JÜLICH
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Polarized ^{3}He neutron spin filters for neutron polarization analysis

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Mitglied der Helmholtz-Gemeinschaft

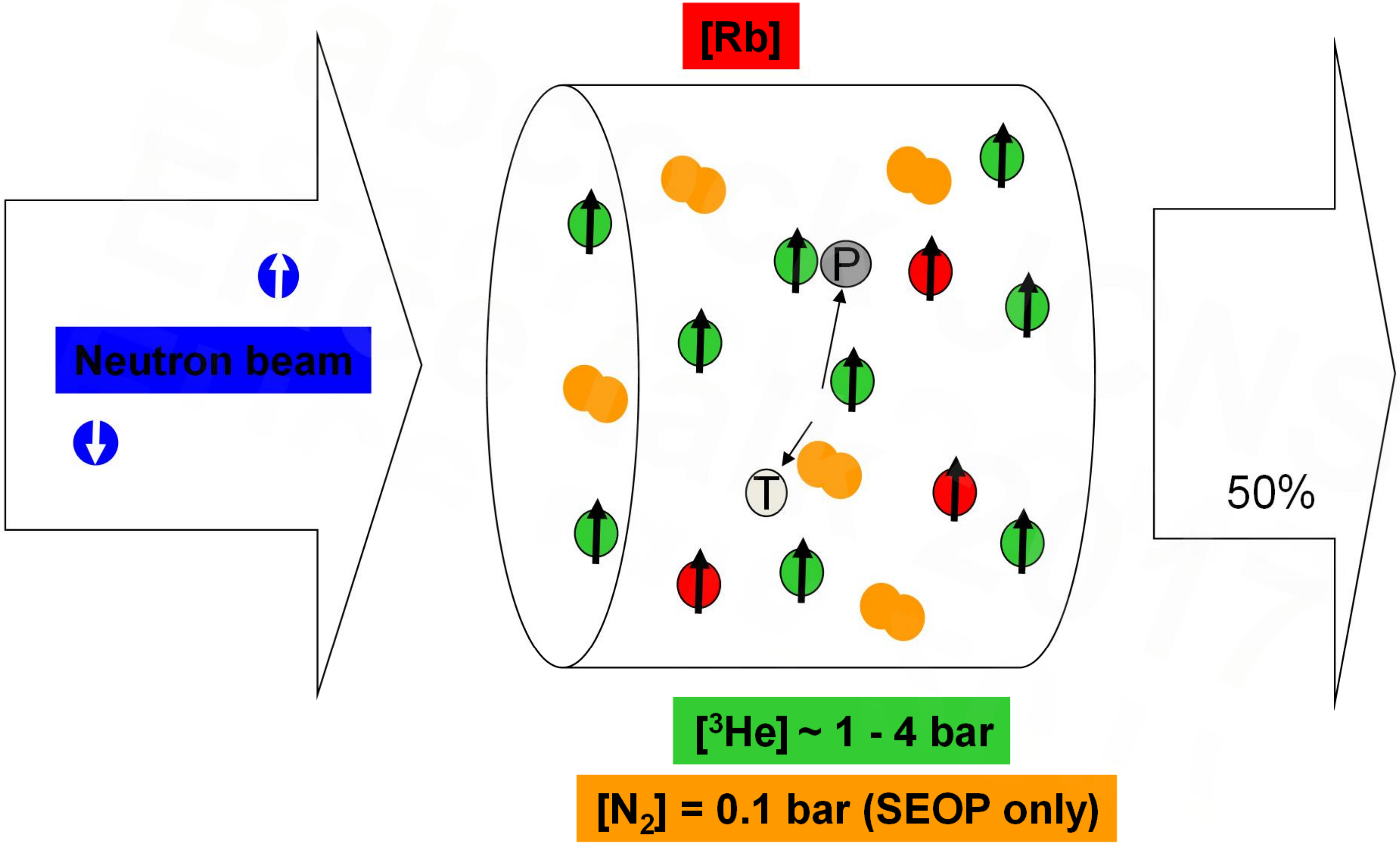
Outline of an introduction to ^{3}He spin filters

- How they polarize neutrons
- SEOP spin-exchange optical pumping
- MEOP metastable-exchange optical pumping
- Central polarization service
- In-situ devices
- Magnetic systems / polarization relaxation
    - Transporters
    - On-beam cavities / complete magnetic designs
- The non-ideal effects
    - Time-decay
    - Geometry
    - Cell transmission
- AFP spin flipping of the spin-filter
- Deterministic polarization data corrections
    - Instrument calibration
    - Matrix method for FULL correction
- Examples of worldwide capabilities from ILL, ISIS, ANSTO, NIST, FRM2, JERRI/JPARC
- When to use a ^{3}He NSF *why the above applications chose them*
    - notes on comparisons to SM
    - A few real world examples
- Discussion

It’s spelled POLARIZATION

Neutron polarization from polarized ^{3}He

the most ideal neutron polarizer *in the ideal case*



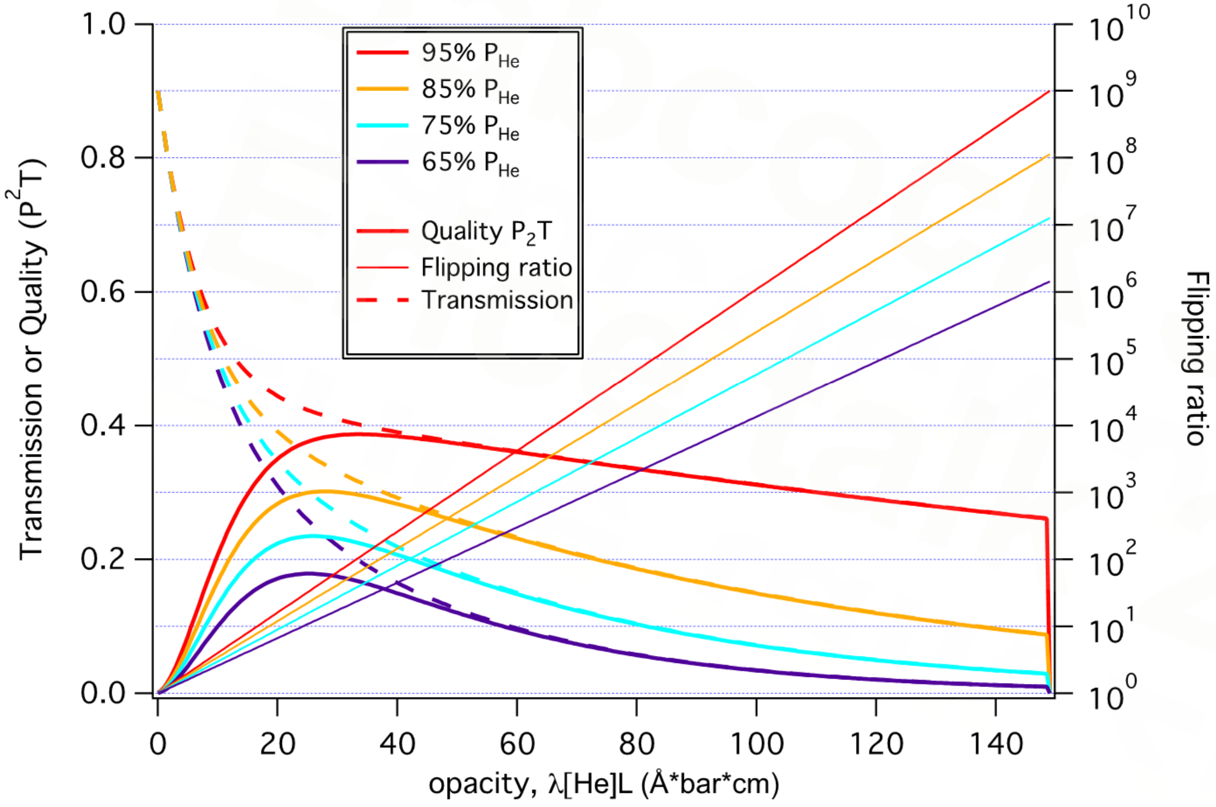
[Rb]

Neutron beam

[^{3}He] ~ 1 - 4 bar

[N_2] = 0.1 bar (SEOP only)

Typical performance P_n T_n and P^2T



$$P_n = \tanh(O\lambda P_{He}\sigma)$$

$$T_n = T_0 e^{(O\lambda\sigma)} \cosh(O\lambda P_{He}\sigma)$$

Follows from the spin dependent neuron absorption cross section of ^3He

$$T_n \pm = T_0 \exp(-O\lambda\sigma(1 \mp P_{He}))$$

where

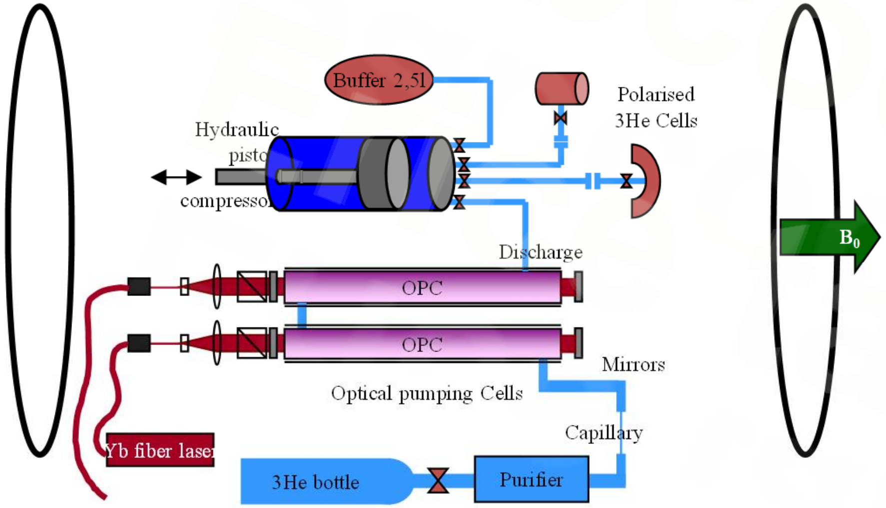
$\sigma = 0.0732$ bar^{-1}cm^{-1}Å^{-1}

$\sigma = 5333$ barn

Two polarization methods

MEOP

Metastable Exchange Optical Pumping



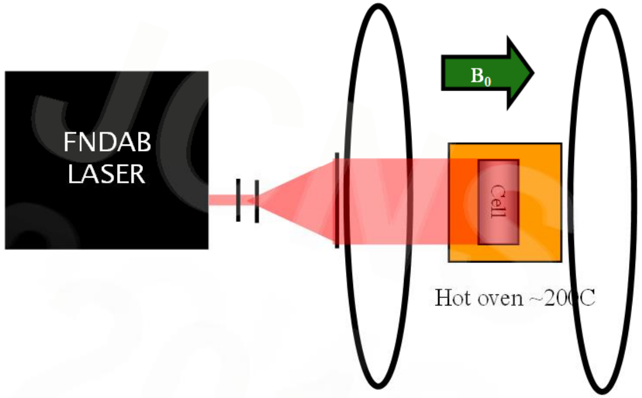
$\tau \simeq 2$ min

Pressure 1 mbar

Compress 1 hour→1 bar liter

SEOP

Spin Exchange Optical Pumping concept



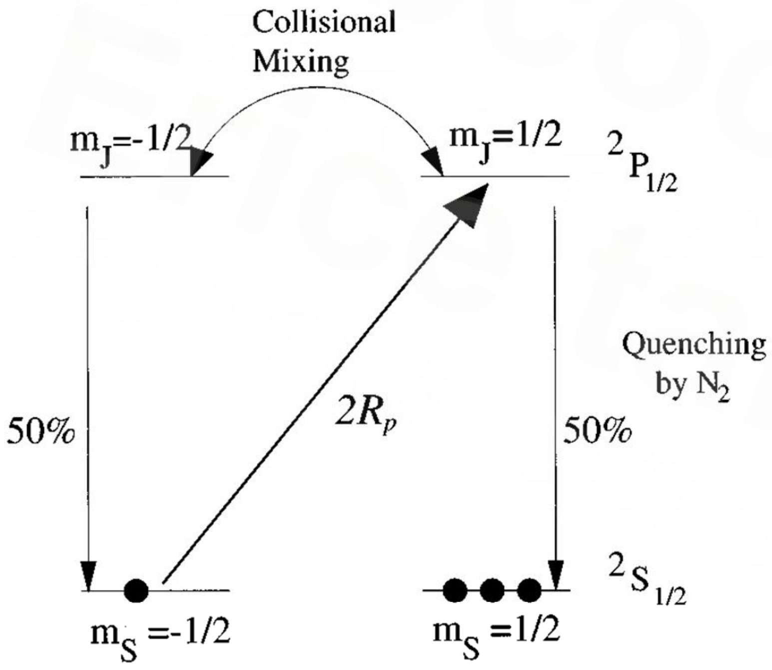
$\tau \simeq 2$-10hours

Pressure 1 to 4bars+

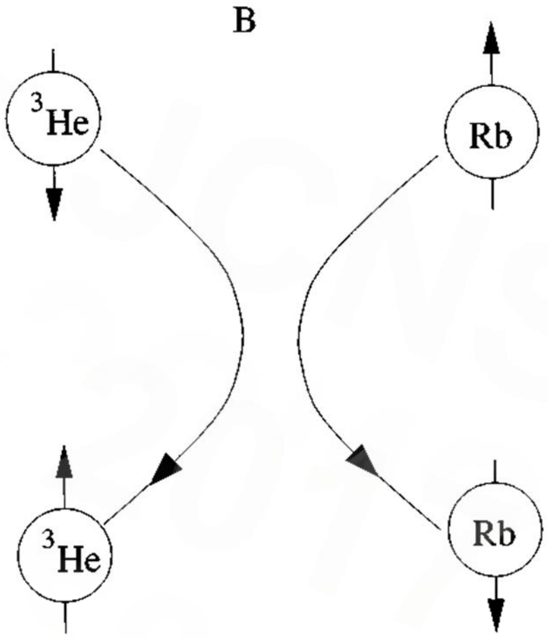
Pump to ~3τ

SEOP

Optical pumping
(on Rubidium)

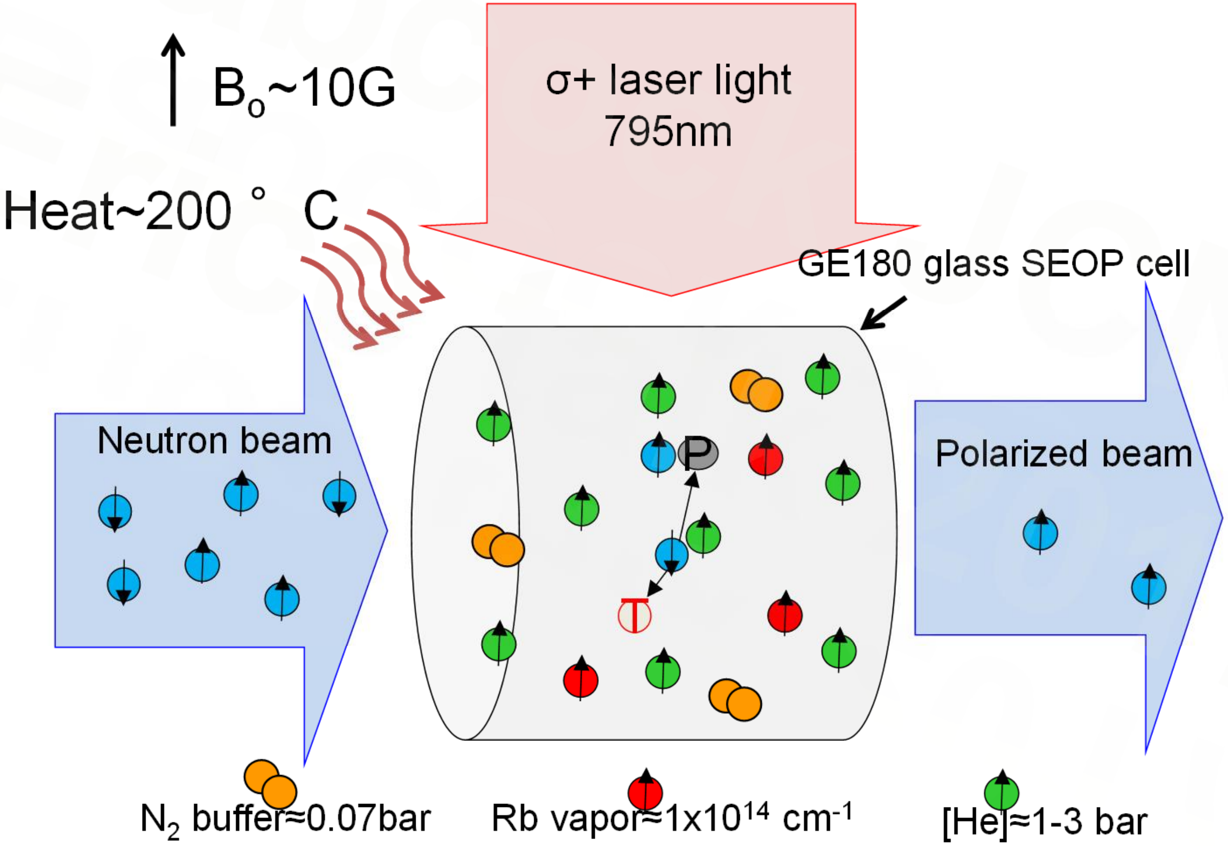


Spin-exchange
(to helium)

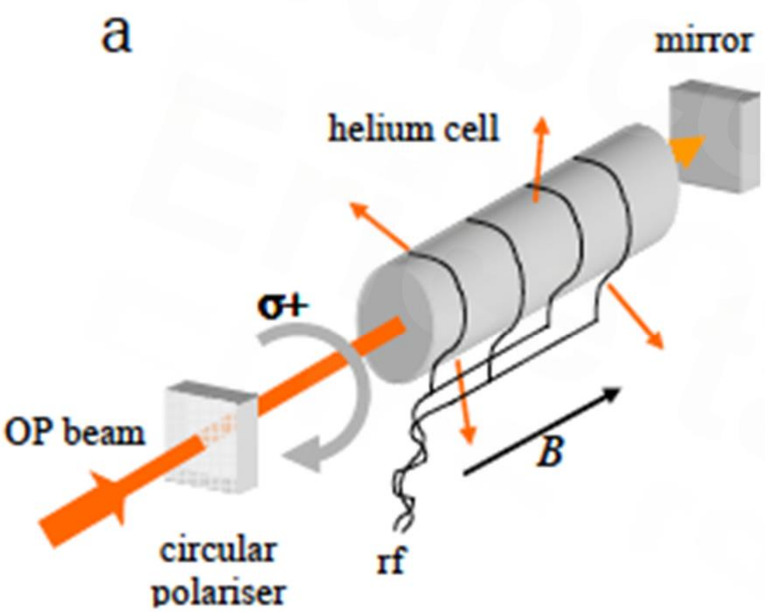


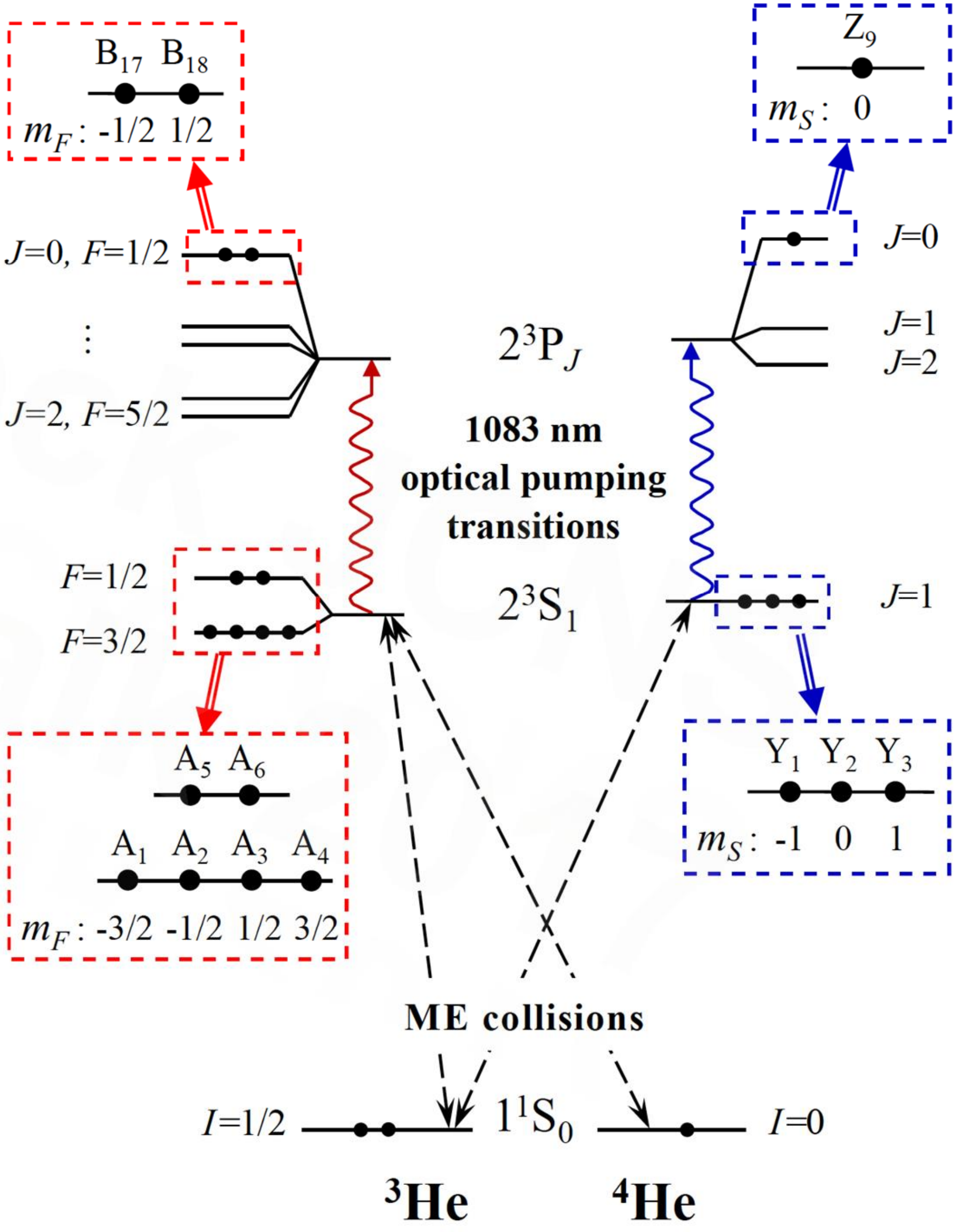
SEOP ^{3}He in-situ neutron spin filter

Spin Exchange Optical Pumping



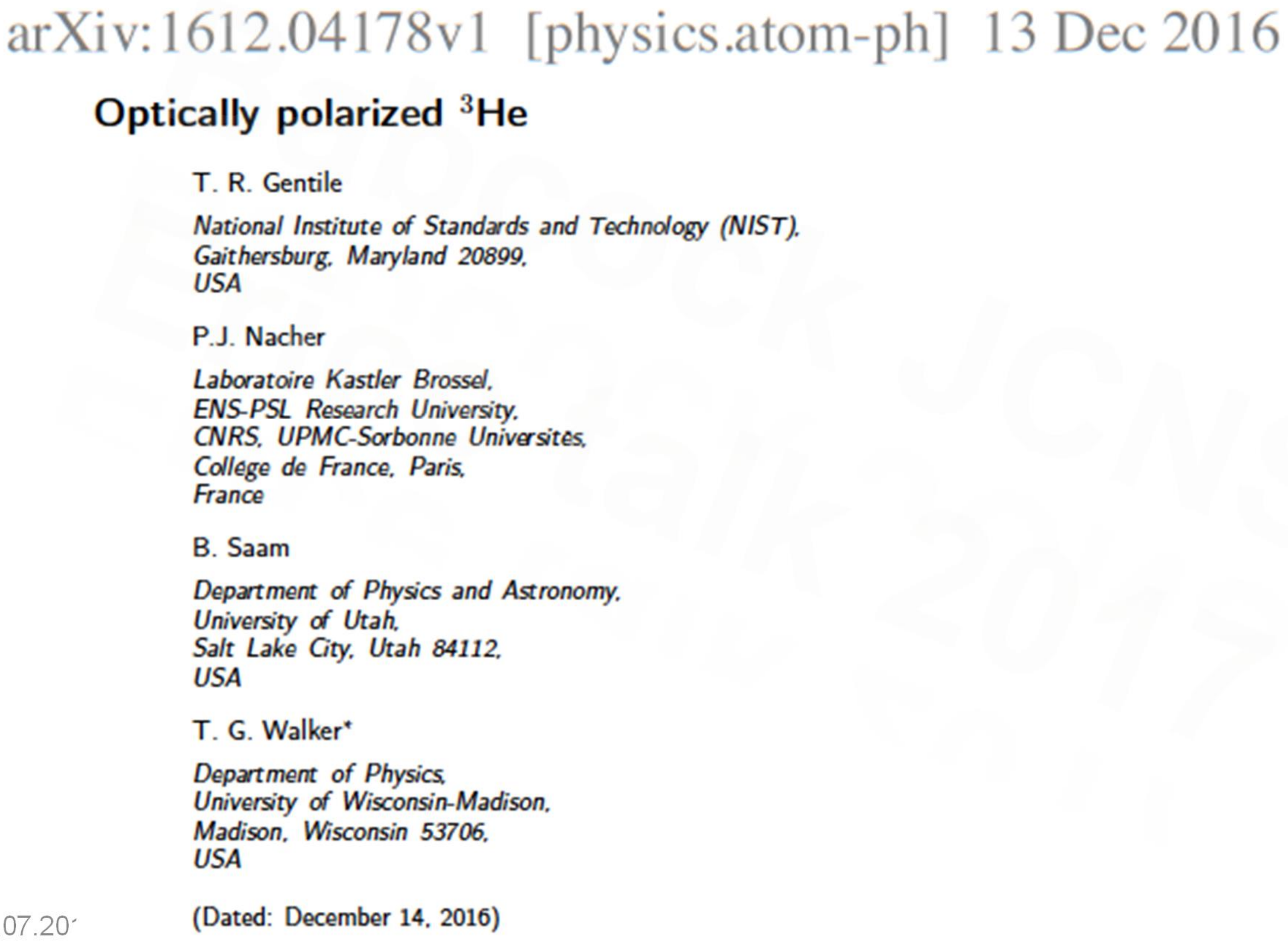
MEOP, metastable-exchange optical pumping





A recent summary of ^{3}He optical pumping

In submission to Reviews of Modern Physics



arXiv:1612.04178v1 [physics.atom-ph] 13 Dec 2016

Optically polarized ^{3}He

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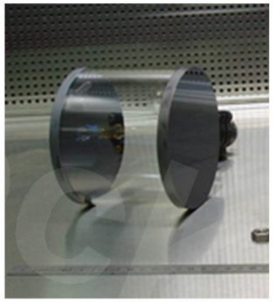
(Dated: December 14, 2016)

MEOP offline polarized spin filter cells

TREX polarizer at ILL

Valved spin filter cell

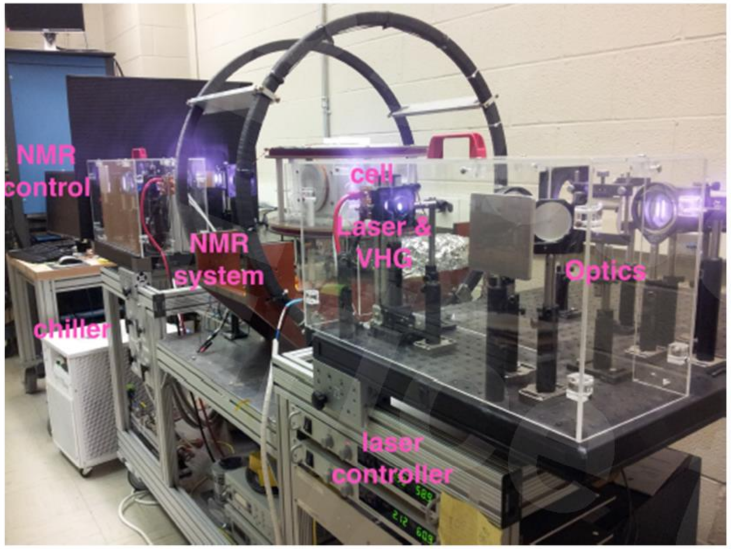


B_0 field for instrument
“magic box”

Magnetic transporter box

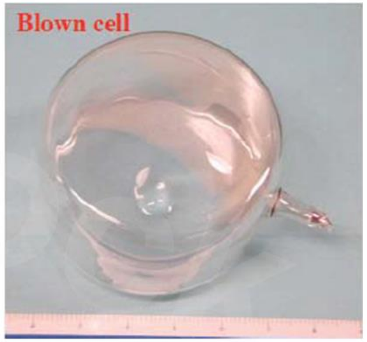
^{3}He recovery

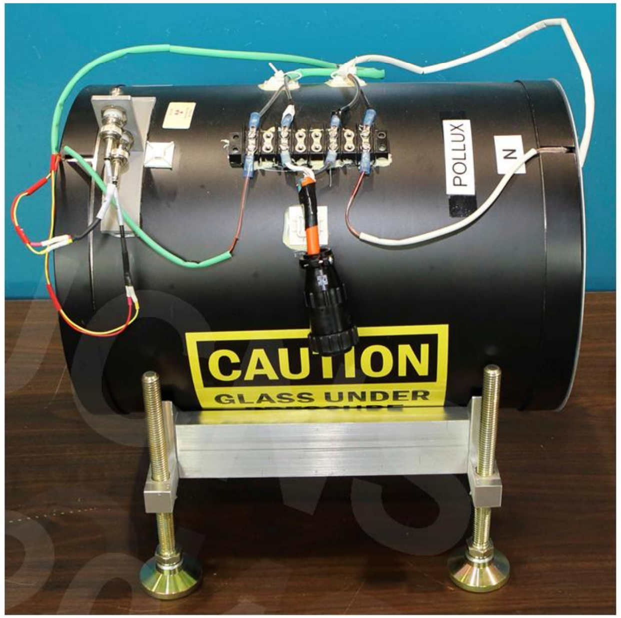
SEOP offline polarized spin filter cells, NIST



One of three polarizers at NIST

sealed spin filter cell



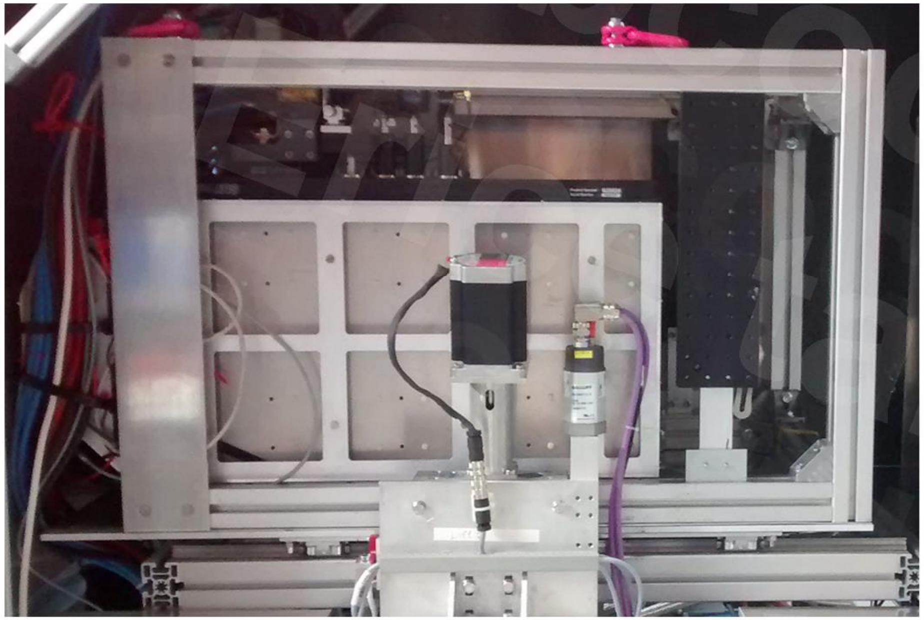


B_0 field for instrument shielded solenoid

Battery powered transporter solenoid

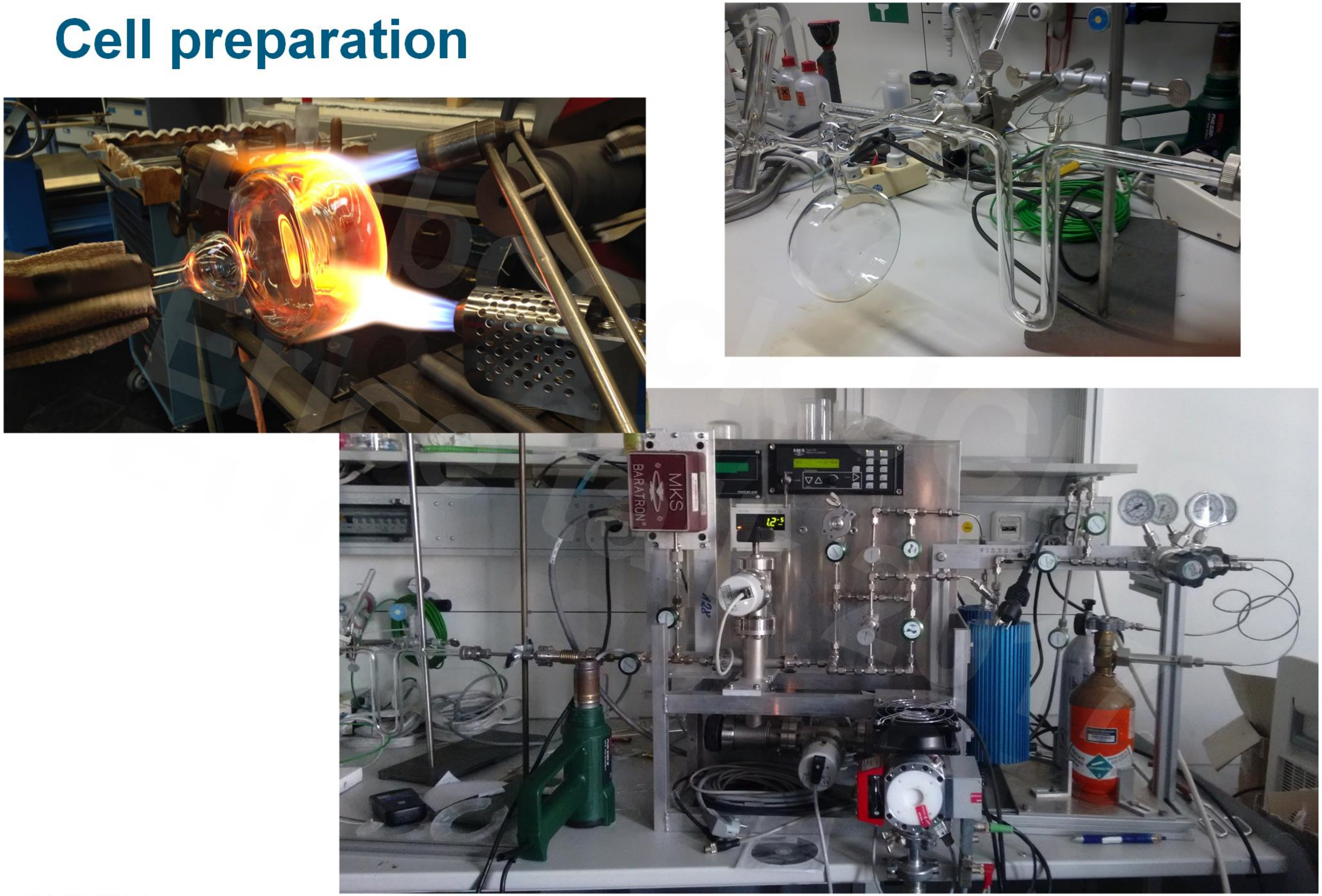
In-situ polarized cells as instrument components

MARIA analyzer



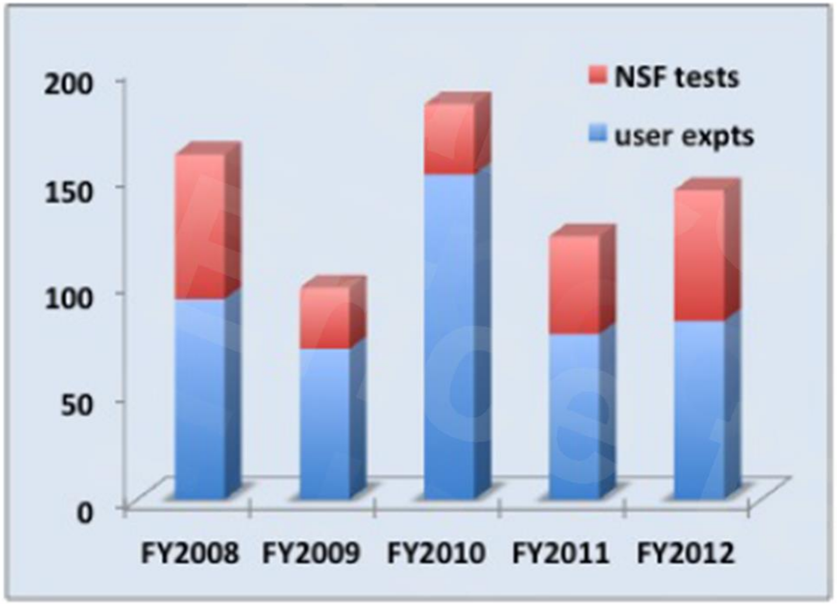
Idafix cell D=12.5 cm
1.2 bar liters

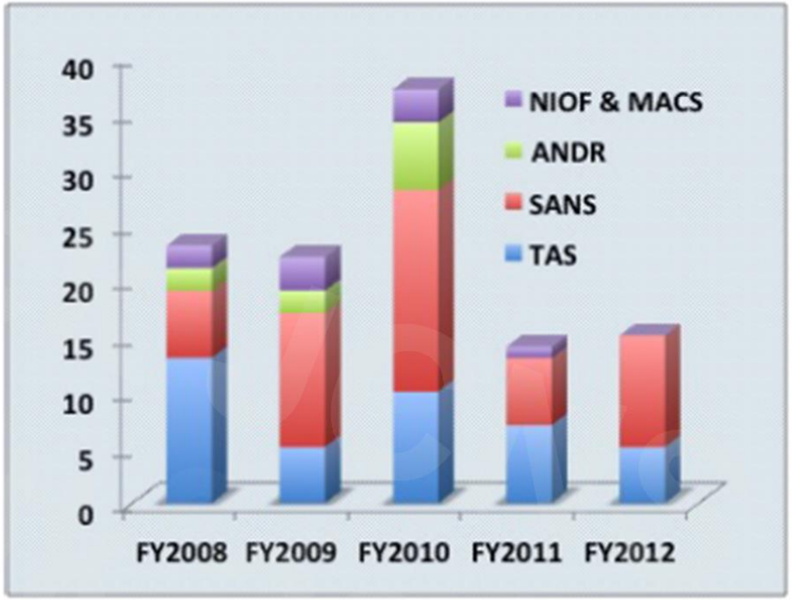
Cell preparation

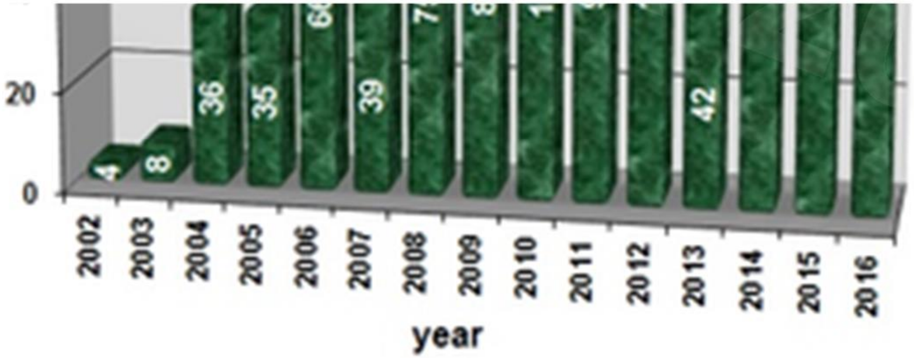


Central facility polarized ^{3}He production

NIST SEOP central polarization service

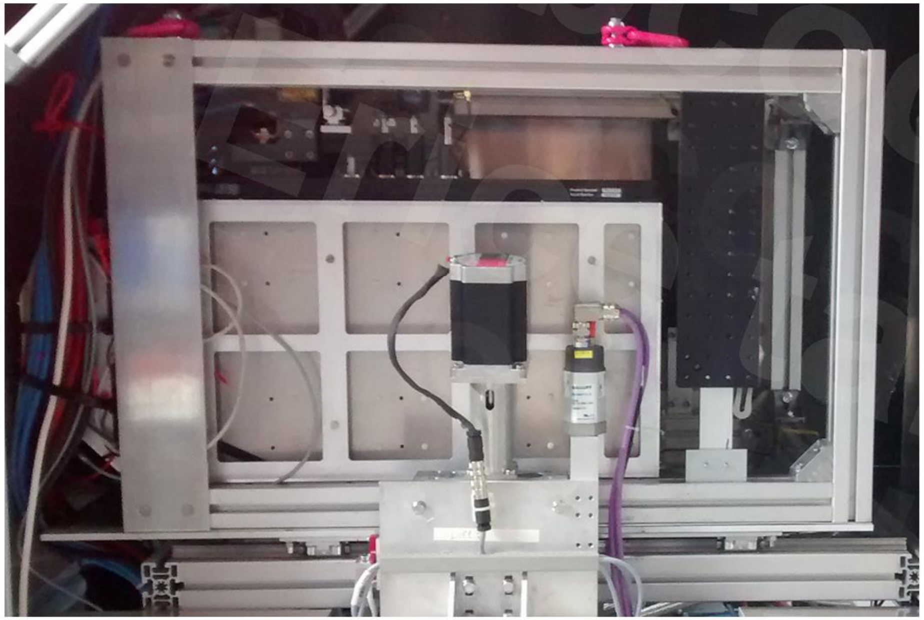






In-situ polarized cells as instrument components

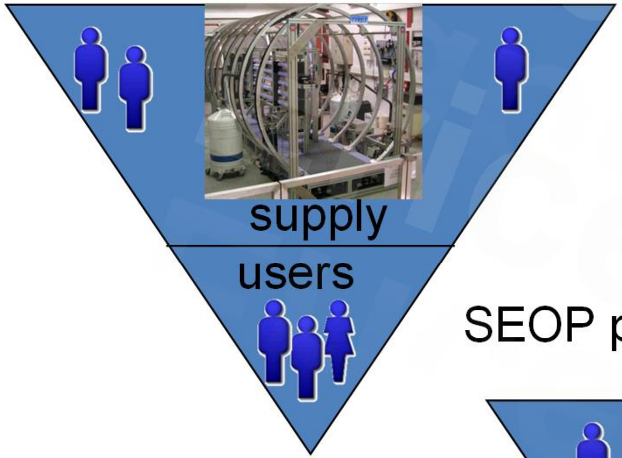
MARIA analyzer



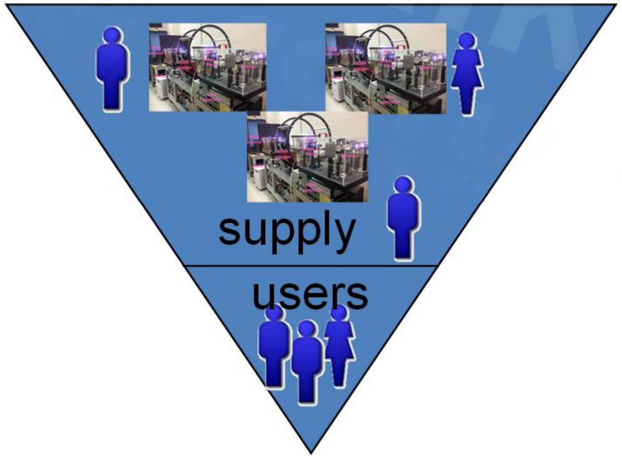
- Sealed SEOP cell
  - D=12.5 x L=8 cm
  - 1.2 bar
- V=0.98 liter about 1.2 bar liters
- FRM2 reactor has 4x60 days per year
- 288 bar liter days of polarized ^{3}He
- Last cycle 28 days (34 bar liter days)

Central service vs. in-situ polarization

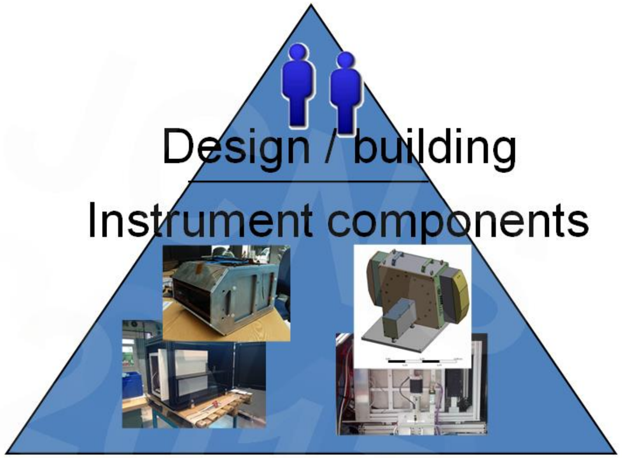
MEOP polarization filling station ILL



SEOP polarization station NIST

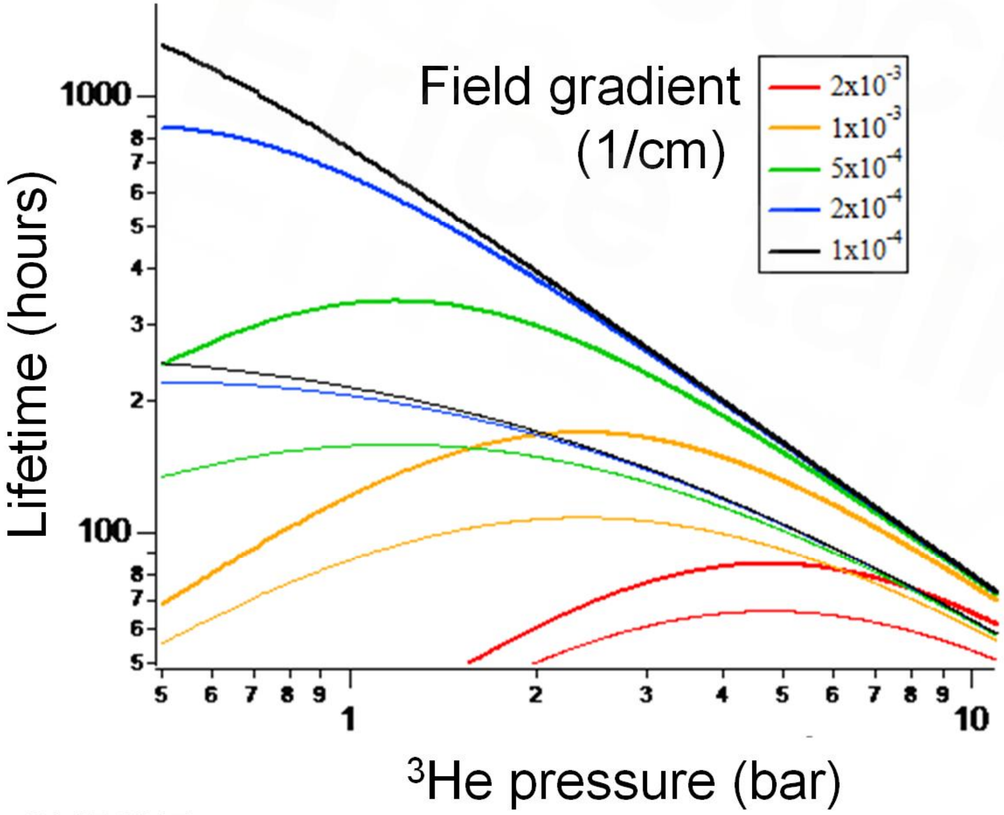


Online ^{3}He polarizers JCNS



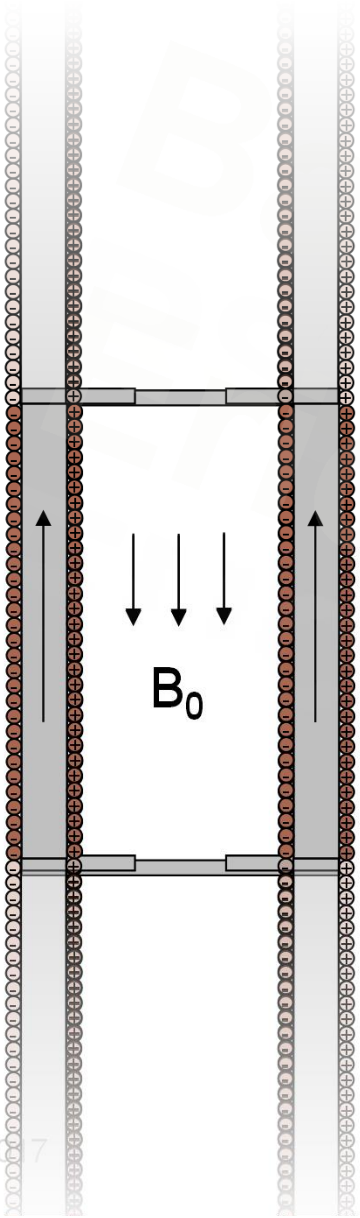
Magnetic field gradient relaxation of ^{3}He

$$\frac{1}{T_1} = \frac{C}{P}\frac{(\nabla B_Y{}^2 + \nabla B_X{}^2)}{B^2} + \frac{P}{800} + \frac{1}{T_{wall}}$$



- for most neutron applications **the ^{3}He lifetime would be saturated at 2x10^{-4}** levels of field gradients for any cell pressure
- **Obtaining multi-hundred hour lifetimes is very important** for long term use because of reduced labor and maintenance / better polarization
- One can use a ^{3}He cell for about 1 day per 100 hours of on-beam lifetime

Shielded solenoid on-beam B_0 Field



- Use μ-metal to generate a uniform field
- relies on geometric symmetry and mirror planes
- "shielding" because μ-metal is below saturation *(i.e. μ is still large)*

- top and bottom pole plates are mirrors

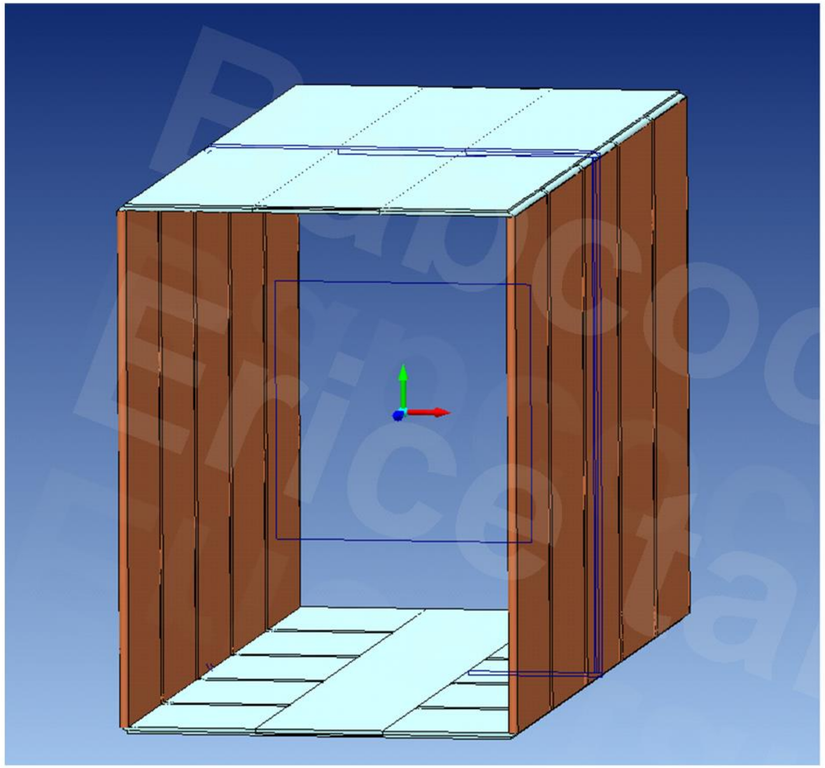
therefore field B_0 follows Ampere's law:

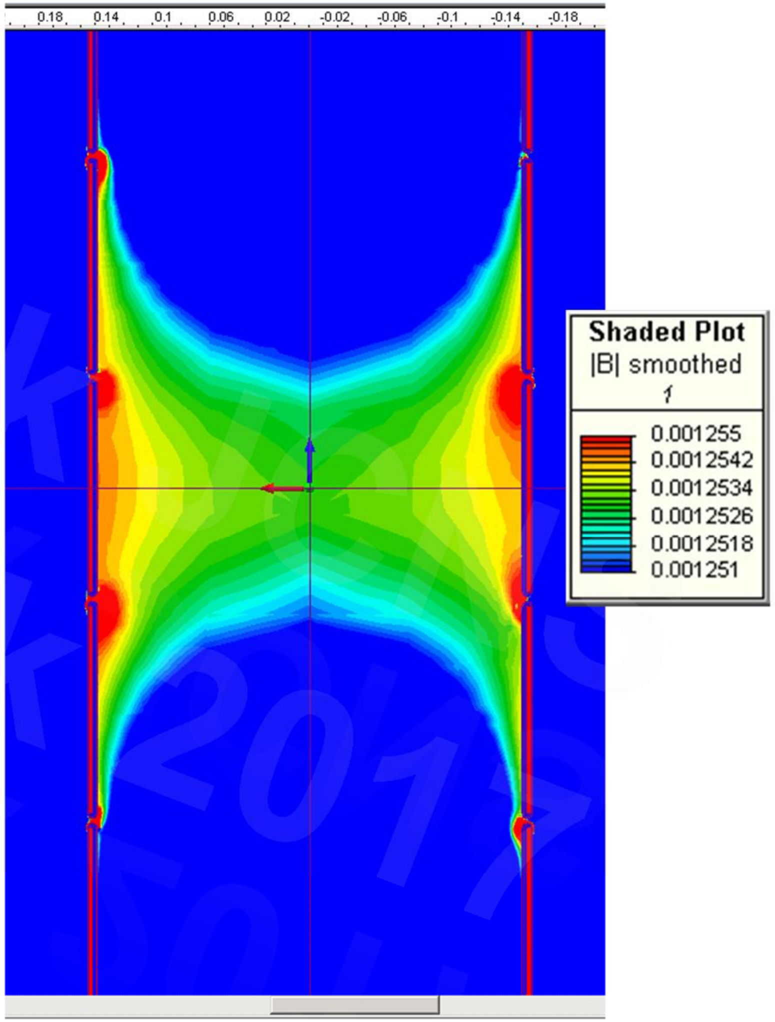
$$B_0 = \mu_0 n I$$

$\mu_0 = 4\pi 10^{-7}$ (Tm/A),
n=turns per meter
I=current

For example 1 turn per 1 mm and 1 A=12.546 G

Box magnetic fields





- 76 cm long
- Shielding comes from length
- Field in middle 10 cm is the field of an Infinite solenoid,
- the cell doesn't see the outside

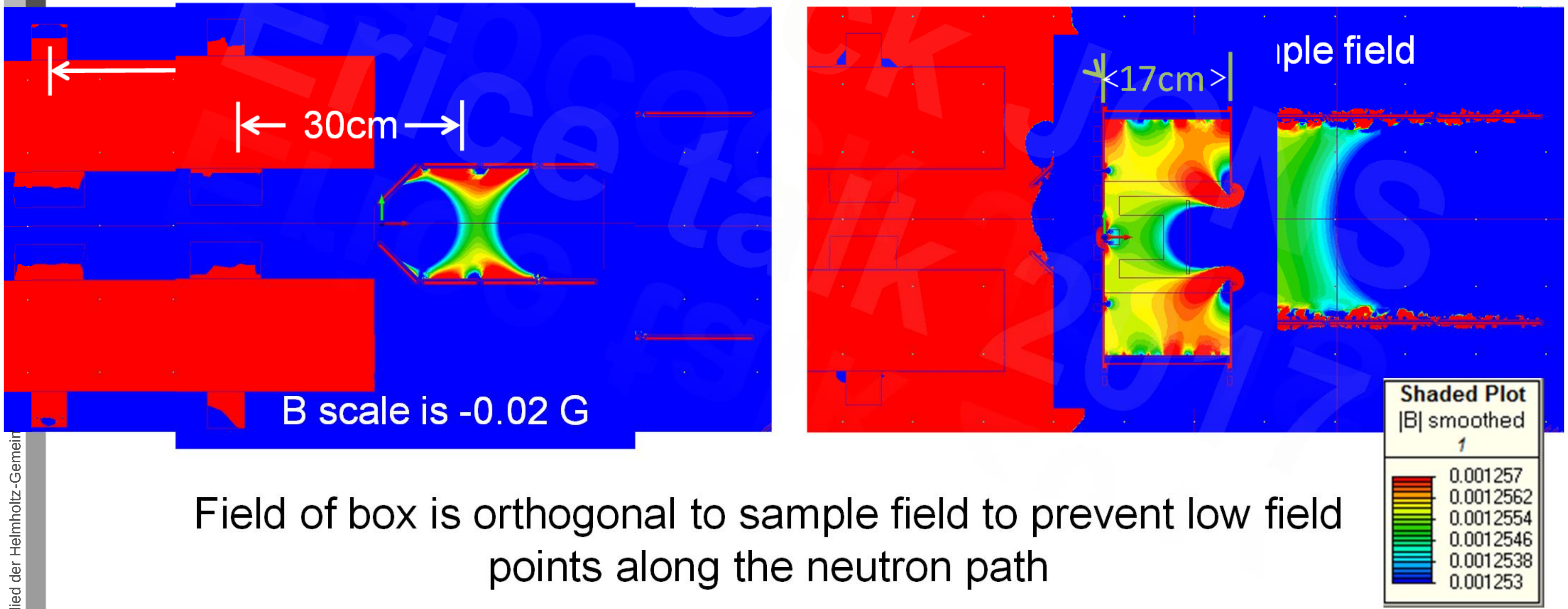
Magnetic holding fields

- MARIA L=50cm Φ=12.5 cm $q_{max} \leq \pm 0.17$ Å^{-1} (0.12 Å^{-1}) $T_1 \approx 400$ hours (mag>1300 hours)
    - KWS1 L=32cm Φ=7 cm $q_{max} \leq \pm 0.20$ Å^{-1} (mag lifetime expected 150-250 hours)
  - KWS2 (compact solenoid) L=9cm Φ=6cm $q_{max} \leq \pm 0.85$ Å^{-1} (mag lifetime 400 hours measured)

KWS1 magic box: 50% scale of MARIA box, minus one pair of yokes [illegible]

28 cm x 20 cm x 15 cm [illegible]

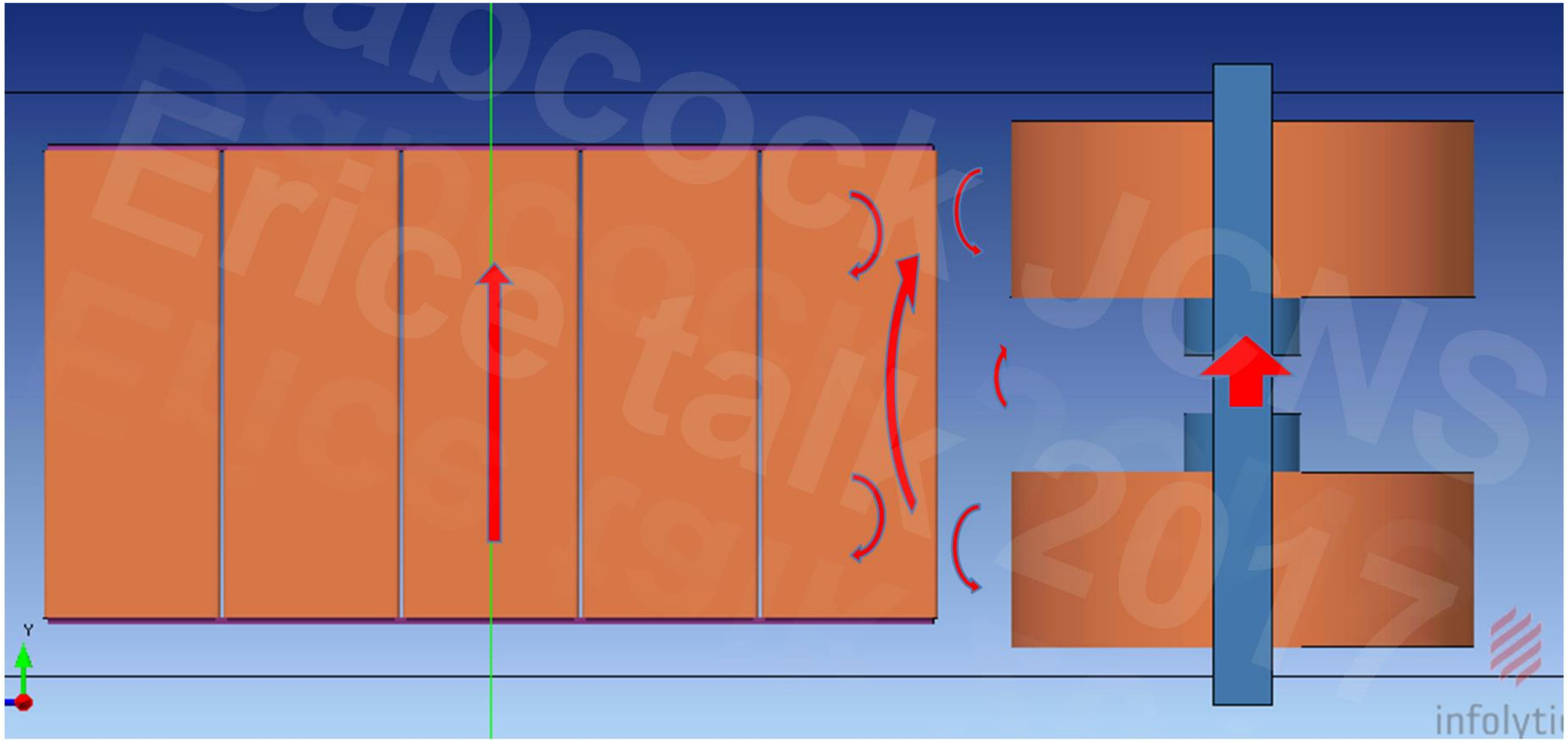
Near full decoupling from sample magnet



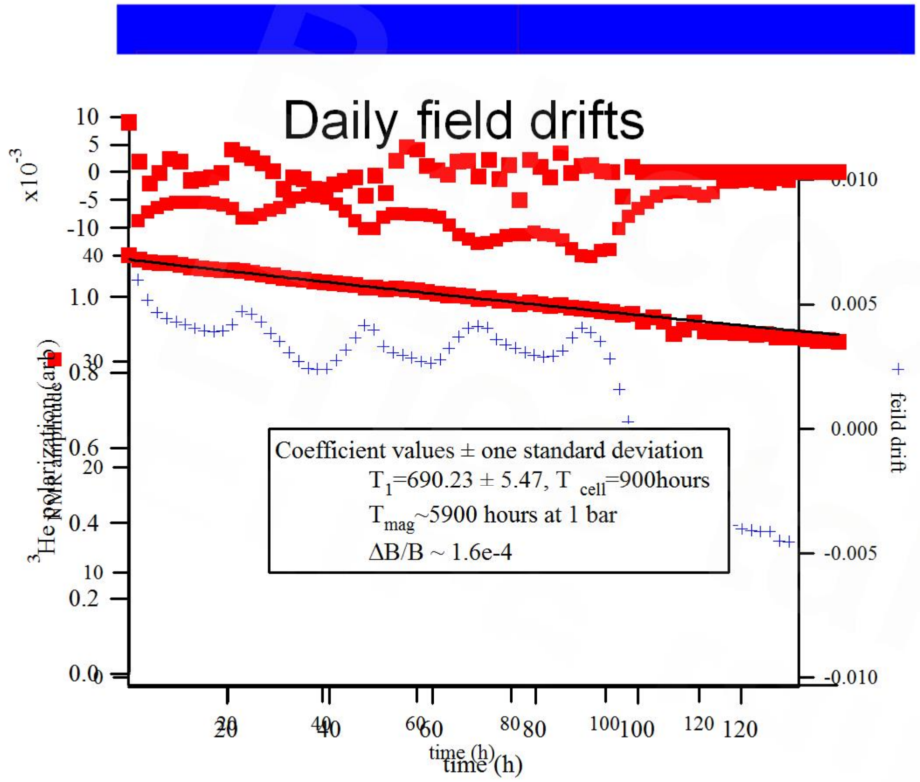
Field of box is orthogonal to sample field to prevent low field points along the neutron path

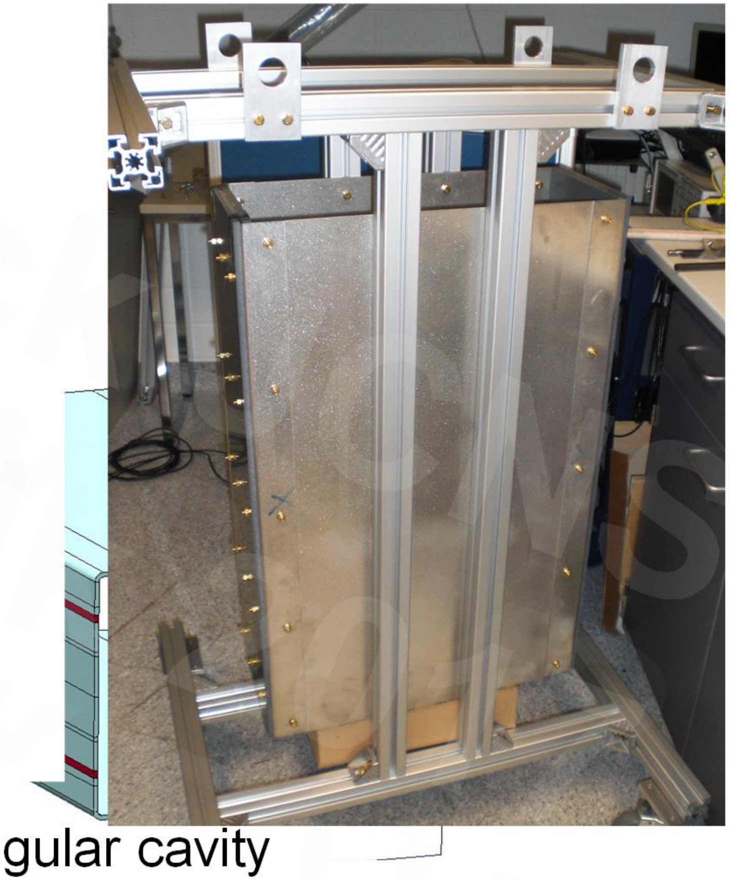
Beware of coupling between components

original MARIA configuration



Permanent Magnetic transporters

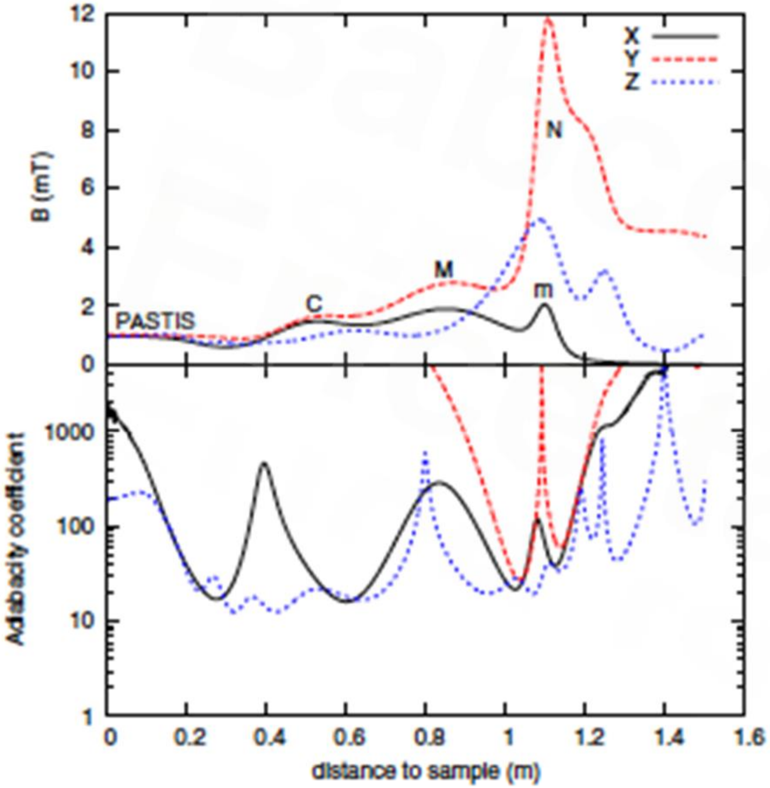




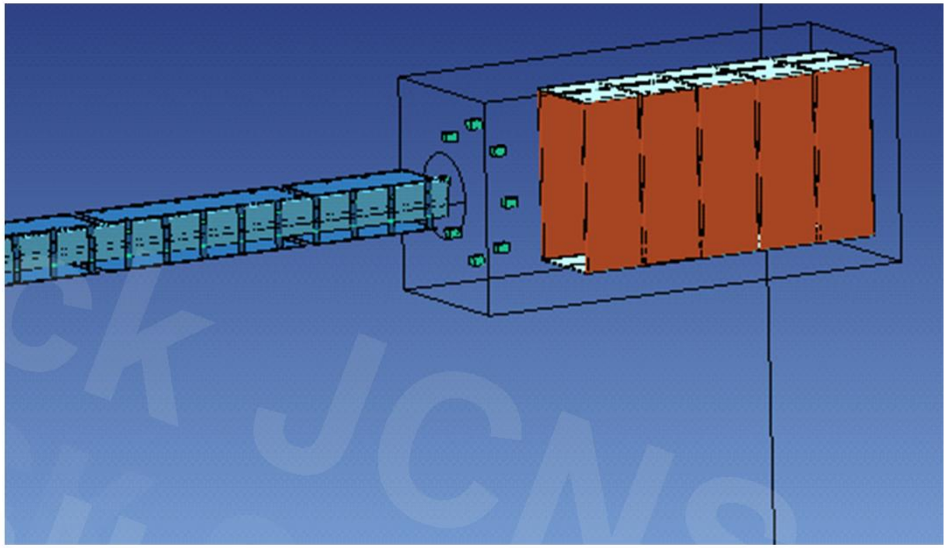
- Simple mu-metal rectangular cavity
- two strips of permanent magnets in the yokes
- Saturation of magnets 0.25 T

24.07.2017

PASTIS modeled with the guide fields



Adiabaticity is high over the whole neutron path



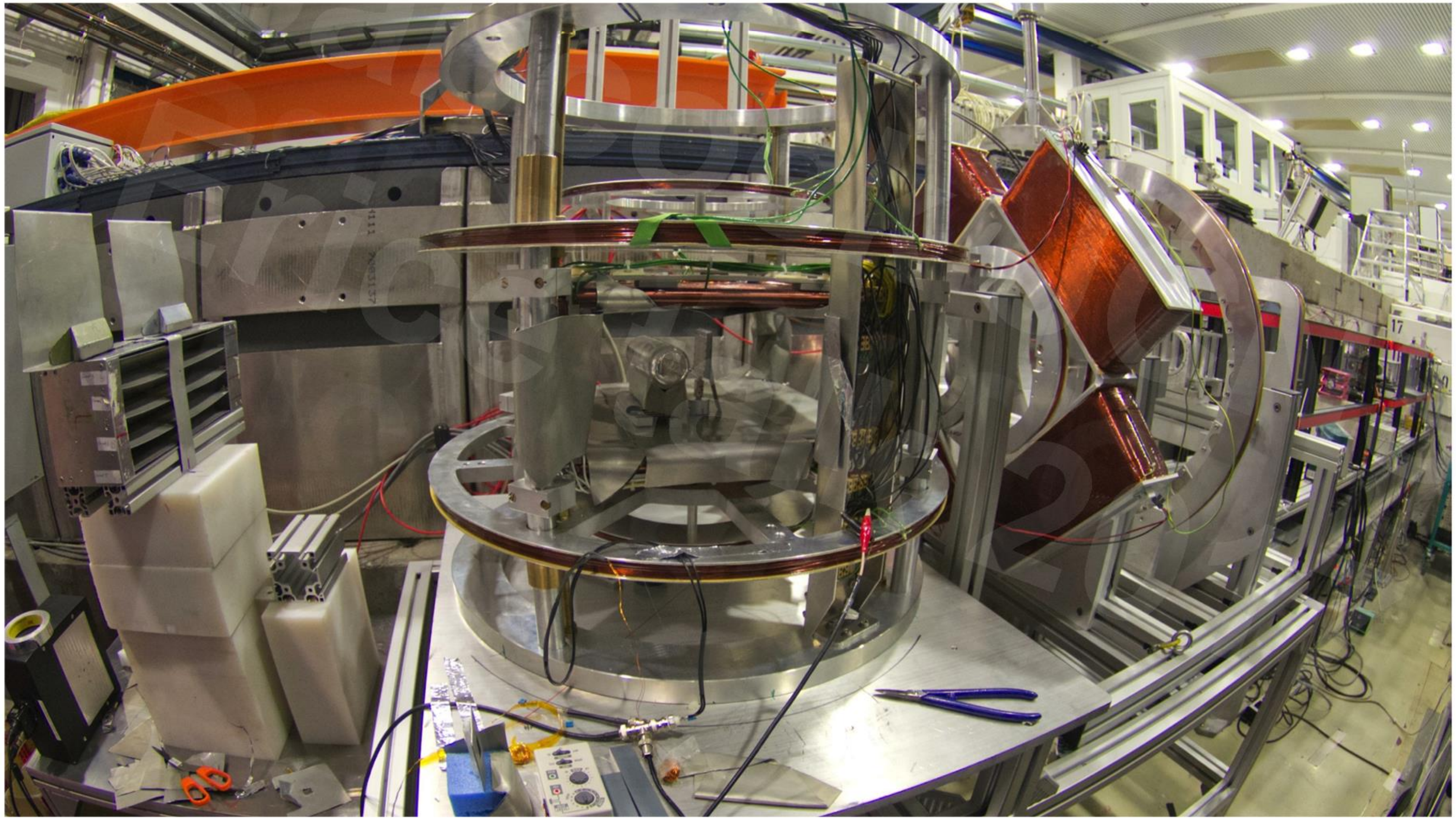
Guide field must not influence PASTIS homogeneity

Field must bridge gaps caused by instrumentation, i.e. vacuum vessel and choppers and exist in available space

TOPAS and guide field config in;
J. Voigt et al, European Physical J. Conf. 83:03016 (2015)

Photos on V20 at HZB ESS simulator test-beamline

PASTIS, with a ^{3}He cell and sample installed on V20 at HZB Berlin



Time decay of the ^{3}He

a performance difference between offline and in-situ polarization

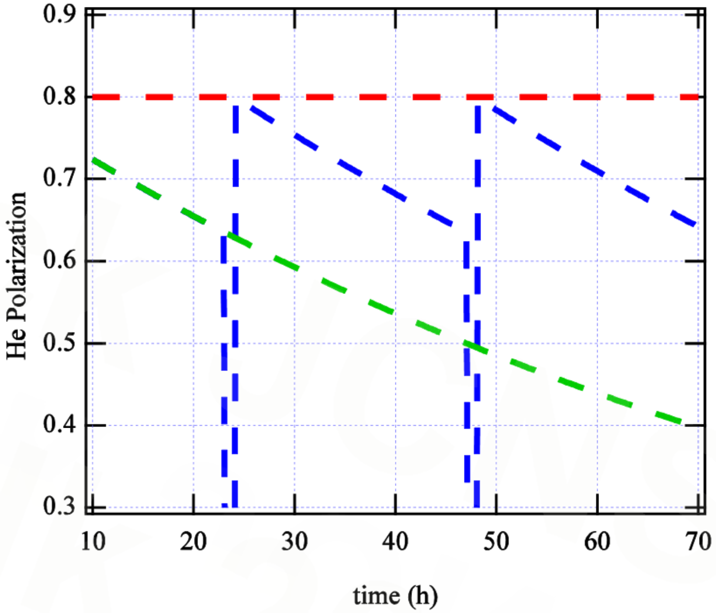
online polarization improves quality such that lower maximum polarization can out perform higher offline polarization when integrated over time

Example

P_{He}=80%, P_n=95%, T_n=29%, "Quality factor"=$P_n^2T_n$=0.26

But for the same cell when **P_{He}=63%, P_n=90%, T_n=20%, $P_n^2T_n$=0.16**

- **This is the cell's performance after one day with a 100 hour lifetime**
- **P_{He}=71% but constant, will have same time integrated performance as a P_{He}=80% offline polaized cell**



^{3}He polarization vs. time

One can measure about 1 day per 100 hours of cell lifetime and maintain reasonable performance

Time decay problem vs. in-situ polarization

(origin of the bar liter day)

online polarization improves quality such that lower maximum polarization can out perform higher offline polarization when integrated over time

Example **P_{He}=80%, P_n=95%, T_n=29%, “Quality factor”=$P_n^2T_n$=0.26**

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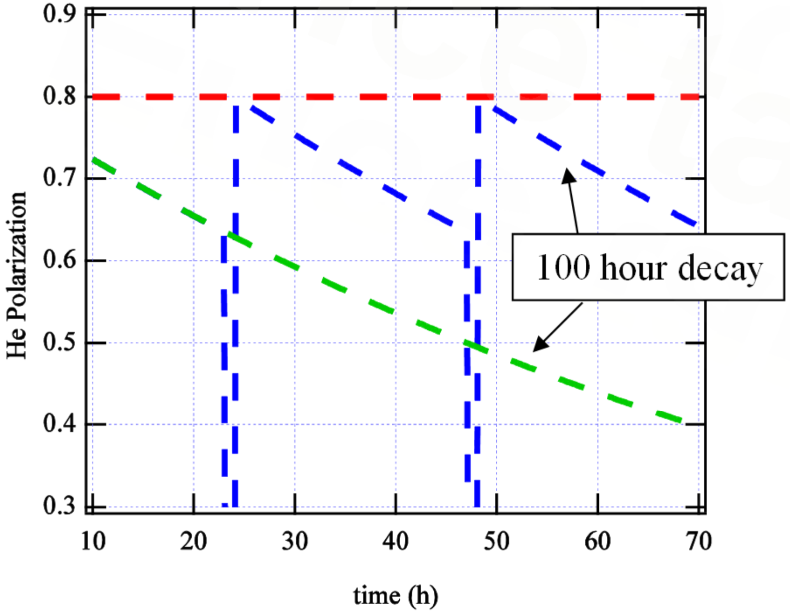
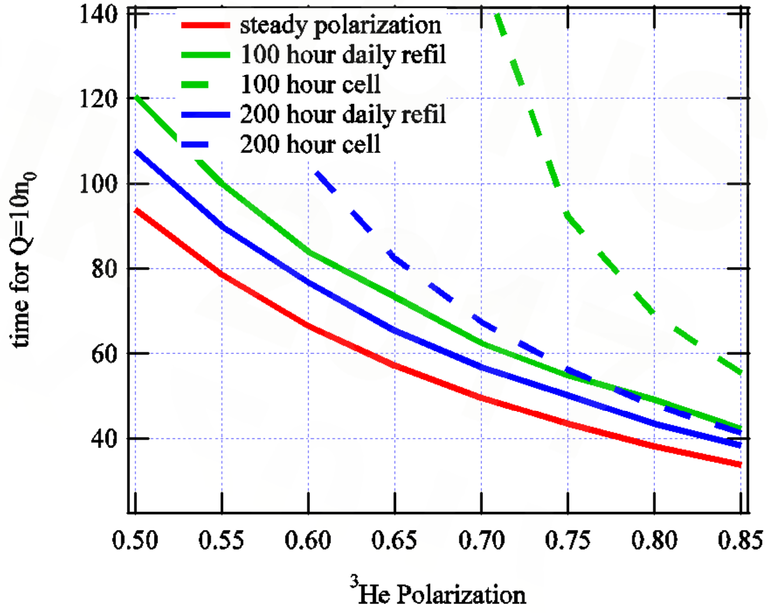


^{3}He polarization vs. time



Integrated quality vs. ^{3}He polarization

Cells, cells cells


Puck


Astrix

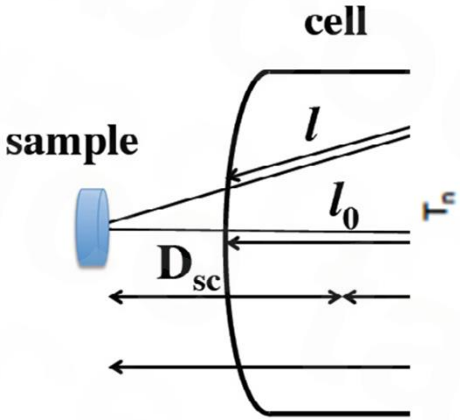

Homer

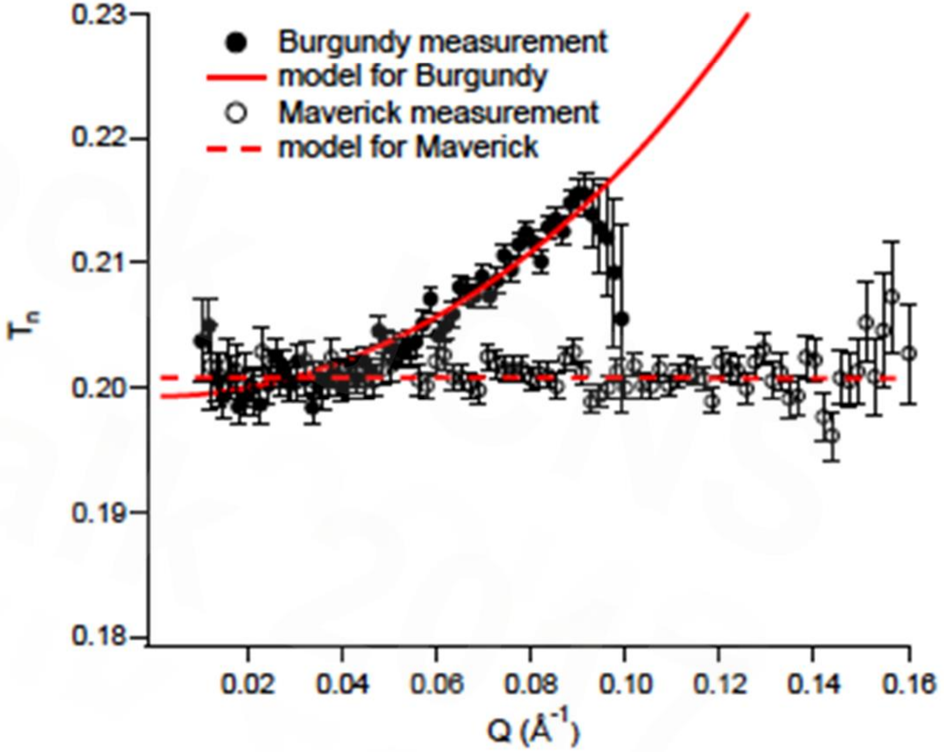
name	D x L (cmxcm)	[He] (bar)	K/Rb D	T_1 (h)	$T_{1\ \mathrm{dipole}}$ (h)
Maja	5 x 5	0.93	0	80	860
Puck	6 x 5	1.0	1.24	500	800
Kurt	6 x 5	2.3		350	350
Willy	6 x 5	2.3	2.79	370	350
Homer	22 x 8	0.5	0	680	1600
Obelix	12 x 5	2.1	0.69	340	380
Asterix	12 x 5	2.7		280	295
Spider	6 x 5	2.7		280	280
Gremilda	6 x 5	2.7	2.52	300	280
Jimmy	6 x 5	1.9	6.45	210	420
Ulasen	6 x 5	0.5		560	1600

J of Phys: Conference Series **528** (2014) 012015 doi 10.1088/1742-6596/528/1/012015, Z Salhi, E Babcock, P Pistel and A Ioffe

Geometric corrections

W.C. Chen et al. / Physics Procedia 42 (2013) 163 – 170

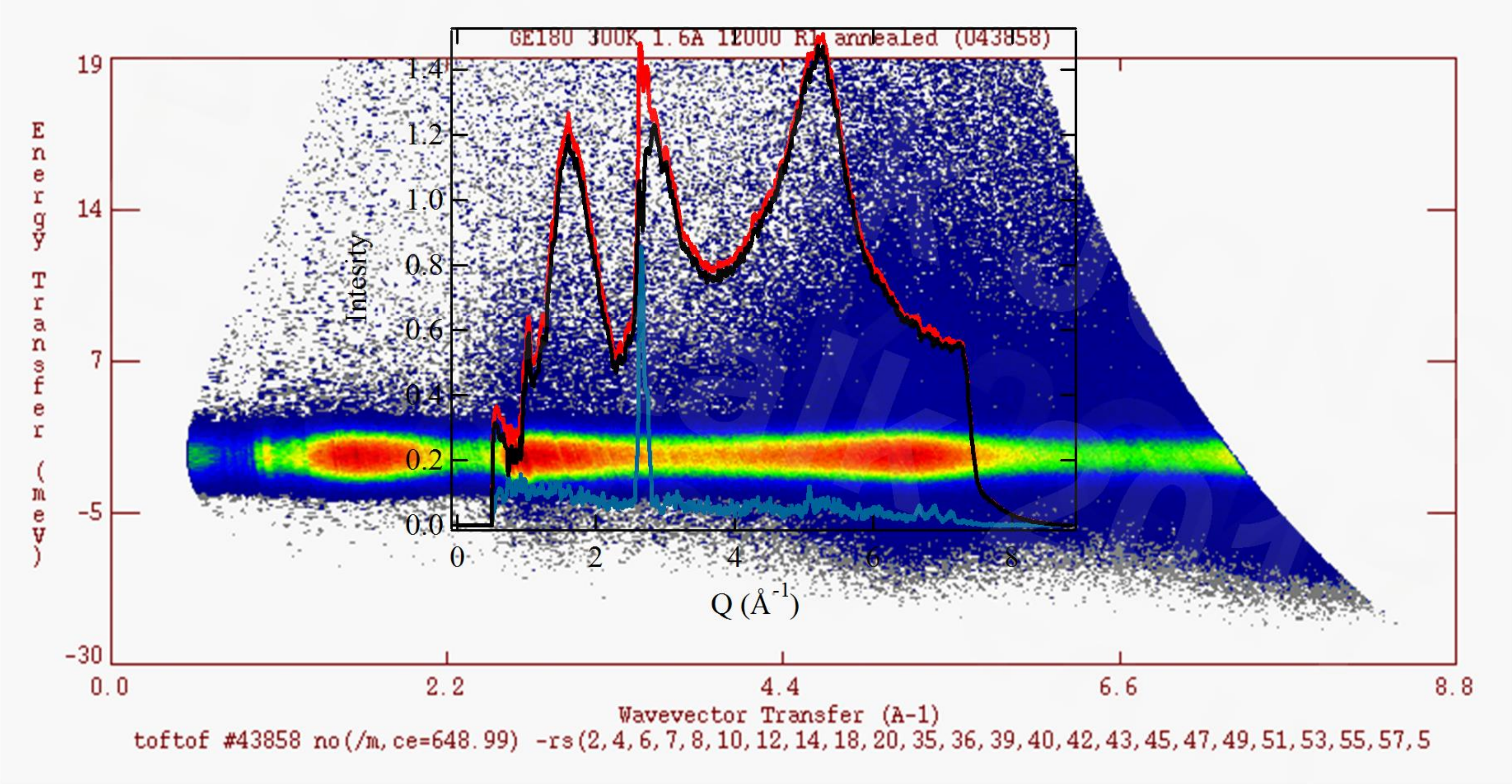




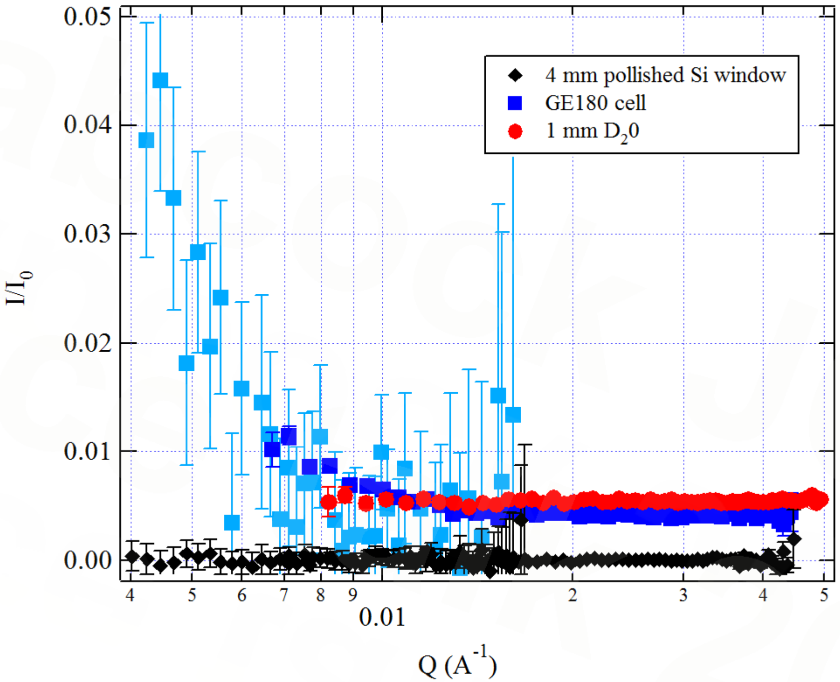
$$\frac{l}{l_0} \simeq 1 + \left[\frac{1}{2}\left(1 - \frac{l_0}{2R}\right) - \frac{D_{sc}^2}{Rl_0}\right]\tan^2(2\theta) + \left[\frac{1}{2}\left(1 - \frac{l_0}{2R}\right) - \frac{D_{cd}^2}{Rl_0}\right]\frac{A_S}{2\pi D_{sd}^2}$$

Cell transmission effects

measurements on TOF TOF with G. Simeoni



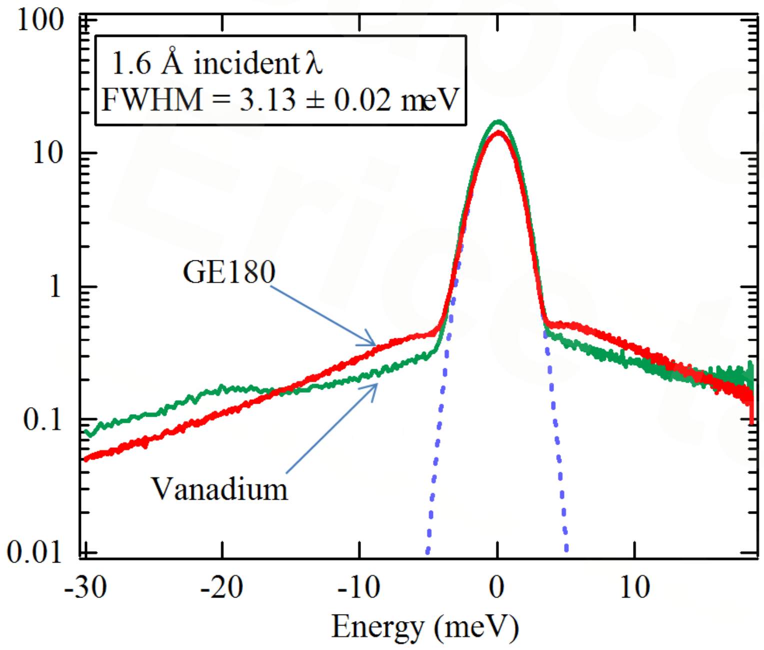
SANS scattering from GE180

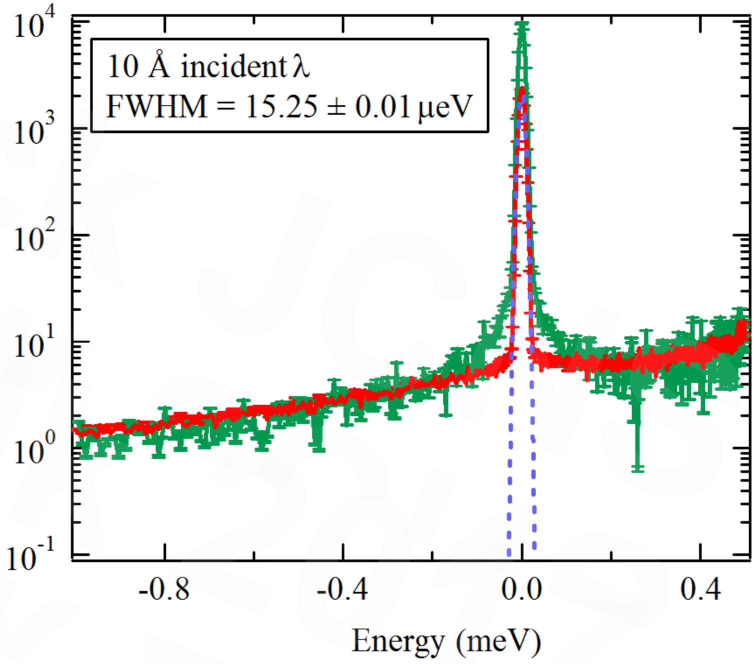


- For $Q > 1\mathrm{x}10^{-2}$ blown GE180 cells are weak scatterers
- i.e below the level of 1 mm of D_2O
- single cystal silicon has essentially 0 scattering,
- however Si windowed cells have not been polarized dirrectly to date
- a „double cell“ or offline polarization would be required
- GE180 has some structure above 9 Å whereas Si has absorption

Does GE180 affect (energy) resolution

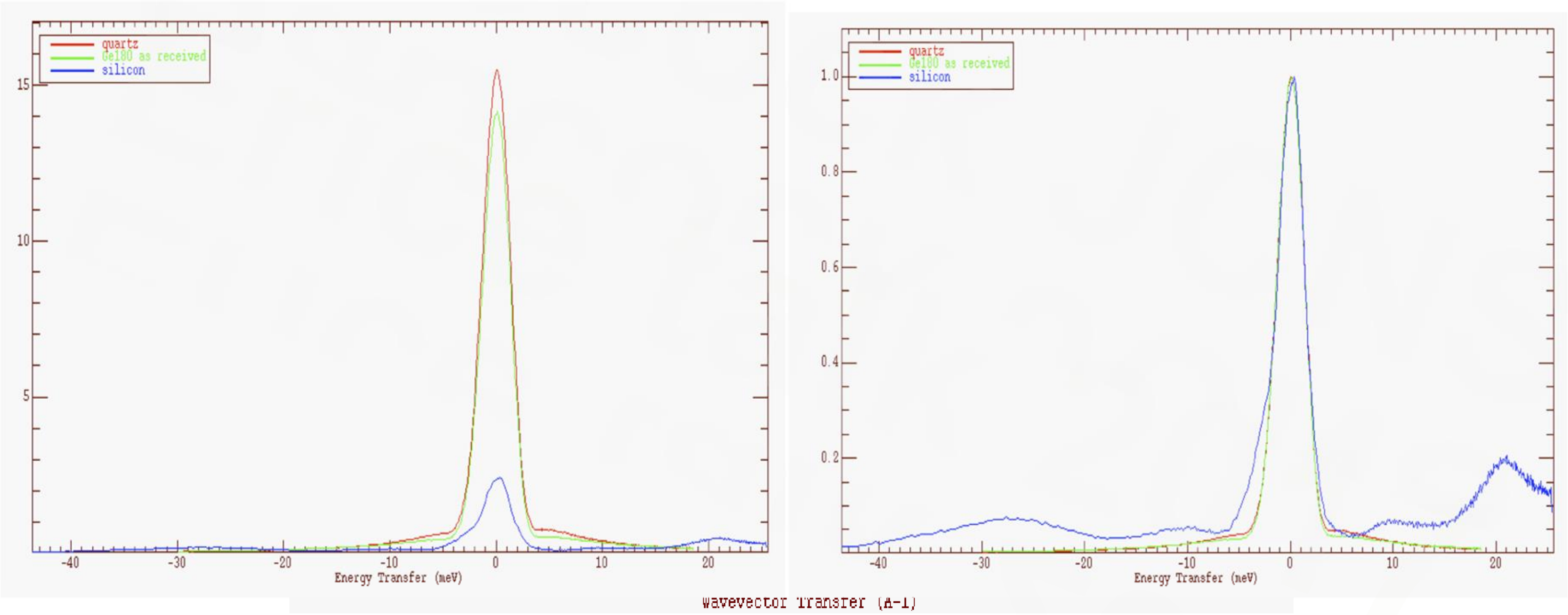
Spectrum measurements on *TOFTOF* with G. Simeoni





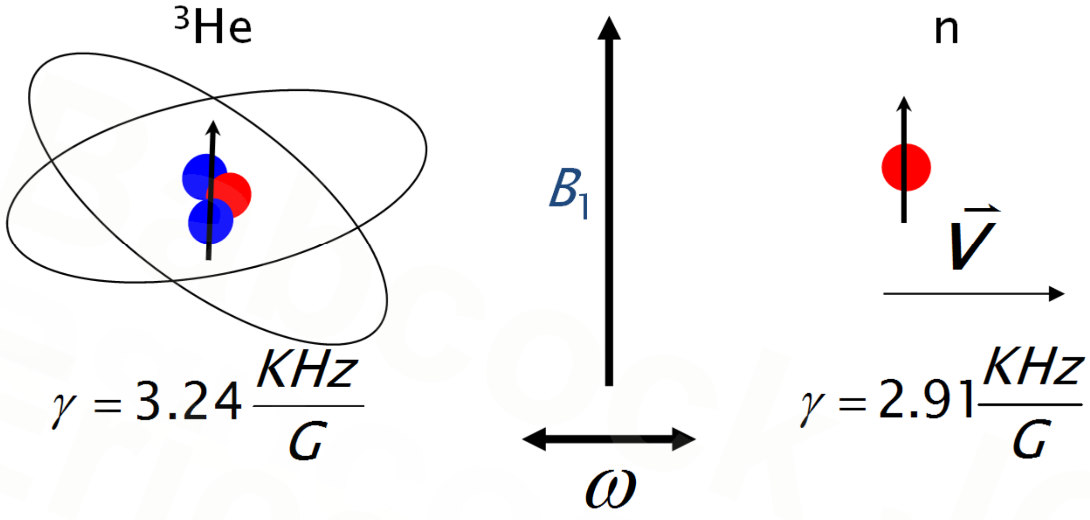
How about silicon crystal cells?

measurements on TOF TOF with G. Simeoni



Data taken with 1.6 Å incident beam

AFP flipping

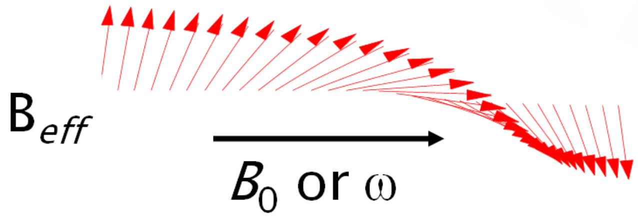


$$\gamma = 3.24 \frac{KHz}{G} \qquad \gamma = 2.91 \frac{KHz}{G}$$

In rotating frame the field experienced by the spins will be

$$\mathrm{B}_{eff} = \left(B_0 + \frac{\omega}{\gamma} \right) \hat{k} + B_1 \hat{i}$$

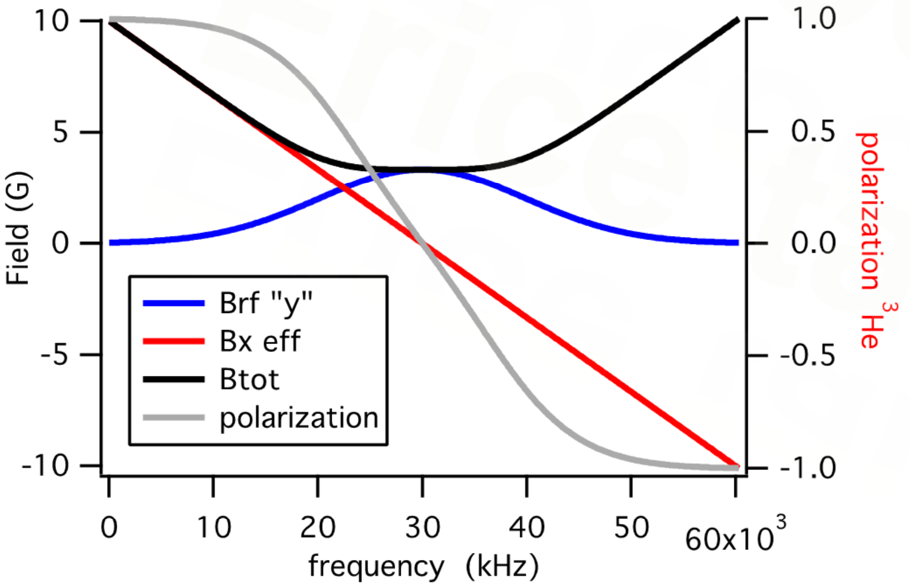
When one sweeps through the Larmor frequency, $\omega_L = -\gamma B_0$, using either field or frequency, B_{eff} and thus P_{He} or P_n is reversed

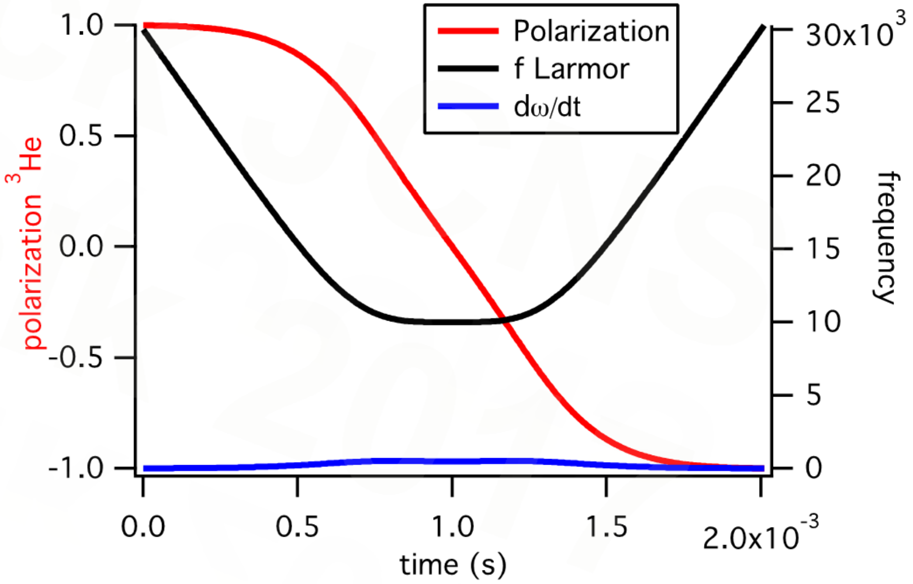


The Adiabatic Condition

The sweep must be slow with respect to ω_L
but fast with respect to the transverse relaxation time for the ^{3}He,

$$B_{eff} = \left(B_0 + \frac{\omega}{\gamma}\right)\hat{k} + B_1\hat{i} \qquad \gamma B_{eff} >> \frac{\dot{\omega}}{\gamma B_1} >> \frac{D\left|\Delta B_z\right|^2}{B_1^2}$$



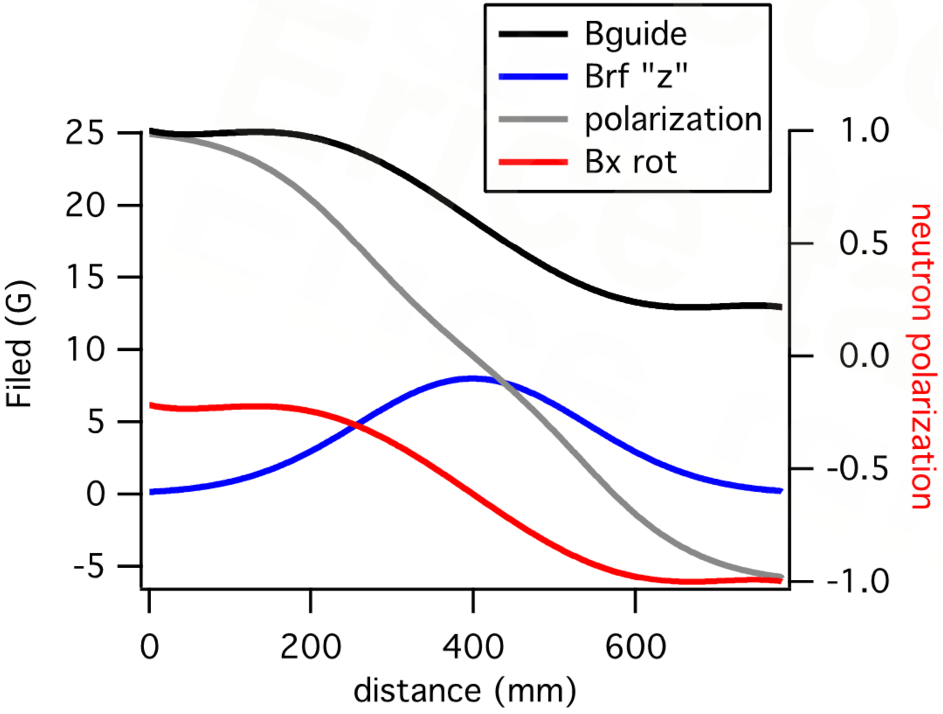


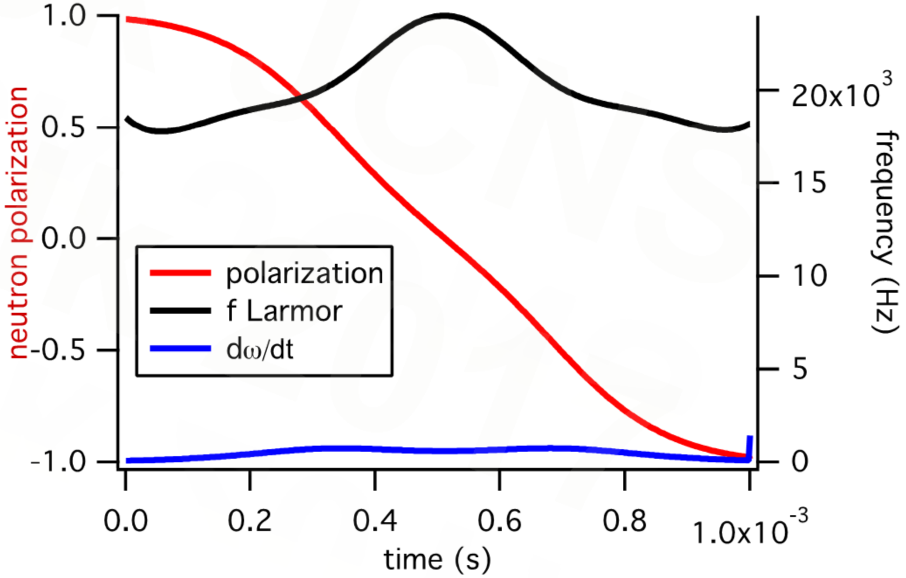
The Adiabatic Condition

The sweep must be slow with respect to ω_L
but fast with respect to the transverse relaxation time for the ^{3}He,

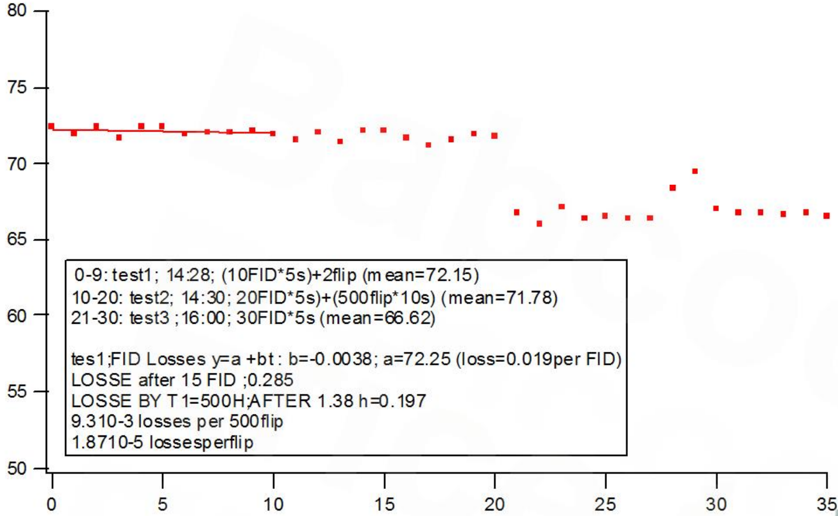
$$B_{eff} = \left(B_0 + \frac{\omega}{\gamma}\right)\hat{k} + B_1\hat{i}$$

$$\gamma B_{eff} >> \frac{\dot{\omega}}{\gamma B_1}$$



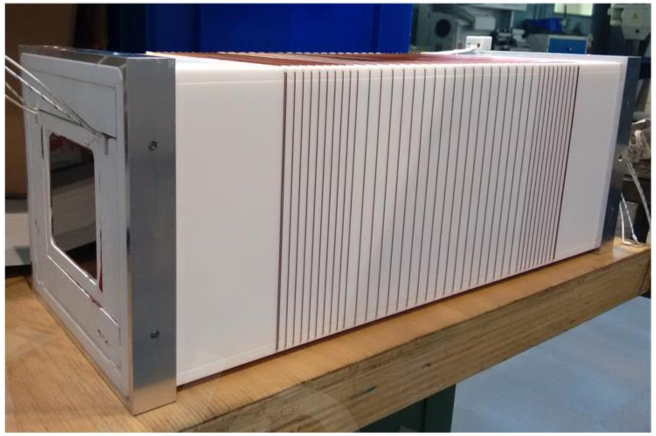


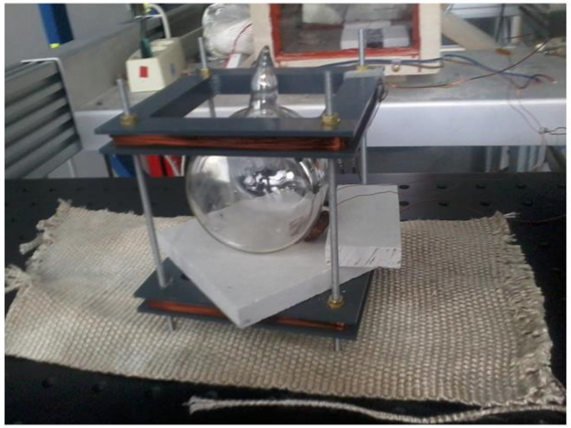
AFP in practice

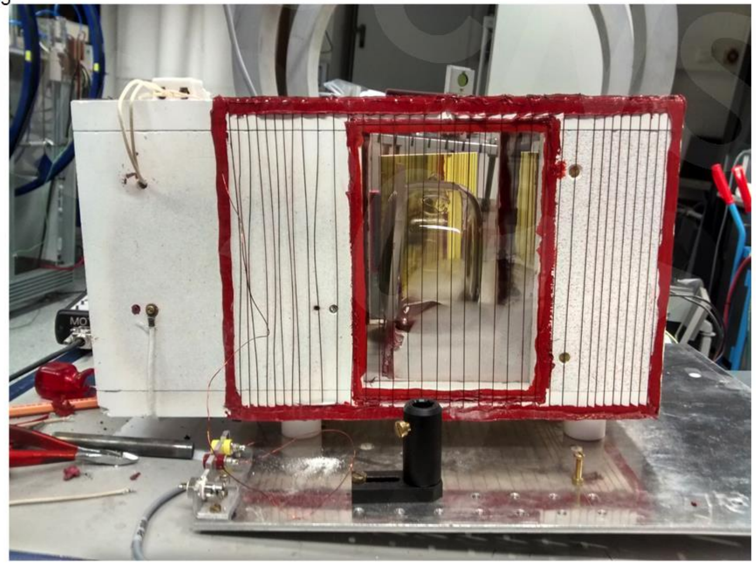


0-9: test1; 14:28; (10FID*5s)+2flip (mean=72.15)
10-20: test2; 14:30; 20FID*5s)+(500flip*10s) (mean=71.78)
21-30: test3 ;16:00; 30FID*5s (mean=66.62)

tes1;FID Losses y=a +bt : b=-0.0038; a=72.25 (loss=0.019per FID)
LOSSE after 15 FID ;0.285
LOSSE BY T1=500H;AFTER 1.38 h=0.197
9.310-3 losses per 500flip
1.8710-5 lossesperflip







Deterministic instrument calibration

Without ^{3}He NSF + AFP

2 polarizers, 2 flippers,
only 2 measurements...

$$R_0 = \frac{1 + A_p A_a}{1 - A_p \varepsilon_{fa} A_a} \qquad R_1 = \frac{1 + \varepsilon_{fp} A_p \varepsilon_{fa} A_a}{1 - \varepsilon_{fp} A_p A_a}$$

Problem is under determined......

With ^{3}He + AFP

2 polarizers, one flipper,
“3” measurements

measure 2 flipping ratios and A_{He}
(without sample)

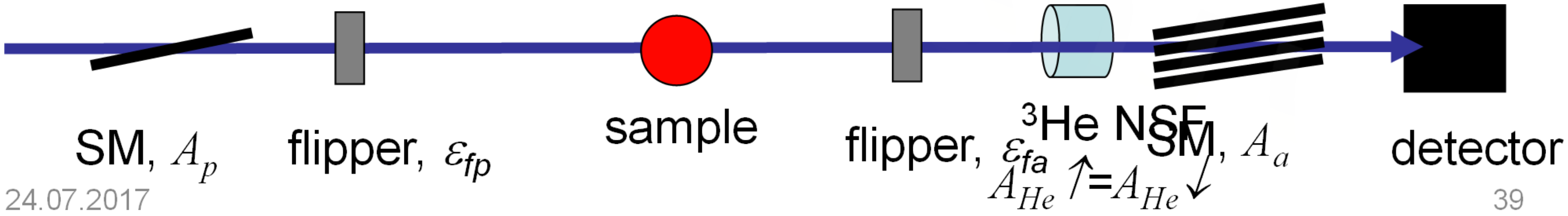
$$\boxed{R_0 = \frac{1 + A_p A_{He}}{1 - \varepsilon_{fp} A_p A_{He}}} \quad \boxed{R_1 = \frac{1 + A_p A_{He}}{1 - A_p A_{He}}}$$

$$A_{He} = \tanh(\Theta P_{He})$$

$$\boxed{T_p = T_0 \cosh(\Theta P_{He})}$$

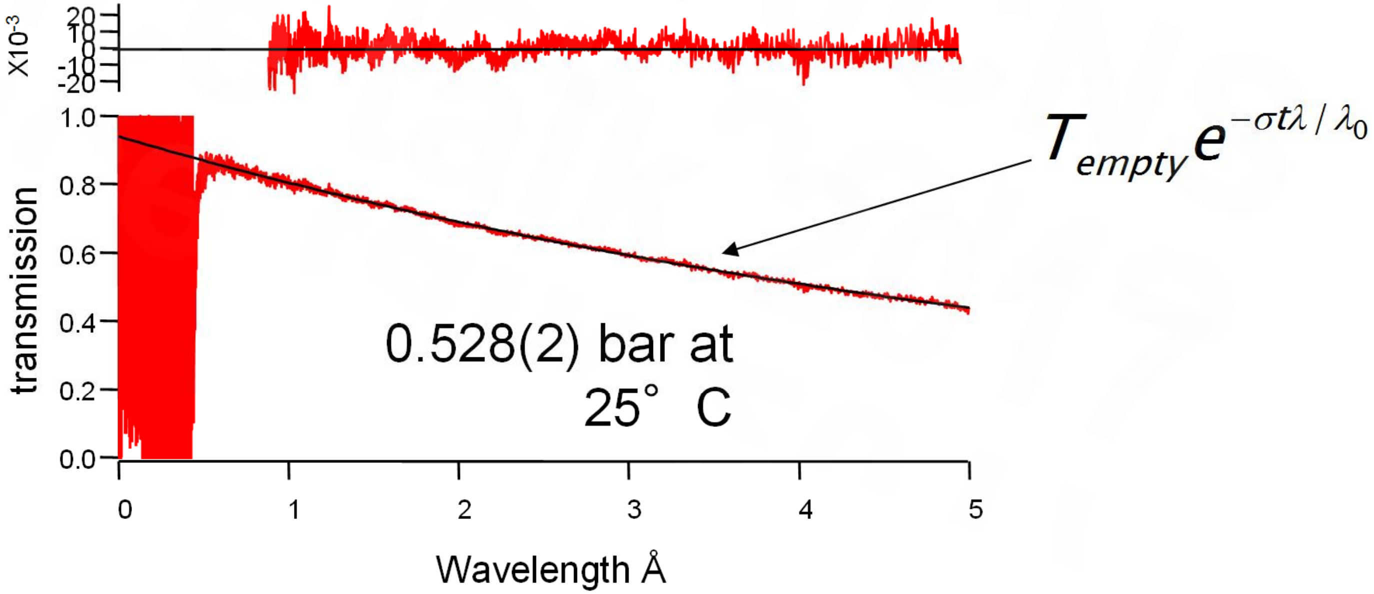
$$\boxed{T_0 = T_{cell} e^{-\Theta}}$$

$$\frac{T_p}{T_0} = \cosh(\Theta P_{He})$$



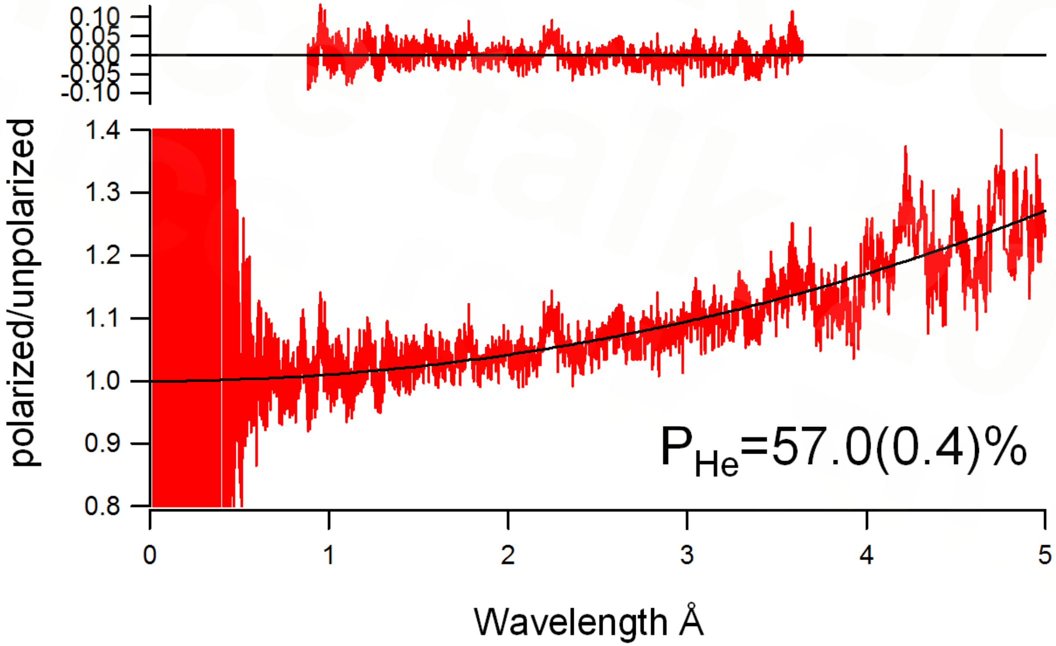
Neutron transmission unpolarized cell

$$T_N = T_0 \frac{N_\uparrow + N_\downarrow}{N_0} = T_{empty} e^{-\sigma t \lambda / \lambda_0} \cancelto{1}{\cosh(\sigma t P_{He} \lambda / \lambda_0)}$$



Neutron Transmission Polarized cell

$$\frac{T_{polarized}}{T_{unpolarized}} = \frac{T_{empty}\, e^{-\sigma t \lambda/\lambda_0} \cosh(\sigma t P_{He} \lambda/\lambda_0)}{T_{empty}\, e^{-\sigma t \lambda/\lambda_0} \cosh(\sigma t \cdot 0 \cdot \lambda/\lambda_0)} = \cosh(\sigma t P_{He} \lambda/\lambda_0)$$



P_{He}=57.0(0.4)%

Fully correctable data

E. Babcock et. Al., J. of Phys. Conf. Series 862(1):012001 (2017)
DOI: 10.1088/1742-6596/862/1/012001

$$\begin{bmatrix} I^{00} \\ I^{01} \\ I^{10} \\ I^{11} \end{bmatrix} = \begin{bmatrix} (1-p_1) & 0 & p_1 & 0 \\ 0 & (1-p_1) & 0 & p_1 \\ p_1 & 0 & (1-p_1) & 0 \\ 0 & p_1 & 0 & (1-p_1) \end{bmatrix} \begin{bmatrix} (1-p_2) & p_2 & 0 & 0 \\ p_2 & (1-p_2) & 0 & 0 \\ 0 & 0 & (1-p_2) & p_2 \\ 0 & 0 & p_2 & (1-p_2) \end{bmatrix}$$

$$\times \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ f_1 & 0 & (1-f_1) & 0 \\ 0 & f_1 & 0 & (1-f_1) \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ f_2 & (1-f_2) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & f_2 & (1-f_2) \end{bmatrix} \begin{bmatrix} \Sigma^{++} \\ \Sigma^{+-} \\ \Sigma^{-+} \\ \Sigma^{--} \end{bmatrix}$$

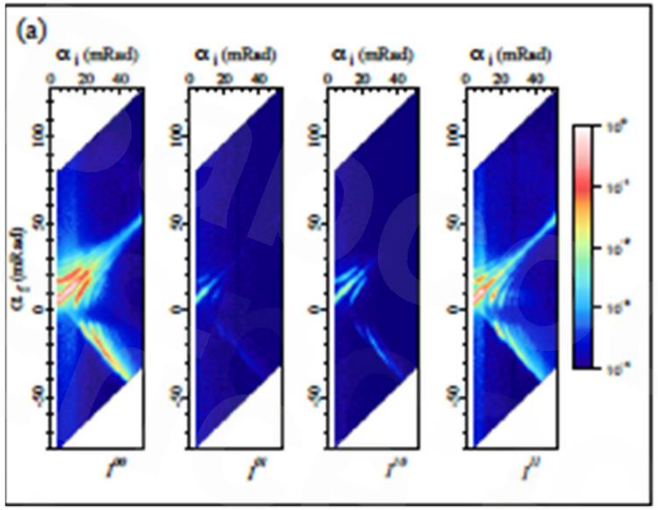
$$\begin{aligned} \Sigma^{++} &= \frac{I^{00}((1+p_1p_2-p_1-p_2)(1-f_1)-f_1(p_1p_2-p_1))}{(1-2p_1)(1-2p_2)(1-f_1)} \\ &+ \frac{I^{01}((p_1p_2-p_2)(1-f_1)-p_1p_2f_1)+I^{10}(p_1p_2-p_1)+I^{11}p_1p_2}{(1-2p_1)(1-2p_2)(1-f_1)} \\ \Sigma^{-+} &= \frac{I^{10}(1+p_1p_2-p_1-p_2)}{(1-2p_1)(1-2p_2)(1-f_1)} \\ &+ \frac{I^{11}(p_1p_2-p_2)+I^{00}((p_1p_2-p_1)(1-f_1)-f_1(p_1p_2-p_1))+I^{01}(p_1p_2(1-f_1)+p_2f_1)}{(1-2p_1)(1-2p_2)(1-f_1)} \end{aligned}$$

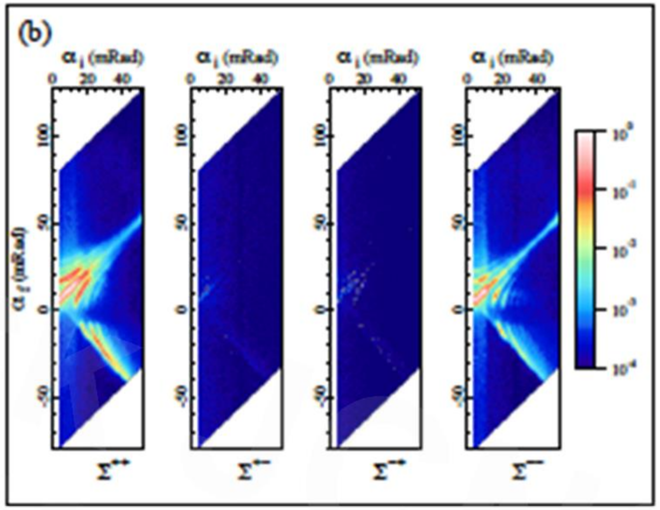
Wildes A 1999 *Review of Scientific Instruments* **70** (11):4241-4245. [DOI: 10.1063/1.1150060]
Wildes A R 2006 *Scientific Reviews: Neutron Polarization Analysis Corrections Made Easy, Neutron News* **17:2** 17-25 [DOI: 10.1080/10448630600668738]

Reflectometry example

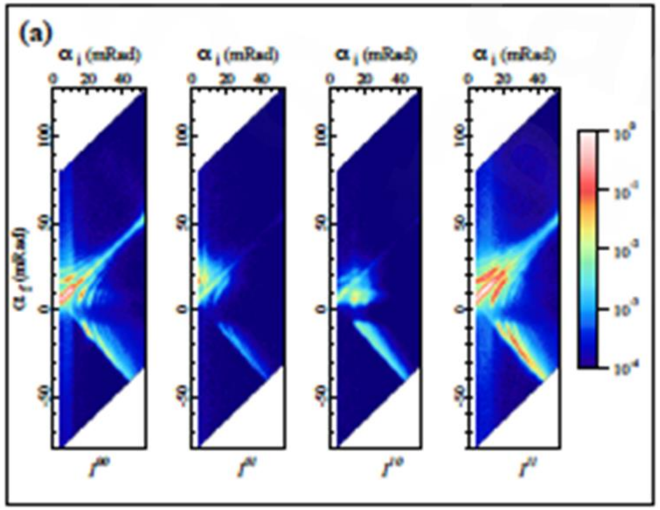
FeFe58 supertalice (10 nm, 10x) with a 10 μm grating

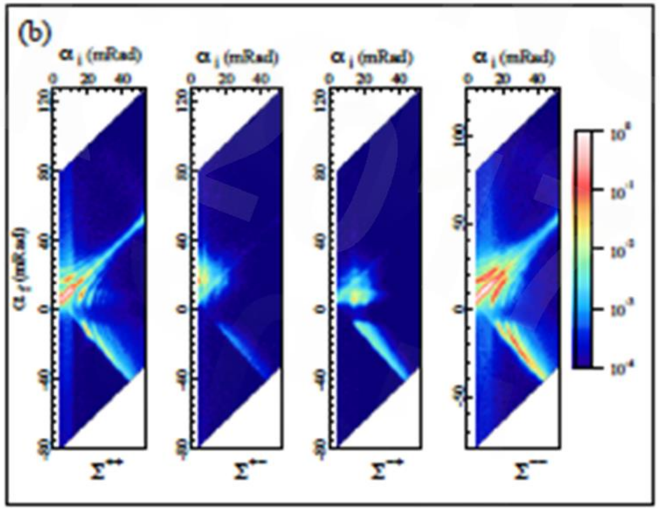
0.7 T





Remanent
(10G)





Deterministic instrument calibration

Without ^{3}He NSF + AFP

2 polarizers, 2 flippers,
only 2 measurements...

$$R_0 = \frac{1 + A_p A_a}{1 - A_p \varepsilon_{fa} A_a} \qquad R_1 = \frac{1 + \varepsilon_{fp} A_p \varepsilon_{fa} A_a}{1 - \varepsilon_{fp} A_p A_a}$$

Problem is under determined......

With ^{3}He + AFP

2 polarizers, one flipper,
"3" measurements

measure 2 flipping ratios and A_{He}
(without sample)

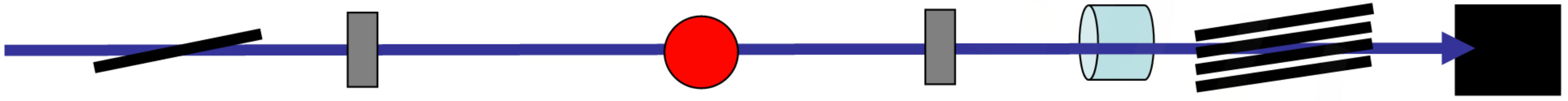
$$\boxed{R_0 = \frac{1 + A_p A_{He}}{1 - \varepsilon_{fp} A_p A_{He}}} \qquad \boxed{R_1 = \frac{1 + A_p A_{He}}{1 - A_p A_{He}}}$$

$$A_{He} = \tanh(\Theta P_{He})$$

$$\boxed{T_p = T_0 \cosh(\Theta P_{He})}$$

$$\boxed{T_0 = T_{cell} e^{-\Theta}}$$

$$\frac{T_p}{T_0} = \cosh(\Theta P_{He})$$



SM, A_p

flipper, ε_{fp}

sample

flipper, ε_{fa}

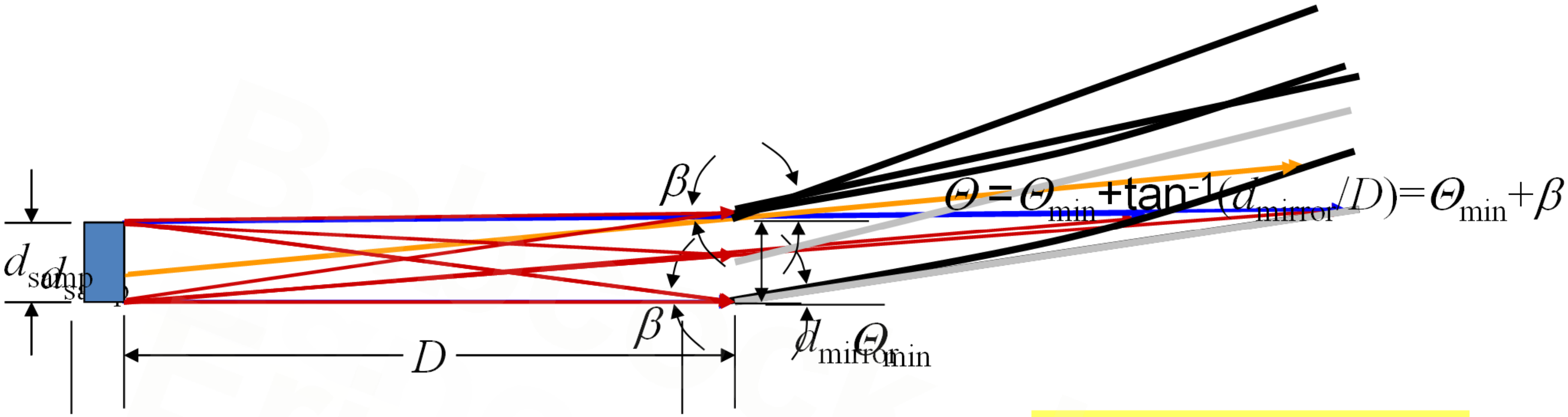
^{3}He NSF

SM, A_a

$A_{He}\uparrow = A_{He}\downarrow$

detector

A comparison to SM its all about the sample



- assume radial collimation focused at sample position
- Source (isotropic scatter) of size d_{samp}
  - maximum divergence on analyzer β, is determined by d_{samp} and sample to analyzer distance D
- mirror must be curved, say Δi is approximately uniform regardless of location of incidence along mirror
- i_{max} will be smaller than β for some λ (hot wavelengths) for a given d_{samp}

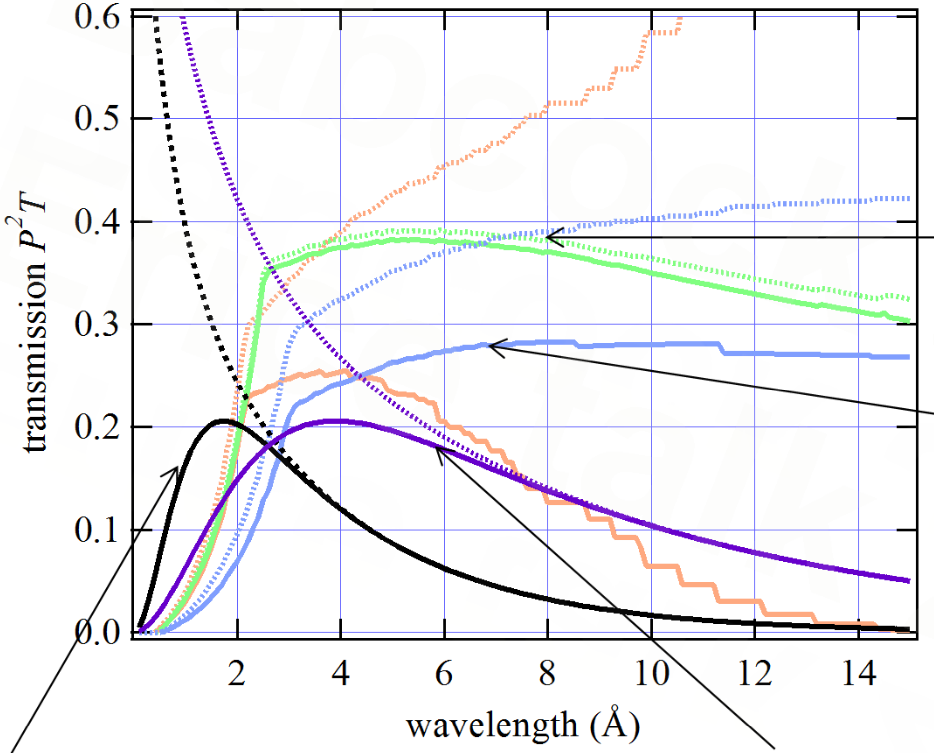
β=tan$^{-1}(d_{samp}/D)$

$\Theta_{min}=m_{min}\lambda_{MAX}\Theta_{critical}$

$i_{max}<m\lambda\Theta_{critical}$

$\Theta_{min}<i<\beta$ or $m\lambda\Theta_{critical}$

Why ^{3}He Polarization or Analysis



FeSi solid state SM fan analyzer array

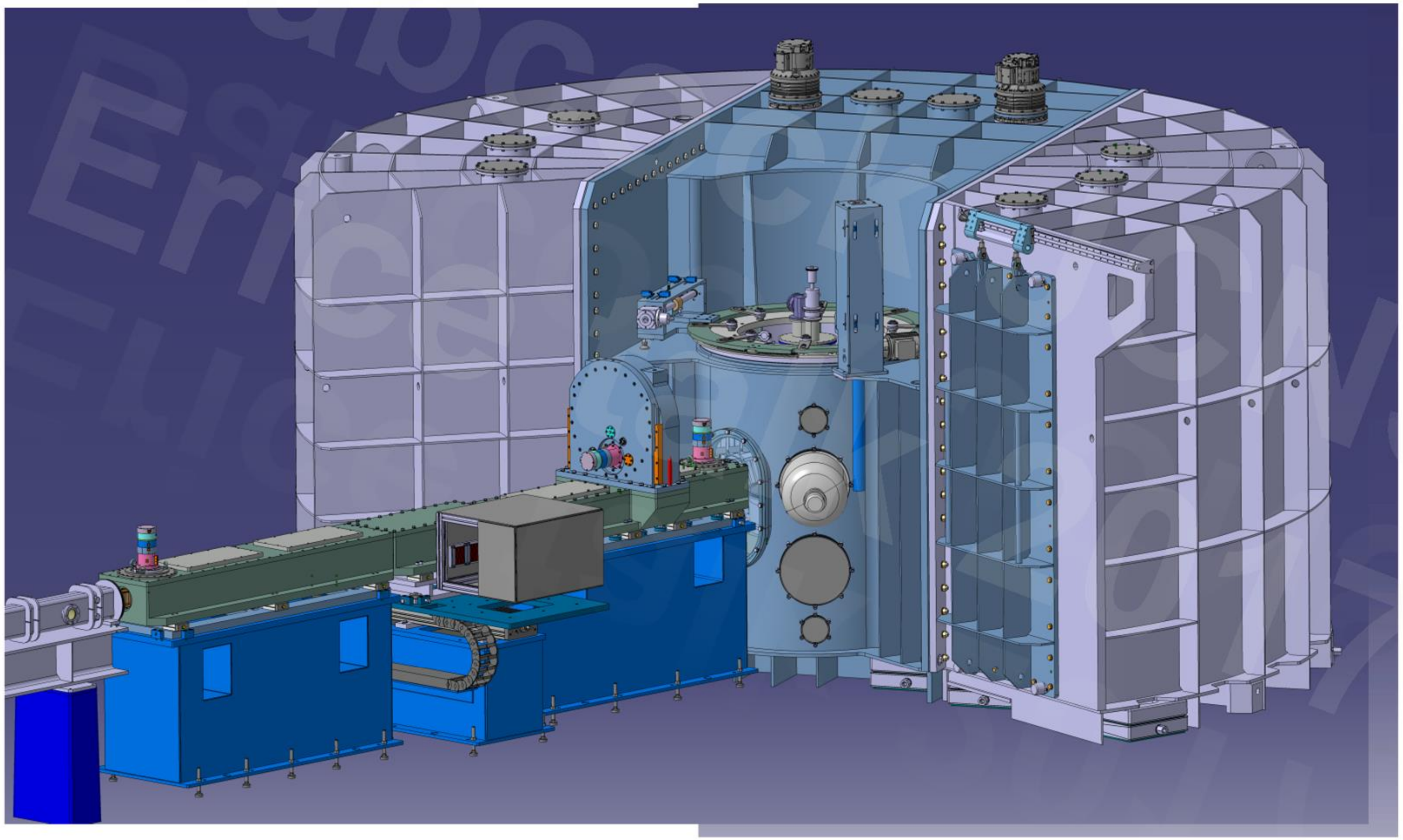
CoTi SM fan analyzer array

^{3}He at 6.7 bar cm and 70% P_{He}

^{3}He at 15 bar cm and 70% P_{He}

E. Babcock et al, submitted to Journal of Physical Society of Japan S.E., proceedings of QENS/WINS 2012, Nikko Japan

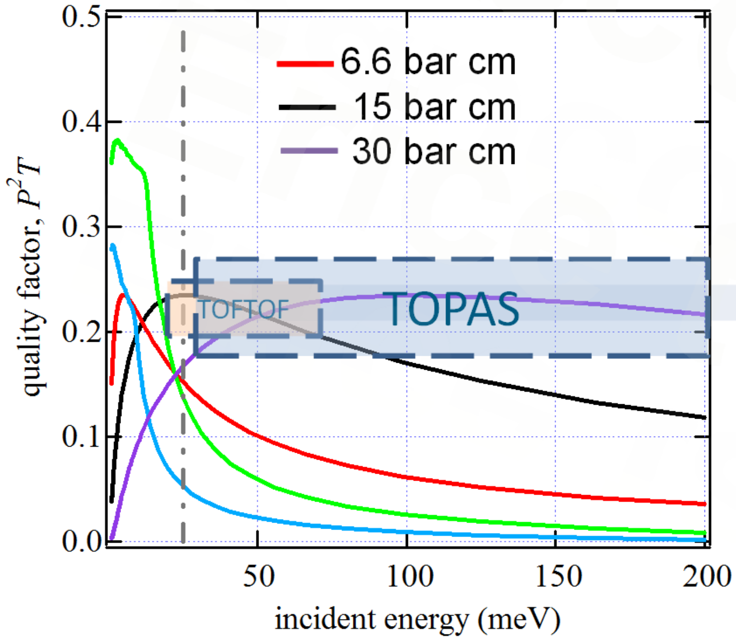
TOPAS, thermal TOF with full PA

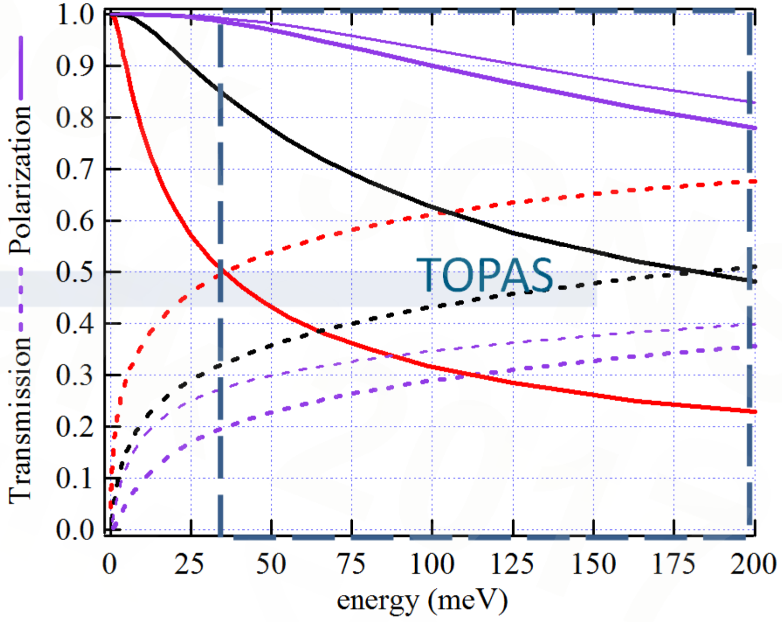


Guide changer

For spectroscopy with thermal incident energy

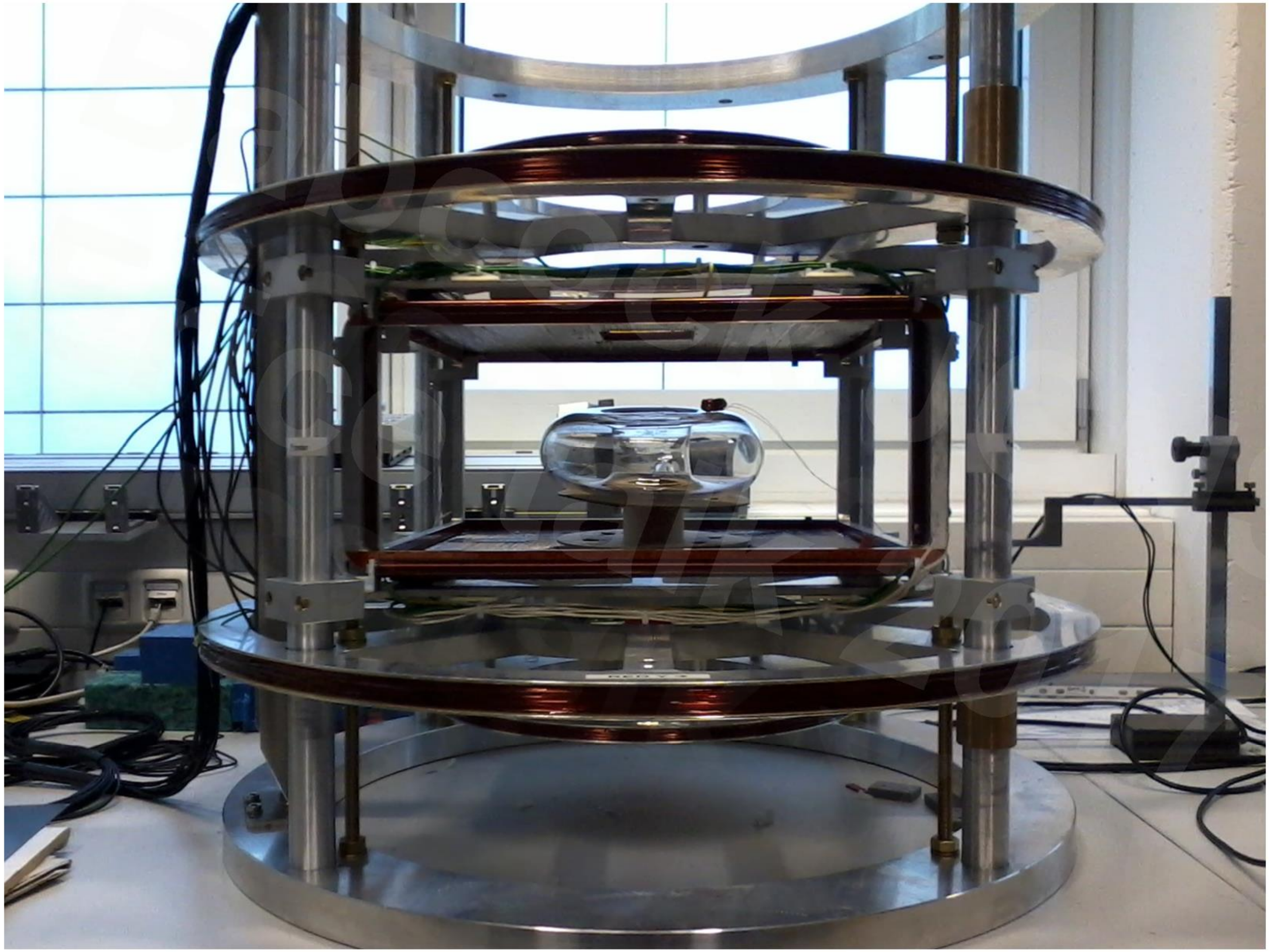
P^2T of wide angle SM and ^{3}He at different pressure-lengths



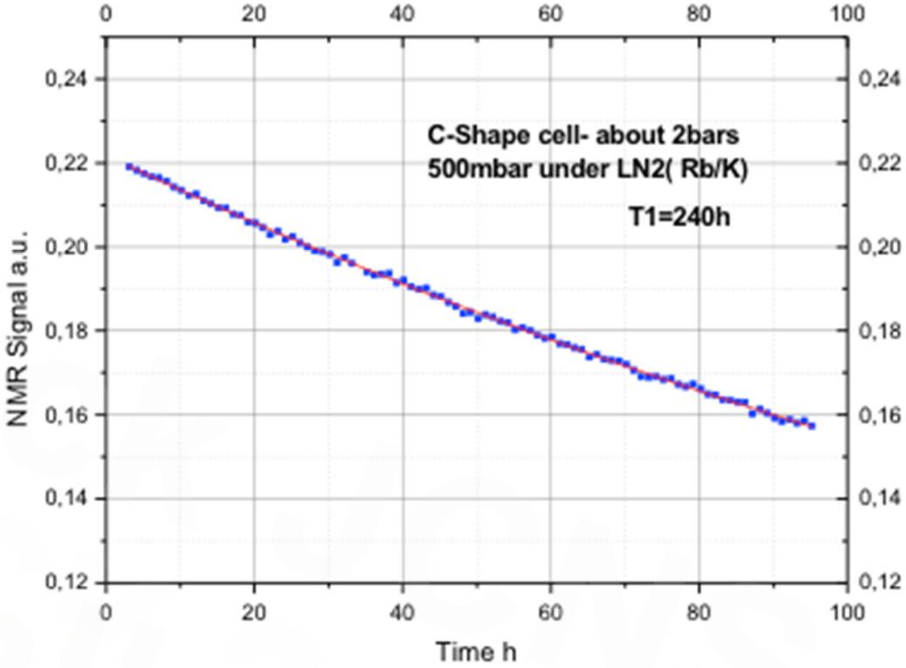


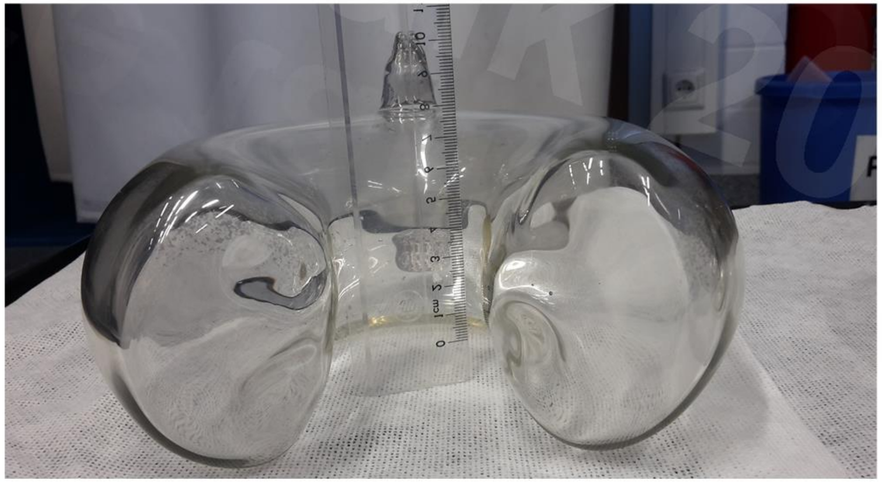
- Quality factor P^2T for various opacities of ^{3}He with SM curves for comparison. The 100 meV line has 30 bar cm of polarized ^{3}He at 75%
- Neutron polarization and transmission for various ^{3}He opacities at 75% polarization, light line 85% polarization and 30 bar cm

TOPAS / PASTIS

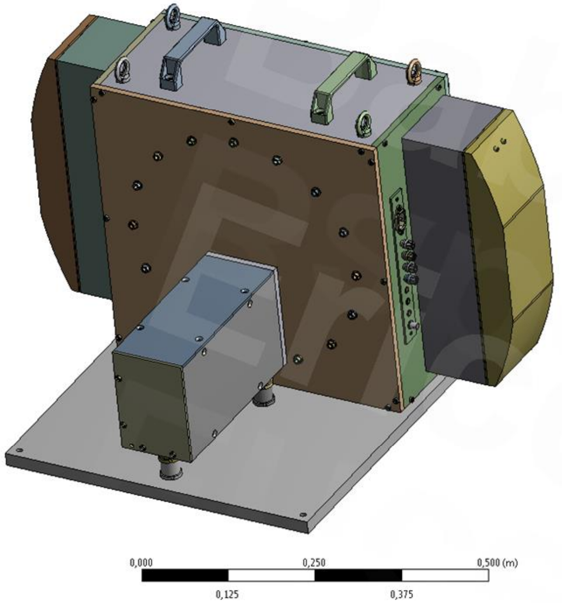


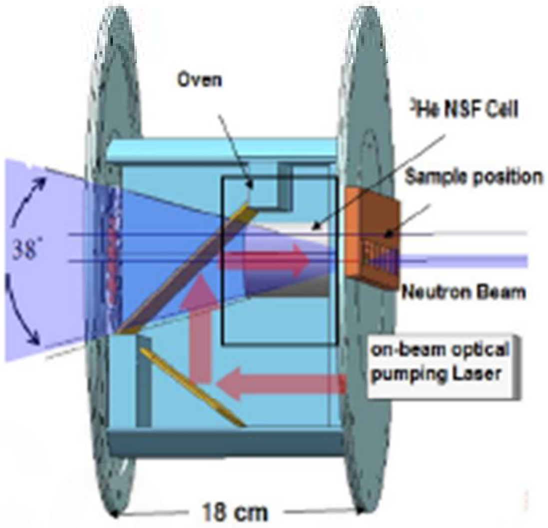
Wide angle cells



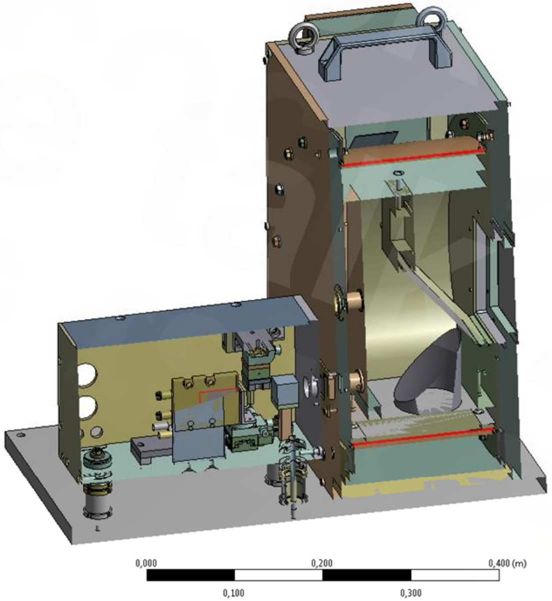


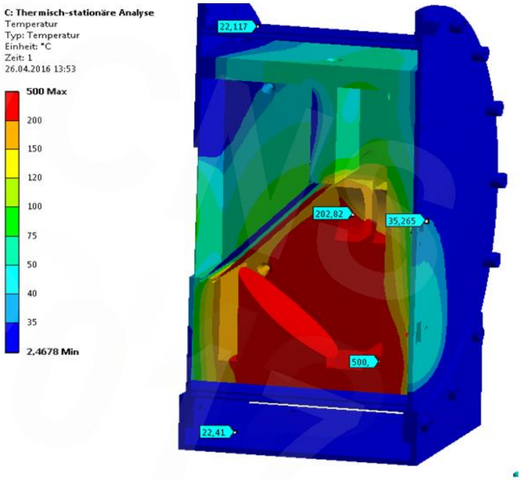
KWS2





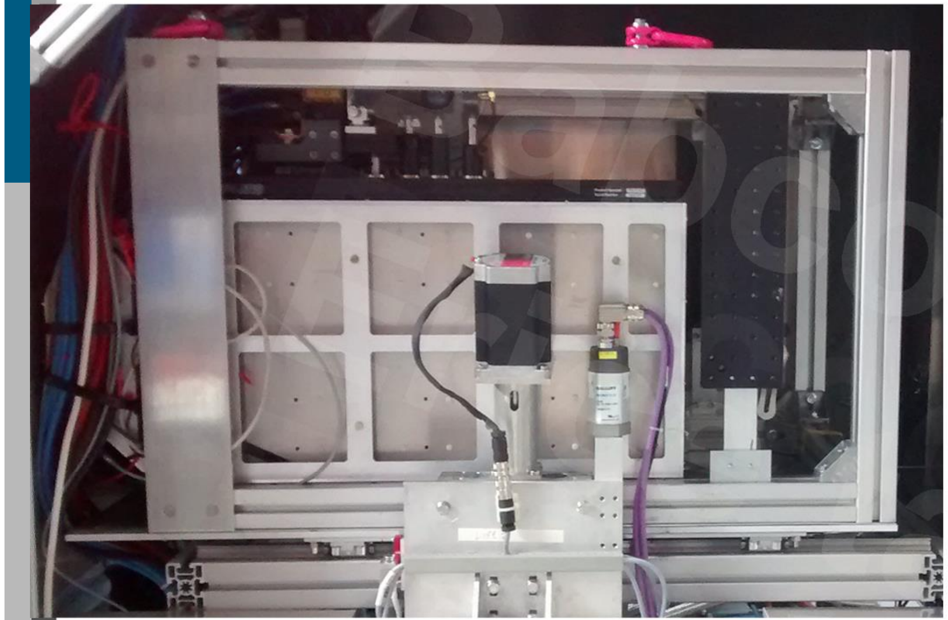
Thermal calculations

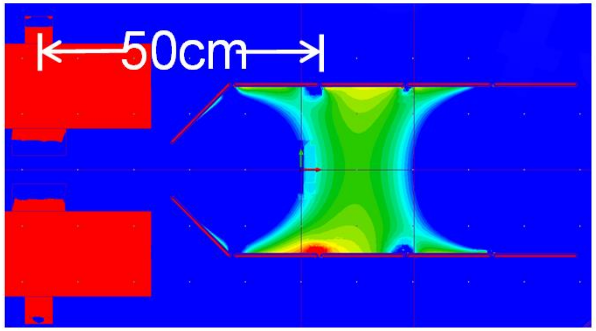




Final details, soon under construction

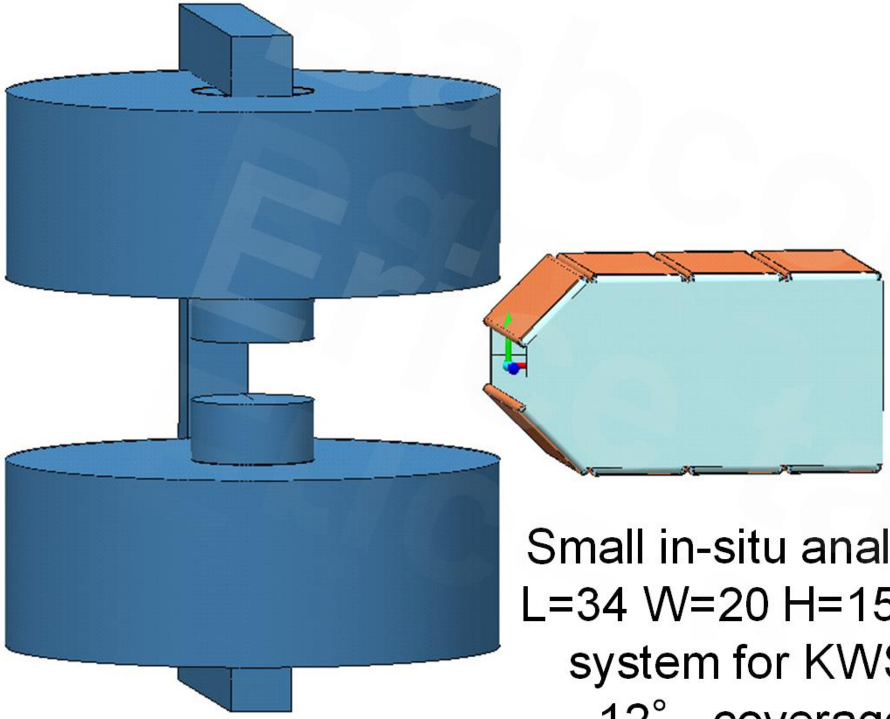
MARIA

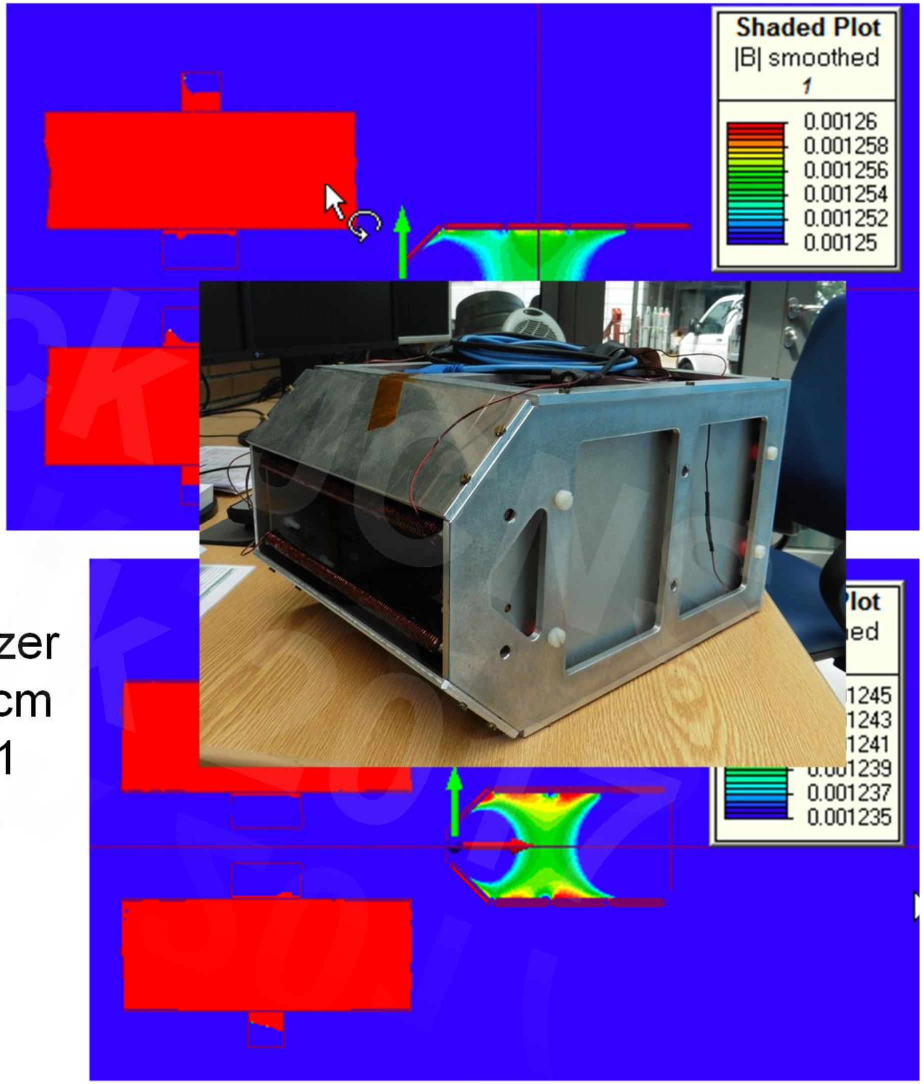




- ~12° coverage with 12.5 cm cell
- Updated "angled" magnetic cavity
  - Cell about 50 cm from magnet
  - $q_{max} \leq \pm 0.35$ Å^{-1} (0.25 Å^{-1})
  - 70cm x 40cm x 30cm
- Uses 2 VBG narrowed 100W lasers
  - LC waveplates
- Integrated NMR
  - Monitor via FID
  - Flip via AFP (frequency sweep)
- All electric heating using cartridge heaters
- 300+ hour 3He lifetime
- ^{3}He polarization >70%

KWS1, Hard matter SANS

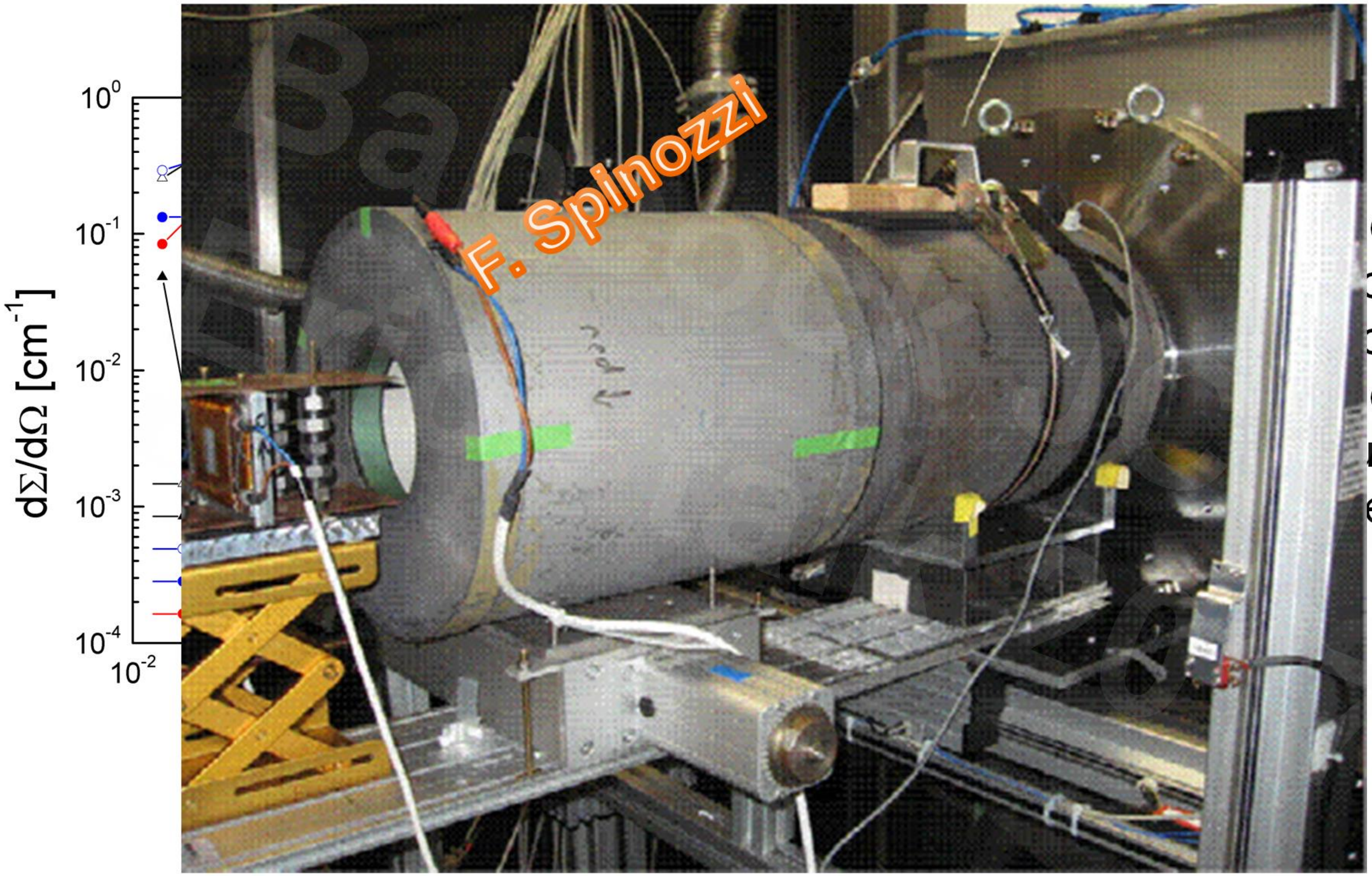




Small in-situ analyzer
L=34 W=20 H=15 cm
system for KWS1
12° coverage

To provide magnetic shielding with good Q-range in the shortest space
D=32cm Φ=7.5 cm $q_{max} \leq \pm 0.35$ Å^{-1}

Neutron Methods, PA SANS



coherent
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^{3}He Group, KWS1&2, MARIA, TOPAS-PASTIS team, V20 (ESS) and NEAT (HZB)

JCNS @ MLZ

- Zahir SALHI, Earl BABCOCK, Denis STAROSTIN, Johann SCHMEISSNER, Tobias THEISSELMANN, Artem FEOKTYSTOV, Stefan MATTAUCH, Aurel RADULESCU, Kendal BINGOL, Vladimir OSSOVYI, Simon STARINGER, Jörg VOIGT, Emmanuel KENTZINGER, Alexander IOFFE, Thomas Brückel

FZ-Jülich ZEA-1

- Helmut SOLTNER, Patrick PISTEL, Klaus BUSSMANN, Achim HEYNEM, Hans KAMMERLING, Fabian BEULE, Frank SUXDORF, Ramil GAINOV

ESS

- Robin WORACEK

HZ-Berlin

- Margarita RUSSINA