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Photon Collider Laser

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Photon Collider Laser

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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

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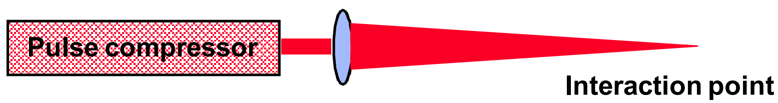
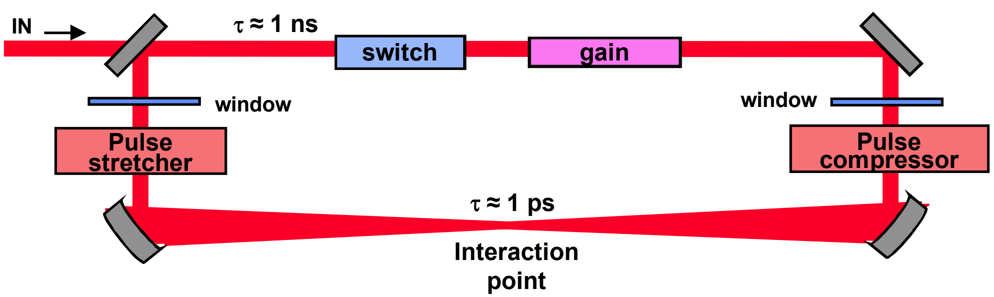
- **5 Hz x 2820 x 5 J ≈ 70 kW average power laser**

Laser requirements depend on interaction configuration



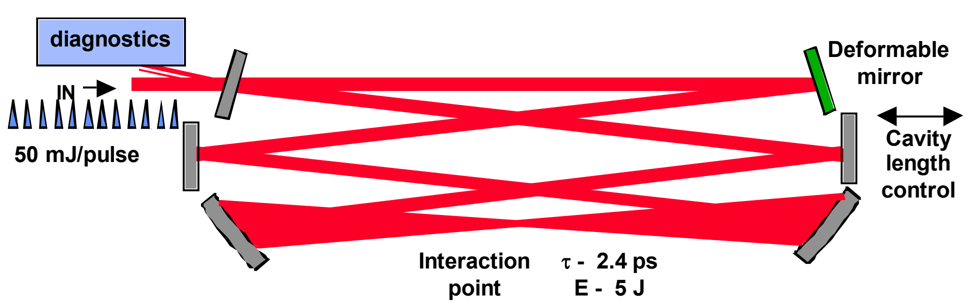
Brute force:

- High average power (~70 kW)



Recirculating cavity:

- 5-30x enhancement
- Gain replenishes loss each round trip
- Need very high efficiency optics (including gratings)



Resonant cavity:

- 100-300x enhancement
- Stringent requirements on pulse spatial/ temporal overlap (nm)

Short-pulse lasers

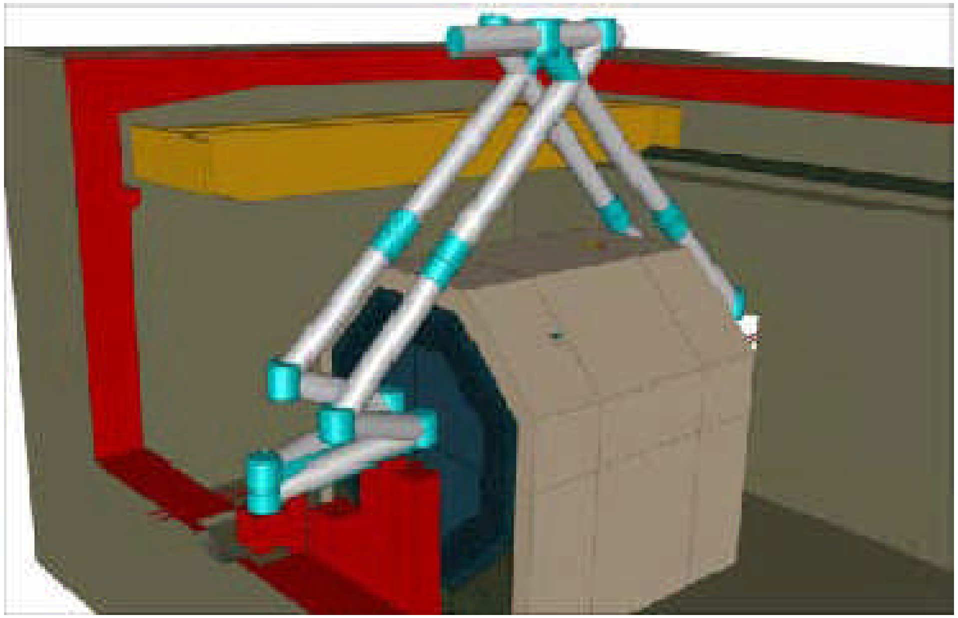
- **Chirped pulse amplification**
  - **Stretch pulses temporally before amplification to avoid nonlinear effects in optical system, then temporally compress after passing through most or all material**

- **State of the art**
  - **Jena fiber systems:**
    - **325 W average (8.2 μJ, 40 MHz, 375 fs, 30 μm Yb-PCF core)[1]**
    - **70 W average (0.7 mJ, 100 kHz, 800 fs, 80 μm Yb-PCF core)[2]**
  - **Long-pulse:**
    - **42 W average (4.3 mJ, 9.6 kHz, 1 ns, 100 μm Yb-PCF core)[3]**
    - **280 W average (150 μJ, 1.9 MHz, 3 ns, 41 mm Yb-LMA core)[4]**

[1] T. Eidam, et al., IEEE J. Sel. Top. Quant. Elect. 15, 187 (2009)
[2] F. Roser, et al., Opt. Lett. 32, 3495 (2007)
[3] C.D. Brooks and F. Di Teodoro, Appl. Phys. Lett. 89, 111119 (2006)
[4] W. Li, et al., Opt. Exp. 17, 10113 (2009)

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)**



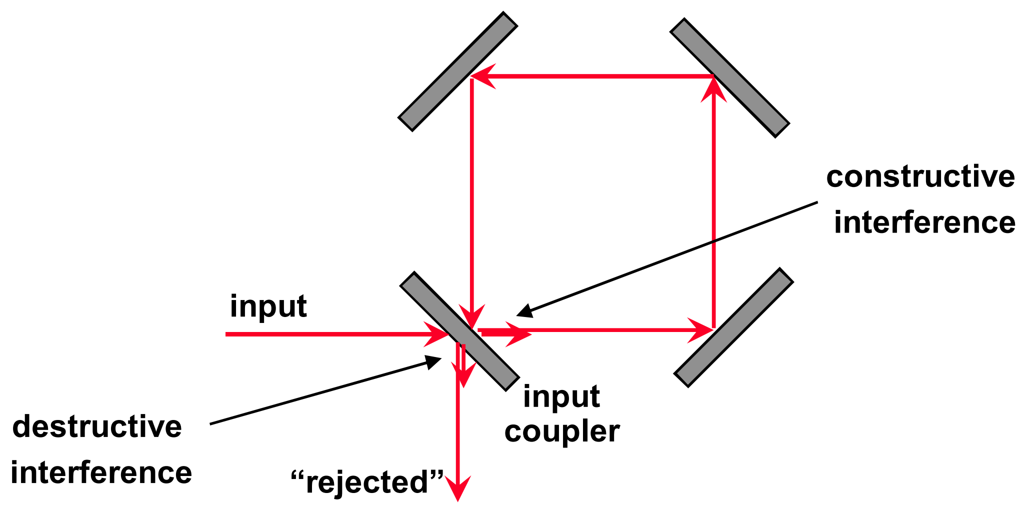
* I.Will, T. Quast, H. Redlin andW. Sander, “A Laser System For The TESLA Photon Collider Based On An External Ring Resonator”, *Nucl. Instrum. Meth.* A **472** (2001) 79.

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

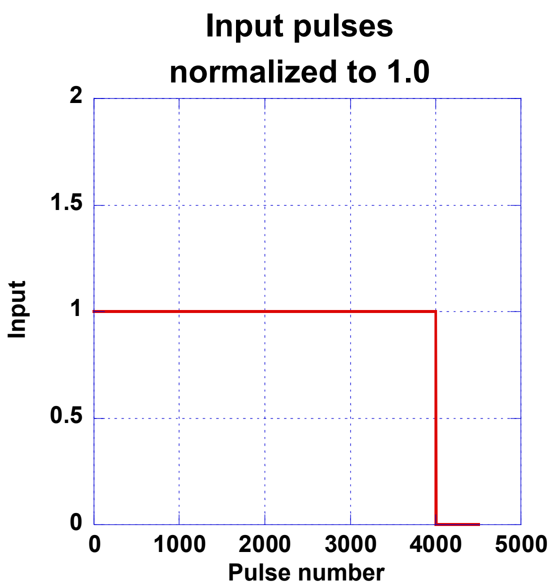
- Only ~10^{-9} of laser energy used in each interaction
  — Reuse photons, replenish cavity losses

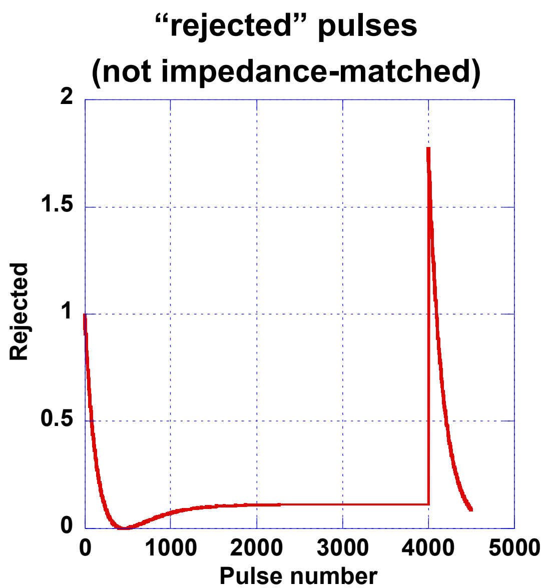
- Coherent addition of pulses in cavity requires extreme control of laser and cavity parameters

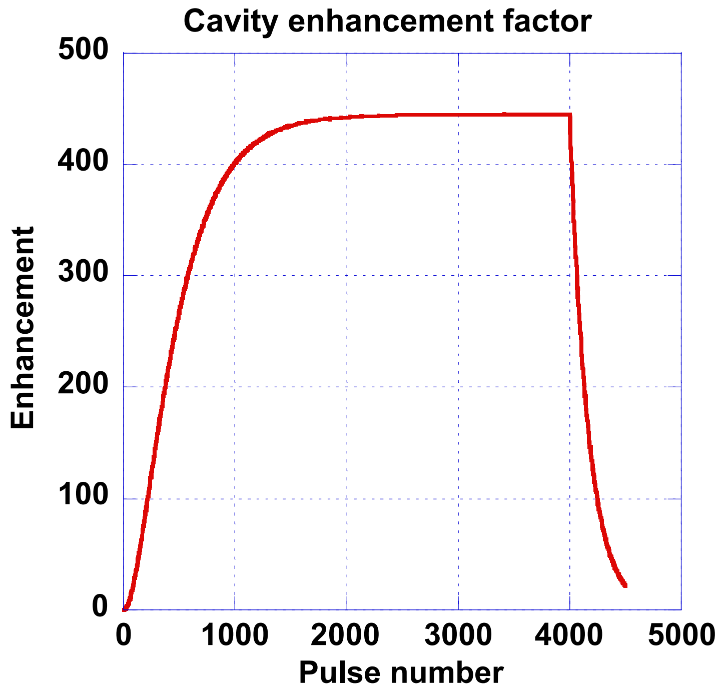


Resonant stacking cavity

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

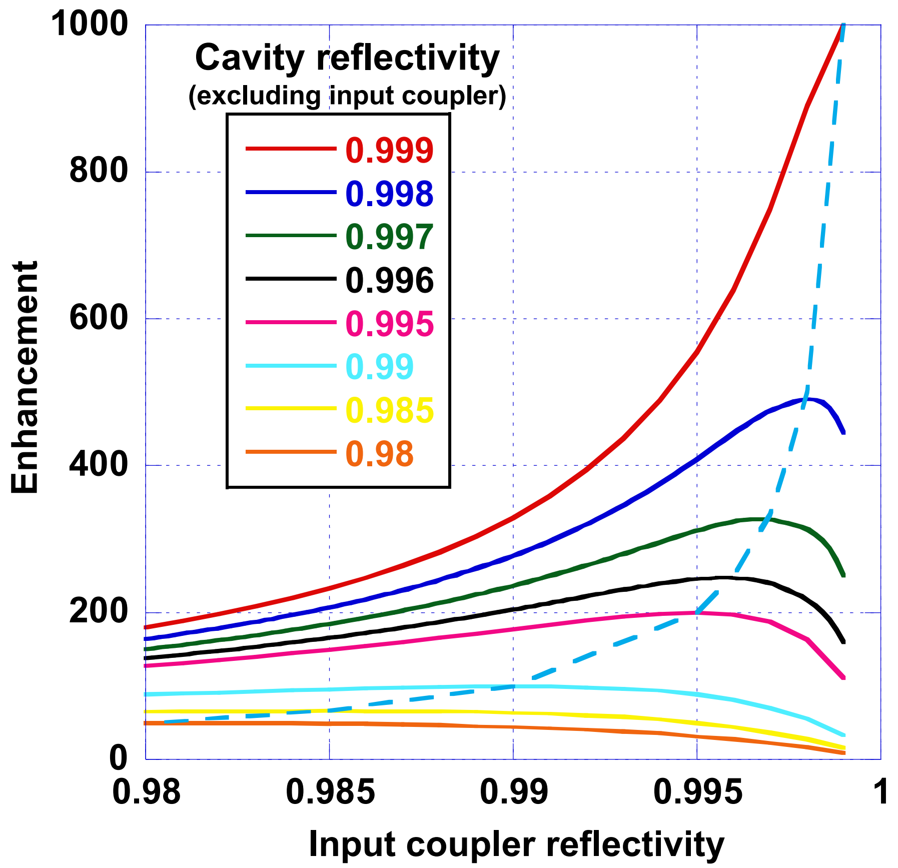






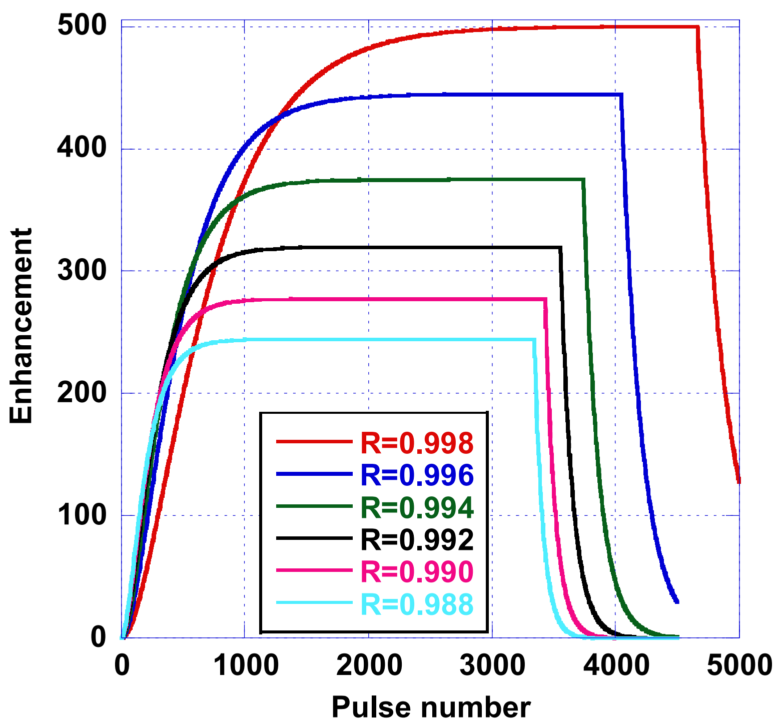
Enhancement as a function of mirror reflectivities

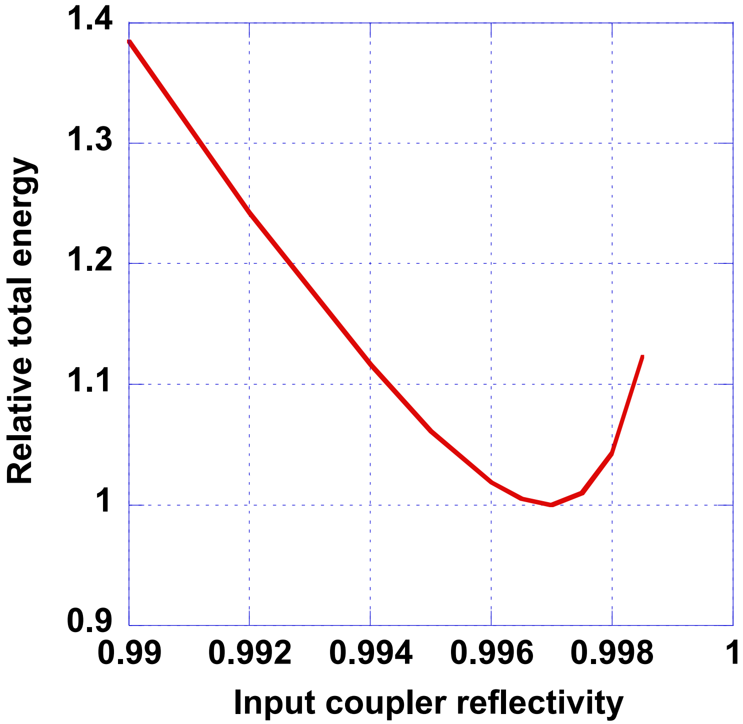
- Impedance-matched cavity (equal cavity and input coupler reflectivity) gives greatest enhancement for given cavity reflectivity
- For given input coupler, increasing cavity reflectivity increases enhancement



There is an optimum input coupler to minimize total energy

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





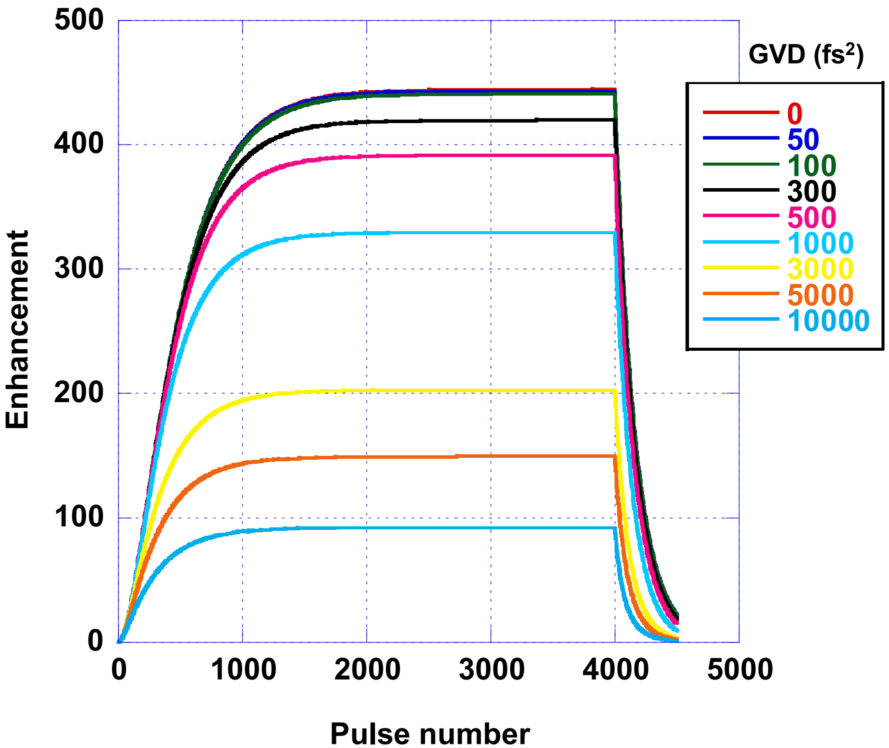
Resonant cavity enhancement puts stringent requirements on the laser and optics

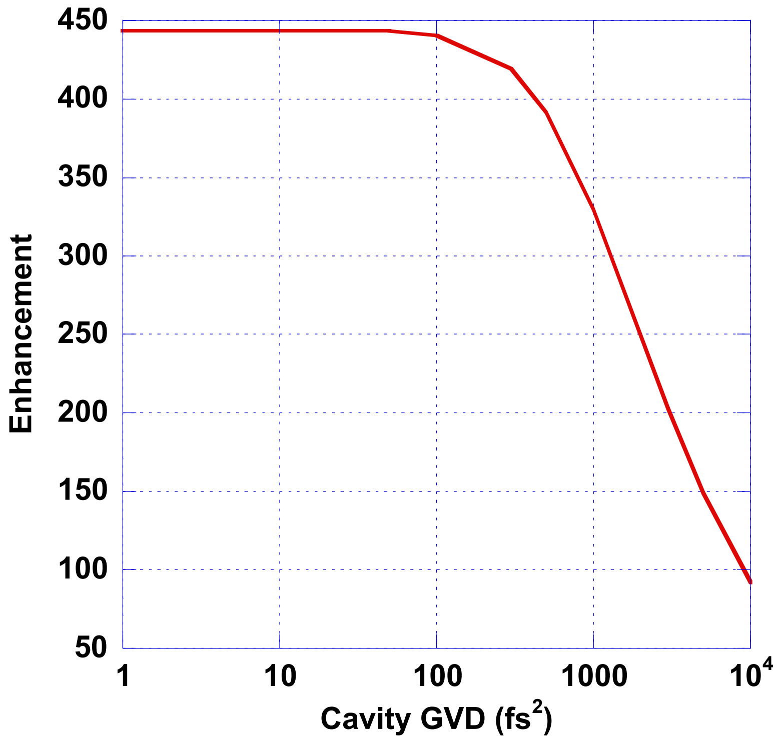
- Dispersion in resonant cavity
- Phase noise
- Cavity length/laser repetition frequency
- Amplitude noise
- Pointing through pulse compressor

- Coating damage due to scattered electrons and synchrotron radiation

Total cavity GVD should be less than 100 fs^2

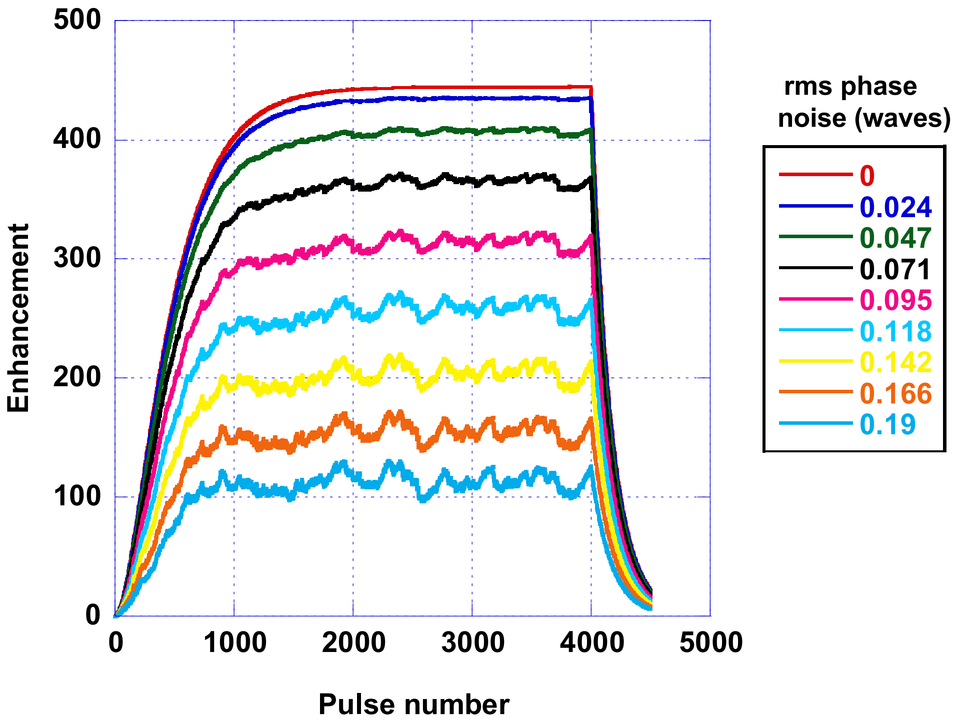
- Low-dispersion mirrors can be manufactured with < 10 fs^2 GVD
  - — Negative GVD mirrors also available

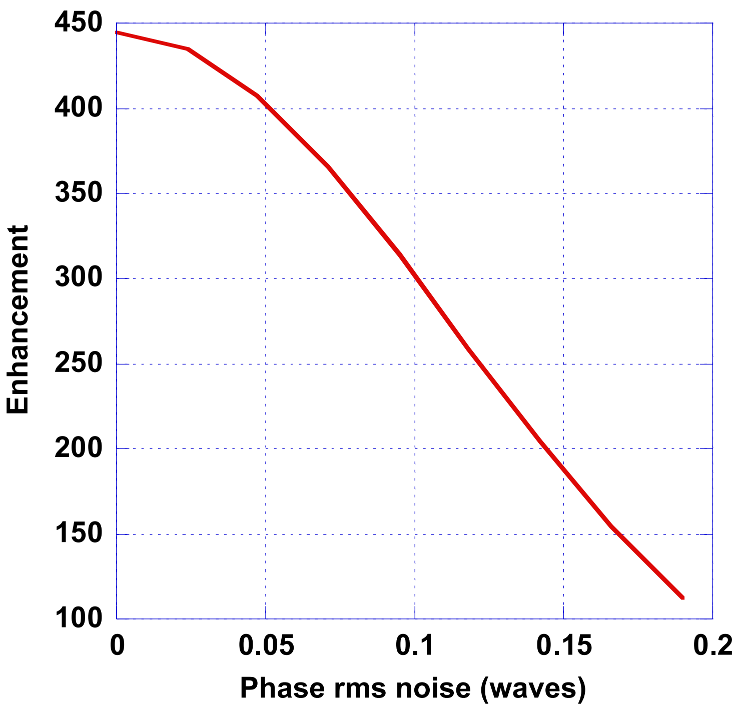




Phase noise

- 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)**



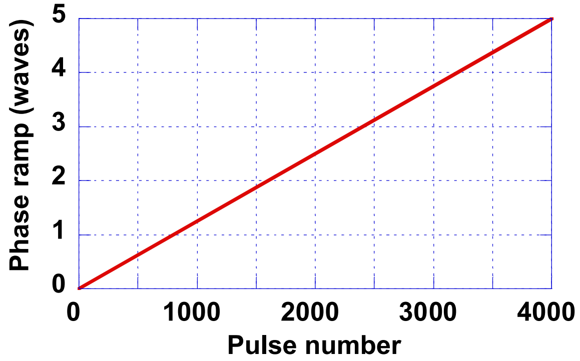


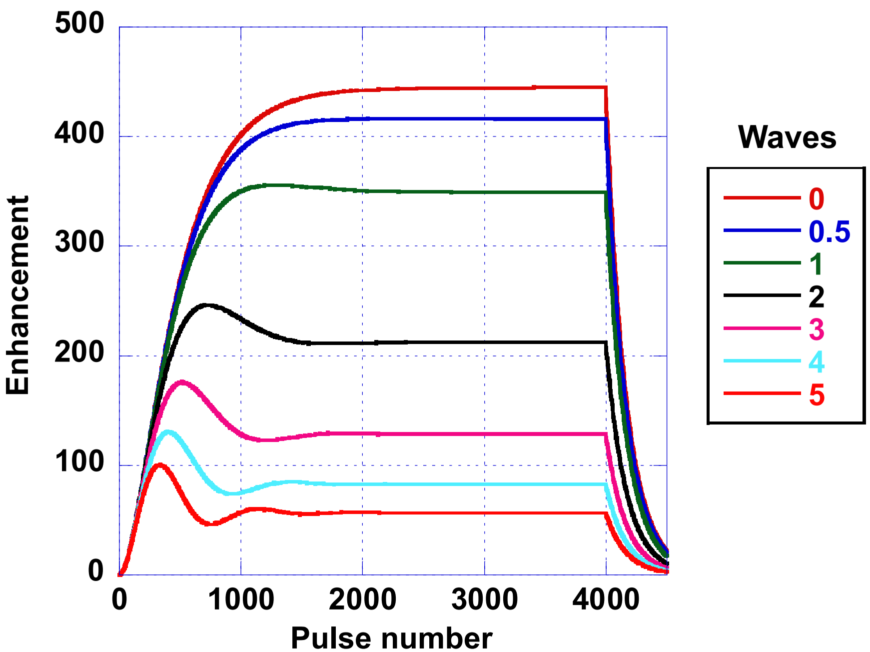
* E. Gagnon, et al., Opt. Lett. 31, 1866 (2006)

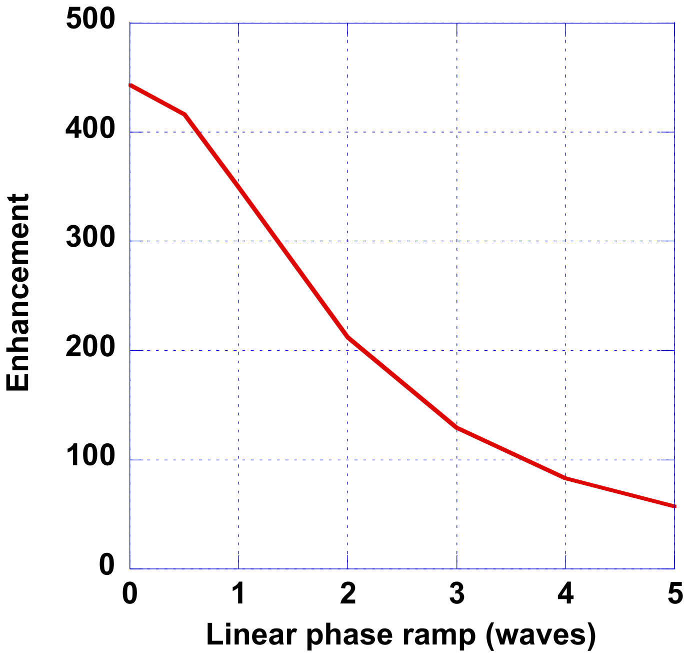
** A. Ozawa, et al., New J. Phys. 11, 083029 (2009)

Linear phase ramp through bunch

- Can relate to cavity length:
  1 wave ≈ 1 μm
  1 wave/bunch ≈ 0.7 mm/s

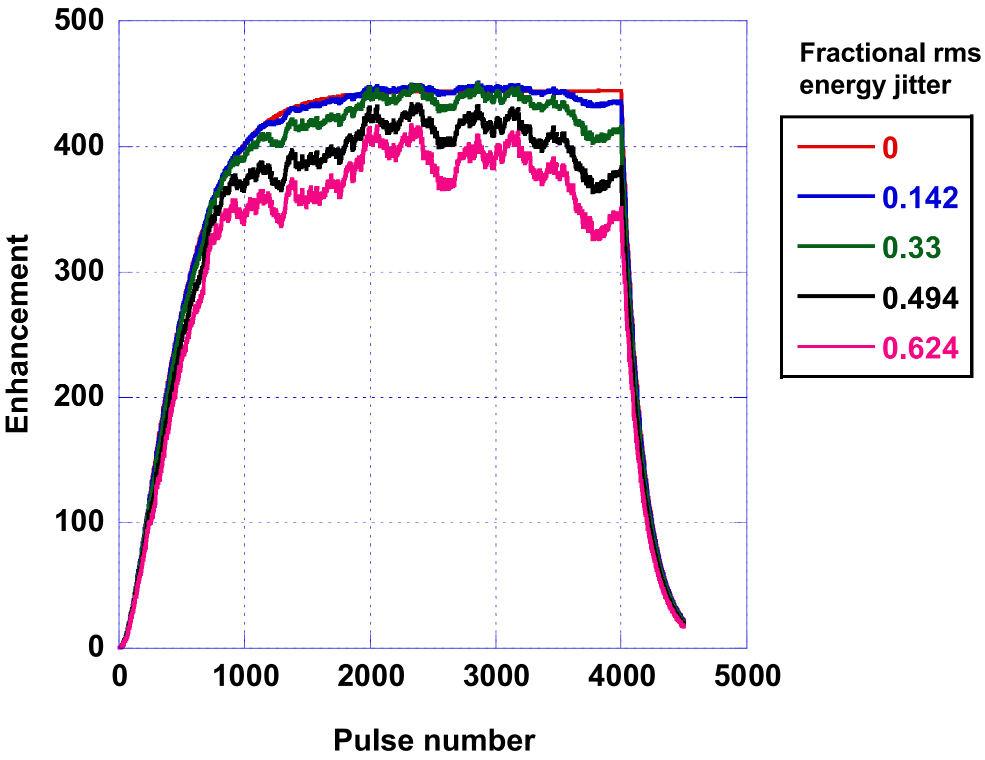


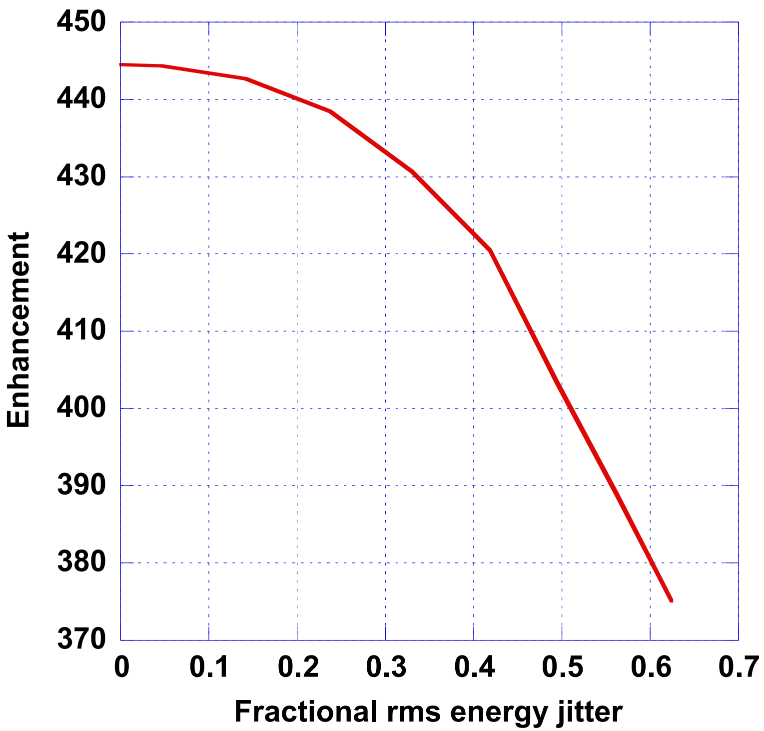




Energy jitter

- No B-integral (phase) variation





The B-integral is a measure of nonlinear phase accumulation

Refractive index:

$$n(r,t) = n_o + \gamma I(r,t)$$

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):

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

Optical Kerr effect results in:

- **Self-focusing and spatial beam collapse for B>3**
- **Self-phase modulation and temporal distortions for B>1**

At 1 J/cm^2 and 1064 nm, B=1 for:

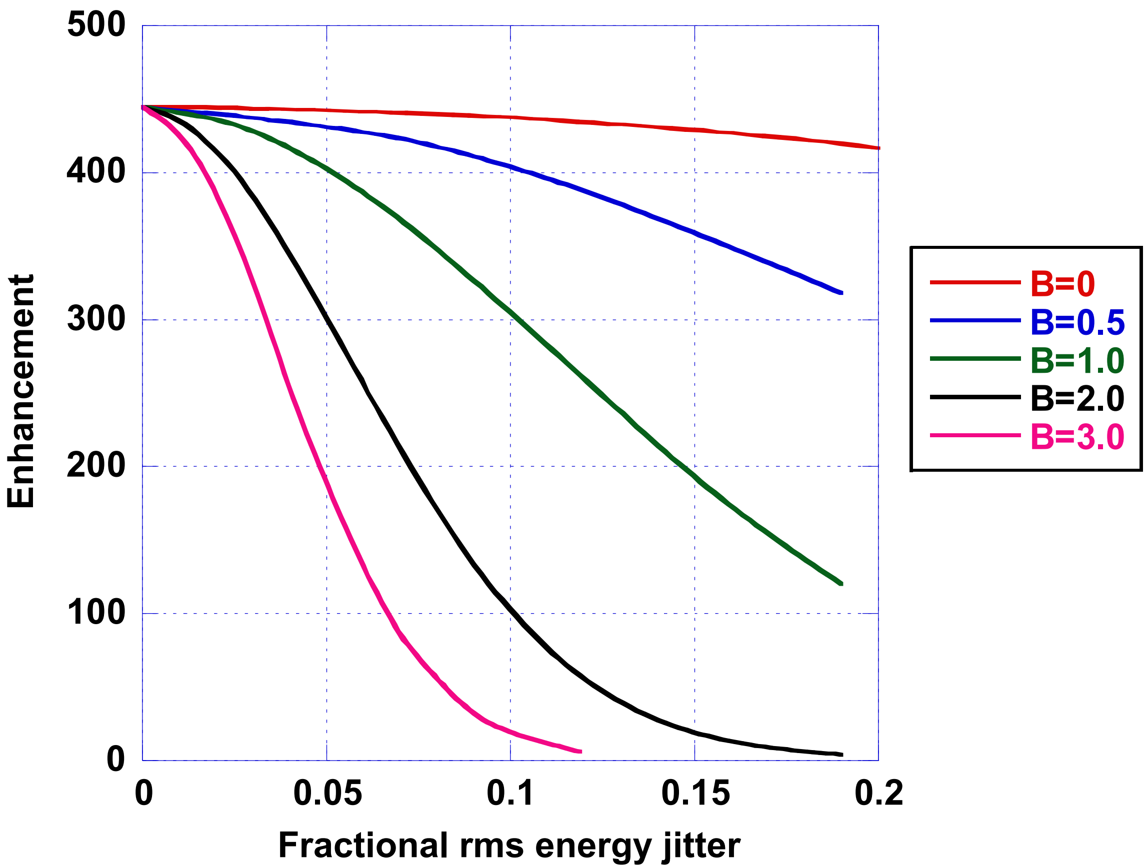
- **169 cm fused silica at 3 ns**
- **0.56 mm fused silica at 1 ps**

Fused silica:

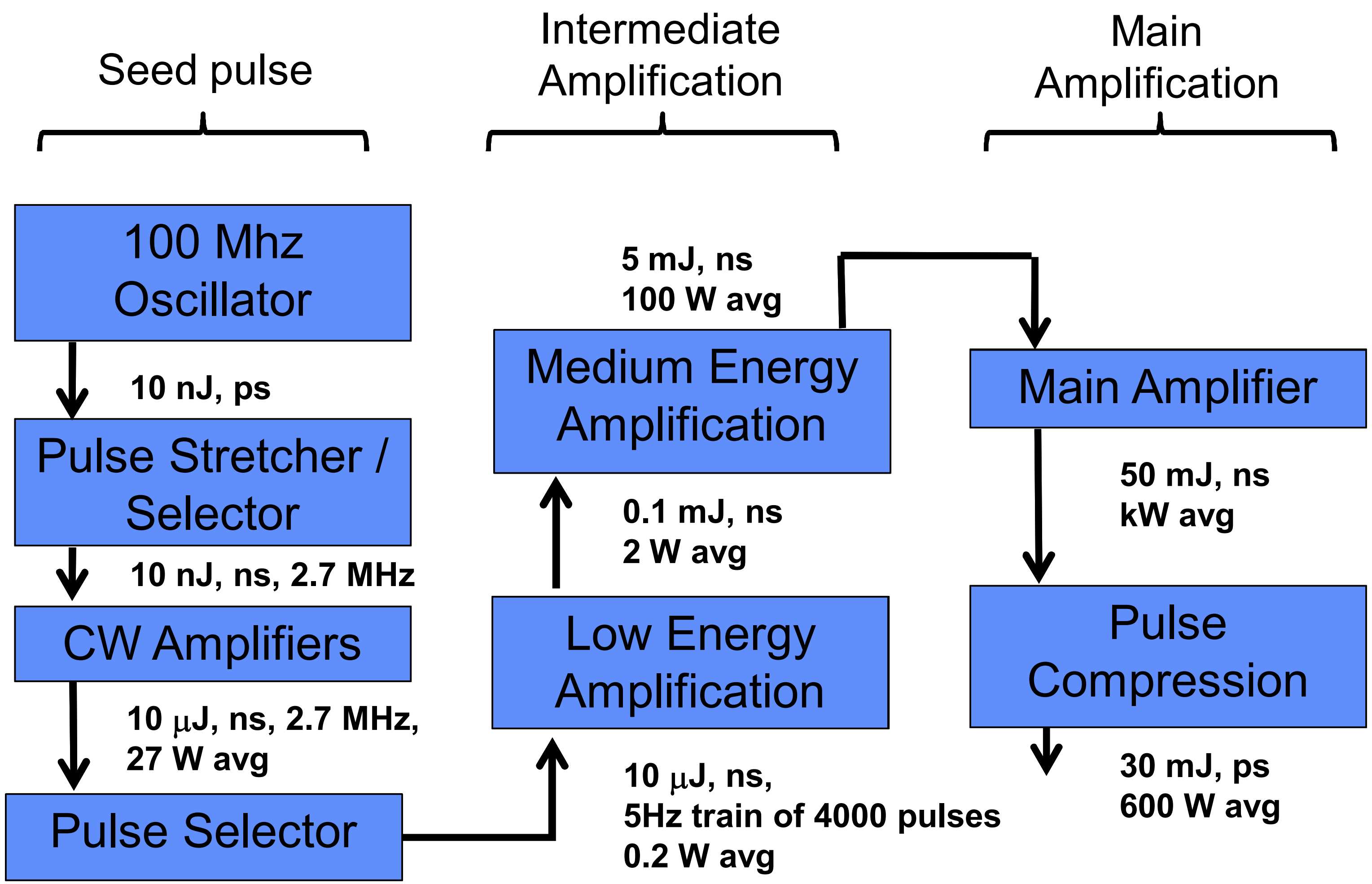
γ=3x10^{-16} cm^2/W

Energy jitter with B-integral

- Typical short-pulse lasers run with B<2, but some fiber-laser designs have B>5



Laser system concept



Pulse injection

100 MHz Oscillator

↓ 10nJ, ps

Pulse Stretcher / Selector

↓ 100nJ, ns, 2.7 MHz

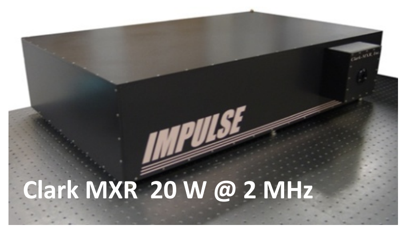
CW Amplifier

↓ 10μJ, ns, 2.7 MHz
27 W avg

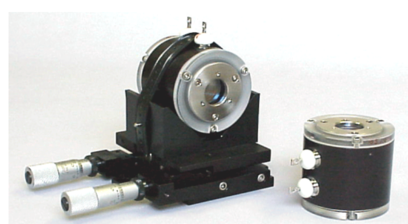
Pulse Selector


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™

Cutting Edge Optronics RBA PowerPULSE

- “Off-the-shelf” technology exists to reach this power level
- 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
kW avg

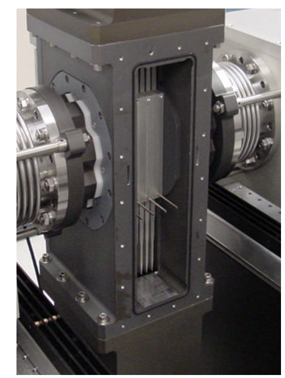
- **Not commercially available**
- **Basic enabling technologies exist:**
  - — **Diode pumping**
  - — **Thermal management**

Diode pumping

Higher efficiency and reliability, Lower thermal effects

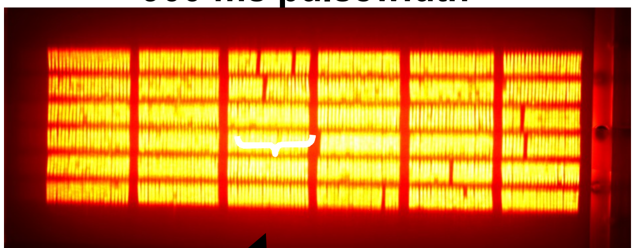
Forced cooling

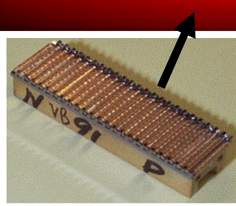
Allows 10-Hz operation



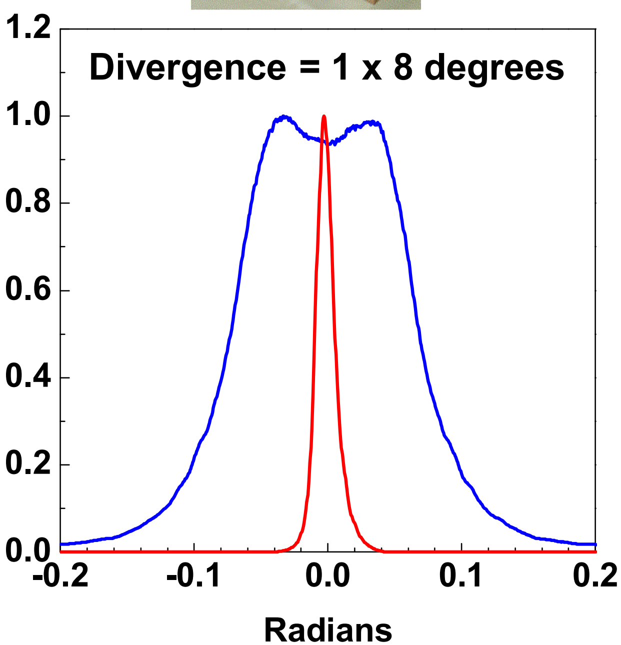
The Mercury laser at LLNL uses four 80 kW diode arrays for a total of 320 kW of peak diode power

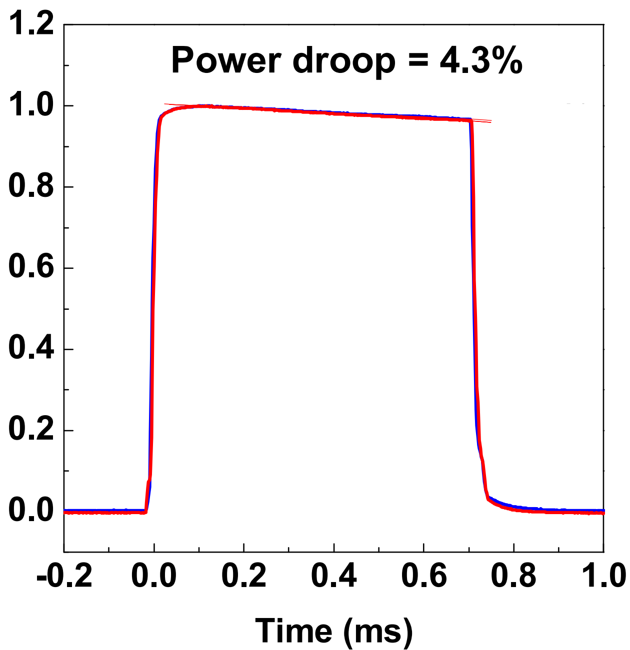
Operated at:
- 120 W/bar at 10 Hz
- 900 ms pulsewidth

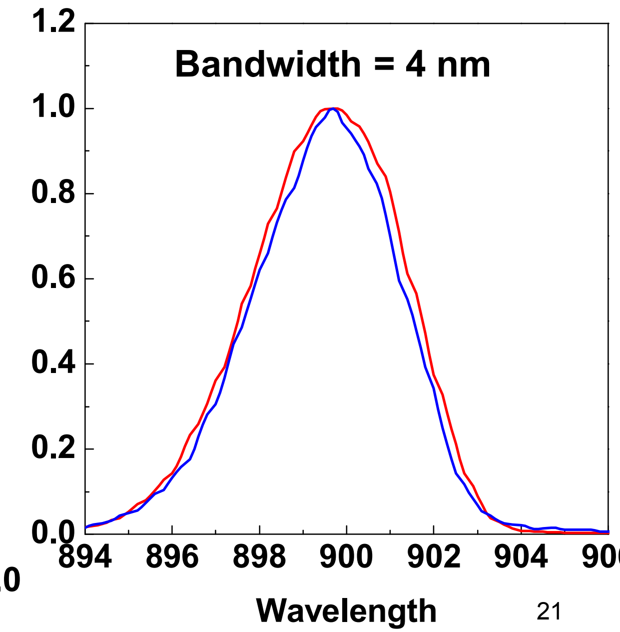




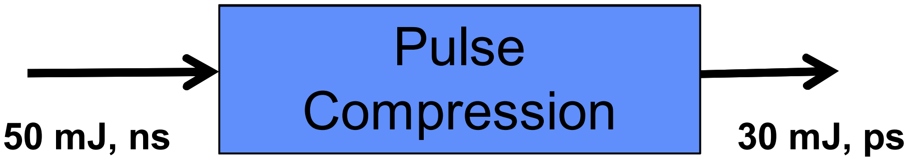
tile with 23 diode bars







Pulse Compression



- System will be in vacuum after compression
- Large gratings are needed to keep power levels low

Vacuum compressor (Titan – LLNL)

World's largest dielectric gratings (LLNL)

Work to be done

- Design of final amplifiers
  - Gain material
  - Pumping/extraction geometry
  - Minimize thermal effects
- Modeling of 2D sensitivities
  - Pointing jitter
  - Diffraction losses
  - Optical aberrations
- Conceptual design of laser system
- Conceptual design of control system