Polarized ^{3}He Target

On Behalf of the JLab Polarized ^{3}He Target Group

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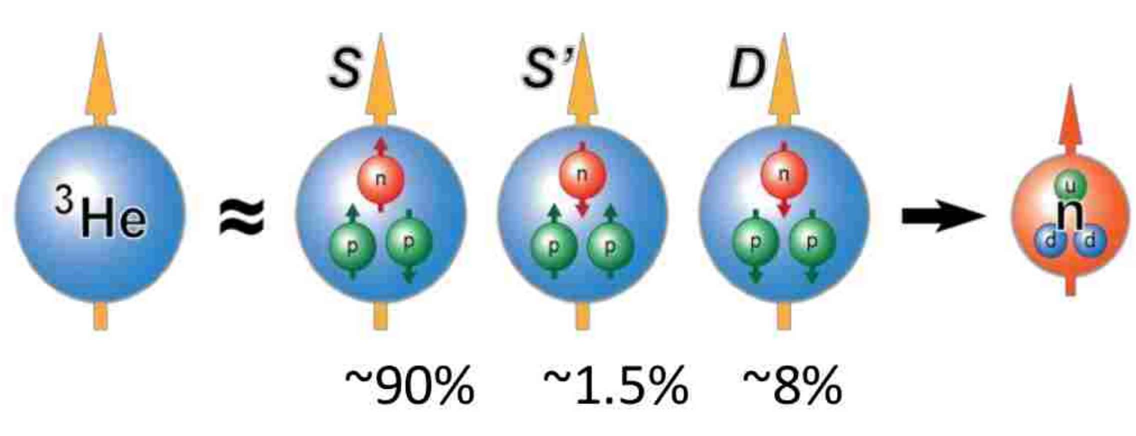
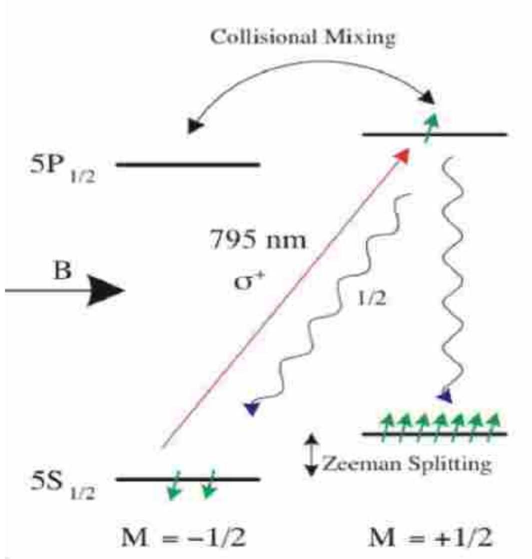
February 17, 2022

Introduction to ^{3}He Polarization

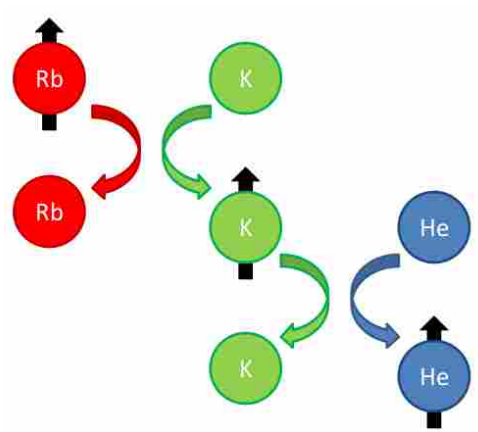


- Polarized target for study the spin structure of nucleon.
- Free neutron mean lifetime: 880.2 s.
- The unpaired neutron carries the majority of the ^{3}He nucleus polarization.
- Polarized ^{3}He is a good effective polarized neutron target.

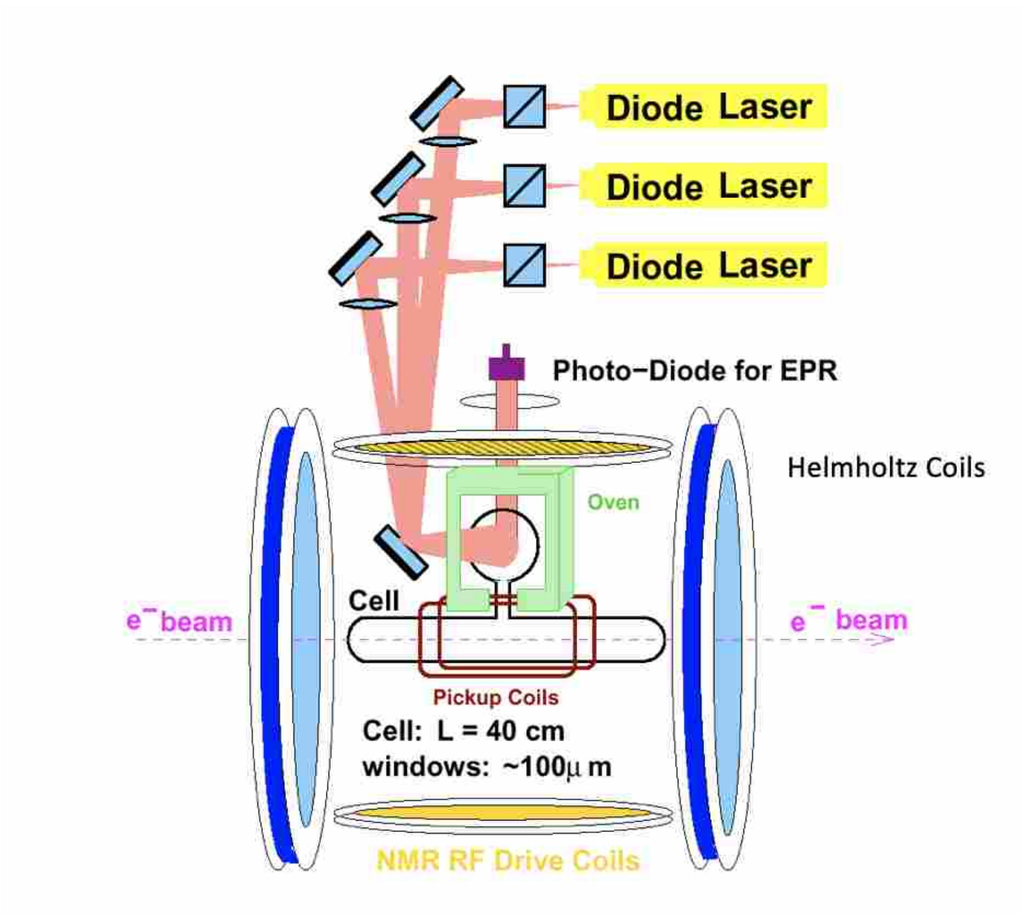
Spin Exchange Optical Pumping
(SEOP)



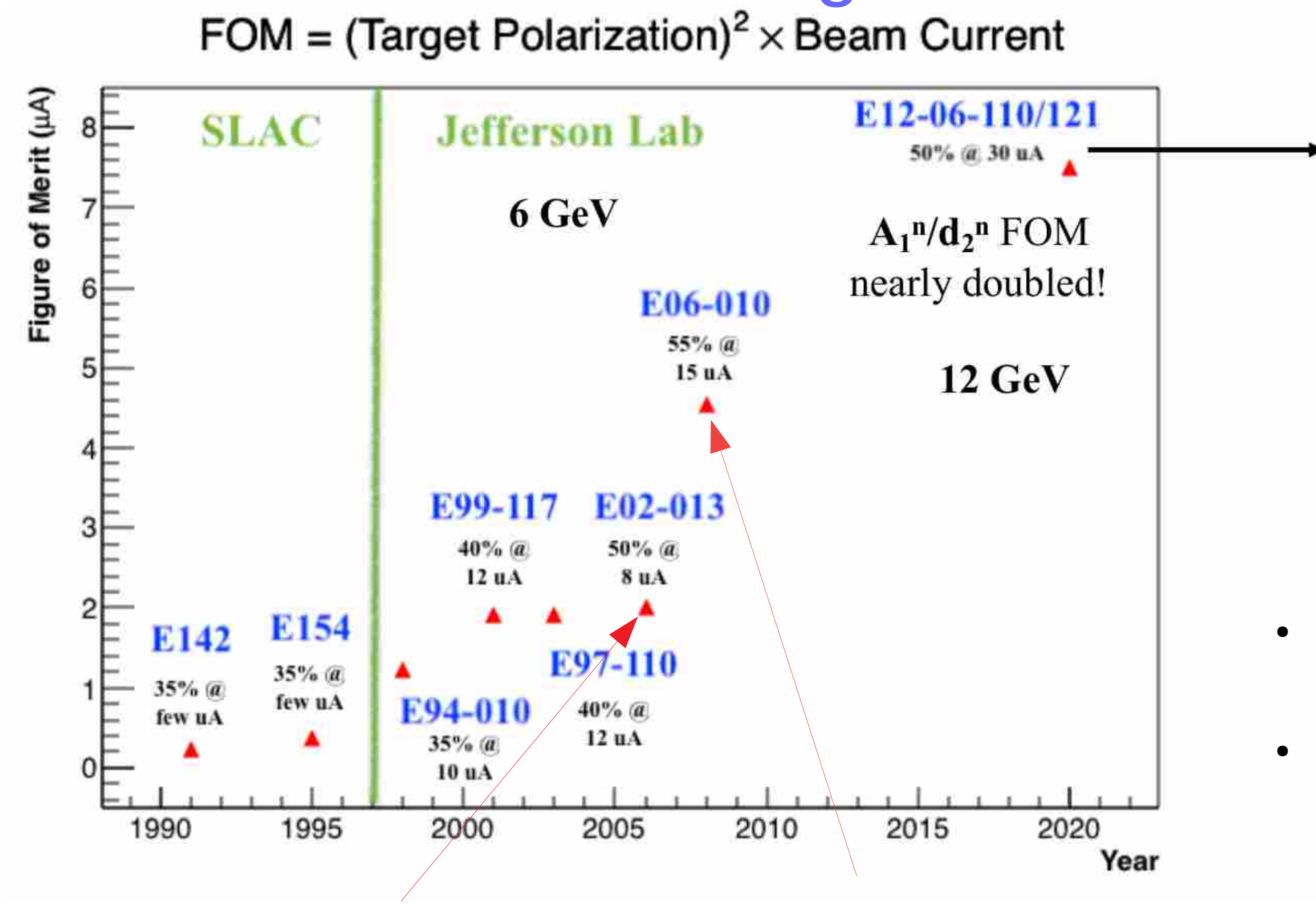
1. Optical Pumping

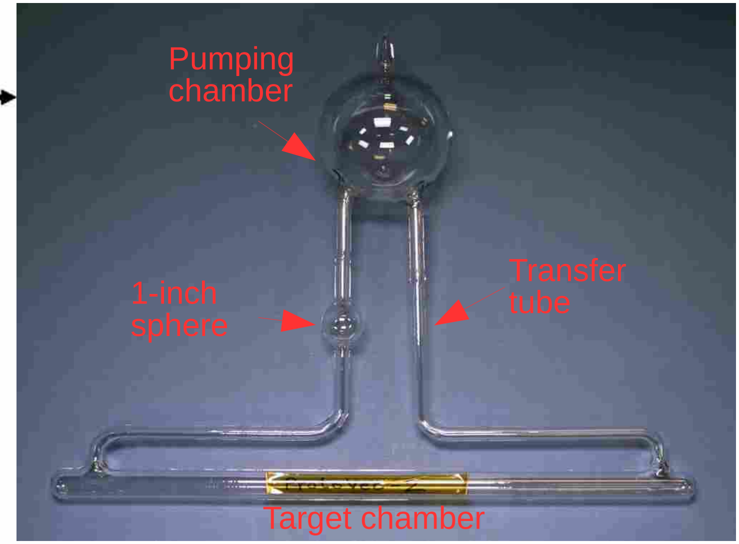


2. Spin Exchange



Polarized ^{3}He Targets Performance Evolution





- 12 GeV era Target Cell:

  Target chamber length: 40 cm

- Beam Current: 30uA

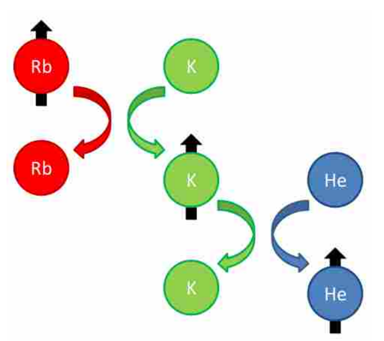
  Reached over 50% in beam polarization

  Luminosity: ~ 2.2×10^{36} $cm^{-2}s^{-1}$

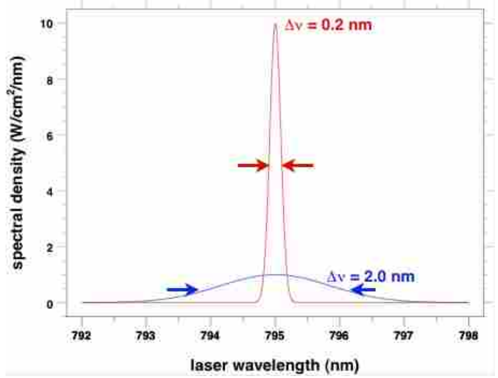
- Convection Cell (instead of diffusion cells used in the 6 GeV era)

  → convection allows for more uniform polarization between target and pumping chamber

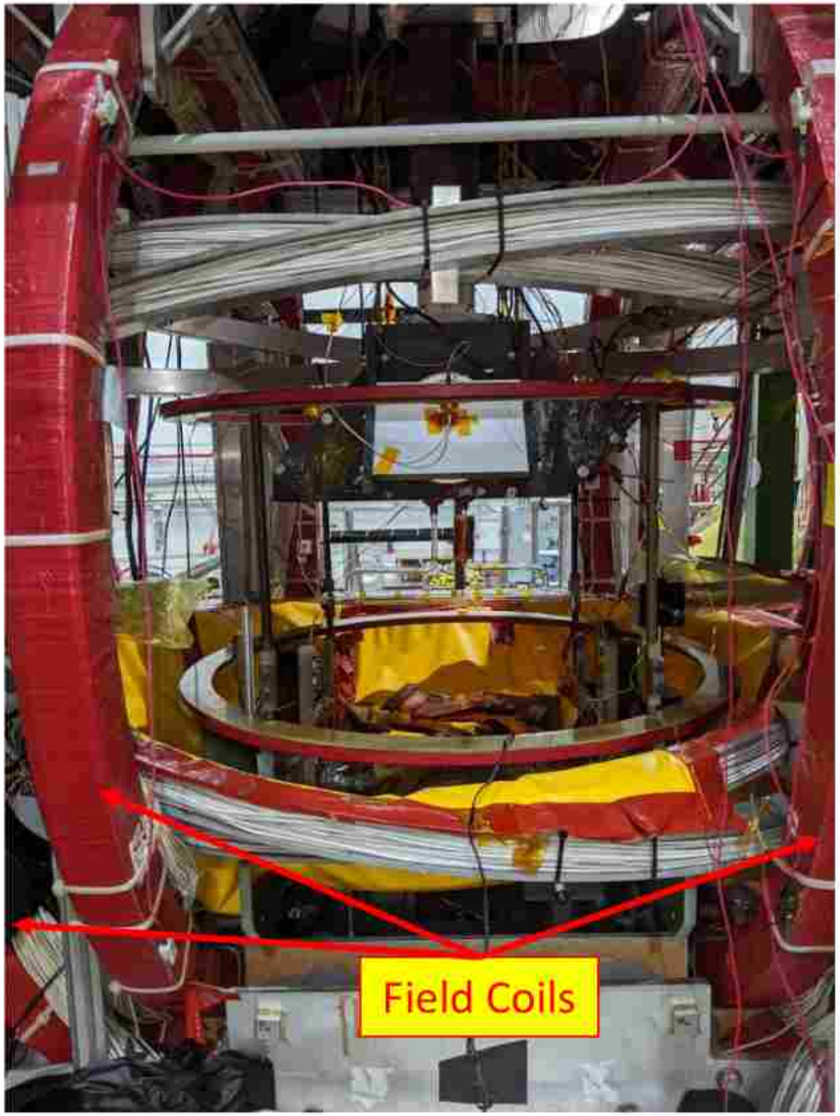
G_E^n (E02-013):
Started to use Rb/K hybrid alkali cell.

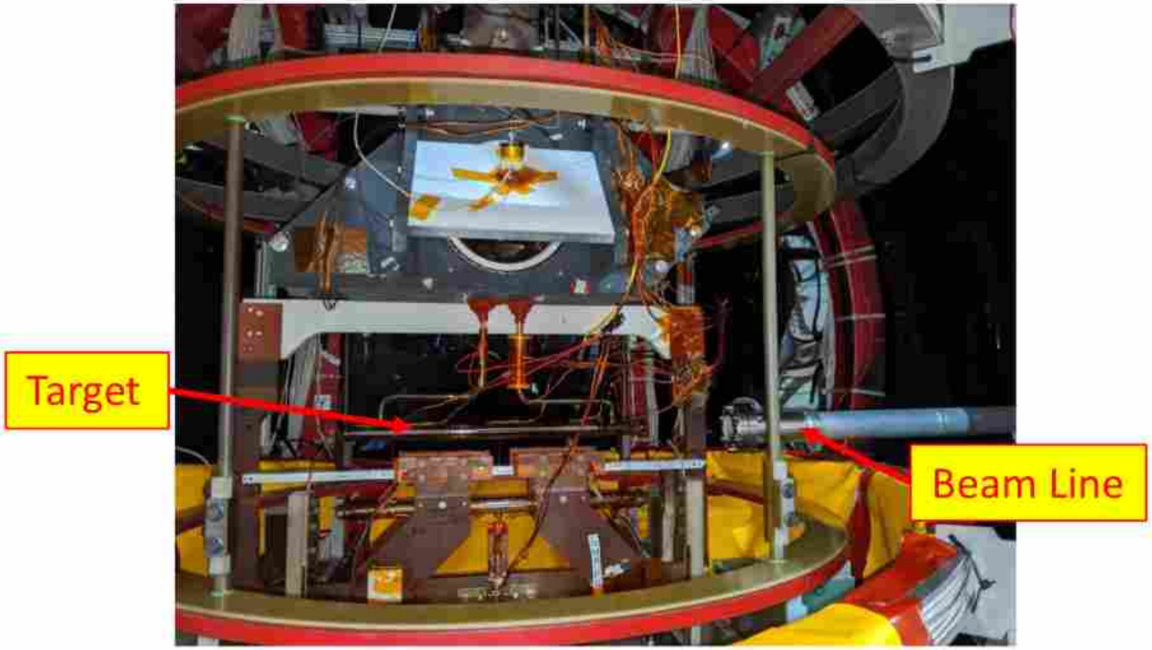


Transversity (E06-010):
Started to use narrow band laser.

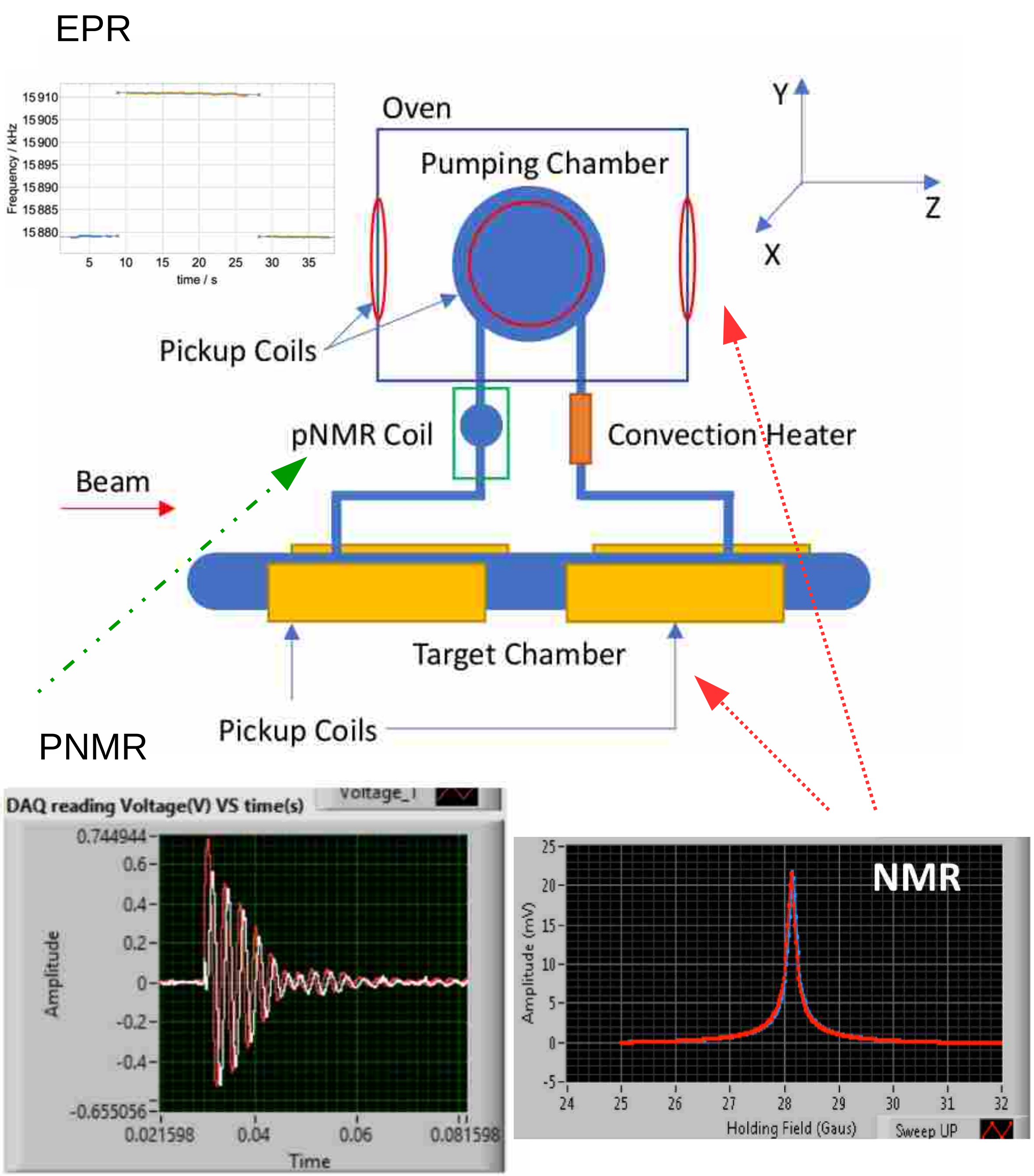


Polarized ^{3}He Target in Hall C





Polarimetry for ^{3}He in Target Cell



1. Adiabatic Fast Passage Nuclear Magnetic Resonance (AFP-NMR)

- Magnetic Resonance of ^{3}He Nucleus
- Sweep the holding field under AFP condition to flip the Nucleon spin direction back and forth.
- Relative measurement, calibrate with water NMR or EPR.

2. Pulse NMR

- Use resonance RF pulse at ^{3}He Larmor frequency to tilts the Nucleon spin to a certain angle.
- Relative measurement, calibrate with AFP-NMR.
- Implemented for the first time on polarized ^{3}He target.

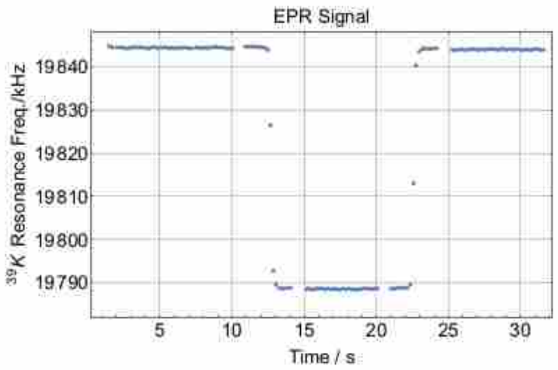
3. Electron Paramagnetic Resonance (EPR)

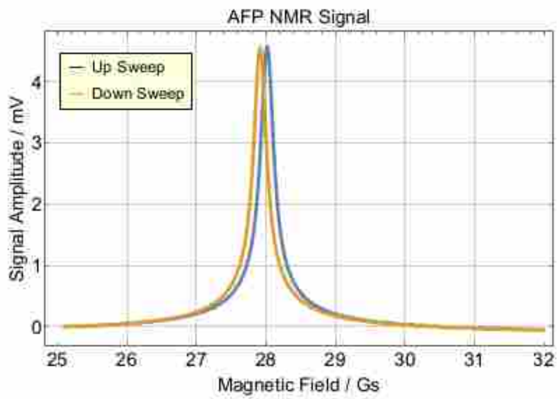
- Magnetic resonance of the alkali atoms
- Resonance shifted due to polarized ^{3}He, get the resonance frequency difference by flipping the ^{3}He polarization direction.
- Get ^{3}He polarization from resonance frequency difference. Absolute measurement.

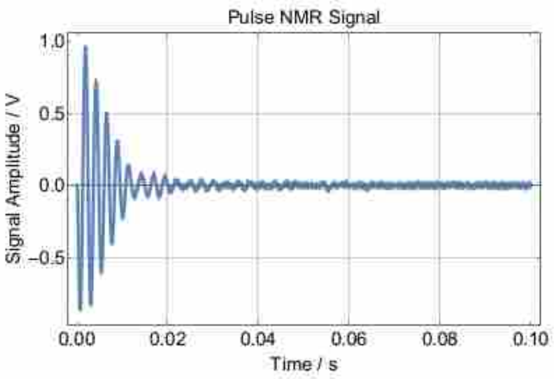
Polarimetry Analysis

Extracting target polarization when the target is in production (in beam)

- Calibrate the NMR signals with EPR measurements
- Calibrate measurement loss
- Calibrate target density
- Calibrate time constants of target



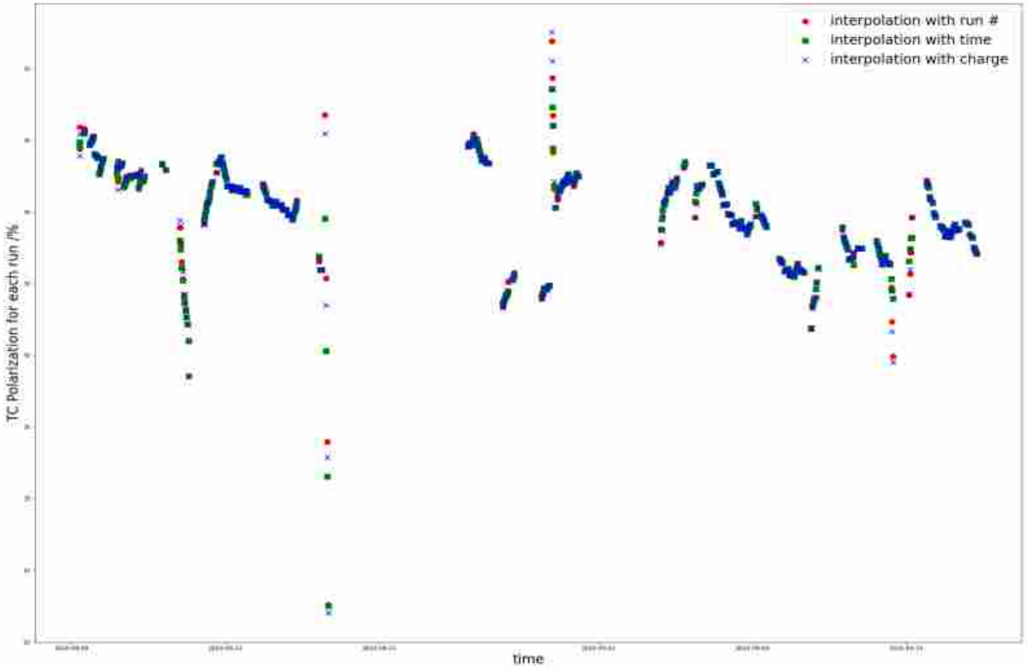




Polarimetry goal: ±3% relative uncertainty

Polarization Interpolation for Each Run

Polarization for d2n runs



Polarization interpolation done with

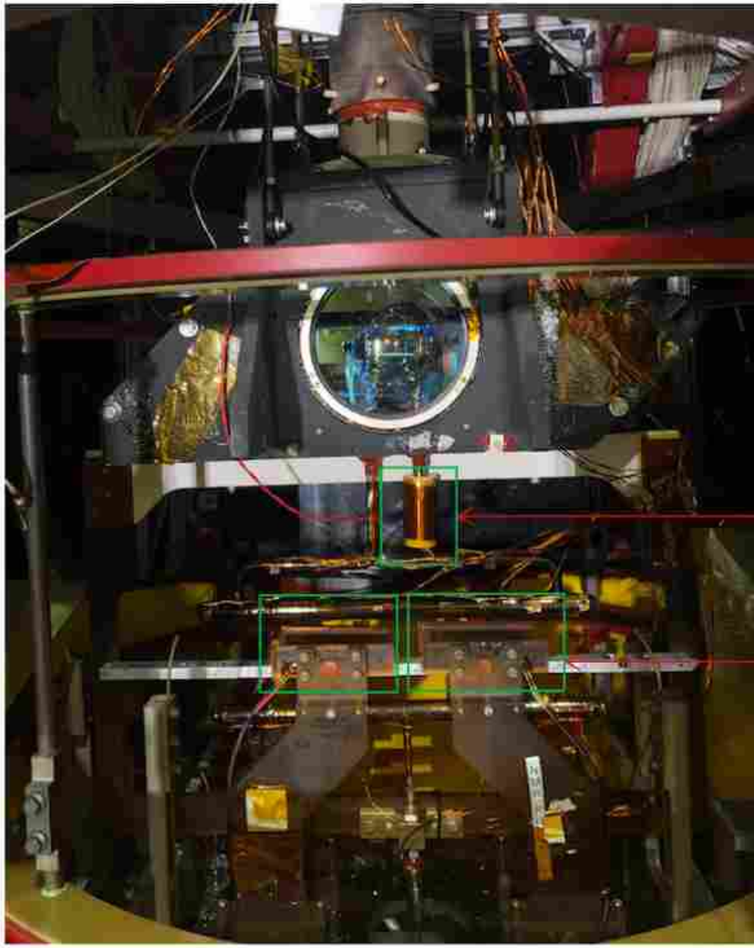
- Run time
- Charge accumulated for each run

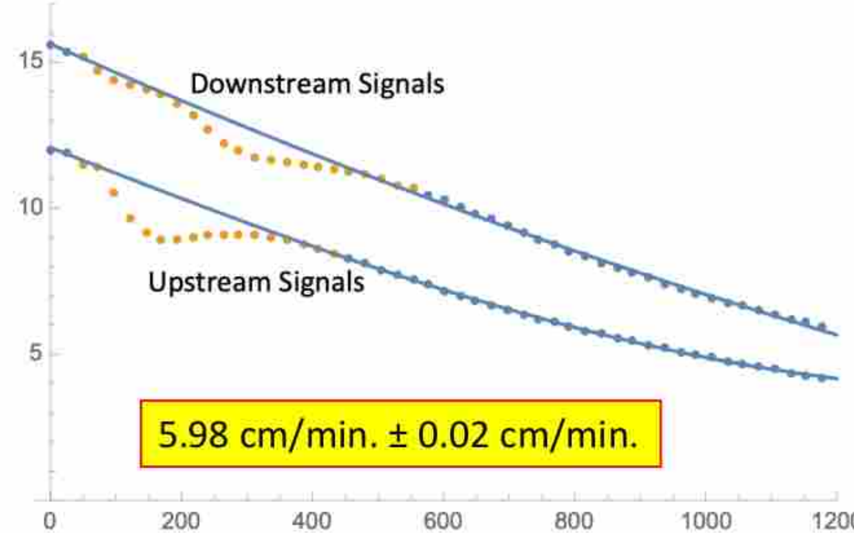
Current Status

- For periods with good optical pumping conditions, results are consistent over different interpolation methods,
- Still working on runs with abnormal optical pumping conditions,
- Still need to manually check each run's polarization based on its running condition.

- Credit to Junhao Chen (W&M)

Convection Speed Test





pNMR Pickup coil give a pulse to locally destroy polarization.

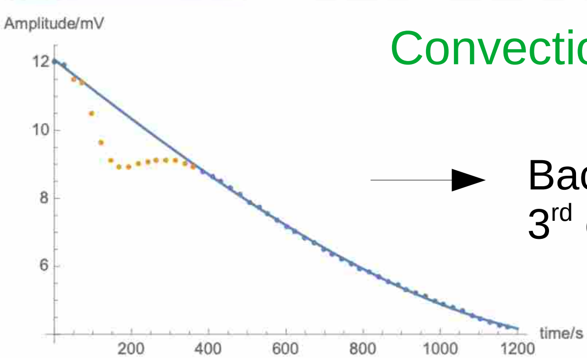
Continuously monitor the signals in upstream and downstream pickup coils, get the time difference for the signal dips in the two locations.

Status:

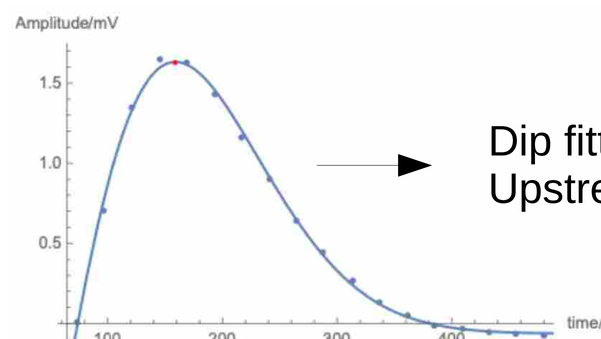
- Got a reasonable result.
- The result is used for AFP loss study and pumping chamber temperature correction study.

- Credit to Junhao Chen (W&M)

Convection Speed Fit



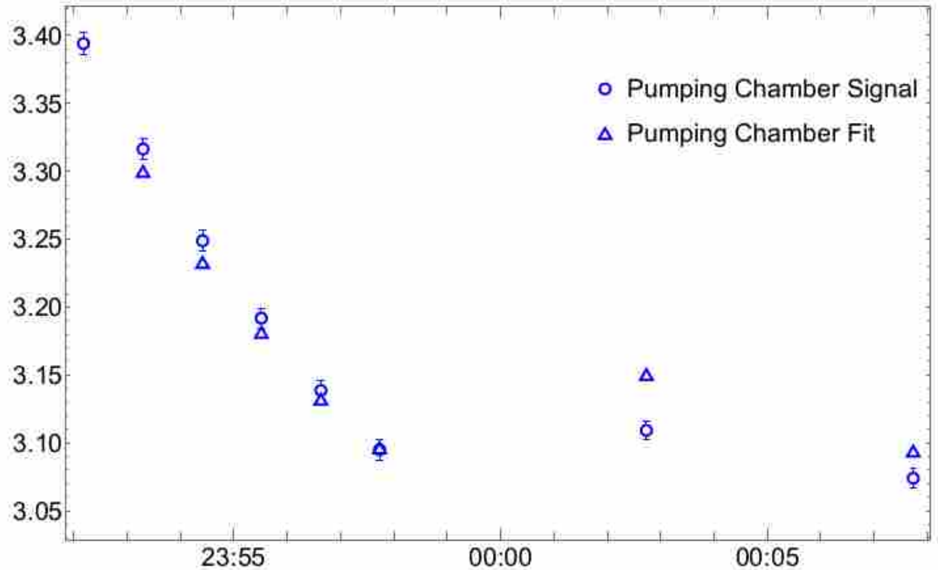
Background Fit:
3rd order polynomial

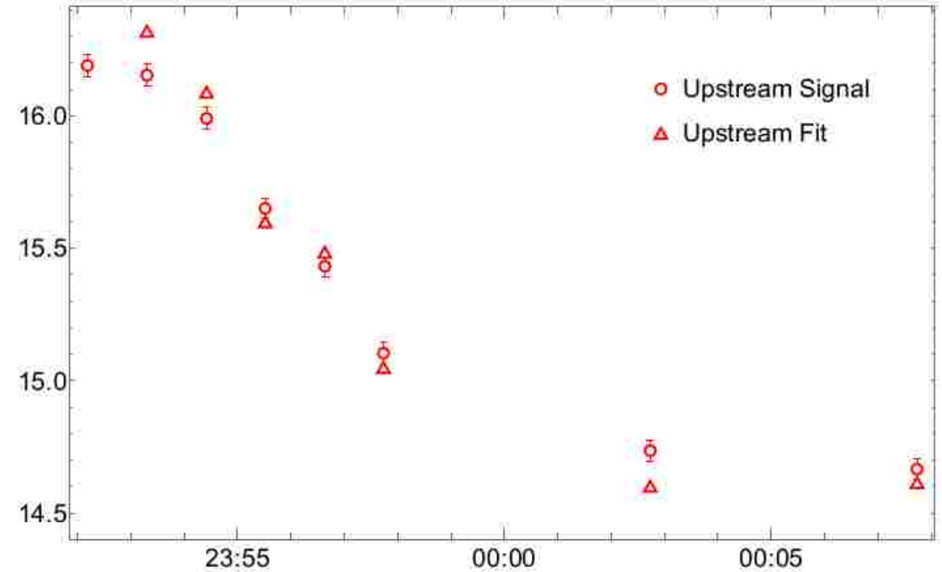


Dip fitting:
Upstream, Distorted Gaussian

AFP Loss Calibration

1. AFP loss are different for different chambers:
   - Pumping chamber: ~ 0.8% to 2%; Target chamber: ~ 0.4% to 1%.
2. Used simplified two chambers convection model for fitting the AFP Loss Signals.
3. The uncertainty is estimated with fully parameterized convection model and whole target AFP loss.

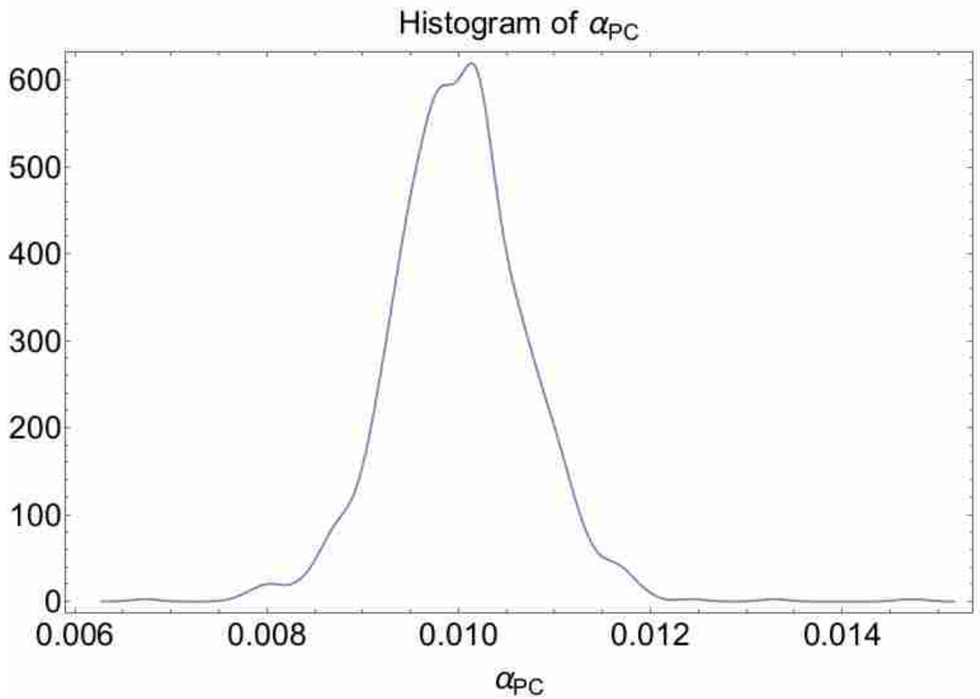




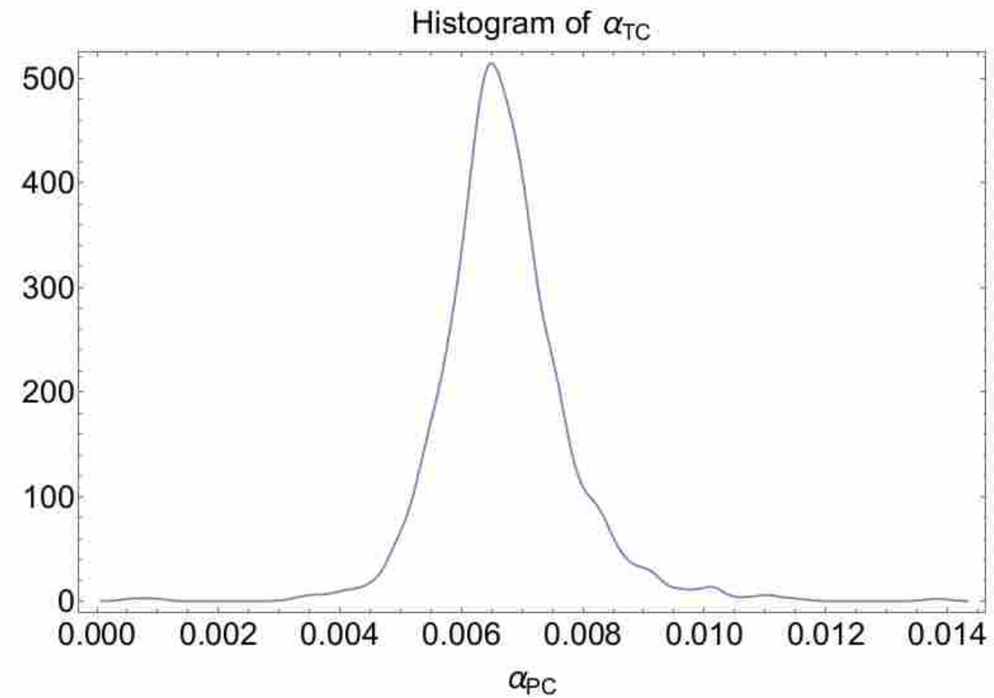
Current Status
- Calibration finished for all a1n and d2n cells
- For all conditions there is a 20% relative uncertainty

- Credit to Junhao Chen (W&M)

Systematic uncertainty from parameterization w/ full convection model



$1\% \pm 0.07\%$



$0.7\% \pm 0.1\%$

Results with 1000 simulations, analyze the AFP loss results

- Credit to Junhao Chen (W&M)

Pumping Chamber Temperature Calibration

Because of laser heating, the pumping chamber internal temperature will be higher than what is measured at the exterior glass surface.

Calibration Method: signal ratio between pumping chamber and target chamber will be different with the laser turned on or off

$$\frac{S_{PC}^{on(off)}}{S_{TC}^{on(off)}} = \frac{n_{PC}^{on(off)} P_{PC}^{on(off)} G_{circuit\_PC}^{on(off)} V_{PC}}{n_{TC}^{on(off)} P_{TC}^{on(off)} G_{circuit\_TC}^{on(off)} V_{TC}}$$

Assumptions are:

- Target reached both polarization and mass equilibrium within the test period
- Circuit gain for NMR do not change with laser on or off

Signal ration between pumping chamber and target chamber with be proportional to the density ratio between these two chamber

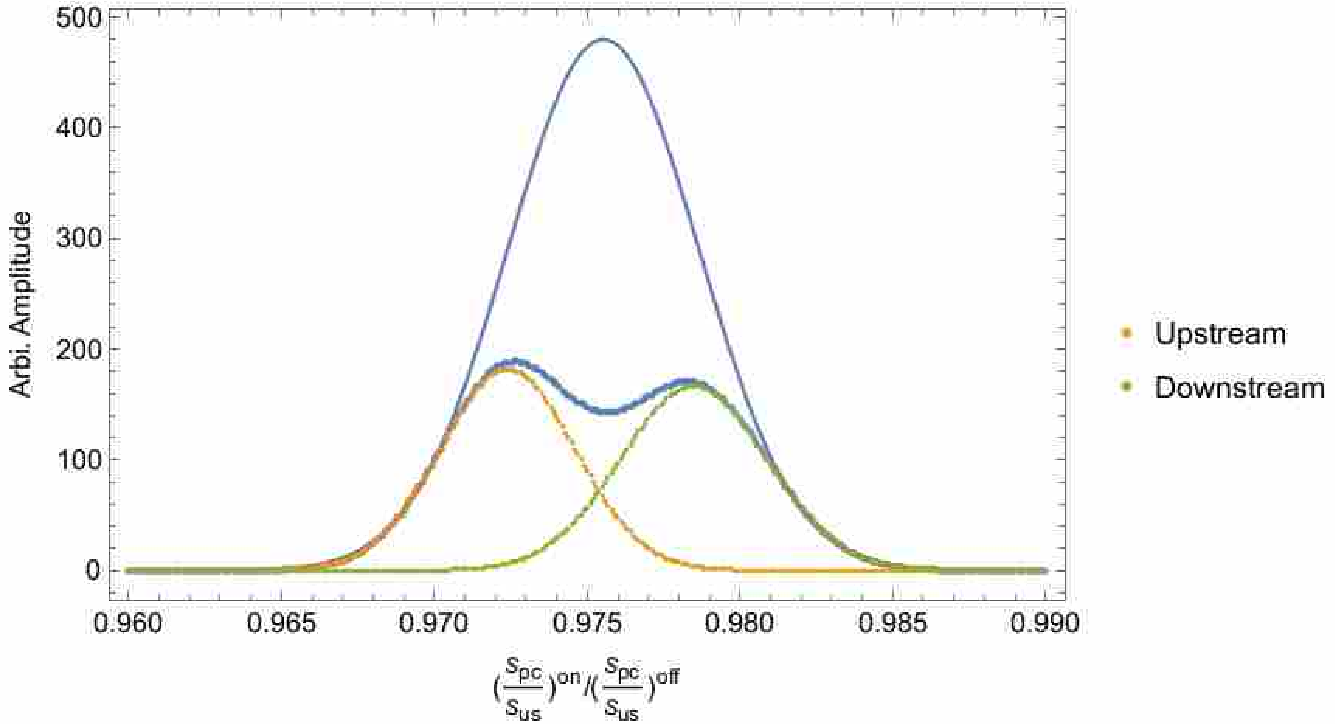
$$\frac{n_{PC}^{on}}{n_{TC}^{on}} = \frac{S_{PC}^{on}}{S_{TC}^{on}} / \left(\frac{S_{PC}^{off}}{S_{TC}^{off}} / \frac{n_{PC}^{off}}{n_{TC}^{off}} [T_{PC}, T_{TC}, T_{TT}]\right)$$

Current Status

- Calibration finished for all a1n and d2n cells
- Results are around 245°C ± 5°C

- Credit to Junhao Chen (W&M)

Averaged $\frac{S_{PC}^{on}}{S_{TC}^{on}} / \frac{S_{PC}^{off}}{S_{TC}^{off}}$ across target chamber for evaluating temperature test systematic error



Systematic uncertainty from the signal ratio difference between two signal locations

- Credit to Junhao Chen (W&M)

AFP Loss and Uncertainty In the case of Tommy One Pass 180 degree field

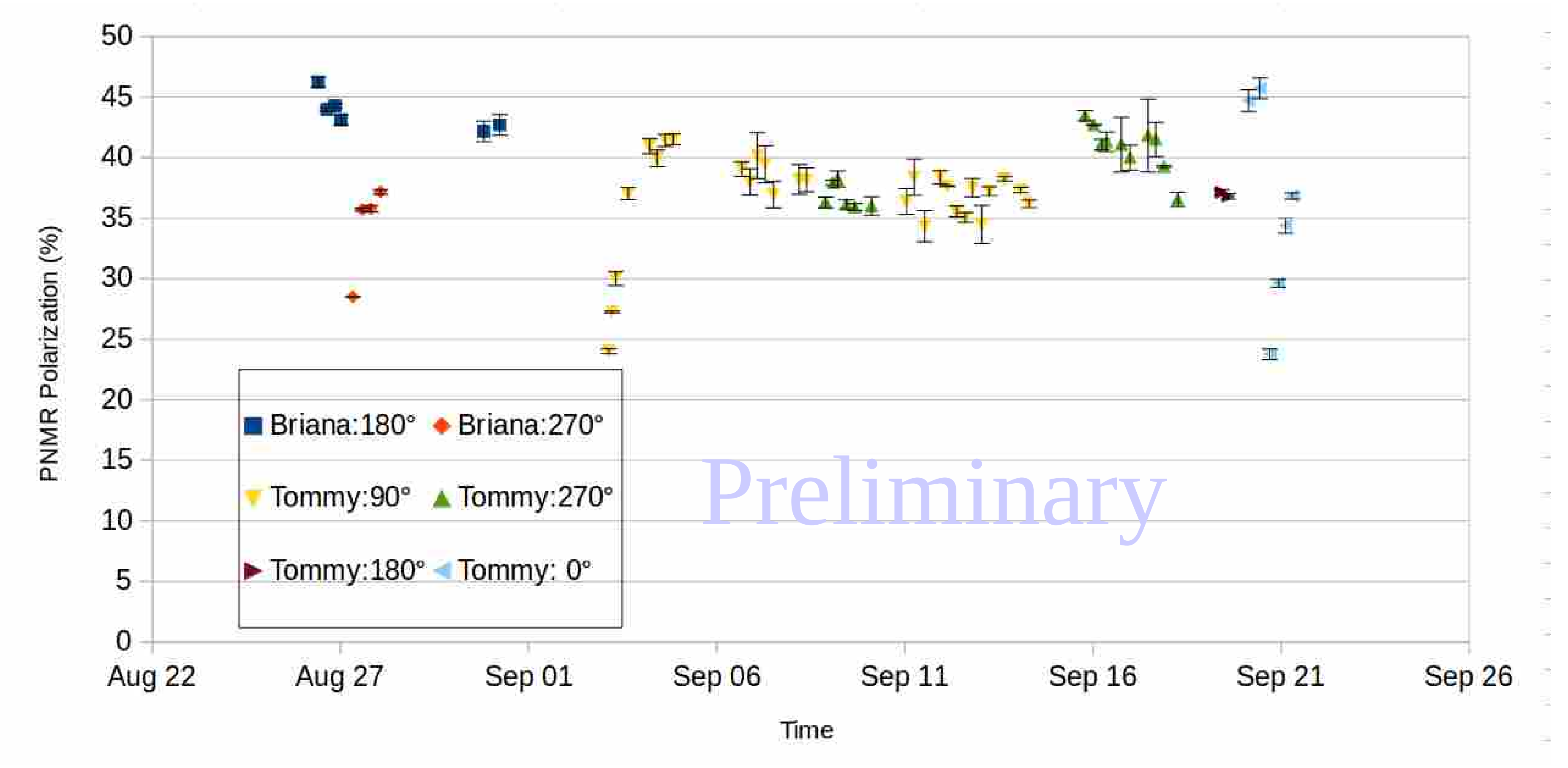
	AFP Loss / %			Uncertainties as for Simplified Convection Model		
	Simplified Convection Model	Full Convection Model (Parameterized)	Non-convection Model (online analysis)	Statistical Uncertainty / %	Systematic Uncertainty from Parameterization / %	Systematic Uncertainty from Model (Discrepancy with whole target loss) / %
P.C.	1	1	0.85	0.03 (Rel. 3%)	0.07 (Rel. 7%)	0.12 (Rel. 12%)
T.C.	0.63	0.7	0.4	0.04 (Rel. 6%)	0.1 (Rel. 14%)	0.12 (Rel. 17%)

Overall estimate rel. 20% uncertainties for all AFP Loss test

- Credit to Junhao Chen (W&M)

Pulse NMR Measurements

(during d_2^n experiment)

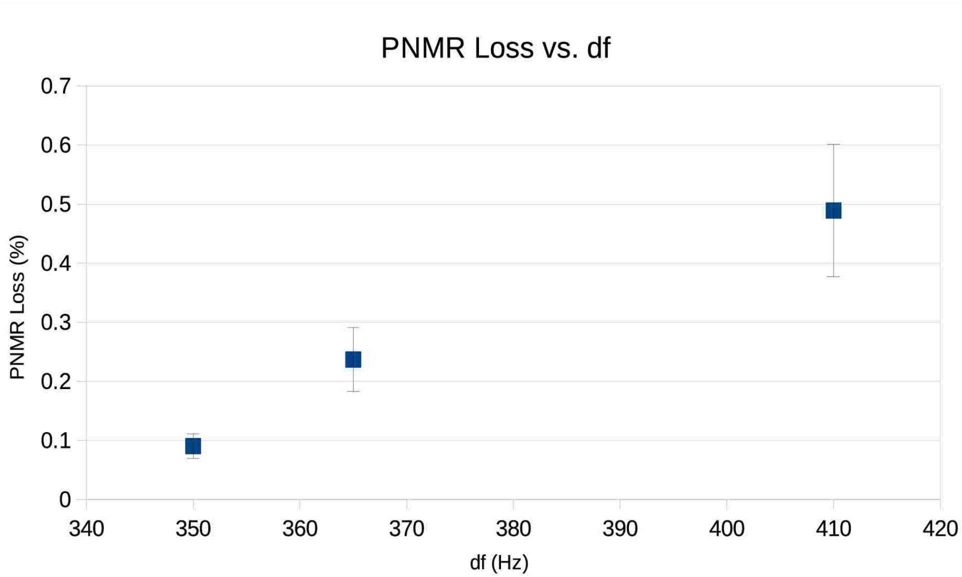


- PNMR was performed at transfer tube which was calibrated by AFP-NMR at pumping chamber. For most of the measurements, polarization from PNMR agrees with NMR within ±2%.
- Still working on uncertainty for PNMR measurement due to holding field drift and PNMR loss during the experiment.

Post Experiment PNMR Loss Study

(at EEL Target Lab on Cell "Butterball")

Field Direction (deg)	Oven Temp (deg C)	Laser Power (W)	Corr. Coil HL (V)	Corr. Coil HS (V)	Conv ection PS (V)	Target Position	PNMR Loss per Measure ment (%)	Pulse Freq (kHz)	Reference Freq (kHz)	Cell Name	PNMR sweeps/ Δt(s)	Larmor freq-Ref freq: df (Hz)	Comment
Long	205	off	3	0	7	Pick-up Coils	0.266 ±0.061	81.415	81.035	Butterball	10/0.1	380	
Long	205	off	3	0	9	Pick-up Coils	0.386 ±0.065	81.415	81.035	Butterball	10/0.1	380	



- PNMR loss is also related to "Larmor freq-PNMR Ref freq" (df)
- The PNMR loss uncertainty is the statistical uncertainty from multiple PNMR loss tests.

Goal: Help determine the in beam ^{3}He polarization after PNMR and NMR measurements.

1) PNMR loss per measurement is determined during NMR hot spin down.
2) HL Corr coil at 3.0 V gives a horizontal holding field gradient which keeps PNMR T2 at 6.457 msec, this is close to PNMR in Hall C (T2~7 msec). However, in Hall C the holding field gradient is mostly in vertical direction.
3) Still working on deriving PNMR loss during d_2^n experiment based on the post experiment PNMR loss study.

Summary

- For the first time, install the upgraded polarized ^3He target for 12 GeV era in JLab Hall C.
- The target reached the expected performance with over 50% ^3He polarization in 30 uA electron beam during the recent A_1^n/d_2^n experiments in 2020.
- Target luminosity has been doubled for the A_1^n/d_2^n experiments.
- Target luminosity will be further tripled for the next polarized ^3He target experiment (GEn for Hall A).
- Have finished offline target calibration.
- Have got preliminary polarization interpolation results. Dealing with abnormal optical pumping conditions. Final check ongoing.

Acknowledgments

People

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PhD Candidates Spokespeople

Institutions

A.I. Alikhanian National Science Laboratory; Argonne National Laboratory; Artem Alikhanian National Laboratory (AANL).; Christopher Newport University; Duke University; Florida International University; Hampton University ; James Madison University ; Jefferson Lab; Kent State University; Mississippi State University; Ohio University; Old Dominion University; Rutgers University; Syracuse University; Temple University; The College of William and Mary; Univ. of Ljubljana; University of Connecticut; University of Kentucky; University of Kentucky; University of New Hampshire; University of Regina; University of Tennessee; University of Virginia; University of Virginia; University of Zagreb

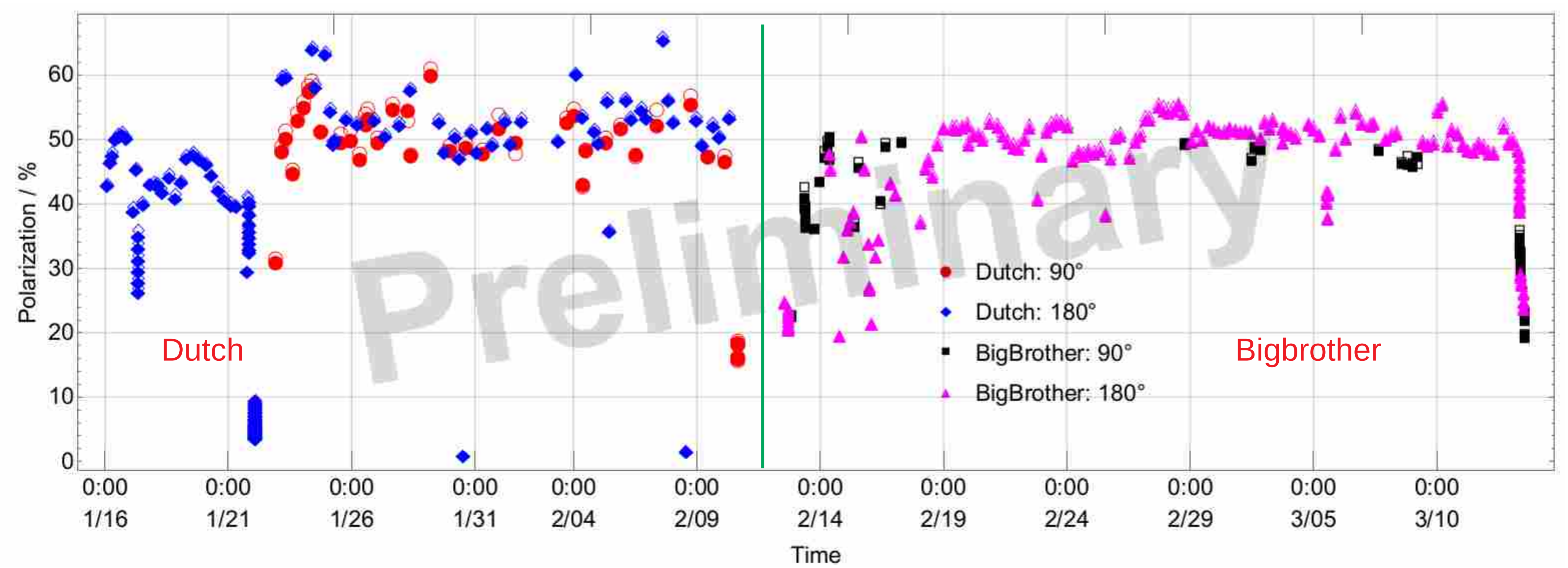
Backup Slides

Production Cell Performance

(for targets used in A_1^n experiment)

A_1^n Experiment Target Performance

- Two production cells used
- Polarization: maximum reach 60+%, 55% in beam



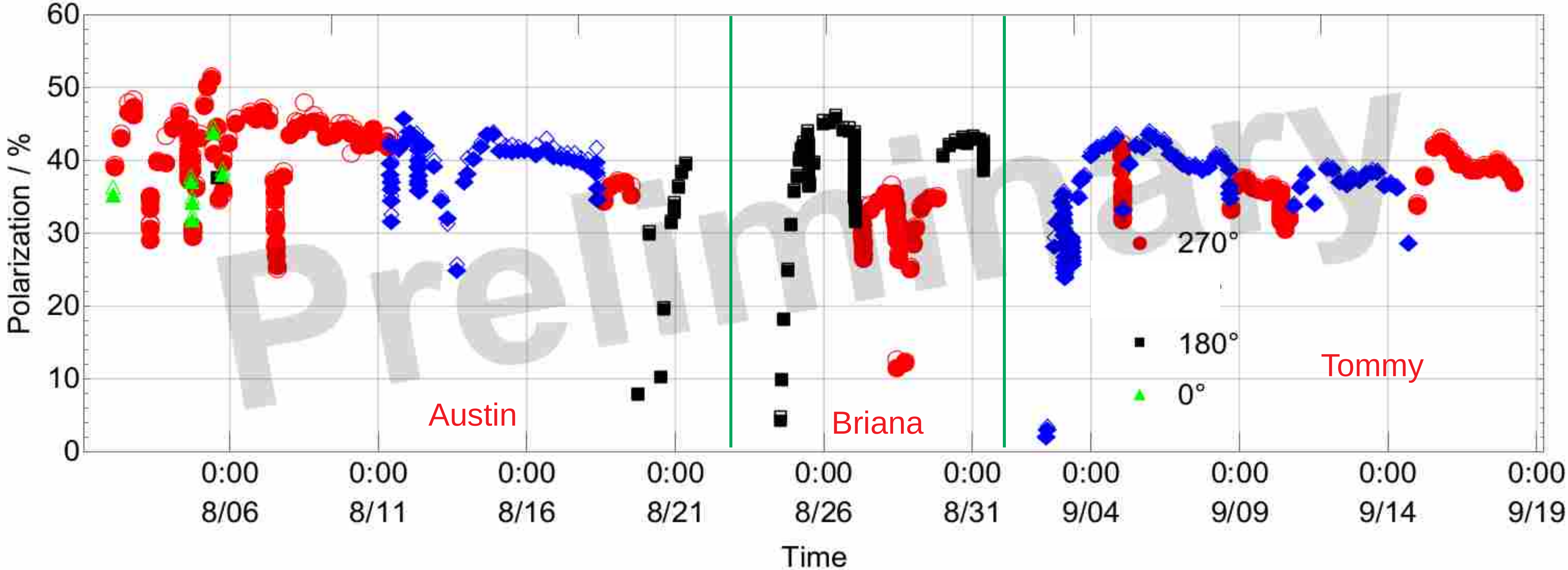
Production Cell Performance

(for targets used in d_2^n experiment)

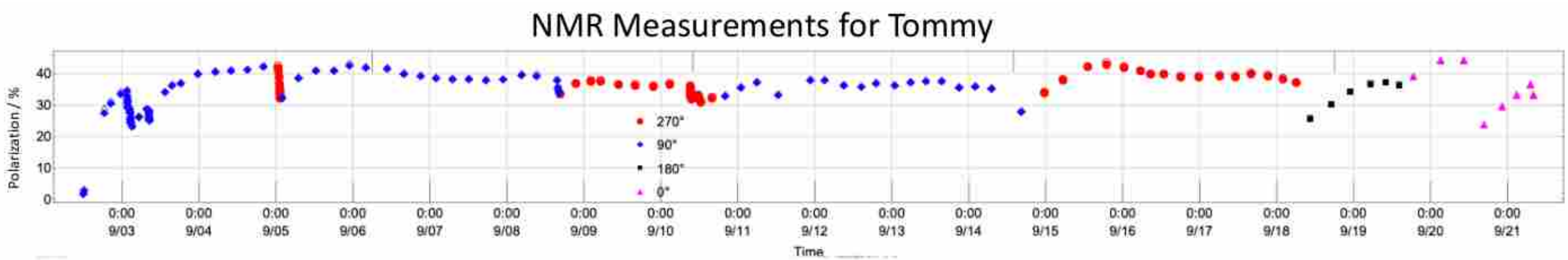
d_2^n Experiment Target Performance

• Three production cells used

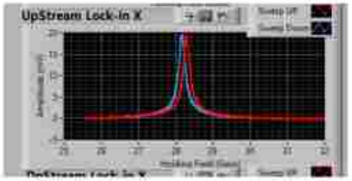
• Polarization: ~45% in beam



Typical Polarimetry Procedure during Production



- EPR:
  - The only absolute polarimetry for A1n/d2n experiment.
  - During the experiment, EPR are used to calibrate NMR signals
- pNMR:
  - Measured for every 4 to 5 hours during polarization target production runs.
  - Calibrated with NMR signals.
- NMR:
  - Measured for every 4 to 5 hours during polarization target production runs.
  - Typically follows a pNMR within 1 minute.
- Other Calibrations:
  - NMR AFP Loss Test
  - Pumping Chamber Temperature Test
  - Spin Up/Spin Down Test
  - Convection Speed Test



Derive Target Polarization for Certain Run

Polarization Interpolation: Equations I

- $P_{TC}^{init} = \frac{S_{PC}^{upsweep}\beta^2 + S_{PC}^{downsweep}\beta}{2} C_{PC}^{EPR} C_{TCPC}$ (polarization before runs)
  - Assuming the peak amplitude is not affected by afp loss
- $P_{TC}^{end} = \frac{S_{PC}^{upsweep} + S_{PC}^{downsweep}/\beta}{2} C_{PC}^{EPR} C_{TCPC}$ (polarization after runs)
- β: whole cell polarization loss

$$\beta = 1 - \frac{\alpha_{PC}\, n_{PC} V_{PCC} + \alpha_{TC}\, n_{TC} V_{TC}}{n_{PC} V_{PC} + n_{TC} V_{TC}}$$

- C_{PC}^{EPR}: EPR calibration constant
- C_{TCPC}: Polarization ratio between TC and PC

- Credit to Junhao Chen (W&M)

Derive Target Polarization for Certain Run

Equations: TC Polarization

- Interpolate with run time
  - $P_{TC}^{run\_n} = P_{TC}^{init} + \left(P_{TC}^{end} - P_{TC}^{init}\right)\frac{T_{run\ n}^{midpoint} - T_{nmr}^{init}}{T_{nmr}^{end} - T_{nmr}^{init}}$
- Interpolate with beam charge
  - $P_{TC}^{run\_n} = P_{TC}^{init} + \left(P_{TC}^{end} - P_{TC}^{init}\right)\frac{C_{run\ 0\ to\ run\ n} - \frac{1}{2}C_{run\ n}}{C_{total}}$
- Interpolate with run number
  - $P_{TC}^{run\_n} = P_{TC}^{init} + \left(P_{TC}^{end} - P_{TC}^{init}\right)\frac{n - 1/2}{N}$
- n(N): number(total) of run between two sequential NMRs

- Credit to Junhao Chen (W&M)

NMR AFP Loss Study

Two Chambers Convection Model

Analytical form:

$$
\begin{aligned}
P_p(t,X,Y) &= C_p e^{-\Gamma_f t} + (-P_p^\infty - C_p + X)e^{-\Gamma_s t} + P_p^\infty, \\
P_t(t,X,Y) &= C_t e^{-\Gamma_f t} + (-P_t^\infty - C_t + Y)e^{-\Gamma_s t} + P_t^\infty,
\end{aligned}
$$

Differential form:

$$
\begin{aligned}
\frac{dP_p}{dt} &= \gamma_{SE}(P_A - P_p) - \Gamma_p P_p - d_p(P_p - P_t), \\
\frac{dP_t}{dt} &= -\Gamma_t P_t + d_t(P_p - P_t),
\end{aligned}
$$

$$
\Gamma_f = \frac{1}{2}[(d_p + \Gamma_p + d_t + \Gamma_t + \gamma_{SE}) + \sqrt{(d_p + \Gamma_p + \gamma_{SE} - d_t - \Gamma_t)^2 + 4d_p d_t}],
$$

$$
\Gamma_s = \frac{1}{2}[(d_p + \Gamma_p + d_t + \Gamma_t + \gamma_{SE}) - \sqrt{(d_p + \Gamma_p + \gamma_{SE} - d_t - \Gamma_t)^2 + 4d_p d_t}],
$$

$$
P_p^\infty = \frac{P_A \gamma_{SE}(d_t + \Gamma_t)}{(d_p + \Gamma_p + \gamma_{SE})(d_t + \Gamma_t) - d_p d_t},
$$

$$
P_t^\infty = \frac{d_t}{d_t + \Gamma_t} P_p^\infty,
$$

$$
C_p = \frac{\Gamma_s P_p^\infty - \gamma_{SE} P_A + X(\gamma_{SE} + \Gamma_p + d_p - \Gamma_s) - Y d_p}{\Gamma_f - \Gamma_s},
$$

$$
C_t = C_p \frac{d_t}{\Gamma_t + d_t - \Gamma_f} = \frac{\Gamma_s P_t^\infty - X d_t + Y(\Gamma_t + d_t - \Gamma_s)}{\Gamma_f - \Gamma_s}.
$$

- Credit to Junhao Chen (W&M)

NMR AFP Loss Study

Simplified Convection Model

$$P_p(t,X,Y) = C_p e^{-\Gamma_f t} + (-P_p^\infty - C_p + X)e^{-\Gamma_s t} + P_p^\infty,$$

$$P_t(t,X,Y) = C_t e^{-\Gamma_f t} + (-P_t^\infty - C_t + Y)e^{-\Gamma_s t} + P_t^\infty,$$

$$\Gamma_f = \frac{1}{2}[(d_p + \Gamma_p + d_t + \Gamma_t + \gamma_{SE}) + \sqrt{(d_p + \Gamma_p + \gamma_{SE} - d_t - \Gamma_t)^2 + 4d_p d_t}],$$

dp + dt

$$\Gamma_s = \frac{1}{2}[(d_p + \Gamma_p + d_t + \Gamma_t + \gamma_{SE}) - \sqrt{(d_p + \Gamma_p + \gamma_{SE} - d_t - \Gamma_t)^2 + 4d_p d_t}],$$

From spin up time constant

$$P_p^\infty = \frac{P_A \gamma_{SE}(d_t + \Gamma_t)}{(d_p + \Gamma_p + \gamma_{SE})(d_t + \Gamma_t) - d_p d_t},$$

From maximum signal

$$P_t^\infty = \frac{d_t}{d_t + \Gamma_t} P_p^\infty,$$

From maximum signal

$$C_p = \frac{\boxed{\Gamma_s P_p^\infty - \gamma_{SE} P_A} + X(\boxed{\gamma_{SE} + \Gamma_p} + d_p - \boxed{\Gamma_s}) - Y d_p}{\Gamma_f - \Gamma_s},$$

$$C_t = C_p \frac{d_t}{\Gamma_t + d_t - \Gamma_f} = \frac{\boxed{\Gamma_s P_t^\infty} - X d_t + Y(\boxed{\Gamma_t} + d_t - \boxed{\Gamma_s})}{\Gamma_f - \Gamma_s}.$$

Ignored terms in red block

- Credit to Junhao Chen (W&M)

NMR AFP Loss Study

Fully Parameterized Convection Model

1. Get Γ_P, Γ_P and γ_{SE} through equations:

$$\frac{a}{a+1}(\Gamma_P + \gamma_{SE}) + \frac{1}{a+1}\Gamma_T = \frac{1}{\tau_{spin\ up}}$$

$$\frac{a}{a+1}(\Gamma_P) + \frac{1}{a+1}\Gamma_T = \frac{1}{\tau_{cold\ spin\ down}}$$

$$\frac{\gamma_{SE}}{a\,\Gamma_t + \Gamma_P + \gamma_{SE}} = b$$

- $d_p = a\, d_t = \frac{n_{TC}V_{TC}}{n_{PC}V_{PCC}} d_t \approx \frac{n_{TC}V_{TC}}{n_{PC}V_{PCC}} \frac{v}{L}$
- $P_P^{\infty} = b\, P_A = P_A \frac{\gamma_{SE}(d_t+\Gamma_t)}{(d_p+\Gamma_P+\gamma_{SE})(d_t+\Gamma_t)-d_t d_p} \approx P_A \frac{\gamma_{SE}}{a\,\Gamma_t+\Gamma_P+\gamma_{SE}}$

- Credit to Junhao Chen (W&M)

Post Experiment PNMR Loss Study

(at EEL Target Lab)

PNMR Loss Measurement: during Hot spin down with convection

a) NMR measurement at 0 min: $P_0=\beta^2 P_a$

b) 10 PNMR measurements take within 1 sec at 1 min: (for T2 ~7 msec)

c) NMR measurement at 30 min: $P(t)=P_c$

d) NMR measurement at 60 min: P_d

For τ be Hot spin down time constant and known β=1-AFP$_{Loss}$ (NMR AFP loss per sweep)

Then from c), d) get P_0' after all PNMR measurement: (Δt=0.5 hr)

$$\boxed{P_c=P_0' e^{-\Delta t/\tau}}$$

$$\boxed{P_d=P_c \beta^2 e^{-\Delta t/\tau}} \longrightarrow \boxed{P_0'=\frac{P_c{}^2\beta^2}{P_d}}$$

- Polarization time evolution:

$$\boxed{P(t)=P_0 e^{-t/\tau}}$$

Using a), c) to found out PNMR ^{3}He spin tip angle: (n=10)

$$\boxed{P_0'=(1-\cos(\theta_{tip}))^n * P_0}$$

Assume the PC and TC reached equilibrium after 30 min (with convection speed ~6 cm/min)

Thus PNMR loss per measurement is:

$$\boxed{PNMR_{loss}=1-\alpha_{loss}}$$

$$\boxed{\alpha_{loss}=1-\cos(\theta_{tip})=\left(\frac{P_0'}{P_0}\right)^{1/n}=\left(\frac{P_c^2}{P_d P_a}\right)^{1/n}}$$

PNMR Loss Study Post the Experiment

(on Cell Butterball)

PNMR Loss study:

Field Direction (deg)	Oven Temp (deg C)	Laser Power (W)	Corr. Coil HL (V)	Corr. Coil HS (V)	Convection PS (V)	Target Position	PNMR Loss per Measurement (%)	Pulse Freq (kHz)	Reference Freq (kHz)	Cell Name	PNMR sweeps/ Δt(s)	Larmor freq-Ref freq: df (Hz)	Comment
Long	205	off	0	0	7	Pick-up Coils	0.127	81.32	81.035	Butterball	10/0.1	380	
Long	205	off	3	0	7	Pick-up Coils	0.327	81.415	81.035	Butterball	10/0.1	380	
Long	205	off	3	0	7	Pick-up Coils	NA	81.415	81.035	Butterball	5/60	380	
Long	205	off	3	0	7	Pick-up Coils	0.205	81.415	81.035	Butterball	10/1.0	380	
Long	205	off	3	0	9	Pick-up Coils	0.450	81.415	81.035	Butterball	10/0.1	380	
Long	205	off	3	0	9	Pick-up Coils	0.321	81.415	81.035	Butterball	10/0.1	405	
Long	205	off	3	0	9	Pick-up Coils	0.231	81.415	81.035	Butterball	10/0.1	405	set t_pulse=0.8 msec
Long	205	off	3	0	7	Pick-up Coils	0.0903	81.38	81.09	Butterball	10/0.1	350	
Long	205	off	3	0	7	Pick-up Coils	0.237	81.40	81.065	Butterball	10/0.1	365	
Long	205	off	3	0	7	Pick-up Coils	0.489	81.475	81.02	Butterball	10/0.1	410	

PNMR Loss Study During the Experiment

(on Cell Austin and Cell Tommy)

PNMR Loss study:

SHMS angle (deg)	HB momentum (GeV)	Field Direction (deg)	Oven Temp (deg C)	Laser Power (W)	Corr. Coil VL (A)	Corr. Coil VS (A)	Convection PS (V)	Target Position	PNMR Loss per Measurement (%)	Pulse Freq (kHz)	Reference Freq (kHz)	Δf (Hz)	df (Hz) Larmor -ref freq	Cell Name
11	7.5	180	210	80	4.7	6.9	9	Pick-up Coils	1.03*	80.57	80.28	290	350	Austin
8.5	2.1286	0	208	80	0.0	0.0	7	Pick-up Coils	3.90*	81.465	81.13	335	350-380	Tommy
8.5	2.1286	180	208	80	3.6	4.5	7	Pick-up Coils	2.93*	83.595	83.26	335	350-380	Tommy
11	7.5	270	208	80	4.1	6.0	7	Pick-up Coils	4.25*	82.265	81.93	335	350-380	Tommy
11	7.5	90	208	80	4.0	6.0	7	Pick-up Coils	4.13*	82.565	82.23	335	350-380	Tommy
18	5.6	90	208	80	4.4	6.0	7	Pick-up Coils	3.53*	82.385	81.93	455	410	Tommy

Note: "*" means that PNMR loss is not finalized yet.

Goal: Help determine the in beam ^{3}He polarization after PNMR and NMR measurements.

1) Since PNMR loss per measurement depends on the PNMR ^{3}He spin tip angle, the holding field magnitude drift will affect the PNMR loss.
2) PNMR loss study during the experiment is not ideal for determine PNMR loss.
3) Need to do additional post experiment PNMR loss study at EEL target lab to finalize the PNMR loss per measurement during the experiment.

Production Cells for the Experiment

Cell name	Start time and end time	Cold spin down lifetime [hrs]	Max polarization Measured (no beam) [%]	Status
Dutch	01/04/2020 to 02/10/2020	29.4 (UVa)	52 (UVa)	Used for A_1^n production run
Bigbrother	02/12/2020 to 03/13/2020	26 (UVa)	60 (UVa)	Used for A_1^n production run
Austin	03/20/2020 to 08/21/2020	20 (UVa)	52 (UVa)	Used for d_2^n production run
Briana	08/23/2020 to 08/31/2020	15.3 (UVa)	52.1 (UVa)	Used for d_2^n production run
Tommy	09/03/2020 to 09/21/2020	15.2 (UVa)	54 (UVa)	Used for d_2^n production run
Butterball	NA	19.0 (UVa)	56 (UVa)	Spare target cell (for post-experiment PNMR loss study)

- Production cells are fabricated and filled by Gordon's group at UVa. Professor Todd Averett at W&M helped to fill some of the cells.