Dual H&D Cavity for the PAX Target Polarimeter

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\begin{itemize}
\item PAX polarimeter - requirements
\item Tuned twin lines - principle of operation
\item Technical realization and test
\item Conclusions
\end{itemize}
Overview of the PAX target
Principle of the Breit-Rabi Polarimeter

- SFT, MFT = RF-transitions
- Sextupoles for state selection
- QMA with chopper and single-ion counting

By measuring many combinations of hf states one can extract all four hydrogen occupation numbers $N_1 - N_4$ → nuclear polarization
“Adiabatic” RF transitions

**Required:**

- RF field with appropriate orientation of oscillating B field
- Static B field (usually transverse to atomic beam, AB) with adjustable gradient

→ adiabatic passage through resonance enables 100% efficiency [for the exchange of hf states (Abragam & Winter 1958)]

Semi-classical picture of the adiabatic rf-transition: the magnetization \( M \) is reversed during passage of the resonance (taken from Haeberli 1967), resulting in \( m_F \leftrightarrow -m_F \)

\[ z' = z, \ y': \text{rotating system} \]
Low frequency \([\leq 50 \text{ MHz}]\):

solenoid coil with axis \(\parallel\) to AB axis (field longitudinal)

Implies \(B_{RF} \perp B_{stat}\), i.e. \(\Delta m_F = \pm 1\), and \(\Delta F = 0\) (\(\pm 1\) not possible at low frequency).

\(\rightarrow\) Used for WFT = weak field transition \(m_F \leftrightarrow -m_F\), MFT = medium field transition = incomplete WFT.

High frequency \([\approx 330 \text{ MHz for deuterium (D), 1430 MHz for hydrogen (H)}]\):

tuned twin lines!
Example of a “strong field” transition SFT

Note: “Strong field” purely historical!
Better: “Two-level transition”

Two-level transitions ($\Delta F = 1$):
level spacing is of the order $\Delta W$

- RF fields in the range 100 MHz to few GHz are produced by means of resonating structures. Most flexible: a resonator, e.g. a $\lambda/4$ rod, in a conducting Cu box. Results in $Q \approx$ few 100.
- The length of a $\lambda/4$ rod is 5.3 cm for hydrogen (H) and 23 cm for deuterium (D). While for H such a rod fits to the length of a rf transition, it has to be reduced for D.

<table>
<thead>
<tr>
<th>Species</th>
<th>$\Delta W / h$ [MHz]</th>
<th>$B_{\text{critical}}$ [mT]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>1421.4</td>
<td>50.7</td>
</tr>
<tr>
<td>Deuterium</td>
<td>327.4</td>
<td>11.7</td>
</tr>
</tbody>
</table>

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E. Steffens: Dual H&D Cavity
Tuned Twin Lines

- In the early days: standard method for atomic beam resonance machines
- Improved version: tuned twin lines in a conducting box, e.g. silver plated for higher Q (used at ORNL, ANAC/Glavish, PSI/Basel group)

Example: 300 MHz resonator of the polarized Lithium source at MPI Heidelberg [Steffens et al., 1977]

Two $\lambda/2$ strip lines, excited by coupling loop; rf field monitored by pick-up loop at the center.

Two “open ends”: $\lambda/2$ resonator with maximum voltage amplitude at the ends, and current maximum in the center (virtual ground).

One end grounded: $\lambda/4$ resonator; works as well.
The $\lambda/2$ twin line is excited by means of a coupling loop, as shown before. A simpler twin line resonator consists of two coupled $\lambda/4$ resonator with a grounded end and an open end with load capacity to ground, in order to tune the frequency at a fixed length. The coupling is done here simply by galvanic coupling to one of the rods close to ground.
Conducting rod of length \( a \) grounded at the left corner. The voltage and current distribution of a fictitious rod of length \( \lambda/4 = a + \Delta \) is shown. The difference \( \Delta \) is accounted for by a load capacity between the end of the rod and the ground to the right.

The quantity \( \Delta \) is given by:

\[
\Delta = (\lambda_R / 2\pi) \arctan(\omega C Z_L)
\]

with

- \( \lambda_R \) = wavelength on the line resonator (in good approximation equal to \( l_{\text{free-space}} \))
- \( \omega \) = resonance angular velocity
- \( C \) = capacity between end of rod and ground
- \( Z_L \) = impedance of rod resonator

This expression can be used for estimating the load capacity \( C \).
Effect of a tilted twin line plane

By tilting the normal of the twin line plane from parallel to $B_{\text{stat}}$ to 45°, one has both parallel and perpendicular components of the RF field with respect to $B_{\text{stat}}$, i.e. $\Delta m_F = 0$ and ± 1 are enabled. This is important for Deuterium ($F = \frac{1}{2}$ and $\frac{3}{2}$) in particular.

A tilted plane also provides space for an additional pair of lines!
Cavity seen along AB direction

Plane of Deuterium twin line

Oscillating field $B_{RF}$, static field $B_{Stat}$

$\rightarrow$ Both parallel and perp. components, i.e. $\sigma$ and $\pi$ transitions can be excited!

Same for Hydrogen twin line
Photo of the Dual Cavity

The upper wall is removed. The atomic beam axis is (approx.) vertical. The two pairs of rods (H & D) are arranged in two planes, tilted by ± 45° to the plane of paper. 1: Upper left D rod with grounding point and galvanic coupling to the power cable. 2: Free end of D rod loaded by a set of two trim capacitors (the left one set to a fixed value, the right one screwed to the wall and tunable from outside) which are needed to reach the required capacity of about 10 pF. 3: Upper right H rod with grounding point and coupling. The rod can be tuned by means of a screw inside the bottom wall which points to the free end of the rod. 4: Ends of the H rods and tuning plates. 5: Fixed pick-up loops are located at each uncoupled rod close to the grounding point, the D loop is visible below.
Dual H&D cavity – different views

LEFT
- top: grounded ends of the rods with galvanic coupling and pick-up loops;
- bottom: tuning capacitors

RIGHT
- top: open ends of the rods with tuning capacitors
- bottom: micro coax lines
Tuning of the resonators and result

The frequency scans were performed by means of a Network Analyzer (Agilent E 4402B).

Hydrogen  
Scan of the hydrogen resonator between 1.39 and 1.45 GHz. The vertical linear scale shows the PU voltage of the fixed coil placed near the grounded end of the uncoupled H rod (see Fig. 3 and 8). The upper peak at 1.432 GHz corresponds to the required counter mode, the lower one to the common mode.
Deuterium  Scan of the deuterium resonator between 290 and 350 MHz. The vertical linear scale shows the PU voltage of the fixed coil placed near the grounded end of the uncoupled D rod (see Fig. 3 and 8). The upper peak at 330.7 MHz corresponds to the required counter mode, the lower one to the common mode.
Test results for the Dual cavity

**Hydrogen twin line**

With 3 – 5 W of RF power, a field amplitude of 0.06 – 0.1 mT has been obtained. This results in 30 – 60 precessions of F around the RF field component which ensures adiabatic passage conditions.

**Deuterium twin line**

Up to now, tuning only of the twin line has been performed. The full test requires a power amplifier for the 350 MHz-range, which were not available at the time of the test.
Conclusions

- A tuned twin line dual cavity has been developed which works both on Deuterium and Hydrogen frequencies in the “tilted” mode, i.e. all possible two-level transitions can be excited.

- The cavity has been tested electronically using a Network Analyzer. For hydrogen a sufficient RF field strength has been demonstrated. The deuterium twin line is still to be tested, but no problems are to be expected.

- The cavity will be installed soon at the Jülich PAX target and tested with atomic H&D beams.

Thank you!