The polarized deuteron target at COMPAS in 2022

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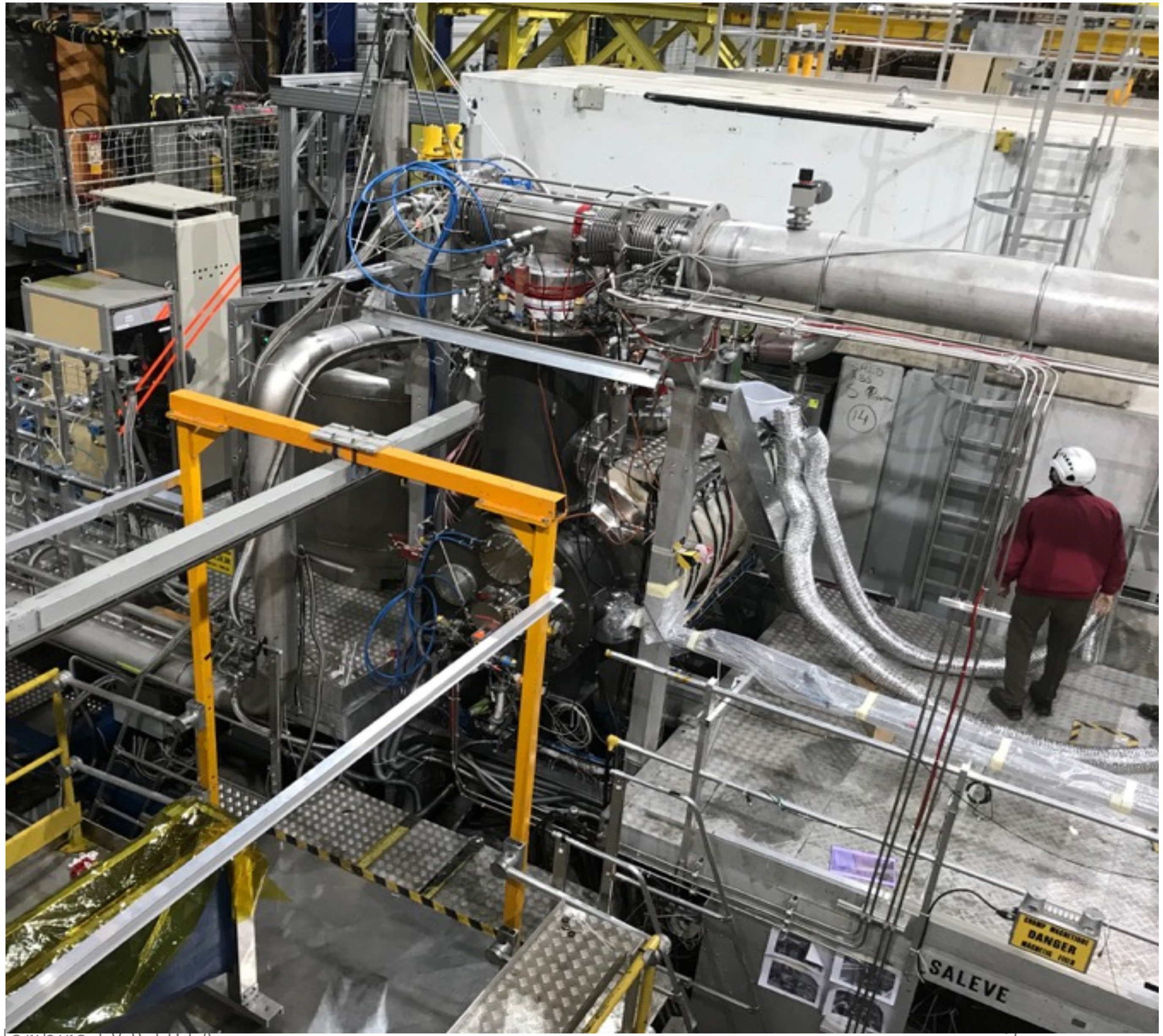
Outline

- COMPASS experiment
- COMPASS PT system
  - 6LiD with muon beam
- Polarization
  - DNP
  - Polarization determination
- Long term operation
  - Relaxation time
- Other measurements



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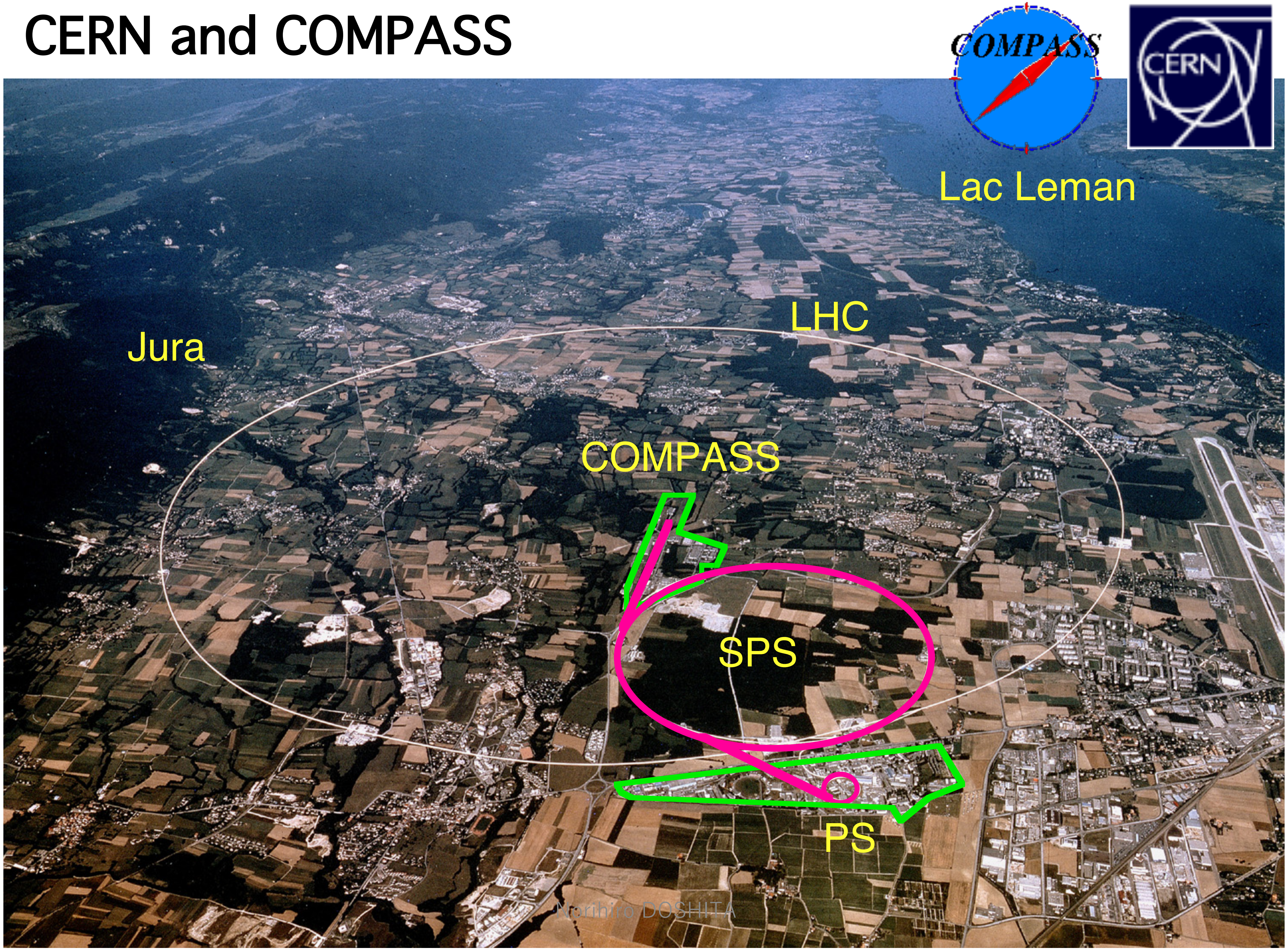
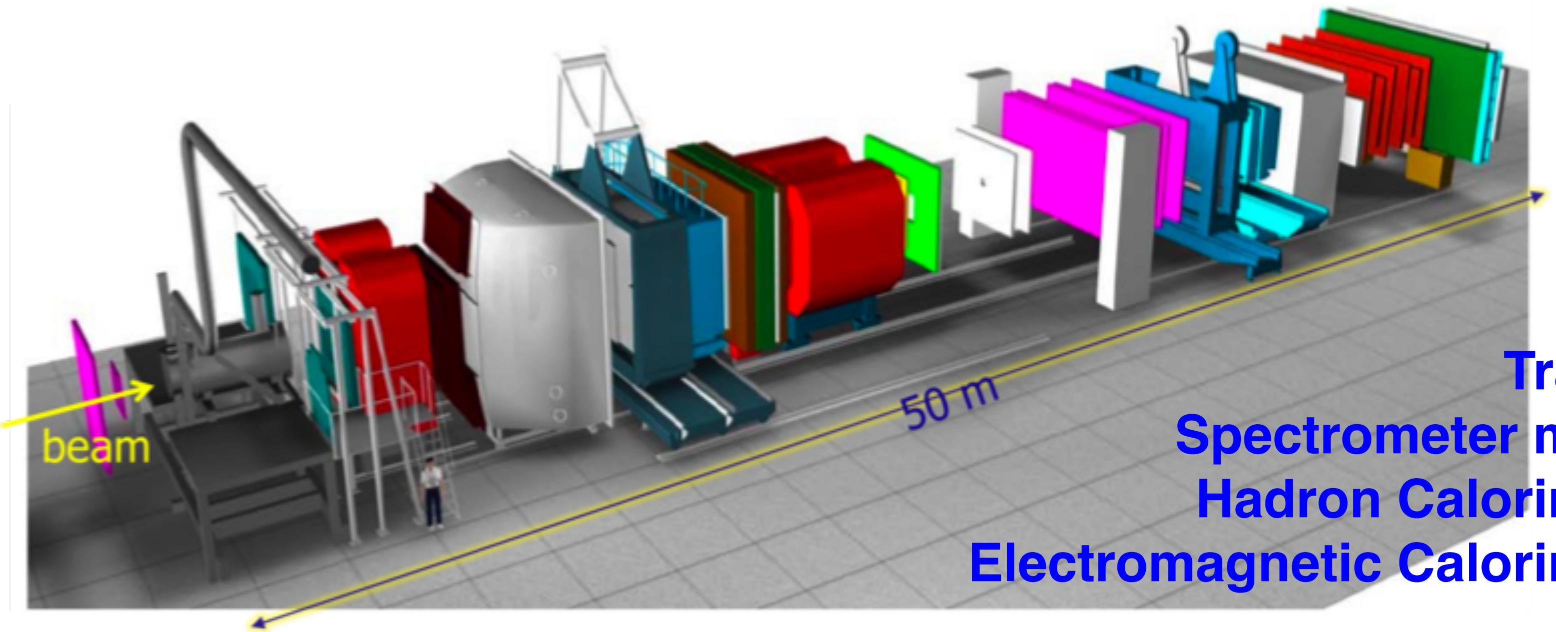
CERN and COMPASS



COMPASS set up



Trackers
Spectrometer magnet
Hadron Calorimeters
Electromagnetic Calorimeters

Beam :

Polarized lepton beam : μ^+, μ^- 50-280 GeV/c (80% polarization @ 160GeV)
Hadron beam : π^+,π, K^+, K^-,P

Target :

Polarized proton and deuteron target
Liquid hydrogen target
Nuclear target

Many combinations of the beam & the target

History of COMPASS PT

Bielefeld, Bochum, Bonn, Illinois, Helsinki, Lisbon, Nogoya, Prague, Sacley, Yamagata

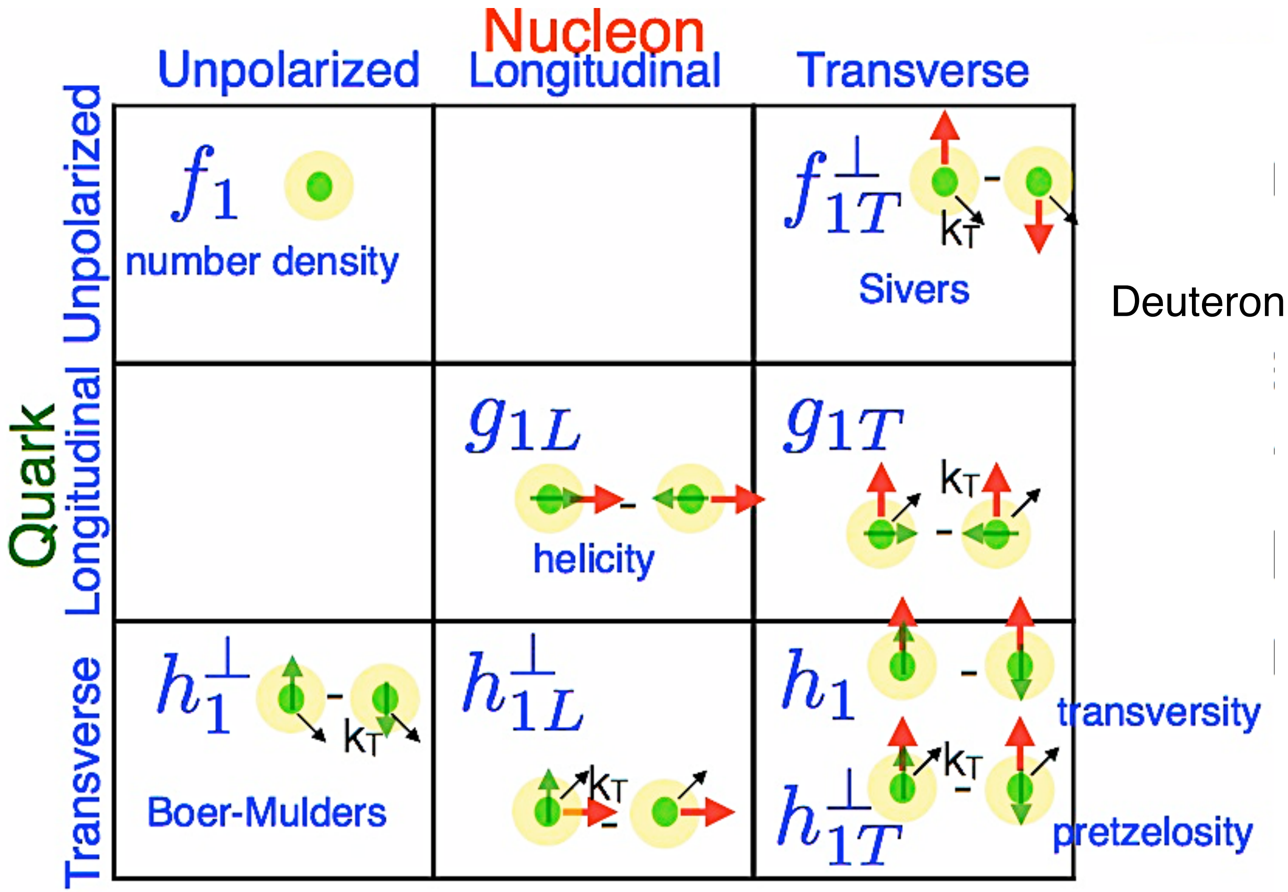
Year	Spin	Material	Cell configuration	Program (with muon beam)
2002 – 2004	L, T	^{6}LiD	L: 60-60 cm, D: 3 cm	$\Delta g/g$, TMD
2006	L	^{6}LiD	L: 30-60-30 cm, D: 3 cm	$\Delta g/g$
2007	L, T	NH_3	L: 30-60-30 cm, D: 4 cm	TMD, g1
2010	T	NH_3	L: 30-60-30 cm, D: 4 cm	TMD
2011	L	NH_3(new)	L: 30-60-30 cm, D: 4 cm	g1,A1 with 200 GeV muon
2014 - 2015	T	NH_3	L: 55-55 cm, D: 4 cm	TMD (DY with pion beam)
2018	T	NH_3	L: 55-55 cm, D: 4 cm	TMD (DY with pion beam)
2021 - 2022	T	^{6}LiD	L: 30-60-30 cm, D: 3 cm	TMD

Phase1 (2002 – 2011)

Phase2 (2014 – 2022)

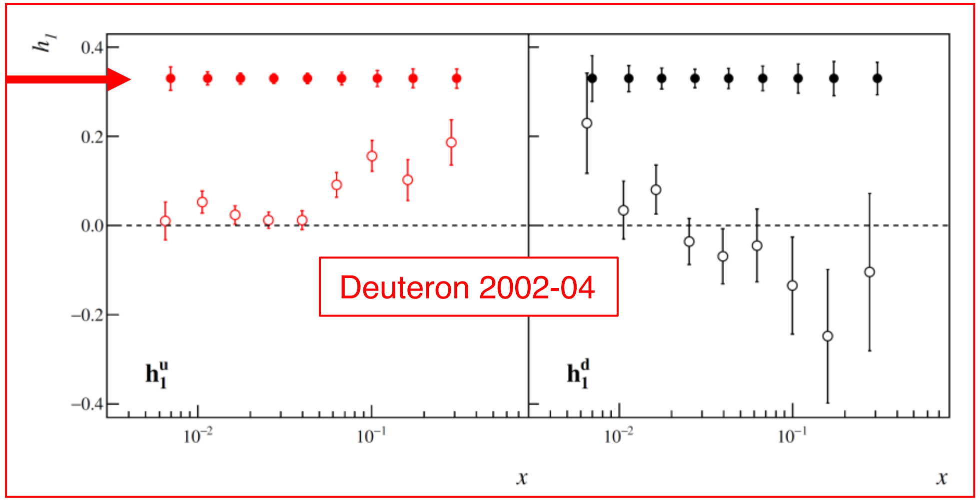
Transverse Momentum Dependent parton distributions

- 8 intrinsic transverse momentum dependent PDFs at LO
- Asymmetries with different angular dependences on hadron and spin azimuthal angles, ϕ_h and ϕ_s



Deuteron transiversity PDF (2002-2004)
Projected uncertainties for 2022

Deuteron 2022



Quark tensor charge ↔ transiversity

Quark Tensor Charge (TC)

Nucleon Electric Dipole Moment (EDM)

$$d_N = \delta u \cdot d_u + \delta d \cdot d_d$$

$d_{u,d}$ Quark EDM

$\delta u, \delta d$ Quark TC

- Quark EDM predicted by BSM
- Split-SUSY model : quark EDM ~ 10^{-29} e cm (arXiv: 1506.04196)
- Present nEDM(d_n) upper limit : $d_N < 2.6 \times 10^{-26}$ e cm
  → BSM effect not yet observed.

- Quark TC changes appearance of quark EDM.
  → Quark TC is important in determining the upper limit of quark EDM.
- Quark TC is related with Transversity PDF $h_1(x, Q^2)$

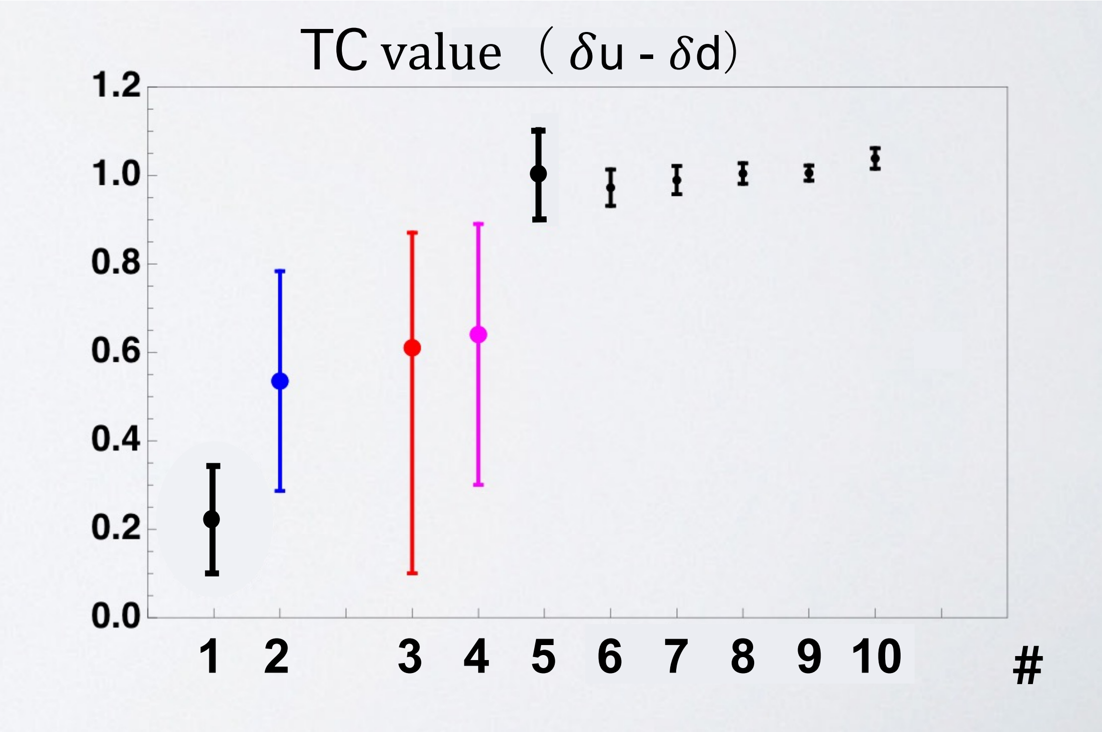
$$\delta q = \int_0^1 dx \left[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)\right]$$

Quark TC estimation

TC estimation

- <u>Analysis with experimental data</u>(#1-#4)
  COMPASS, HERMES, JLab
  → Large uncertainty:
  more data of Transversity d-quark needed
- Lattice QCD calculation (#5-#10)
- Differences btw both methods

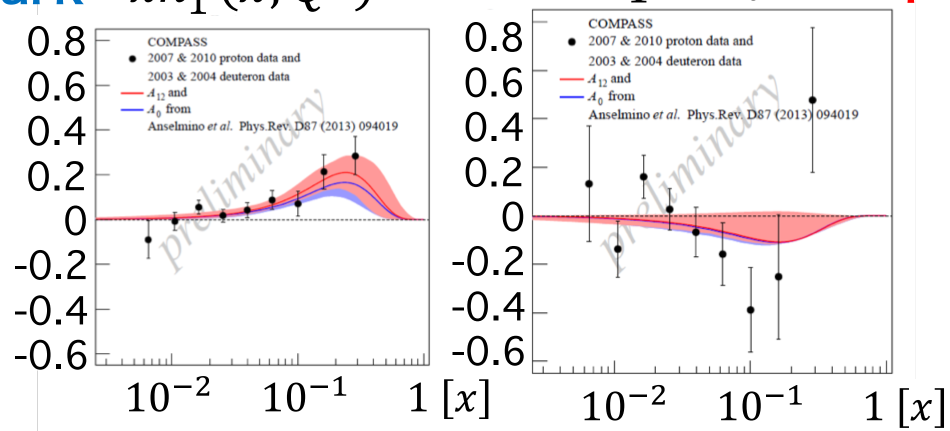
M. Radici PacSPIN2019



#1 : M. Radici PacSPIN2019
#2 : Radici, Bacchetta PRL 120 (18) 192001
#3 : Kang et al. PRD 93 (2016) 014009
#4 : Anselmino et al. PRD 87 (2013) 094019
#5 – #10 : Lattice QCD calculation

COMPASS Transversity results

u-quark $xh_1^u(x;Q^2)$ $xh_1^d(x;Q^2)$ d-quark



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COMPASS PT system

Dilution refrigerator

- 50mK
- 350mW cooling power at 300mK

Magnet

- 2.5T solenoid（Polarization、longitudinal）50 ppm homogeneity
- 0.6T dipole（Transverse）
- 180mrad acceptance

Target cell

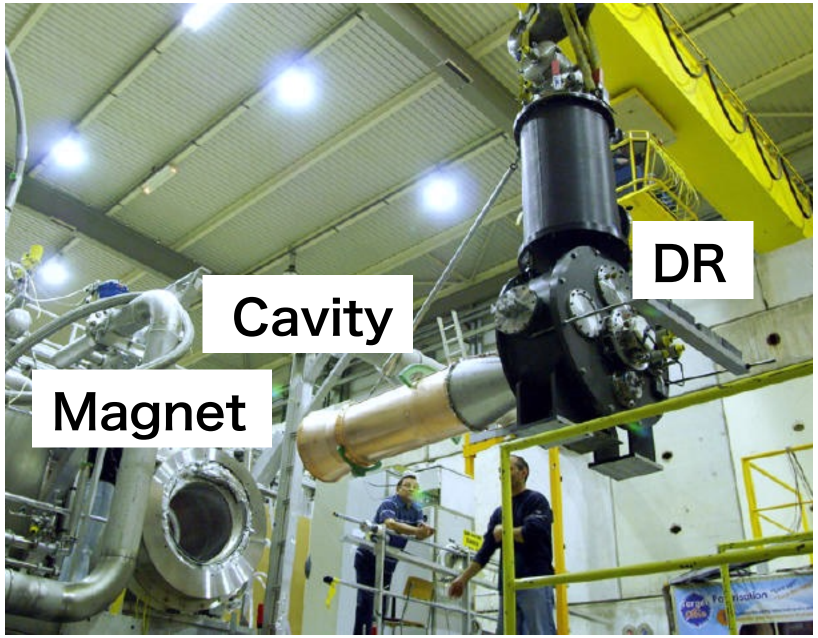
- 3 cells (30, 60, 30cm long)
  or 2 cells (55, 55 cm long)
- Diameter 3 or 4 cm

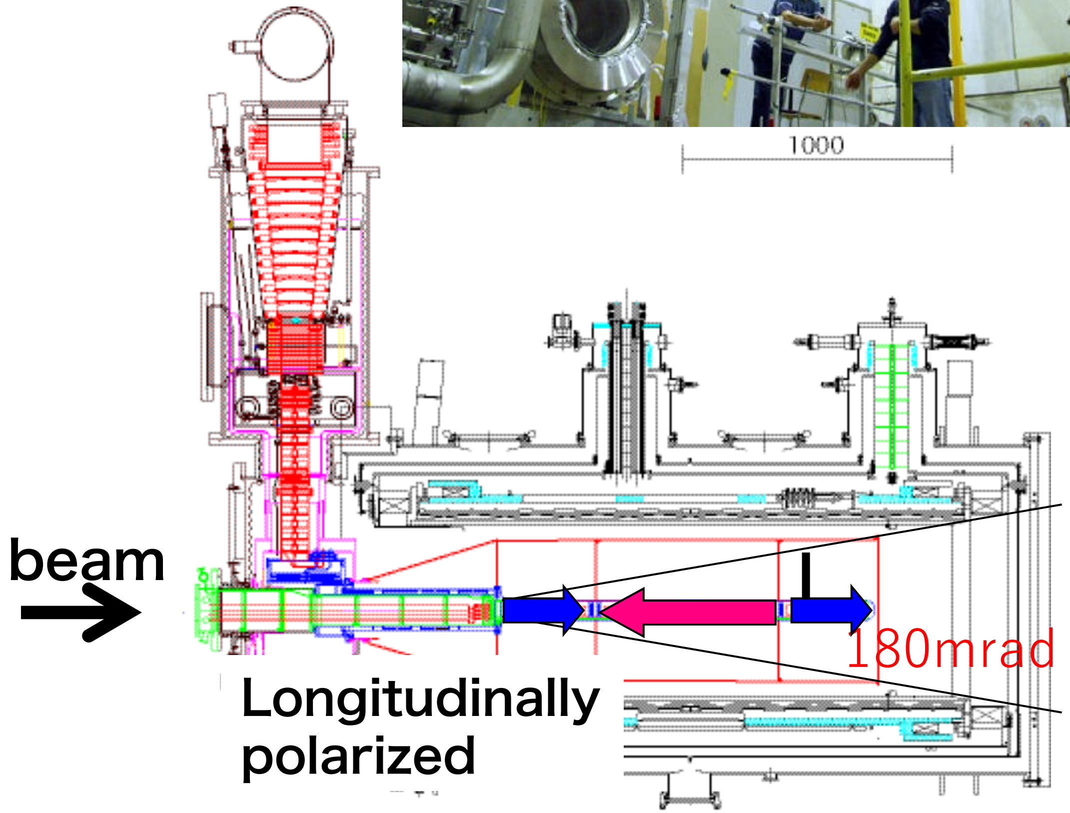
Microwave

- 2 sets of EIO (20W)
- 3 sets of Gunn Diode (3W)

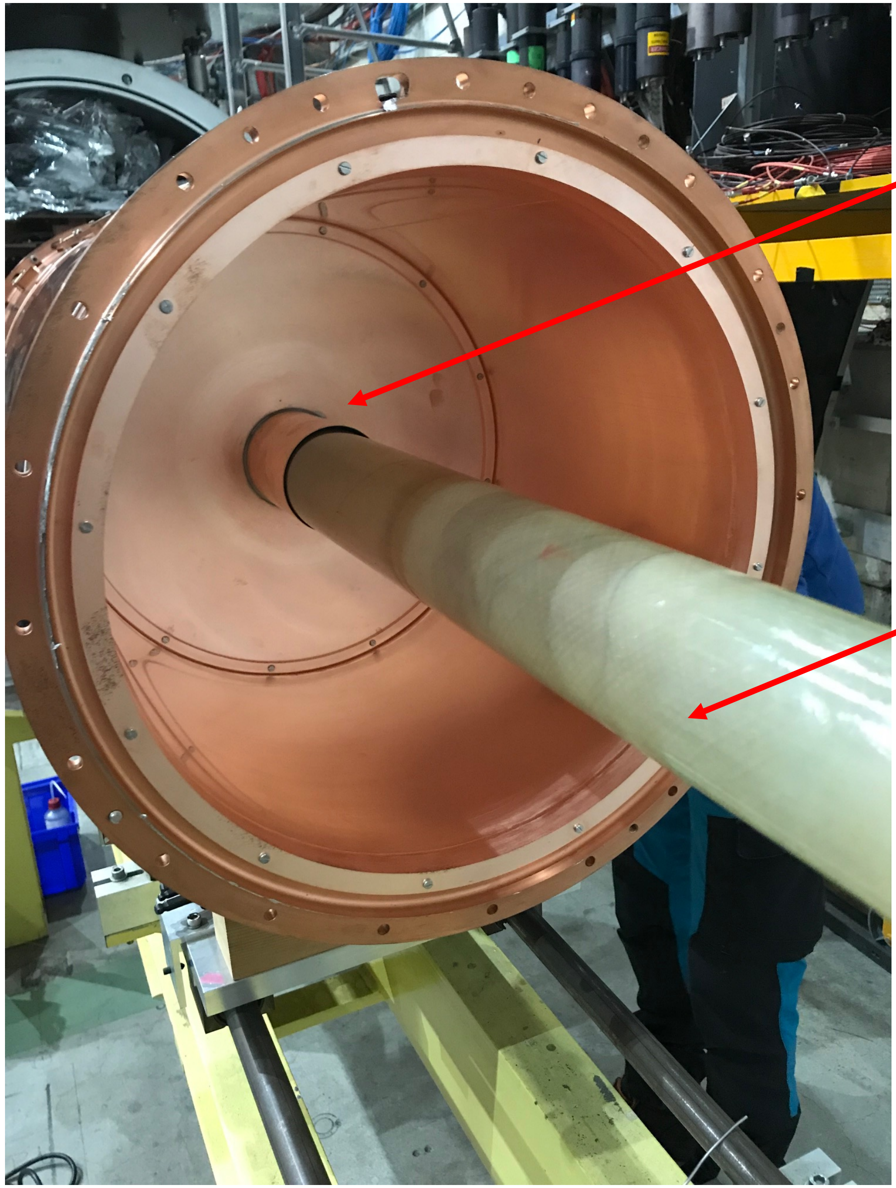
NMR

- 10 cannels (3, 4, 3) or (5,5)





Microwave cavity for 3 cells



Up/central separation

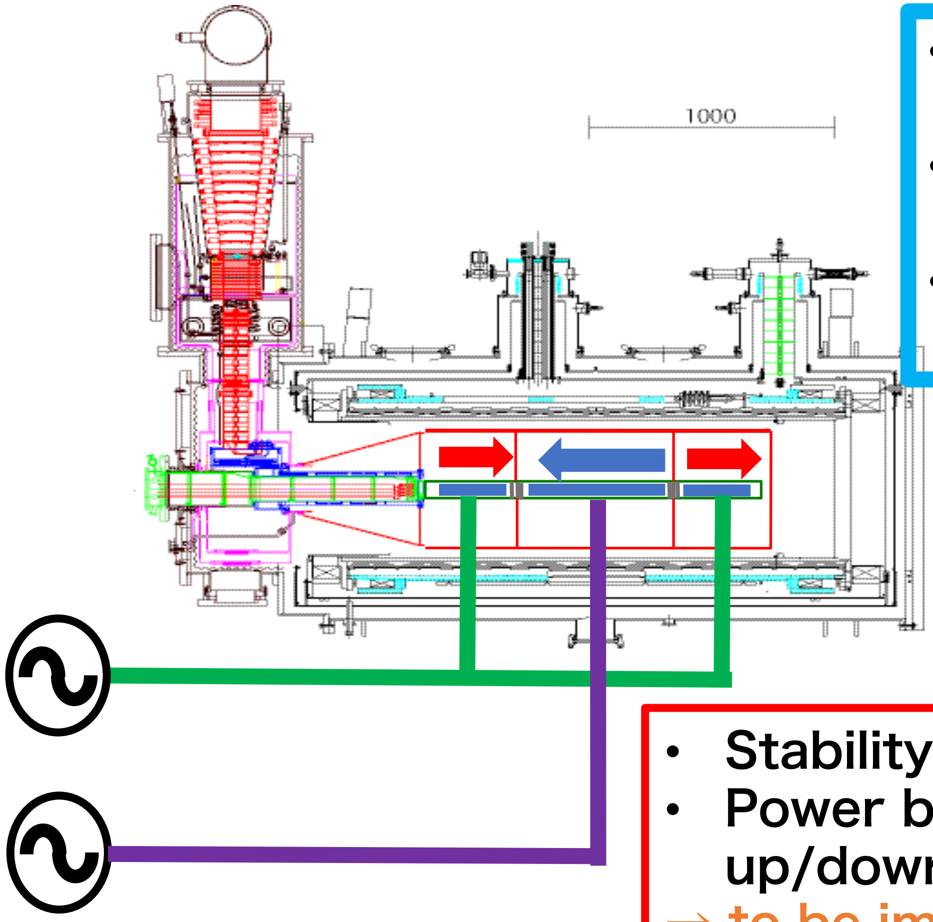
Mixing chamber

Refrigerator

Downstream of mixing chamber

EIO microwave system

Gunn system in 2022

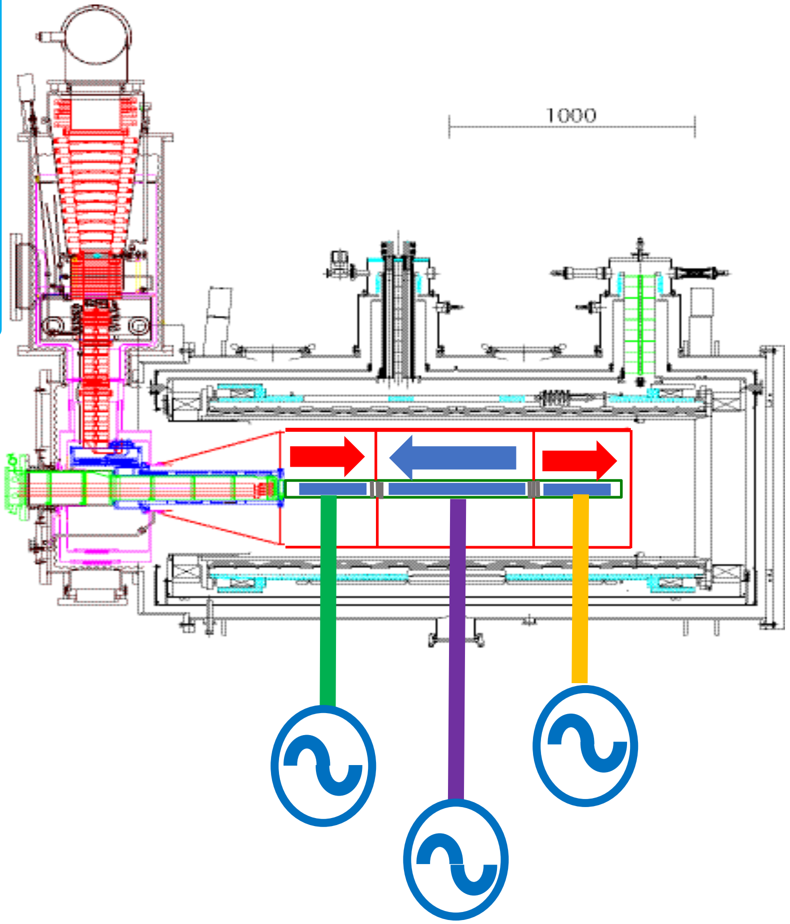


- Polarization : pos. & neg.
  (two different frequency)
- 100-200 mW power required for each cell
- Frequency and power adjustment

- **Stability of frequency**
- **Power balance of up/down**

→ to be improved

20W EIO (70GHz)
20m long waveguide

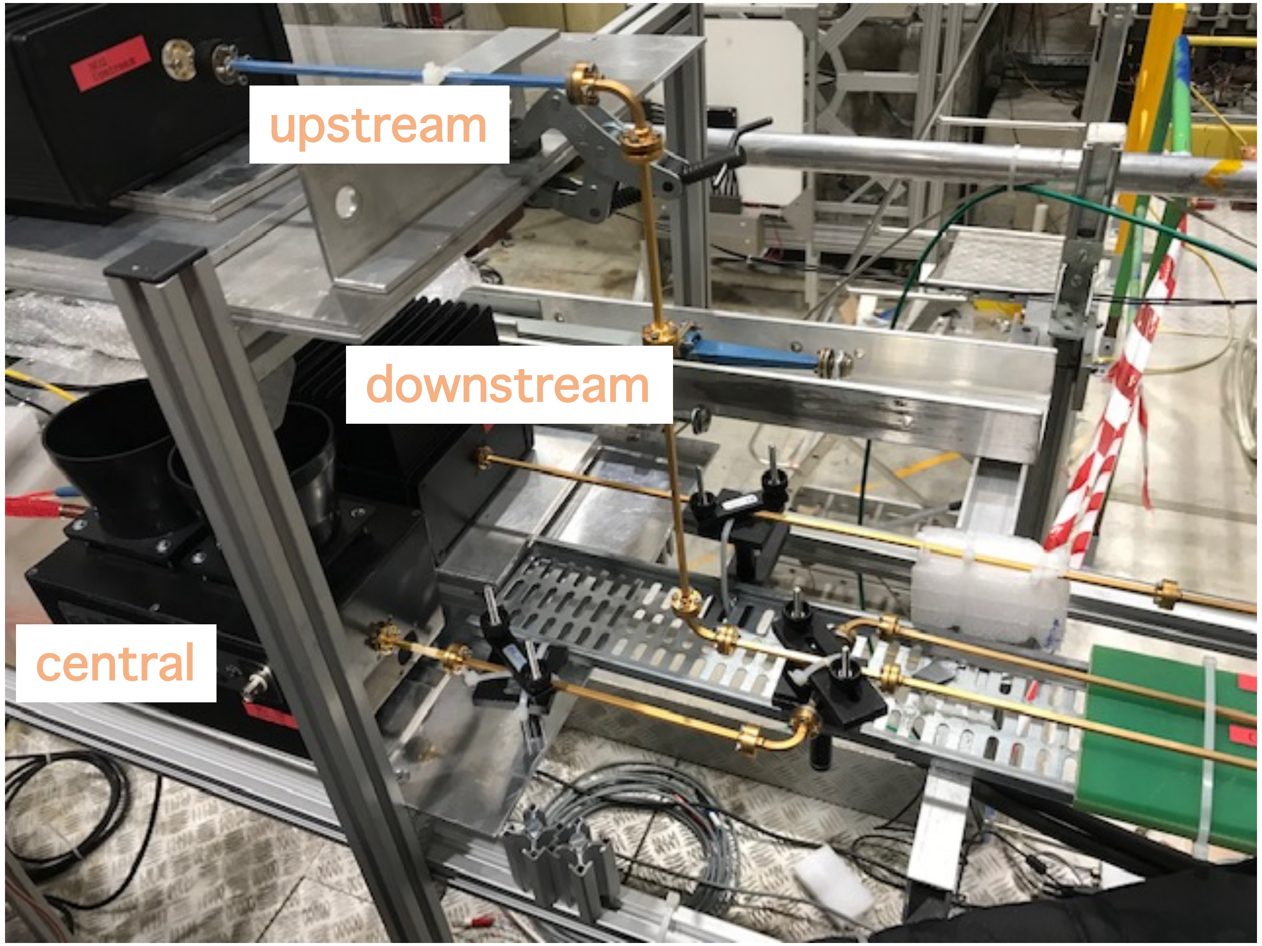


Three Gunn Diode 3W （ELVA-1）
1.5m long waveguide

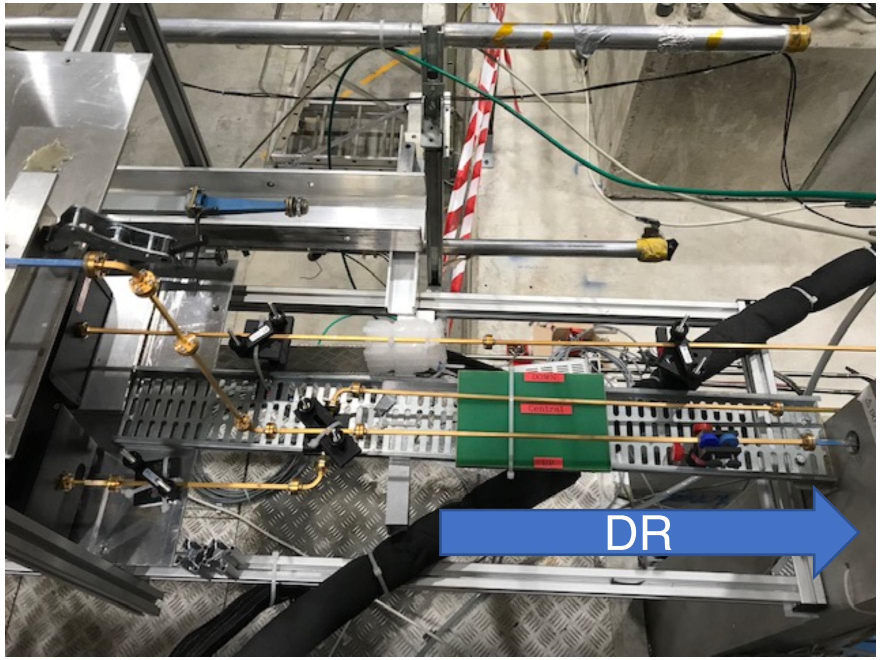
Microwaves

ELVA-1
3 W power

1.5 m far from DR
Cannot be closer due to fringing field



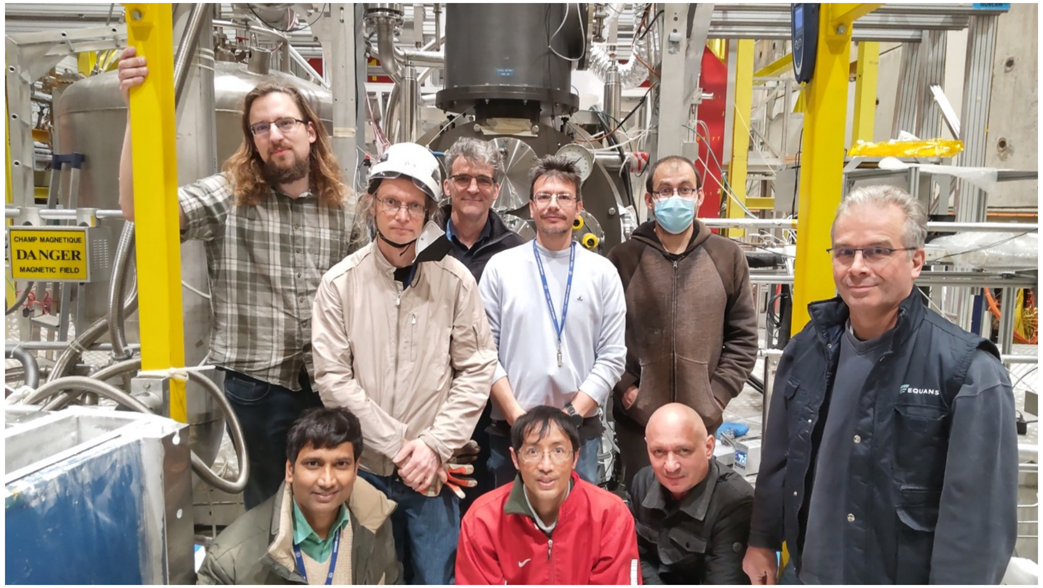
Generation test in 2020



Target material loading

- About 400 g of 6LiD material in to 3 cells in 2022
- Material irradiated in 2000
- Storage in LN2 dewar
- Loaded under 80 K
- Collect materials for each cell independently after the data taking

Loading done in the LN2 bath



Deuteron target materials

Figure of Merit

$$PT_{FoM} = f^2 \times P_T^2 \times \rho \times F_f$$

f : dilution factor
ρ : density
F_f : packing factor

	ND_3	D- butanol	^6LiD
P_T	0.30 – 0.40	0.80 **	0.55 (D) 0.54 (^6Li)
ρ	1.00	1.12	0.820
f	0.300	0.238	0.250 (D) 0.250 (^6Li)
F_f	0.58	0.62	0.52
PT_{FoM}	1 – 1.8	5.4	6.9

-Normalized by ND_3 .
-Magnetic field 2.5T
- Relaxation time
^6LiD 1500h at 0.42T and 60 mK.

** S.T. Goertz et al, NIM. A 526 (2004) 43.

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Dynamic Nuclear Polarization (DNP)

Polarization P of spin ½ at thermal equilibrium (boltzmann distribution)

$$P = tanh\left(\frac{\mu B}{K_B T}\right)$$

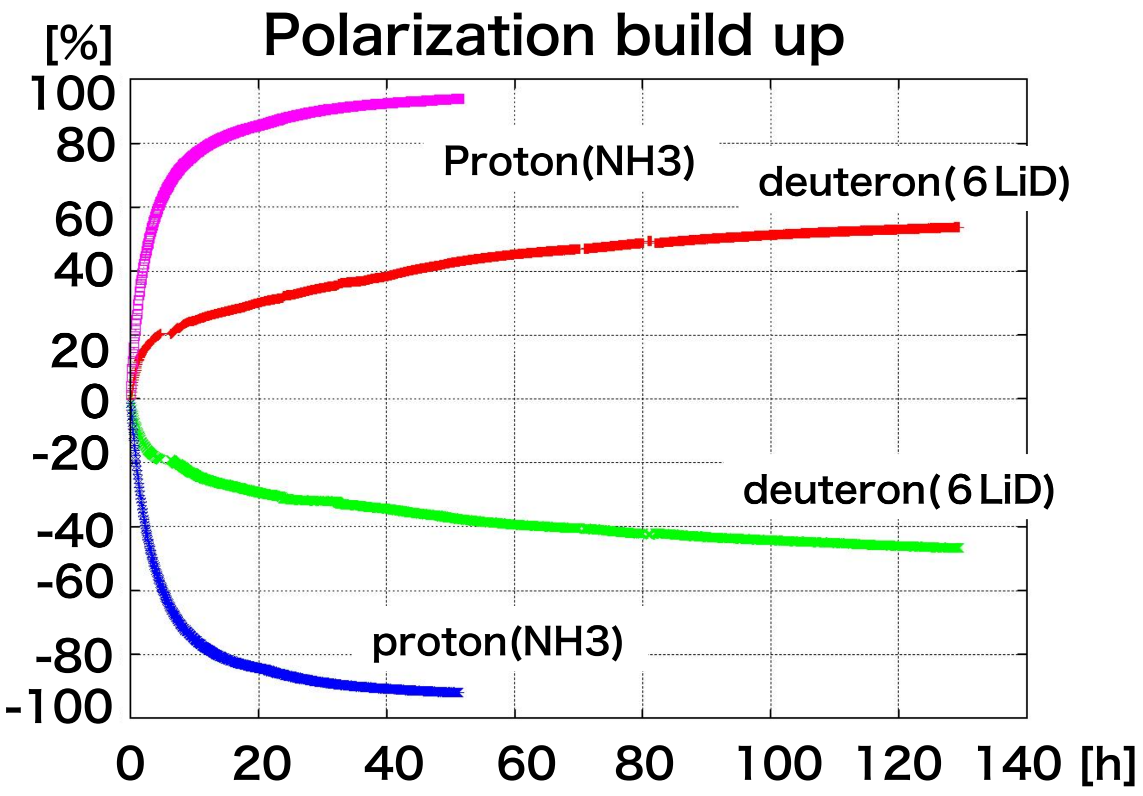
μ : magnetic moment
B : magnetic field
K_B : boltzmann constant
T : temperature

Polarization at thermal equilibrium@2.5T

	electron	proton	deuteron
4.2 K	66.4 %	0.061 %	0.012 %
1.0 K	99.8 %	0.26 %	0.052 %
0.1 K	99.9 %	2.6 %	0.52 %

DNP: Transfer the high electron polarization to nucleon by MW

- Free radical dope to Material (NH_3、^{6}LiD)
- Electron spin relaxation ＜ Nucleon spin relaxation



DNP(@2.5T)
Polarizing
longitudinally

Data taking(@0.6T)
Transversal position

TE analysis for deuteron in 2022

1 % accuracy
In total a few %

Polarization determination at DNP

$$P = E \cdot S$$

The enhancement factor can be measured
By TE calibration at 2.5 T.

$$P_{TE} = ES_{TE}$$

$$S_{TE} = \frac{1}{E} P_{TE}$$

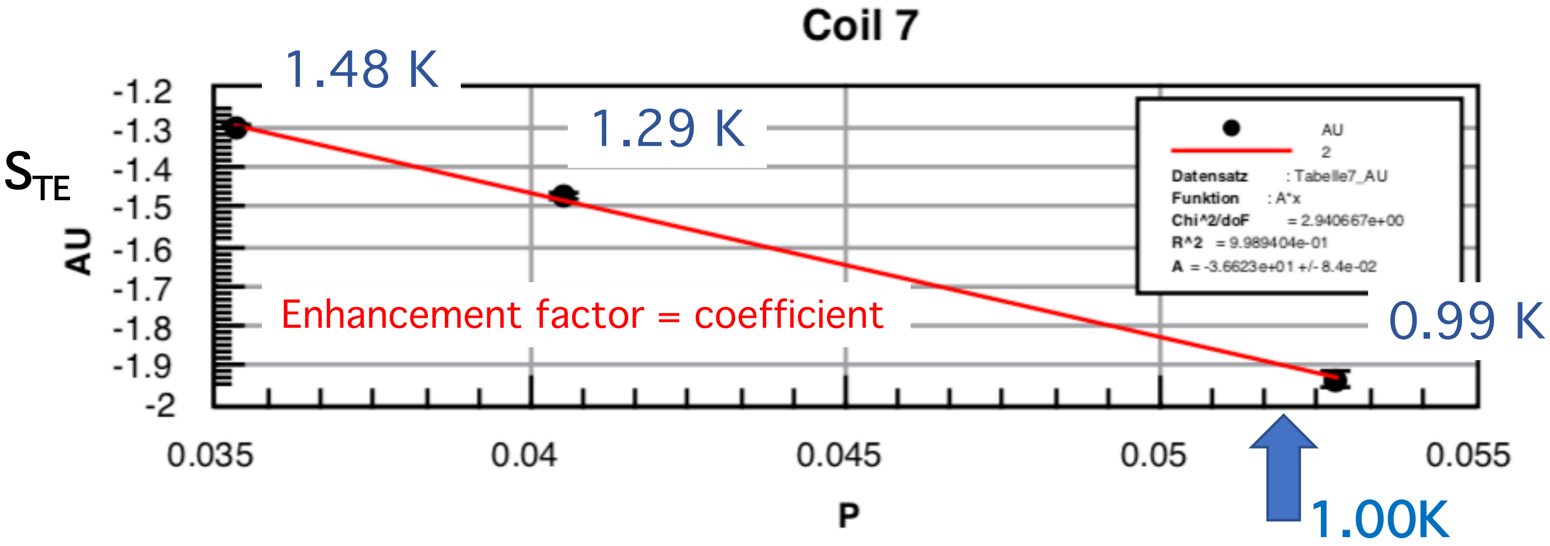
$$P_{TE=1K} = 0.0522789\ \%$$

$$P_{DNP} = ES_{DNP}$$

Polarization can be determined
with DNP NMR signal.

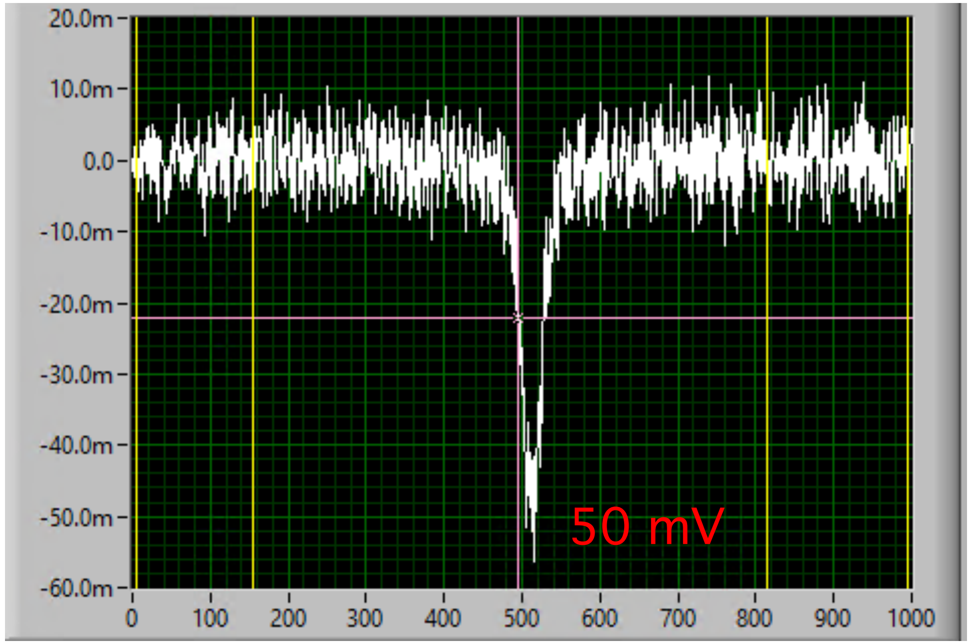
E = Enhancement factor

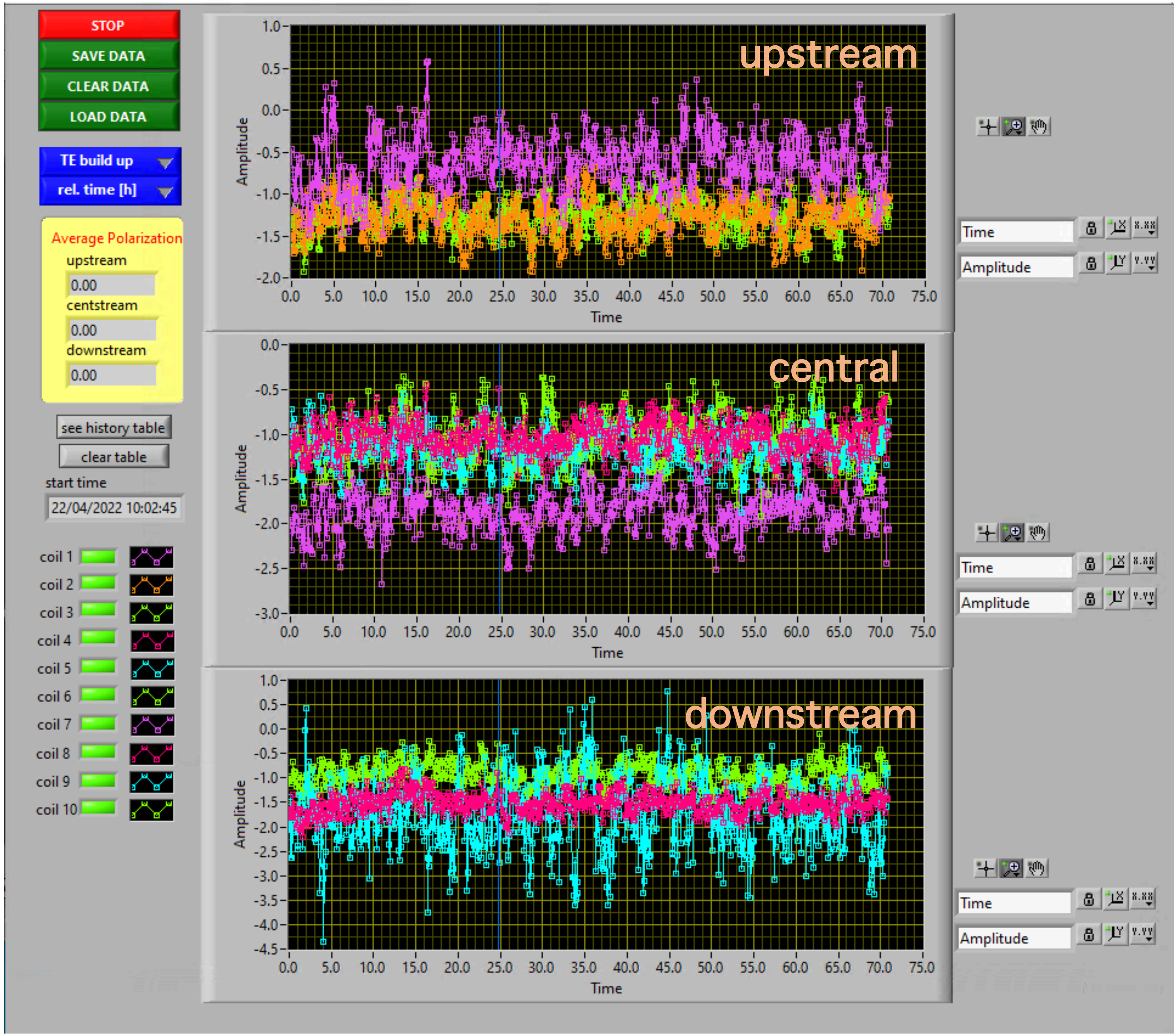
Coil	1/E	d1/E	d1/Erel	E	dE
1	-10.47	0.12	-1.2	-0.09548	0.0011
2	-24.53	0.11	-0.47	-0.04077	0.00019
3	-24.31	0.074	-0.3	-0.04113	0.00013
4	-19.87	0.077	-0.39	-0.05033	0.0002
5	-22.36	0.097	-0.43	-0.04472	0.00019
6	-20.39	0.079	-0.39	-0.04905	0.00019
7	-36.62	0.084	-0.23	-0.0273	6.3e-05
8	-29.83	0.073	-0.25	-0.03352	8.2e-05
9	-31.9	0.12	-0.37	-0.03135	0.00012
10	-17.13	0.1	-0.59	-0.05836	0.00034



TE deuteron NMR measurements (1.0 K)

Coil #7 at 1.0 K

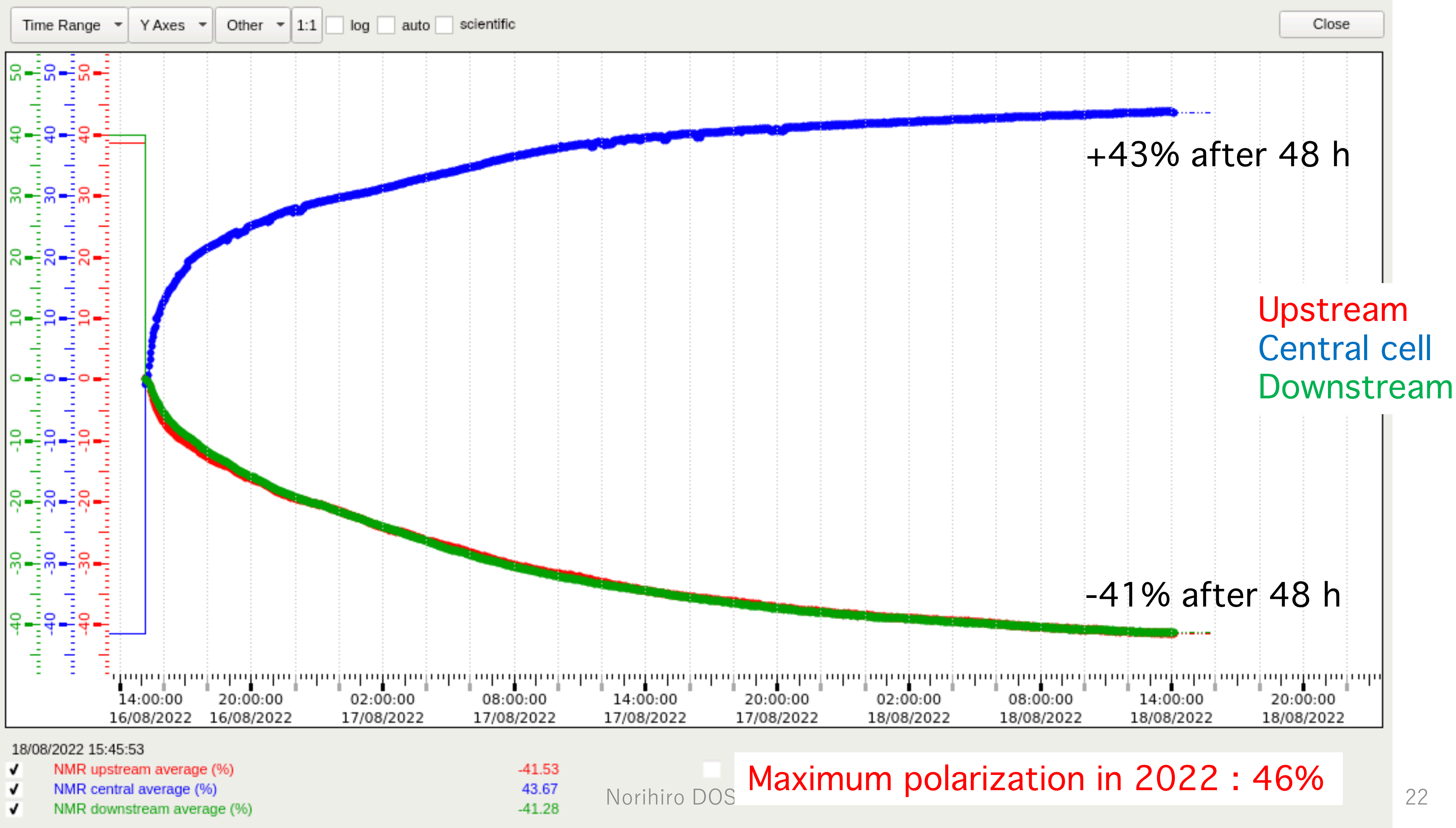




Gain factor measurement

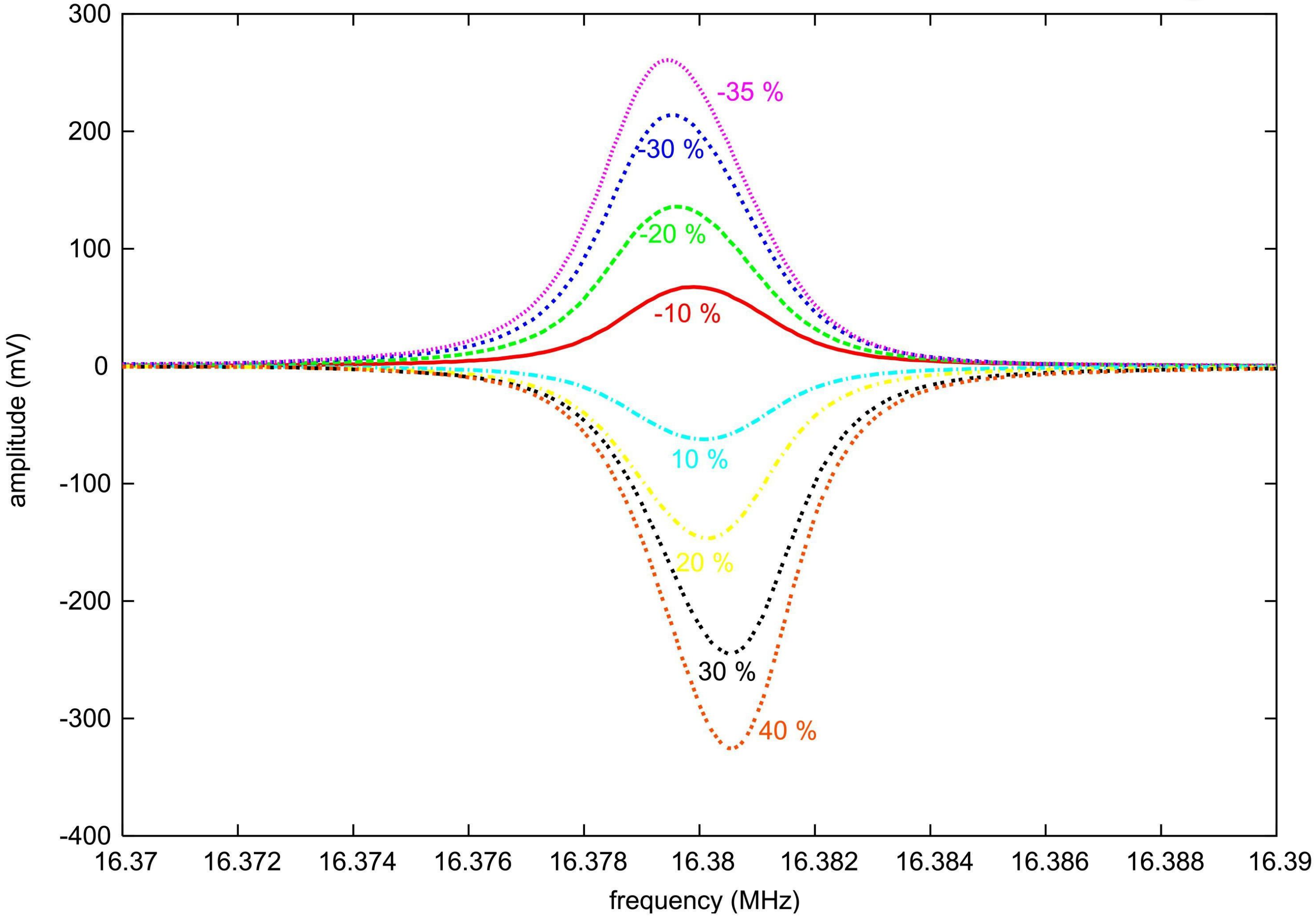
coil	gain2015/2018	gain2022	2022/2015	cell average
1	216.201	214.12	0.990	
2	214.013	213.13	0.996	1.000
3	211.979	214.86	1.014	
4	213.52	214.38	1.004	
5	212.402	207.29	0.976	
6	211.6	208.94	0.987	0.995
7	213.843	216.14	1.011	
8	212.995	211.61	0.993	
9	215.306	211.09	0.980	0.994
10	213.928	215.77	1.009	

Polarization build up in 2022 (Deuteron)

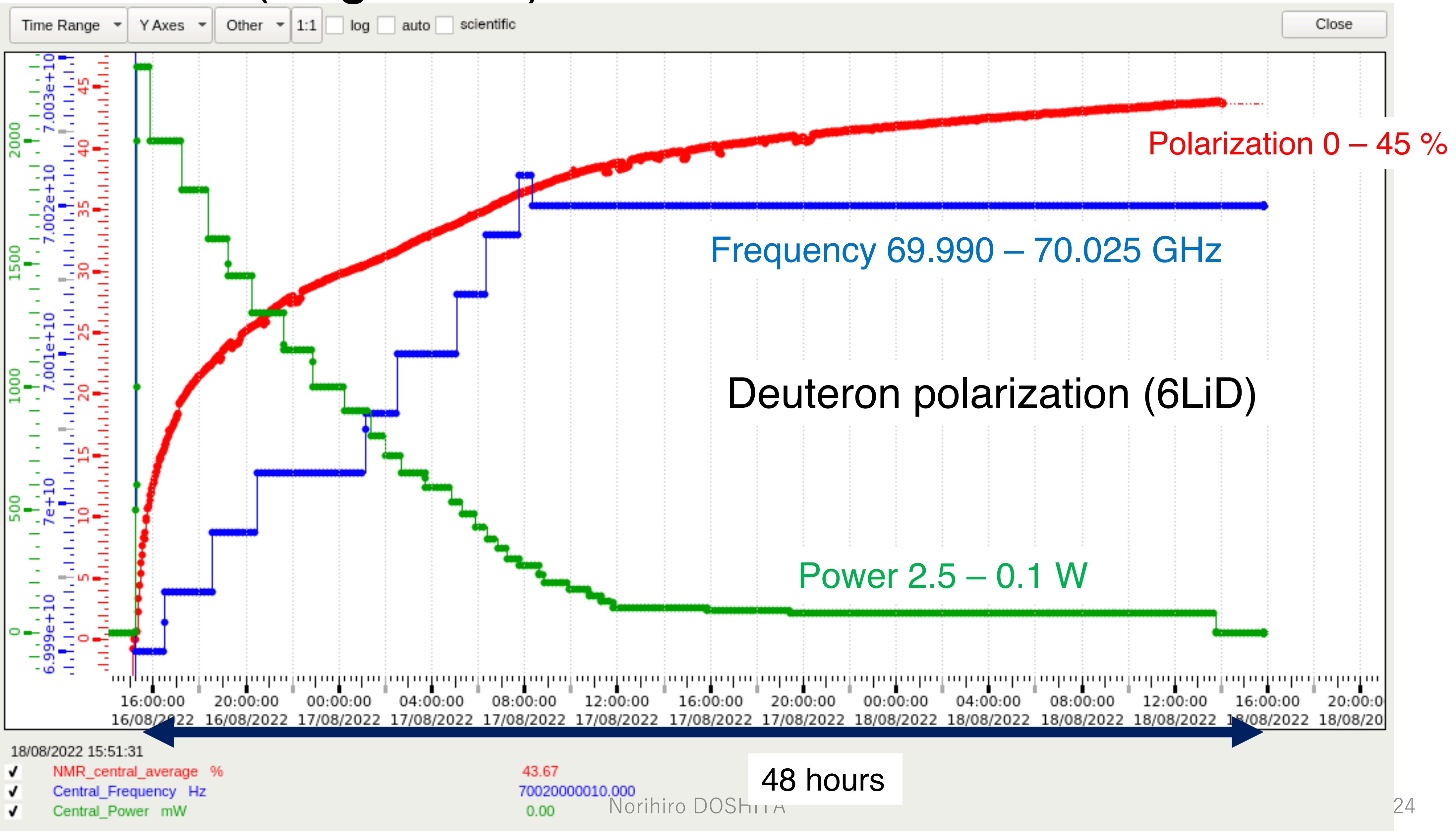


Maximum polarization in 2022 : 46%

Enhanced deuteron NMR signals



Central cell (Aug. 2022)



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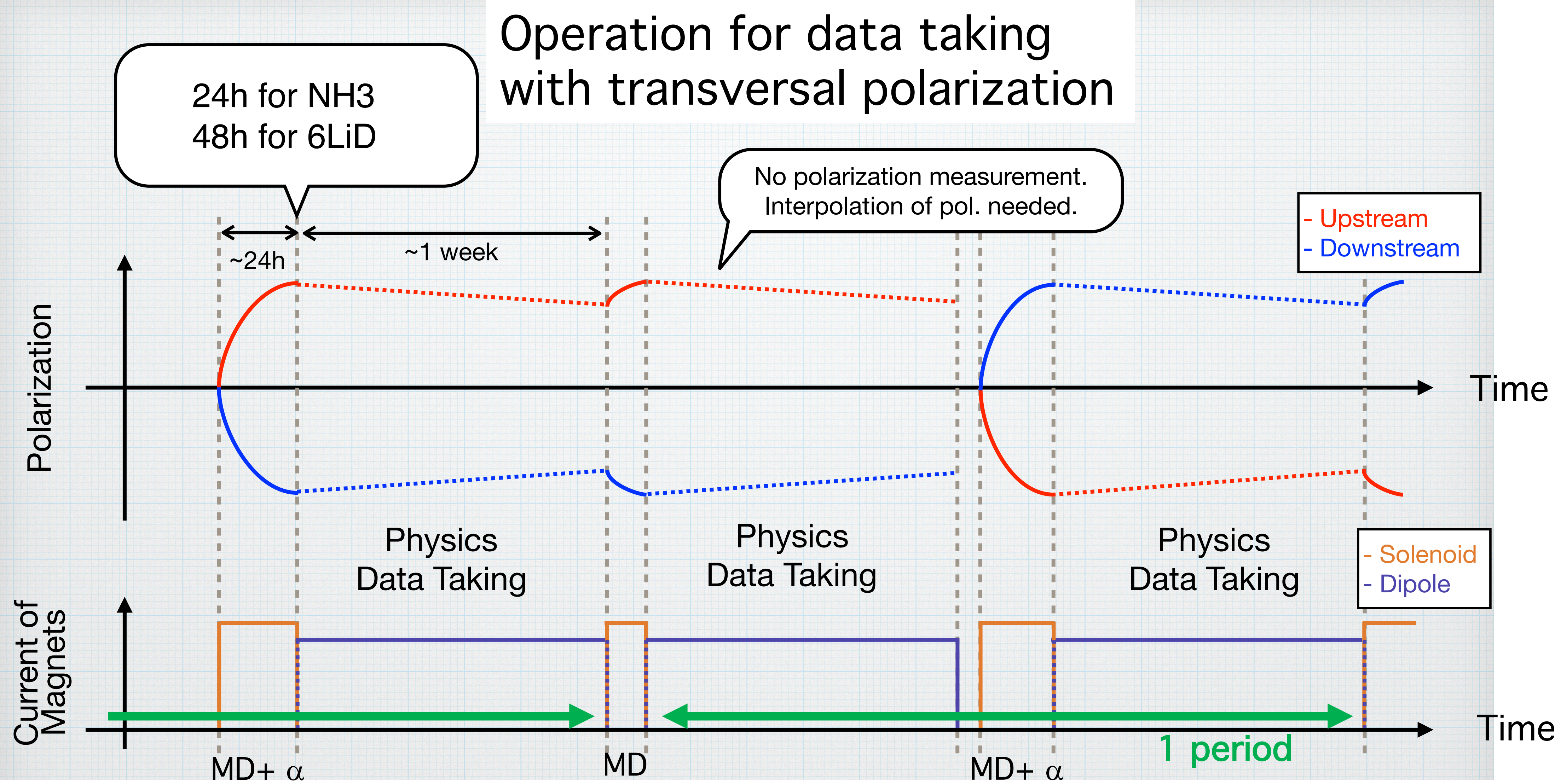
Operation for data taking with transversal polarization



Beam intensity : 10^8 /s for 5 s and then no beam for 10 s or more in 2018

Relaxation time

Temperature ~60mK

production	Material	Magnetic field	Relaxation time
2002 - 04	^{6}LiD	2.5 T	>15000 h
2006	^{6}LiD	1.0 T	~ 10000 h
2002 - 04	^{6}LiD	0.4 T	~ 1500 h in 2004
2022	^{6}LiD	0.6 T	~ 3000 h for +, ~ 5000 h for -
2007	NH_3 (SMC)	0.6 T	~ 4000 h
2010	NH_3 (SMC)	0.6 T	~ 9000 h
2015	NH_3	0.6 T h-beam	~ 1200 h for + , ~ 1000 h for -
2018	NH_3	0.6 T h-beam	~ 1200 h for + , ~ 1000 h for -
2018	NH_3	0.0 T	~ 11 min. for positive ~ 7 min. for negative

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EST Concept

- Equal Spin Temperature

  -- Spin temperature can be applied during DNP.

  -- The spin temperature is shared with other nuclei.

- Polarizing deuteron at first
- Measured 6Li and 7Li polarization

→ Support the EST concept

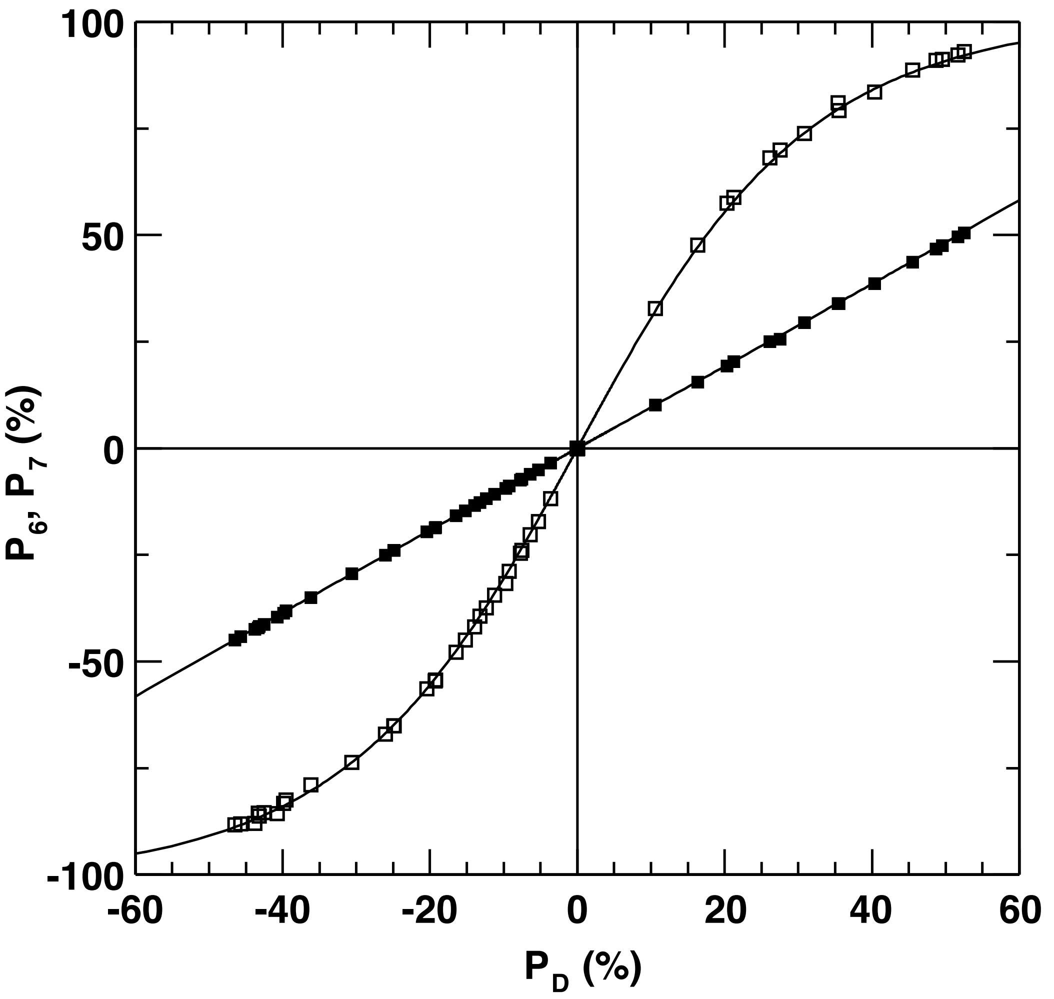


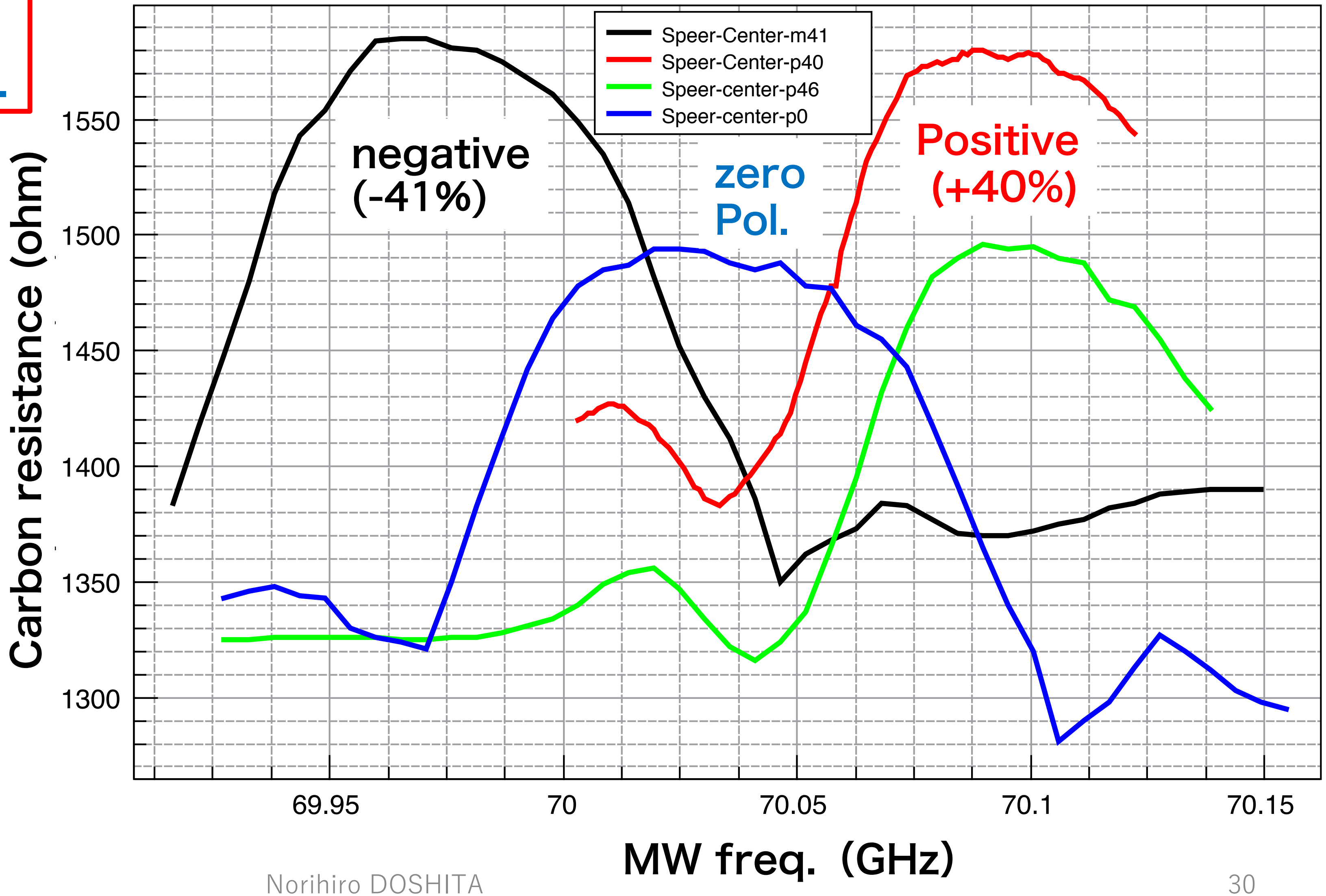
Fig. 6. The polarizations of the ^{6}Li and the ^{7}Li nuclei versus that of the deuteron. The closed (open) squares are the measured polarization of ^{6}Li (^{7}Li). The lines are the prediction by EST concept. The measurements are consistent with the EST concept.

NIMA498(2003)101

EPR (Electron Paramagnetic Resonance)

Carbon temperature sensor
：absorption of MW
：high resistance=low temp.

Frequency dependence of MW absorption by 6LiD



condition

- MW power is constant
- Scanning magnetic field
- Mag. field corresponds to MW freq.
- MW Absorption : DNP → increasing resistance

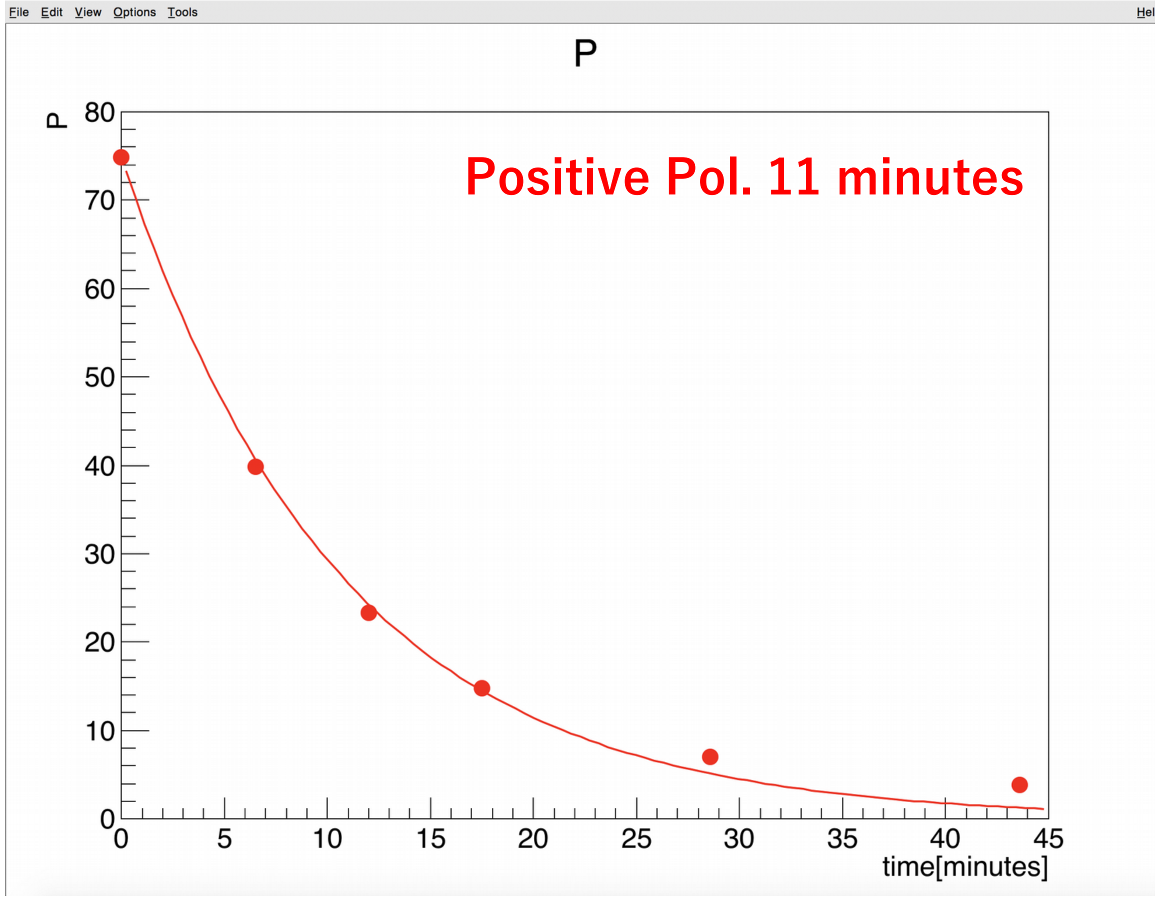
Optimization of DNP

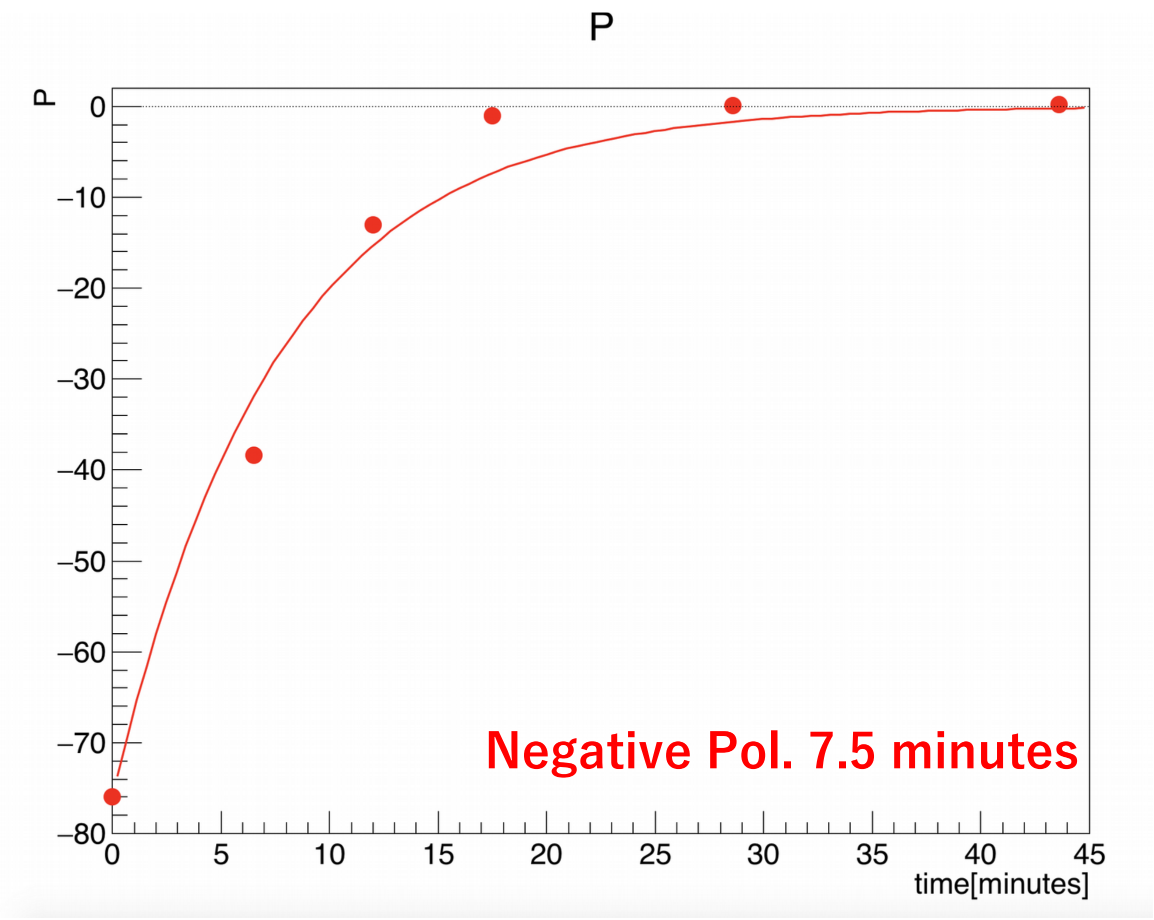
Summary

- COMPASS PT has been running for 20 years.
- 2.5 T and 100 mK combination
- 6LiD have been used as deuteron target material.
- Property of material slightly changed.
  - longer build up time, longer relaxation time
    - -- difference of positive and negative polarization

Back up

Relaxation time at 0 T



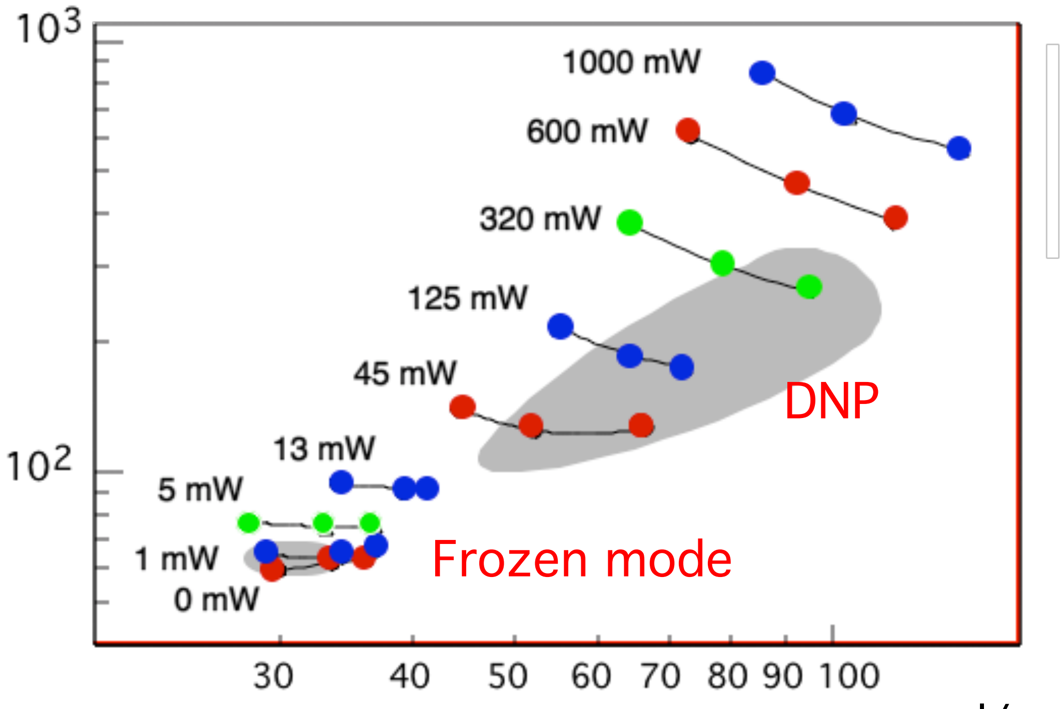


Dilution refrigerator

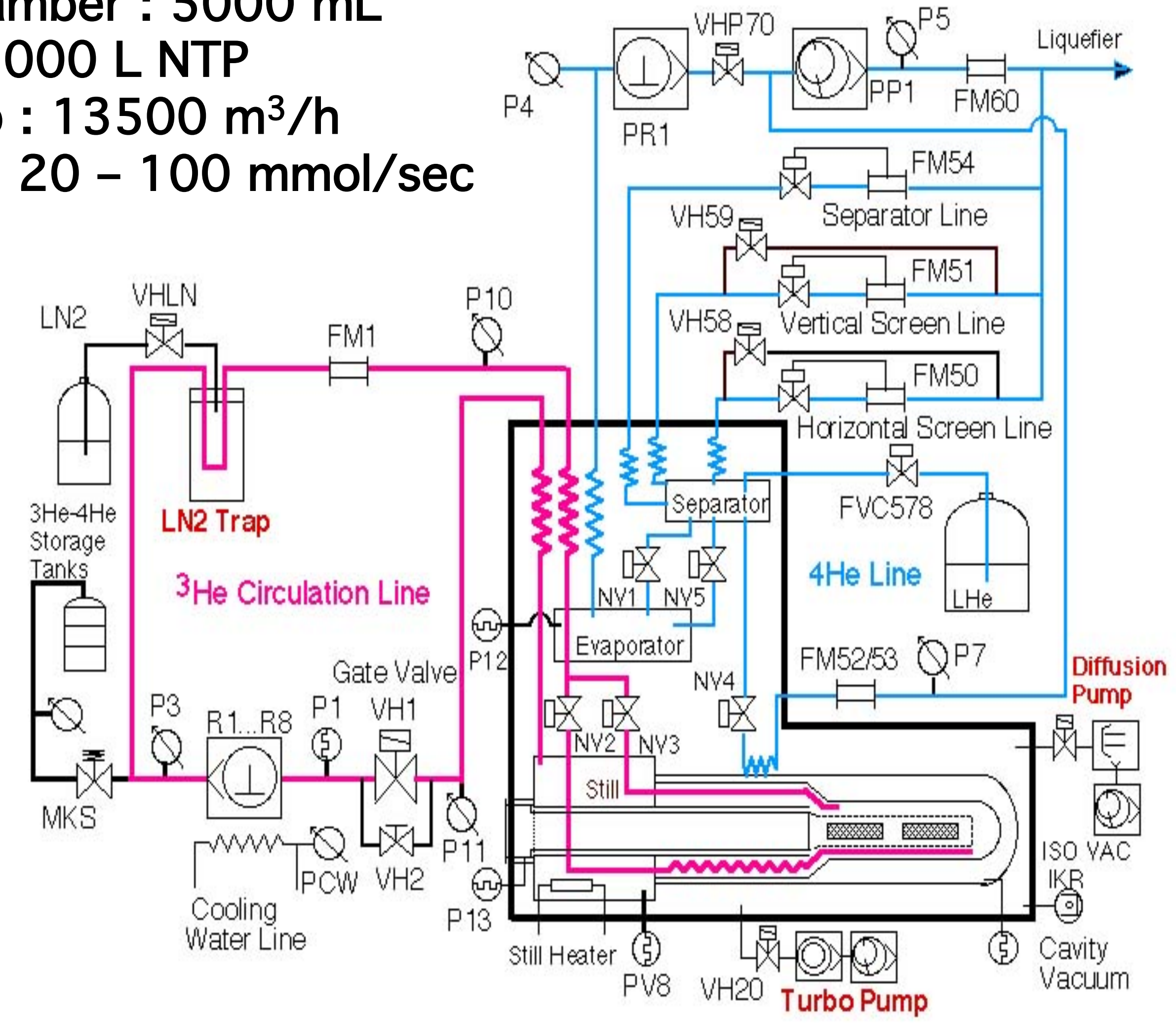
- Min. temperature : 50 mK
- Mixing chamber : 5000 mL
- 3He gas 1000 L NTP
- 3He pump : 13500 m³/h
- 3He flow : 20 – 100 mmol/sec

Refrigerator Temp. [mK]

Cooling power



mmol/sec



Accuracy of Polarization

proton 2015 and 2018

Deuteron 2003

Table 3
Error ($\Delta P/P$) estimated for the polarization measurement in 2003

	upstream (%)	downstream (%)
TE calibration error	3.38	1.84
Circuit nonlinearity	<0.5	<0.5
Enhanced signal fitting	0.1	0.1
Field polarity	0.2	0.2
Field shift	0.18	0.07
Q-curve off-centering	0.15	0.17
LF gain variation	0.087	0.037
Subtotal	3.43	1.83
Microwave effect	0.1	0.1
Total	3.5	1.9

tic uncertainty	
ity	
Q-curve for TE	
-curve for enhanced signal	
g	
nal	
surement	0.8
	3.2

Table 1: Results of the TE calibration and the empty cell measurement in 2015 and in 2018.

	2015		2018	
Coil #	Calibration constant	Statistical error (%)	Calibration constant	Statistical error (%)
1	-38.13	0.52	-55.38	0.41
2	-17.71	1.70	-21.40	0.90
3	-27.36	0.47	-47.26	0.33
4	-21.33	1.14	-23.73	1.79
5	-33.40	0.22	-43.10	0.39
6	-15.06	1.20	-13.39	0.98
7	-9.00	1.77	-18.63	1.18
8	-17.55	0.36	-33.67	0.43
9	-14.70	0.58	-13.91	1.26
10	-36.22	0.37	-42.25	0.57