Photon Collider Laser Design

Brent Stuart, Jeff Gronberg
Lawrence Livermore National Laboratory

ILC2010
Beijing, China
March 27, 2010

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

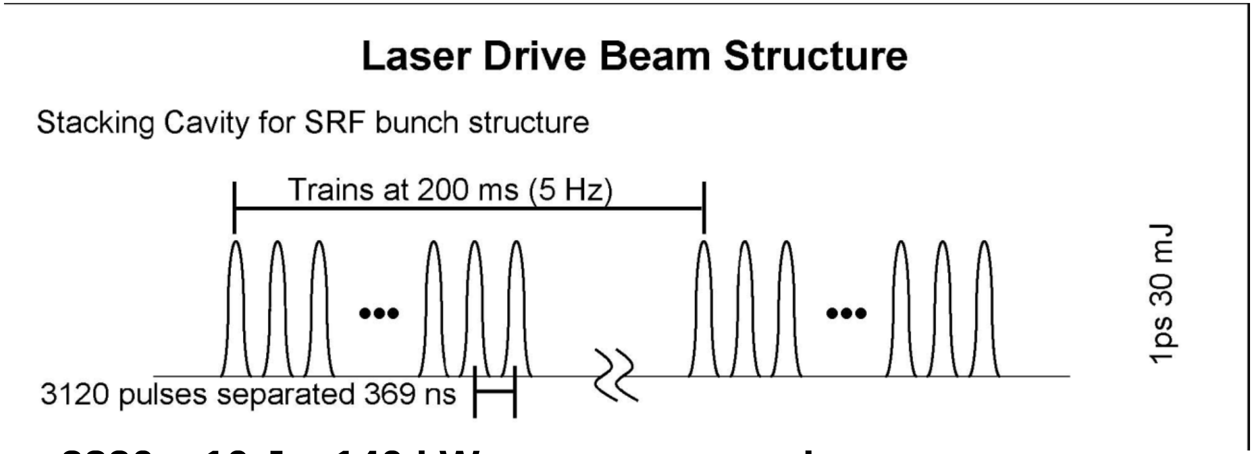
Outline

- Laser requirements
- Resonant cavity
- Sensitivities
- Laser concept

Is it feasible to build the laser?

Requirements at interaction point:

- Energy ~ 5-10 J
- Spot size ~ 10-20 μm (diffraction-limited)
- Wavelength ~ 1 μm
- Pulse length ~ 2.4 ps FWHM (σ = 1 ps)
- Circular polarization
- Rep rate/pulse train for superconducting L-band accelerator:
  - 369 ns bunch spacing
  - 2820 bunches/train
  - 5 Hz train repetition rate



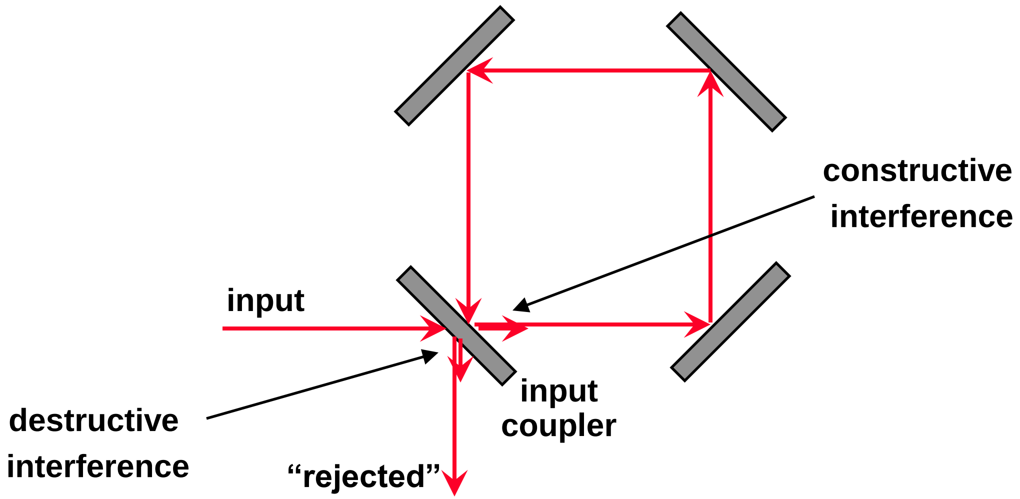
Laser Drive Beam Structure

Stacking Cavity for SRF bunch structure

- 5 Hz x 2820 x 10 J ≈ 140 kW average power laser

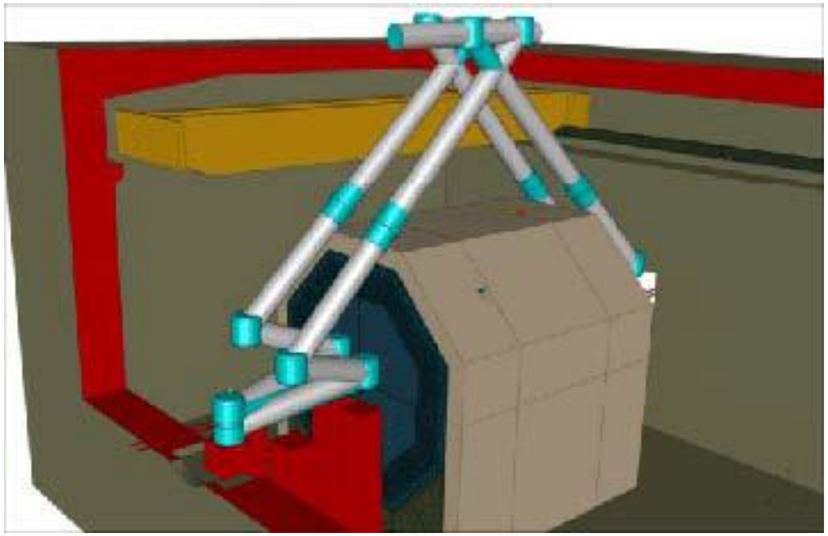
A resonant stacking cavity greatly reduces the required laser average power

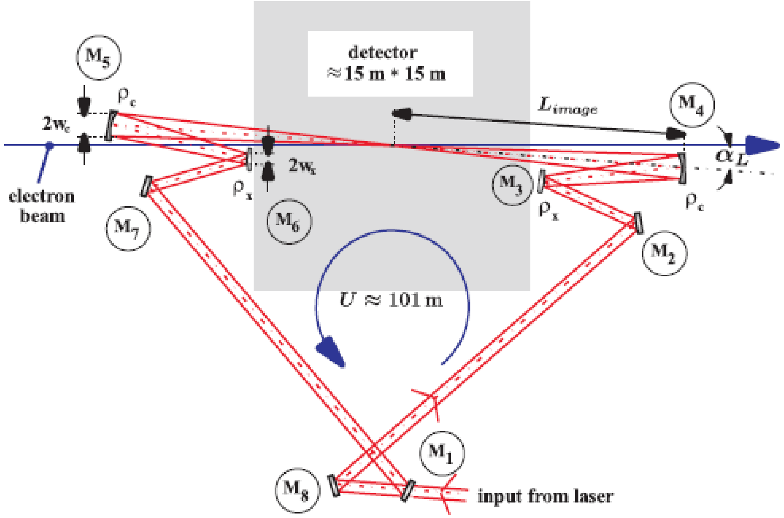
- Only ~10^{-9} of laser energy used in each interaction
  - Reuse photons, replenish cavity losses
- Coherent addition of pulses in cavity requires extreme control of laser and cavity parameters
- Goal of 300-400 enhancement (30 mJ input, 10 J interaction beam)



Conceptual design for a resonant stacking cavity by DESY-Zeuthen and MBI*

- **Design for L-band accelerator**
  - **— 369 ns pulse spacing (111 m cavity length)**



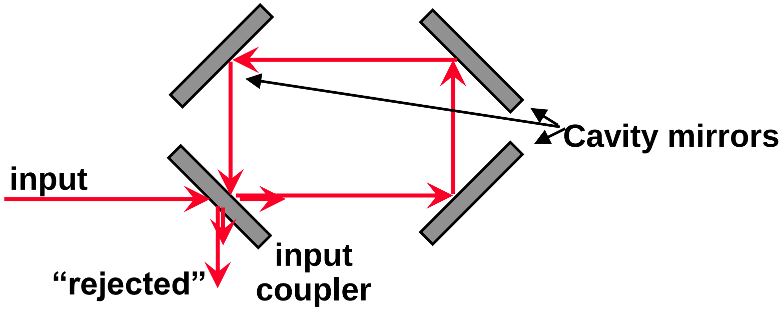


* I.Will, T. Quast, H. Redlin andW. Sander, “A Laser System For The TESLA Photon Collider Based On An External Ring Resonator”, *Nucl. Instrum. Meth.* A **472** (2001) 79.

G. Klemz, K. Monig, I. Will, “Design study of an optical cavity for a future photon-collider at ILC”, *Nucl. Instrum. Meth.* A **564** (2006) 212.

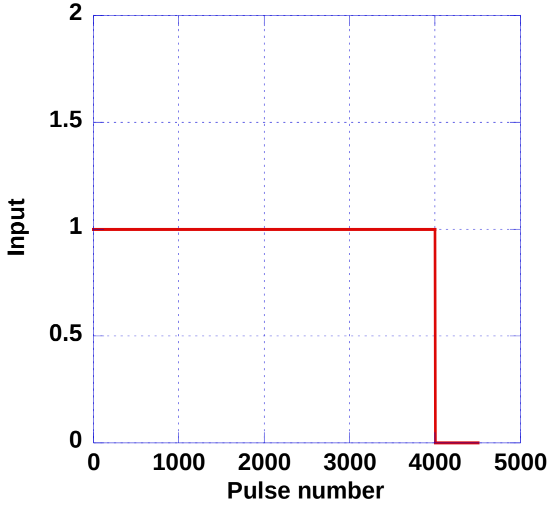
Resonant stacking cavity

- **Baseline case: input coupler R=0.996, cavity mirrors R=0.998**

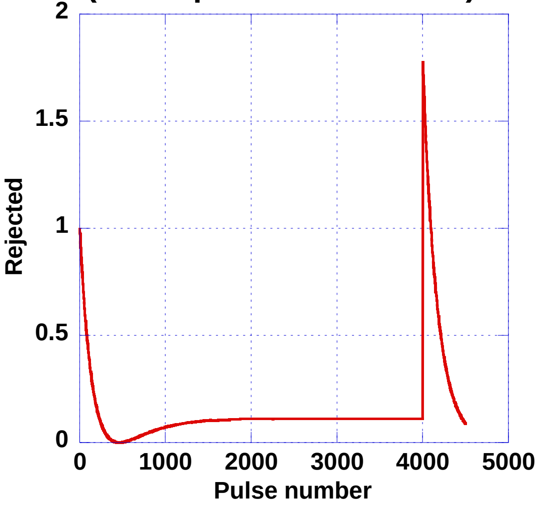


Cavity round-trip lifetime ≈ 225 pulses

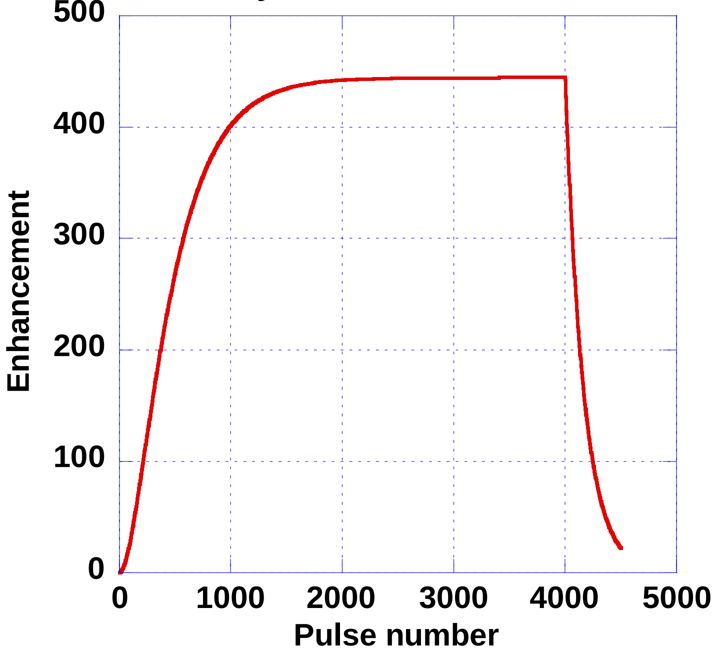
Input pulses normalized to 1.0



"rejected" pulses (not impedance-matched)

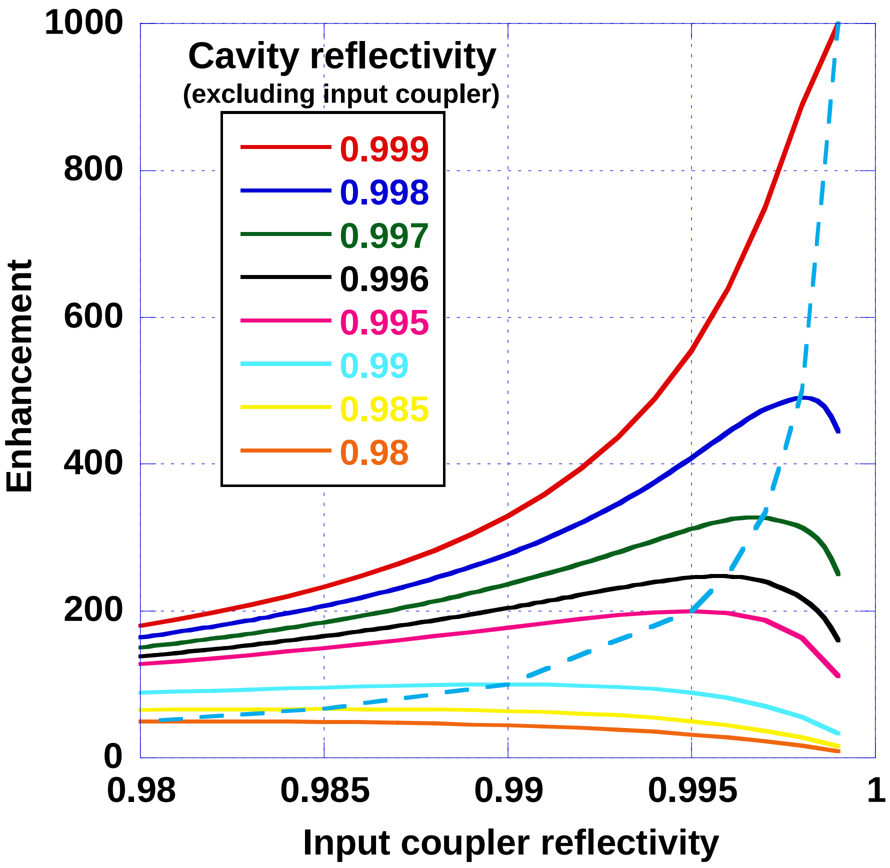


Cavity enhancement factor



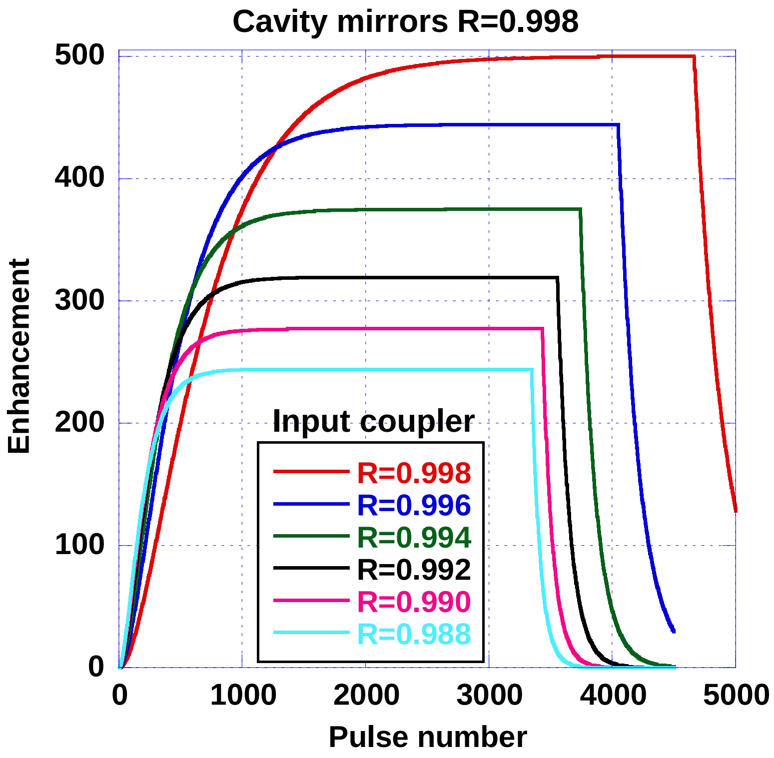
Enhancement as a function of mirror reflectivities

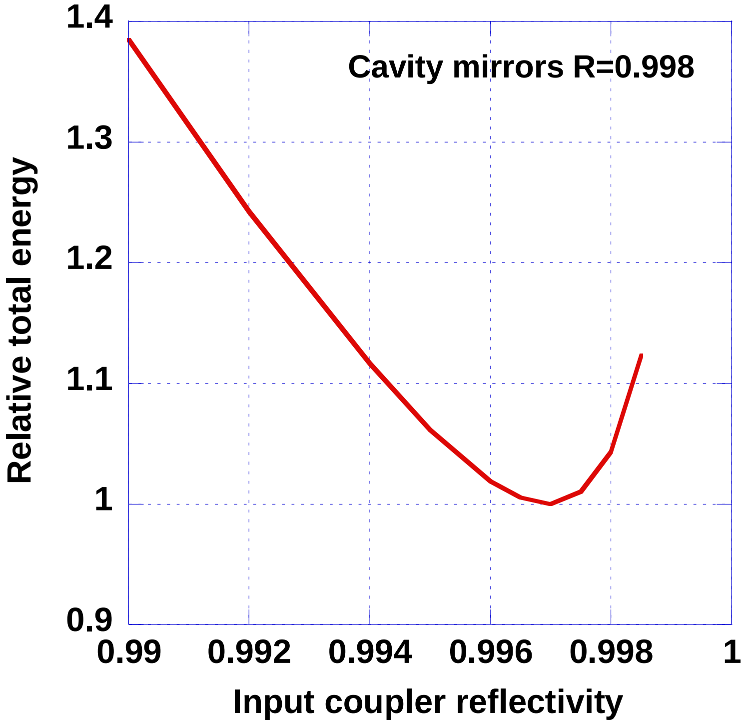
- **Impedance-matched cavity (equal cavity and input coupler reflectivity) gives greatest enhancement for given cavity reflectivity**
- **For given input coupler, increasing cavity reflectivity increases enhancement**



There is an optimum input coupler to minimize total input energy

- Lower reflectivity input coupler gives faster cavity loading, but reduced enhancement
- Total energy ∝ (# loading pulses to 95% + 2820)/enhancement





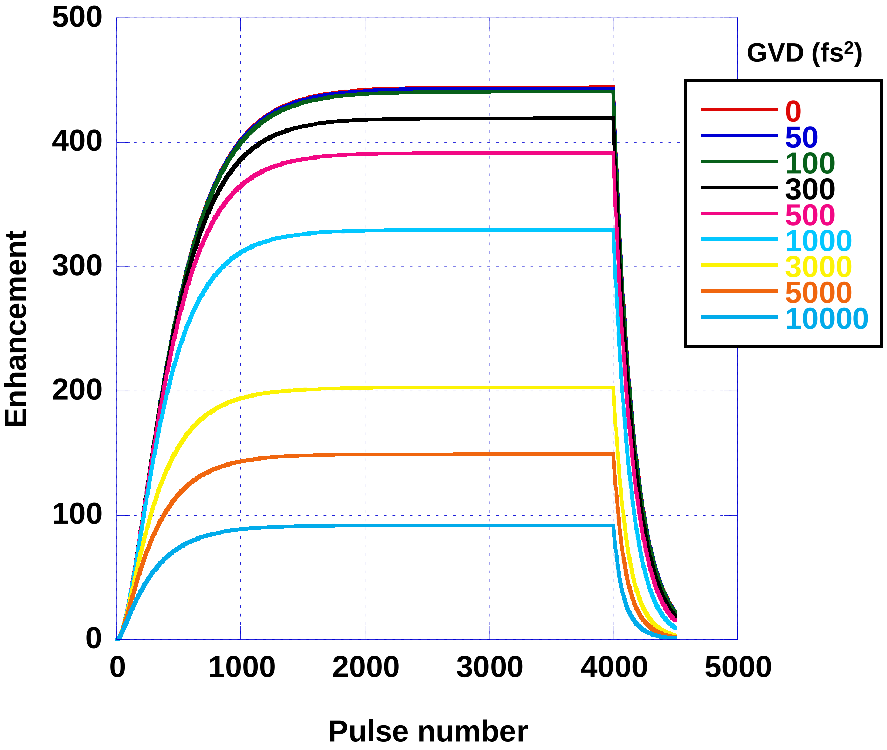
Resonant cavity enhancement puts stringent requirements on the laser and optics

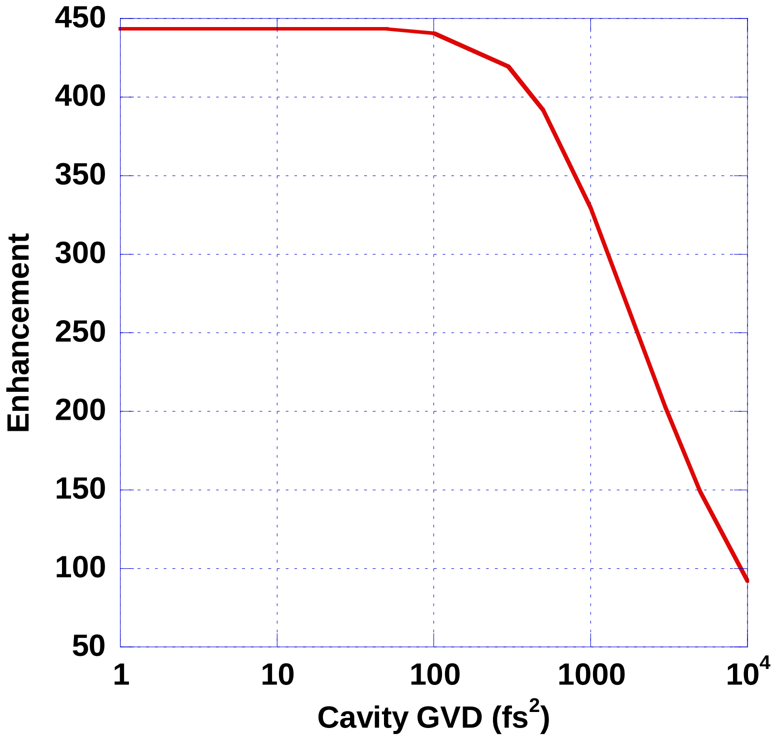
- Dispersion in resonant cavity
- Phase noise
- Cavity length/laser repetition frequency
- Amplitude noise
- Thermal changes to refractive index in amplifiers/optics
- Pointing stability

- Coating damage due to scattered electrons and synchrotron radiation can reduce mirror reflectivity
  - Seven mirrors for total R=0.998 ⇒ R=0.9997 each

Total cavity Group Velocity Dispersion (GVD) should be less than 100 fs^2

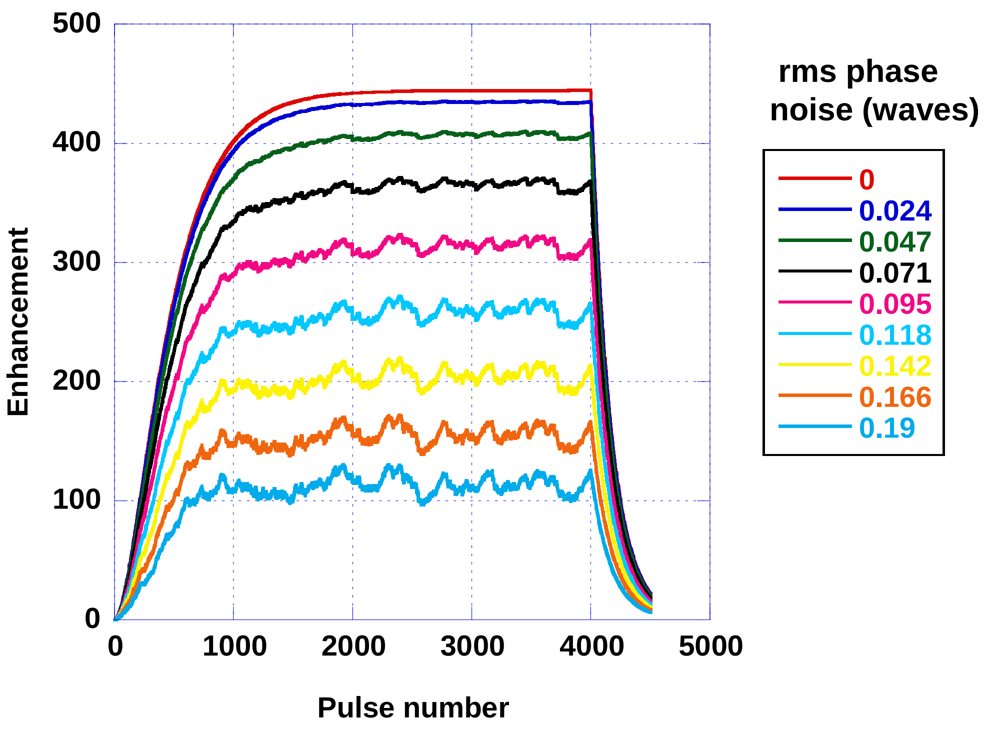
- Low-dispersion mirrors can be manufactured with < 10 fs^2 GVD
  - — Negative GVD mirrors also available

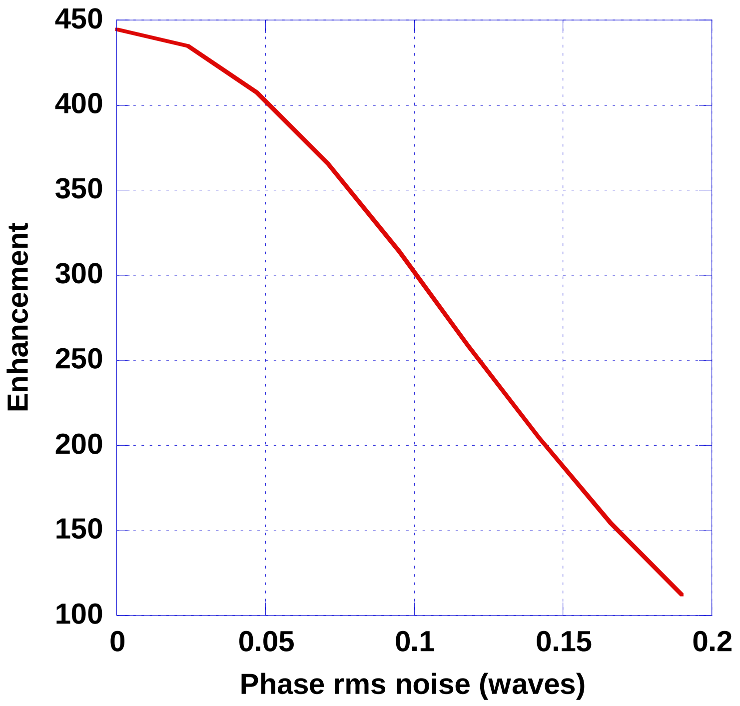




1 ps (FWHM) transform-limited input pulses

Phase noise





- **0.10 wave (650 mrad) achieved in CEP stabilized Ti:Sapphire system (1.4 mJ @ 1 kHz)***
- **0.03 wave (171 mrad) achieved with single amplifier (21 nJ, 75 MHz)****

*** E. Gagnon, et al., Opt. Lett. 31, 1866 (2006)**

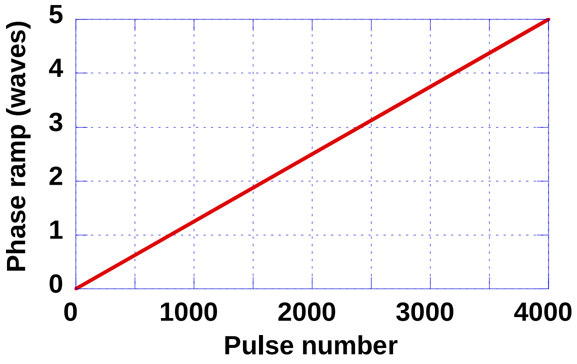
**** A. Ozawa, et al., New J. Phys. 11, 083029 (2009)**

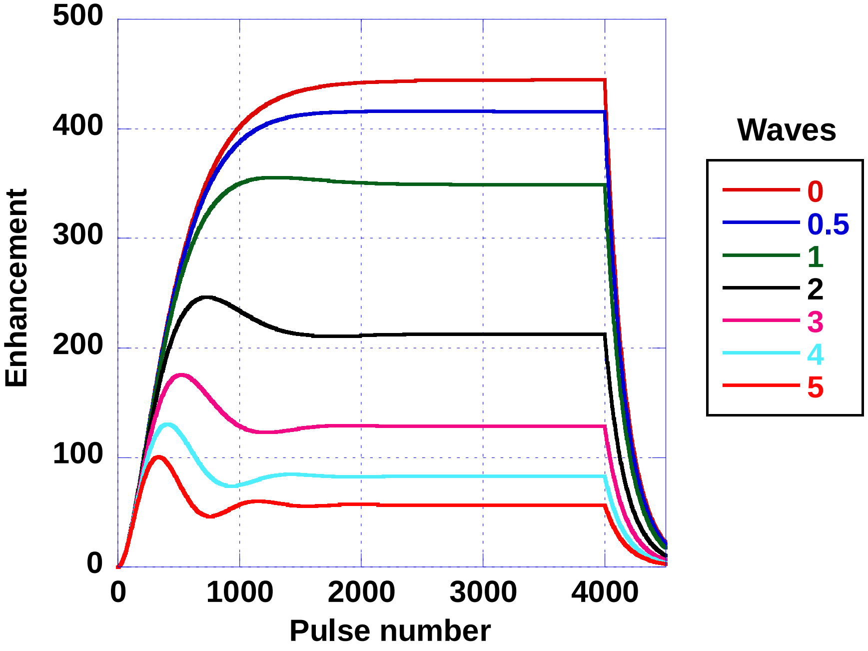
Linear phase ramp through bunch (cavity length stability or thermal loading)

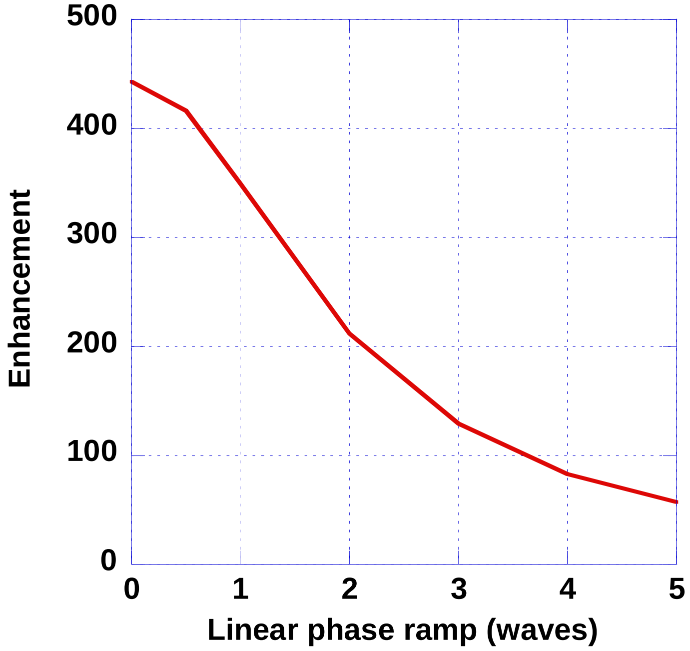
- **Can relate to cavity length:**

  1 wave ≈ 1 µm

  1 wave/bunch ≈ 0.7 mm/s

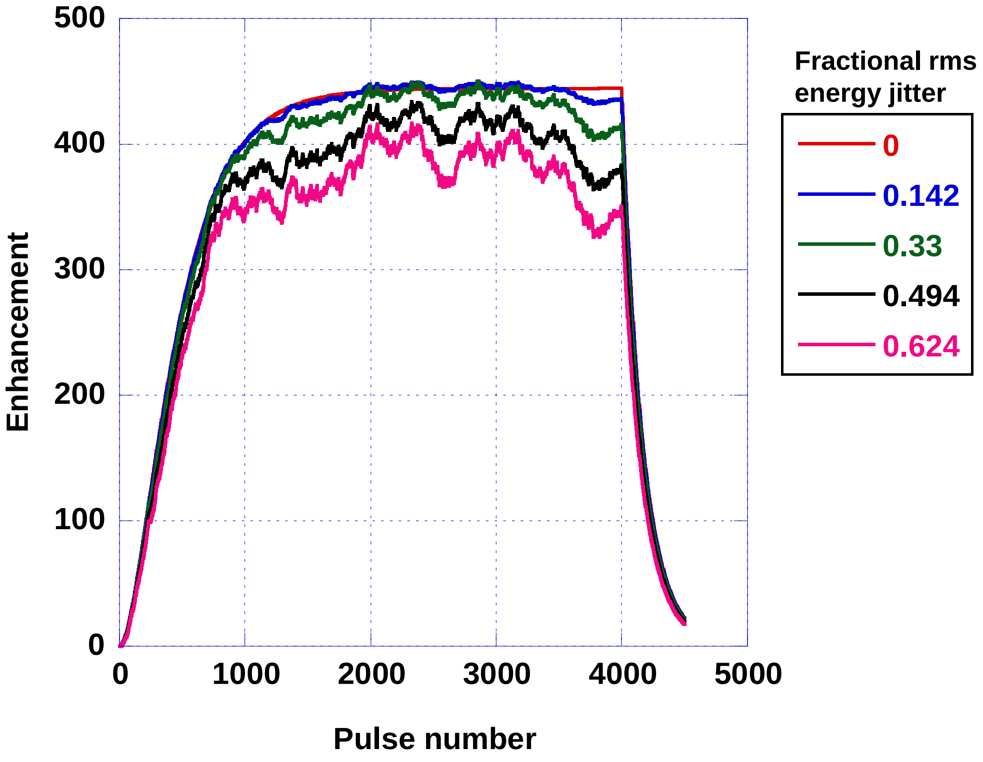


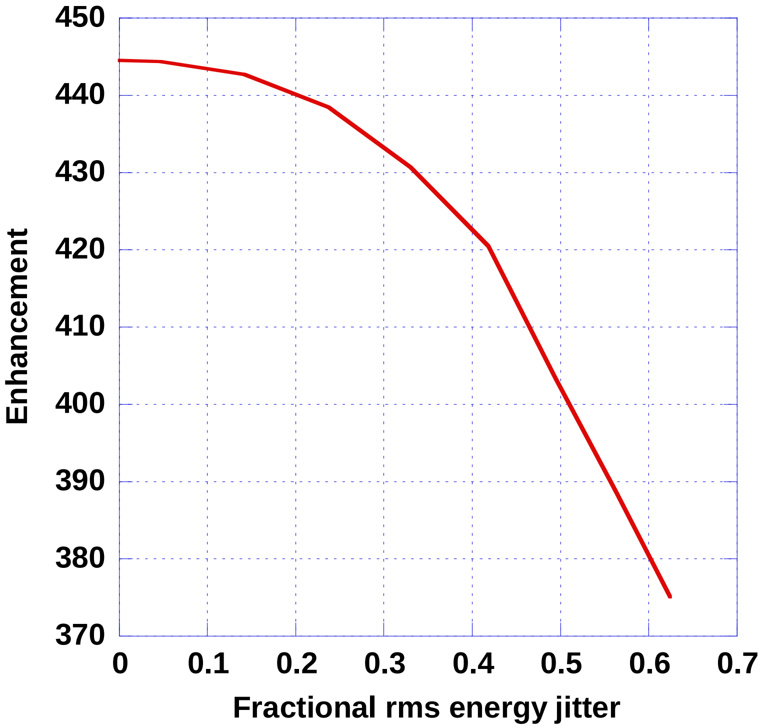




Energy jitter

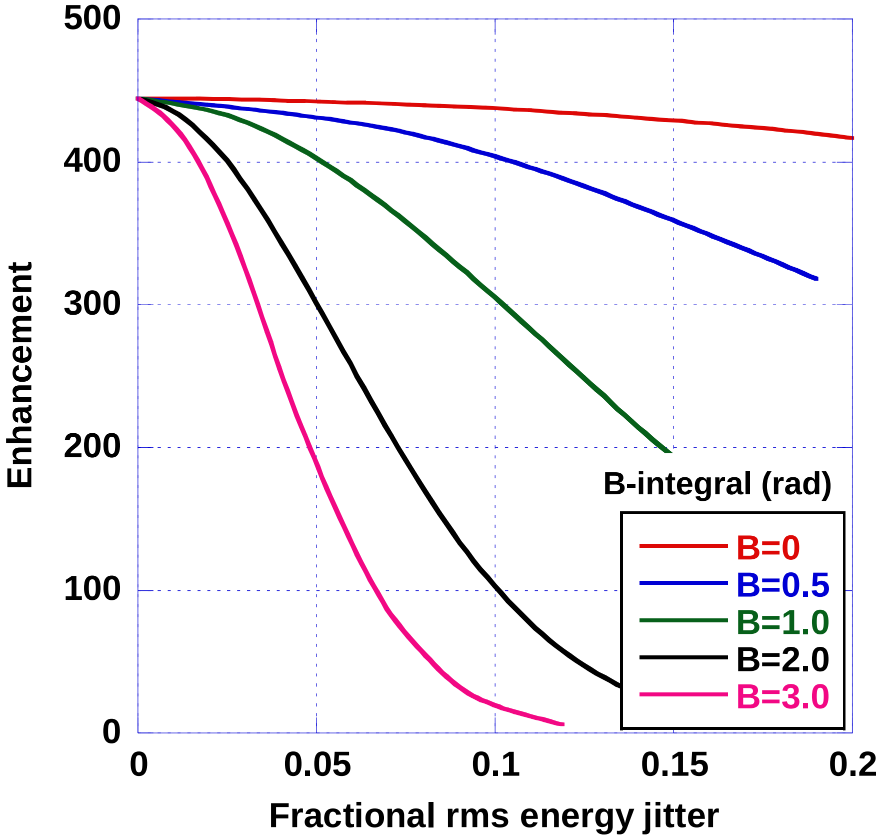
- **Large jitter acceptable with no B-integral (phase) variation**





Energy jitter with B-integral

- Nonlinear effects transform energy jitter into phase jitter
- Typical short-pulse lasers run with B<2, but some fiber-laser designs have B>5



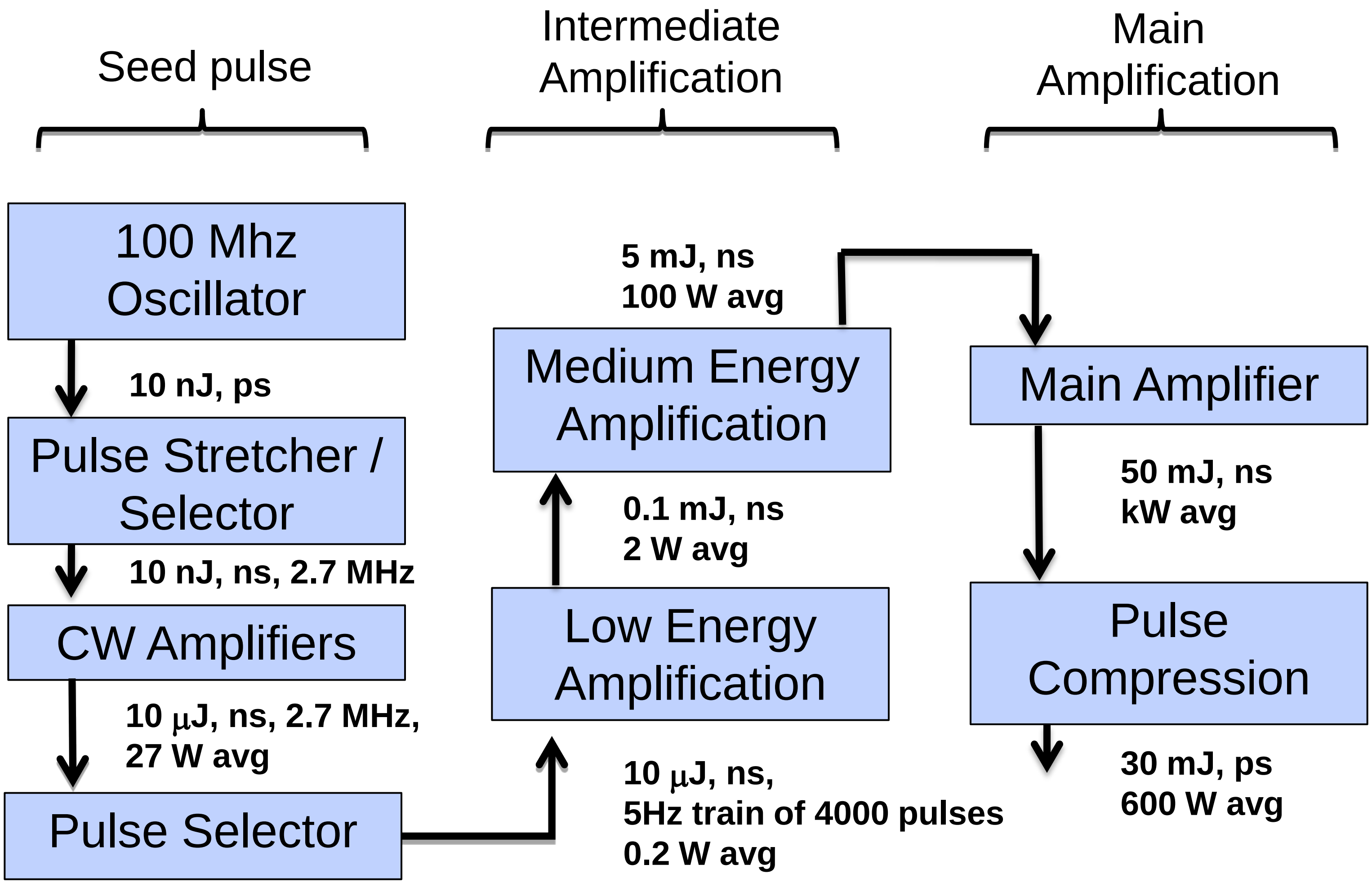
Phase:

$$\phi = \int k\, dz = \frac{2\pi}{\lambda}\int n(r,t)\, dz = \frac{2\pi n_o L}{\lambda} + B(r,t)$$

B-integral (nonlinear phase accumulation):

$$B(r,t) = \frac{2\pi}{\lambda}\int \gamma I(r,t)\, dz$$

Laser system concept



Seed pulse

Intermediate Amplification

Main Amplification

100 Mhz Oscillator

10 nJ, ps

Pulse Stretcher / Selector

10 nJ, ns, 2.7 MHz

CW Amplifiers

10 μJ, ns, 2.7 MHz,
27 W avg

Pulse Selector

10 μJ, ns,
5Hz train of 4000 pulses
0.2 W avg

Low Energy Amplification

0.1 mJ, ns
2 W avg

Medium Energy Amplification

5 mJ, ns
100 W avg

Main Amplifier

50 mJ, ns
kW avg

Pulse Compression

30 mJ, ps
600 W avg

Pulse injection

100 MHz Oscillator

↓ 10 nJ, ps

Pulse Stretcher / Selector

↓ 100 nJ, ns, 2.7 MHz

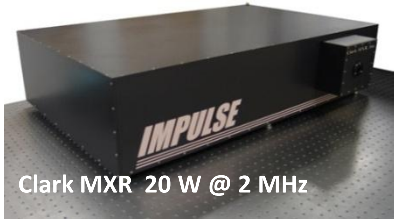
CW Amplifier

↓ 10 μJ, ns, 2.7 MHz
27 W avg

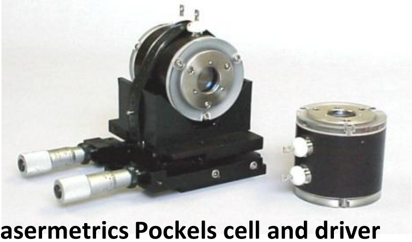
Pulse Selector


High Q Laser femtoTrain


KM Labs pulse stretcher/compressor

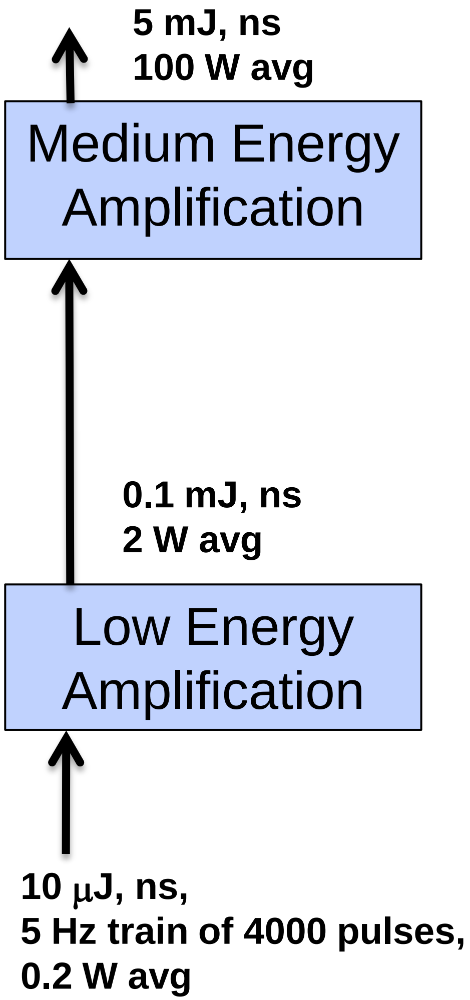


Clark MXR 20 W @ 2 MHz


Lasermetrics Pockels cell and driver

- **“Off-the-shelf” technology**
- **Similar to lasers for ILC photogun**
- **Special photon collider requirements:**
  - **Need phase-locked oscillator at 1 μm**

Intermediate Amplification



5 mJ, ns
100 W avg

Medium Energy Amplification

0.1 mJ, ns
2 W avg

Low Energy Amplification

10 μJ, ns,
5 Hz train of 4000 pulses,
0.2 W avg

Cutting Edge Optronics' slab pumphead, the Whisper MiniSlab^{TM}

Cutting Edge Optronics
RBA PowerPULSE

- “Off-the-shelf” technology exists to reach this power level
- Must be adapted to ILC pulse format – pulsed diode pumping
- At this level non-linear and thermal effects begin to be important

Main Amplifier

5 mJ, ns
100 W avg

Main Amplifier

50 mJ, ns
1 kW avg

- **Not commercially available**
- **Basic enabling technologies exist:**
  - **Pulsed diode pumping**
  - **Thermal management**
- **Must be adapted to ILC pulse format**

400 W Yb:YAG Innoslab fs-amplifier [1],
(5.3 μJ, 76 MHz, 682 fs, ΔT=18°K, CW pump)

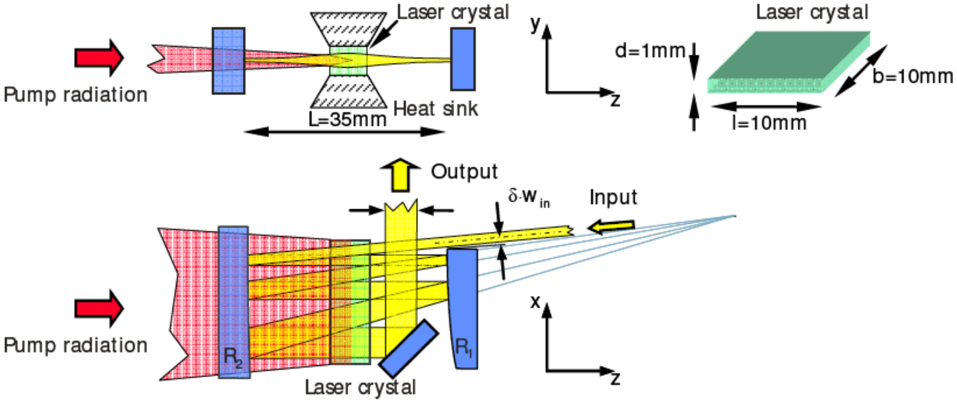


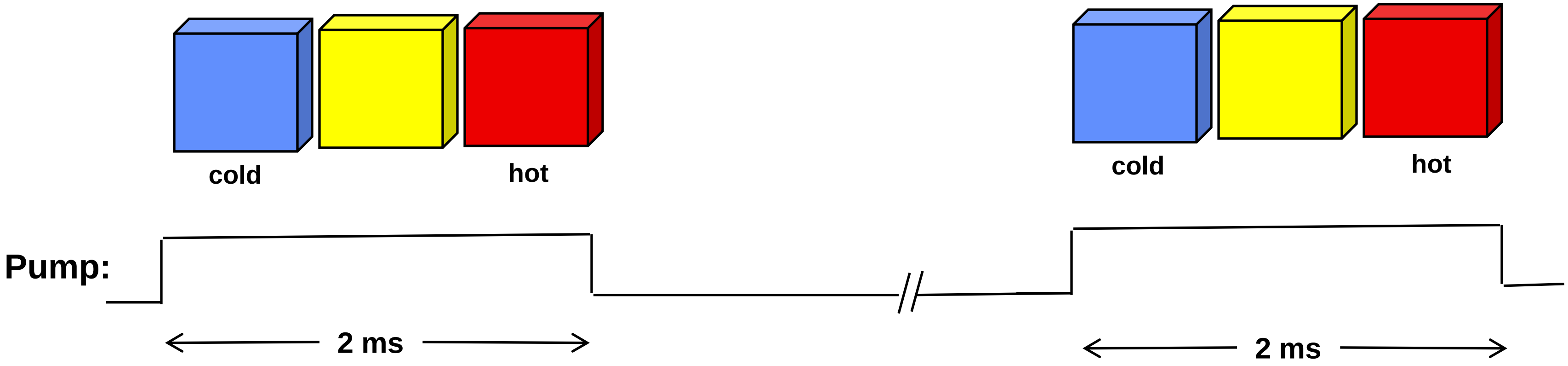
Fig. 2. Schematic setup of an Innoslab amplifier

Commercially available from EdgeWave (Aachen, Germany)

[1] P. Russbueldt, et al., Opt. Exp. 17, 12230 (2009)

Final amplifier design must balance energetics with heat removal

- **Would like to maintain spatially uniform temperature profile through pulse train**
- **Would like to remove all heat before next train**
  - **High thermal conductivity and low heat capacity for gain medium**
- **Thermal effects may drive choice of flat-top vs. Gaussian beam shape in amplifiers**
- **Need gain of 10 or more (can multipass)**
- **Gain medium must support ps pulses**



Thermal effects in main amplifier

Pulsed diode pumping in final amplifiers will change material index of refraction n_o

Linear phase: $$\phi = \int k\, dz = \frac{2\pi}{\lambda}\int n(r,t)\, dz = \frac{2\pi n_o L}{\lambda}$$

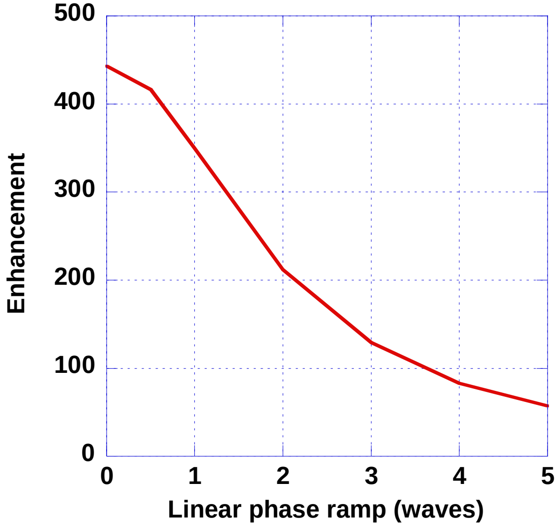
For Yb:YAG:

$dn/dT \approx 7\times10^{-6}$ /°K

Heating Yb:YAG with 200 J/bunch:

$\Delta T = 200\ \mathrm{J}/((0.59\ \mathrm{J/gK})(4.56\ \mathrm{g/cm^3})(10\ \mathrm{cm^3}))$

$\Delta T = 7.4$ °K (5 λ over 10 cm)

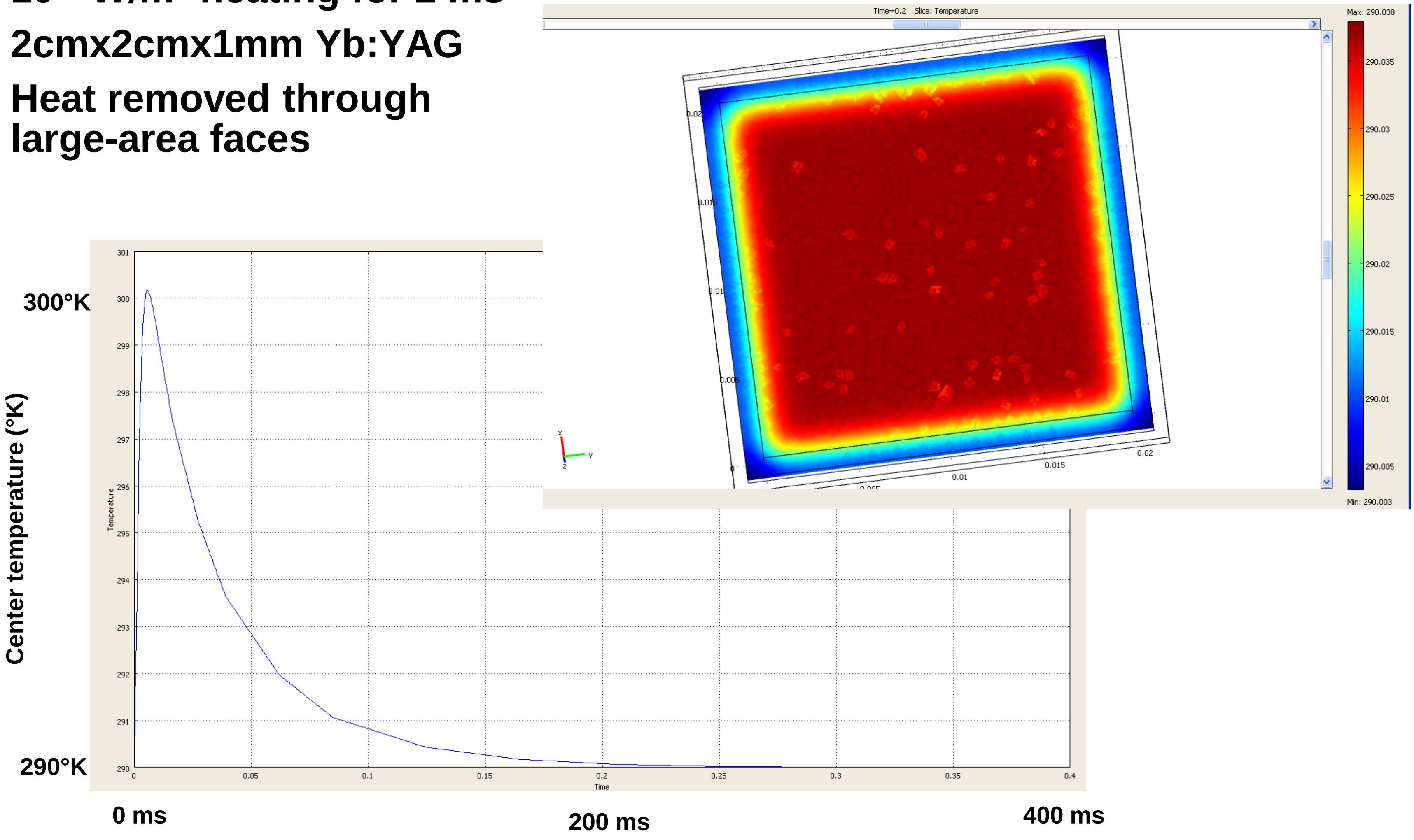


Phase modulator can potentially compensate thermal effects, assuming phase variation is spatially uniform

Reducing and compensating for the thermal loading in the final amplifiers is our main laser challenge

We have begun finite element modeling of heating and cooling

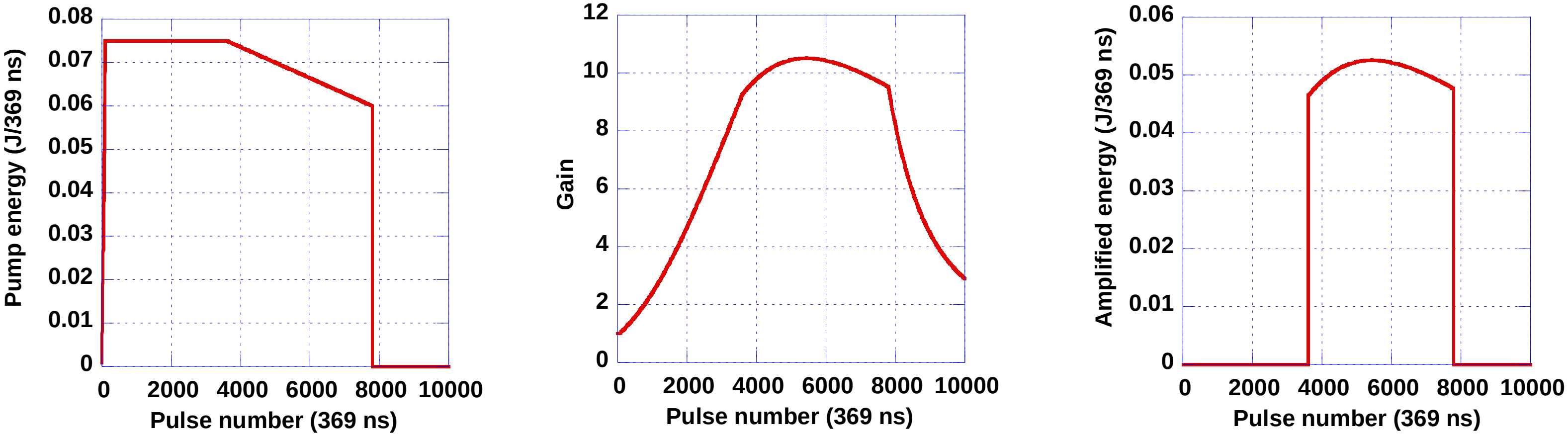
- 10^{10} W/m^3 heating for 2 ms
- 2cmx2cmx1mm Yb:YAG
- Heat removed through large-area faces



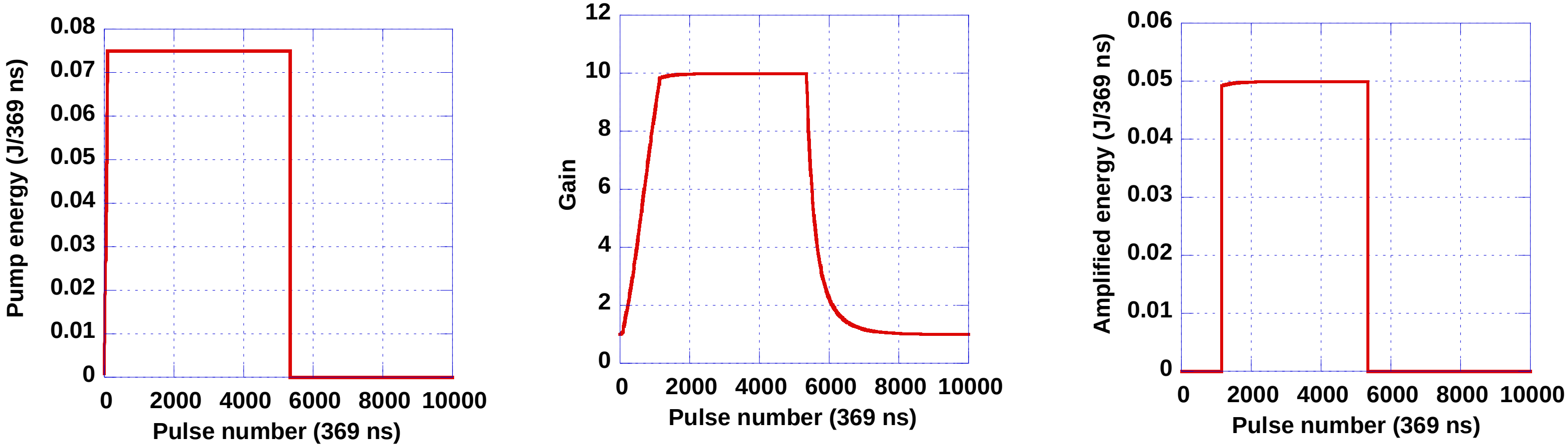
Final amplifier energetics depend on gain medium characteristics

Pump **Gain** **Output**

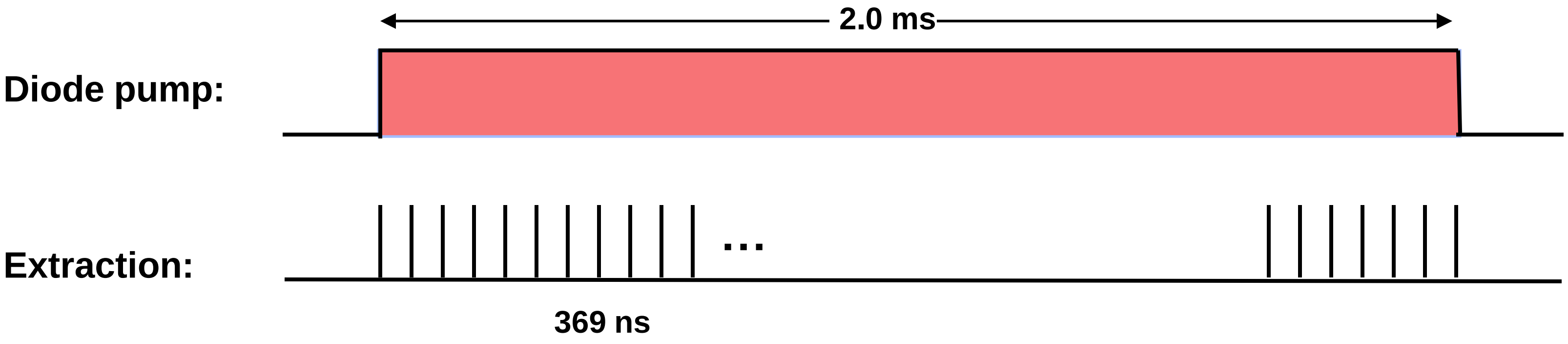
Yb:YAG $\sigma_a = 0.8\times10^{-20}$ cm², $\sigma_s = 1.9\times10^{-20}$ cm², $\tau = 1.08$ ms, total pump energy = 550 J/train



Nd:YAG $\sigma_a = 7.7\times10^{-20}$ cm², $\sigma_s = 28\times10^{-20}$ cm², $\tau = 0.23$ ms, total pump energy = 400 J/train



Diode pumping can be achieved at reasonable cost



Diodes:

50 mJ/369 ns = 136 kW peak $\overset{\text{40\% eff.}}{\Rightarrow}$ 339 kW peak

at \$5/peak W $\Rightarrow$ \$1.7 M for diodes/drivers

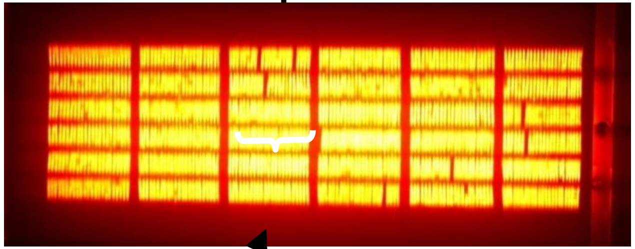
~ 3500 bars at 100 W/bar

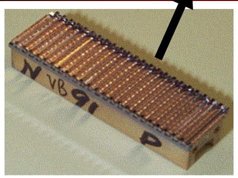
Lifetime ≈ 5×10^9 shots = 31.7 years @ 5 Hz

The Mercury laser at LLNL uses four 80 kW diode arrays for a total of 320 kW of peak diode power

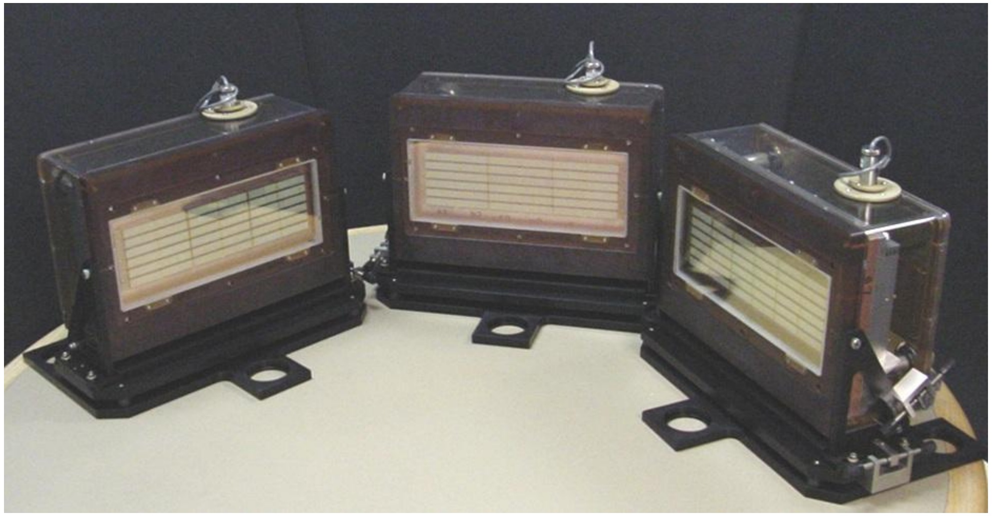
Operated at:

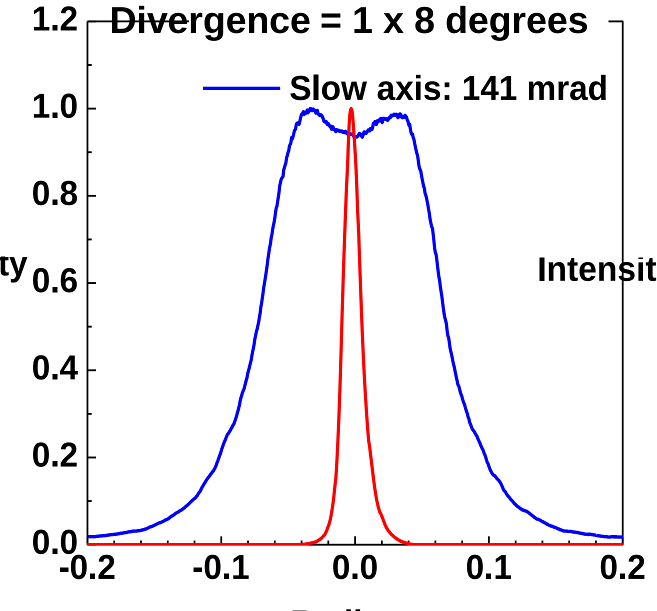
- 120 W/bar at 10 Hz
- 900 ms pulsewidth



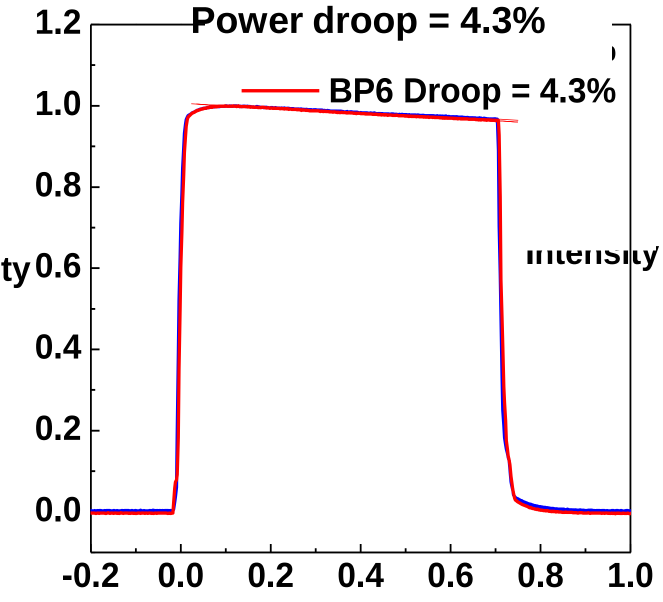


tile with 23 diode bars

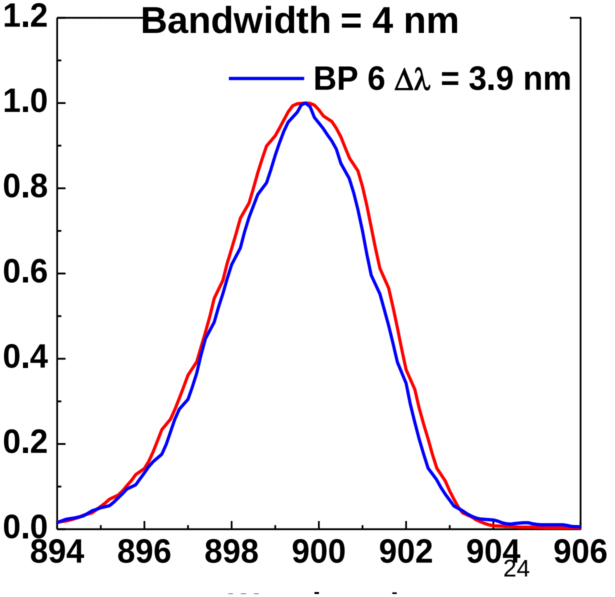




Divergence = 1 x 8 degrees



Power droop = 4.3%



Bandwidth = 4 nm

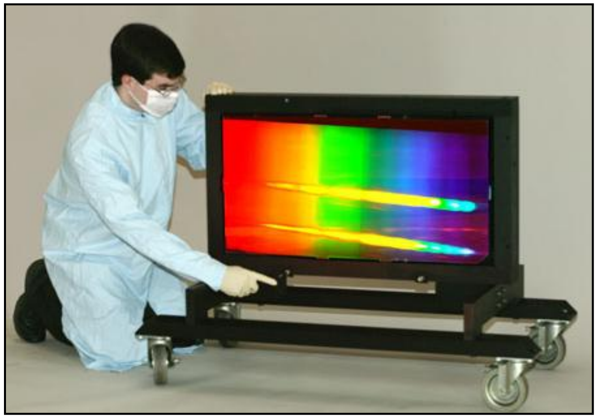
Pulse Compression

50 mJ, ns → Pulse Compression → 30 mJ, ps

- **System will be in vacuum after compression**
- **Average power testing of Multi-Layer Dielectric (MLD) gratings:**
  - — 30 W/cm^2, no wavefront distortion
  - — 100 kW/cm^2 small spot - no damage
  - — 30-60 ppm absorption (preliminary)
- **High efficiency (>96%) gratings for linear polarization**
  - — Waveplate after compressor to make circular polarization

Vacuum compressor (Titan – LLNL)

World's largest dielectric gratings (LLNL)



Work to be done

- Detailed design of final amplifiers (FY2010)
  - Gain material
  - Pumping/extraction geometry
  - Minimize thermal effects
    - Cryo-cooling increases thermal conductivity and reduces heat capacity, but adds complexity

- Modeling of 2D sensitivities
  - Pointing jitter (FY2010)
  - Diffraction losses
  - Optical aberrations

- Conceptual design of laser system (FY2010)

- Conceptual design of control system

Summary

- **System will be challenging, but no show-stoppers identified yet**
  - **Thermal effects in main amplifiers will have to be controlled and compensated**
  - **Extensive control system will be necessary to maintain phase coherence in resonant cavity**
- **We plan to complete a conceptual design this year**