Polarized $^3$He Target for A1n/d2n in Hall C

Jian-ping Chen, Jefferson Lab
Experimental Readiness Review, March 19, 2018

- Polarized $^3$He target: introduction and overview
- Target for A1n/d2n
  - Upgrade
  - Make it work in Hall C
- Current status and plan
  - Engineering/mechanical
  - Target system
- Safety consideration and documents
- Summary
JLab Polarized $^3$He Target

- **Effective pol neutron target**
- **Longitudinal, transverse** (and vertical)
- **Luminosity** = $10^{36}$ (1/s) (highest in the world)
  - Upgrade: x2 (stage I)
  - Additional x3 (stage II)
- **High in-beam polarization**
  - 60% (>70% no beam)
- 13 completed experiments
  - 9 approved with 12 GeV (A/C)
Polarized $^3$He Performance for 6 GeV Experiments

- luminosity/cell: $10^{36}$ with 15 uA on 40 cm cell, 
  $\sim$10 atm $^3$He, 3-inch diameter sphere pumping chamber

- polarization:
  - < 40% in 1998
  - with K-Rb hybrid pumping and narrow-width lasers 
    improved to $> 70\%$ (no beam) in 2008 
    $\sim 60\%$ (with beam/flip) 
    $\sim 55\%$ (average for transversity experiment)

- polarimetry:
  - NMR-AFP/water +EPR, with Rb only, reached 3%
  - transversity: Rb-K hybrid and longer transfer tube
    total uncertainty @ target, only reached $\sim 5\%$
    diffusion (2-3%), $\kappa_0$ for EPR (2-3%)
Polarized He3 Target Upgrade for A1n/d2n

Hall C A1n/d2n goals:
• 30 uA on 40 cm, ~10 atm, L ~ 2.2x10^{36} cm^{-2}s^{-1}
• In-beam polarization ~ 55-60%,
• Polarization measurement precision ~ 3%

Approaches:
• Re-use existing Helmholtz coils and most existing hardware, electronics and optics
• Convection flow
• Target cell, pumping chamber size 3.5”, glass cell
• Polarimetry ~ aim for 3%, Pulse NMR calibrated with AFP NMR
  absolute calibration with EPR, AFP-NMR with water optional
• Modification to Hall C pivot area and new platform/laser optics line

Project mostly complete, cell production on-going

Started preparation for hall installation (Walter Kellner’s talk)
  identifying installation requirements: space, shielding, electronics, cables, …
Progress Summary

Engineering/Design:
• target design complete: oven, ladder, support, optical line, enclosure, pivot area, access platform, ...
• installation design mostly complete

Mechanical:
• New parts ordered
• Target ladder manufactured
• Pivot area modified (poster cut)
• Existing parts (in storage) checked will test in advance

Field gradients at target area:
• Study bender field at and magnetic material near the target region
• Correct field gradients with correction coils (talk by Lassiter/Cates)
Target Oven, Ladder and Cell
Progress Summary (cont.)

• New oven manufactured/installled/tested

• Target cells
  ✓ prototyping convection cell extensively tested,
    cell production started
  o 1st good cell: lifetime > 48 hours, tested at UVa, now at JLab for full characterization
  o five cell ordered and production started
  o five more cell order will be placed in FY18
  o order more in FY19 until reaching the goal of having 6-8 good cells.
  o produce/characterize ~one cell per month

• Lasers/long optical fibers:
  ✓ five new lasers delivered/tested
    more will be ordered as spares and for future
  ✓ ten long fibers delivered, tested
  ✓ five 4-1 combiners ordered, prototype tested
  ✓ polarization compensation study complete
Progress Summary (cont.)

- **Polarimetry:**
  - pulse NMR systematic study/calibration (Nguyen Ton)
  - EPR study (Kai Jin)
  - $\kappa_0$ measurement (W&M/UVa) in progress (Averett/Cates)
  - will continue study to understand and improve systematics

- **Cell characterization:**
  - Density measurement (August Williams)
  - Wall and window thickness measurements
  - Maximum polarization
  - Spin up
  - Spin down/ AFP loss study

Cold spindown with convection at transfer tube

\[
\chi^2 / \text{ndf} = 42.73 / 18 \\
\text{Prob} = 0.0008734 \\
slope = 17.08 \pm 0.04544 \\
bkgd = -2.985 \pm 0.3259
\]

EPR

Water NMR
Instrumentation locations in the hall
# Cable lists

<table>
<thead>
<tr>
<th>Cable type</th>
<th>Quantity</th>
<th>Length (ft)</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>37</td>
<td>2 EPICs</td>
</tr>
<tr>
<td>3</td>
<td>X</td>
<td>7</td>
<td>2 EPICs+1 ladder and control</td>
</tr>
<tr>
<td>1</td>
<td>Y</td>
<td>7</td>
<td>1 ladder and control</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>Rotate waveplate</td>
</tr>
<tr>
<td>BNC</td>
<td>11</td>
<td>X</td>
<td>5 NMR+2 PNMR+2 EPR+2 EPIC</td>
</tr>
<tr>
<td>2</td>
<td>X</td>
<td>21</td>
<td>2 PNMR</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>37</td>
<td>2 EPIC</td>
</tr>
<tr>
<td>18</td>
<td>&gt;7</td>
<td></td>
<td>3 PNMR+ 2 EPR+13 NMR</td>
</tr>
<tr>
<td>20</td>
<td>7</td>
<td>&lt;7</td>
<td>20 (within a rack)</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>5 (within a rack)</td>
</tr>
<tr>
<td>RTD type</td>
<td>6</td>
<td>X</td>
<td>1 ovenRTD+1 heater relay+2 reference/cooling(?)+1 airflow</td>
</tr>
<tr>
<td>TC</td>
<td>1</td>
<td>X</td>
<td>1 thermal couple</td>
</tr>
<tr>
<td>RTD</td>
<td>10</td>
<td>X</td>
<td>10 RTD</td>
</tr>
<tr>
<td>RTD</td>
<td>5</td>
<td>21</td>
<td>1 heater relay+4 reference/cooling (2 to counting, 2 to target)</td>
</tr>
<tr>
<td>RTD</td>
<td>12</td>
<td>7</td>
<td>1 ovenRTD+10 RTD+1 airflow</td>
</tr>
<tr>
<td>RTD</td>
<td>2</td>
<td>7</td>
<td>2 reference/cooling (wire type?)</td>
</tr>
<tr>
<td>RTD</td>
<td>12</td>
<td>Z</td>
<td>12 RTD for laser monitor</td>
</tr>
<tr>
<td>Power wire (9&amp; 16 AWG)</td>
<td>16</td>
<td>37</td>
<td>8 main field + 8 correction field</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>7</td>
<td>8 main field + 8 correction field</td>
</tr>
<tr>
<td>Power cable (12 AWG)</td>
<td>2</td>
<td>21</td>
<td>2 heater</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>7</td>
<td>2 heater</td>
</tr>
<tr>
<td>GPIB</td>
<td>12</td>
<td></td>
<td>5 (in Hall)+7 (counting house)</td>
</tr>
</tbody>
</table>

**Cable lists**

X: counting house – patch panel
Y: optic table – further shielded
Z: laser room – optic table
Peoplepower/User Contributions

At JLab: students + engineer/designer + JP (supervisor/coordinator)
- Engineering/Design: Bert Metzger and Al Gavalya (work with JP)
- Magnetic field modelling: Steve Lassiter (work with UVa group)
- two graduate students, Kai Jin and Nguyen Ton (UVa, Xiaochao’s group) work under JP’s supervision

- New students planned to be on site once ERR passed

User contributions:
- UVa (Gordon Cates):
  - cell fabrication
  - $\kappa_0$ measurement

- W&M (Todd Averett)
  - $\kappa_0$ measurement
  - Reference cell system/cooling jets

- Kentucky (Wolfgang Korsch)
  - field direction measurement

Working at JLab polarized 3He target lab
Kai Jin (UVa), Nguyen Ton (UVa)
Safety and documents

Laser safety, same as used in Hall A with update
Use CANS system to lock the hall for laser alignment

OSP following what were used in Hall A with update
Main safety issue is the glass cell rupture when handling a cell

Draft OSP and LSOP ready
Cell rupture and beam conditions

Cell rupture during running, beam line windows materials/thickness as tested

Minimize cell rupture:
experience from 6 GeV running (12-15 uA on 40 cm, 10 atm glass cell):

1) 5 cell rupture during first running period, no more than one since then

2) most ruptures from pumping chamber, likely accumulation of radiation
damage: cells last ~ 4 weeks for transversity running condition

3) direct beam hitting caused two cell rupture:
   • one due to raster turned off (cell ruptured 5-10 minutes unrastered beam)
   • one due to beam hitting inside of the cell wall (joint of window with cell body)
   • beam size limits to not too small, also not too large
     200-300 um (FWHM) beam size with ~ 2-4 mm diameter raster size

4) used cooling jets and slow beam ramping rate

For A1n/d2n, 30 uA on 40 cm, 10 atm glass cell

• with longer distance from pumping chamber to beam line, simulation shows
  accumulated radiation about the same as transversity
  <200-300 um (sigma) beam size, raster 5 mm diameter circular
Summary

- Polarized 3He target reliably used for many 6 GeV experiments in Hall A

- Upgrade (double luminosity) and make it work in Hall C

- Progresses:
  - Engineering/Design complete, parts fabricated and delivered
  - Hall C pivot area work (post cut) complete
  - New oven tested, convection cell extensively tested.
  - pulsed NMR established, reached 1% precision in cross calibration
  - New lasers, new optical fiber cables
  - 1st good cell delivered
  Target is ready and cell production started and on-going

- Installation design mostly complete, preparation started, plan discussed (Walter Kellner’s talk)

- Field gradient study/correction coils design (Lassiter/Cates talk)

- OSP/LSOP draft ready
Backup
Spin exchange Optical Pumping for $^3\text{He}$

Diagram showing the levels $5P_{1/2}$ and $5S_{1/2}$ with transitions at 795 nm. Zeeman splitting indicated with $M = -1/2$ and $M = +1/2$. Collisional mixing shown with an arrow from $5P_{1/2}$ to the $5S_{1/2}$ level.
Rb-K Hybrid Optical Pumping Spin Exchange

Collisional Mixing

\[ 5S_{1/2} \quad 795 \text{ nm} \quad 5P_{1/2} \]

\[ \sigma^+ \quad 1/2 \]

\[ M = -1/2 \quad M = +1/2 \]

Zeeman Splitting

\[ \text{Rb} \quad \text{K} \]

\[ \text{K} \quad ^3\text{He} \]

\[ ^3\text{He} \quad \text{K} \]
Figure of Merit \equiv (Target\ Polarization)^2 \times Beam\ Current

Performance History for High Luminosity Polarized $^3$He

SLAC

Jefferson Lab

- E06-010: 60% @ 15 \mu A
- E99-117: 40% @ 12 \mu A
- E02-013: 50% @ 8 \mu A
- E94-010: 35% @ 10 \mu A
- E97-110: 40% @ 12 \mu A
- E142: 35% @ few \mu A
- E154: 35% @ few \mu A

Year

Pulse NMR

Challenge: to improve signal to noise ratio

Send RF pulse

Receive free-induction-decay signal

Pulse NMR signal vs time

Challenge: to improve signal to noise ratio
Pulse-NMR calibrate with AFP-NMR (Spin-Down)

PNMR vs NMR

χ² / ndf = 18.91 / 15
Prob = 0.218
slope = 21.21 ± 0.1554
bkgd = -1.976 ± 1.549

PNMR vs time

NMR vs time

Target Chamber
### Spinup time, AFP loss and lifetime for protovec-1

<table>
<thead>
<tr>
<th>AFP loss</th>
<th>Pumping chamber(%)</th>
<th>Target chamber(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool without convection</td>
<td>1.18</td>
<td>0.21</td>
</tr>
<tr>
<td>Hot without convection</td>
<td>0.95</td>
<td>0.37</td>
</tr>
<tr>
<td>Hot with convection</td>
<td>1.43</td>
<td>1.44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lifetime</th>
<th>Pumping chamber(hr)</th>
<th>Target chamber(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cool without convection</td>
<td>26.57</td>
<td>23.11</td>
</tr>
<tr>
<td>Hot without convection</td>
<td>13.49</td>
<td>15.97</td>
</tr>
<tr>
<td>Hot with convection</td>
<td>14.56</td>
<td>14.54</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spinup time</th>
<th>Pumping chamber(hr)</th>
<th>Target chamber(hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5.3</td>
<td>9.6</td>
</tr>
</tbody>
</table>
Calibrate Pulse NMR at transfer tube versus NMR at target chamber

Cold spindown with convection at transfer tube

\[ \chi^2 / \text{ndf} = 42.73 / 18 \]
\[ \text{Prob} = 0.0008734 \]
\[ \text{slope} = 17.08 \pm 0.04544 \]
\[ \text{bkgd} = -2.985 \pm 0.3259 \]

Cold spindown at transfer tube

\[ \chi^2 / \text{ndf} = 36.58 / 21 \]
\[ \text{Prob} = 0.01878 \]
\[ \text{slope} = 14.92 \pm 0.2159 \]
\[ \text{bkgd} = -8.563 \pm 1.715 \]

With convection

Without convection

Measurements were done every 2 hours for each data point.

Systematic uncertainty study is in progress. Several tests were done without convection and it showed a strong contribution from diffusion.

From diffusion study for hot spindown, the diffusion constant (between pumping and target chamber) \( d_{pc} = 0.091 \) (~11 hours) and \( d_{tc} = 0.065 \) (~16 hours).
Cell Characterization (Protovec I)

Pumping Chamber

Spin up

5.3 hours

Spin down (PC vs time)

~13 hours

Target Chamber

Spin up vs time (TC)

9.6 hours

Spin down (TC vs time)

~16 hours

Both PNMR and NMR
Field gradient

- By measuring $H_1$ as a function of NMR amplitude:

$$S(H_1) = \frac{H_1}{2b_0} \ln \sqrt{\frac{H_1^2 + b_0^2}{\sqrt{(H_1^2 + b_0^2)}}} + b_0$$

\[\chi^2/\text{ndf} = 0.1442 / 9\]
\[\text{Prob} = 1\]
\[b_0(\text{mG}) = 34.46 \pm 0.7172\]
\[p_1 = 17.4 \pm 0.02681\]

At Hall C pivot: SHMS Bender, one order of magnitude higher being modeled and studied, correction coils needed

\[<\sim 10 \text{ mG/cm}\]

Gaussmeter:

\[5 \text{ mG} < \frac{\partial B_z}{\partial z} < 10 \text{ mG}\]
Convection speed measurement

Use pulse-NMR coil destroy $^3$He polarization in at left transfer tube, and measure the time interval between two NMR signal dips.

convection speed=5.8 cm/s
From target chamber to pumping chamber : 8 min.
Compare to diffusion (~40 min), convection is faster.
Radiation @ Pumping Chamber vs. Shielding

Average Dose (Gy) Versus Lead Thickness (mm) At Pumping Chamber (350 hours 8.8 GeV)

- $A_{1n}$ with no oven plate
- $A_{1n}$ with regular oven
- $A_{1n}$ with oven + 1mm lead

Transversity (350 hours)
Reference Cell Broken During Transversity