# Target System

## for Hyperon-Nucleon Spectrometer

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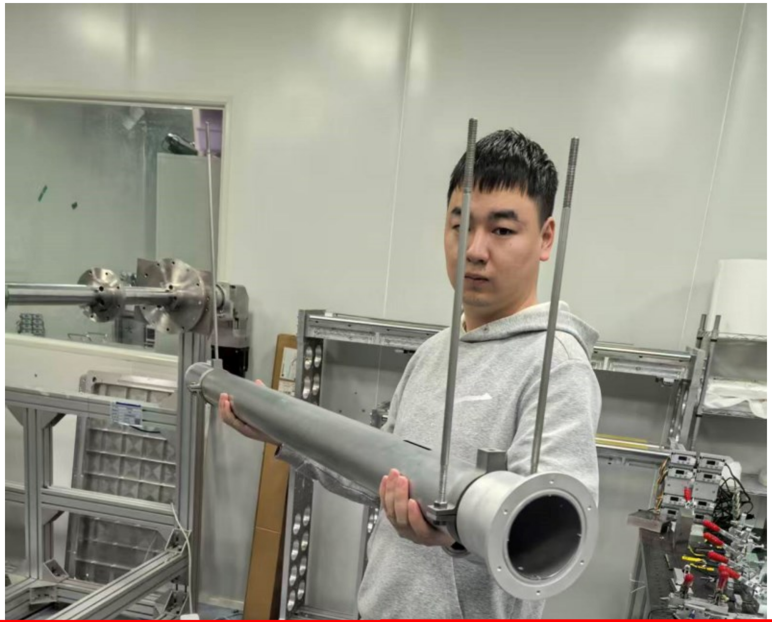
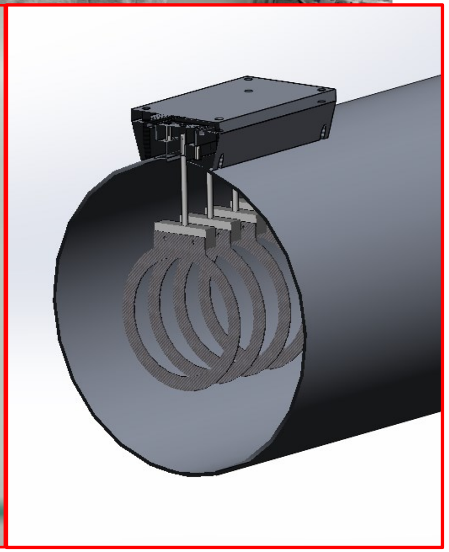
近代物理研究所

# Content

- Nuclear target
- Liquid hydrogen target
- Polarized targets
  - $^3$**He** target
  - DNP target
  - HD target

# Nuclear solid target





**Well established technique（CEE)**

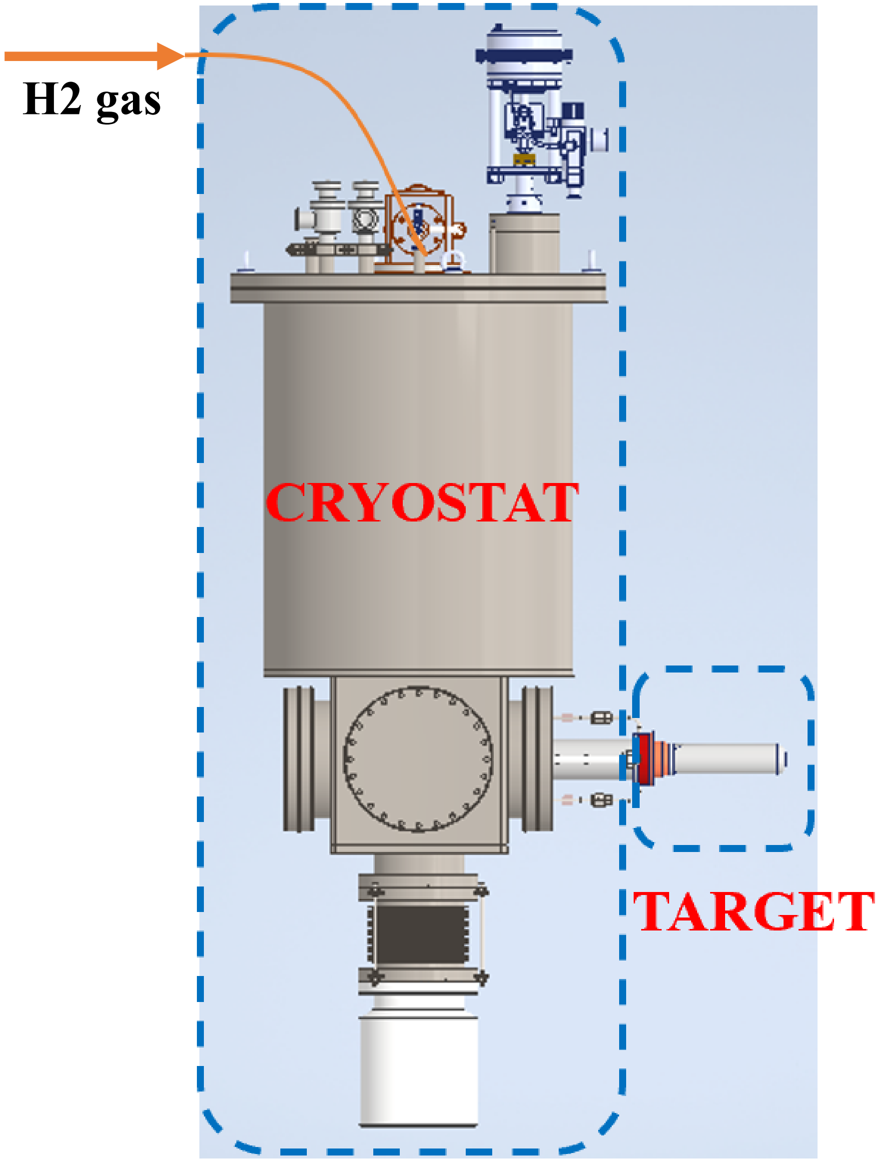
**Time：1~2 yr**

**Cost：200 k**

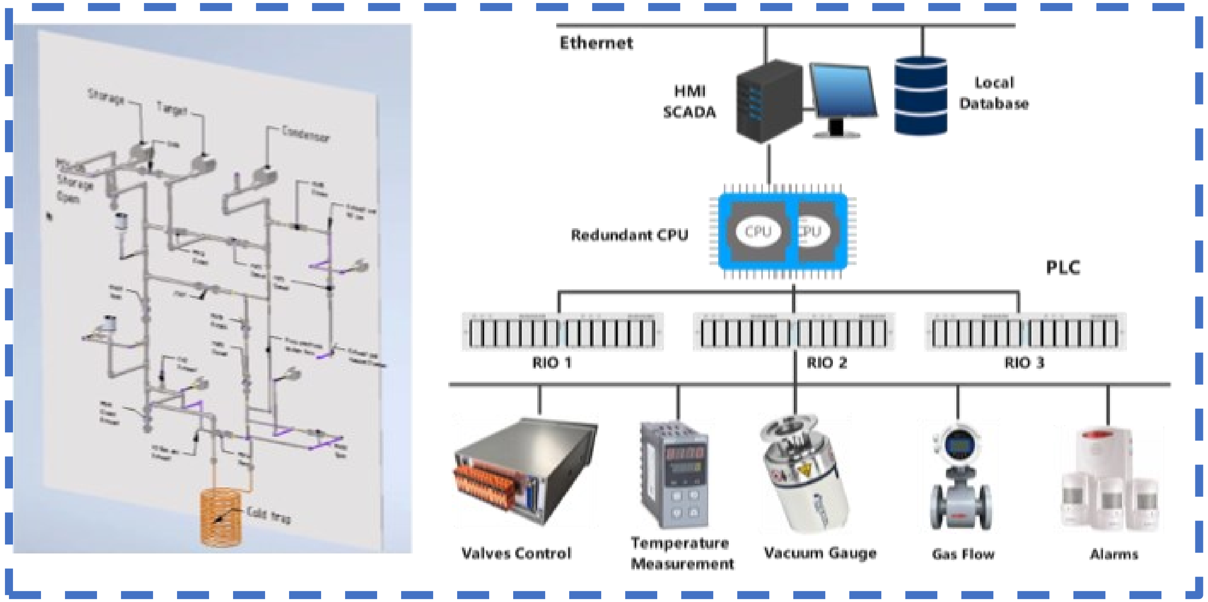
# Liquid Hydrogen Target

# Content

## Cryostadt + Target cell




## Gas circuit + Slow control




**Hydrogen circulation driven by thermosiphone**

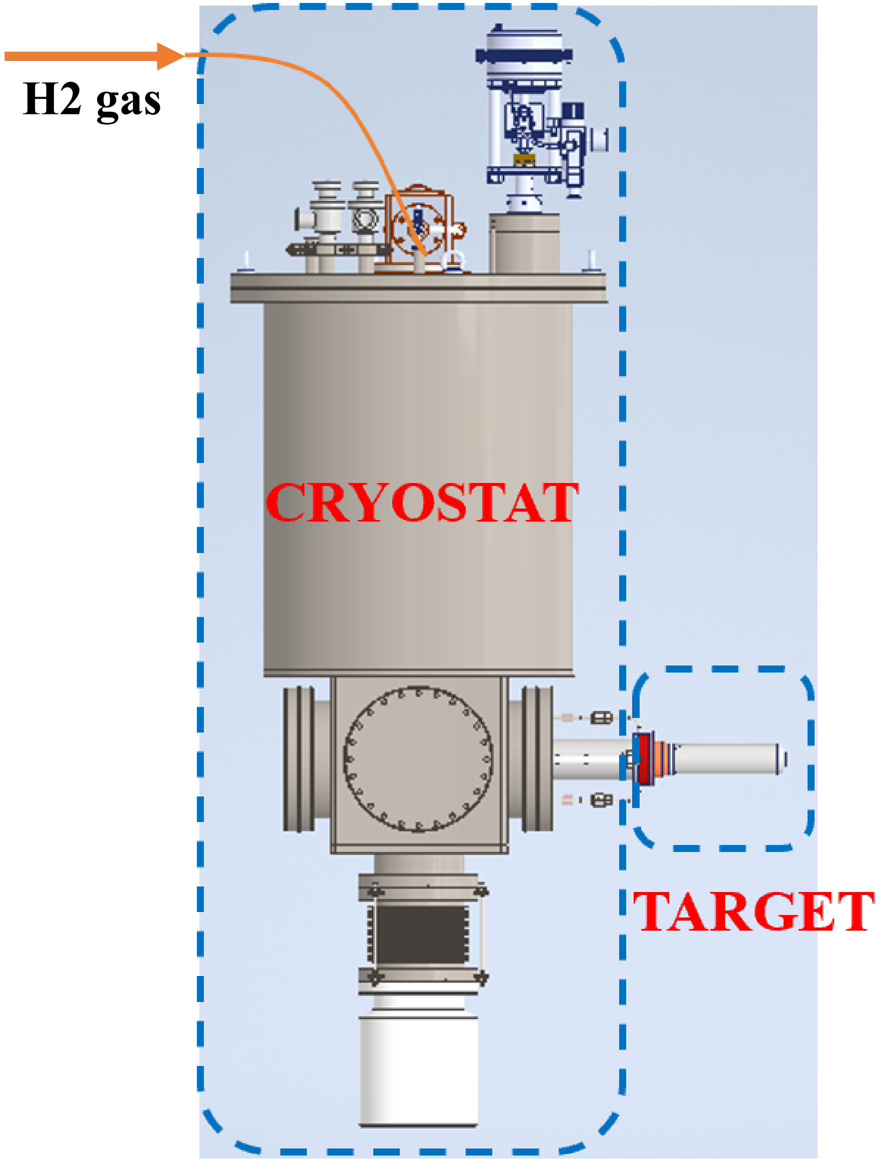
**Target cell: Thin window**
**LH2 at 20 K, Operated in vacuum**
**Continous data taking: ~ 1 month**
**Remote control**

**MULAN LH2 target designed for HIAF-HIRIBL is now under test at BNU.**

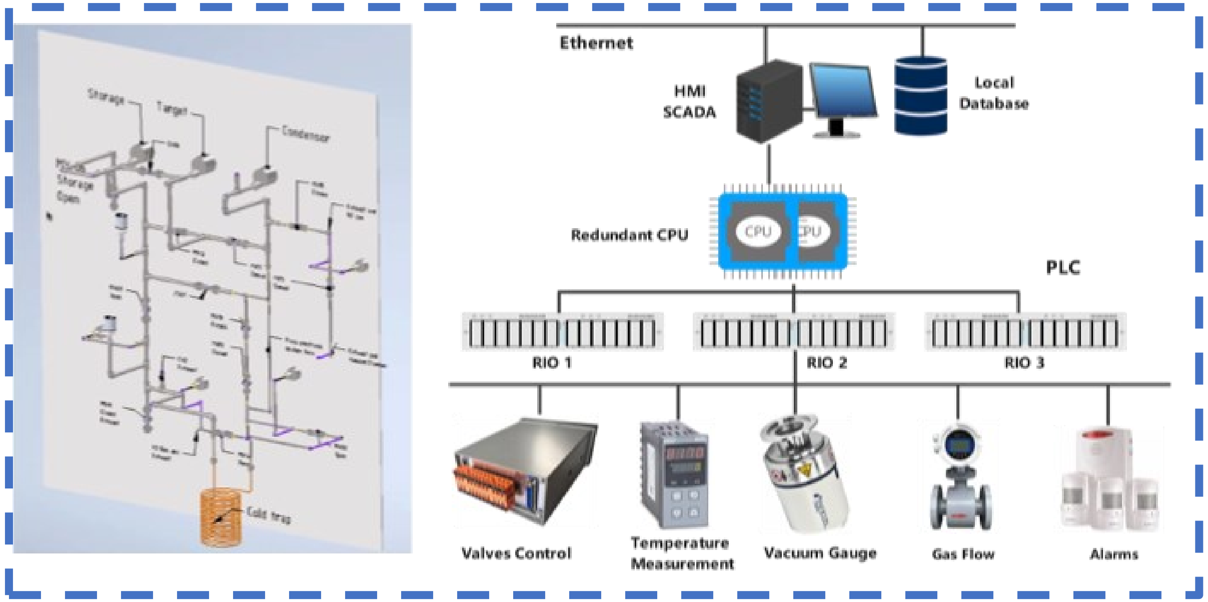
Cost: RMB 3 million
Target+Cryostadt+Vacuum pumps
Gas circuit+Control command

# Content

## Cryostadt + Target cell




## Gas circuit + Slow control




**Hydrogen circulation driven by thermosiphone**

技术成熟、可在1~2年内建成
- 靶腔体：6个月
- 冷却、循环、慢控：8个月
- 测试：4个月

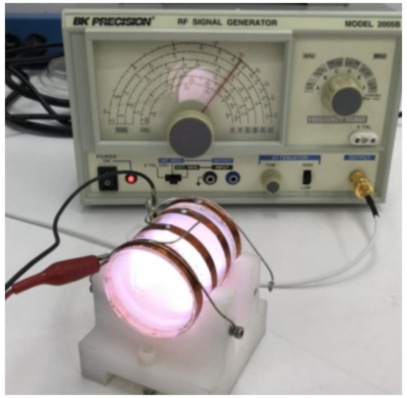
**MULAN LH2 target designed for HIAF-HIRIBL is now under test at BNU.**

Cost: RMB 3 million
Target+Cryostadt+Vacuum pumps
Gas circuit+Control command

# Polarized $^3$He Target

# Metastability-exchange optical pumping (MEOP)

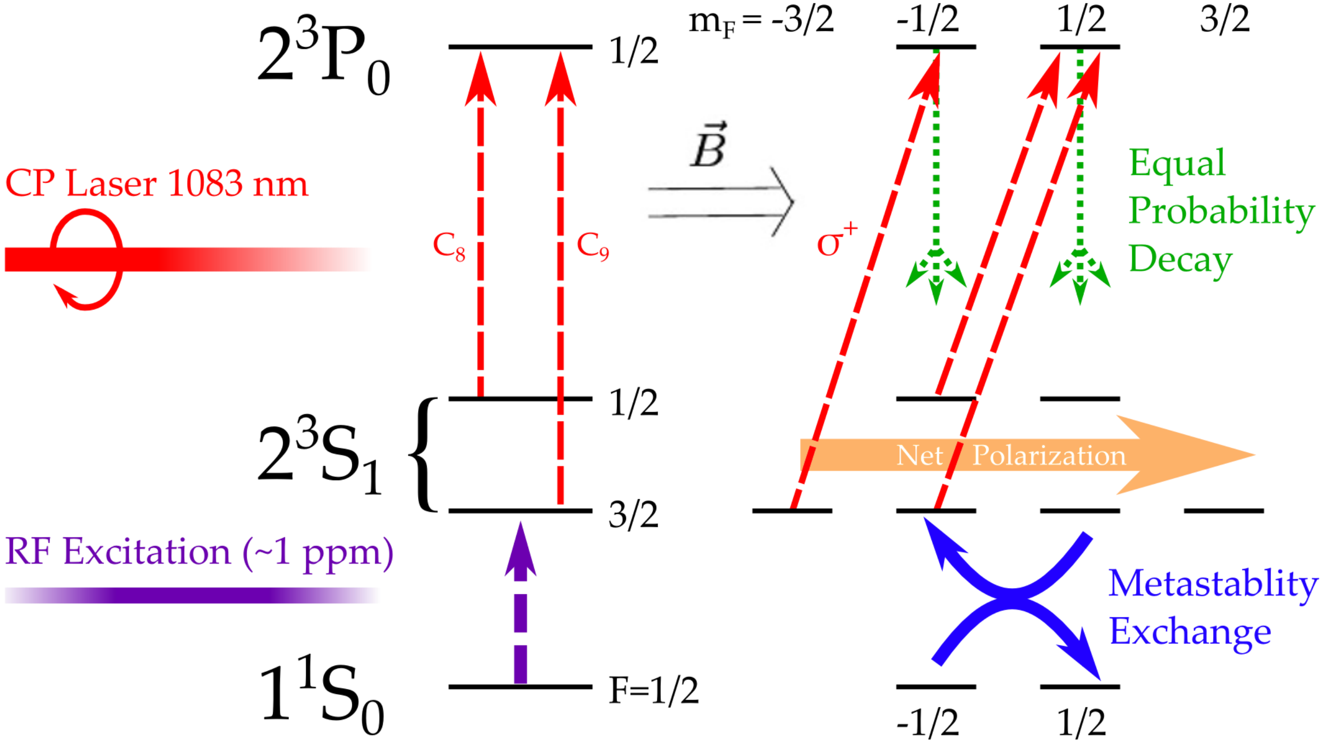
I. RF excitation: promote a small portion of $^3$He atoms to $2^3S_1$ metastable state




II. Optical pumping: laser driven polarization of $2^3S_1$ atoms

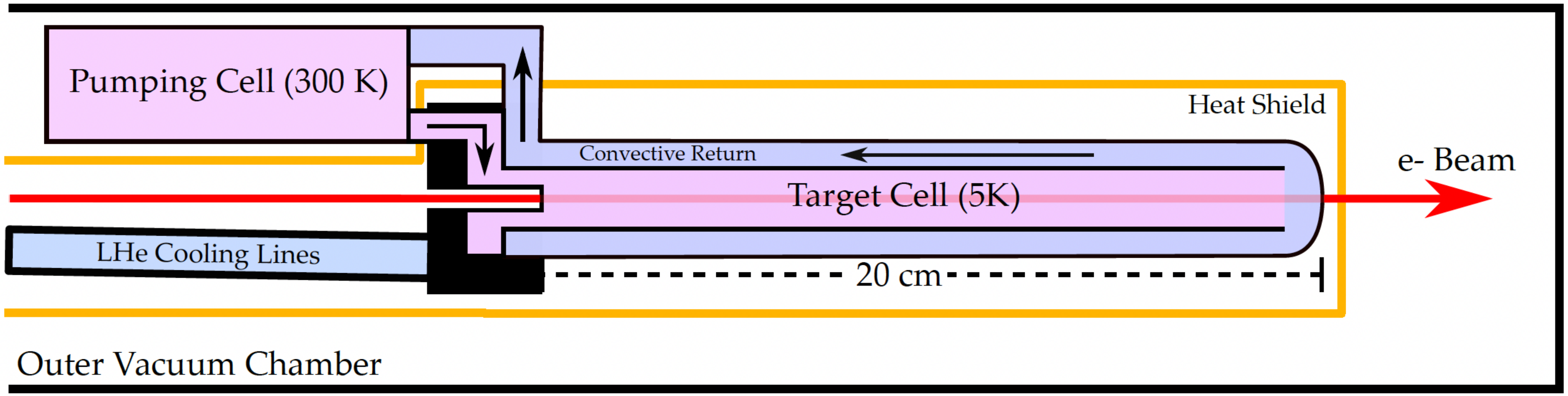
III. Metastability exchange collisions between $2^3S_1$ and ground state polarize $^3$He nuclei

Colegrove, Schearer, Walters, PRL 132, 2561 (1963)




Courtesy of Xiaqing Li

# CLAS12 polarized $^3$He target conceptual design




J.D. Maxwell and R.G. Milner, Nucl. Instr. and Meth. A **1012,** 165590 (2021)

## Pumping cell (293 K)

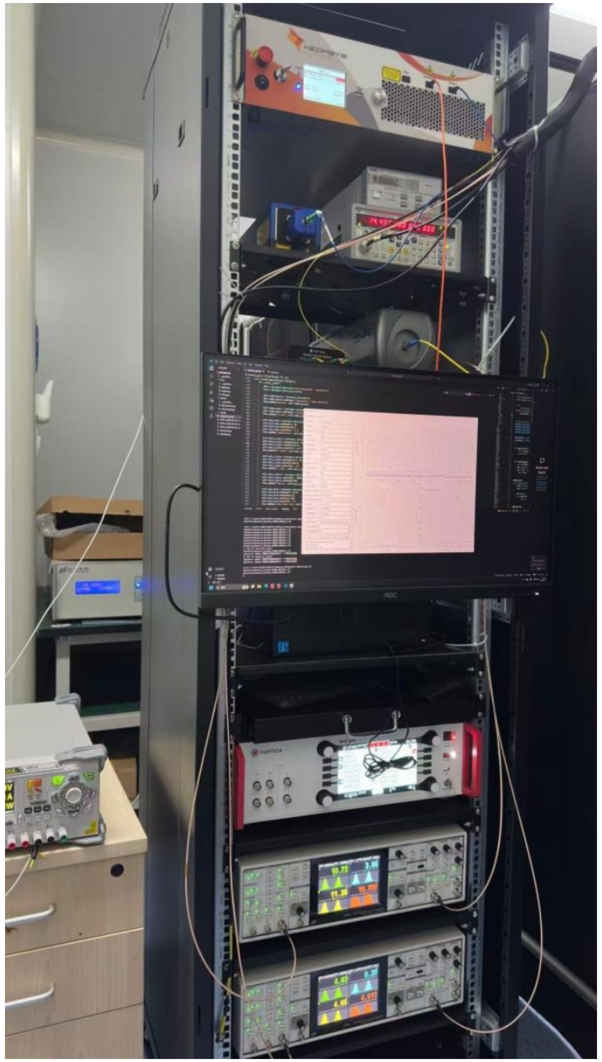
- Borosilicate glass cell
- MEOP to 60% polarization
- Annular cylindrical volume

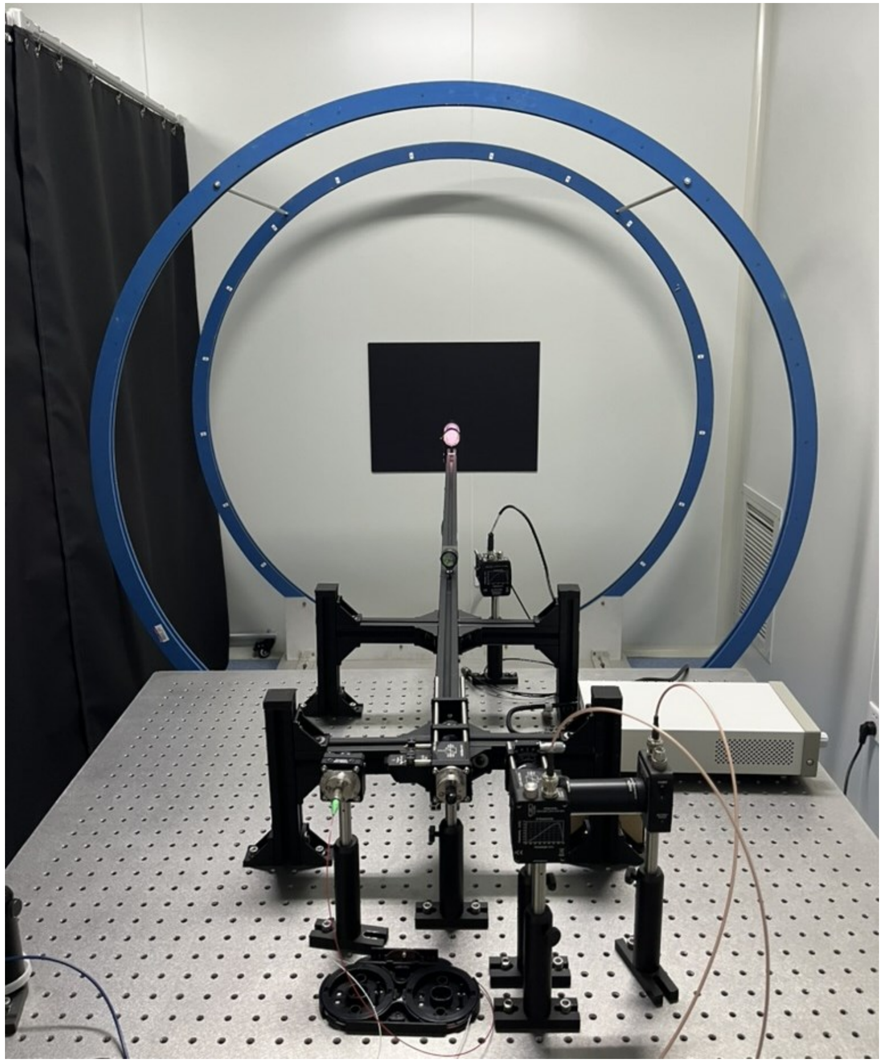
## Target cell (5 K)

- 100 $cm^3$, 20-cm aluminum cell coated with cryogenic layer
- Cooled by LHe heat exchanger
- Luminosity: $2.7\times10^{34}$ nucleons/$cm^2$/s at 0.5-µA beam current

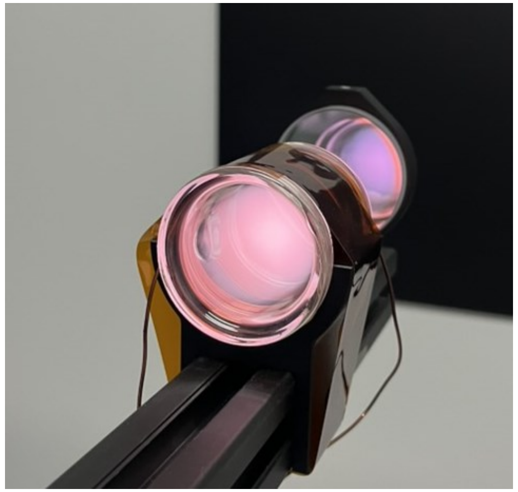
Courtesy of Xiaqing Li

# New Polarized 3He Lab at Shandong University





- Establishing low field MEOP system at SDU polarized $^3$He lab
- High field MEOP upgrading in 2027 with extended lab space on campus



1 mbar $^3$He glass cell produced at CSNS

Courtesy of Xiaqing Li

# Timeline and cost

技术路线
- 光泵浦方法实现气体极化
- 低温或气体压缩方法增加靶厚

研制计划
- 概念设计 ~ 0.5年
- 关键技术测试 1-2年
- 系统组装 ~ 1年
- 调试 ~ 0.5年

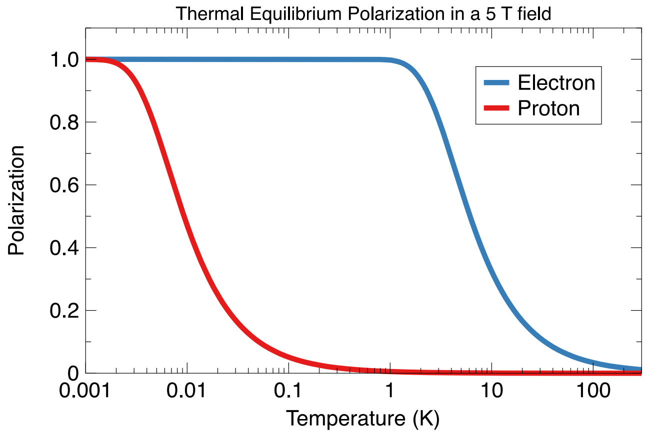
经费预估
- 激光系统 ~ 100万元
- 真空系统 ~ 100万元
- 低温系统 ~ 200万元
- 电子学和DAQ ~ 150万元
- 耗材/运维/机械等 ~ 350万元
- 总计约900万元

# Polarized Solid H/D Target

# Polarized solid target – how it works

H-like system at a low temperature in a strong B field (1K, 5T)

- 2 out of 4 Zeeman states dominate:
  - $\downarrow\uparrow\ \downarrow\downarrow$ ✓ $(P_e \approx 1, P_p \approx 0)$
  - $\uparrow\uparrow\ \uparrow\downarrow$ ×

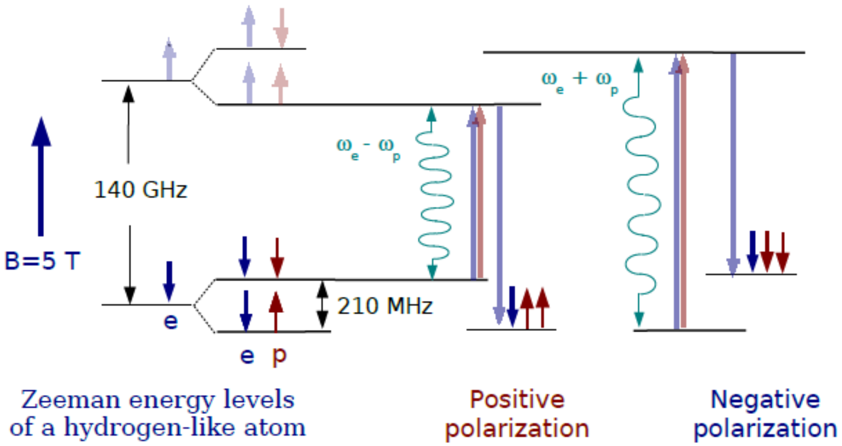



$$n_{\uparrow\downarrow} = n_0 \cdot e^{\frac{\vec{u}\cdot\vec{B}}{\kappa T}}$$

$$\mu_e/\mu_p \approx -658$$

$$B/T \geq 5:1$$

- electron polarization transferred to the proton with resonant microwave
  - $\omega_e - \omega_p$: $\begin{matrix}\downarrow\downarrow \\ \downarrow\uparrow\end{matrix} \Rightarrow \uparrow\uparrow \Rightarrow \begin{matrix}\downarrow\uparrow \\ \downarrow\uparrow\end{matrix}$
  - $\omega_e + \omega_p$: $\begin{matrix}\downarrow\downarrow \\ \downarrow\uparrow\end{matrix} \Rightarrow \uparrow\downarrow \Rightarrow \begin{matrix}\downarrow\downarrow \\ \downarrow\downarrow\end{matrix}$



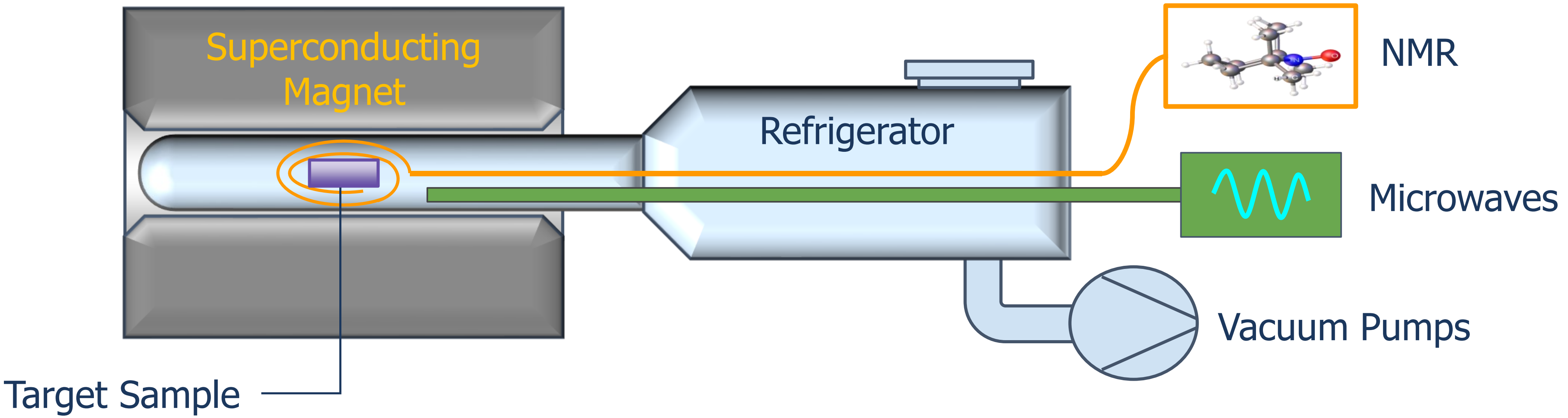

$$\omega_e = 140\ \text{GHz}$$
$$\omega_p = 210\ \text{MHz}$$

D. G. Crabb and W. Meyer, Annual Review of Nuclear and Particle Science, 47(1):67–109, 1997.

# Polarized solid target – how it looks like

Five major components

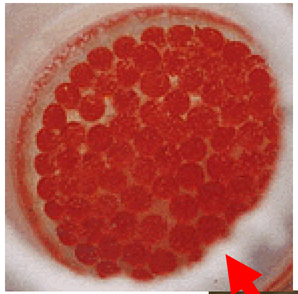
1. Target sample
2. Polarizing magnet **(strong B) +** cryostat **(low temperature)**
3. Holding magnet + dilution refrigerator **(ultralow temperature)** for frozen spin mode
4. Microwaves **(resonant spin flip)**
5. NMR **(polarimetry)**



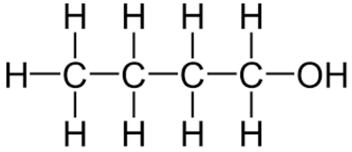
# An example – PST at MAMI

Target material:
TEMPO-doped butanol

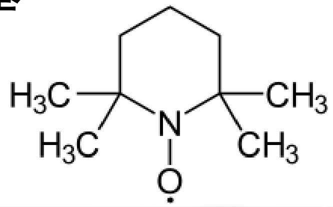
**TEMPO: Butanol** $\approx 1{:}10^4$

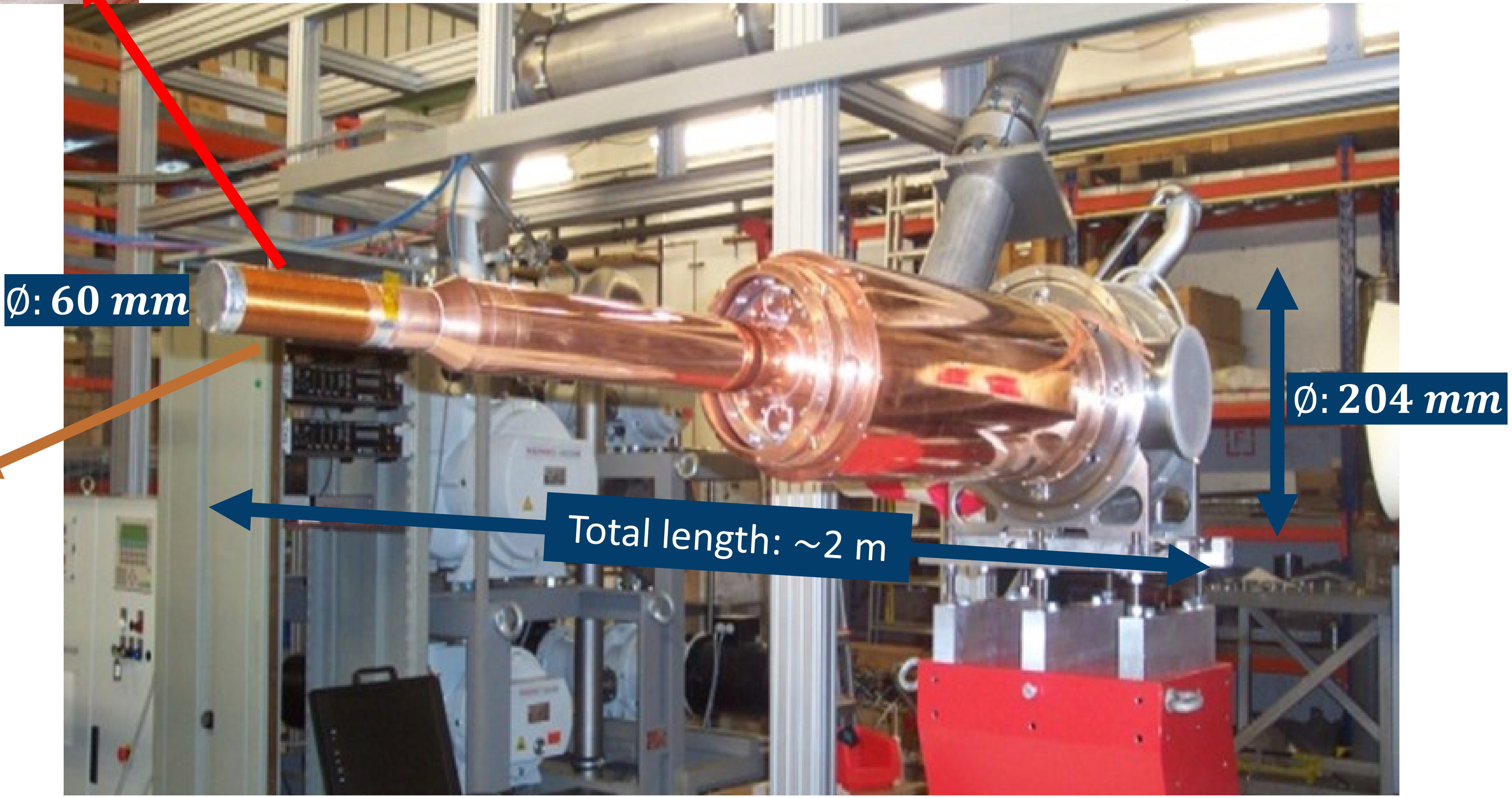


Butanol has 10 free protons
丁醇

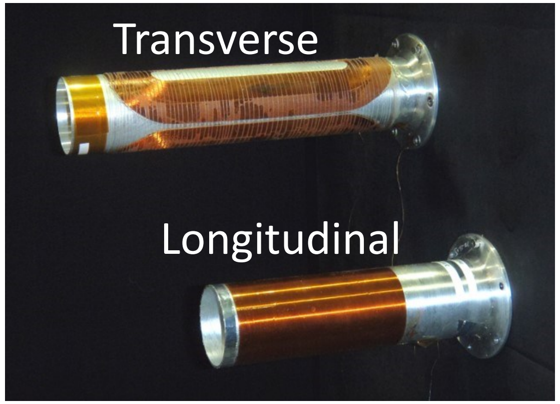


TEMPO has one unpaired electron
四甲基哌啶氧自由基

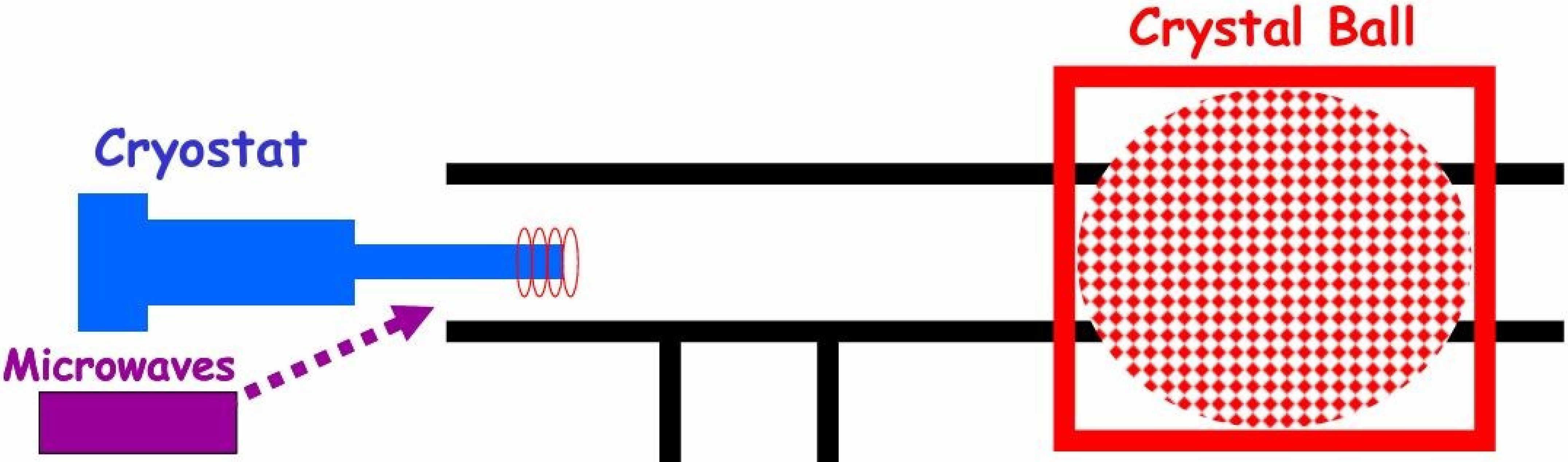




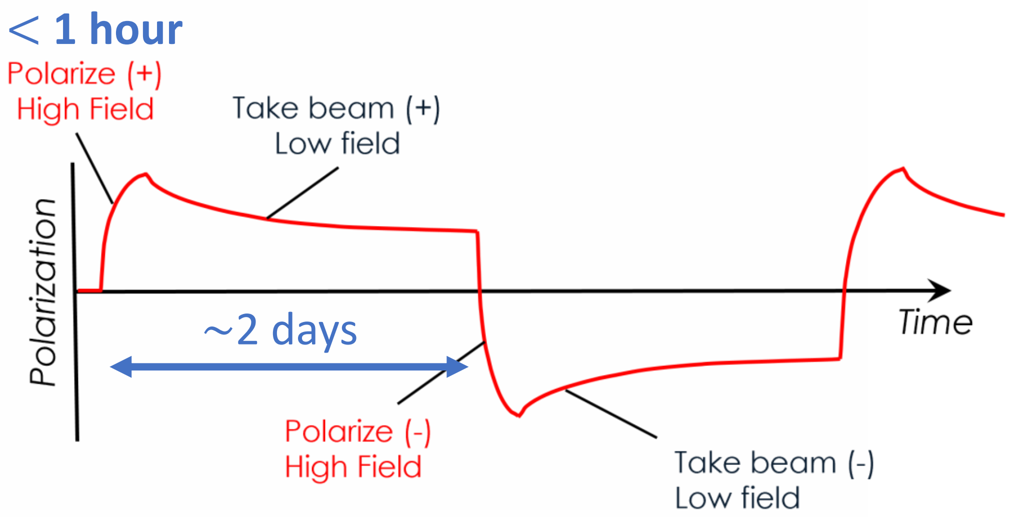

**Polarization holding magnets**



# An example – PST at MAMI

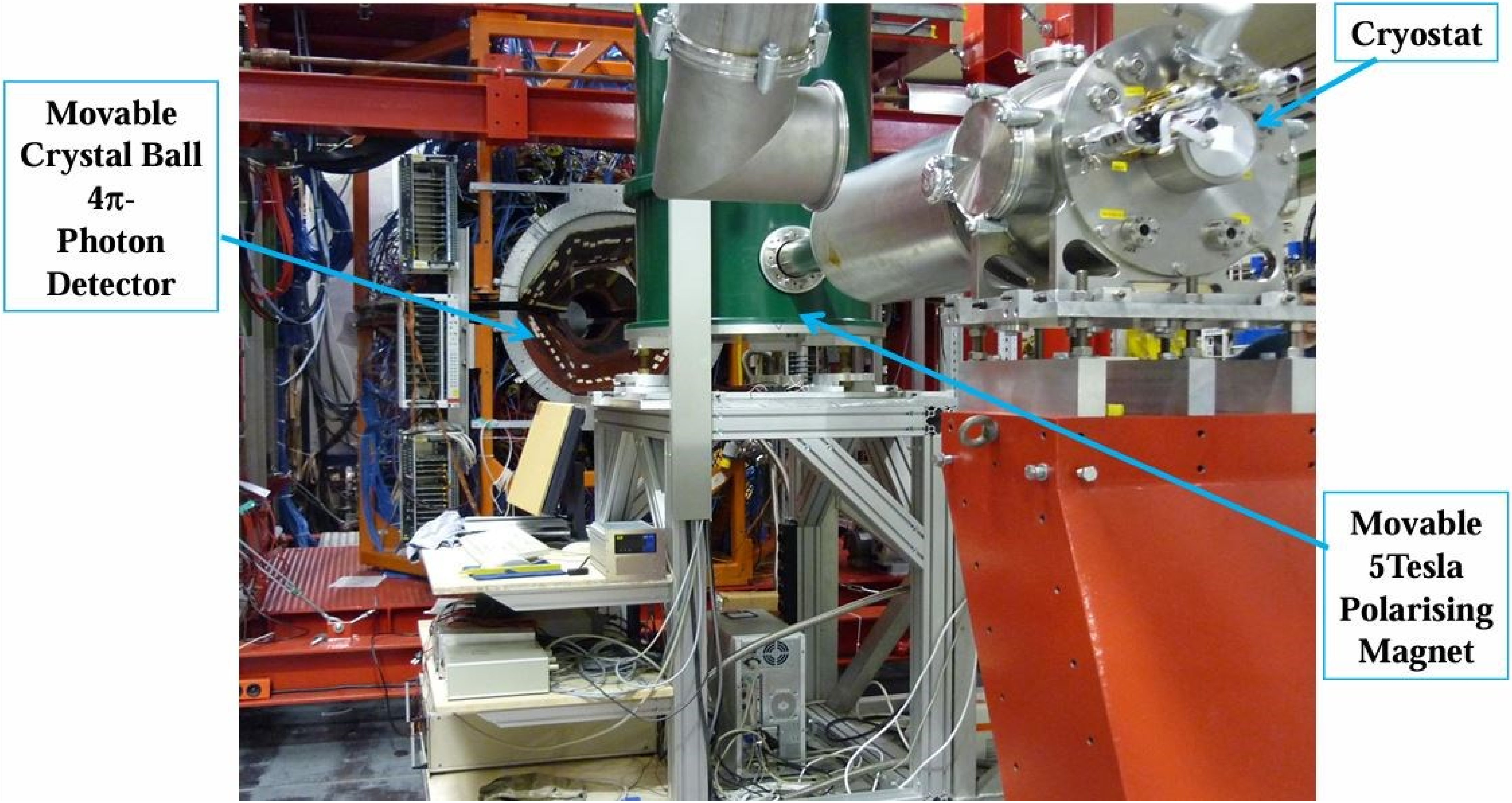



1. External magnet (2.5 T, 0.5 K)
2. Polarize with microwaves
3. Internal holding coil (0.7 T, 20 mK)
4. Remove external magnet
5. Move CB detector in.
6. Data taking.
7. Repolarization




Slides from A. Thomas, JGU

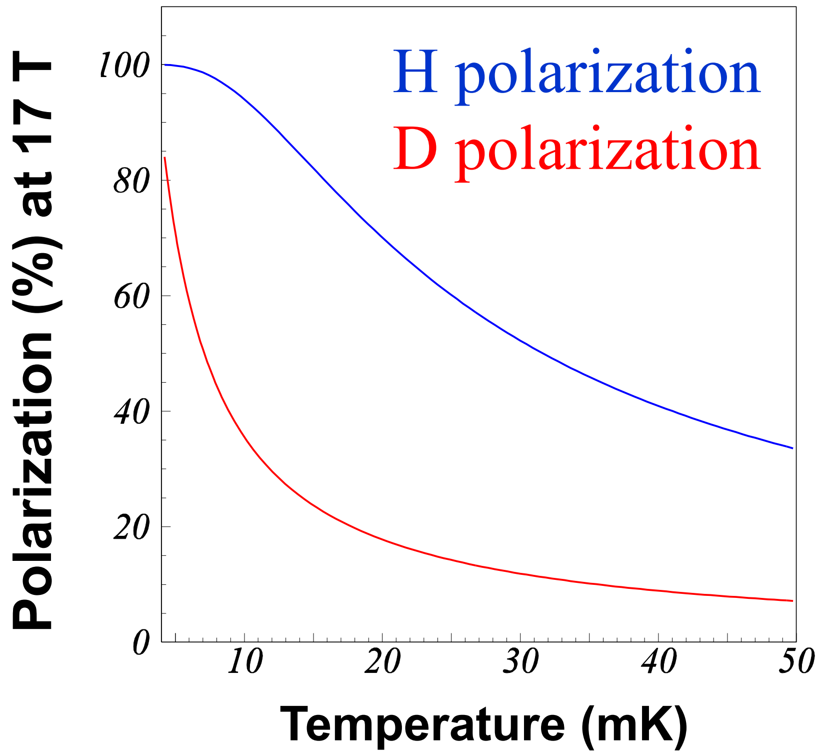
# An example – PST at MAMI



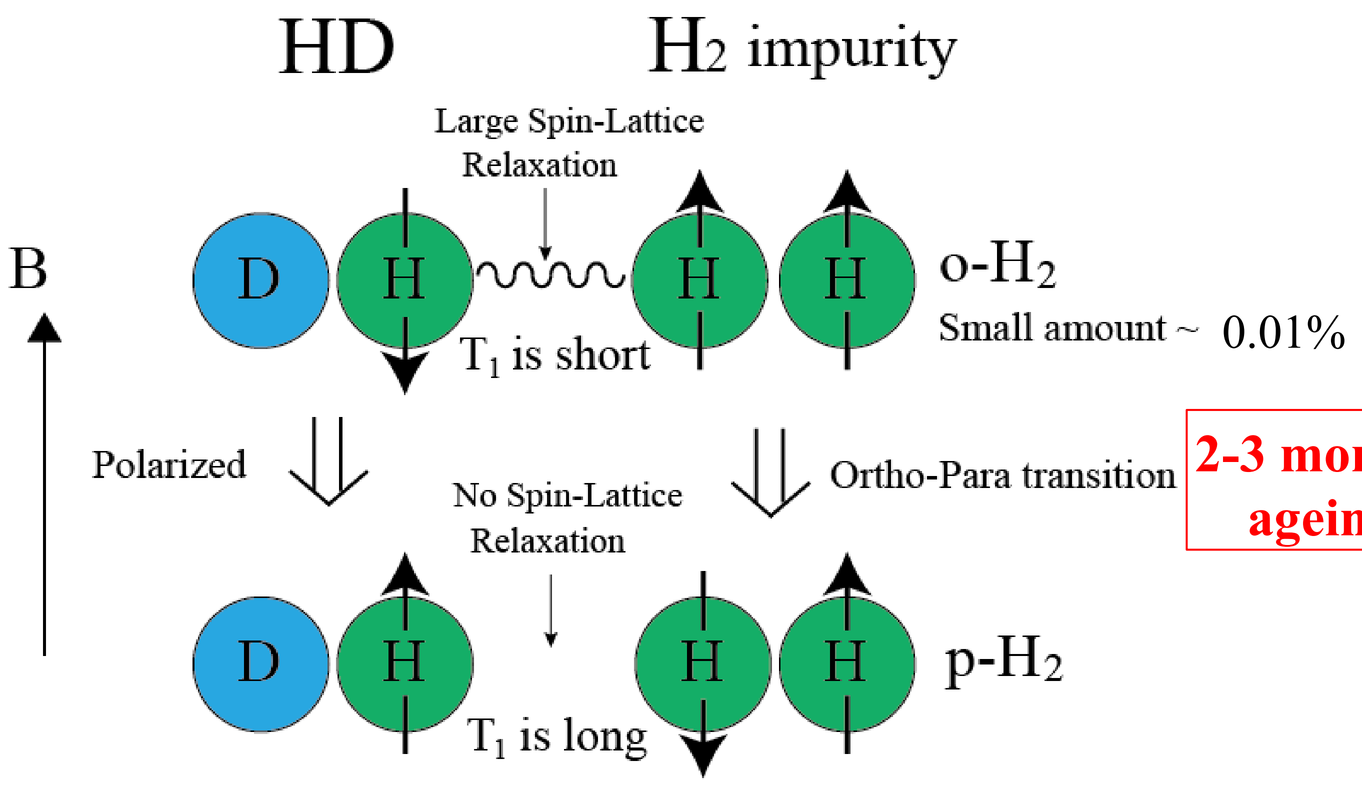
# Polarized HD Target

# Polarized HD target

**Brute force polarization**
$P = \tanh(\mu_p B/kT)$
Proton at 17 T & 10 mK: **P ~ 90%**



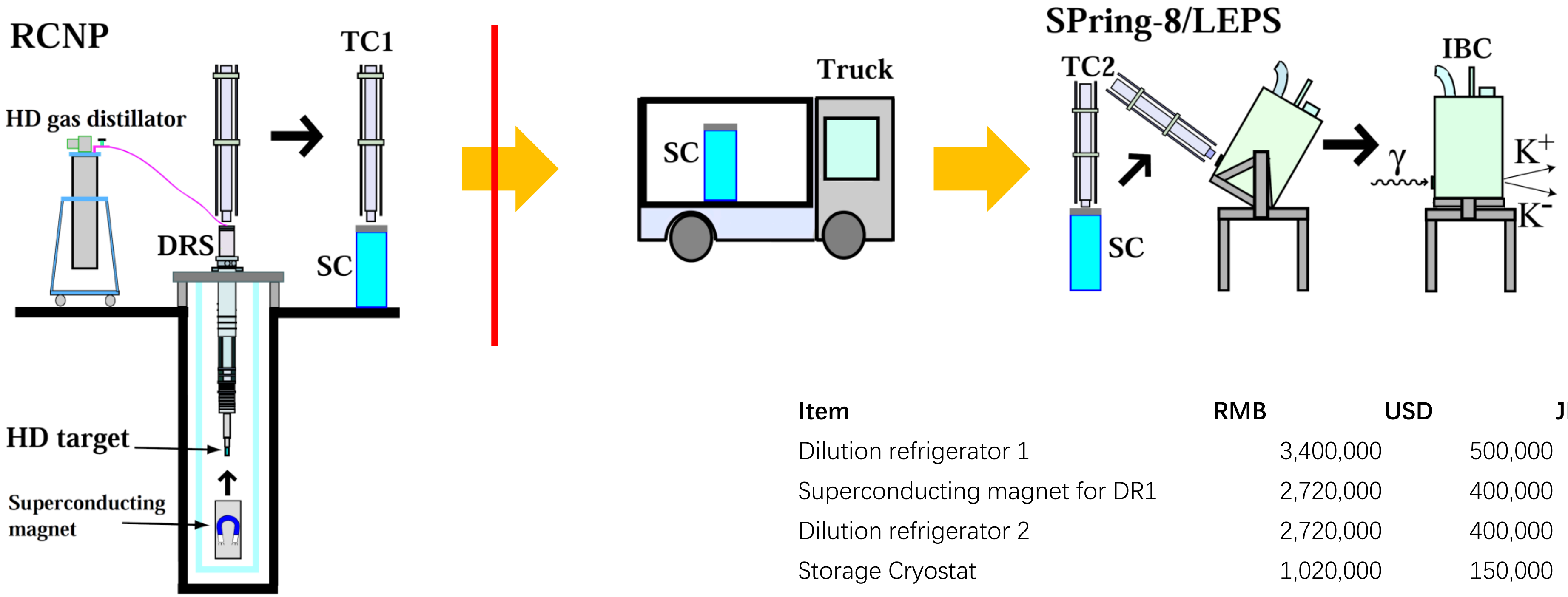

*It is not practical to keep 17 T & 10 mK during the experiment…*




**2-3 months ageing**

**Polarization is frozen for a long time (~1 year) even with a lower B-field & a higher temperature.**
(For $D_2$, the roles of ortho and para are reversed due to Bose statistics.)

# Polarized HD target




- Gas distillator & analyzer
- Superconducting magnet
- DRS: Dilution Refrigerator System
- TC : Transfer Cryostat (1 & 2)
- SC : Storage Cryostat
- IBC : In-Beam Cryostat

| Item | RMB | USD | JPY |
|---|---|---|---|
| Dilution refrigerator 1 | 3,400,000 | 500,000 | 80,000,000 |
| Superconducting magnet for DR1 | 2,720,000 | 400,000 | 64,000,000 |
| Dilution refrigerator 2 | 2,720,000 | 400,000 | 64,000,000 |
| Storage Cryostat | 1,020,000 | 150,000 | 24,000,000 |
| Transfer Cryostat 1 | 1,360,000 | 200,000 | 32,000,000 |
| Transfer Cryostat 2 | 1,360,000 | 200,000 | 32,000,000 |
| NMR system | 272,000 | 40,000 | 6,400,000 |
| Gas distillator | 340,000 | 50,000 | 8,000,000 |
| Gas analyzer | 272,000 | 40,000 | 6,400,000 |
| HD gas (100 L) | 68,000 | 10,000 | 1,600,000 |
| 3He gas (50 L) | 1,360,000 | 200,000 | 32,000,000 |
| **TOTAL** | **14,892,000** | **2,190,000** | **350,400,000** |

国内没有经验，需要国际合作（RCNP）
研制时间：4~5年

# Summary

**Baseline (1~2 yr)**

- **Solid nuclear target**
  - O, Ga, Au…
  - employed at CEE
- **LH2 target**
  - p
  - Developed for HIRIBLL
  - Hongna Liu@BNU

**Second stage (4~5 yr)**

- **Polarized $^3$He gas target**
  - $\vec{n}$
  - Xiaqing Li@SDU
- **DNP polarized target**
  - $\vec{p}\,,\vec{d}$ (impurity: C, N, O, Li)
  - Dubna, Mainz, Tsinghua?
- **Polarized HD target**
  - $\vec{p}\,,\vec{d}$
  - Osaka, N.Muramatsu@IMP

# BACKUP SLIDES

# What is the polarized HD target?

**Boltzmann distribution**

$N_- = N exp(-E_-/kT)$

$N_+ = N exp(-E_+/kT)$

$N_-/N_+ = exp((E_+ - E_-)/kT)$

$= exp(\Delta E/kT)$

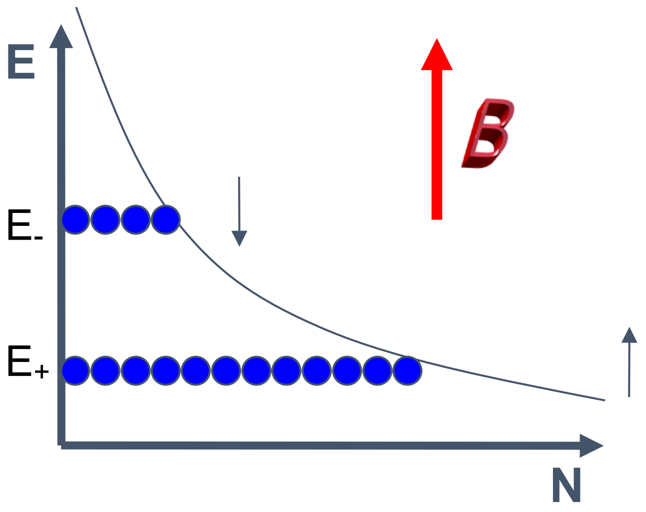
$= exp(2\mu_p B/kT)$

$k$ : Boltzmann constant

$\mu_p$: Proton magnetic moment

$B$ : Magnetic field

$T$ : Temperature



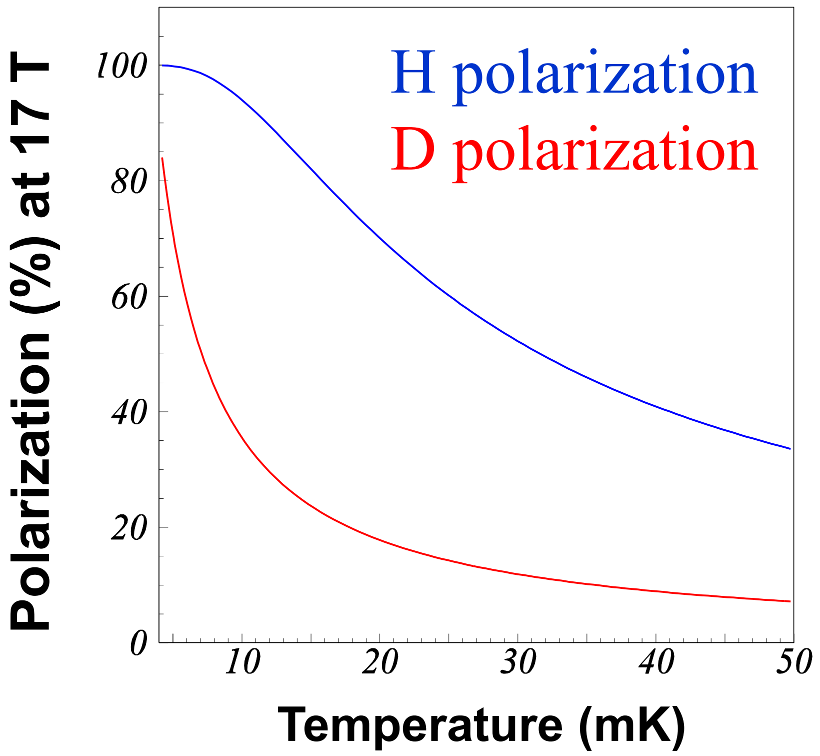

**Proton polarization**

$P = (N_+ - N_-)/(N_+ + N_-) = \tanh(\mu_p B/kT)$

In case of B = 17 Tesla & T = 10 mK, **P ~ 90%**

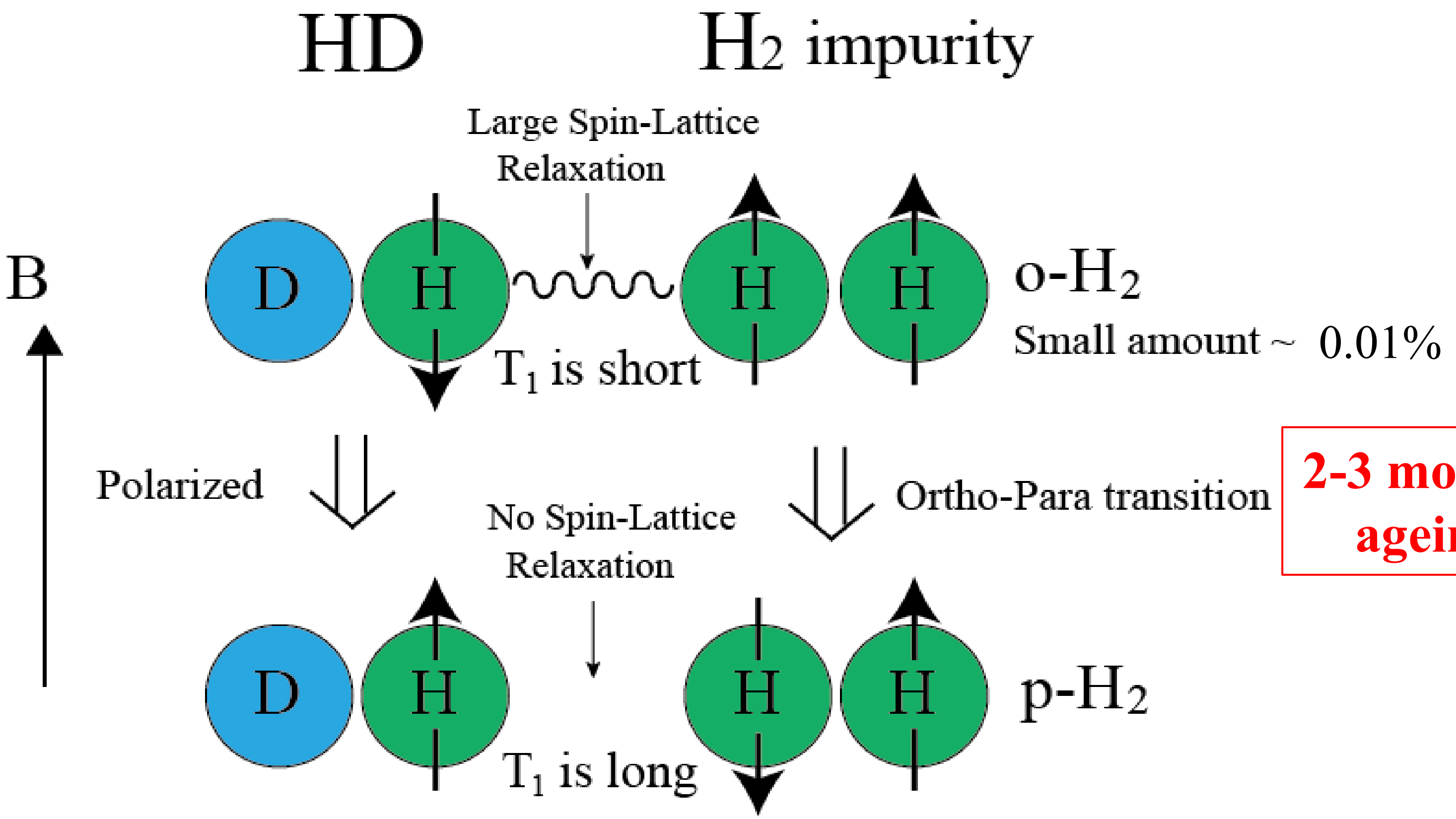
⇒ Static polarization method

(**"brute force"**)



# What is the polarized HD target?

😓 *It is not practical to keep 17 T & 10 mK during the experiment…*

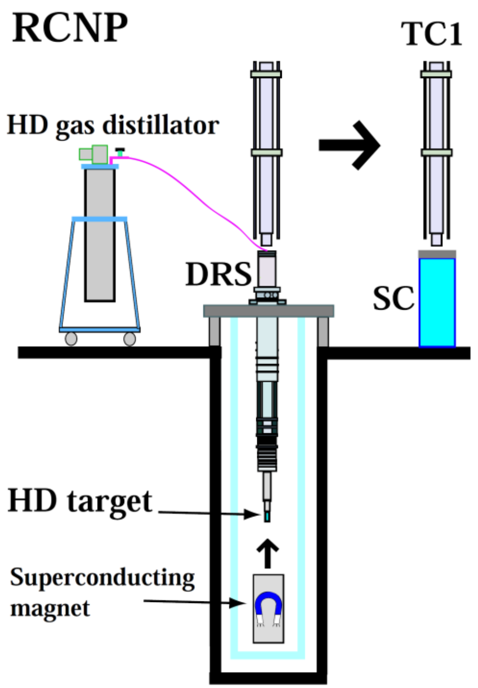


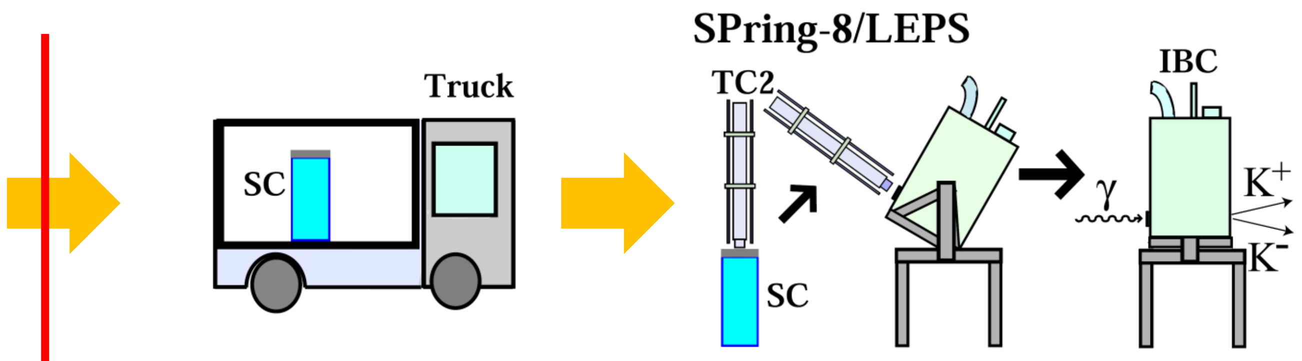

**2-3 months ageing**

**Polarization is frozen for a long time (~1 year) even with a lower B-field & a higher temperature.**

(For $D_2$, the roles of ortho and para are reversed due to Bose statistics.)

# Original concept of the target operation




*Finally, the project has finished at this stage because of the world helium crisis, etc.*


**DRS: Dilution Refrigerator System**
**TC : Transfer Cryostat (1 & 2)**
**SC : Storage Cryostat**
**IBC : In-Beam Cryostat**

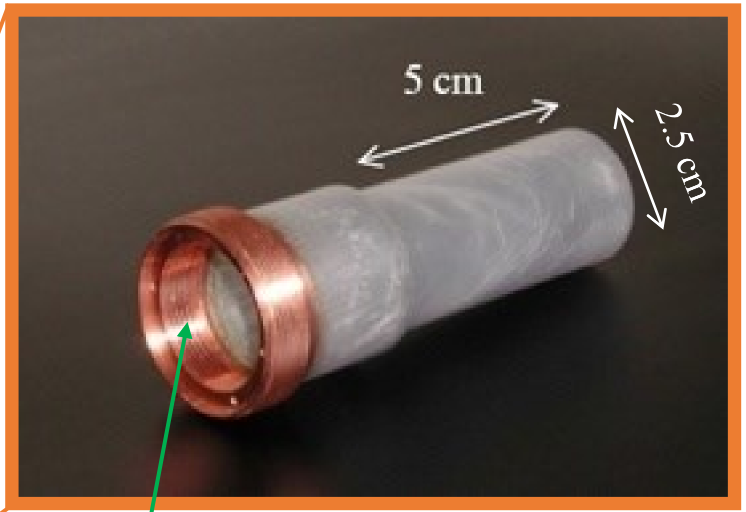
# Dilution refrigerator

Leiden Cryogenics **DRS-2500**

Cooling power : **2500μW at 120 mK**

Lowest temperature : **6 mK**

$^3$He/$^4$He mixing chamber to cool down the cold finger.



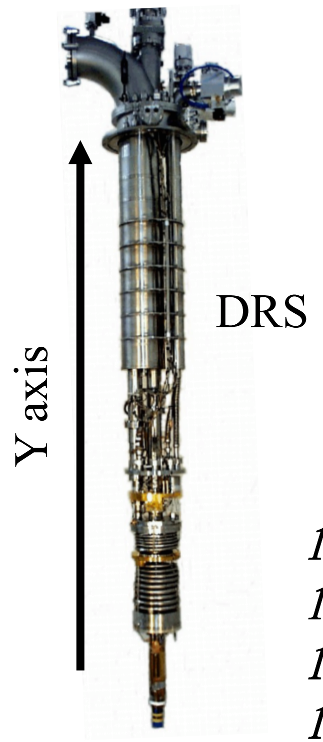

**HD target cell**

- Kle-F container (p-free for NMR)
- Narrow Al wires (20% in weight)

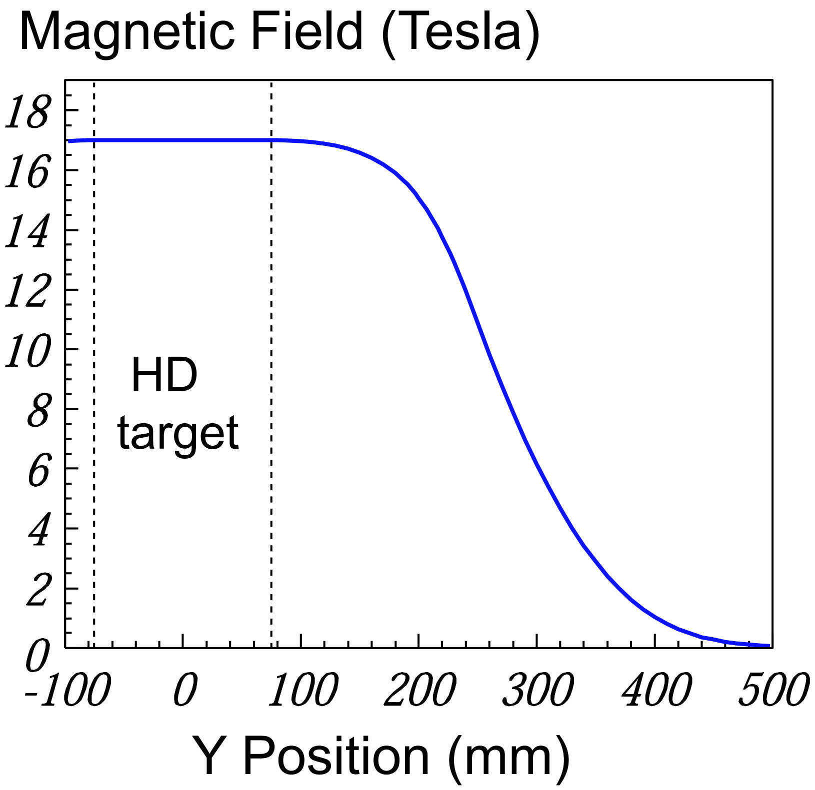
Inner thread is used when taking out the cell by a TC.

# Superconducting magnet

Magnetic Field : **17 Tesla**
Homogeneity of Magnetic Field : **$5 \times 10^{-4}$** for 15 cm







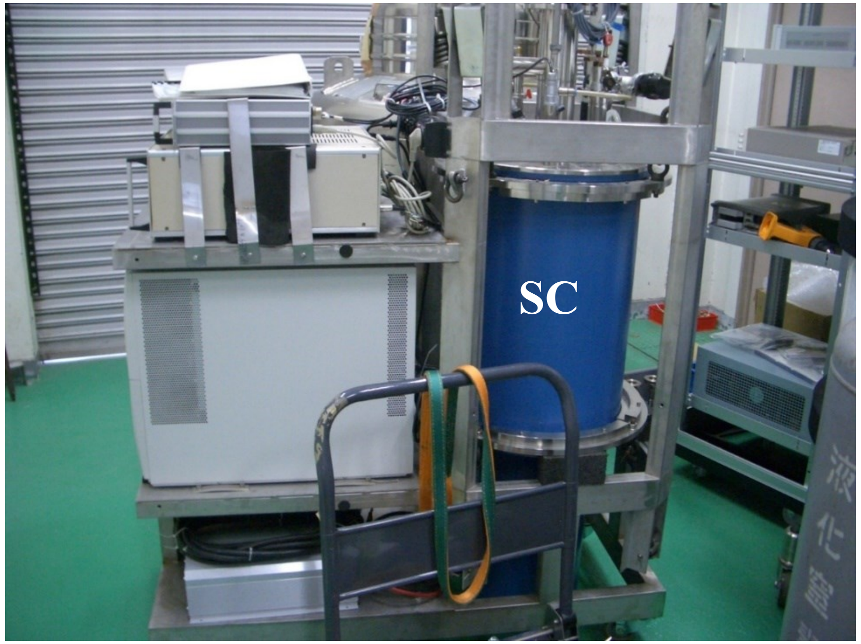

*The cell can be taken out from the top part.*

*The HD production system is embedded under ground.*

# Transfer cryostats & Storage cryostat

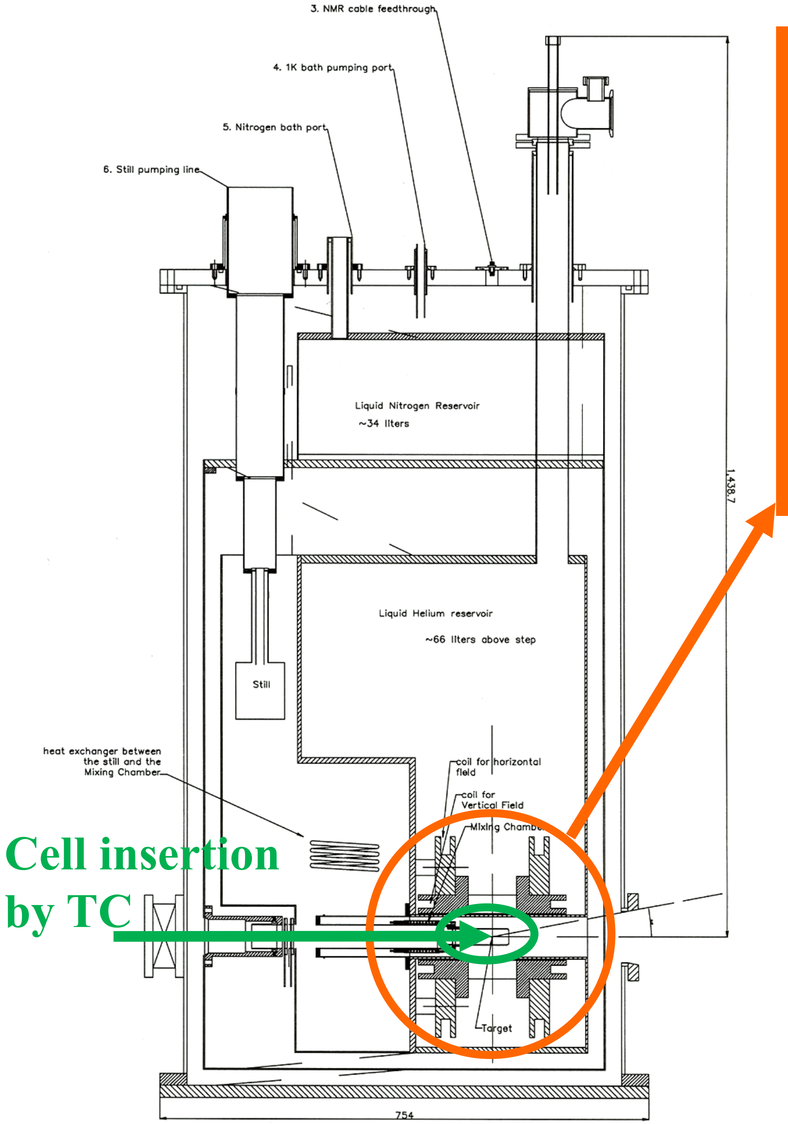
*Both are $^4He$ cryostats & provided from the Orsay group.*

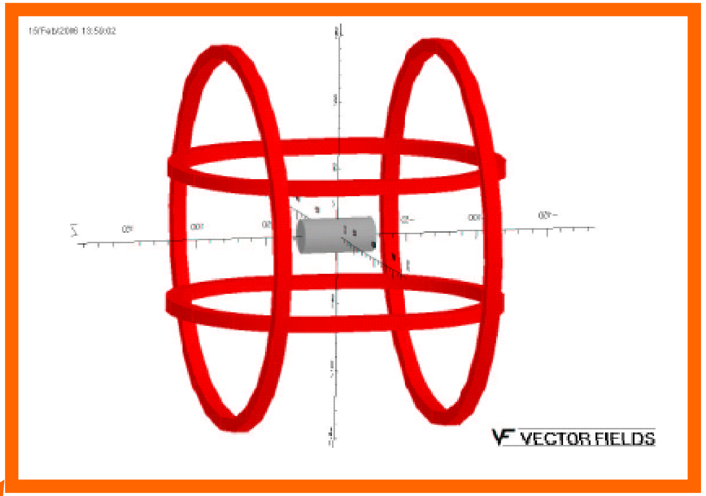

Magnetic Field : ~0.2 Tesla
Temperature : T ~ 4.2 K




Magnetic Field : 2.5 Tesla
Temperature : T~1.5 K
Homogeneity : $10^{-4}$
for target region

# In-beam cryostat



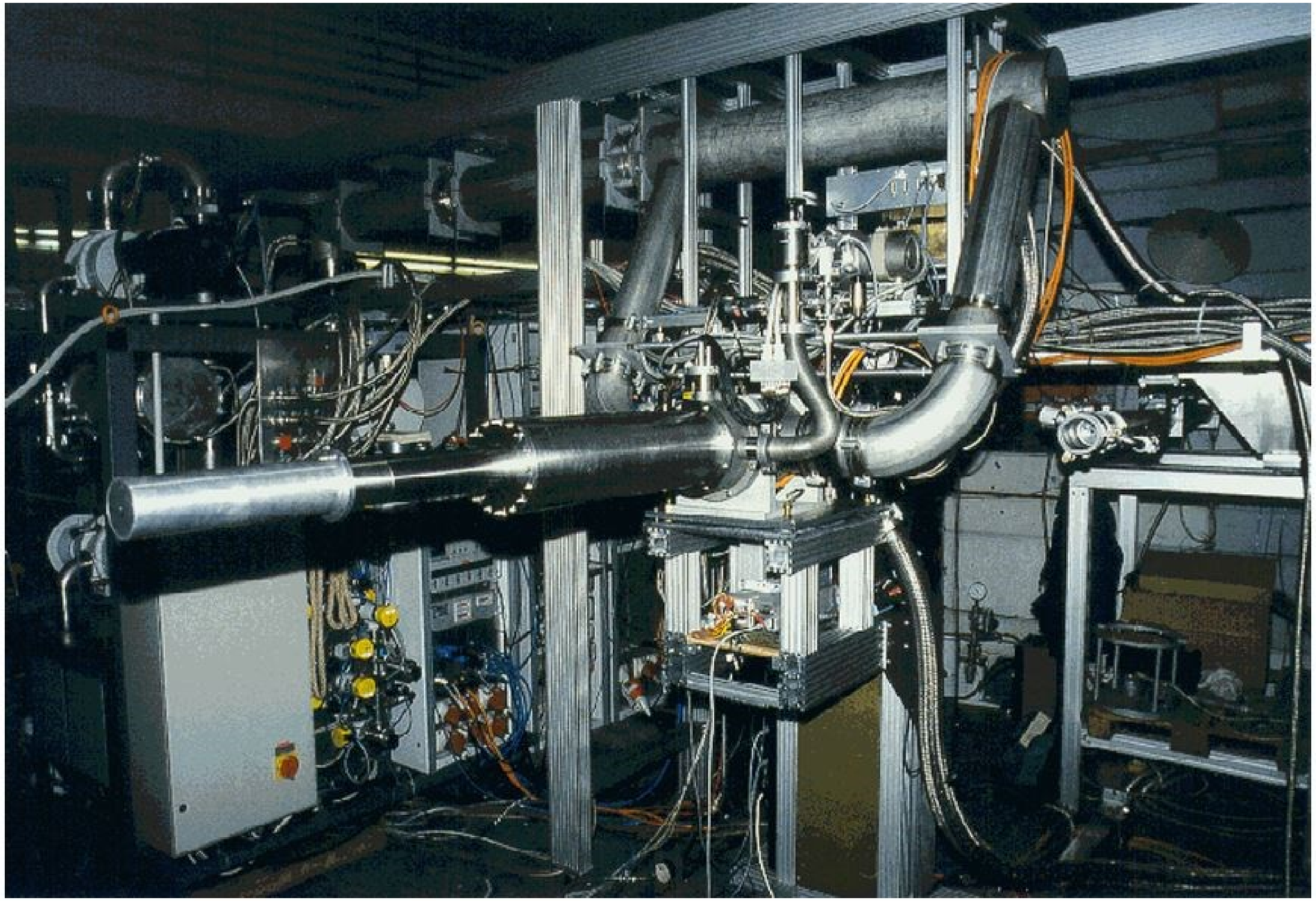




T=300 mK
B=1 T

Target polarization can be changed to the **longitudinal** or **transverse** directions by coils.

Many polarization observables can be obtained by combining with the **circular** or **linear** polarization of γ-ray beam.

# Bonn PST

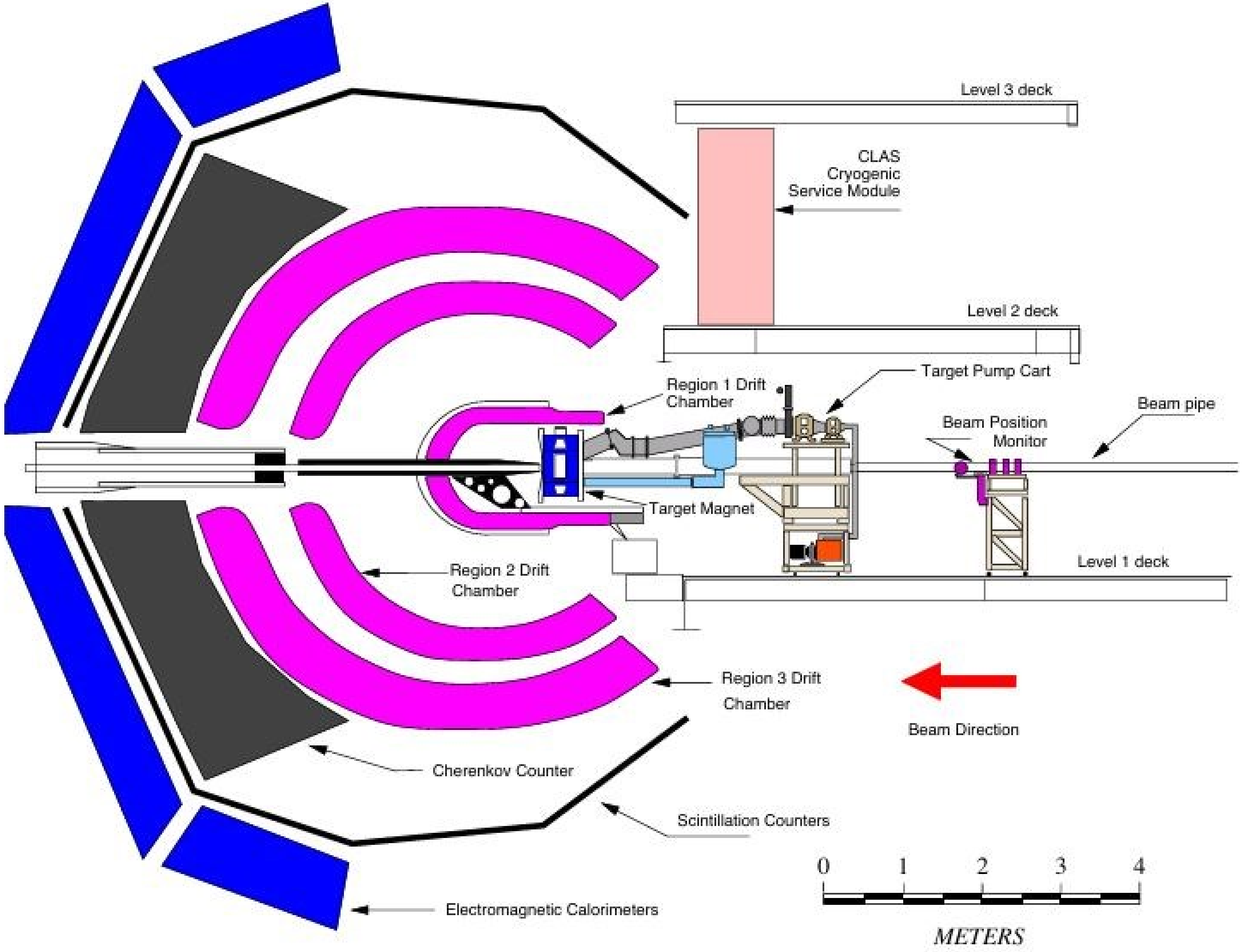


Bonn Frozen Spin Target at A2 / MAMI

[C.Bradtke et al., NIM **A436**, 430 (1999)]

**First measurement of GDH sum rule.**
**Polarisation observable E with 4 $\pi$ detector DAPHNE.**
**Prototype for CLAS/FROST and MPT.**

# Another example – PST at JLab



# One more example – PST at COMPASS