HL - POLARIZED ION AND LEPTON SOURCES AND TARGETS
- 19 TALKS EVENLY DISTRIBUTED BETWEEN SOURCES AND TARGETS

Christopher Keith
Jefferson Lab
- Targets

Kurt Aulenbacher,
Johannes Gutenberg-Universität Mainz
- Sources

Spin 2018
23rd INTERNATIONAL SPIN SYMPOSIUM
FERRARA - ITALY
10 - 14 SEPTEMBER 2018
Apart from polarization degree, progress is measured by improving

- Peak current/brightness (storage ring based research), → RHIC, NICA, EIC,....
  - talks by Zelenski (BNL); Finushkin (JINR)
- Average current →
  c.w. LINACS/dc machines i.e. CEBAF/MAMI/MESA /LHeC
  - talks by Aulenbacher (Mainz), Tsentalovitch (MIT), Y.Plis, (JINR)
- Neutral Particle flux e.g. polarized Nuclei in Molecules
  talks by R. Engels, L Huxold (Jülich), D. Sofikitis (FORTH),
PROTON
High-brightness proton beam inside strong 2.5 T solenoid field produced by atomic H beam ionization in the He-gas ionizer cell.

The primary proton beam and Equivalent atomic H intensity current is 2.5 A at 6.5 keV beam energy!
Beam intensity and polarization at 200 MeV

- Reliable long-term operation of the source was demonstrated.
- Very high suppression of un-polarized beam component was demonstrated.
- Small beam emittance (after collimation for energy separation) and high transmission to 200 MeV.

<table>
<thead>
<tr>
<th>Rb-cell thickness-NL</th>
<th>4.5</th>
<th>5.5</th>
<th>7.5</th>
<th>10.4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linac Current, μA</td>
<td>440</td>
<td>520</td>
<td>740</td>
<td>950</td>
</tr>
<tr>
<td>Booster Input ×10^{11}</td>
<td>10.0</td>
<td>12.0</td>
<td>14.0</td>
<td>17.1</td>
</tr>
<tr>
<td>Pol. %, at 200 MeV</td>
<td>86</td>
<td>86</td>
<td>84.5</td>
<td>83</td>
</tr>
</tbody>
</table>

A. Zelenski
BNL

Rb-cell thickness, NL ×10^{13} atoms/cm^2
RHIC Polarized beam in Run 2013-17

OPPIS → 1.0 mA x 300us → 18 \cdot 10^{11} \text{ polarized } H^- /pulse.

LINAC → 9.0 \cdot 10^{11} \text{ polarized } H^- /pulse at 200 MeV routinely in Run-17, Polarization-85%.

Booster → (2.5-3.0) \cdot 10^{11} \text{ protons /pulse at 2.3 GeV}

AGS → (2.0-2.5) \cdot 10^{11} \text{ p/bunch, P-70%}

~1.8 \cdot 10^{11} \text{ p/bunch, P~65-75\% at 100 GeV}
P ~ 60-65\% at 255 GeV

A. Zelenski
BNL
UNDER DEVELOPMENT: HIGH INTENSITY

$^3$HE SOURCE AT BNL
"Extended" EBIS upgrade with new "injector" solenoid for polarized $^{3}\text{He}^{++}$ ion production.

Polarization and ionization in high magnetic field will produce $^{3}\text{He}^{++}$ ion beam with $P \geq 80\%$

3$\text{He}^{+}$ → Ionization to $^{3}\text{He}^{++}$ → Up to $2 \times 10^{11}$ $^{3}\text{He}^{++}$ ions/pulse

(A. Zelenski)
Extended EBIS superconducting solenoids, April 2018

5.0 T field, about 1.0 T field at minimal solenoid separation-30 cm
ELECTRON SOURCE: HIGH AVERAGE CURRENT AT MIT (E. TSENTALOVICH, MIT)

• High brilliance source at Mainz (increased Field strength 1MV/m → 2.5MV/M)
• High current developments at MIT → ERL application
Cathode cooling

- HV
- Coolant in
- Coolant out (Fluorinert)
- Manipulator
- Crystal
- Cathode
- Laser
- Cathode puck (Moly)
- Heat exchanger
- Up to 40 W of laser power

E. Tsentalovich, MIT
Hope to achieve very high charge lifetimes!

>>1000C?   → Important for ERL based EIC like LHeC!!

E. Tsentalovich, MIT
NUCLEAR SPIN MOLECULES TO PRODUCE, (E.G.), HD ICE (R. ENGELS (JÜLICH), L. HUXOLD, D. SOFIKITIS (FORTH))

- Generate pol. Nuclei in Molecules by chemical or optical orientation
Experimental results
Measurements on Fomblin Oil (Perfluoropolyether PFPE)

HFS 3

\[ T_{\text{Cell}} = 100 \text{ K} \quad P_m = -0.87 \]

\[ P_m = -0.81 \pm 0.02 \]
\[ n = 174 \pm 19 \quad c = 0.993 \pm 0.005 \]


\[ H_2^+ \quad P_m = -0.84 \pm 0.02 \]
\[ n = 277 \pm 31 \]

R. Engels (Jülich),
Recombination on Fomblin (?)

B_{ext}

Fused Quarz

R. Engels (Jülich),
We can produce polarized H\textsubscript{2}, D\textsubscript{2} and HD molecules with large vector- and tensor-polarization (\textasciitilde 0.8) in many spin combinations.

**For what it is usefull?**

1.) **More dense polarized targets.**

2.) Spectroscopy of the molecules or molecular ions (Contact with the University of Düsseldorf).

3.) New insights in chemical reactions / surface physics.

4.) Polarized fuel to increase the energy output of Fusion reactors. \textcolor{red}{\textit{-> see talk on Wednesday, 2:30 pm}}

5.) Polarized targets for laser acceleration. \textcolor{red}{\textit{-> see talk by M. Büscher on Wednesday, 5:05 pm}}

6.) EDM measurements?

7.) An option to produce polarized molecules for medical application?

R. Engels (Jülich),
PART 2: Polarized Targets at SPIN 2018

Thanks to all my polarized target colleagues for making this an interesting and stimulating SPIN symposium!

Gerhard Reicherz (Bochum)  COMPASS Polarized Target in 2018 and 2021
Erhard Steffans (Erlangen)  Design of a Polarized Gas Target for the LHC
James Brock (JLab)  Design & Construction Techniques for the CLAS12 Polarized Target
James Maxwell (JLab)  NMR Measurements for Jefferson Lab's Solid Polarized Targets
Josh Pierce (ORNL)  Dynamic Polarization for Neutron Macromolecular Crystallography
Harmut Dutz (Bonn)  Recent Activities of the Bonn Polarized Target Group
Marcel Bronstein (Bonn)  Design and calculation of 4Pi-Continuous-Mode-Target current leads
Stefan Runkel (Bonn)  Polarized Target at the CBELSA/TAPS Experiment
Andy Sandorfi (JLab)  Potential use of Solid Frozen-Spin HD Targets with Electron Beams
Marco Statera (INFN Ferrara)  Measurements of transverse magnetization of a bulk MgB2 cylinder

Thanks also to two plenary speakers:

Don Crabb (Virginia)  More Than Fifty Years of Polarized Targets
Arnaud Comment (Cambridge)  Hyperpolarizing 13C spins by DNP for MRI applications
Instrumentation for a typical polarized (solid) target

Interesting developments in nearly all aspects of target instrumentation:
Magnets for polarized (solid) targets

Most targets have one or two superconducting magnets

- High field, high homogeneity (2.5 – 5 T, 100 ppm) for polarizing
- Lower field, higher acceptance for holding polarization (Frozen spin only)

5 Tesla Split-coil Magnet

1/2 Tesla, internal holding coils
Magnets for polarized (solid) targets

Recent activities of the Bonn Polarized Target Group

Research Objectives: high field thin s.c. magnets

DNP requires $\Delta B/B \leq 10^{-4}$

High precision winding technique to guarantee ‘orthozyclic winding’

Harmut Dutz (Bonn): Design, construction, and testing of a high-field, thin, internal polarizing magnet (and many other topics!)
Recent activities of the Bonn Polarized Target Group

Research Objectives: high field thin s.c. magnets

First DNP-signals in the new internal thin s.c. polarizing magnet

\[ T_P = 1 \text{K}, \quad B_P = 2 \text{ Tesla}, \quad F_{\mu_w} = 56 \text{ GHz} \]

4\(\pi\)-continuous mode scheme has been proven

Next: 8-layers coil for the new refrigerator

more information next talk: Marcel Bornstein “Design and calculation of the 4\(\pi\)-Continuous-Mode-Target current leads”
Magnets for polarized (solid) targets

Results - Temperature distribution

Boundary conditions

- Inlet: Gas-Temperature 40 K
- Flow: 13 mmol s⁻¹
- Outlet-Pressure 50 mbar
- Current: 90 A

Result: Lower end temperatures by thermal decoupling of each sink with optimised bridges

Joule heating: 2 x 4.15 W (consistent with McFee)
Joule heating: 2 x 3 W
Magnets for polarized (solid) targets

Current leads concept - Impressions

Marcel Borstein (Bonn): FEA modelling and construction of current leads for internal polarizing magnet
Magnets for polarized (solid) targets

Double Cells with Opposing Polarization

- Access $\pm$ polarization with $\nu_{\mu \pm} = \nu_{EPR} \pm \nu_{NMR}$ in a single holding field (COMPASS)
- OR change local fields so that $\nu_{\mu +} = \nu_{\mu -}$
- Microwave freq static, must change shim fields, NMR tune

James Maxwell (JLab): Demonstration of double-sample polarization with internal shim coils
Magnets for polarized (solid) targets

Double Cell, Opposing Polarization

![Image of magnets and double cell]

Spin 2018 — Sept 10, 2018

James Maxwell (JLab): Demonstration of double-sample polarization with internal shim coils
Magnets for polarized (solid) targets

A BULK TRANSVERSE MAGNET?

bulk cylinder

• \( \text{MgB}_2 \)
• longitudinal shield
• transverse magnetization

features

• no current leads
• Cu free
• self tuning
• simple
• low making cost
• few mm thickness
• external magnet (magnetization)

existing sample (courtesy of G. Giunchi)
diameter 39 mm - length 90 mm
thickness ~1 mm

Marco Statera (INFN Ferrara): Bulk superconducting magnet (and shield!) for transverse polarized target
Magnets for polarized (solid) targets

**SHIELDING VS TRAPPED FIELD**

- field trapping: residual field
- shielding: shielded field

Marco Statera (INFN Ferrara): Bulk superconducting magnet (and shield!) for transverse polarized target
Refrigerators for polarized (solid) targets

12 GeV POLTAR Target Design

Modular Geometric Truss structure

- Conical HX Spring loaded into Pump Tube to ensure good thermal contact with Pump Tube Heat Sink
- All Refrigerator Components are modular and can be uncoupled without cutting or grinding of parts
Refrigerators for polarized (solid) targets

12 GeV POLTAR Plug and Play Target

Transportation Configuration
- Refrigerator Retracted Over Cart
- Isolation Valve for Refrigerator
- Modeling Complete Target System Allows Strategically Place Lifting Points Based on COG

James Brock (JLab): Innovative design and construction techniques for the CLAS12 polarized target
Refrigerators for polarized (solid) targets

$4\pi$-Continuous Target
Refrigerators for polarized (solid) targets

Heat Exchanger 1

- Data for \( \dot{n}_\text{He} = 1 \text{ mmol s}^{-1} \).
- Well defined temperature gradient along the heat exchanger.
- Temperature after the last stage of 8 K is reached.
- Simulation performed for all heat exchangers and a circulation rate of 1 to 20 mmol s\(^{-1}\).

<table>
<thead>
<tr>
<th>Simulation</th>
<th>Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>HE(<em>{1})(</em>\text{in} )</td>
<td>170 K</td>
</tr>
<tr>
<td>HE(<em>{1})(</em>\text{middle} )</td>
<td>43 K</td>
</tr>
<tr>
<td>HE(<em>{1})(</em>\text{out} )</td>
<td>8 K</td>
</tr>
<tr>
<td>(\rho^3\text{He}_{\text{in}} )</td>
<td>100 mbar</td>
</tr>
<tr>
<td>(\rho^3\text{He}_{\text{out}} )</td>
<td>(2.1 \times 10^{-2} ) mbar</td>
</tr>
<tr>
<td>(\rho^4\text{He}_{\text{out}} )</td>
<td>15 mbar</td>
</tr>
</tbody>
</table>
Materials for polarized (solid) targets

**Neutron protein crystallography**

- Usually, macromolecular crystallography uses X-ray facilities to measure molecular structure
  - Modern light sources have incredibly high flux
- Using neutrons for crystallography has pros/cons:
  - Comparatively low flux
  - Sensitivity of the neutron cross section to lighter elements (especially hydrogen)
  - Sensitivity to isotopes
- NPX is a unique experimental tool for the experimental location of key hydrogen atoms and water molecules in biological macromolecules, but use is limited by requirement for huge crystals.

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Josh Pierce (ORNL): Neutron crystallography of dynamically polarized protein samples
T4 Lysozyme Results

- Doped with TEMPO
- “Large” crystals
  - ~0.5mm-1.0mm on edge
- Detector was uncalibrated, and shifted between frames
- Short hold times in “frozen spin” mode
  - ~60-180 min $T_1$
  - Very high temperatures
    - ~230 mK
- Measured diffraction pattern change
- Enhancements of 2-3 in integrated diffraction pattern for anti-aligned spins
  - The enhancement of individual reflections depends on the relative contribution of hydrogen
- Consistent with maximum polarizations of around 50%
Materials for polarized (solid) targets

**energy deposited in HD**

Electron energy loss in 5 cm of HD:

- **loss dominated by bremsstrahlung**
- deposition dominated by Møllers
  \[ \sigma_{\text{Møller}} \sim (1 + 1/\gamma)^2 \]
  ~ independent of beam energy
- deposition: \( 2 \text{ Mev/e}^- = 1 \text{ mW/e}^- \times \text{nA} \)
  ~ independent of beam energy

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SPIN’2018 – Sept 11, 2018

Andy Sandorfi (JLab): testing solid HD target (HDice) with electron beams
Materials for polarized (solid) targets

Testing eHD at Jlab’s **Upgraded Injector Test Facility (UITF)**

Energy: $7 - 10$ MeV; $\sigma_E/E < 10^{-3}$
Current: 100 pA – 5 nA CW
100 nA Tune-mode
Size: $50 \, \mu m < \sigma_{x,y} < 150 \, \mu m$
Stability: within $\sigma_{x,y}$
Beam Halo: $< 10^{-4}$
Polarization: $> 70\%$
Helicity flip: 1-30 Hz

Andy Sandorfi (JLab): testing solid HD target (HDice) with electron beams
Gerhard Reichertz (Bochum): Performance of COMPASS target in 2018, prospects for use in 2021

**Polarized (solid) targets**

**COMPASS Polarized Target**

First time hadron beam was used with the COMPASS PT system

- 2.5 T solenoid + 0.6 T dipole
- 50 mK dilution refrigerator
- 2 x 55 cm long target cells
- NH$_3$ as proton target (17% df)
- DNP by microwave of 70 GHz
- 10 NMR coils
- Frozen spin mode at 50mK
Polarized (solid) targets

Polarization in 2018

Maximum Polarization
upstream : 78.1%, -82.8%
downstream: 81.3%, -80.5%

preliminary

Gerhard Reichertz (Bochum): Performance of COMPASS target in 2018, prospects for use in 2021
Overview: Polarized Gas Target for the LHC

Design considerations for a PGT

- Physics accessible at LHC (no polarized beam): Single Spin Azimuthal Asymmetries (SSAA), measured with transverse polarization of the target $S_T$ and $\Phi$-dependence of the final-state hadrons.

- Polarized gas target similar to HERMES (see sketch), incl. Atomic Beam Source (ABS), Storage Cell (SC) target with strong transverse guide field, target gas analyzer (TGA) and polarimeter (BRP), powerful differential pumping, etc.

- All narrow openings in the LHC, like the VELO detector, have to be openable during injection and tuning ($r_{\text{min}} \approx 27$ mm at IP8). This holds for the PGT set-up as well, with cell, wake field suppressors, detectors, diaphragms etc.
Polarized (gas) targets

Estimate of the areal density of the PGT

Assumed:

- $I_H (100 \% \text{ HERMES ABS flow}) = 6.5 \cdot 10^{16}/s$, may be limited by LHC vacuum constraints or space limitations for the PGT;

- Cell 30 cm long, 1.0 cm i.d., at 100K, with standard feed tube 10 cm long, 1.0 cm i.d.

The resulting 100% density of the polarized gas target is $\theta = 1.2 \cdot 10^{14}/\text{cm}^2$, comparable with HERMES.

For the future HL-LHC-25ns, the Luminosity achievable with the PGT would be up to $8.3 \cdot 10^{32} \text{ /cm}^2 \text{ s}$. To which extent such densities can be realized and exploited in a real experiment, depends on many factors and has to be investigated in more detail.