Antihydrogen Formation from **Cold Nonneutral Plasmas**

**What**
- antimatter
- hyperfine measurement

**How**
- getting antiprotons
- mixing them with a positron plasma

**My contribution**
- control of plasma shape and density
- diagnosis of plasma temperature
- minimizing plasma temperature
- diagnosis of quantum state distribution

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and the Stefan Meyer Institute
Dark Energy  Dark Matter  Ordinary Matter
ASACUSA’s spin flip proposal

1. Cusp forms a polarized $\bar{H}$ beam
2. Count low-field-seeking $\bar{H}$ on target
3. Flip the spin with a resonant microwave cavity

Atomic Spectroscopy and Collisions Using Slow Antiprotons
\( e^+ \) plasma + \( \bar{p} \) plasma

\[ \rightarrow \text{H atoms} \]

Simulations of antihydrogen formation suggest:
1. maximize interaction of \( \text{H} \) with \( e^+ \)
2. minimize plasma temperature

FIG. 1. Antihydrogen bound-state level population distribution after evolution of 10 \( \mu \)s (circle), 20 \( \mu \)s (square), and 50 \( \mu \)s (triangle) and the thermal equilibrium level population distribution (solid line) for positron temperature of \( T_e = 50 \) K and positron density \( n_e = 10^{14} \text{ m}^{-3} \) (with \( 10^6 \) antiprotons).

Control of plasma parameters

length
= electrode potentials

number of particles, temperature
= forced evaporation

density, radius
= rotating wall (next slide)
**SDR:** Rotating wall in the Strong Drive Regime

‘Rotating’ electrostatic field creates a torque, when the plasma rotation is slower than the field rotation frequency → Plasma rotation frequency asymptotes to RW frequency

The plasma density

\[ n_0 = \frac{2\varepsilon_0 m}{q^2} \omega_r (\Omega_c - \omega_r) \]

is proportional to the plasma rotation frequency → Plasma density proportional to RW frequency

\[ N = 3.5 \times 10^6 \]

Danielson et al. (2015). Plasma and trap-based techniques for science with positrons
SDR + EVC = SDREVC

→ Simultaneous control of all plasma parameters

→ Reproducible results independent of initial state

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean</th>
<th>SD</th>
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</thead>
<tbody>
<tr>
<td>$r_p$ (mm)</td>
<td>0.417</td>
<td>0.003</td>
</tr>
<tr>
<td>$T$ (K)</td>
<td>360</td>
<td>30</td>
</tr>
<tr>
<td>$N_f$ ($10^6$)</td>
<td>11.0</td>
<td>0.3</td>
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Newton’s law of cooling

\[ \frac{dT}{dt} = -\Gamma (T - T_w) + H \]

\[ \Rightarrow T_f = T_w + \frac{H}{\Gamma} \]
What if the radiation environment is hotter than the ~35 K electrodes? 
Measure the temperature of the plasma with the thermal shield in different positions

closed  partly open  fully open
Field ionizers

One ionizer: measure n-state distribution (# ionized atoms vs. applied voltage)
Two ionizers: measure antihydrogen temperature (time of flight)
Backup slides
Temperature measurement

\[ f(E) \propto e^{-E/kT} \]

\[ I(t) = G \cdot f(E(t)) \frac{dE}{dt} \]
\[ \propto a + be^{ct} \]

Figure 3.6: Extraction trace for a hot, \( N = 3 \cdot 10^6 \) e\(^-\) plasma. y axis is the voltage on the

Figure 3.7: Extraction trace for a cold, \( N = 3 \cdot 10^6 \) e\(^-\) plasma. This is the “same” plasma as in Fig. 3.6 after 8 s of resonant cooling.
Plasma temperature is usually reduced by reducing RF noise on the electrodes and the plasma expansion rate.

These are both very low in our trap.
EVC: EVaporative Cooling

Slowly reduce axial electrostatic confinement potential. The most energetic particles escape first
→ Plasma temperature is reduced
→ Plasma space charge set by final well depth

\[ \phi(r) = \frac{qnr^2}{4\varepsilon_0} \left[ 1 + 2 \ln \left( \frac{r_w}{r_p} \right) \right] - \frac{qnr^2}{4\varepsilon_0} \]

but plasma radius is not controlled
Purcell Effect
Resonant interaction with cavity modes can increase the cyclotron cooling rate

Cavity 1 -- TE_{131} -- 34.1 GHz -- qB/m at 1.22 T)

Cavity 2 -- TE_{131} -- 19.6 GHz -- qB/m at 0.70 T)
Cooling Rate

B = 0.78 T

B = 0.96 T
Antimatter and matter in the universe: broken symmetry

The Antiproton Decelerator (AD) at CERN