A POTASSIUM VAPOR MAGNETOMETER OPTICALLY PUMPED BY A DIODE LASER

N. Beverini[a,b], E. Alzetta[a], C. Carmisciano[b], O. Faggioni[b], F. Francesconi[a], E. Maccioni[a]

[a]*Dipartimento di Fisica dell'Università di Pisa, and INFM (Italy)*
[b]*Consorzio Universitario della Spezia (Italy)*

INTRODUCTION

The magnetometer, that is described here, has been developed to be used in geomagnetic surveys. Since optical pumping was proposed by Kastler (1), as a powerful method to produce large changes in the relative population of Zeeman sublevels or hyperfine levels of the ground states of atoms through optical irradiation, the precise measurement of weak magnetic fields has been one of the many practical application. A number of optically pumped magnetometers are currently in use for the measure of the geomagnetic fields near the earth surface, in the earth magnetosphere, or of planetary and interplanetary fields in the outer space. The ground state of alkali atoms is particularly suitable for this kind of application; in particular, devices working with cesium have been commercially developed and are currently in use from many years.

ALKALI VAPOR OPTICALLY PUMPED MAGNETOMETERS

Essentially, an optically pumped atomic magnetometer measures the Zeeman splitting of an atomic state, which is approximately proportional to the magnetic field value. In 1957 Bell and Bloom (2) analyzed the possible operating schemes for measuring the Zeeman resonance frequency. In the first one (*locked magnetometer* or M_z *magnetometer*) the atomic sample is optically pumped in the direction of the static magnetic field (z-direction), and a VCO is phase-locked to the transition. In the second scheme (*self-oscillating magnetometer* or M_x *magnetometer*) the atomic sample is pumped in a direction transverse to the static magnetic field (at an angle close to 45°). If a resonant rf field drives in phase the precession motion of the oriented atoms, a macroscopic rotating magnetic moment is generated, that modulates the atomic sample transmission. By sending the amplified photodiode signal in positive feedback on the rf coils, a self-oscillating system at the Larmor frequency is thus generated. A third scheme is also possible, in which no rf. field is applied to the cell while the light source is modulated in amplitude at the resonance frequency (3). This scheme suffers however of a theoretical signal-to-noise ratio a factor 2 lower than in the other two cases.

In the presence of an external magnetic field **B**, the frequencies of the Zeeman transitions in an alkali atom with a nuclear spin *I* are given by the well known Breit-Rabi formula:

$$\nu_{F,m_F \to F,m_F-1} = g_I \frac{\mu_B}{h} B \pm$$
$$\frac{W}{2}\left[\sqrt{1 + \frac{4m_F}{2I+1}x + x^2} - \sqrt{1 + \frac{4(m_F-1)}{2I+1}x + x^2}\right] \quad (1)$$

where $F = I \pm 1/2$ is the total angular momentum of the two hyperfine levels of the ground state, W is the hyperfine frequency separation, g_J and g_I are the electronic and the nuclear Landé factors, μ_B is Bohr's magneton, and
$x = (g_J - g_I)\mu_B \cdot B / hW$.

Eq. (1) can be expanded in series of powers as:

$$\nu_{F,m_F \to F,m_F-1} =$$
$$\gamma_F B + \alpha_m^{(2)} \cdot \gamma^{(2)} B^2 + \alpha_m^{(3)} \cdot \gamma^{(3)} B^3 + \dots \quad (2)$$

where $\gamma_F = \frac{\mu_B}{h}\left[(g_J - g_I)/(2I+1) + g_I\right]$,

$$\gamma^{(2)} = \frac{1}{W}\left(\frac{\mu_B}{h}\frac{g_J - g_I}{2I+1}\right)^2,$$

$$\gamma^{(3)} = \frac{1}{W^2}\left(\frac{\mu_B}{h}\frac{g_J - g_I}{2I+1}\right)^3,$$

$$\alpha_m^{(2)} = (1 - 2 m_F),$$

$$\alpha_m^{(3)} = 2\left(1 - 3m_F + 3m_F^2\right) - \frac{1}{2}(2I+1)^2.$$

The most important parameters for the naturally available isotopes of Cs, Rb and K are reported in Table I.

The presence of non-linear terms produces a slight difference between the frequencies of the Zeeman transitions. Cesium has the largest hyperfine structure, and thus the smallest $\gamma^{(2)}$ factor, while the opposite appears for the two potassium isotopes. At a typical earth field level ($B \approx 50000$ nT) the separation between two nearby transitions is 6.67 Hz and 958.3 Hz in the case of Cs and ^{41}K, respectively.

Because the typical linewidth of the Zeeman transitions in a magnetometer is in the range 10 - 100 Hz, in the case of Cs the different transitions overlap, producing a non-symmetrical profile with the peak shifted in frequency. The relative weight of the different transitions is a complex function of all the physical conditions of the magnetometer (temperature of the vessel, intensity of the pumping source, relative alignment of the magnetometer and the local magnetic field, ...), this effect is the source of relative large errors, of the order of 10 nT or more. A skilled design of the magnetometer allows to compensate this asymmetry by combining the signals of two apparatus acting with opposite polarization (4). This design, in the self-oscillating scheme is applied to the commercial Cs magnetometers. The exact balance between the two signals is

however critical and limits the accuracy to some hundreds pT, while the sensitivity can be up to three order of magnitude better. ^{87}Rb magnetometer is very similar, but a bit more sensitive because of the doubled gyromagnetic ratio. On the contrary, in the case of K, it is quite easy to obtain well resolved lines, and a very good laboratory self-oscillating magnetometer was realized by Alexandrov and al. (5).

The choice of Cs or Rb for commercial application is due to the difficult operation of K low pressure spectral lamp, because its vapor attacks and darkens usual glasses, reducing the lifetime of the lamp. Moreover, the two fine components of an alkali atom resonance line D_1 and D_2 pump the vapor in opposite directions, imposing a filtering. This can be easily done for Cs and Rb, but it is rather difficult for K, whose fine structure is only 3 nm.

The use of a diode laser as optical source overcomes all these difficulties connected with potassium spectral lamps.

EXPERIMENTAL APPARATUS

The experimental apparatus is schematized in fig. 1. Our magnetometer uses a single mode diode laser, working in free-running mode. The radiation is tuned at the exact wavelength of the potassium D_1 line (769.9 nm), by carefully controlling the temperature and the current in the diode. Low power lasers, developed for compact disk drivers, are suitable for our apparatus. The diode laser is connected to the probe by a 15 m long multimode optical cable. The radiation exiting the cable is circularly polarized and sent in the vapor cell, parallel to its axis, as a cylindrical beam of about 15 mm of diameter. The transmitted radiation is focused on a silicon photocell.
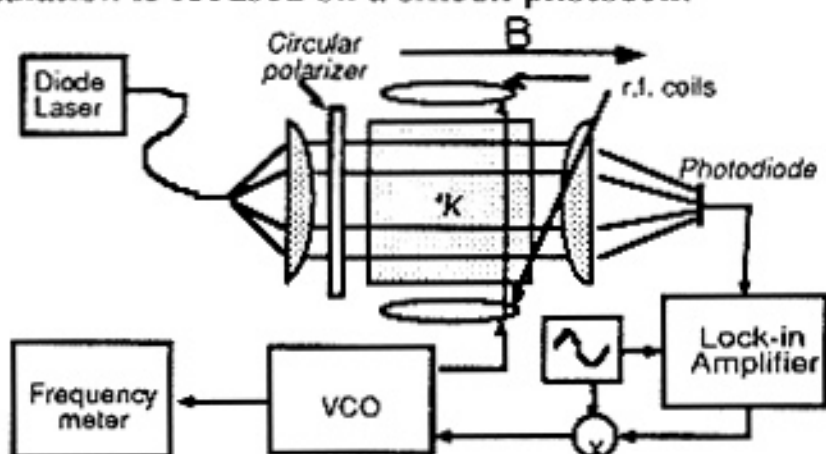

Figure 1: Experimental apparatus

The magnetometer works presently in the locked configuration. The resonant rf, produced by a frequency sinthetizer, is applied to the vapor cell by a couple of Helmotz coils, placed orthogonally to the cell axis. A frequency modulation at 10 - 20 Hz is superimposed to the rf, and the in-phase signal is detected through a lock-in amplifier. The lock-in ouput is sent to control the synthetizer frequency through a servo loop with an attack time variable between 400 ms and 2 s.

The probe is a sealed off Pyrex cell, 25 mm in length and 22 mm in diameter, filled of atomic potassium by vacuum distillation. In order to avoid the fast relaxation of the atomic spin in the collision against the walls, we added a diamagnetic buffer gas. We chose to use nitrogen, that is also very effective in quenching the fluorescence from the excited K atoms, thus avoiding the presence of resonance radiation, that could perturb the pumping process. A N_2 pressure of the order of some kPa produces also a broadening of some hundreds MHz (6), that is of the same order of the hyperfine structure and of the Doppler thermal linewidth. Thus, each atom can interact with the radiation, independently from its velocity and its hyperfine level, increasing the optical pumping efficiency. The cell is warmed by a antiinductive wired resistor, powered in a.c. at a frequency ($\approx$1.5 kHz), high enough to avoid interference with the optical pumping, and the temperature is controlled with a precision better than 0.1 °C.

Preliminary we measured the relaxation time of the potassium spin orientation at different N_2 pressures (Fig. 2) in identical cells, in order to find the optimum pressure values. Some cells were previously coated by a silicon diamagnetic film. This coating appears effective in reducing the relaxation rate, avoiding the use of a too high buffer gas pressure and a consequent too large line broadening. The coated cells, however, present a lower K vapor pressure at a given temperature and have a working temperature higher of almost 10 -20 °C.

Finally, we have made as magnetometer probe a coated cell, filled with isotopically enriched potassium (99.17% ^{41}K and 0.83% ^{39}K) in presence of 6.1 kPa (at 0°C) of N_2.
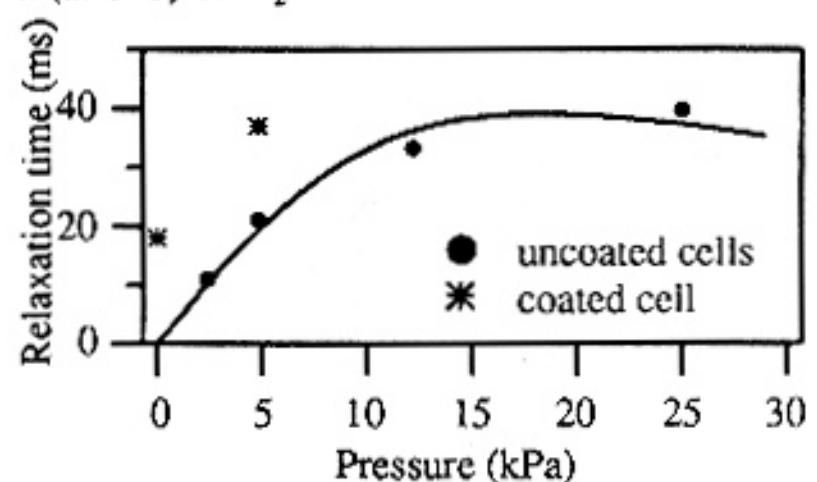

Figure 2: Relaxation time as a function of the pressure.

EXPERIMENTAL RESULTS

The whole Zeeman spectrum, recorded by sweeping the rf around the resonance and detecting directly the photodiode signal in a cell filled with natural K (91% ^{39}K and 9% ^{41}K), is shown in Fig. 3. The pumping power is about 10 μW, while rf power is about -55 dBm. The absorption signal shows the well resolved different Zeeman components of ^{39}K and ^{41}K. We observe a resonance linewidth $\Delta v \leq 80$ Hz, limited by the field dishomogeneity.
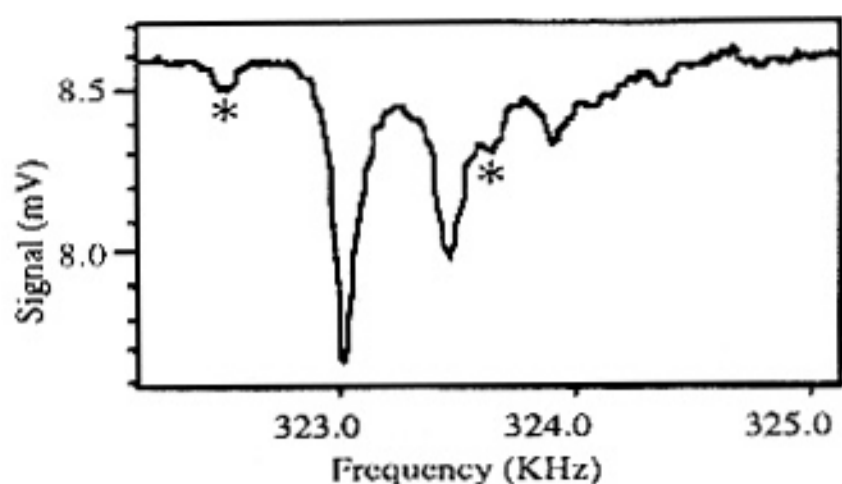
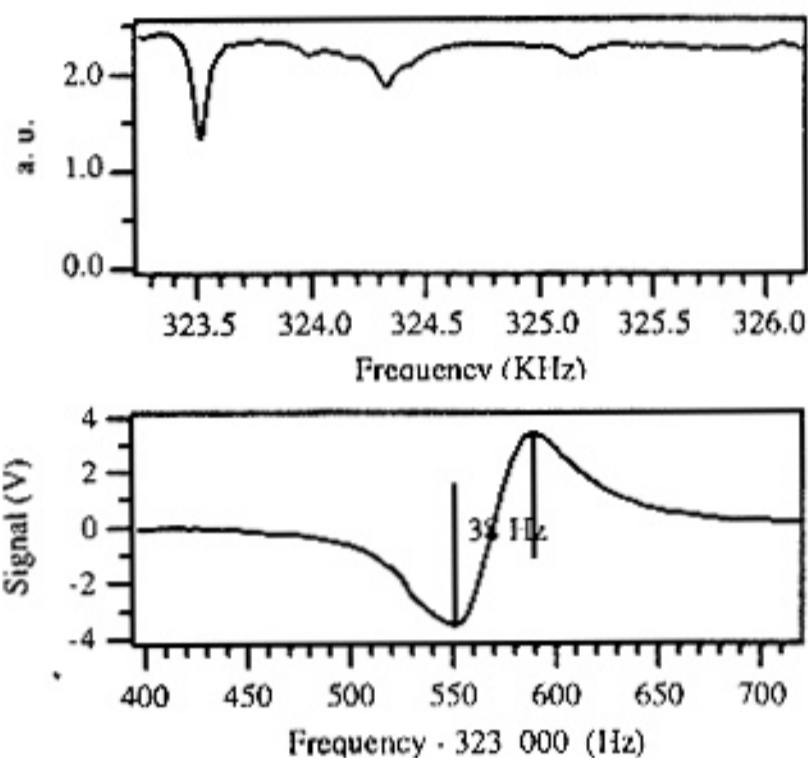Figure 3: Absorption spectrum in a cell with natural potassium. ^{41}K transition are indicated by *.

Figue 4: upper side, the Zeeman spectrum of the ^{41}K; lower side, the magnetometer transition.

By using isopically enriched potassium in a magnetically cleaner location, the spectrum of Fig. 4 was obtained. The derivative signal obtained from the lock-in amplifier (at rigth) demonstrate a linewidth of the order of 38 Hz. The actual values of the linewidth and of the S/N ratio gives an instrumental sensitivity $(\delta B)_{min} \approx 1.5 \, pT \cdot Hz^{-1/2}$.

The magnetometer has been tested in a location satisfying the condition for a magnetic observatory for a period of 60 minutes. The integration time of the loop was choosen of the order of 1 s, and the geomagnetic field value was read every 2 s. The recorded magnetogram is shown in Fig. 5, together with the magnetogram recorded by a commercial proton resonance magnetometer, whose sample time was setted at 1 minute. The probes of the two instru-

ments were kept quite far (≈ 10 m) one from the other, in order to avoid reciprocal perturbation, and this explicates the small difference in the readings.

CONCLUSION

Work is in progress in order to build a magnetometer in self-oscillating configuration. The apparatus appears particularly suitable for application of the kind of field gradient measurement. In this case a single diode laser may pump two identical cells, placed at a fixed distance. The different sources of unaccuracy of the field reading (ligth shift, pressure shift, frequency pulling by the nearby transition,...) are then identical. With a distance between the two probes compatible with a portable instrument, gradient sensitivities better than 1 pT/m can be easily achieved.

REFERENCES

(1) A. Kastler: Prodution et détection optique d'une inégalité de population, J. Phys.Rad. 11, 255-265 (1950)

(2) W.E. Bell, and A.L. Bloom: Phys. Rev. 107, 1559 (1957)

(3) W.E. Bell, and A.L. Bloom: Phys. Rev. Lett. 6, 623 (1961)

(4) T. Yabuzaki, and T. Ogawa: Frequency shifts of self-oscillating magnetometer with cesium vapor, J. Appl. Phys. 45, 1342-1355 (1974)

(5) E.B. Alexandrov, M.V. Balabas, V.A. Bonch-Bruevich, S.V. Provotorov, and N.N. Jacobson: Fast optically pumped potassium magnetometer of high precision, in Geomagnetics Measurements and devices, pp. 5-23. Moscow, IZMIRAN (1986); E.B. Alexandrov, V.A. Bonch-Bruevich: Optically pumped atomic magnetometers after three decades, Opt. Engin. 31, 711-717 (1992)

(6) N. Allard and J. Kielkopf: The effect of neutral nonresonant collisions on atomic spectral lines, Rev. Mod. Phys. 54, 1103-1182 (1982)
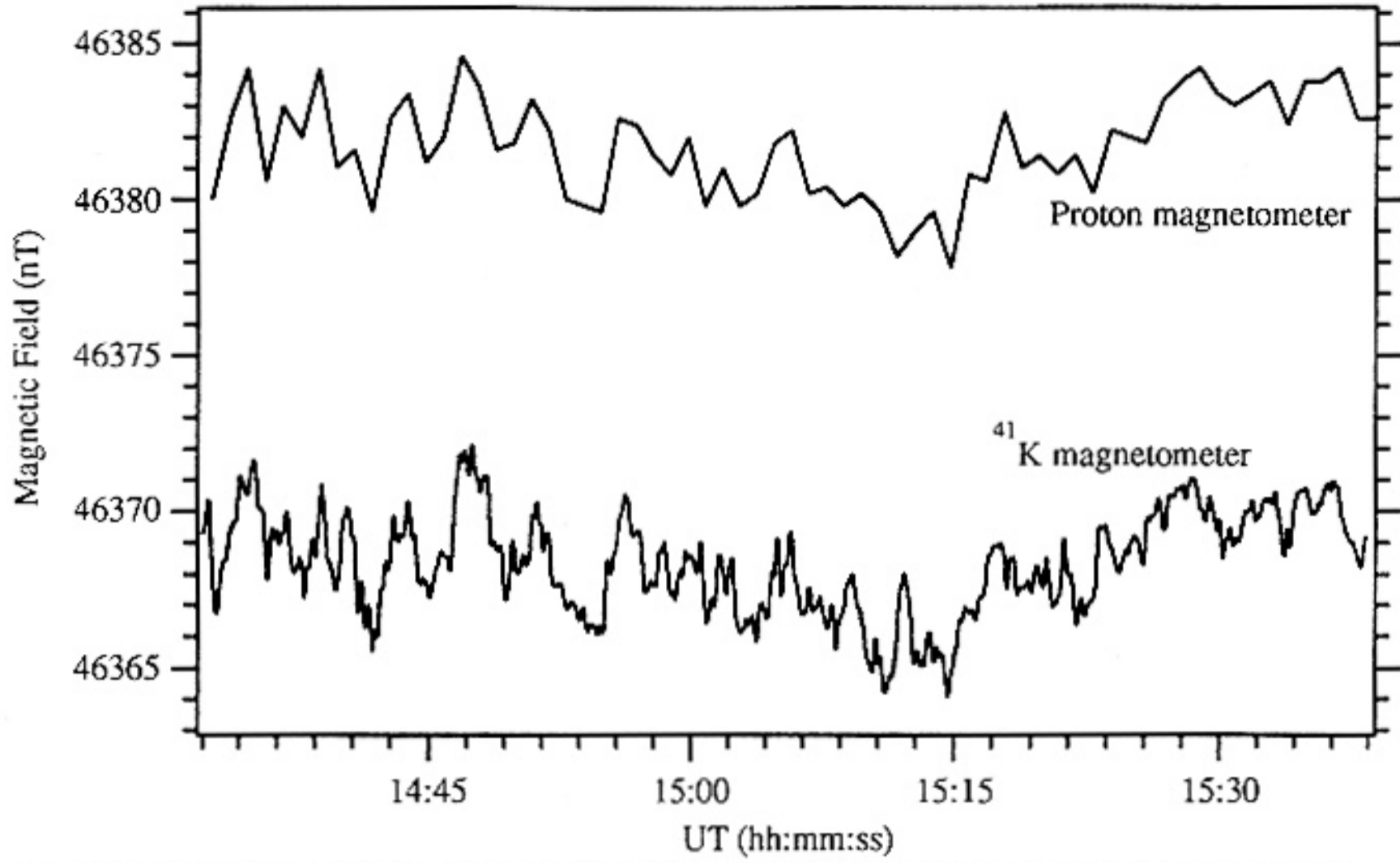
JULIAN DAY 1998.26

Figure 6: Magnetogram recorded by potassium magnetometer in locality Corvara (La Spezia, Italy)

TABLE I - Ground state alkali atoms parameters important for magnetometric application.

	C s	^{85}Rb	^{87}Rb	^{39}K	^{41}K
I	7/2	5/2	3/2	3/2	3/2
W (MHz)	9192.631770	3035.732439	6834.682613	461.7197202	254.013871
g_J	2.00254032	2.00233113	2.00233113	2.00229421	2.00229421
g_I	$-3.9885395 \cdot 10^{-4}$	$-2.936400 \cdot 10^{-4}$	$-9.951414 \cdot 10^{-4}$	$-1.4193489 \cdot 10^{-4}$	$-0.779060 \cdot 10^{-4}$
γ_F (Hz/T)	$3.49862 \cdot 10^9$	$4.66743 \cdot 10^9$	$6.99583 \cdot 10^9$	$7.00466 \cdot 10^9$	$7.00533 \cdot 10^9$
$\gamma^{(2)}$(Hz/T^2)	$1.33579 \cdot 10^9$	$7.18879 \cdot 10^9$	$7.18932 \cdot 10^9$	$1.06327 \cdot 10^{11}$	$1.93257 \cdot 10^{11}$
$\gamma^{(3)}$(Hz/T^3)	$5.0920 \cdot 10^8$	$1.1062 \cdot 10^{10}$	$7.3735 \cdot 10^9$	$1.6135 \cdot 10^{12}$	$5.3306 \cdot 10^{12}$
v @50000 nT	$\approx$174.90 kHz	$\approx$233.28 kHz	$\approx$349.77 kHz	$\approx$349.43 kHz	$\approx$348.82 kHz
δv @50000 nT	6.67 Hz	35.9 Hz	35.9 Hz	529.2 Hz	958.3 Hz

315