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

- Alignment
- Structural deformation
- Coulomb explosion
- X-ray emission
- Nuclear fusion

Coulombic regime
Relativistic regime

Laser field intensity (W/cm²)

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:
$\sim 10^6$ photons/pulse, 120 ps, 0.7 eV bandwidth

• 13.476 keV (Br 1s $\rightarrow$ $\sigma^*$ )

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

$\rightarrow$ need to use the full flux offered by the APS!

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: \[
\frac{\text{used x-rays}}{\text{unused x-rays}} = 0.00015
\]
High Rep-Rate Laser at 7ID-D

*Time Bandwidth DUETTO*

- $\lambda = 1064$ 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

100 cm from laser output

$1/e^2$ diameters:
- $X = 2.031$ mm
- $Y = 2.029$ mm

![Graph showing power and energy per pulse versus repetition rate](image-url)
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:**
- 76 MHz, 130x amplification, 13 W

**Intracavity High Harmonic Generation**
- Femtosecond enhancement cavity
- 100 MHz, 600x amplification, $I \sim 10^{14}$ W/cm$^2$
- HHG from intracavity gas jet
Fabry-Perot resonator basics

Resonance condition: \( n \lambda = 2L \)

Free spectral range: \( \Delta v_{\text{fsr}} = \frac{c}{2L} \)

Intracavity pulse amplification factor:
\[
N = \frac{4T}{(\text{losses})^2} = 4T \left( \frac{F}{2\pi} \right)^2 = \frac{F}{\pi} \quad \text{(impedance Matched)}
\]
How does this work for pulsed lasers?

- Match cavity modes to frequency comb

Rep. Rate = \frac{c}{2L} \quad (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
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:**
- Monitor reflected light
- Detect (indirectly) phase of reflected light
Pound Drever Hall locking

- Phase modulate laser beam, with frequency $\Omega$, to create sidebands at $(\omega \pm \Omega)$
- Choose $\Omega$ so that sidebands are outside resonance width
  - On resonance, sidebands are reflected from cavity
- Photodetector sees wave with nominal frequency $\omega$, but with an envelope displaying a beat pattern with frequencies:
  - $\Omega$ (interference between carrier and sidebands)
  - $2\Omega$ (interference between sidebands)
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 transducers:
  - 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