Polarized He-3 production, storage and transport

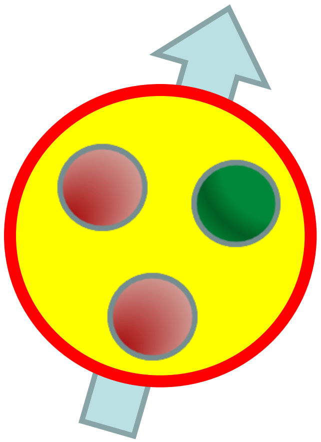
Sergei Karpuk, Werner Heil, Christian Mrozik, Ernst Otten

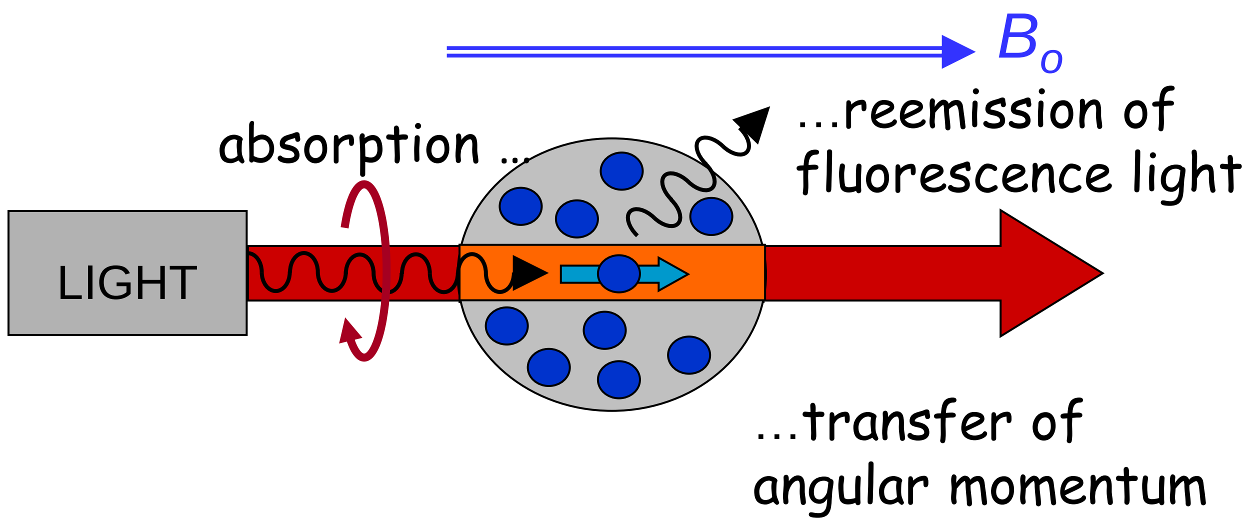
Workshop on Opportunities for Polarized He-3 in RHIC and EIC

Institut für Physik, Johannes Gutenberg-Universität Mainz

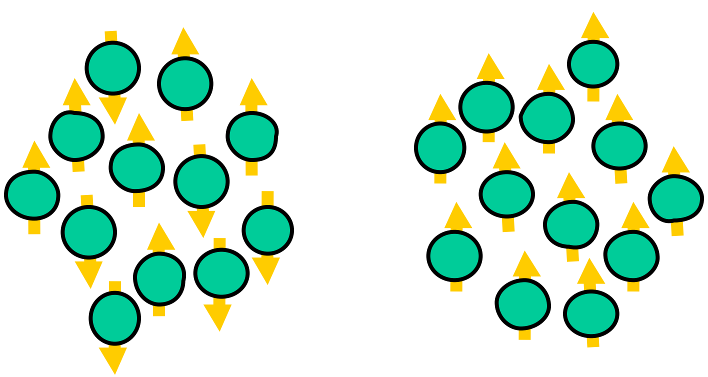
Contact: karpuk@uni-mainz.de

Optical pumping of ^{3}He





$P \approx 0$ $\quad$ $P \rightarrow 1$

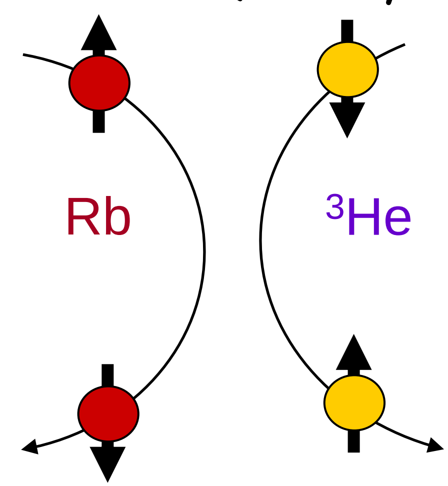


$m_I = -I, -I+1, -I+2, \ldots, I-1, I$

$I = 1/2$: $\quad P = \dfrac{n(\uparrow) - n(\downarrow)}{n(\uparrow) + n(\downarrow)}$

SEOP: Spin exchange with optically pumped alkali metal atoms (usually Rb)

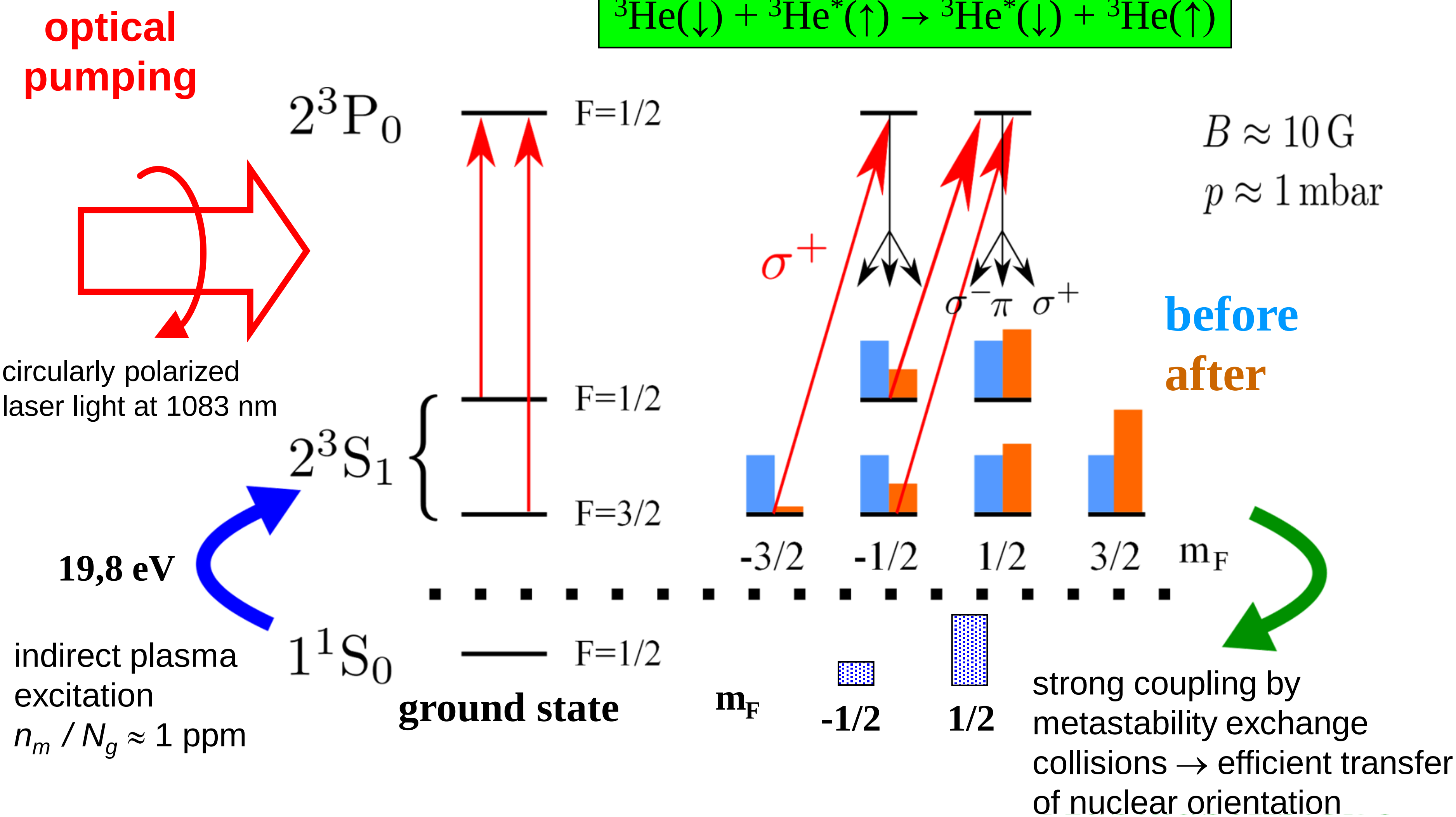
M.A.Bouchiat et al., Phys. Rev. Lett. **5** (1960) 373



Principle of Metastability Exchange Optical Pumping (MEOP) in ^3He

F.D.Colegrove et al., Phys. Rev. **132** (1963) 2561

$$^3He(\downarrow) + {}^3He^*(\uparrow) \rightarrow {}^3He^*(\downarrow) + {}^3He(\uparrow)$$



Polarized ^{3}He targets in medium energy physics at MAMI

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Electron scattering

J.Krimmer, M.Distler, W.Heil, S.Karpuk, D.Kiselev, Z.Salhi, E.W.Otten "A highly polarized ^{3}He target for the electron beam at MAMI". NIM A **611** (2009) 18-24

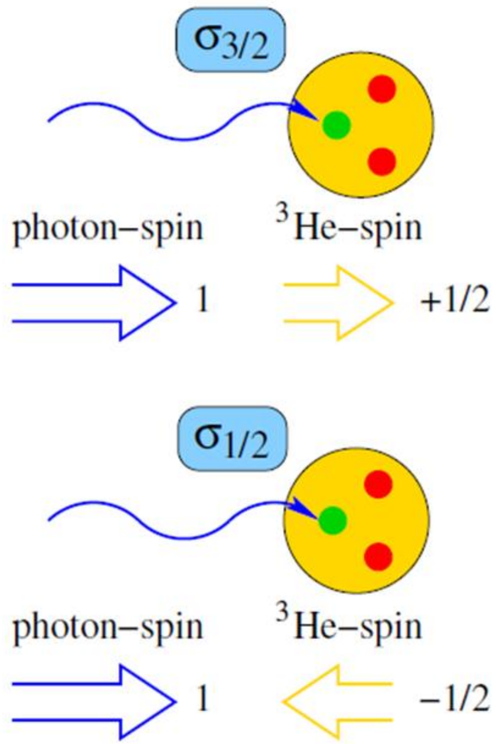
–spin structure of ^{3}He: effective polarized neutron target

neutron electric form factor G_{en}

–experimental access via double polarized quasi elastic electron scattering

Photon beam

J.Krimmer, P.Aguar Bartolomé, J.Ahrens, S.Altieri, H.J.Arends, W.Heil, S.Karpuk, E.W.Otten, P.Pedroni, Z.Salhi, A.Thomas "A polarized ^{3}He target for the photon beam at MAMI". NIM A **648** (2011) 35-40



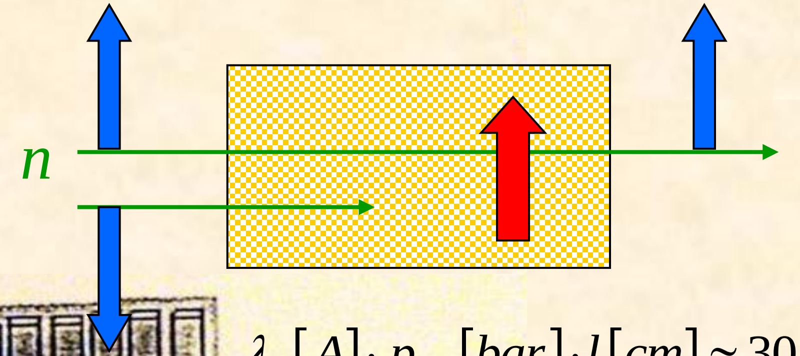
W.Heil, K.H.Andersen, R.Cywinski, H.Humblot, C.Ritter, T.W.Roberts, J.R.Stewart “Large solid-angle polarisation analysis at thermal neutron wavelengths using a ^{3}He spin filter“. NIM A **485** (2002) 551-570

$^3\overrightarrow{He}\,(\overleftarrow{n},p)\,T$

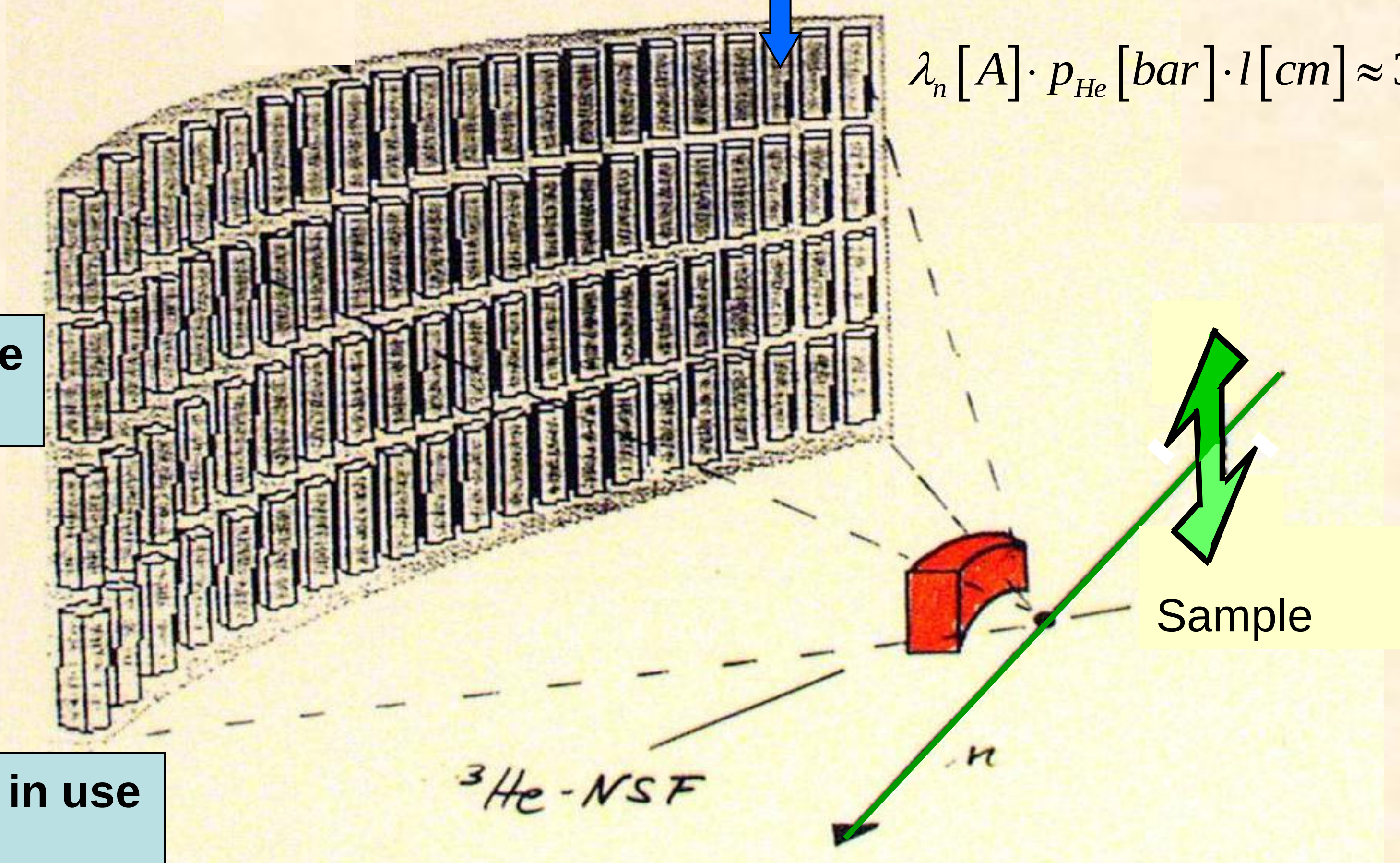
$^3\overrightarrow{He}\,(\overrightarrow{n},n..\,)$

$\sigma(\uparrow\downarrow)[barn] \approx 6000 \cdot \lambda[Å]$

$\sigma(\uparrow\uparrow)[barn] \approx 5$



$\lambda_n[A] \cdot p_{He}[bar] \cdot l[cm] \approx 30$



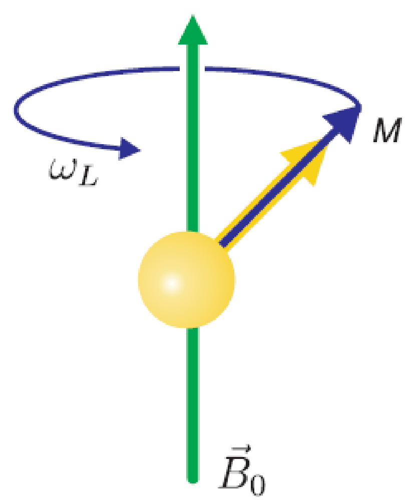
Large solid angle detector

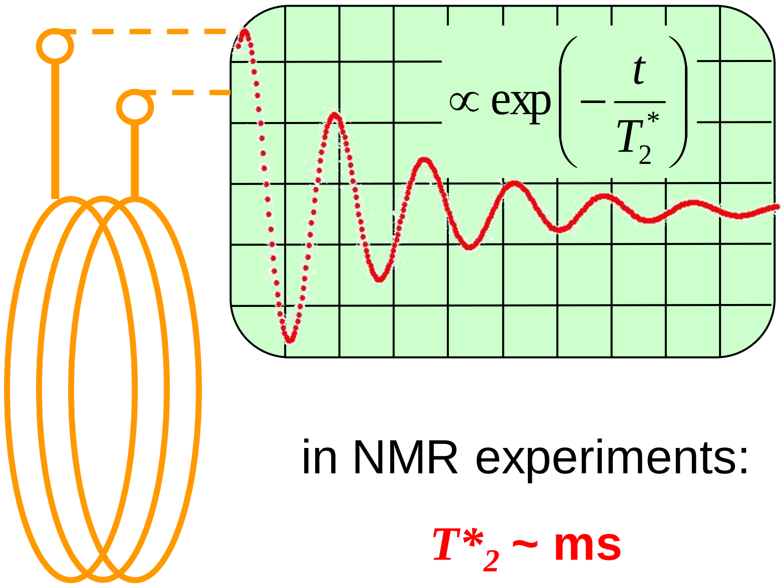
NSF-technology in use at ILL-Grenoble

Clock based on nuclear spin precession: „spin-clock"

- Atoms with nuclear spin I (e.g. ^{3}He and ^{129}Xe: I=1/2)
- Alignment of nuclear spins through optical pumping → magnetization M
- Flip → Precession of M in magnetic guiding field B_0:

$$\omega_L = 2\pi\upsilon_L = \gamma\left|\vec{B}_0\right|$$





in NMR experiments:

T^*_2 ~ ms

BMSR 2, PTB Berlin

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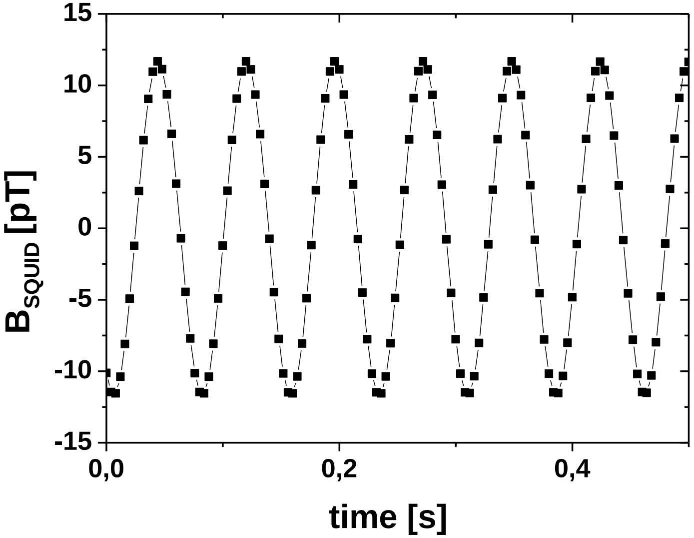
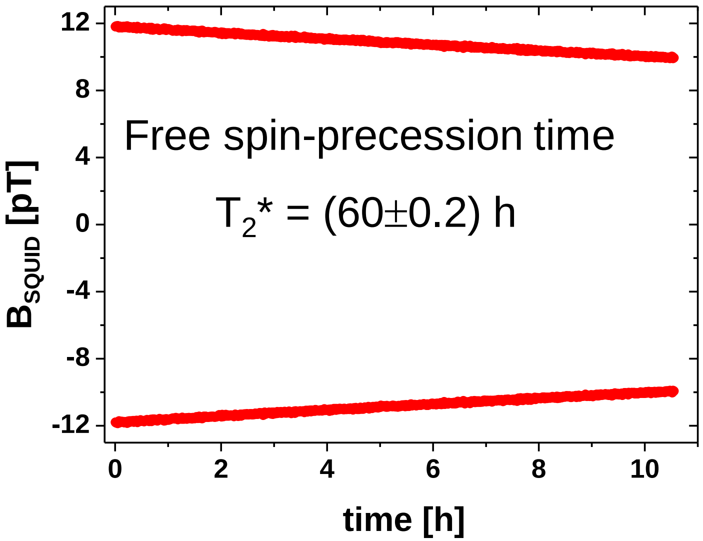
Atomic clock

SNR > 5000:1

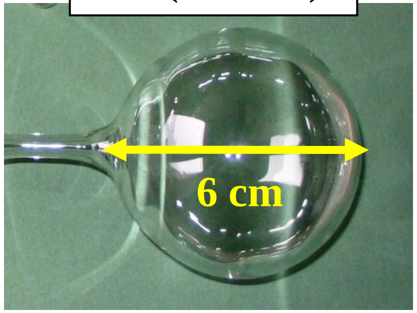




The 7-layered magnetically shielded room (residual field < 2 nT)

C.Gemmel et. al. "Ultra-sensitive magnetometry based on free precession of nuclear spins". The European Physical Journal D **57** (2010) 303-320

^{3}He (4 mbar)



magnetic guiding field ≈ 0.4 μT (Helmholtz-coils)

$^{3}He/^{129}Xe$ Clock-Comparison Experiments

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The detection of the free precession of co-located $^{3}He/^{129}Xe$ sample spins can be used as ultra-sensitive probe for non-magnetic spin interactions

- Search for a Lorentz Invariance violating sidereal modulation of the Larmor frequency:

$$\Delta\omega = V(r)/\hbar = \langle \tilde{\mathrm{b}} \rangle \hat{\varepsilon} \cdot \vec{\sigma} / \hbar$$

- Search for spin-dependent short-range interactions:

$$\Delta\omega = V(r)/\hbar = c\,\vec{\sigma} \cdot \hat{n} / \hbar$$

$$V(r) = \underbrace{-\vec{B} \cdot \vec{\mu}}_{\text{Magnetic interaction}} \underbrace{- \langle \tilde{\mathrm{b}} \rangle \hat{\varepsilon} \cdot \vec{\sigma} + c\,\vec{n} \cdot \vec{\sigma}}_{\text{Non-magnetic interaction}}$$

$^{3}He/^{129}Xe$ Co-Magnetometer

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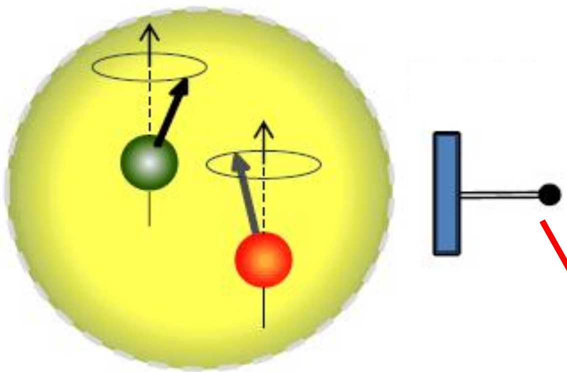
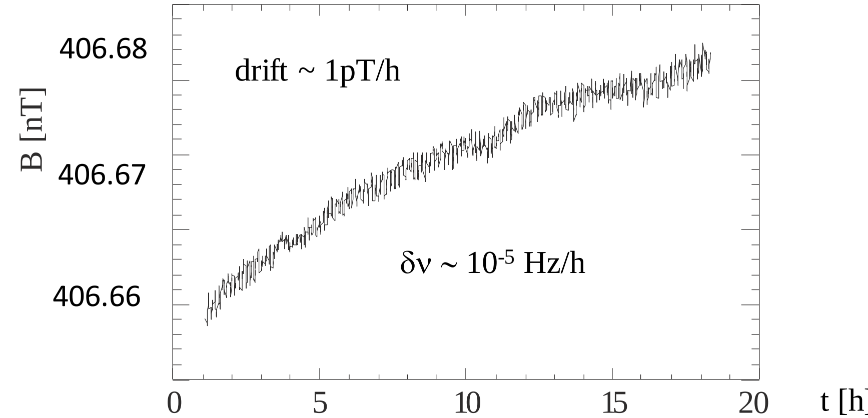
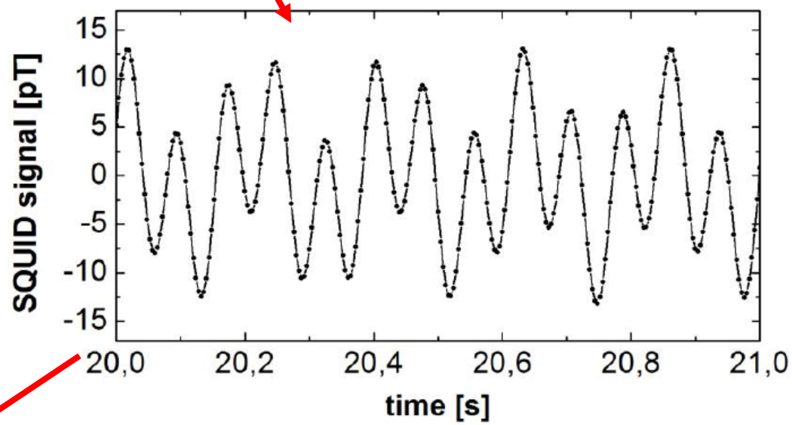


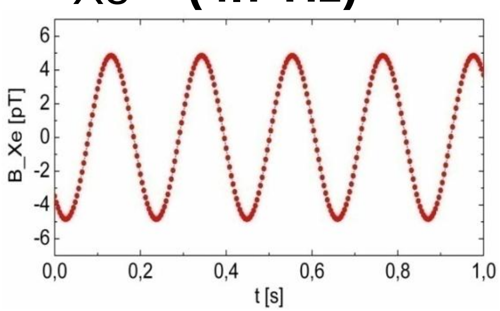


Zeeman-term drops out in the weighted frequency or phase difference



$$\omega_{L,i}(t) = 2\pi \cdot \nu_{L,i} = \gamma_i \cdot B(t)$$

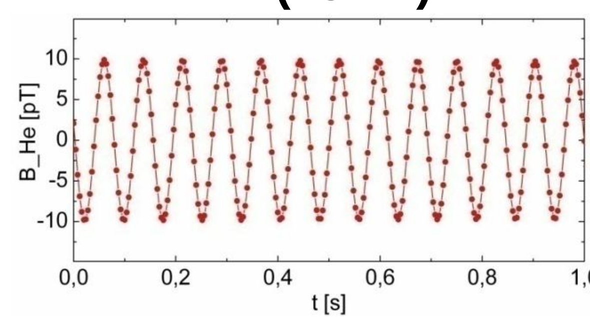
^{129}Xe **(4.7 Hz)**



$$\Delta\omega = \omega_{L,He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \omega_{L,Xe} \overset{!}{=} const.$$

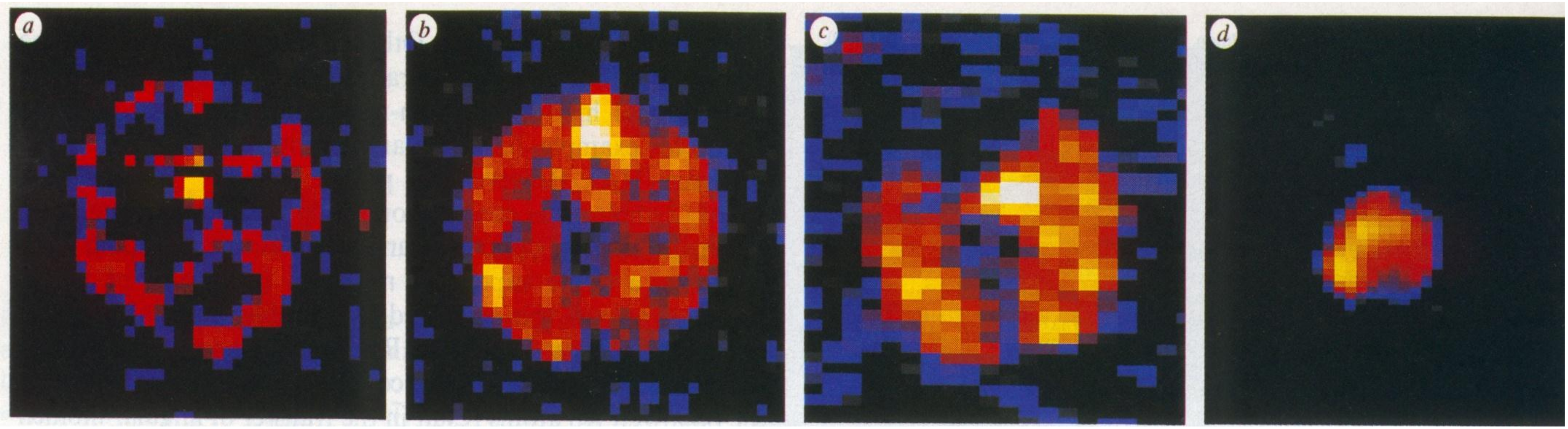
$$\Delta\Phi = \Phi_{He} - \frac{\gamma_{He}}{\gamma_{Xe}} \cdot \Phi_{Xe} \overset{!}{=} const.$$

^{3}He **(13 Hz)**



MRI using hyperpolarized noble gases

History: *M.S.Albert, G.D.Cates, B.Driehuys, W.Happer, B.Saam, C.S.Springer Jr & A.Wishnia, Nature* ***370*** *(1994) 199-201*

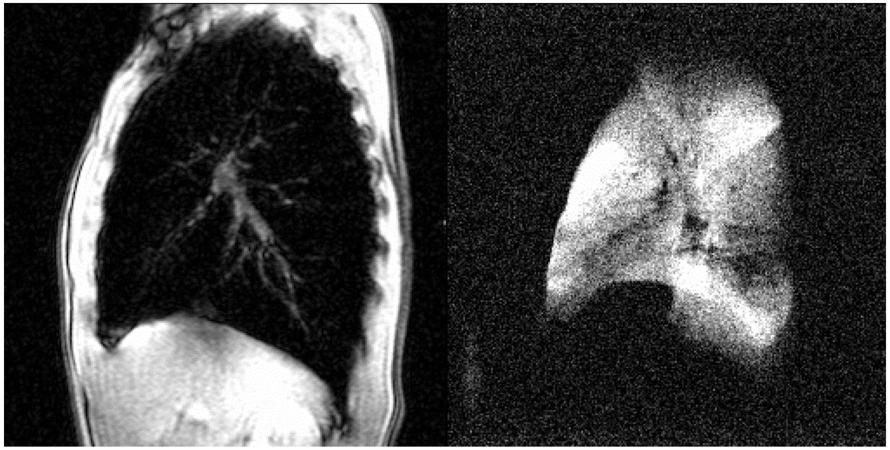


Magnetic resonance images of the excised lungs and heart of a mouse using laser-polarized ^{129}Xe

Medical applications of spin polarized ^{3}He

- **morphological MRI studies**
  (spin density imaging)

- **dynamics of lung functioning**
  - diffusion weighted imaging
  - ^{3}He-MRI based measurements of the intrapulmonary oxygen partial pressure
  - ultra-fast imaging



proton - MRI   Helium - MRI

M.Ebert, T.Großmann, W.Heil, E.W.Otten, R.Surkau, M.Leduc, P.Bachert, M.V.Knopp, L.R.Schad, M.Thelen "Nuclear magnetic resonance imaging with hyperpolarised helium-3" *The Lancet* ***347*** *(1996) 1297-1299*

Concept of central production of the hyperpolarized ^3He

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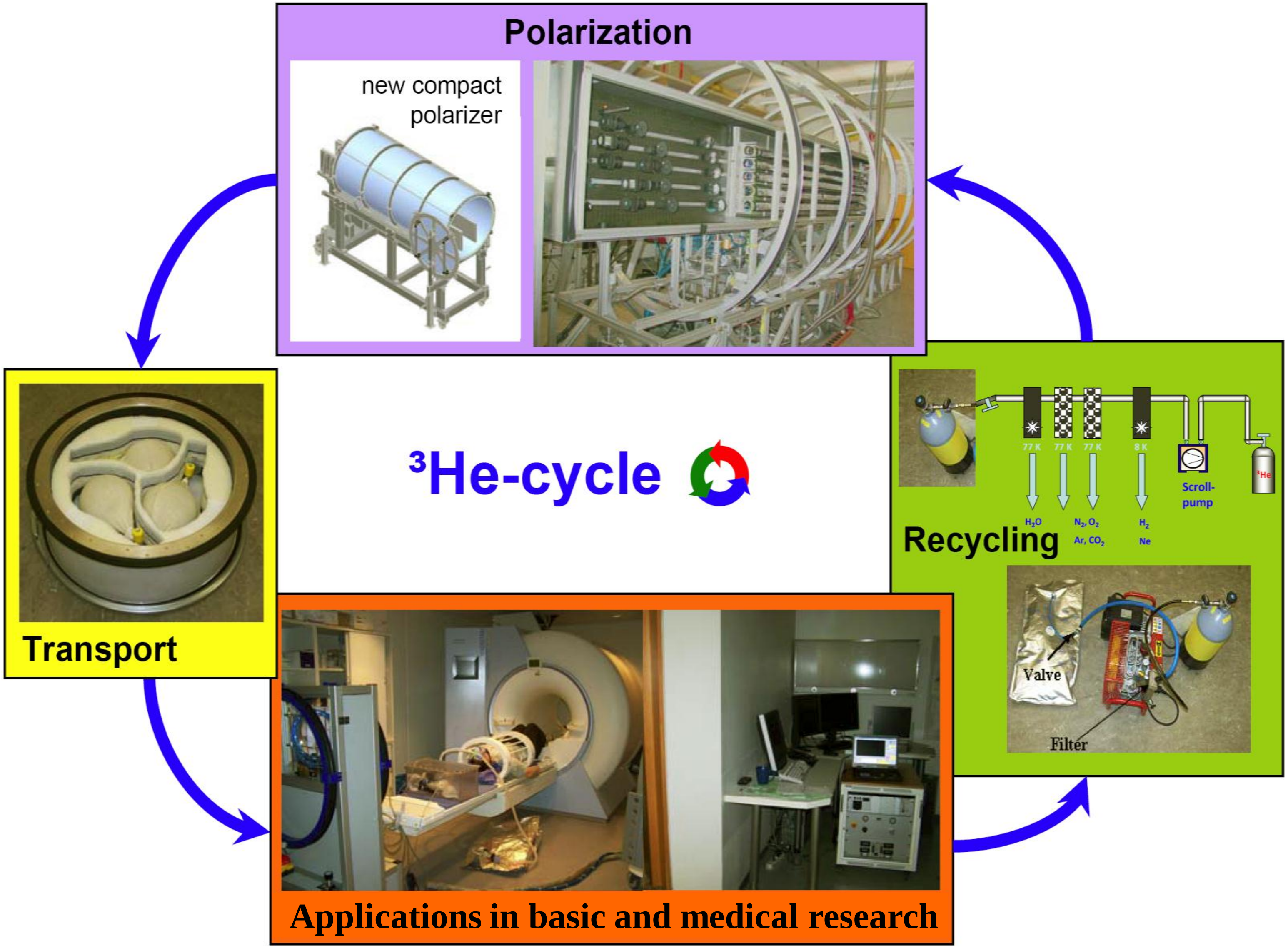
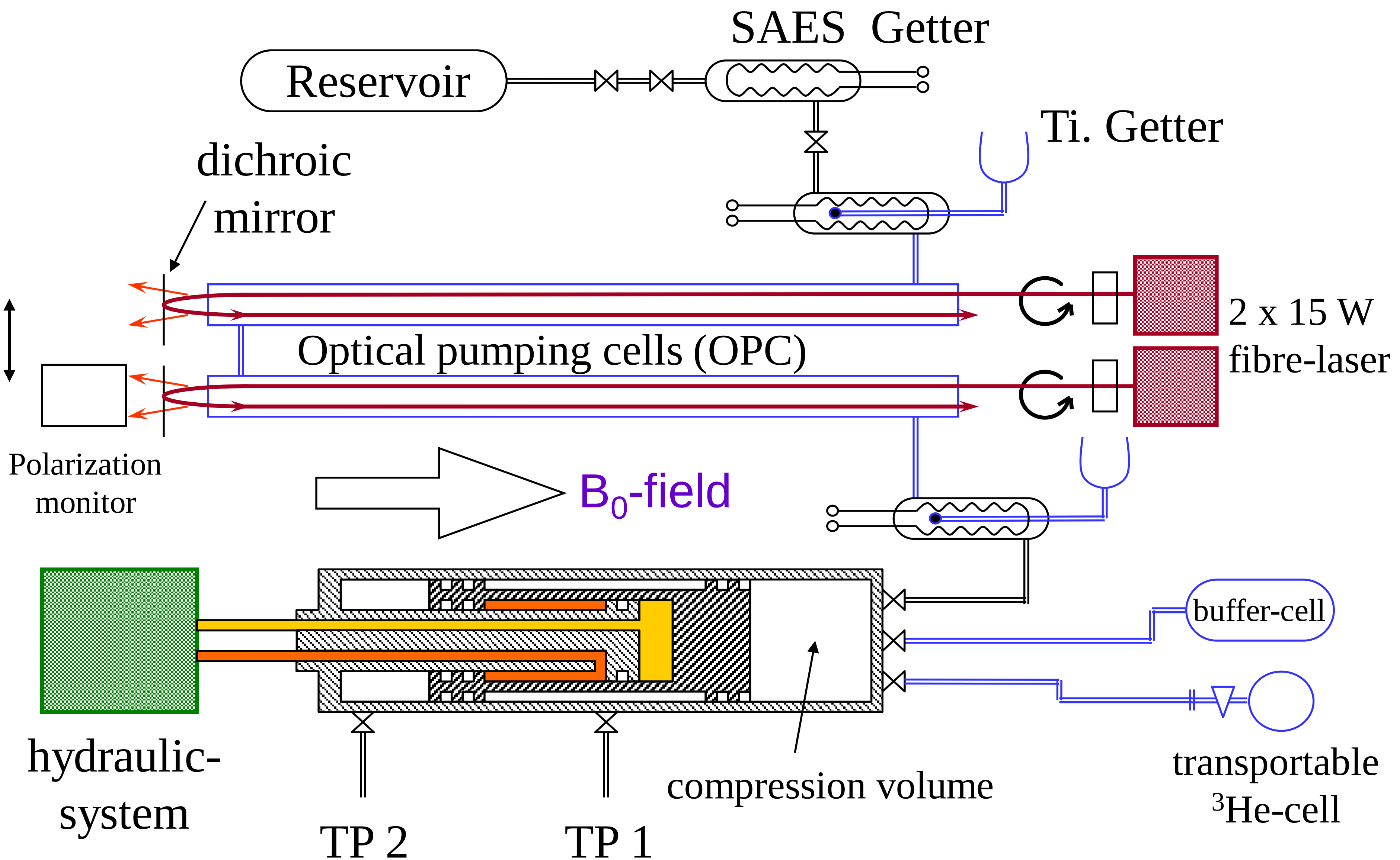
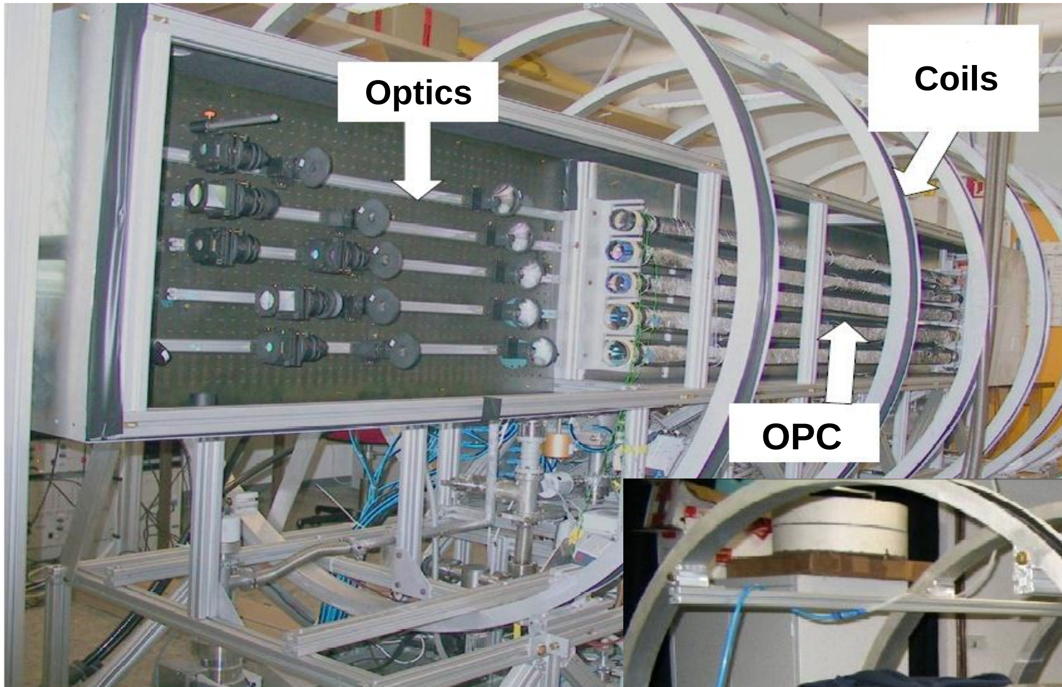
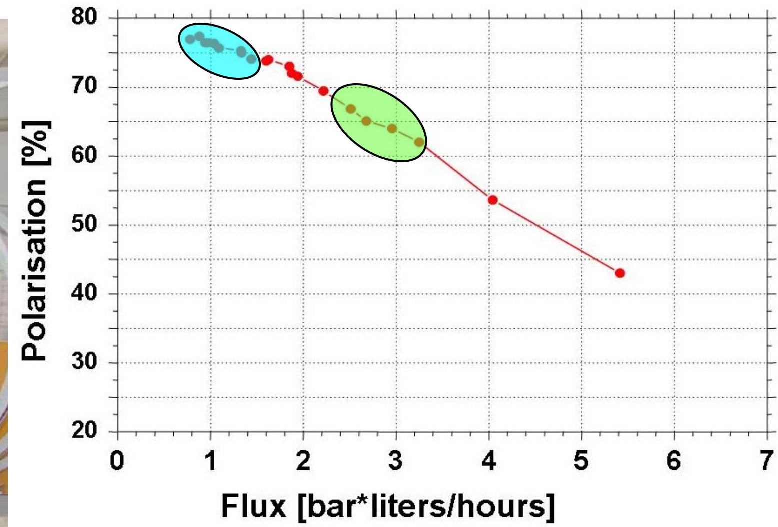


^{3}He polarizer in Mainz I



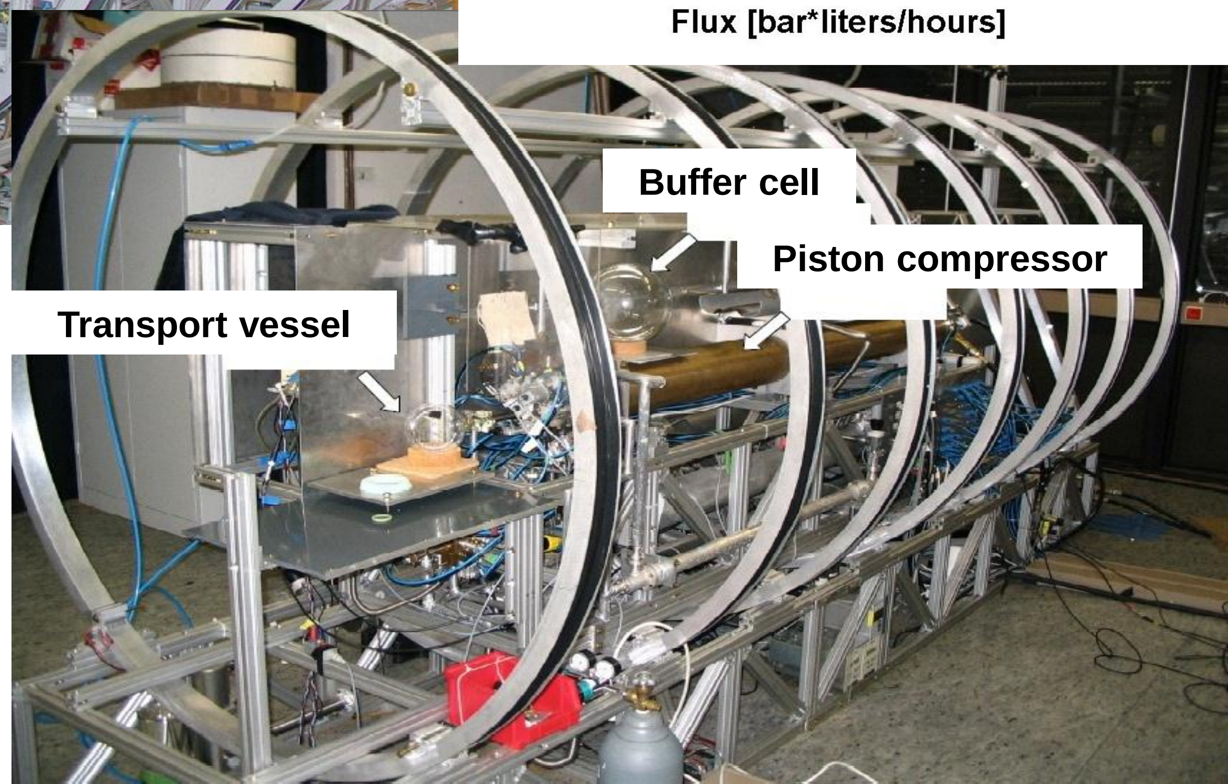
^{3}He polarizer in Mainz II





Optical Pumping of ^{3}He at low pressure (≤1 mbar)

Compression without significant polarization losses up to 5 bar



^{3}He polarizer in Mainz III

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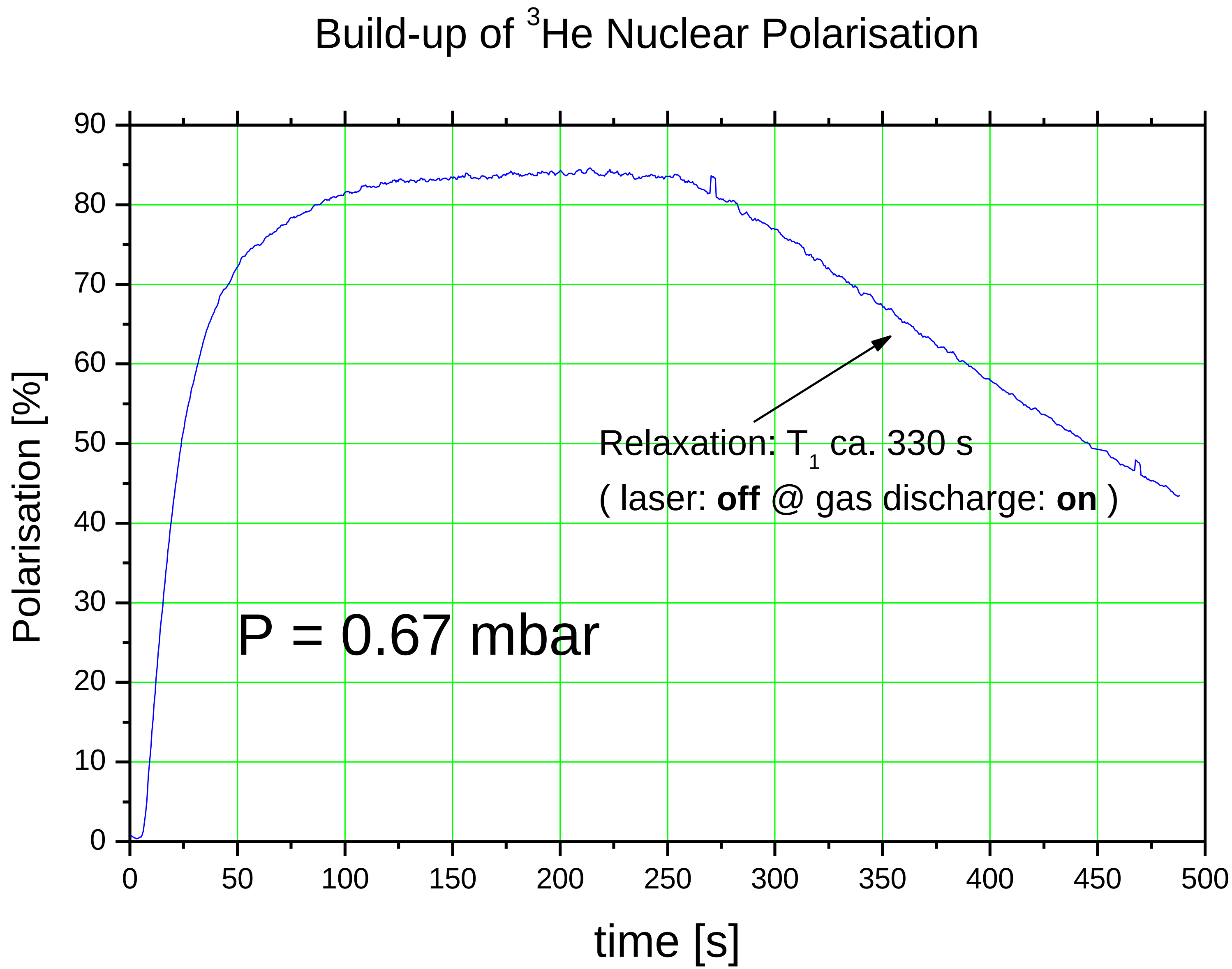
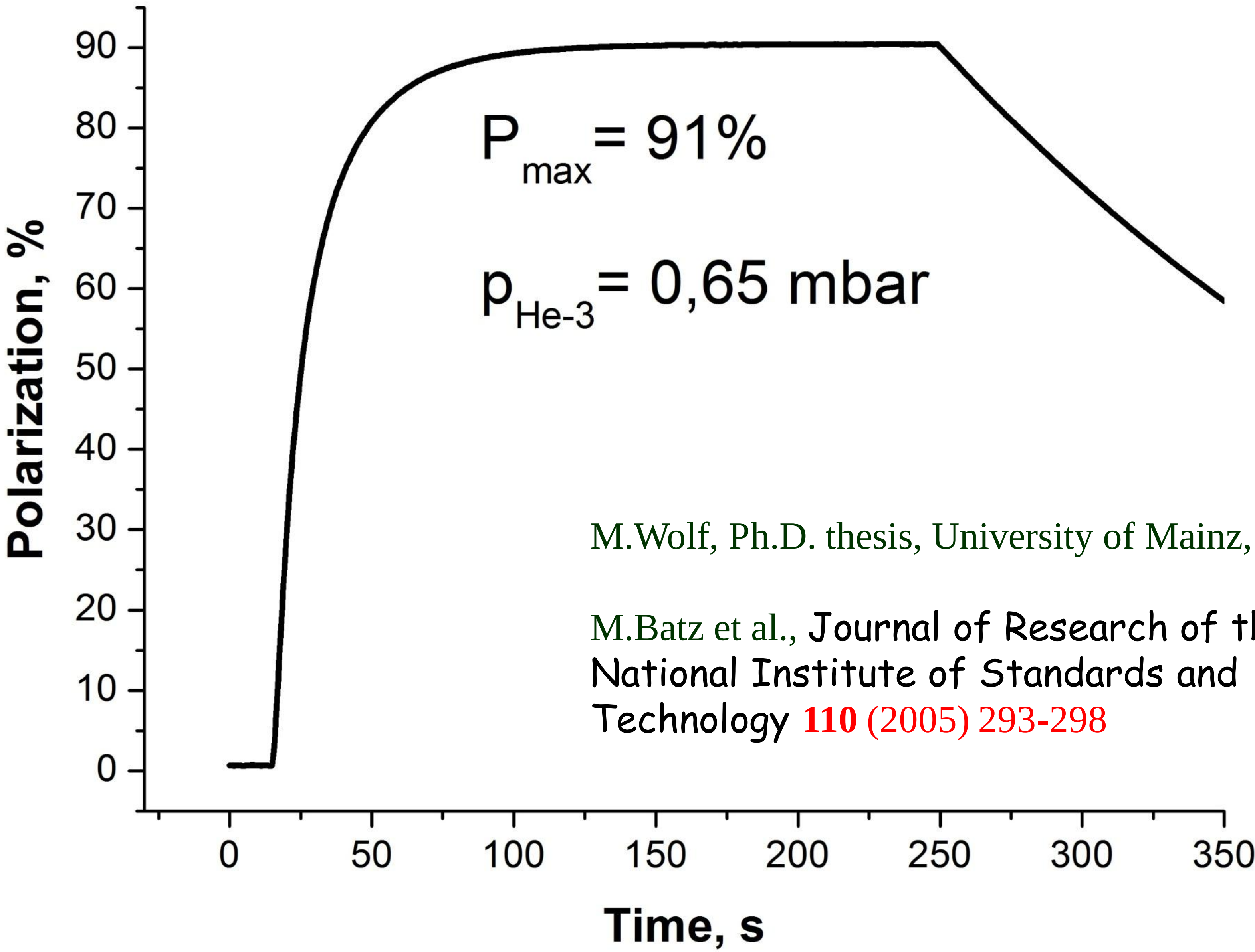


Sealed-off optical pumping cell



M.Wolf, Ph.D. thesis, University of Mainz, 2004

M.Batz et al., Journal of Research of the National Institute of Standards and Technology **110** (2005) 293-298

Central production: storage and transport I

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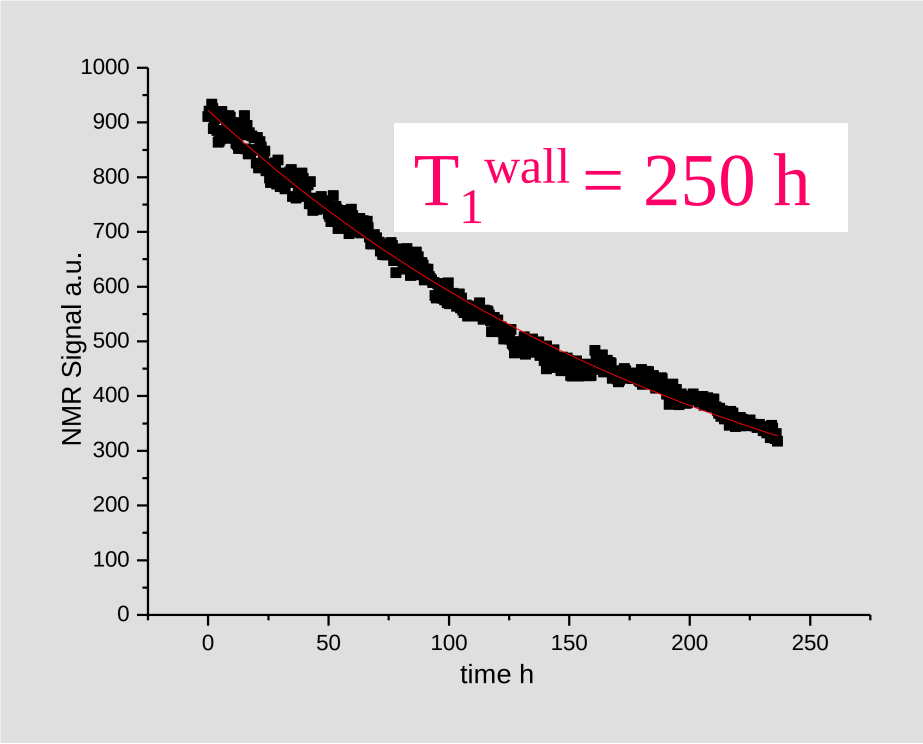
- no surface-coating
- no time-consuming bake-out procedure
- high T_1-reproducibility after re-use

iron-free aluminosilicate-glass flasks (GE-180) on special demand from Schott Duran Group Mainz

Volume: V ≈ 1,1 litre
Transport pressure: p = 2.7 bars



Paramagnetic relaxation of spin polarized ^{3}He at bare glass surfaces (Eur. Phys. J. D **38** (2006) 427)

Paramagnetic relaxation of spin polarized ^{3}He at coated glass walls (Eur. Phys. J. D **38** (2006) 439)

Relaxation of spin polarized ^{3}He by magnetized ferromagnetic contaminants (Eur. Phys. J. D **38** (2006) 445)

Central production: storage and transport II

$$\frac{1}{T_1} = \frac{1}{T_1^{grad}} + \frac{1}{T_1^{wall}} + \frac{1}{T_1^{dd}}$$

$$\frac{1}{T_1^{grad}} = D \cdot G_r^2$$

G. D. Cates, S.R. Schaefer, and W. Happer, Phys. Rev. A 37, 2877 (1988)

$$T_1^{grad}[h] \approx \frac{1}{6900} \frac{p[bar]}{G_r^2[cm^{-2}]} \qquad T_1^{grad} \propto \frac{1}{G_r^2}$$

$$G_r = \sqrt{(\vec{\nabla} B_x)^2 + (\vec{\nabla} B_y)^2} \Big/ B \qquad Z \uparrow\uparrow \vec{B}$$

Magnetically shielded transport box

$|\mathrm{grad}B/B| \leq 10^{-3}/\mathrm{cm} \Rightarrow$
$T_1^{\mathrm{grad}} \geq 400$ h (@2.7 bar)

S.Hiebel, T.Großmann, D.Kiselev, J.Schmiedeskamp, Y.Gusev, W.Heil, S.Karpuk, J.Krimmer, E.W.Otten, Z.Salhi “Magnetized boxes for housing polarized spins in homogeneous fields“. Journal of Magnetic Resonance **204** (2010) 37-49

Hyperpolarized ^{3}He administration

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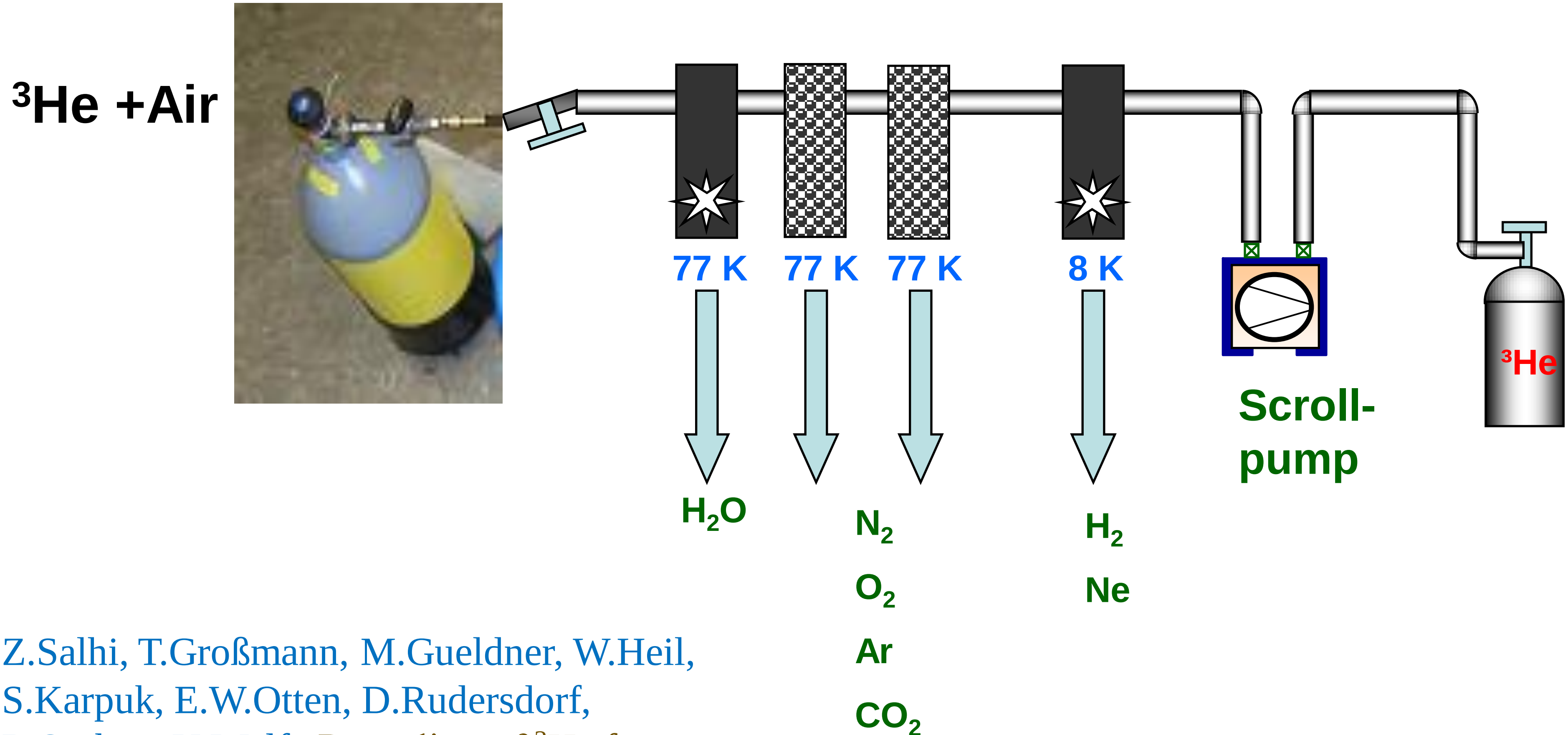
- volume-control:
  $\Delta V/V = 3\%$

- gas administration at predefined times during inspiration

- use of gas mixtures (^{3}He, ^{129}Xe)

- gas recovery !!! (shortage of ^{3}He)

^3He recycling unit



Z.Salhi, T.Großmann, M.Gueldner, W.Heil, S.Karpuk, E.W.Otten, D.Rudersdorf, R.Surkau, U.Wolf „Recycling of ^3He from lung magnetic resonance imaging“.
Magnetic Resonance in Medicine
Article first published online: 29 AUG 2011
DOI: 10.1002/mrm.23154

recovery efficiency: ≈ 95%

gas purity: ≈ ppm

Problems caused by the shortage of ^3He

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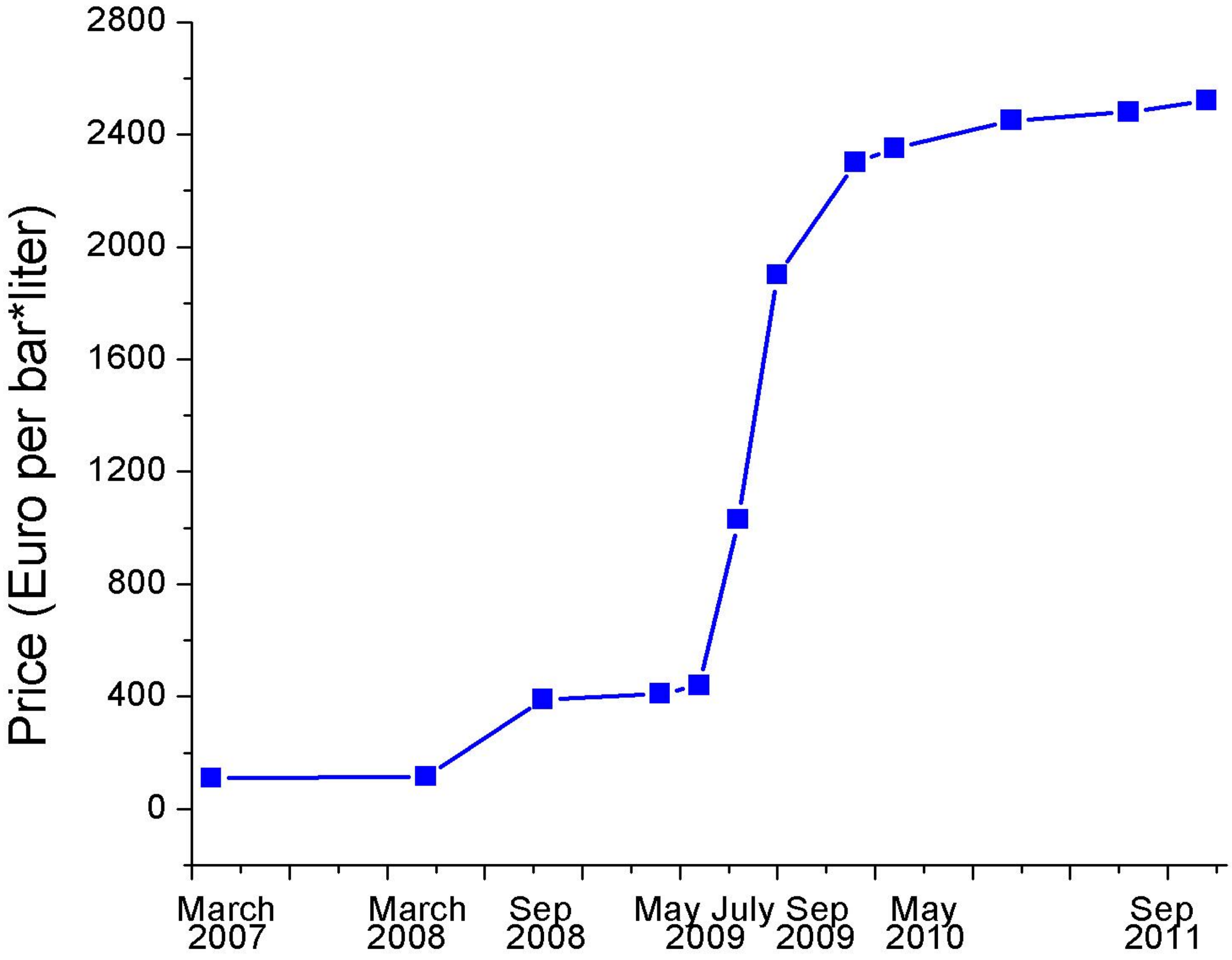
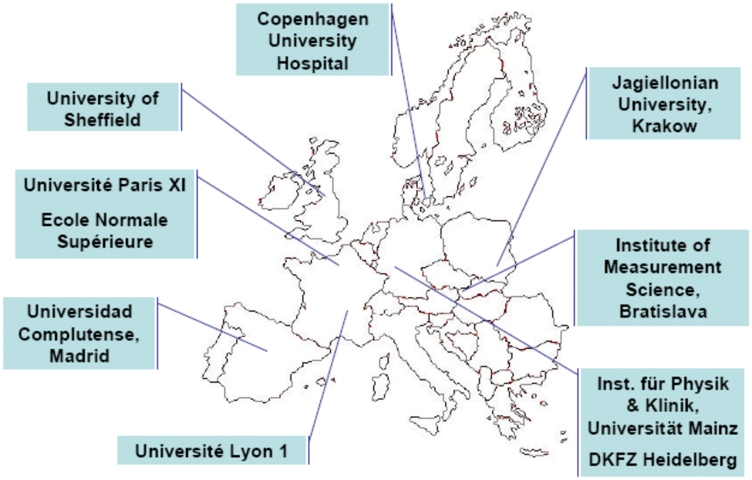
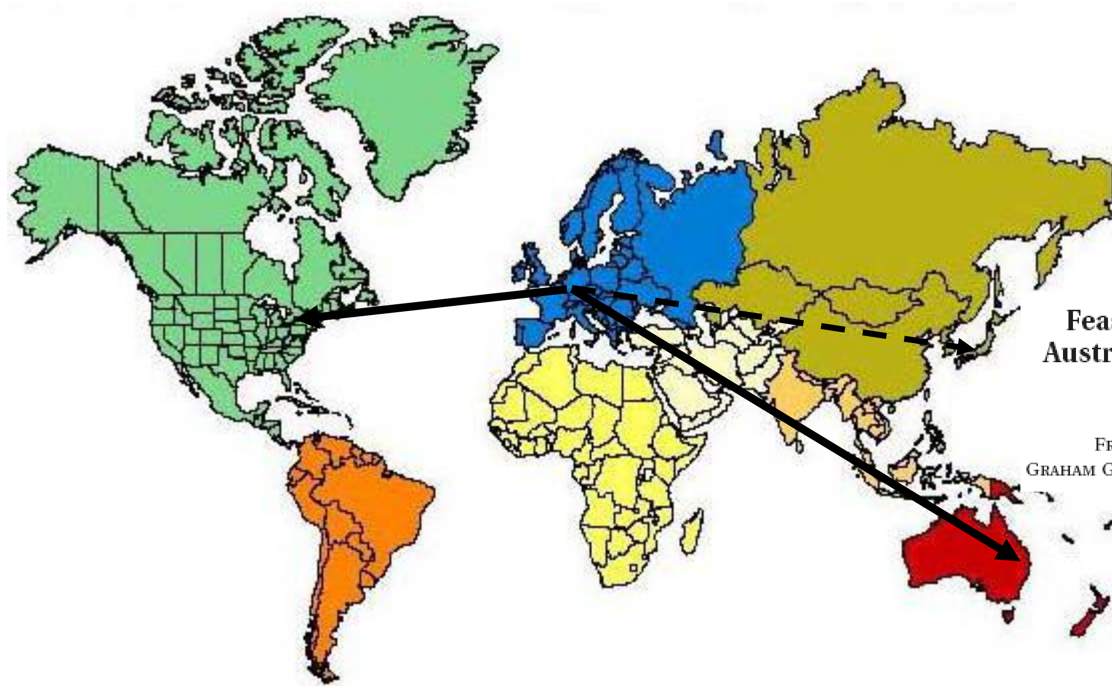


Gas delivery

Research & Training Network (RTN)
Marie Curie Actions
FP 6 (2007-2011)

PHeLINet
Polarized Helium Lung Imaging Network





Respirology (2008) 13, 599–602

Feasibility of functional magnetic resonance lung imaging in Australia with long distance transport of hyperpolarized helium from Germany

Francis Thien,[1] Marlies Friese,[2] Gary Cowin,[2] Donald Maillet,[2] Deming Wang,[2] Graham Galloway,[2] Ian Brereton,[2] Philip J. Robinson,[3] Werner Heil[4] and Bruce Thompson[1]

≈ 100 shipments/year @ 500 bar·liters

The compact polarizer

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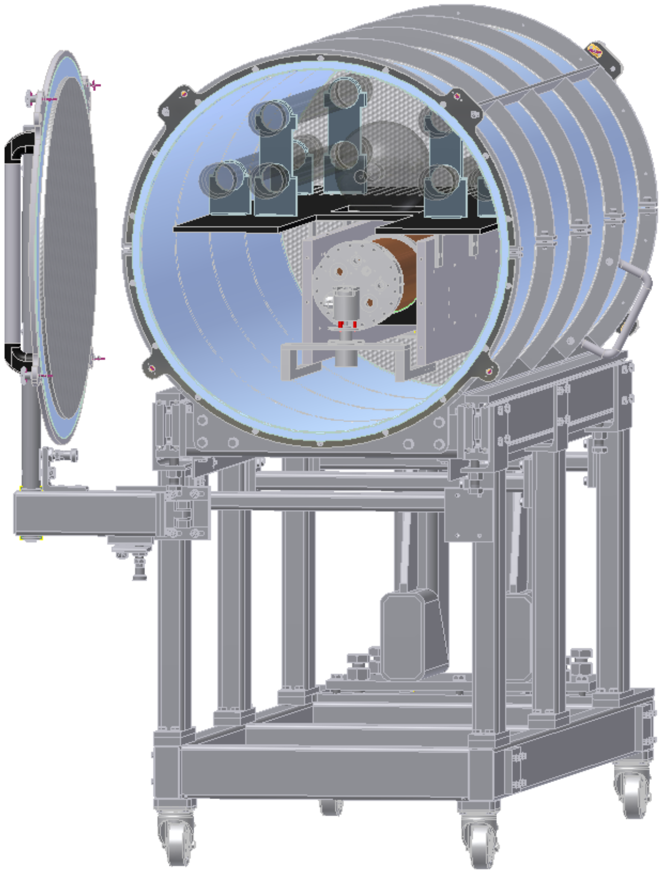
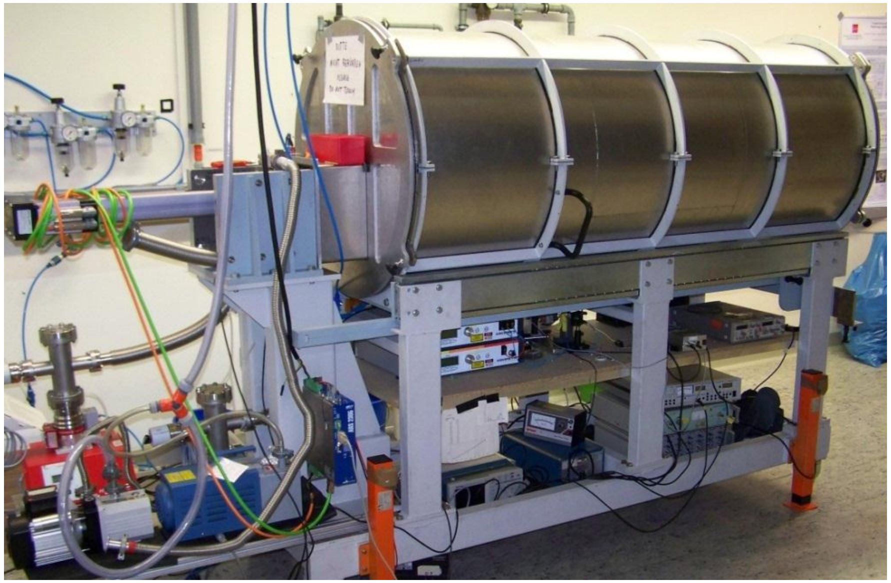
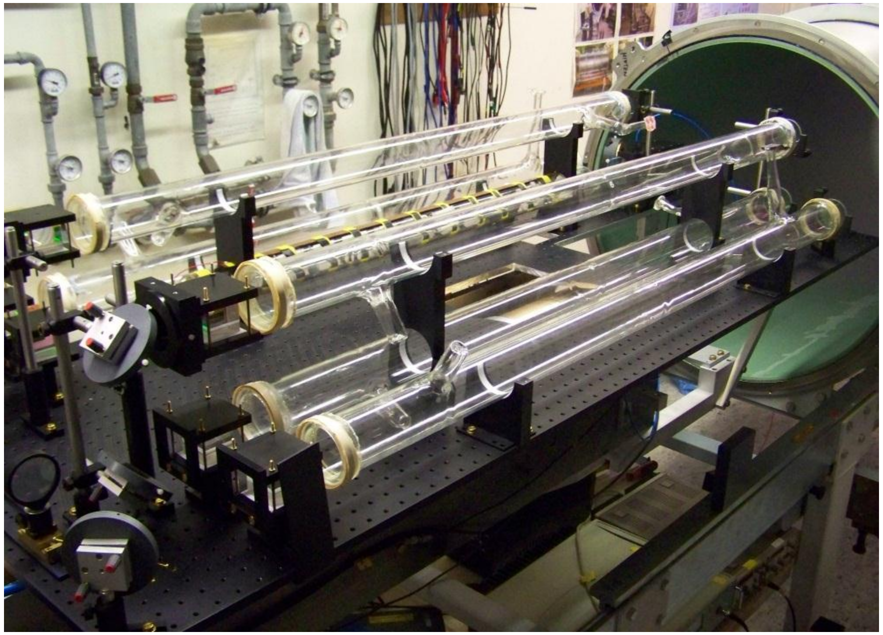






dimensions

length ≈ 3 m

height ≈ 1.8 m

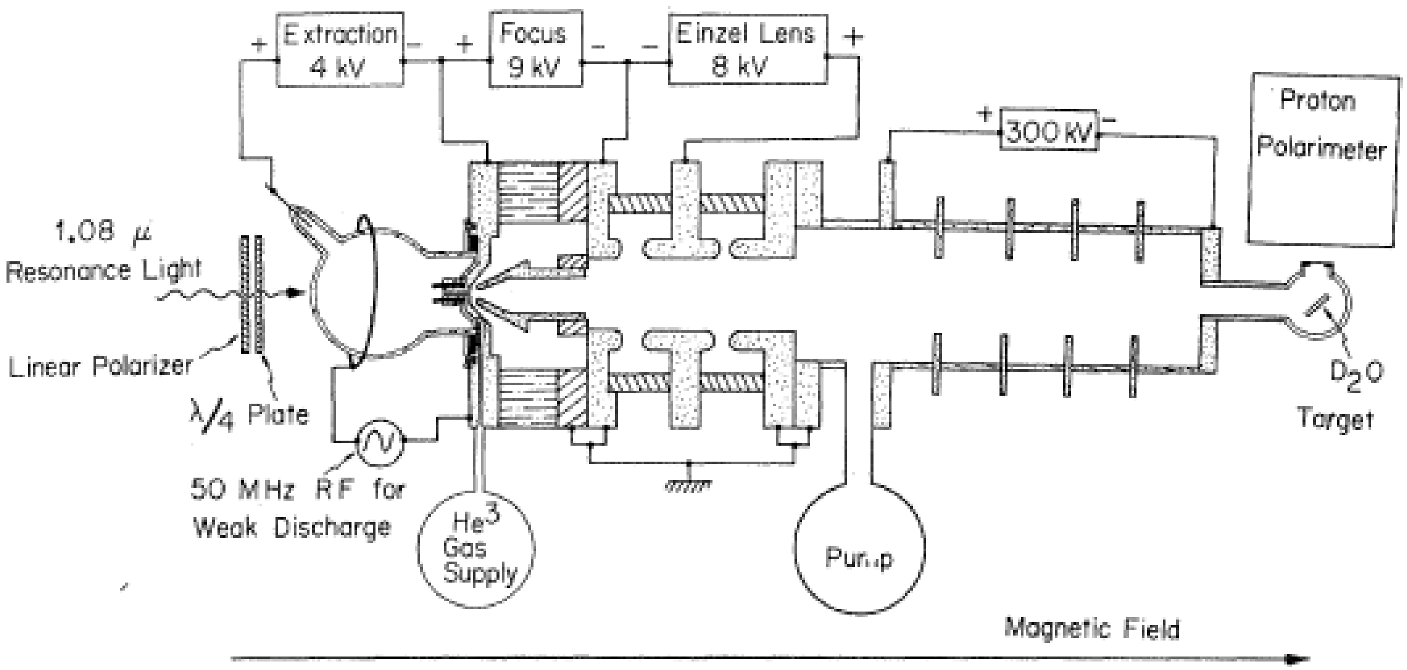
width ≈ 0.9 m

Polarized $^3He^+$ Ions I

VOLUME 20, NUMBER 14 PHYSICAL REVIEW LETTERS 1 APRIL 1968

POLARIZED He^3-ION BEAM*

S. D. Baker,† E. B. Carter,‡ D. O. Findley,§ L. L. Hatfield,
G. C. Phillips, N. D. Stockwell,‖ and G. K. Walters
Physics Department, Rice University, Houston, Texas
(Received 26 February 1968)



"The gas polarization in the optical pumping cell was measured by means of an optical technique to be 0.05±0.01, which, within experimental error, is the measured value of the ion polarization. This substantiates …expectation that ionization exchange collisions do, in fact, bring the ion polarization into equilibrium with the ground-state atom polarization before extraction."

Polarized $^3He^+$ Ions II

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Nuclear Instruments and Methods in Physics Research B 193 (2002) 66–70

Charge states distribution of 0.16–3.3 MeV He ions transmitted through silicon

M. Bianconi *, G.G. Bentini, R. Lotti, R. Nipoti

CNR-Istituto LAMEL, via Gobetti 101, I-40139 Bologna, Italy

The equilibrium charge state distribution of He ions transmitted through silicon in a random direction was measured in the energy range 0.16–3.3 MeV. The surface contamination, investigated by back-scattering spectrometry, amounted to a few monolayers. The measured data, integrated with the available literature points, cover a wide range of conditions. At the lower end (velocity ~ 1 a.u.) there is a consistent fraction of neutral He and the process is strongly influenced by solid state effects; at the higher end (velocity ~ 6 a.u.) most of the ions are stripped and the process can be described by individual He–Si collisions. The use of a semi-classical approach, based on the early theory of Bohr, allows for a satisfactory description of the He^+/He^{2+} ratio in the whole energy range.

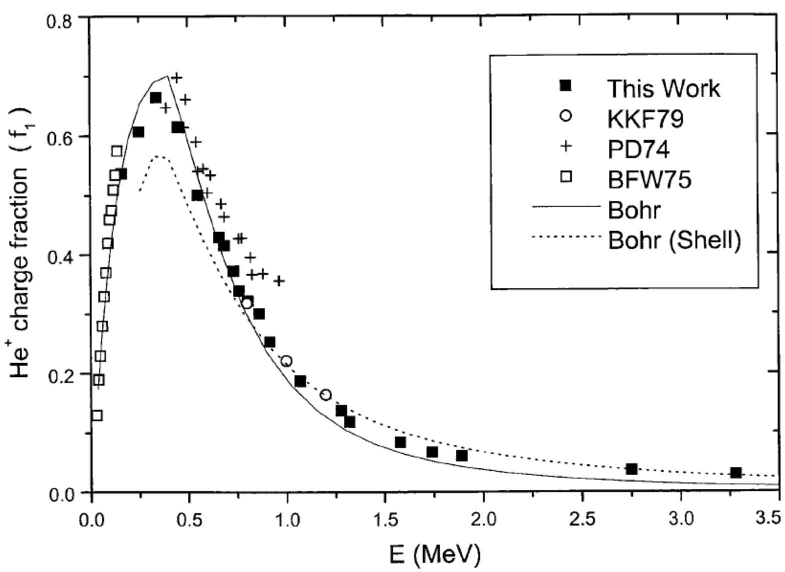

Fig. 2. He^+ fraction (f_1) of the transmitted beam: (■) this work, (□) BFW75 [8], (+) PD74 [9], (○) KKF79 [11]. Solid and dotted lines are different calculations of the f_1 charge fraction based of the theory of Bohr [1] (see text).

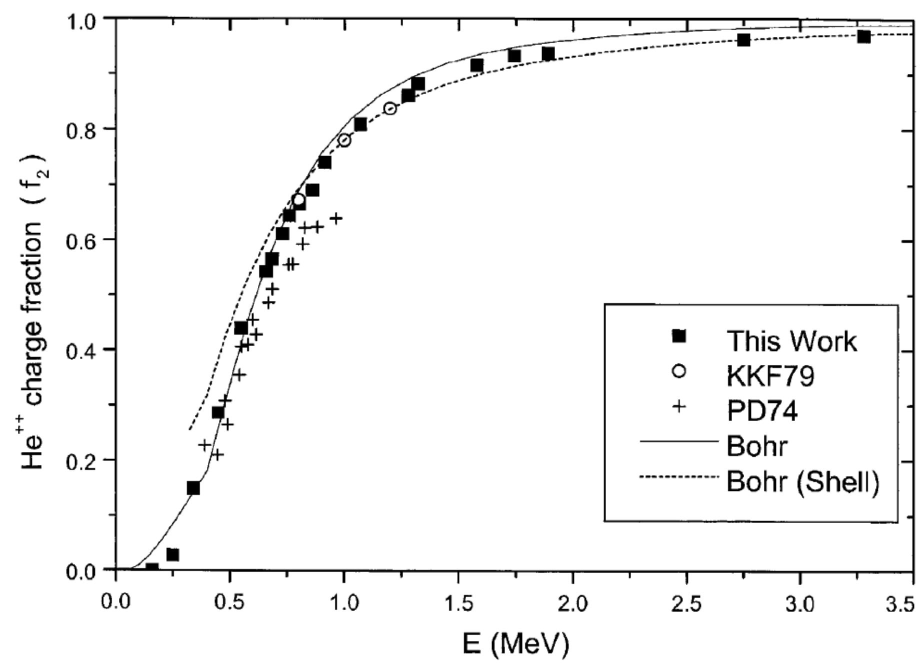

Fig. 3. The same as Fig. 2 for the He^{2+} fraction (f_2).

Summary

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- Concept of central production of the hyperpolarized ^3He: ^3He production facility, storage and transport, gas administration, ^3He recovery

- Applications of hyperpolarized ^3He in different fields of physics and applied science

Thanks for your attention!