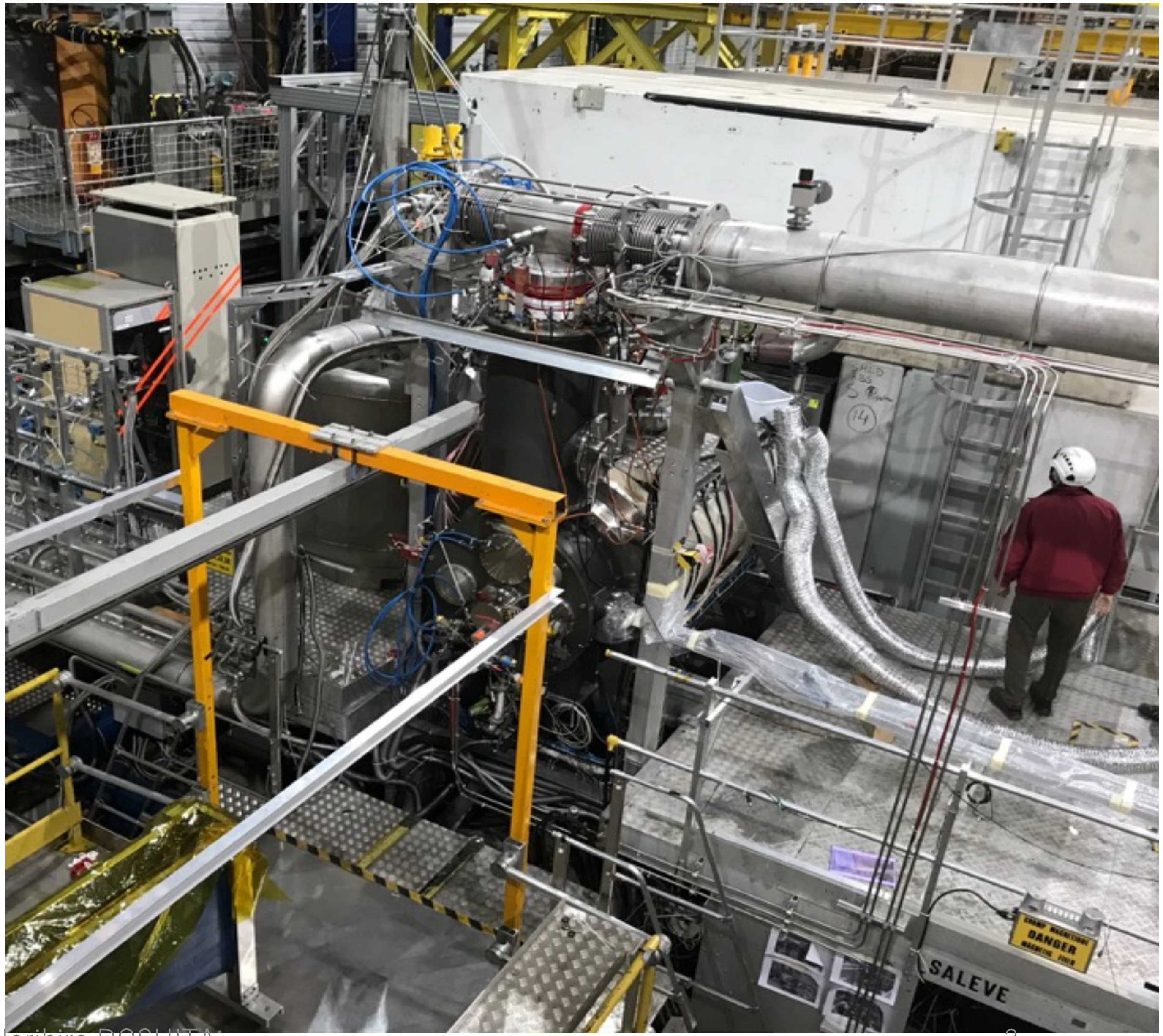
COMPASS Polarized Target 2002 - 2022

Norihiro DOSHITA
Yamagata University

Outline

- COMPASS experiment
- COMPASS PT system
  - 6LiD with muon beam
  - NH3 with hadron beam
- Polarization
  - DNP
  - Polarization determination
- Long term operation
  - Relaxation time
- Other measurements



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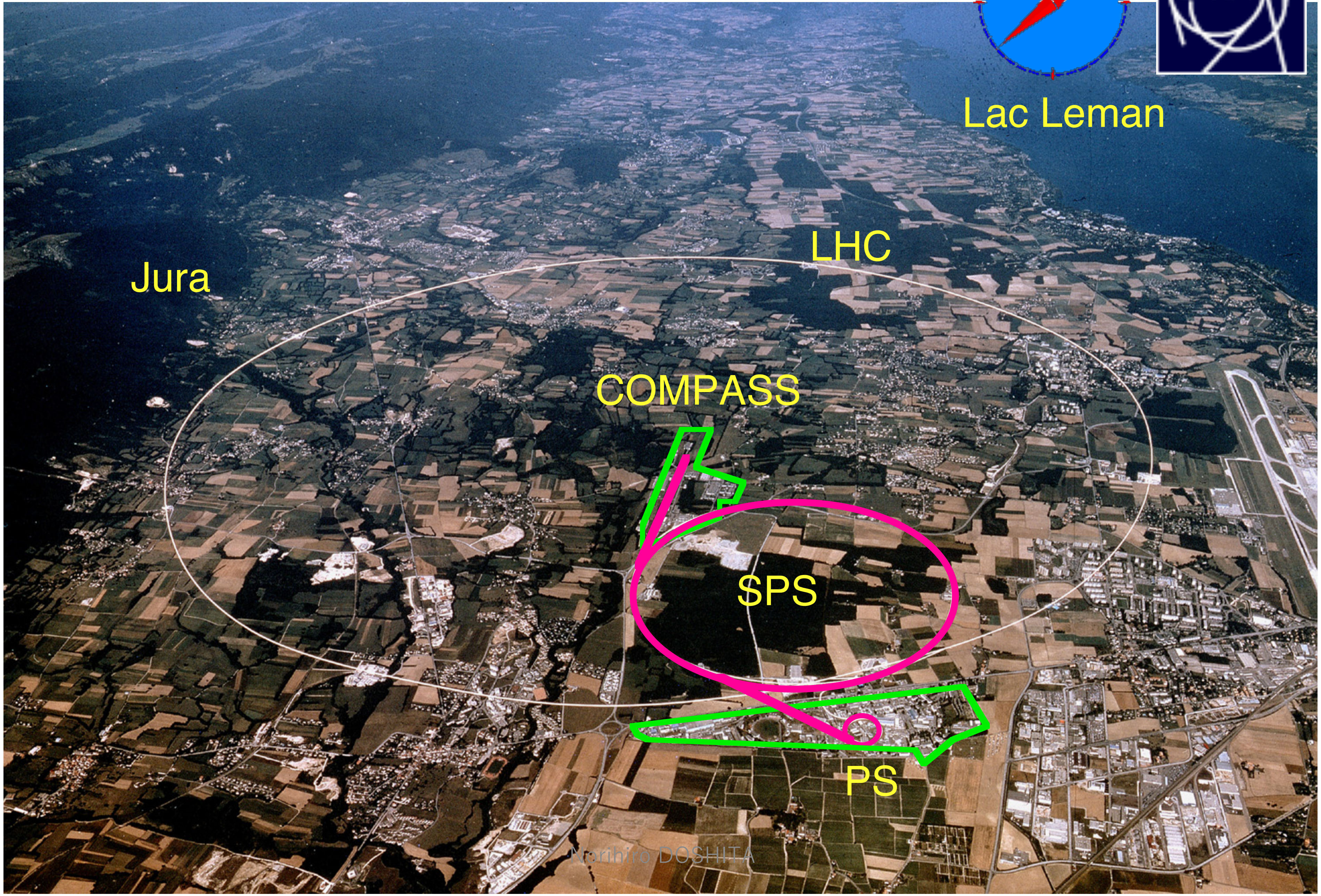
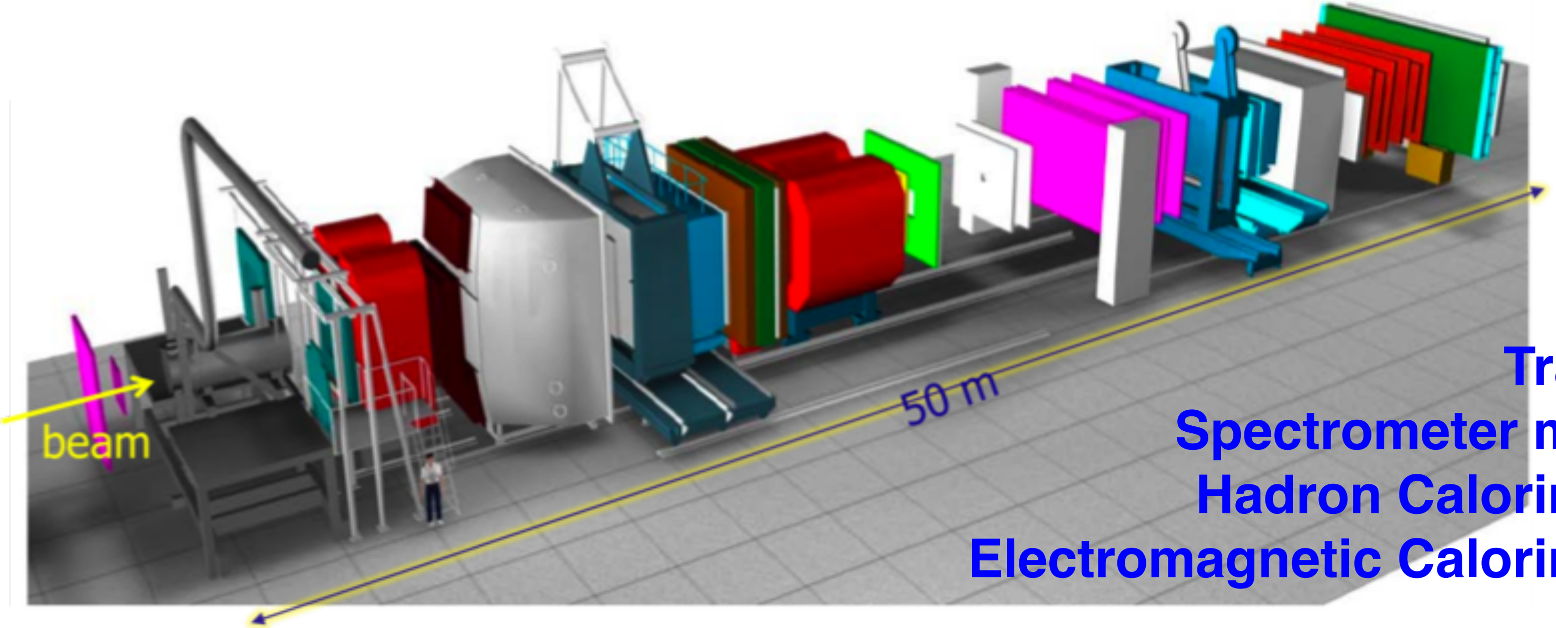
CERN and COMPASS



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

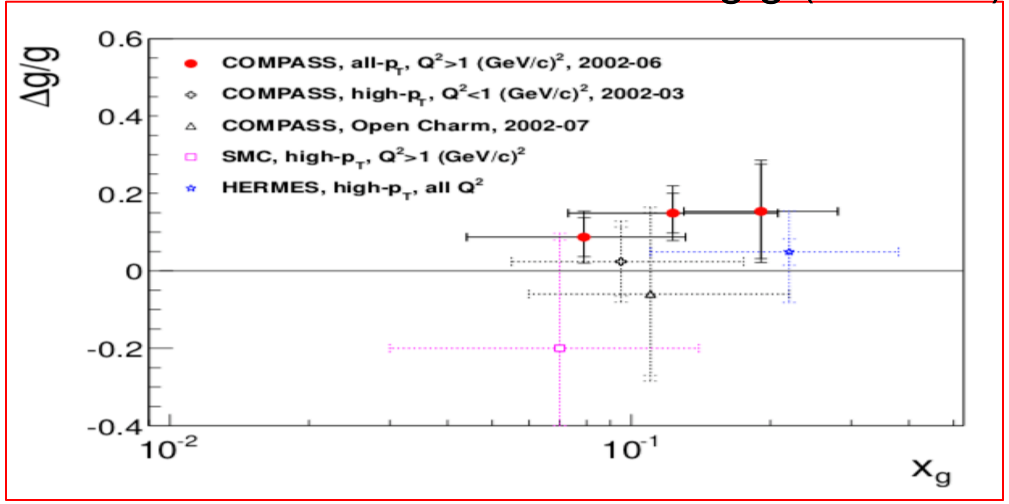
Year	Spin	Material	Cell configuration	Program (with muon beam)
2002 – 2004	L, T	^{6}LiD	L: 60-60 cm, D: 3 cm	Δg/g, TMD
2006	L	^{6}LiD	L: 30-60-30 cm, D: 3 cm	Δg/g
2007	L, T	NH_3	L: 30-60-30 cm, D: 4 cm	TMD, g1
2010	T	NH_3	L: 30-60-30 cm, D: 4 cm	TMD
2011	L	NH_3(new)	L: 30-60-30 cm, D: 4 cm	g1,A1 with 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)

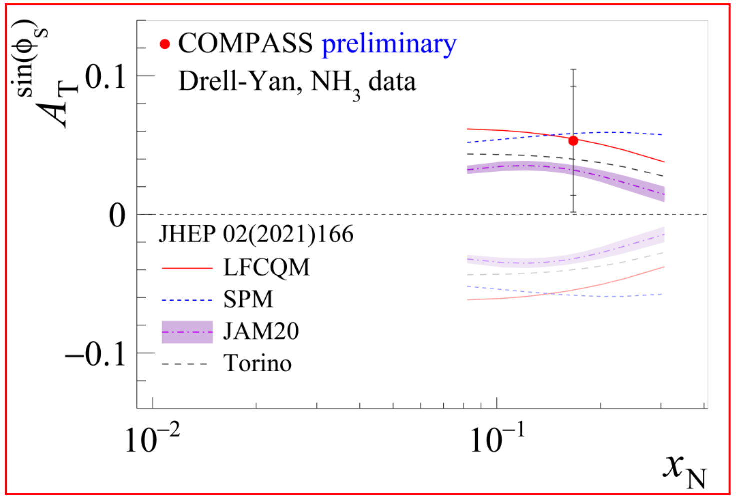
Phase2 (2014 – 2022)

Pick up of results

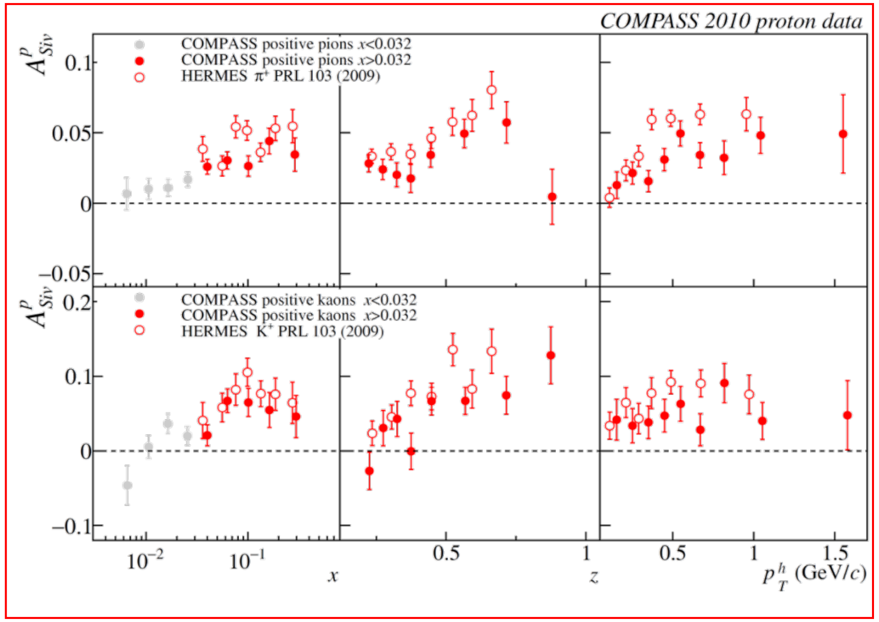
Δg/g (2002-06)



Sivers PDF with DY(2015,18)

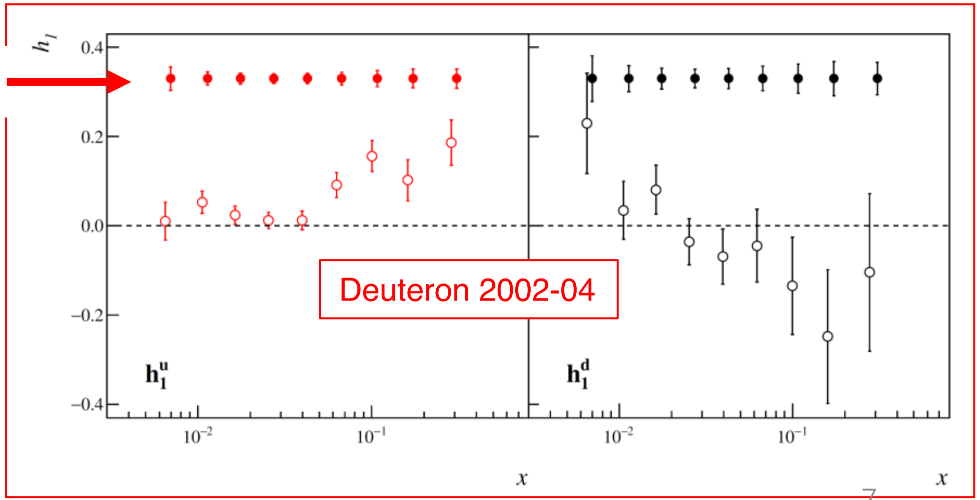


Sivers PDF with SIDIS(2010)



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

Deuteron 2022



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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

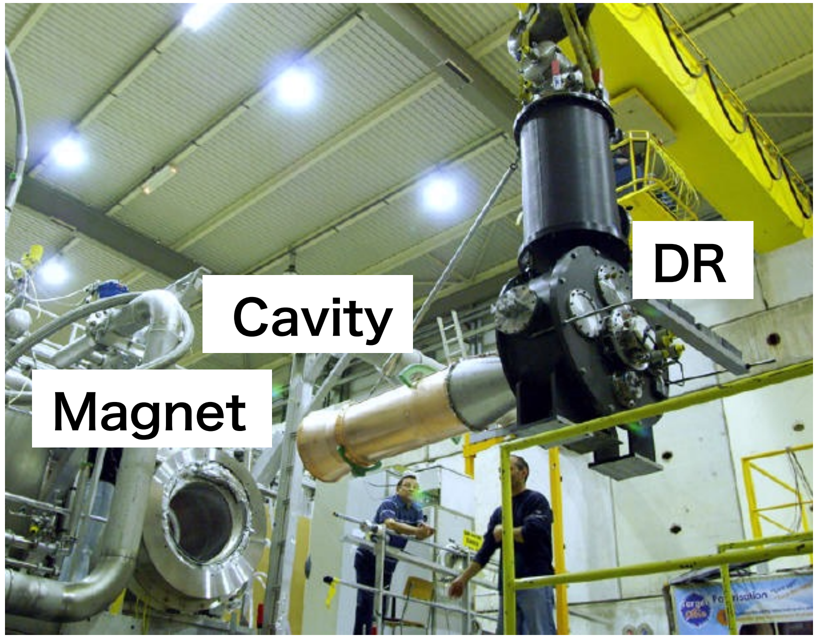
- 3 cells (30, 60, 30cm long)
  or 2 cells (55, 55 cm long)
- Diameter 3 or 4 cm

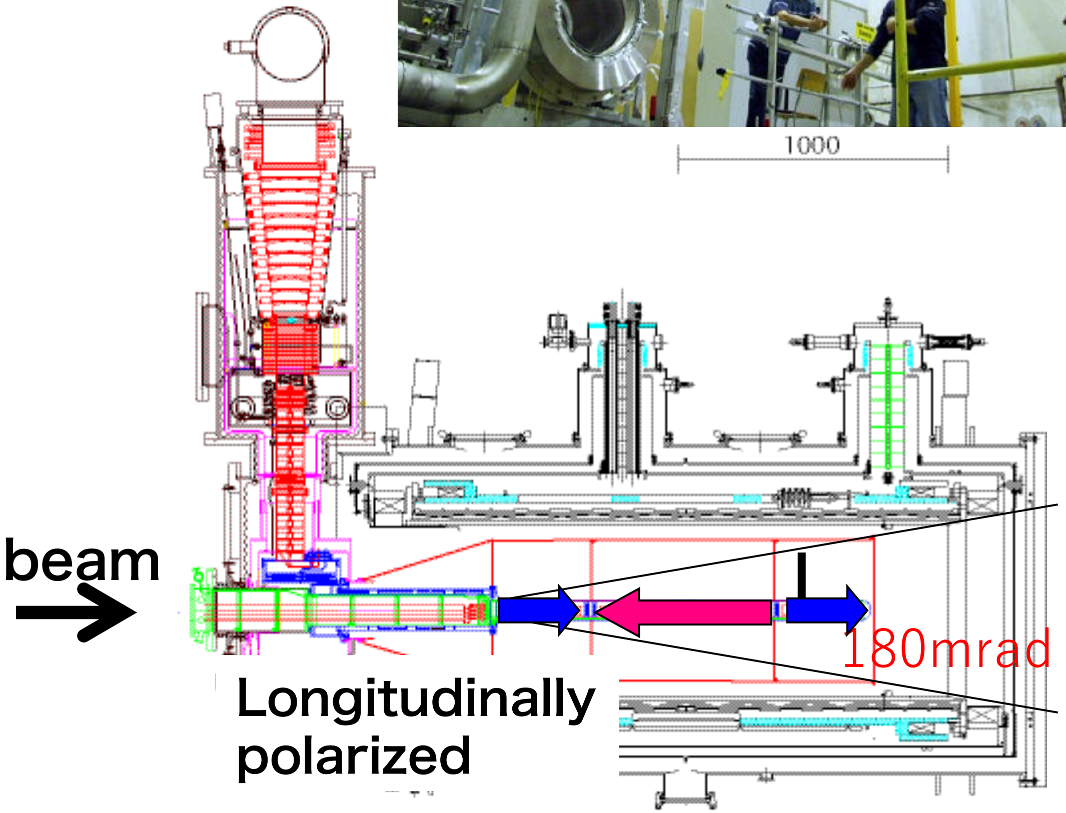
Microwave

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

NMR

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





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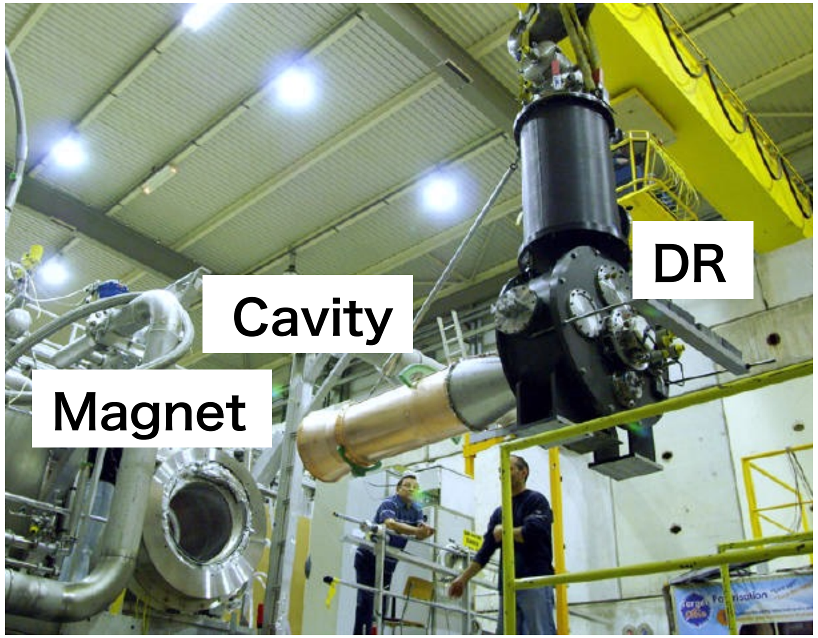
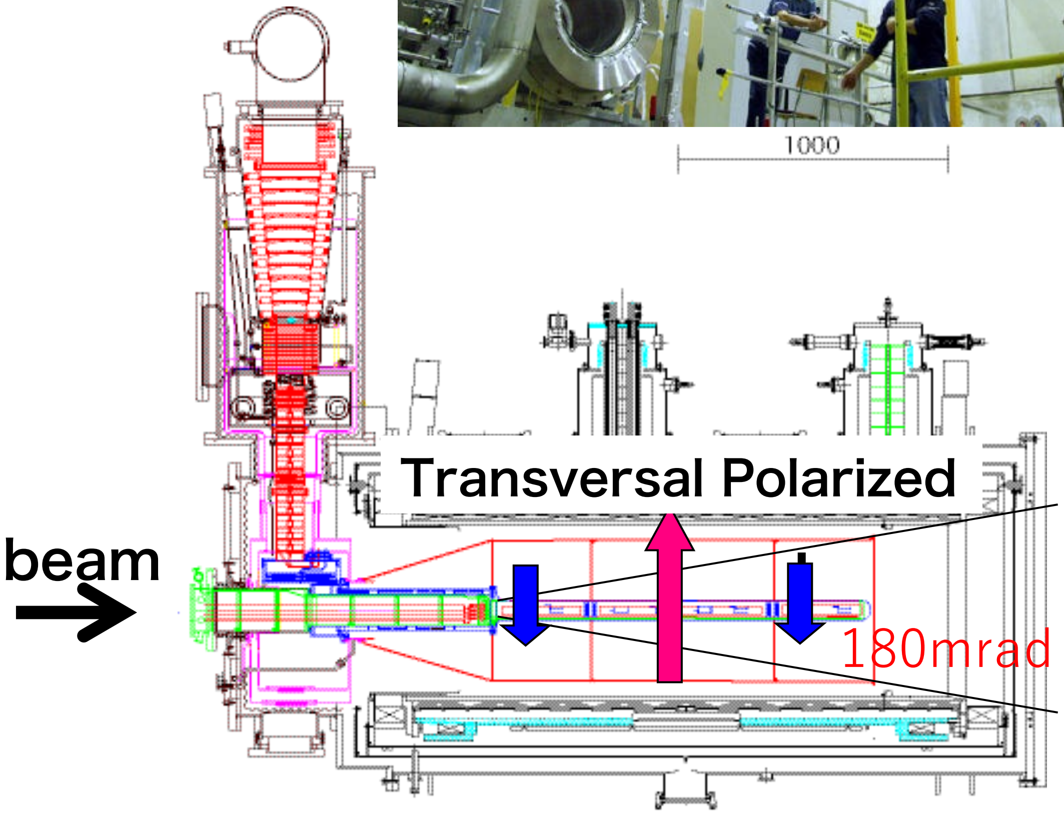


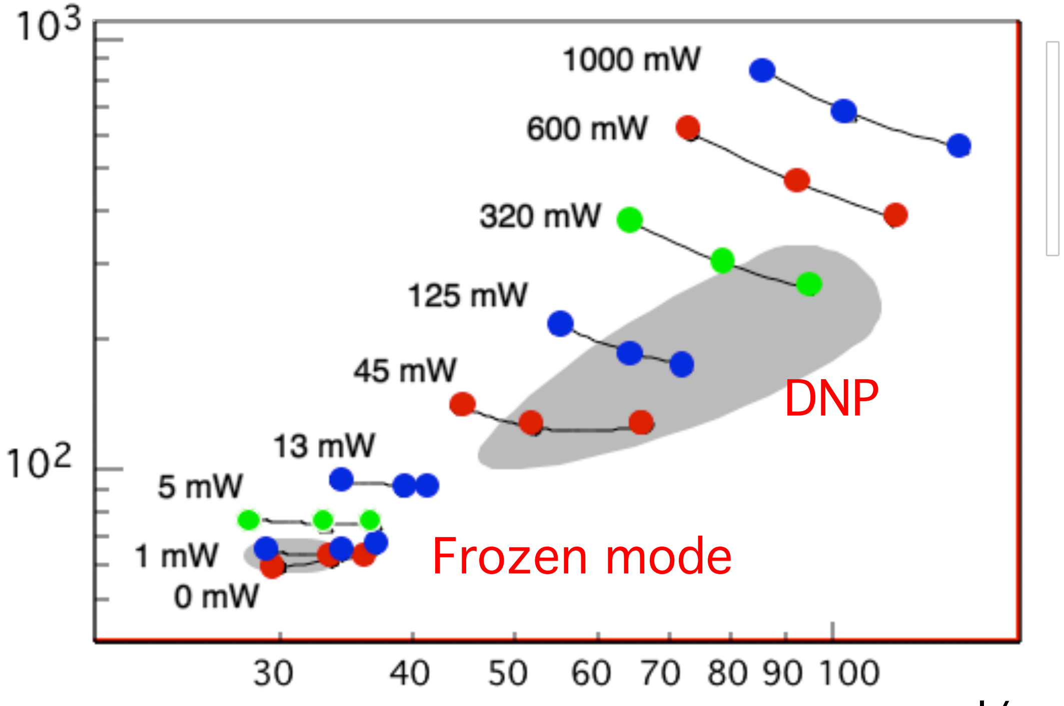


Dilution refrigerator

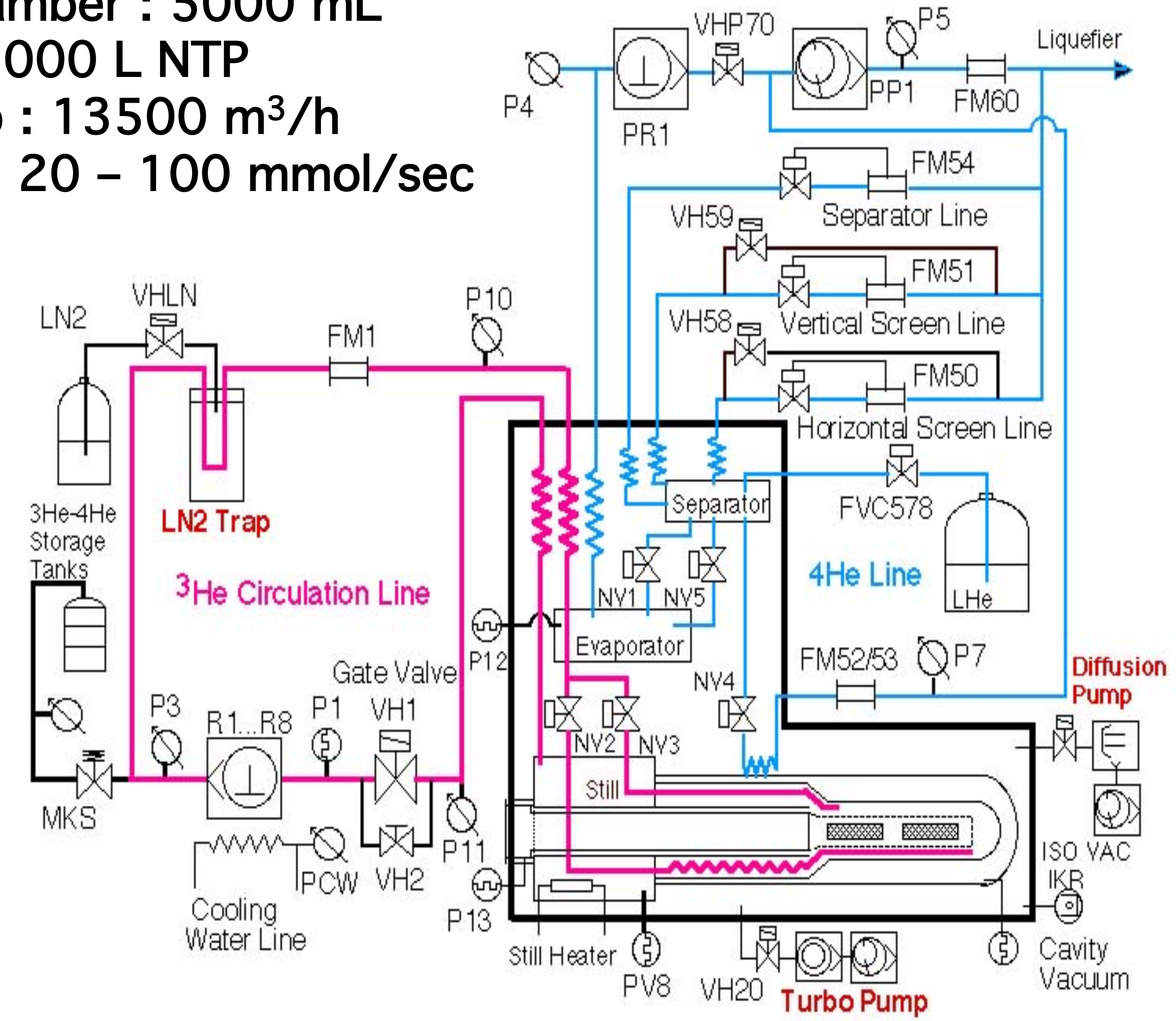
- Min. temperature : 50 mK
- Mixing chamber : 5000 mL
- 3He gas 1000 L NTP
- 3He pump : 13500 m³/h
- 3He flow : 20 – 100 mmol/sec

Refrigerator Temp. [mK]

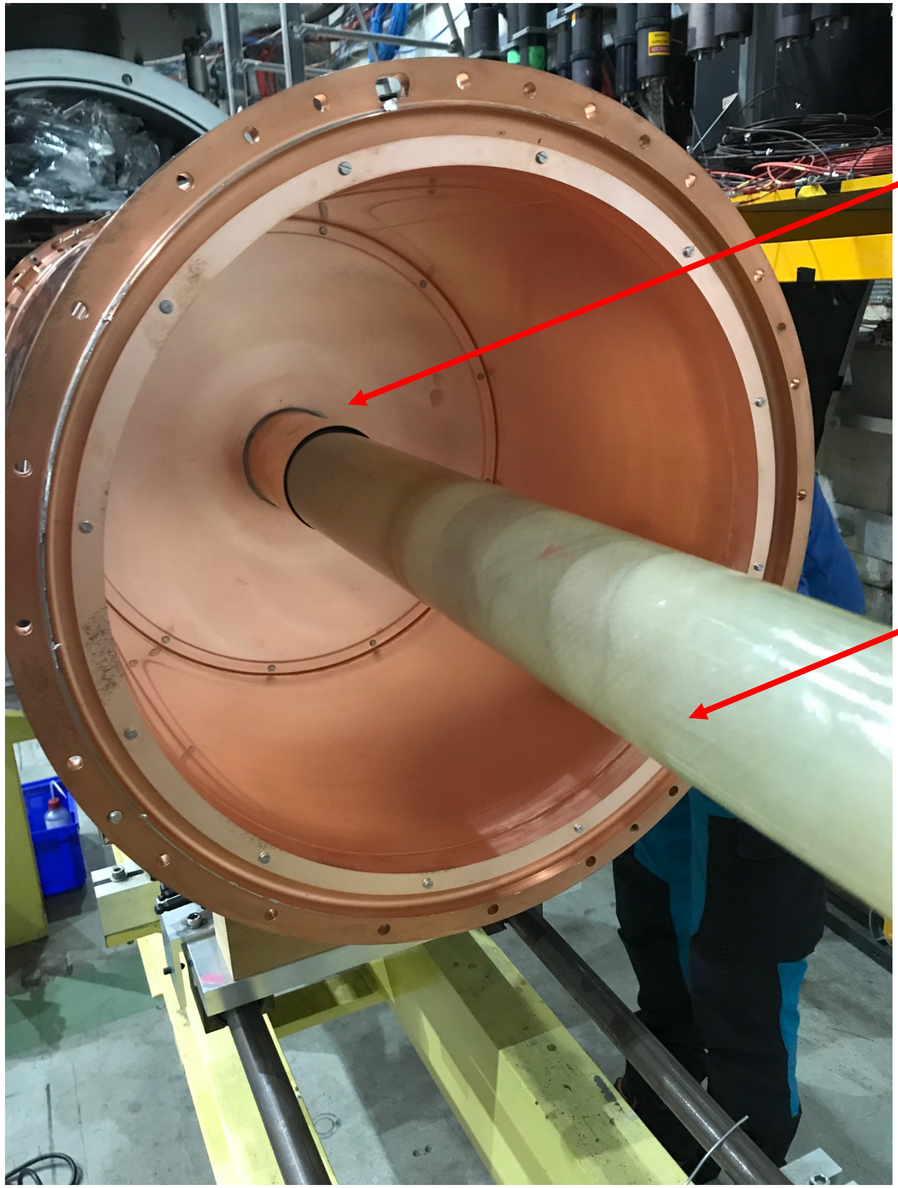
Cooling power



mmol/sec



Microwave cavity for 3 cells



Up/central separation

Mixing chamber

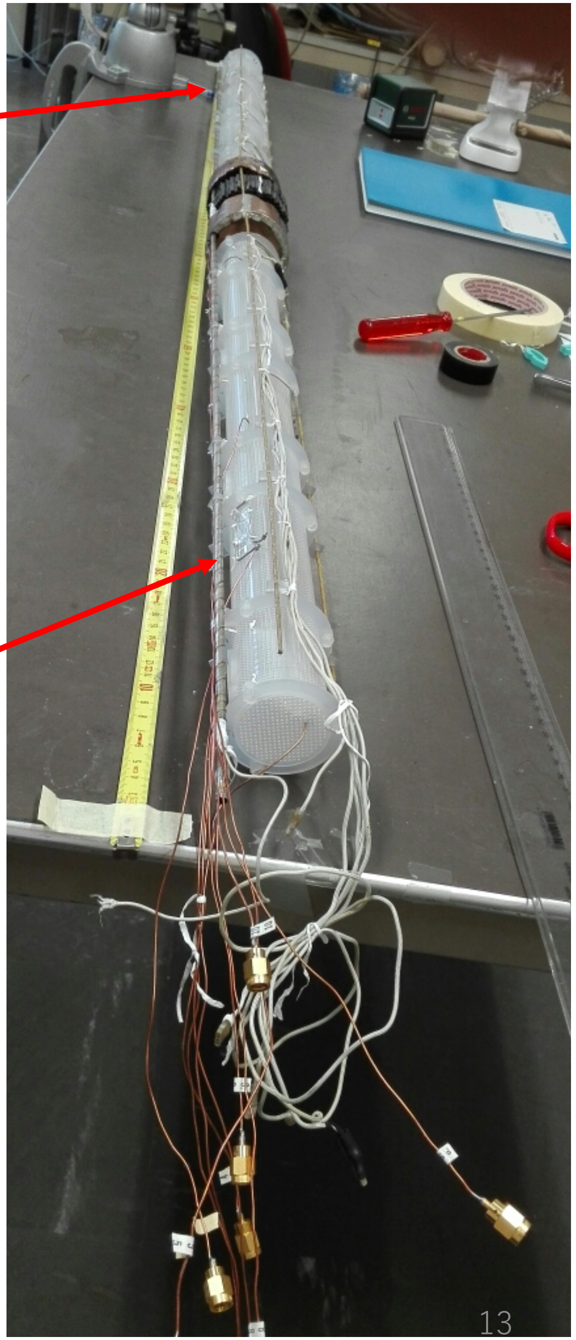
Refrigerator

Downstream of mixing chamber

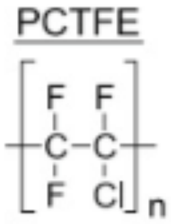
Proton free target cell

Used in 2015 and 2018

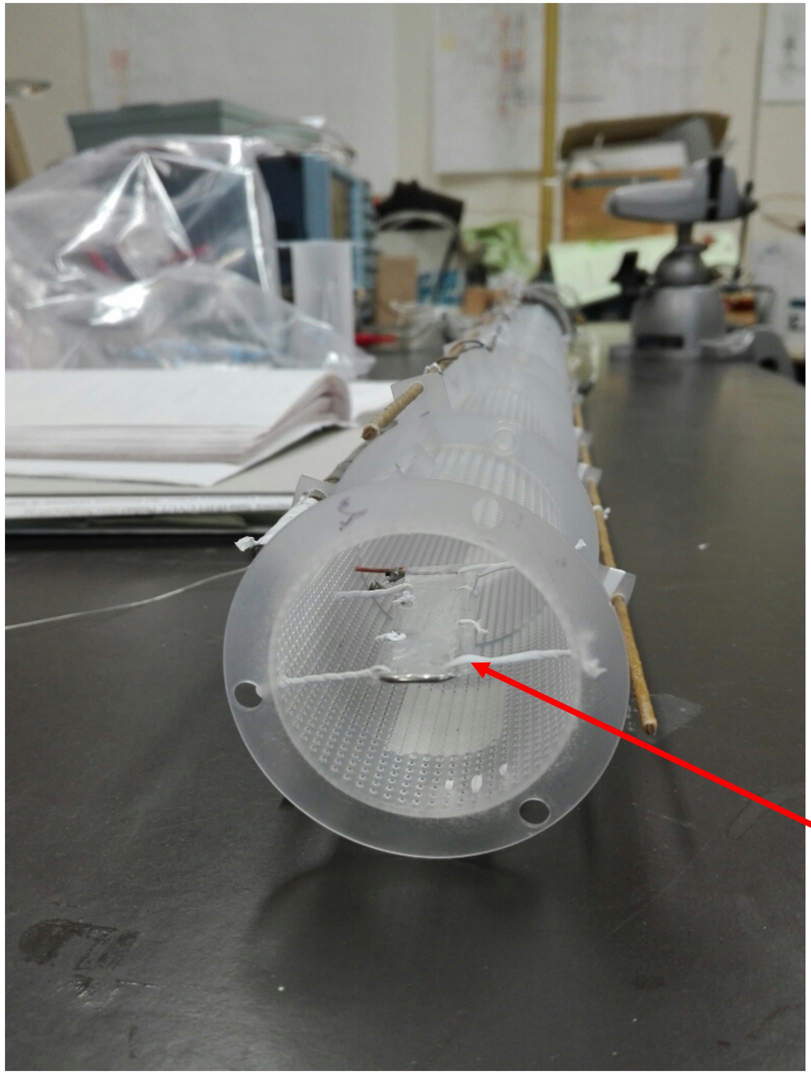
downstream cell



Material : PCTFE

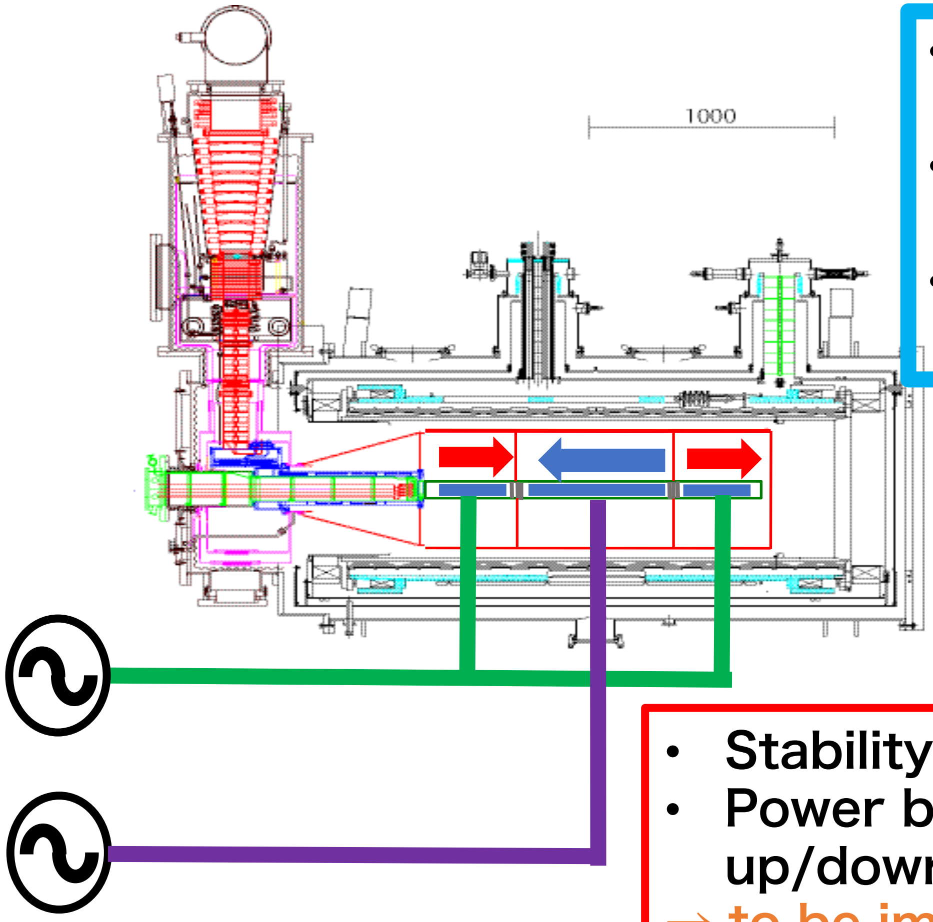


upstream cell



NMR coil

EIO microwave system



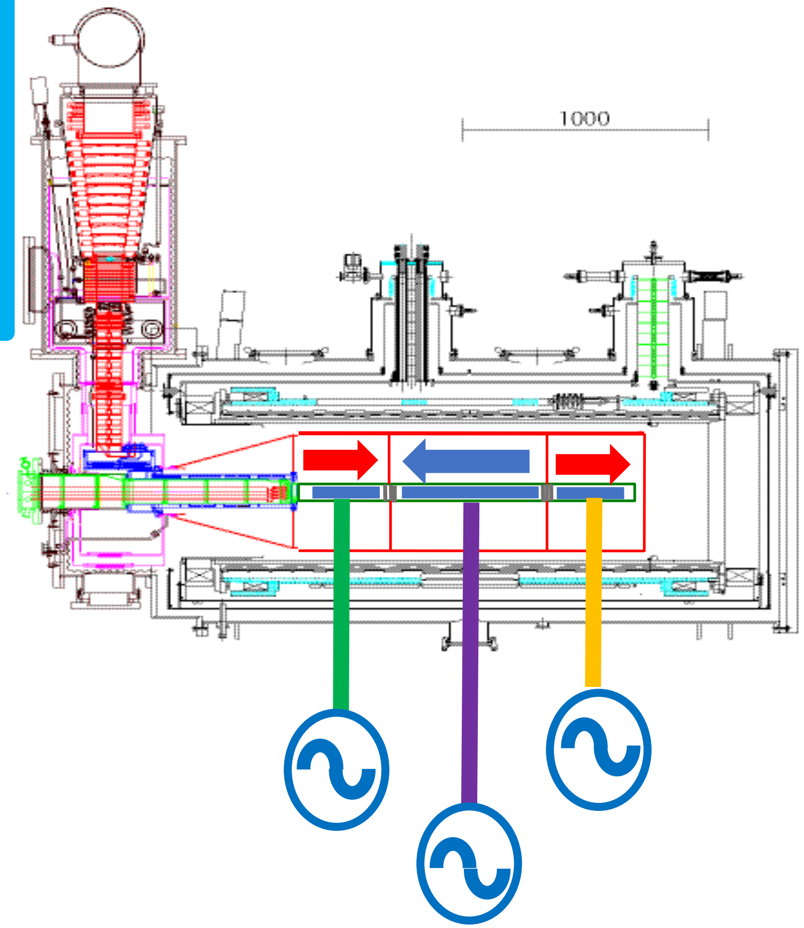
- Polarization : pos. & neg. (two different frequency)
- 100-200 mW power required for each cell
- Frequency and power adjustment

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

→ to be improved

20W EIO (70GHz)
20m long waveguide

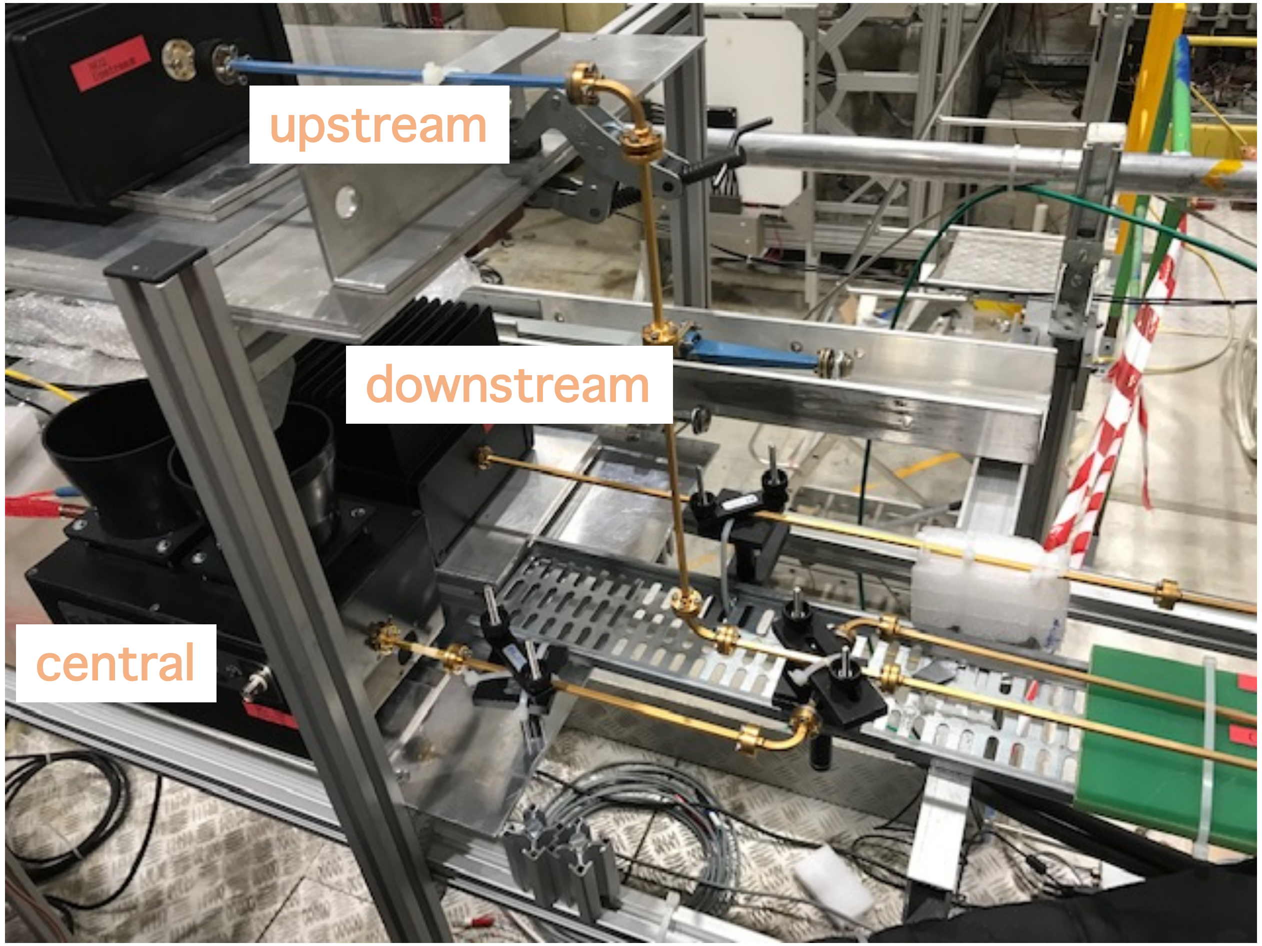
Gun system in 2022



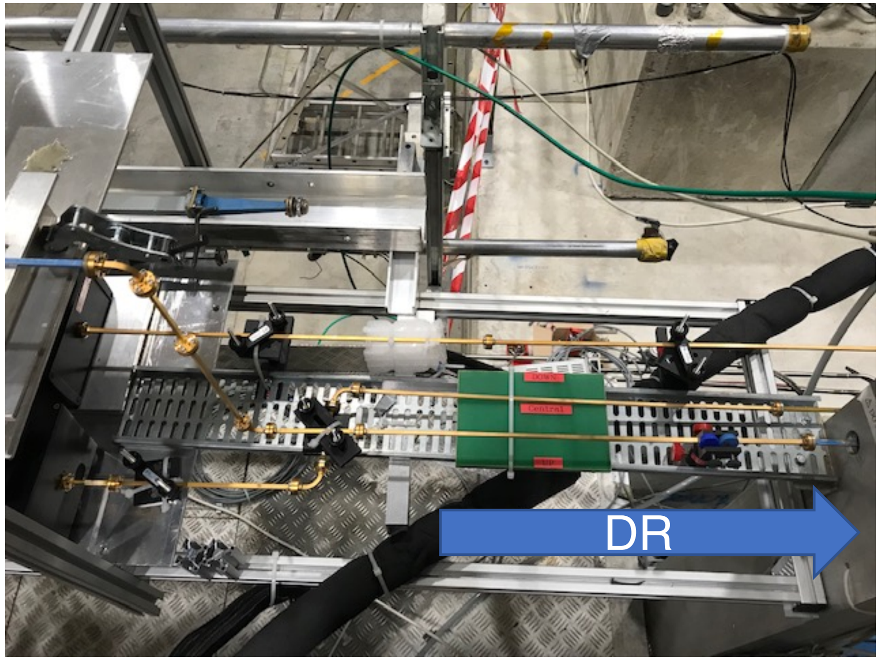
Three Gunn Diode 3W （ELVA-1）
1.5m long waveguide

Microwaves

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

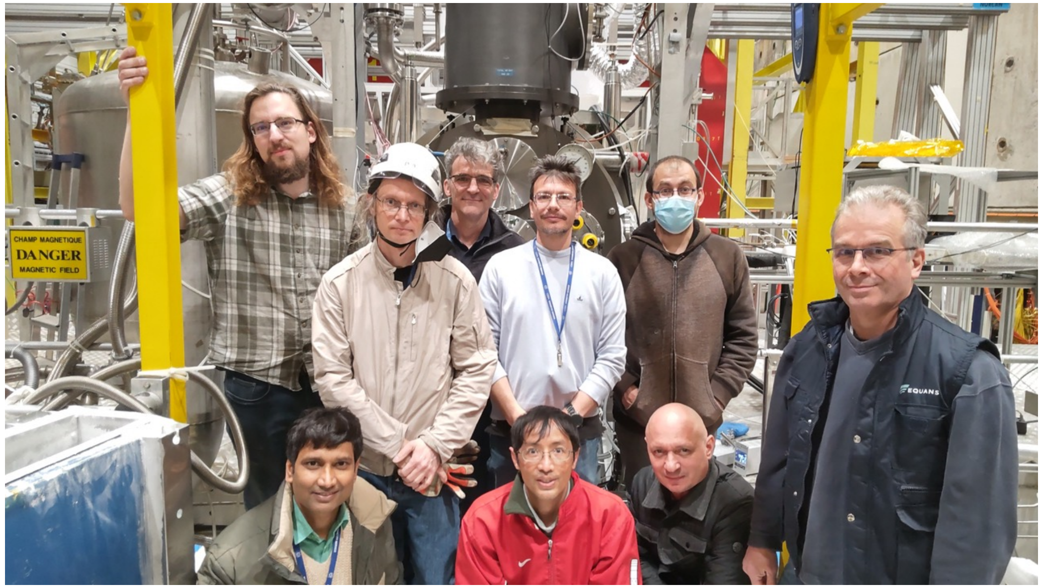


Generation test in 2020



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



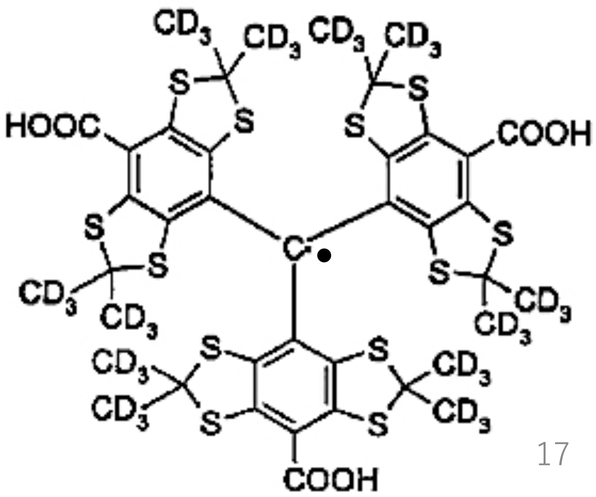
Loading done in the LN2 bath

Target materials production

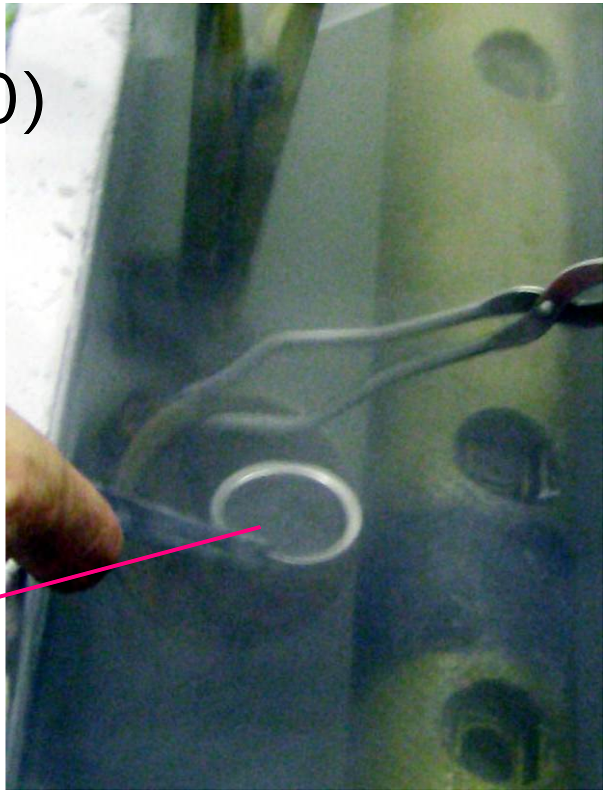
DNP needs paramagnetic centers into solid target materials

- **Radiation dope method**
  - NH3 material for COMPASS
    - NH3 melting point is 195K
    - 2-3 mm beads size
    - 20 MeV e- beam irradiation in the liquid Argon bath (87K)
    - paramagnetic centers of ~10^19 /cm3 doped
  - 6LiD material for COMPASS
    - 2-3 chips size
    - 20 MeV e- beam irradiation in 190 K bath
    - 2 x10^19 /cm3 doped
- **Chemical dope method**
  - Butanol (C_4H_9OH), D-Butanol (C_4D_9OD)
    - -EHBA ($Na[C_{12}H_{20}O_7Cr(V)]$) introduced
    - -Finland D36 (AH110355) newly found (NIM A 526(2004)43)

Finland D36



COMPASS Target material NH3



- NH_3 used as proton target (produced in 1996, 2010)
- Free radicals are produced
  by electron beam in the liquid argon.
- Critical temperature is 117K
  (W. Meyer, 1984 Bonn)

The old material produced in SMC (1996)→2007,2010

- Stored for more than 10 years in LN2
- Material property changed
  color : violet → pale
  free electron density : 6 x 10^{19} → 4.3 x 10^{19} /cm^3 in 2007 → **2010**
  relaxation time : 500h at 0.5T → 4000h at 0.6T → 9000h at 0.6T
- New target produced in 2010 autumn.

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

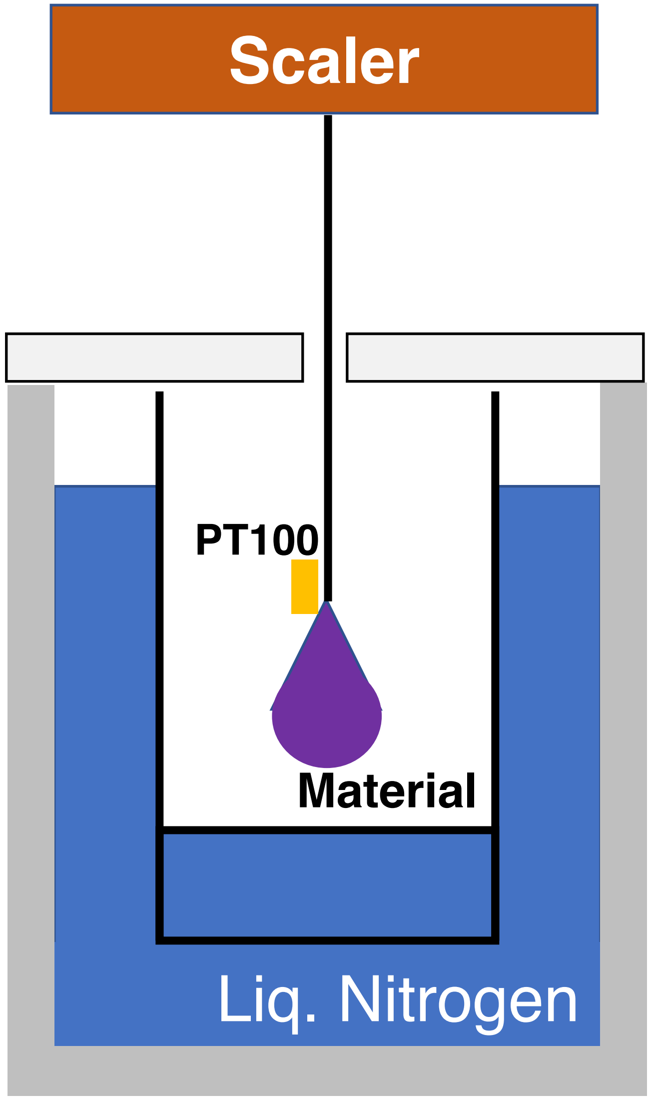
-Normalized by ND_3 .
-Magnetic field 2.5T
- Relaxation time
^{6}LiD 1500h at 0.42T and 60 mK.

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

NH3 weight measurement in 2018

- Material kept in Liq. N2 bath
- Four socks (two for upstream and two for downstream)
- 10 hours for one measurement
- Kept the sock below 100 K

	Weight (g)	Packing factor
upstream	329 +/- 1	0.558 +/- 0.002
downstream	310 +/- 1	0.526 +/- 0.002



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Dynamic Nuclear Polarization（DNP)

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

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

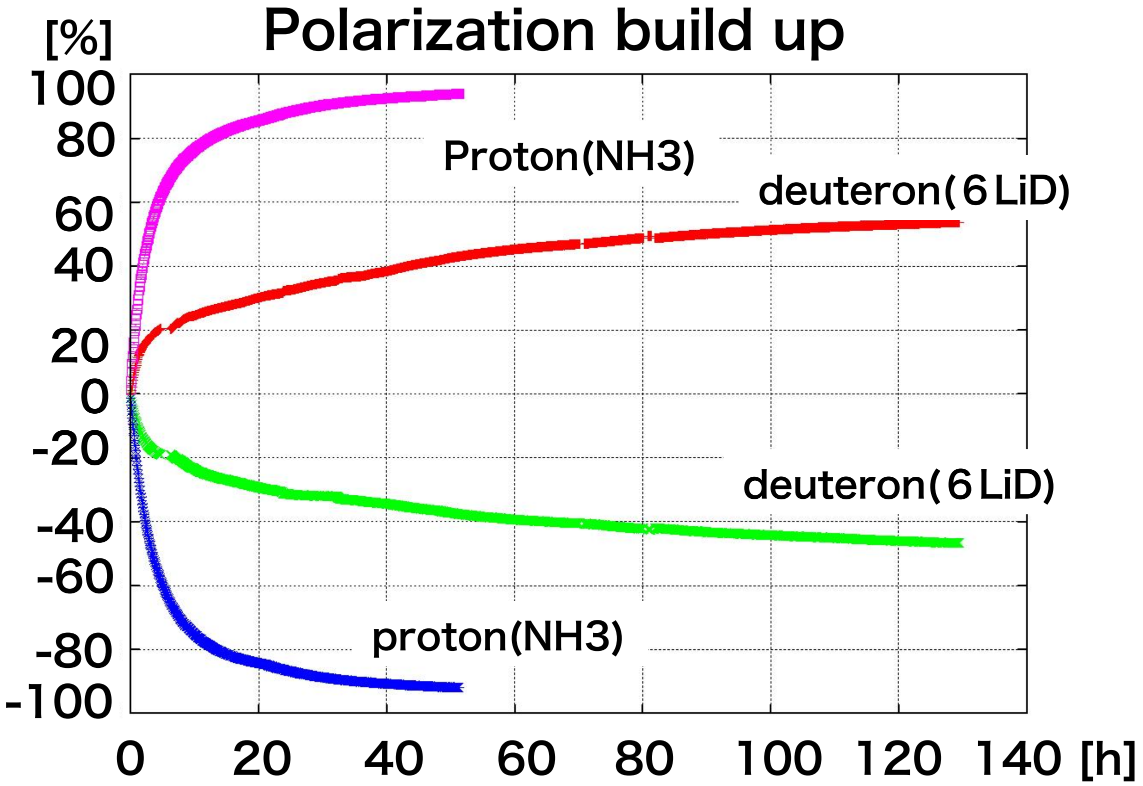
μ : magnetic moment
B : magnetic field
K_B : boltzmann constant
T : temperature

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

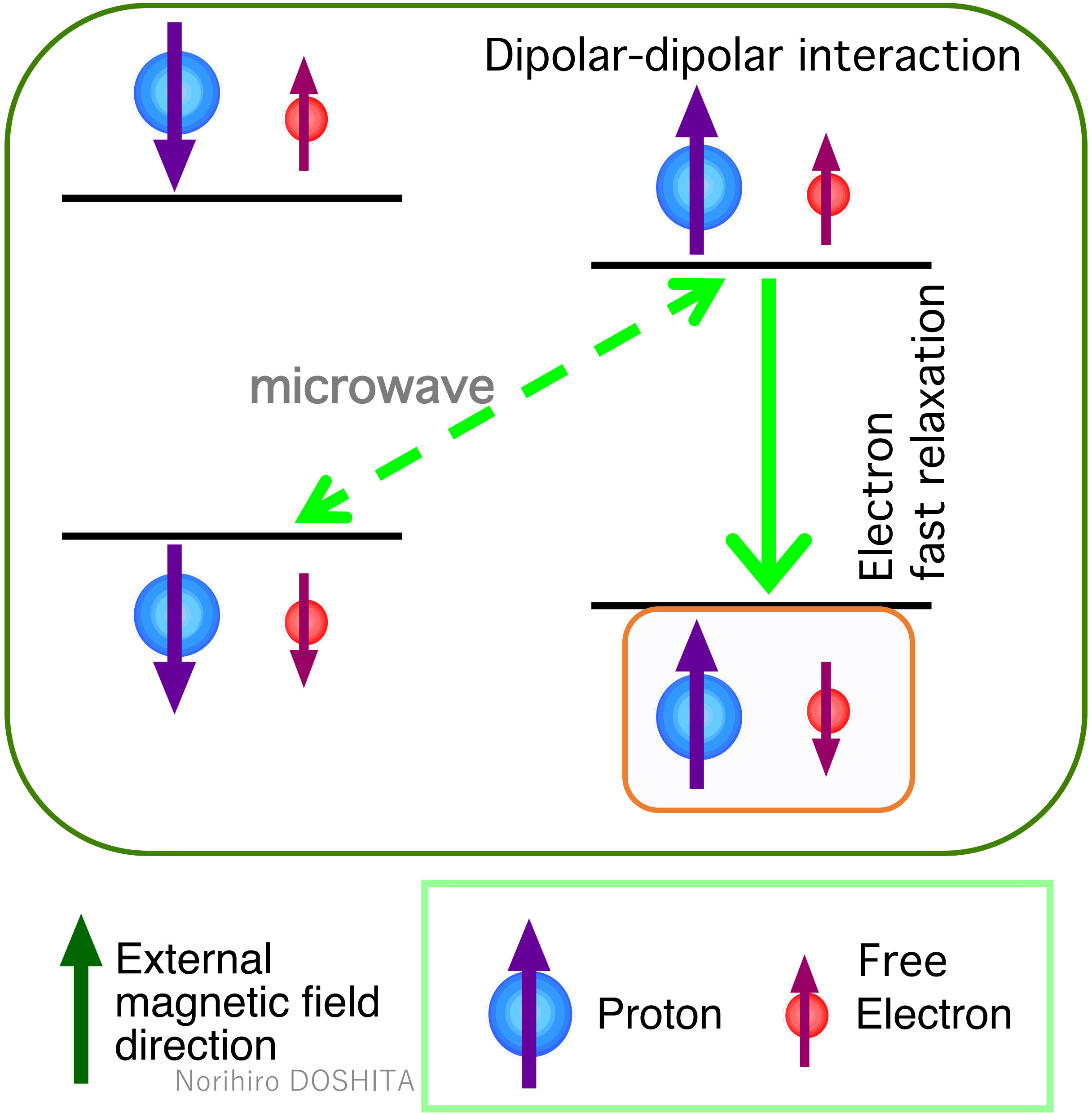
Dynamic Nuclear Polarization

Paramagnetic centers (Free electrons) are doped.

Polarization
@2.5T and 0.1K
Electron: 99.9%
Proton: 2.6%

↓

Transfer the high electron polarization to proton polarization



Norihiro DOSHITA

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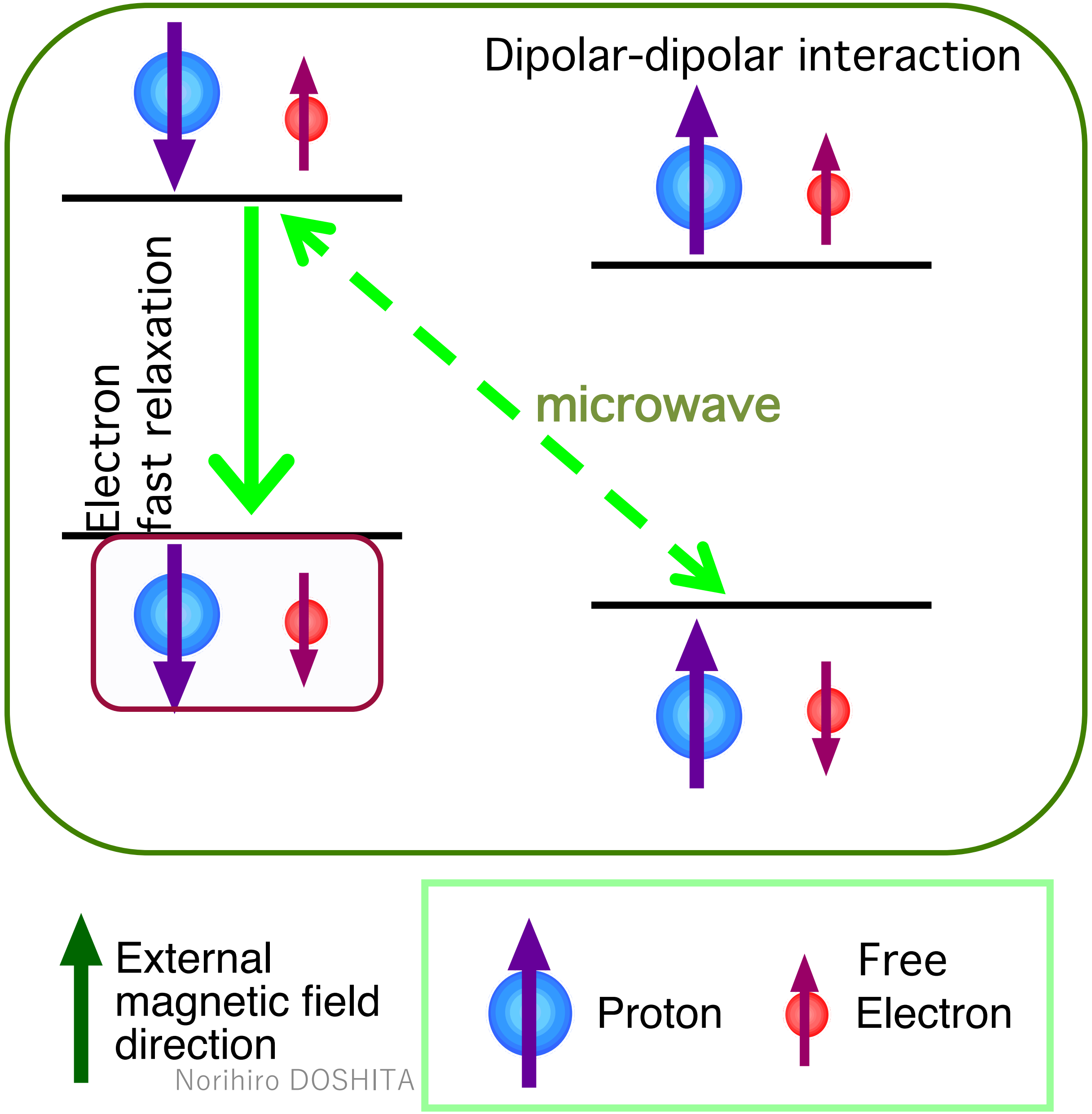


TE analysis for deuteron in 2022

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.

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

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

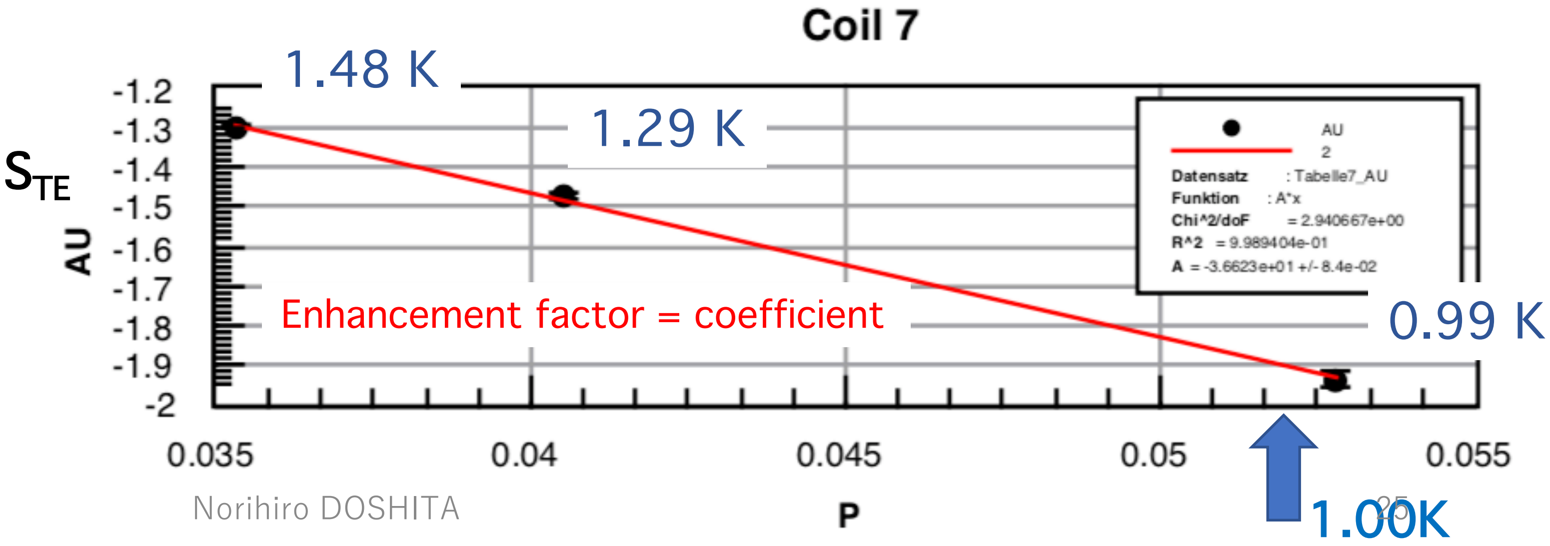
$$P_{TE=1K} = 0.0522789\ \%$$

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

Polarization can be determined
with DNP NMR signal.

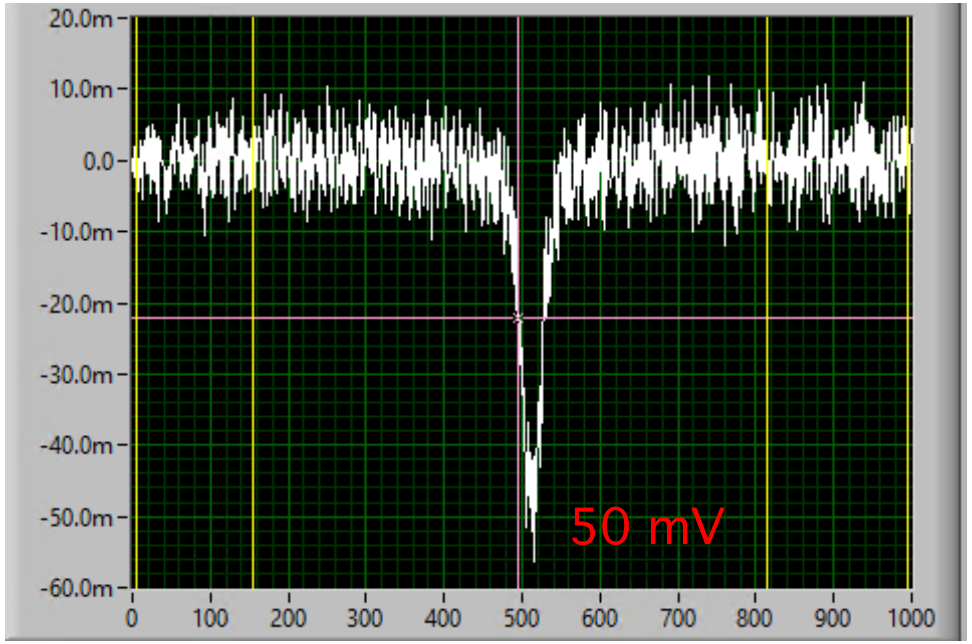
E = Enhancement factor

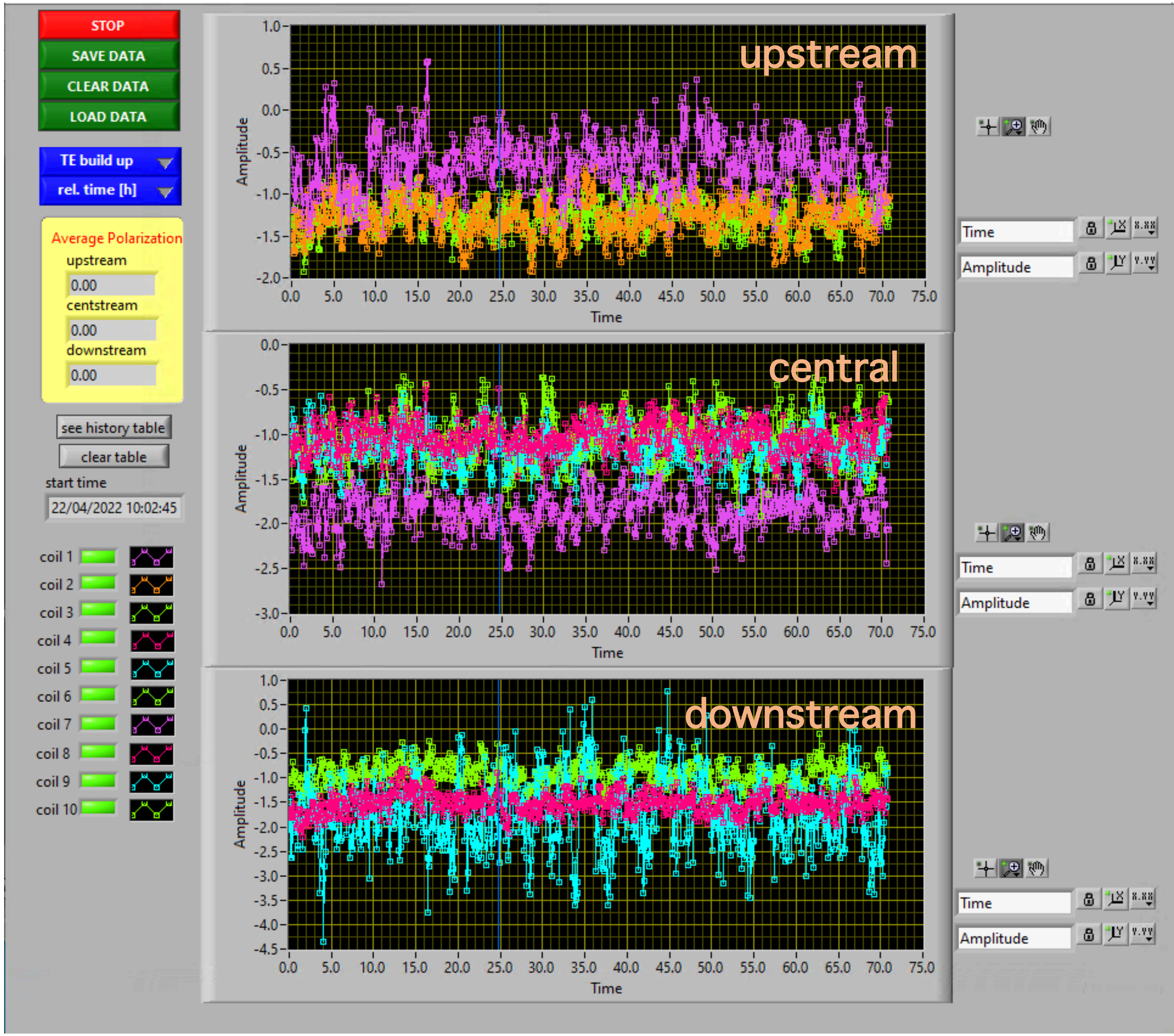
Coil	1/E	d1/E	d1/Erel	E	dE
1	-10.47	0.12	-1.2	-0.09548	0.0011
2	-24.53	0.11	-0.47	-0.04077	0.00019
3	-24.31	0.074	-0.3	-0.04113	0.00013
4	-19.87	0.077	-0.39	-0.05033	0.0002
5	-22.36	0.097	-0.43	-0.04472	0.00019
6	-20.39	0.079	-0.39	-0.04905	0.00019
7	-36.62	0.084	-0.23	-0.0273	6.3e-05
8	-29.83	0.073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

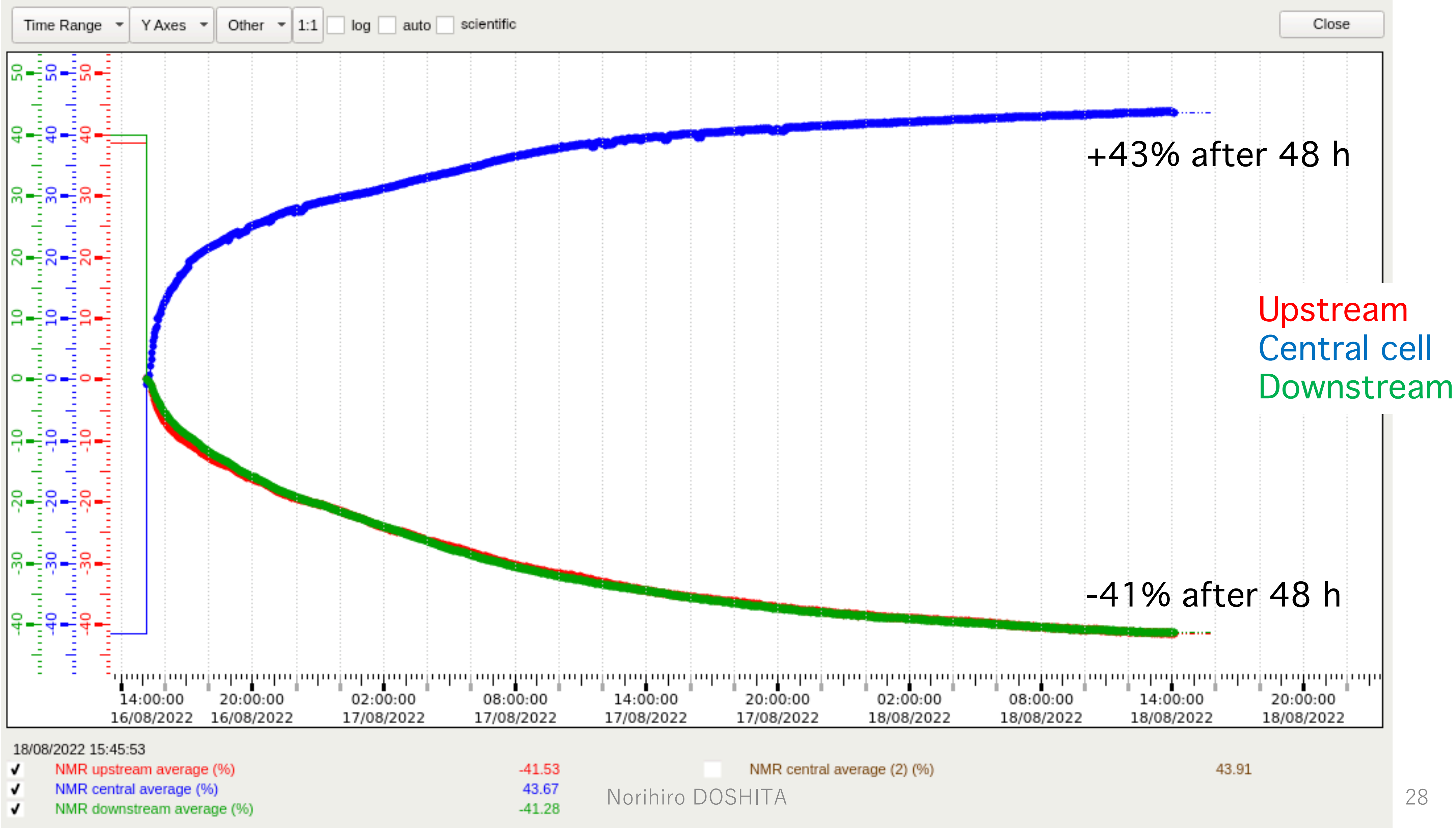




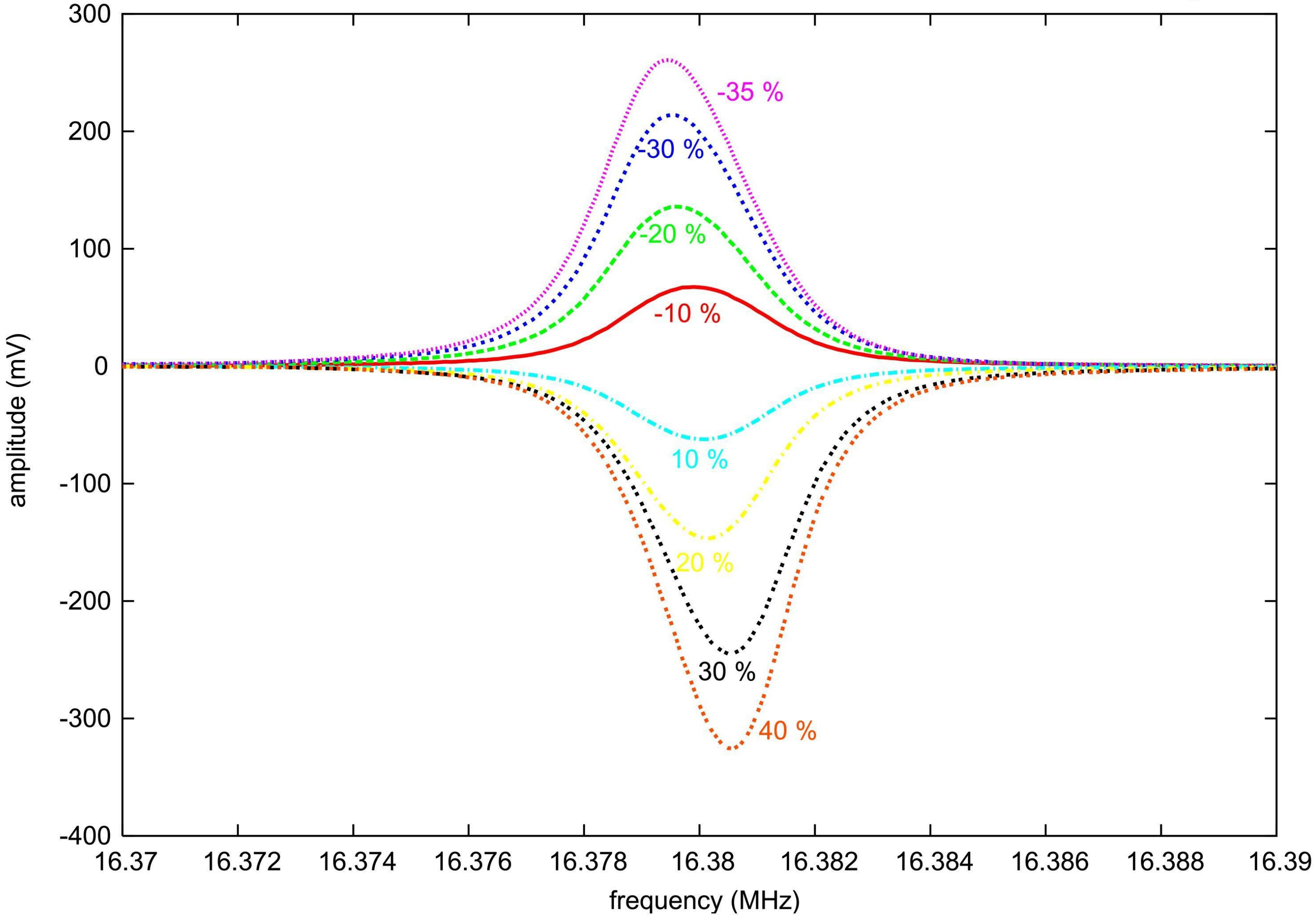
Gain factor measurement

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	

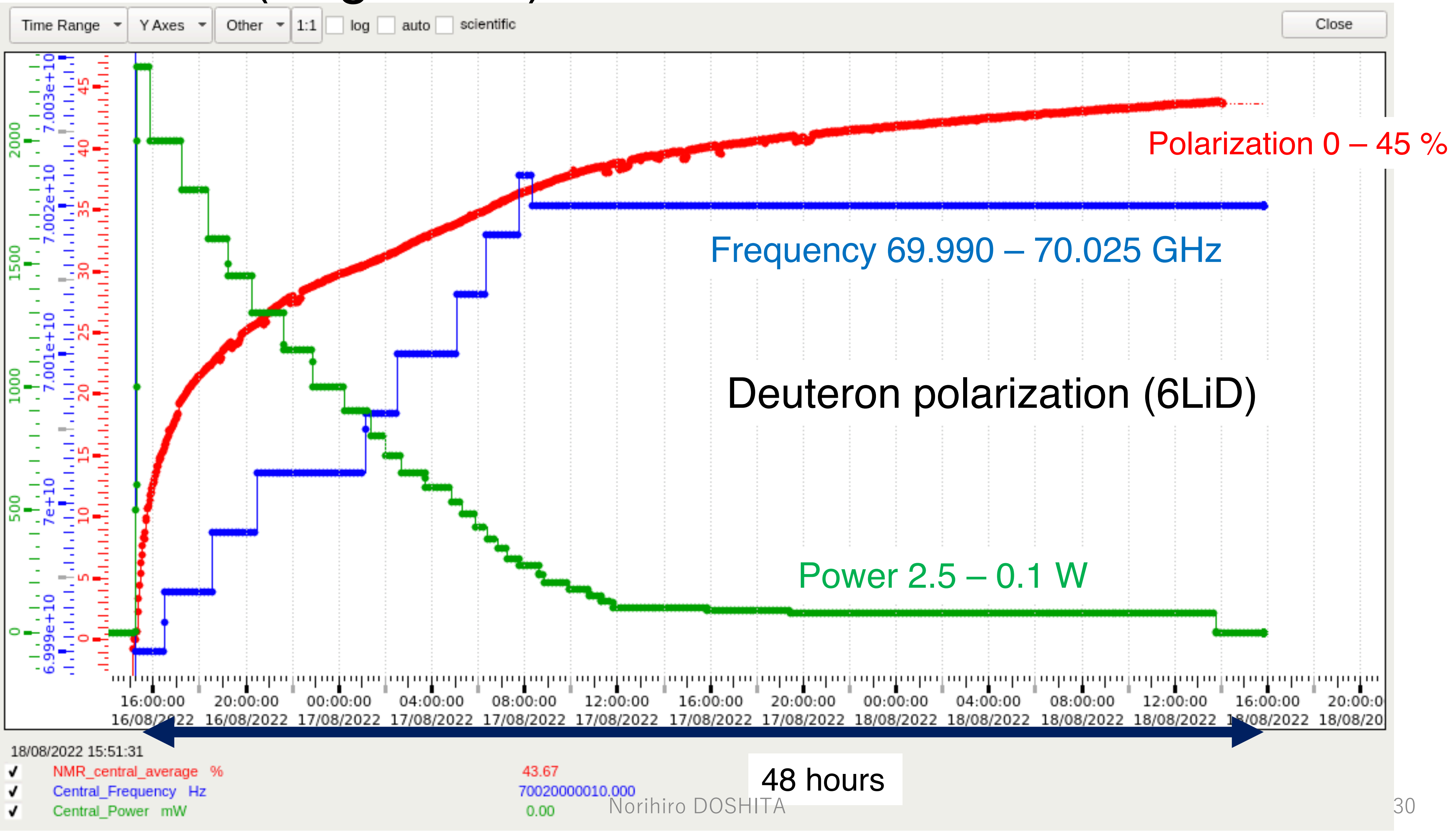
Polarization build up in 2022 (Deuteron)



Enhanced deuteron NMR signals



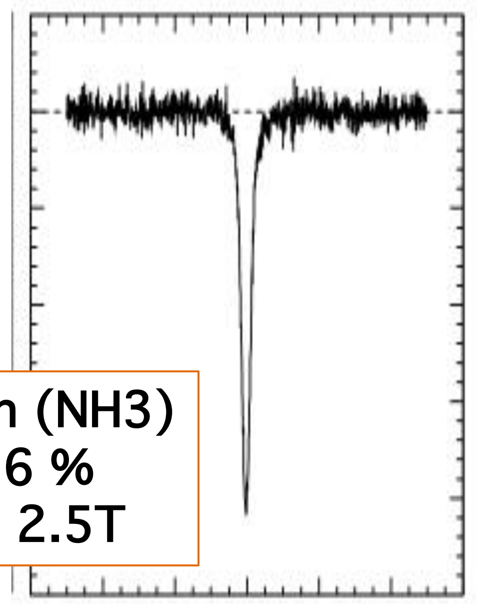
Central cell (Aug. 2022)



NH3 Polarization Measurement

Areal NMR signal is in proportion to its polarization.

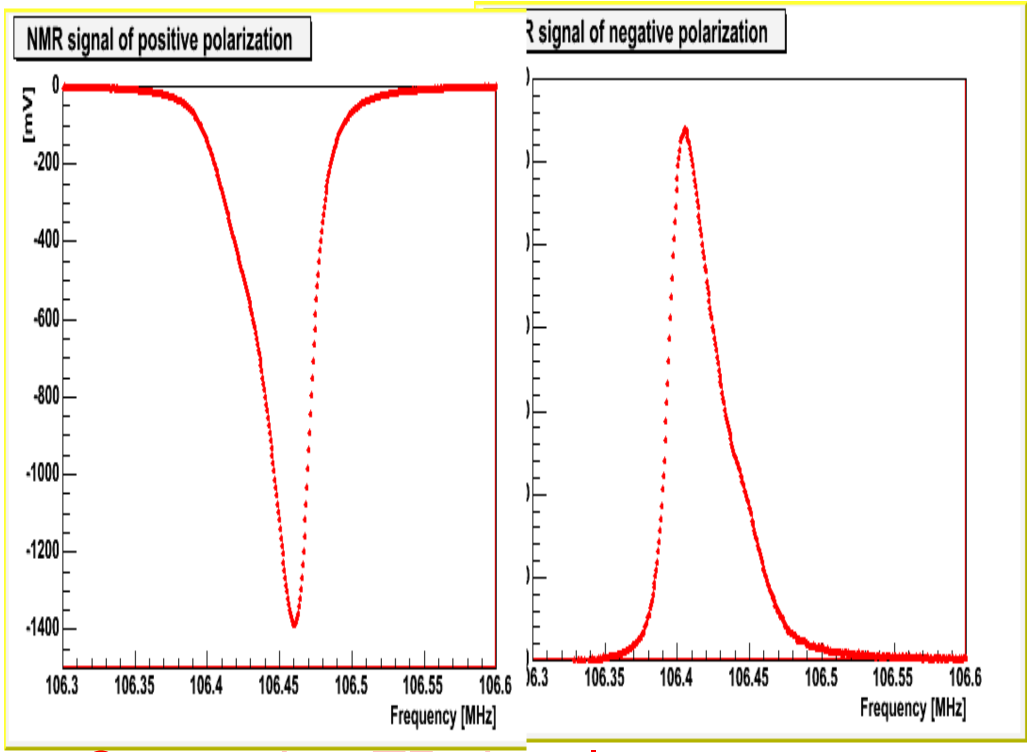
Thermal equilibrium signal



Proton (NH3)
P=0.26 %
@ 1K, 2.5T

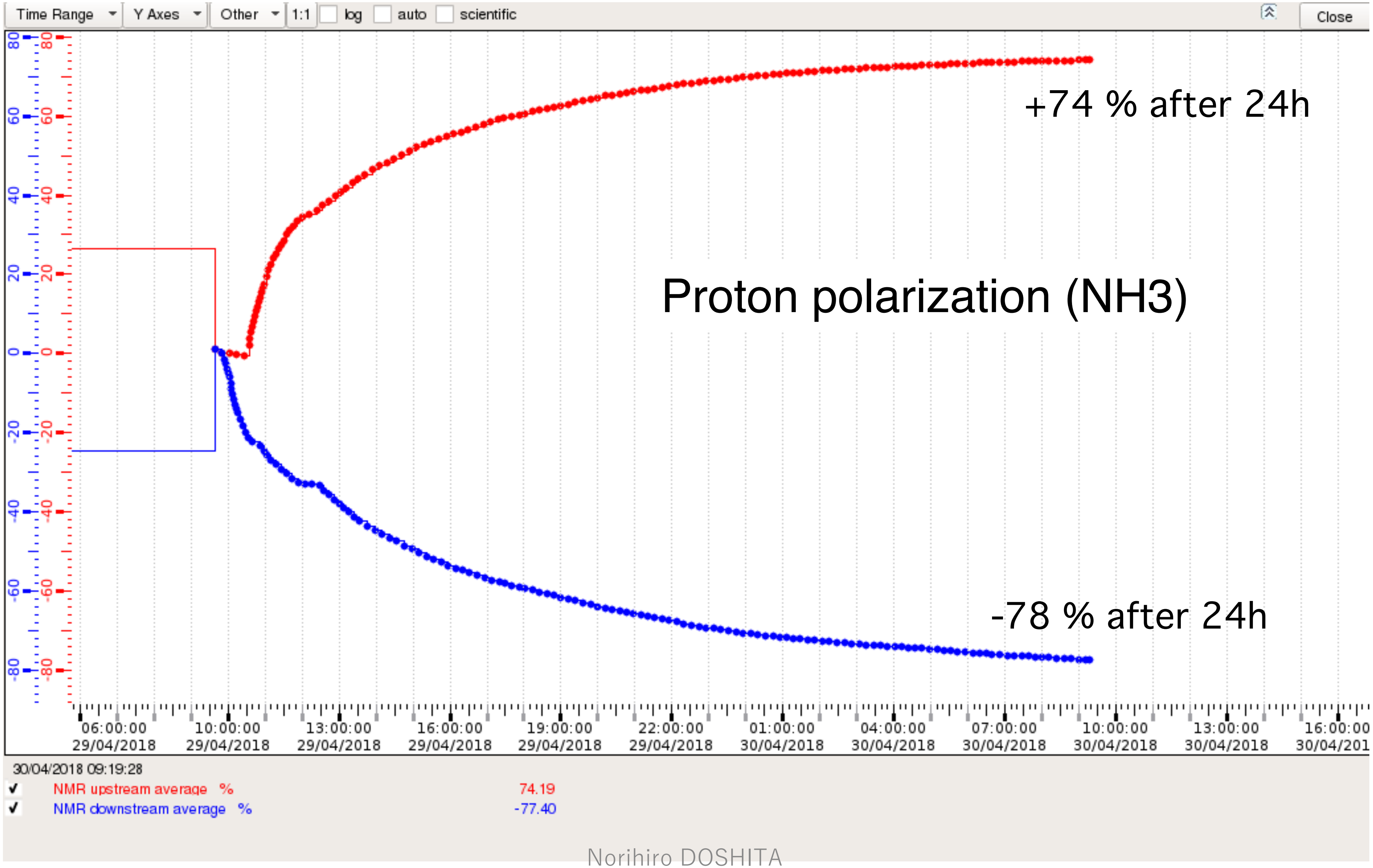
Polarization is calculated with temperature and magnetic field.

Dynamically enhanced NMR signals



Comparing TE signal area, the absolute polarization is obtained.

Polarization build up in 2018 (Proton)



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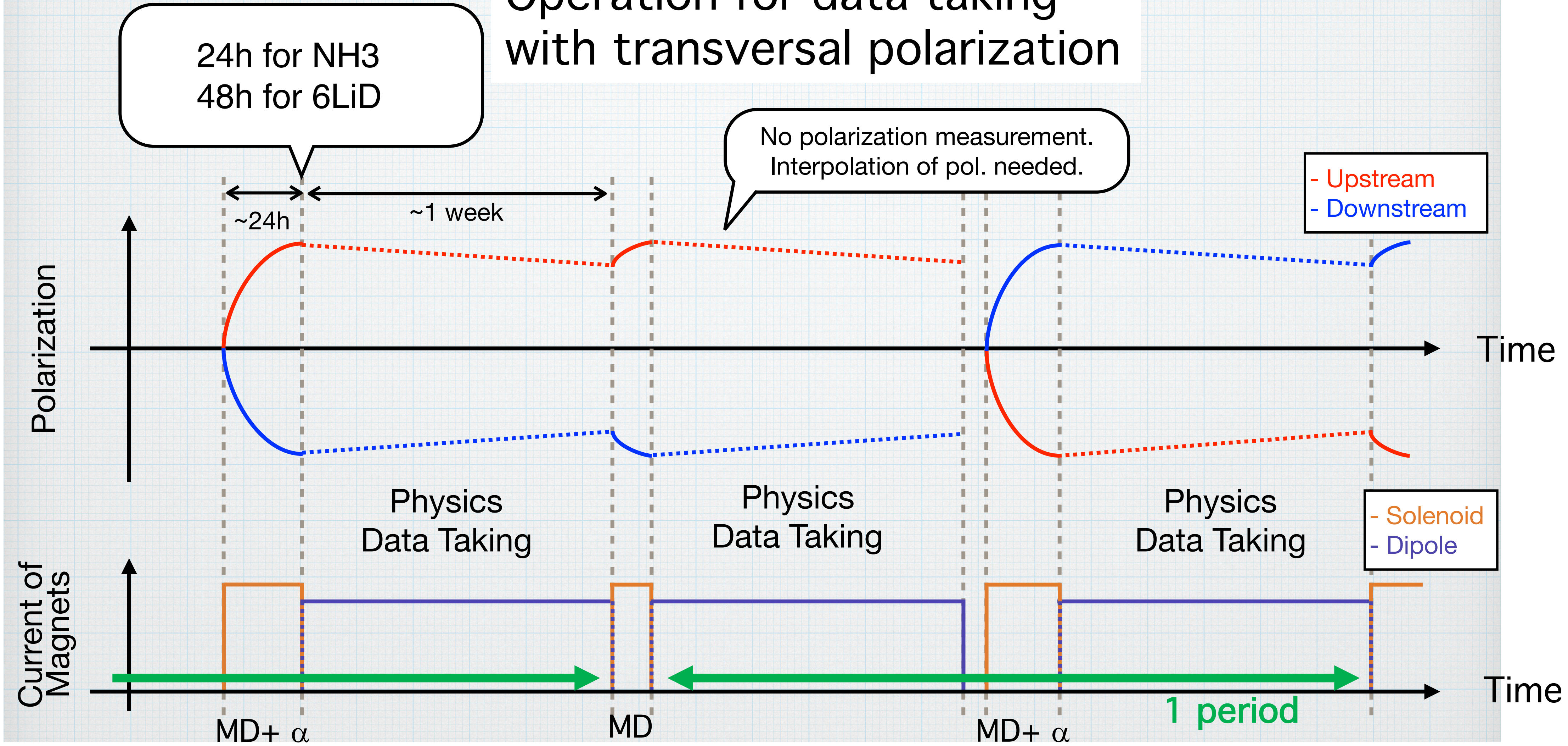
Operation for data taking with transversal polarization



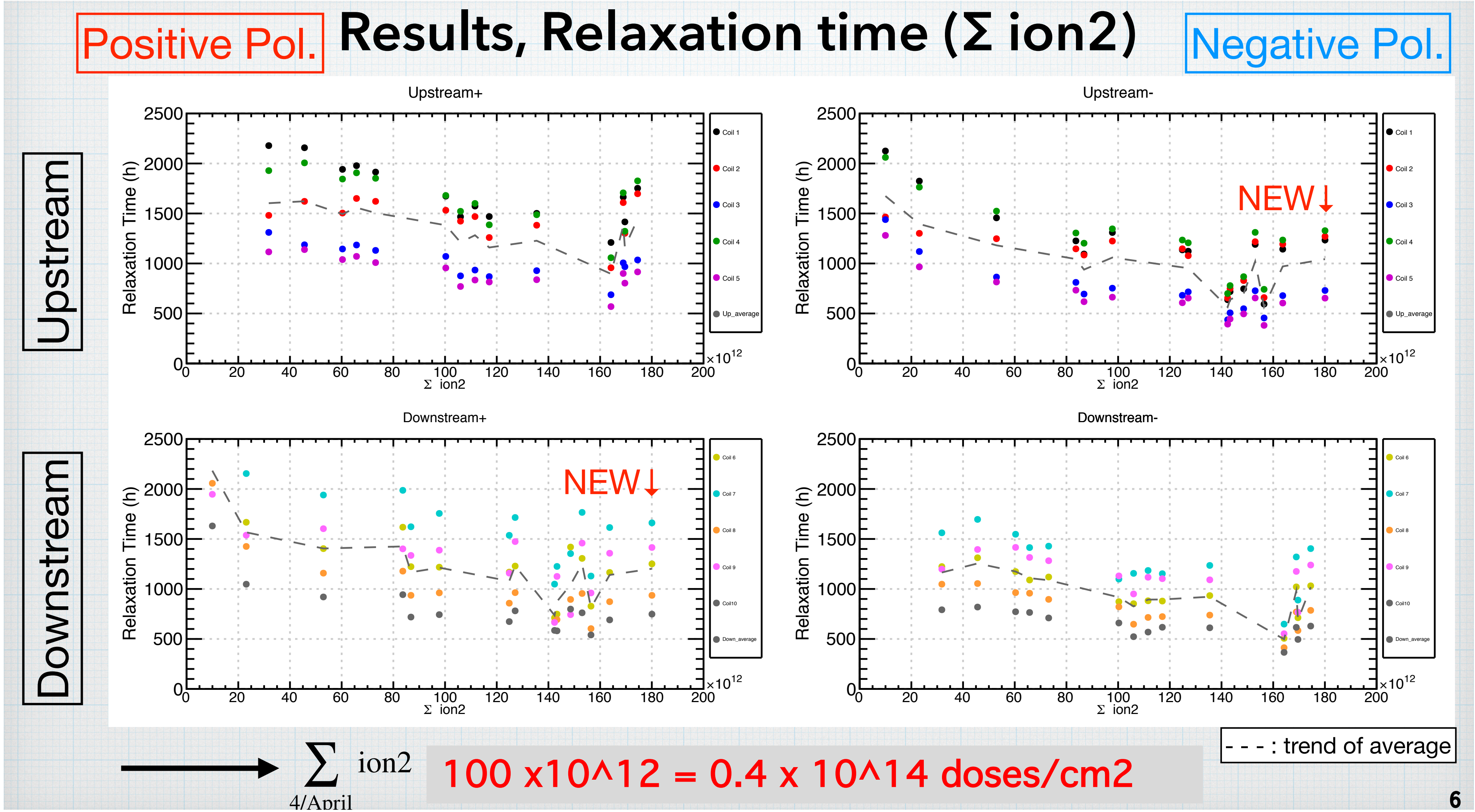
Beam intensity : 10^8 /s for 5 s and then no beam for 10 s or more in 2018

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

Relaxation time in 2018 vs accumulated incoming pions



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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

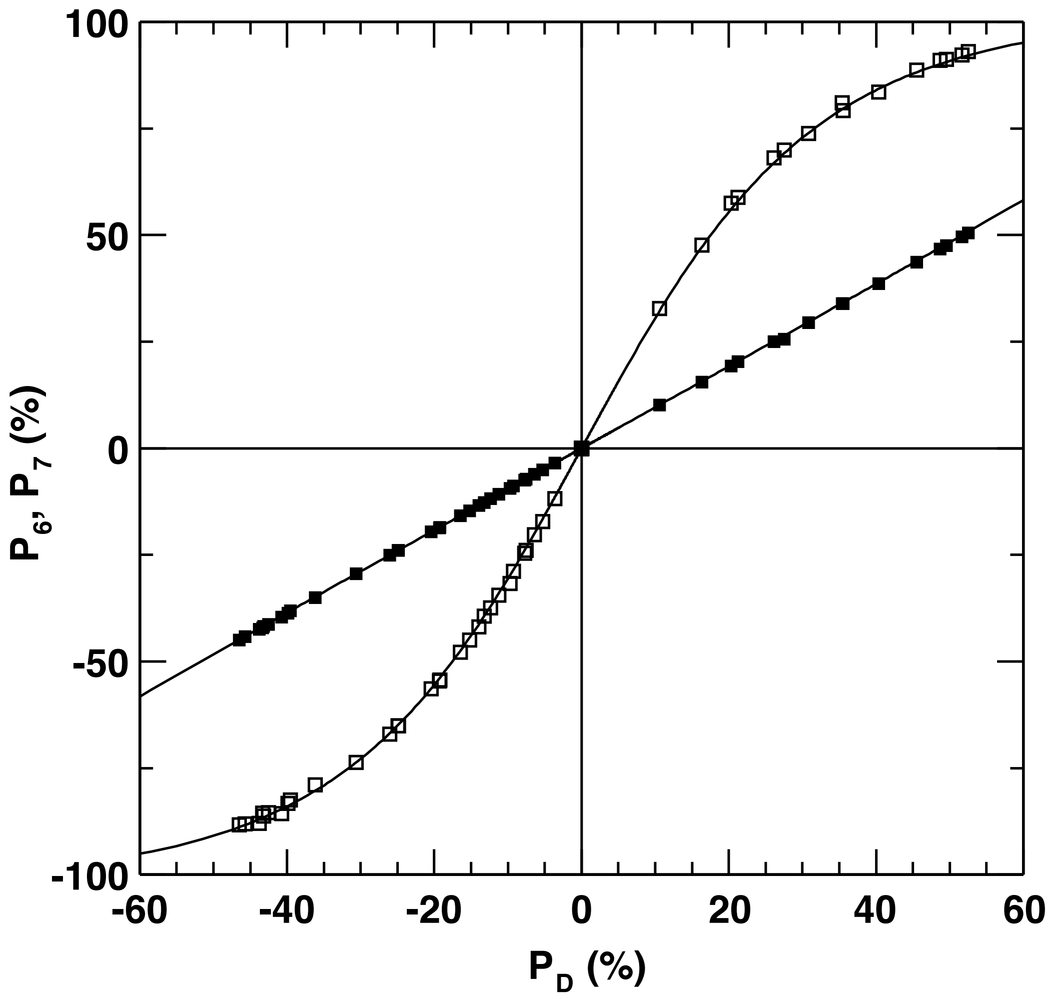
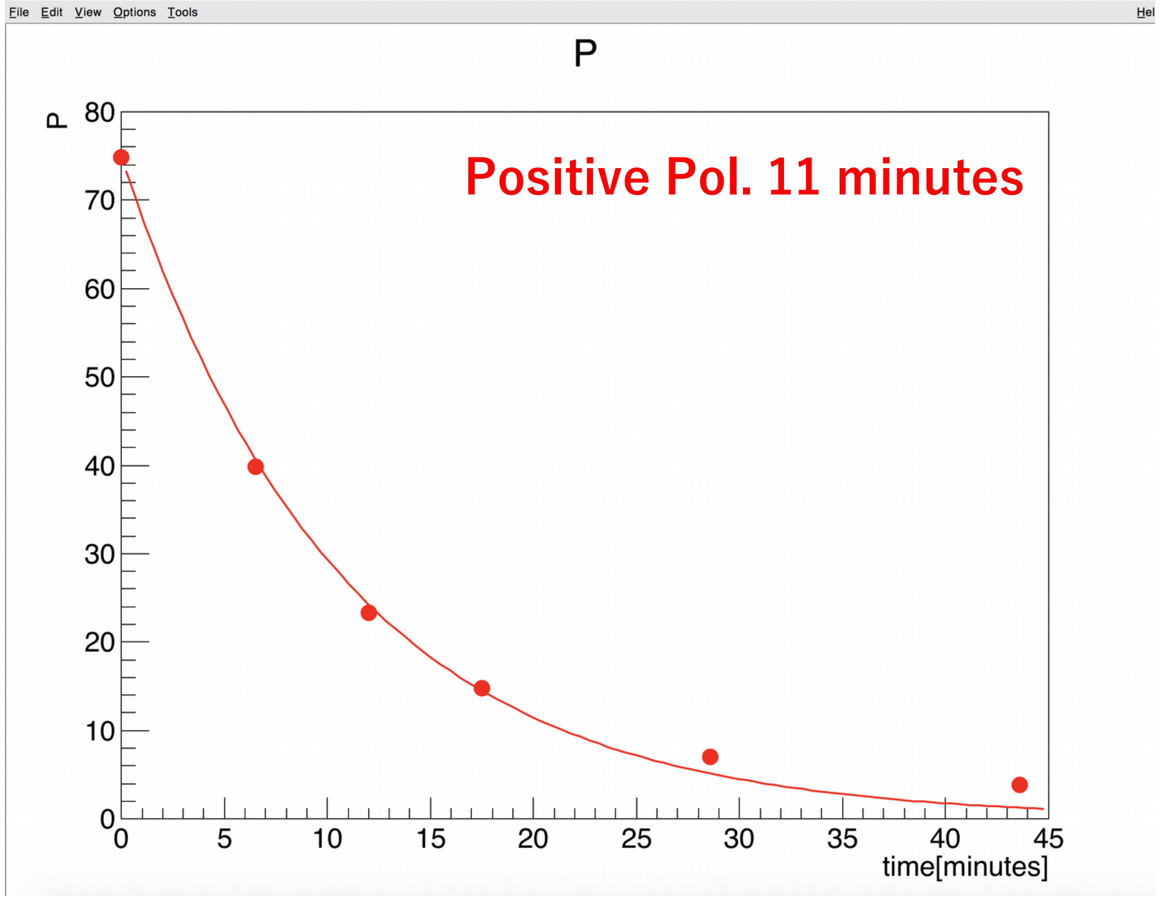
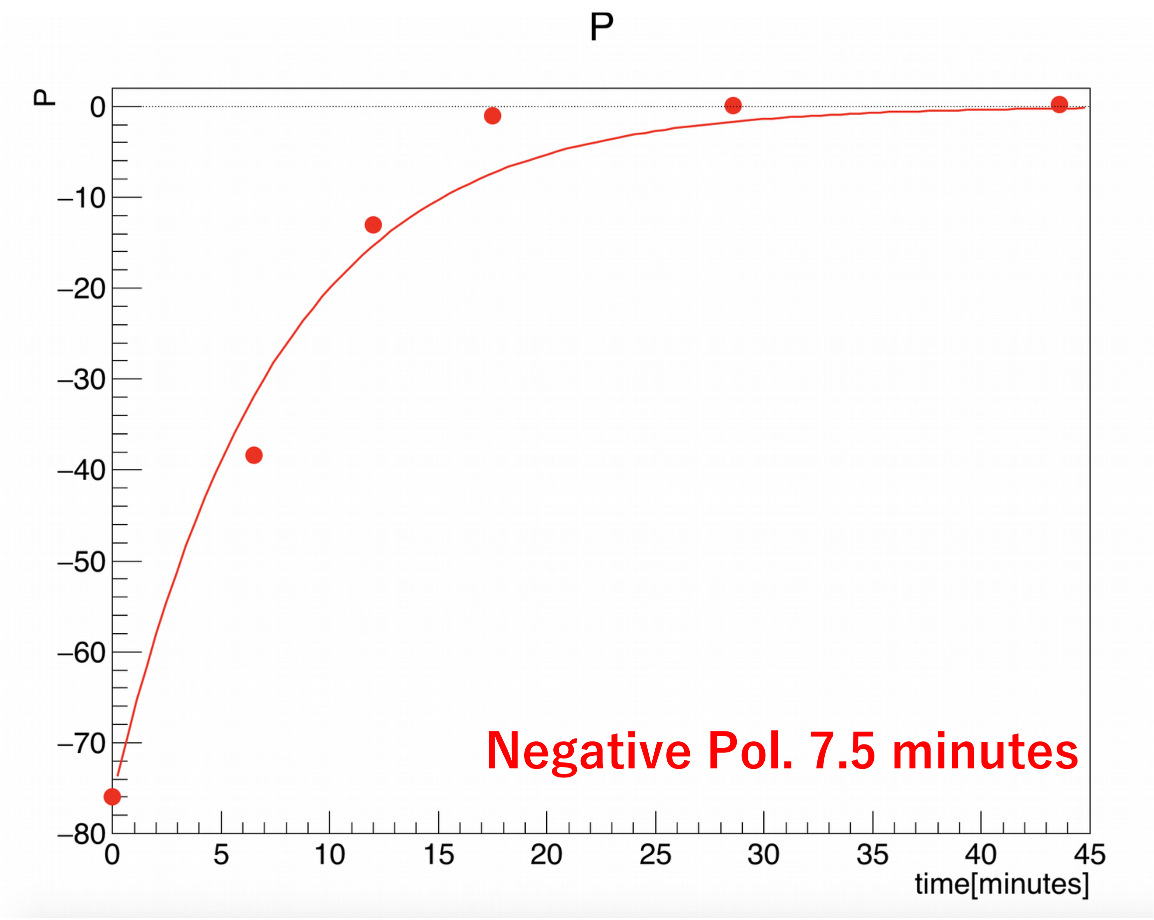


Fig. 6. The polarizations of the ^{6}Li and the ^{7}Li nuclei versus that of the deuteron. The closed (open) squares are the measured polarization of ^{6}Li (^{7}Li). The lines are the prediction by EST concept. The measurements are consistent with the EST concept.

NIMA498(2003)101

Relaxation time at 0 T

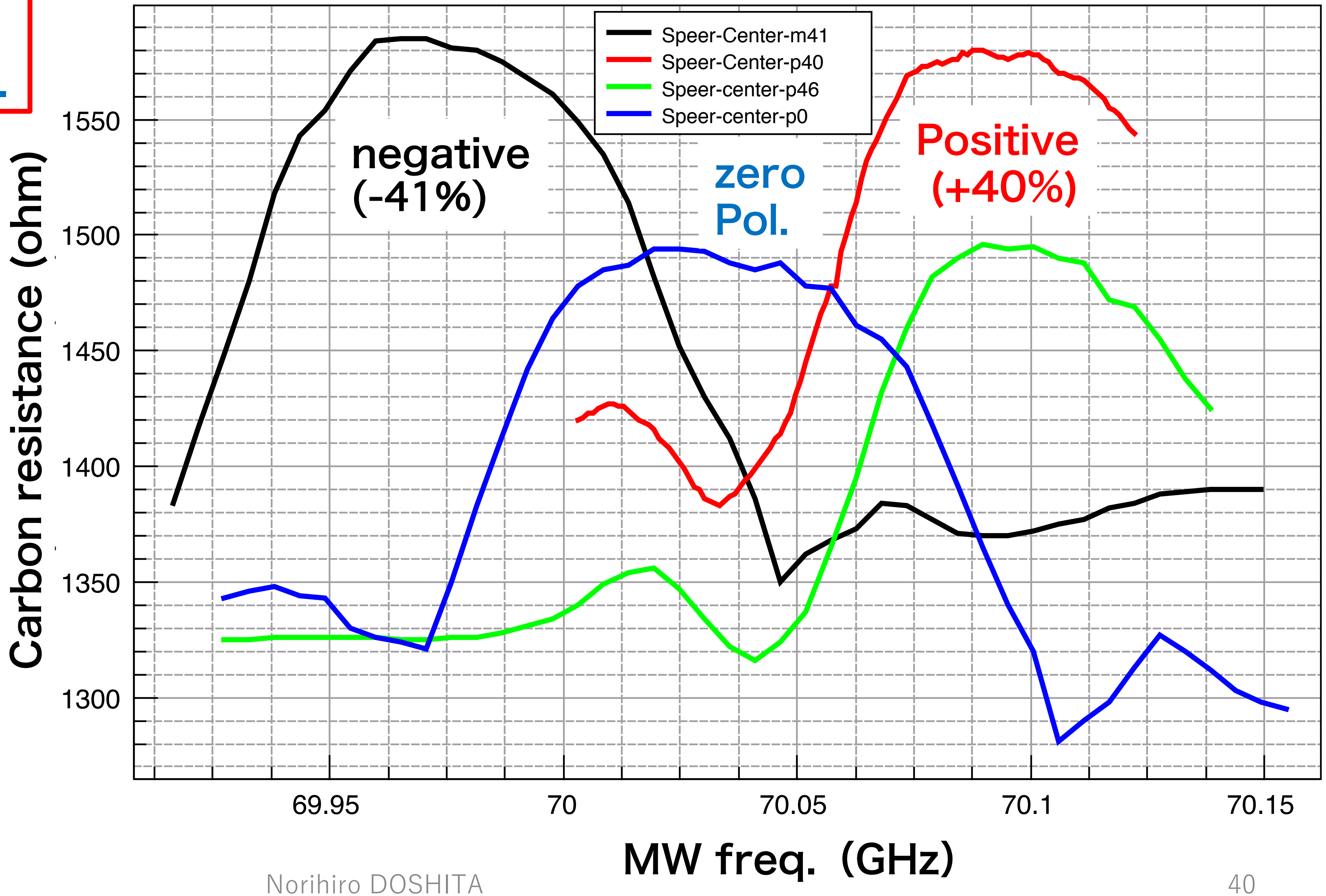




EPR (Electron Paramagnetic Resonance)

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.
- 6LiD and NH3 have been used as deuteron and proton target material.
- 2.5 T and 100 mK combination
- Stable and high polarizations provided for 20 years

Back up

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

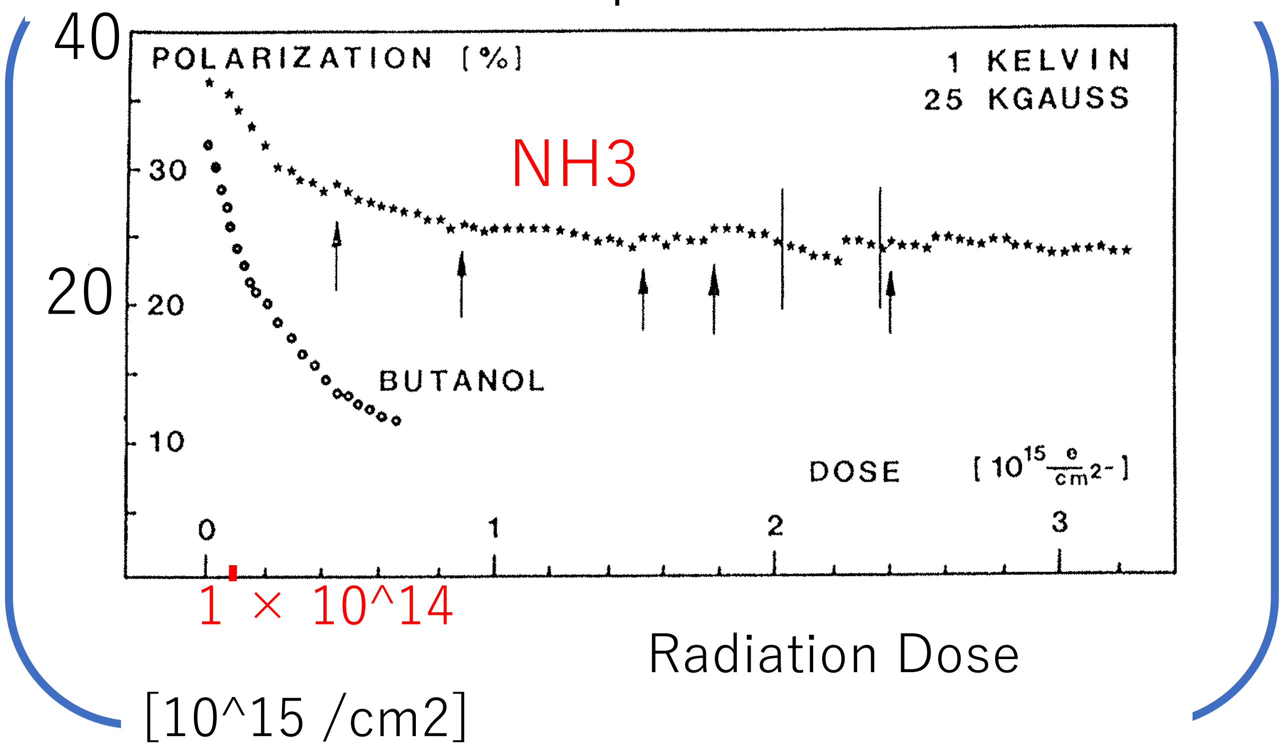
Radiation damage

Additional radicals are produced by beam.

W. Meyer et. al., Proceedings of the 4th international workshop on Polarized target materials and techniques (1984)

The polarization drops to 1/e of maximum polarization is 7 × 10^15 particles/cm2 (electrons) for ammonia

Radiation effect to polarization at 1K and 2.5T

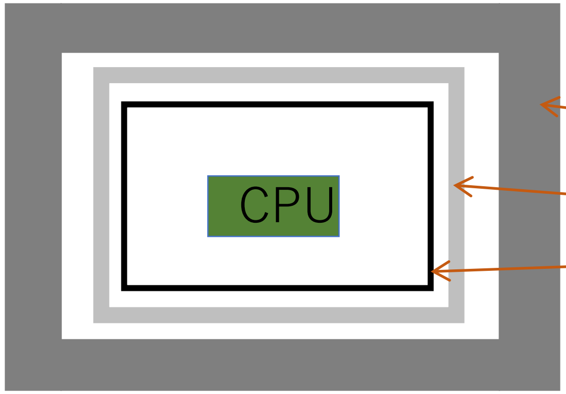


For safe margin, we propose

To keep flux of the pion beam below 1 × 10^14 /cm2 for 1 year.

Protection of PLC CPU for the magnet

Not only material but also PLC CPU suffered from radiation (neutron).



Concrete : For high energy neutrons
Polyethylene : for low energy neutrons
Boron-carbid : to stop thermal neutrons

Top cover of Polyethylene with Boron-carbid

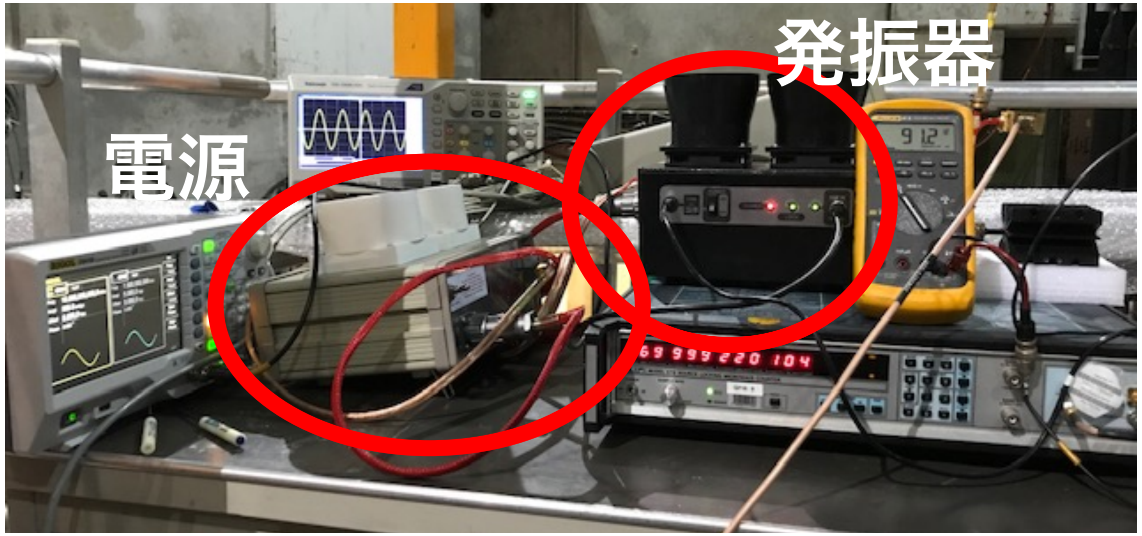
Boron-carbid

~10 μSv/h area

No interruption in 2018

ELVA -1製２W Gunn ダイオード発振器

2020年12月の発振テスト風景



設置風景
1.５mの導波管
数百mW到達の確認

- Covid19で納期が遅延
- 最大４W出力
- 周波数変調機能
- 狭いターゲットプラットフォームに設置可能
- ２0mTのもとでのテスト
- 2台追加導入：テスト中

標的物質
- 2000年に制作された^{6}LiD
- 電子ビーム照射による不対電子導入
- 2006年以来の偏極

核子構造とTMD PDFs

- 核子の内部構造
  クォークとグルーオンが構成要素で詳細は解明されていない

- クォークが内在して持つ横方向運動量k_Tを考慮した８つのTransverse Momentum Dependent Parton Distribution Function (TMD PDF)

- 準包括的深非弾性散乱（SIDIS)
  COMPASSではミューオンビームと横偏極重陽子標的を用いる

- d-クォークのSivers関数 $f_{1T}^{\perp}(x, k_T^2)$、Transversity関数 $h_1(x, k_T^2)$ のデータ収集

- Transversity関数とクォークテンサーチャージとの関係にも注目

核子とクォークのスピン状態に応じたPDF

クォークの偏極状態 ＼ 核子の偏極状態	無偏極	縦偏極	横偏極
無	f_1 number density q		$f_{1T}^{\perp}$ Sivers
縦		g_1 helicity Δq	g_{1T}
横	$h_1^{\perp}$ Boer Mulders	$h_{1L}^{\perp}$	h_1 transversity $h_{1T}^{\perp}$

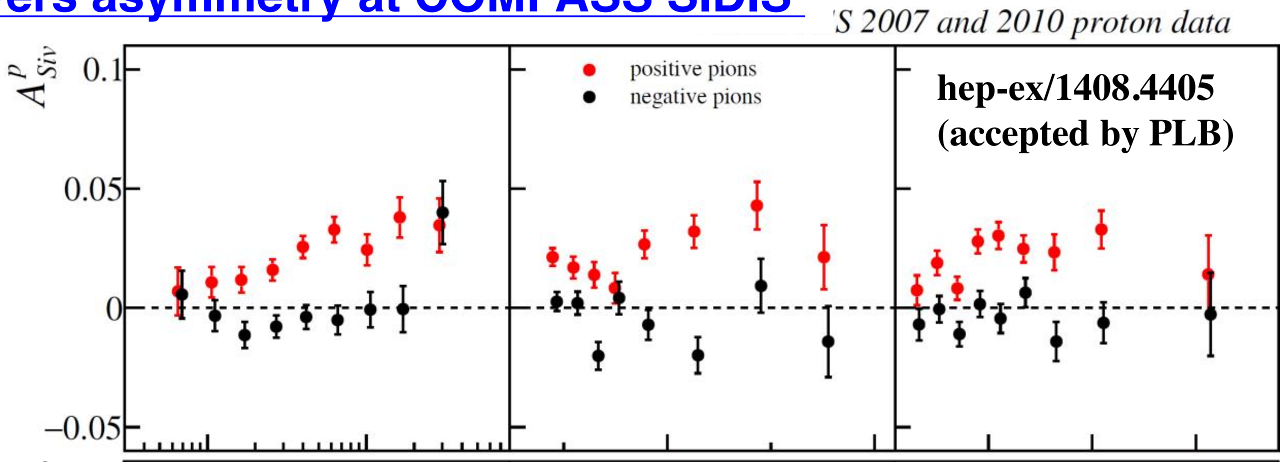
Universality of TMD PDFs

Because Sivers and Boer-Mulders PDFs are "Time-reversal odd", they are expected to change the sign when measured from SIDIS or from DY:

$$f_{1T}^{\perp}\Big|_{DY} = -f_{1T}^{\perp}\Big|_{SIDIS} \qquad h_1^{\perp}\Big|_{DY} = -h_1^{\perp}\Big|_{SIDIS}$$

We have the opportunity to test this sign change using the same spectrometer and the transversely polarized target at COMPASS.

Sivers asymmetry at COMPASS SIDIS



Positive hadron
Negative hadron