UC Berkeley

EE C245 – ME C218
Introduction to MEMS Design
Fall 2011

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Berkeley, CA 94720

Lecture Module 2: Benefits of Scaling

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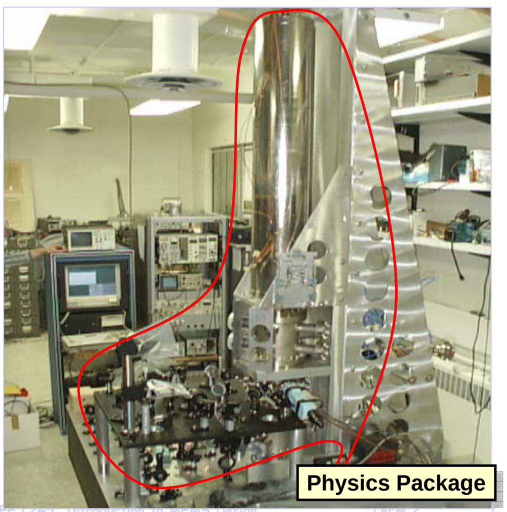
Chip-Scale Atomic Clocks (CSAC)

NIST F1 Fountain Atomic Clock

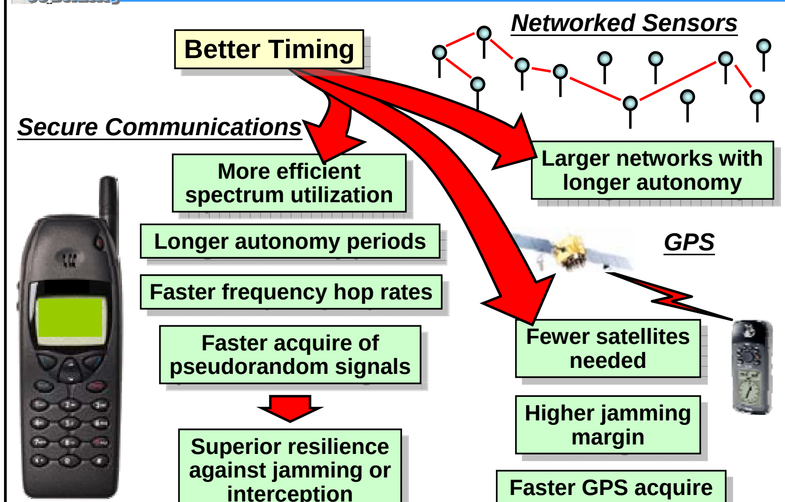


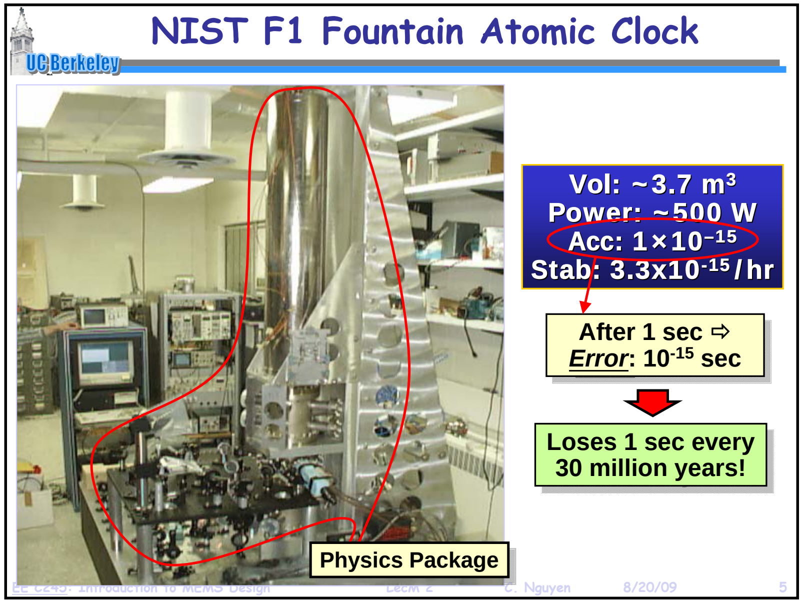
Vol: ~3.7 m^3
Power: ~500 W
Acc: 1×10^{-15}
Stab: 3.3×10^{-15}/hr

After 1 sec ⇨ *Error*: 10^{-15} sec

Loses 1 sec every 30 million years!

Benefits of Accurate Portable Timing




NIST F1 Fountain Atomic Clock
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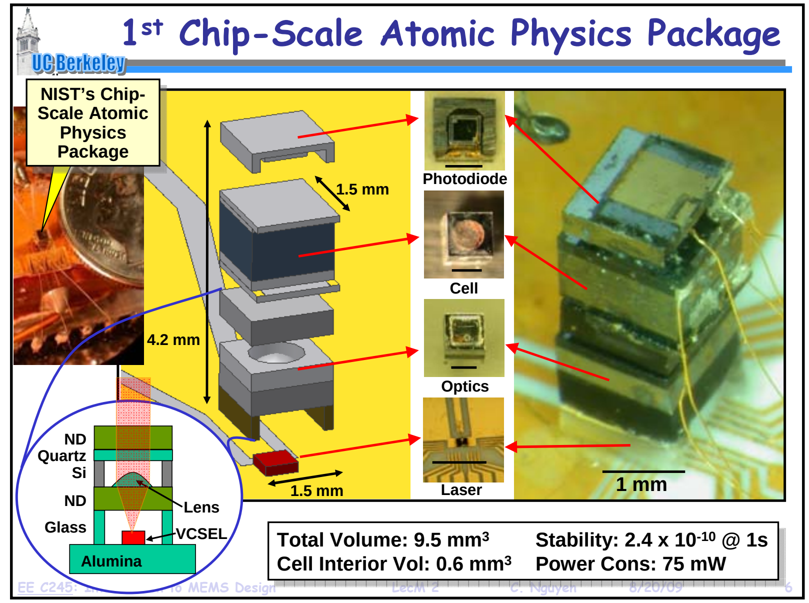
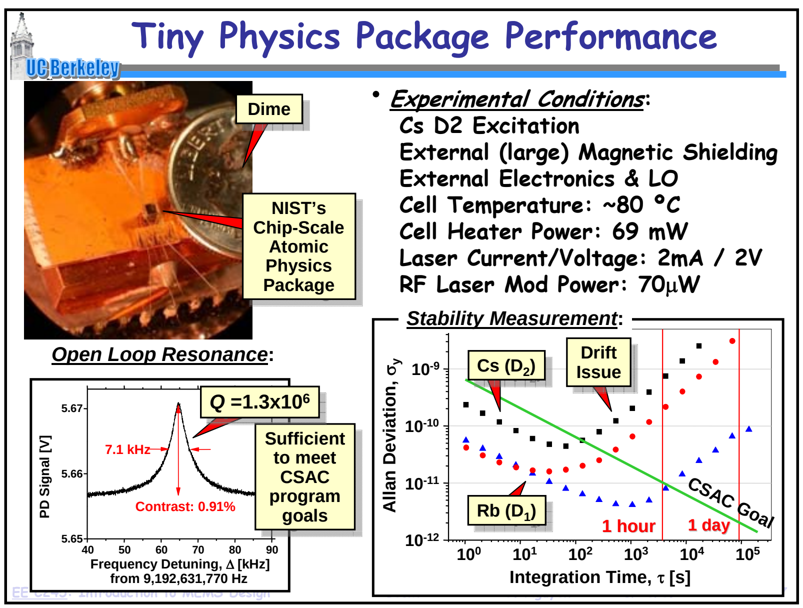
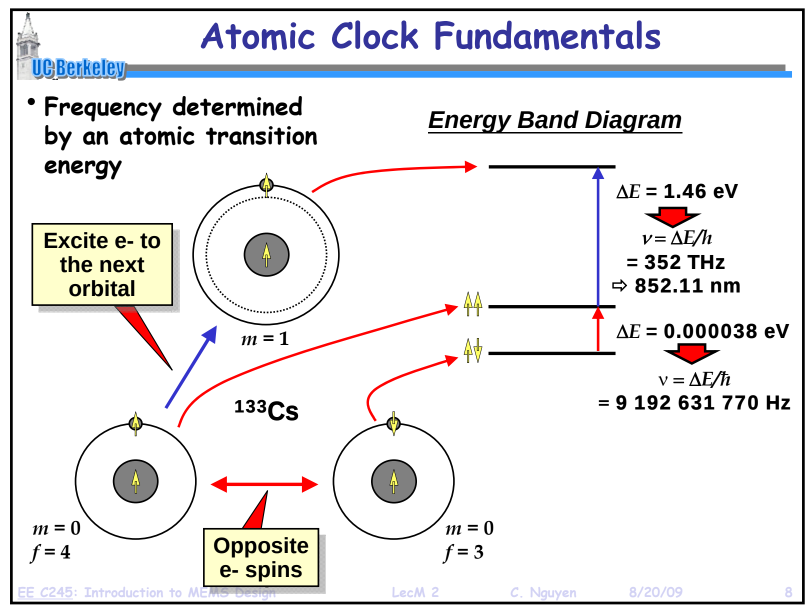
Vol: ~3.7 m³
Power: ~500 W
Acc: 1×10⁻¹⁵
Stab: 3.3x10⁻¹⁵/hr
After 1 sec ⇨
Error: 10⁻¹⁵ sec
Loses 1 sec every
30 million years!
Physics Package


1st Chip-Scale Atomic Physics Package
UC Berkeley
NIST's Chip-Scale Atomic Physics Package
1.5 mm
4.2 mm
1.5 mm
Photodiode
Cell
Optics
Laser
1 mm
ND
Quartz
Si
ND
Glass
Lens
VCSEL
Alumina
Total Volume: 9.5 mm³
Cell Interior Vol: 0.6 mm³
Stability: 2.4 x 10⁻¹⁰ @ 1s
Power Cons: 75 mW


Tiny Physics Package Performance
UC Berkeley
Dime
NIST's Chip-Scale Atomic Physics Package
Open Loop Resonance:
Q =1.3x10⁶
7.1 kHz
Contrast: 0.91%
PD Signal [V]
Frequency Detuning, Δ [kHz] from 9,192,631,770 Hz
Sufficient to meet CSAC program goals
Experimental Conditions:
Cs D2 Excitation
External (large) Magnetic Shielding
External Electronics & LO
Cell Temperature: ~80 °C
Cell Heater Power: 69 mW
Laser Current/Voltage: 2mA / 2V
RF Laser Mod Power: 70μW
Stability Measurement:
Cs (D2)
Drift Issue
Rb (D1)
CSAC Goal
1 hour
1 day
Allan Deviation, σy
Integration Time, τ [s]


Atomic Clock Fundamentals
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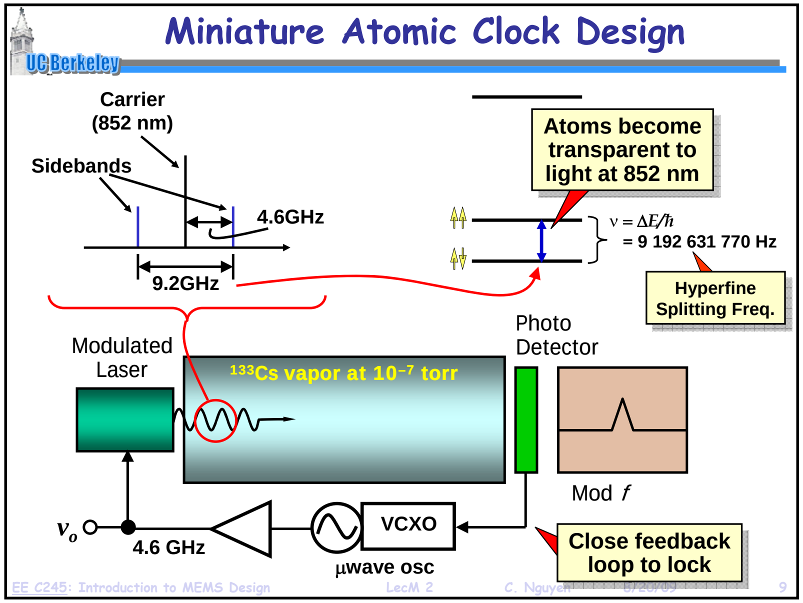
Frequency determined by an atomic transition energy
Energy Band Diagram
Excite e- to the next orbital
m = 1
133Cs
m = 0
f = 4
m = 0
f = 3
Opposite e- spins
ΔE = 1.46 eV
ν = ΔE/h
= 352 THz
⇨ 852.11 nm
ΔE = 0.000038 eV
ν = ΔE/ħ
= 9 192 631 770 Hz


Miniature Atomic Clock Design
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Carrier
(852 nm)
Sidebands
4.6GHz
9.2GHz
Atoms become transparent to light at 852 nm
ν = ΔE/ħ
= 9 192 631 770 Hz
Hyperfine Splitting Freq.
Modulated Laser
133Cs vapor at 10−7 torr
Photo Detector
Mod f
v_o
4.6 GHz
VCXO
μwave osc
Close feedback loop to lock
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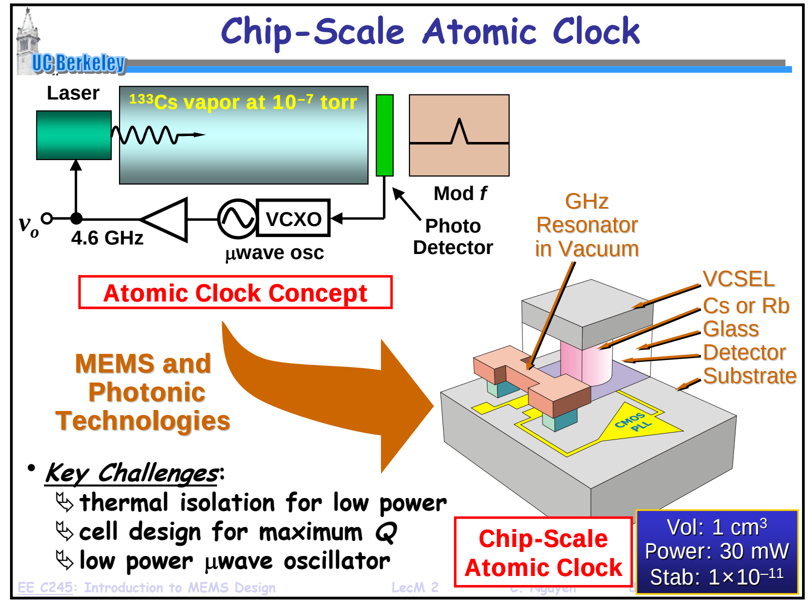
Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo Detector
v_o
4.6 GHz
VCXO
μwave osc
Atomic Clock Concept
GHz Resonator in Vacuum
VCSEL
Cs or Rb
Glass
Detector
Substrate
MEMS and Photonic Technologies
• Key Challenges:
thermal isolation for low power
cell design for maximum Q
low power μwave oscillator
Chip-Scale Atomic Clock
Vol: 1 cm³
Power: 30 mW
Stab: 1×10−11
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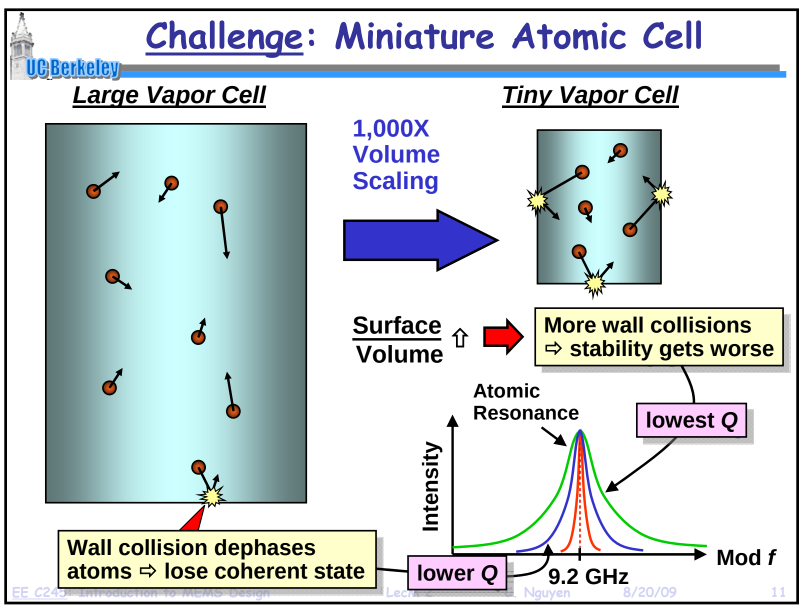
Challenge: Miniature Atomic Cell
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Large Vapor Cell
Tiny Vapor Cell
1,000X Volume Scaling
Surface / Volume ⇧
More wall collisions ⇨ stability gets worse
Atomic Resonance
lowest Q
Intensity
Mod f
9.2 GHz
lower Q
Wall collision dephases atoms ⇨ lose coherent state
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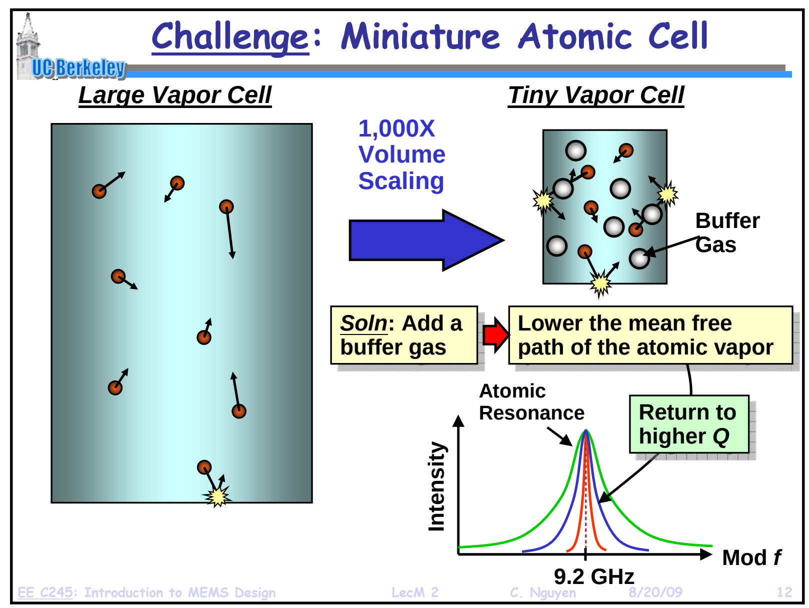
Challenge: Miniature Atomic Cell
UC Berkeley
Large Vapor Cell
Tiny Vapor Cell
1,000X Volume Scaling
Buffer Gas
Soln: Add a buffer gas
Lower the mean free path of the atomic vapor
Atomic Resonance
Return to higher Q
Intensity
Mod f
9.2 GHz
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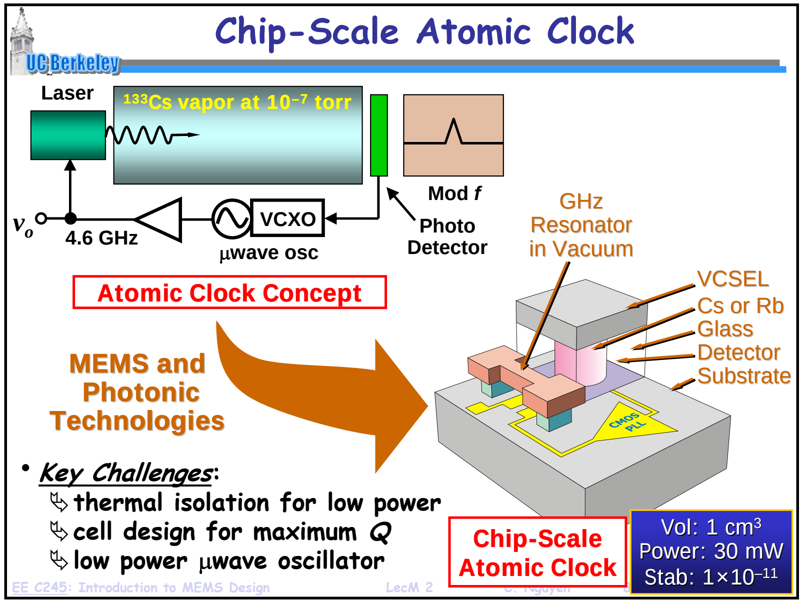
Chip-Scale Atomic Clock
UC Berkeley
Laser
133Cs vapor at 10−7 torr
Mod f
Photo Detector
v_o
4.6 GHz
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Atomic Clock Concept
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MEMS and Photonic Technologies
CMOS PLL
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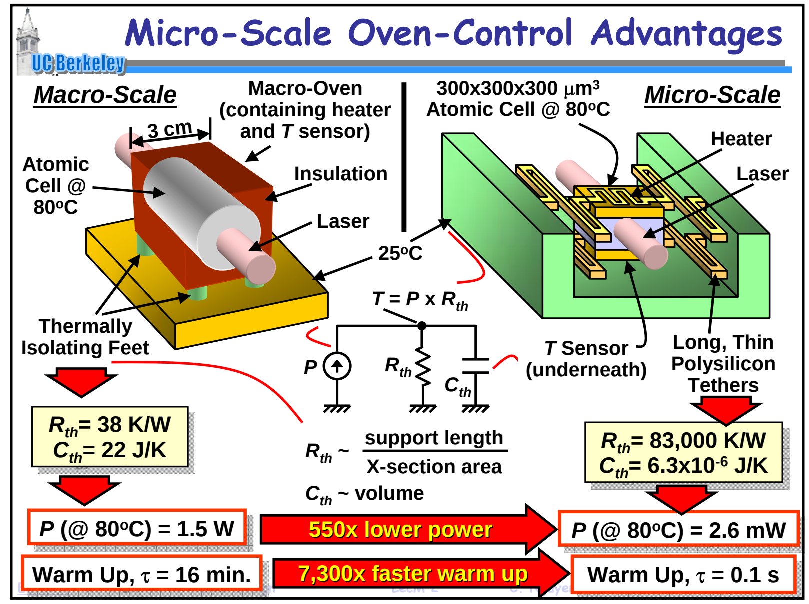
Micro-Scale Oven-Control Advantages
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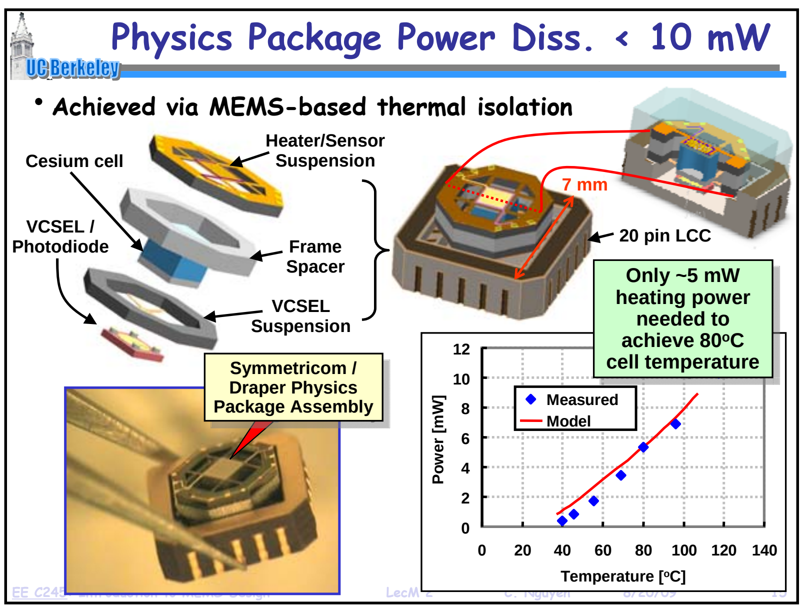
Macro-Scale
Macro-Oven (containing heater and T sensor)
3 cm
Atomic Cell @ 80°C
Insulation
Laser
25°C
Thermally Isolating Feet
300x300x300 µm³ Atomic Cell @ 80°C
Micro-Scale
Heater
Laser
T = P x Rth
P
Rth
Cth
T Sensor (underneath)
Long, Thin Polysilicon Tethers
Rth= 38 K/W
Cth= 22 J/K
Rth ~ support length / X-section area
Cth ~ volume
Rth= 83,000 K/W
Cth= 6.3x10-6 J/K
P (@ 80°C) = 1.5 W
550x lower power
P (@ 80°C) = 2.6 mW
Warm Up, τ = 16 min.
7,300x faster warm up
Warm Up, τ = 0.1 s


Physics Package Power Diss. < 10 mW
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• Achieved via MEMS-based thermal isolation
Cesium cell
Heater/Sensor Suspension
VCSEL / Photodiode
Frame Spacer
VCSEL Suspension
7 mm
20 pin LCC
Only ~5 mW heating power needed to achieve 80°C cell temperature
Symmetricom / Draper Physics Package Assembly
Measured
Model
Power [mW]
Temperature [°C]
0 2 4 6 8 10 12
0 20 40 60 80 100 120 140