HFML
Science in High Magnetic Fields

FOM

NWO
Netherlands Organisation for Scientific Research

EMFL
European Magnetic Field Laboratory

Physical phenomena in high magnetic fields

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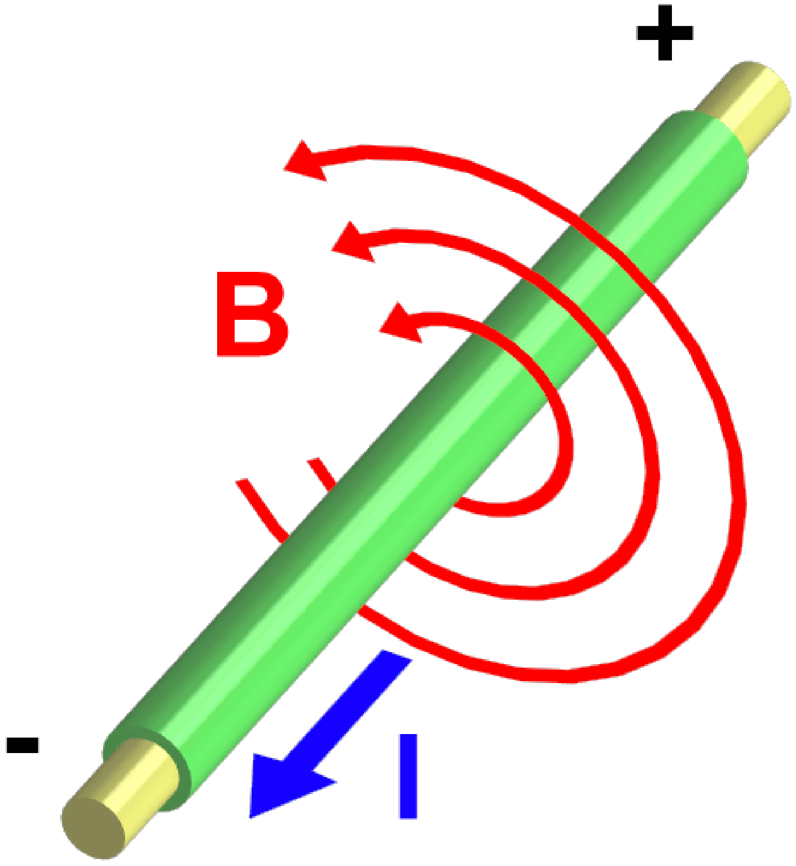
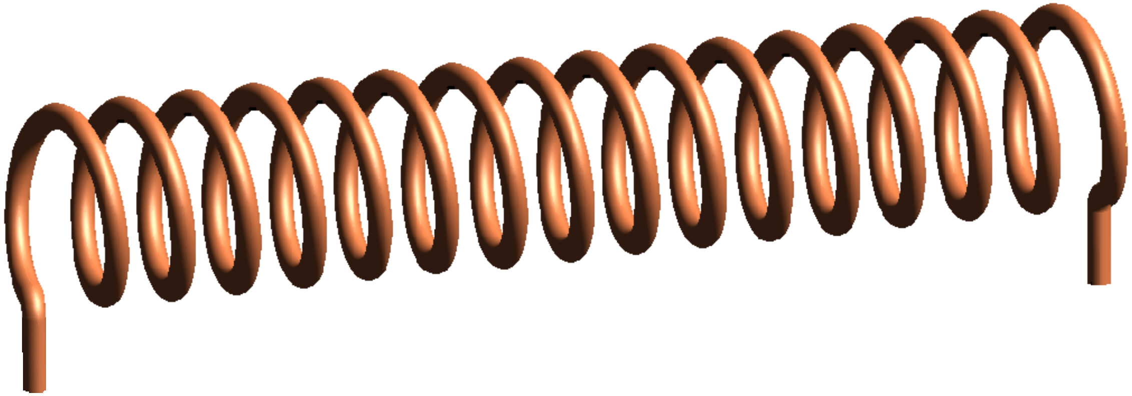
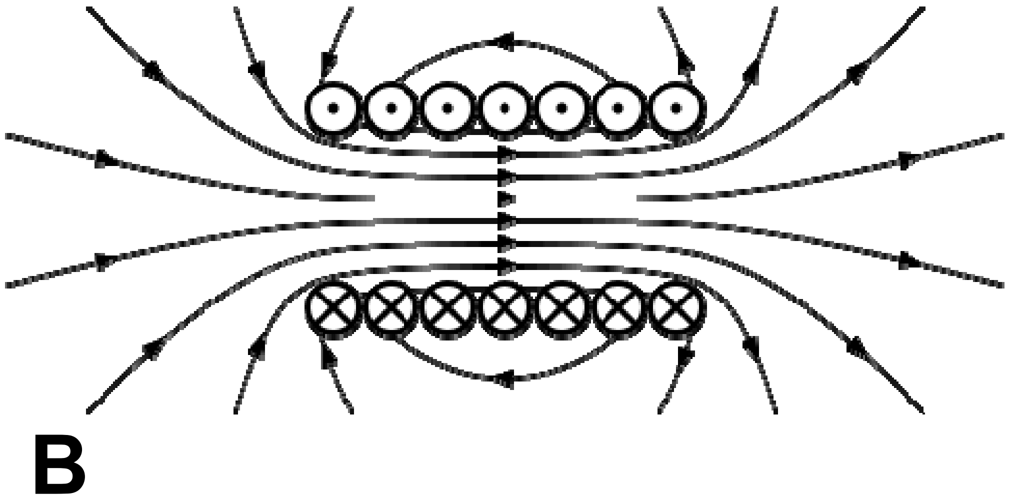
Radboud University

FELIX and HFML

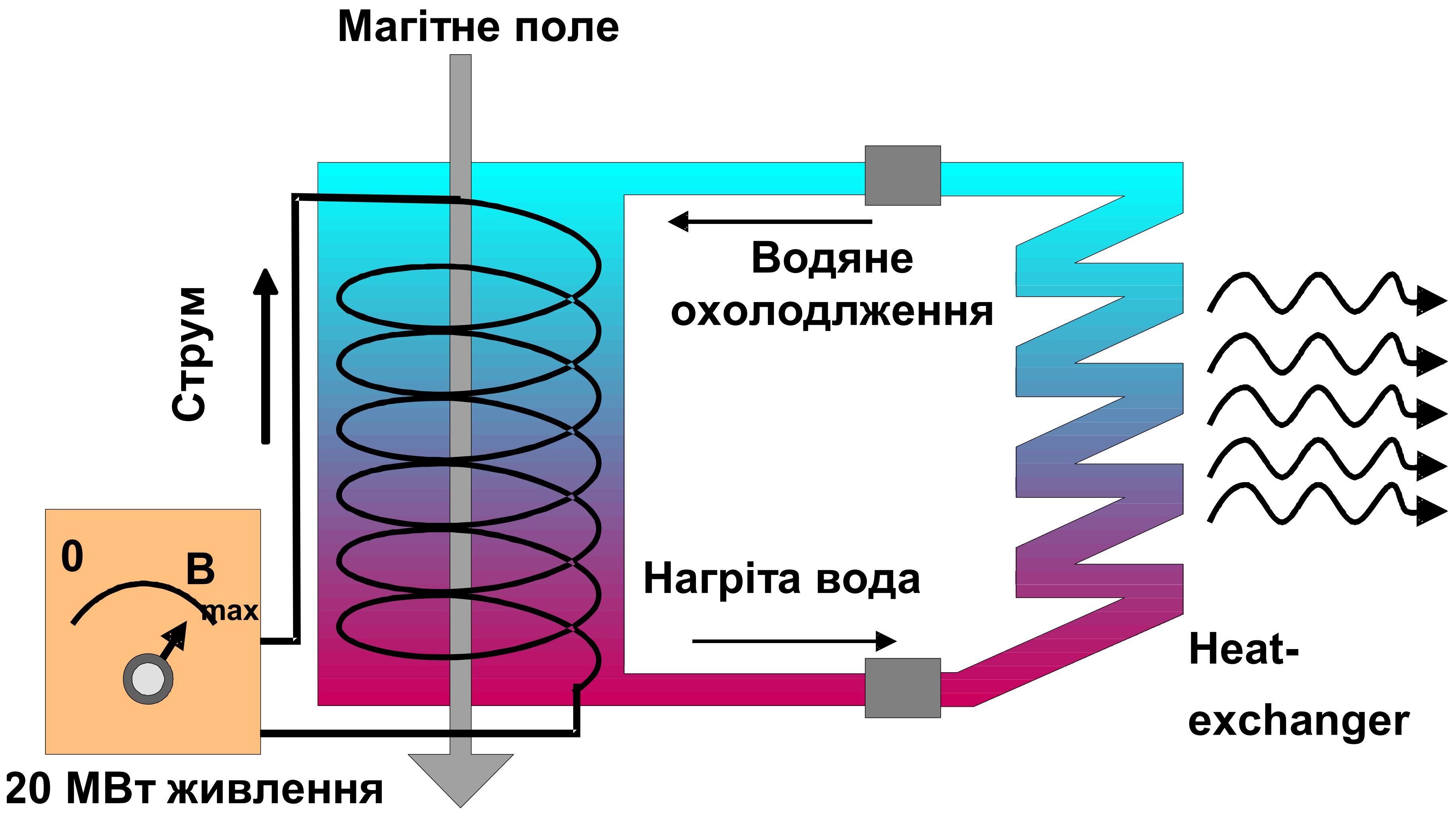
Що таке магнітне поле?





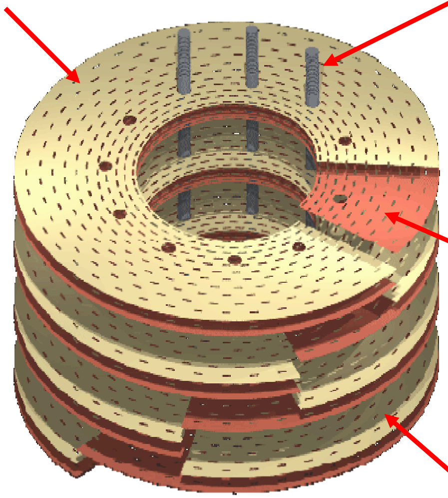


Як отримати сильне магнітне поле?



33 Тесла резистивний магніт

дизайн Біттера

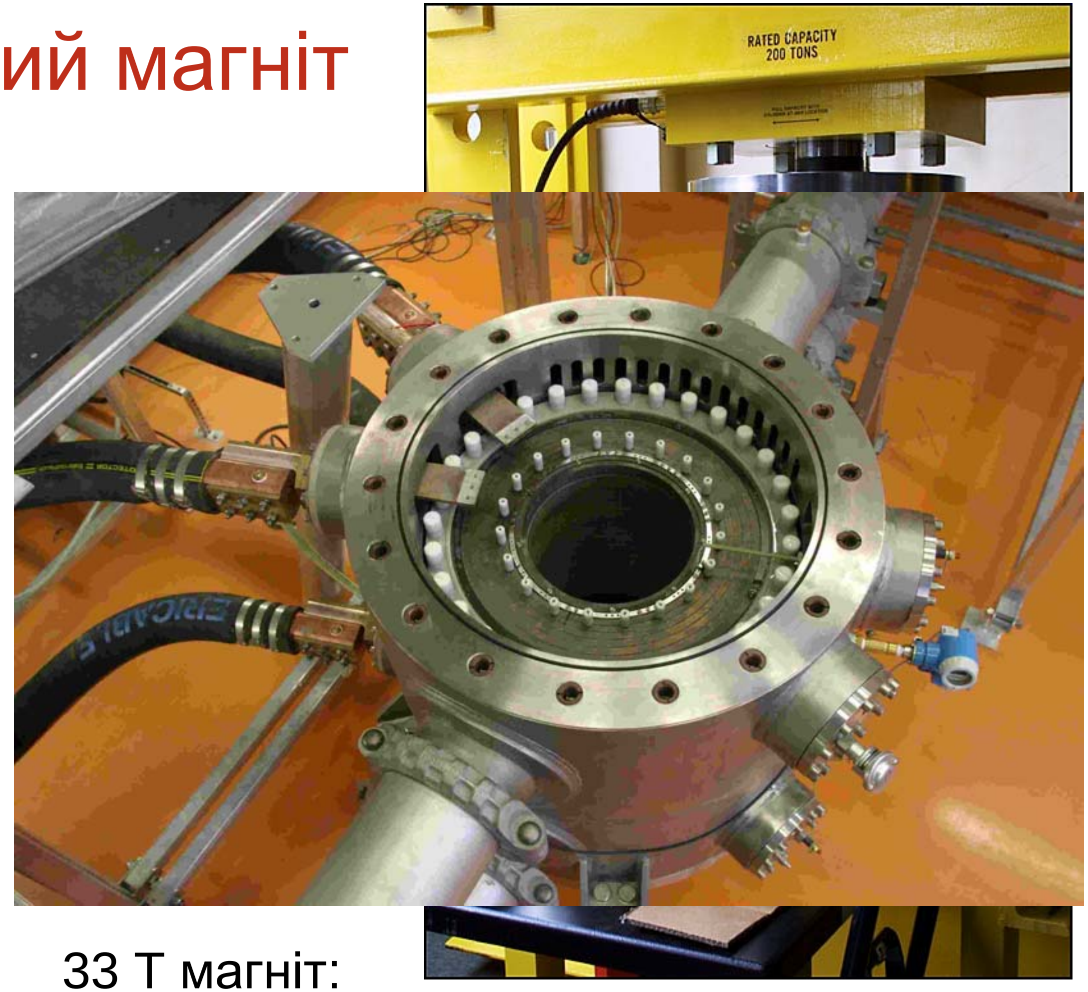


Отвори для охолодження

Стрижні для фіксації дисків

Cu диск

Ізоляція



33 Т магніт:

Складається з 3-х катушок

- 36 кА, 18 МВт
- 145 літрів/сек вода

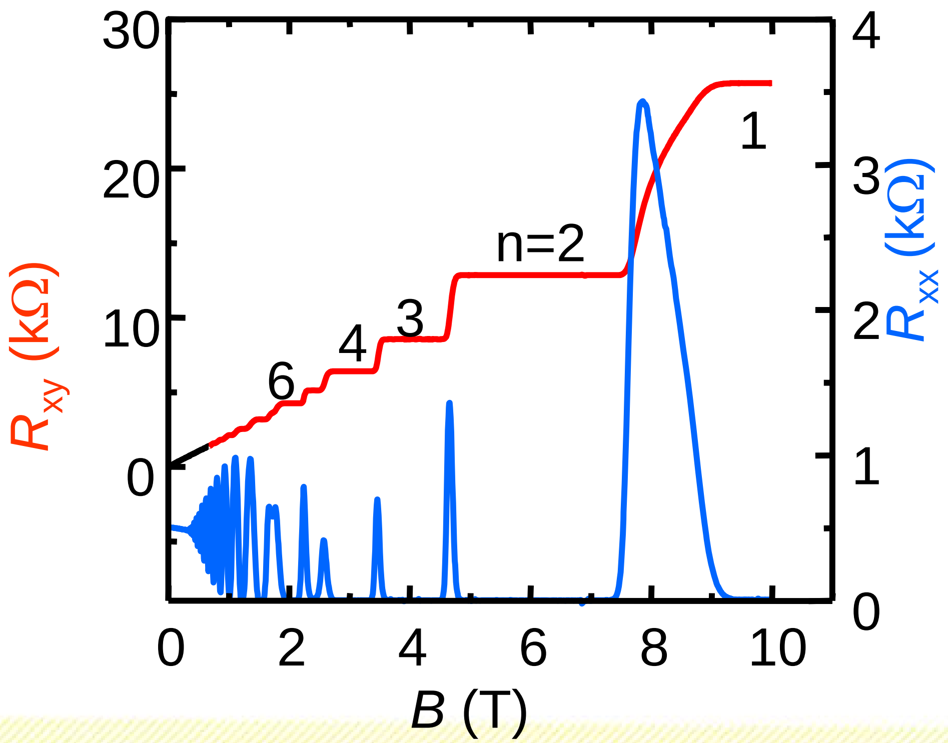
Why we want to have high magnetic fields?

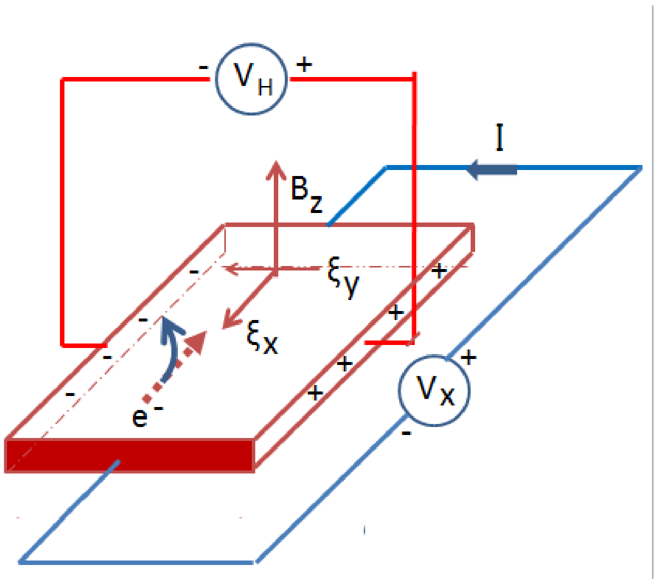
- To put materials in extreme conditions

Hall effect

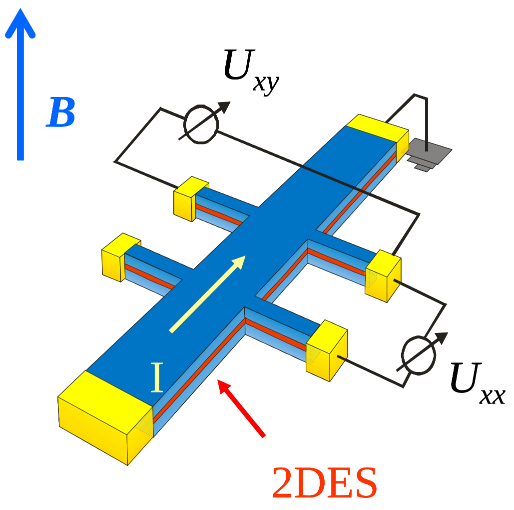
- Free electrons in a magnetic field.

$$F_L = q\mathbf{v}\times\mathbf{B} \qquad V_H = \frac{1}{ne} jB$$

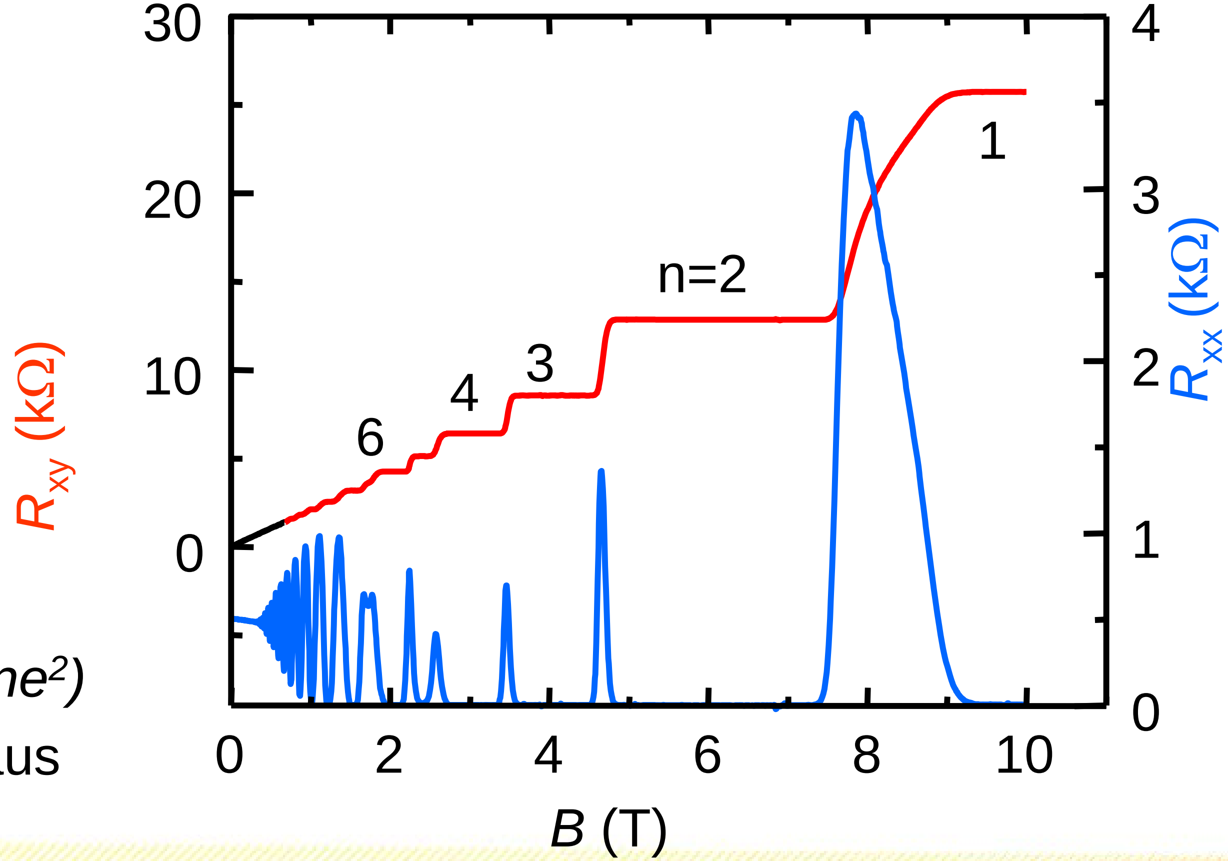




Quantum Hall effect

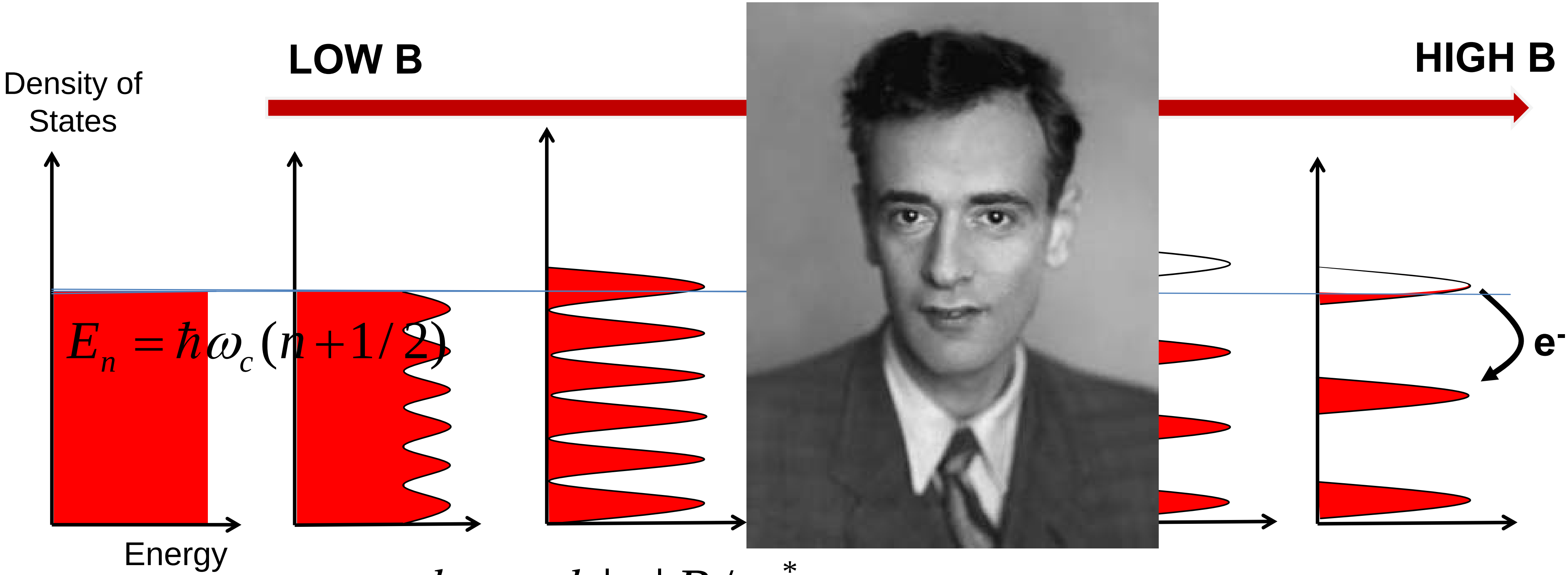


The Nobel Prize in Physics 1985
Klaus von Klitzing

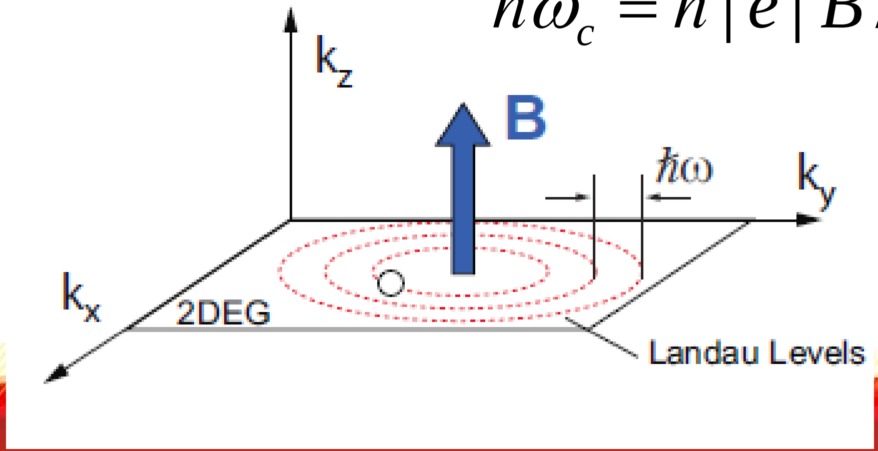


- ⇒ $1/B$-periodic oscillations in R_{xx}
- ⇒ quantized plateaus in $R_{xy} = (h/ne^2)$
- ⇒ $R_{xx} \rightarrow 0$ in quantum Hall plateaus

Landau quantization



$$\hbar\omega_c = \hbar|e|B/m_c^*$$

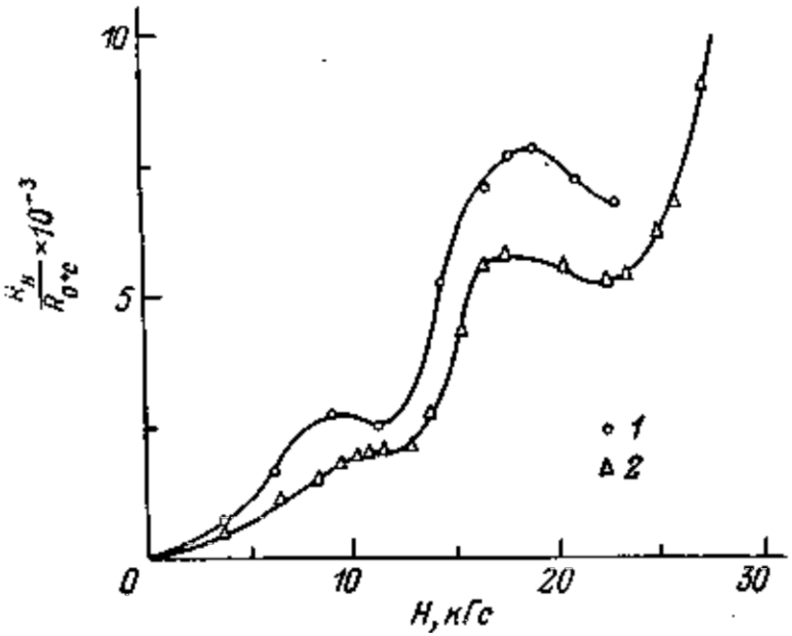


Periodic 1/B Oscillations in the sample properties:
Electrical Resistivity, Magnetisation etc

Shubnikov de Haas oscillations

1930

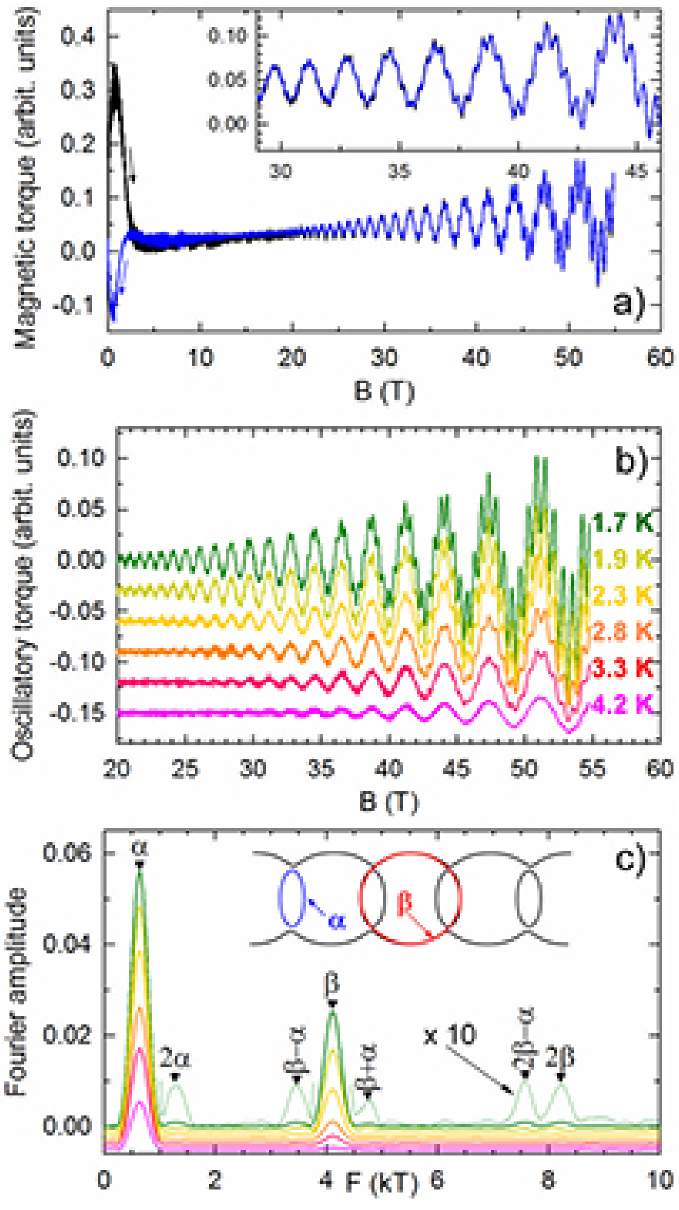
Shubnikov - de Haas oscillations



$$\Delta\rho_{xx} = \sum_{i,p} R_{ip} \exp\left(-\alpha_i T_{D_i}\right) \frac{\alpha_i T}{\sinh(\alpha_i T)} \sin\left(\frac{2\pi p f_i}{B} + \frac{\pi}{4}\right)$$

Lifshitz – Kosevich formula

Quantum oscillation in organic metal κ-$(ET)_2Cu(SCN)_2$

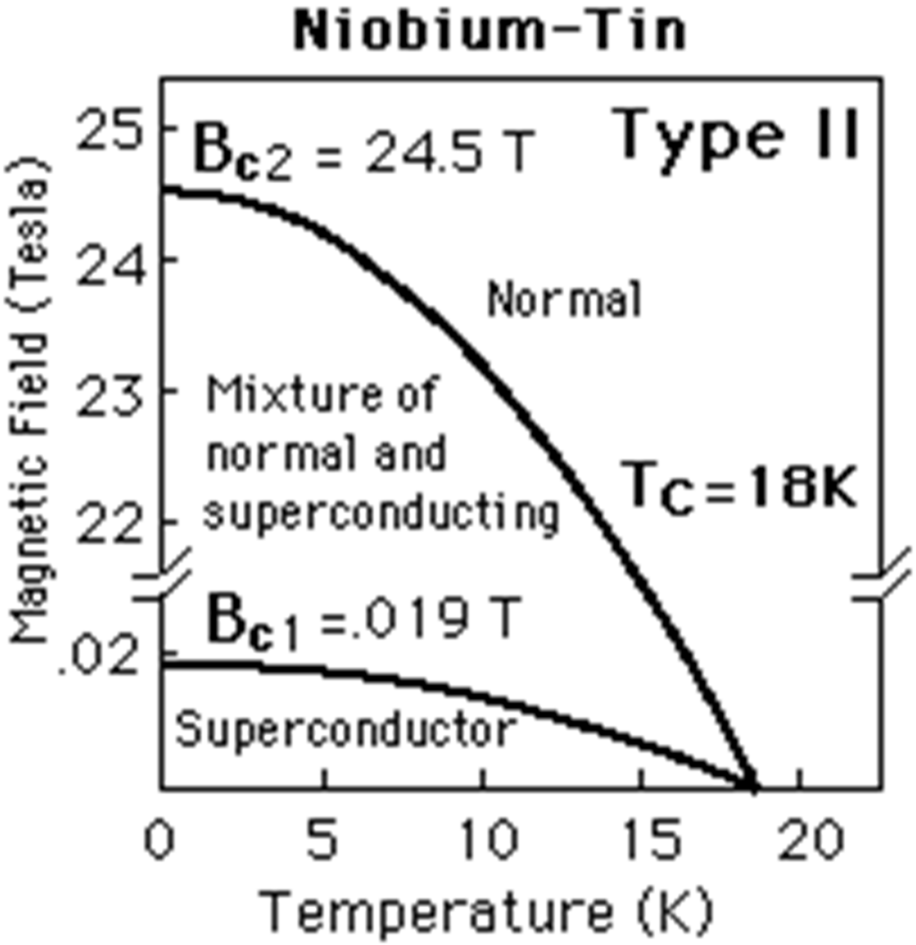


Quantum oscillations provide unique information about Fermi surface of solids

It requires high magnetic fields!

J. Phys.: Condens. Matter **28** (2016) 275702

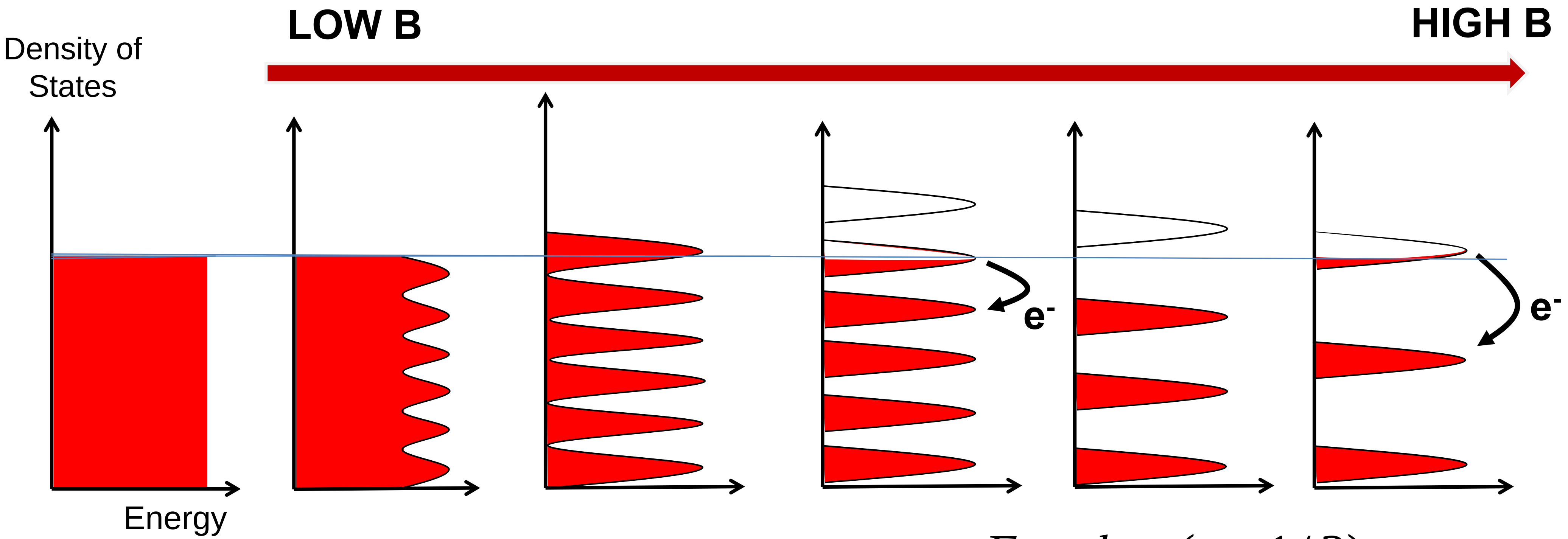
Shubnikov phase in superconductors



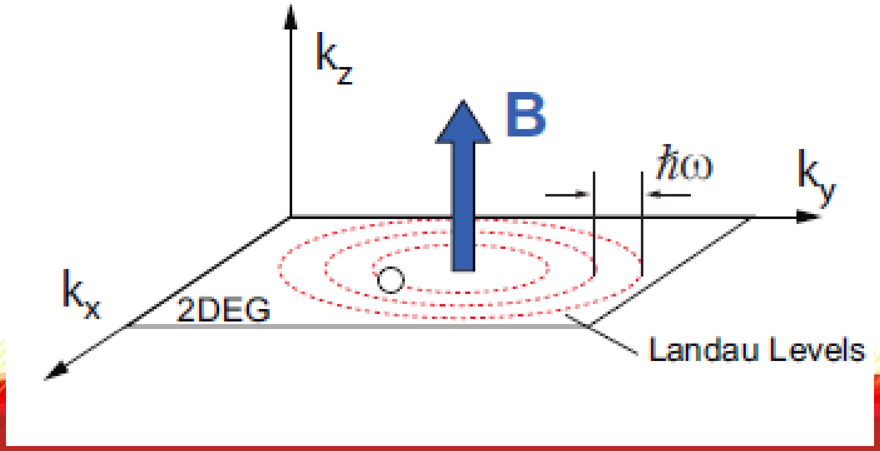
"Thus, in a crystal having 2.5% of thallium at a temperature of 1.92 K, the breakup of the superconductivity occurs in the field interval of 734–1110 Gs. At the same time, H_k only slightly differs from the values for pure lead becoming slightly smaller than these values when the temperature decreases."

L.V. Shubnikov, V.I. Khotkevich,
Y.D. Shepelev, Y.N. Ryabinin
Zh. Eksper. Teor. Fiz. **7**, pp. 221–237 (1937)

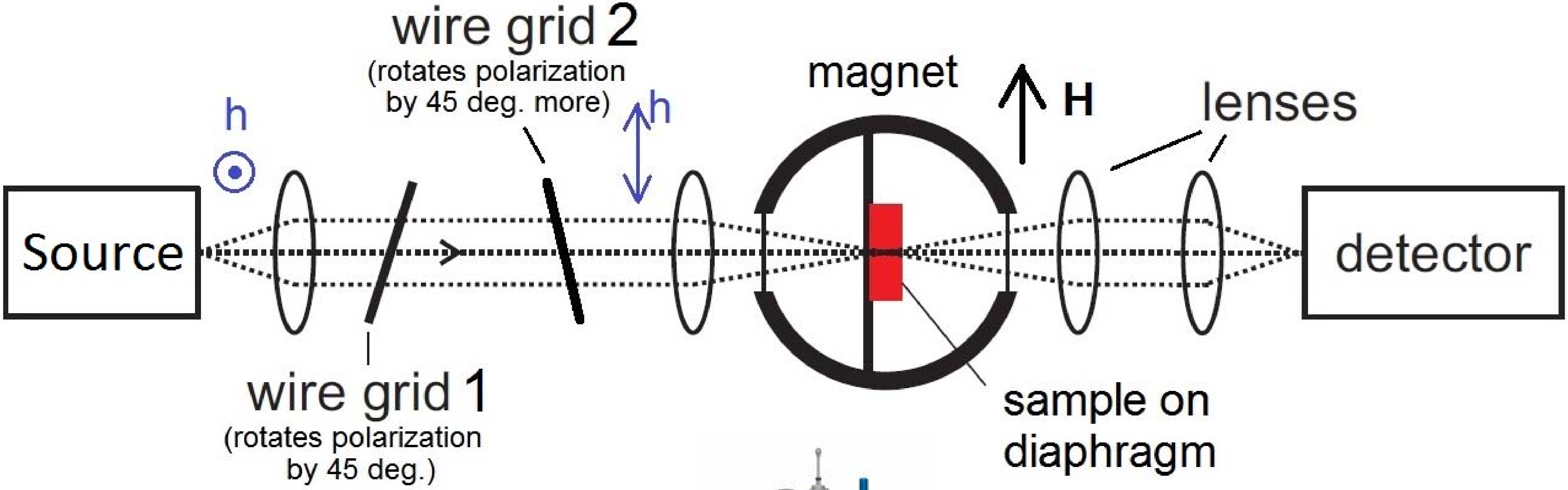
Landau quantization



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



How do we measure CR?



Superconducting Spectromag
B up to 12 Tesla

Two types of experiments:

- constant B, scan ω
- constant ω, sweep B

Solids from spectroscopy point of view

Metals – a lot of electrons.

Reflects the radiation below plasma frequency:

$\omega_p = \sqrt{\frac{n_e e^2}{m\varepsilon_0}}$ – ultraviolet for the metals

Semiconductors – have some charge carriers.

The properties of the carriers could be studied by the cyclotron resonance.

Dielectrics – no charge carriers.

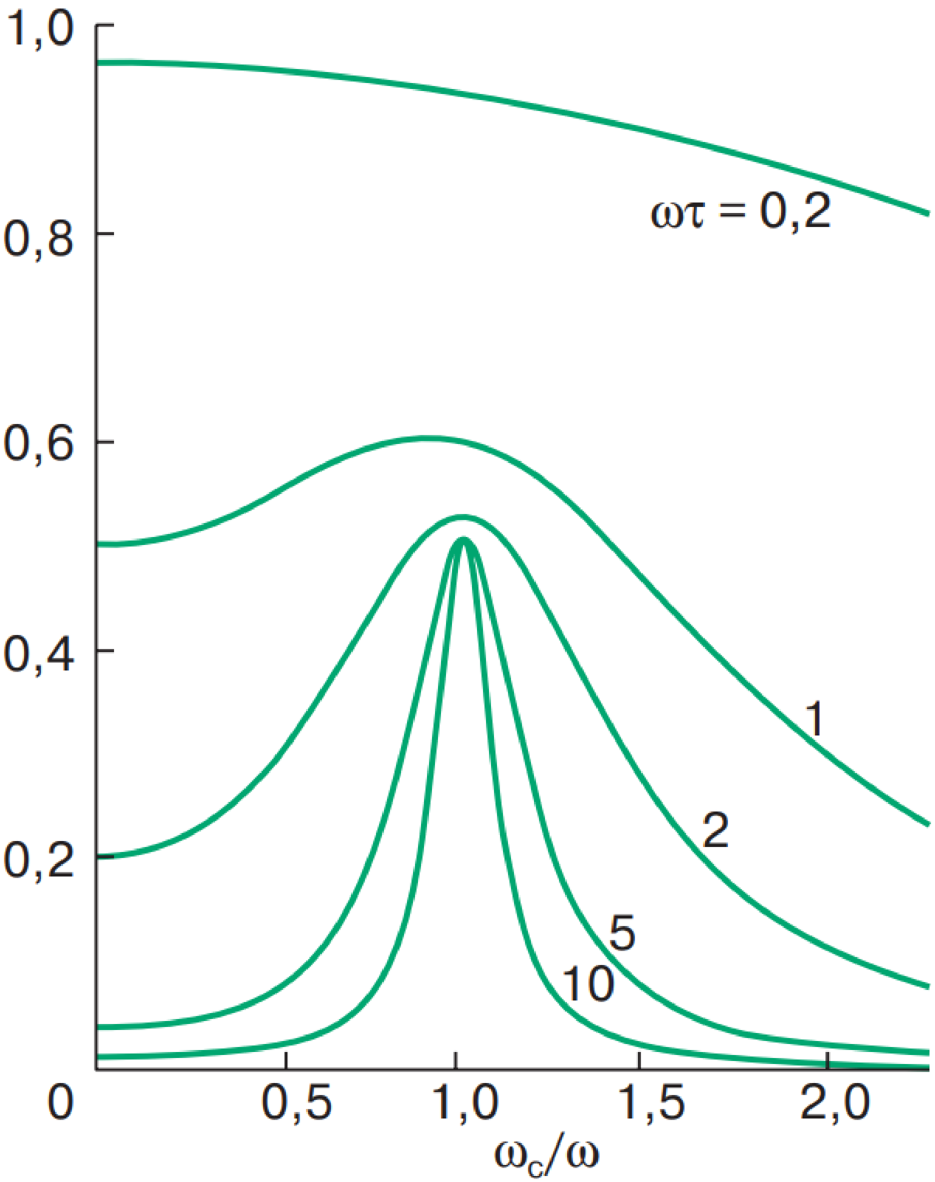
The properties of the magnetic ions or impurities could be studied by means of paramagnetic resonance

Practical requirements

- **E**$^{\omega}$ perpendicular to **H**
- $\omega_c\tau>1$
  τ - carrier scattering lifetime
  electron can complete its
  cyclotron orbit unhindered
- $$\hbar\omega_c > k_B T$$
  - To have population differences between levels

τ~10^{-12}

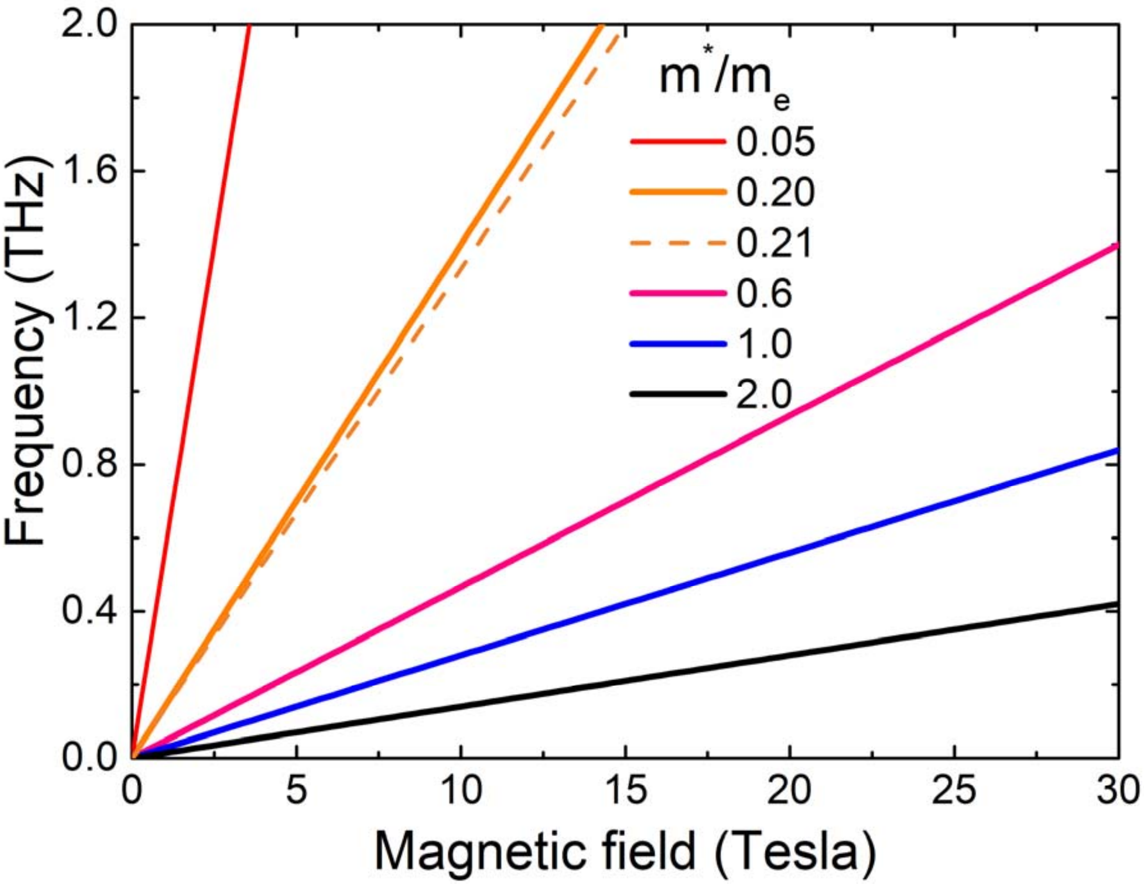
ω_c > 1 THz



Estimation of energies

ω_c - What frequencies we are talking about?

$$\omega_c = |e|B/m_c^*$$

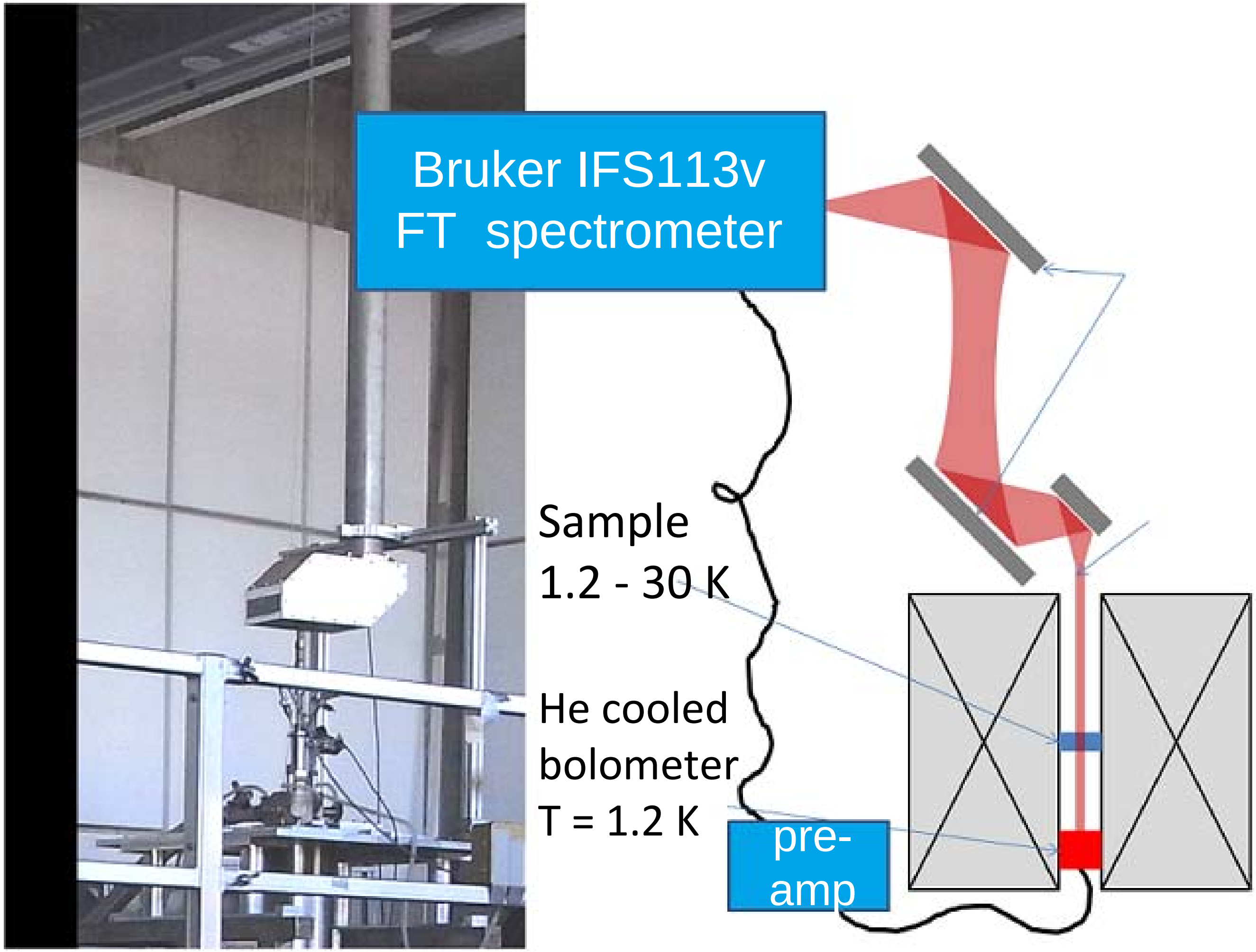


Crystal	Electron	Heavy Hole	Light Hole	Split-off Hole
InSb	0.015	0.39	0.021	0.11
InAs	0.026	0.41	0.025	0.08
InP	0.073	0.4	0.078	0.15
GaSb	0.047	0.3	0.06	0.14
GaAs	0.066	0.5	0.082	0.17
Cu_2O	0.99	-	0.58	0.69

$\omega_c\tau>1$,

$\tau \approx 10^{-12}$ s → $\omega_c > 1$ THz

High field FT-FIR transmission setup



Bruker IFS113v
FT spectrometer

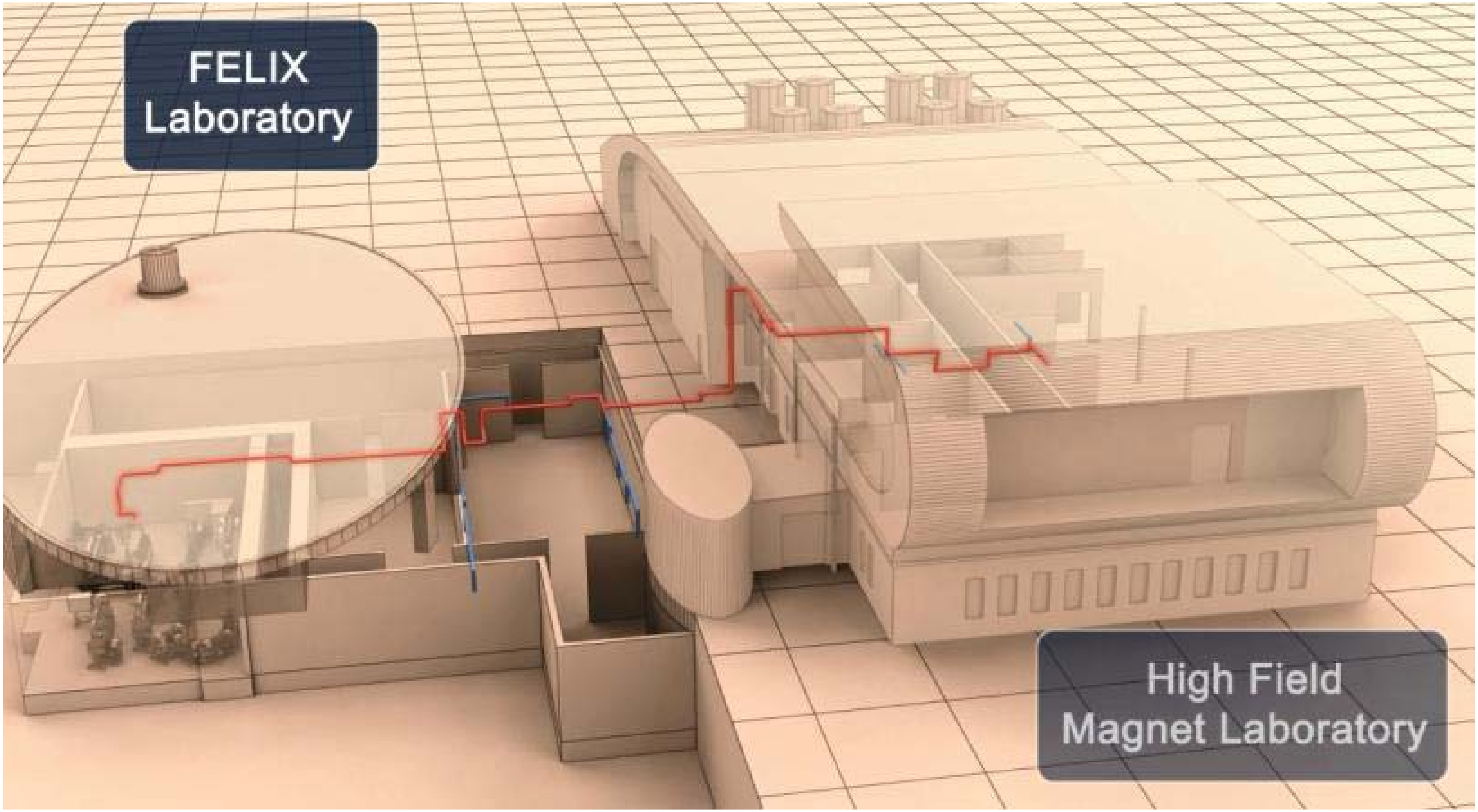
Sample
1.2 - 30 K

He cooled
bolometer
T = 1.2 K

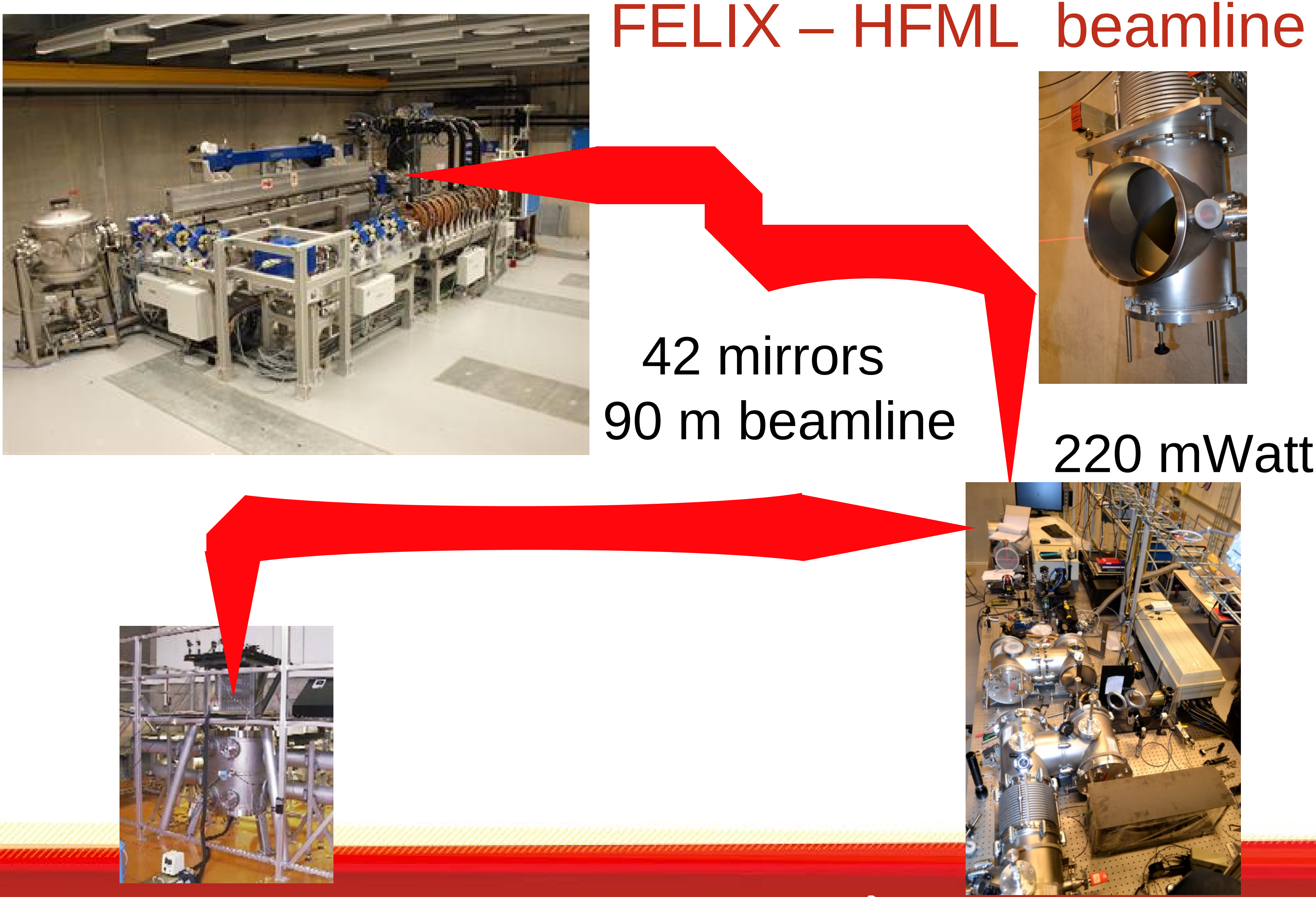
pre-
amp

33 T bitter
magnet

Coupling between FELIX and HFML



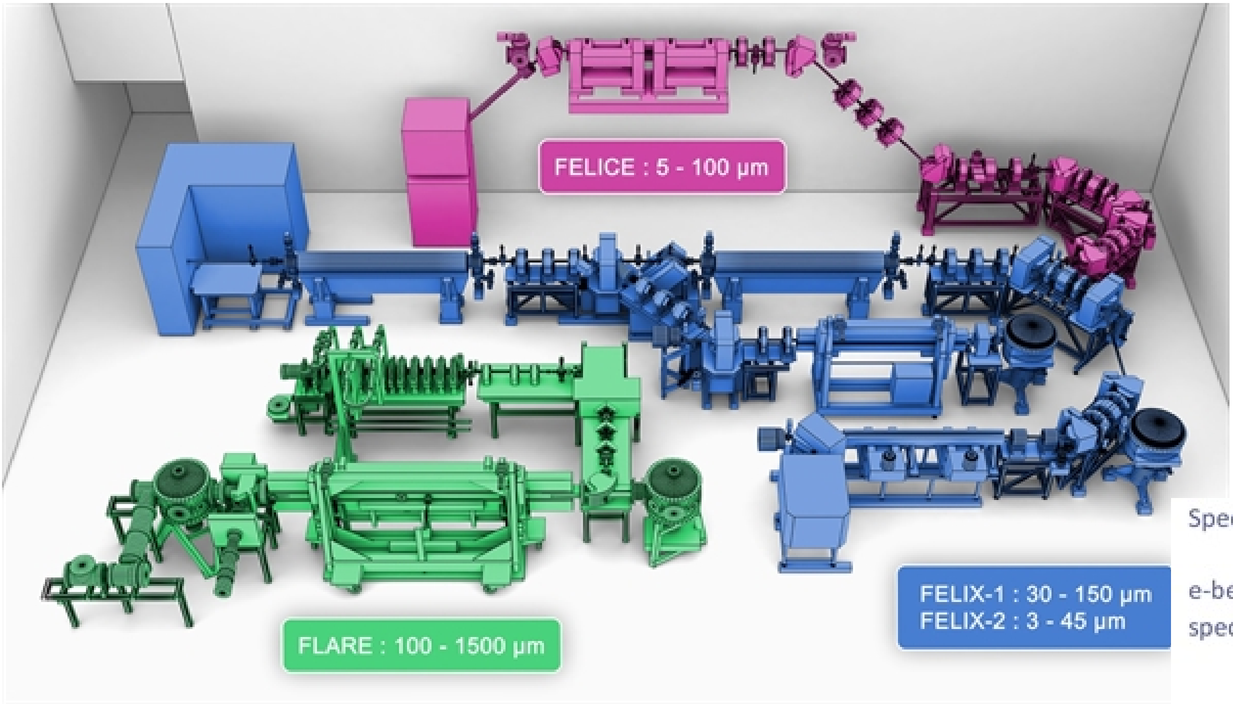
FELIX – HFML beamline

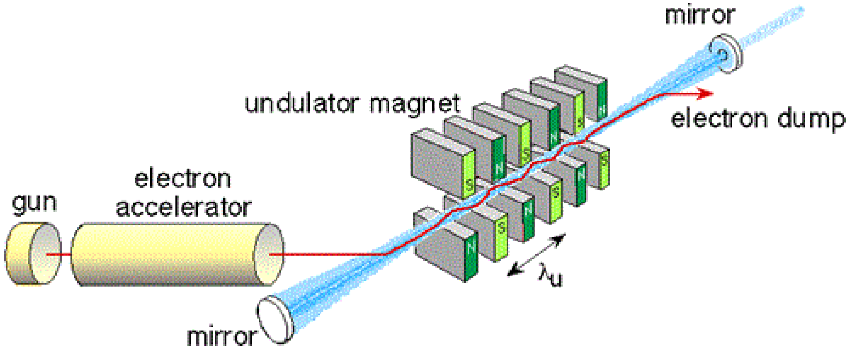


42 mirrors
90 m beamline

220 mWatt

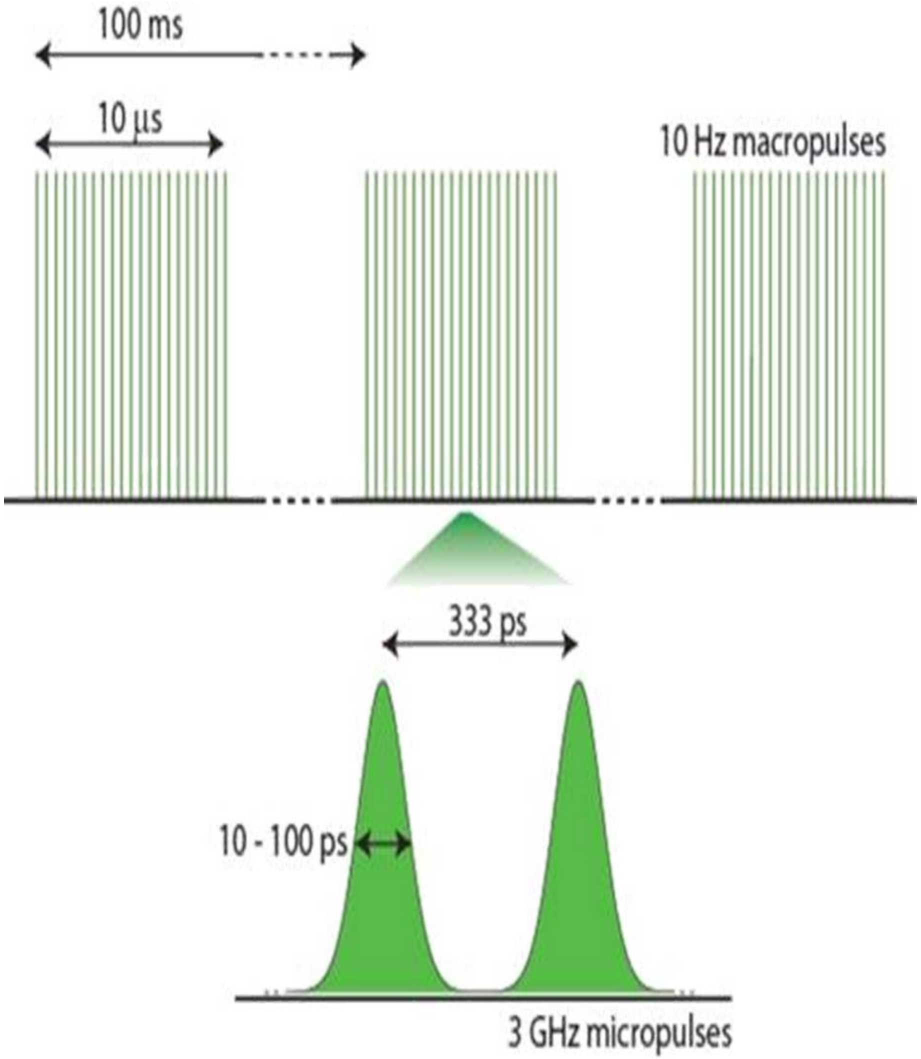
FELIX facility





Specs:	FELIX:	FLARE:
e-beam energy	50/45 – 15 MeV	15 – 10 MeV
spectral range	2.7 – 150 micron	100 - 1500 micron
	3600 - 66 cm^{-1}	100 - 6 cm^{-1}
	120 – 2 THz	3 – 0.25 THz
	450 – 8 meV	12 – 0.75 meV
pulse structure	micro / macropulse	micro / macropulse
rep. rate	25 MHz/1 GHz@10 Hz	3 GHz@10 Hz
micropulse energy	1-20 µJ	≈ 5 µJ
macropulse energy	≤ 100 mJ @ 1 GHz	≤ 100 mJ @ 3 GHz
peak power	≤ 100 MW	≤ 10 MW
polarisation	linear	linear
spectral bandwidth	0.2 - 5%	≤ 1%
(FWHM)		spectral mode ≤10^{-4}
continuous tunability	200 - 300 %	?

FLARE radiation profile

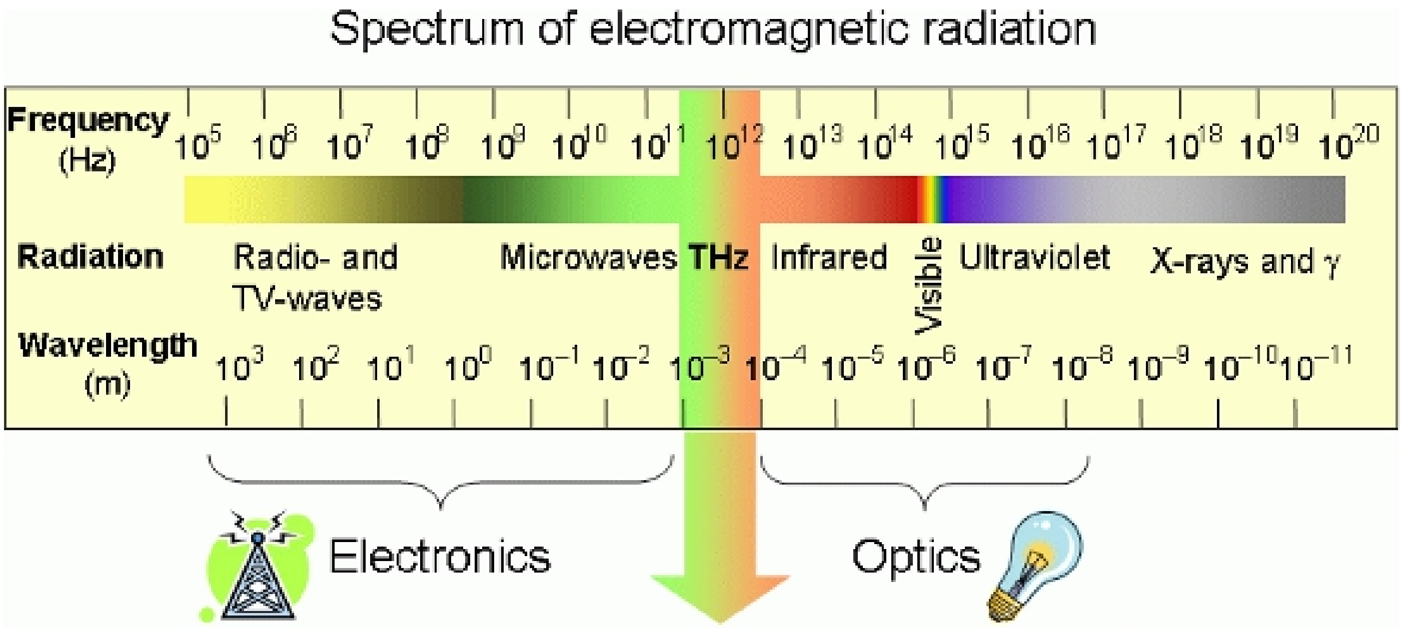


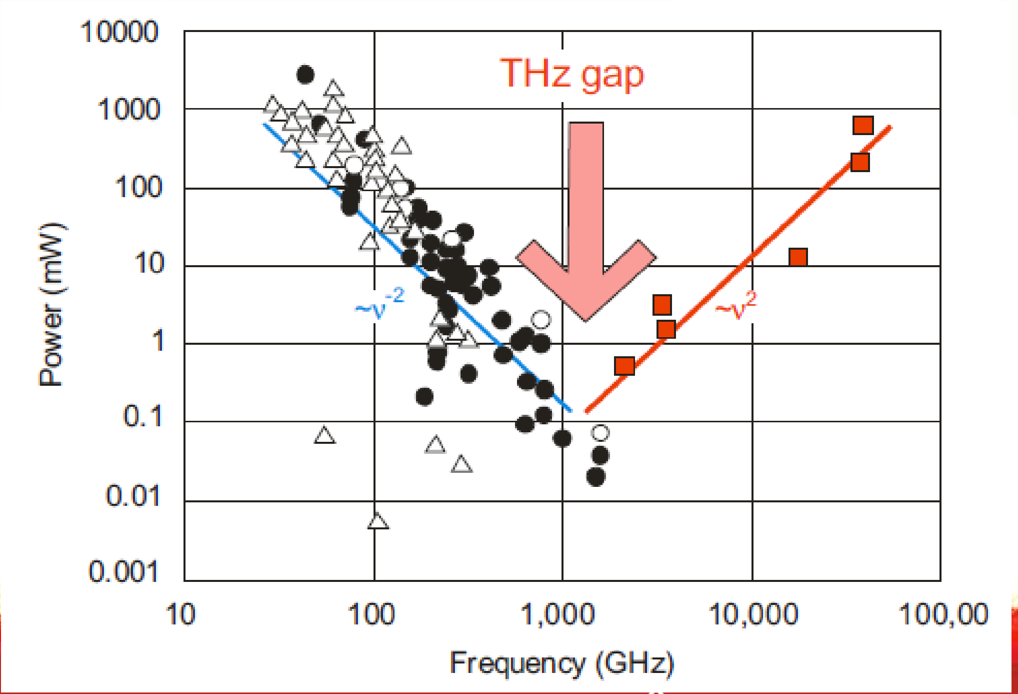
- Frequency range: 7 – 100 cm^{-1} (0.2 – 3 THz)
- Average power up to 1W
- photon flux ~ 10^{21} photons/second

Macropulse ≈ 90mJ
Duty cycle 10 µs/100 ms = 10^{-4}
10kW during macropulse
i.e. 10^{20} photons

Micropulse ~50ps, 3µJ
~10^{16} photons per pulse
~100kW during a micropulse

THz gap

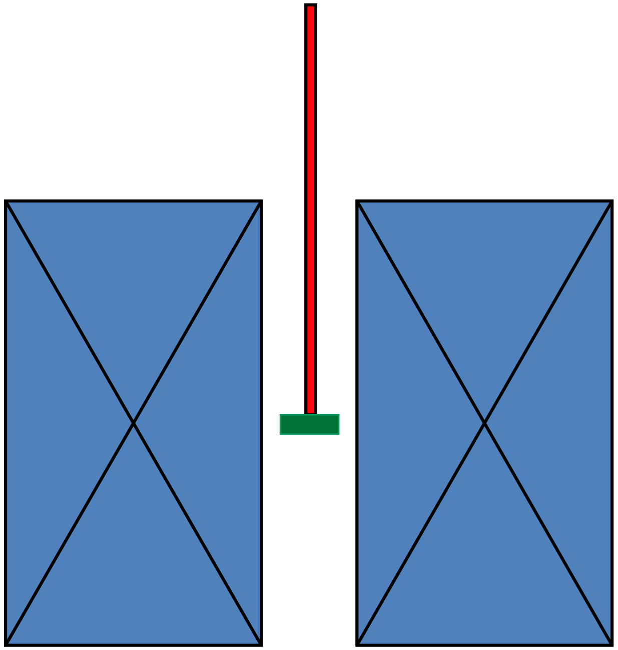

Spectrum of electromagnetic radiation
Frequency (Hz)
10^5 10^6 10^7 10^8 10^9 10^10 10^11 10^12 10^13 10^14 10^15 10^16 10^17 10^18 10^19 10^20
Radiation
Radio- and TV-waves
Microwaves
THz
Infrared
Visible
Ultraviolet
X-rays and γ
Wavelength (m)
10^3 10^2 10^1 10^0 10^-1 10^-2 10^-3 10^-4 10^-5 10^-6 10^-7 10^-8 10^-9 10^-10 10^-11
Electronics
Optics


THz gap
Power (mW)
10000
1000
100
10
1
0.1
0.01
0.001
~ν^-2
~ν^2
10
100
1,000
10,000
100,00
Frequency (GHz)

FELIX + HFML = unique opportunities!

- Magnetotransmission
  over unique ranges
  of fields, frequencies, powers

-Pump-probe experiments
  to study materials in unique
  environment

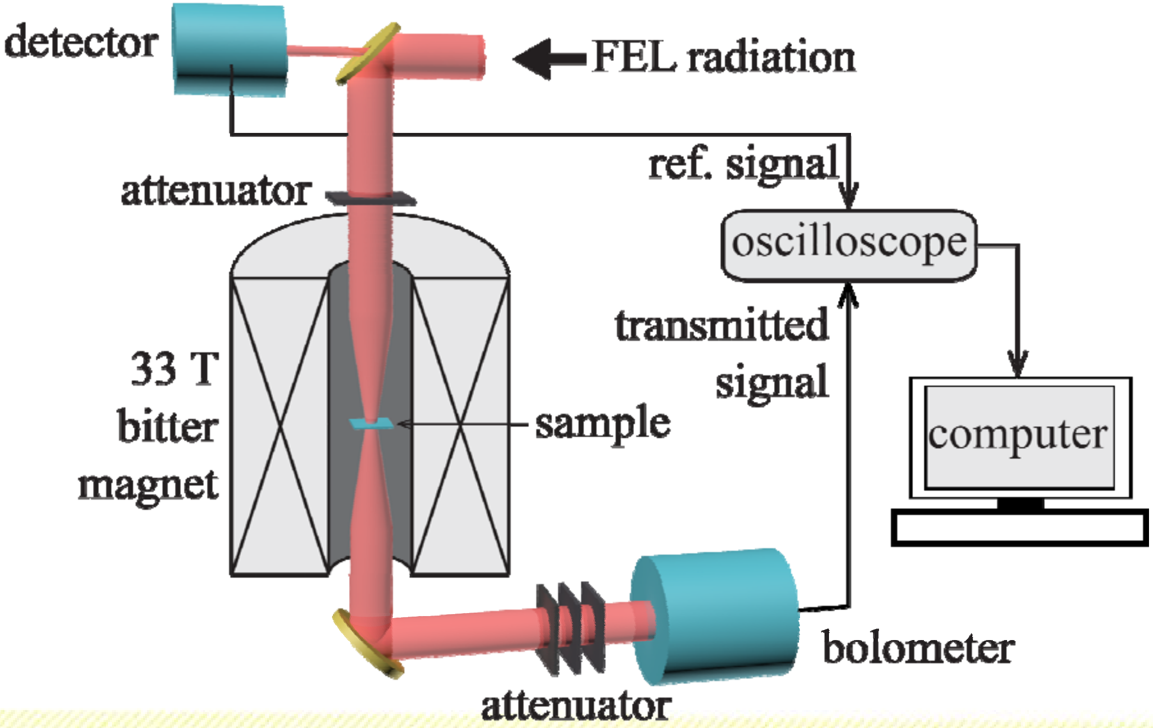


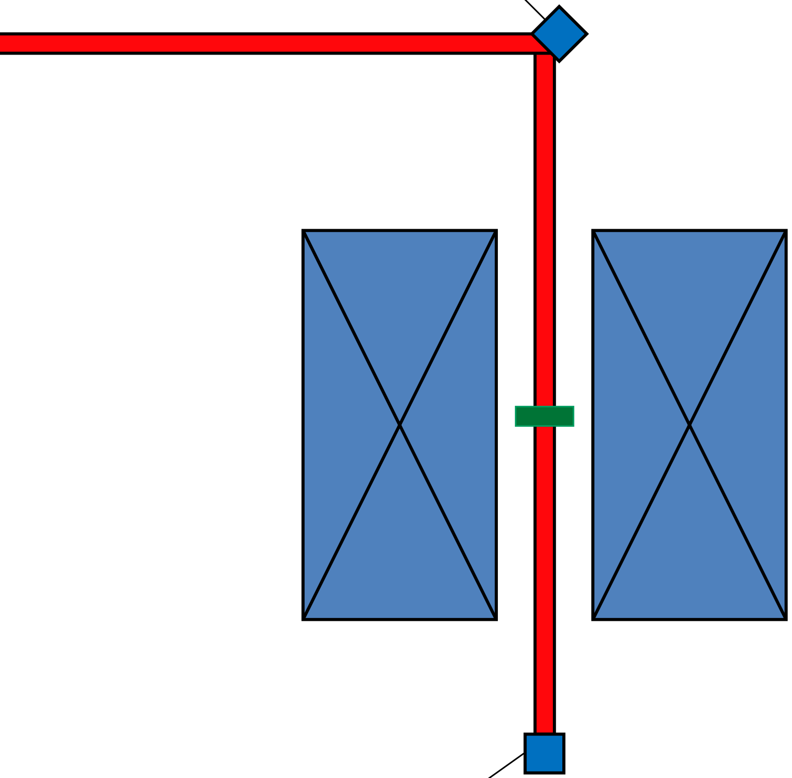
THz radiation

Bitter magnet
Up to 33 Tesla

Transmission measurement

- 1 - 10 Hz macropulse,
- 10μs duration:
- Duty cycle ~ 10^{-4}
- Lock-in no good:
  Use oscilloscope

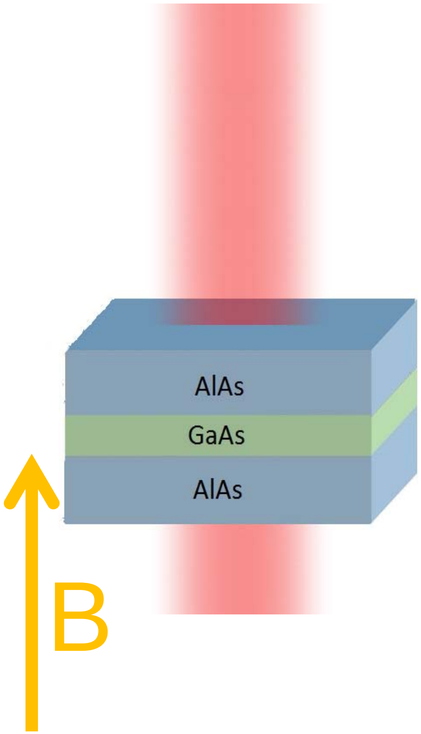




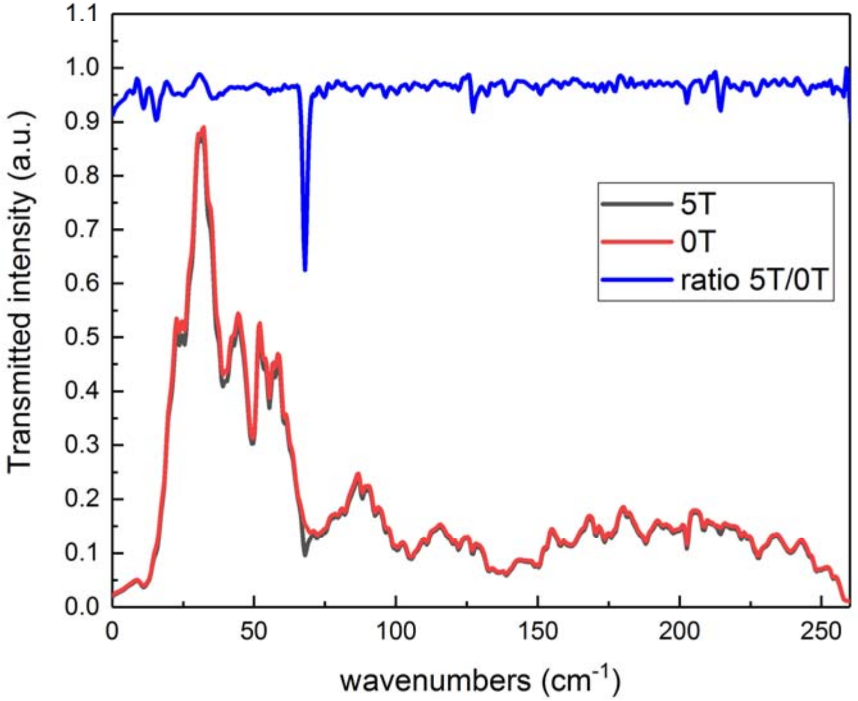
Pyro-electric detector,
Initial power I_0

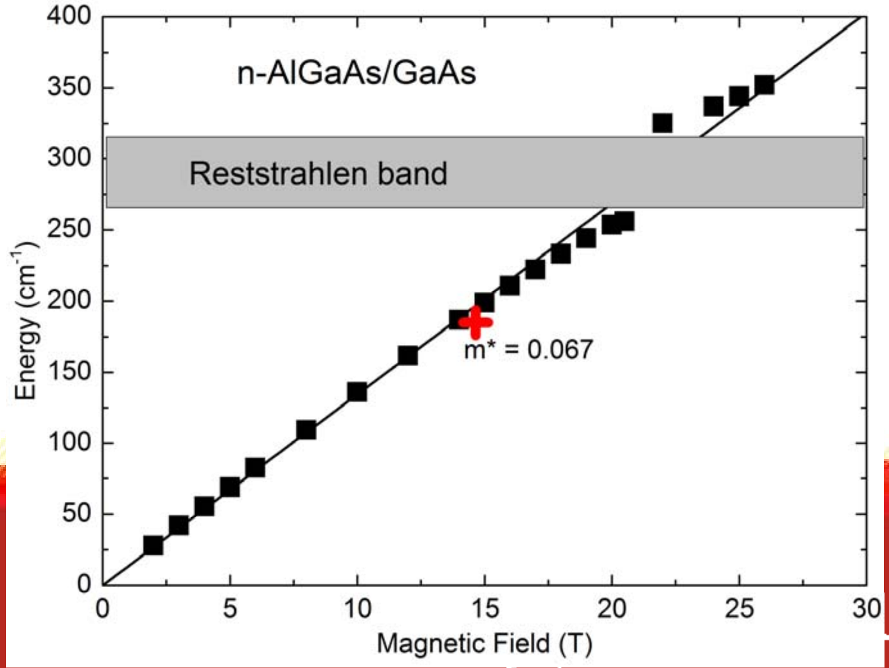
Fast detector,
Transmitted power, I

CR experiments on GaAs QW

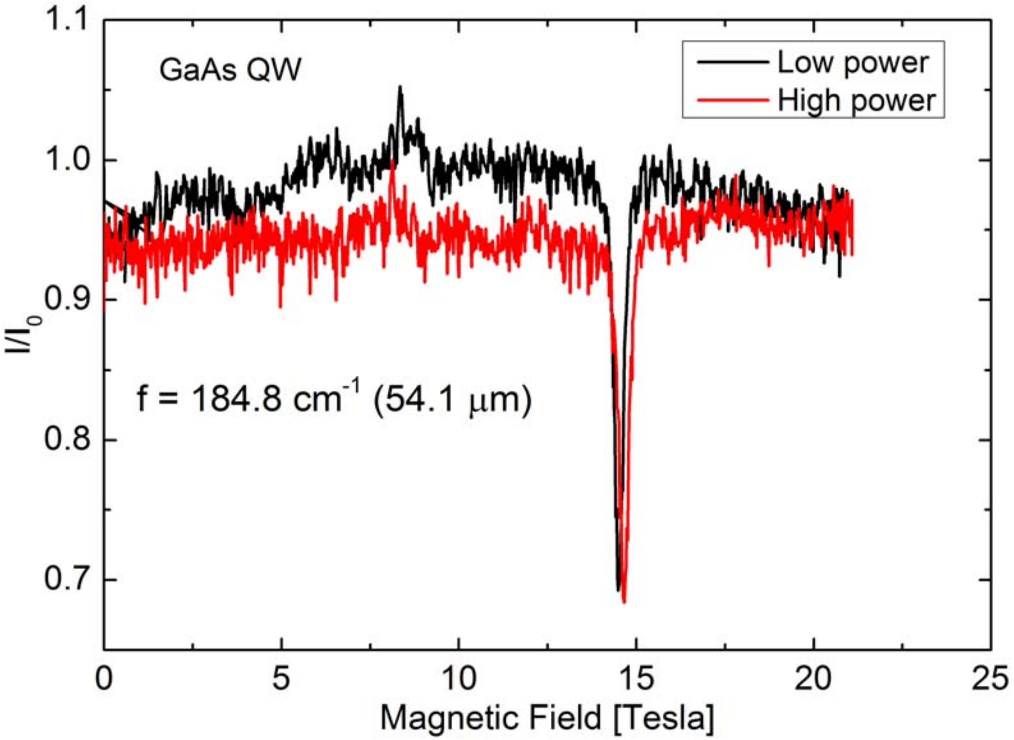


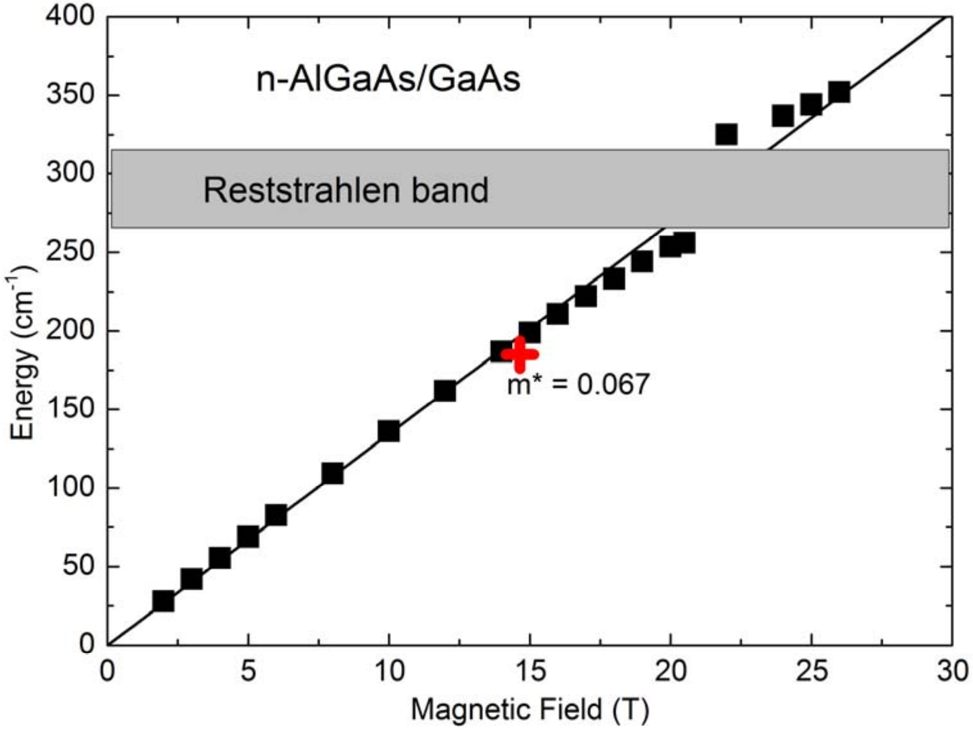
$$\omega_c = |e|B/m_c^*$$





Experiments with free electron laser





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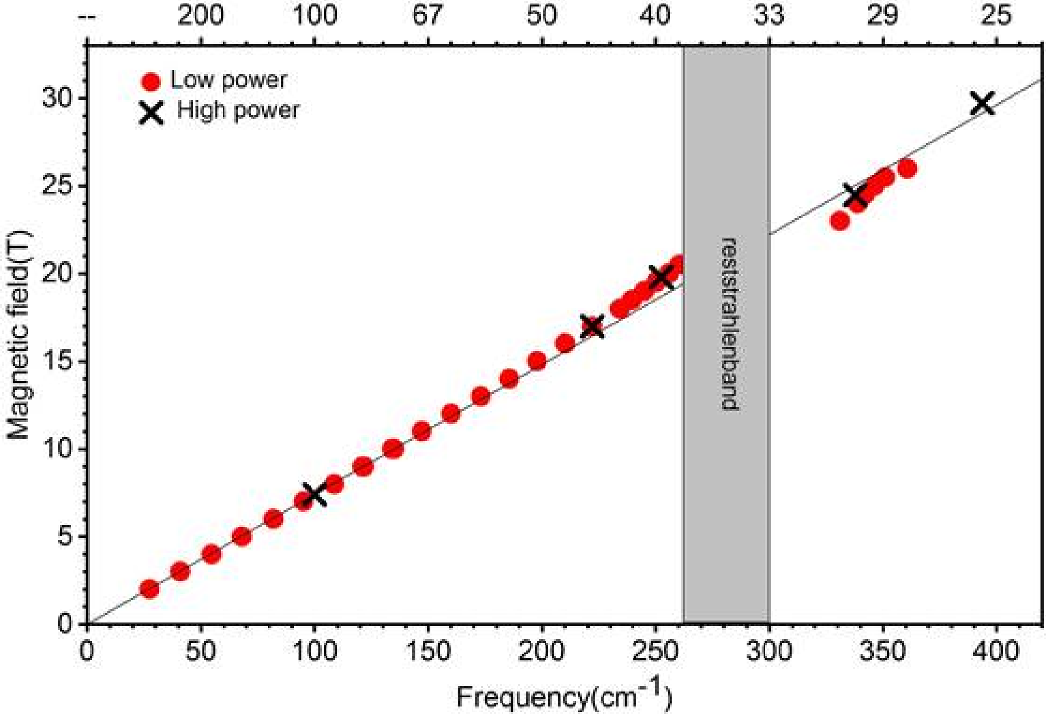
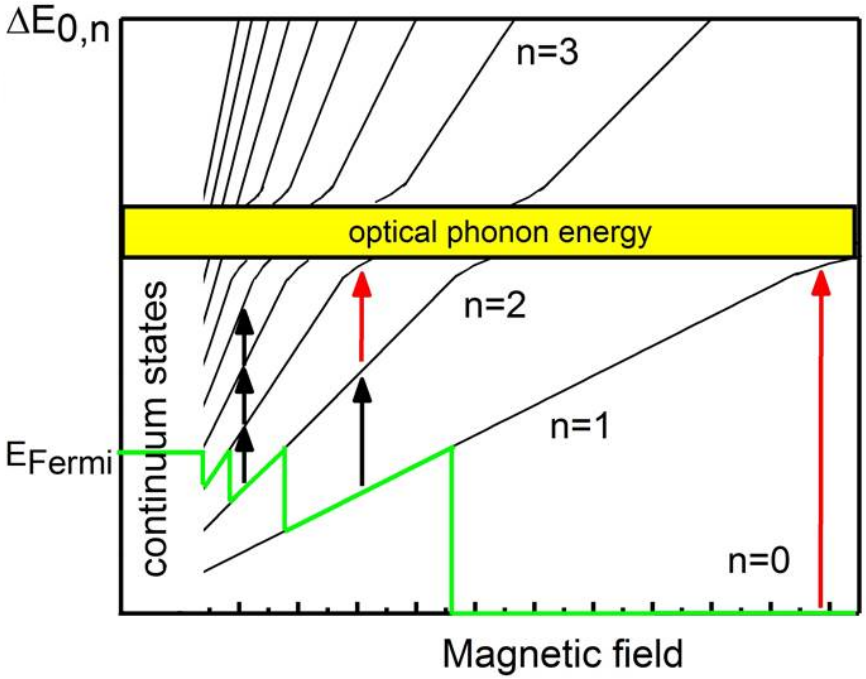
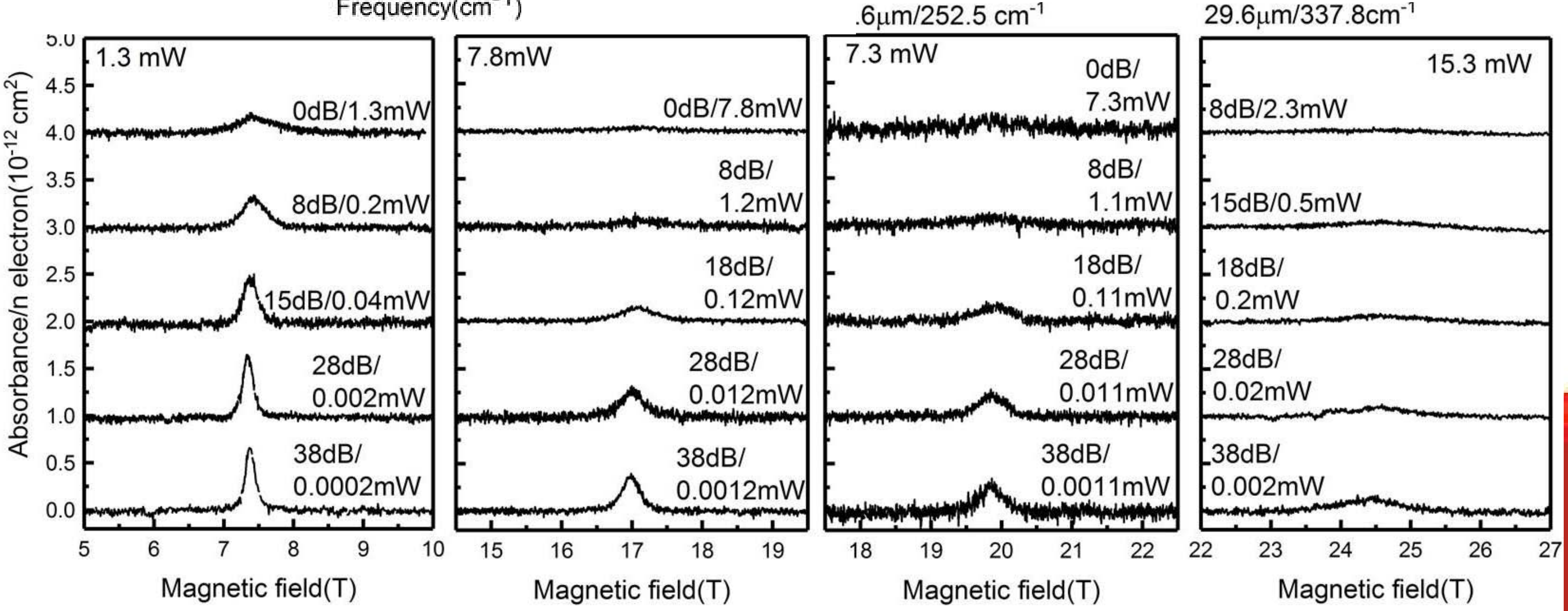
High power behavior

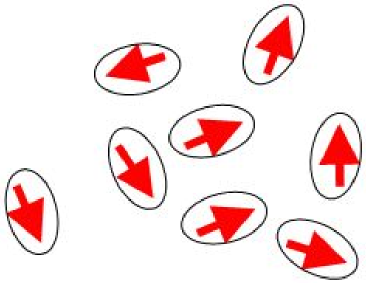




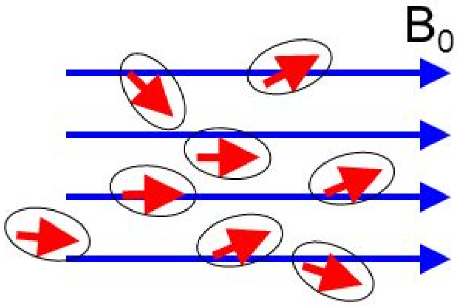


Магнітний момент (спін) у магнітному полі

B = 0



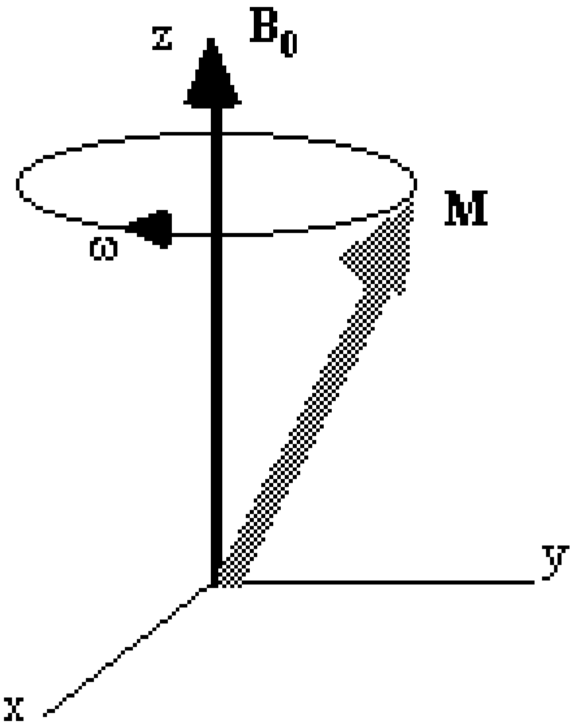
$B = B_0$



Magnetic particles in magnetic field

$$\frac{d\vec{\mu}}{dt} = \gamma\vec{\mu}\times\vec{B}_0$$

$$\vec{\tau} = \vec{\mu}\times\vec{B}_0$$



$$\left.\begin{aligned}\frac{d\mu_x}{dt} &= \gamma\mu_y B_0\\ \frac{d\mu_y}{dt} &= -\gamma\mu_x B_0\\ \frac{d\mu_z}{dt} &= 0\end{aligned}\right\} \begin{aligned}\mu_x &= A\cos(\omega t+\phi)\\ \mu_y &= -A\sin(\omega t+\phi)\end{aligned}$$

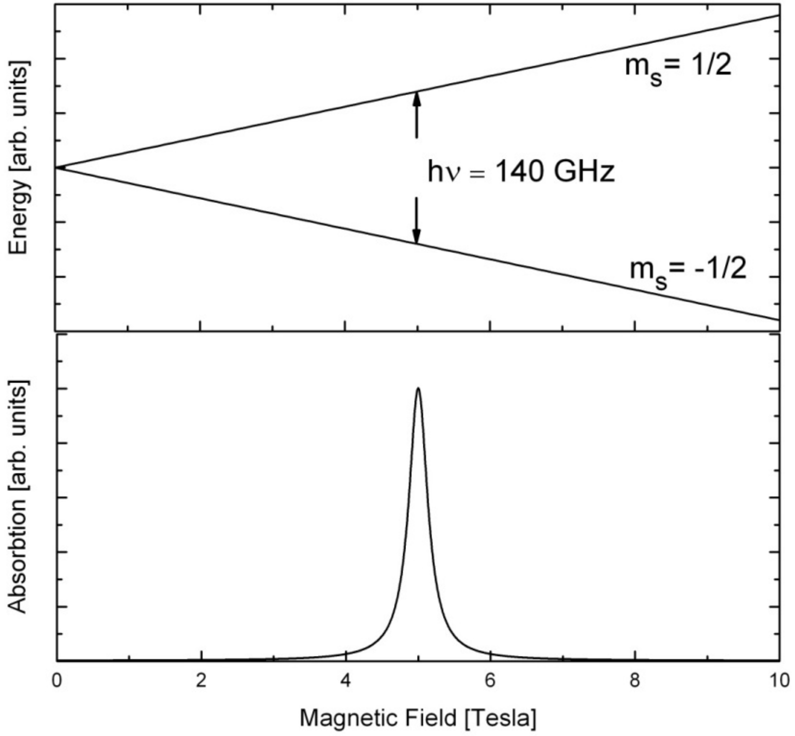
$$\omega = \gamma B_0$$

$$\gamma = \frac{eg}{2m}$$

$$\mu_B = \frac{e\hbar}{4\pi m}$$

$$h\nu = g\mu_B B_0$$

How is it in quantum terms?

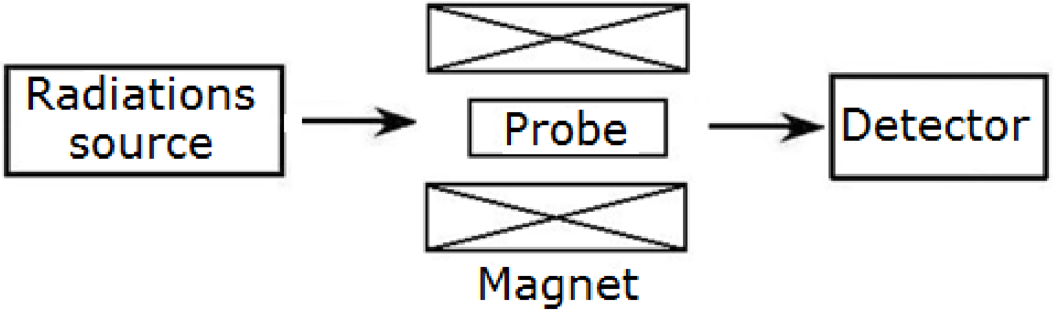


$$\Delta E = \hbar\omega = g\mu_B H$$

μ_B – Bohr magneton.
g – factor Lande.

Studied parameters:
resonance field,
resonance linewidth,
lineshape.

140 GHz = 5 Tesla



Where are magnetic moments?

- Radicals, spin traps
- Nitroxides, spin labels
- Paramagnetic Transition Metal Ions (*d* and *f* ions)

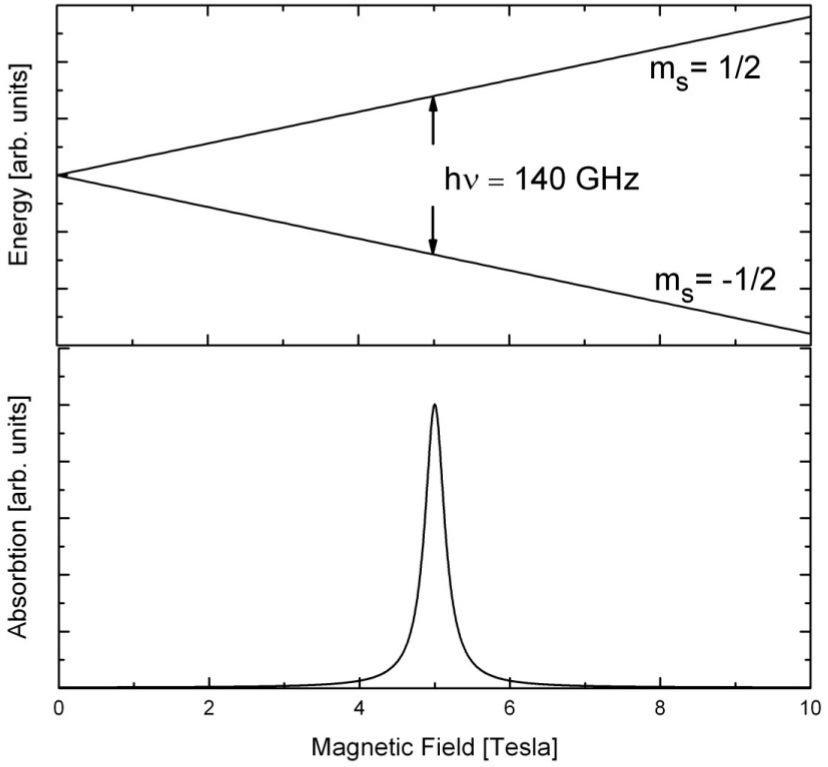
EPR or ESR

- Nuclei with magnetic moments (^{1}H, ^{14}N, ^{15}N, ^{17}O *etc*)

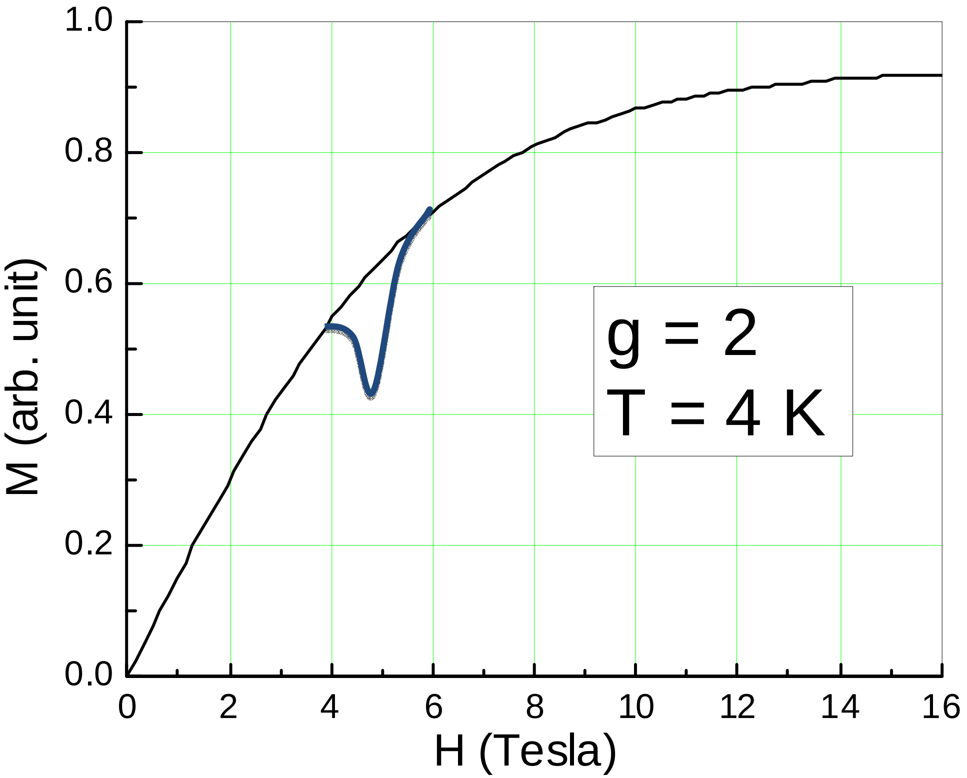
NMR

Magnetically detected EPR

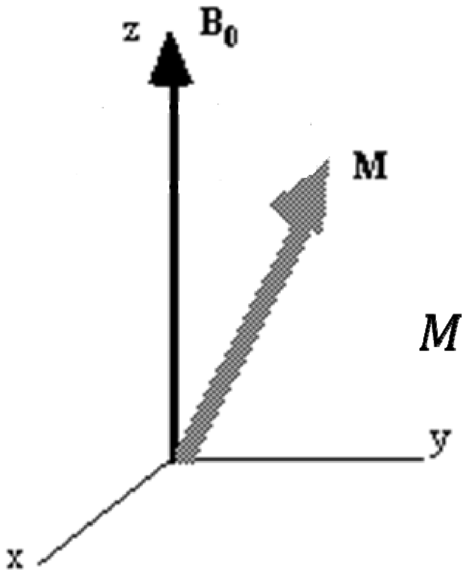
Energy levels



Magnetization

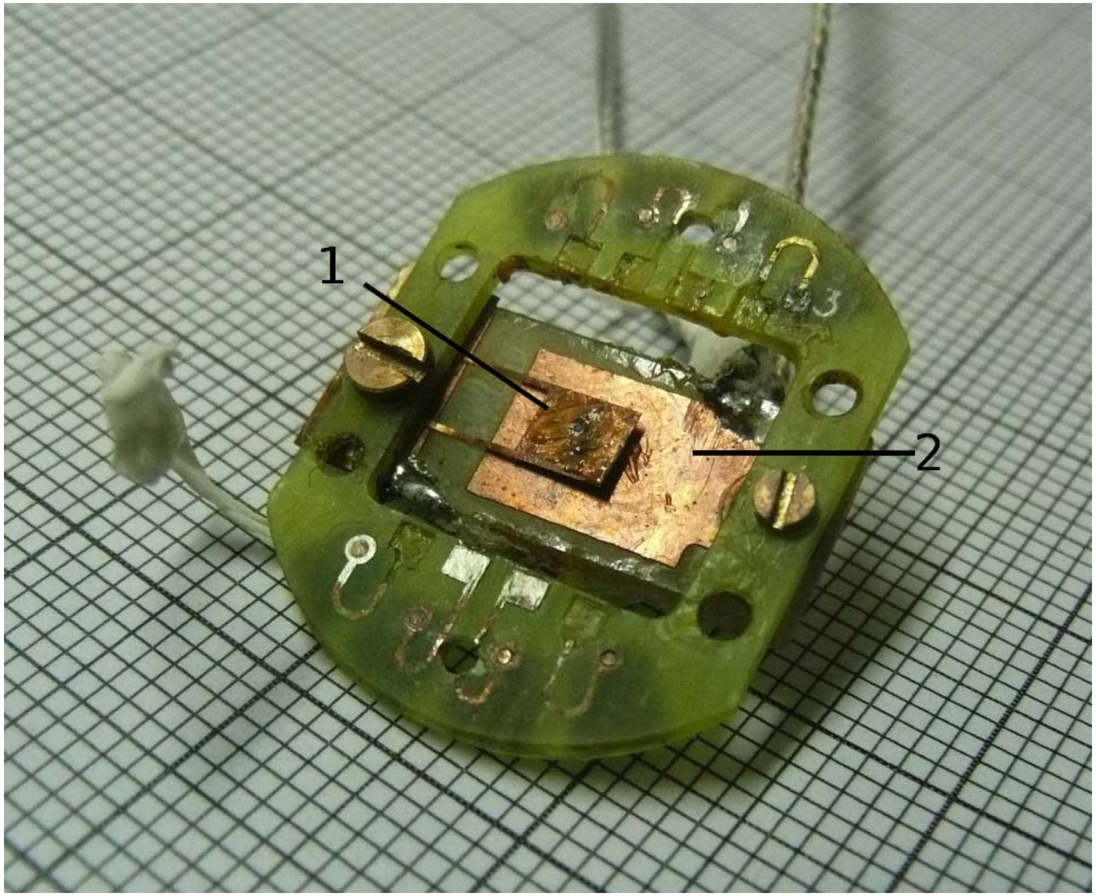


How to measure magnetization



$$\vec{\tau} = \vec{M} \times \vec{B}_0$$

$$M \sim B \rightarrow \tau \sim B^2$$



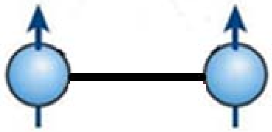
\+ Sensitivity increase with B fields
\+ Transparency does not matter!

\- Anisotropy required!
\- Relatively low sensitivity @ fields about 2-3 Tesla

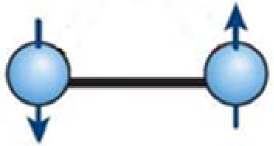
Spin – spin exchange interaction

$$E = J\overrightarrow{S_1} \cdot \overrightarrow{S_2}$$

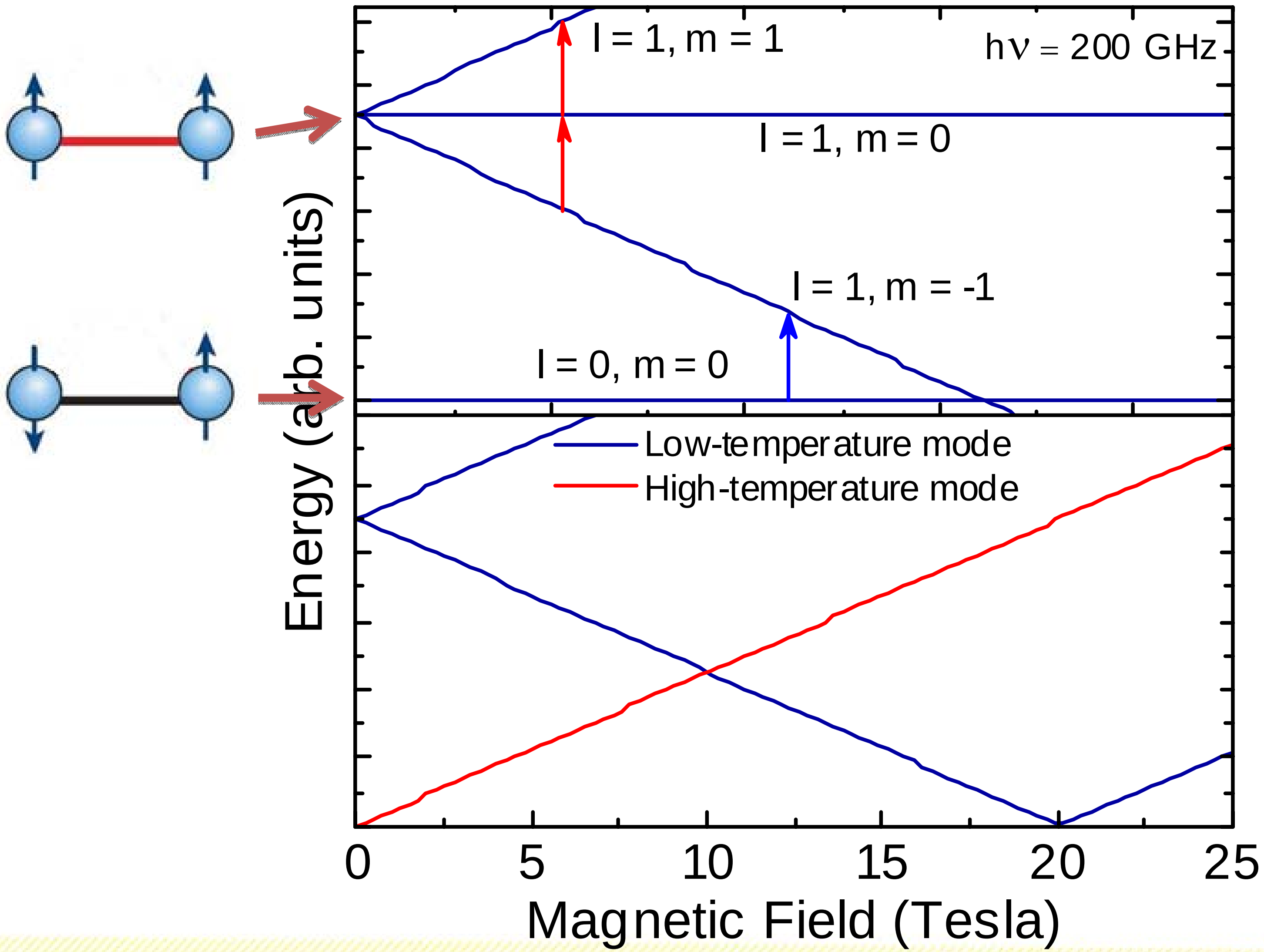
$J > 0$ Ferromagnetic exchange



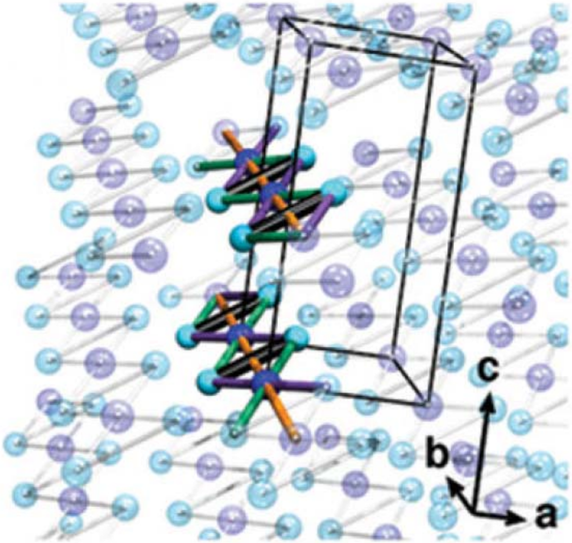
$J < 0$ Antiferromagnetic exchange

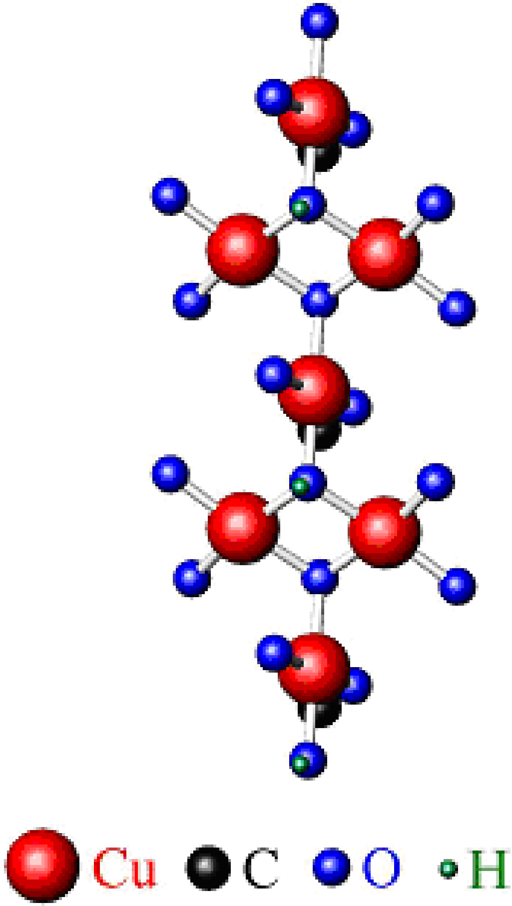


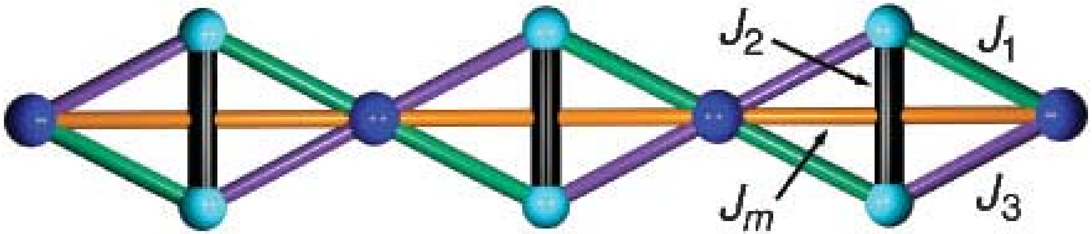
Energy diagram of spin-dimer system



Azurite ($Cu_3(CO_3)_2(OH)$)

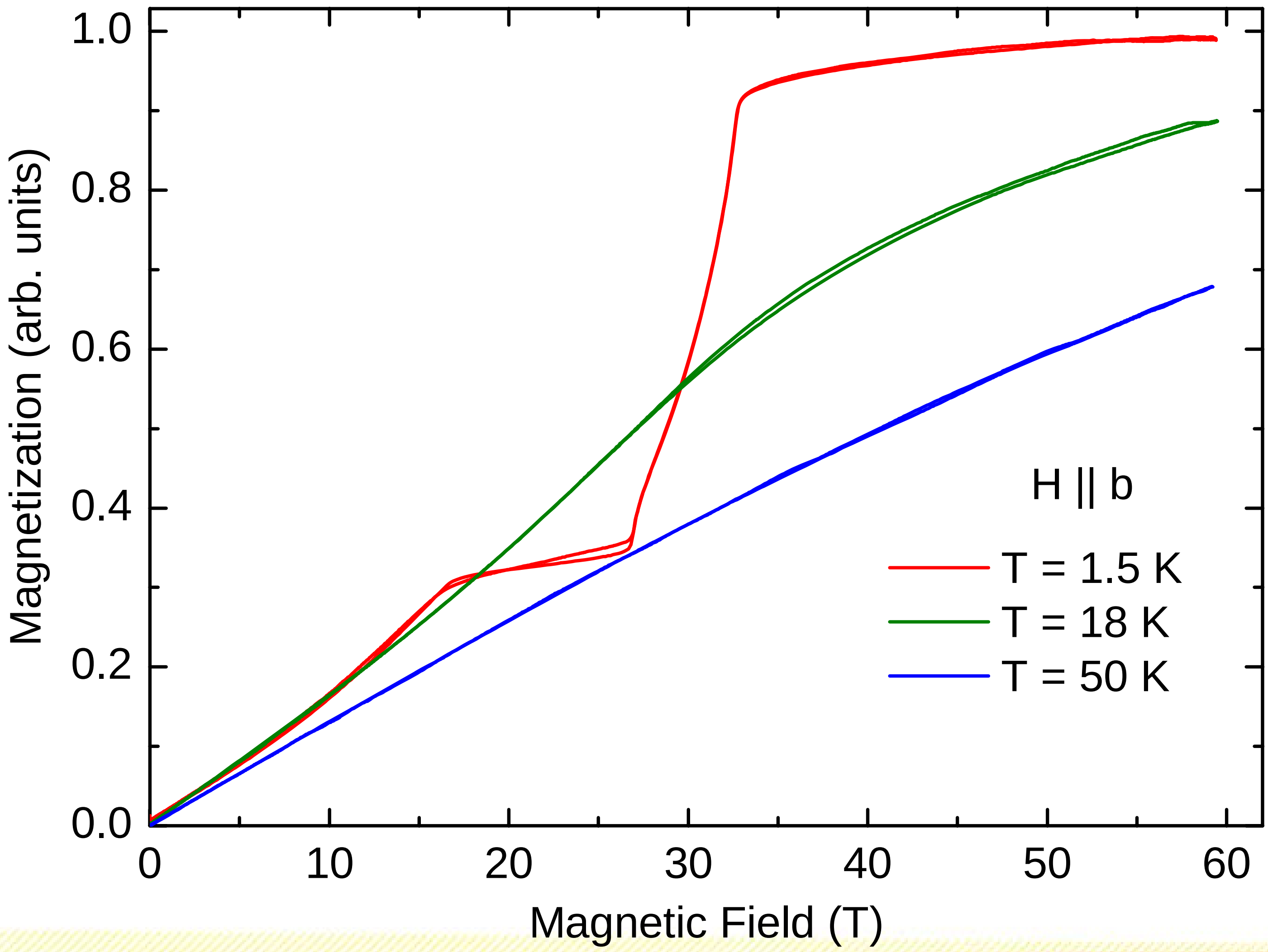




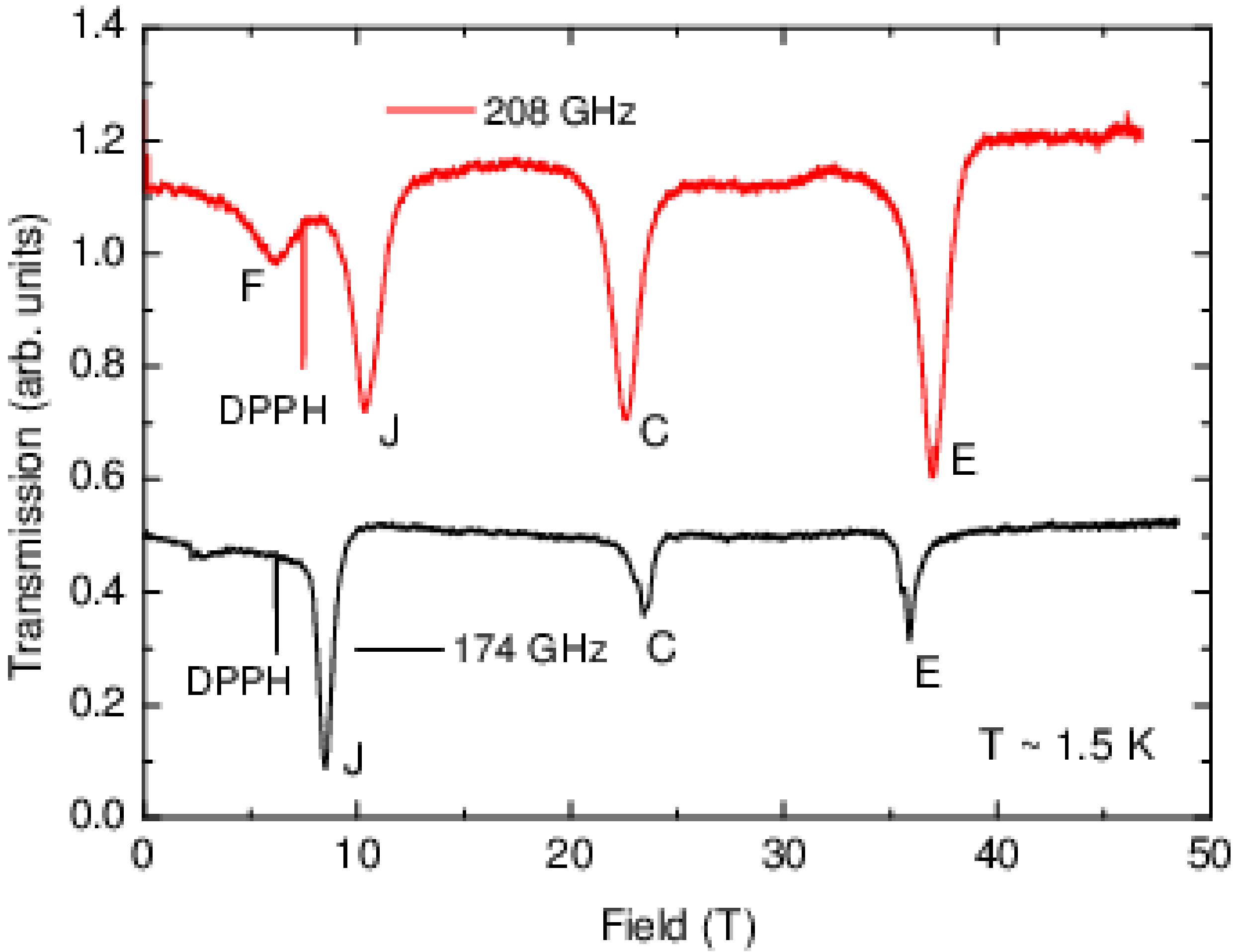


H. Jeschke *et al*, Phys. Rev. Lett 106, 217201 (2011).

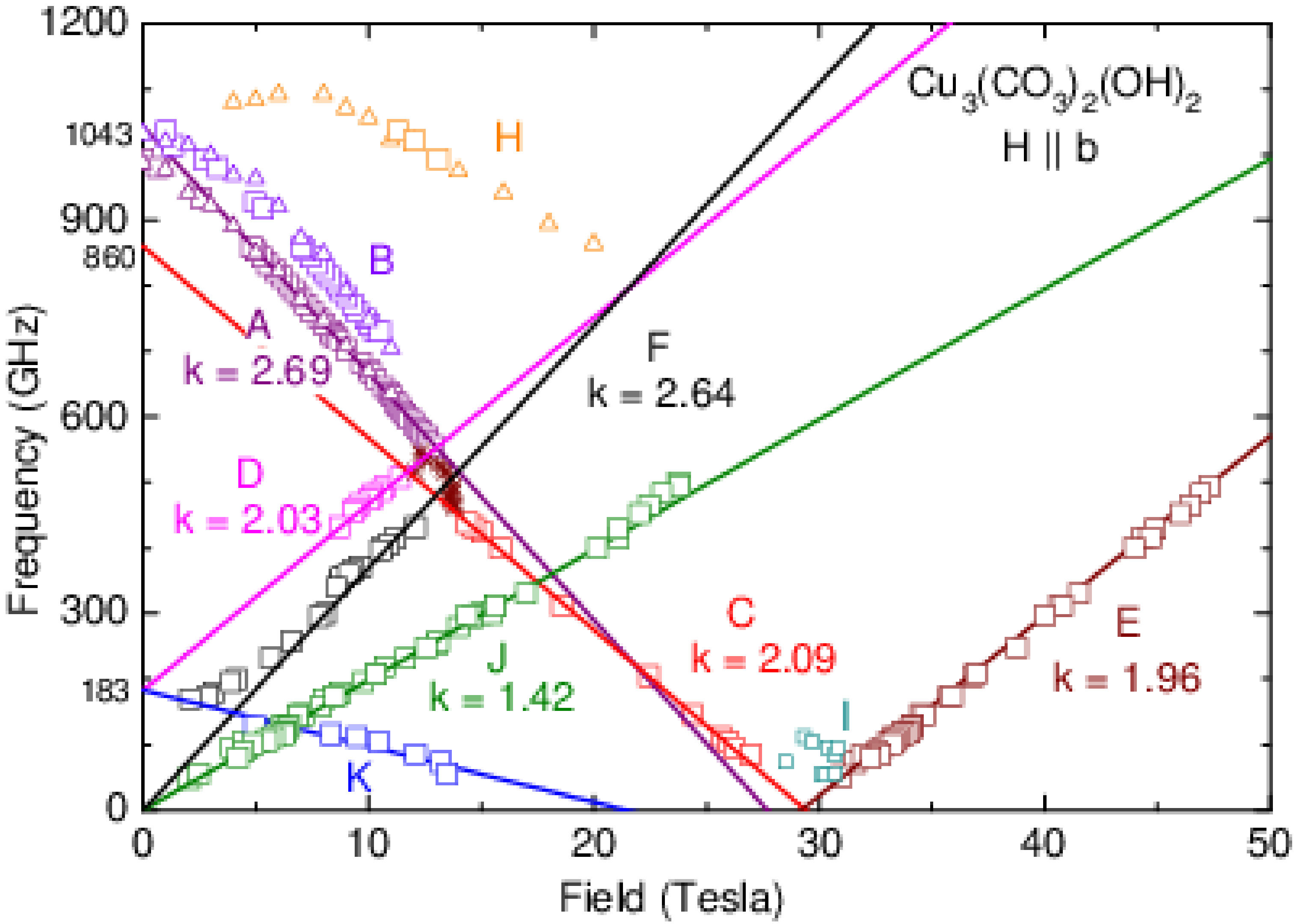
Magnetisation plateau



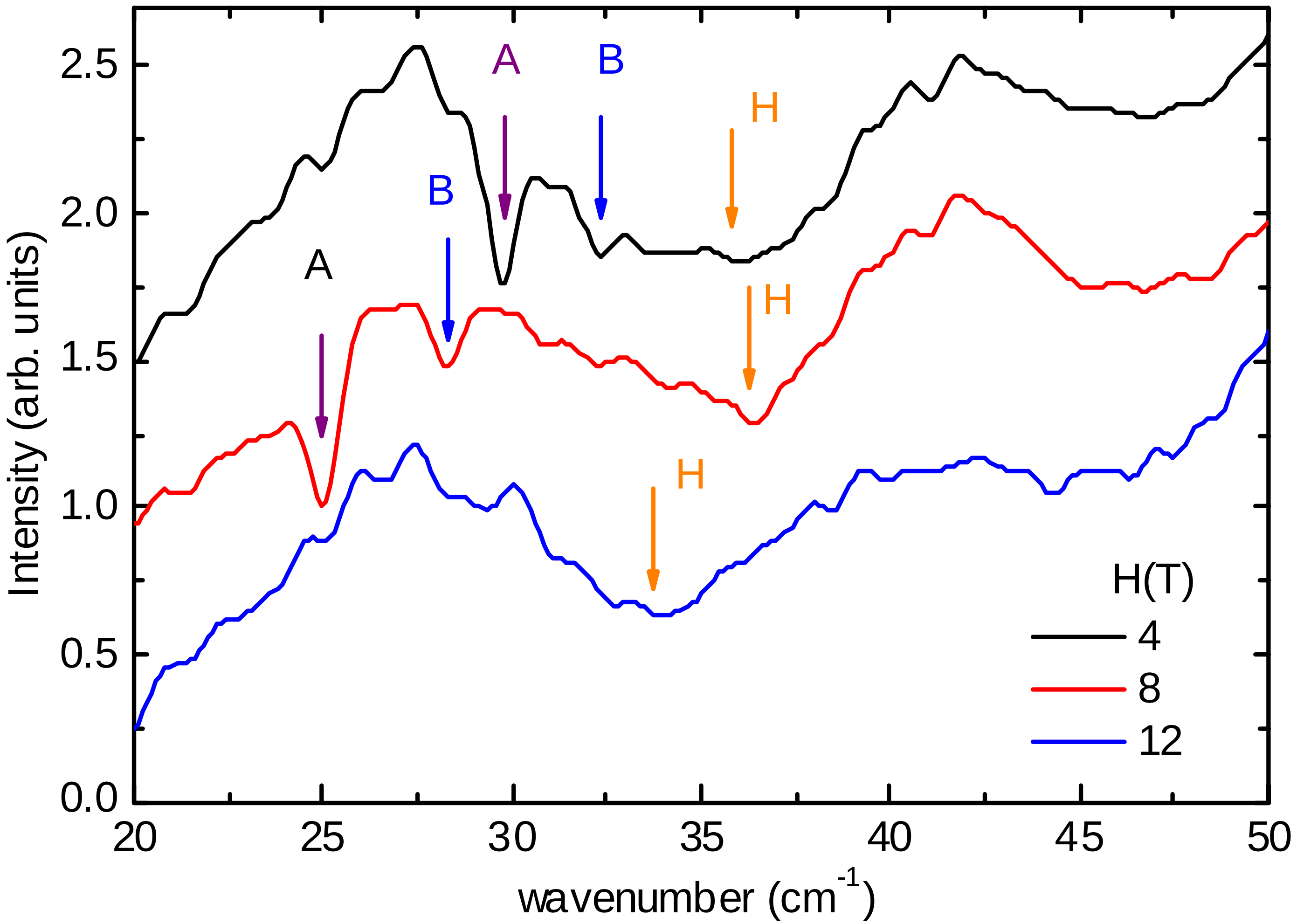
ESR spectra in pulsed fields



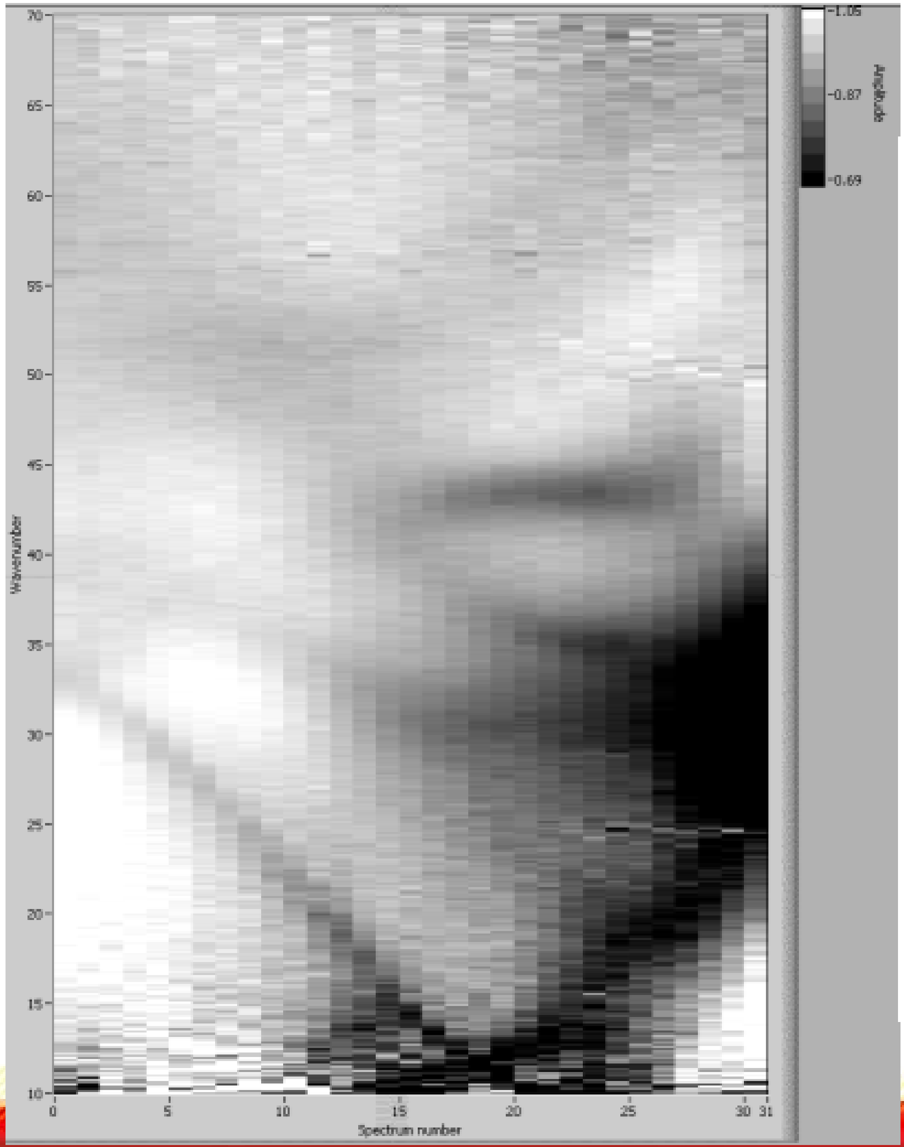
Frequency-field dependence



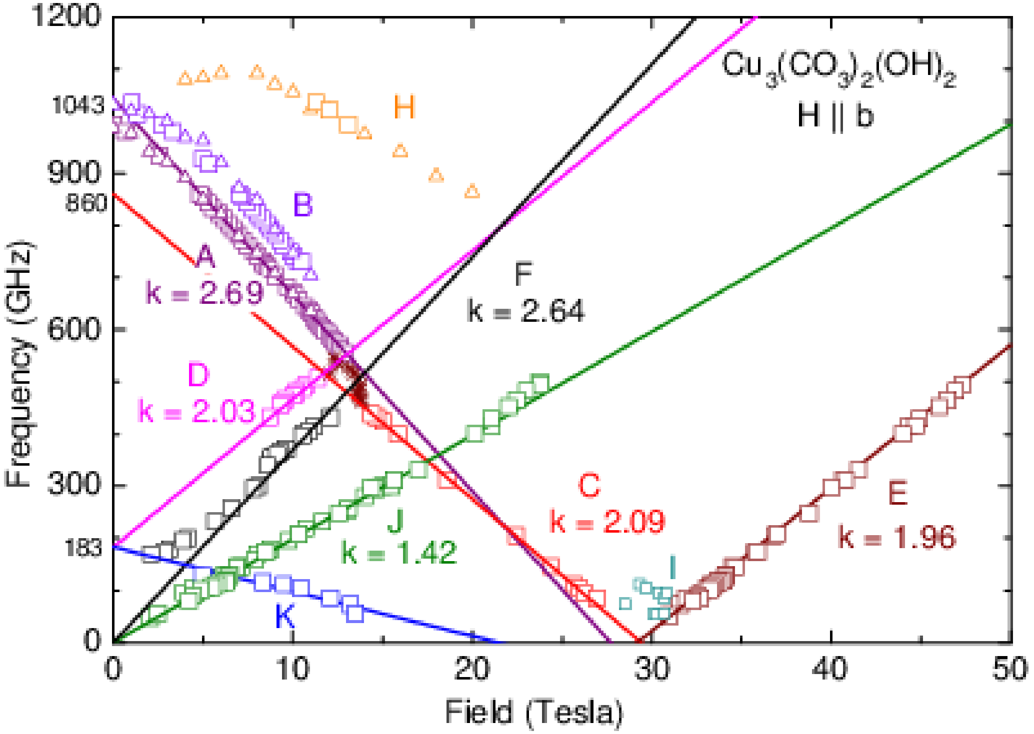
FIR spectra in magnetic field



FIR and ESR



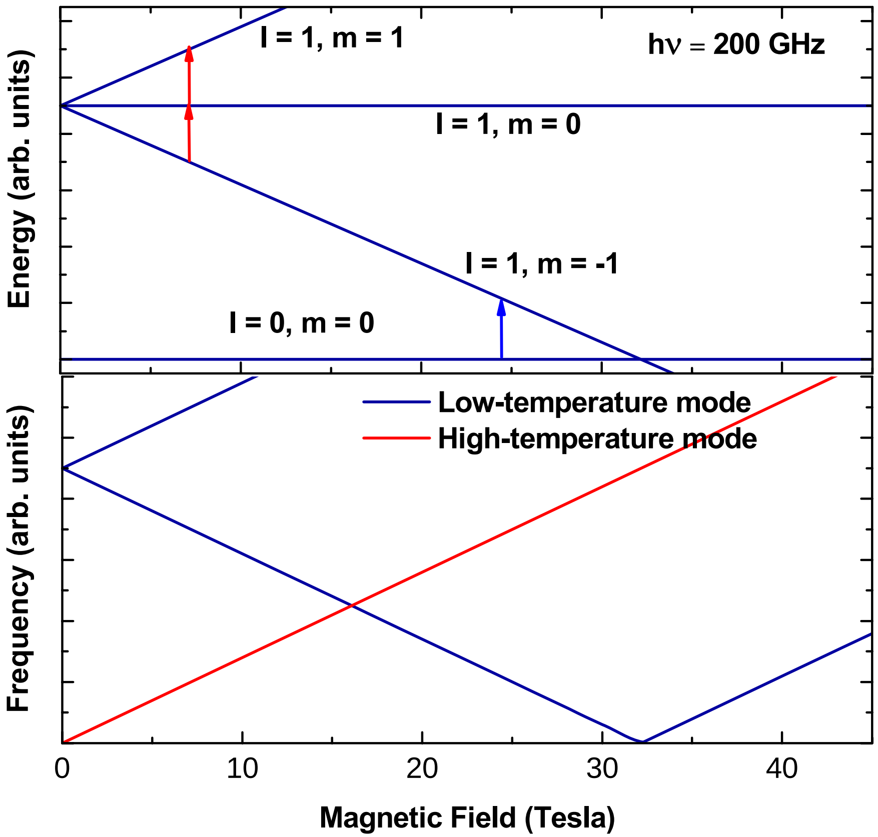
70
65
60
55
50
45
40
35
30
25
20
15
10
Wavenumber
0
5
10
15
20
25
30
31
Spectrum number
1.05
0.87
0.69
Amplitude



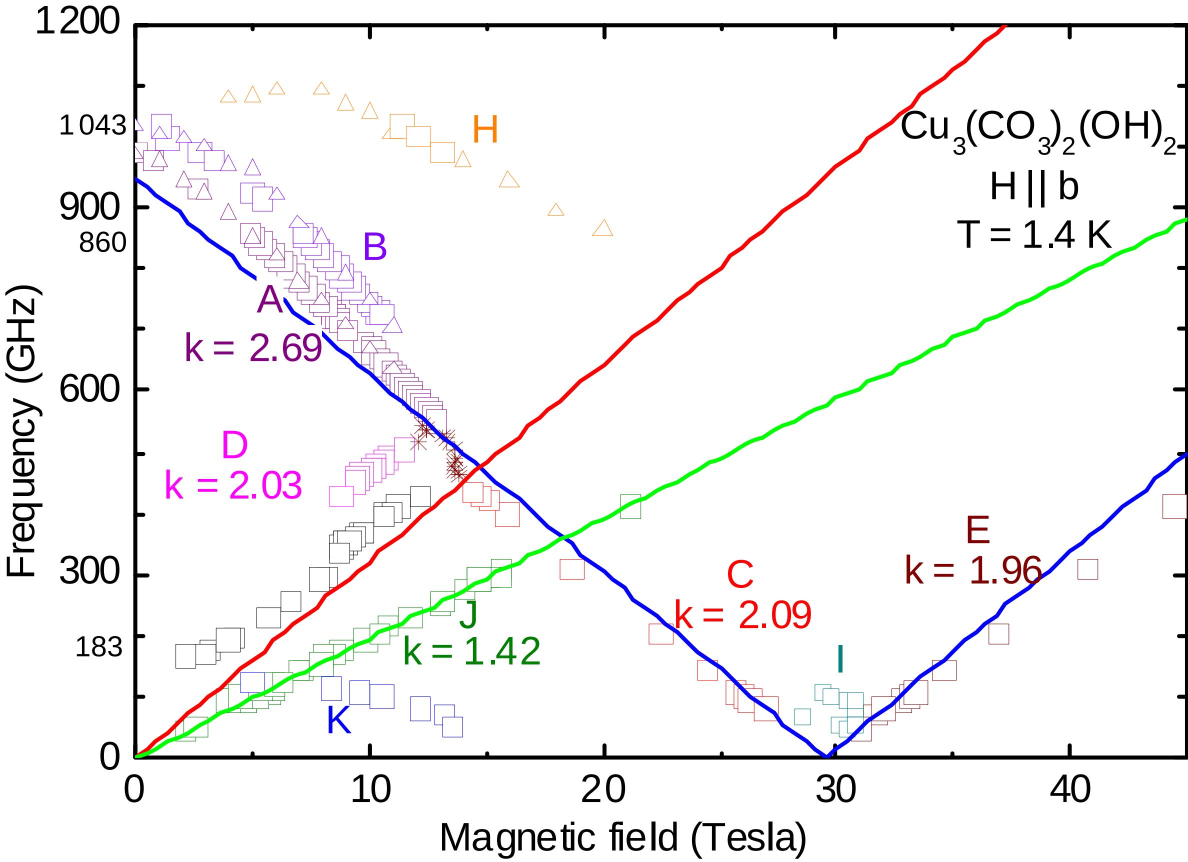
$Cu_3(CO_3)_2(OH)_2$
H || b
H
B
A
k = 2.69
F
k = 2.64
D
k = 2.03
C
k = 2.09
E
k = 1.96
J
k = 1.42
I
K
Frequency (GHz)
1200
1043
900
860
600
300
183
0
0
10
20
30
40
50
Field (Tesla)

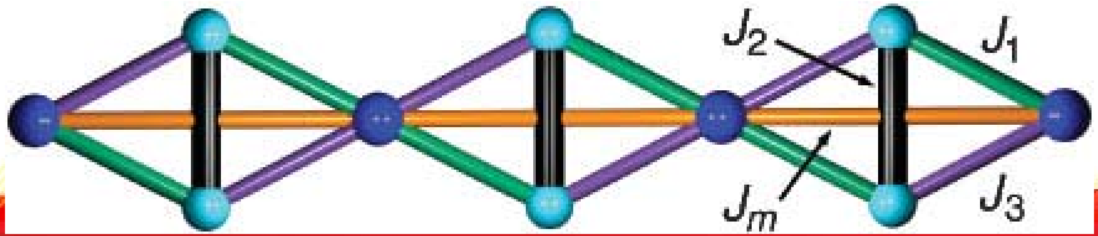
Dimer-monomer model

Dimers subsystem

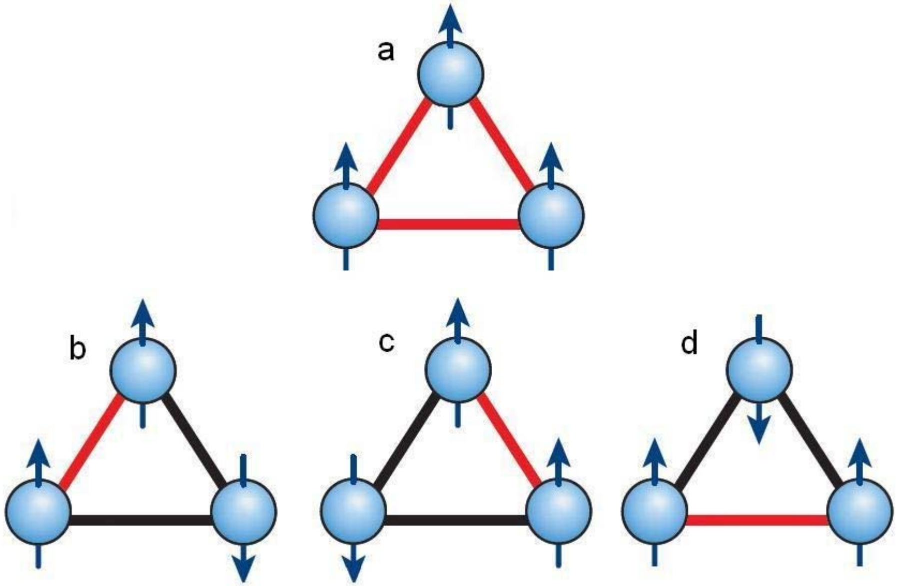


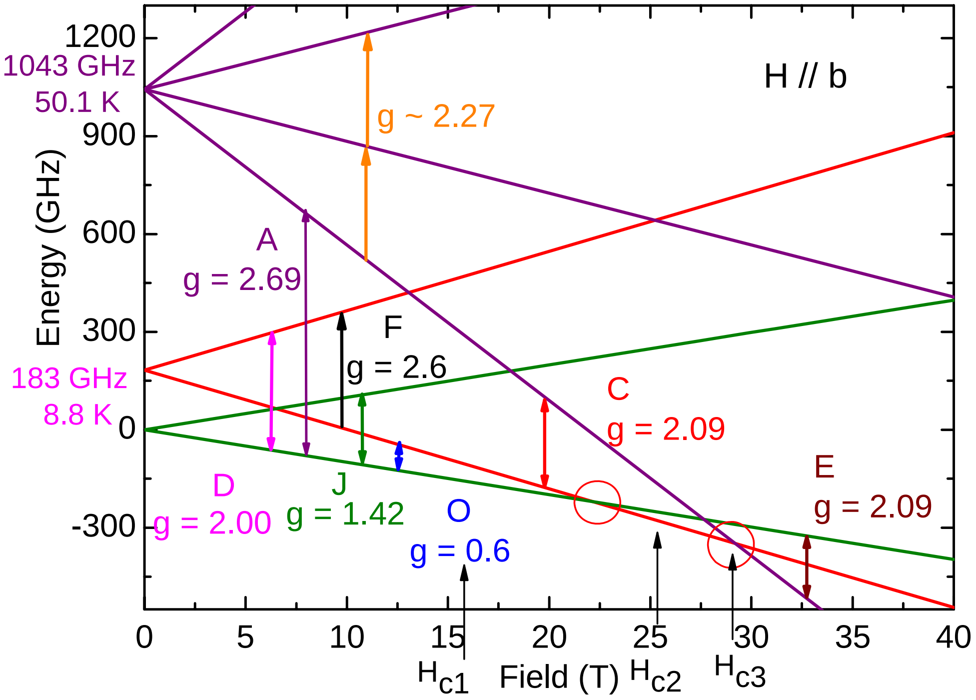
Experimental results





“Triangular“ model

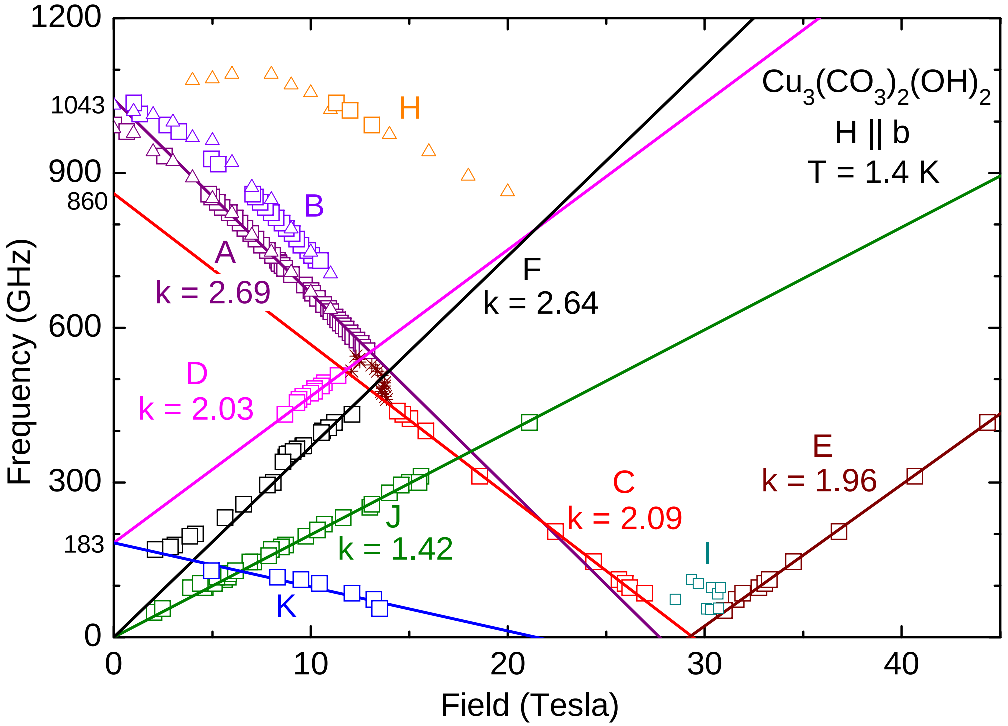




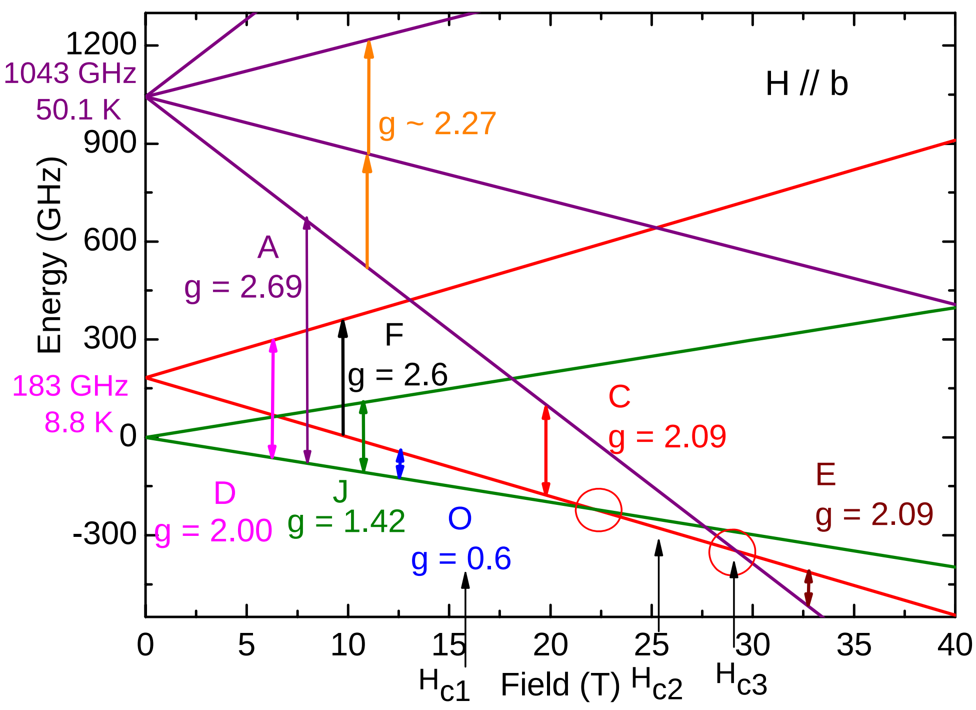
1 level with **S** = 3/2

3 levels with **S** = 1/2

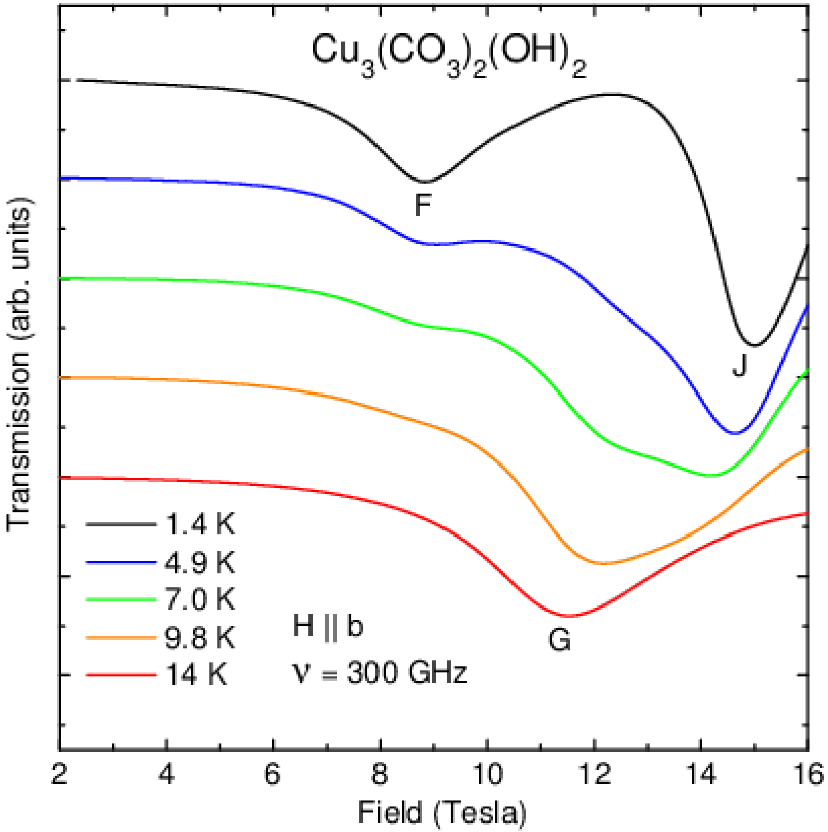
Frequency-field dependance

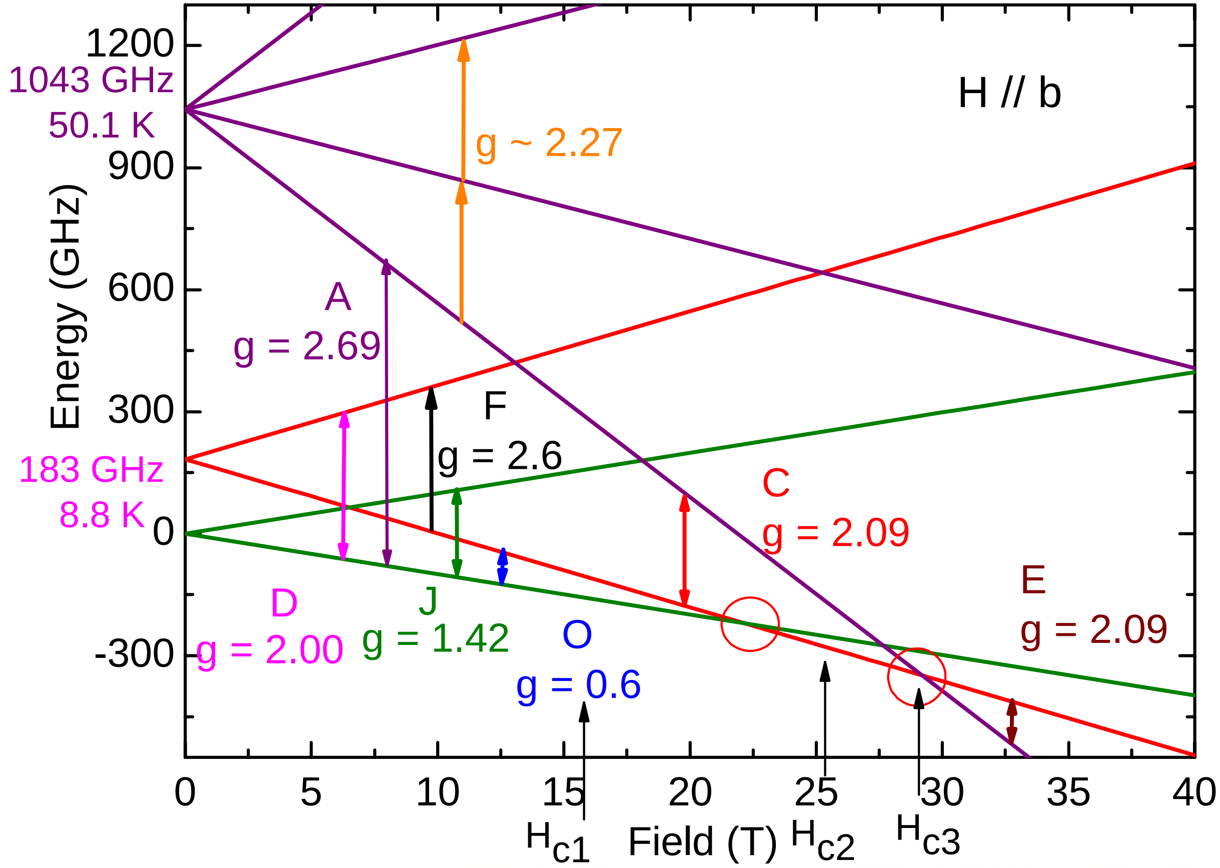


Energy diagram

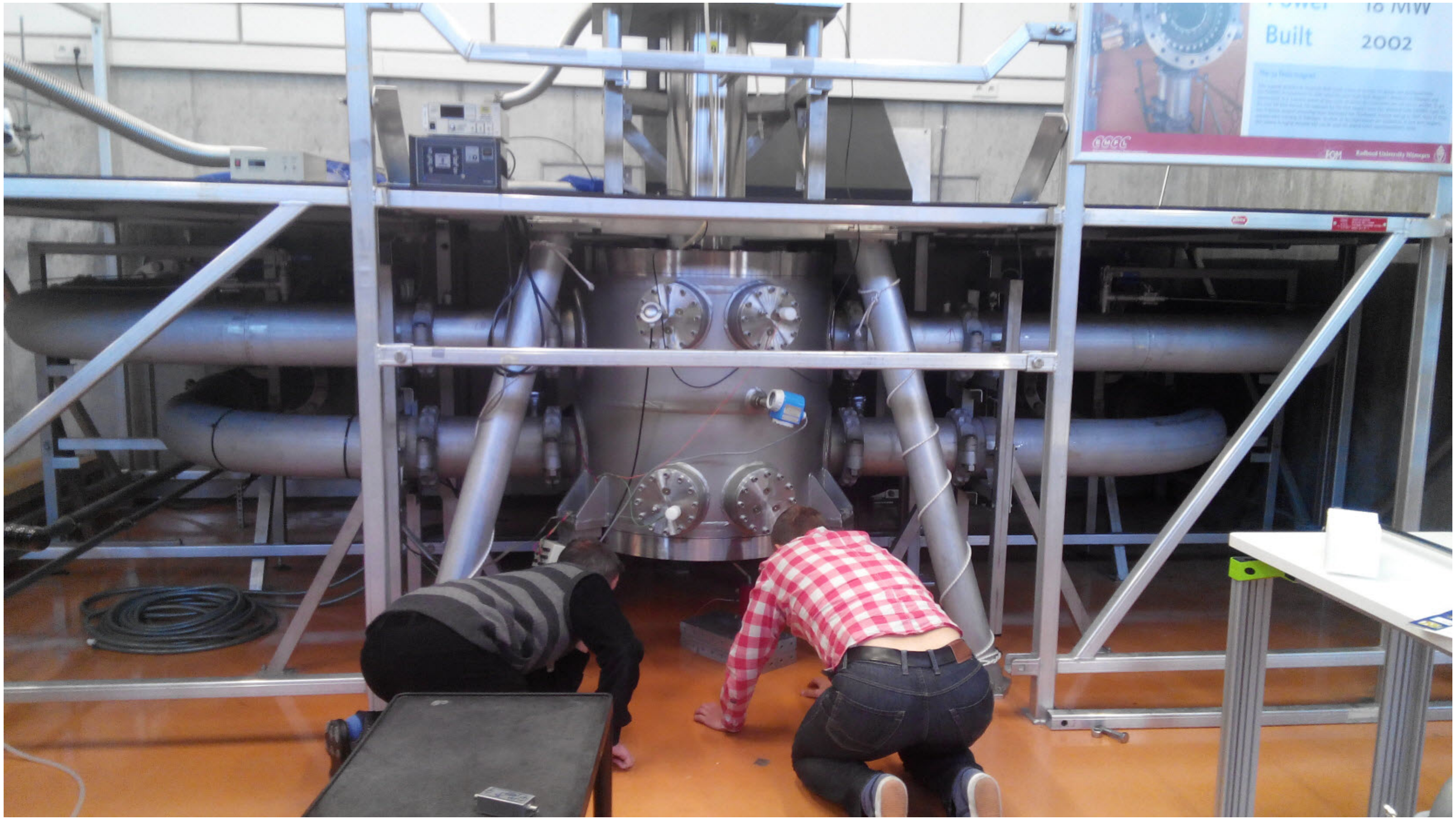


Temperature evolution of the spectrum





Thank you for your time



Summary

The connection between FELIX and HFML facilities .

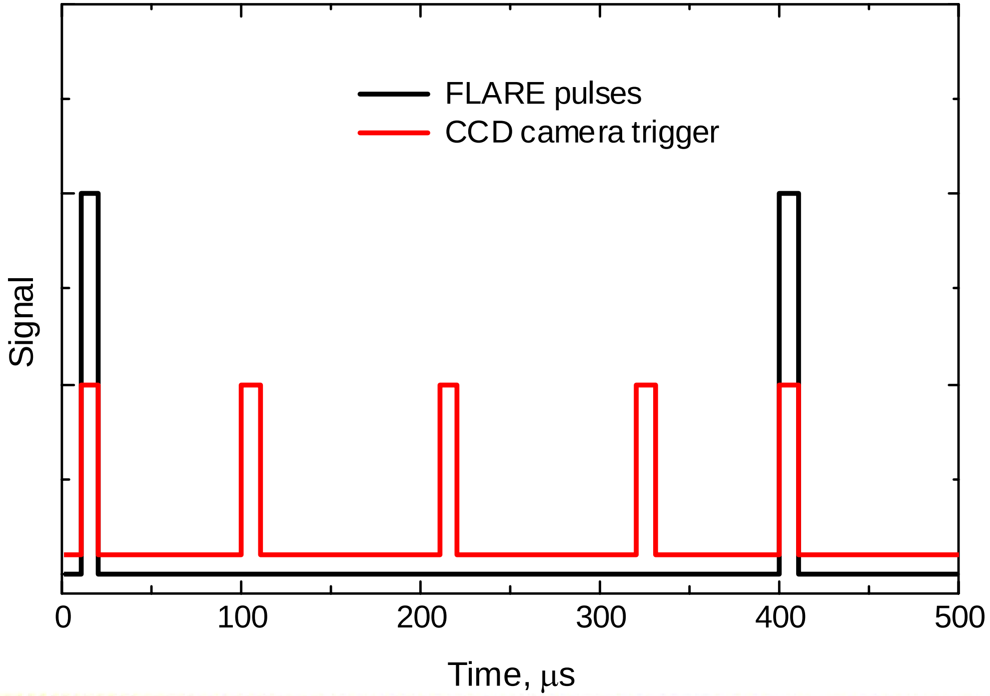
Magneto-transmission setup is working routinely. Magnetic and cyclotron resonance studies are possible over unique ranges of fields, frequencies, radiation powers.

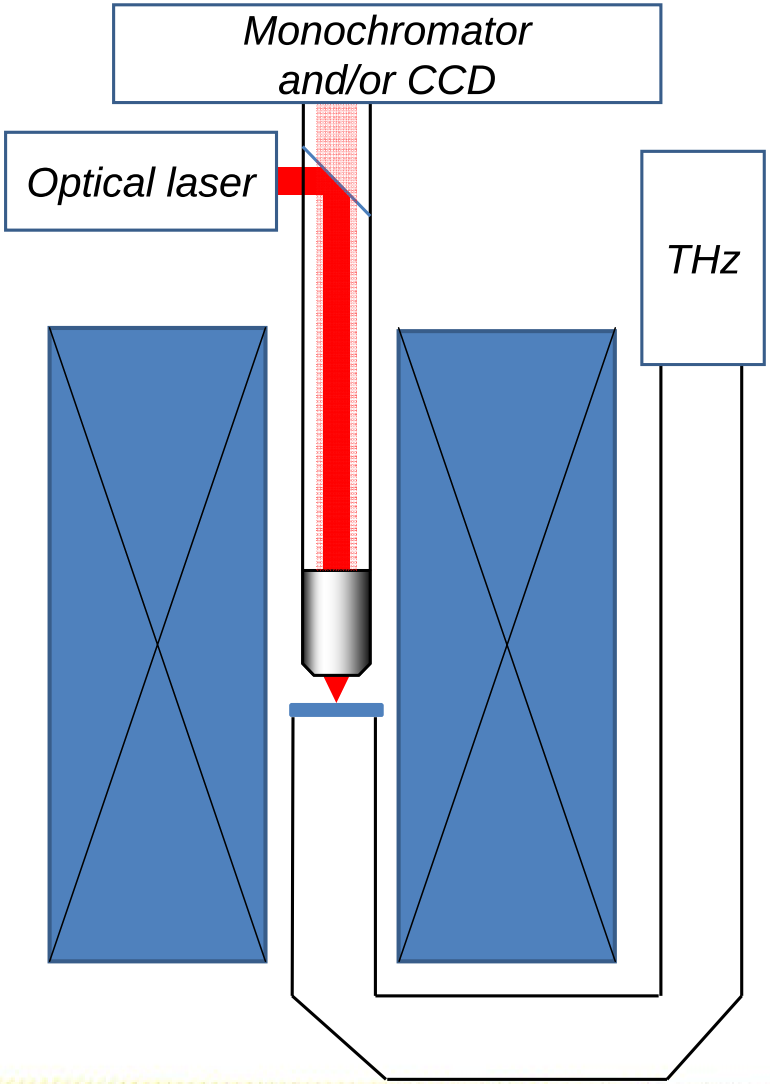
First photoluminescence measurements are successfully performed.

The development of others pump-probe setups in progress

THz pump, PL probe

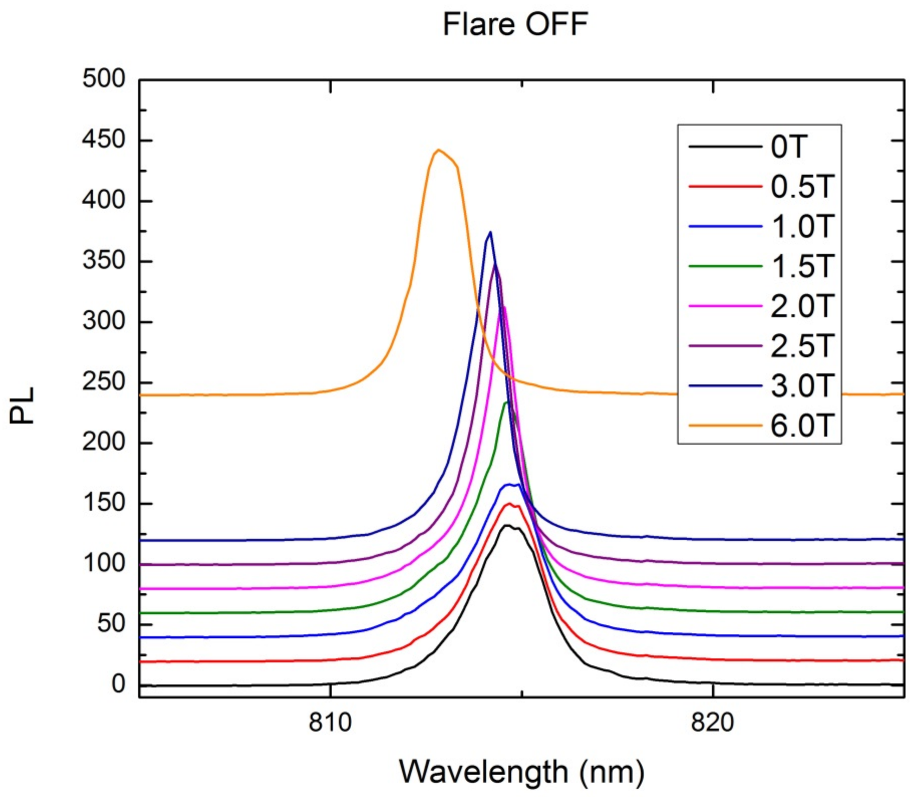
- Optical photoluminescence spectra as a function of magnetic field and THz radiation (frequency and power).
- THz spectroscopy at optical resolution



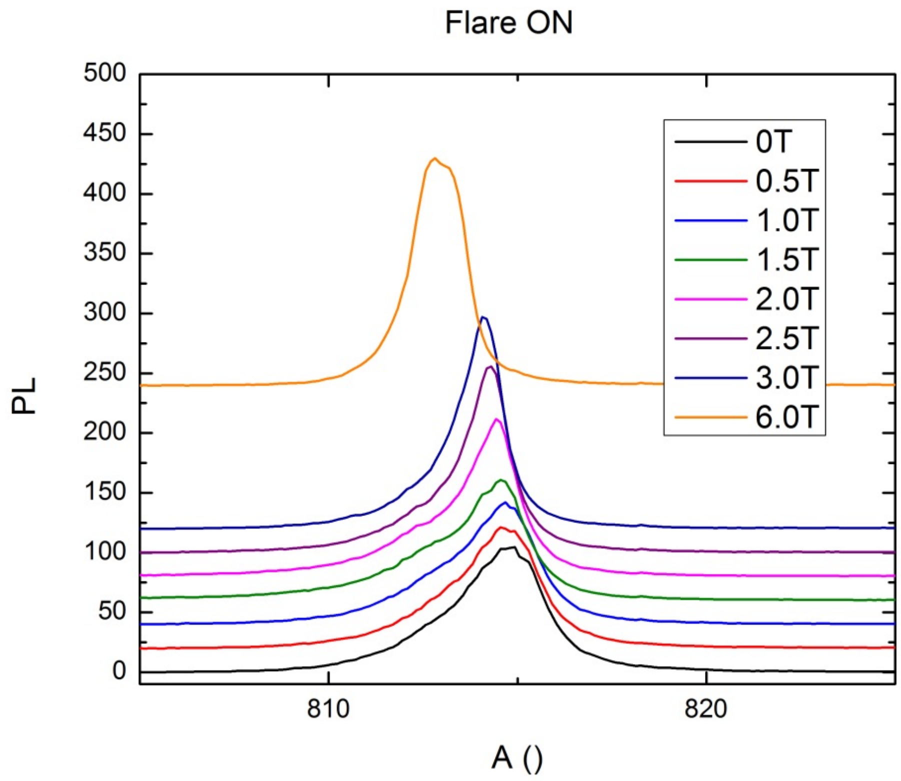


GaAs QW Photoluminescence spectra

PL Spectra

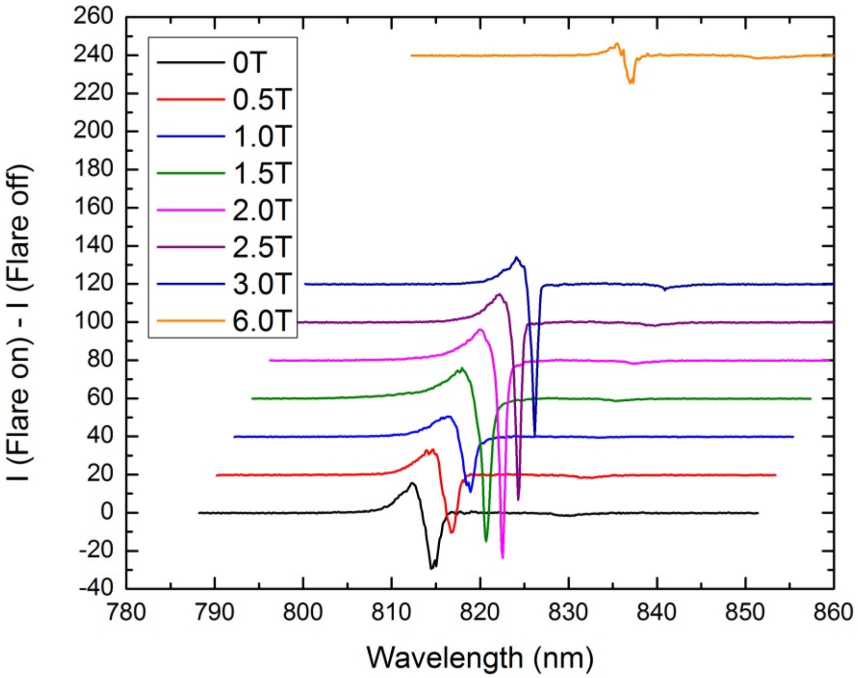


PL Spectra + High THz power (34 cm^{-1})



GaAs QW

Difference between PL Spectra with and without FLARE



Cyclotron frequency:

$$h\nu = eB/m^*$$

$$m^* = 0.07m_e$$