Magnetic resonance in Dense Atomic Hydrogen Gas

S. Vasiliev

University of Turku, Finland

Magnetic resonance in Dense Atomic Hydrogen Gas

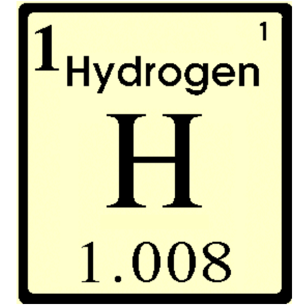
Sergey Vasiliev

University of Turku

<u>H group at Turku:</u>

Janne Ahokas
Otto Vainio
Ville Virtanen
Sergey Sheludyakov
Denis Zvezdov*

*also at Kazan Federal University, Kazan, Russia



Why to study H gas?

- The only gas at T=0
- Bose-Einstein Condensation
- H-H interactions, cold collisions
- Magnetic resonance
- Spin waves, BEC of magnons

Basic parameters

$$n = 10^{17} - 10^{18}\ \mathrm{cm}^{-3} \quad T = 100 - 500\ \mathrm{mK} \qquad B \approx 4.6\ \mathrm{T}$$

$$\lambda_0 = \frac{1}{4\pi a^2 n} \leq 0.1\ \mathrm{mm} \qquad \Lambda_{th} = \left(\frac{2\pi\hbar^2}{m k_B T}\right)^{1/2} \approx \frac{17.4\text{Å}}{\sqrt{T}}$$

$$\Lambda_{th} \approx 36\text{Å at } T = 0.3\ \mathrm{K}$$

$$a_S \approx 0.72\text{Å}$$

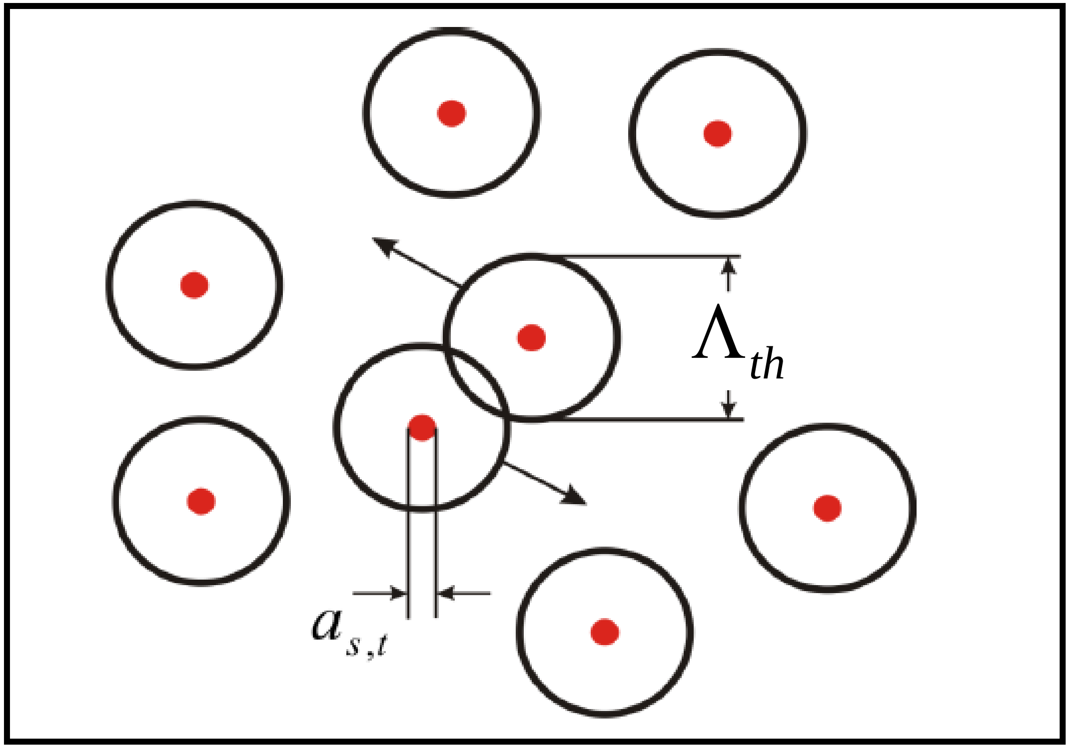
Quantum gas limit

$$\Lambda_{th} \geq a$$

Onset of quantum degeneracy

$$n\Lambda_{th}^3 \sim 1$$

Cold collisions, Spin waves



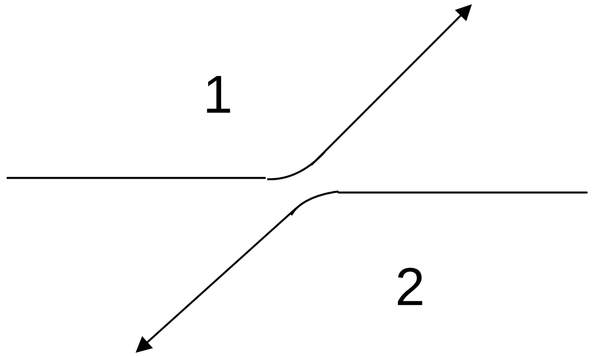
Spin waves in quantum gases

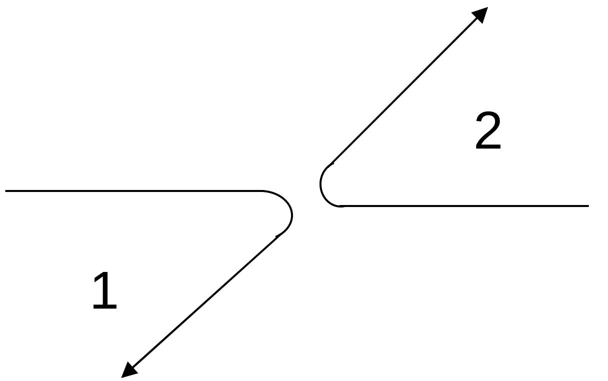
V. P. Silin, JETP 6,945 (1958)
A.J. Legett and M.J. Rice, PRL, 20, 586 (1968)
E.P. Bashkin, JETP Lett. 33, 11 (1981)
C. Lhuillier and F. Laloe, J. Phys (Paris) 43, 197 (1982)

liquid [3]He (Silin; Legett and Rice)

spin-polarized gases (Bashkin; Lhuillier and Laloe)

$$\mu \sim \frac{\Lambda_{th}}{a} >> 1$$

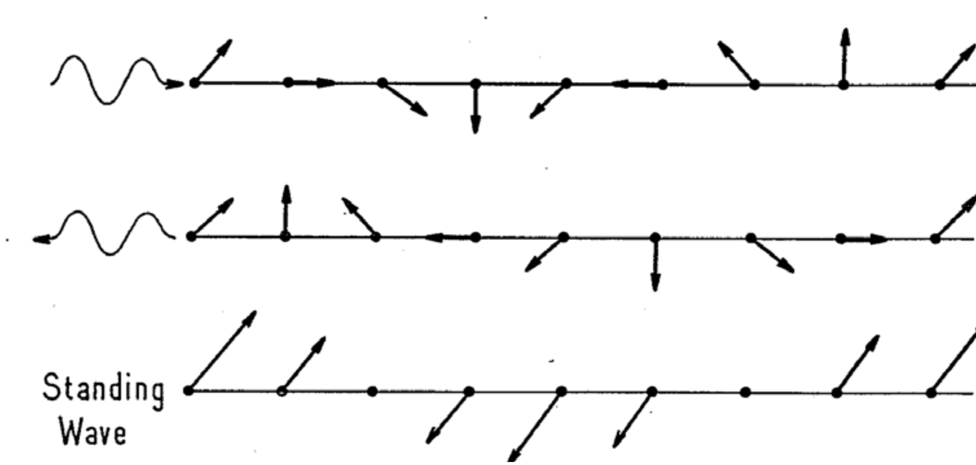




$$\Psi_0 = A\left|\uparrow\right\rangle + B\left|\downarrow\right\rangle$$

$$\Psi = Ae^{i\varphi_1}\left|\uparrow\right\rangle + Be^{i\varphi_2}\left|\downarrow\right\rangle$$

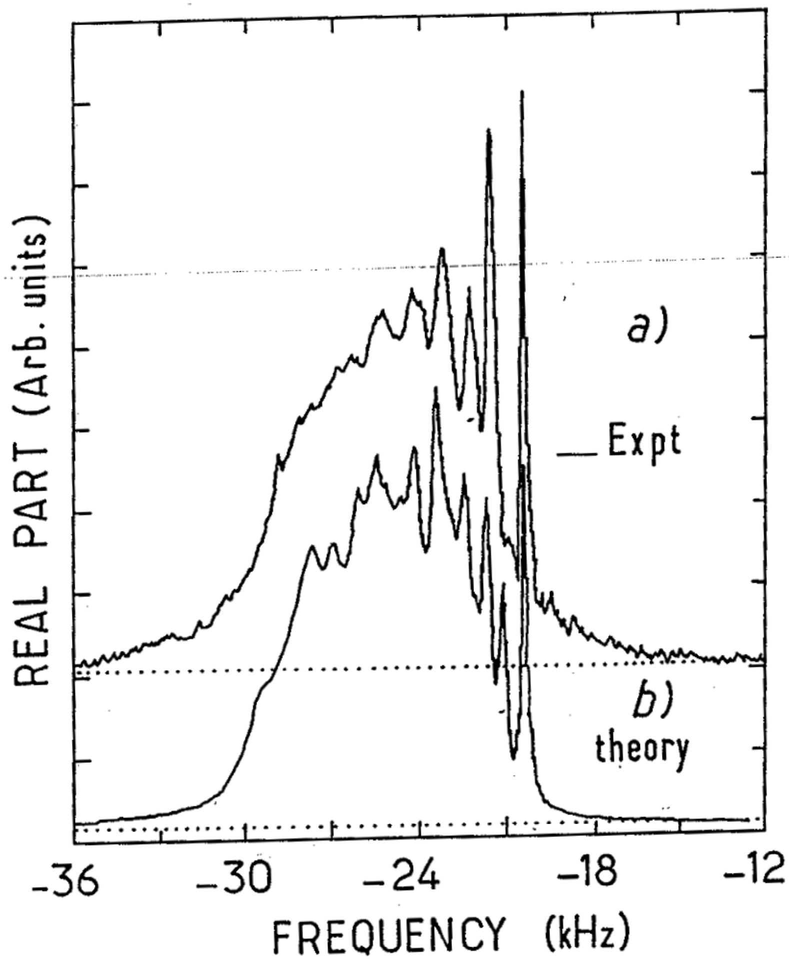
Identical
Spin Rotation
Effect (ISR)

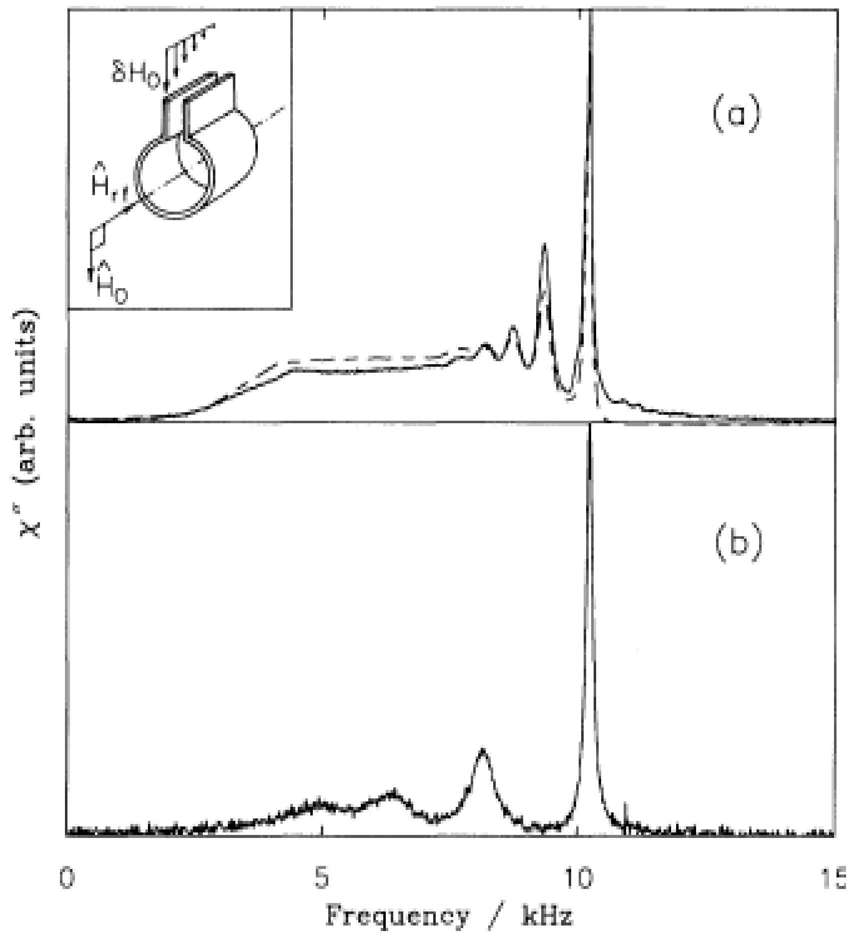


Nuclear spin waves in H↓ gas

Pulsed NMR, spectra after FT

D.M. Lee at Cornell University





B. R. Johnson *et al.*, PRL **52**, 1508 (1984)

Basic equations of ISR spin waves

C. Lhuillier and F. Laloe, J. Phys (Paris) 43, 197 (1982)

$$M_+ = M_x + iM_y$$

$$\frac{\partial M_+}{\partial t} = -i\gamma\delta B_0 M_+ + D_0 \frac{1 - i\varepsilon\mu M_z}{1+\mu^2 M^2} \nabla^2 M_+$$

$\varepsilon = \pm 1$ for bosons/fermions

D_0 – spin diffusion coefficient in unpolarized gas

$\mu \sim \dfrac{\Lambda_{th}}{a}$ - spin wave quality factor

$$\omega(k) = -D_0 \frac{i + \mu\varepsilon M_z}{1+\mu^2 M^2} k^2 \sim \frac{T}{n} k^2$$

Schrödinger type equation:

$$\left.\begin{array}{l} \mu \sim \dfrac{\Lambda_{th}}{a} >> 1 \\ M_{+} \ll M_{z} \approx M \end{array}\right\}$$

$$i\hbar \frac{\partial M_{+}}{\partial t} = \underbrace{\frac{D_0 \varepsilon \hbar}{\mu}}_{\text{kinetic}} \nabla^2 M_{+} + \underbrace{\hbar \gamma \delta B_0}_{\text{potential}} M_{+}$$

Particle	ε	γ	μ
^{3}He	-1	negative	neg/pos
H proton	+1	positive	negative
H electron	+1	negative, large	negative

High field seekers

$$m^* = -\frac{\mu \hbar}{\varepsilon D_0} \sim -\mu n$$

Low field seekers

Calculations of μ for H and ^{3}He

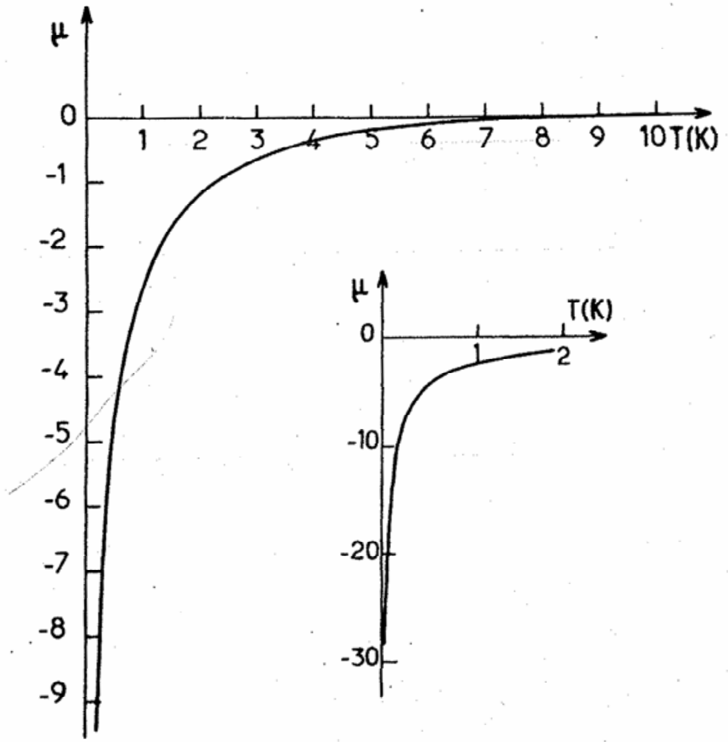


Fig. 13. — « Identical spin rotation » coefficient μ in H↑ *versus* temperature.

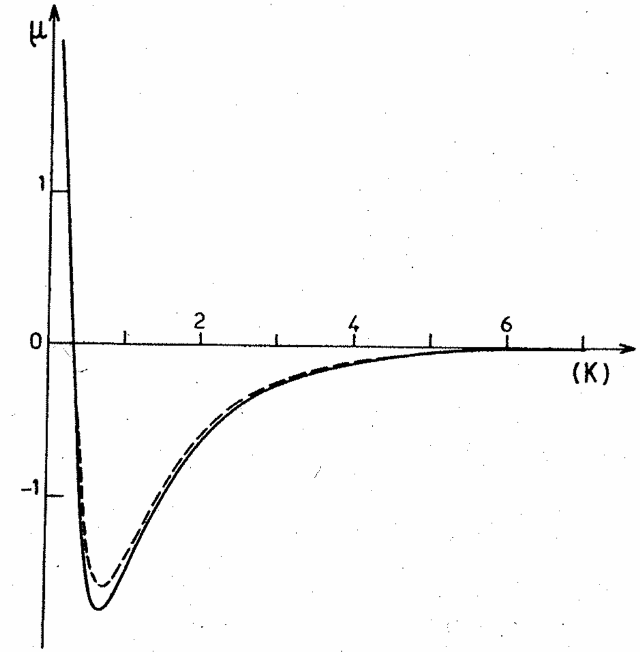
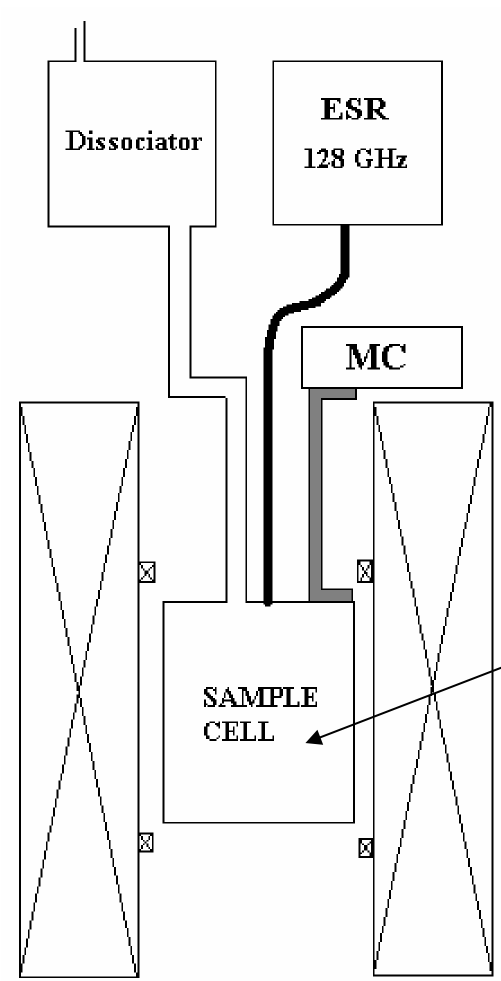


Fig. 14. — « Identical spin rotation » coefficient μ in ^{3}He *versus* temperature. The full line curve has been calculated with the Lennard-Jones potential (Eq. 2), the dashed one with the Aziz potential (Eq. 3).

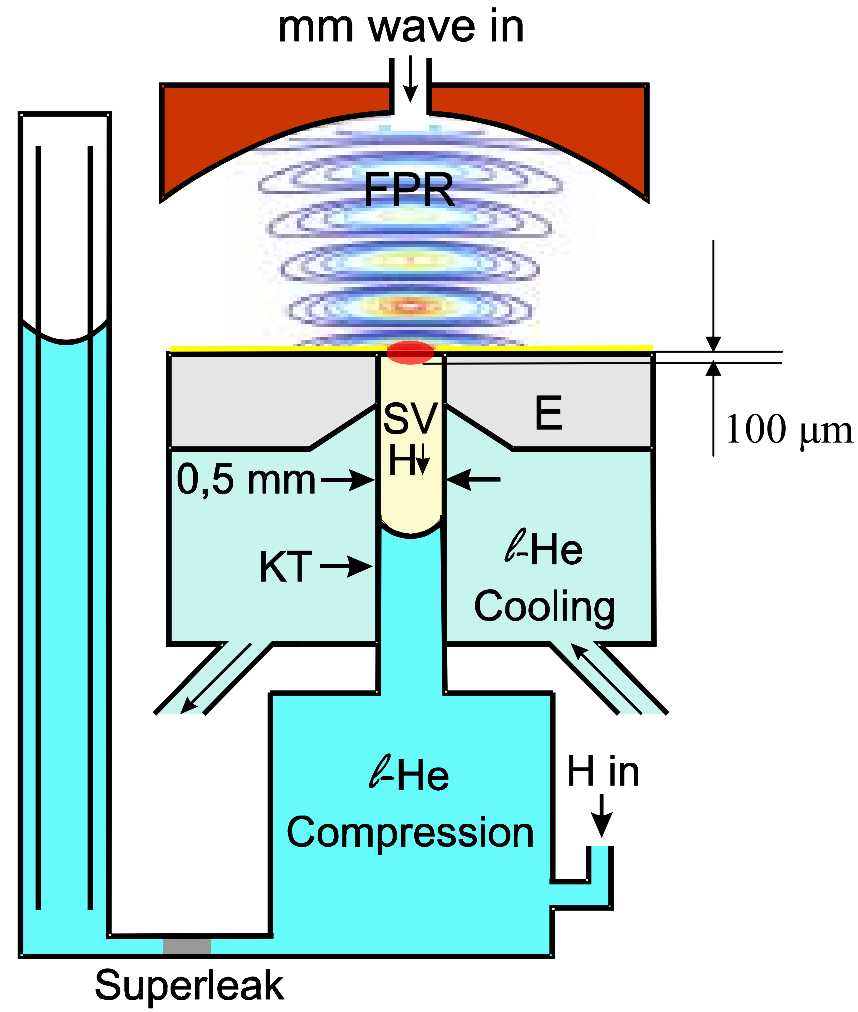
C. Lhuillier, *J. Physique* **44**, 1-12 (1983)

Experimental setup



B≈4.6 T
T=0.2-0.5K

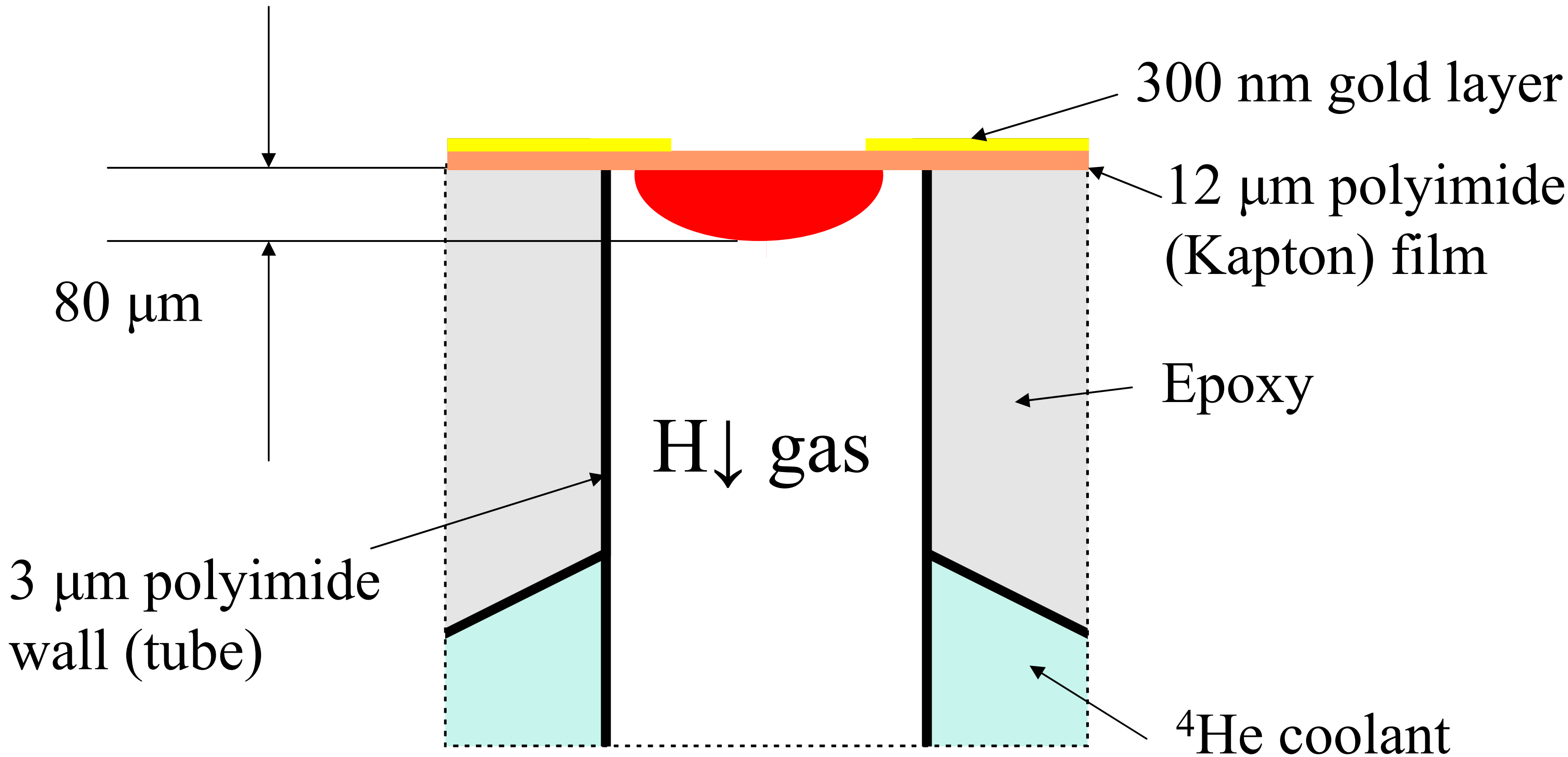
$n \sim 10^{15}$ cm^{-3}



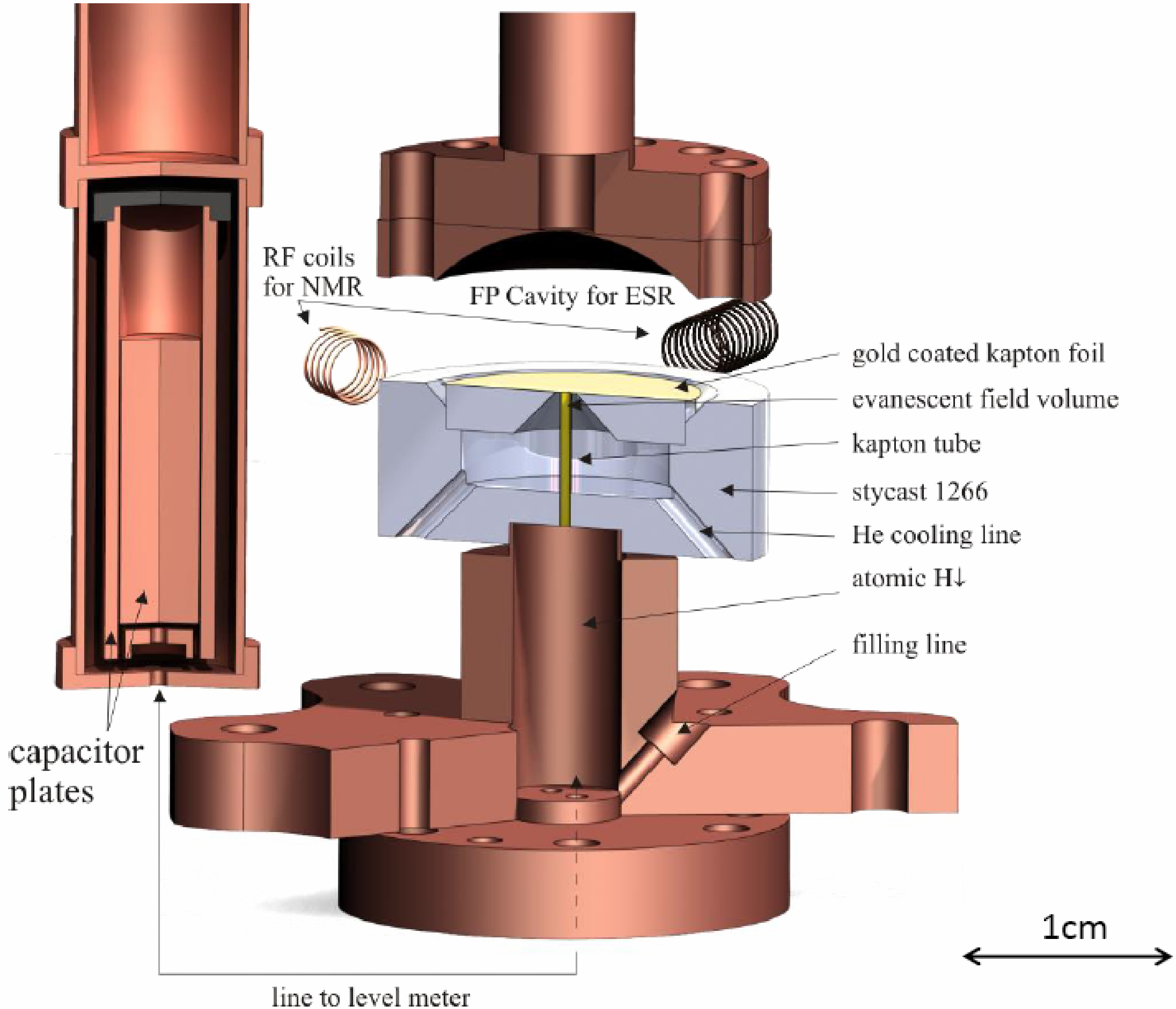
$n \rightarrow 10^{18}$ cm^{-3}

Sample lifetime ~3-100 min

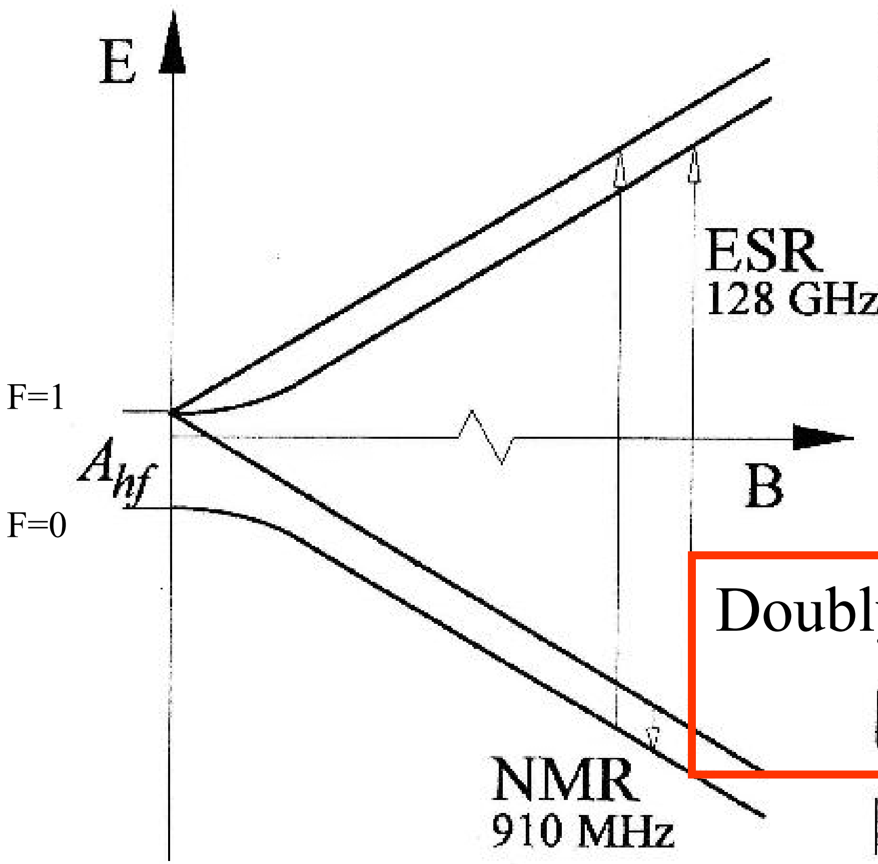
Compression region



Current Sample Cell



Hyperfine structure of H atom ground state in magnetic field



	m_S, m_I
$|d\rangle = |\uparrow\Uparrow\rangle$	**½, ½**
$|c\rangle = \cos\theta|\uparrow\Downarrow\rangle + \sin\theta|\downarrow\Uparrow\rangle$	**½, -½**
$|b\rangle = |\downarrow\Downarrow\rangle$	**-½, -½**
$|a\rangle = \cos\theta|\downarrow\Uparrow\rangle - \sin\theta|\uparrow\Downarrow\rangle$	**-½, ½**

$$\mathrm{tg}\, 2\theta = \frac{A_{hf}}{2\mu_B B}$$

Doubly polarized H gas

$|b\rangle = |\downarrow\Downarrow\rangle$

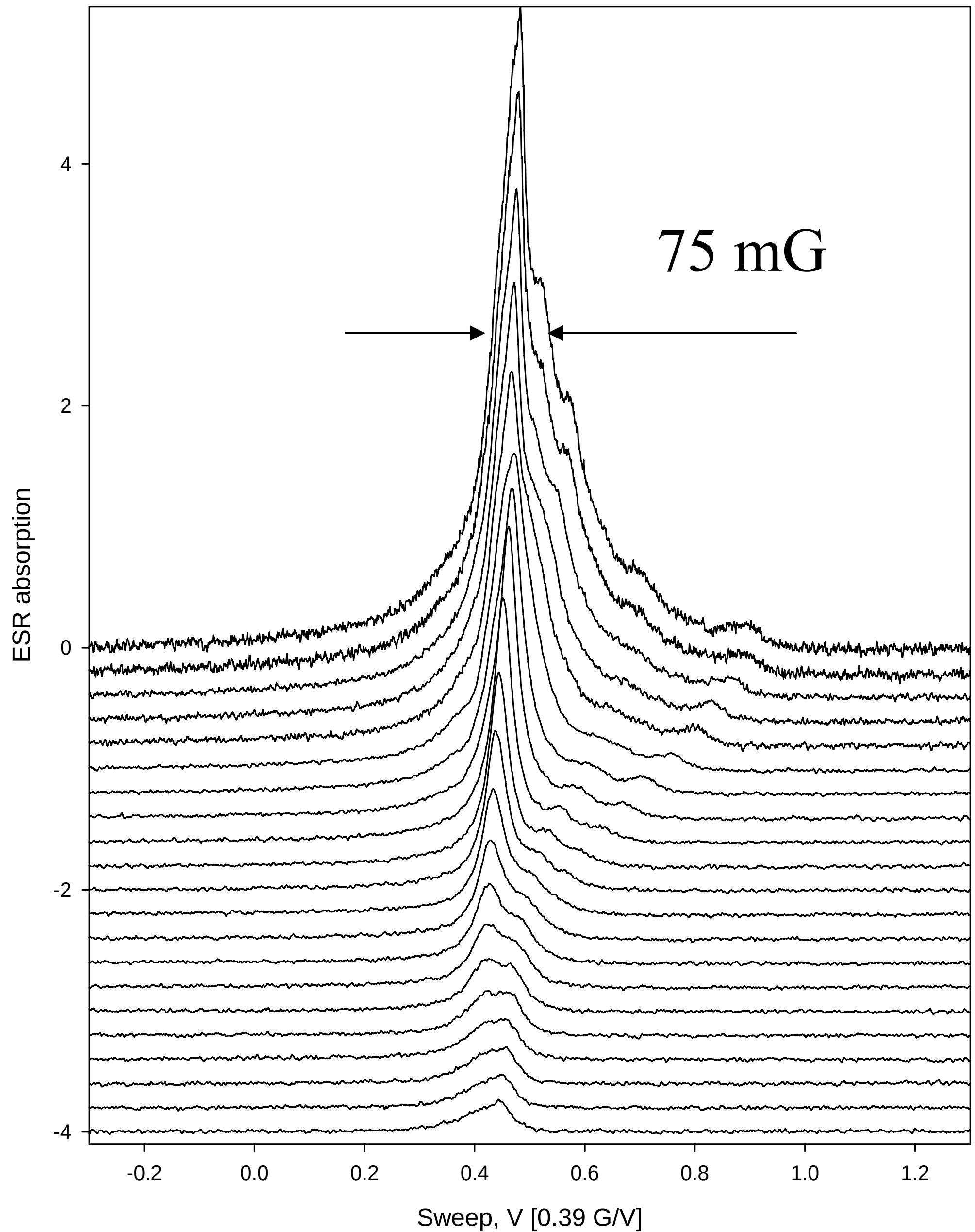
hyperfine state selective recombination:

$$a + a + \mathrm{M} = \mathrm{H}_2 + \mathrm{M}$$

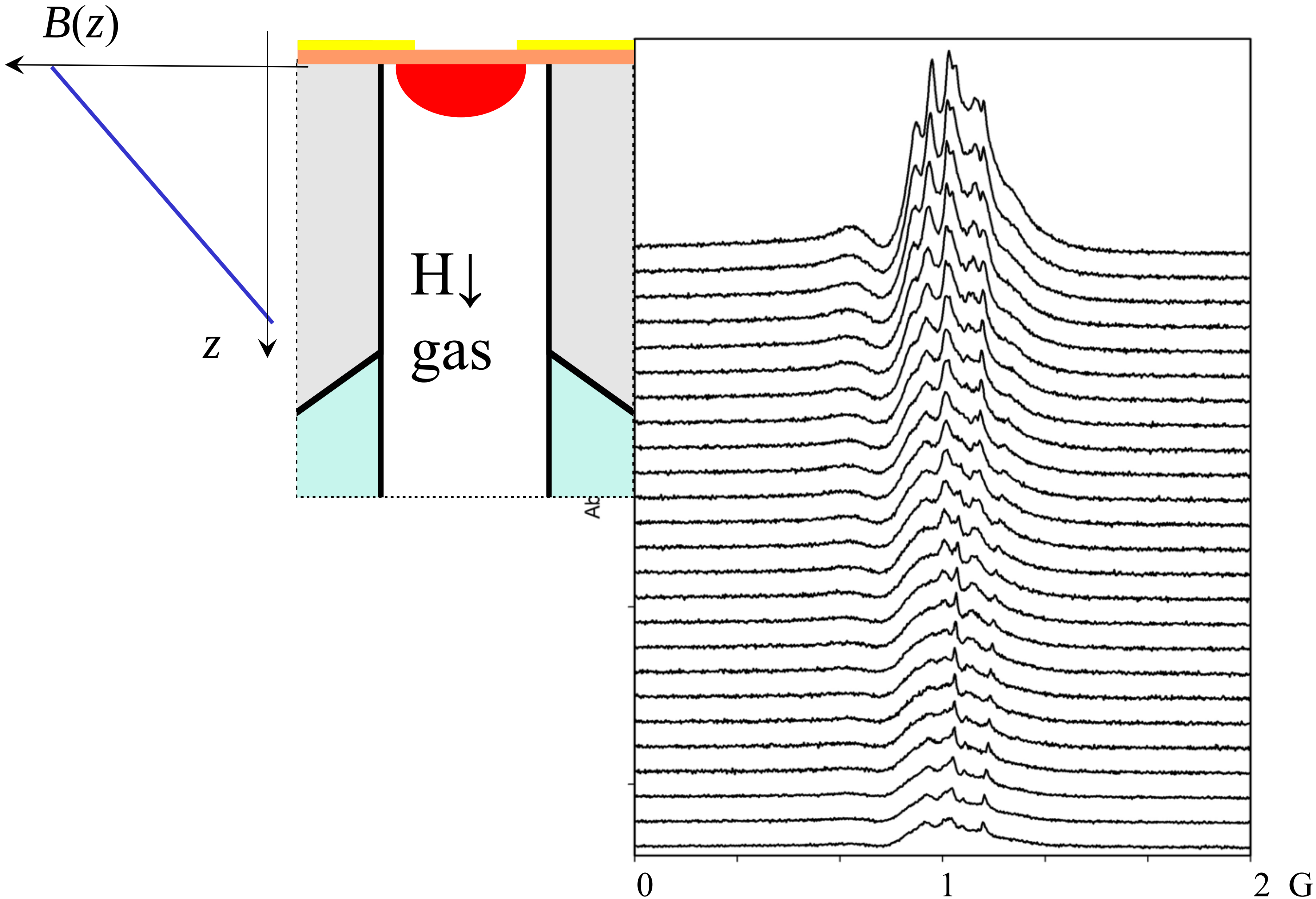
$$a + b + \mathrm{M} = \mathrm{H}_2 + \mathrm{M}$$

$$b + b + b = \mathrm{H}_2 + b$$

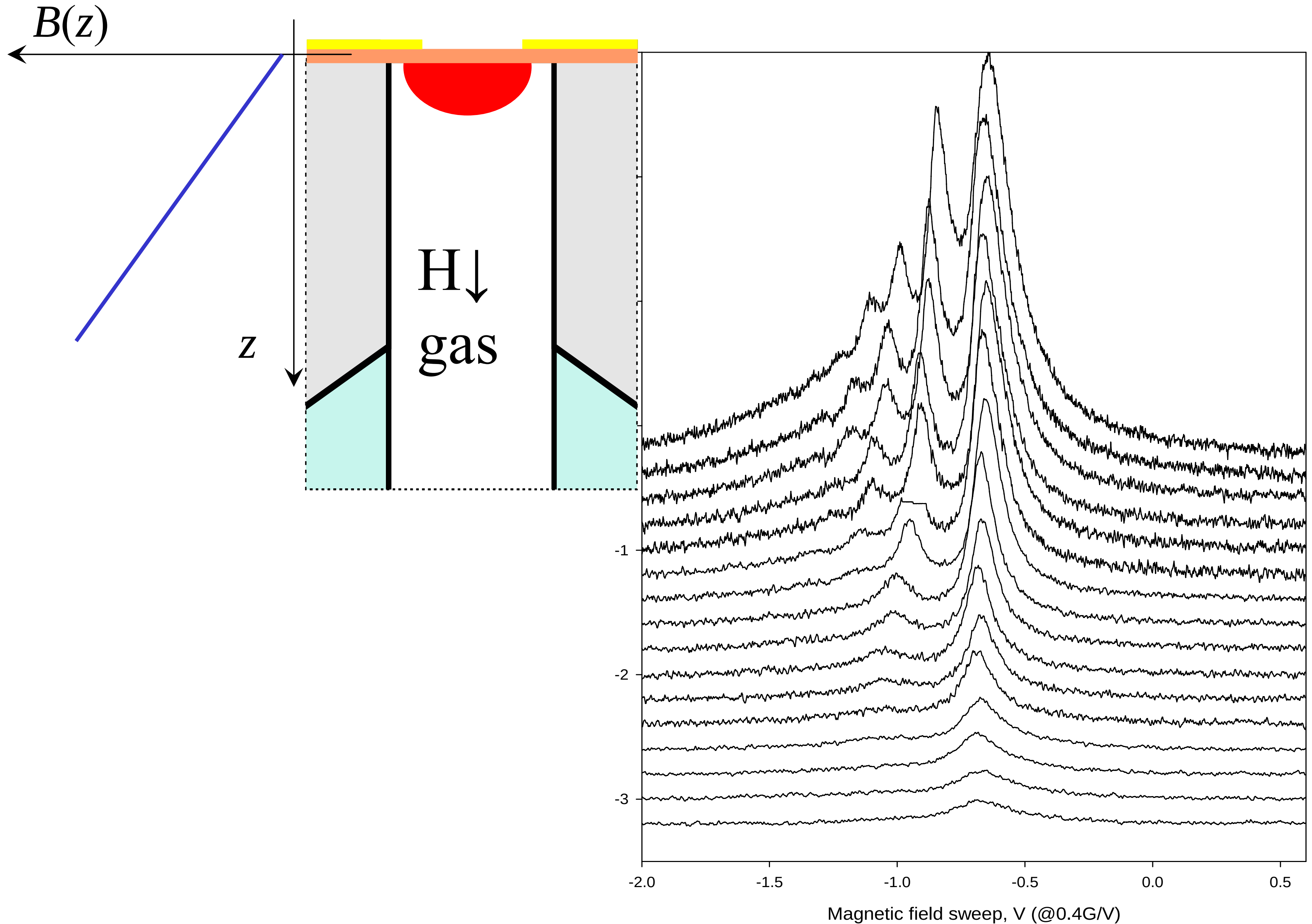
CW spectra in static field of optimized homogeneity



Large positive gradient ~40G/cm



Large negative gradient ~40G/cm



CW spectra in static field of optimized homogeneity

$$\omega = \frac{D_0}{\mu} k^2$$

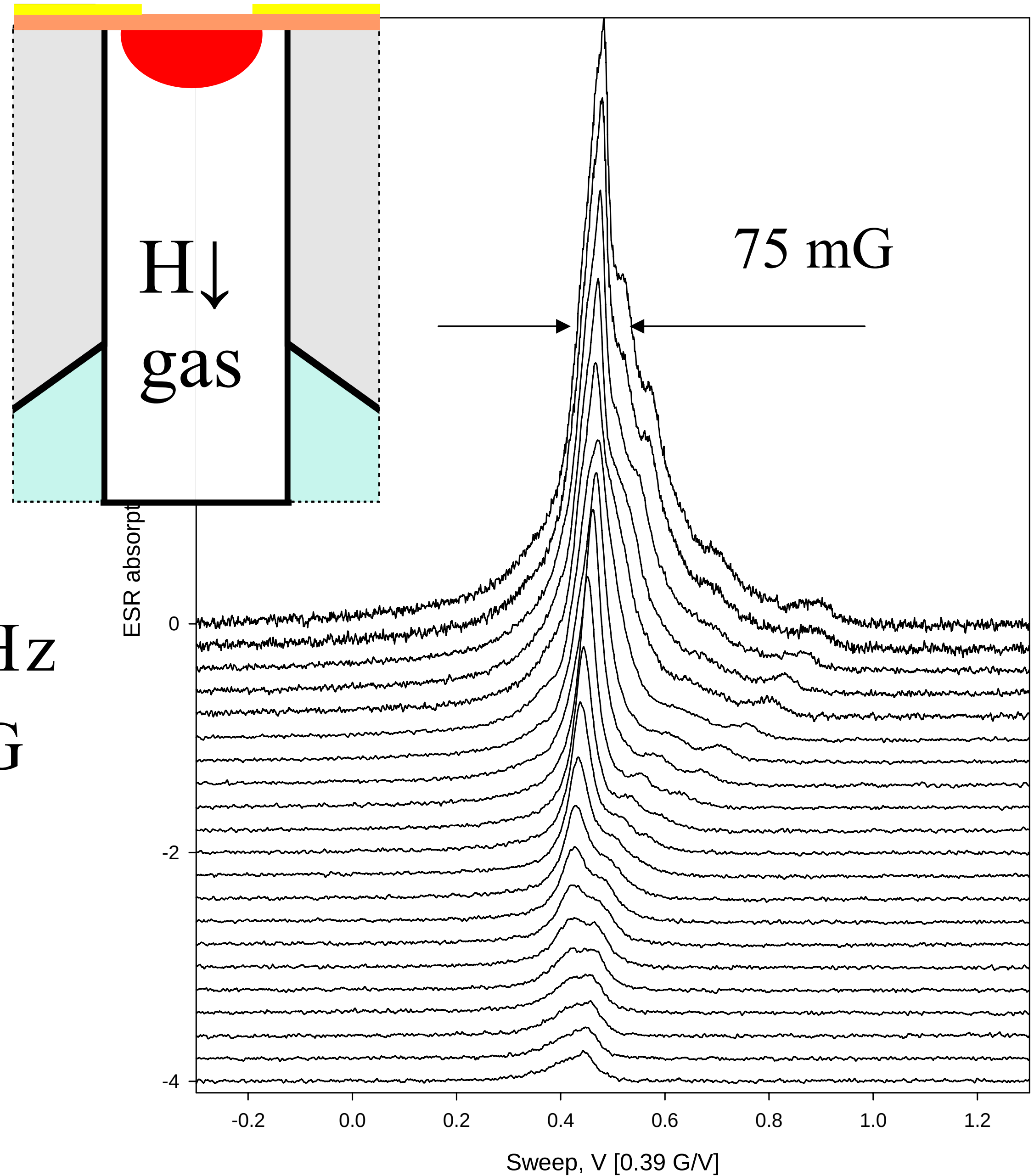
$$k = \frac{2\pi}{\lambda} = \frac{\pi}{L} n$$

$$\Delta\omega \leq \frac{\pi D_0}{\mu L^2} \approx 1.5 \text{ kHz}$$

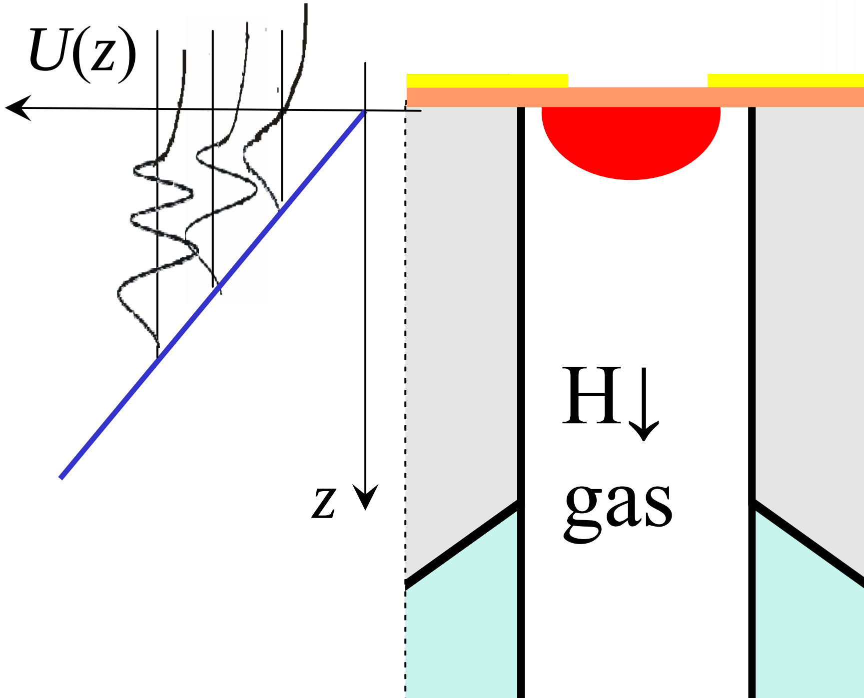
$$\approx 0.5 \text{ mG}$$

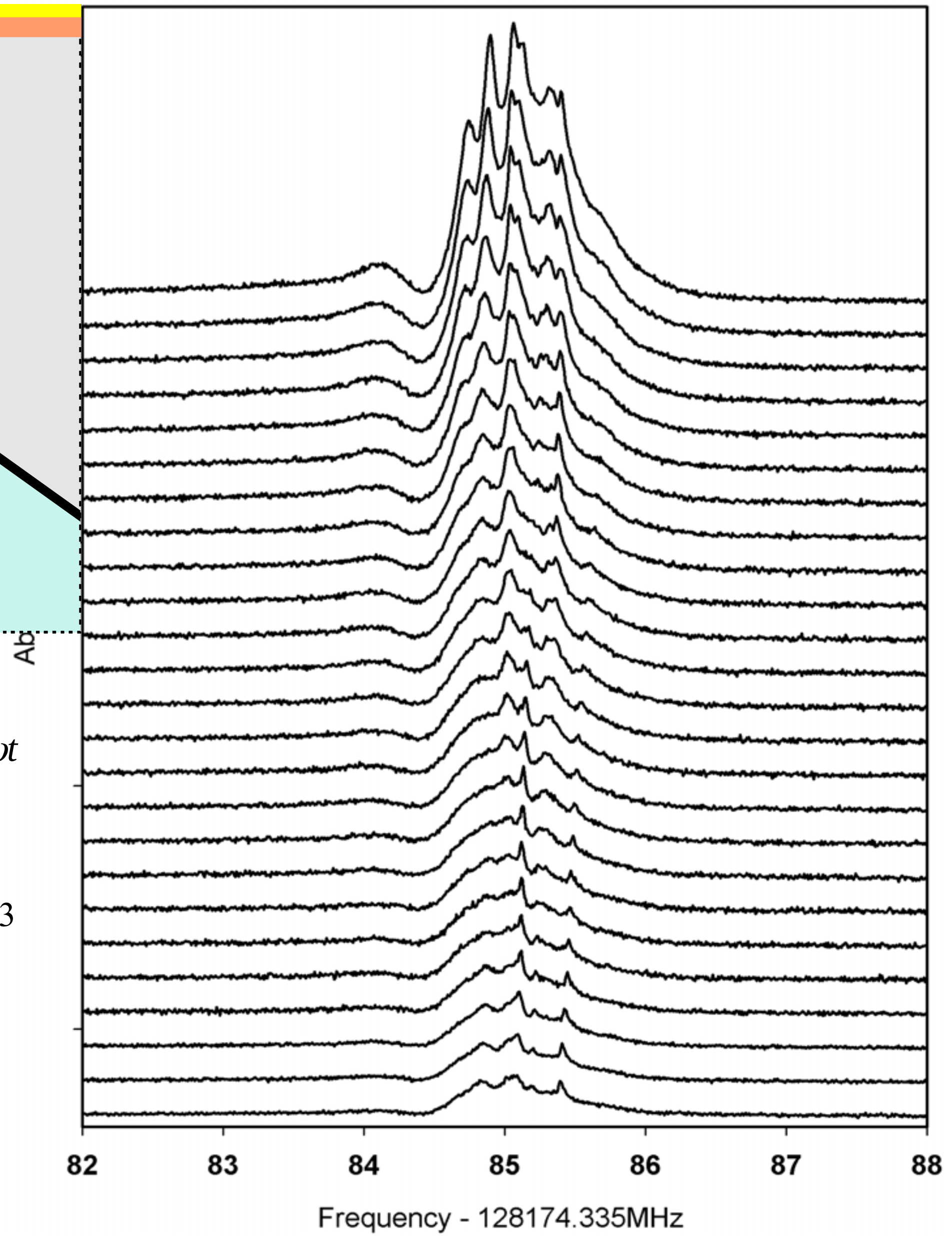
For L=0.5 mm

n=10^{17} cm^{-3}



Large positive gradient ~40G/cm, CW

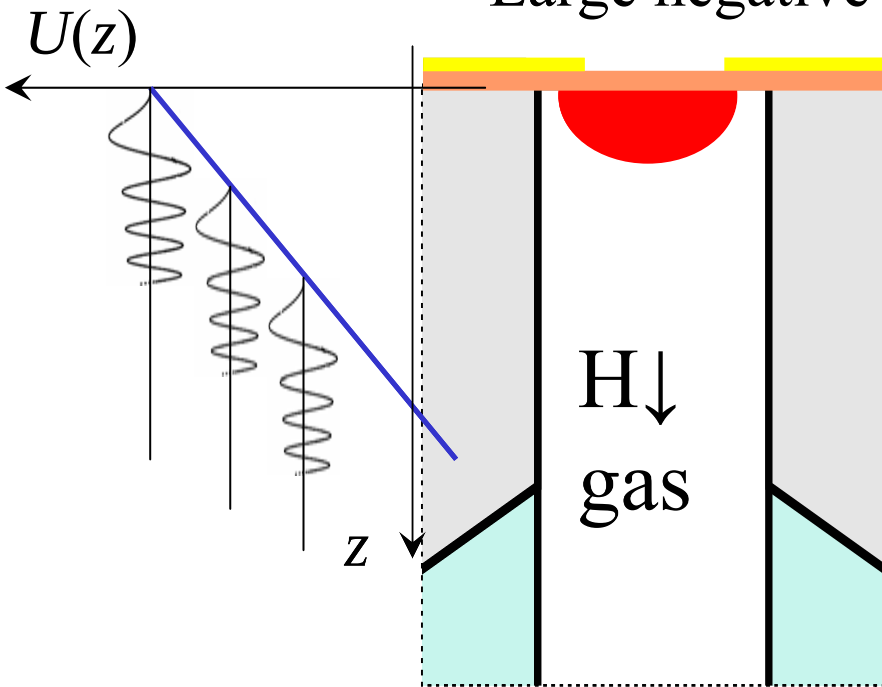


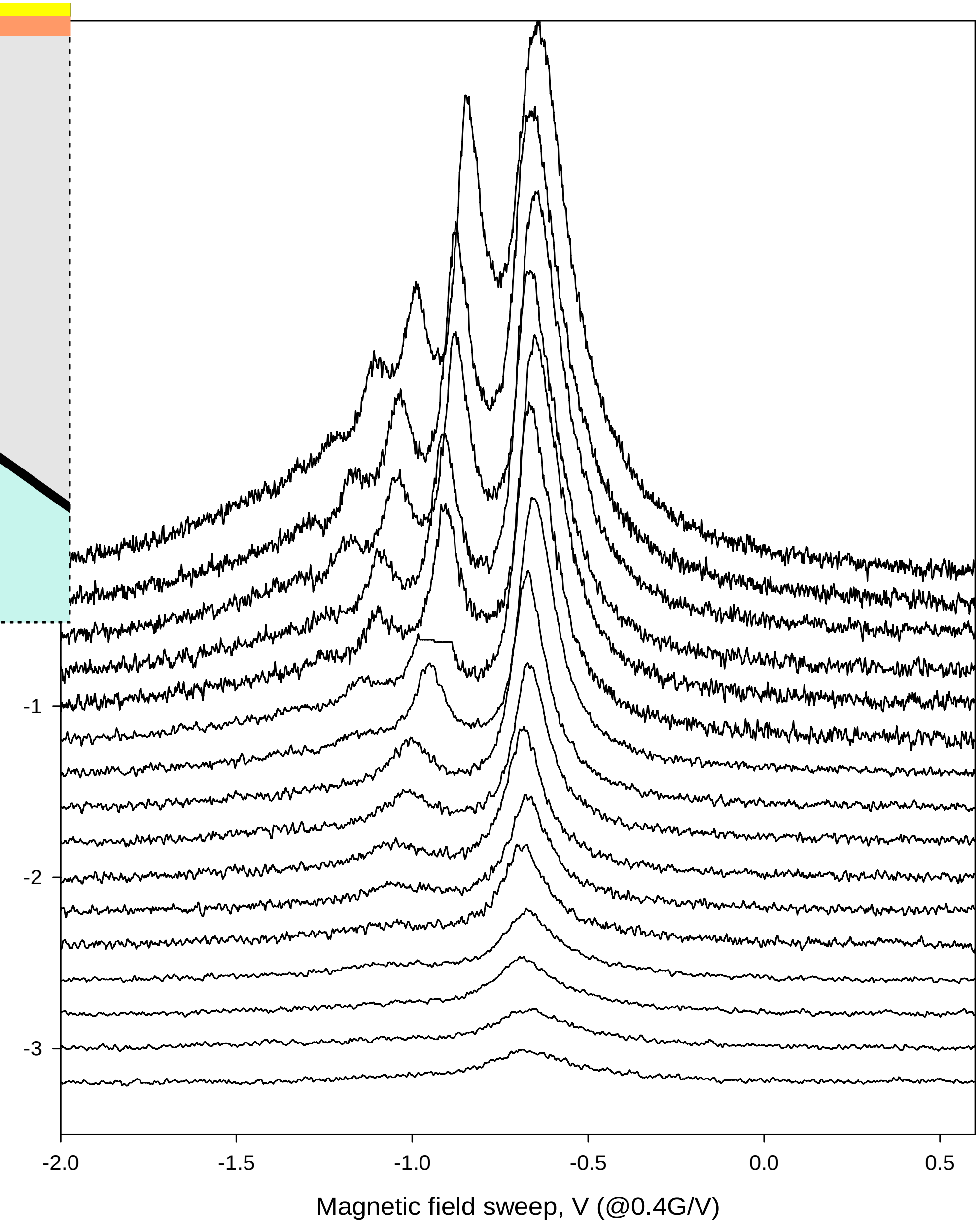


$$M_+ = J_0(\kappa r) Ai\left(\frac{z}{\lambda} + \lambda^2 k_z^2\right) e^{i\omega t}$$

$$\kappa^2 = \frac{\mu\omega}{D_0} \qquad \lambda = \left(\frac{D_0}{\gamma_e G_z \mu}\right)^{1/3}$$

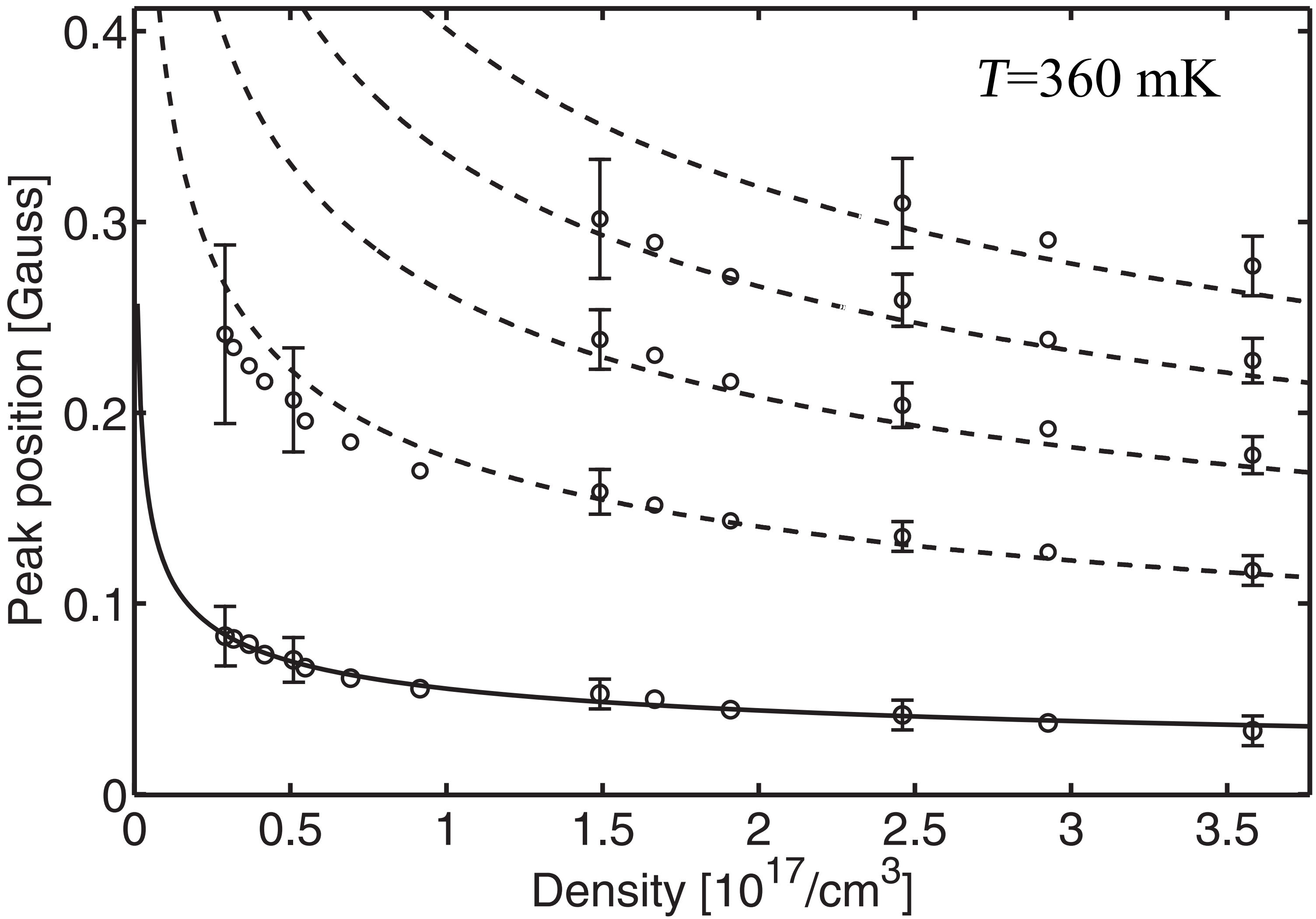
Large negative gradient ~40G/cm





$$M_{+} = J_0(\kappa r) Ai\left(\frac{z}{\lambda} + \lambda^2 k_z^2\right) e^{i\omega t}$$

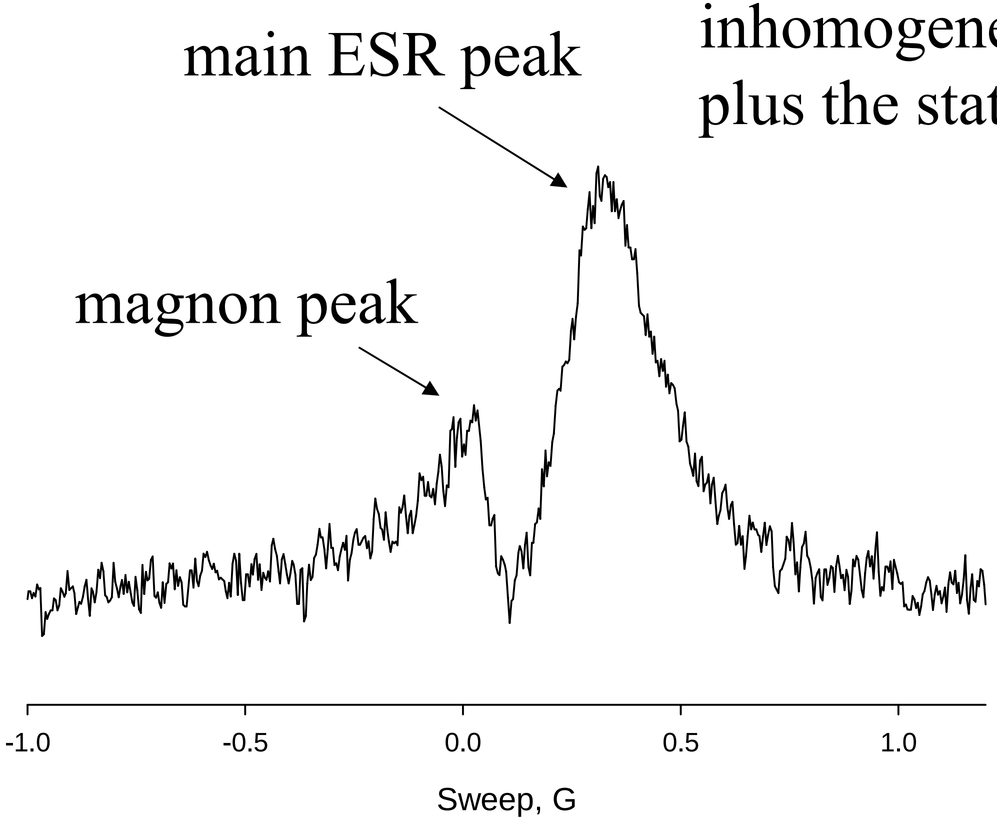
$$\kappa^2 = \frac{\mu\omega}{D_0} \qquad \lambda = \left(\frac{D_0}{\gamma_e G_z \mu}\right)^{1/3}$$



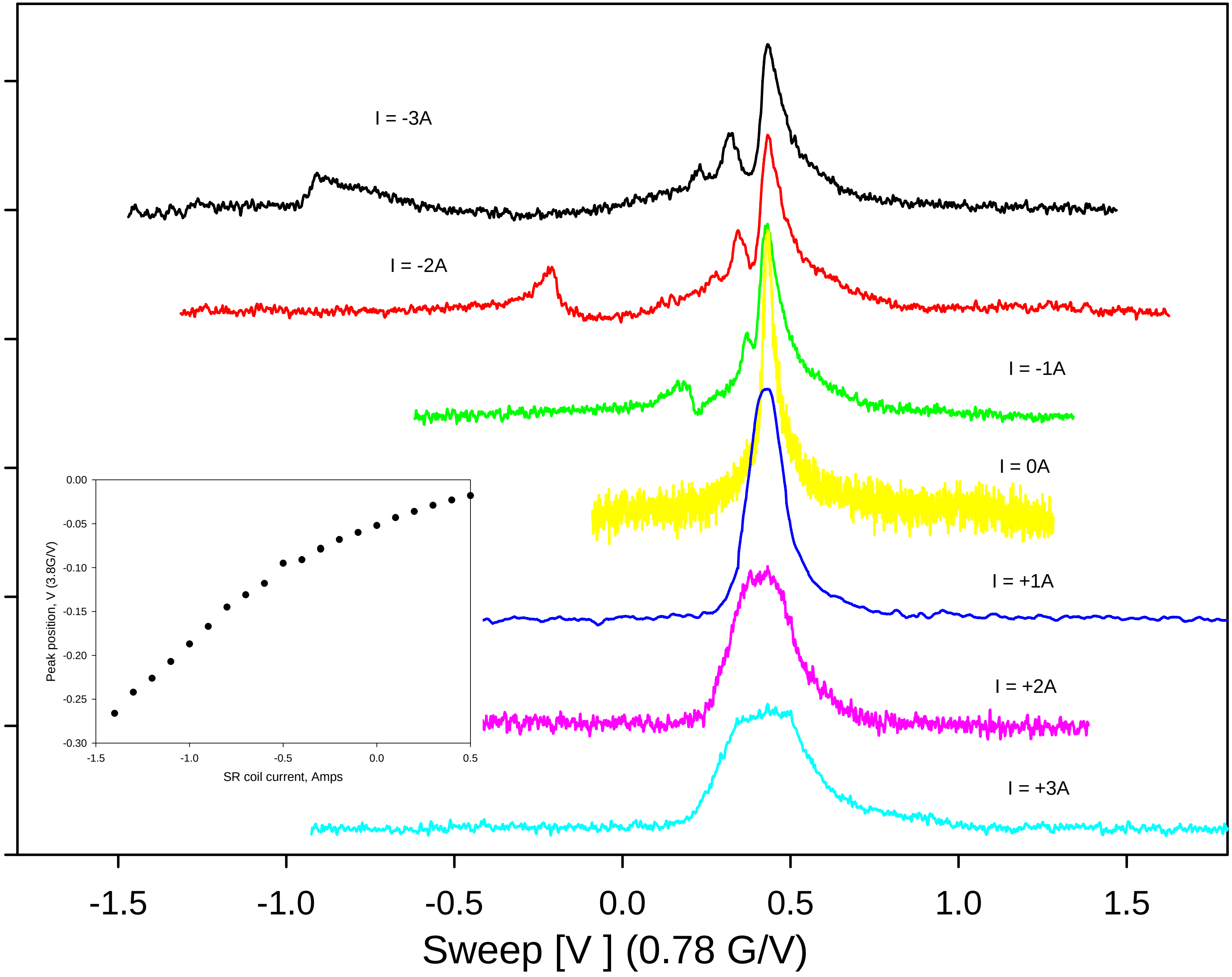
Fit result: $\mu \approx 8$

ESR spectra with no gradients applied

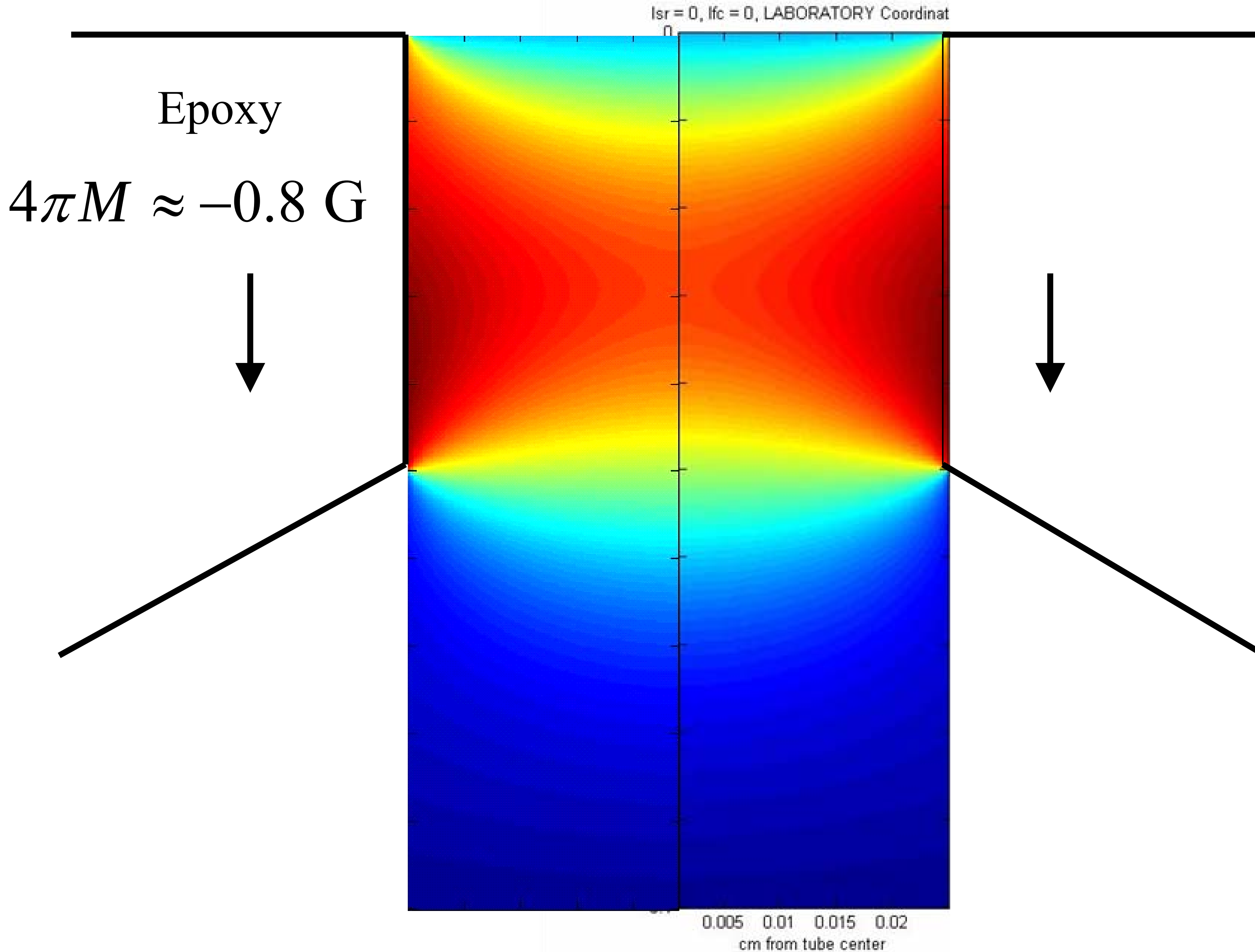
Is the observed lineshape caused by inhomogeneity of RF field plus the static field inhomogeneity?



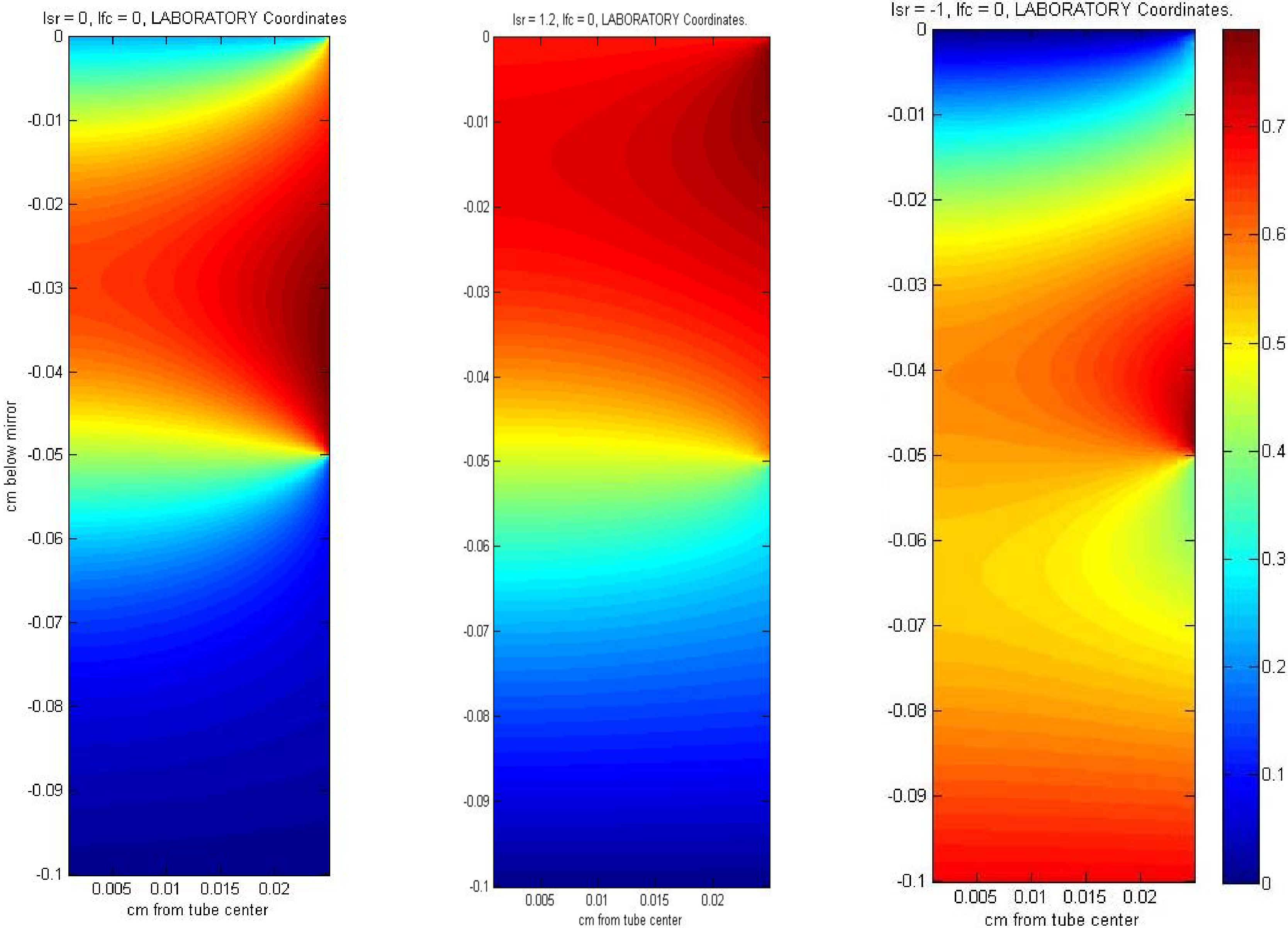
Spectra in various gradients



Static magnetic field profile, no gradients applied

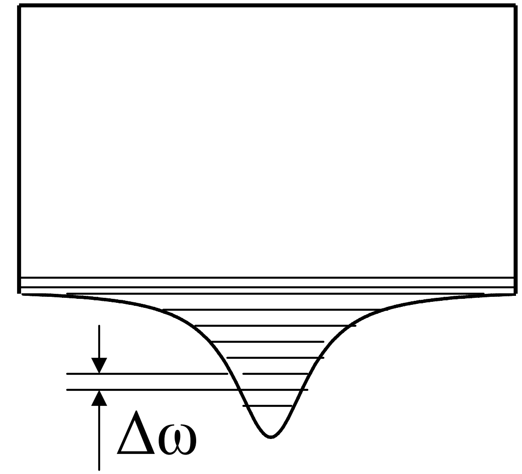


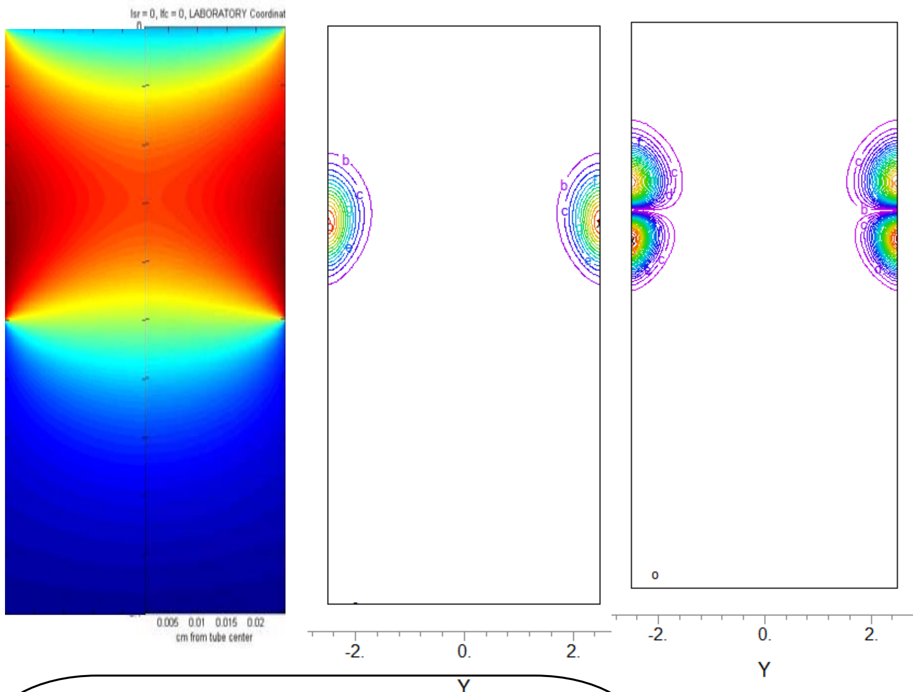
Moving trap position with applied gradients

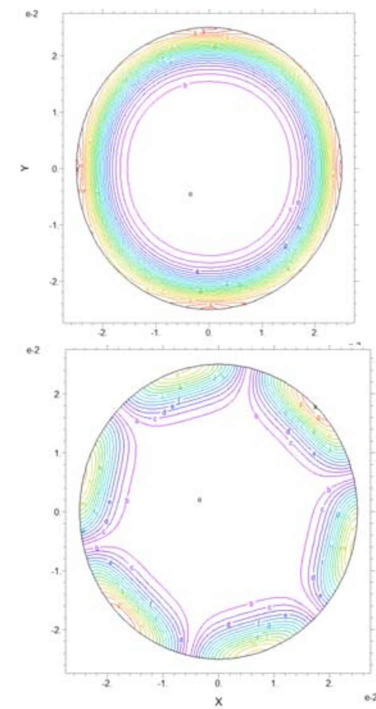


Particle in a box + parabolic potential

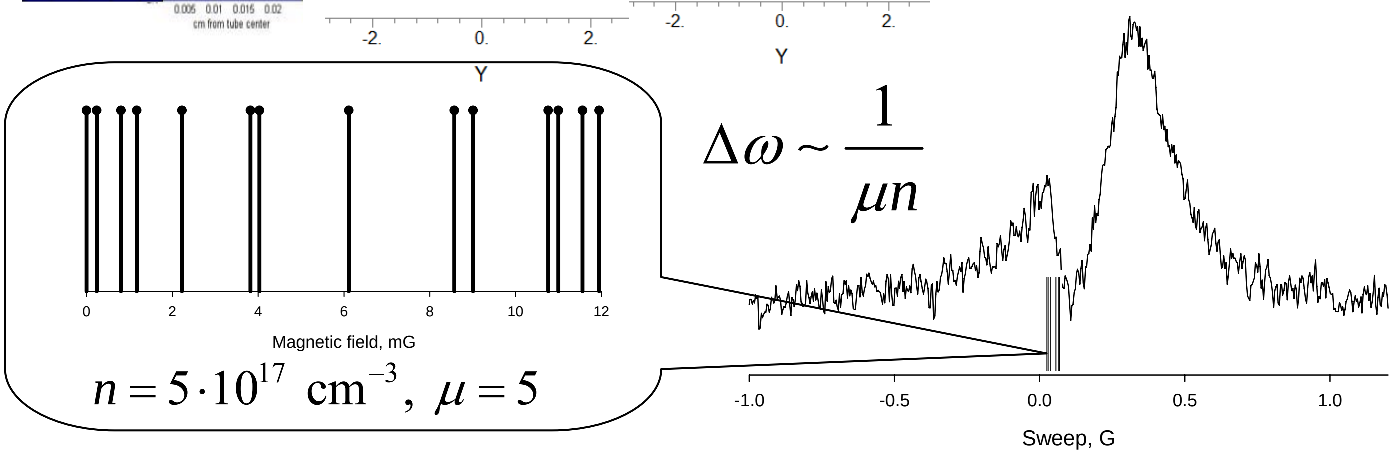
$$i\hbar\frac{\partial M_+}{\partial t}=\frac{D_0\varepsilon\hbar}{\mu}\nabla^2 M_+ + \hbar\gamma\delta H_0 M_+$$



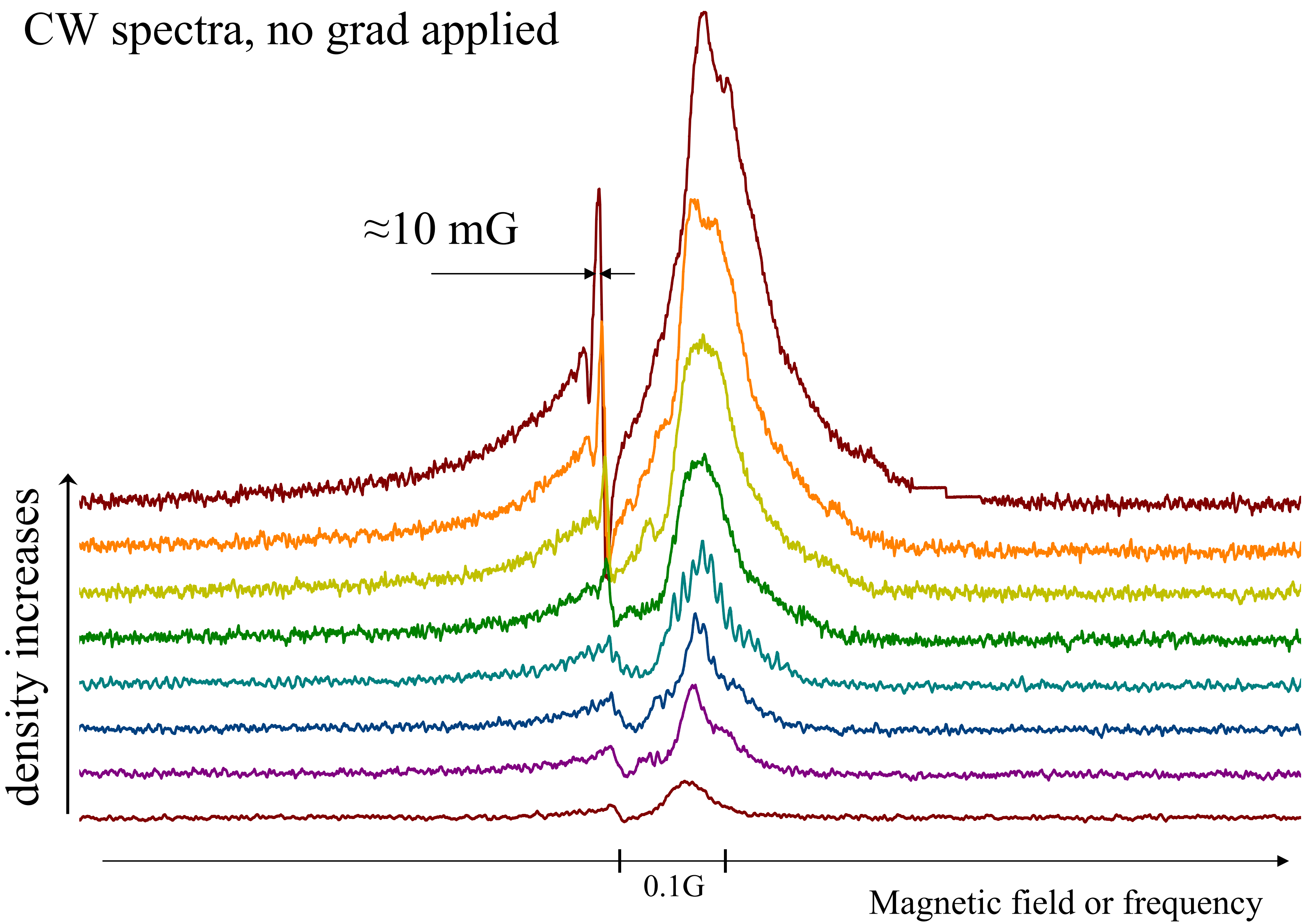




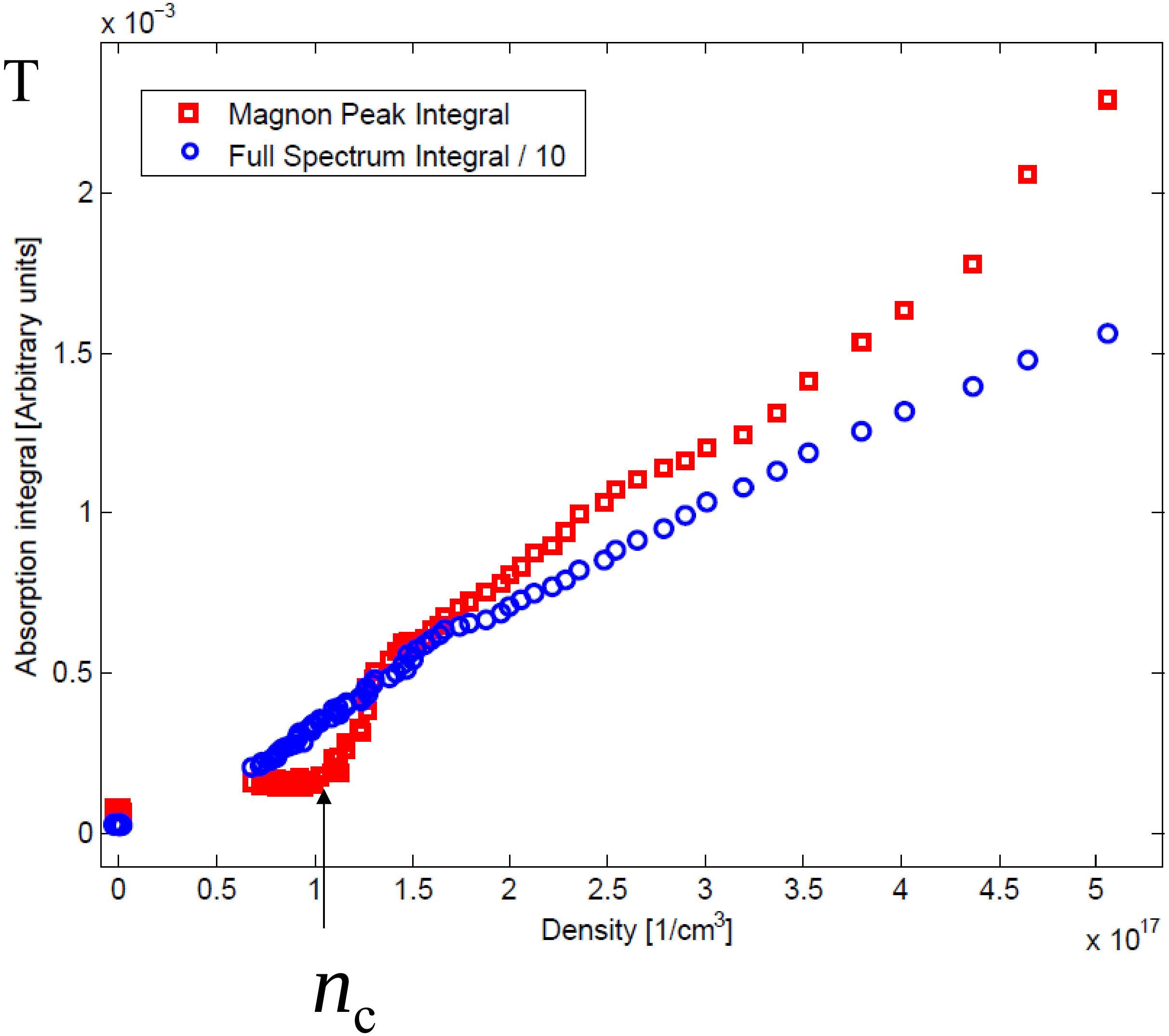
$$\Delta\omega \sim \frac{1}{\mu n}$$



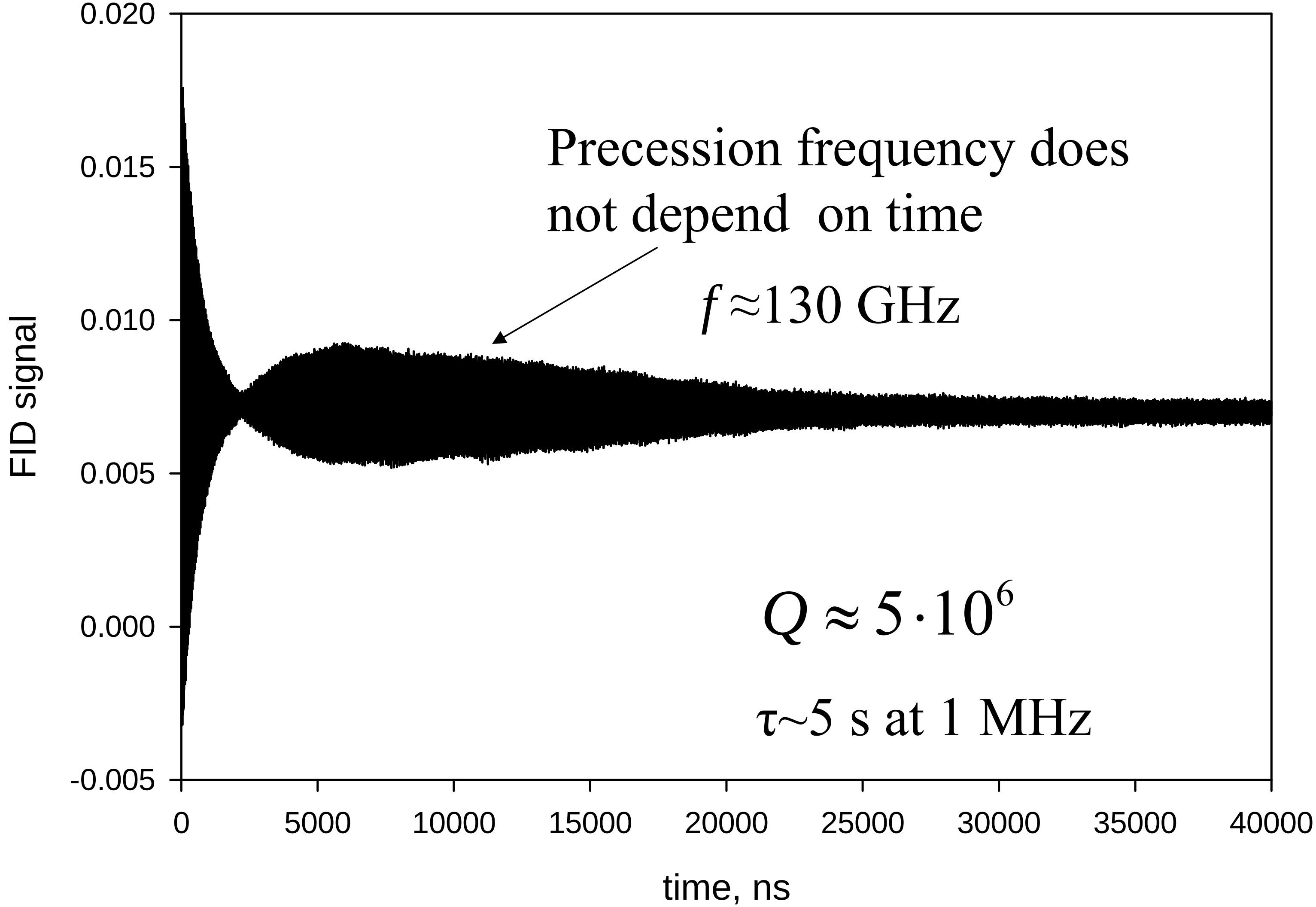
$$n = 5\cdot 10^{17}\ \mathrm{cm}^{-3},\ \mu = 5$$


CW spectra, no grad applied
≈10 mG
density increases
0.1G
Magnetic field or frequency

n_c increases at higher T and shallower trap



Free Induction Decay



Conclusions

- Spin-polarized H gas is a rich system where a large number of magnetic excitations (magnons) can be studied by means of magnetic resonance.

- We identified four basic types of magnon modes, distinguished by their behavior in magnetic field gradient, at different densities, sample shapes and gas temperatures.

- Applying negative axial magnetic field gradients we observed magnon modes of exchange origin, caused by the ISR effect. These modes do not depend on the sample shape, and are not pure standing waves.

- We found a spectrum of magnon modes trapped in the magnetic field maximum. At high enough gas densities we observed excessive occupation of the ground state in this trap, with long coherent precession of magnetization, similar to the HPD in experiments with liquid ^{3}He.