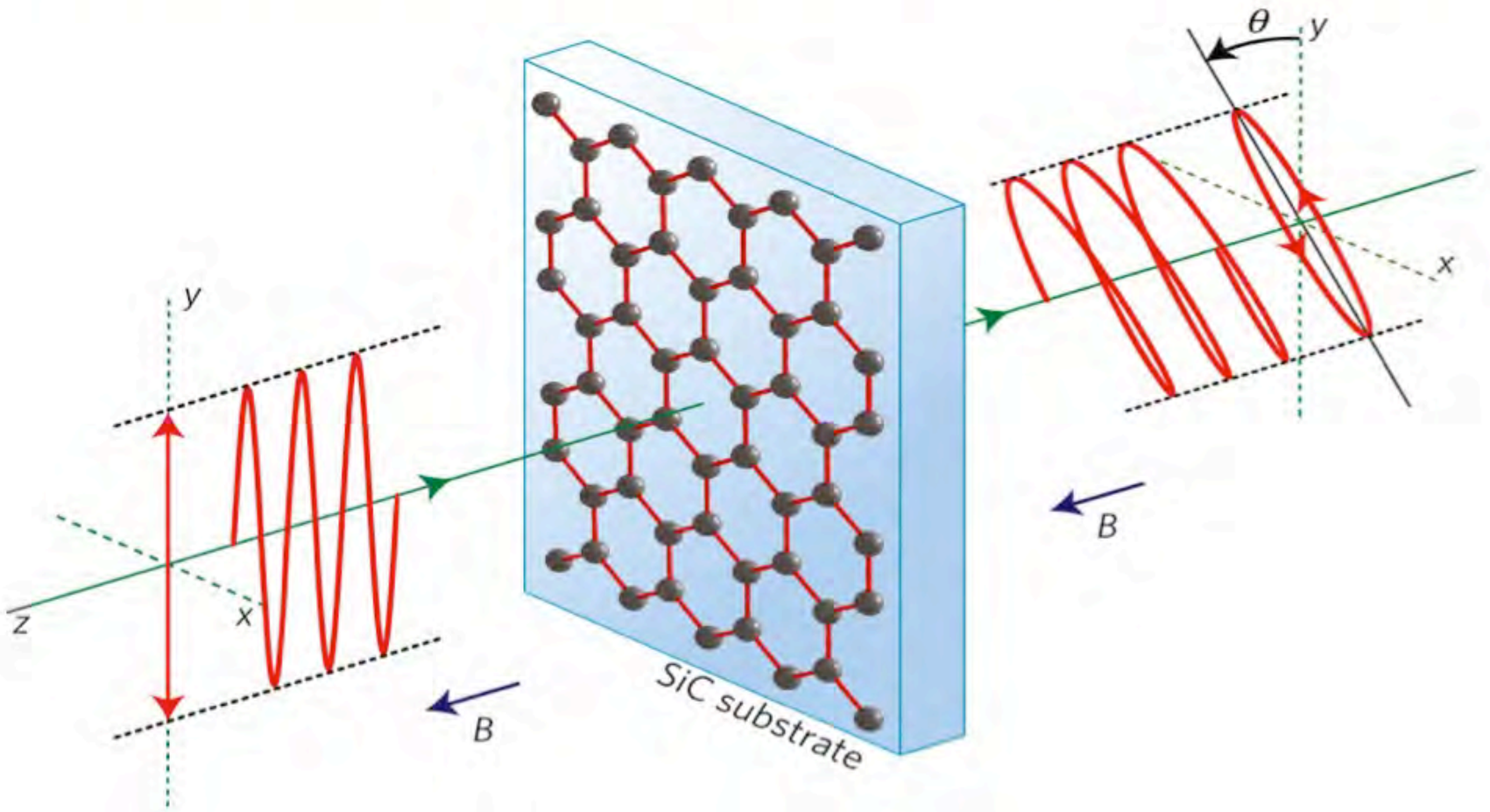


Future Hybrid coil 42T

(LNCMI-Grenoble)



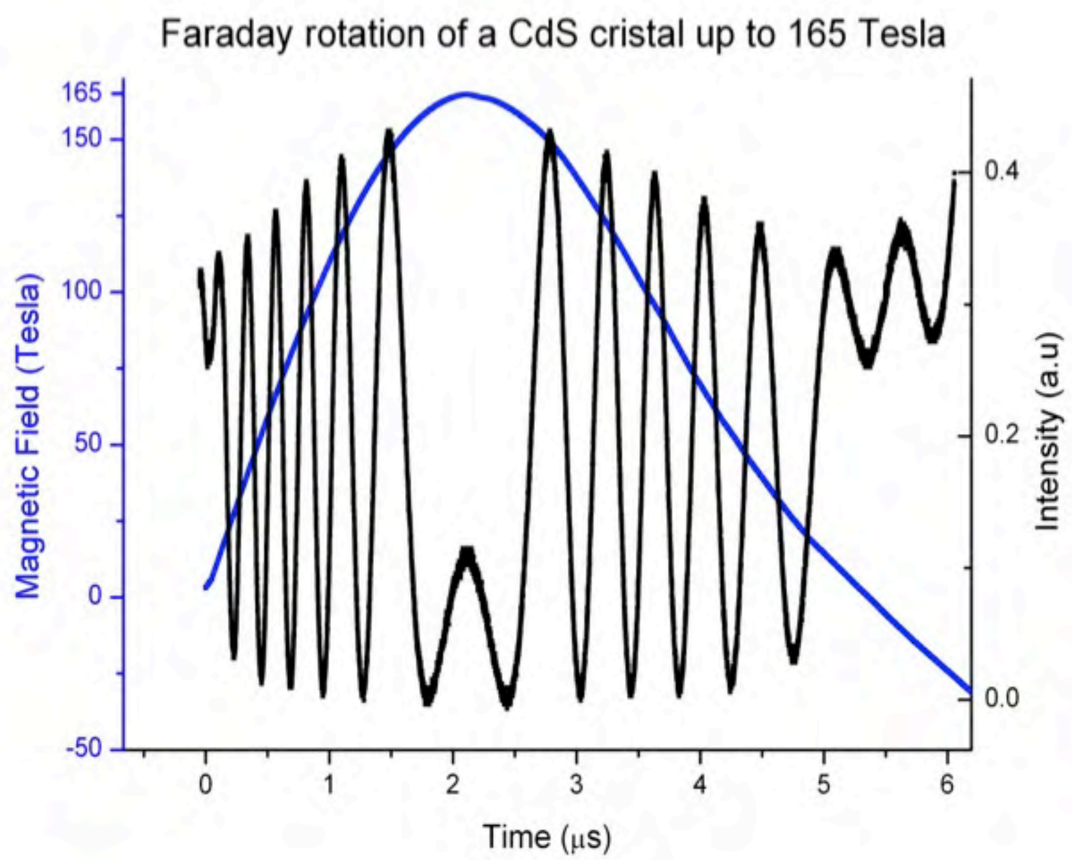
Additionnal slides : Faraday Rotation

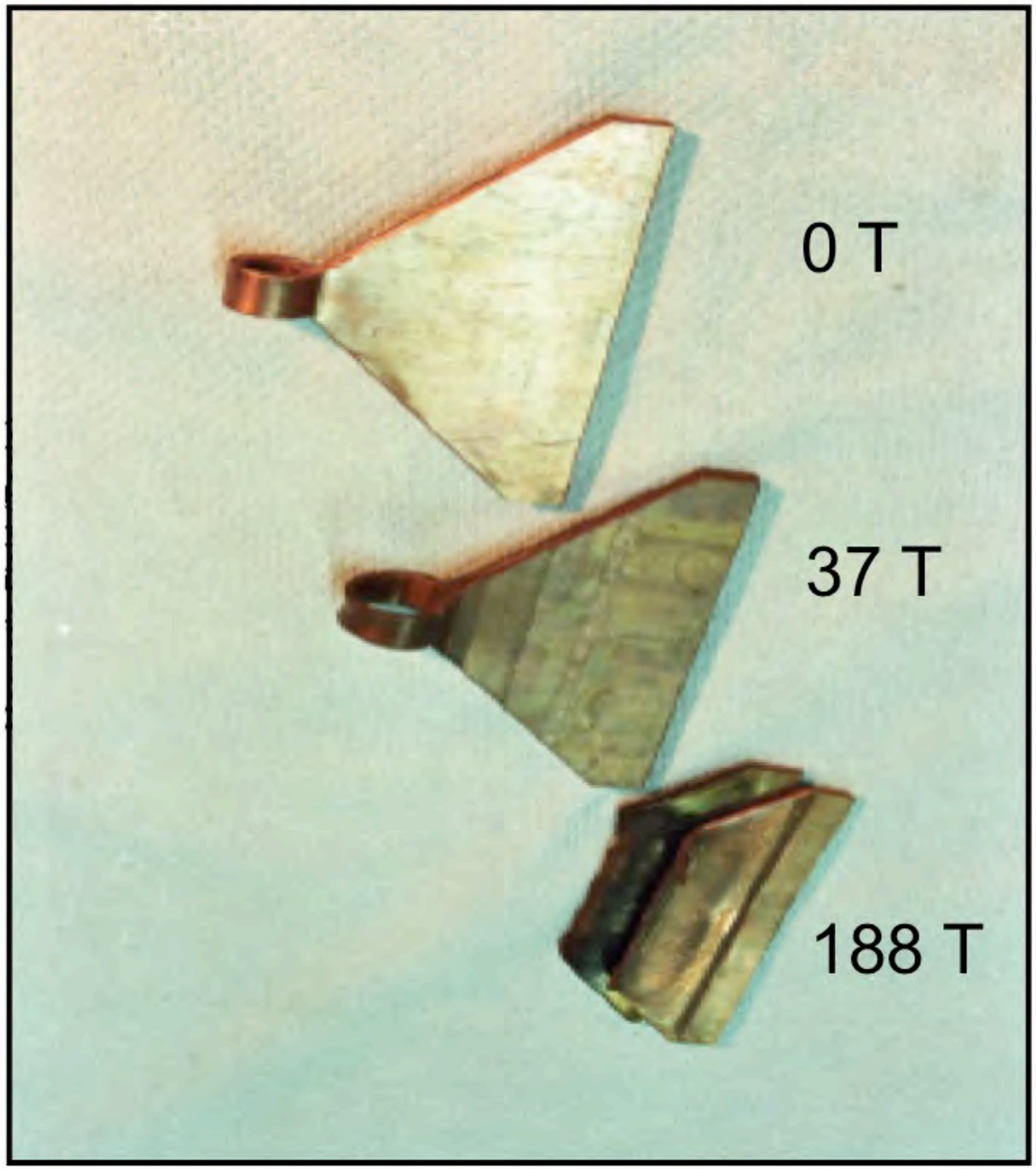


I. Crassee et Al, Nature Physics 7, 48–51 (2011)

$\Theta = V B l$ *with, V Verdet Constant, B Magnetic Field and l length*

Generator MEGAGAUSS : Principle





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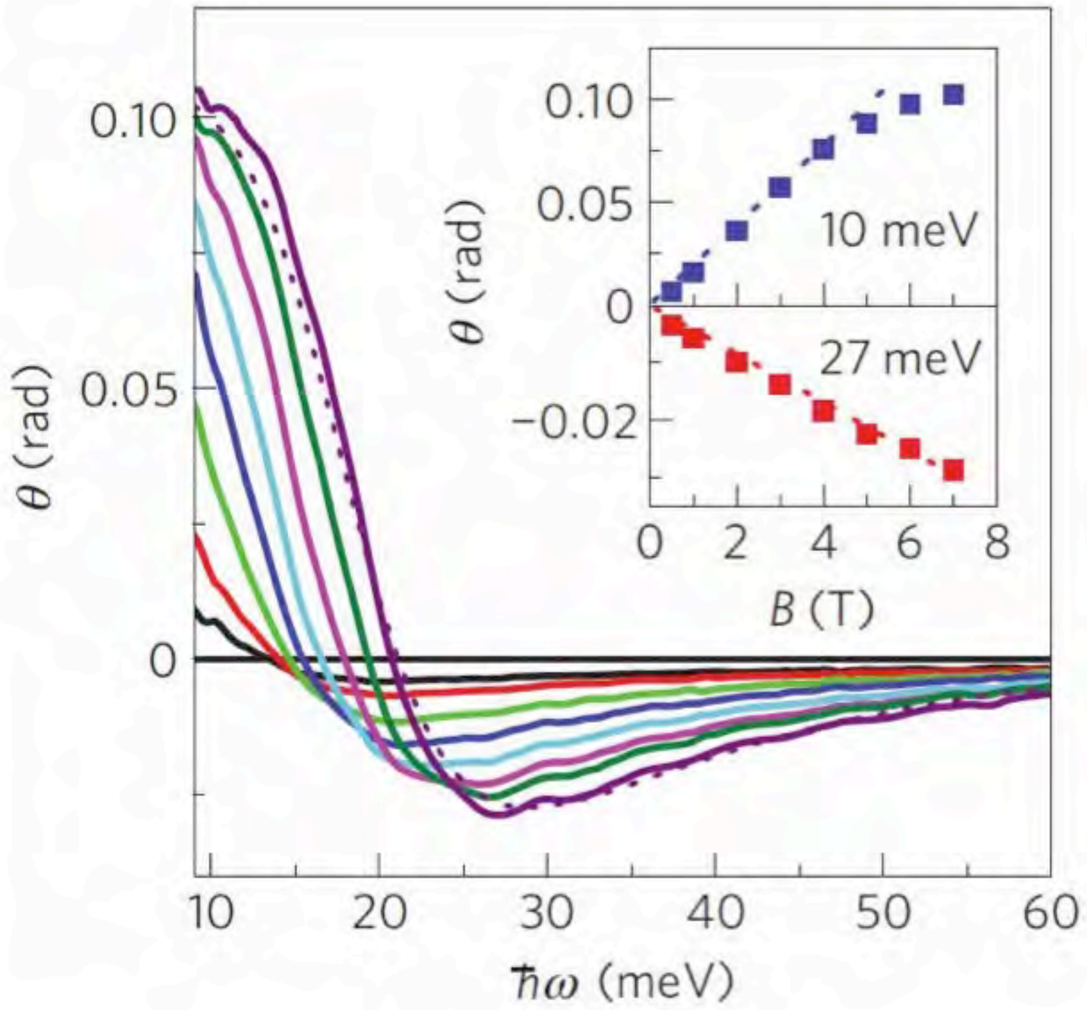
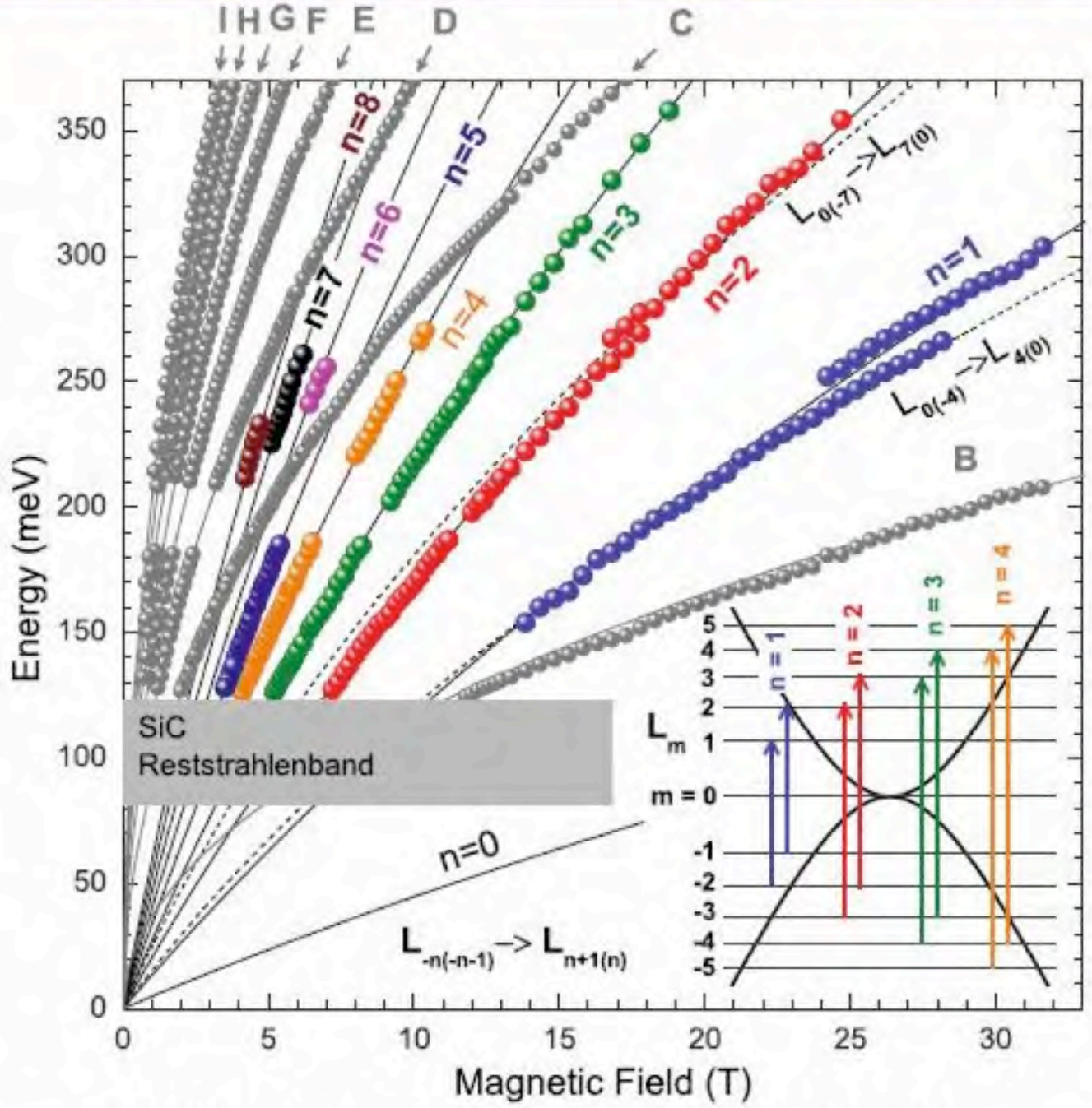


6° for 5 Tesla ~1° by Tesla

For 1 layer

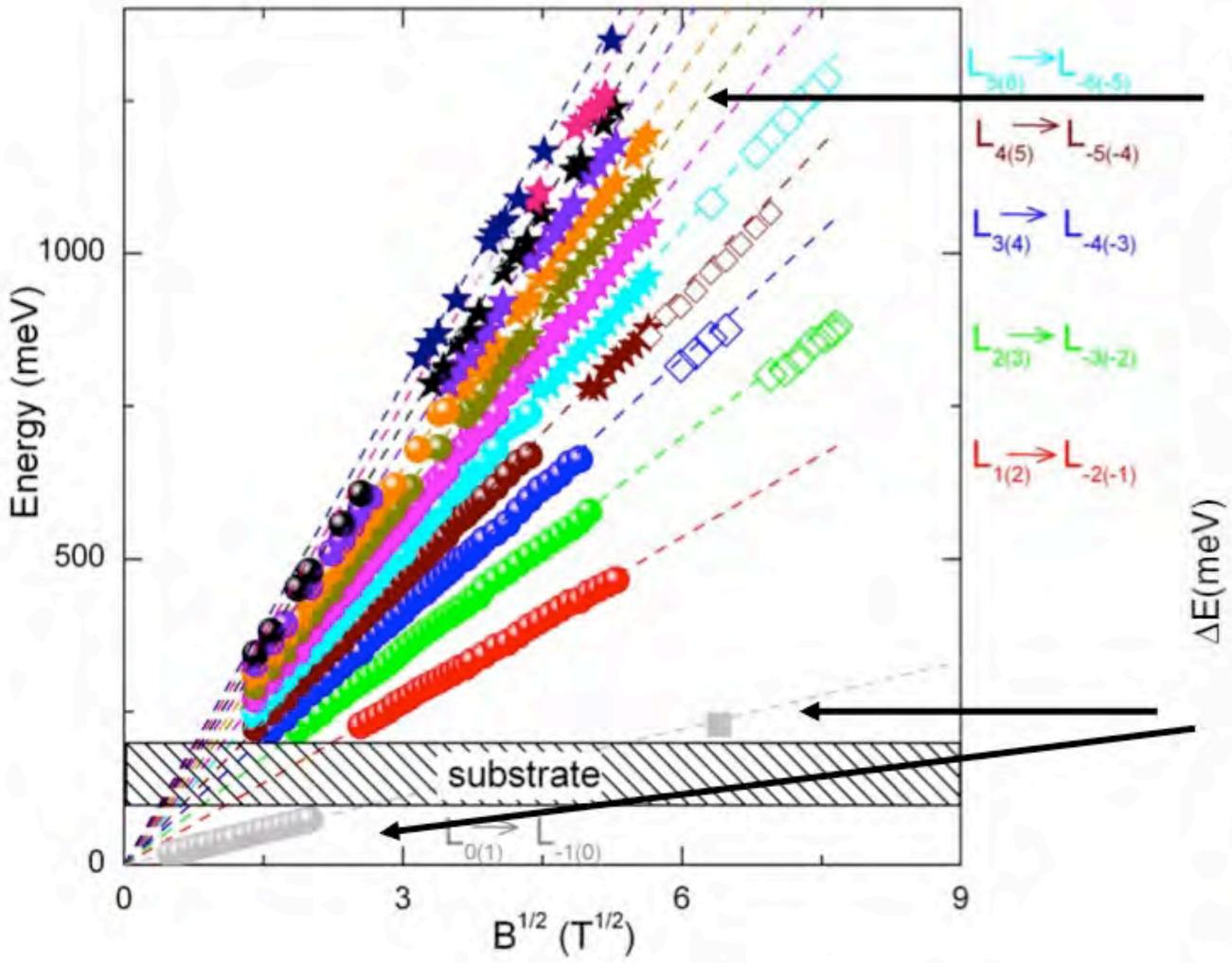
Additionnal slides : Bilayer inclusion



Orlita et Al, PRB 83, 125302 (2011)

Cyclotron Resonance : $L_{-1(0)} \rightarrow L_{0(1)}$ transition

Fan-Chart of Landau level transitions in multi-layered epitaxial graphene grown on SiC



Observed deviation from the square-root dependance for large-n transition