Development of a short-pulse laser enhancement cavity for intense-laser/x-ray pump-probe experiments at 6.5 MHz

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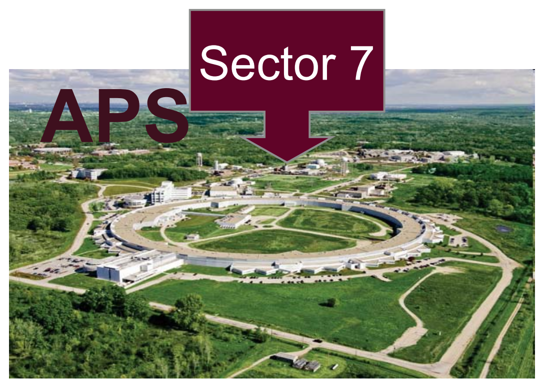


Outline

- Scientific motivation for high repetition rate intense-laser/x-ray pump-probe experiments

- Laser amplification at high rep rate using a passive optical cavity
  - Passive optical cavity basics
  - Active stabilization of cavity length using a feedback control loop and the Pound Drever Hall locking technique
  - Characteristics of enhancement cavity at 7ID-D to amplify ps pulses at 6.5 MHz

- Summary

Scientific Motivation

- Combine ultrafast, strong-field laser techniques with x-ray absorption and scattering techniques to understand and control the behavior of atoms and molecules on ultrafast time scales

Molecules in Strong Laser Fields

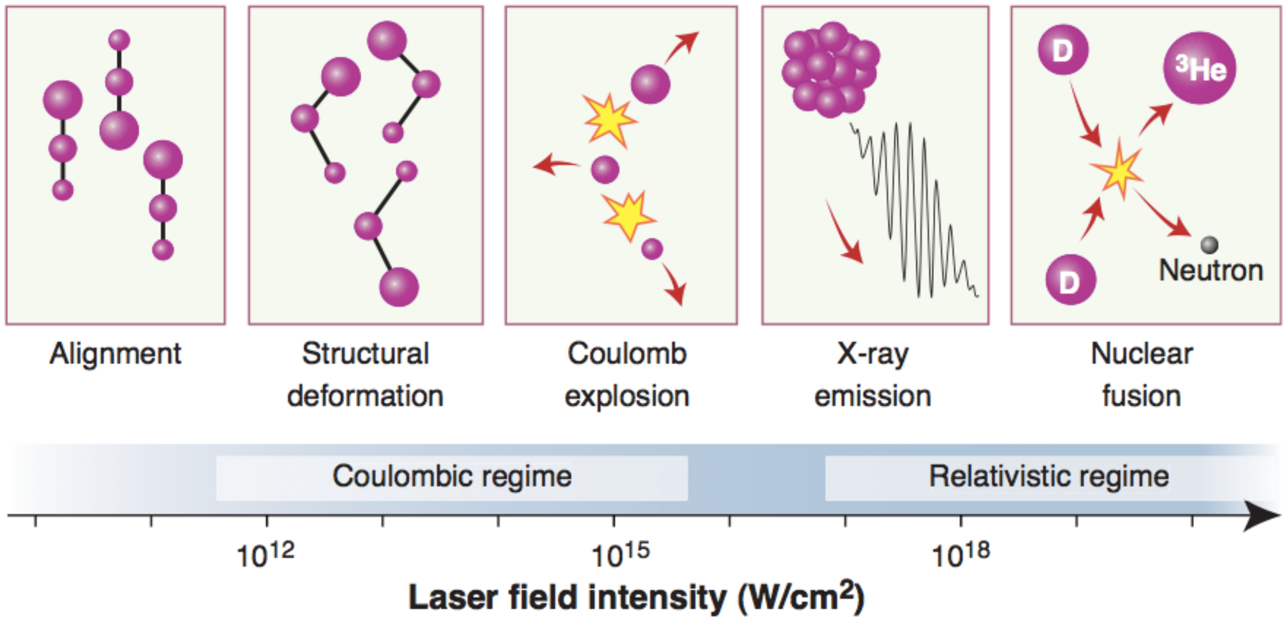


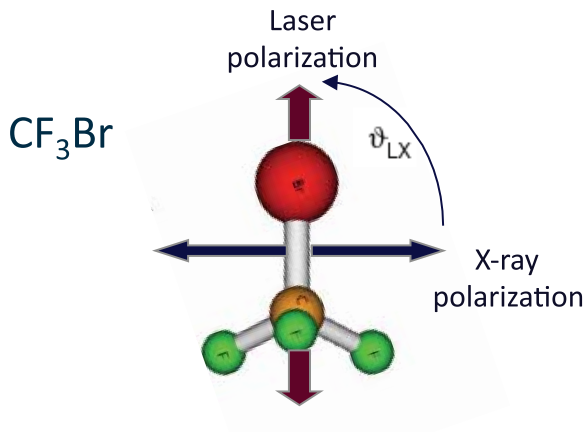
Figure from Science 295, 1659 (2002)

- To achieve these intensities, need amplified, short-pulse laser systems

"standard" CPA ti:sapphire laser system:

~1 mJ, 100 fs, 1 kHz

Demonstrated Control Over Molecular Alignment and X-ray Absorption



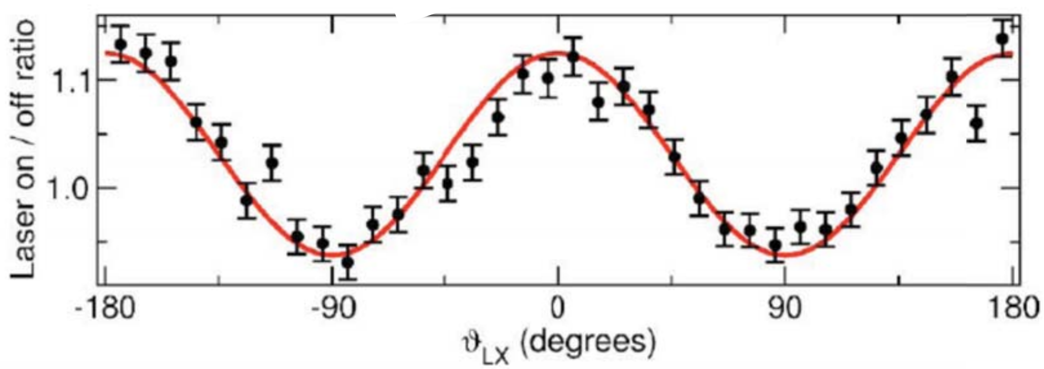
Laser parameters:

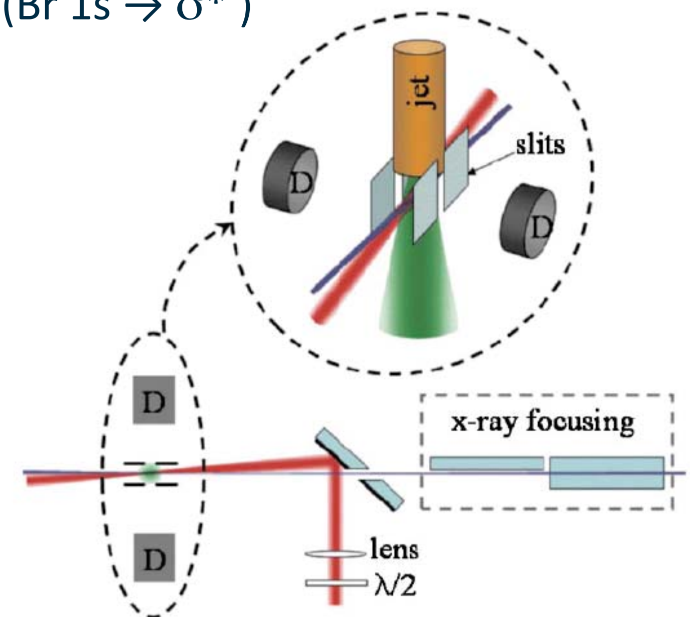
1.9 mJ, 95 ps, 1 kHz, 10^{12} W/cm^2, 800 nm

X-ray parameters:

~10^6 photons/pulse, 120 ps, 0.7 eV bandwidth

•13.476 keV (Br 1s → σ^*)





Dilute sample, signal is weak, we're looking for changes that are subtle

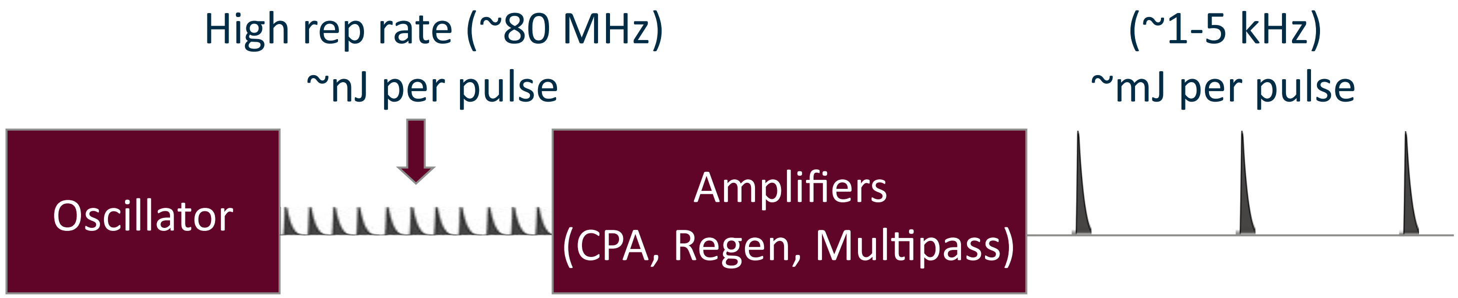
⟶ ***need to use the full flux offered by the APS!***

Appl. Phys. Lett. **92**, 094106 (2008)

Typical Laser, Synchrotron X-ray Rep-Rate Mismatch

- APS 24 bunch mode: x-ray rep rate = **6.5 MHz**

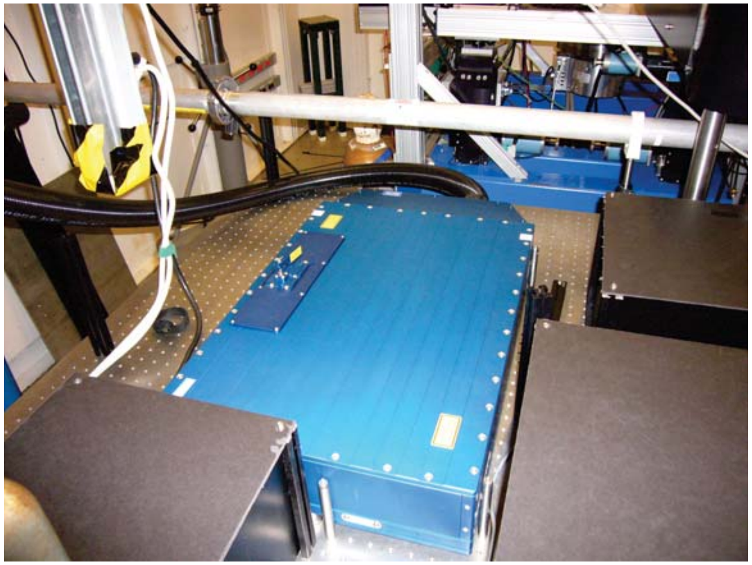
- Typical Intense Laser System: laser rep rate = **1 kHz**

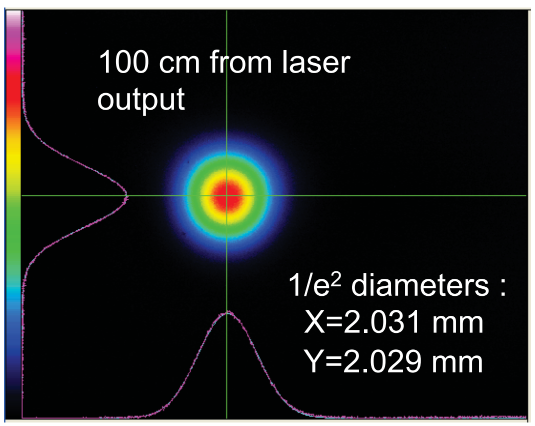


- Typical pump/probe experiment: $\frac{\text{used x} - \text{rays}}{\text{unused x} - \text{rays}} = 0.00015$

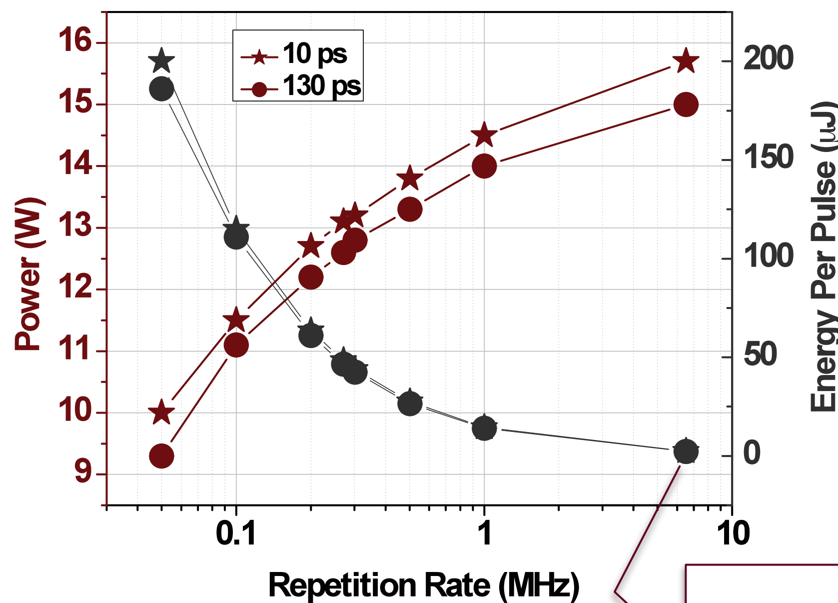
High Rep-Rate Laser at 7ID-D

Time Bandwidth DUETTO



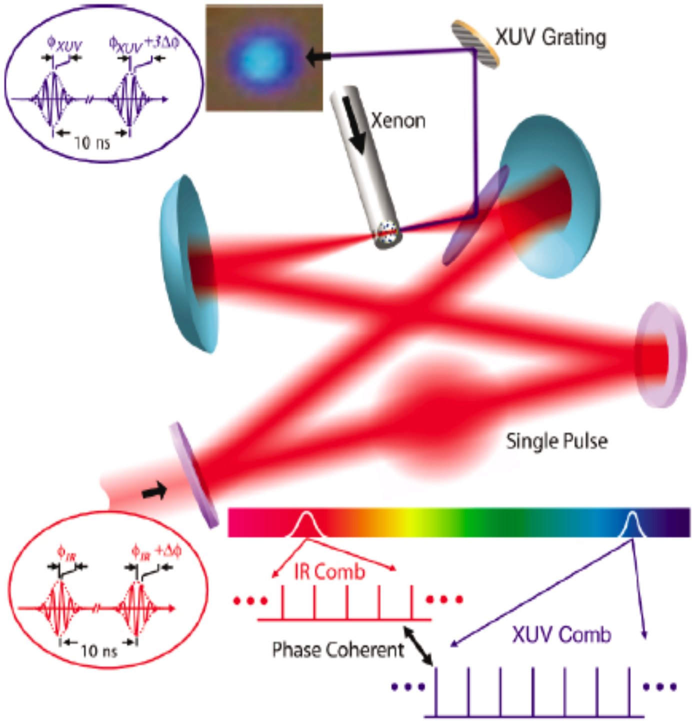


- λ=1064 nm (frequency double to 532 nm)
- Variable Repetition Rate, 50 kHz – 6.52 MHz
- 2 modes: 10 ps and 130 ps
- Customized pulse picker to allow for synchronization with x-rays



Amplifying while maintaining a high repetition rate
Passive Enhancement Cavity

- Coherently add subsequent laser pulses within a high finesse optical cavity
- Carry out XAS experiment within the cavity

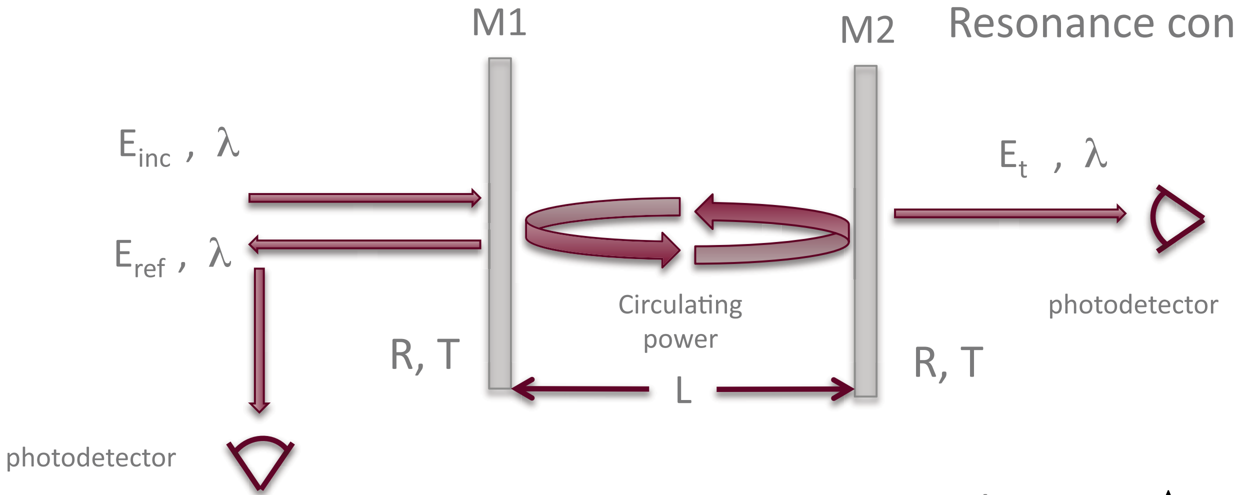


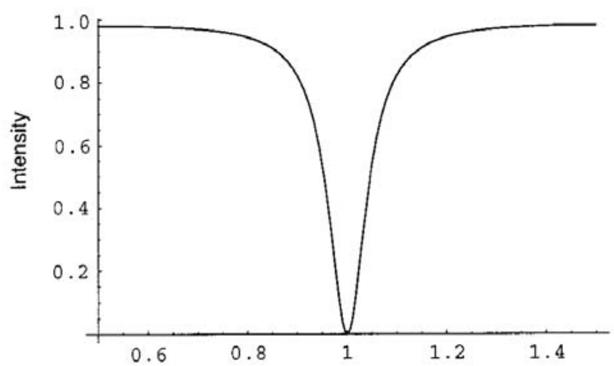
- **Demonstration with picosecond pulses:**
  - E.O. Potma et al, Opt. Lett., **28**, 1835 (2003)
  - 76 MHz, 130x amplification, 13 W

- **Intracavity High Harmonic Generation**
  - R. J. Jones, et al, PRL, **94**, 193291 (2005)
  - Femtosecond enhancement cavity
  - 100 MHz, 600x amplification, I ~ 10^{14} W/cm^2
  - HHG from intracavity gas jet

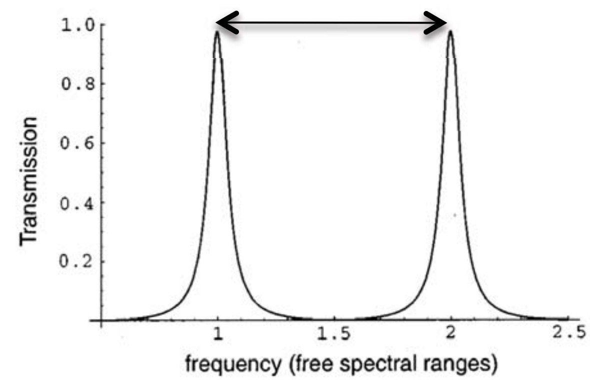
Fabry-Perot resonator basics

Resonance condition: $n\lambda = 2L$





Free spectral range: $\Delta\nu_{fsr} \equiv \frac{c}{2L}$

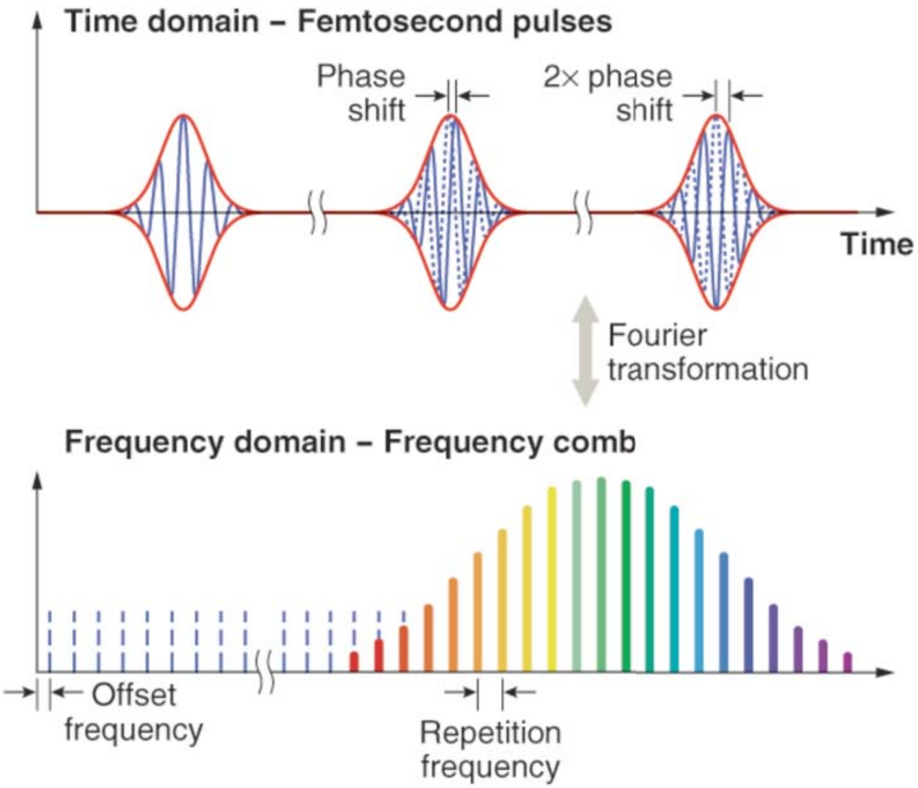


Finesse

Intracavity pulse amplification factor: $N = \frac{4T}{(losses)^2} = 4T\left(\frac{F}{2\pi}\right)^2 = \frac{F}{\pi}$ (impedance Matched)

E. C. Black Am. J. Phys., **69,** 79 (2001)

How does this work for pulsed lasers?



- Match cavity modes to frequency comb

$$\text{Rep. Rate} = \frac{c}{2L} \quad \text{(Free spectral range)}$$

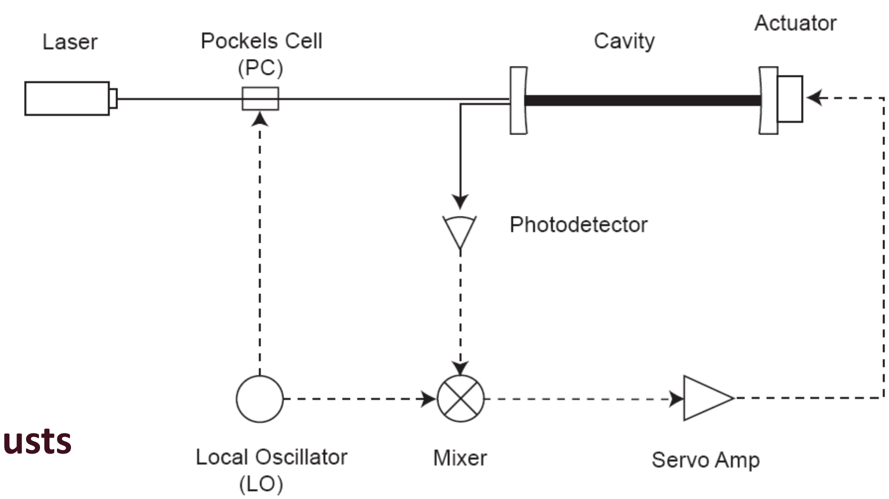
Active stabilization of cavity length

- Noise in the frequency of the laser and noise in the positions of the mirrors of the cavity
- Feedback loop to keep the cavity and laser in resonance

Measure δf and generate error signal

Loop filter to adjust amplitude and phase

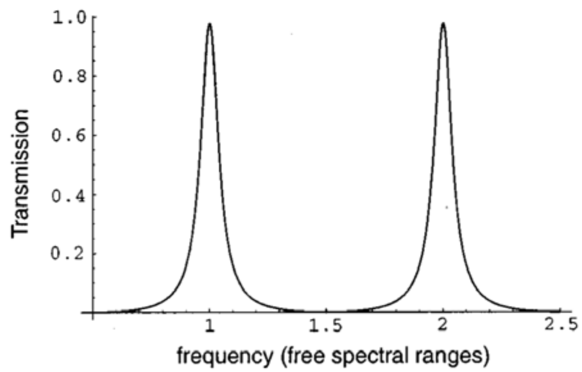
Actuator adjusts length



Generating the error signal: Pound-Drever-Hall locking technique

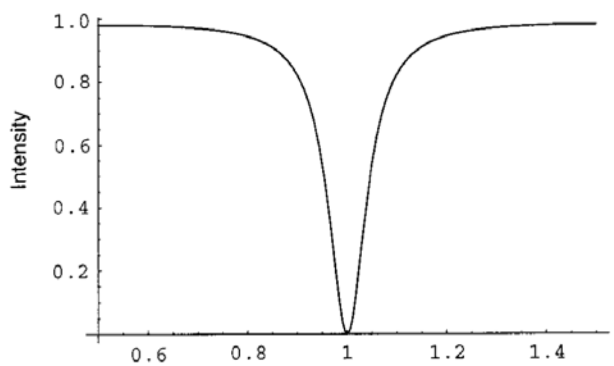
First, a comparison with alternate techniques:

- **Monitor transmitted power, lock to side of peak**



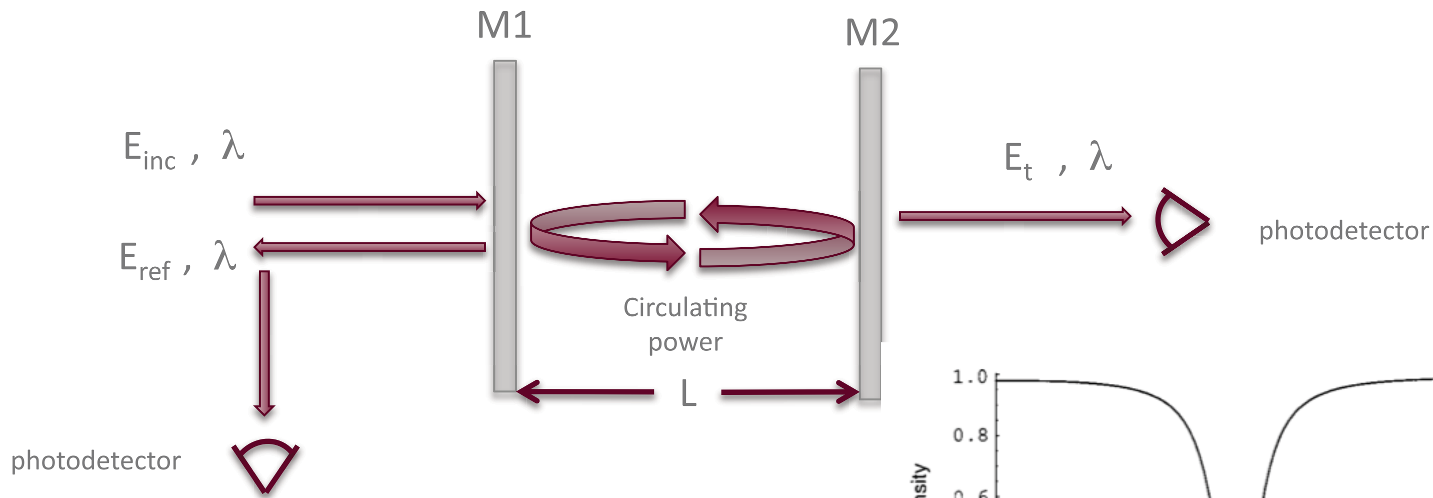
- Change in frequency corresponds to change in intensity
- But, cannot distinguish between frequency noise and amplitude noise

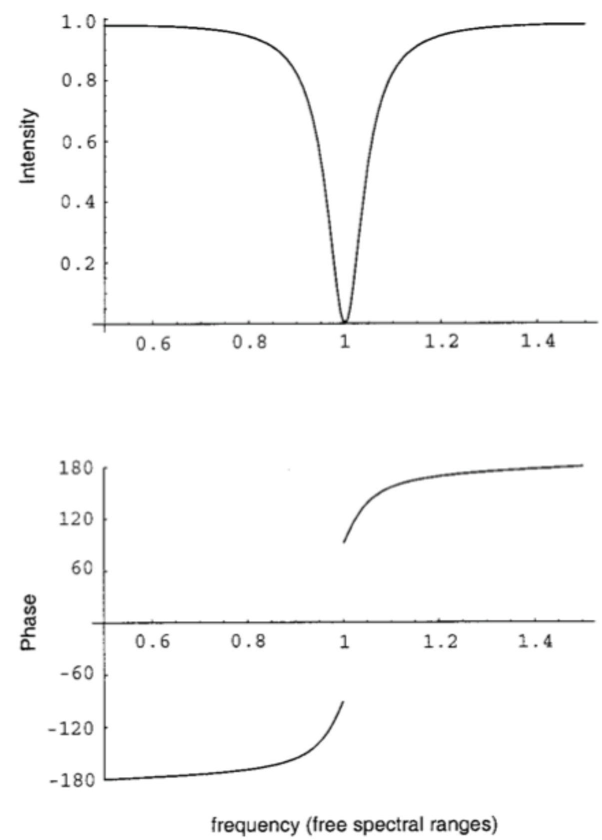
- **Monitor reflected power, lock to zero**



- Decouples amplitude and frequency noise
- But, intensity is symmetric about resonance (don't know whether to increase or decrease cavity length to bring back to resonance)

Pound Drever Hall locking basics





- Reflected light is a coherent sum of two beams: light immediately reflected and leakage from cavity

  → phase depends on cavity length, is asymmetric about resonance

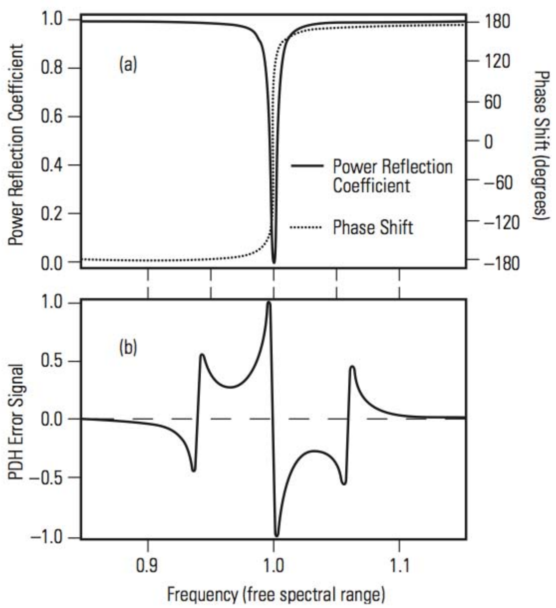
PDH:

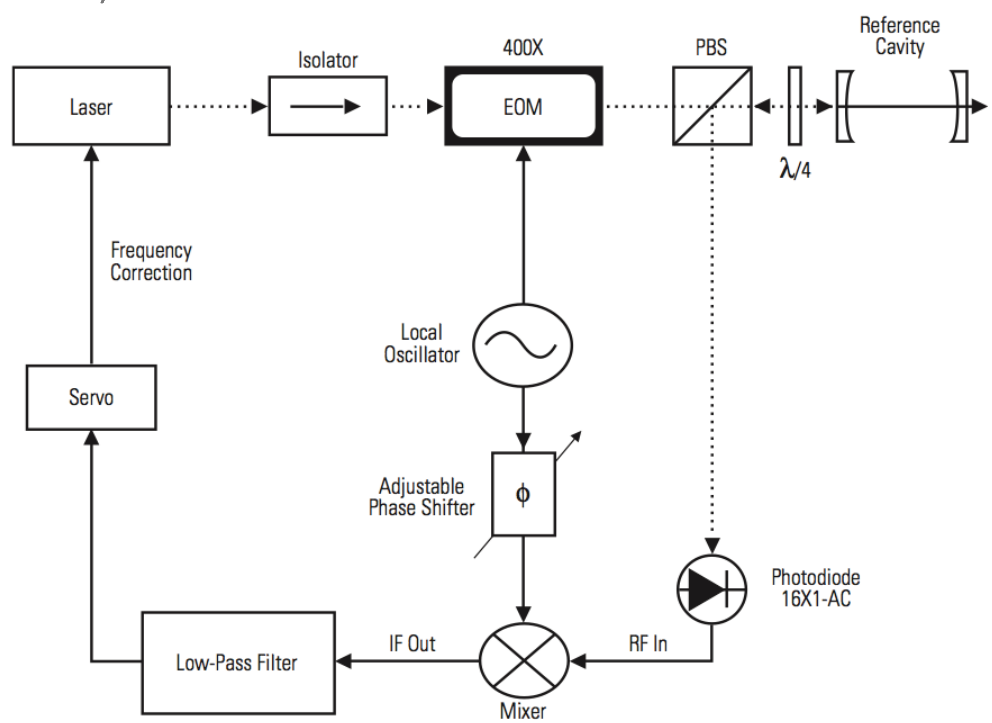
- Monitior reflected light
- Detect (indirectly) phase of reflected light

Pound Drever Hall locking

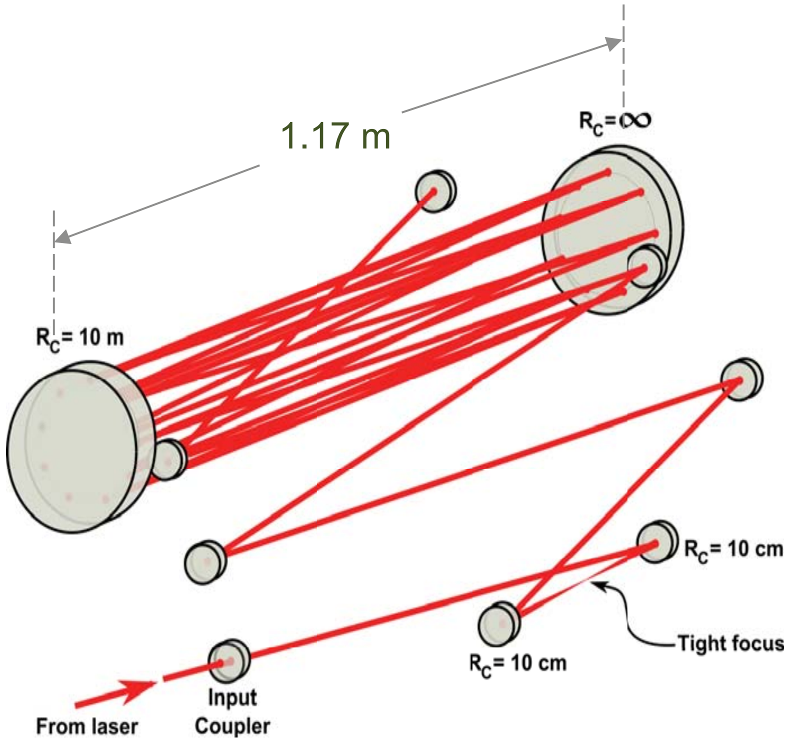
- Phase modulate laser beam, with frequency Ω, to create sidebands at (ω ± Ω)
- Choose Ω so that sidebands are outside resonance width
  - On resonance, sidebands are reflected from cavity
- Photodetector sees wave with nominal frequency ω, but with an envelope displaying a beat pattern with frequencies:
  - Ω (interference between carrier and sidebands) ← **Isolate this part**
  - 2Ω (interference between sidebands)

Error signal





Enhancement Cavity for Duetto at 6.5 MHz



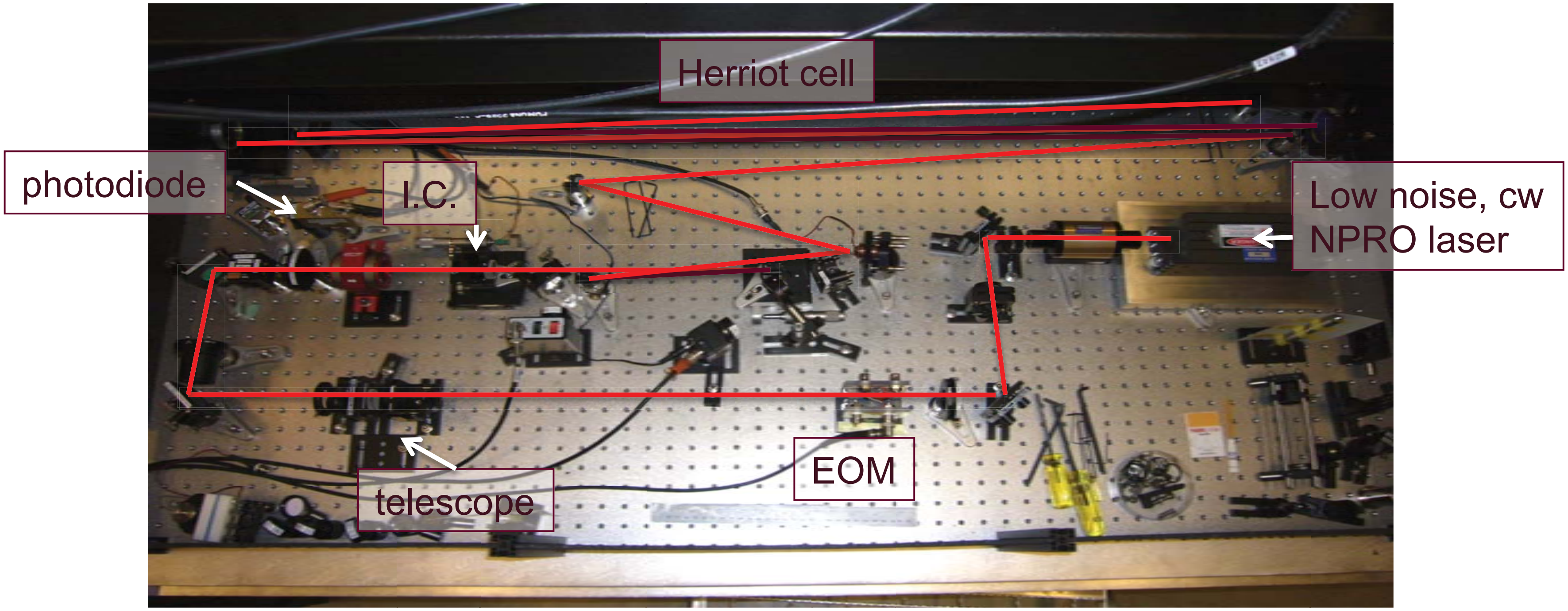
- 6.5 MHz → 46 m long cavity
  - Herriott cell geometry
- 99.99% mirror reflectivity, 46 mirror bounces
  - ~0.5% loss
- Impedance matched cavity: F = ~600
  - ~100x pulse energy enhancement
  - ~10 kHz cavity resonance width

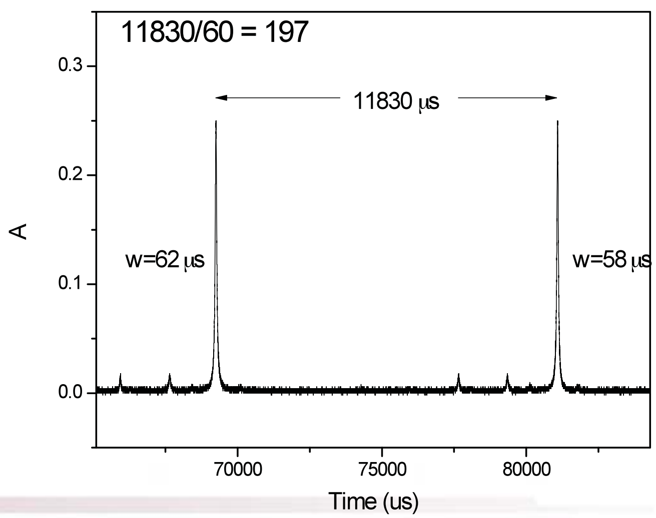
Cavity Stabilization:

- Pound-Drever-Hall technique
- Combination of tranducers:
  - Fast piezo-actuated mirror in cavity
  - Slow piezo with larger dynamic range in cavity
  - EOM in beam before cavity to compensate for fast noise

Setup in 7ID-D

Cavity Layout

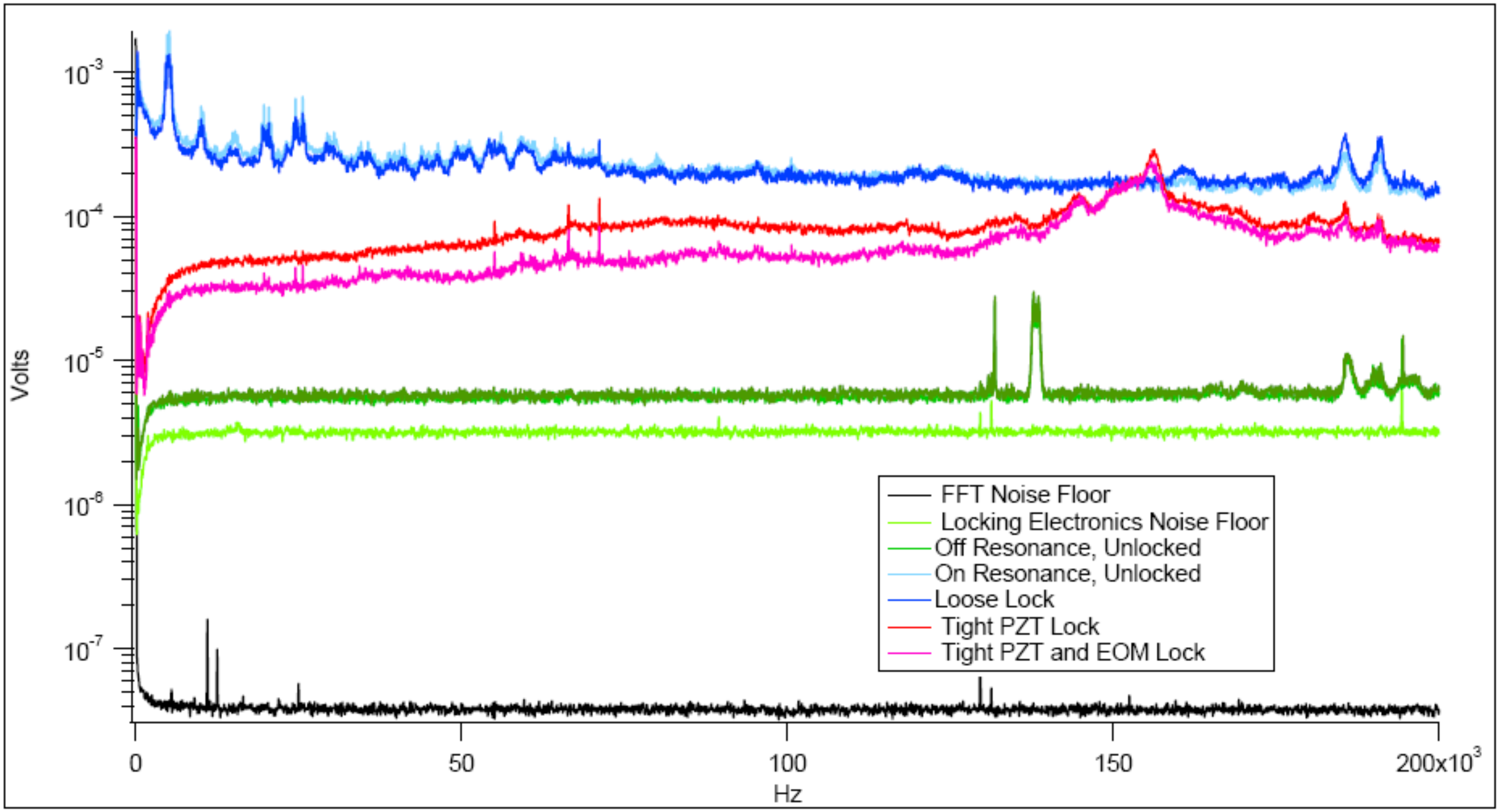




- 2.5 % input coupler in place
- Finesse ≈ 197
- 2.6 m (round trip) cavity length→FSR=115 MHz
- Cavity resonance has linewidth = 600 kHz

Analyzing Performance

- Look at Fourier components of the in-loop error signal



Summary

- High repetition rate amplified laser systems are needed for precision experiments utilizing ultrafast, strong-field laser techniques and x-ray techniques
- Passive enhancement cavities are a challenging, but promising solution
- Development is under way of an enhancement cavity to amplify 130 ps, 1064 nm laser pulses at 6.5 MHz, enabling intense-laser/x-ray pump probe experiments that utilize the full flux available at the APS