26th International Symposium on Spin Physics
A Century of Spin

JINR
JOINT INSTITUTE FOR NUCLEAR RESEARCH

Dubna, Polarized Targets, history and plans

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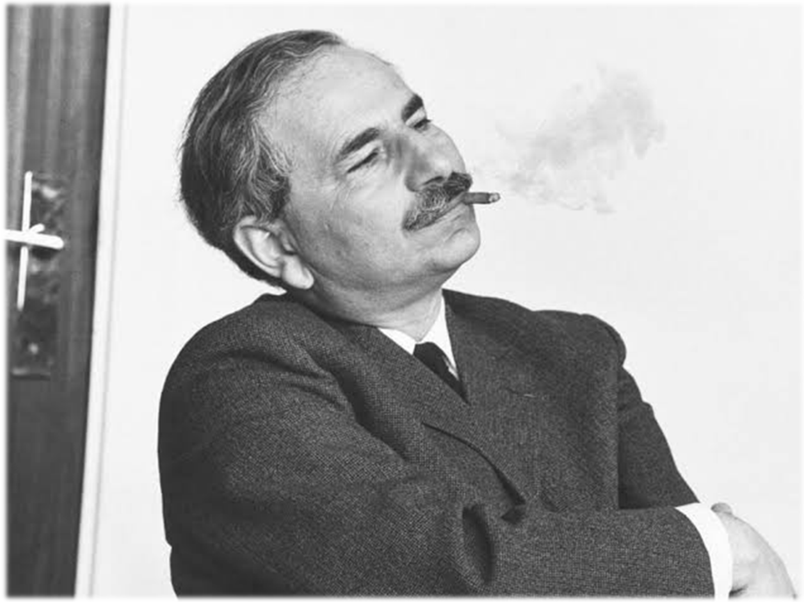
Co-authors: Nikolai Borisov, Ivan Gorodnov, Alexander Neganov, Yury Usov, https://dlnp.jinr.ru/snt/en/

Dynamic nuclear polarization

1953: Dynamic Nuclear Polarization was proposed by **Albert Overhauser** (post-doc, U. Illinois).
Overhauser's idea was initially met with great skepticism by experts in magnetic resonance field (Rabi, Bloch, Ramsey and others)

Albert Overhauser (1925-2011)

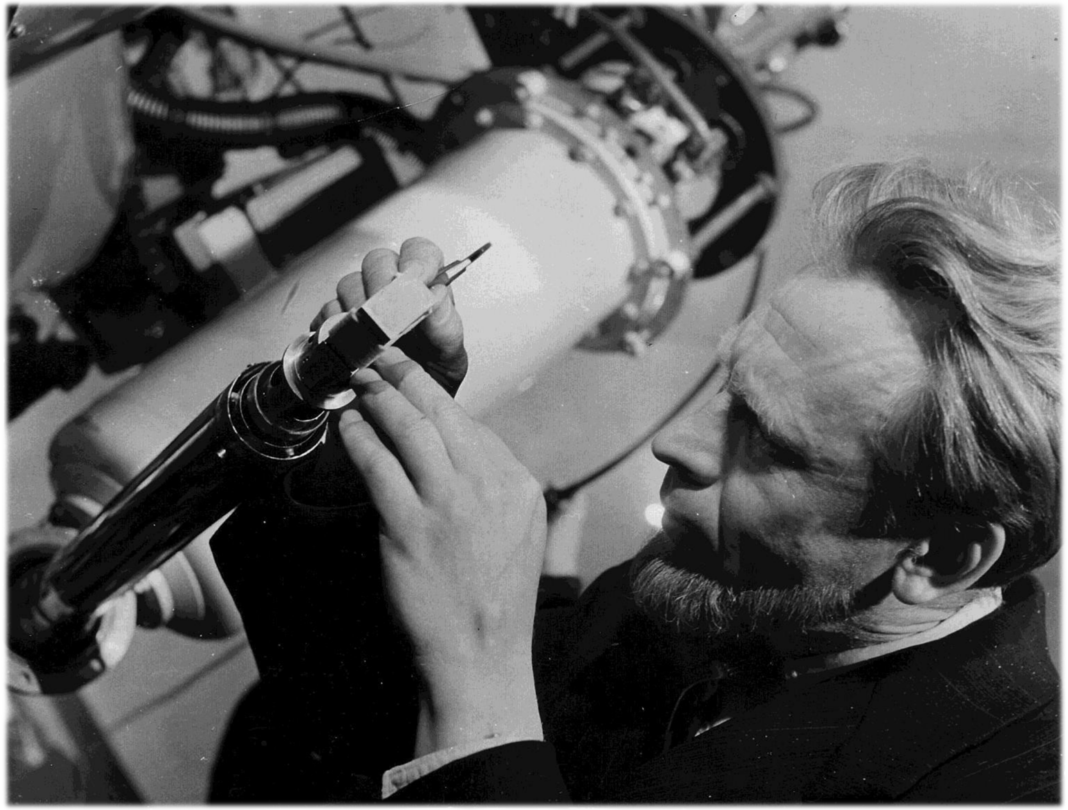
Anatole Abragam (1914-2011)



In **1962**, **Anatole Abragam's** group reported on what was the first experiment to measure the scattering of polarized protons – in this case a 20 MeV beam derived from the cyclotron at Saclay – off a polarized proton target (Abragam et al. 1962). The target was a single crystal of lanthanum magnesium nitrate (La2Mg3(NO3)12.24H2O or LMN), with 0.2% of the La3+ replaced with Ce3+, yielding a proton polarization of 20%

Dynamic nuclear polarization

LMN target development started at Dubna in **1964**.
The target prepared by **Luschikov**, **Neganov**, **Parfenov** and **Taran** (Sov. Phys. JETP, 1966, Vol. 22, p. 285) was first used pp-scattering at 660 MeV at the Dubna Synchrocyclotron



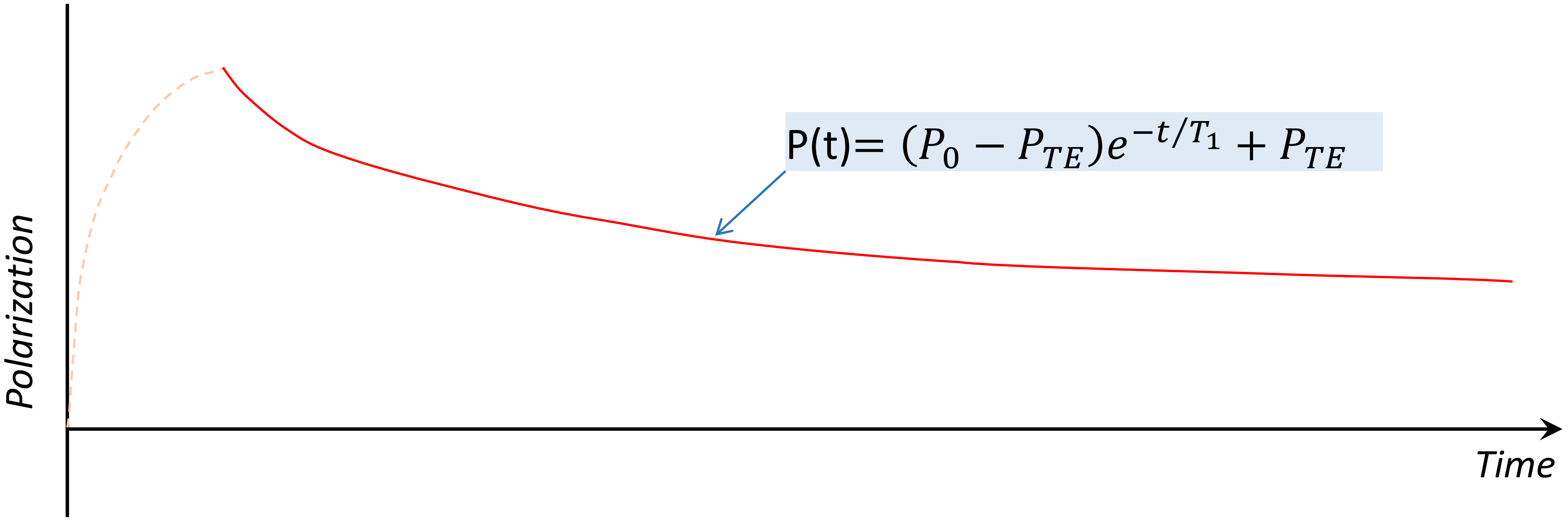
Neganov B.S. during tuning of 1K Dynamic Polarized target (**1965**)

Dynamic nuclear polarization

- **Dynamic Nuclear Polarization** (DNP) is used to increase the polarization of the target sample (up to 90% or higher)
- Microwave transitions transfer high polarization of paramagnetic impurities (free electron spins) to nuclear spins
- Field is typically 2.5 or 5 T (higher is usually better)
- Temperature during polarization is in the range from ~ 0.2 K to 1 K
- Takes a few hours (sometimes for a whole day)

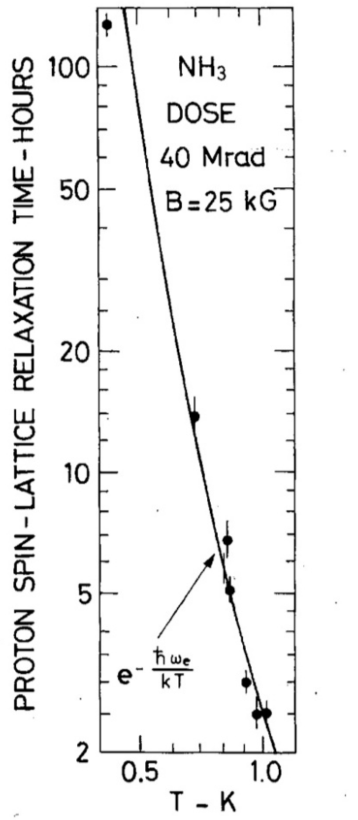
Nuclear spin relaxation

- Once DNP is stopped, the polarization begins to decay towards its natural, thermal-equilibrium value
- Decay is exponential, with T_1 *(spin-lattice time constant)* of a few days to a few months
- Holding field is typically ~½ Tesla (higher is better)
- Temperature is typically < 50 mK (lower is better)

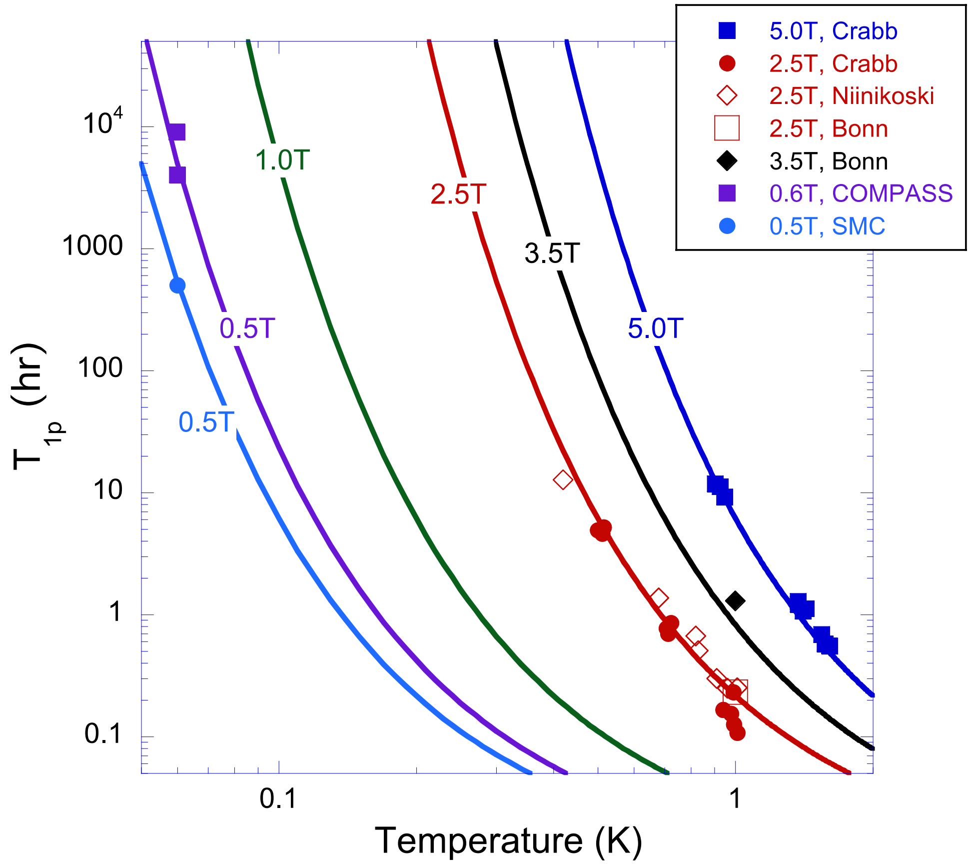


Nuclear spin relaxation: freezing the spins

T.O. Niinikoski and J.M. Rieubland, (Phys. Lett. A, 1979, Vol. 72, p. 142)

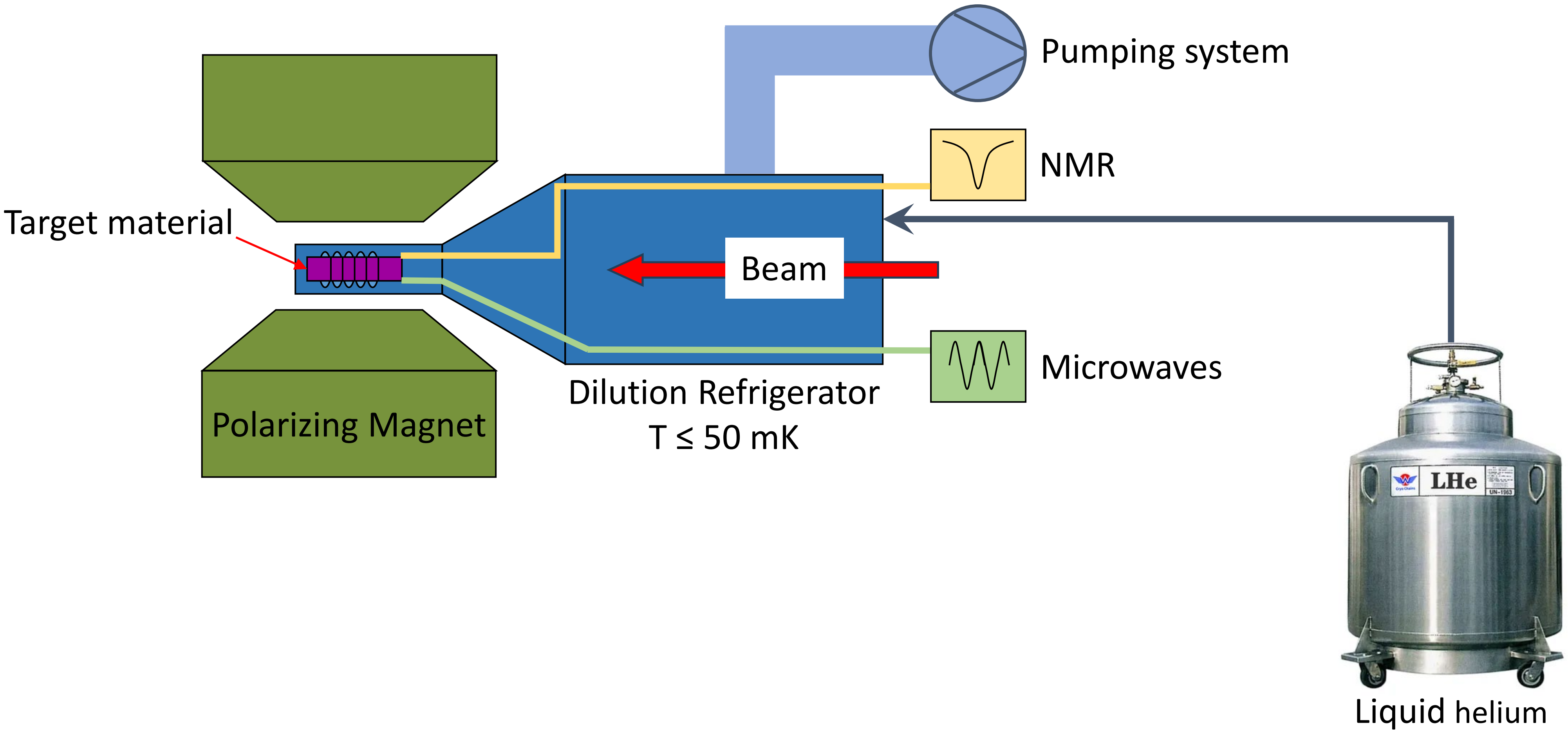


Spin-lattice relaxation times for protons in irradiated ammonia (NH_3) (C.D. Keith)



The lower the sample temperature, the better, as the relaxation time increases, and accordingly the number of interruptions in the process of collecting statistics on the accelerator decreases. To obtain and maintain such ultra-low temperatures, **$^3He/^4He$ dilution refrigerators** are used, which allow achieving cooling temperatures of less than 50mK (down to 2mK)

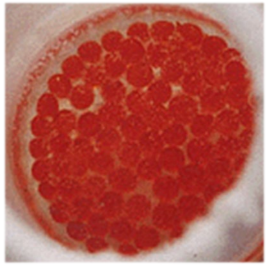
Frozen Spin Polarized Target: instrumentation

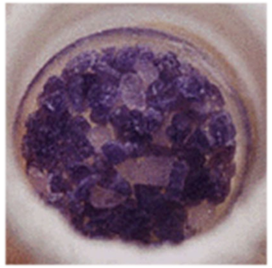


Target material

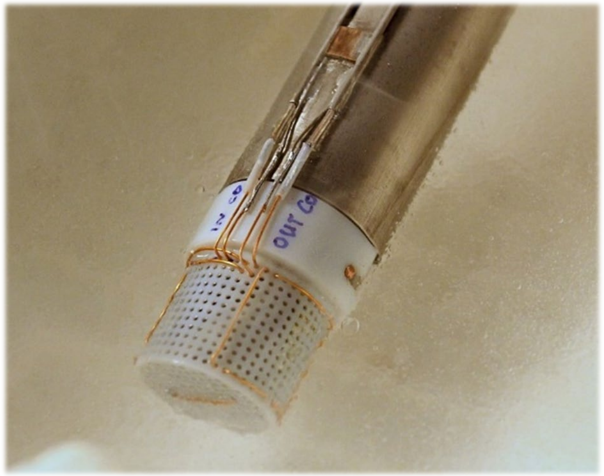
Target material is characterized by four important criteria:

1. Maximum polarization (higher is better)
2. Dilution factor (ratio of free polarizable nucleons to their total number)
3. Radiation resistance
4. Polarizable background nuclei





Material	Butanol, C_4H_9OH	Ammonia, NH_3	Lithium hydride, ^7LiH
Dil. Factor (%)	13.5	17.7	25.0
Polarization (%)	> 90%	> 90%	90%
Pol. background	none	^{14}N, ^{15}N	^7Li
Material	D-Butanol, C_4D_9OD	D-Ammonia, ND_3	Lithium deuteride, ^6LiD
Dil. Factor (%)	23.8	30.0	50.0
Polarization (%)	> 80%	50%	55%
Pol. background	none	^{14}N, ^{15}N	^6Li
Rad. resistance	moderate	high	extremely high
Comments	Easy to produce and handle	Works well at 5T and 1K	Slow polarization, long relaxation



Container with target material and 2 NMR coils in liquid nitrogen

Polarizing magnet

Typical polarizing magnet for Frozen Spin Targets: 2.5 – 5.0 T superconducting, warm-bore solenoid

Liquid cooled superconducting magnet
(Cryomagnetics)

Cryogen-free superconducting magnet
(Cryomagnetics)

$^3He/^4He$ Dilution Refrigerator

Heinz London
(1907 - 1970)

1952: The principle of the method of dissolving ^3He in ^4He was proposed by Heinz London

1962: H. London, G.R. Clarke and E. Mendoza proposed a design for a continuously operating $^3He/^4He$ dilution refrigerator

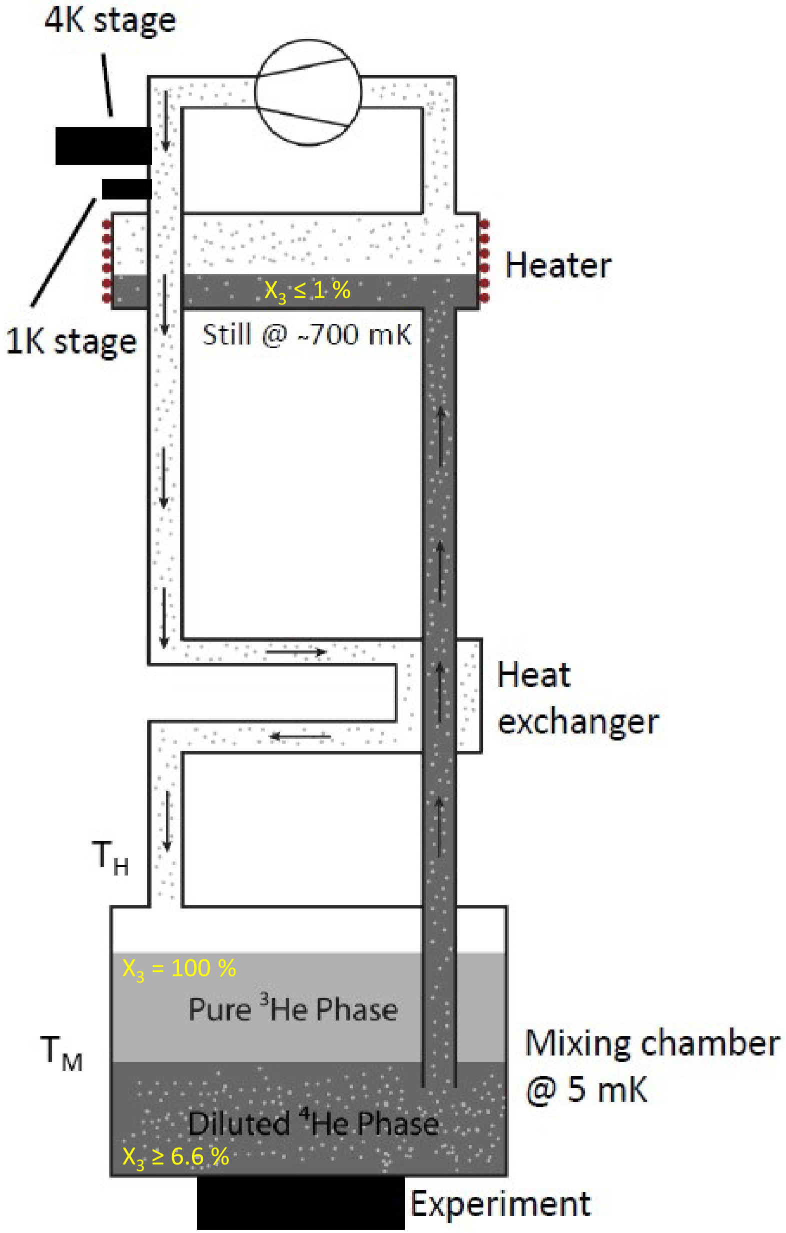
1965: The world's first dilution refrigerator was created at Leiden University. Das P., Ouboter R.B., Taconis K.W. (**$T_{min} \approx$ 220 mK**)

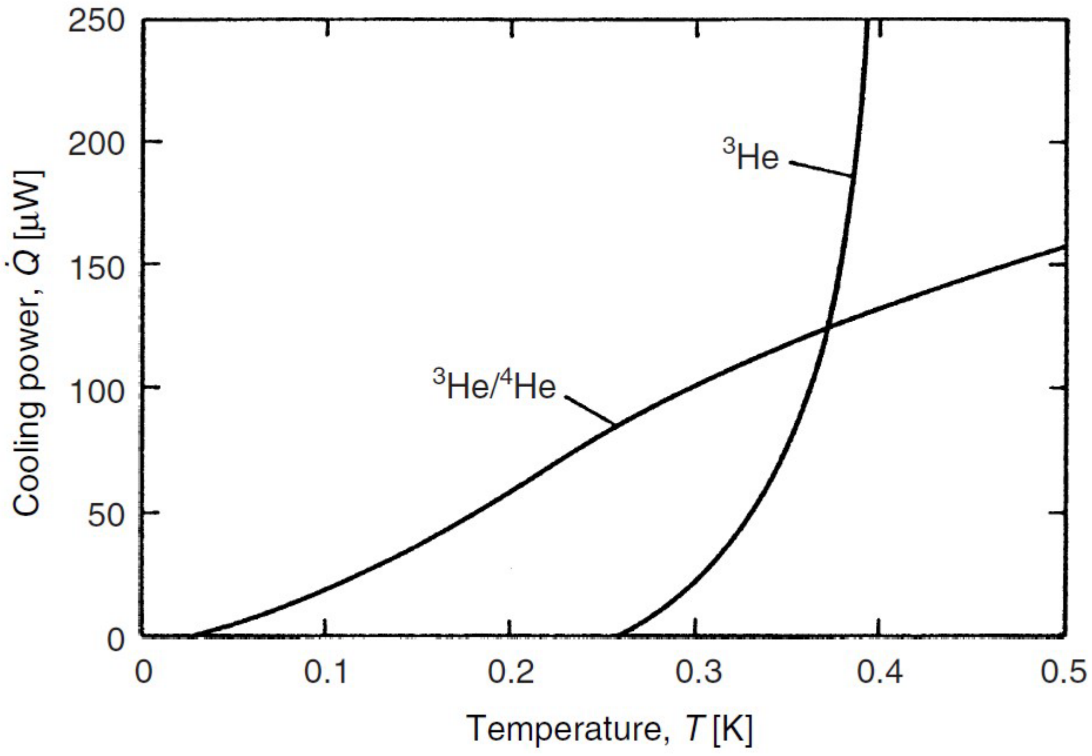
1966: Neganov B.S., Borisov N.S. and Liburg M.Yu. created a dilution refrigerator at JINR that allows obtaining a temperature of **25 mK** in circulation mode, and in 1968 they managed to get **5.5 mK** in single-shot mode, which was a world record for that time

Today: Modern dilution refrigerators allow obtaining temperatures in the range of 5 – 50 mK. The lowest temperature obtained with a dilution refrigerator is **$T_{min} \approx$ 2 mK**

Boris Neganov
(1928 - 2012)

$^3He/^4He$ Dilution Refrigerator





- Pre-cooling of circulating ^3He is carried out in units cooled by ^4He
- **Still**: has a temperature of ≈ 700 mK to maintain a higher vapor pressure of ^3He

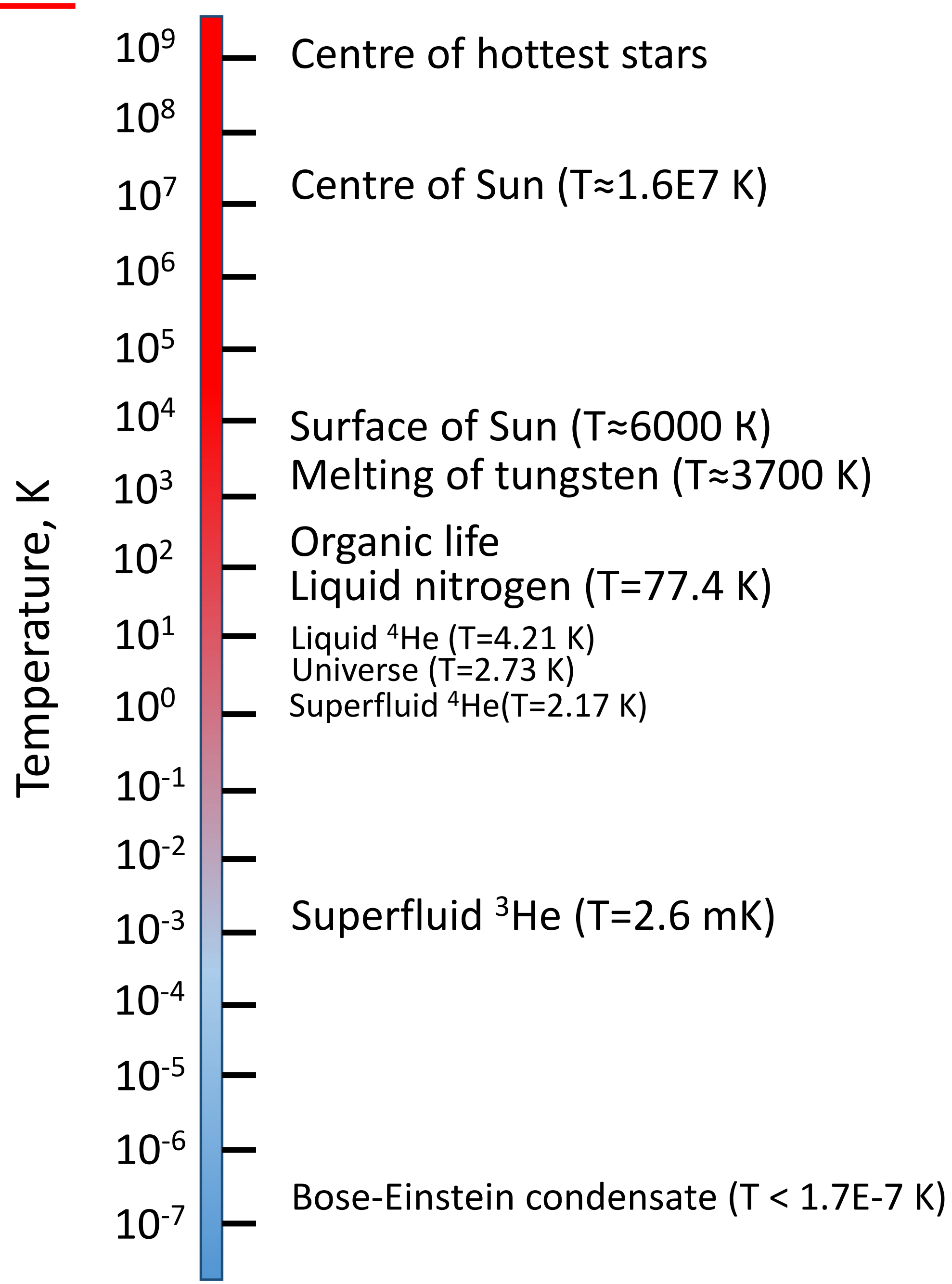
$$p_{3He} >> p_{4He}$$

- **Heat exchanger**: crucial for the final temperature of the cryostat (T_M)

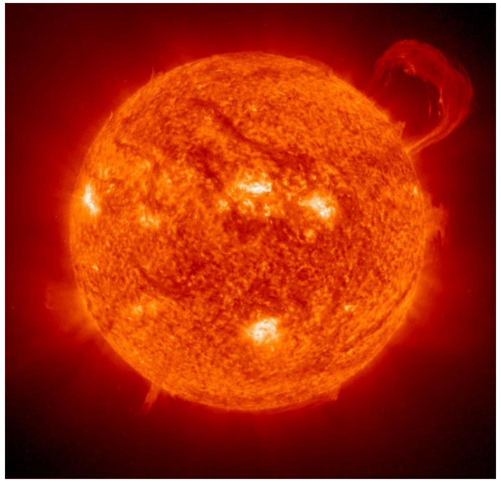
$$\frac{T_H}{T_M} = 2.8 \;@\; \dot{Q} = 0$$

- **Refrigerator cooling capacity** : $\dot{Q} = \dot{n}(95T_M^2 - 11T_H^2)$

Temperature



Surface of Sun ≈ 6000 K



X 20

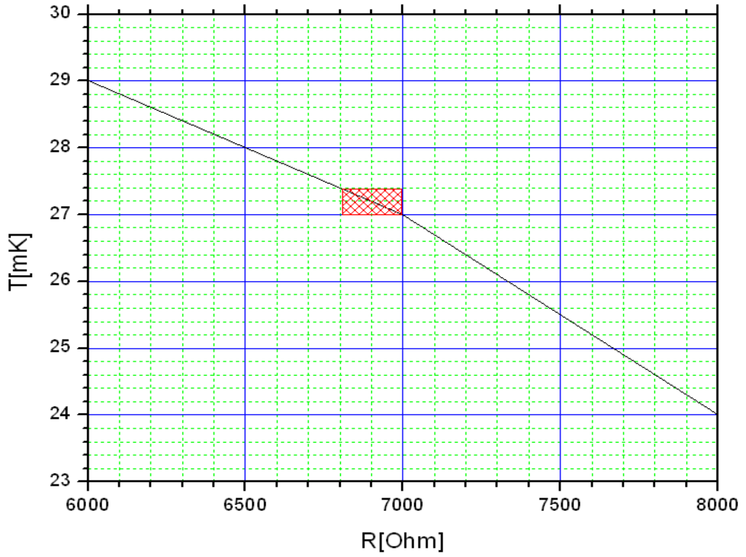
Room temperature ≈ 300 K

X 30000

Dilution refrigerator ≈ 10 mK

Typical temperature in JINR dilution refrigerators

Part of the thermometer calibration curve

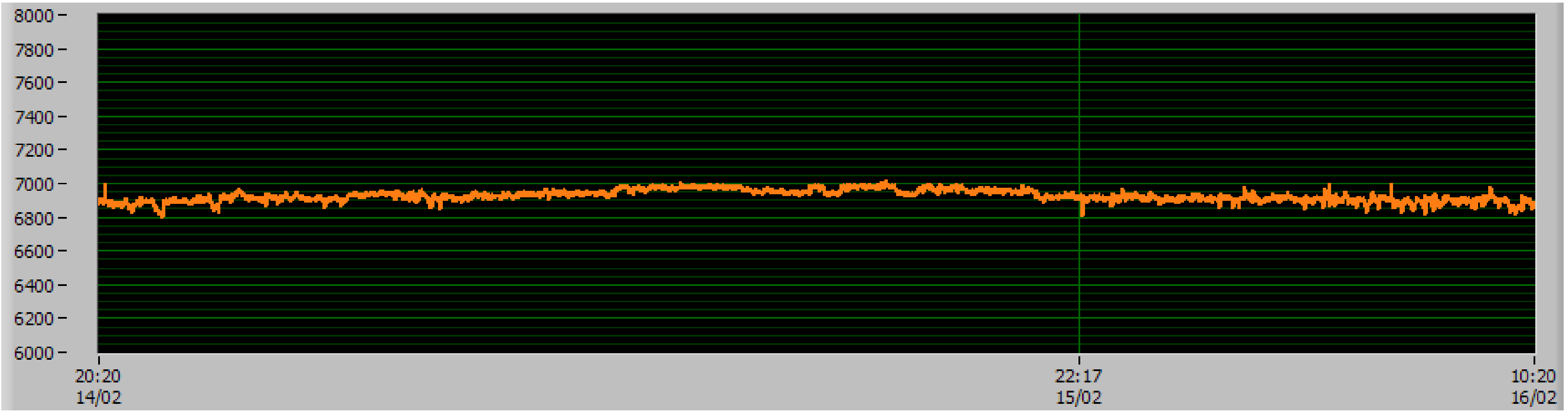


An example of temperature stability in a dilution refrigerator created at JINR for a polarized target in Mainz @ MAMI

T=24mK

T=27mK

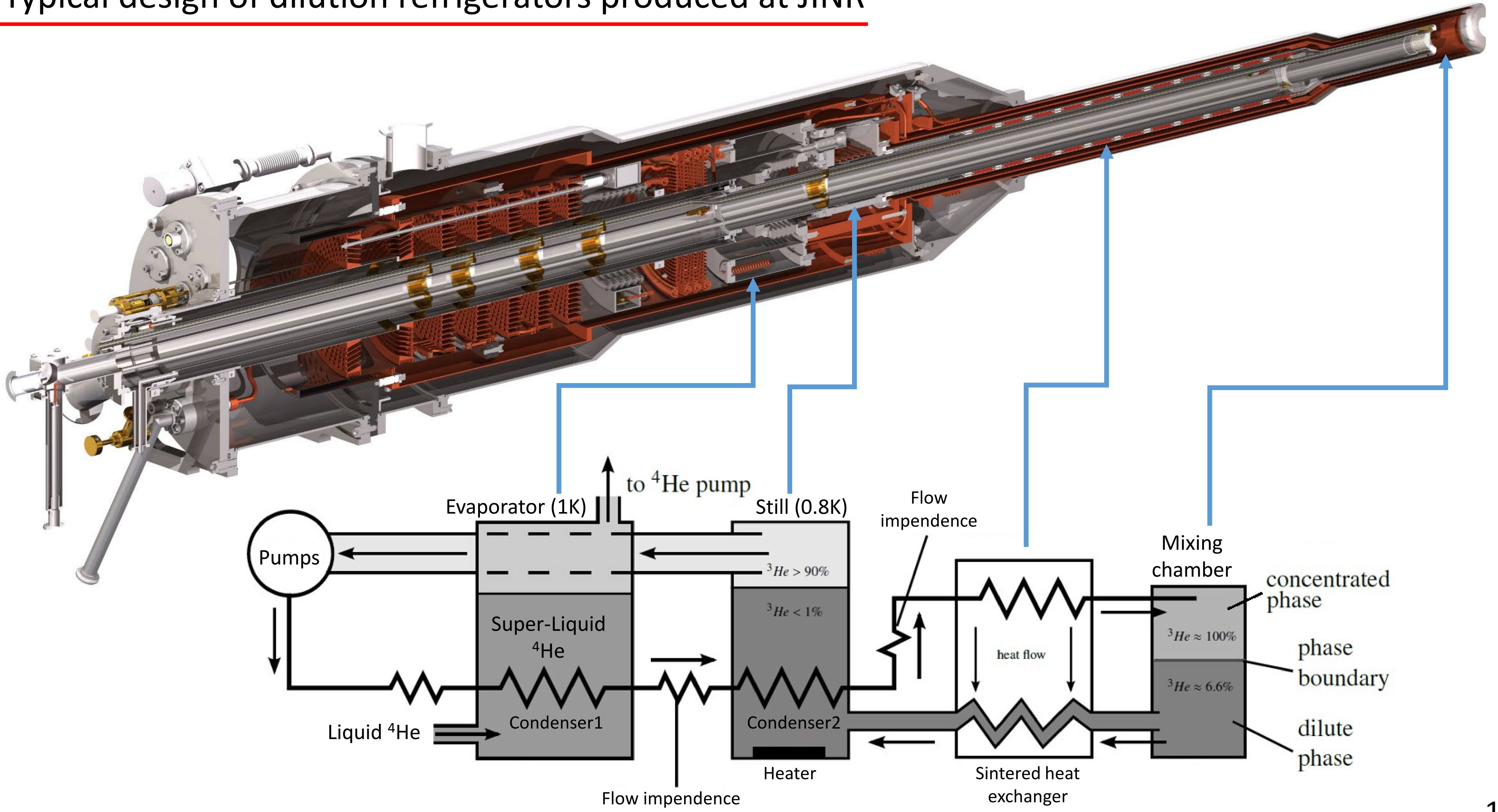
T=29mK



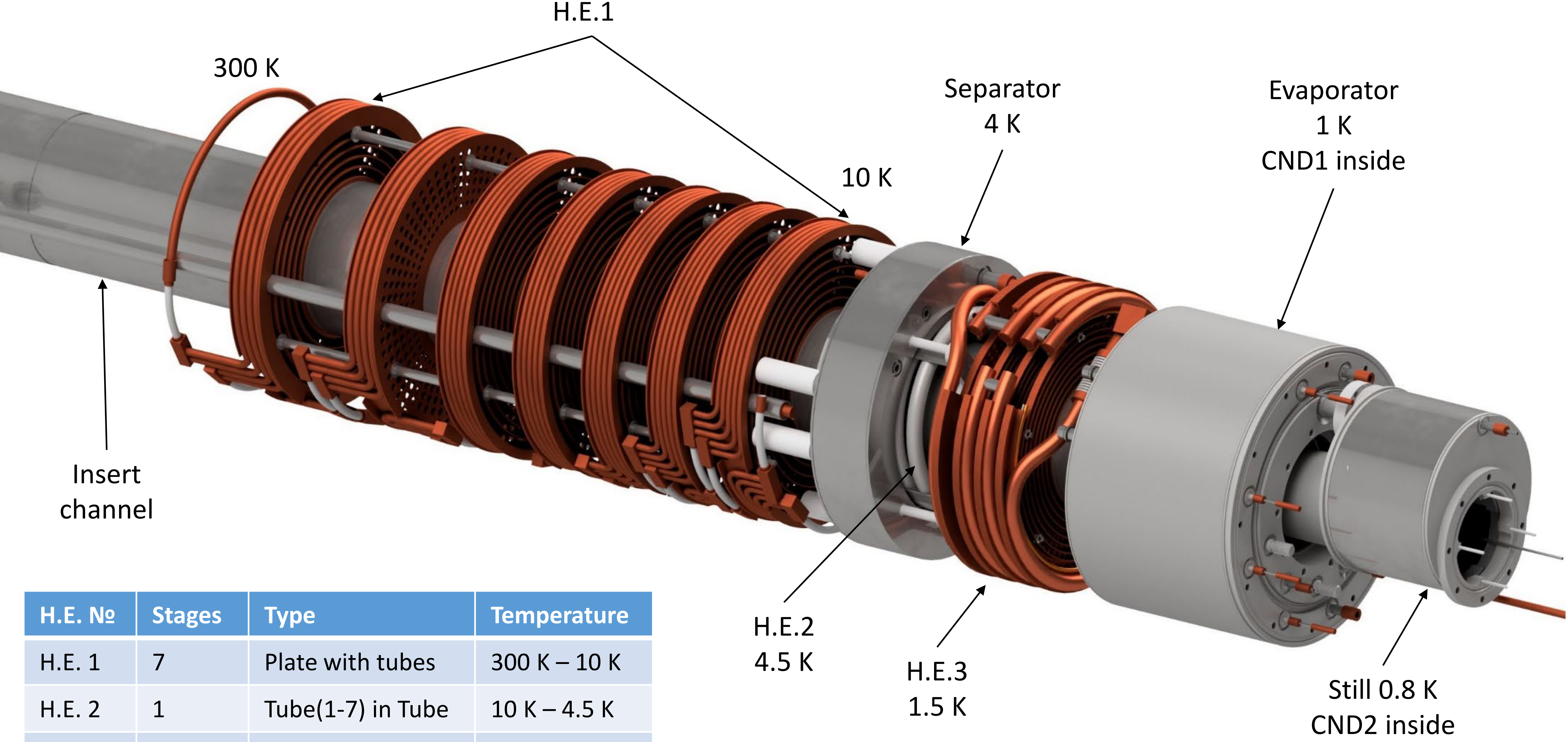
Δt=40h

Temperature stability: ΔT ~ ± 0.25mK (all day)

Typical design of dilution refrigerators produced at JINR



Precooling stage of refrigerators produced at JINR

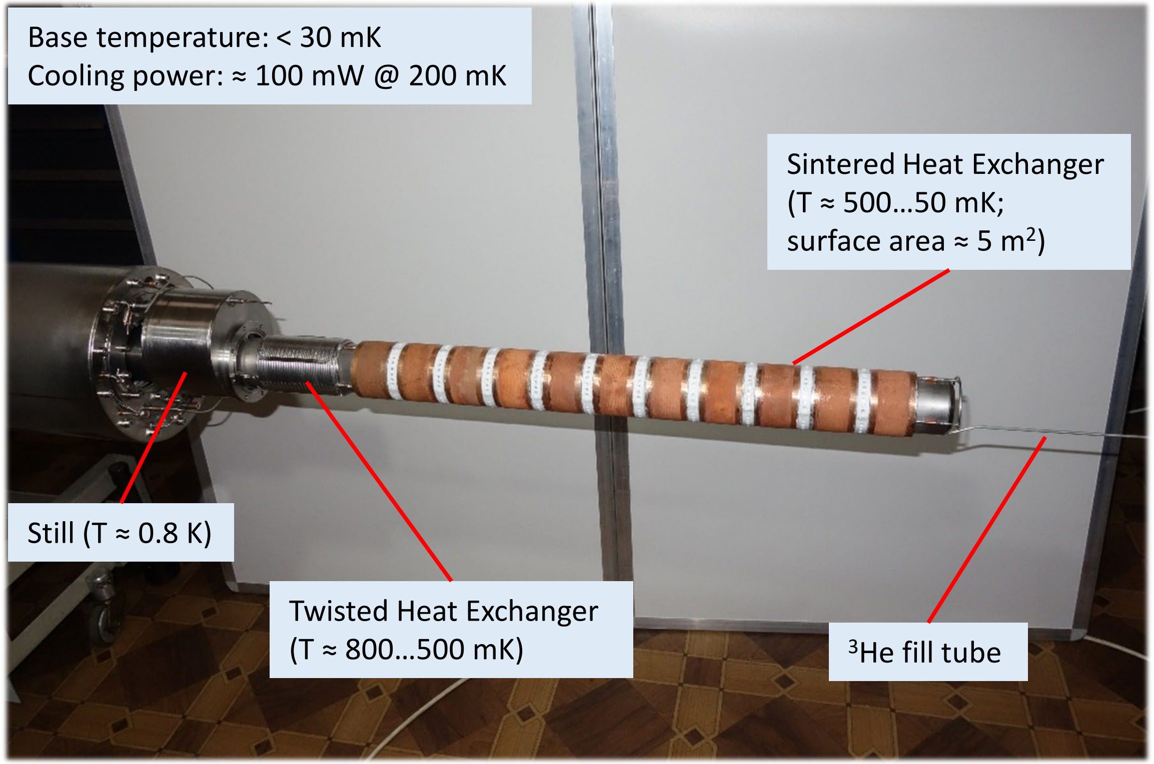


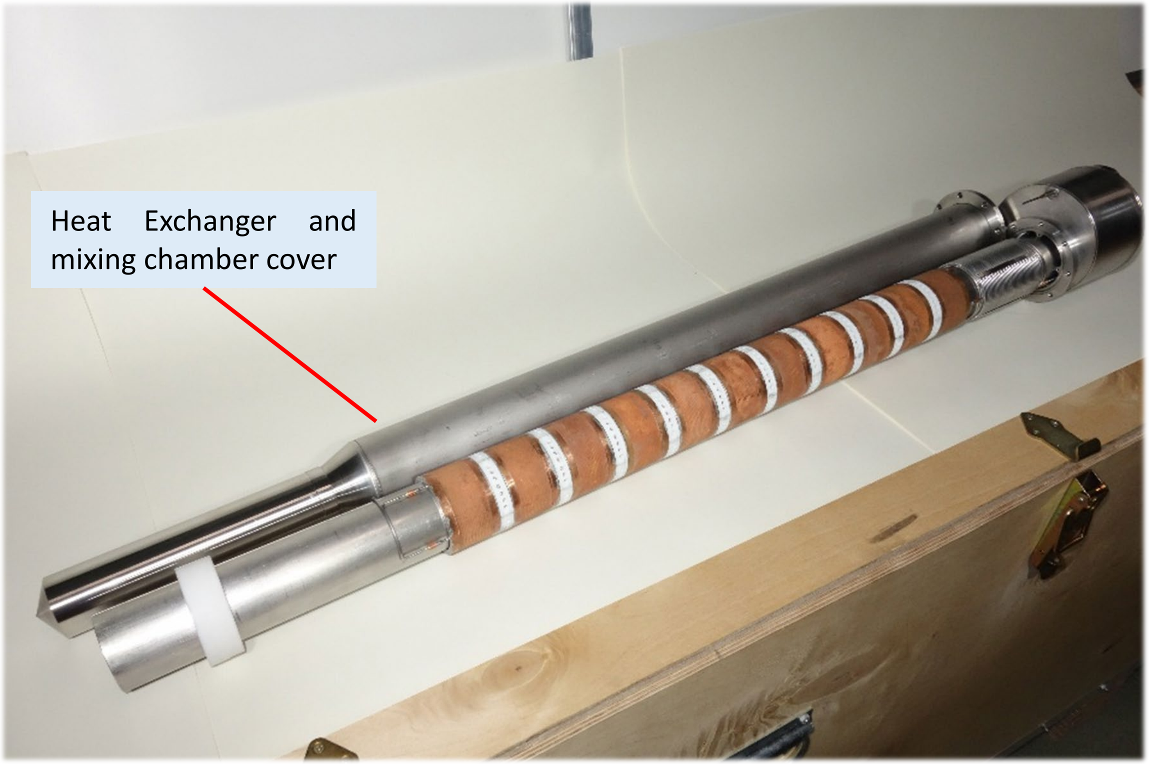
H.E. №	Stages	Type	Temperature
H.E. 1	7	Plate with tubes	300 K – 10 K
H.E. 2	1	Tube(1-7) in Tube	10 K – 4.5 K
H.E. 3	4	Plate with tubes	4.5 K – 1.5 K

Dilution stage of refrigerators produced at JINR

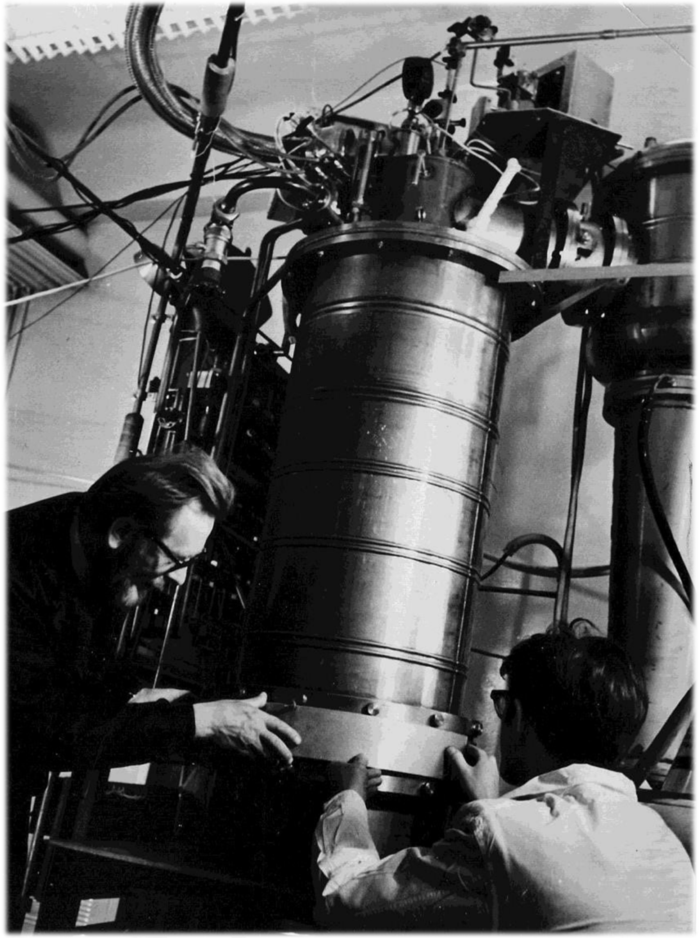
^3He-^4He dilution refrigeration is the only cooling method able to maintain the required temperatures for operation of Frozen Spin Polarized Targets.
Refrigerators, produced at JINR, are always custom-made for frozen spin targets

- Usually, ***horizontal refrigerator*** for access inside detector
- Require ***high cooling power*** for DNP at 200-300 mK
- Requires sample ***inside mixing chamber*** for optimal cooling





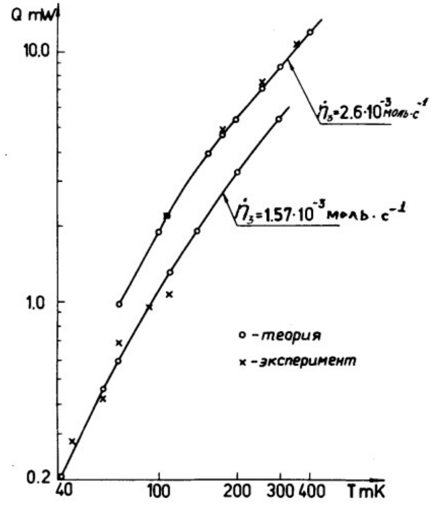
Frozen Spin Targets: history and evolution

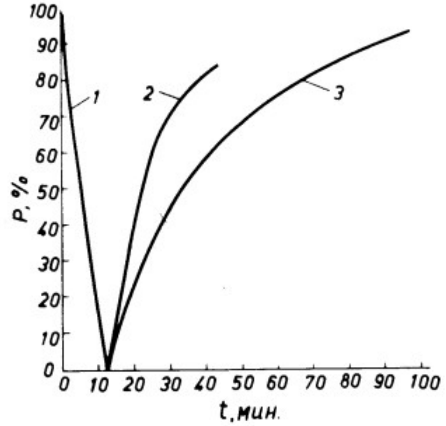


The first Frozen Spin Polarized Target at JINR (**1975**) during tests preparation. (**N.S. Borisov**, et al., JINR Preprints 1976 [13-10253](), [10-10257](). [Prib. Techn. Exp. 1978, Vol. 2, p. 32]())

Dilution stage and sample container of the first Frozen Spin Target at JINR

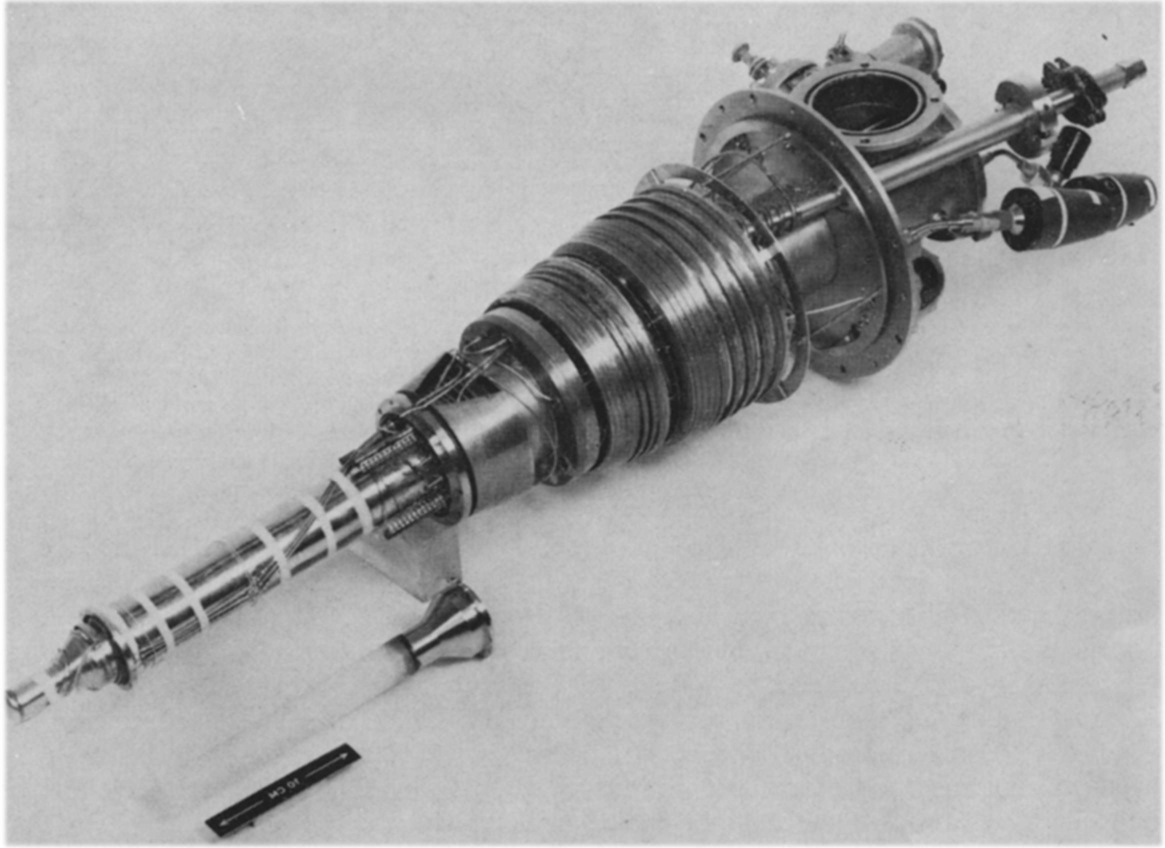
Refrigerator cooling capacity





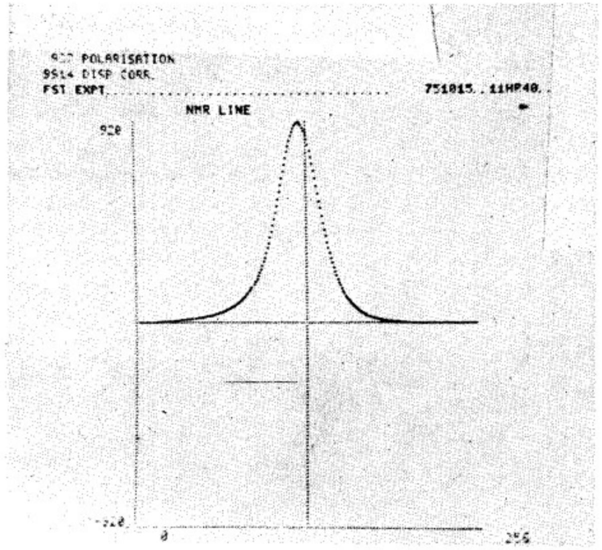
Dependence of target polarization on pumping time (2 and 3) and polarization destruction (1)

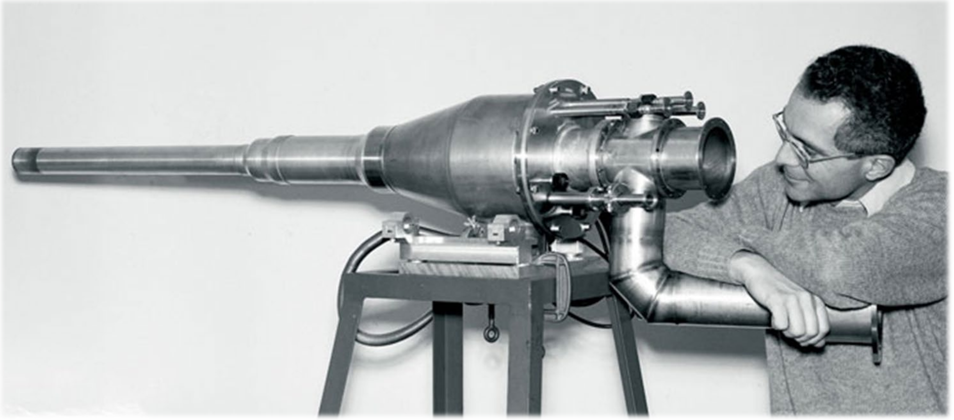
Frozen Spin Targets: history and evolution



The first Frozen Spin Target at CERN
T.O. Niinikoski *and* ***F. Udo****,*
NIM 134 (1976) 219

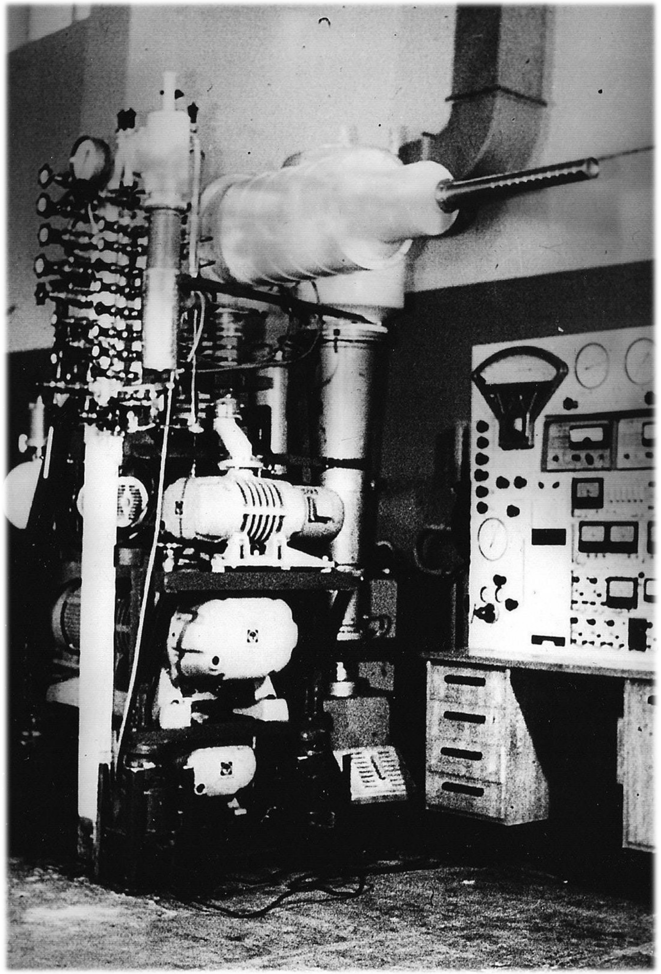
NMR signal at 106 MHz, 93.7% polarization



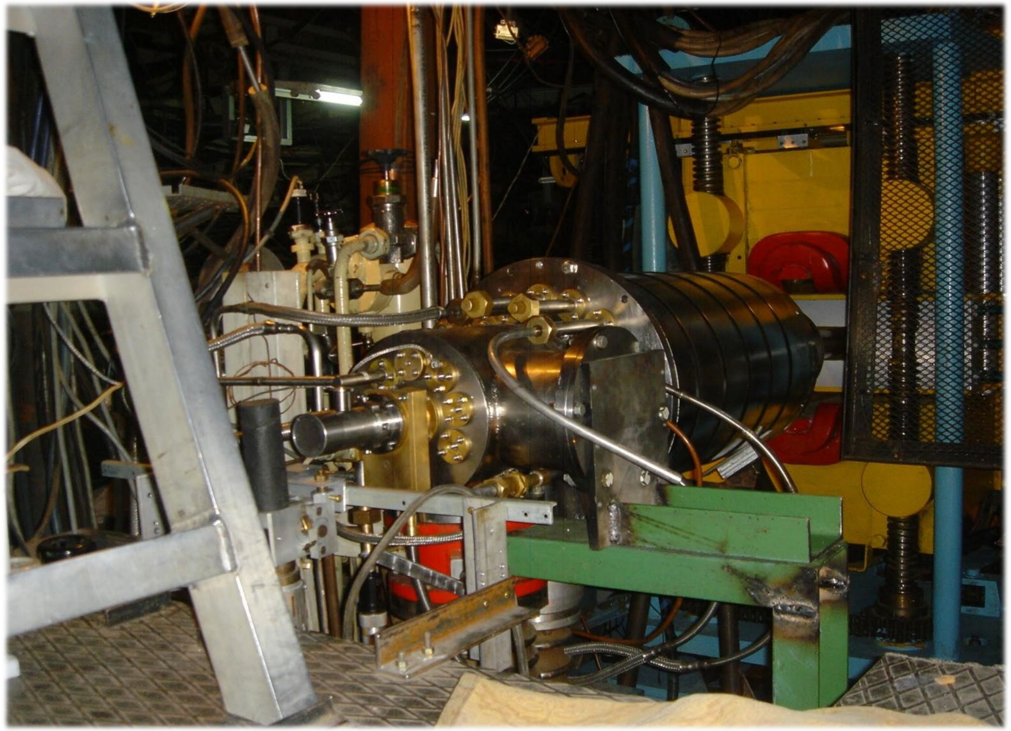


Michel Borghini (1934 - 2012)

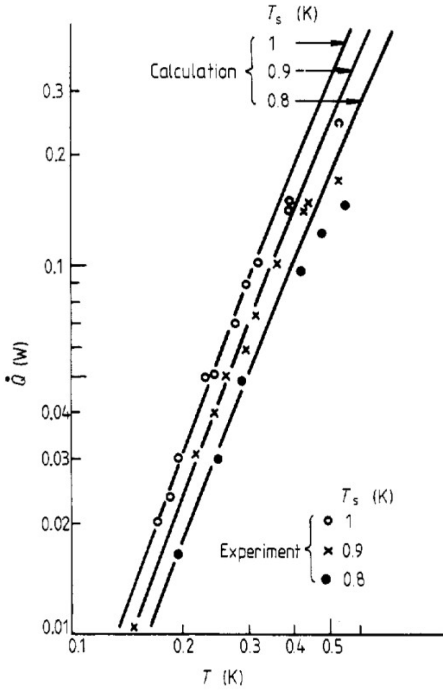
Frozen Spin Targets: history and evolution



Second, made in JINR, FPT before transportation to IHEP (Protvino)



Target with length 20 cm and 60 cm³ in volume, at beam area. Which has been used for experiments with 70 GeV protons at the accelerator (Protvino) since **1978**. In 1988 this Target was upgraded to deuteron mode.
(N.S. Borisov et al., J. Phys. E: Sci. Instrum., 1988, Vol. 21, p. 1179-1182)



The cooling power of the dilution refrigerator.

Table 1. Target dimensions: diameter 19.6 mm, $l = 200$ mm, $V = 60$ cm^3. Dynamic polarisation mode: $T = 0.3$ K, microwave power = 90 mW, $\nu = 56$ GHz, $\dot{n}_3 = 3 \times 10^{-2}$ mol s^{-1}, polarising time to obtain 0.8 P_{max} = 35 min. Frozen spin mode: $T = 0.02$ K, $\dot{n}_3 = 2 \times 10^{-3}$ mol s^{-1}.

Material	Ethanediol	Propanediol
Weight percentage of deuterium	17.6	19.0
Maximum polarisation	±(37±3)%	+(37±2.5)% −(40±2.5)%
Relaxation time	$\tau_+ \simeq 500$ h $\tau_- \simeq 300$ h	$\tau_+ \simeq 1500$ h $\tau_- \simeq 750$ h
Holding magnetic field	0.45 T	0.53 T

Frozen Spin Targets: history and evolution

CERN: EMC, SMC, COMPASS

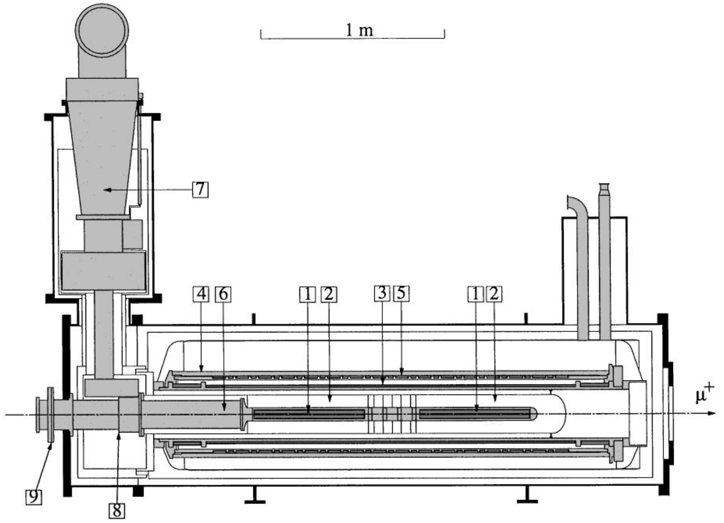


Fig. 1. The SMC target cryostat with the target holder as used in 1993. The muon beam traverses the cryostat from left to right. (1) Target cells, (2) microwave cavity, (3) solenoid coil, (4) dipole coil, (5) correction coils, (6) dilution refrigerator, (7) precooler of ^{3}He, (8) indium seal, and (9) external seal.

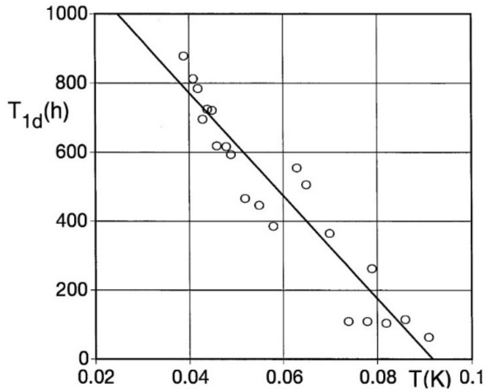


Fig. 20. Nuclear spin relaxation times T_1^d in deuterated butanol as a function of temperature T and a magnetic field of 0.5 T.

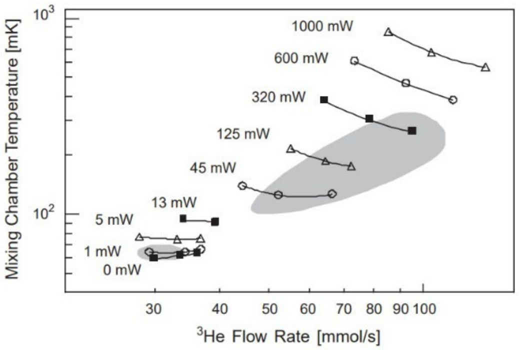


Fig. 4. The mixing chamber temperature as a function of the ^{3}He flow. The values in the figure represent the cooling powers. The wider shadow area represents the condition for the DNP mode and the narrower area is for the frozen spin mode.

SMC/COMPASS

World's largest polarized target

T.O. Niinikoski NIM 192 (1982) 151

D. Adams et al. NIM A 437 (1999) 23

N. Doshita et al. NIM A 526 (2004) 138

Frozen Spin Targets: history and evolution

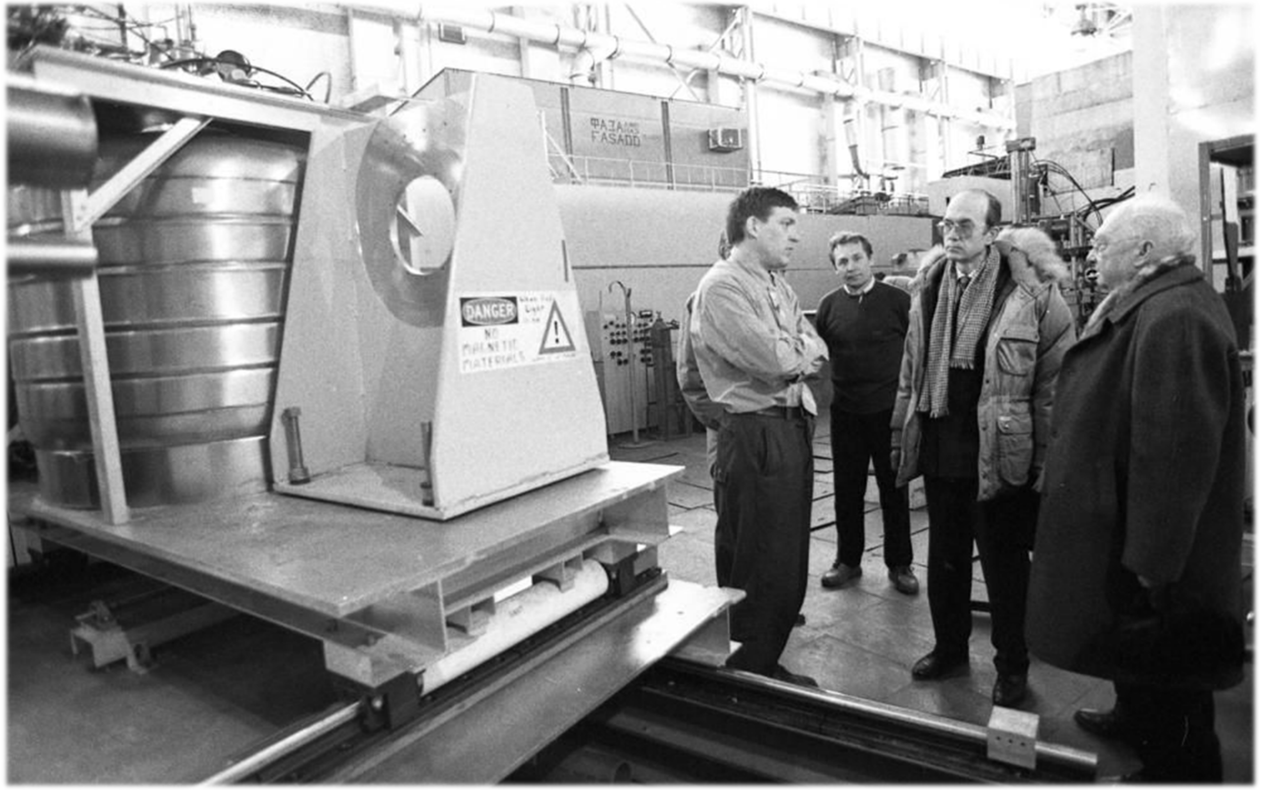
Target, made at JINR, with a frozen nuclear polarization for experiments at low energies at the accelerator at the Nuclear Centre of Charles University (Prague), (NIM A 345, **1994**, 421-428)

Main parameters of the target

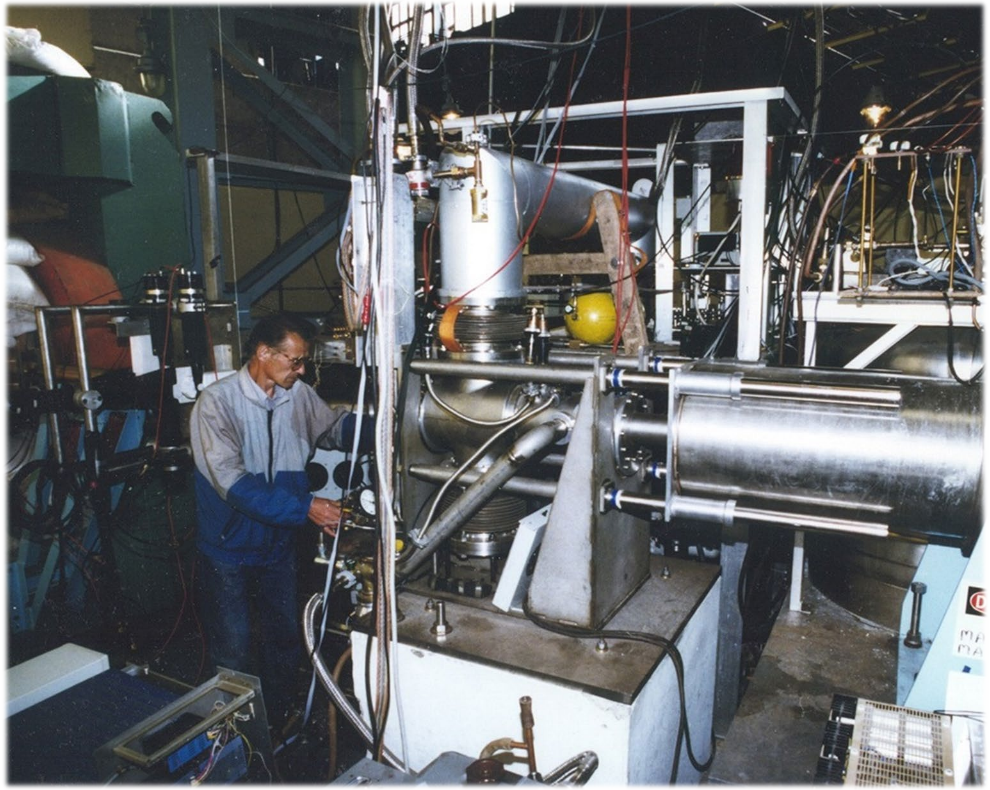
Target dimensions	
Volume	20 cm^3
Length	6 cm
Diameter	2 cm (cylindrical shape)
Target material	$C_3H_8O_2$ – 1.2-propanediol
Target mass	15 g
Cr(V) paramagnetic center concentration	1.5×10^{20} cm^{-3}
Maximum polarization P_{max}	+93%; −98%
Relaxation time (at 0.37 T and 20 mK)	positive: 1000 h, negative: 300 h
Time necessary for $P = 0.8 P_{max}$ buildup	under 1 h
Total time for preparation the target from the beginning of cooling to an experimental run	24 h
Total consumption of liquid helium in the frozen mode	1.2 l/h

Frozen Spin Targets: history and evolution

A movable polarized target has a volume 140 cm^3 (20 cm long and 3 cm diameter). The nuclear spin relaxation time in a frozen mode (at a temperature 50 mK and magnetic field 2.5 T) is over 1000 h. Maximum values of proton polarization obtained were 80% and 85% for positive and negative polarization, respectively.



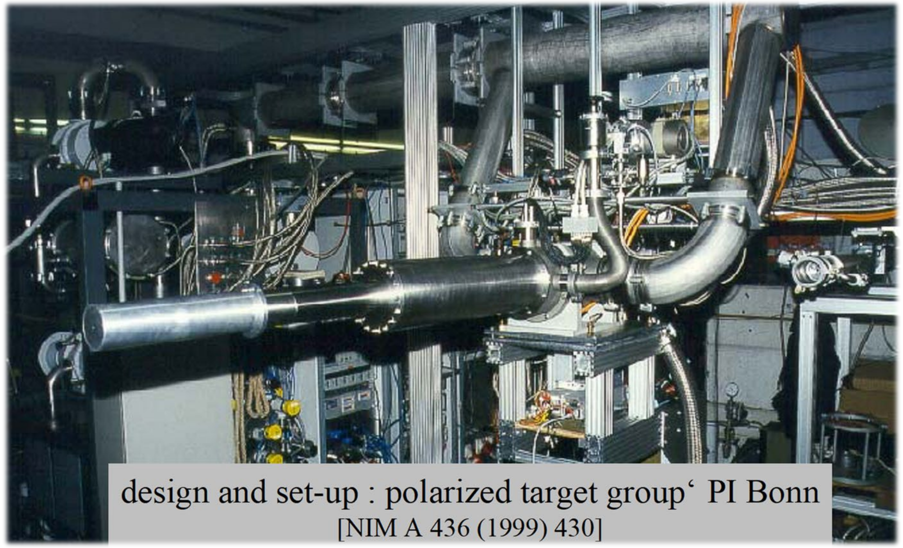
From left to right: G. Durand, CEA, Saclay; Yu.A. Usov JINR, Dubna; Deputy Prime Minister of Russia Saltykov B.G.; Director of H.E. Lab., JINR, Academician A.M. Baldin.
This project was supported by INTAS grants in **1993** and **1995**



Borisov in the process of working with a movable polarized target at accelerator complex of the JINR

Frozen Spin Targets: history and evolution

Bonn introduced the **internal holding coil** (C. Bradtke et al., Nucl. Instrum. Methods A 436, 430, 1999).
The design of the dilution refrigerator and the use of an internal holding coil enabled for the first time the measurement of a spin-dependent total cross section in combination with a polarized solid state target



design and set-up : polarized target group‘ PI Bonn
[NIM A 436 (1999) 430]

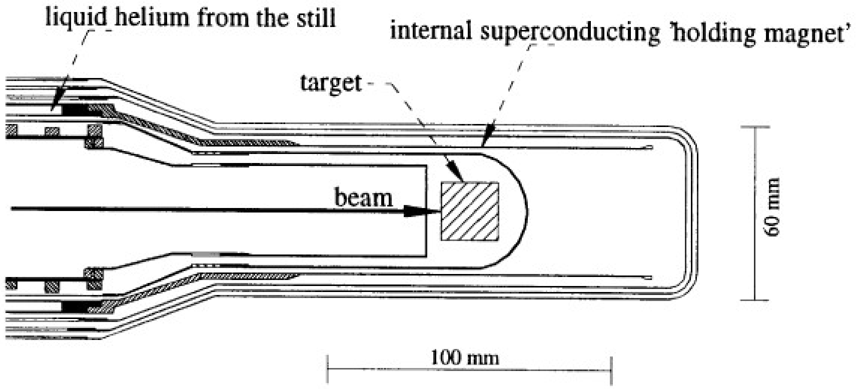


Fig. 6. View of the front part of the refrigerator containing the internal holding coil.

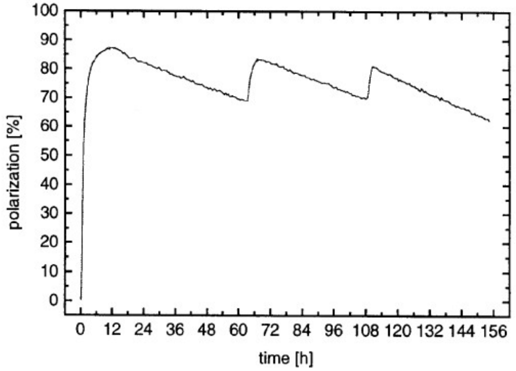
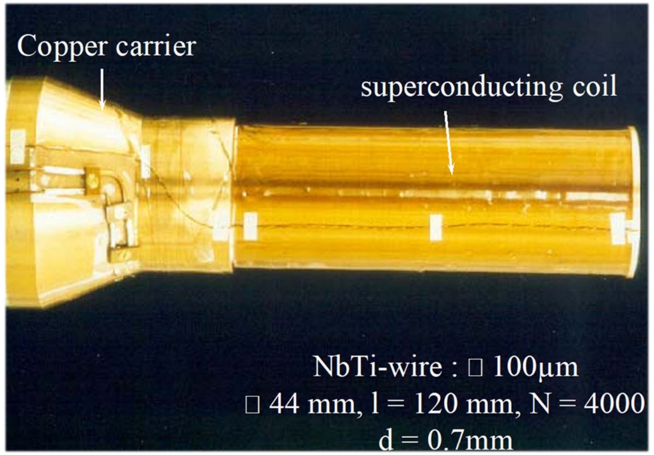
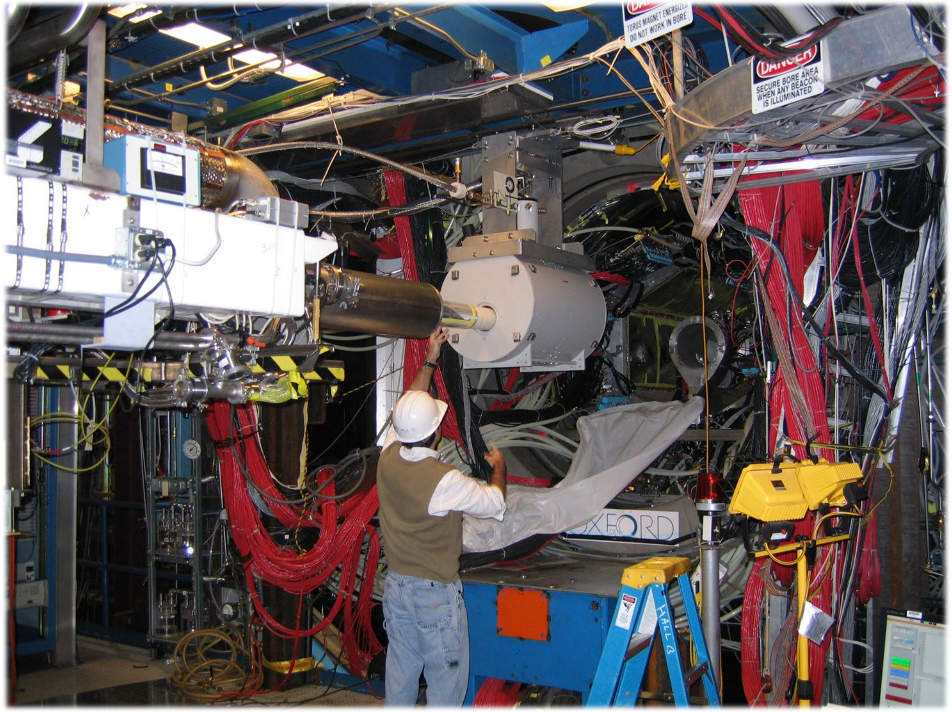


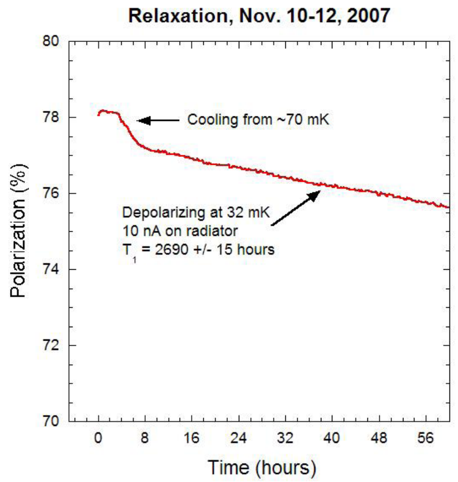
Fig. 12. Proton polarization during three typical frozen-spin cycles.

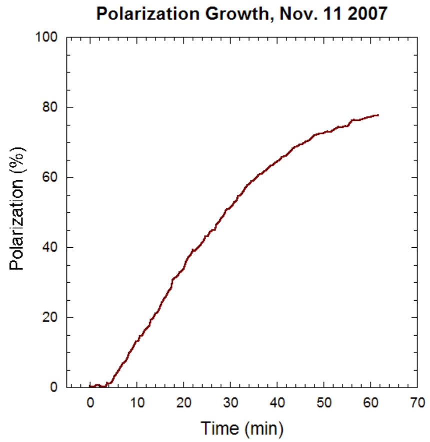


Frozen Spin Targets: history and evolution

Jefferson Lab introduced **both longitudinal and transverse internal coils** (C.D. Keith et al, NIM A 684, 27, 2012).
Photoproduction data were acquired with the target inside the spectrometer at a frozen-spin temperature of approximately 30 mK with the polarization maintained by a thin, superconducting coil installed inside the target cryostat. A 0.56 T solenoid was used for longitudinal target polarization and a 0.50 T dipole for transverse polarization.



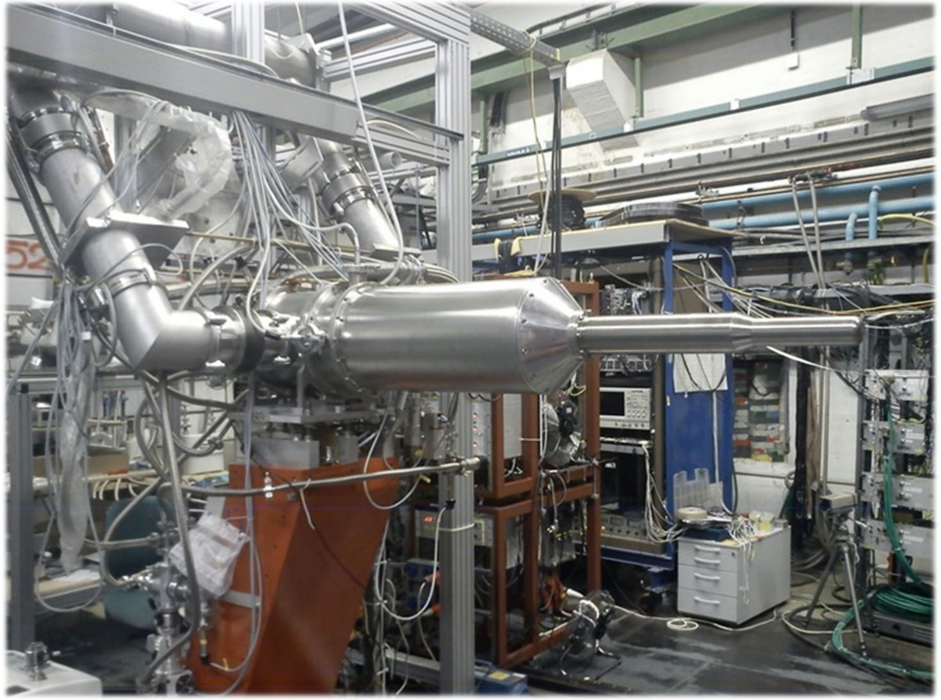


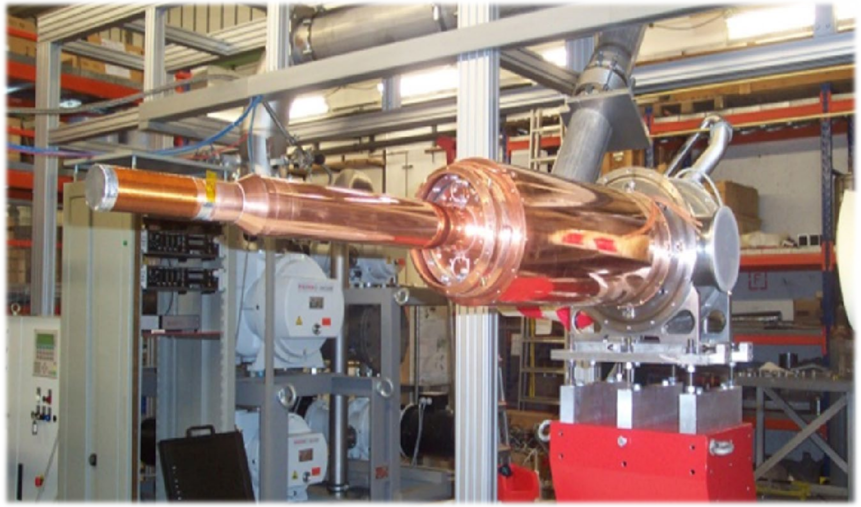


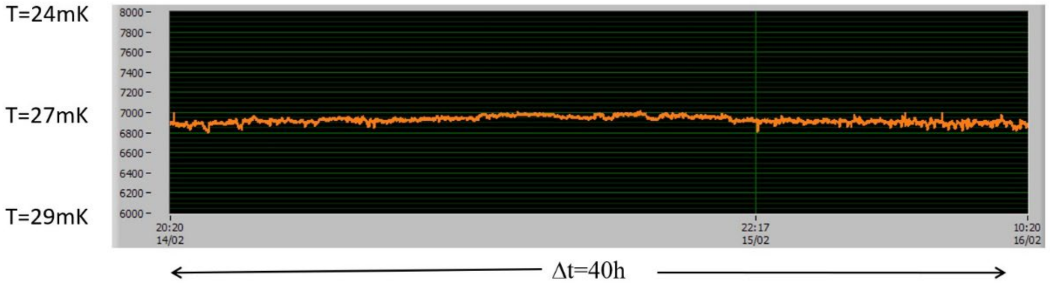
Superconducting holding coils used to maintain target polarization in frozen spin mode

Frozen Spin Targets: history and evolution

Mainz/Dubna Frozen Spin Target at MAMI: **75% deuteron polarization** was achieved (A. Thomas et al, Physics of Particles and Nuclei, 2013, Vol. 44, No. 6, pp. 964–967)







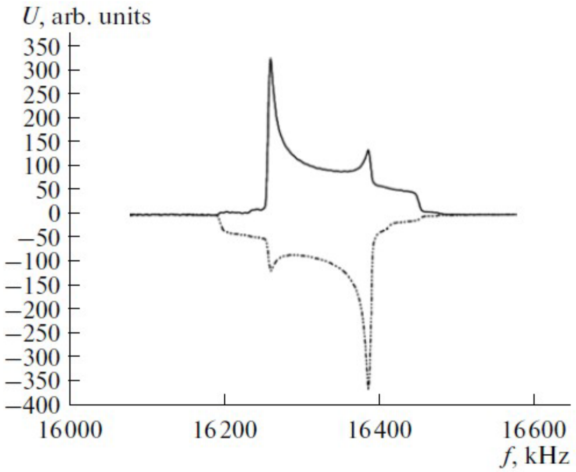
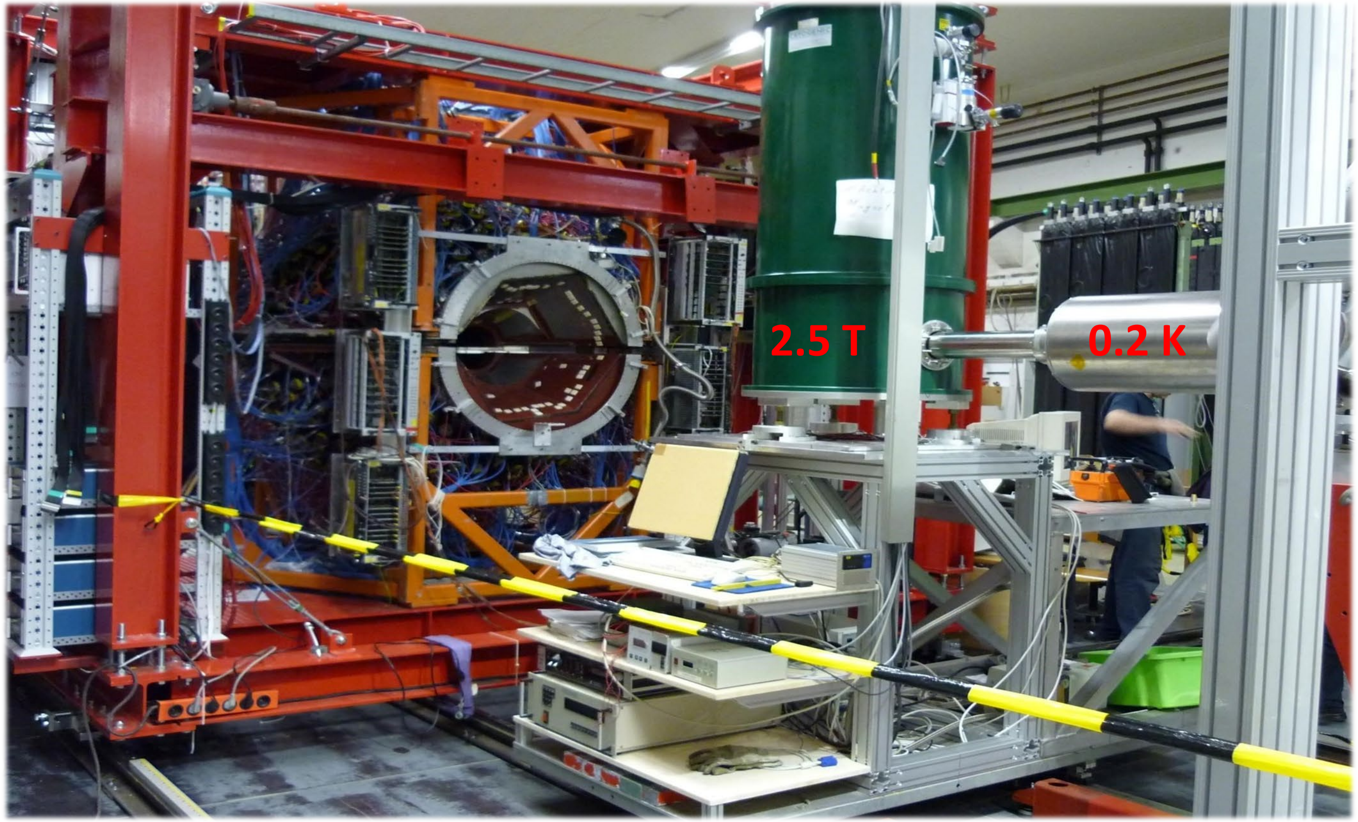


Fig. 9. NMR signals of highly polarized deuterium, positive polarization shown was +75.9%, negative −75.2%.



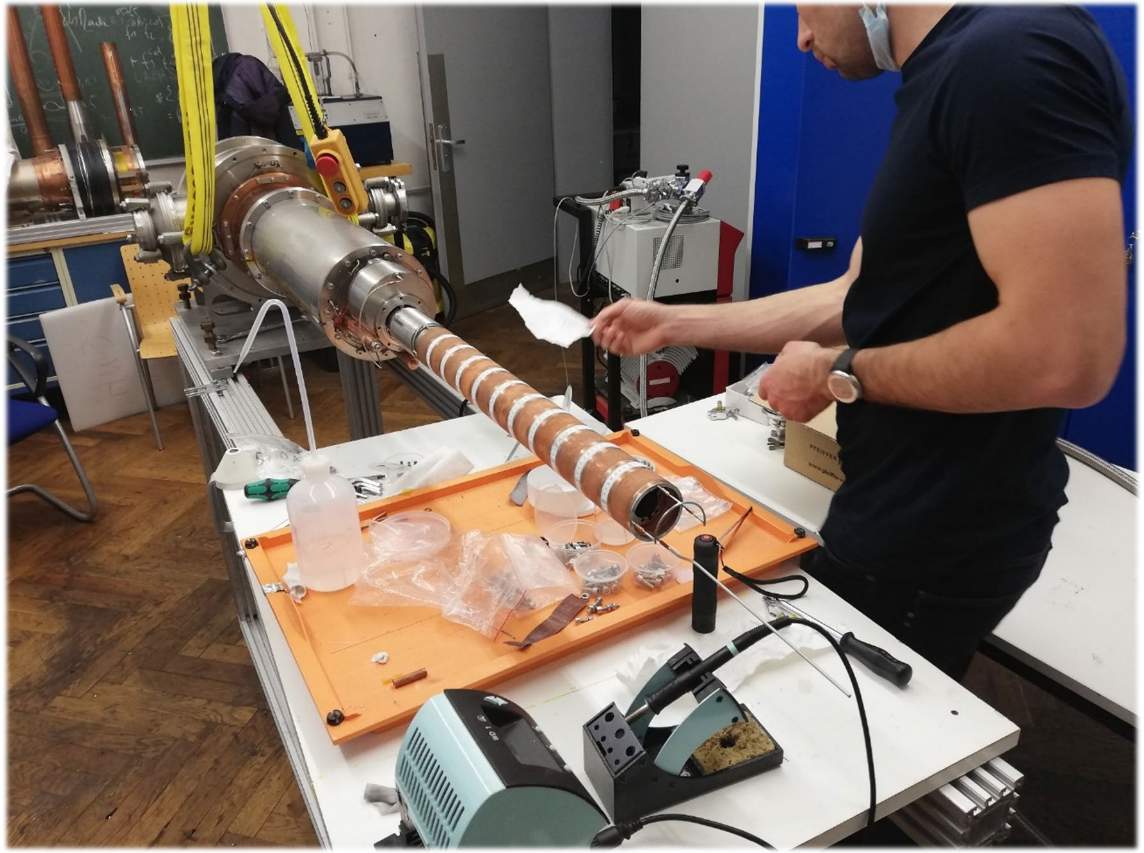
The process of pumping polarization in the Mainz/Dubna Frozen Spin Target at MAMI

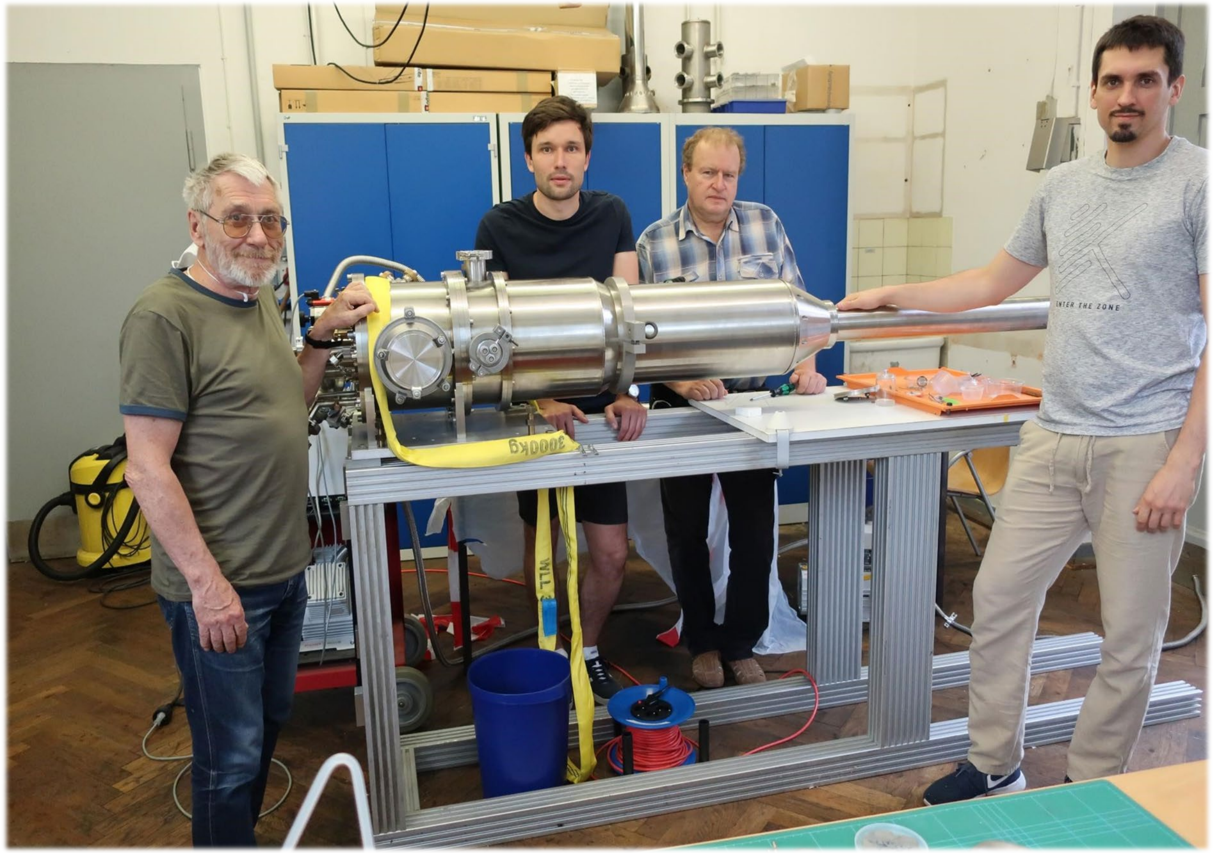
Borisov N.S. in the process of working with the Mainz/Dubna Frozen Spin Target at MAMI

Dilution refrigerator made at JINR for the Bonn Frozen Spin Target at the ELSA accelerator

Parts of the dilution refrigerator during its manufacture at JINR (**2018**)

Dilution refrigerator made at JINR for the Bonn Frozen Spin Target at the ELSA accelerator

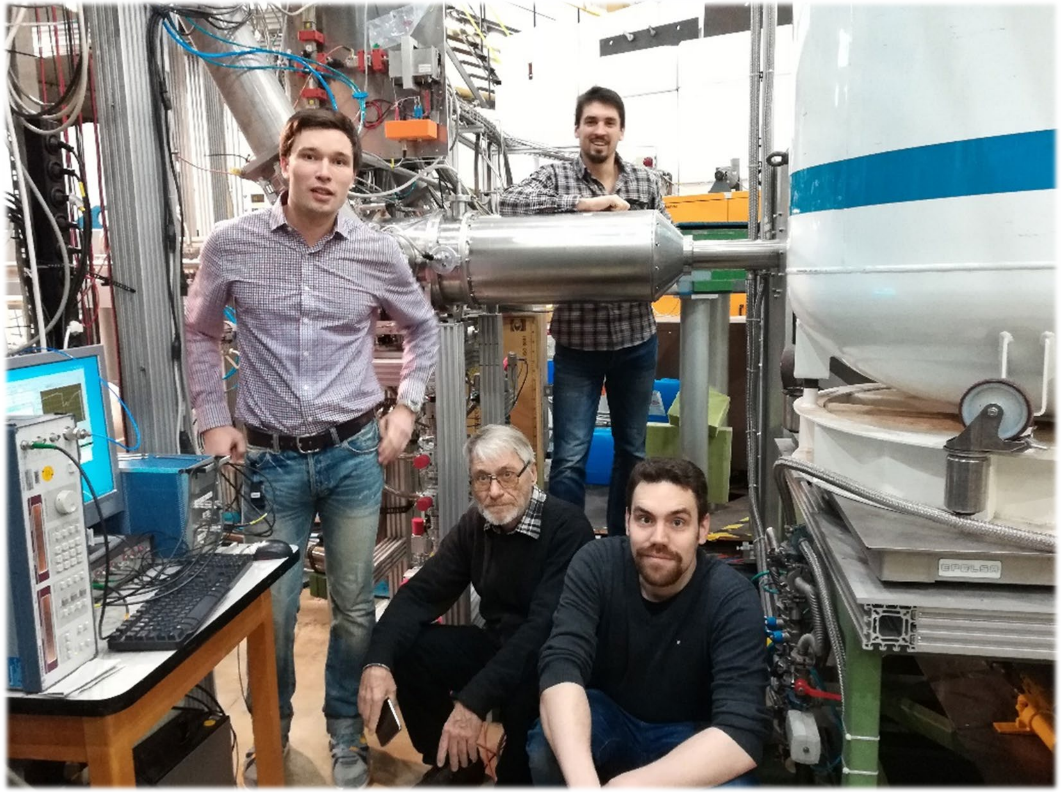




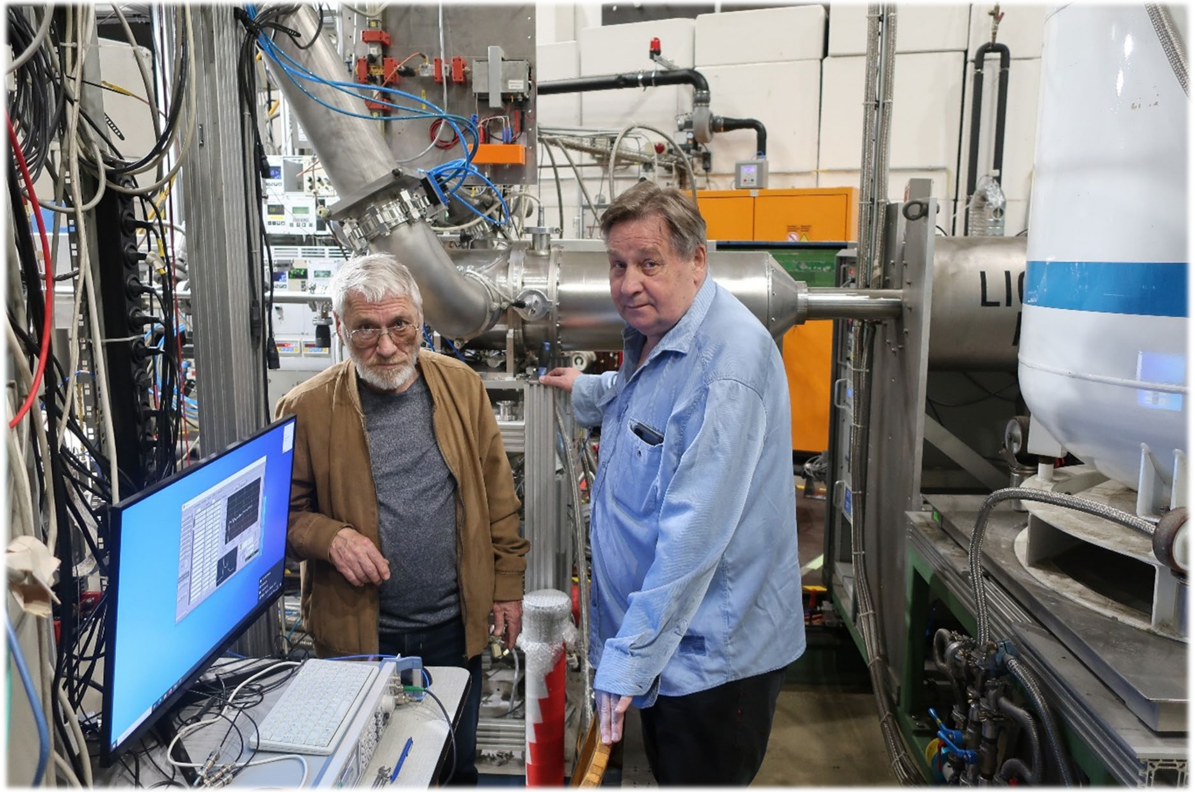
Dilution refrigerator in the process of its assembly at the University of Bonn (**2021**)
(from left to right): A. Neganov, A. Dolzhikov, A. Fedorov, I. Gorodnov

Frozen Spin Target at accelerator ELSA in Bonn

The Dubna-Mainz Frozen Spin Target was used with deuterated butanol (C_4D_9OD, named dButanol) as target material. The target was repolarized every few days using a 2.5 T magnet, whereas a 0.6 T internal holding magnet was used during the data taking. A maximum target polarization degree of 75 % was measured with relaxation times of around 1100 h.
(N. Jermann et al (CBELSA/TAPS Collaboration), Eur. Phys. J. A (2023) 59: 232)



In the process of working with a target/dilution refrigerator (from left to right):
A. Dolzhikov, A. Neganov, I. Gorodnov, S. Runkel



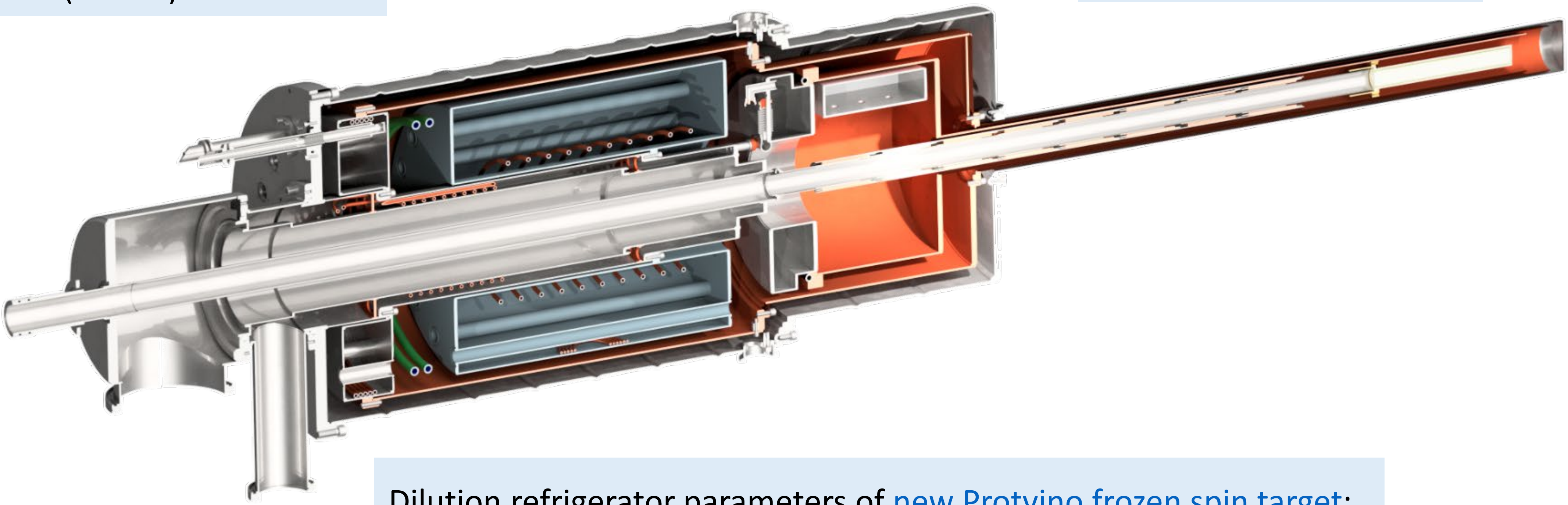
In the process of working with a target/dilution refrigerator:
A. Neganov and Yu. Usov

New Protvino frozen spin target (2024-now)

Precooling with LN_2
With constant or periodical supply
($V \approx 7$ L)

Periodical L^4He supply
as main cold source ($V \approx 40$ L)

Small Ø < 72 mm nose



Dilution refrigerator parameters of new Protvino frozen spin target:

- Target temperature < 30 mK, in long-term mode
- Cooling power at 300 mK > 100 mW with ^3He flow ~ 10 mmol/s
- Low L^4He consumption < 2 L/hr
- Target size: L = 200 mm, Ø = 20 mm

JINR Low Temperature Department Activity Map

Physikalisches Institut Universität Bonn

Bonn, Germany

Contract 200/1548

2460 km

Institut für Kernphisik Johannes Gutenberg University

Mainz, Germany

A2 collaboration on MAMI 2007-2018

P2 experiment at MESA (a new linear Mainz Energy-Recovery Superconducting Accelerator)

Hydro-Möller Polarimeter

https://www.mesa.uni-mainz.de

2435 km

PINP

Gatchina, Russia

JINR Preprints 13-10253, 10-10257, Dubna 1976

Prib Techn. Exp. 2 (1978) 32

645 km

JINR DUBNA

NIM A 372 (1996) 349

260 km

Protvino, Russia

JINR Preprint 1-80-93, Dubna 1980

2000 km

Czech Technical University

Prague, Czech Republic

NIM A 345, (1994) 421-428

Thank you for your attention!