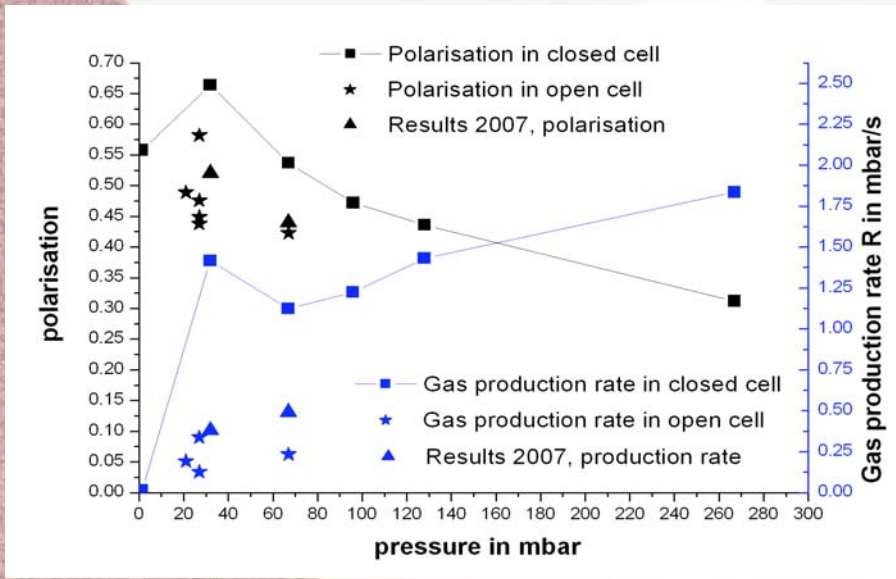
Metastability Exchange Optical Pumping (MEOP) of ^{3}He in situ

Guilhem Collier

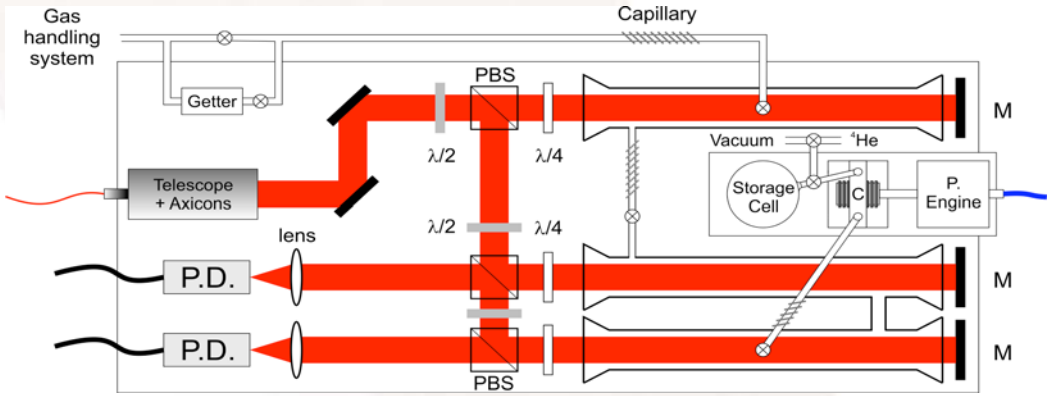
Jagiellonian University

Institute of Physics

Krakow, Poland

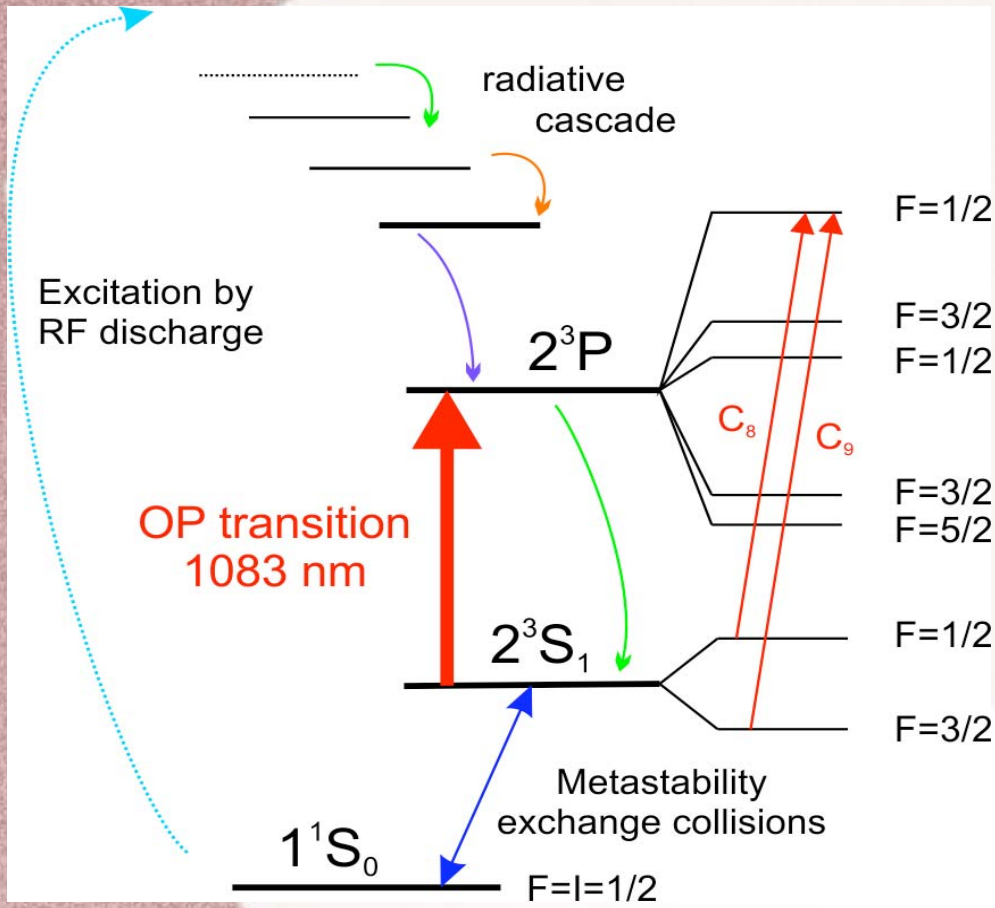


1. Metastability Exchange Optical Pumping theory
2. Upgrade of a low field polarizer
3. Systematic studies of MEOP at high magnetic field
4. High field polarizer



1. MEOP theory

3 step process:



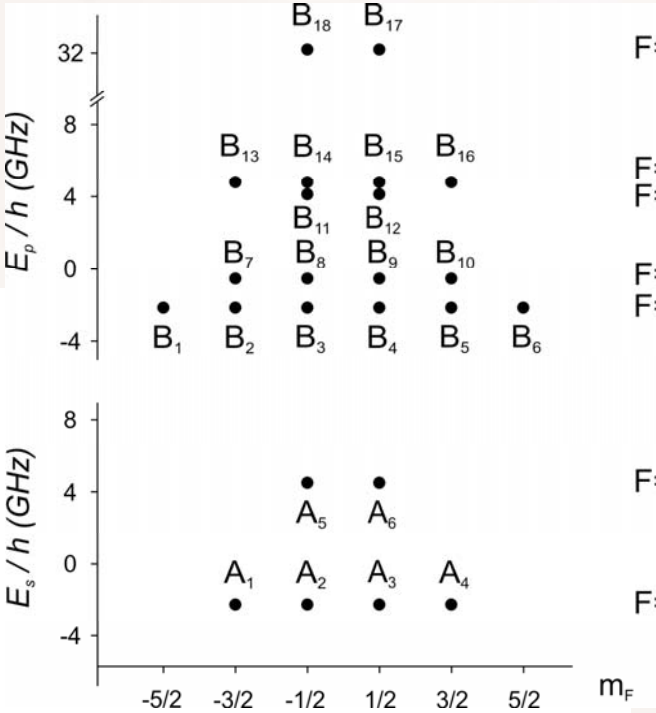
a) weak rf discharge promotes a small fraction (≈ ppm) of atoms into 23S state

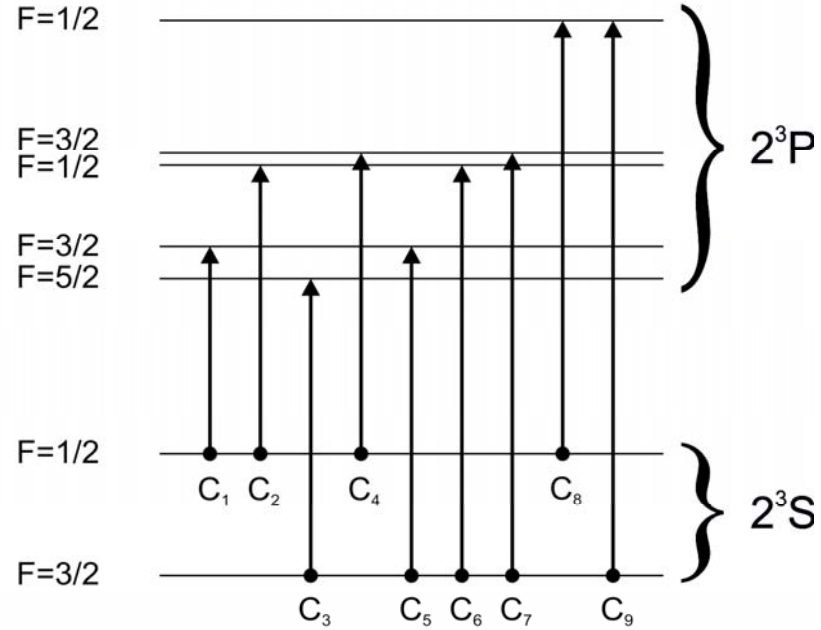
b) OP at 1083 nm simultaneously electronic and nuclear orientation due to hyperfine coupling

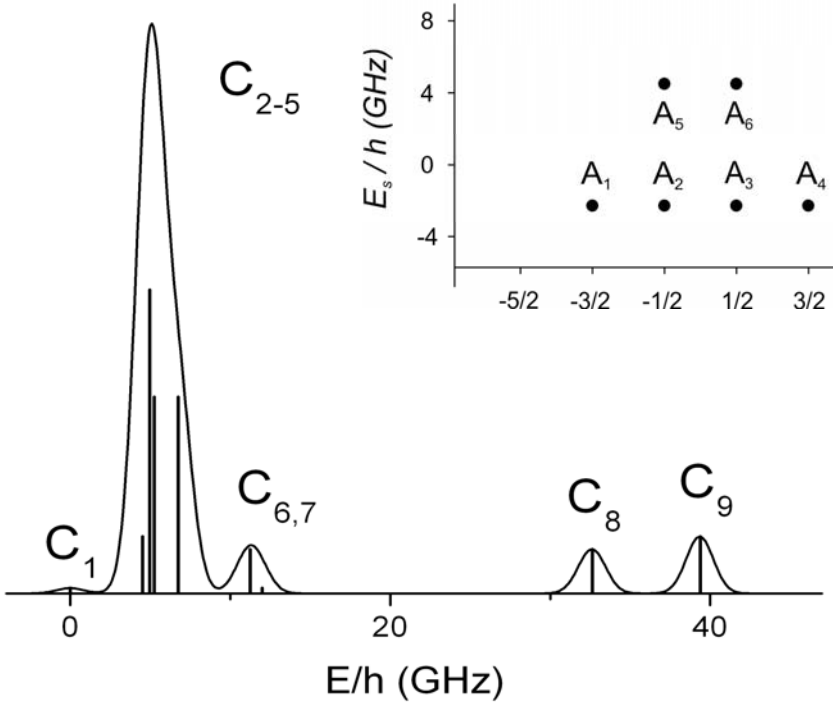
c) ME collisions transfer nuclear polarization into ground state

$$^3He + {}^3He^*_{\uparrow} \rightarrow {}^3He^* + {}^3He_{\uparrow}$$

1. MEOP theory



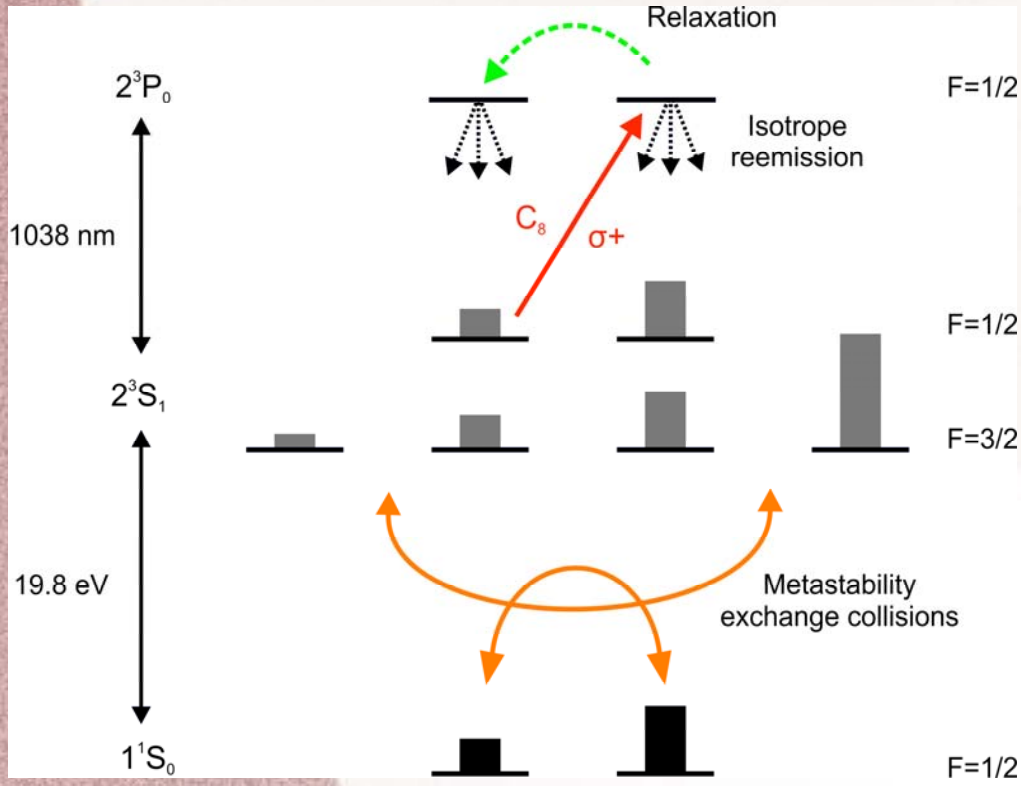




1. MEOP model

Metastability exchange collisions:

$$\left.\frac{da_i}{dt}\right|_{ME} = \gamma_e\left(\sum_{k=1}^{6} a_k(E_{ik} + MF_{ik}) - a_i\right)$$



Optical pumping:

$$\left.\frac{da_i}{dt}\right|_{OP} = \gamma\sum_{j=1}^{18} T_{ij} b_j + \sum_{j=1}^{18}\gamma_{ij}\left(b_j - a_i\right)$$

$$\left.\frac{db_j}{dt}\right|_{OP} = -\gamma b_j + \sum_{i=1}^{6}\gamma_{ij}\left(a_i - b_j\right)$$

Relaxations:

$$\left.\frac{da_i}{dt}\right|_{r} = \gamma_r^S\left(\frac{1}{6} - a_i\right)$$ in 2^3S

$$\left.\frac{db_j}{dt}\right|_{r} = \gamma_r^P\left(\frac{1}{18}\sum_{k=1}^{18} b_k - b_j\right)$$ in 2^3P

$$\frac{dM}{dt} = \Gamma_e\left(M^* - M\right) - \Gamma_g M$$

$$\Gamma_g = \Gamma_{dis} + \Gamma_{dd} + \Gamma_w + \Gamma_{mag}$$

1. MEOP theory

MEOP in **Standard conditions**:

Low pressure ≈ **mbar**
Low magnetic field ≈ **mT**
Polarization up to **80 - 90%** in sealed cell, **30 - 75%** in production systems but ≈ 1 mbar (**high compression factor, low density efficiency**)

Main drawbacks of existing polarizers:

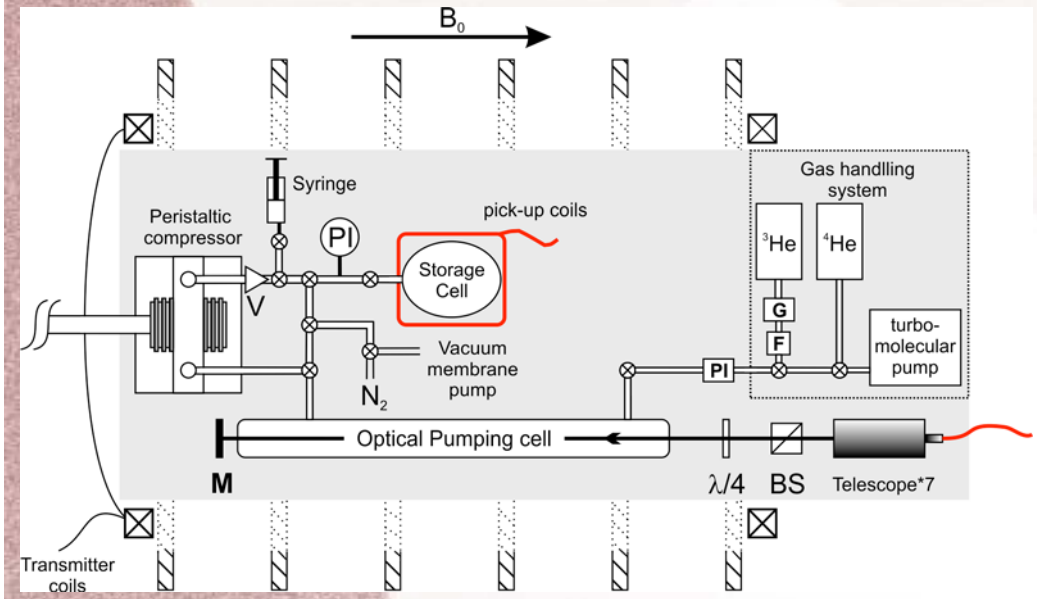
- High efficiency in Mainz but **bulky** system
- Compact in-situ polarizer in Paris but **low throughput** of few scc/min (scc: standard cubic centimeter)
- New compact system in Mainz ? High technology piston compressor for which **price** ?

Two important parameters: Polarization M and production rate R (mbar/s)

$$R = \frac{M \cdot \text{gas pressure}[\text{mbar}]}{t_b}$$

In low field best conditions:
R ≈ 0.16 mbar/s

2. Upgrade of a low field polarizer



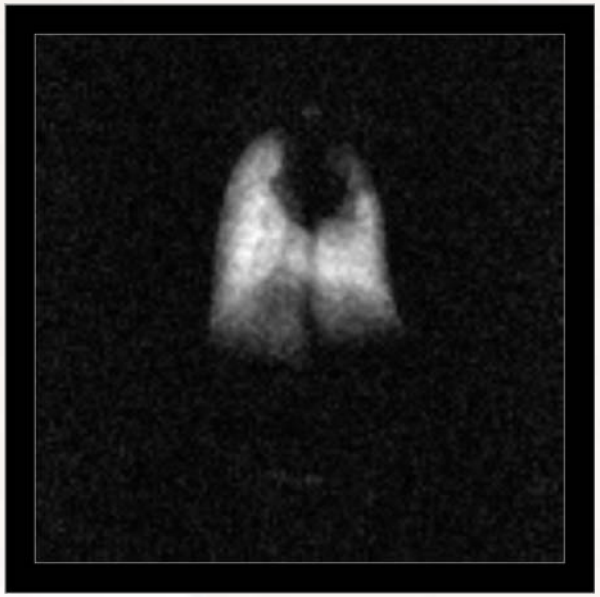
- Design similar to Protlab in Paris
- More homogeneous guiding field
- New NMR more sensitive and calibrated with optical absorption method
- New storage cell (longer T1), OP cell
- New Laser 10W Keopsys
- New design of peristaltic compressor higher efficiency, easier to replace tube
- 30% < M < 40%
- Gas flow: **3 < f < 5 scc/min**

⇒ 2-4 min for rat, => 1h for human

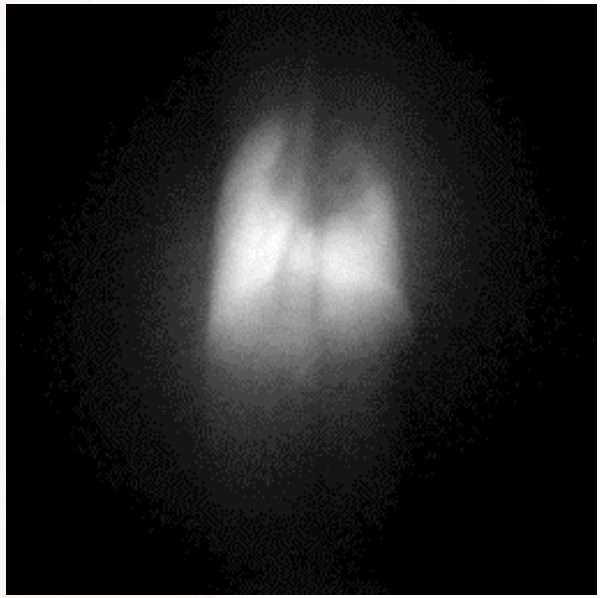
Results sent to review to Optica applicata

2. LFP applications: small animal experiments

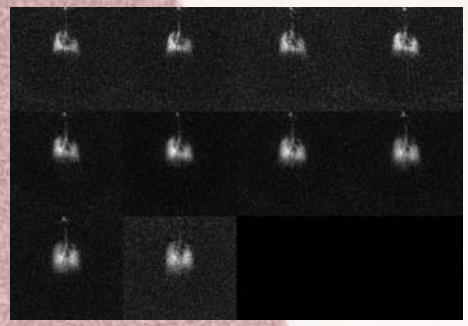
NMR signal improved by a factor of 20



Flash
FOV 80mm 128*128
SW=10kHz



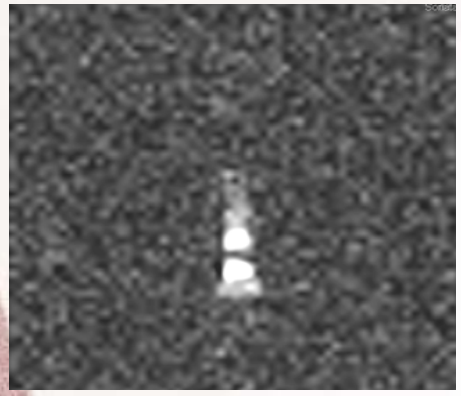
Radial
FOV 80mm SW=10kHz
128 samples per 200 Views



fast version of the radial imaging Sequence (SW=33 kHz, FOV=100 mm, 128 samples per 100 views)

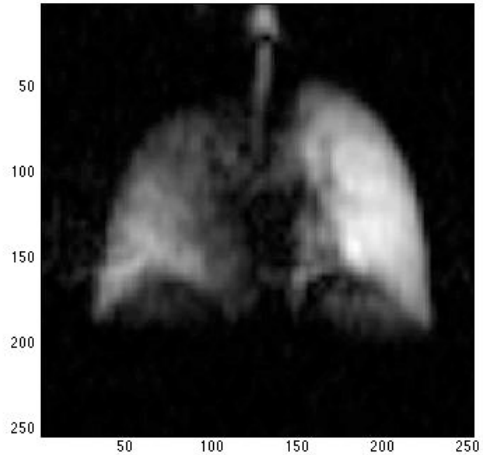
2. LFP applications: small animal experiments

. Acces to the sonata 1.5T scanner in John Paul II hospital since last September
. Birdcage coils from RAPID Biomedical for ^{3}He and ^{129}Xe
. 1st fantom: 250mL cell with 1.36 bar ^{3}He and 0.440 O_2
→ validation of coils and calibration of flip angle.



Programmation of a flash multislice sequence
Test with a sealed cell of 128 mbar, 20 mL polarized on site

Validation of transport box from Mainz

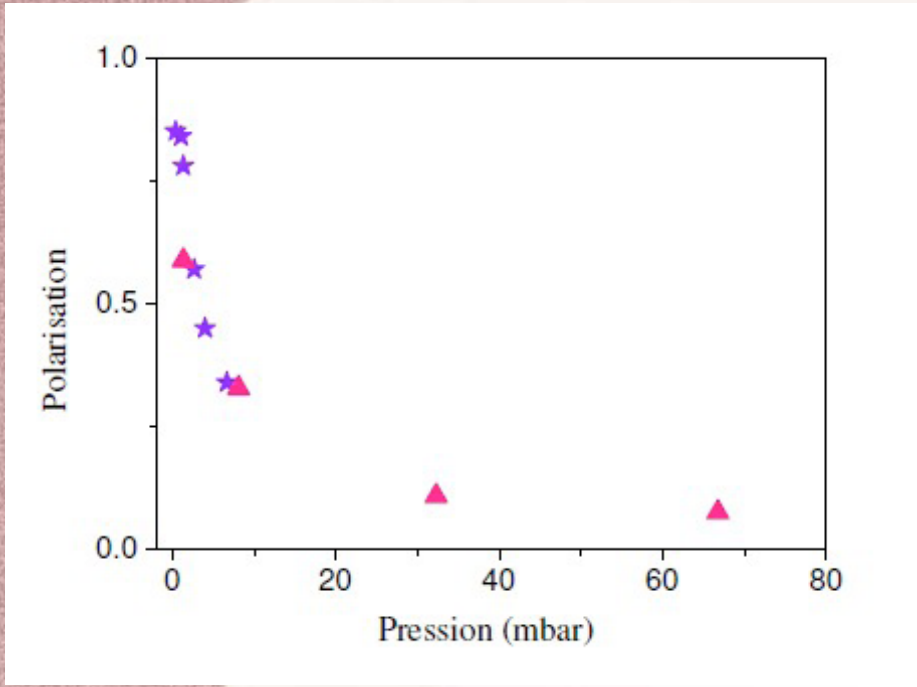


1st human lung picture made in Poland with ^{3}He
(Flash, 64*64, 400*400mm)

3. Systematic studies at high magnetic field

Why going to high field ?

In low field



Abboud Thesis, 2005

Stars: Results published in Gentile 93, 4.5 W

Triangles: C_9 Abboud, 2W

At higher pressure (> 10 mbar) metastable atoms density is reduced due to the increase of ionizing Penning collisions

He* + He* ---> He + He+ +e-

And the increase of 3-body collisions with conversion into a metastable helium molecule

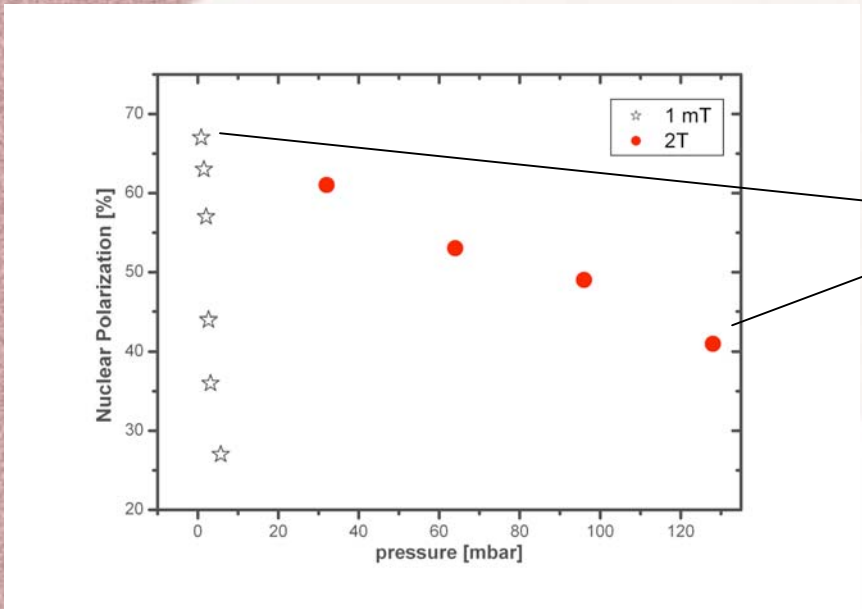
$$He^* + 2He \rightarrow He_2^* + He$$

3. Systematic studies at high magnetic field

JAGIELLONIAN UNIVERSITY IN KRAKOW

Can we polarize at higher pressures ?

Yes, at high magnetic field !



$P^*\rho \approx 90$

Previous results published in Nikiel et al in 2007 (67 mbar):

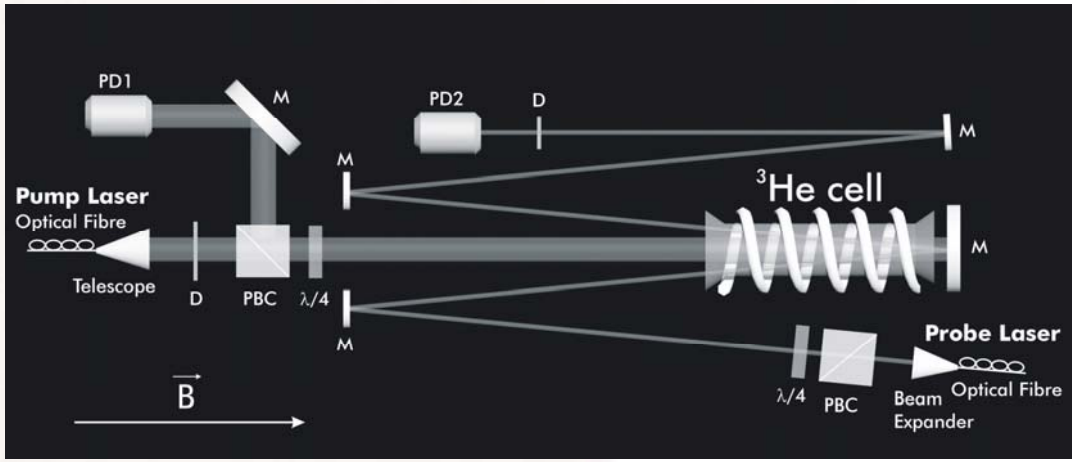
Field [T]	Pump line	M [%]	t_b [s]	T_1 [s]	n_m [at/cm^3]	R [mbar/s]
1.5	$f2^m$	43	84	1934 ±32	$2.4 \cdot 10^{11}$	0.33
	$f4^m$	16	35			0.29
	$f2^p$	30	58			0.33
	$f4^p$	20	42			0.31
2	$f2^m$	51	101	569 ±26	$8.5 \cdot 10^{11}$	0.32
	$f4^m$	31	89			0.22
	$f2^p$	38	80			0.30
	$f4^p$	32	79			0.26

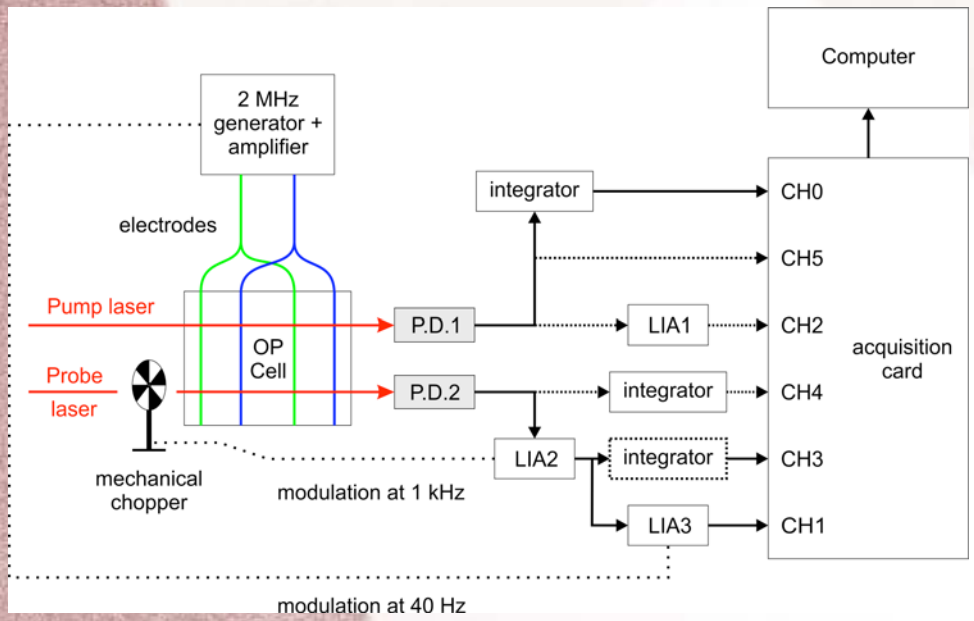
Hyperfine decoupling at high magnetic field inhibits some relaxation channels !

3. Systematic studies at high magnetic field

Systematic experiments carried out:

- at 0.45, 0.9, 1.5, 2 and 4.7 T
- with bone-shape helium cells, 11 cm long, 15 mm diameter
- six different pressures 1.3, 32, 67, 96, 128, 267 mbar
- 3 different discharge conditions
- different laser shapes and powers





Scheme of data acquisition

Double modulation

Close collaboration for data analysis and interpretation of results with Kastler-Brossel Laboratory in ENS, Paris

Optical Measurement of Nuclear Polarisation

Idea of measurement

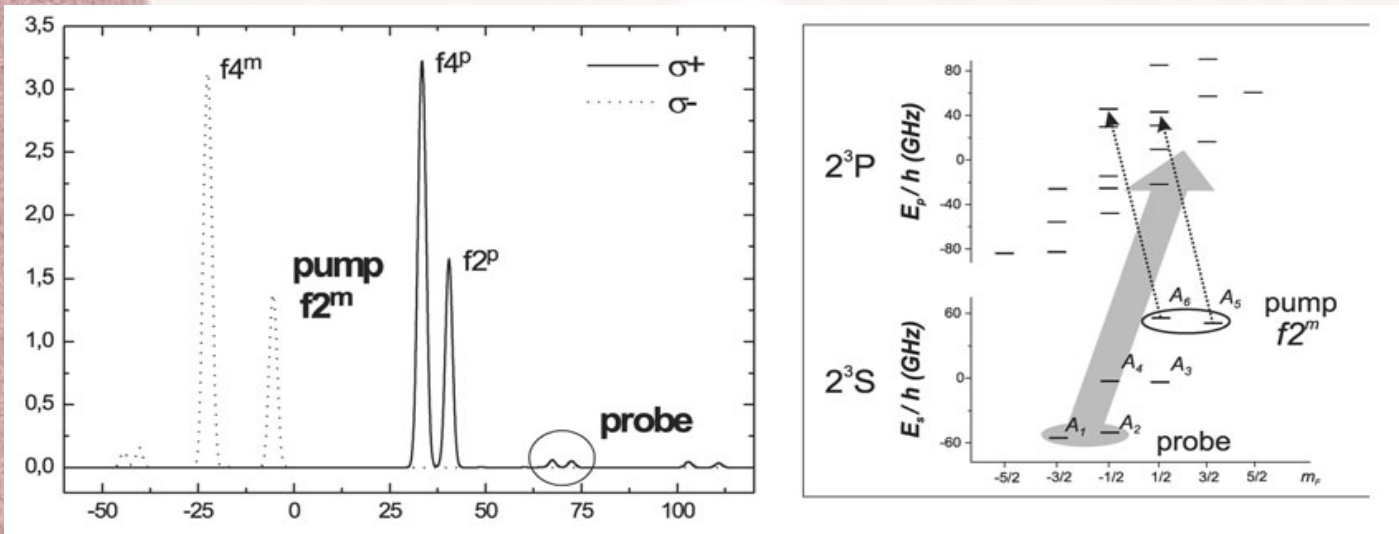
The idea of optical measurement of nuclear polarization relies on absorption measurement of weak probe beam

The populations n_{m_F} of magnetic sublevel m_F of the 2^3S_1

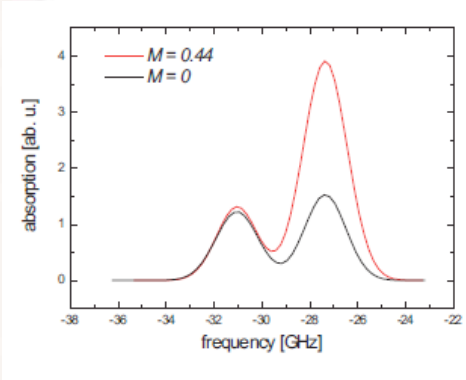
$$N_{m_F} \propto e^{\beta m_F}$$

Where m_F is the magnetic quantum number of total angular momentum and $1/\beta$ represent the spin temperature. Nuclear polarization in the ground state can be determined from folowing form:

$$M = (e^{\beta} - 1)/(e^{\beta} + 1)$$



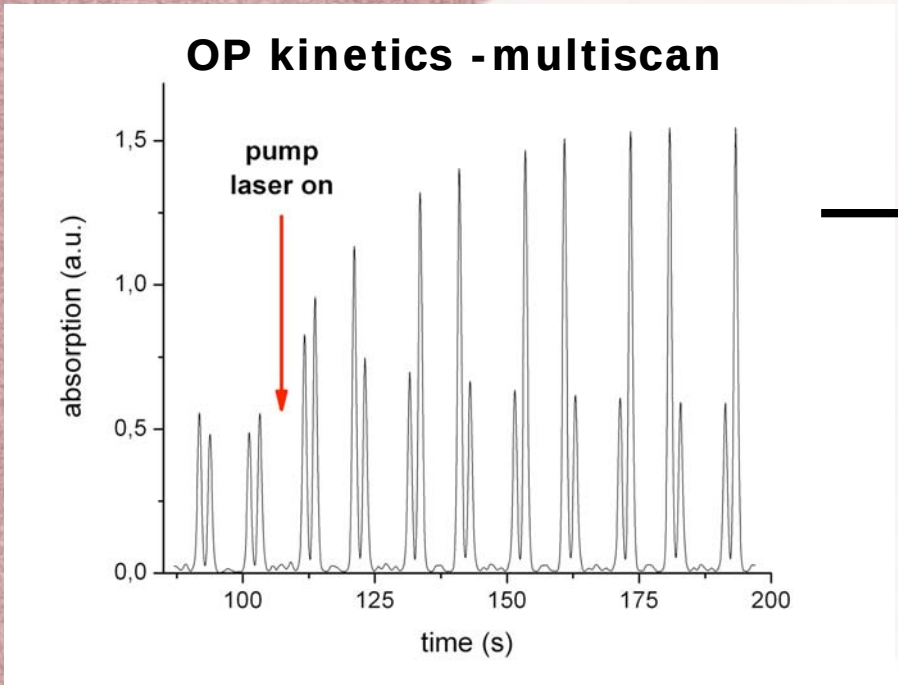
Left: Computed absorption spectra for σ- and σ+ light at 2T (zero is defined as C1 transition frequency at zero magnetic field). Right: 23S-23P hyperfine levels, and the optical pumping and probe schemes for the f2m pumping line.

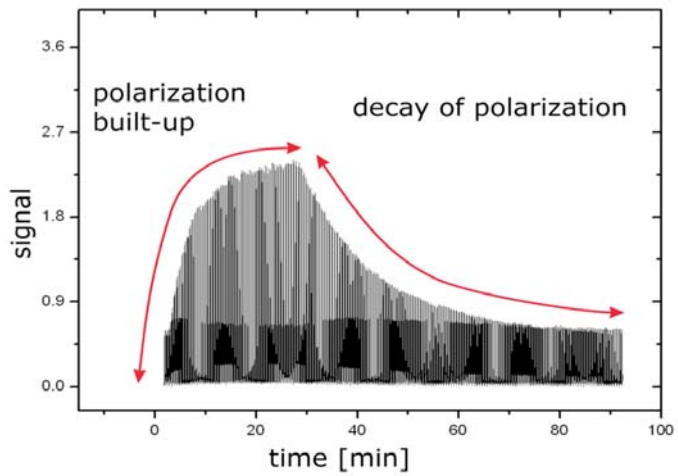


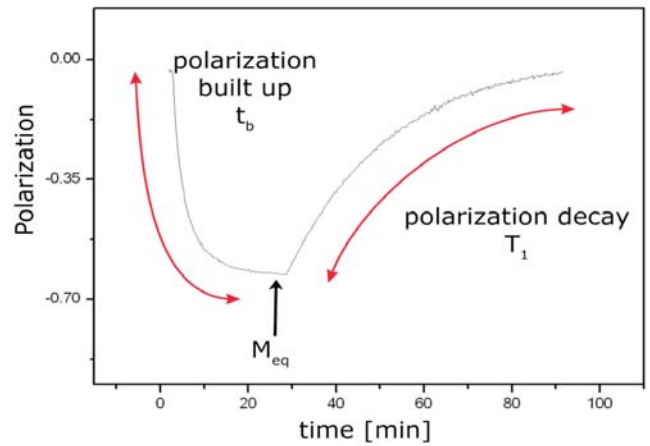
Part of the 3He absorption spectrum containing the probe doublet for M = 0 when the pump is off (black) and for steady state polarization M = 0.44 when the pump is on (red)

Optical Measurement of Nuclear Polarisation

Method:







Optical absorption method offers:

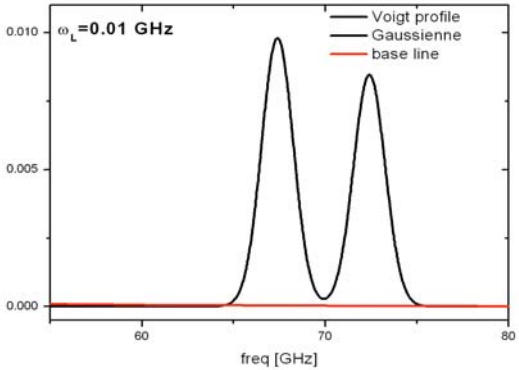
- ✓ high accuracy
- ✓ high signal to noise ratio
- ✓ does not require any calibration

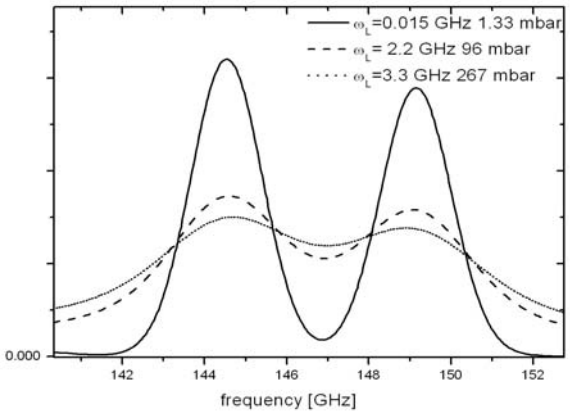
Output parameters:

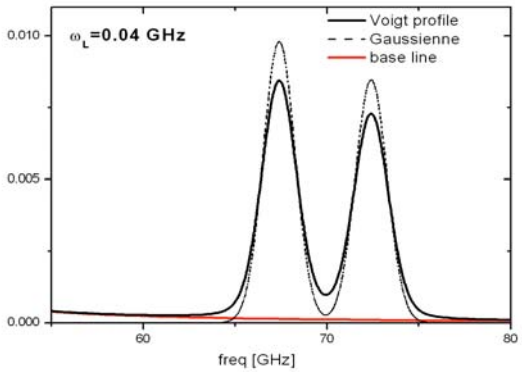
Absorption→nm (pump, probe)

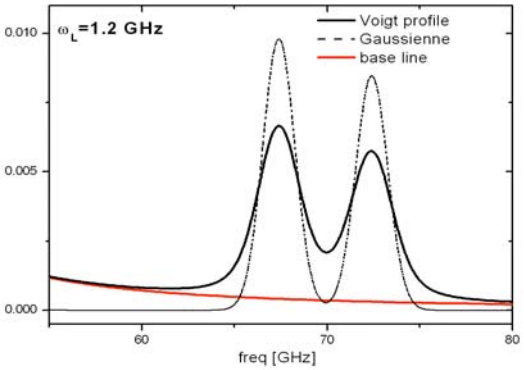
Kinetics→tb, tb(t), T1, M(t), Mstat, R

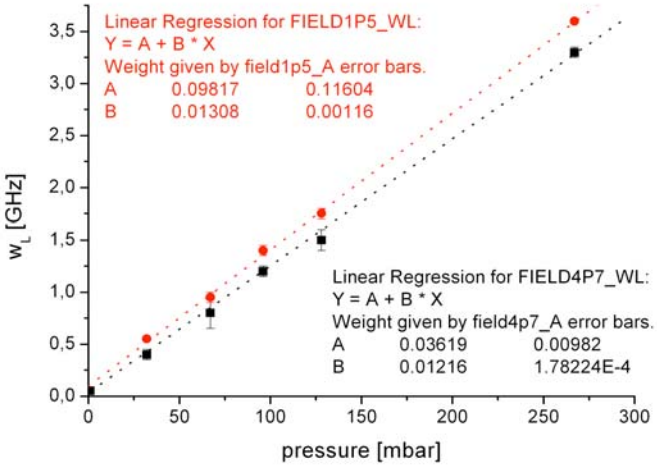
Problems with data processing: Pressure broadening

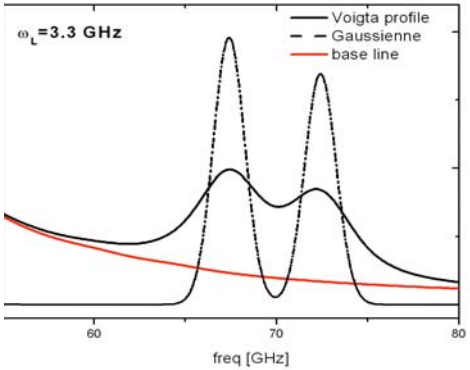






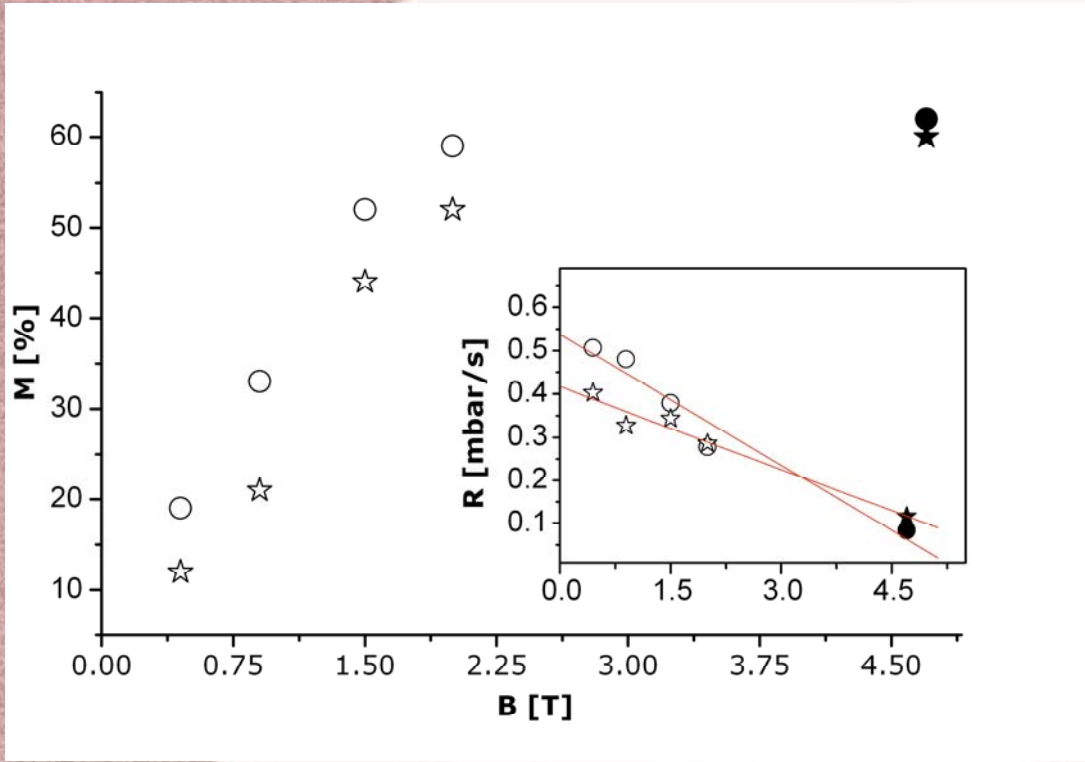






3. Systematic studies at high magnetic field

Magnetic field dependence



Steady state polarization and production rate of optical pumping as a function of magnetic feld B at fixed pump laser power (0.5 W) and weak discharge

Open symbols obtained in our superconducting magnet 0-2 T (Magnex scientific) and solid ones in Bruker 4.7 T (collaboration with insitute of nuclear physics in Krakow)

☆ 67 mbar

○ 32 mbar

Hyperfine decoupling has 2 different effects:

- Mstat increases with magnetic field !
- But efficiency decreases, hyperfine decoupling slows down the build-up process.

- Results obtained with different lasers!

Experimental setup, data analysis and dependence with magnetic field **to be published soon !**

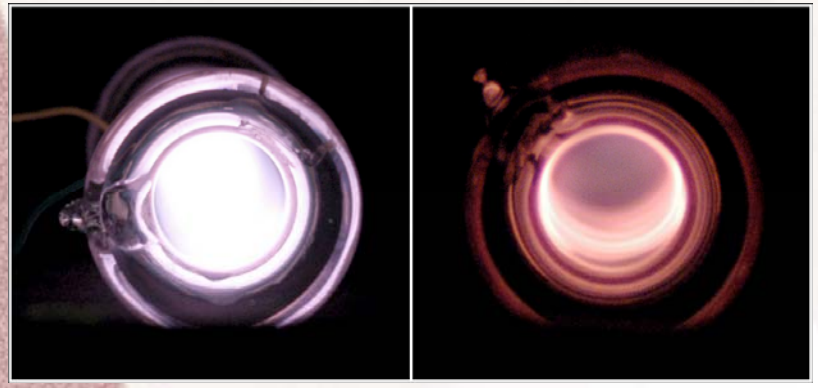
3. Systematic studies at high magnetic field

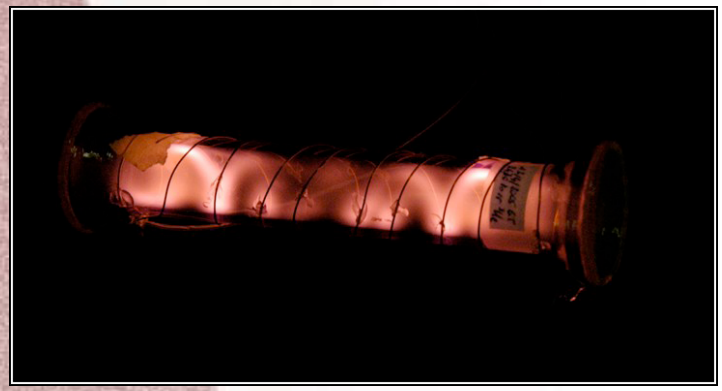
JAGIELLONIAN UNIVERSITY IN KRAKOW

Shaping of the laser beam for improvement of 3He MEOP efficiency at 2 T

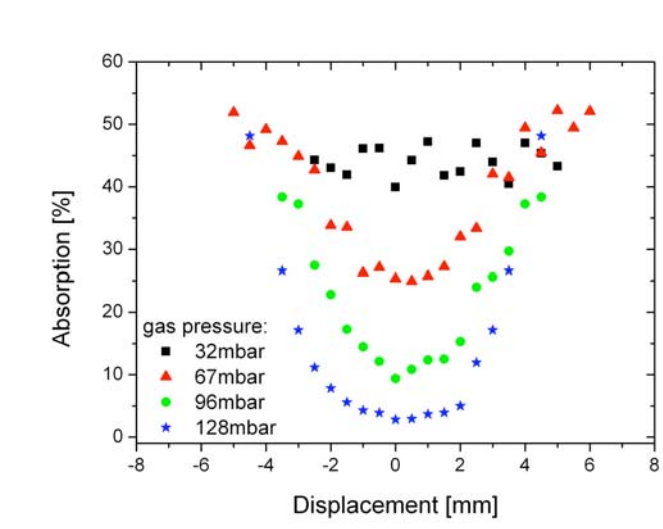
Plasma characteristic

The inhomogeneous distribution of plasma in our experimental cell filled at 1.33 and 32 mbar





Measurement of laser absorption collected for various 3He gas pressures at 2 T

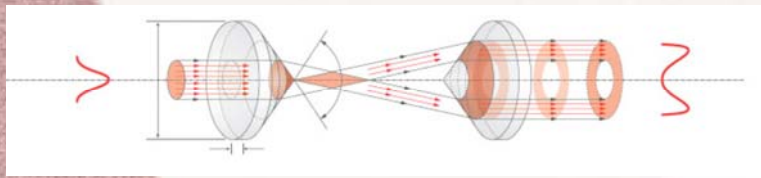


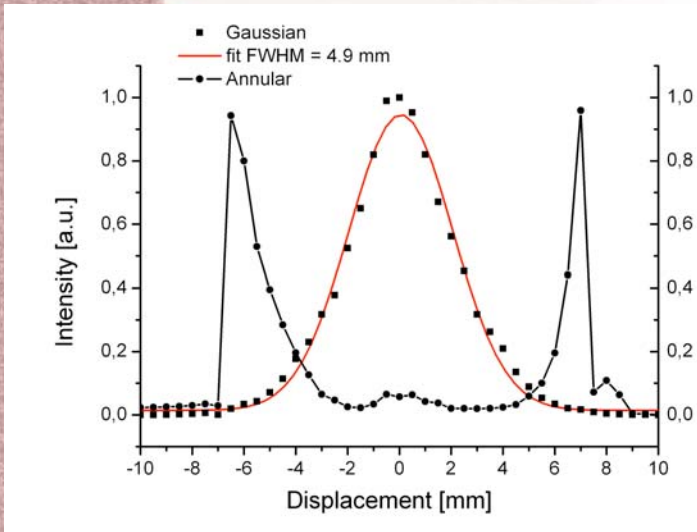
- At higher pressures, plasma molecules and metastable atoms are created in the area of high electric field→close to the electrodes.
- When pressure increases, diffusion of metastable atoms is greatly reduced and absorption of laser matches plasma distribution

3. Systematic studies at high magnetic field

Shaping of the laser beam for improvement of 3He MEOP efficiency at 2 T

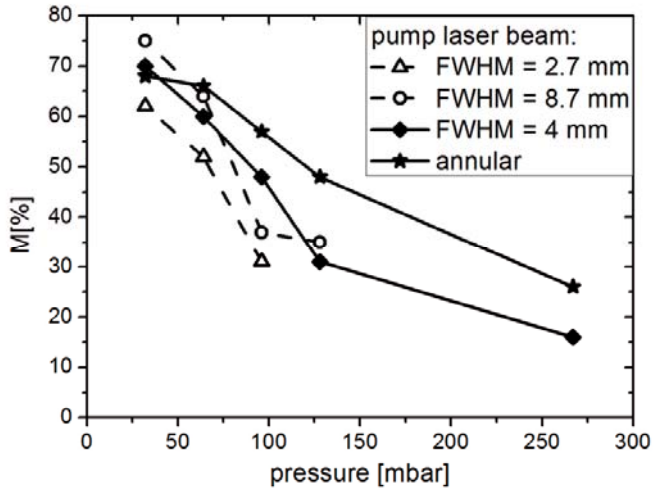
Using pair of axicons to obtain an annular beam shape and match the distribution of metastable state atoms inside the cell

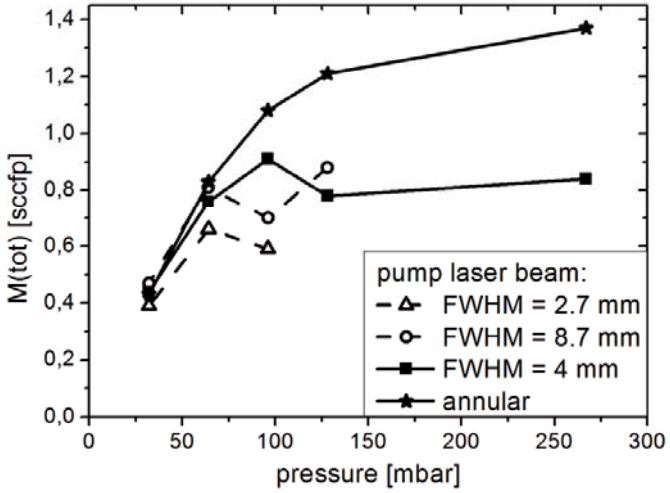




Results of comparative studies performed at 2 T with different linewidth and shape of the pump laser.

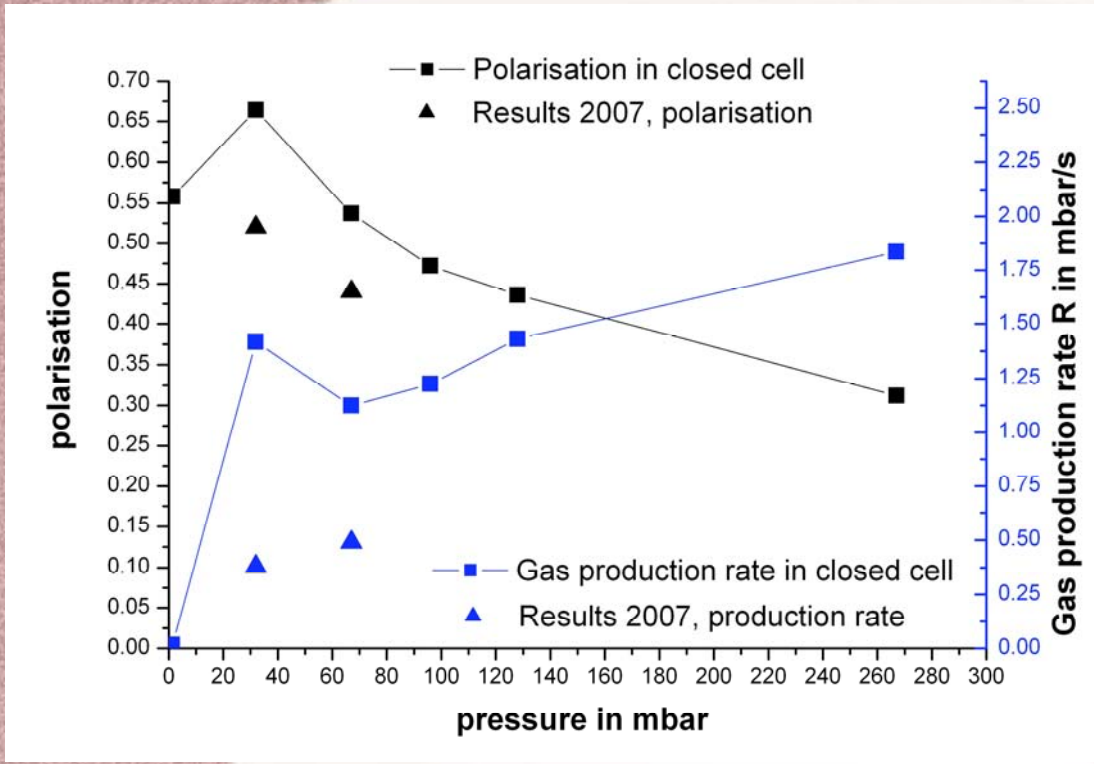
Published in Dohnalik T. & al, *Optimization of the pumping laser beam spatial profile in the MEOP experiment performed at elevated ^{3}He pressures*, The European Physical Journal Applied-Physics **54**, 2011, pp. 20802.





3. Systematic studies at high magnetic field

- Repeat experiments at 1.5 T with optimum laser conditions and new cells



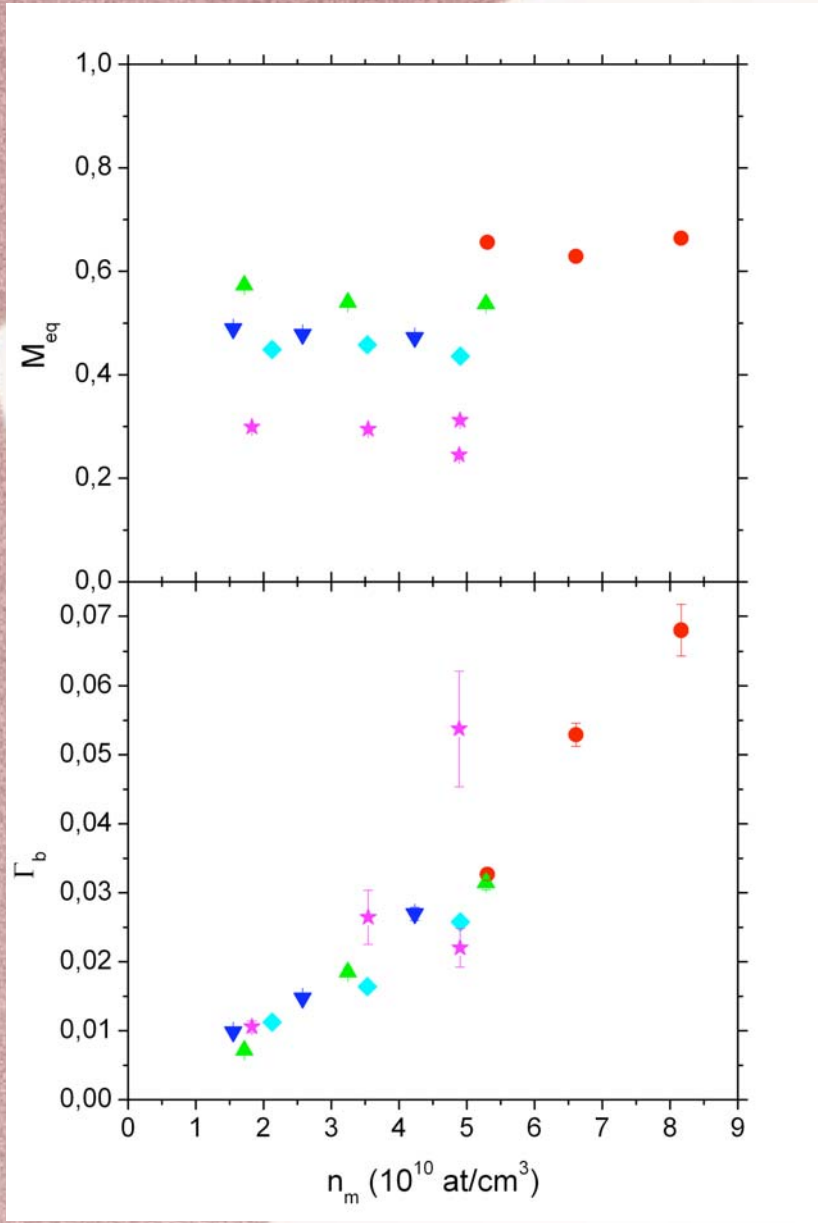
Polarization and production rate vs pressure at 1.5 T with use of axicons

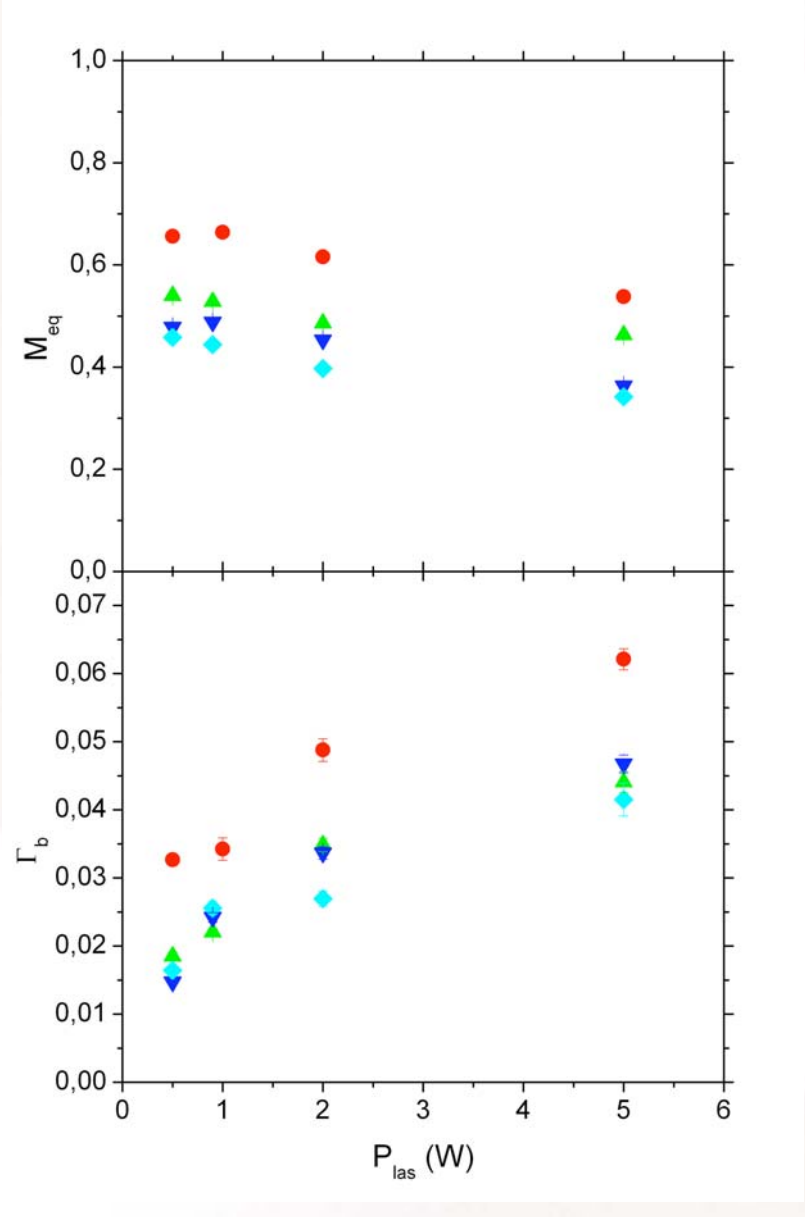
- **25%** increase of Mstat
- Factor 10 increase in efficiency compare to low field !
- 31% achieved at 267 mbar (67% at 32 mbar)
- Axicons not usefull at 1.3 mbar.

→ **compact polarizer for lung imaging applications**

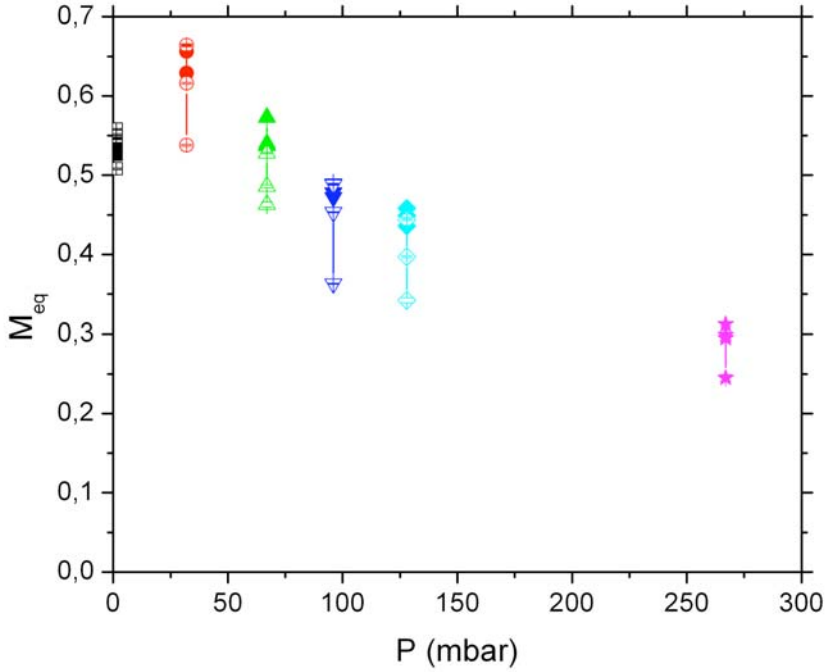
Main idea: Use the guiding field of the most commonly used scanner (1.5T) to produce quickly hyperpolarized ^{3}He for medical applications (lung MRI)

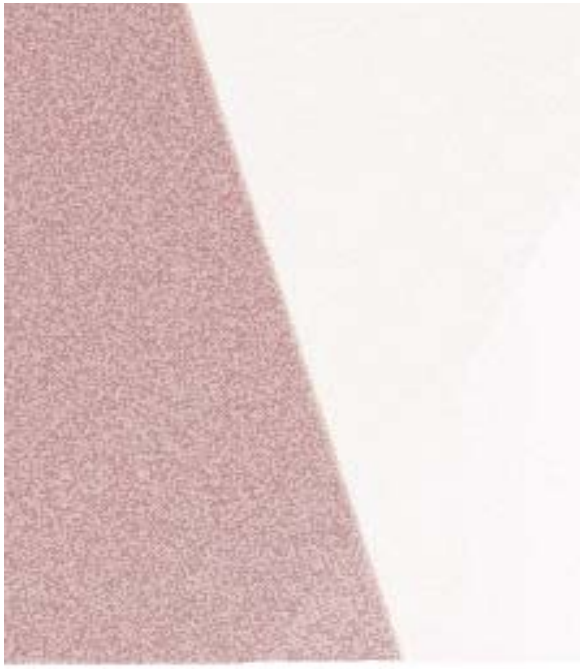
3. Systematic studies at high magnetic field

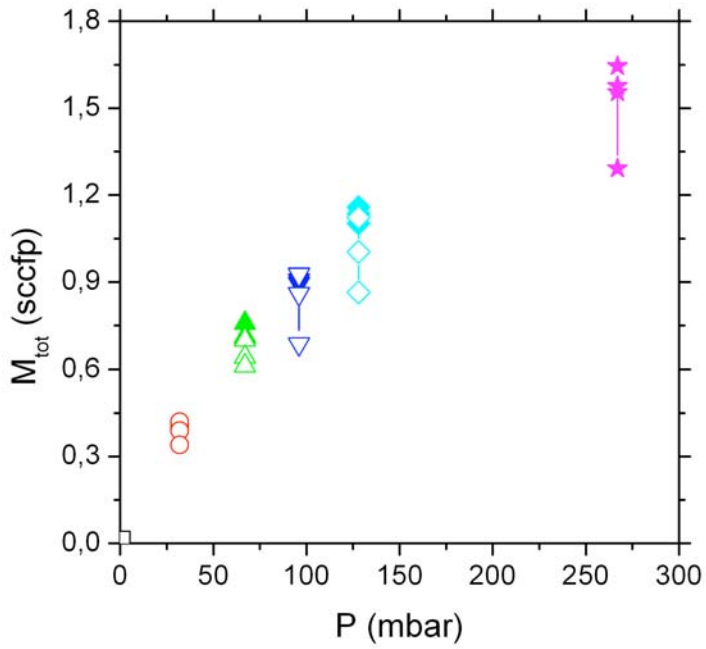


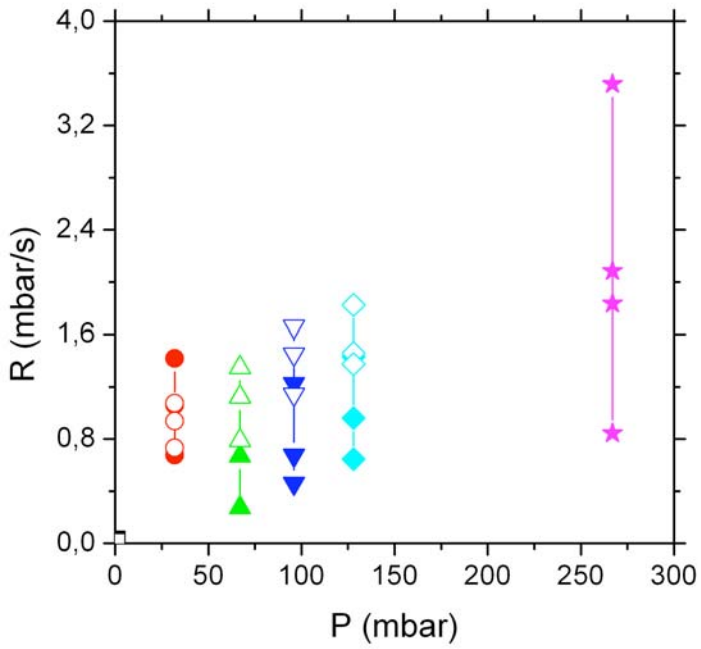


high magnetic field





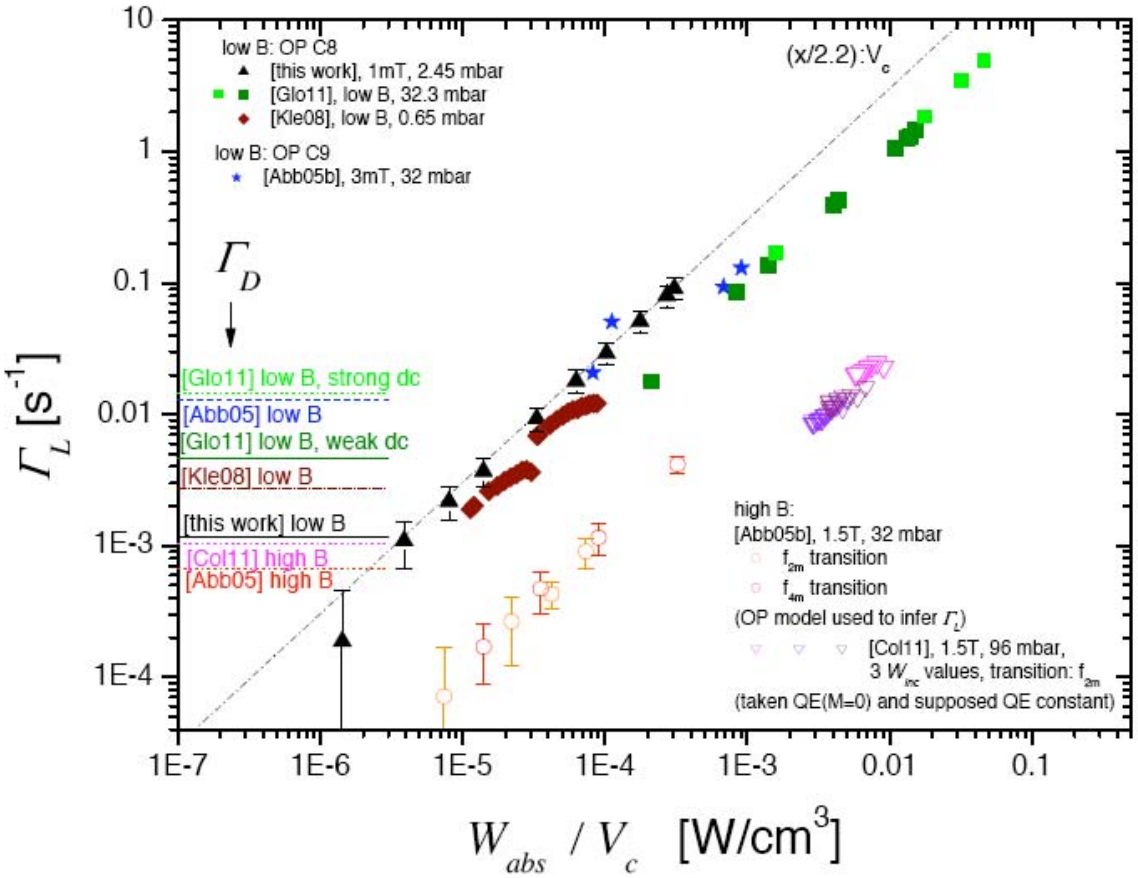




3. Systematic studies at 1.5 T

- Laser induced relaxation Γ_L

$$N_g \frac{dM}{dt} + n_m \frac{dM^*}{dt} = \eta\left(\frac{P_{abs}}{h\nu}\right) - N_g \frac{M}{T_{decay}} - n_m \gamma_r^S M^*$$



$$N_g \frac{dM}{dt} = \eta\left(\frac{P_{abs}}{h\nu}\right) - N_g \frac{M}{T_{decay}}$$

$$N_g \left.\frac{dM}{dt}\right|_{M=0} = \eta\left(\frac{P_{abs}}{h\nu}\right)$$

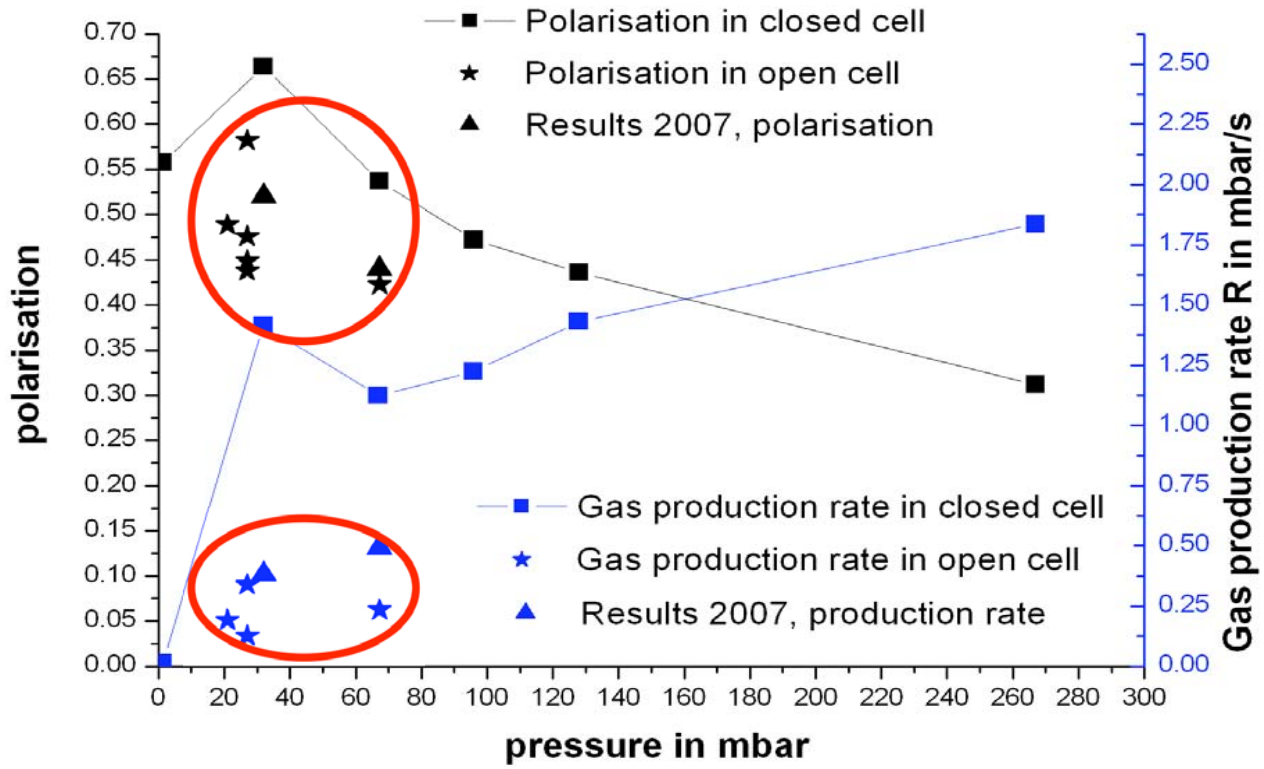
- **One order order of magnitude higher than relaxation rate in absence of OP**

4. Building a compact polarizer in-situ at 1.5 T

First tests with small open cell

Picture of light from plasma inside Ø 30 mm open cell @ 18 mbar

→ **Problem of purity:**
Gas impurities quench excitation and reduce diffusion and number of metastable atoms



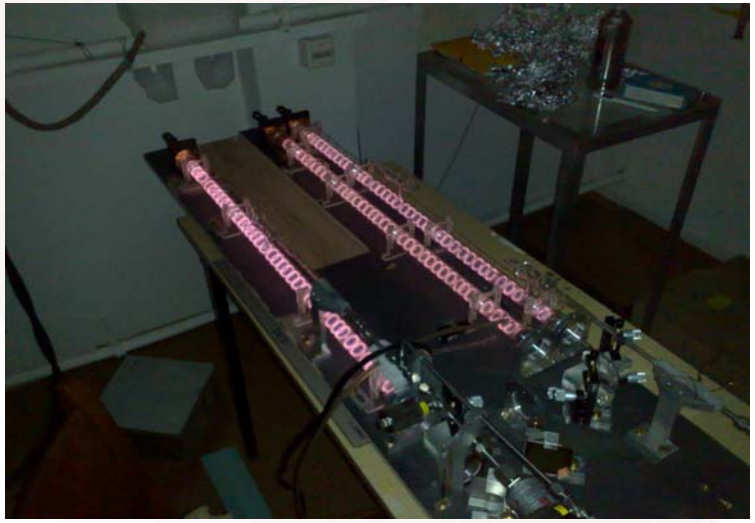
Polarization and production obtained in open cells without flow for different pressures compare with results obtained in sealed cells

But polarization stays relatively high and 10 cm long cell can still produce ~ 0.8 scc/min @ 50 % !

$$R = \frac{M \cdot \text{gas pressure}[\text{mbar}]}{t_b}$$

4. Building a high field polarizer at 1.5 T

→ Preliminary results obtained in closed and open cell shows that it is worth pumping at elevated pressure in high magnetic field as the total magnetization and production increase with pressure.

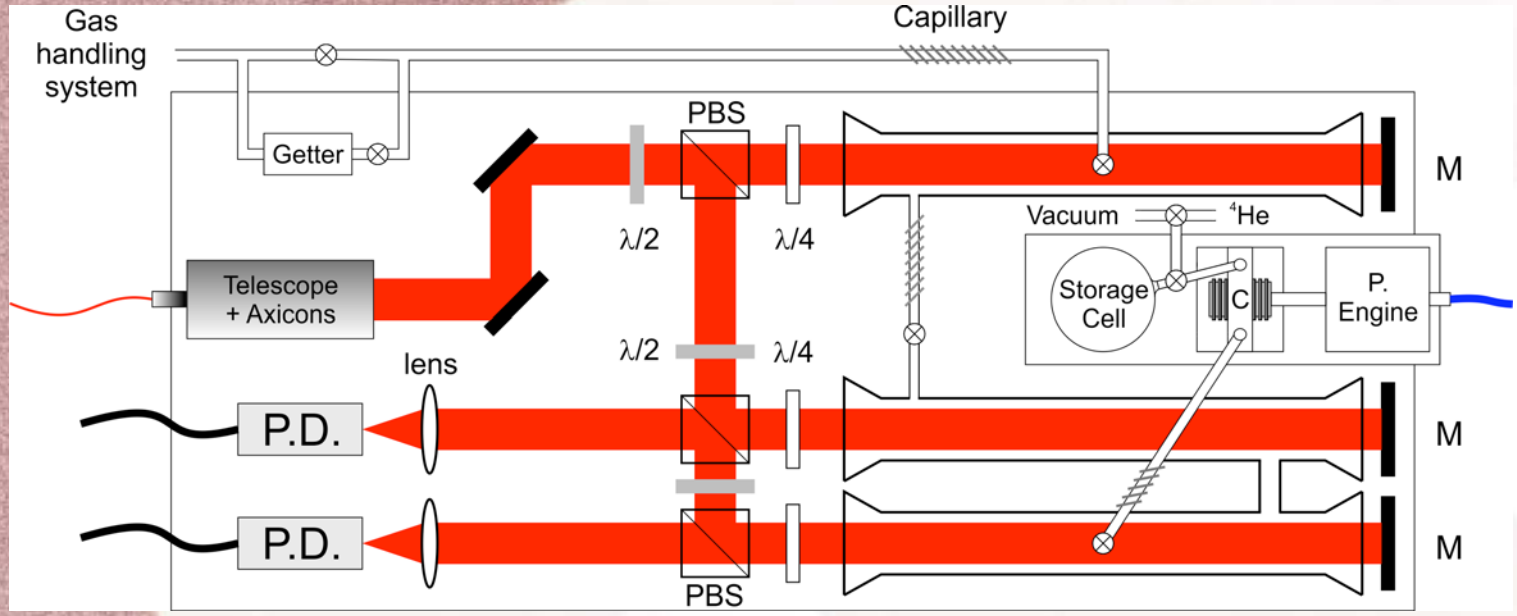


System designed to fit inside our birdcage body coils.

Total length : 1.5 m (3 cells of 80 cm in series, Ø 25 mm)

+ compact gas handling system (80*80 cm)

4. Building a high field polarizer at 1.5 T



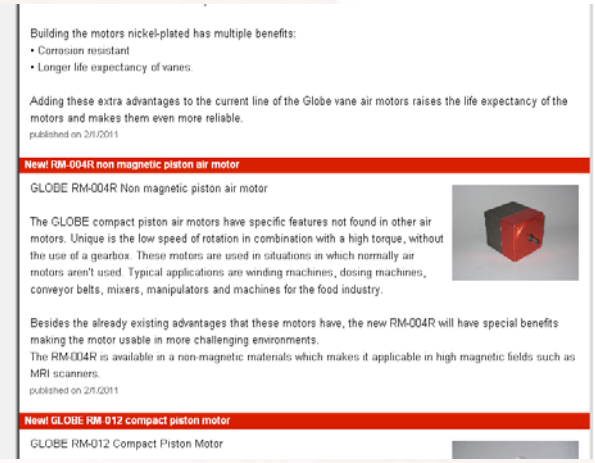
Dimensions:

1.5 m * 30 cm

3 cells of 80 cm in series, Ø 25 mm

Design of a new simple non magnetic and cheap transparent peristaltic compressor to work with pneumatic engine inside scanner.

http://www.globe-benelux.nl/



Building the motors nickel-plated has multiple benefits:
- Corrosion resistant
- Longer life expectancy of vanes.

Adding these extra advantages to the current line of the Globe vane air motors raises the life expectancy of the motors and makes them even more reliable.
published on 2/6/2011

New! RM-004R non magnetic piston air motor

GLOBE RM-004R Non magnetic piston air motor

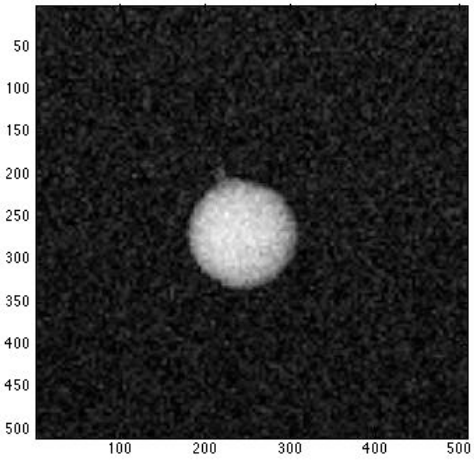
The GLOBE compact piston air motors have specific features not found in other air motors. Unique is the low speed of rotation in combination with a high torque, without the use of a gearbox. These motors are used in situations in which normally air motors aren't used. Typical applications are winding machines, dosing machines, conveyor belts, mixers, manipulators and machines for the food industry.

Besides the already existing advantages that these motors have, the new RM-004R will have special benefits making the motor usable in more challenging environments.
The RM-004R is available in a non-magnetic materials which makes it applicable in high magnetic fields such as MRI scanners.
published on 2/6/2011

New! GLOBE RM-012 compact piston motor

GLOBE RM-012 Compact Piston Motor

4. Building a high field polarizer at 1.5 T



Test of flash sequence with 80 mL of 3He in the 500 mL storage cell

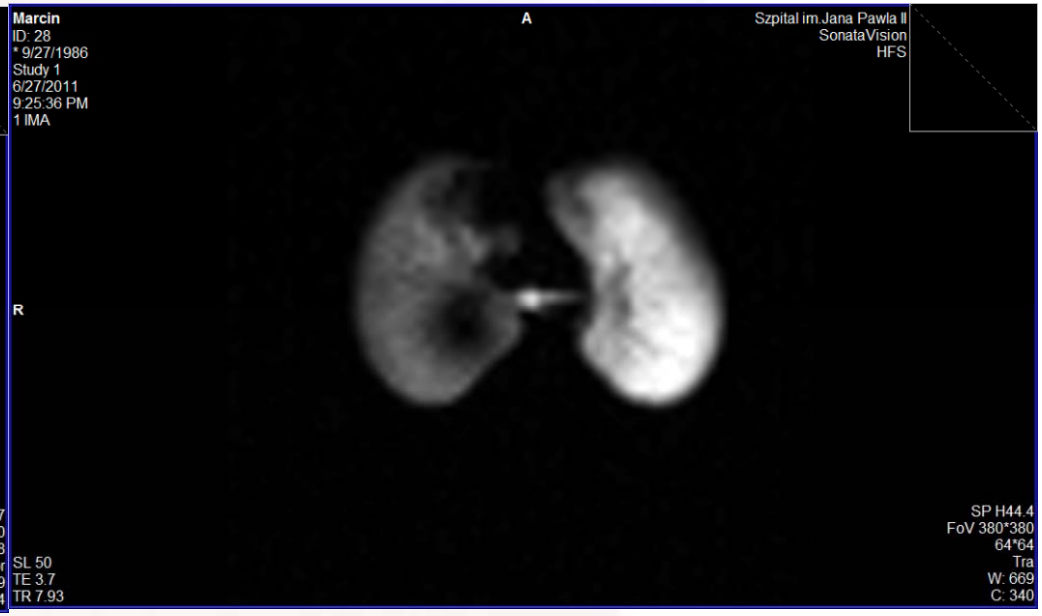
Polarizer has been tested in Siemens Sonata scanner (1.5 T) in May and June 2011.

When not used, the polarizer is connected to a turbo molecular pump (10^-8mbar) for purity issue in an adjacent room.

4. Building a high field polarizer at 1.5 T

Results (to be published)

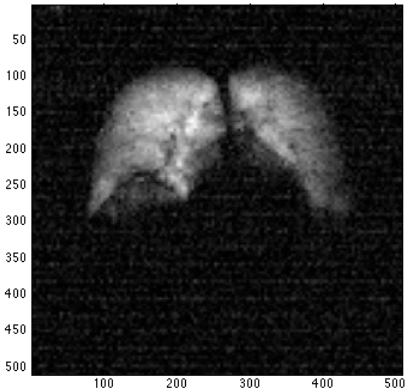
Flash, FOV 380*380, 128*128, 8.5°,
33 kHz bandwidth, Te = 3.7 ms,
Tr =7.93 ms, slice thickness 200

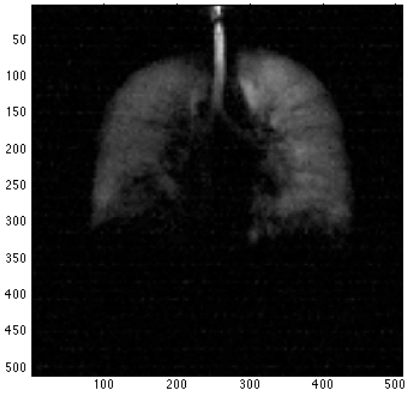


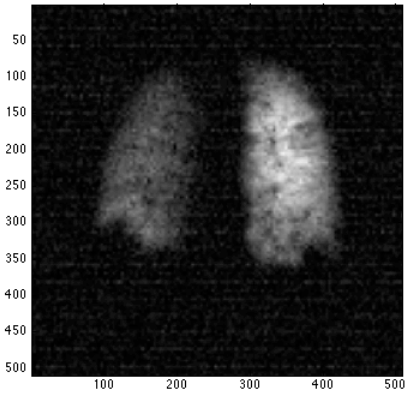
Flash, FOV 380*380, 64*64, 11°,
16.4 kHz bandwidth, Te = 3.7 ms,
Tr =7.93 ms, slice thickness 50

After 9 experiments of accumulation inside the storage cell, typical throughput of the polarizer are **≈ 15 scc/min @ 30 %** (best value 40%).

→ After 40 min of compression 600 mL of polarized 3He (2 scans)

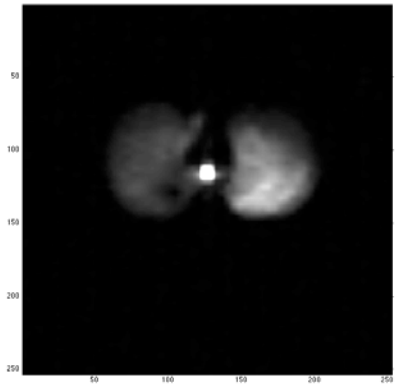
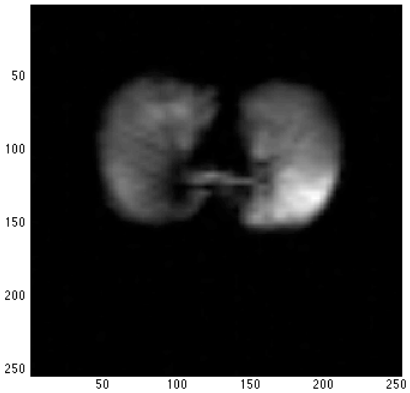
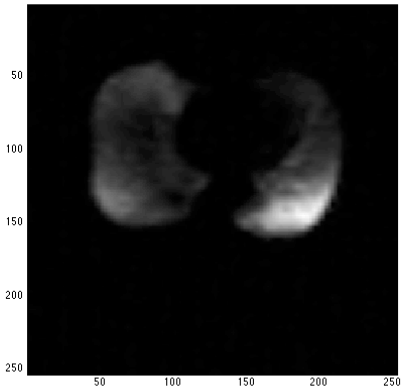






Thanks

Jagiellonian University:
Tomasz Dohnalik
Anna Nikiel
Bartosz Glowacz
Tadeusz Palasz
Anna Wojna

Kastler Brossel Laboratory:
Pierre-Jean Nacher
Geneviève Tastevin
Marion Batz (also in Mainz)

Institute of Nuclear Physics:
Zbigniew Olejniczak