Design Concept for Microwave Interrogation Structure in PARCS

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In a Nutshell

2 $TE_{011}$ cavities
Loaded $Q \approx 18,000$
detuned $\approx 5\Gamma$ from resonance

Resonant coupling structure
$Q \approx 1000$

Common feed

VCA

Cavities in phase
Phase modulation interrogation

9.2 GHz
Some Numbers

PARCS design goal for accuracy: $5 \times 10^{-17}$
Allowed error from end-to-end phase shift $2 \times 10^{-17}$
Ramsey Time 2.5 seconds
(Allowed phase deviation 3μrad)
Cavities matched in phase to within $\pi/20$ rad
Cavity phase stability at 1 day 10μrad
Temperature uniformity spec 100 mK
Temperature stability spec “100 mK”

(common mode?? 4μrad/s/10^{-16} (= 80 μK/s temperature change for copper)
In microgravity, the launch velocity is easily tuned, so the end-to-end phase shift can be evaluated.

(different microwave power settings must have stable phases)
Notation

End-to-end phase shift is $\phi_1' - \phi_2'$
Internal Cavity Phase changes with Temperature

$\phi_1 - \phi_1'$ varies strongly with temperature

On resonance, 3 $\mu$rad stability requires 3 $\mu$K temperature stability!

$$\frac{d\Delta \phi}{dT} \sim \frac{1}{\text{detuning}^2}$$

10 half-linewidths reduces sensitivity by 200

(requires 100 times more RF power)
Effect of Temperature changes on common structure

1) Differential pathlength changes to 2 ends ($\delta \phi_1 - \delta \phi_2$)
   - mitigated by resonating structure

2) Changes in ($\phi_0 - \phi'_0$)
   - Exacerbated by resonating structure
   - Common mode, but not to a single atom

\[
\frac{d\phi}{dt} \sim \frac{dT}{dt}
\] For linear temperature slope, this is a fixed (but bounded) frequency error
Resonating the coupling structure

\[ \frac{L}{2} = 7.5 \, h = 50 \text{ radians} \]

To keep the cavities matched in traveling wave would require temperature matching of two halves of structure to 3.8 mK (spec is 100 mK)

Absolute length critical in traveling wave, mitigated by resonating
Thermal Stability of PARCS Cavities

Ramsey Tube Temperatures

Initial warm up $\Delta T = -5 \, ^\circ C$

Temperature rate of change $< 2.5 \, \mu K/s$

From Jim Stultz, JPL, PARCS Thermal Engineer
Fountain Clock Sidebar

This not-quite-common-mode cavity analysis applies to fountains which nominally suffer no end-to-end phase shift.

(30 μK/s is $1 \times 10^{-15}$ – average can still be zero)
Summary

- End-to-end phase shift is hard in beam geometry
- inside-outside cavity phase difference is what makes it hard in PARCS
- Detuning cavities helps reduce sensitivity ($\sim 1/detuning^2$)
  - better than spoiling Q with coupling ($1/detuning$)
- Resonant coupling structure provides immunity to temperature gradient changes
- time-varying phases are not common mode to individual atoms and cannot be measured by varying Ramsey time

Detailed design of the coupler and cavity couplings is underway by an RF engineer (Dan Hoppe, of JPL)