# Optics Capabilities for SNS Laser-Assisted H- Beam Stripping

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# Outline

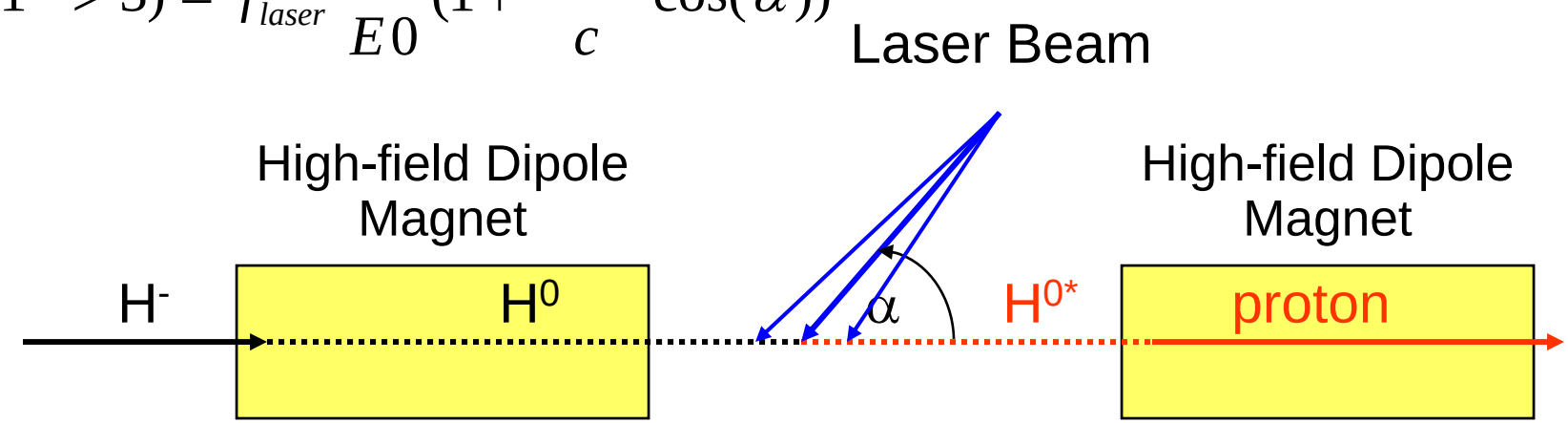
- Laser optics for proof-of-principle H- stripping experiment (W. Grice, Y. Braiman, Y. Liu )
- Macro-pulse laser system (Continuum, W. Grice, L. Wax, Y. Liu)
- Beam recycling optical resonator development (Z. Zhao, Y. Liu)

# Three-Step Stripping Scheme

Main problem –beam energy spread

$$f(1->3) = f_{laser}\frac{E}{E0}(1+\frac{v_{beam}}{c}\cos(\alpha))$$

- Our team developed a novel approach for laser-stripping which uses a three-step method employing a narrowband laser




Step 1: Lorentz Stripping

$H^- \rightarrow H^0 + e^-$

Step 2: Laser Excitation

$H^0\ (n=1) + \gamma \rightarrow H^{0*}\ (n=3)$

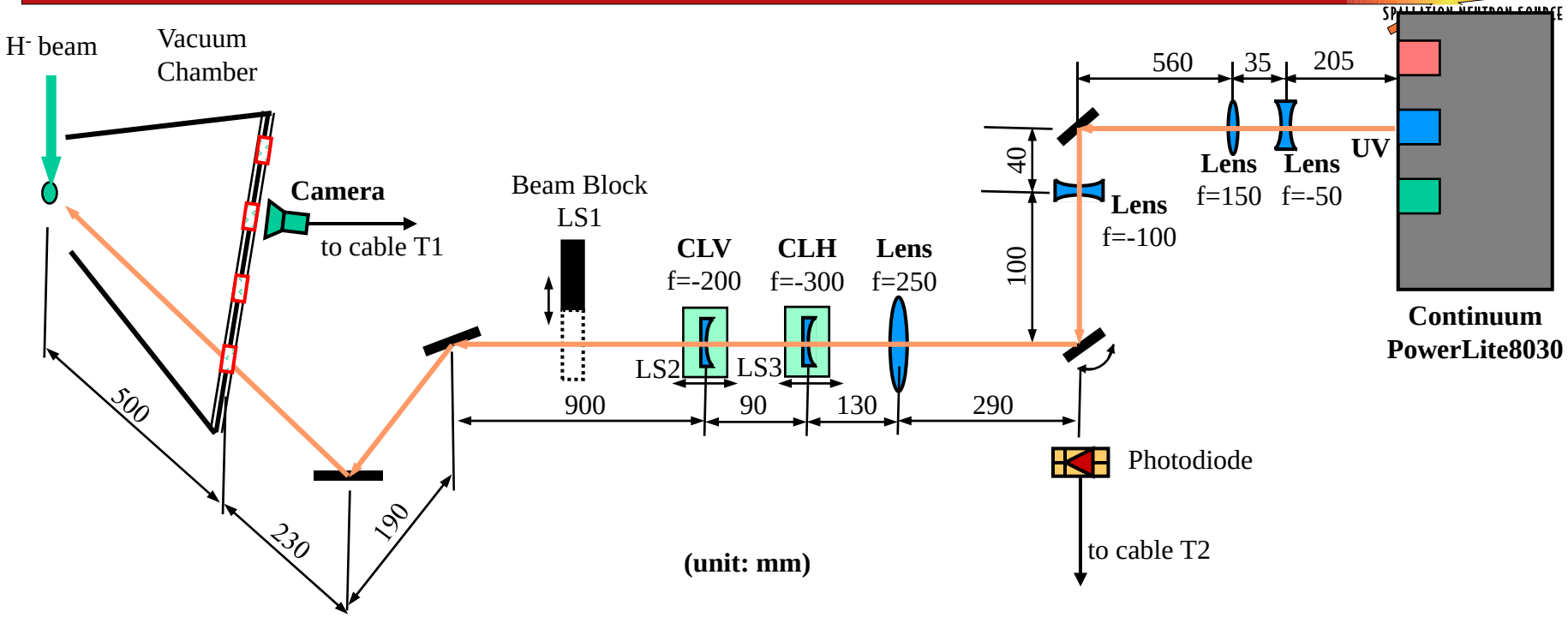
Step 3: Lorentz Stripping

$H^{0*} \rightarrow p + e^-$

# Four Sets of Experiments Description

- 1st experimental run (December 2005)-no stripping seen. We wish we could get the answer to this puzzle
- 2nd experimental run preparation – laser moved to the table. It tripled the laser beam power
- Laser beam incident angle and beam parameters (energy of the ions) were more carefully measured
- Second run (March 2006) led to a first success (about 50% of stripping)
- Third run (August 2006) –successful (around 85% of stripping achieved)
- Fourth (final) run (October 2006) – 90% stripping achieved, additional effects studied

# First-Stage Experiment Laser Optics Diagram




**Targeted beam parameters:**

$w_h = 2.5$ mm, $\theta_h = -3$ mrad, $w_v = 1$ mm, $\theta_v = -2.5$ mrad.

Linear stage #1: beam block (insert position)

Cables: #1918 (flash lamp trigger in), #1919 (Q-switch trigger in), #T1 (camera), #T2 (photodiode)

Vertical cylindrical lens (CLV) position (linear stage #2)

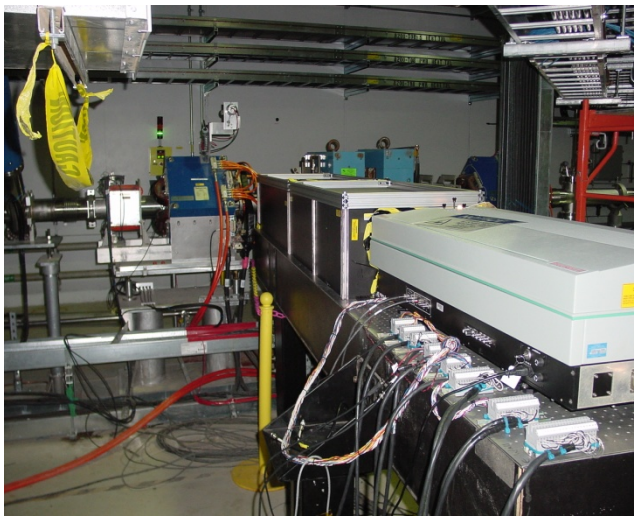
$$\frac{dw_v}{dz} = -0.31, \quad \frac{d\theta_v}{dz} = -0.15 \frac{\text{mrad}}{\text{mm}}$$

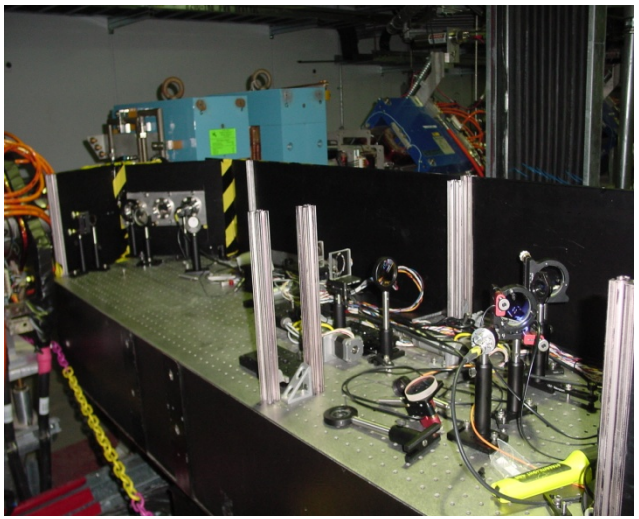
Horizontal cylindrical lens (CLH) position (linear stage #3)

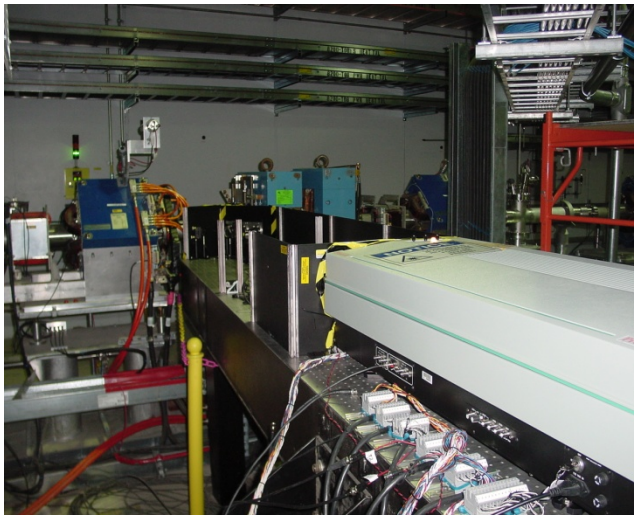
$$\frac{dw_h}{dz} = -0.225, \quad \frac{d\theta_h}{dz} = -0.1 \frac{\text{mrad}}{\text{mm}}$$

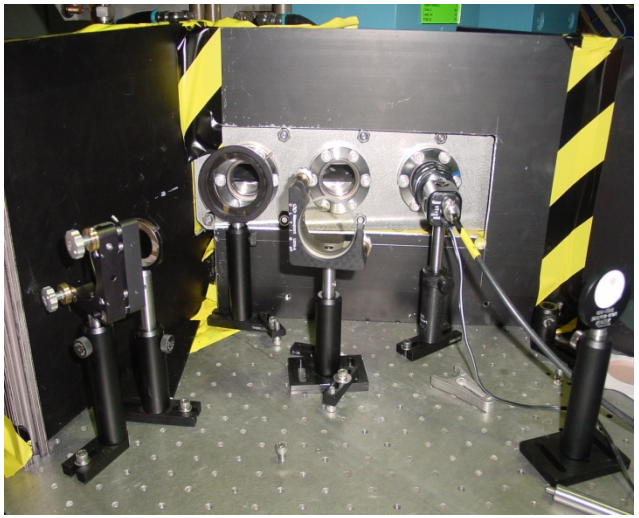
$dz$>0: moving toward vacuum direction

# Optics Setup



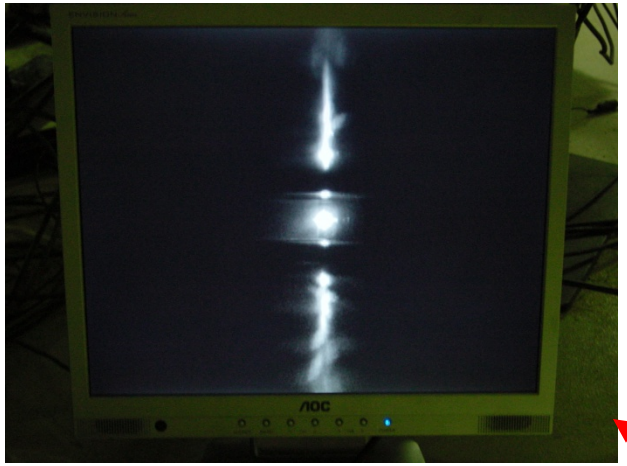




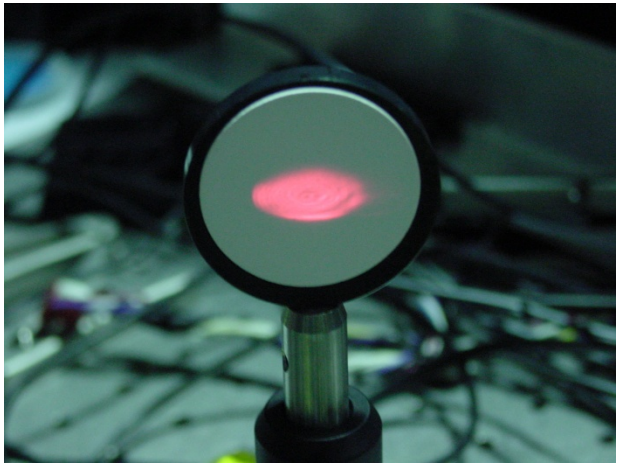


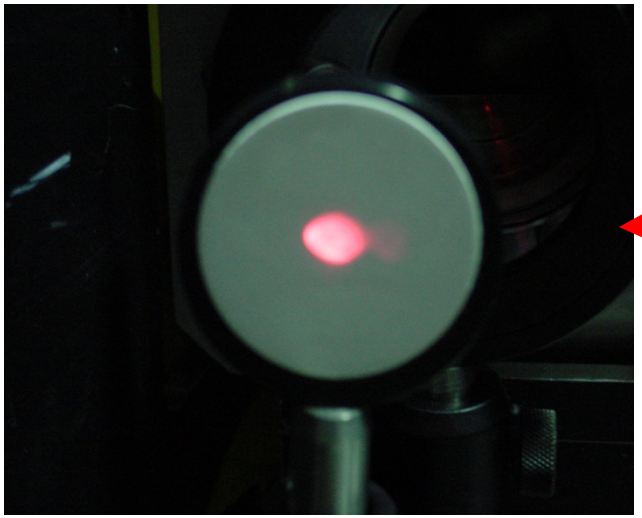
# Laser Beam Profiles

Inside vacuum chamber

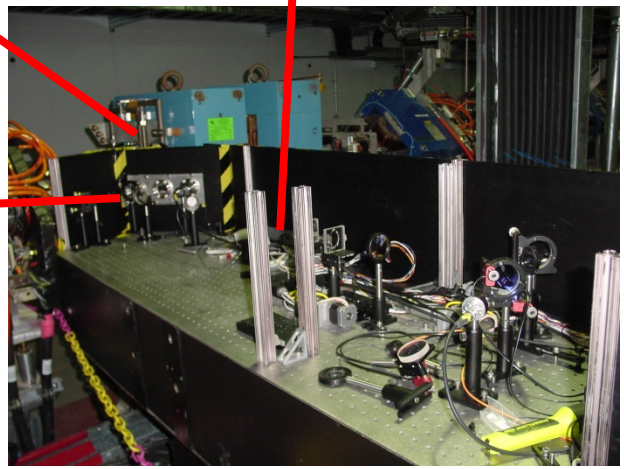


After telescope (screen size: ϕ40 mm)

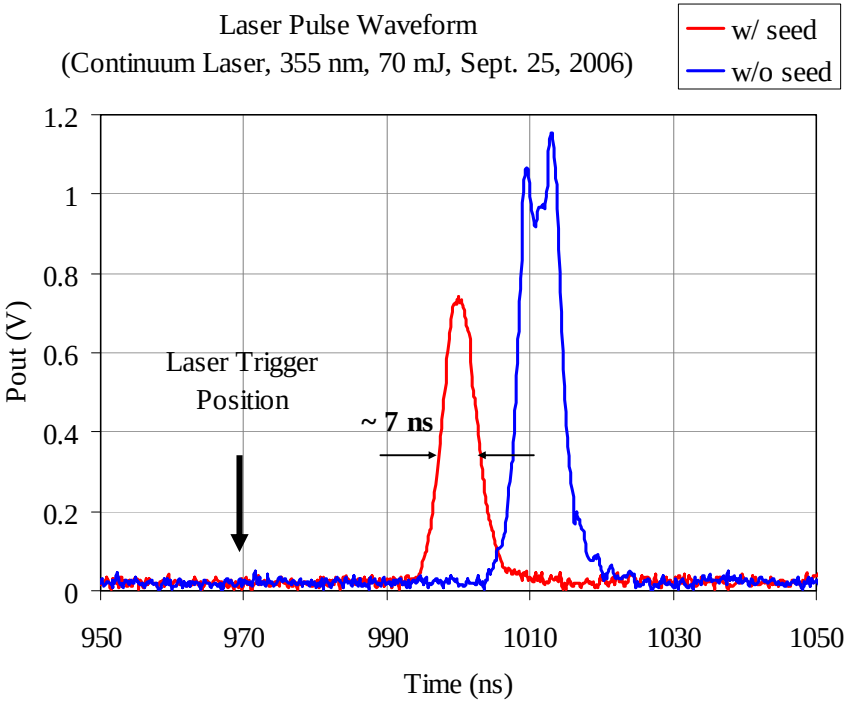


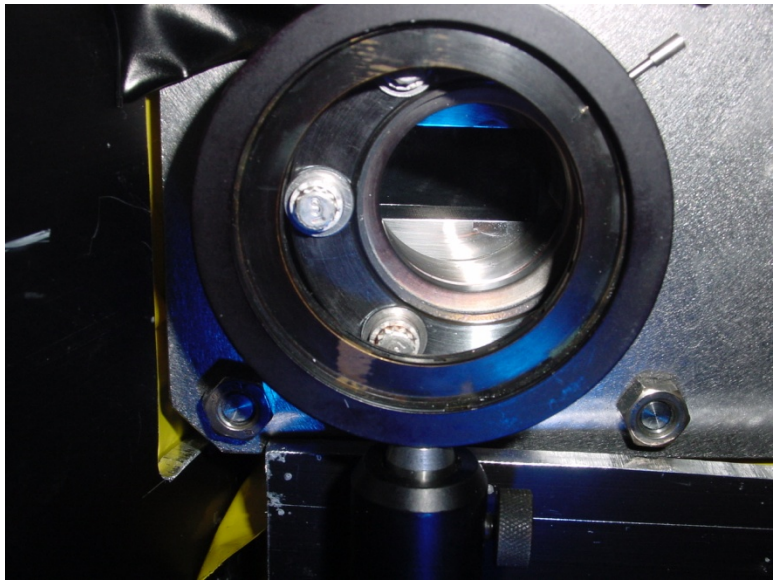


Before vacuum window



# Laser Beam Parameters



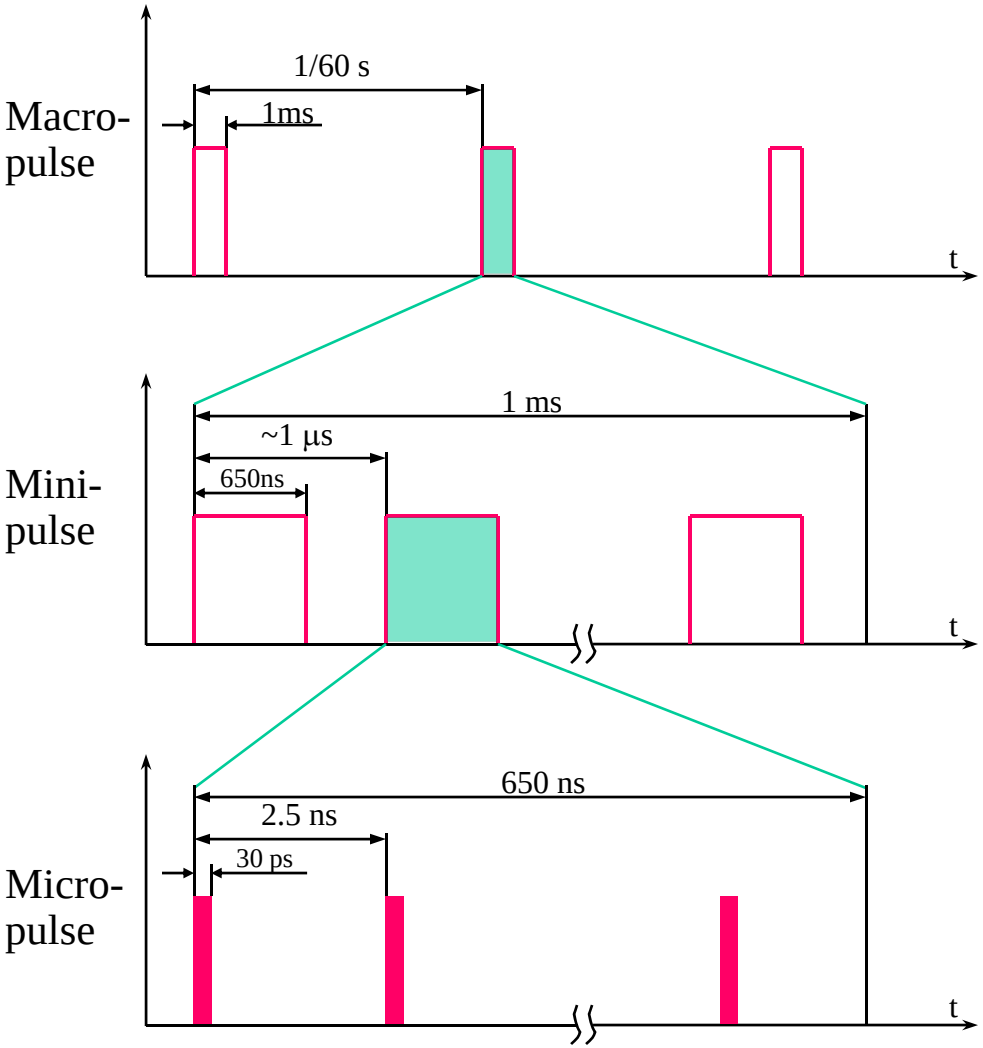
Changes of pulse shape and position indicate seed laser is working well!

No laser damage on vacuum windows!

$$2w_{//} = 8.2 \text{ mm}, \; 2\theta_{//} = -7.5 \text{ mrad}$$

$$2w_{\perp} = 7.0 \text{ mm}, \; 2\theta_{\perp} = -3.7 \text{ mrad}$$

# Challenge of Laser Power Requirement for Full-Cycle SNS H- Stripping



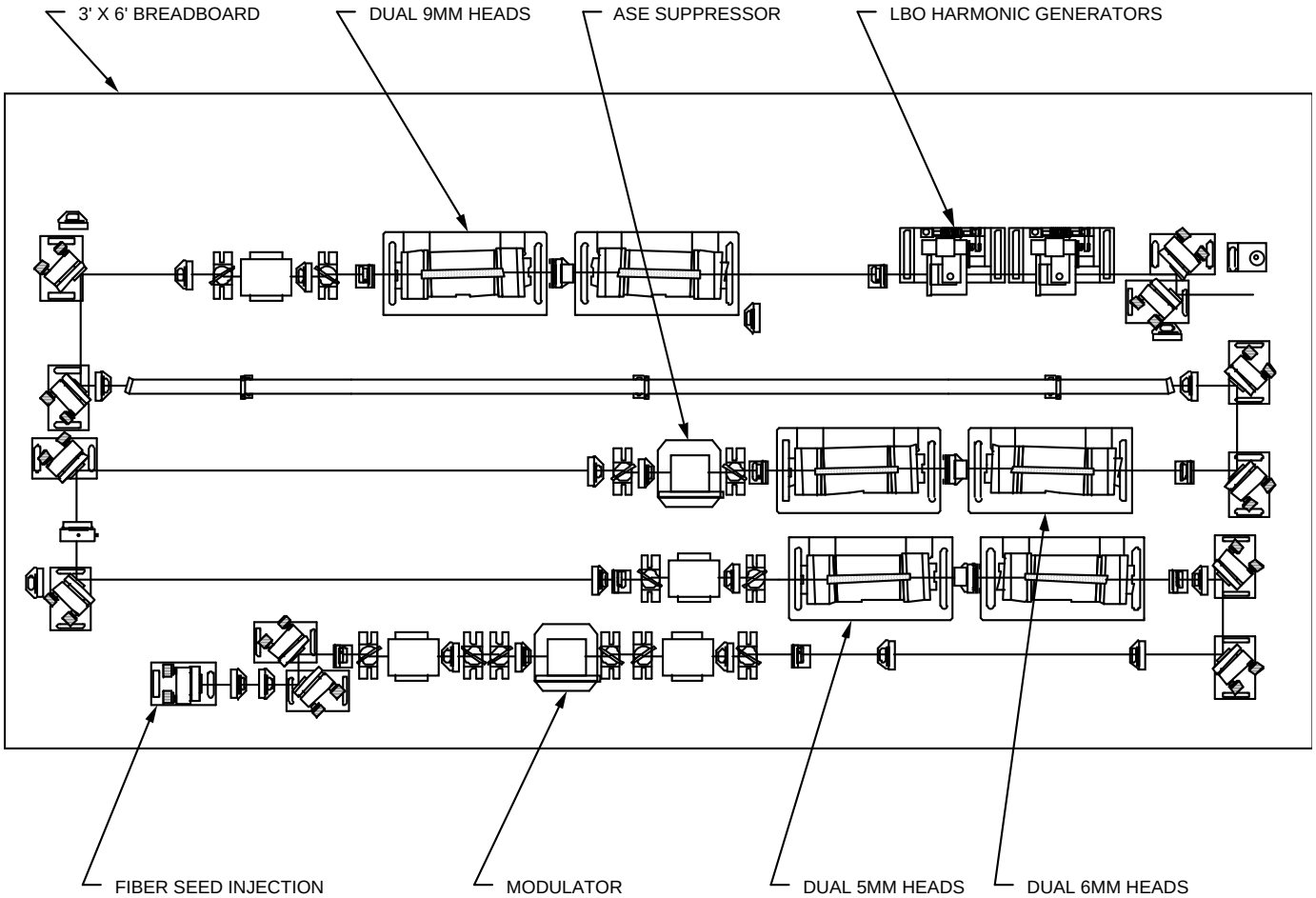

To cover 400 MHz, 30 ps H- pulses with a 1 MW peak power mode-locked laser beam, the required average laser power is 12 kW at the UV wavelength regime.

**We need to bring down the requirement by at least 3 orders of magnitude!**

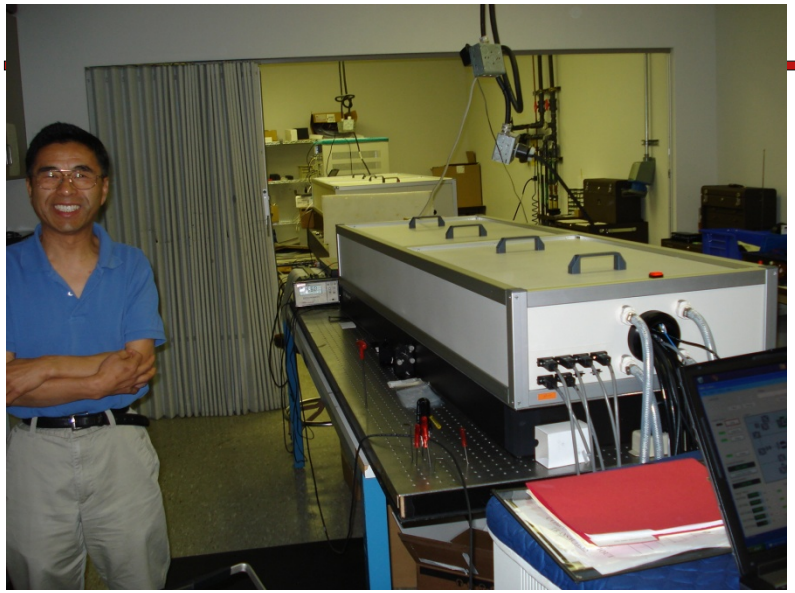
# Macropulse Laser System (Ideal)

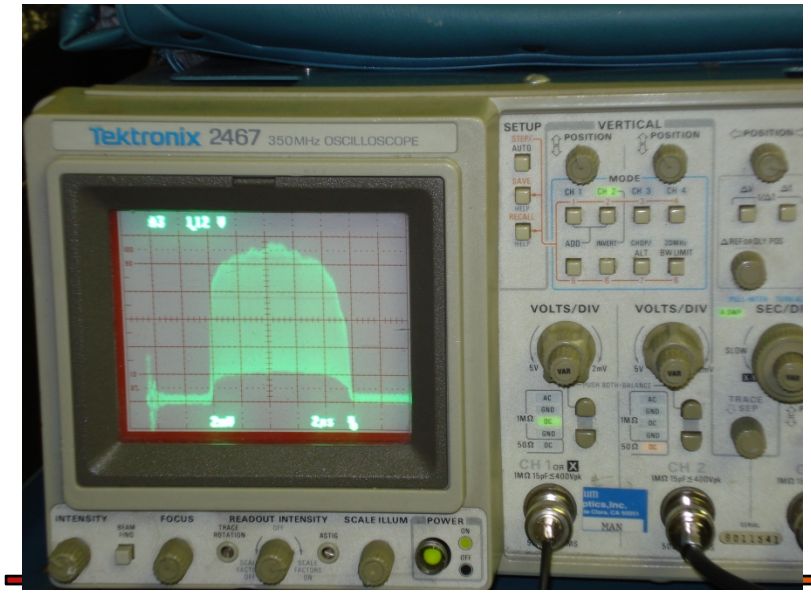
- 402.500 MHz mode-locked seed laser with micro-pulse width ~ 30 ps
- Amplification of seeder light within 1 ms (macro-pulse) at a repetition rate of 60 Hz
- Harmonic generation with 355 nm output
- Each micro-pulse has ~ 30 μJ pulse energy
- Average power:
  - 30(μJ)×402.5(MHz) × 1(ms) × 60(Hz) = 0.72 KW @ UV
  - 5-10 KW @ IR

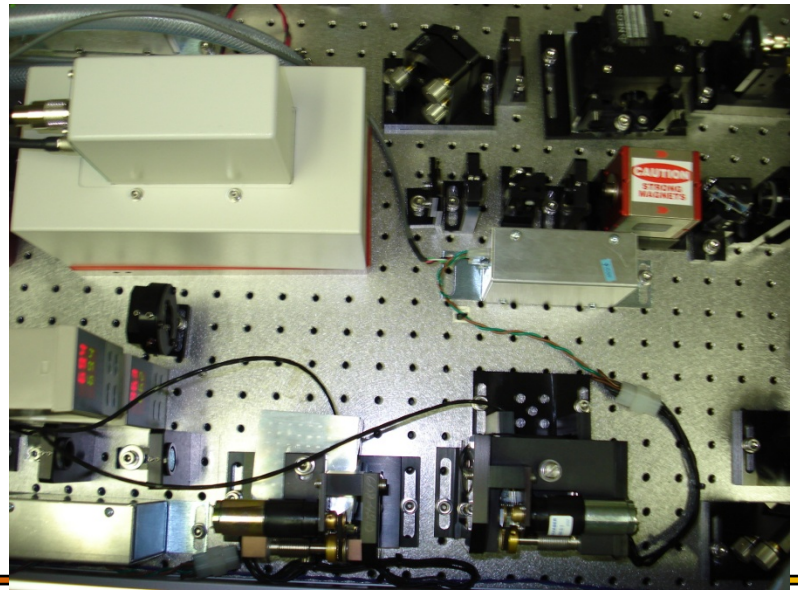
# Continuum Macropulse Laser Layout



# Customized Macropulse Laser



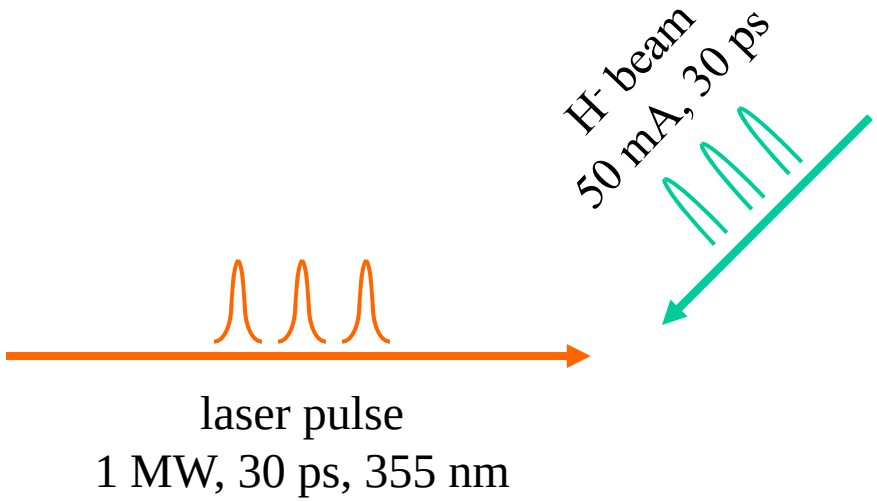


# Macropulse Laser System (Actual)

- 402.500 MHz mode-locked seed laser with micro-pulse width ~ 60 ps
- Amplification of seeder light within 10 μs (macro-pulse) at a repetition rate of 10 Hz
- Harmonic generation with 355 nm output
- Each micro-pulse has ~ 40 μJ pulse energy
- Average power:
  - 40(uJ)×402.5(MHz) × 10(μs) × 10(Hz) = 1.6 W @ UV
  - 18 W @ IR
  - 50W@IR immediately upgradable
  - 500W@IR approachable

# Negligible Photon Loss in Laser-Ion Beam Interaction



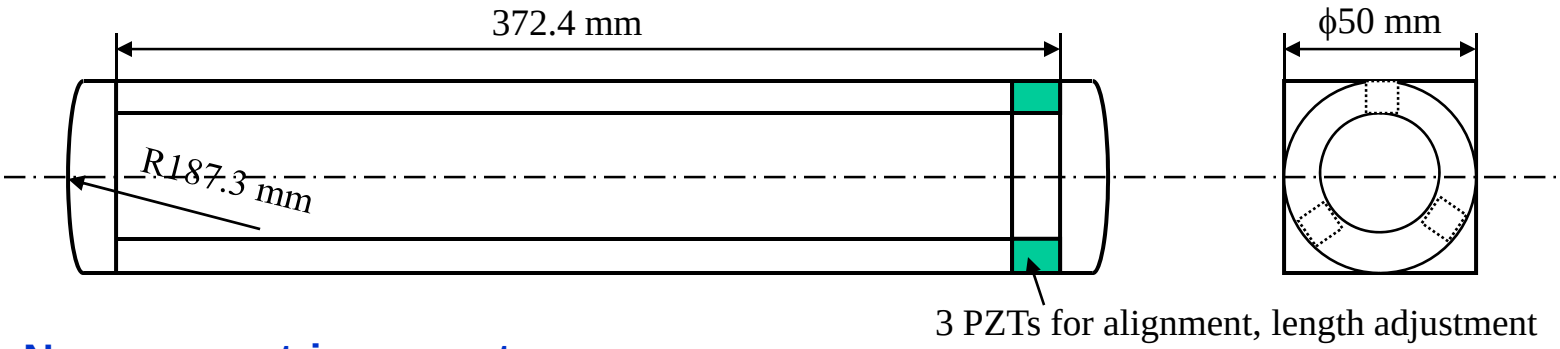

Number of electrons in single pulse: $9.4\times10^{6}$

Number of photons in single pulse: $5.4\times10^{13}$

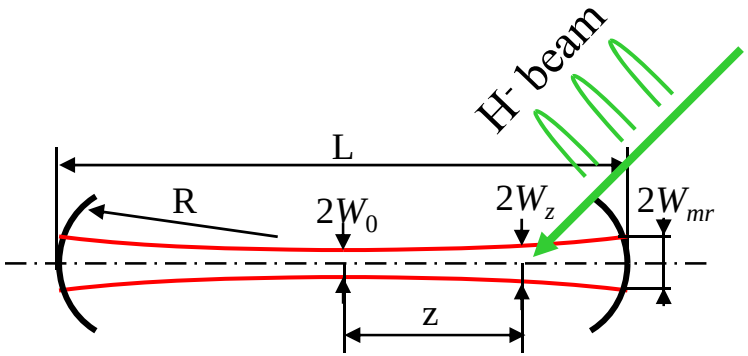
**Less than 2 photons out of 10 millions are needed even in a 100% stripping!**

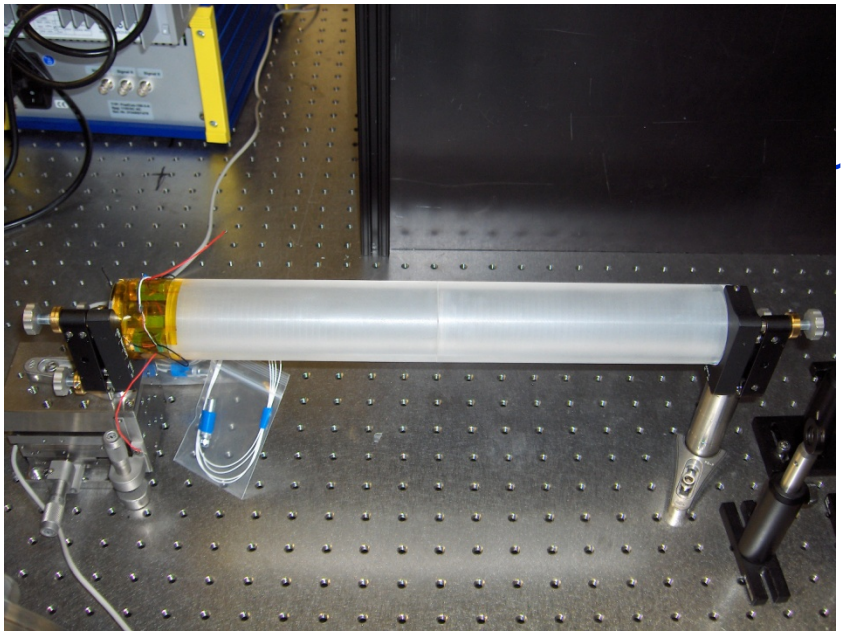
**It is natural to recycle photons with some sort of resonator.**

# Beam Recycling Resonator I (FP Cavity)

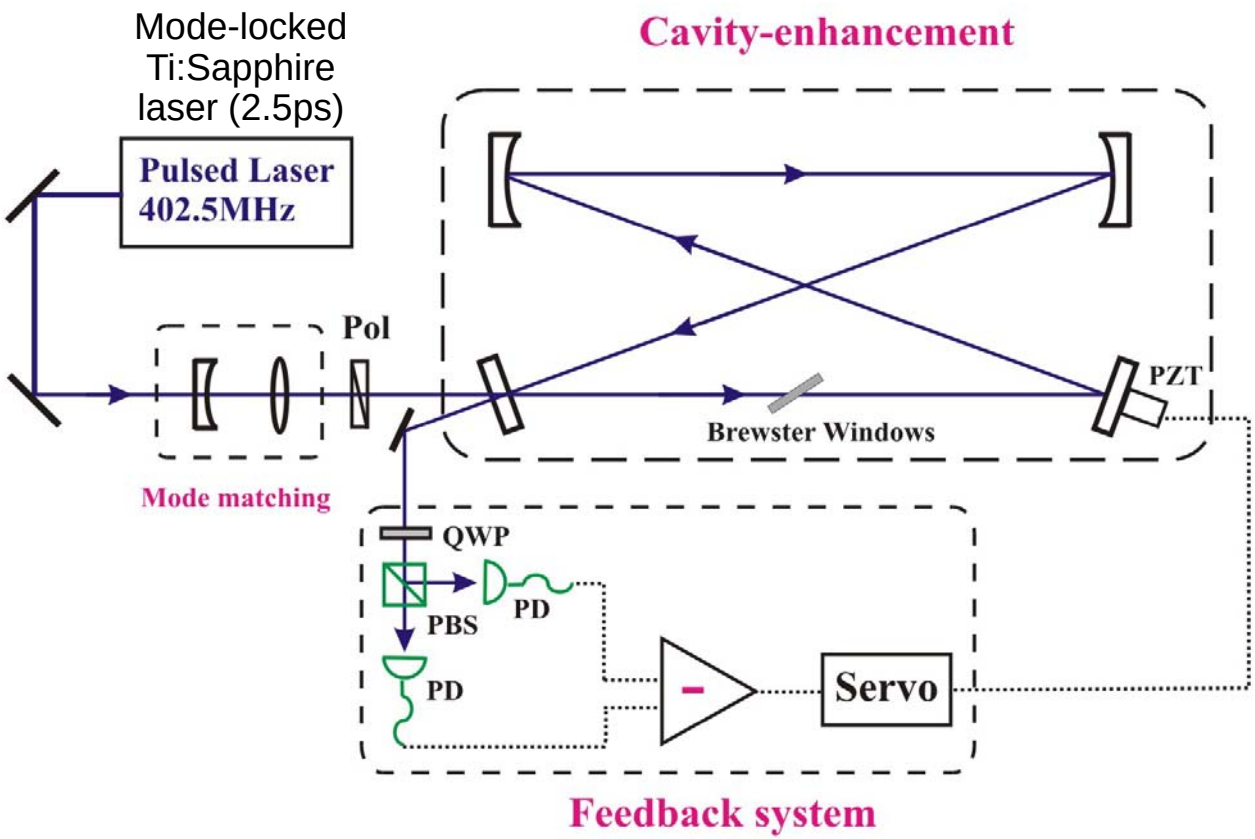



- **Near concentric resonator**
- **Spacer and mirror material: fused silica**
- **402.5 MHz FSR in vacuum**
- **Mirror coating of nominally *r* > 92% at 355 nm**

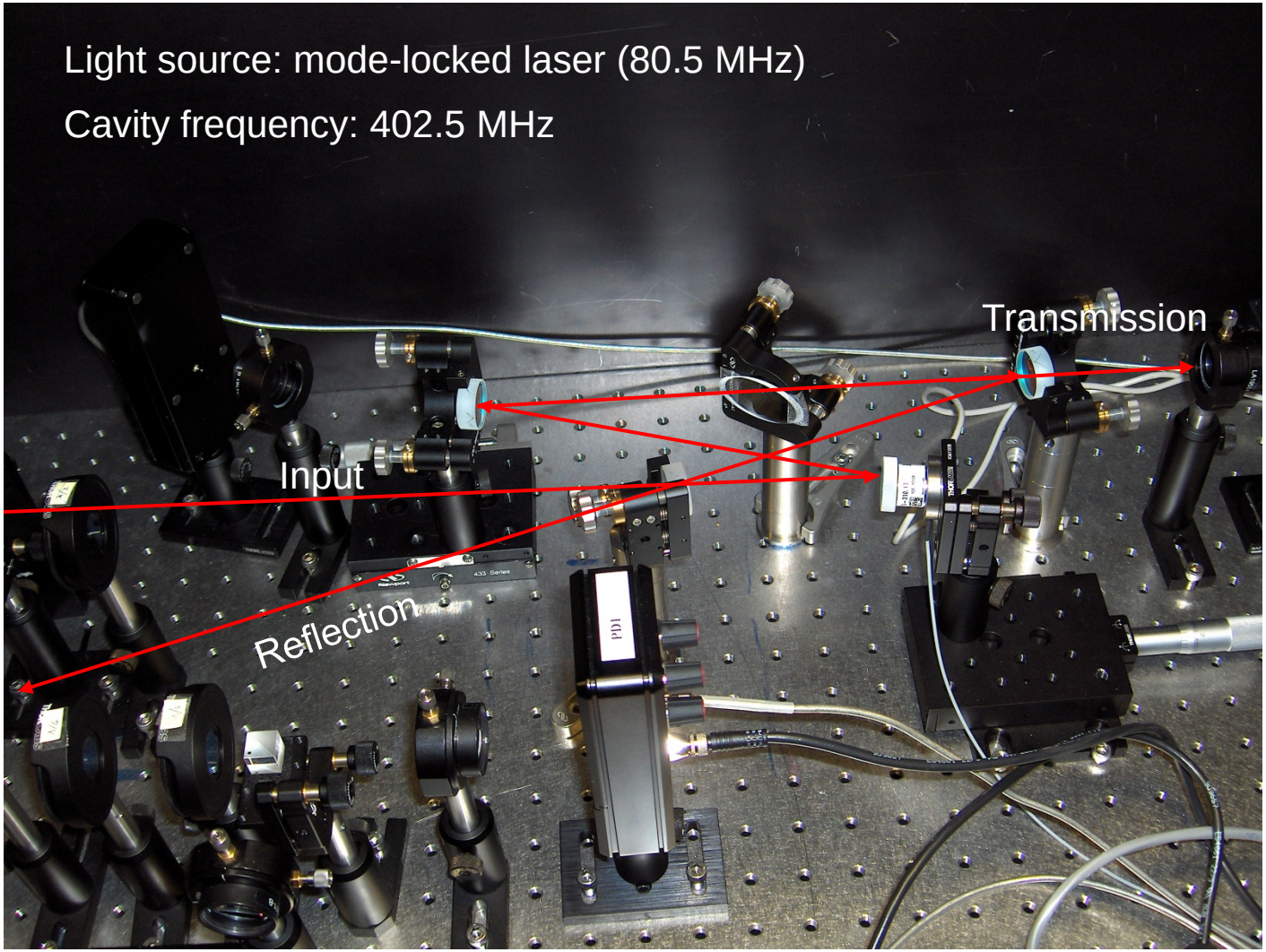


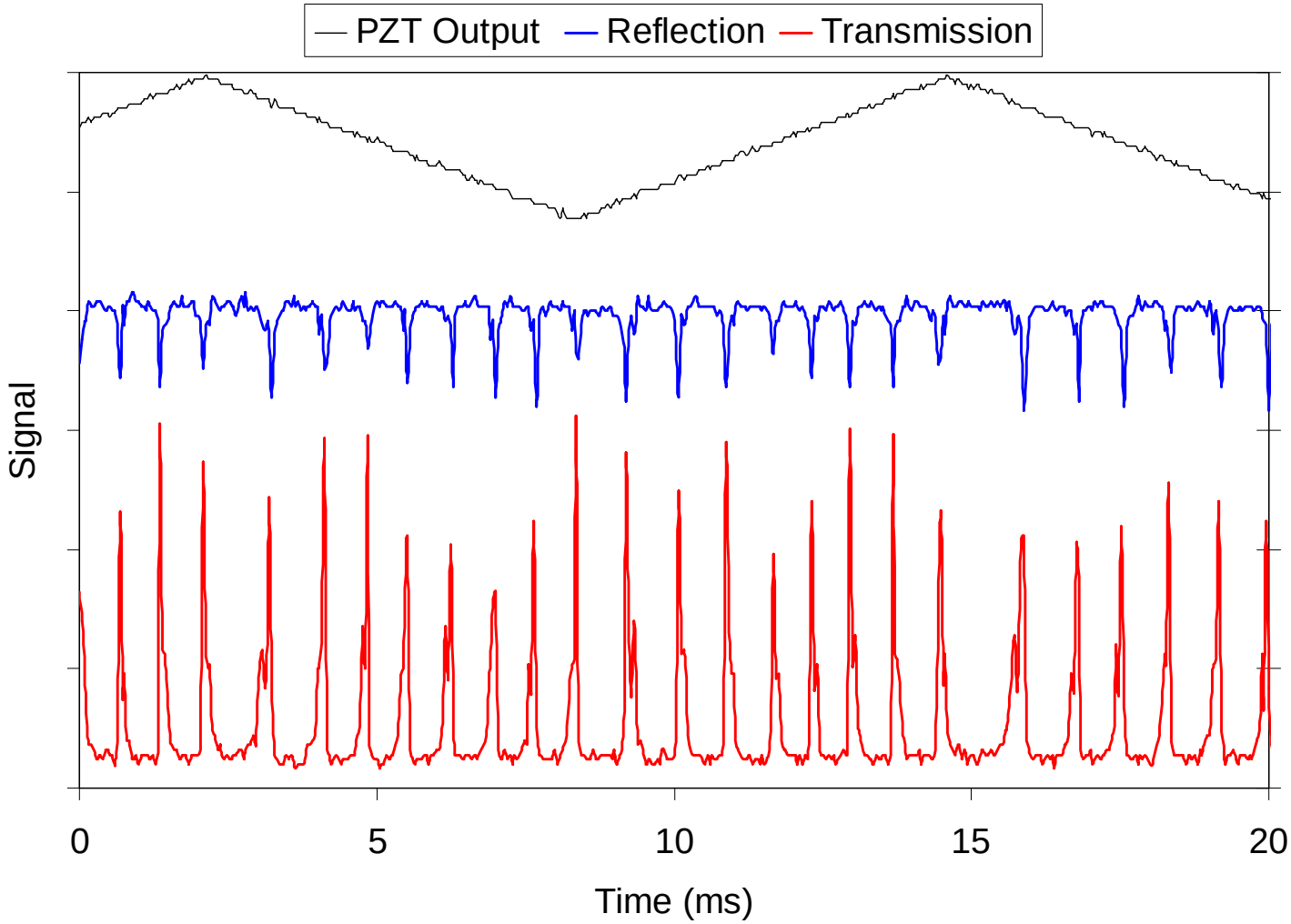
# Beam Recycling Resonator II (Ring Cavity)



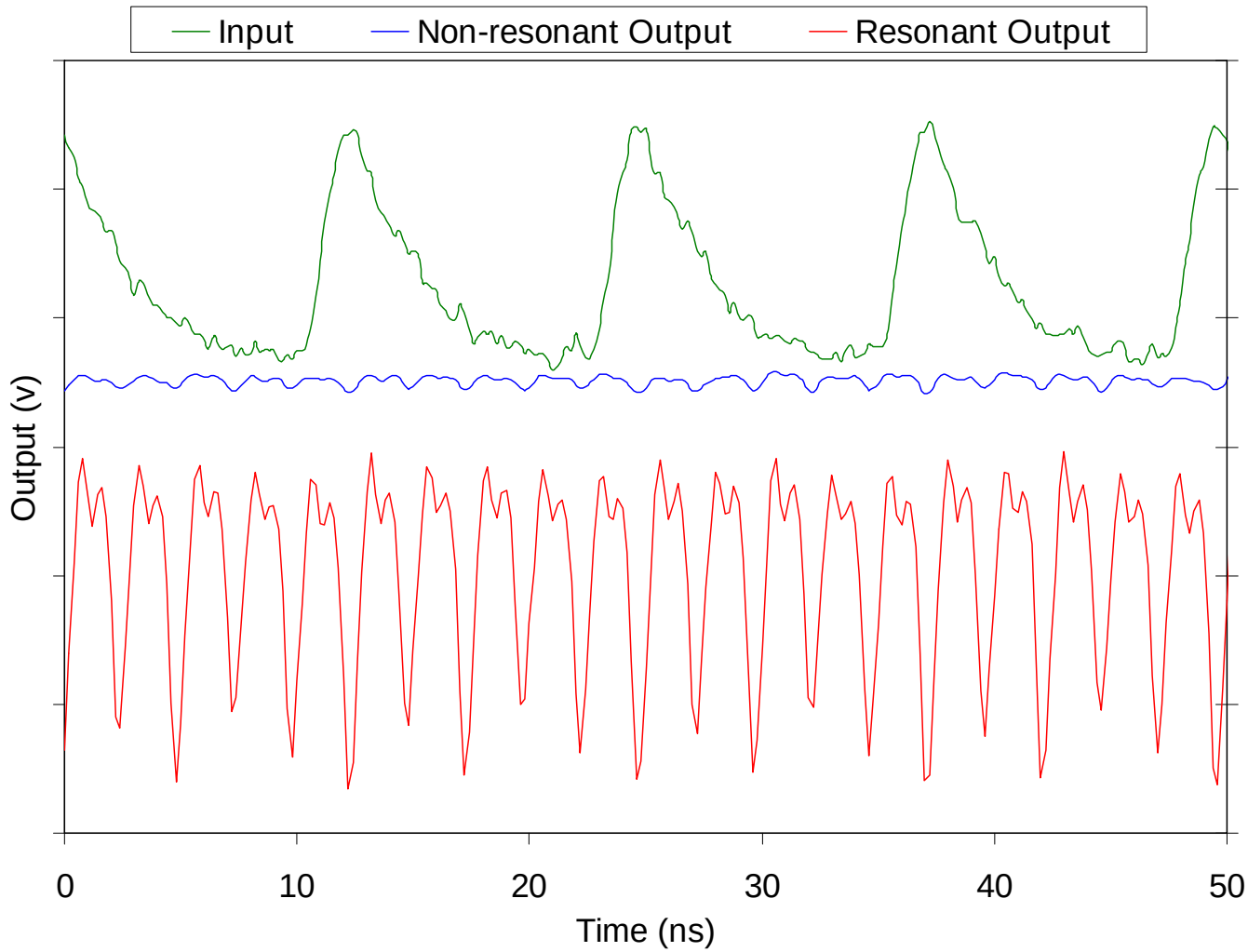
# Optical Setup of Ring Cavity



# Transmitted Light from Resonator

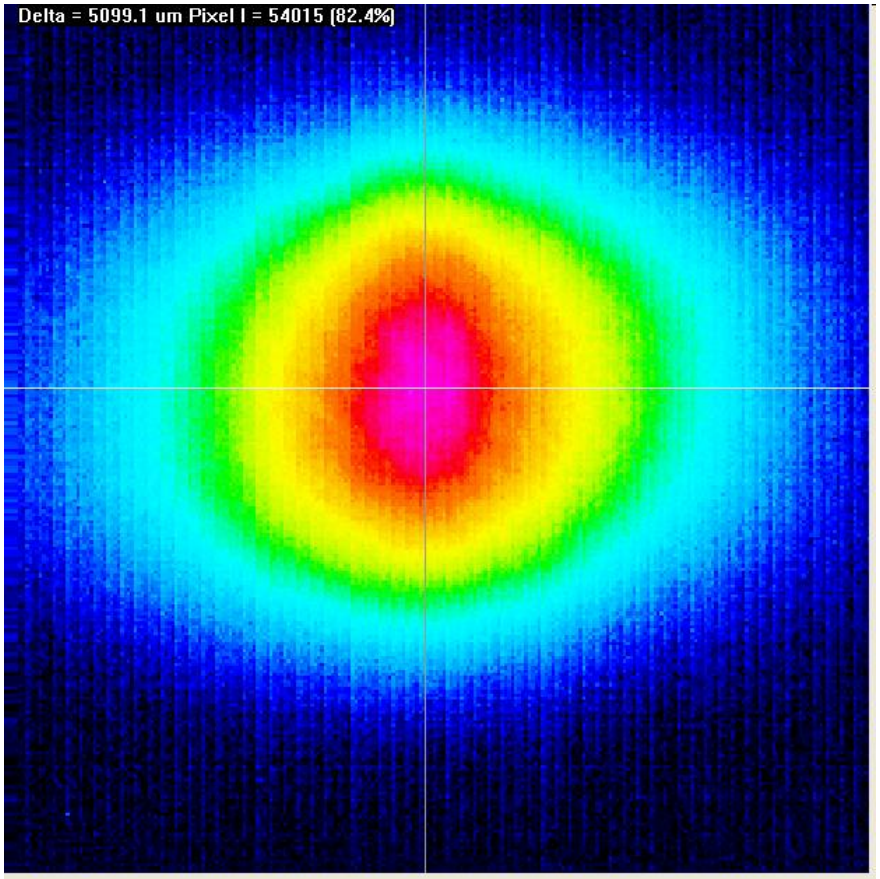


# Transmitted Light from Resonator

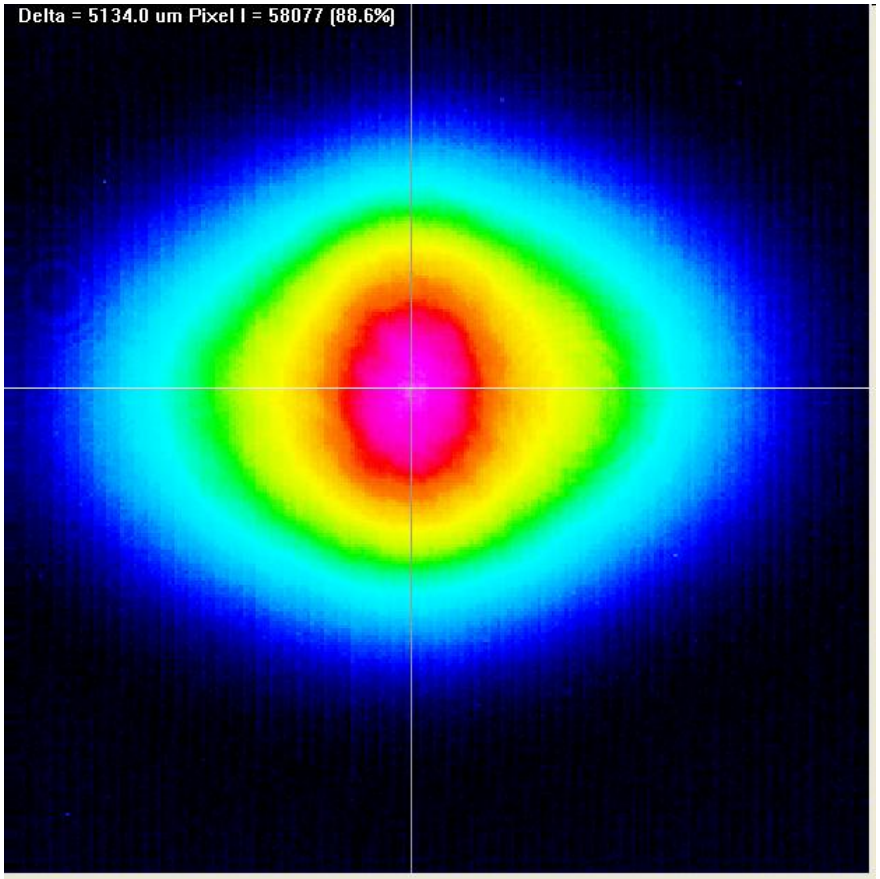


# Spatial Mode inside Cavity

Non-Resonant




Resonant



# Hansch-Couillaud Resonator Stabilization

- **Input field**

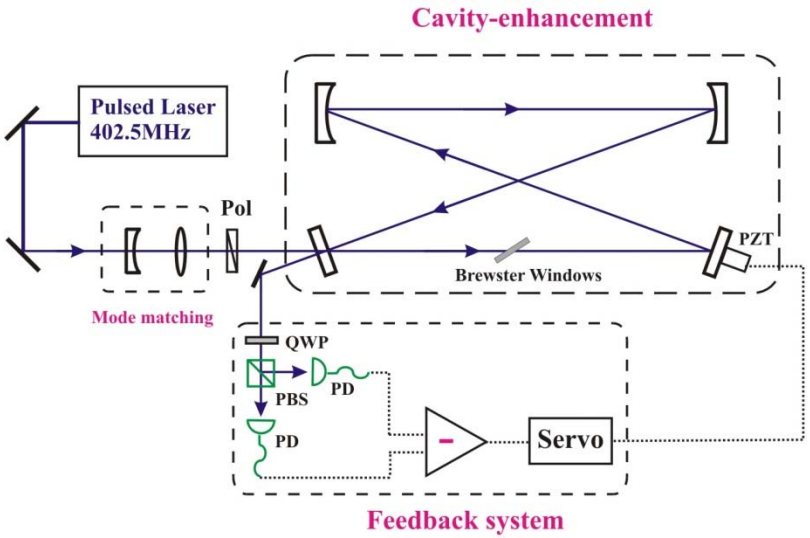
$$A_{//} = A_i \cos\theta,\ A_\perp = A_i \sin\theta$$

- **Reflected components**

$$A_{//}^{(r)} = A_{//}(r_1 - t_1^2 r_2 e^{i\delta} - t_1^2 r_2 r e^{i2\delta} - t_1^2 r_2 r^2 e^{i3\delta} - \cdots)$$

$$= A_{//}\left(r_1 - t_1^2 r_2 \cdot \frac{e^{i\delta}}{1 - re^{i\delta}}\right)$$

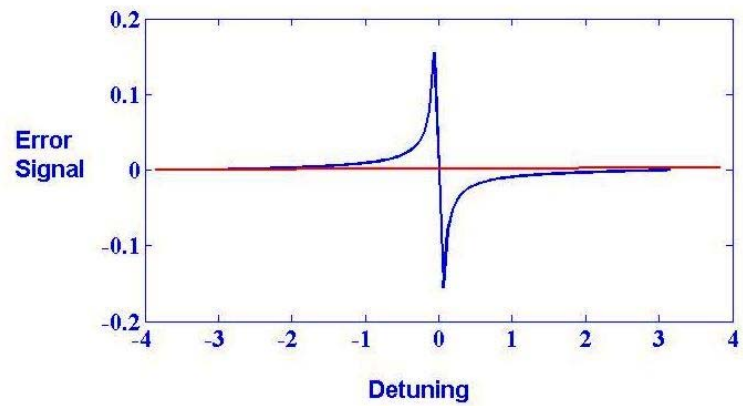
$$A_\perp^{(r)} = r_1 A_\perp = r_1 A_i \cos\theta$$



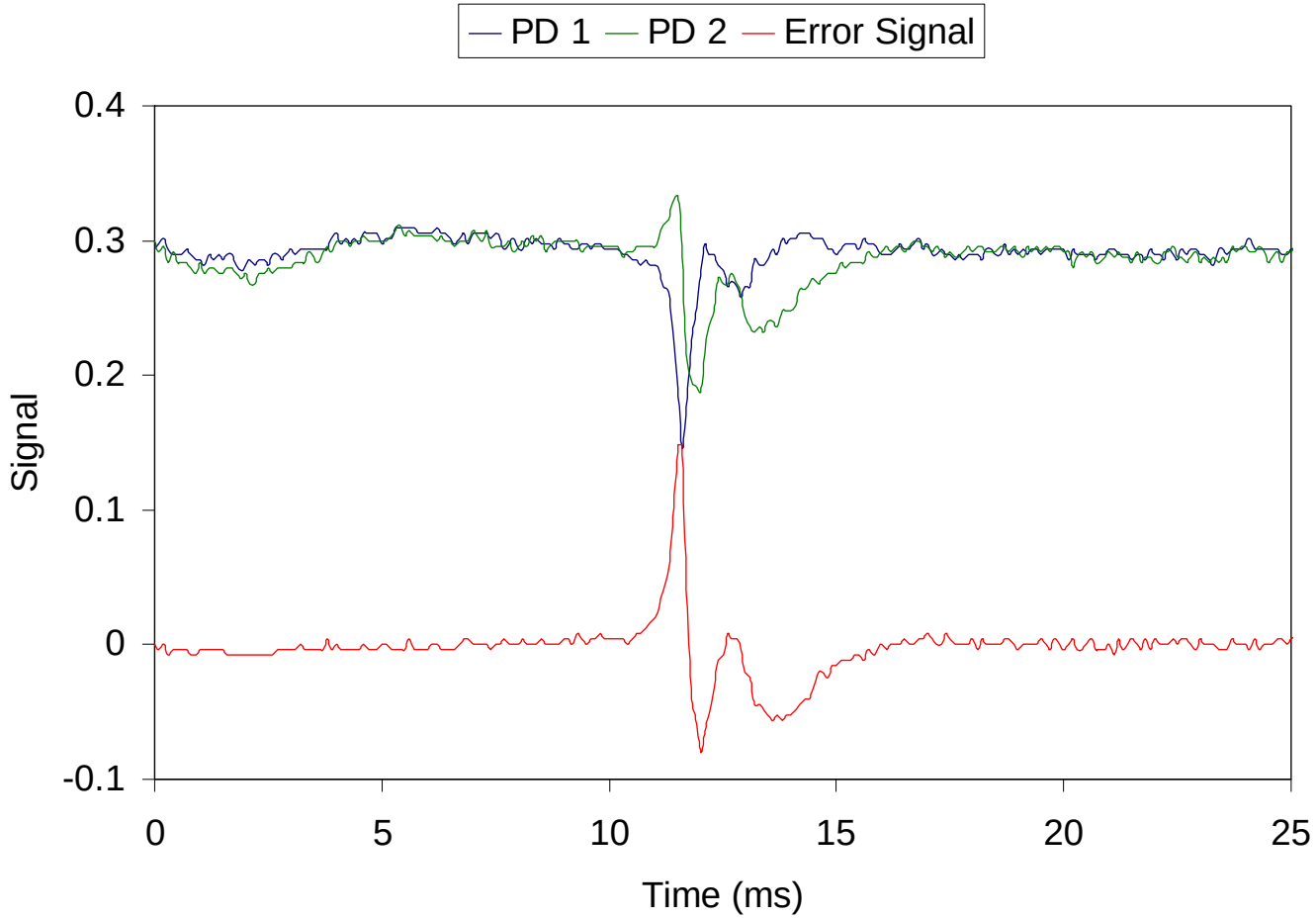

- **Error signal**

$$I_{a,b} = \frac{1}{2} c\varepsilon \cdot \frac{\left|A_{//}^{(r)} \pm iA_\perp^{(r)}\right|^2}{2}$$

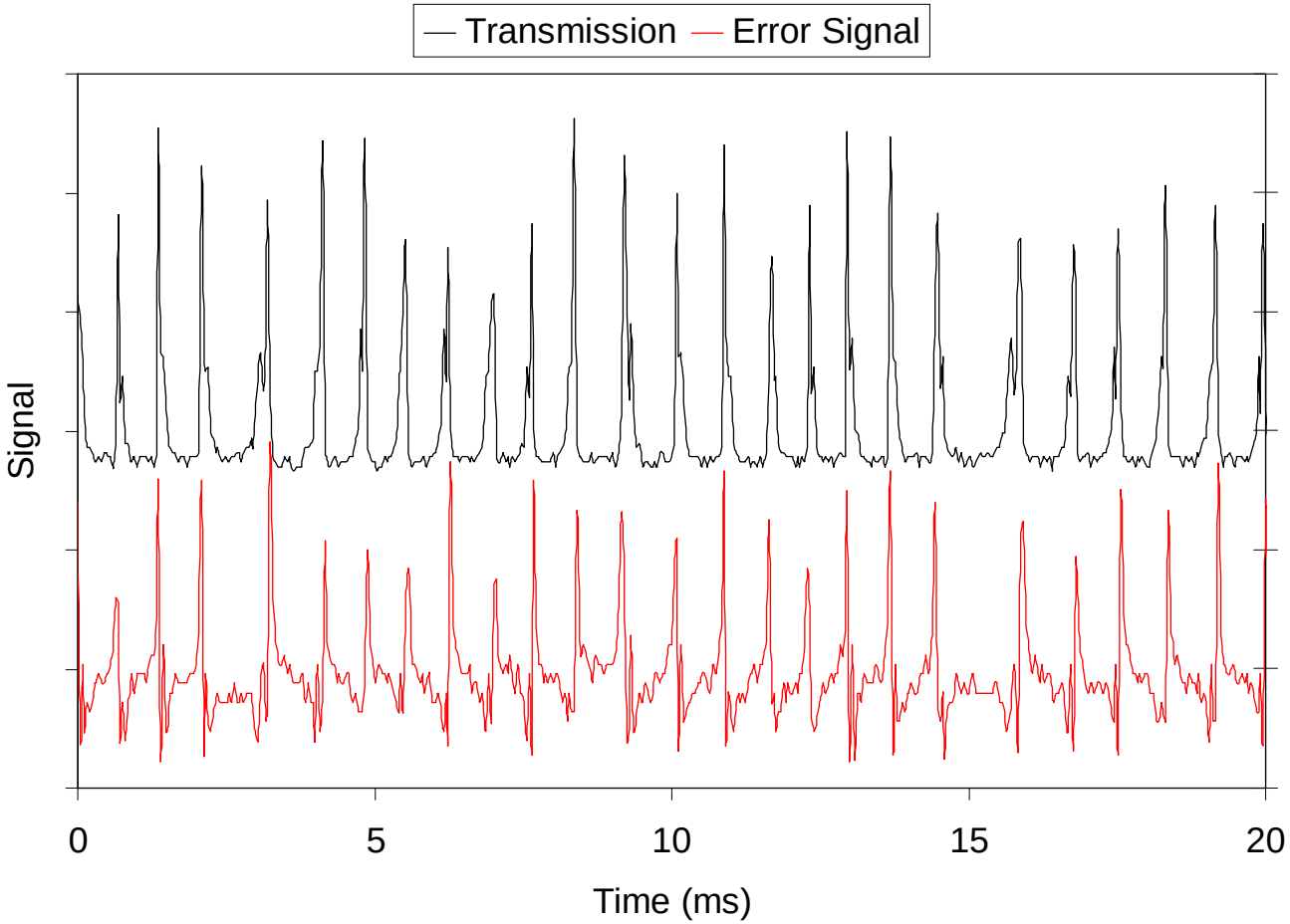
$$\Delta I = I_a - I_b = I_0 \cdot \sin(2\theta) \cdot \frac{t_1^2 r \sin\delta}{(1-r)^2 + 4r\sin^2(\delta/2)}$$



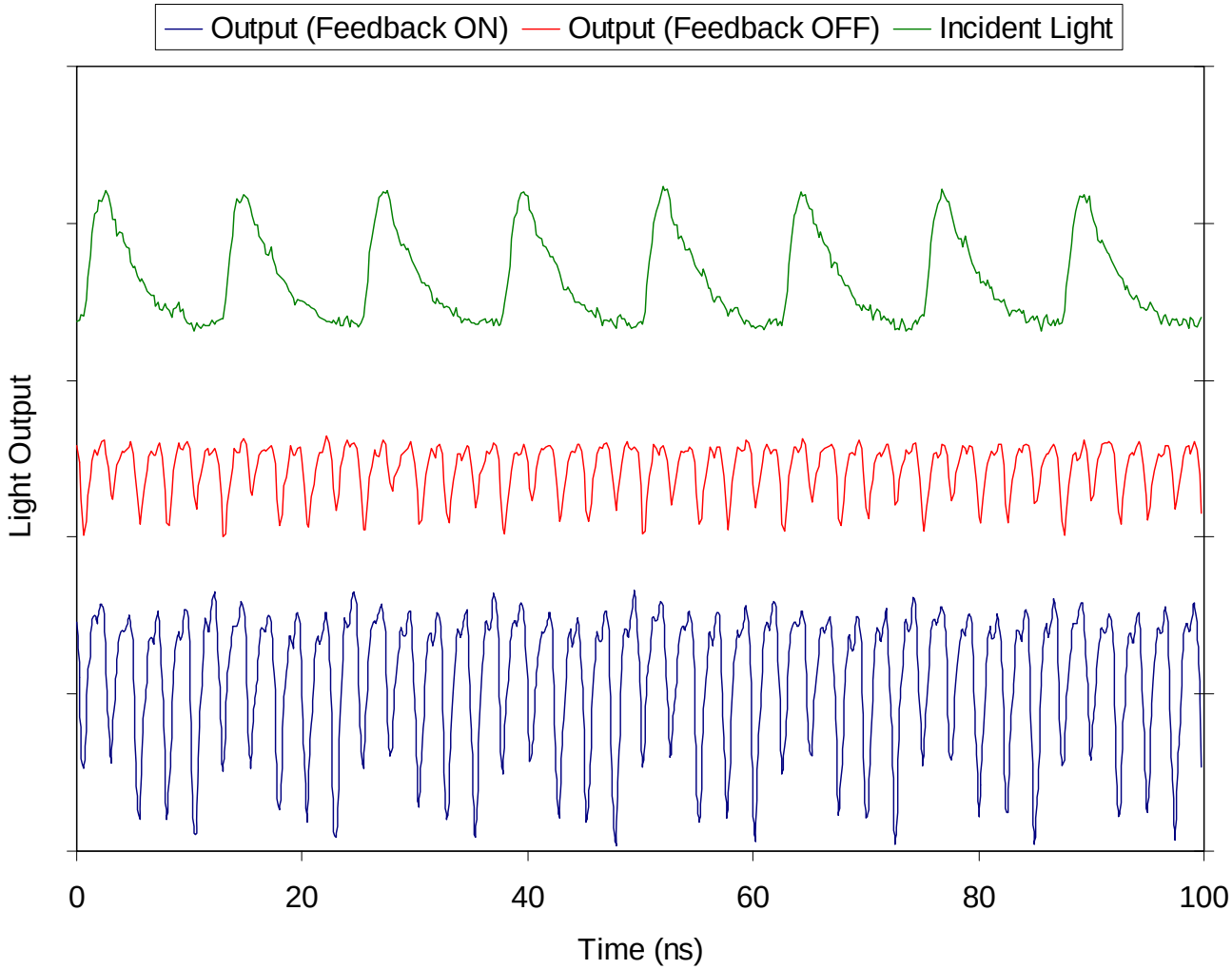
# Error Signal from Resonator



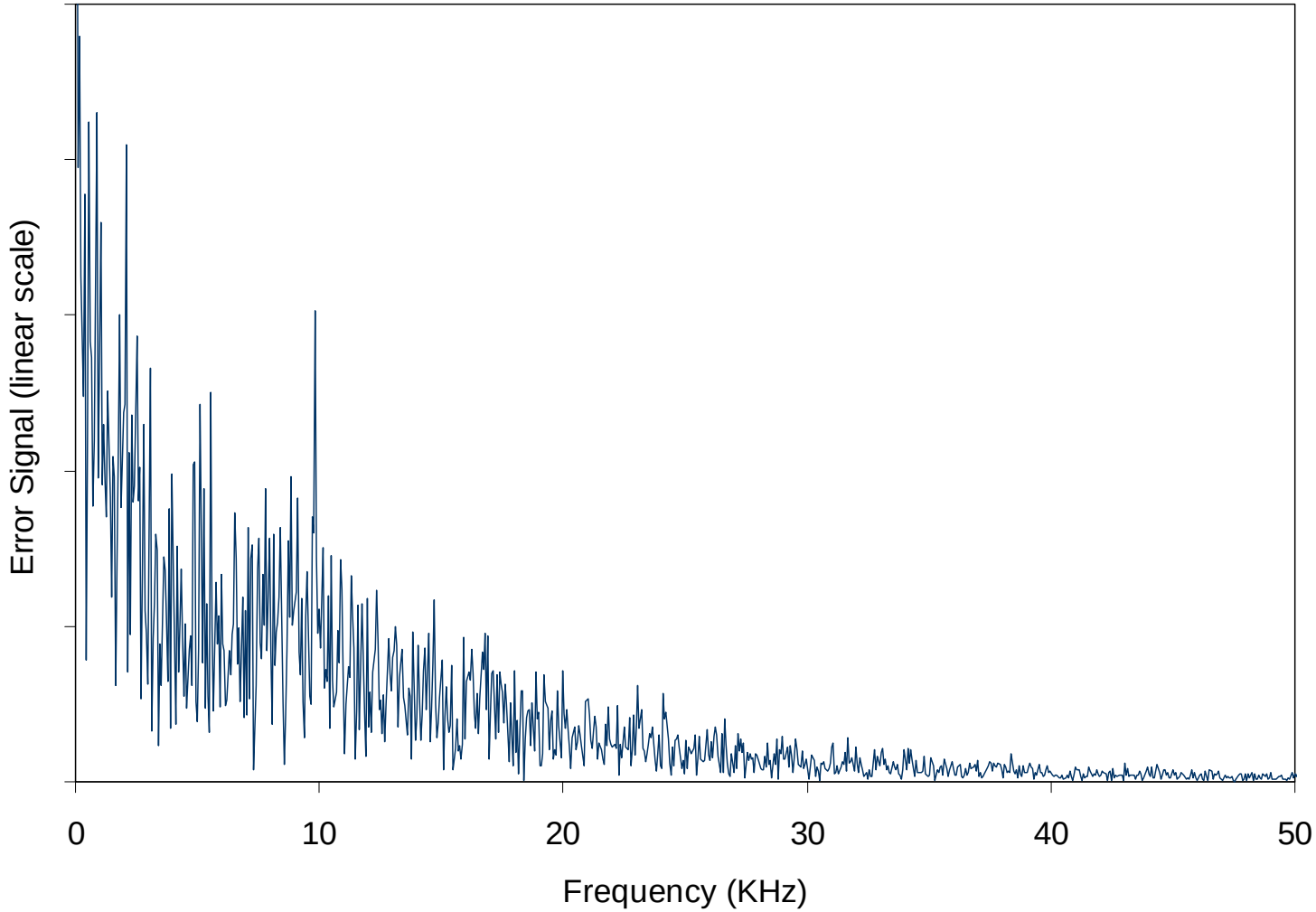
# Resonator Performance



# Resonator Performance



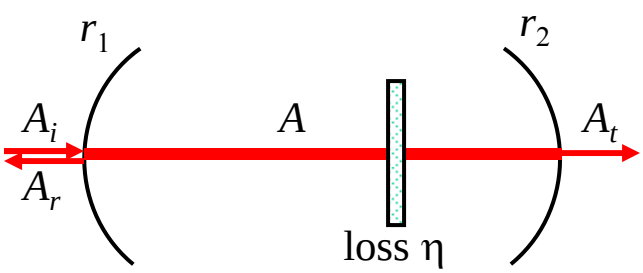
# Bandwidth of Error Signal

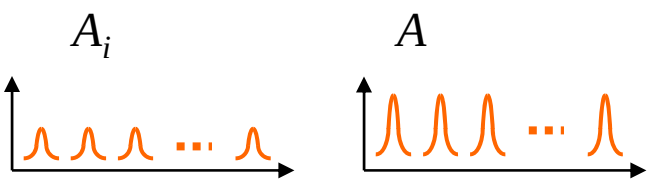


# Summary

- Proof-of-principle laser-assisted H- stripping was achieved using commercial laser
- Full-cycle laser stripping imposes a challenge on laser optics
- Development of macropulse laser system
  - Macropulse laser system has been designed to match the temporal structure of the SNS linac hydrogen ion beam;
  - The laser delivers a 10 us macropulse consisting of 50 ps, 40 uJ, 402.5 MHz UV pulses.
- Beam recycling optical resonators are under development
  - Customized near-concentric Fabry-Perot resonator has been developed;
  - Ring cavity are under study;
  - Optical cavity with harmonic crystal built-in.

# Remarks of Resonator Performance




$$r = r_1 r_2 (1-\eta),$$
$$t_1^2 = 1 - r_1^2,\ t_2^2 = 1 - r_2^2.$$

At resonant condition

$$A = A_i t_1 (1 + re^{i\delta} + r^2 e^{2i\delta} + \cdots) = \frac{A_i t_1}{1 - re^{i\delta}}$$

$$I_{res} = I_i \left( \frac{t_1}{1-r} \right)^2$$

At non-resonant condition

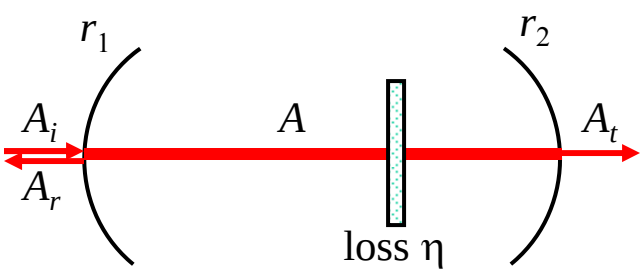
$$I_{nr} = I_i t_1^2 \left(1 + r^2 + r^4 \cdots\right) = \frac{I_i t_1^2}{1 - r^2}$$

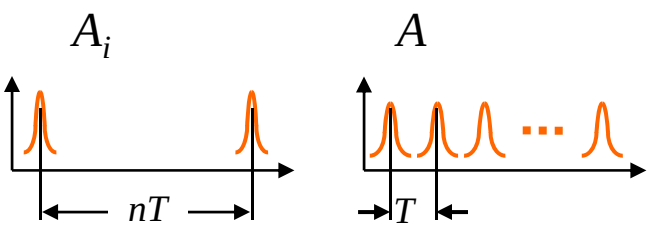
Ratios of power enhancement

$$\xi_1 = \frac{I_{res}}{I_i} = \left( \frac{t_1}{1-r} \right)^2$$

$$\xi_2 = \frac{I_{res}}{I_{nr}} = \frac{1+r}{1-r}$$

# Remarks of Resonator Performance




$$r = \left[ r_1 r_2 (1-\eta) \right]^n$$

<u>*n* = 5</u>

$$r_1 = 0.995, \quad t_1 = 0.1,$$

$$r = 0.995^5 \times (1-0.01)^5 \times 0.999^5 = 0.923,$$

$$\xi_1 = \left( \frac{t_1}{1-r} \right)^2 = 1.3,$$

$$\xi_2 = \frac{1+r}{1-r} = 25.$$

<u>*n* = 1</u>

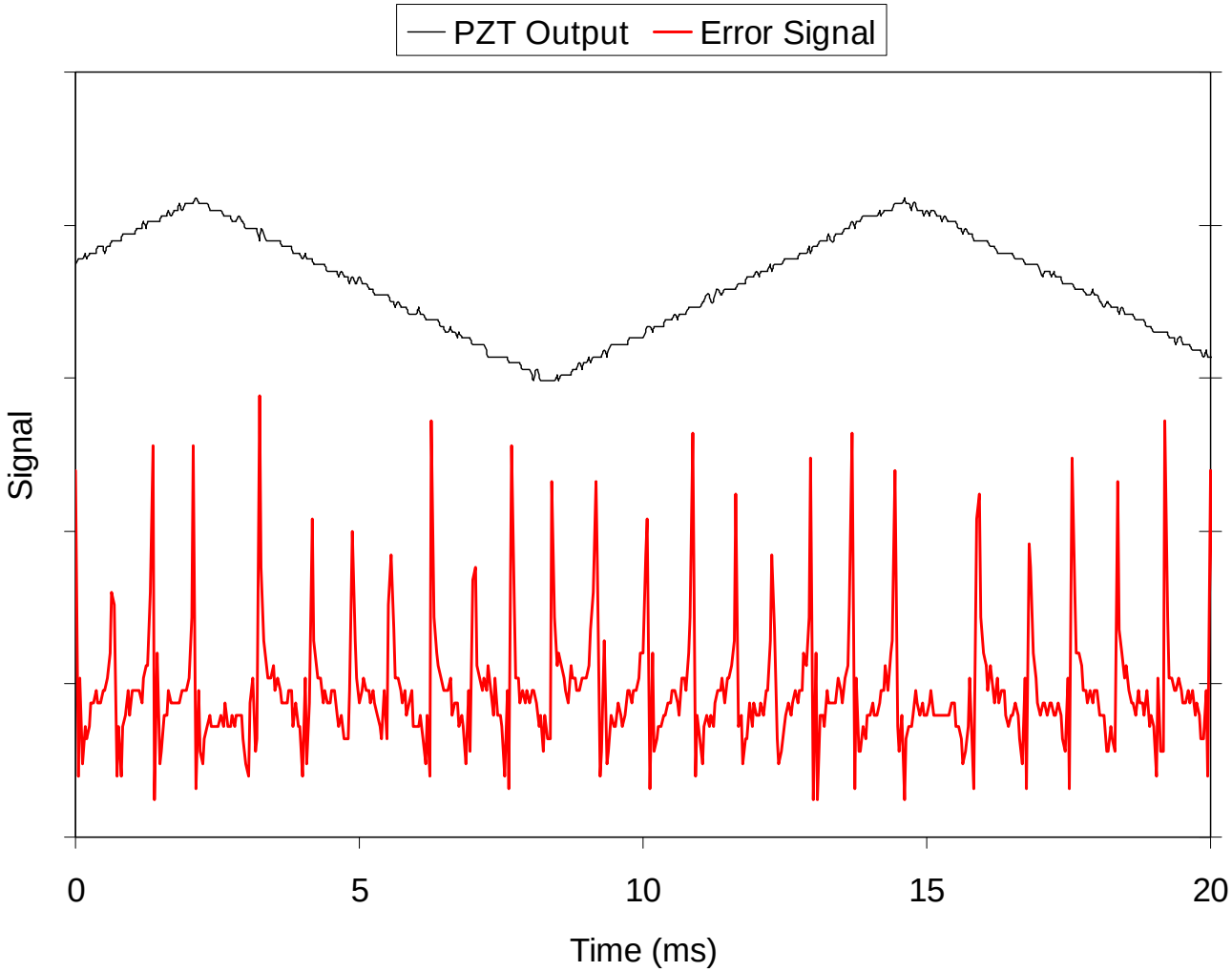
$$r_1 = 0.995, \quad t_1 = 0.1,$$

$$r = 0.995 \times (1-0.01) \times 0.999 = 0.984,$$

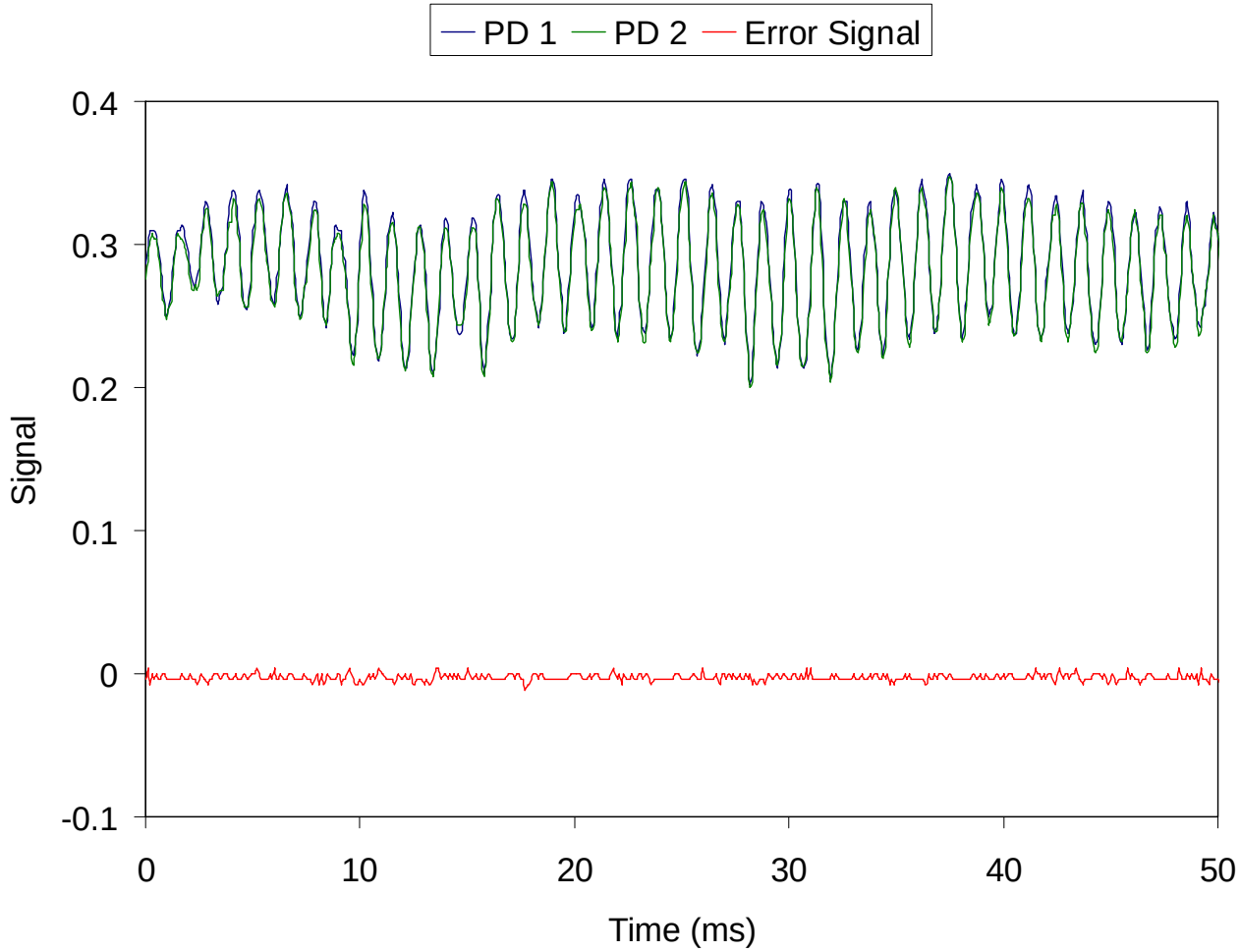
$$\xi_1 = \left( \frac{t_1}{1-r} \right)^2 = 39,$$

$$\xi_2 = \frac{1+r}{1-r} = 124.$$

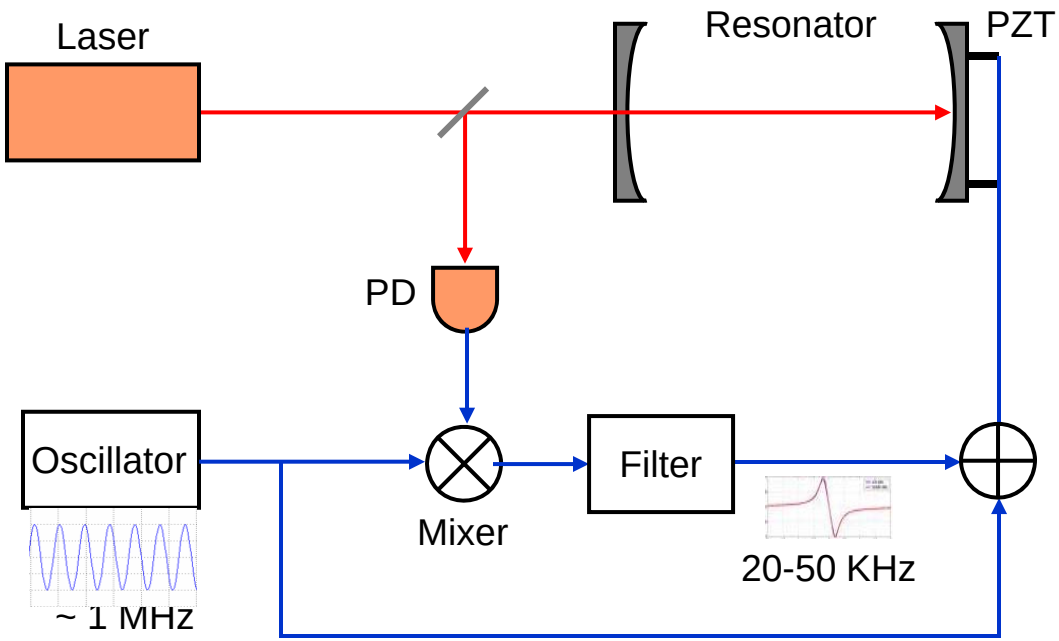
# Error Signal from Resonator



# Error Signal from Incomplete Resonator




Resonator was cut in the middle.

Vibrations are due to environment.

# Pound-Drever-Hall Resonator Stabilization