The Polarised Target at CBELSA/TAPS

Dubna Exchange Week

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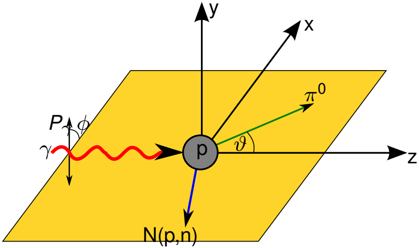

γ		Target		
		x	y	z
Unpolarised	$\boldsymbol{\sigma}$	0	**T**	0
Linear pol.	$-\boldsymbol{\Sigma}$	**H**	$-$**P**	$-$**G**
Circular pol.	0	**F**	0	$-$**E**

$$
\begin{aligned}
\frac{d\boldsymbol{\sigma}}{d\Omega}(\vartheta,\ \phi) = \frac{d\boldsymbol{\sigma}}{d\Omega}(\vartheta)\,[1 &- P_T \boldsymbol{\Sigma}(\vartheta)\cos(2\phi) \\
&+ P_x\left(-P_T \mathbf{H}(\vartheta)\sin(2\phi) + P_\circ \mathbf{F}(\vartheta)\right) \\
&- P_y\left(P_T \mathbf{P}(\vartheta)\cos(2\phi) - \mathbf{T}(\vartheta)\right) \\
&- P_z\left(-P_T \mathbf{G}(\vartheta)\sin(2\phi) + P_\circ \mathbf{E}(\vartheta)\right)].
\end{aligned}
$$

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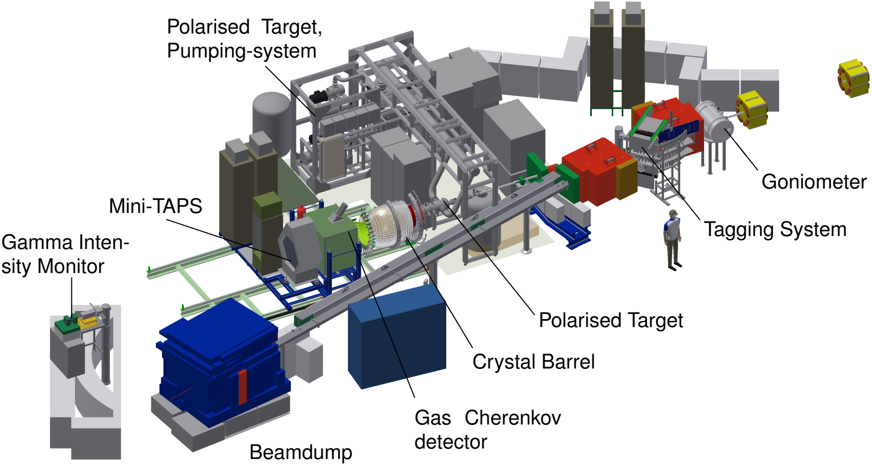

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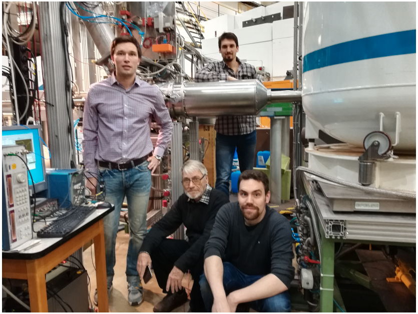

Work in 2017

- Merging the Dubna/Mainz and Bonn Systems.

February Transport of the cryostat, the ^3He-system, temperature measurement to Bonn.

- Connecting the vacuum system.
- Leak test at room temperature.
- Change Front part of the cryostat.
- Implement the Dubna/Mainz DAQ in the Bonn system.
- ...

May First cooling test. $T_{min} = 60$ mK.

September Test of all components, $T_{min} < 30$ mK $P_{\text{max}} \approx 45\,\%$.

November First data taking.

$\Rightarrow$ The Bonn/Dubna/Mainz polarised frozen-spin target is operational and can be used for the next measurements.

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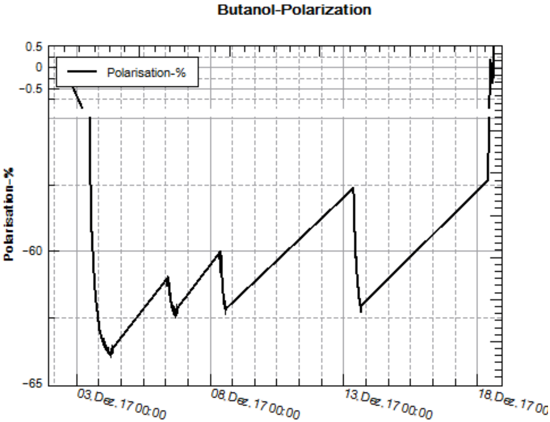

- t_{rel} =1000 h to 1500 h
- $P_{max} \approx 63\,\%$
- Optimise the polarisation for the next run (two weeks)
- Measurement (five weeks) with:
  - Transversely polarised target (proton), coherent edge at 1350 MeV and 1600 MeV
  - Background data taking (C-foam), coherent edge at 1600 MeV
- Start of the target preparations on 15th April.
- Start data taking on 30th April.

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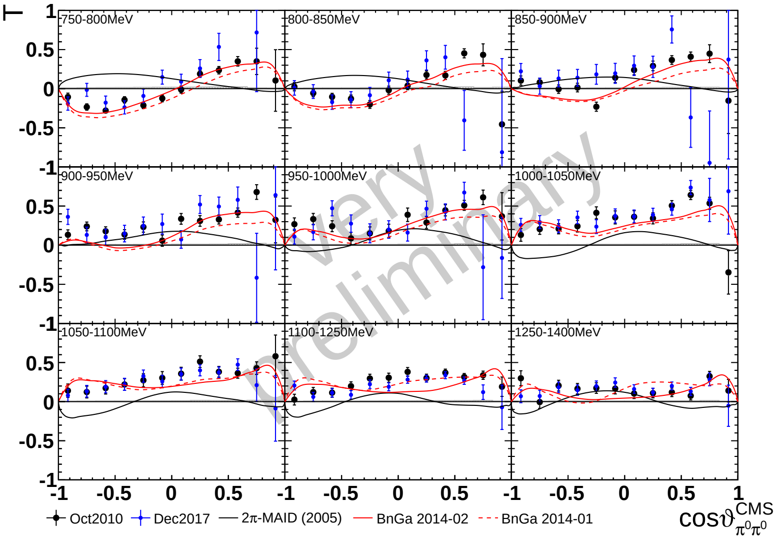

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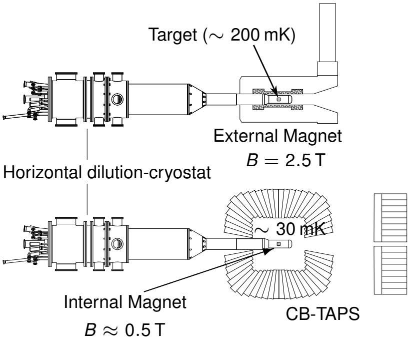

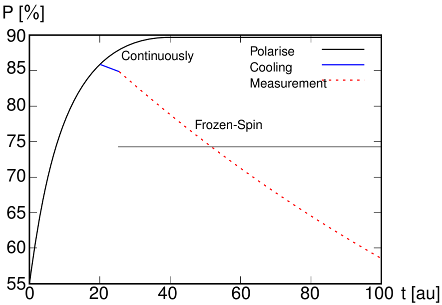

- Current measurements in Bonn with the Dubna/Mainz frozen-spin target.
- A new frozen-spin cryostat is under construction by JINR Dubna. (Part of the discussions at this meeting)
- A continuous mode Target is under construction by Bonn.

4π-continuous Target

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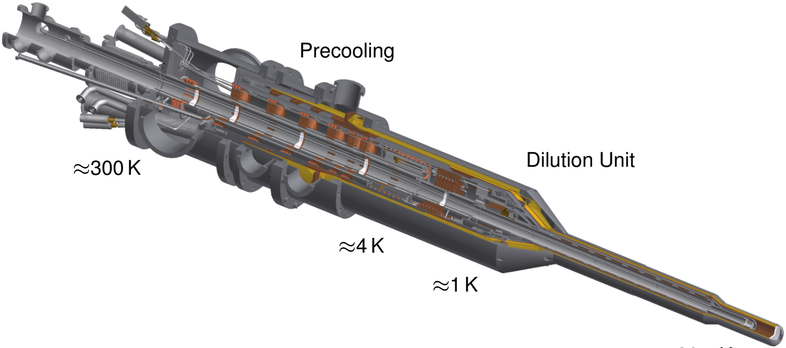

Design conditions:

- Current of 90 A for internal, longitudinal polarisation-magnet.
- Cooling power of 100 mW at 200 mK for DNP.
- Minimal temperature 30 mK for transversal polarised targets.

Internal polarisation magnet - Production (M. Bornstein)

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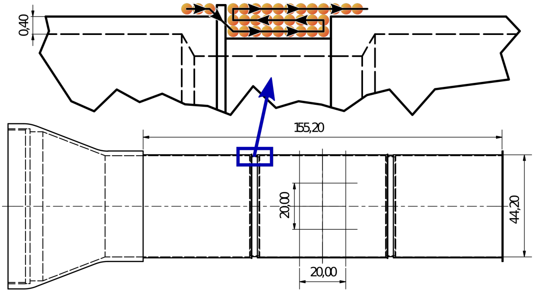

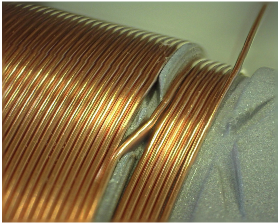

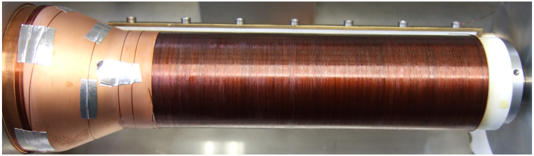

- Carrier thickness + wire $< 2\,\mathrm{mm}$
- NbTi, $= 0.254\,\mathrm{mm}$ ($j_{el} = 2185\,\mathrm{A\,mm^{-2}}$)
- 6×590 windings @90 A @ 1 K + 2×9 windings for each notch
- $|\Delta B / B_0| \leq 4 \times 10^{-5}$
- Inductance $L = 160\,\mathrm{mH}$
- Stored energy $E = 650\,\mathrm{J}$
- Building process by wet wiring.
- Wires are fixed by cryogenic epoxy.
- $V_{\mathrm{hom}} / V_{\mathrm{overall}} = 1/40$

Internal polarisation magnet - Tests (M. Bornstein)

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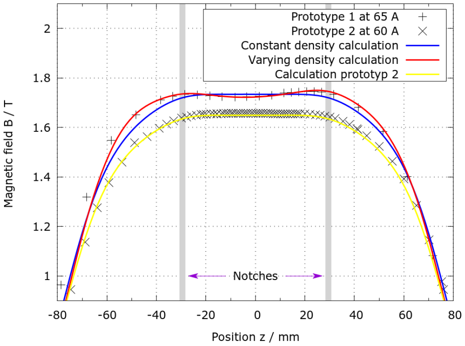
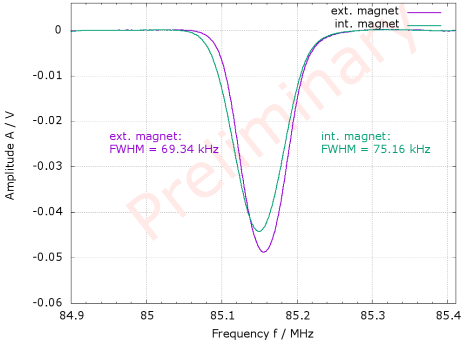
Field measurement at 4.2 K



NMR-signal in ^{4}He-Cryostat at 1.0 K



Prototyp 2

- Flat plateau in the central area.
- $\frac{\Delta B}{B_0} < 10^{-3}$, sufficient for DNP.

- A proton target could be dynamically polarized.
- FWHM is a measure of the homogeneity.
- External magnet: $\Delta B/B0 \approx 5 \times 10^{-6}$

4π-continuous Target

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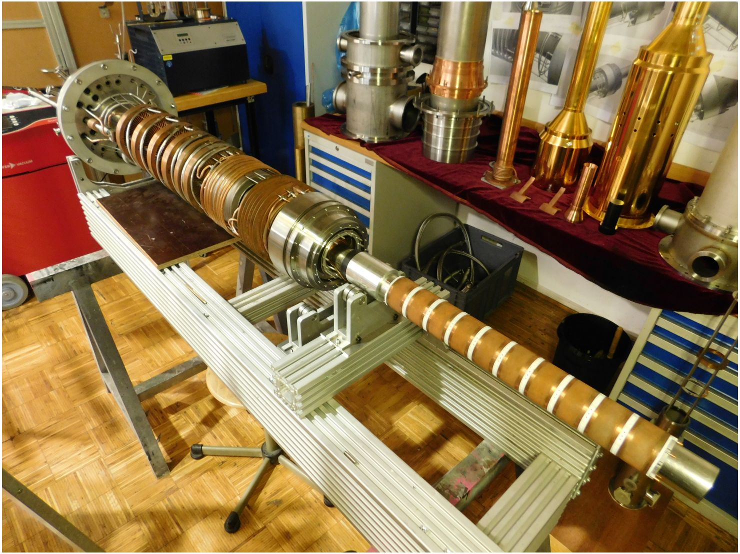
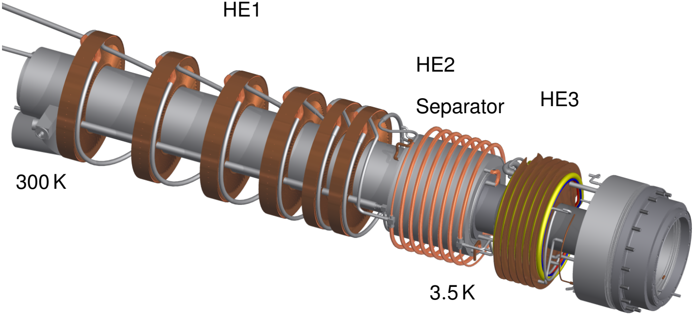


Precooling



- Four heat exchangers and two heat sunks to cool and liquefy the circulating mixture.
- HE4 inside the evaporator to ensure 1 K after the precooling stages.
- Circulating ^{3}He-^{4}He-mixture cooled by ^{4}He from the heat sinks and by evaporating mixture from the dilution unit.

Precooling

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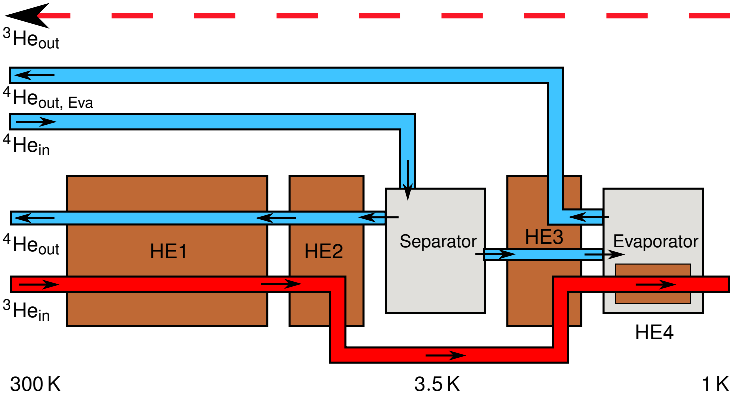
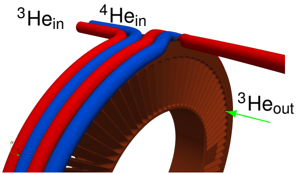
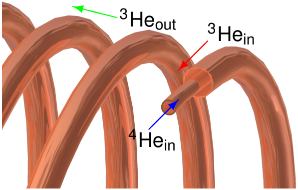
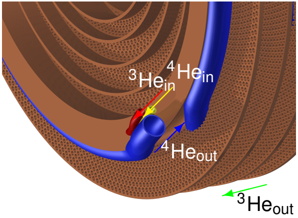


- HE1 - HE3 counterflow heat exchangers with more than two streams.
- Calculations of the precooling stages only with simple models for two stream heat exchangers.

Precooling







- The heat exchange between the different streams and the solid is given by:

$$\dot{Q}_{\text{solid}}(\Delta T_{\text{m}}) = \alpha \cdot A \Delta T_{\text{m}} \quad \text{mit} \quad \alpha \propto \text{Nu}(\text{Re}, \text{Pr}) \cdot \frac{\lambda}{L}.$$

- NUSSELT-, PRANDLT- and REYNOLDS-number are characteristic flow parameter depending on the geometry
- Characteristic flow parameter given by the dimensionless NAVIER-STOKES equations.
- Idea: Solve the NAVIER-STOKES equations with a finite-volume-method.

$\Rightarrow$ CFD-Simulation

Computational Fluid Dynamics

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The basis of almost all CFD simulations is

- ρ: density
- ϕ: fluid dynamic parameter (e.g. fluid velocity $\underline{u}$, enthalpy h)

$$\frac{\partial}{\partial t}(\rho\phi) + \underbrace{\nabla \cdot (\rho \underline{u} \phi)}_{F_\phi} = D_\phi + Q_\phi .$$

Gl.	ϕ	D_ϕ	Q_ϕ
1. KON	1	0	0
2. IMP	$\underline{u}$	$\nabla \cdot \underline{\underline{\sigma}}$	$-\nabla \cdot p + \rho \underline{g}$
3. ENG	h	$\nabla(k\nabla T)$	$\frac{\partial p}{\partial t} + \underline{u} \cdot \nabla p + \nabla \cdot \left(\underline{\underline{\tau}} \cdot \underline{u}\right)$

- F_ϕ: convective flow, describes the transport of the stream given by ϕ
- D_ϕ: diffusive flow, describes the changes in space given by ϕ
- Q_ϕ: all other distributions given by ϕ

$\Rightarrow$ Using openFOAM with snappyHexMesh for the simulation and the creation of the mesh.

Computational Fluid Dynamics

Compressible Fluid:

1. Mass:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \underline{u}) = 0$$

2. Motion:

$$\frac{\partial}{\partial t}(\rho \underline{u}) + \nabla \cdot (\rho \underline{u}\underline{u}) = \nabla \cdot \underline{\underline{\sigma}} - \nabla p + \rho \underline{g}$$

3. Enthalpy:

$$\frac{\partial \rho h}{\partial t} + \nabla \cdot (\rho \underline{u} h) = \frac{\partial p}{\partial t} + \underline{u} \cdot \nabla p + \nabla (k \nabla T) + \nabla \cdot \left(\underline{\underline{\tau}} \cdot \underline{u} \right)$$

- Equations of state (e. g. ideal gas):

$$p = \rho R T$$
$$dh = c_p dT$$

- Specific material equations:

$$\dot{Q} = -k \nabla T$$

- Stress-tensor:

$$\underline{\underline{\sigma}} = \eta \left[2\underline{\underline{S}} - \frac{2}{3} (\nabla \cdot \underline{u}) \underline{\underline{\delta}} \right]$$
$$\underline{\underline{S}} = \frac{1}{2} \left[\nabla \underline{u} + (\nabla \underline{u})^T \right]$$
$$\underline{\underline{\tau}} = \underline{\underline{\sigma}} + p \mathbb{1}$$

Heat Exchanger 1

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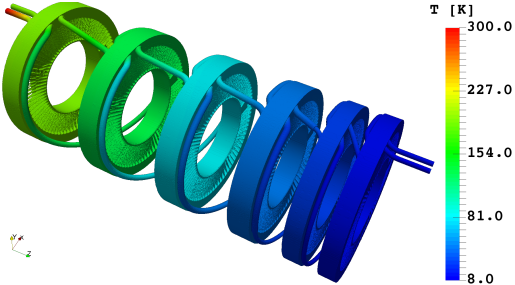
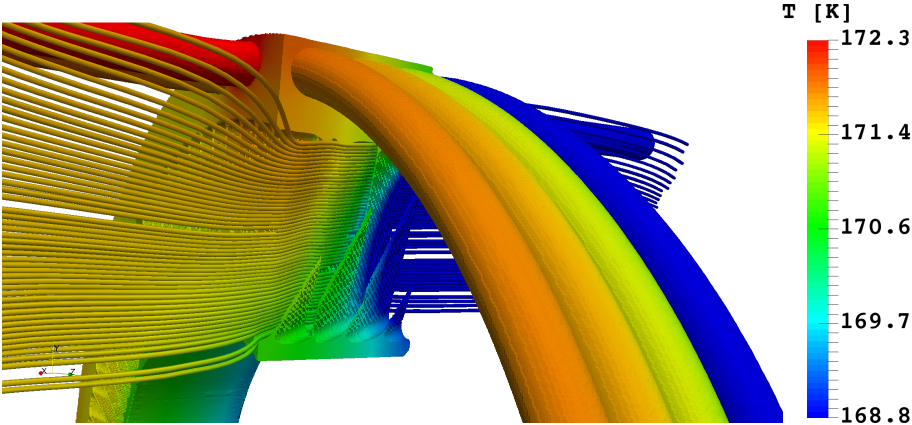


- Data for $\dot{n}_{^3\mathrm{He}} = 1\,\mathrm{mmol\,s^{-1}}$.
- Well defined temperature gradient along the heat exchanger.
- Temperature after the last stage of 8 K is reached.
- Simulation performed for all heat exchangers and a circulation rate of 1 to 20 mmol s^{-1}.

	Simulation	Measurement
$\mathrm{HE1}_{in}$	170(2) K	170(5) K
$\mathrm{HE1}_{middle}$	43 K	43(3) K
$\mathrm{HE1}_{out}$	8 K	8(1) K
$p_{^3\mathrm{He}_{in}}$	100 mbar	105(10) mbar
$p_{^3\mathrm{He}_{out}}$	2.1×10^{-2} mbar	$2.2(2)\times10^{-2}$ mbar
$p_{^4\mathrm{He}_{out}}$	15 mbar	15(3) mbar

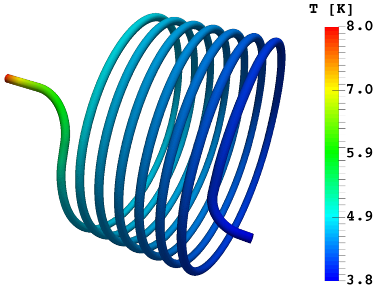
Heat Exchanger 1

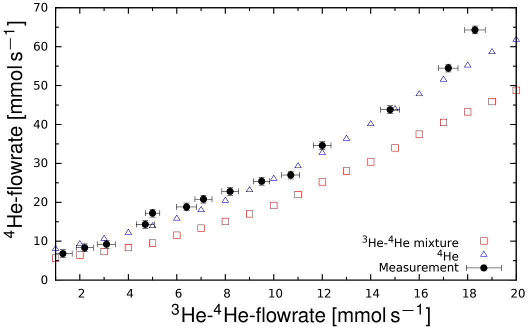
Temperature gradient along first stage:



⇒ Laminar flow through turbine stage.

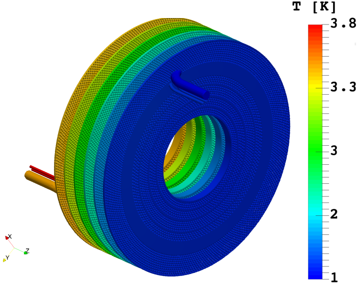
Heat Exchanger 1 & 2

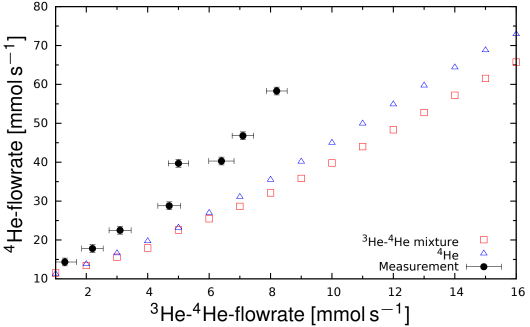




- Heat exchanger 1 & 2 are in series. Thus, they can be seen as one unit.
- ^{4}He-flowrate necessary to cool the circulating ^{3}He-^{4}He-mixture to the temperature of the separator.
- First tests done with ^{4}He, simulation performed up to 15 % ^{4}He in circulating ^{3}He.

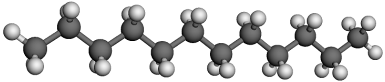
Heat Exchanger 3



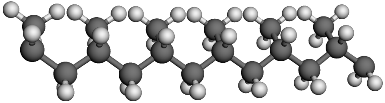


- Condenser: phase-boundary between liquid and gas not included in the mesh.
- $^4He_{in}$, gets superfluid.
  - Only the change in the heat capacity is included.
  - Heat conductivity and viscosity has to be implemented.
- ^{4}He from the evaporator at a higher temperature as calculated.

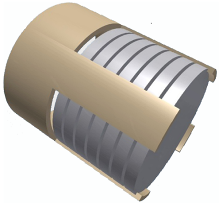
Polymers - Target Materials (S. Reeve)

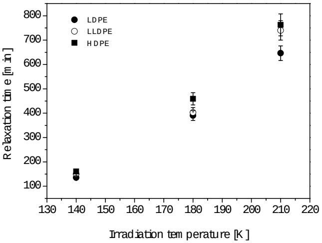


Polyethylene $(CH_2)_n$)



Polypropylene $(CH_2\text{-}CH\text{-}CH_3)_n$)





- High number of "free" protons.
- Spinless background contribution: carbon.
- κ depends on the target holder geometry.
- New target geometry improves $\kappa \approx 55\,\% \rightarrow \kappa > 80\,\%$

Polymers - Target Materials, 1 K Polarisation (S. Reeve)

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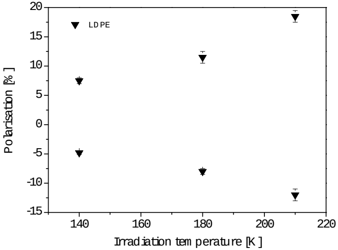
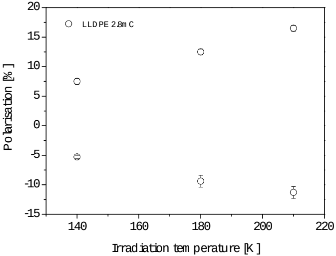
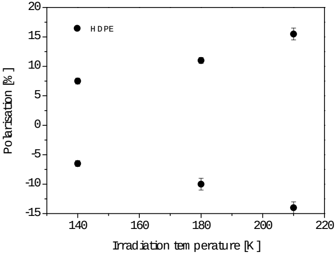




- All samples irradiated with the same dose.
- P_{max} increases to higher irradiation temperatures.
- Material specific asymmetry, source still unknown.
- $P_{\text{max}} \approx 20\,\%$ at 1 K and 2.5 T is a very satisfactory result!
- Relaxation-times: $2.5\,\text{h} \leq \tau \geq 12\,\text{h}$ depending on the irradiation temperature.

$\Rightarrow$ Tests in a dilution cryostat.



Summary & Outlook

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- 2017 the Dubna/Mainz dilution cryostat was send to Bonn and integrated in the Bonn control system.
- First data taking was possible in November/December last year.
- A new frozen-spin dilution cryostat for Bonn is under construction by JINR Dubna.

- Ongoing measurements at CBELSA with the actual setup.
- Finish the assembling of the new frozen spin target.

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- First data taking was possible in November/December last year.
- A new frozen-spin dilution cryostat for Bonn is under construction by JINR Dubna.
- An internal polarisation magnet for a new continuous target was successfully tested. A continuous polarised target at 1.8 T to 2 T is possible.
- First tests of the new continuous mode dilution cryostat were done and compared to the existing simulation data.
- The data of the precooling stages fits well to the simulation data. (Excluding HE3, where some deviations were expected.)
- Promising data at 1 K for irradiated polyethylene and polypropylene as a new target material.

- Ongoing measurements at CBELSA with the actual setup.
- Finish the assembling of the new frozen spin target.

- Building an internal polarisation magnet with 2.5 T.
- Preparing first tests of the continuous dilution refrigerator in Bonn.
- Test the new target materials at temperatures around 200 mK.