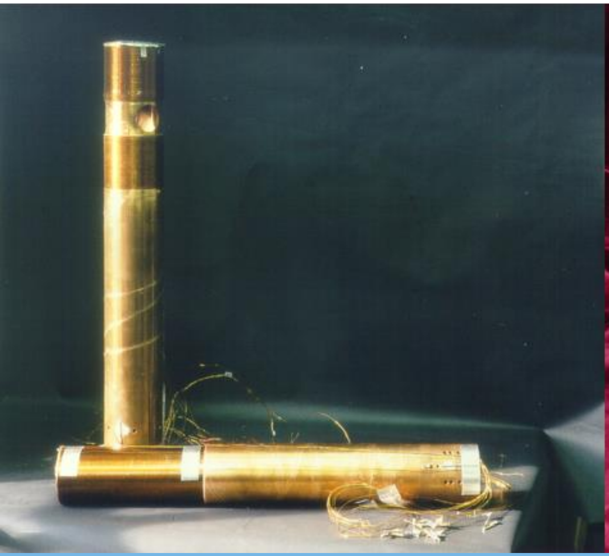
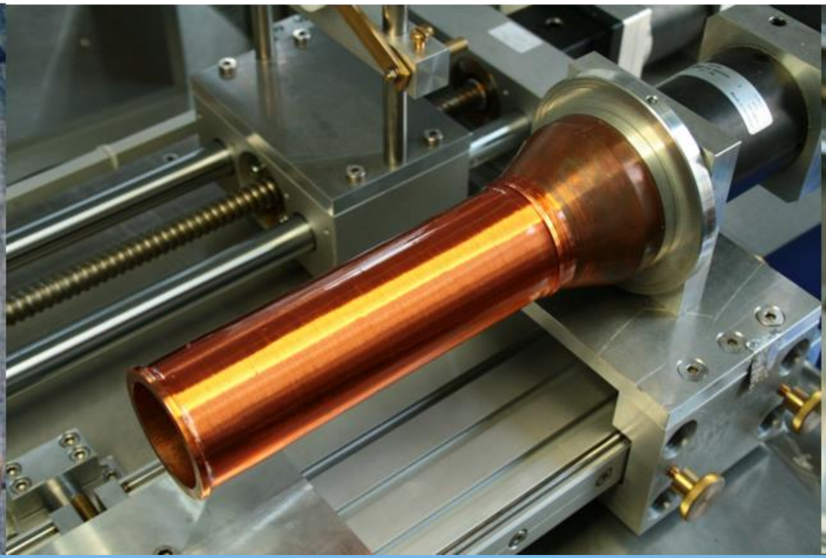
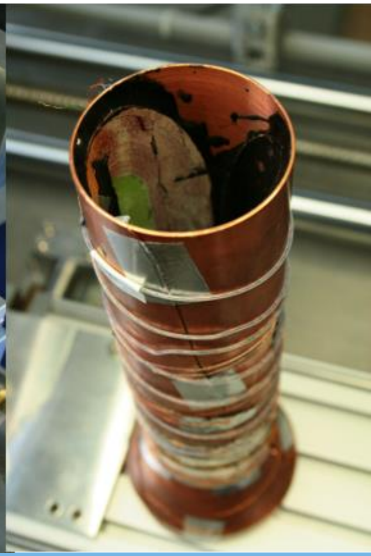


Status of JRA10:CryPTA Task 1, PT UBO

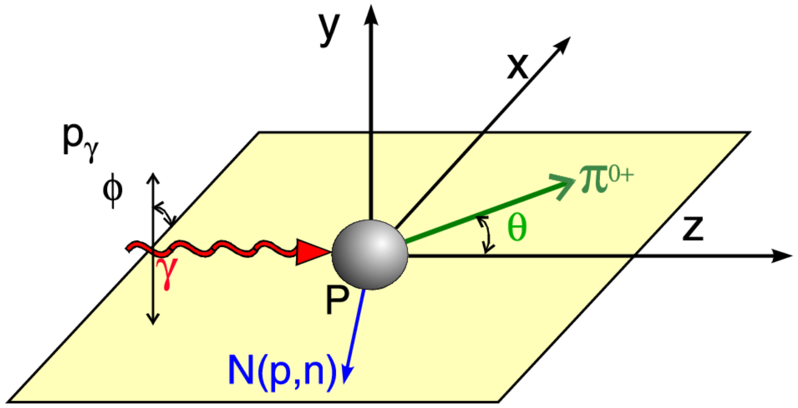
Hartmut Dutz
Physikalisches Institut Universität Bonn

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 824093

Motivation

Structure mapping @ ELSA and Crystal Barrel detector

- → Double polarization experiments
- → Modell independent partial wave analysis
- → Complete experiment



$$\frac{d\sigma}{d\Omega}(\Theta,\phi) = \frac{d\sigma}{d\Omega}(\Theta)\cdot\Big[1 - p_\gamma^{lin}\Sigma(\Theta)\cos(2\phi)$$
$$+ p_t^x\cdot\left(-p_\gamma^{lin}H(\Theta)\sin(2\phi) + p_\gamma^{circ}F(\Theta)\right)$$
$$- p_t^y\cdot\left(+p_\gamma^{lin}P(\Theta)\cos(2\phi) - T(\Theta)\right)$$
$$- p_t^z\cdot\left(-p_\gamma^{lin}G(\Theta)\sin(2\phi) + p_\gamma^{circ}E(\Theta)\right)\Big]$$

Photon		Target		
		x	y	z
unpolarized	σ	0	T	0
linear	(-Σ)	H	(-P)	(-G)
circularly	0	F	0	(-E)

Collaborative target group: Dubna/Mainz/Bochum/Bonn (2015 – 2022)
'Mainz/Dubna frozen spin target' + internal 'holding' coil(s)

Status of JRA10:CryPTA
Task1 PT UBO

Motivation

State of the art set-up: horizontal frozen spin target and internal holding magnet:

Run-time polarized target (cold cryostat)

2017 (long. polarization) ~ 800h b.o.t.

→ max. pol: p_+ = 63 %, (butanol, TEMPO)
→ $\tau \sim$ 1300h (@ 0.4 T, I ~ 10^8/s), $\bar{P} \sim$ 56 %

2018 (transv. polarization) ~ 1000h b.o.t.

→ max. pol: p_+ = 83 %, p_- = 87 % (butanol, porphyrexide)
→ $\tau \sim$ 500 h (@ 0.4 T, I ~ 10^8/s), $\bar{P} \sim$ 78 %

2018 (transv. polarization) ~ 800h b.o.t.

→ max. pol: p_+ = 76 %, p_- = 71 % (d-butanol, trityl)
→ $\tau \sim$ 700 h (@ 0.4 T, I ~ 10^8/s), $\bar{P} \sim$ 70 %

2019 (transv. polarization) ~ 500h b.o.t.

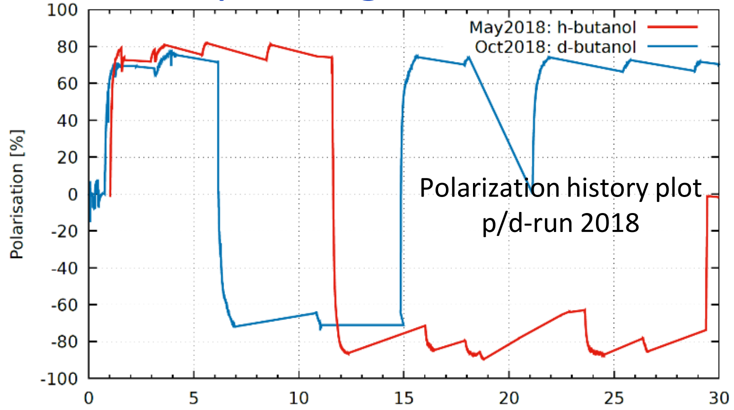
→ max. pol: p_+ = 84 %, p_- = 83 % (butanol, porphyrexide)
→ $\tau \sim$ 800 h (@ 0.4 T, I ~ 10^8/s), $\bar{P} \sim$ 77 %

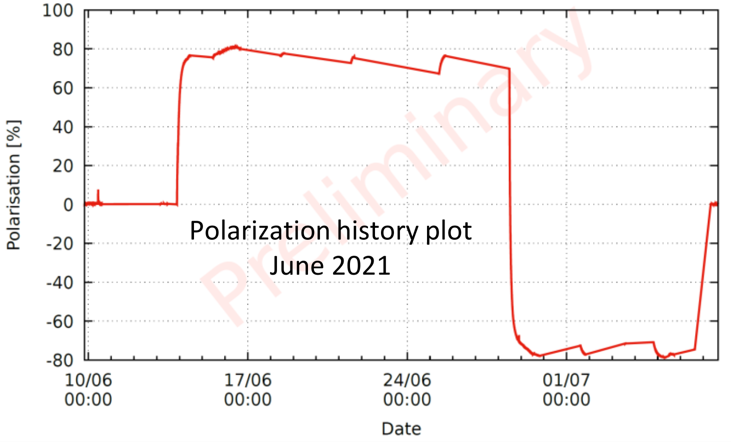
2021 (transv. polarization) ~ 440h b.o.t.

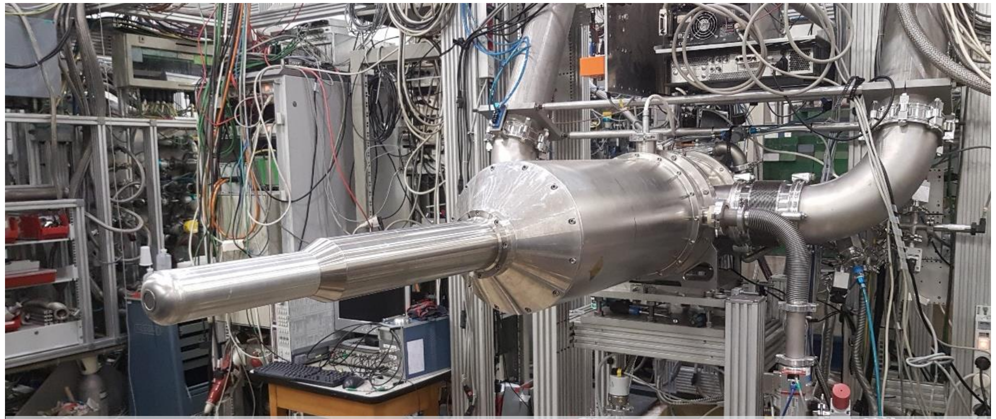
→ max. pol: p_+ = 78 %, p_- = 77 % (butanol, porphyrexide)
→ $\tau \sim$ 700 h (@ 0.4 T, I ~ 10^8/s), $\bar{P} \sim$ 74 %

2021 (transv. polarization) ~ 500h b.o.t.

→ max. pol: p_+ = 63 %, p_- = 75 % (d-butanol, trityl)
→ $\tau \sim$ 500 h (@ 0.4 T, I ~ 10^8/s), $\bar{P} \sim$ 68 %

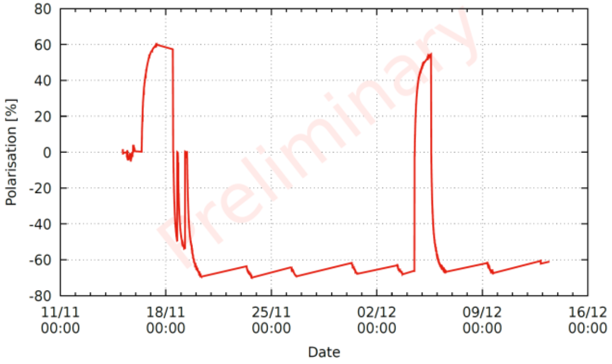






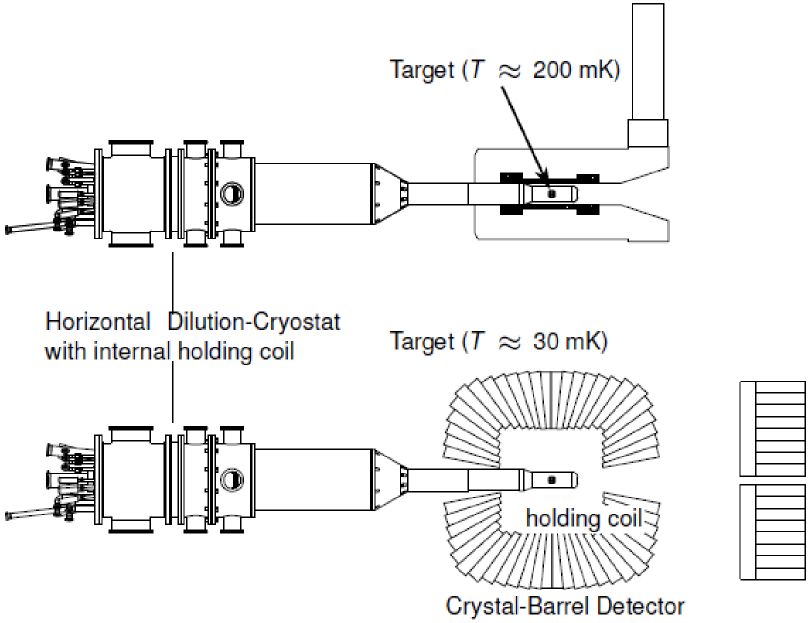
Collaborative target group: Bonn/Dubna/Mainz/Bochum (2015 – 2021)
'Mainz/Dubna frozen spin target' + internal 'holding' coil(s)

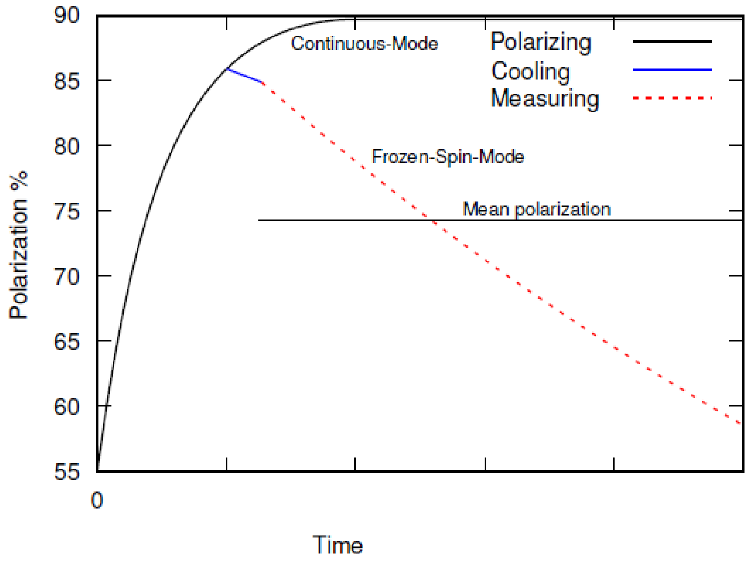
Polarization history plot
November 2021,
d-butanol



Motivation

State of the art set-up: horizontal frozen spin taget and internal holding magnet:





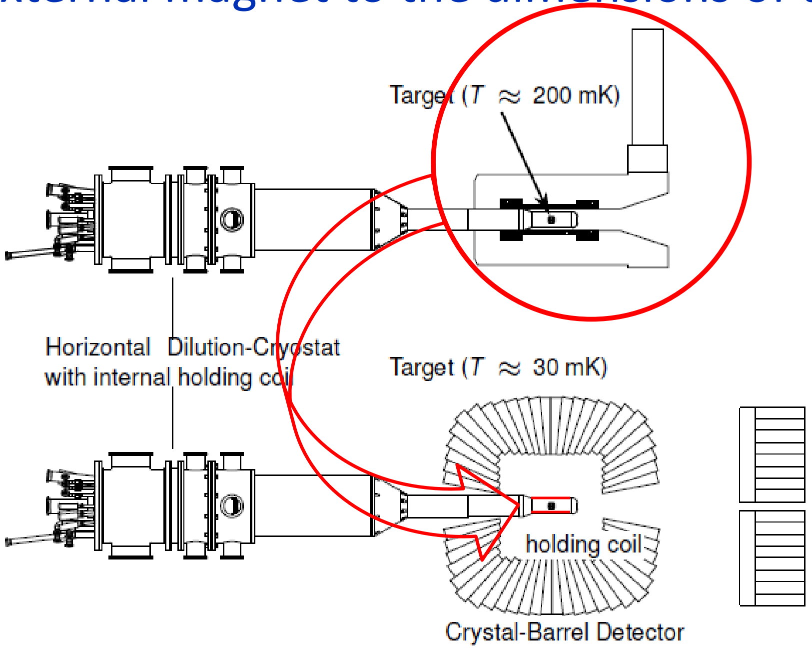
Frozen spin target:

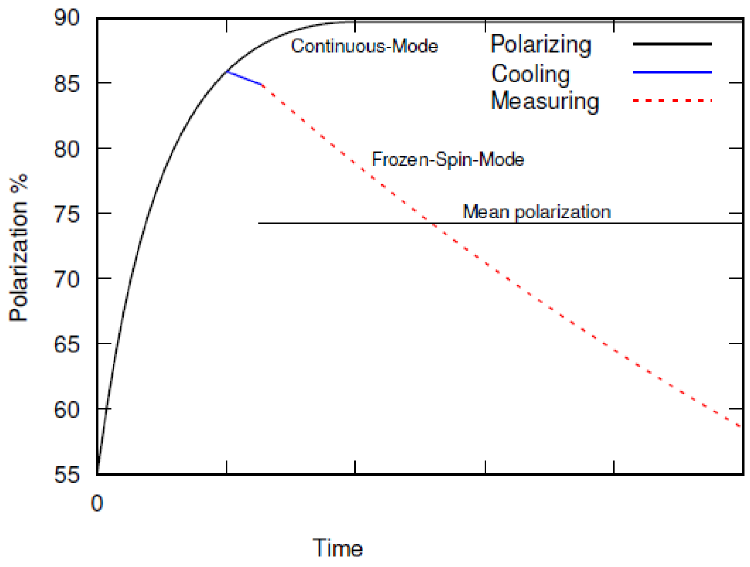
- Set-up: external polarizing magnet (2.5 T), internal holding coil (0.6T)
- Advantage: large angular acceptance, 4π detector
- Disadvantage: loss of polarization, complex handling, limited beam intensity

Status of JRA10:CryPTA Task1 PT UBO

Motivation

Shrink the external magnet to the dimensions of the internal holding coil:





4π-Continuous-Mode Target

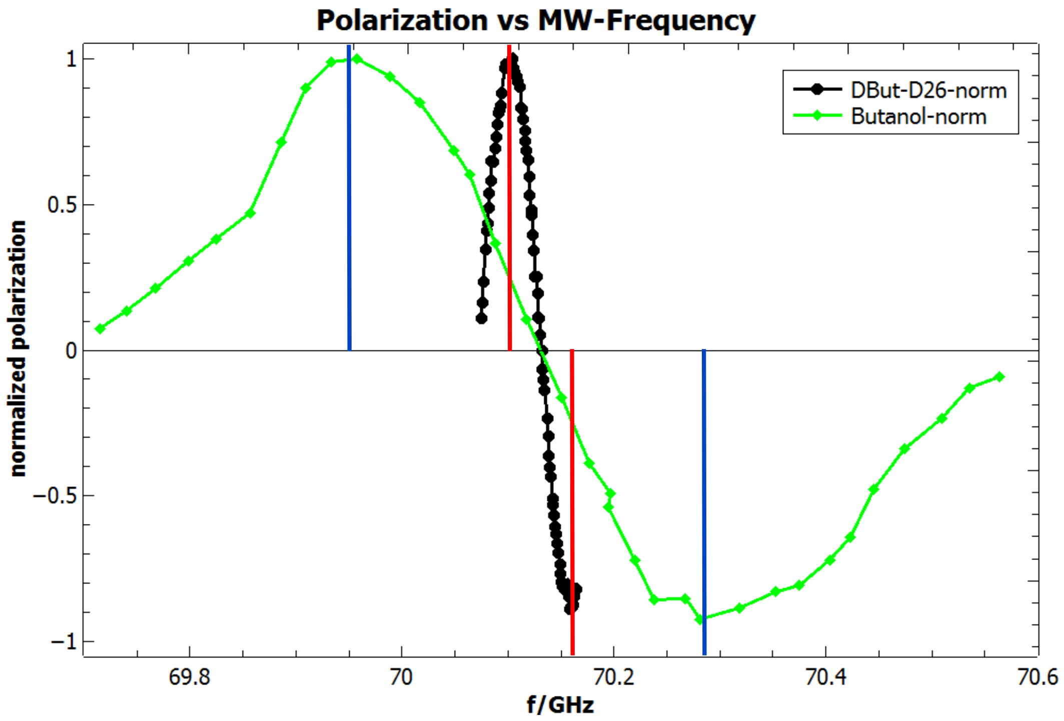
Combines the advantages of high polarisation and the large angular acceptance
Key element: Internal magnet with the same magnetic properties as the external magnet

Status of JRA10:CryPTA Task1 PT UBO

Research Objectives Task1: high field, thin s.c. magnets

Polarized solid state target (DNP @ 0.2 – 0.3 K) (horizontal dilution refrigerator)

- high mag. longitudinal field for DNP (B_{DNP} ~ 2.5 T)
- good homogeneity for DNP $\Delta B/B \leq 10^{-4}$
- thin as possible (like holding coil) < 2mm
- passively cooled



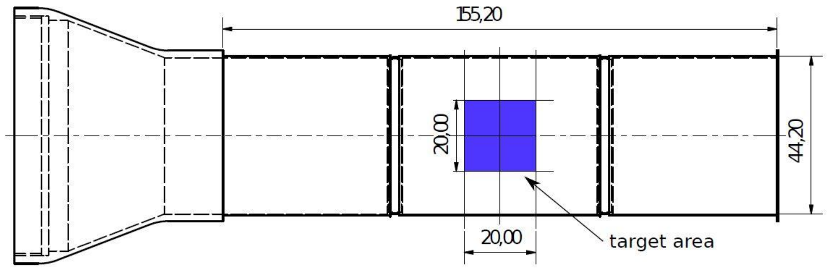
4π – continuous mode target (what do we gain?):

- good angular acceptance (~ 4π)
- high luminosity L ~ $10^{33}/cm^2s^{-1}$ (N ≈ 10^{10}/s) [N < 10^8/s]
- high mean polarization (P_p ~ 90%, P_d ~ 85%) [P_P ~ 75 %]
- good beam time efficiency

Status of JRA10:CryPTA
Task1 PT UBO

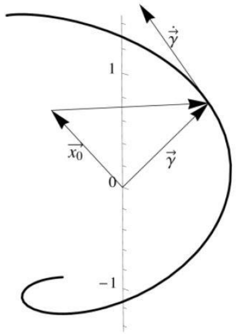
Research Objectives Task1: 6 layer 2.5T polarizing magnet

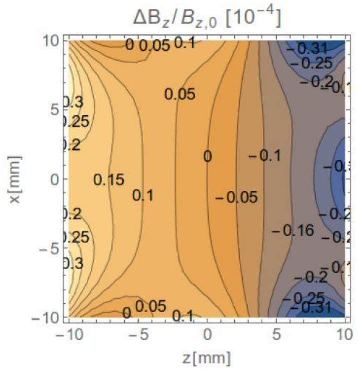
Internal polarisation magnet - Field calculation



Biot-Savart-Law:

$$\vec{B}(\vec{x_0}) = \frac{\mu_0}{4\pi} I \int \frac{(\vec{\gamma}(t) - \vec{x_0}) \times \frac{\dot{\vec{\gamma}}(t)}{|\dot{\vec{\gamma}}(t)|}}{|(\vec{\gamma}(t) - \vec{x_0})|^3} \mathrm{d}t$$





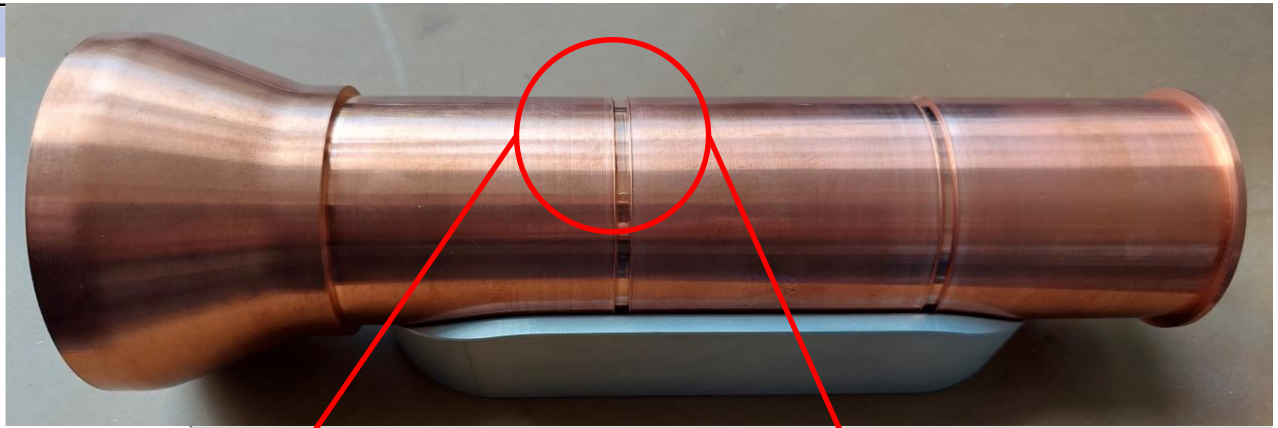
Loop parametrization:

$$\vec{\gamma} = (r\cos(t), r\sin(t), n \cdot d)$$

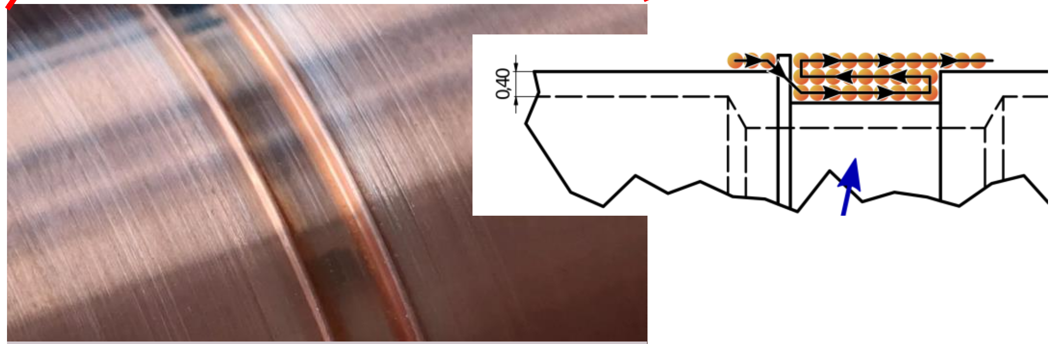
r: radius of each loop
$n \cdot d$: loop position
d: effective distance between 2 wires

DNP requires $\Delta B/B \leq 10^{-4}$

Internal magnet developments for polarized targets 7/14



Coil carrier (cupper core)

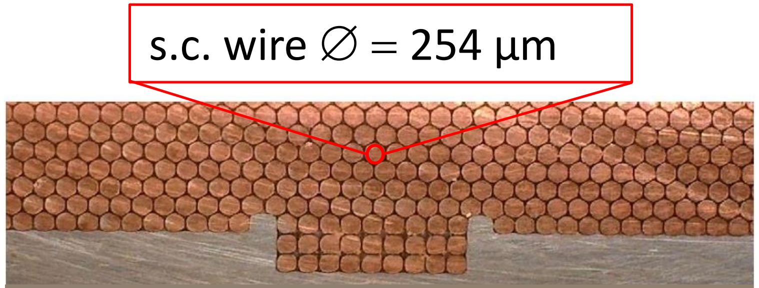


Inverse notched coil

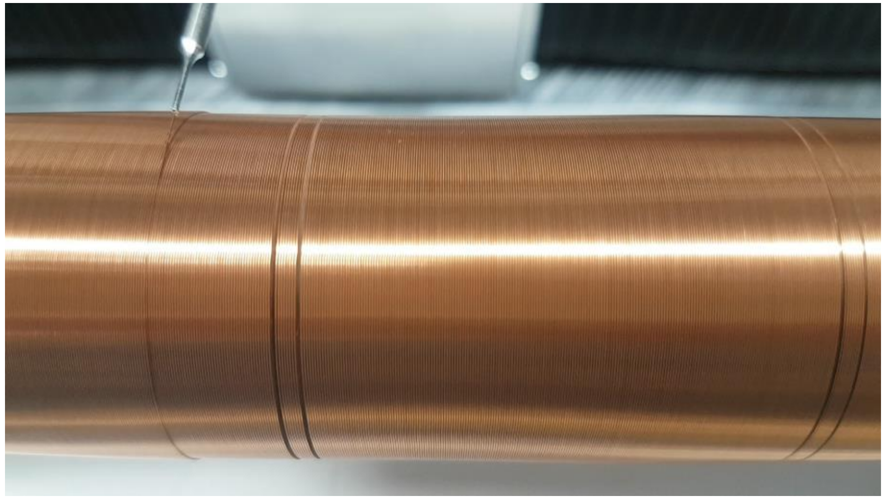
Status of JRA10:CryPTA
Task1 PT UBO

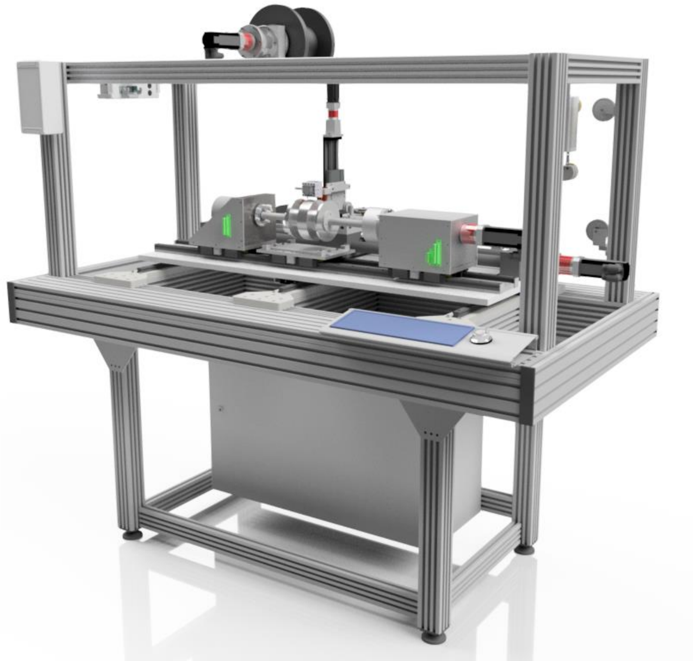
Research Objectives Task1: 6 layer 2.5T polarizing magnet

- Small superconducting magnet (solenoid 150 mm x ∅45 mm x WT 1.8 mm), high field (B=2.5T) and high homogeneity ($\Delta B/B \leq 10^{-4}$, 20 x ∅20 mm)
- Wrap thin s.c. wire (∅254µm) with high precision (orthocyclic, wet winding), 6 layers á 590N + 2*9N
- Displacement ≤ 2.5µm



Cut and grinding of a test winding





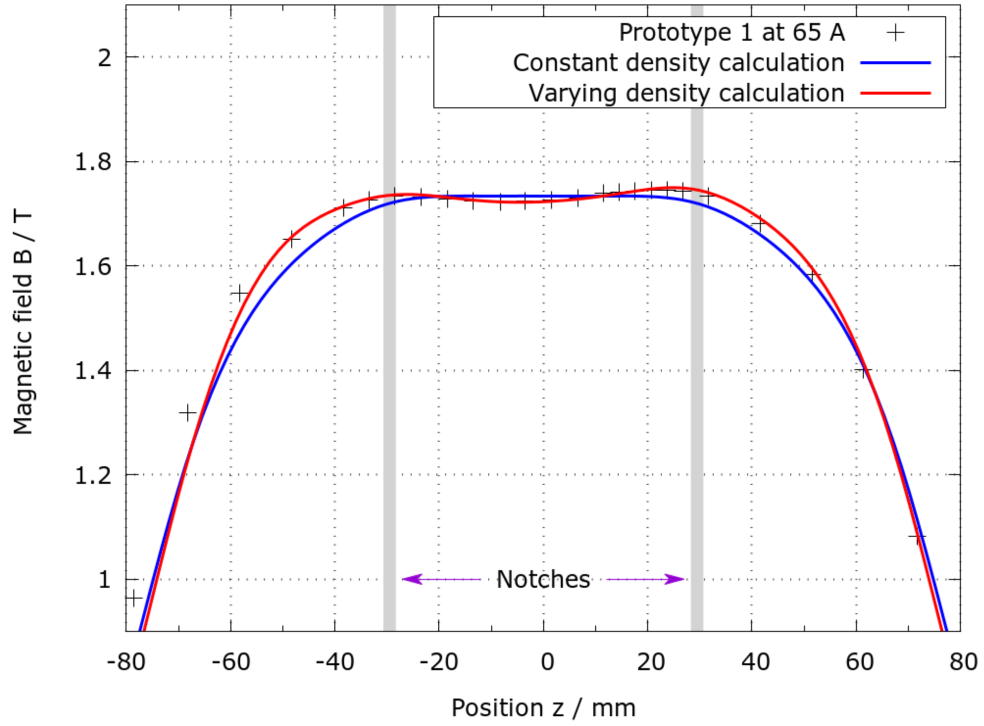
- Not commercially available
- Custom made high precision winding machine fulfill the requirements (MS63)
- Co financed by a collaborative SME research project (BMWI, ZIM) with CryoVac (Germany) and Physics Institute University Bonn

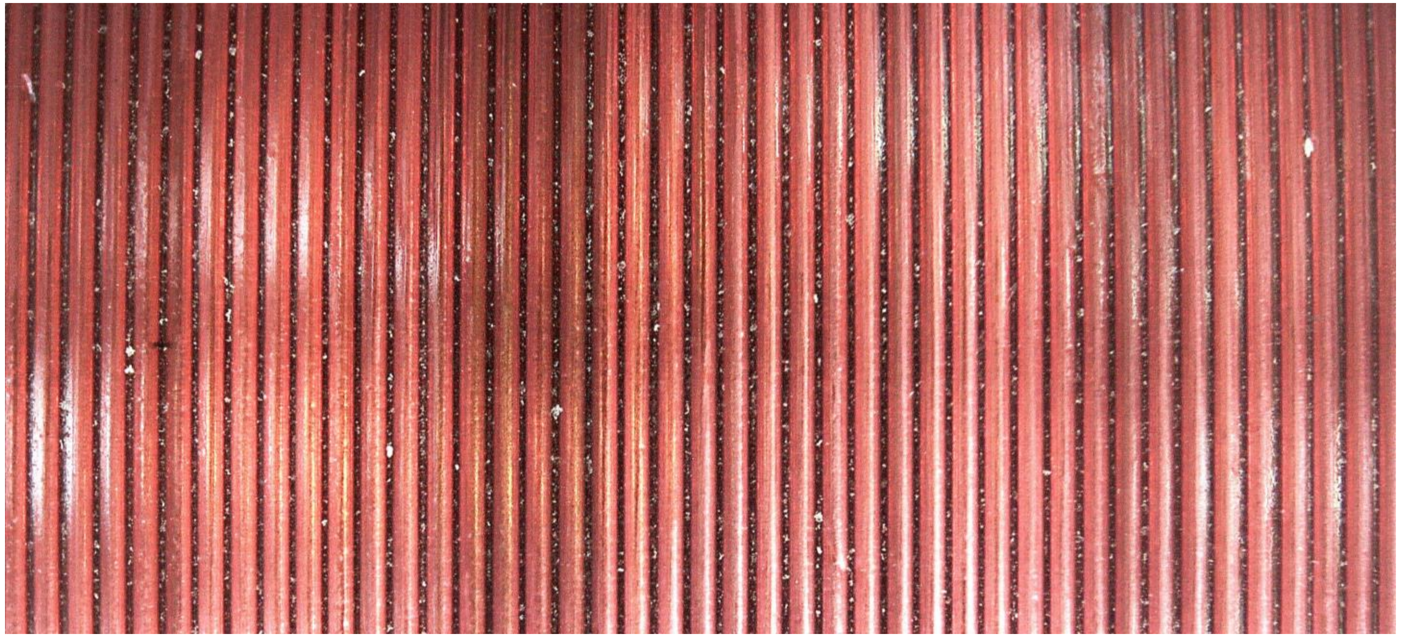
MS63: High precision winding machine for thin superconducting wires: https://www.polarisiertes-target.physik.uni-bonn.de/files/internalreportmilestonewindingmaschine.pdf

Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 6 layer 2.5T polarizing magnet

Why is it so important to do a high precision winding

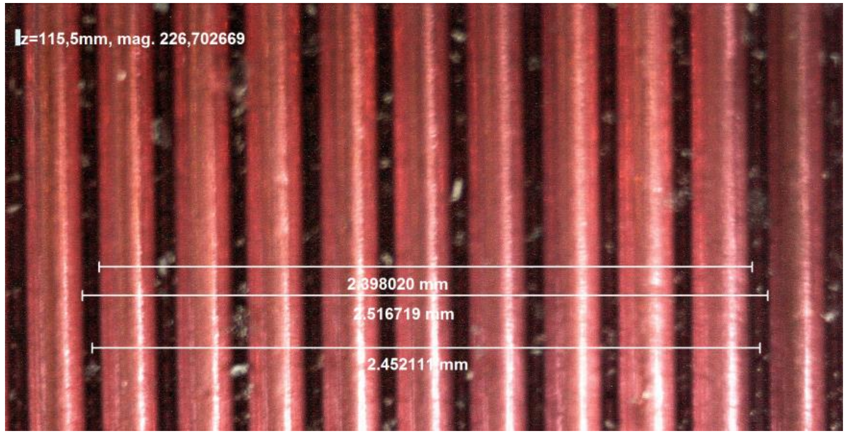


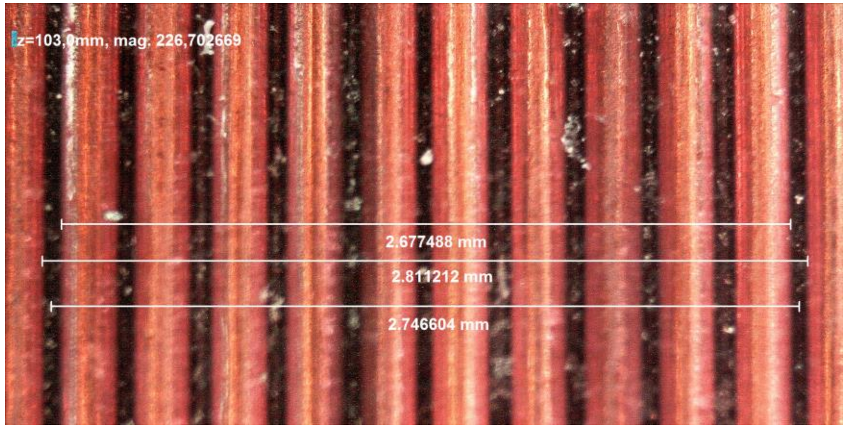


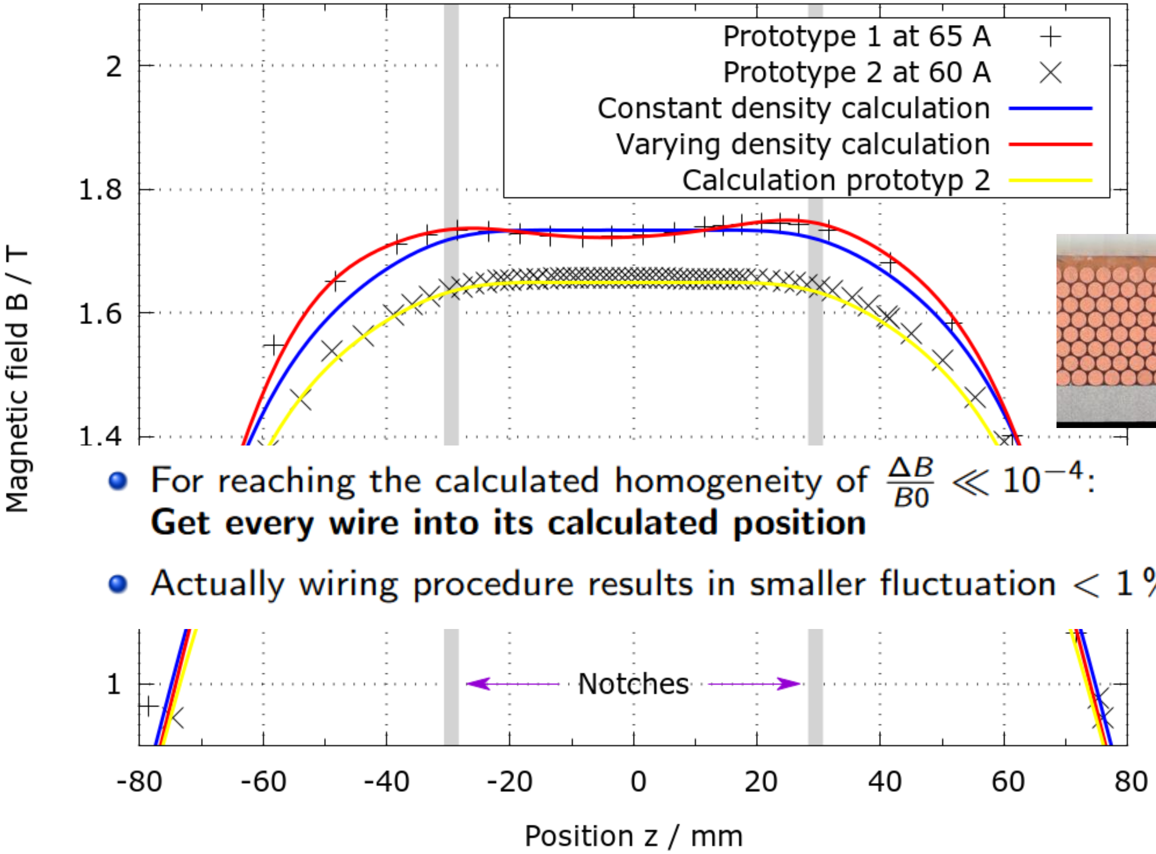
Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 6 layer 2.5T polarizing magnet

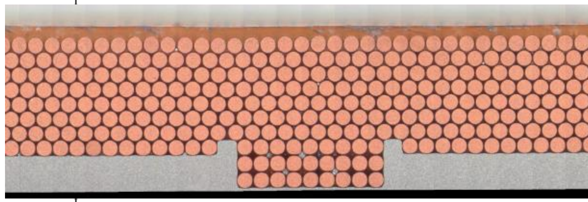
Why is it so important to do a high precision winding







- For reaching the calculated homogeneity of $\frac{\Delta B}{B0} \ll 10^{-4}$:
  Get every wire into its calculated position
- Actually wiring procedure results in smaller fluctuation $< 1\,\%$ of the effective distance

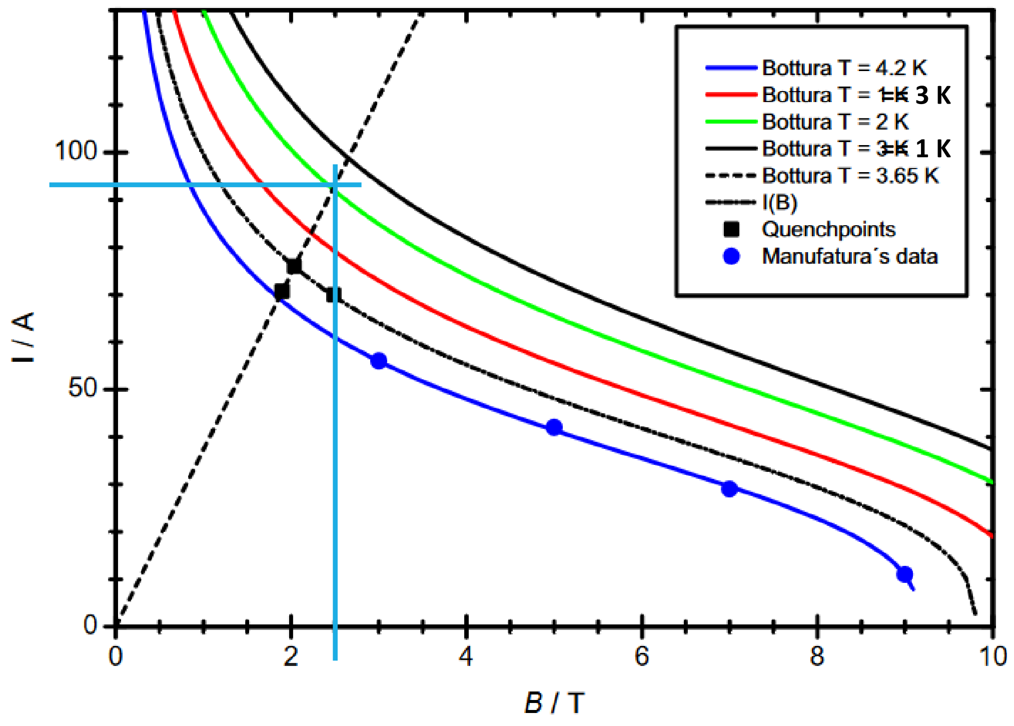


Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 6 layer 2.5T polarizing magnet

Why is it so important to run @ 1K

Estimation[1] and measurement of the critical current $I_c(B)$



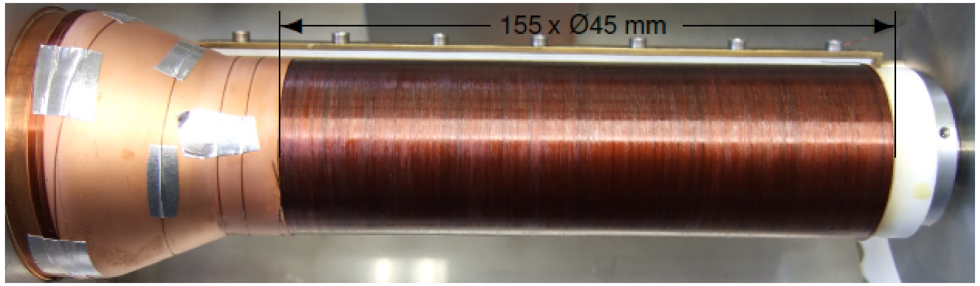
[1] L. Bottura, *A practical fit for the critical surface of NbTi*

	T	B_c	I_c
Bottura	4.2 K	1.86 T	69 A
	1 K	2.5 T	101 A
Experimental	4.2 K	1.9 T	70.7 A
	~3.5 K	2 T	74 A
	~3.5 K	2.5 T[a]	70 A

[a] produced with an additional external field

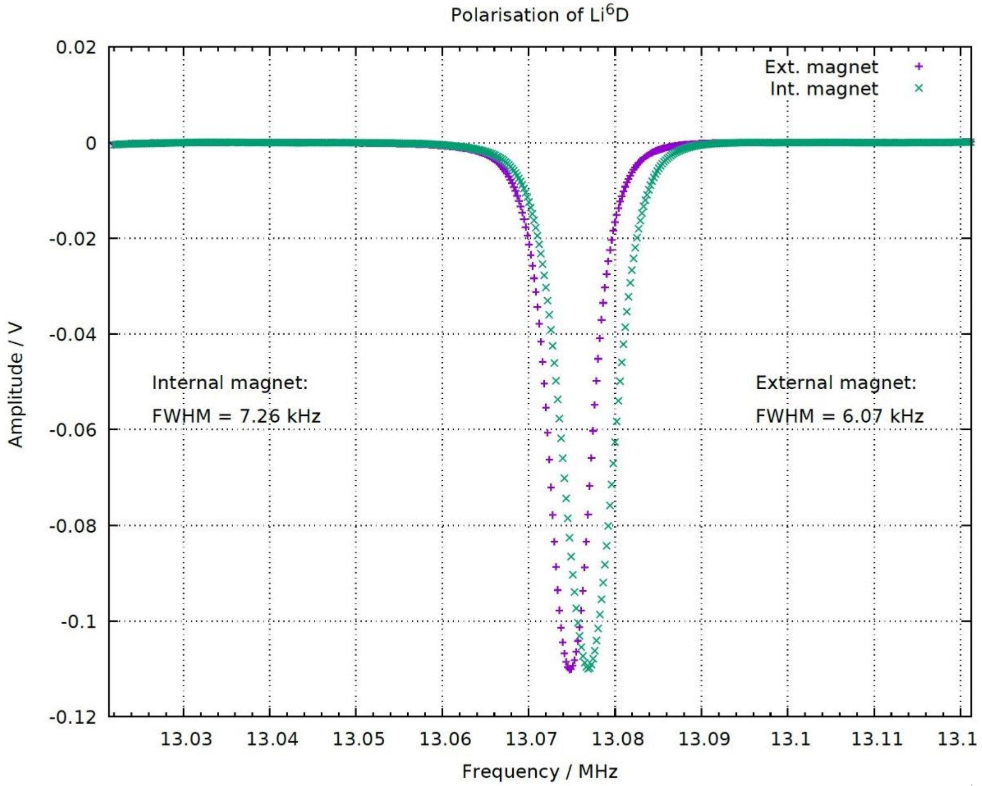
Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 6 layer 2.5T polarizing magnet



- As thin as possible
  $\rightarrow$ Overall thinkness $\leq$ 2 mm
  $\rightarrow$ Passively cooled
- Internal magnet with $B_0 = 2.5\,\text{T}$ @ 90 A @ 1 K
- $\frac{\Delta B}{B_0} \ll 10^{-4}$ @ $1/40\,V_{\text{overall}}$
- Building process by wet wiring (with epoxy)
- Precondiction: Homogeneous (orthocylcic) wire pattern!

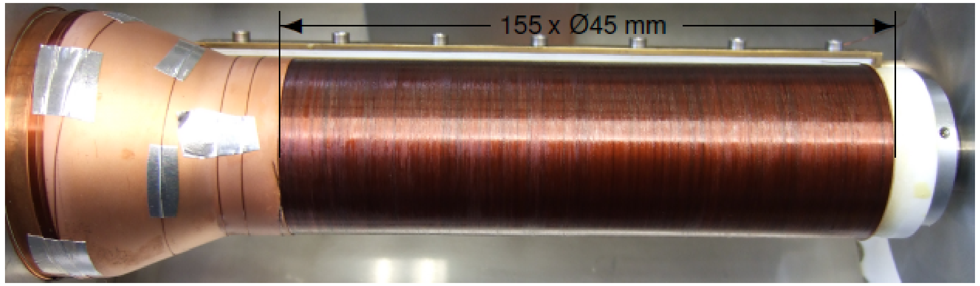
Tests in ^{4}**He Kryostat**: 6LiD at 1 K



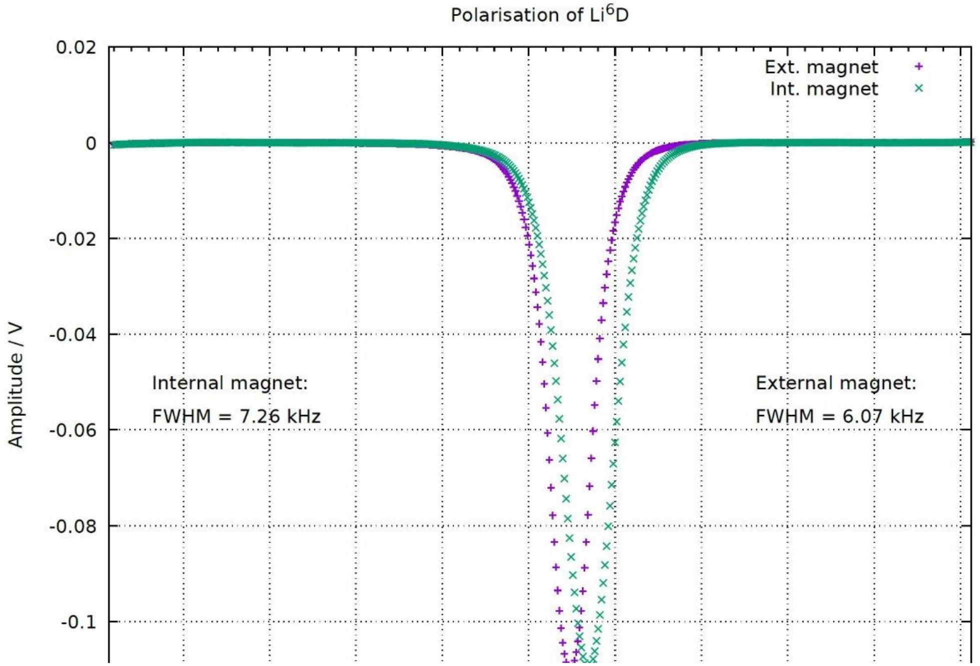
- A proton and a deuteron target could be dynamically polarized with an internal magnet

Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 6 layer 2.5T polarizing magnet



Tests in ^{4}**He Kryostat**: 6LiD at 1 K



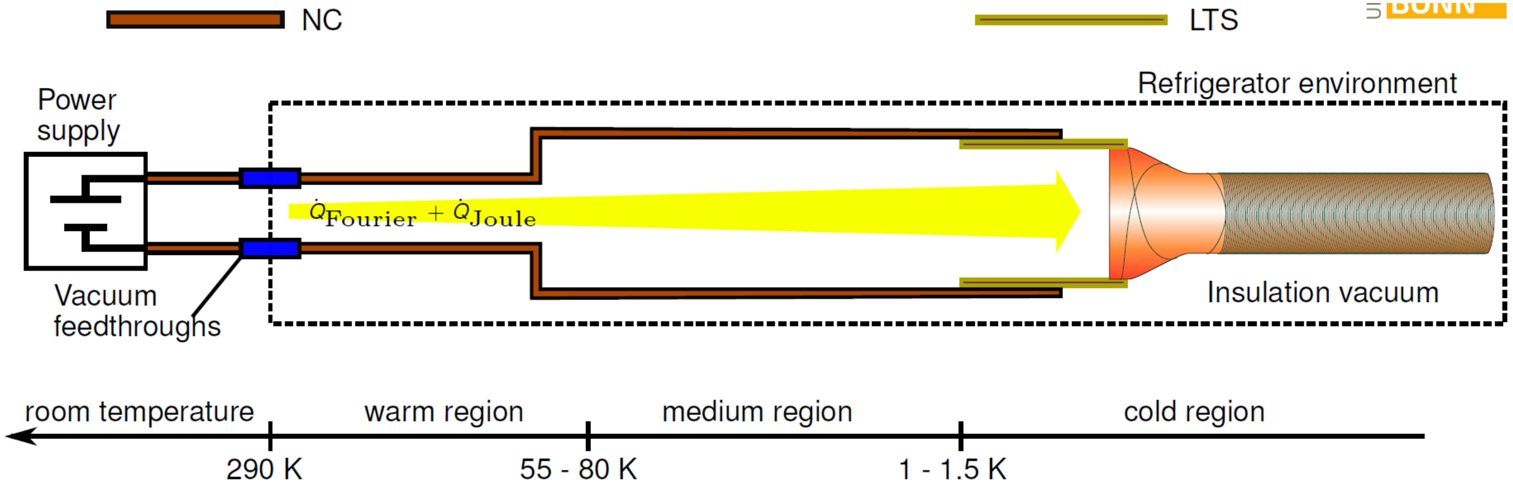
- As thin as possible
  → Overall thinkness ≤ 2 mm
  → Passively cooled
- Internal magnet with $B_0 = 2.5\,\mathrm{T}$ @ 90 A @ 1 K
- $\frac{\Delta B}{B_0} \ll 10^{-4}$ @ $1/40\,V_{\mathrm{overall}}$

For operating an internal magnet

Two (electrical) **stable and low heat generating current leads** are necessary

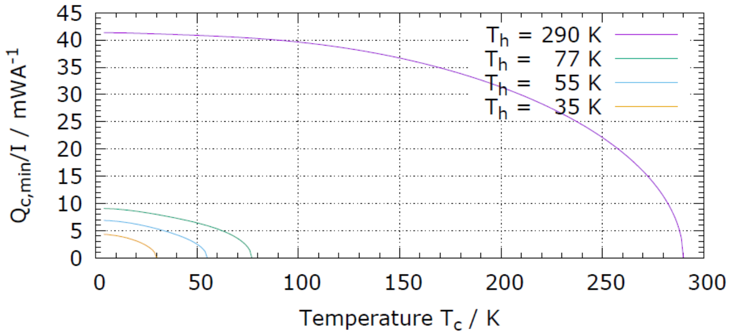
Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 90A hybrid current leads



Problems with normal conducting (NC) current leads:

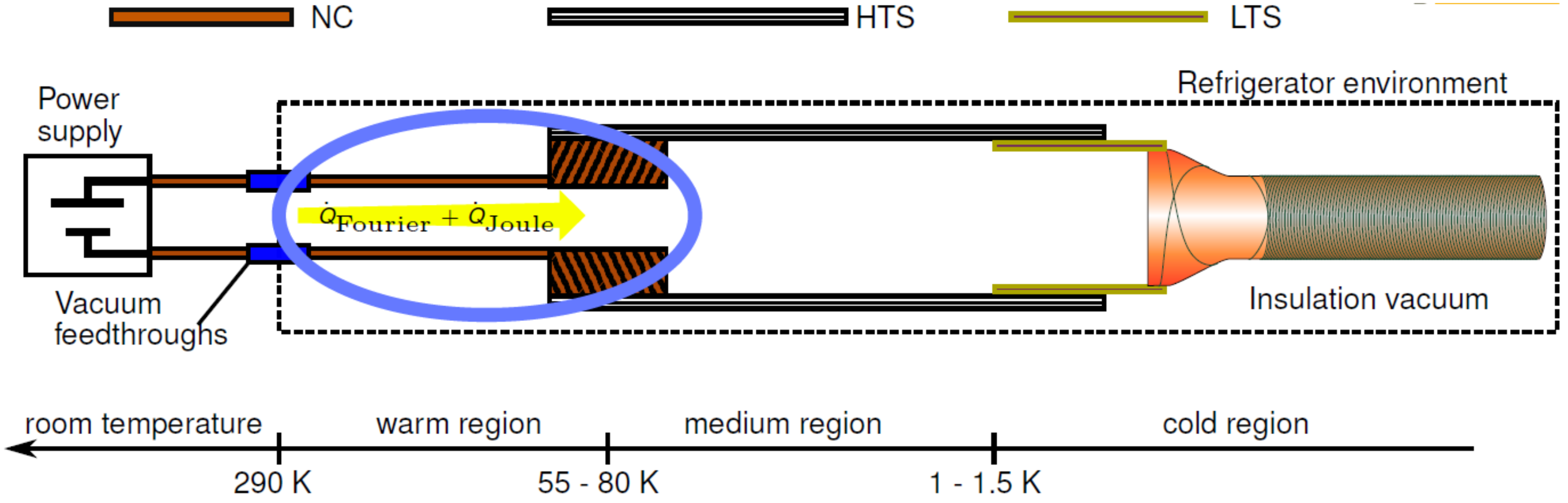
- Large heat load on the cold region due to Fourier's law
- Additional heat load due to Joule heating when energising the magnet
- Cooling of magnet and current leads only by conduction
- Large heat load can lead to a quench of the low temperature superconductor (LTS) / magnet
- There exist a minimum heat flow with $\dot{Q}_{\mathrm{Fourier}} = 0$



R. McFee, "Optimum Input Leads for Cryogenic Apparatus, Rev. Sci. Instrum. Vol. 30, American Institute of Physics, 1959

Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 90A hybrid current leads



Problems with normal conducting (NC) current leads:

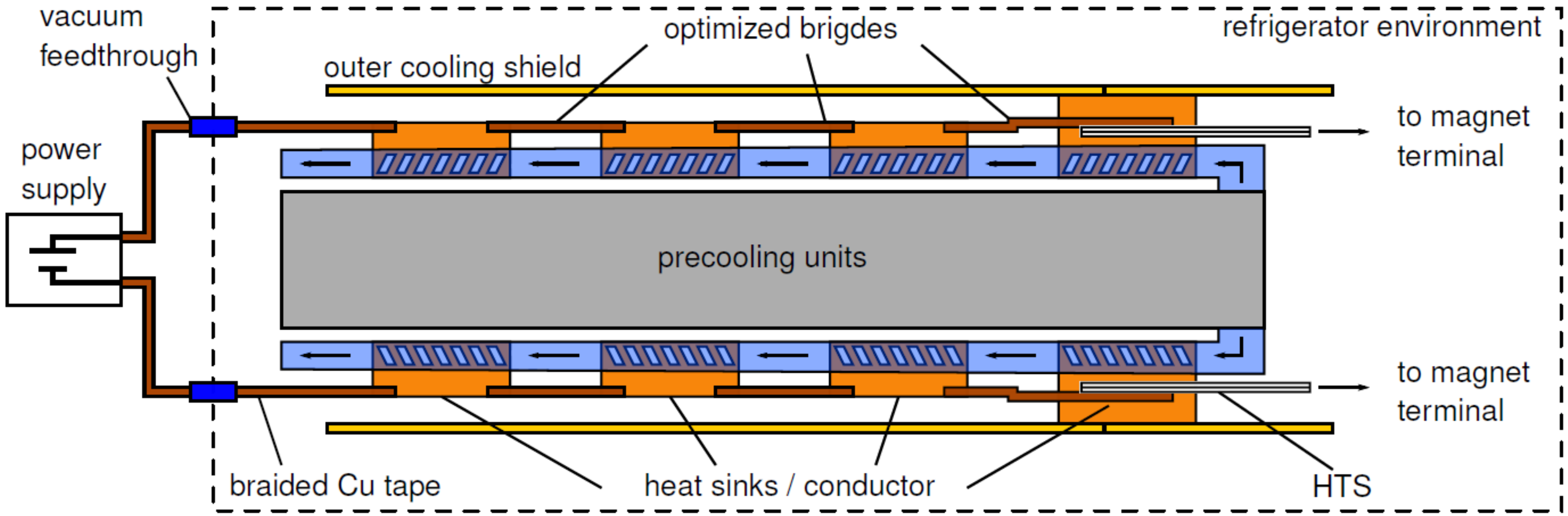
- Large heat load on the cold region due to Fourier's law
- Additional heat load due to Joule heating when energising the magnet
- Cooling of magnet and current leads only by conduction
- Large heat load can lead to a quench of the low temperature superconductor (LTS) / magnet
- There exist a minimum heat flow with $\dot{Q}_{\mathrm{Fourier}} = 0$

Solution for the cold region:

- Thermal decoupling between warm and cold region/LTS
- Can be archived by using a high temperature superconductor (HTS, here: BSCCO)
- But nontheless: Heat load must be minimised up to the NC-HTS junction for not quenching the HTS

Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 90A hybrid current leads



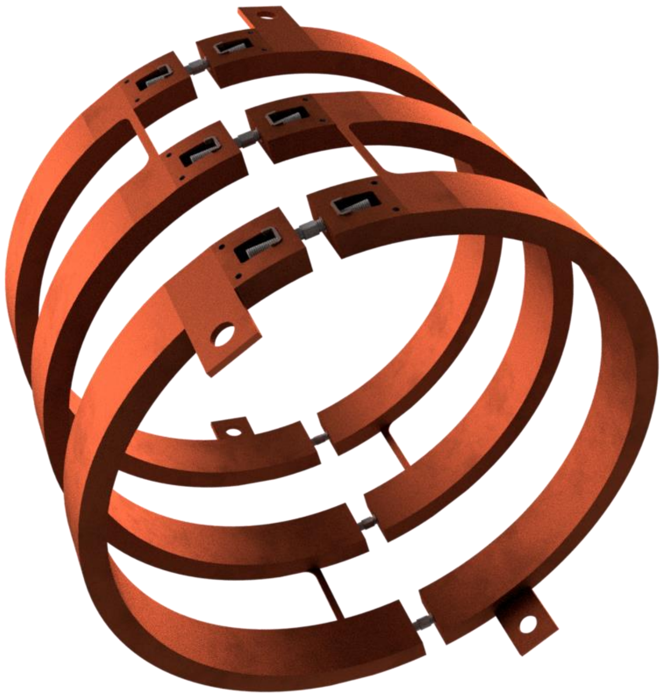
Block scheme from a CFD-simulation for minimum heat load on NC – HTSC junction

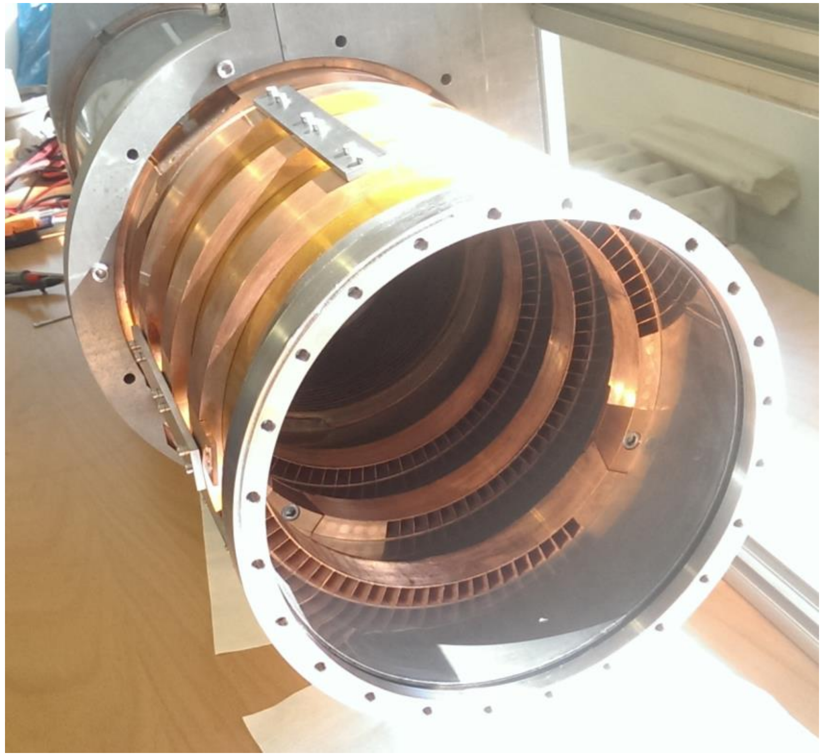
- Braided flexible copper tape ($A = 25\,\text{mm}^2$, $L = 1.4\,\text{m}$)
- 3 (turbine) heat sinks / copper-(half) rings for each terminal ($A = 260\,\text{mm}^2$)
- Ring-conductorss are connected by bridges ($A = 1.5\,\text{mm}^2$, $L = 4\,\text{cm}$))
- Bridges are designed for minimising thermal conduction from one sink to the next when energised
- Thermal decoupling between the heat sinks (McFee)

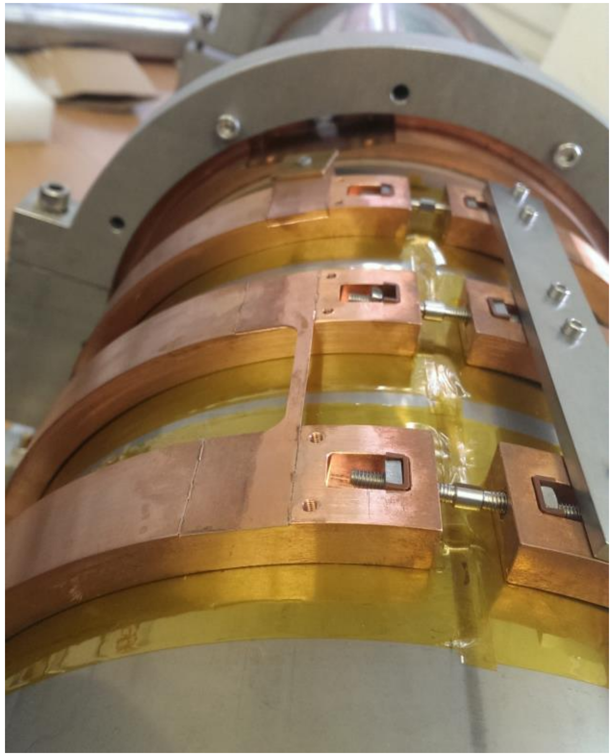
Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 90A hybrid current leads

minimum heat load NC – HTSC junction for the Bonn dilution refrigerator





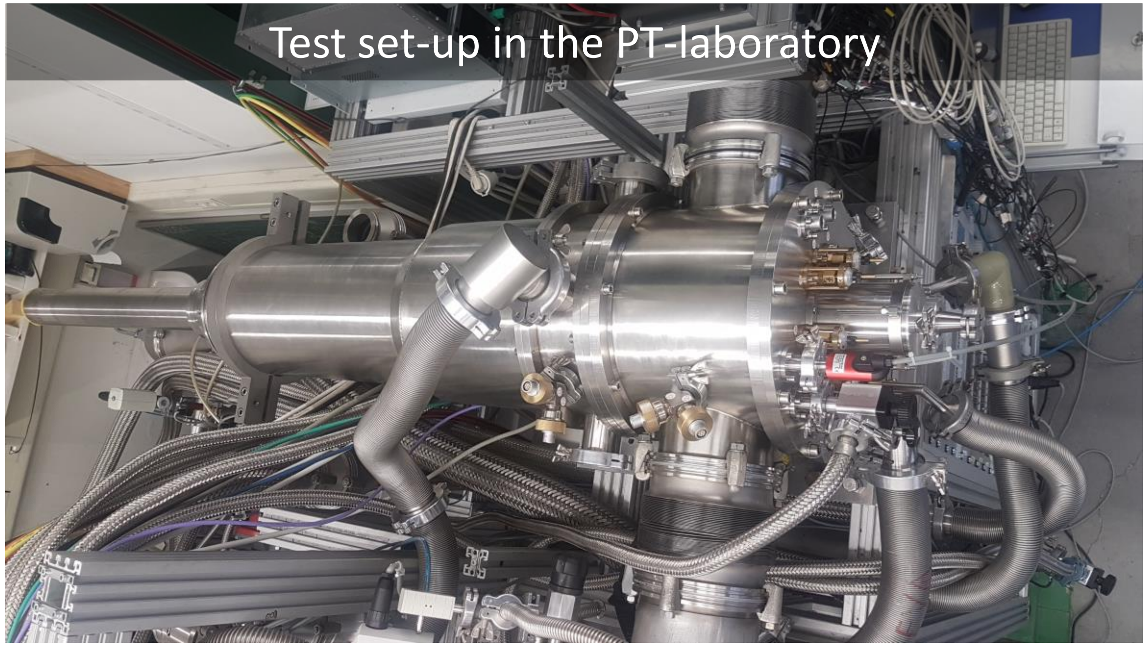


Final test still pending due to super leaks in the refrigerator

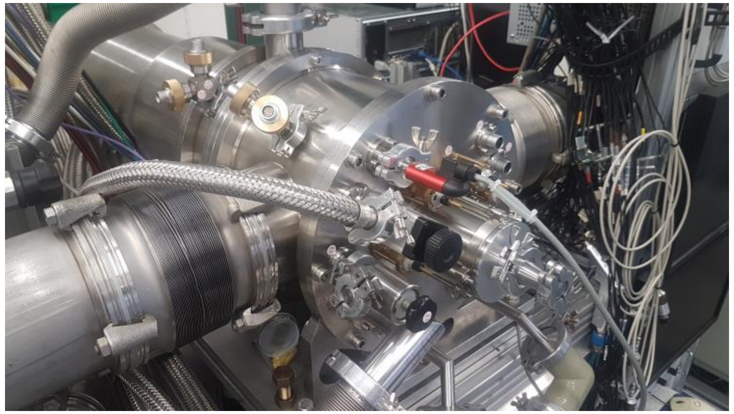
Status of JRA10:CryPTA
Task1 PT UBO

Horizontal dilution refrigerator with int. high field pol. magnets

New horizontal dilution refrigerator for polarization experiments with Crystal Barrel detector @ ELSA
build by cryogenic department of JINR (Dubna)



Central beam line
Target insert for fast and easy target exchange
Designed for various magnet configurations
→ $T_{min} < 30$ mK , TDNP ~ 250 mK
→ I_{max} ~ 40 A



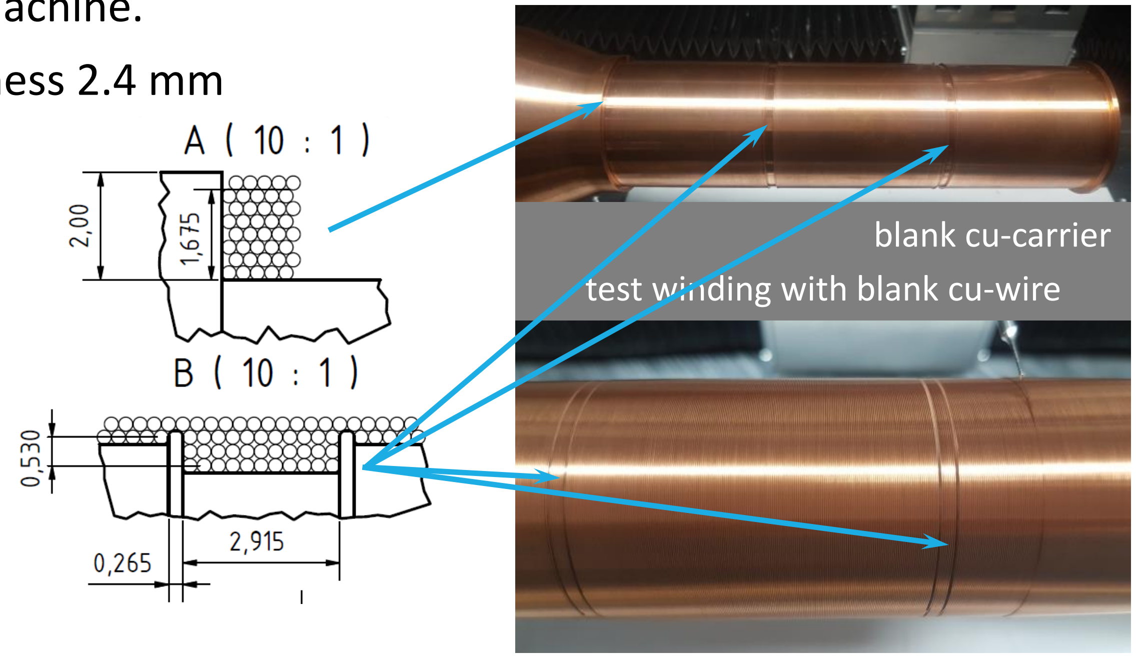
→ Delivered fall 2020, assembled and first 1K tests in summer 2021, commissioning planned for spring 2022
→ First polarization experiment @ ELSA planned for fall 2022 using the combined sc.coil configuration
→ Foreseen for pol. experiments using active polarized target technology

Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: 8 layer 2.5T polarizing magnet

New horizontal dilution refrigerator for polarization experiments with Crystal Barrel detector @ ELSA
Build by cryogenic department of JINR (Dubna)

- new Dubna dilution refrigerator is unable to cool high current leads (I_N ~ 90A @ 2.5T).
- a 8-layers magnet will be wound soon on the new winding machine.
  - N=5116, 8 Layers á 634 + 2*11, 2.5T @ 68.6A/1K, thickness 2.4 mm
  - $F_{\mu w}$ = 70 GHz !
  - Current leads has to be adapted to the refrigerator!

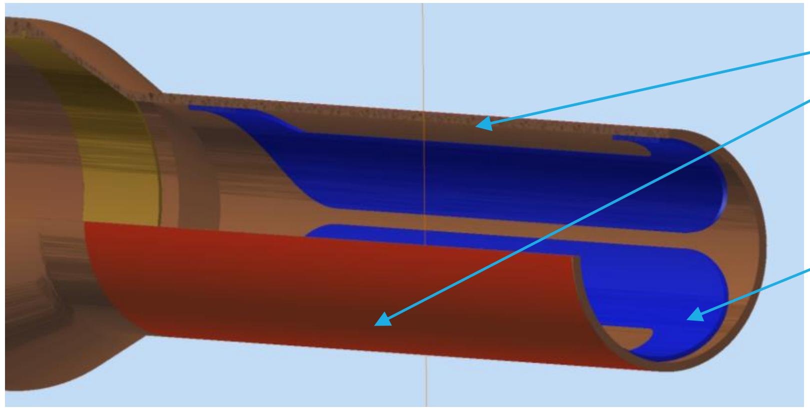


For first double polarization experiments at CB-Detector:
Combined **longitudinal and transverse holding coil** for the new Dubna dilution refrigerator (step back to standard frozen spin set-up)

Status of JRA10:CryPTA
Task1 PT UBO

Research Objectives Task1: combined holding magnet system

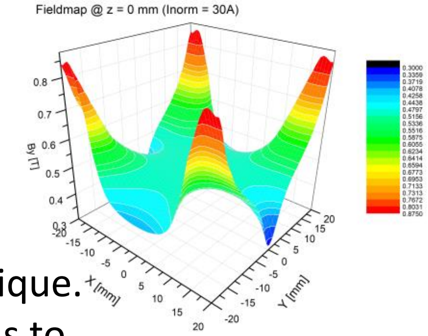
Combined longitudinal and transverse holding coil for the new dilution refrigerator for a variable polarization direction in plane (Milestone MS64)

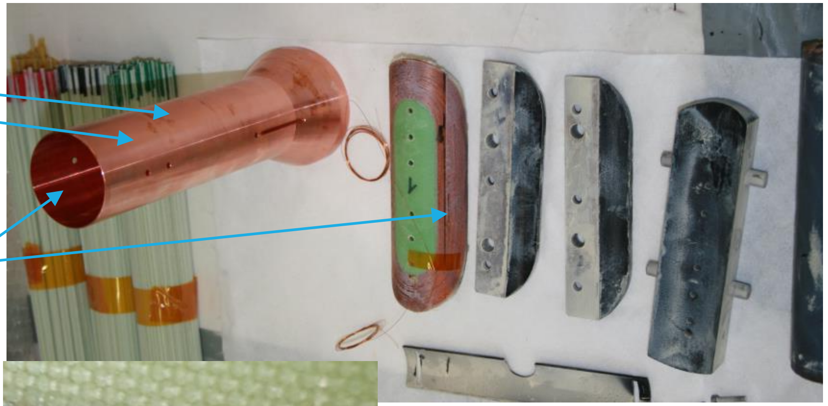


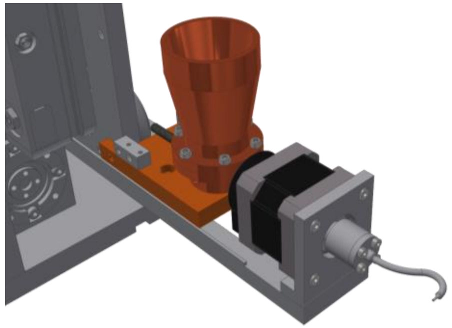
Cu-support (cooling)

Longitudinal field: solenoid (outside)
- → 4 layers á N590
- → I_{max} ~ 32 A
- → B_{max} ~ 0.52 T

Transverse field: race track like dipole (inside)
- → 2 x N525
- → I_{max} ~ 30 A
- → B_{max} ~ 0.50 T







- ➢ Precision wet winding of a solenoid is a well established technique.
- ➢ Wet winding of race tracks with thin superconducting wires has to be improved to guaranty high performance at minimum thickness
- ➢ Problem: inhomogeneous glue distribution within the coil package
- ➢ New wire feeding device is under construction

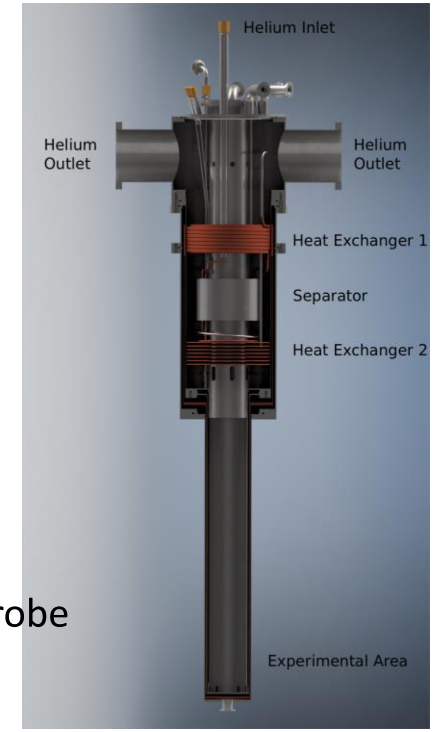
Status of JRA10:CryPTA
Task1 PT UBO

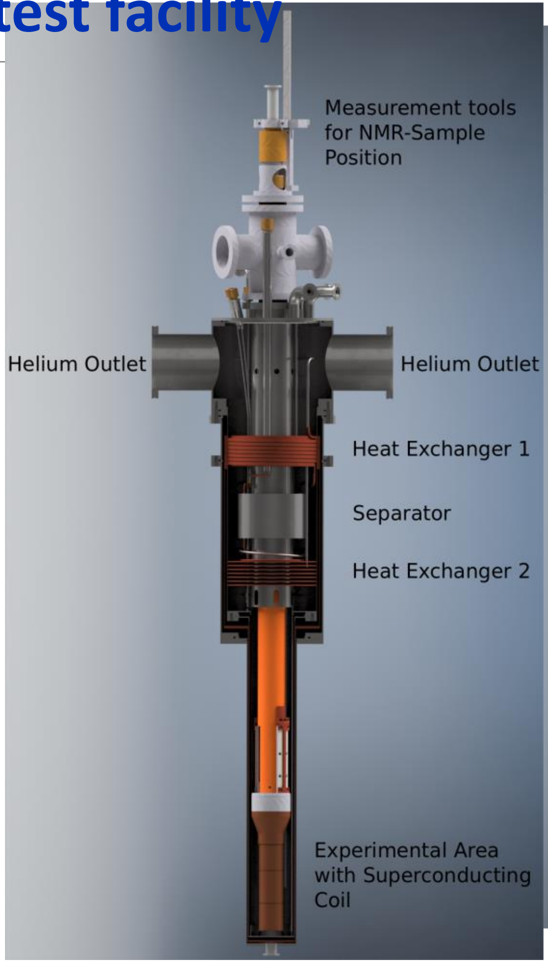
Research Objectives Task1: 1K magnet test facility

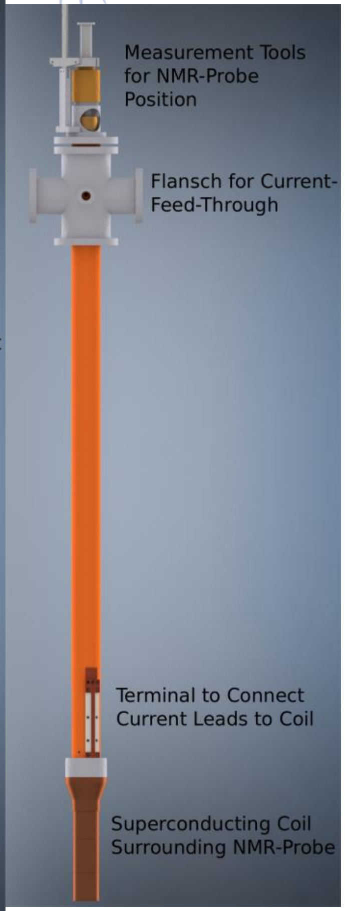
- → Small superconducting magnet designed and build for DNP in a dilution refrigerator (magnet operating parameters: 90A @ 1K)
- → For test measurements (performance tests) of the magnets a simple 1K test facility is required

- → New ^{4}He evaporation refrigerator is under construction
  - → Fits into the external high field DNP-magnet (B_{max} = 6.5T)
  - → Variable temperature range (1K – 70K)
  - → Large low temperature volume (500 mm x ∅75 mm, 2.2l)
  - → Flexible and open access via insert tube

- → (already) available magnet test insert
  - → Current leads (I_{max} =100A)
  - → Field measurement (mapping) by pulsed-, cw-NMR, Hall-probe
  - → Equipped for DNP (50 – 140 GHz)





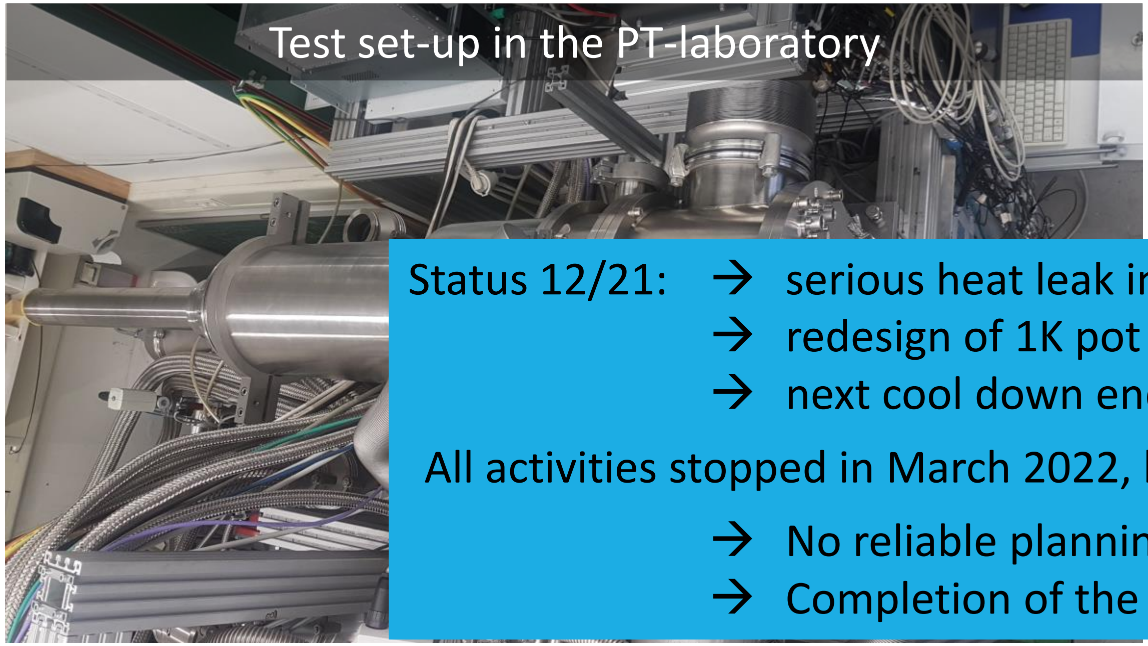


[4]He evaporation refrigerator for magnet tests: https://www.polarisiertes-target.physik.uni-bonn.de/files/InternalReportEinNeuer4HeKryostat_translated.pdf

Status of JRA10:CryPTA
Task1 PT UBO

Horizontal dilution refrigerator with int. high field pol. magnets

New horizontal dilution refrigerator for polarization experiments with Crystal Barrel detector @ ELSA
Build by cryogenic department of JINR (Dubna)



Central beam line
Target insert for fast and easy target exchange
Designed for various magnet configurations
→ $T_{min} < 30$ mK , TDNP ~ 250 mK
→ I_{max} ~ 40 A

Status 12/21: → serious heat leak in the precooling stages (unclear source)
→ redesign of 1K pot planned for spring 2022
→ next cool down end of 2022

All activities stopped in March 2022, because of the Russian invasion of the Ukraine

→ No reliable planning is possible
→ Completion of the 1K magnet test refrigerator

→ Delivered fall 2020, assembled and first 1K tests in summer 2021, commissioning in spring 2022
→ First polarization experiment @ ELSA planned for fall 2022 using the combined sc.coil configuration
→ Foreseen for pol. experiments using active polarized target technology

Status of JRA10:CryPTA
Task1 PT UBO

Summary

Key technology to improve the polarized target performance:

- increase the luminosity, FoM and availability
- gain to new polarization observables

Scheme has been proven @ 1K, 2 Tesla

With the new refrigerator from Dubna and the cooperation with
Mainz/Bochum PT-groups
we hope (realistic, we don’t know when) to realize the
‘4π continuous mode target concept’
for real photon double polarization experiments at ELSA and MAMI (soon).

Status of JRA10:CryPTA
Task1 PT UBO

High precision winding machine

Wet winding of a rectangular coil