The COMPASS 6LiD polarized target in 2022

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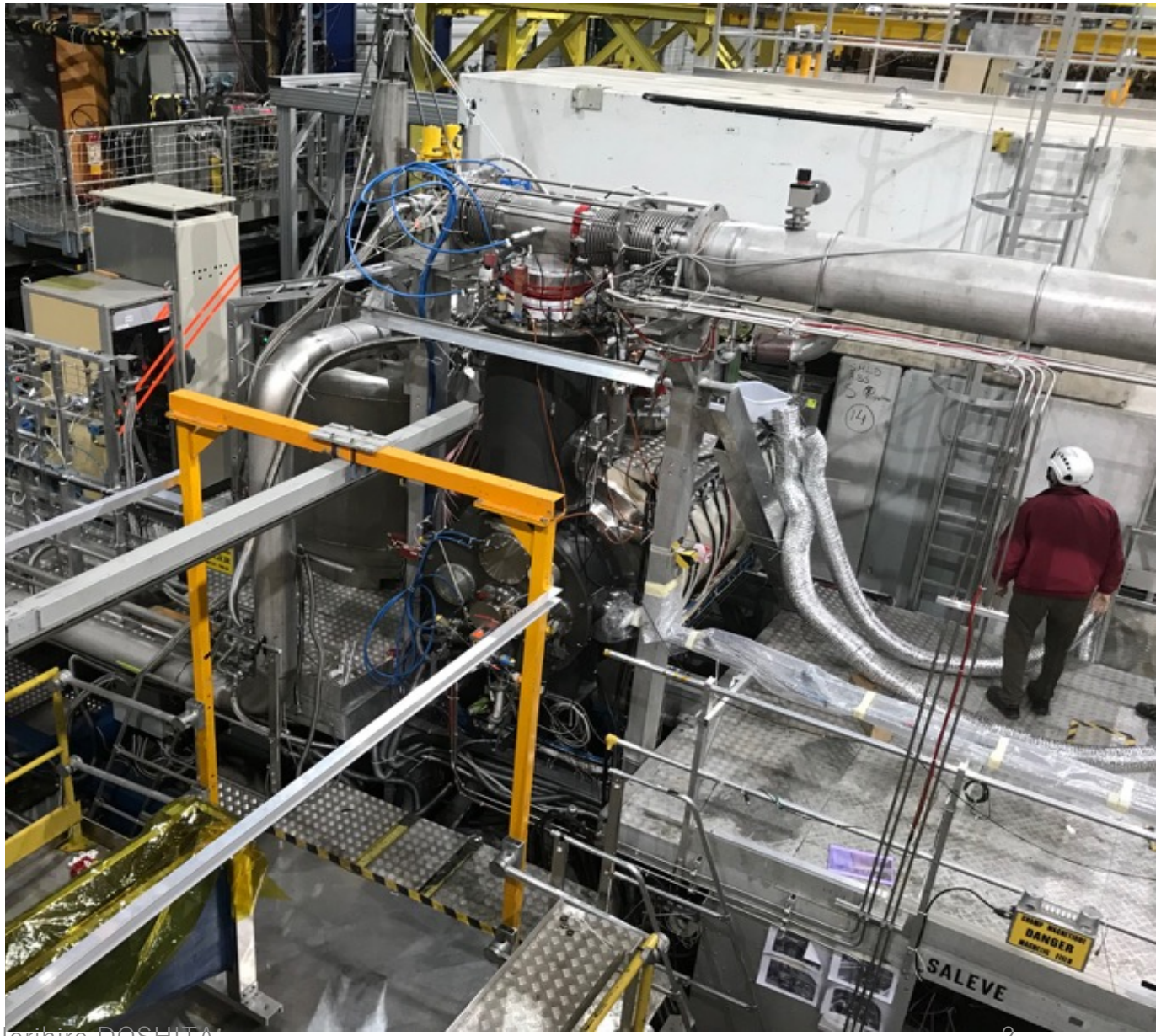
Strong 2020 CryPTA Boppard
Sep. 22 2022

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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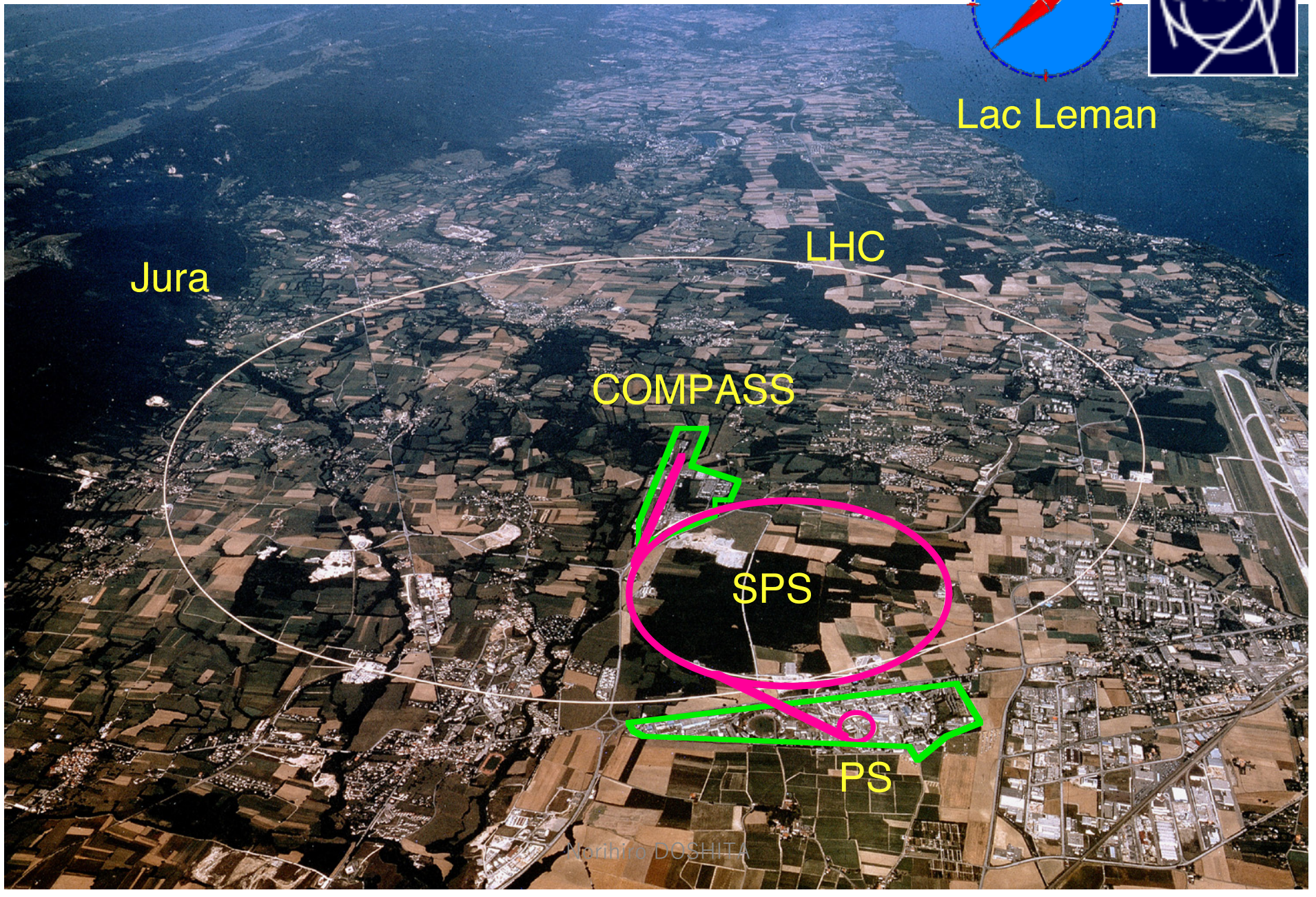
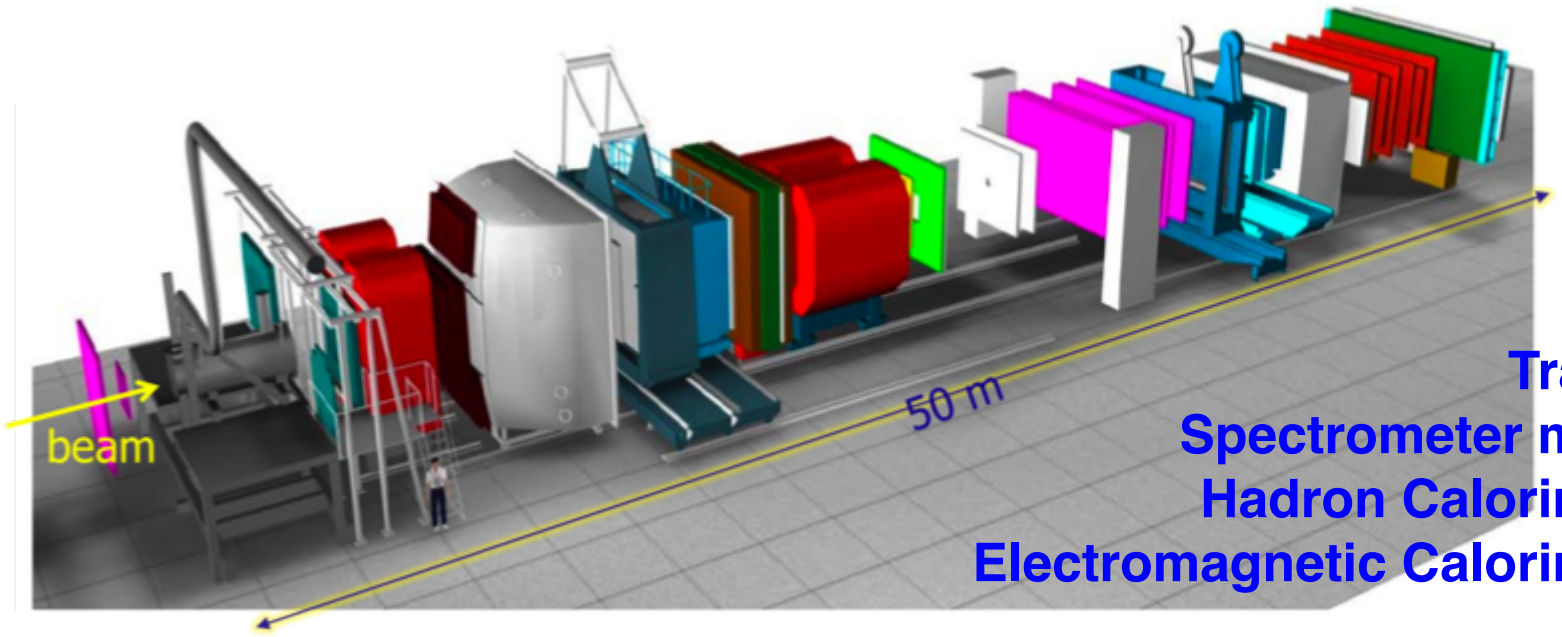
CERN and COMPASS



COMPASS set up



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

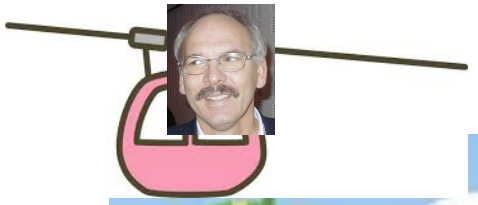
History of COMPASS PT

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

Phase2



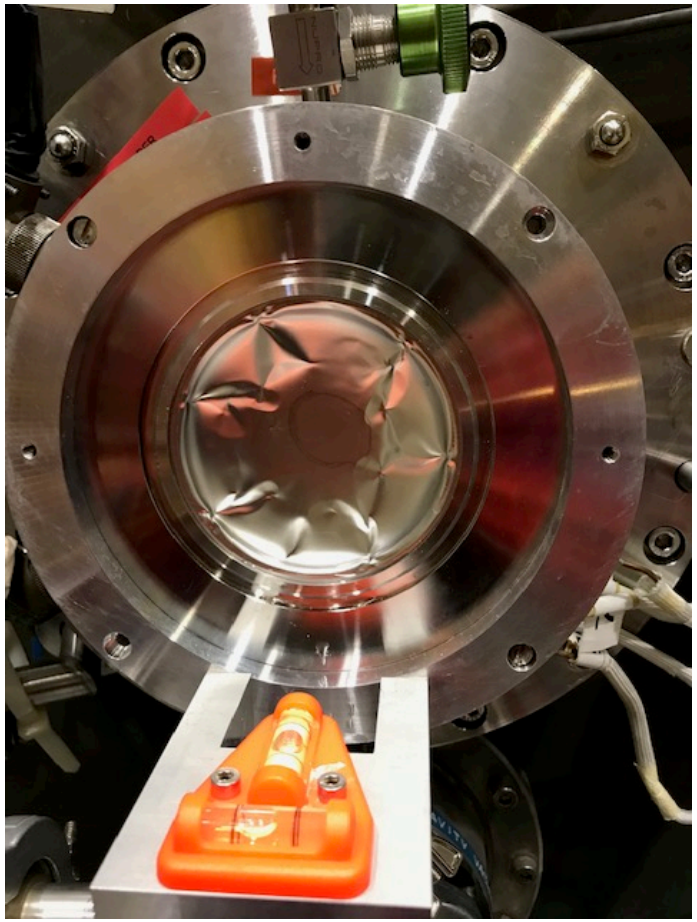
My hiking tour of COMPASS for 20 years

Climb : tiring but nice view
6LiD, NH3 polarizations
New magnet installation

Summit : beautiful scenery of Rhein river
Success of DY experiment

Downhill : unexpected difficulties
Incidents in 2021

Incidents in 2021



Isolation vacuum window almost broken due to superfluid leak

3He pumping pipe collapsion

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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

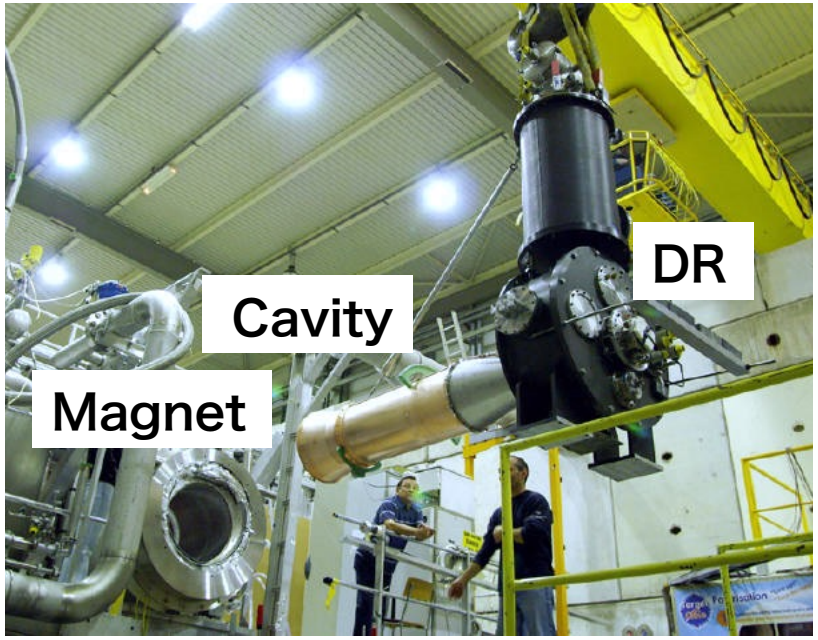
- 3 cells (30, 60, 30cm long)
  or 2 cells (55, 55 cm long)
- Diameter 3 or 4 cm

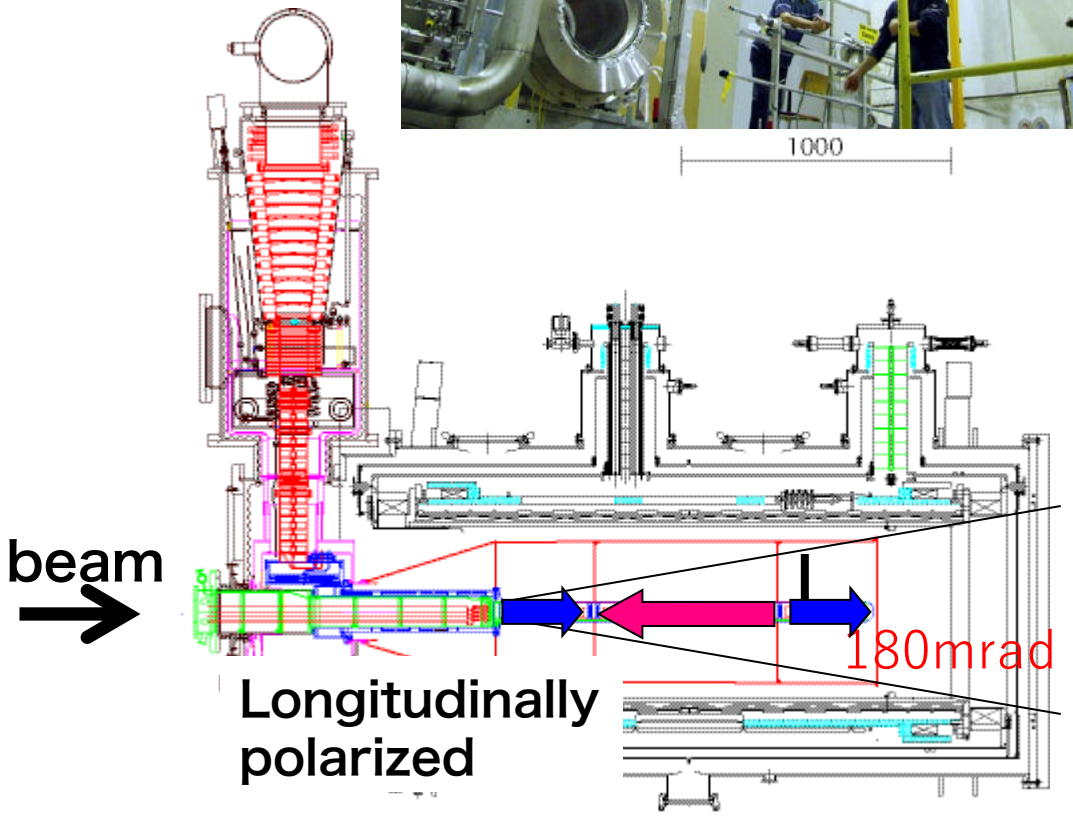
Microwave

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

NMR

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





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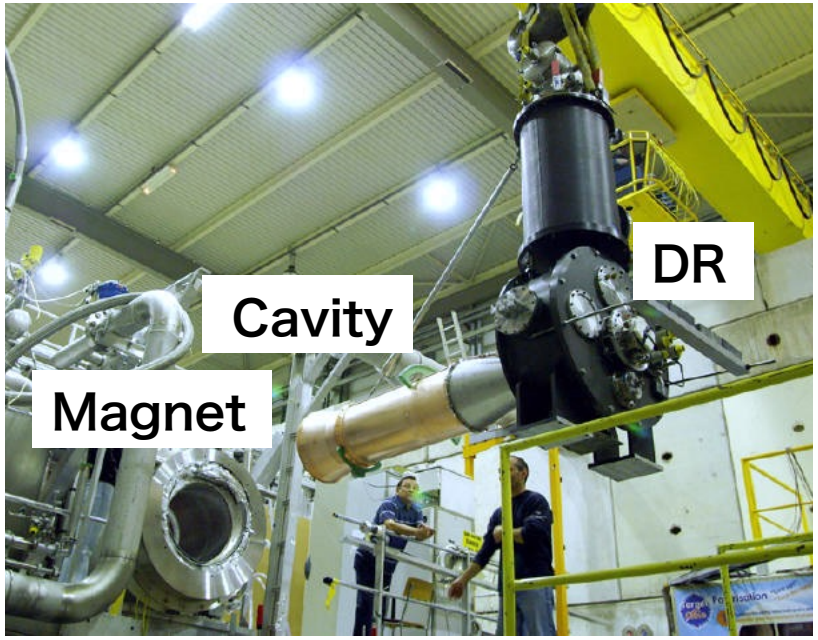
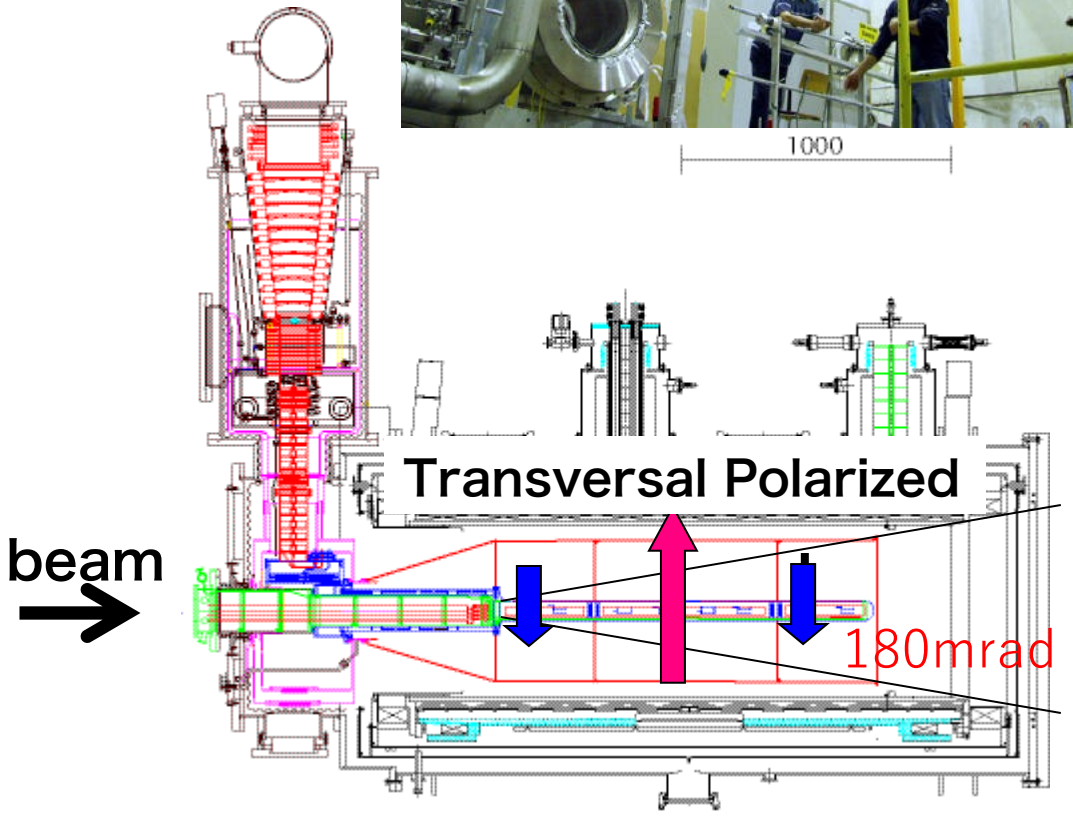
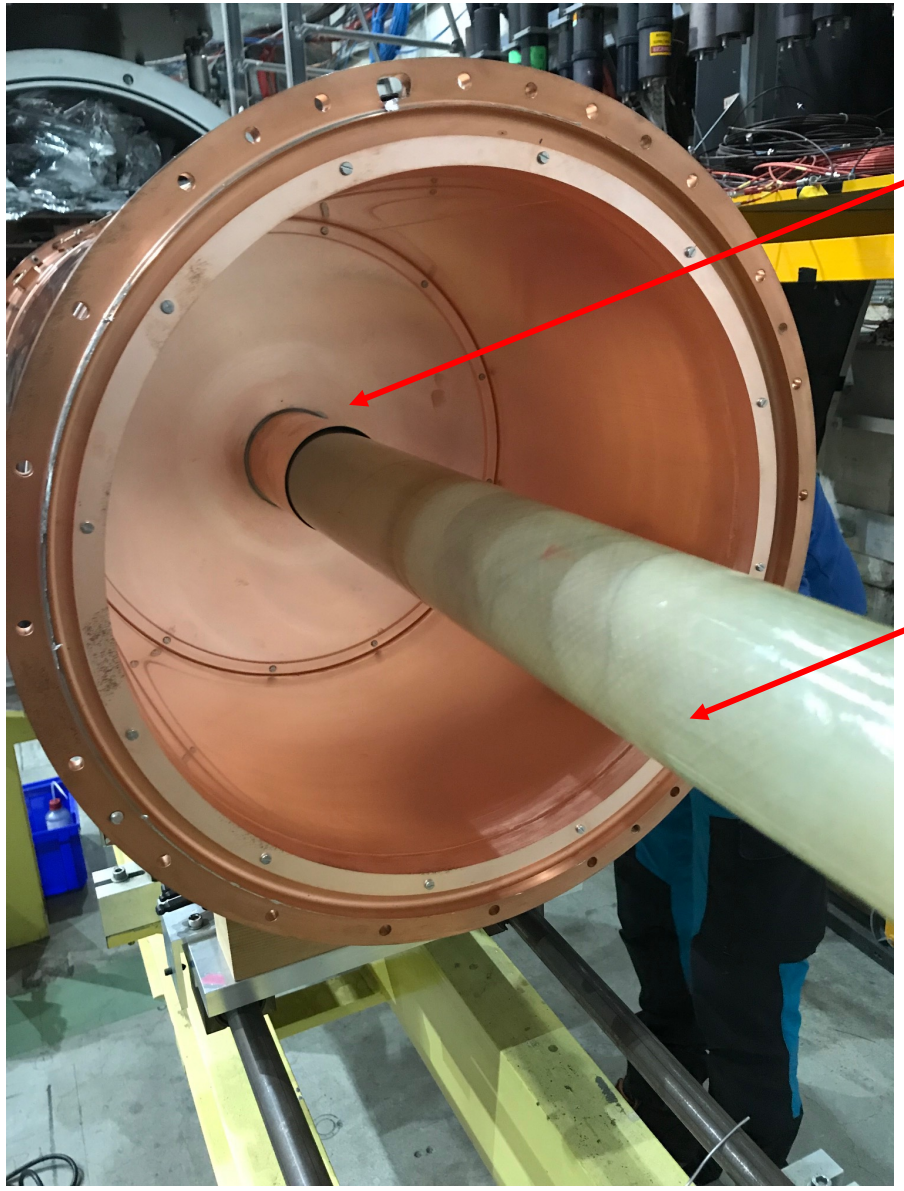
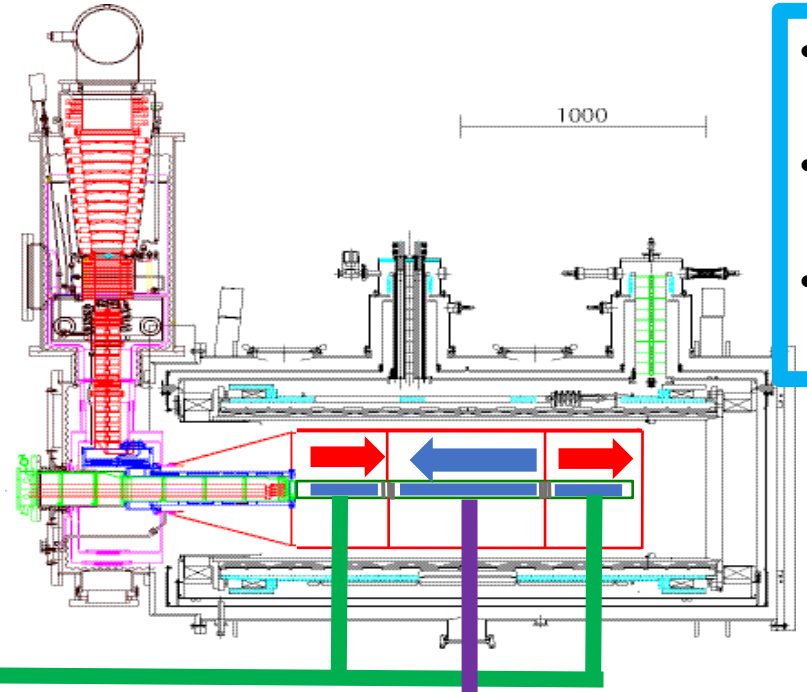




Microwave cavity for 3 cells



EIO microwave system



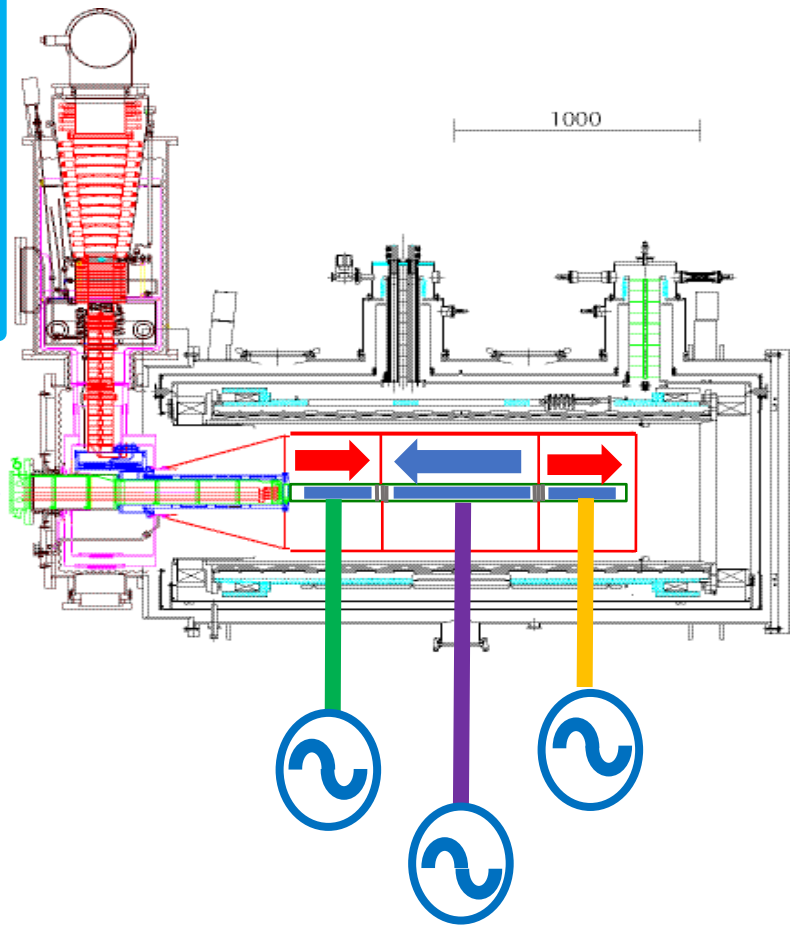
- Polarization : pos. & neg. (two different frequency)
- 100-200 mW power required for each cell
- Frequency and power adjustment

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

→ to be improved

20W EIO (70GHz)
20m long waveguide

Gun system in 2022

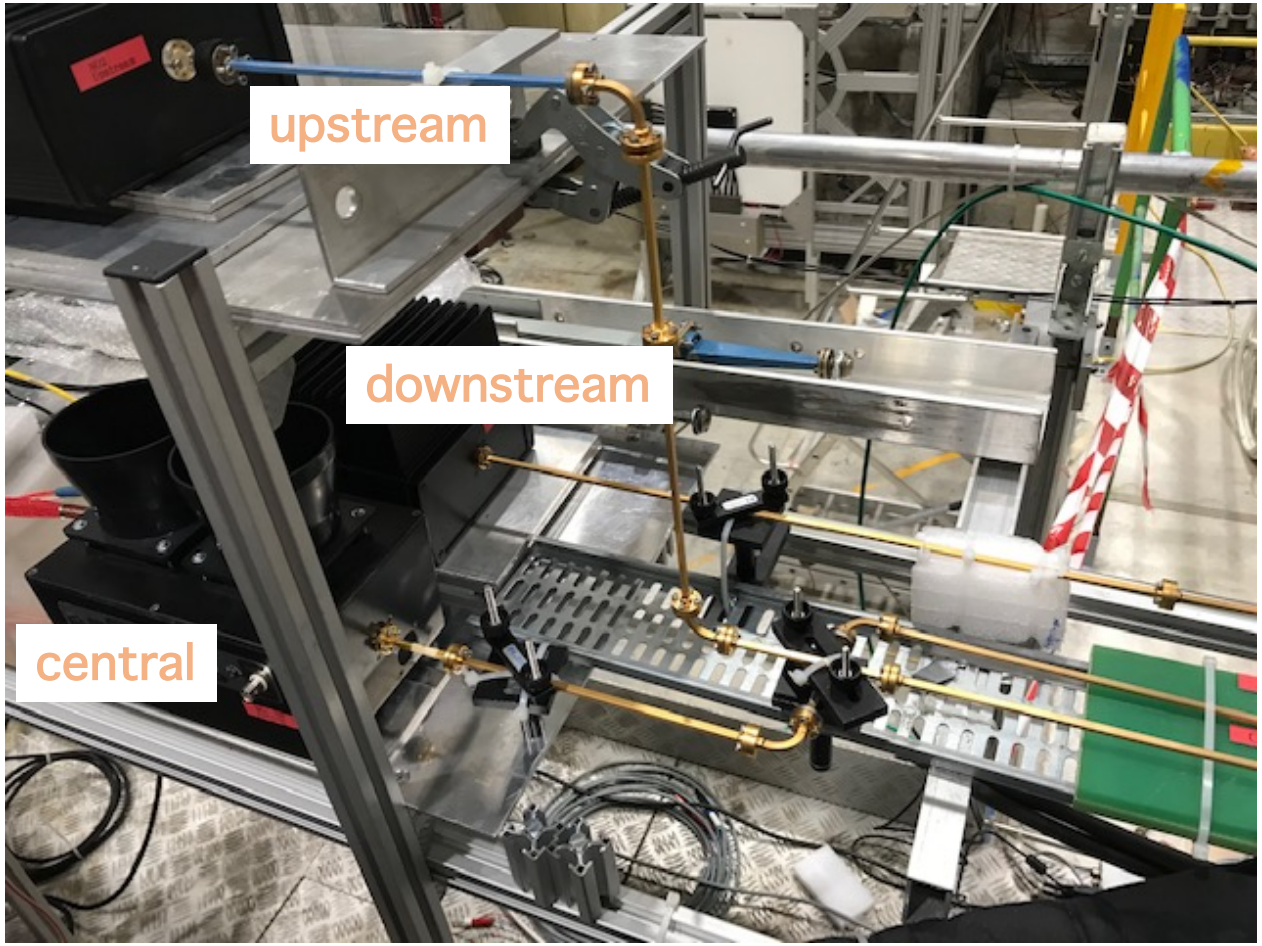


Three Gunn Diode 3W（ELVA-1）
1.5m long waveguide

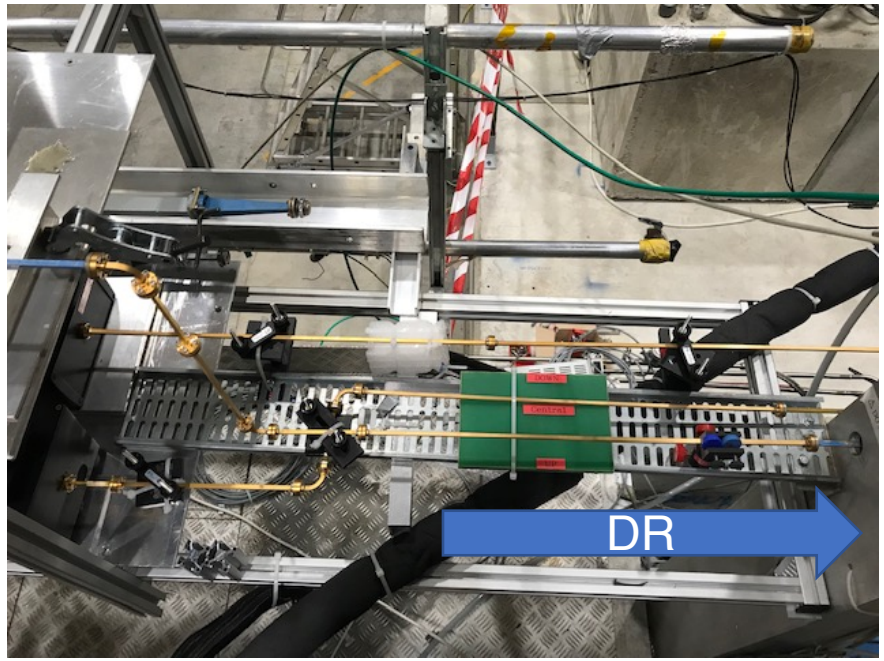
Microwaves

ELVA-1
3 W power

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

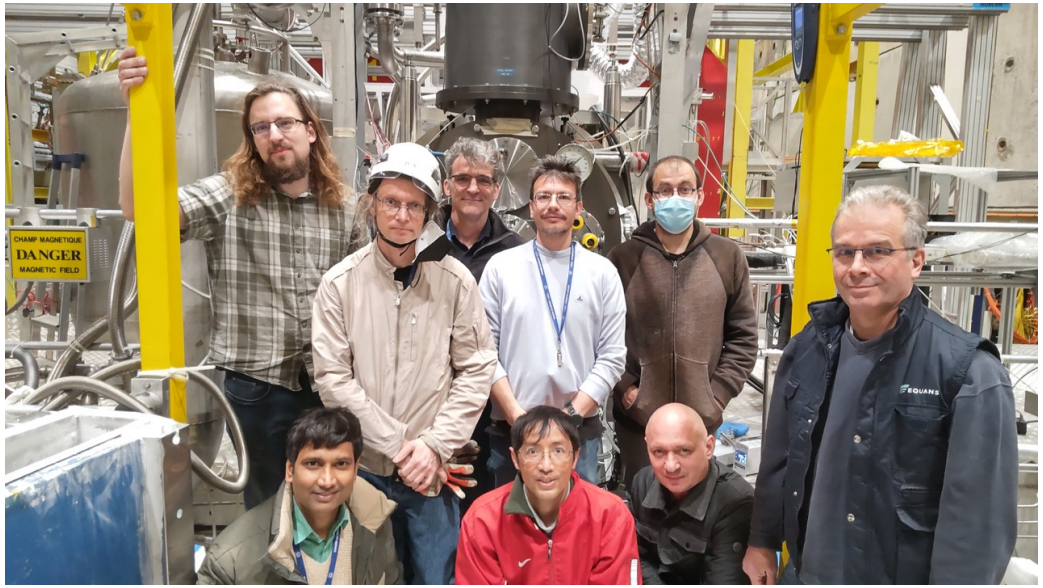


Generation test in 2020



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



6LiD

Loading done in the LN2 bath

port of material cell

Kevlar support

Target holder

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	^{6}LiD
P_T	0.30 – 0.40	0.80 **	0.55 (D) 0.54 (^{6}Li)
ρ	1.00	1.12	0.820
f	0.300	0.238	0.250 (D) 0.250 (^{6}Li)
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
^{6}LiD 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)

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

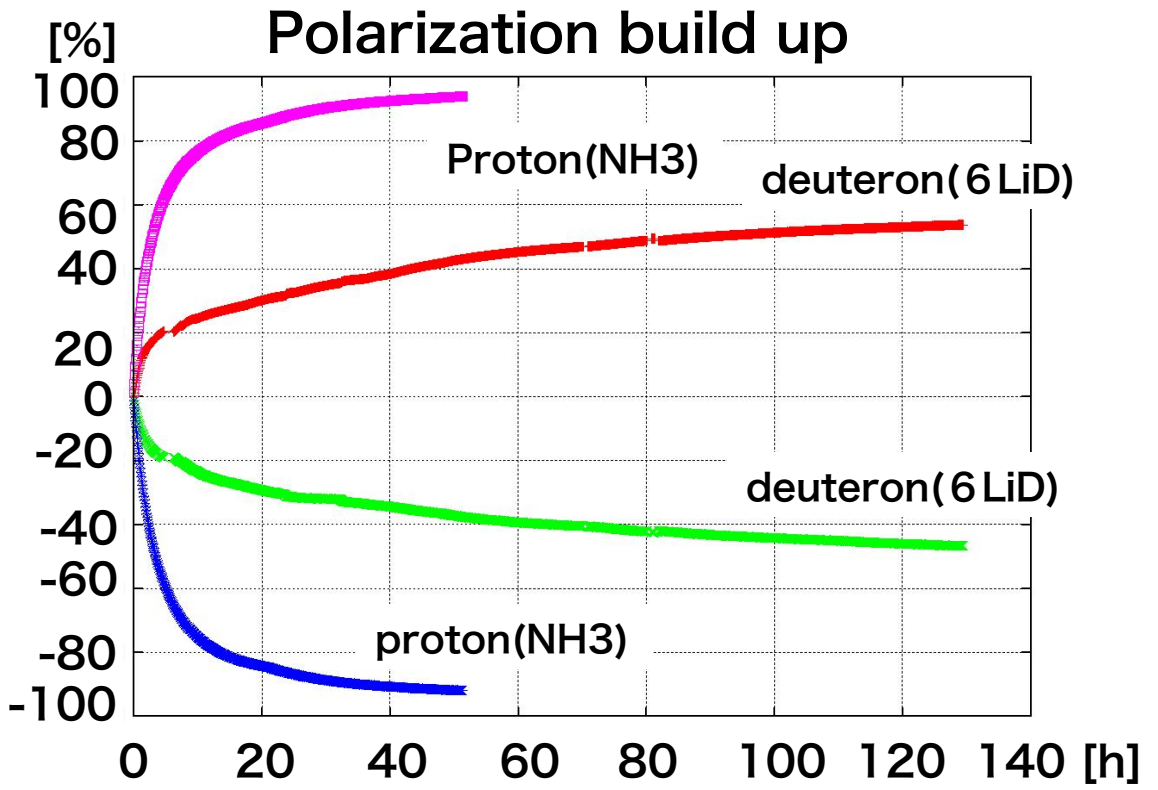
μ : magnetic moment
B : magnetic field
K_B : boltzmann constant
T : temperature

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.

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

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

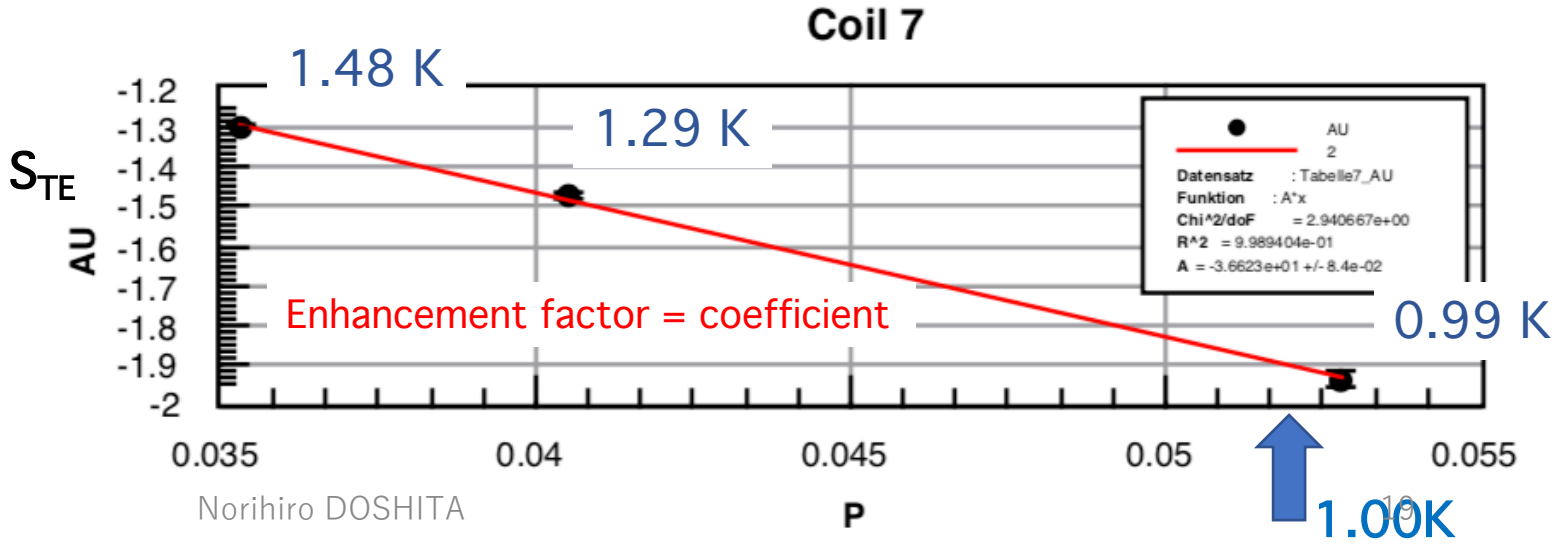
$$P_{TE=1K} = 0.0522789\ \%$$

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

Polarization can be determined
with DNP NMR signal.

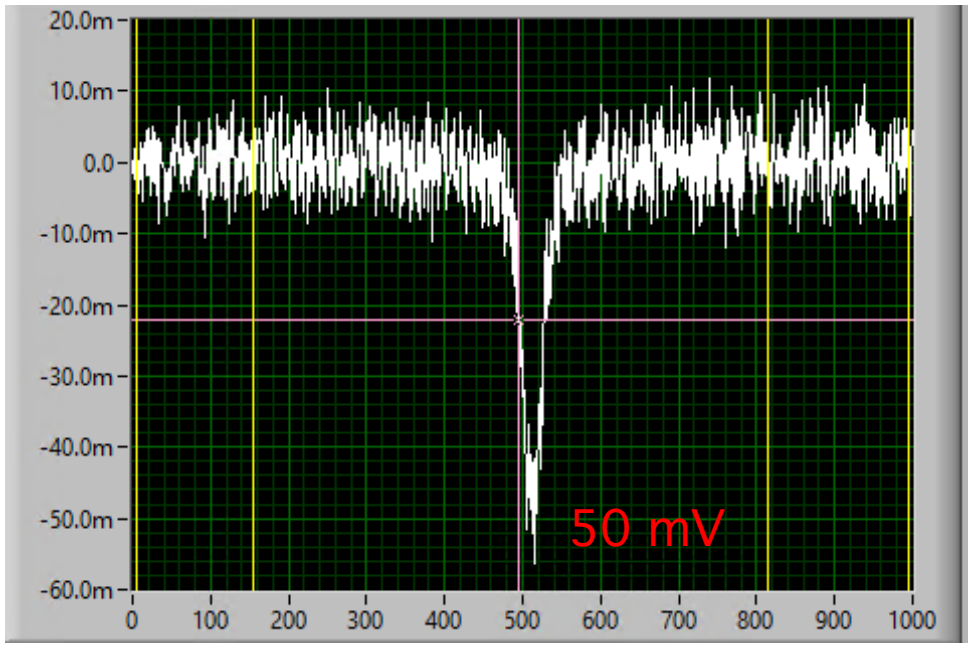
E = Enhancement factor

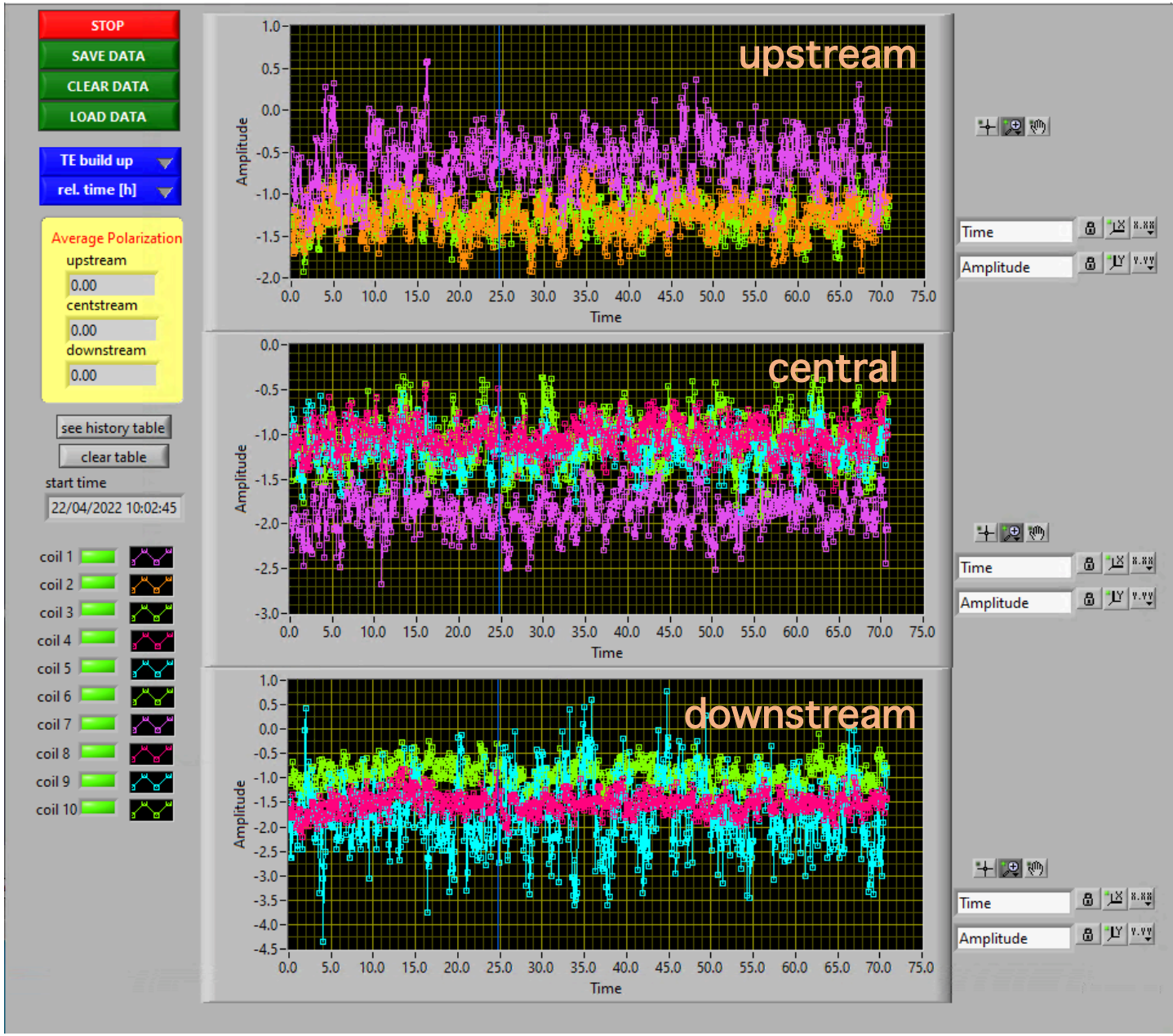
Coil	1/E	d1/E	d1/Erel	E	dE
1	-10.47	0.12	-1.2	-0.09548	0.0011
2	-24.53	0.11	-0.47	-0.04077	0.00019
3	-24.31	0.074	-0.3	-0.04113	0.00013
4	-19.87	0.077	-0.39	-0.05033	0.0002
5	-22.36	0.097	-0.43	-0.04472	0.00019
6	-20.39	0.079	-0.39	-0.04905	0.00019
7	-36.62	0.084	-0.23	-0.0273	6.3e-05
8	-29.83	0.073	-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

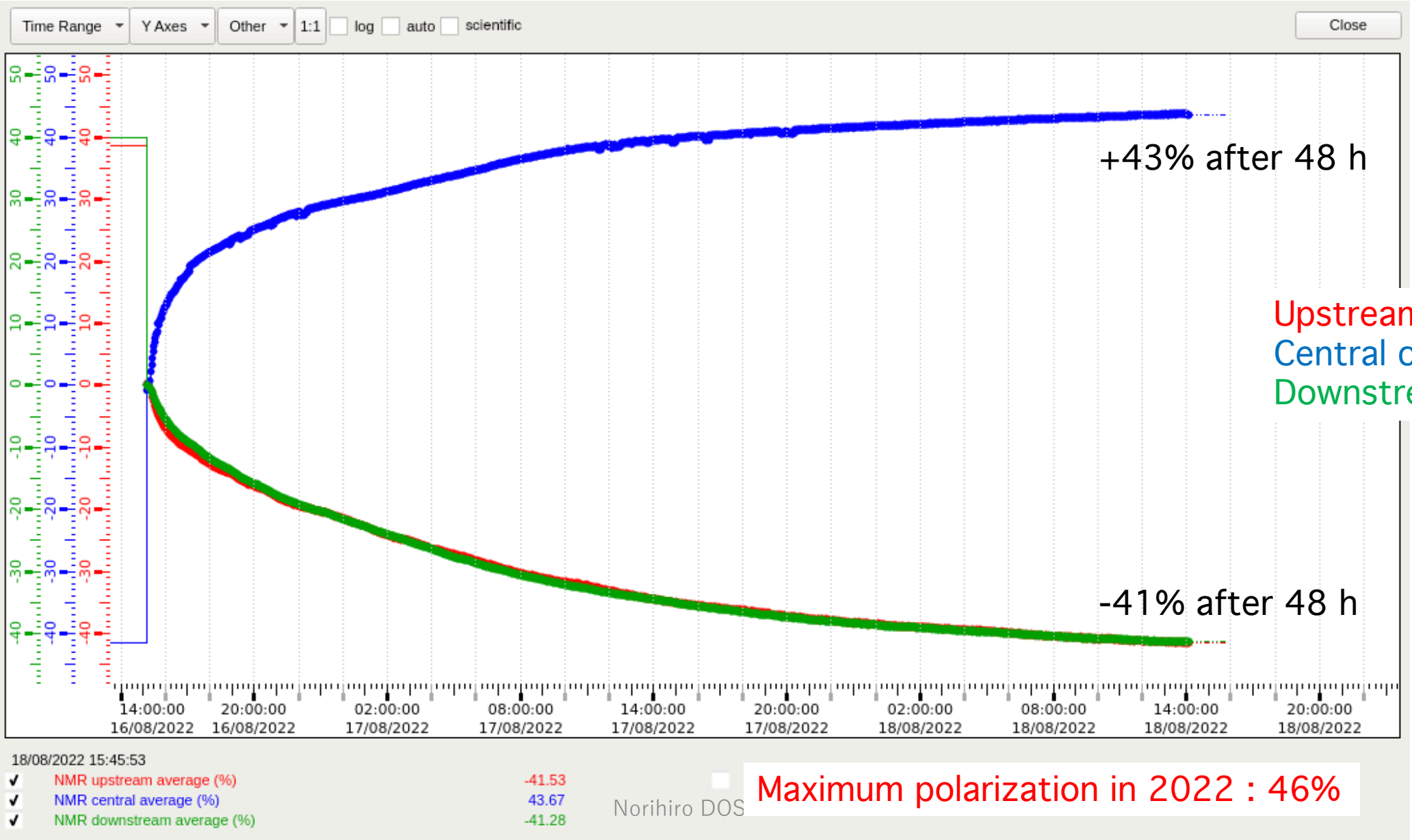




Gain factor measurement

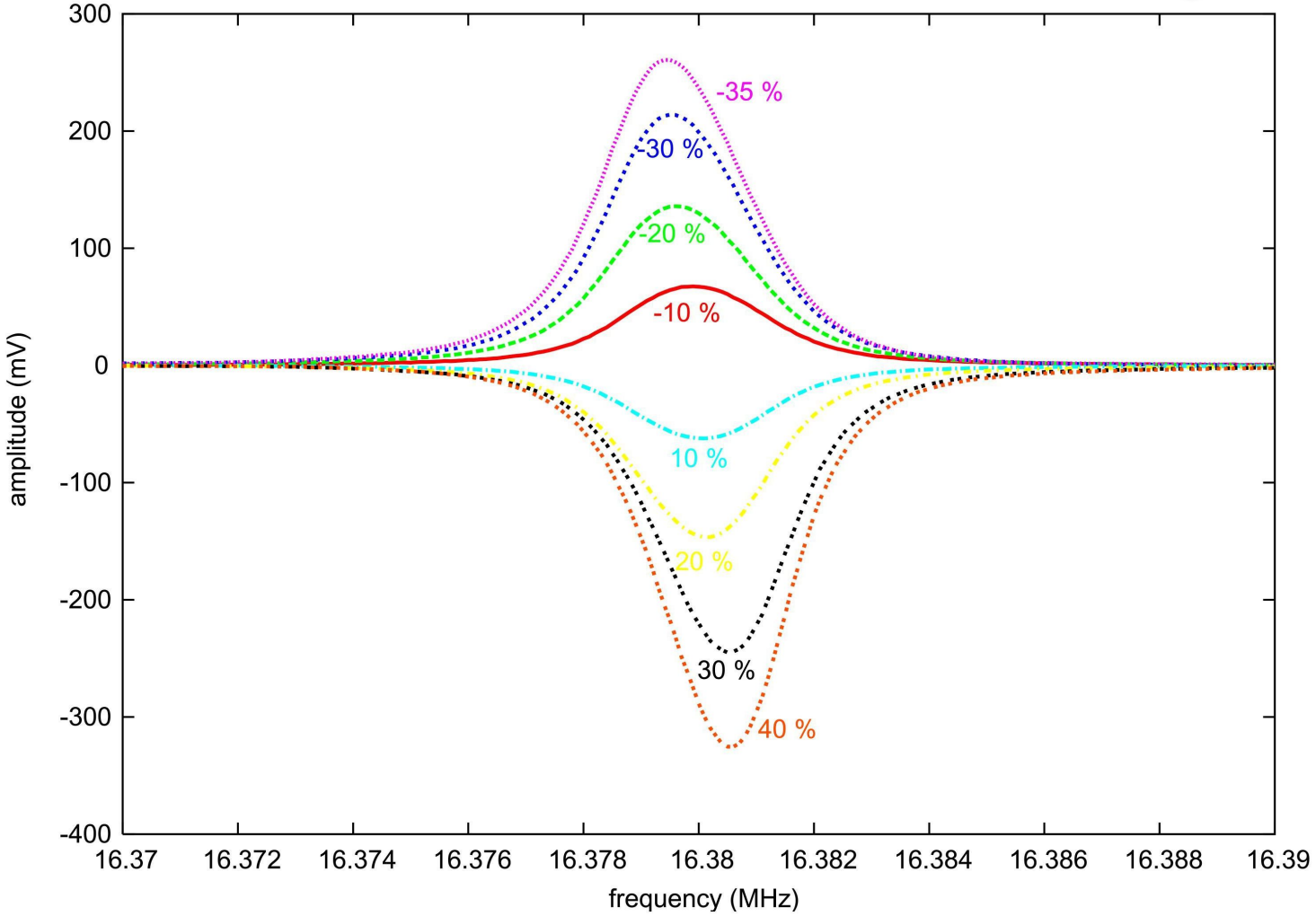
coil	gain2015/2018	gain2022	2022/2015	cell average
1	216.201	214.12	0.990	
2	214.013	213.13	0.996	1.000
3	211.979	214.86	1.014	
4	213.52	214.38	1.004	
5	212.402	207.29	0.976	
6	211.6	208.94	0.987	0.995
7	213.843	216.14	1.011	
8	212.995	211.61	0.993	
9	215.306	211.09	0.980	0.994
10	213.928	215.77	1.009	

Polarization build up in 2022 (Deuteron)

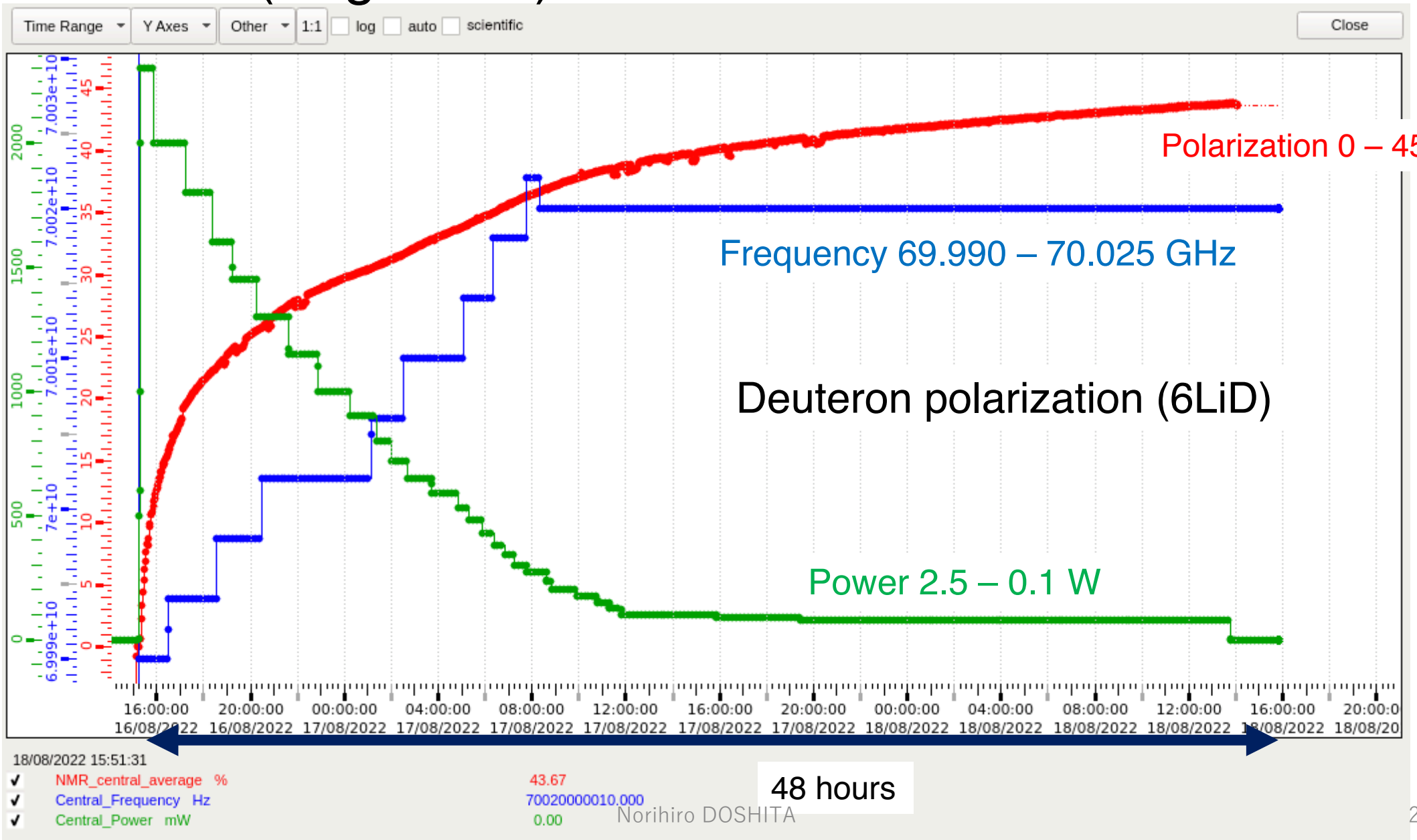


Maximum polarization in 2022 : 46%

Enhanced deuteron NMR signals



Central cell (Aug. 2022)



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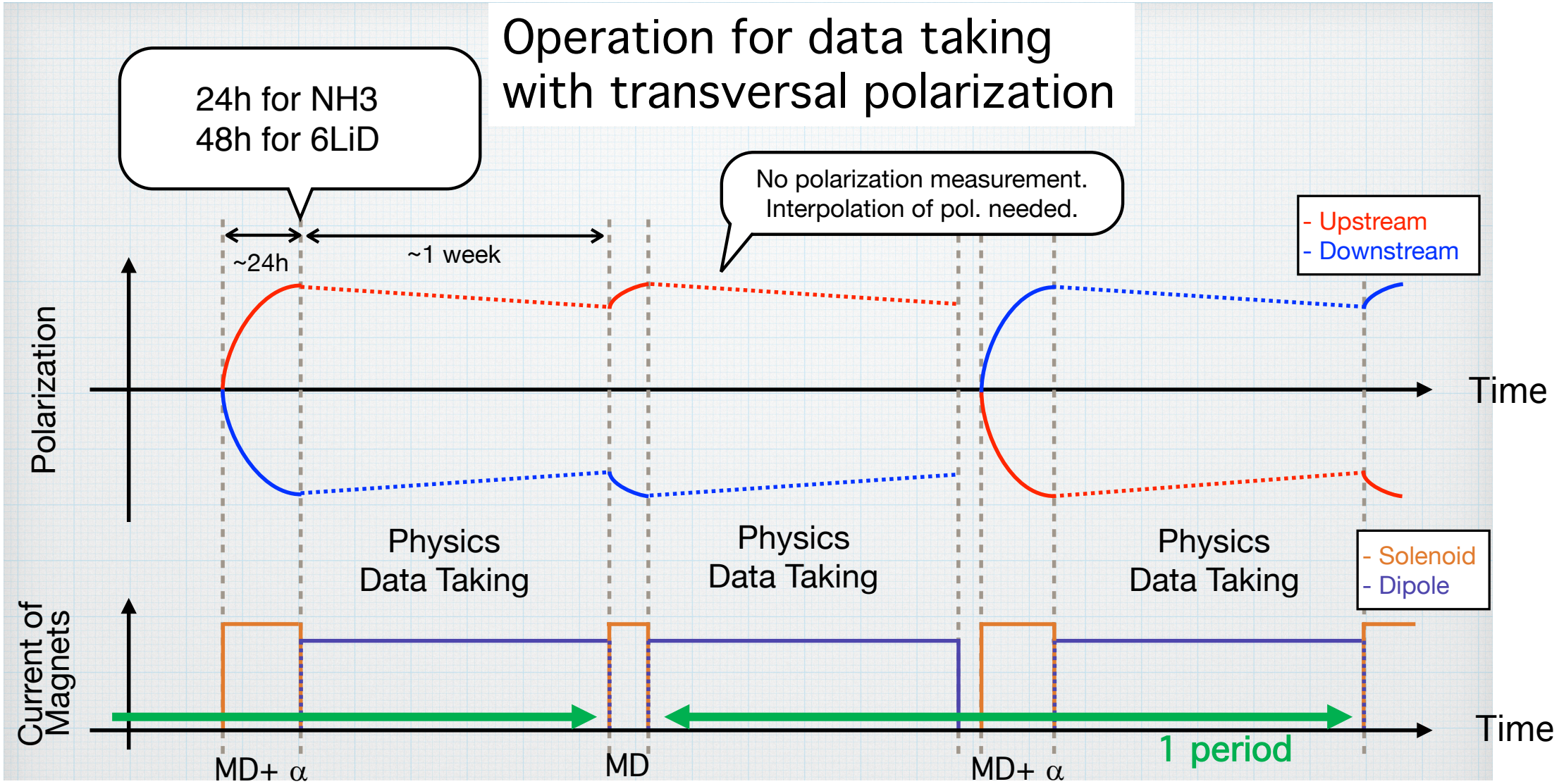
Operation for data taking with transversal polarization



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

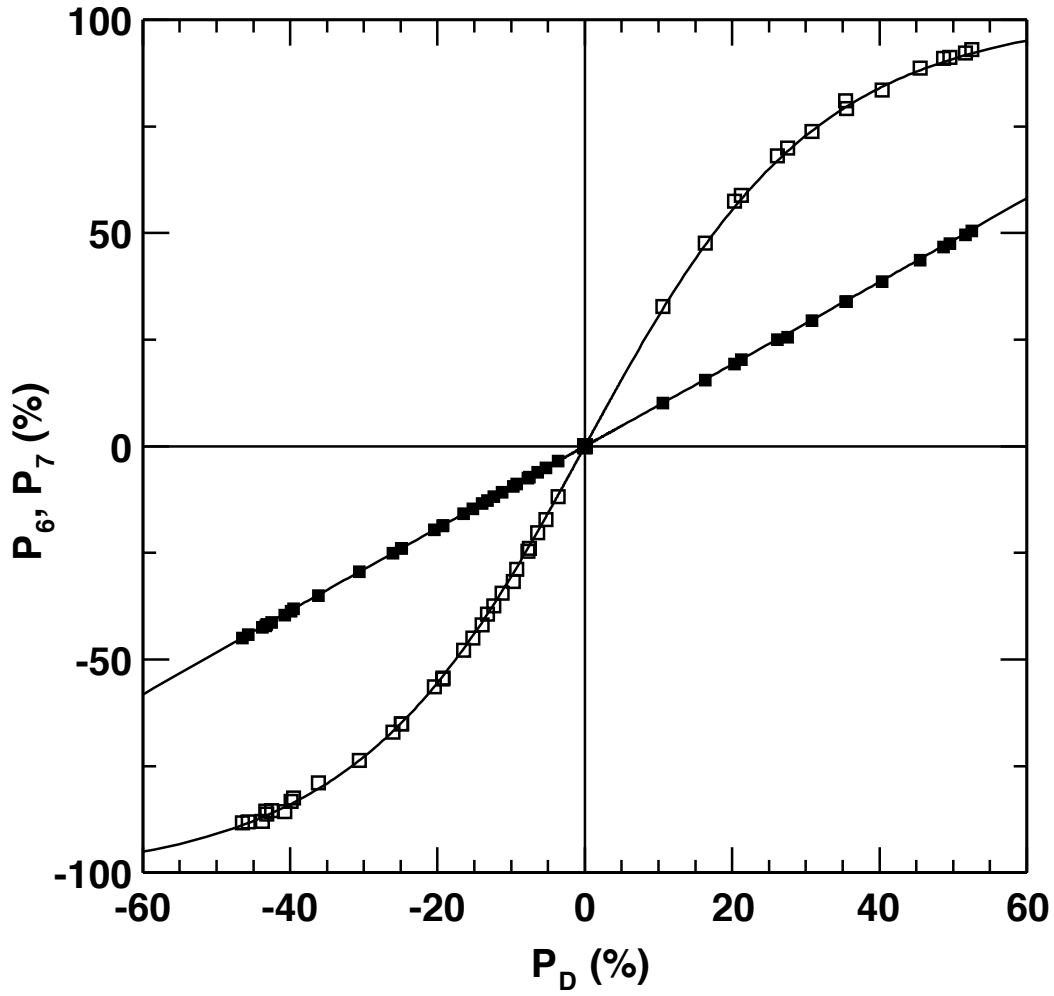


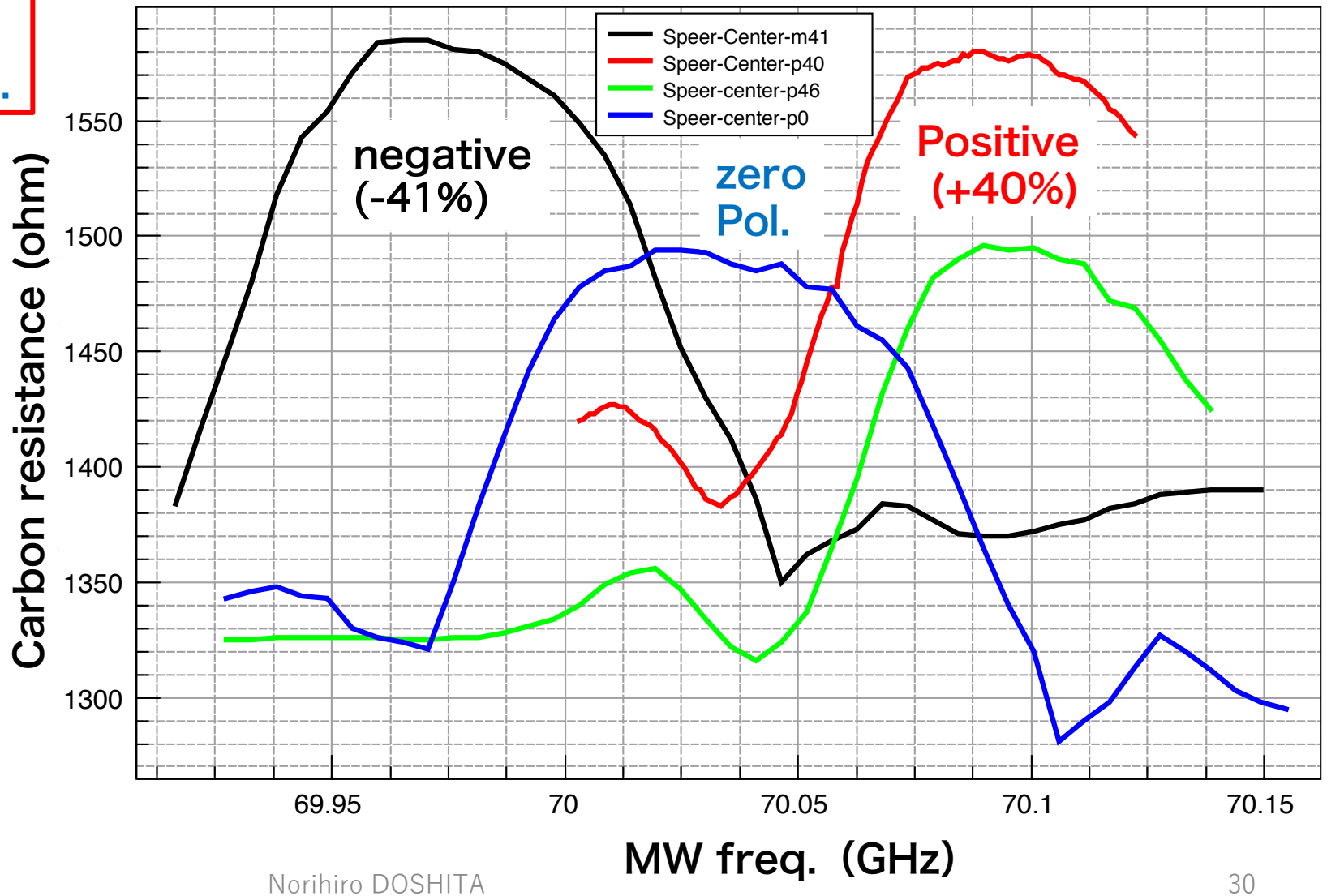
Fig. 6. The polarizations of the ^{6}Li and the ^{7}Li nuclei versus that of the deuteron. The closed (open) squares are the measured polarization of ^{6}Li (^{7}Li). The lines are the prediction by EST concept. The measurements are consistent with the EST concept.

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

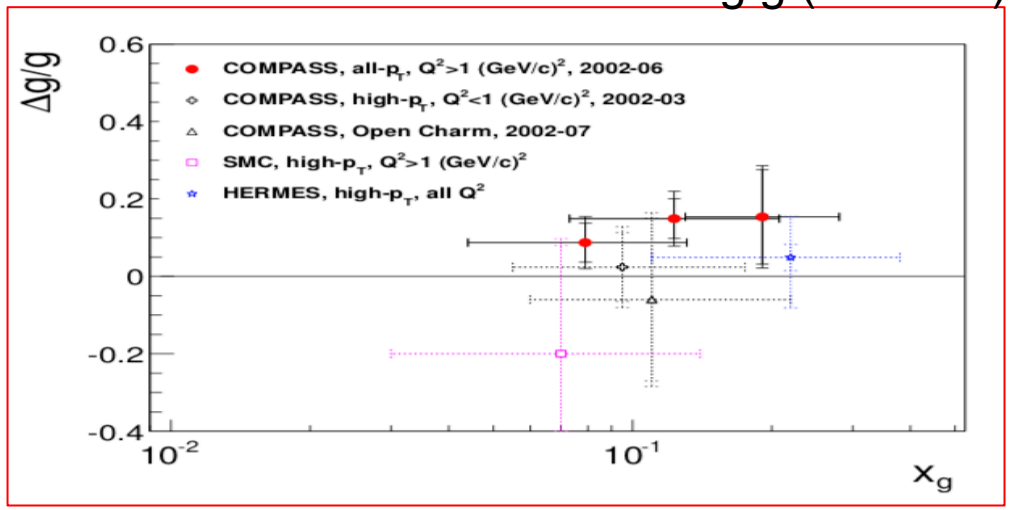
Summary

- 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

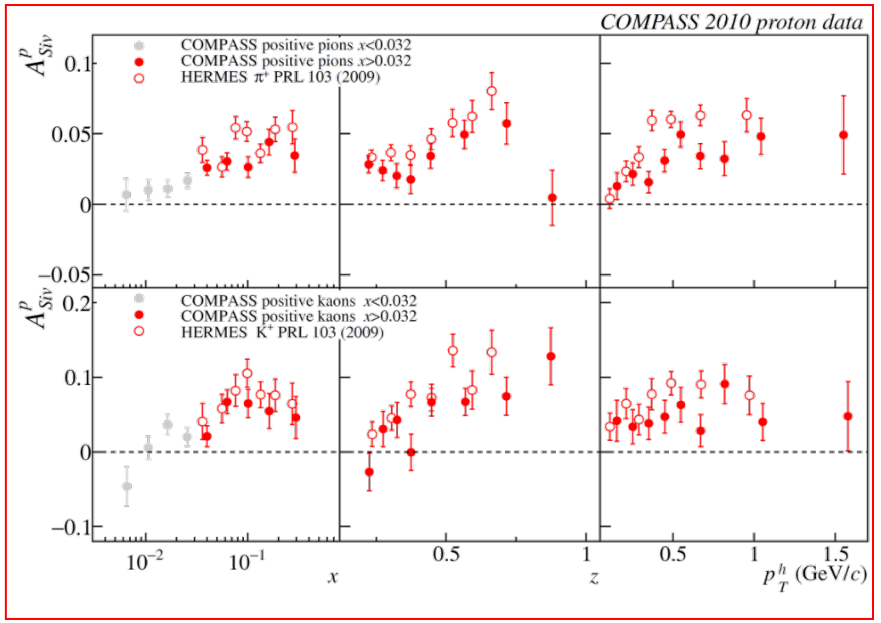
Back up

Pick up of results

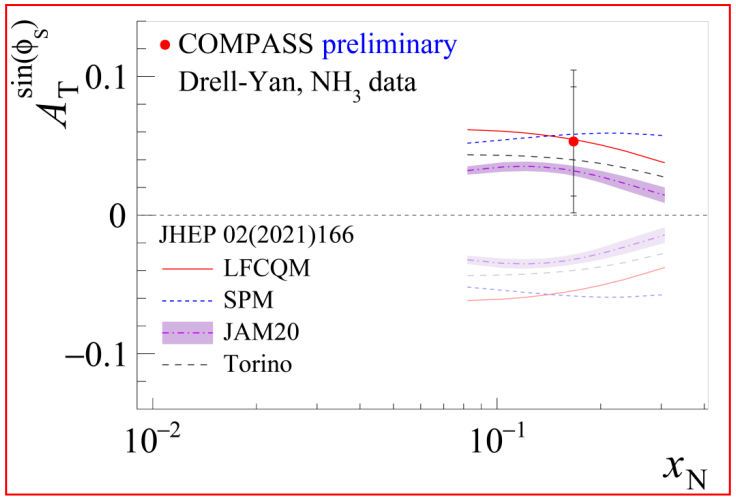
Δg/g (2002-06)



Sivers PDF with SIDIS(2010)

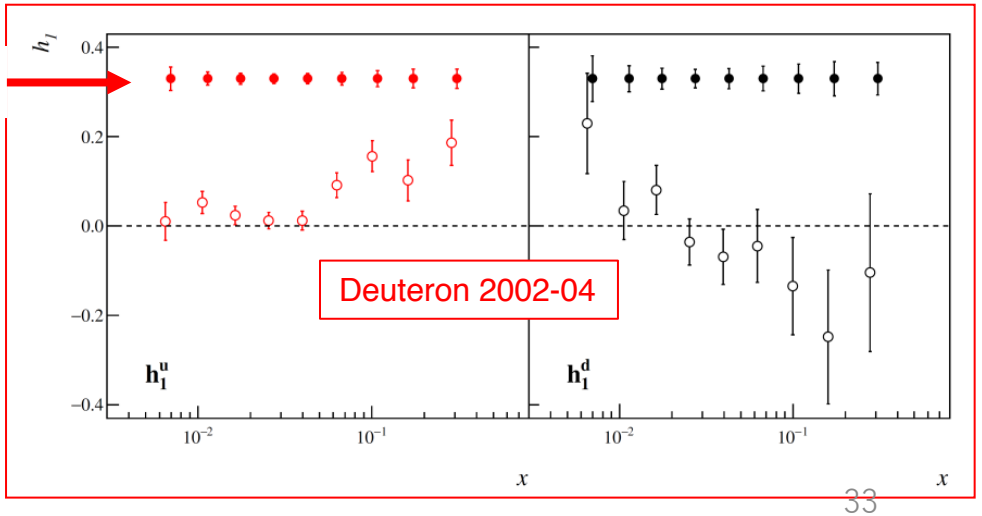


Sivers PDF with DY(2015,18)

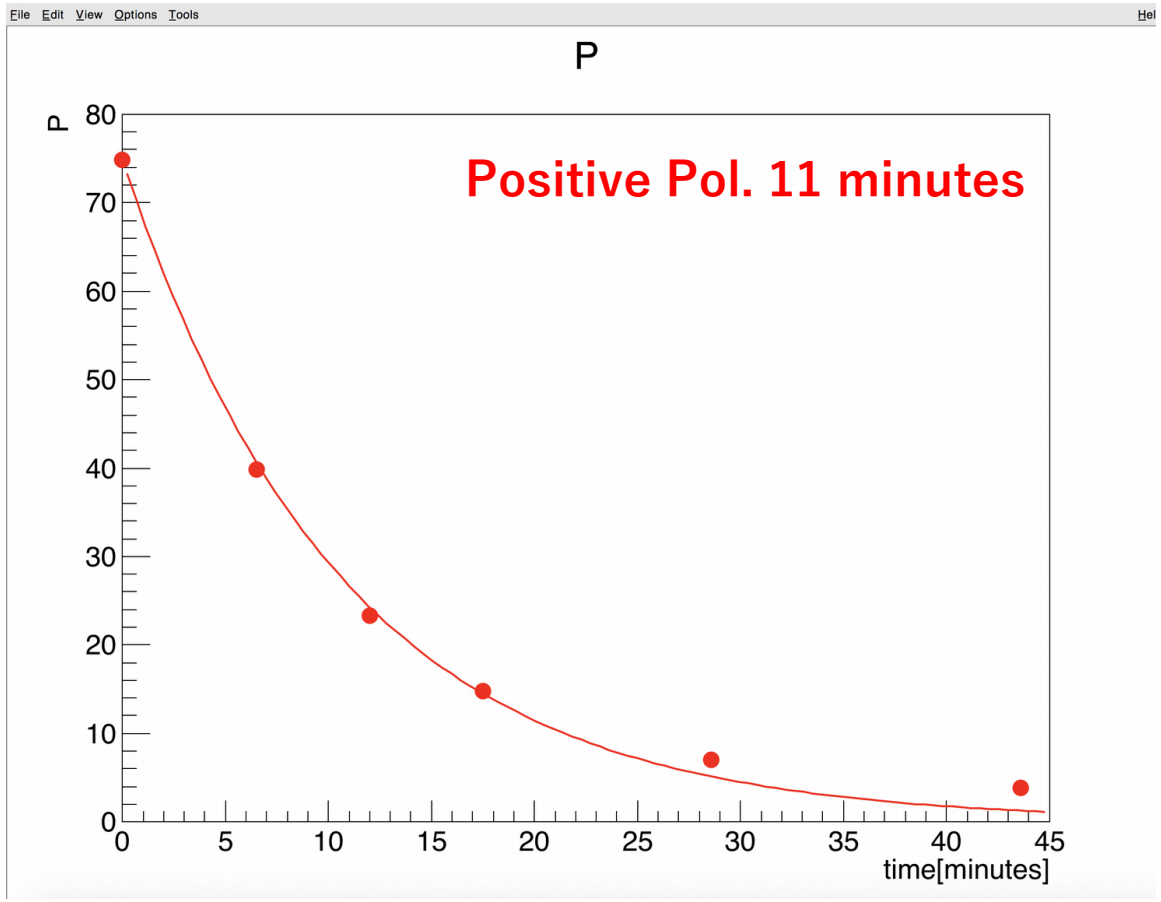


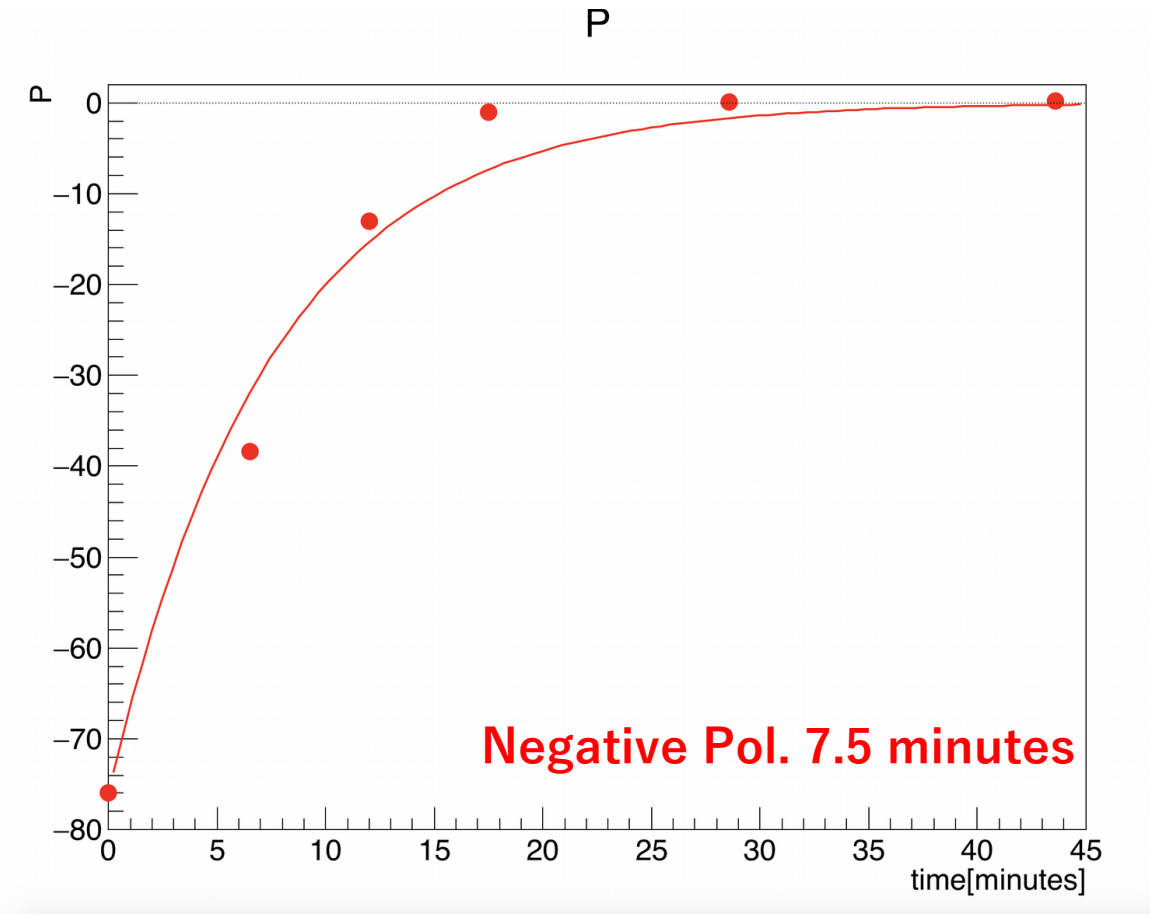
Deuteron transiversity PDF (2002-2004)
Projected uncertainties for 2022

Deuteron 2022



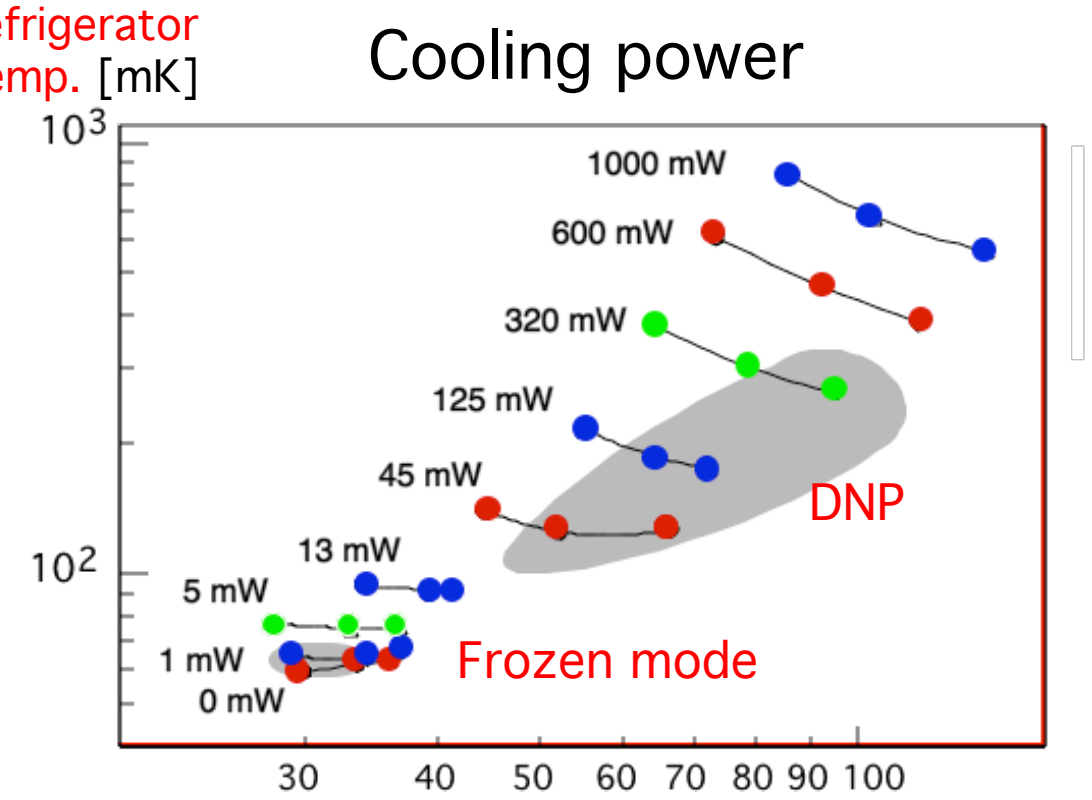
Relaxation time at 0 T

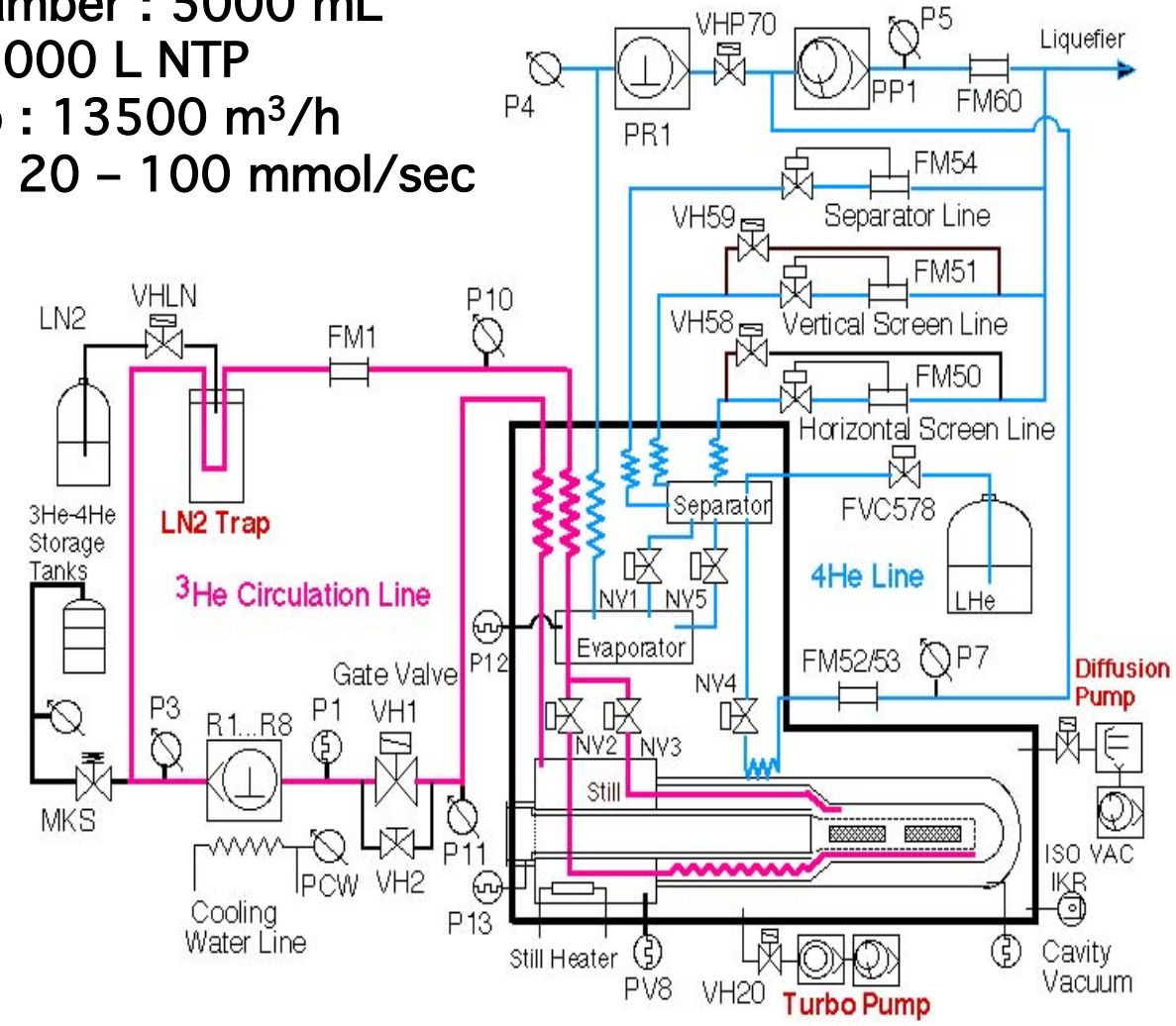




Dilution refrigerator

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





Accuracy of Polarization

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

proton 2015 and 2018

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

Souce of systematic uncertainty	ΔP/P [%]
Circuit non-linearity	0.7
Off-centering of Q-curve for TE	0.2
Off-centeringof Q-curve for enhanced signal	0.2
Ground-line fitting	0.2
Fitting for TE signal	1.0
LF gain variation	0.05
Temperature measurement	0.8
Total	3.2