Photon Collider Laser

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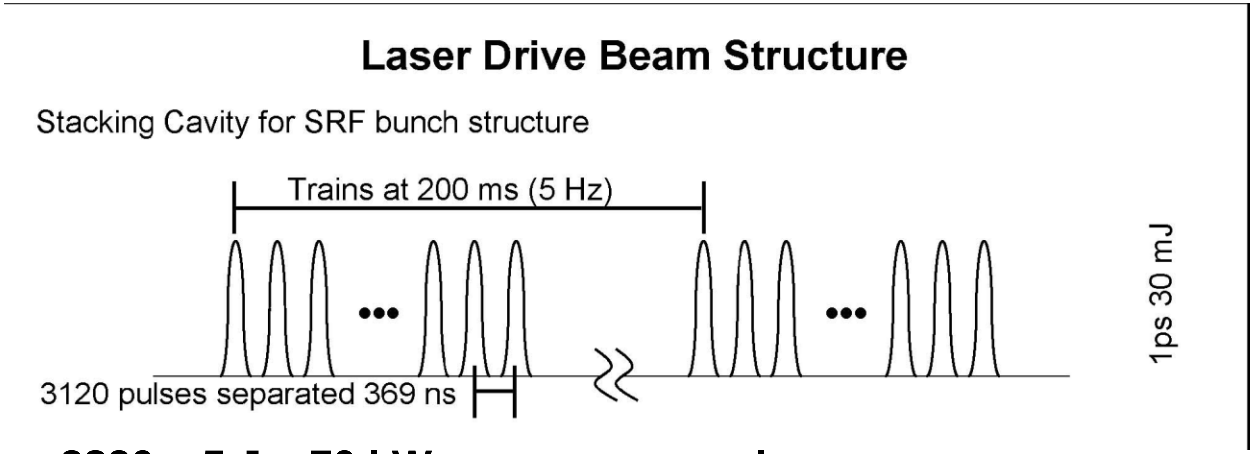
Outline

- 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**



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

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]
  - Innoslab (Aachen):
    - 400 W average (5.3 μJ, 76 MHz, 682 fs, Yb:YAG slab)[3]
  - Long-pulse:
    - 42 W average (4.3 mJ, 9.6 kHz, 1 ns, 100 μm Yb-PCF core)[4]
    - 280 W average (150 μJ, 1.9 MHz, 3 ns, 41 mm Yb-LMA core)[5]

[1] T. Eidam, et al., IEEE J. Sel. Top. Quant. Elect. 15, 187 (2009)

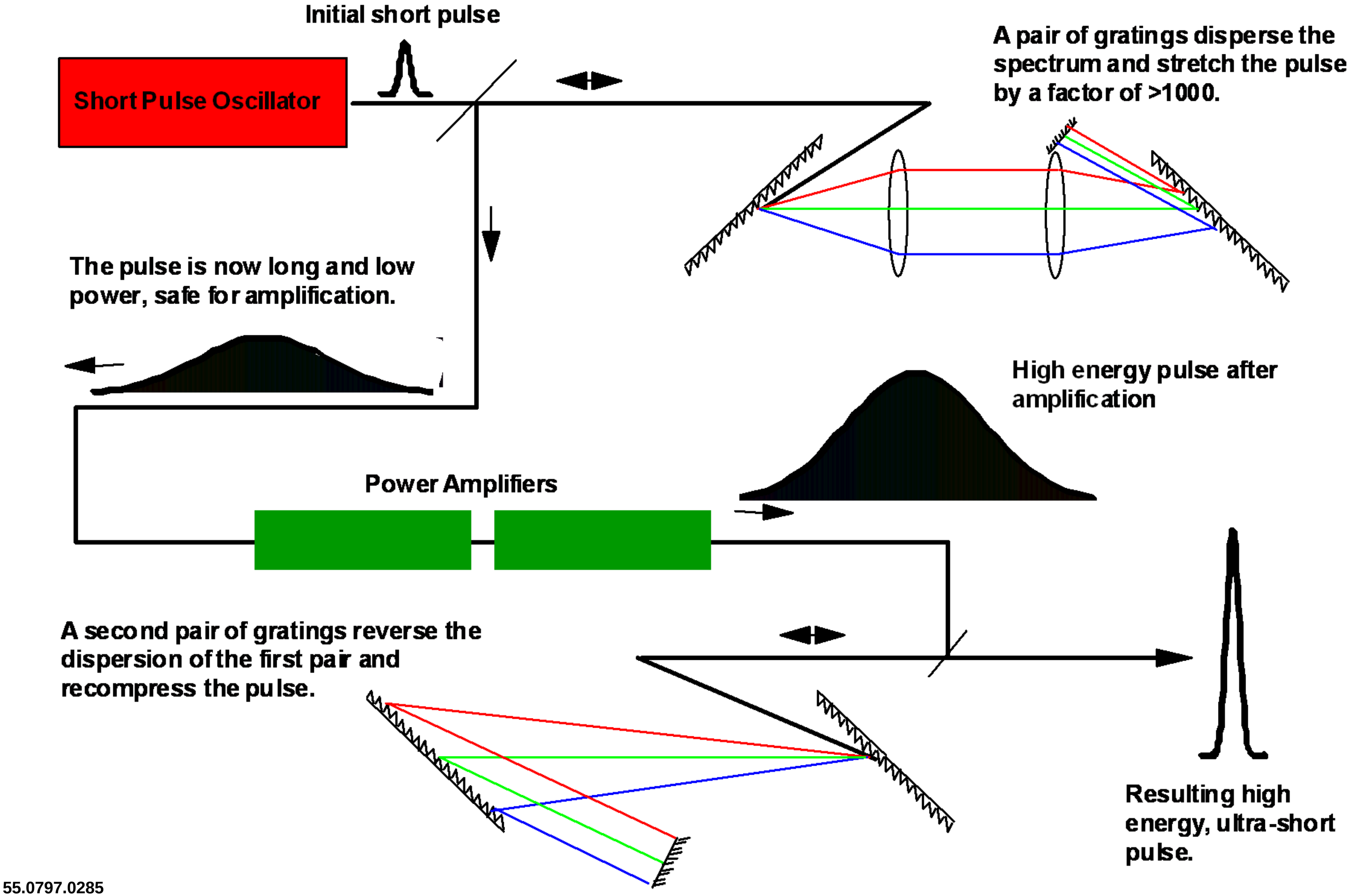
[2] F. Roser, et al., Opt. Lett. 32, 3495 (2007)

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

[4] C.D. Brooks and F. Di Teodoro, Appl. Phys. Lett. 89, 111119 (2006)

[5] W. Li, et al., Opt. Exp. 17, 10113 (2009)

Chirped Pulse Amplification is used to avoid nonlinear effects in amplifiers and other material



Initial short pulse

Short Pulse Oscillator

A pair of gratings disperse the spectrum and stretch the pulse by a factor of >1000.

The pulse is now long and low power, safe for amplification.

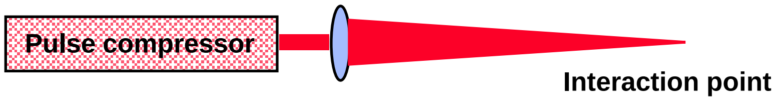
High energy pulse after amplification

Power Amplifiers

A second pair of gratings reverse the dispersion of the first pair and recompress the pulse.

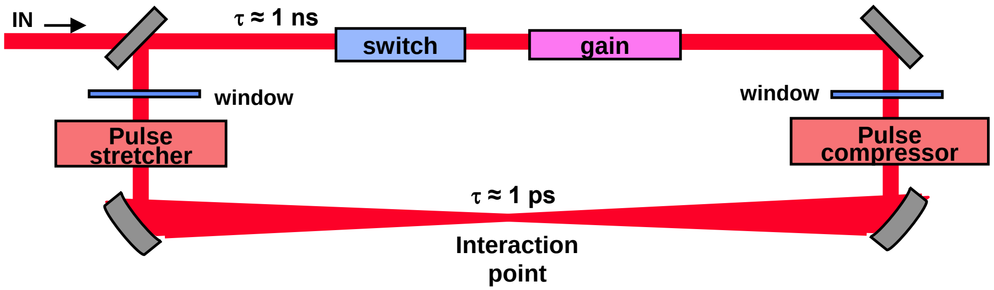
Resulting high energy, ultra-short pulse.

Laser requirements depend on interaction configuration



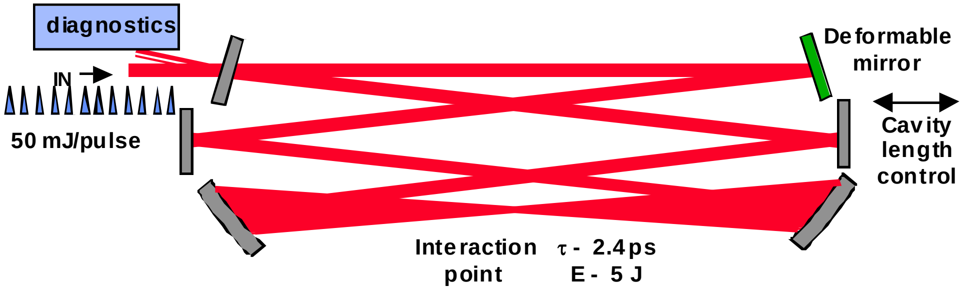
Brute force:

- High average power (~70-140 kW)



Recirculating cavity:

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

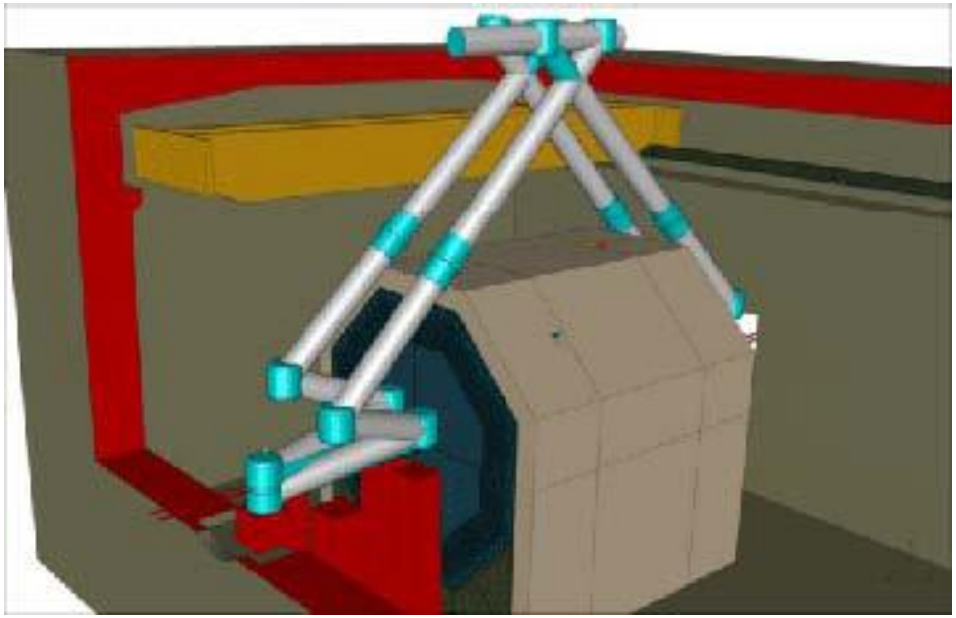


Resonant cavity:

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

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)**

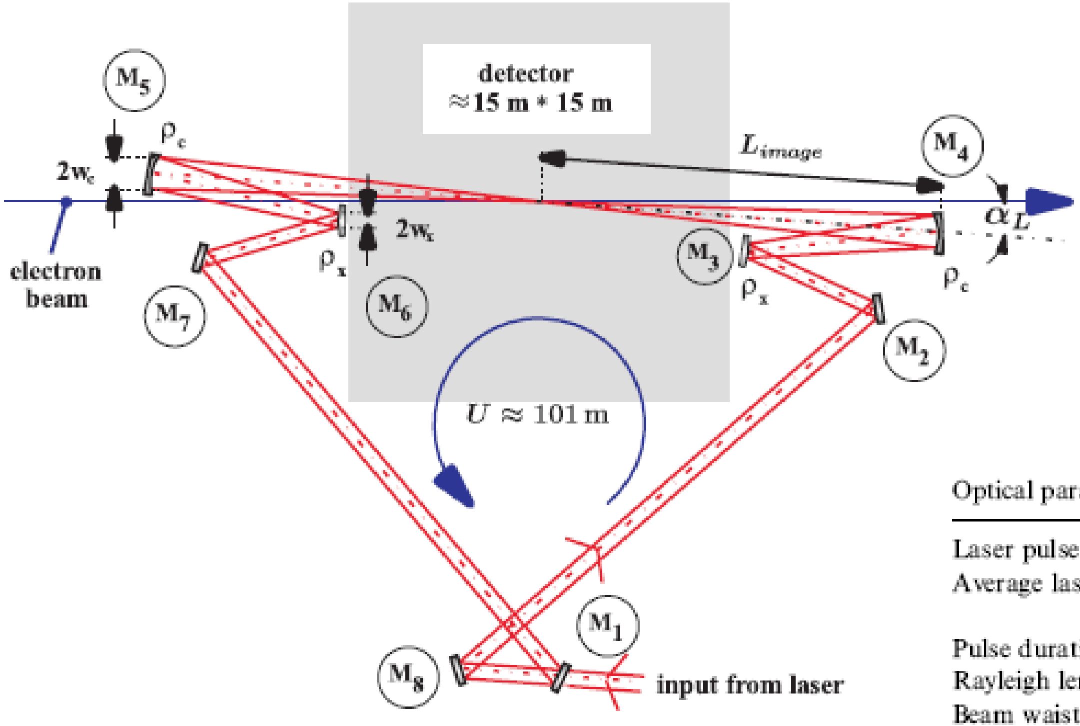


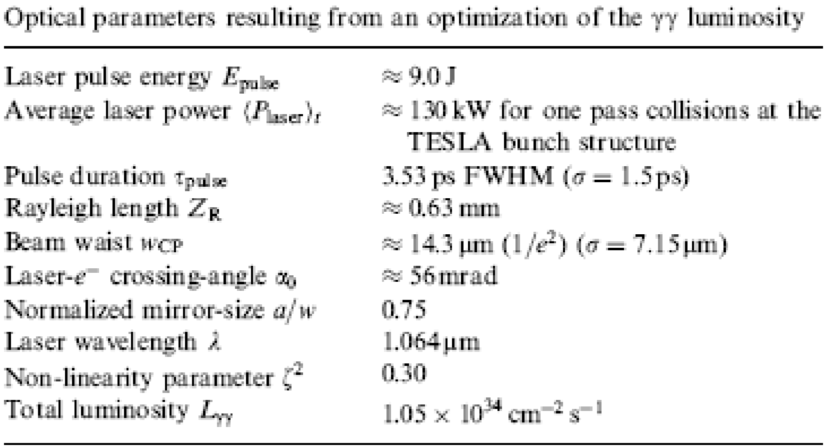
* I.Will, T. Quast, H. Redlin andW. Sander, “A Laser System For The TESLA Photon Collider Based On An External Ring Resonator”, *Nucl. Instrum. Meth.* A **472** (2001) 79.

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.

Conceptual design for a resonant stacking cavity

G. Klemz et al. / Nuclear Instruments and Methods in Physics Research A 564 (2006) 212–224





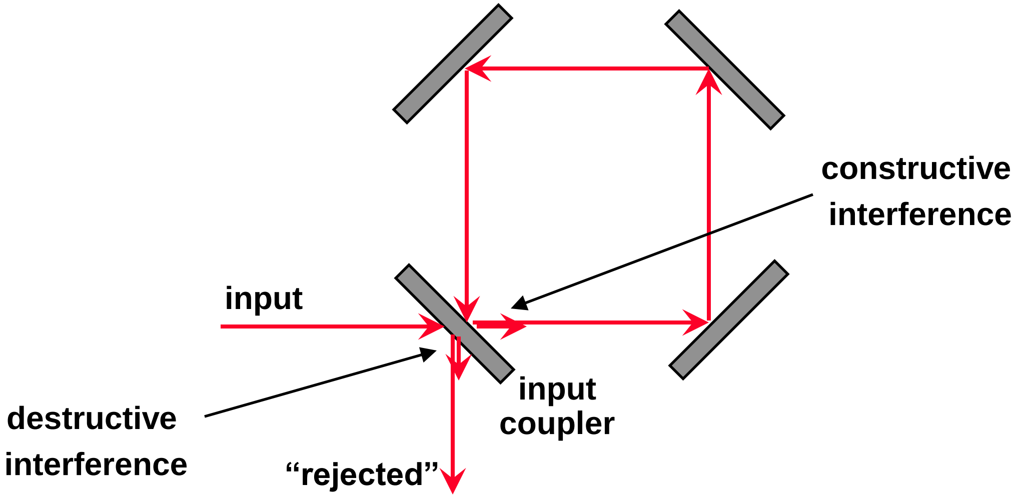
Optical parameters resulting from an optimization of the γγ luminosity

Laser pulse energy E_{pulse}	≈ 9.0 J
Average laser power $\langle P_{\text{laser}} \rangle_t$	≈ 130 kW for one pass collisions at the TESLA bunch structure
Pulse duration τ_{pulse}	3.53 ps FWHM ($\sigma = 1.5$ ps)
Rayleigh length Z_{R}	≈ 0.63 mm
Beam waist w_{CP}	≈ 14.3 µm ($1/e^2$) ($\sigma = 7.15$ µm)
Laser-e^- crossing-angle α_0	≈ 56 mrad
Normalized mirror-size a/w	0.75
Laser wavelength λ	1.064 µm
Non-linearity parameter ξ^2	0.30
Total luminosity $L_{\gamma\gamma}$	1.05×10^{34} cm^{-2} s^{-1}

Resonant stacking cavity

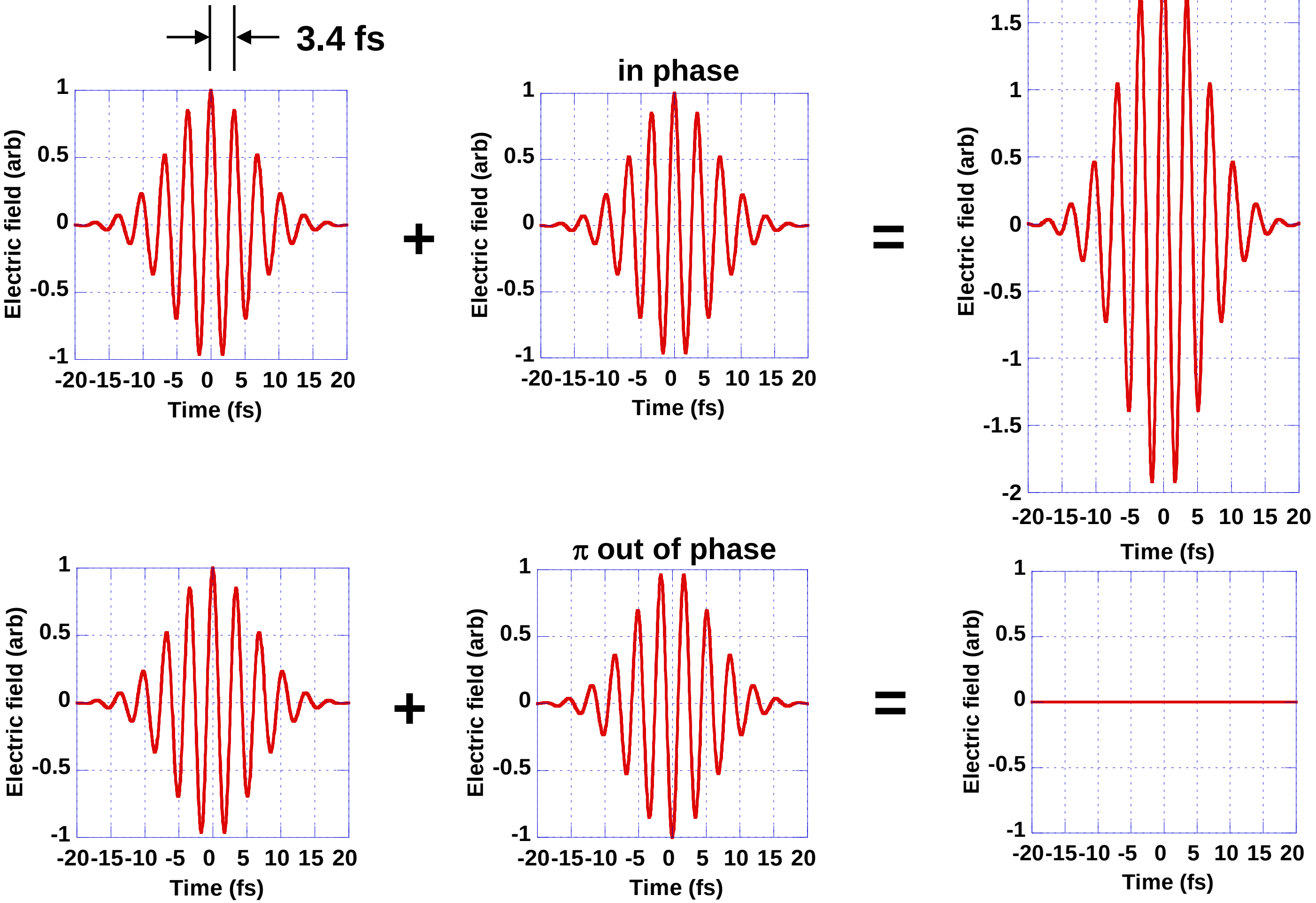
- Only ~10^{-9} of laser energy used in each interaction
  - Reuse photons, replenish cavity losses

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



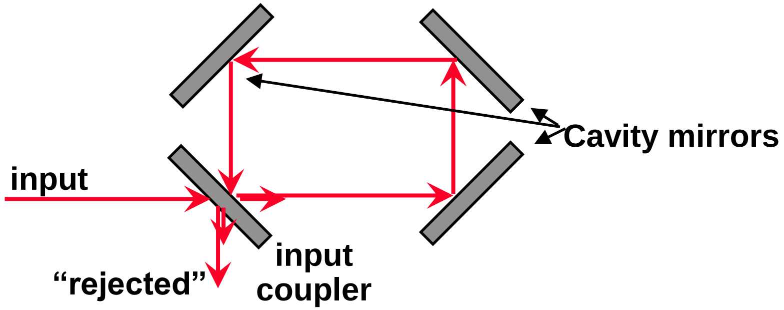
Coherent pulse addition

- **10-fs transform-limited pulses at 1030 nm**



Resonant stacking cavity

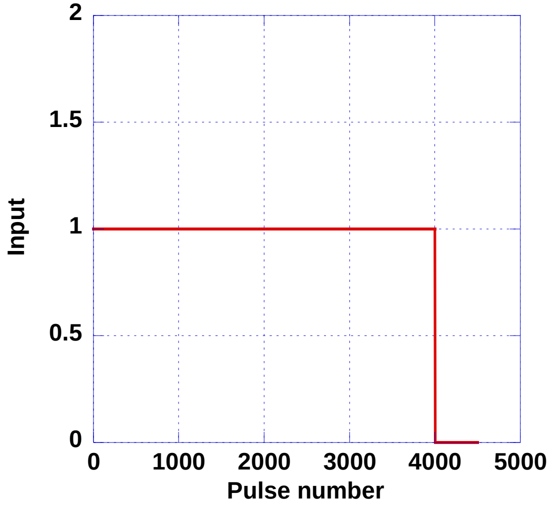
- Baseline case: input coupler R=0.996, cavity mirrors R=0.998



Cavity round-trip lifetime ≈ 225 pulses

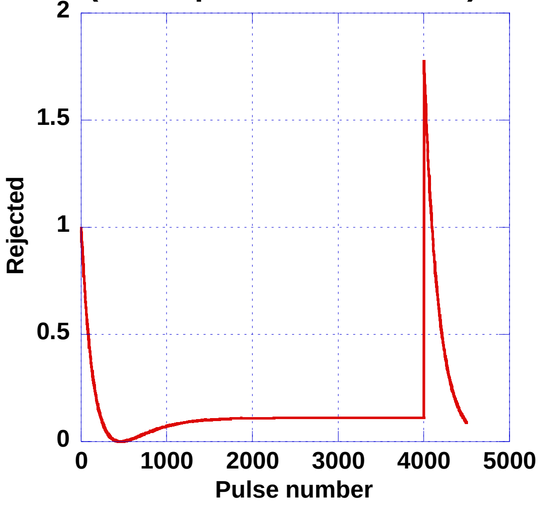
Input pulses

normalized to 1.0

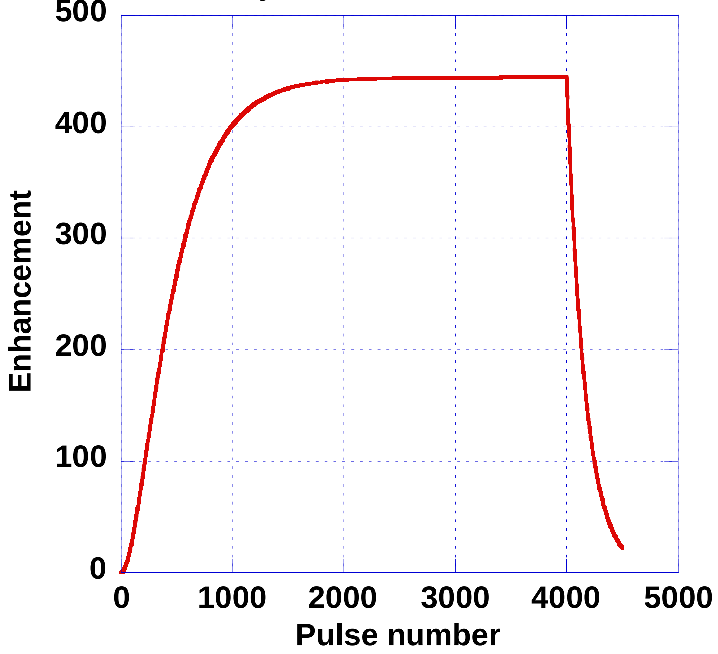


"rejected" pulses

(not impedance-matched)

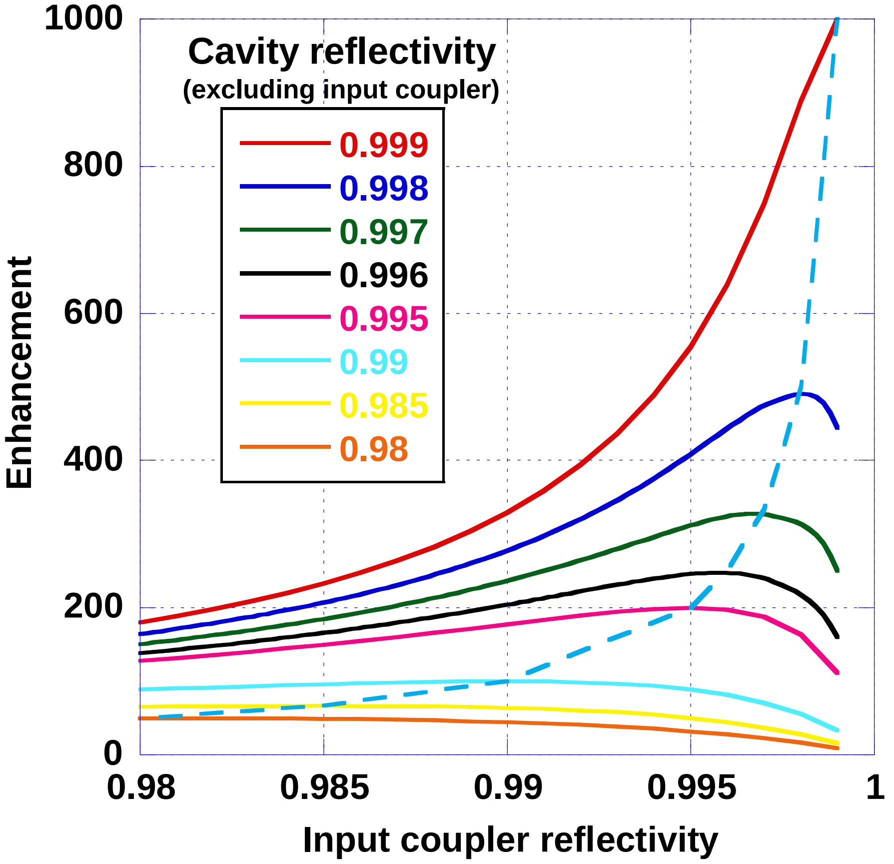


Cavity enhancement factor



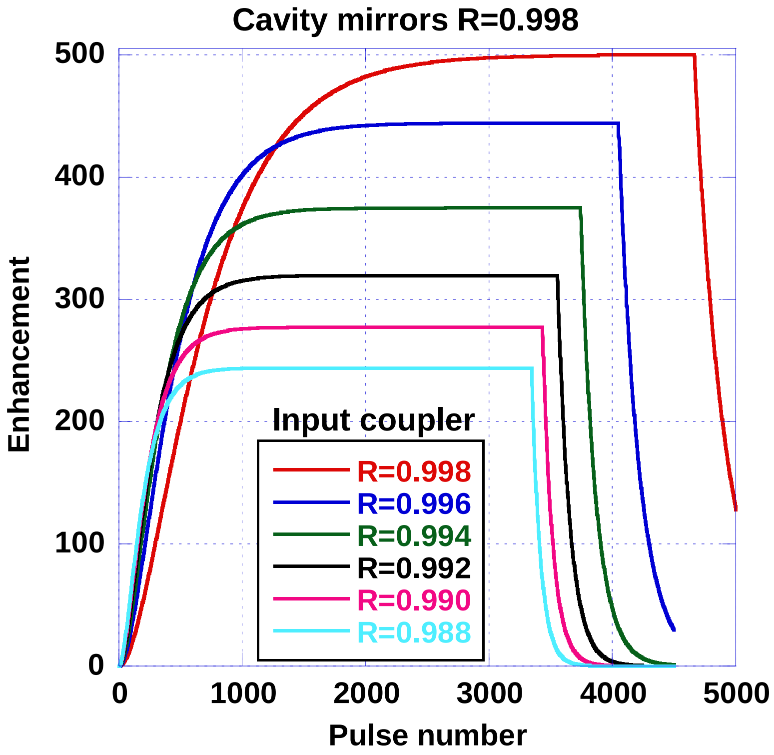
Enhancement as a function of mirror reflectivities

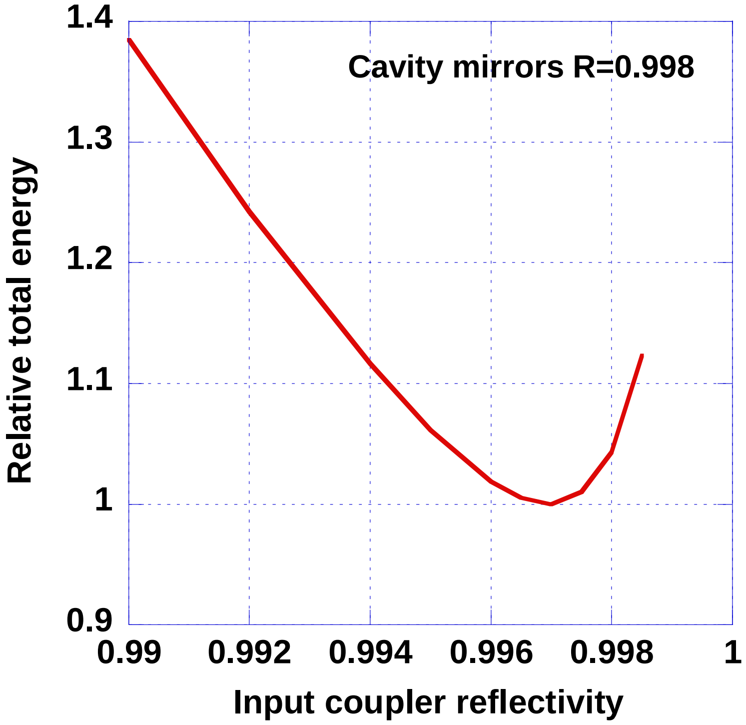
- Impedance-matched cavity (equal cavity and input coupler reflectivity) gives greatest enhancement for given cavity reflectivity
- For given input coupler, increasing cavity reflectivity increases enhancement



There is an optimum input coupler to minimize total energy

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





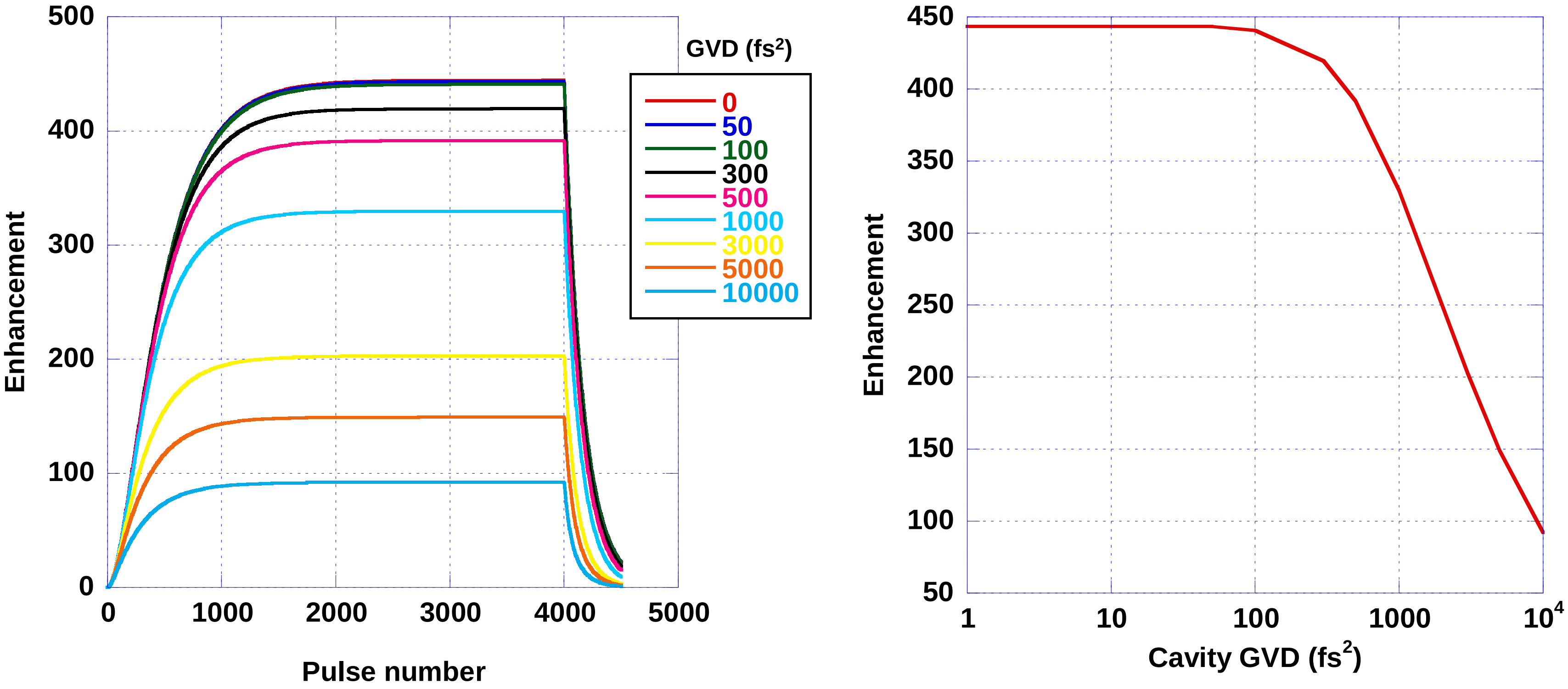
Resonant cavity enhancement puts stringent requirements on the laser and optics

- **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

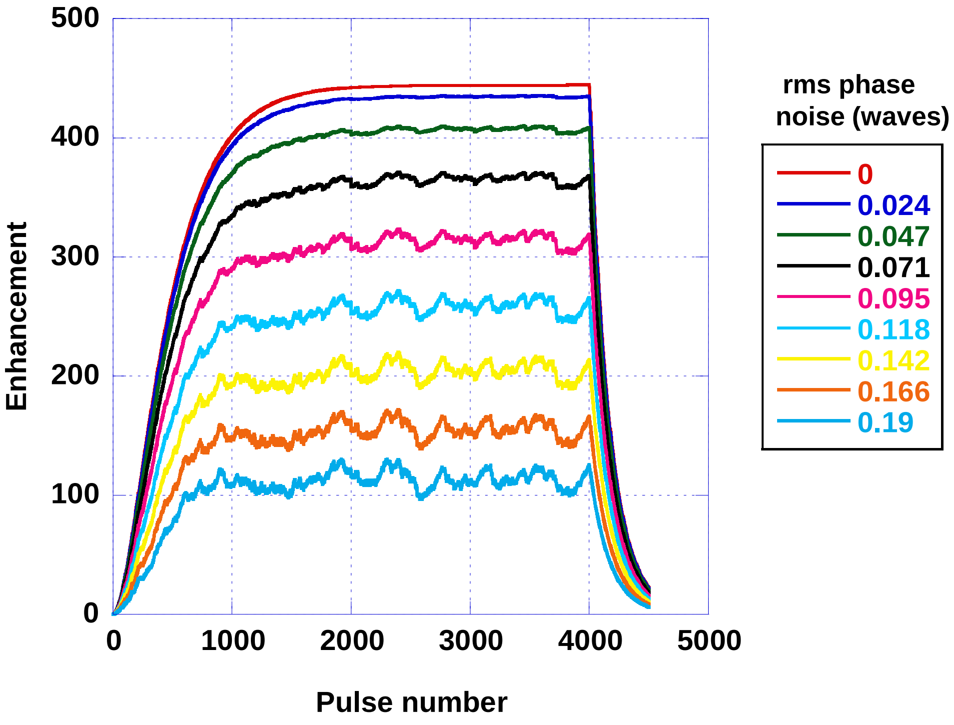
- **Low-dispersion mirrors can be manufactured with < 10 fs^2 GVD**
  - **Negative GVD mirrors also available**

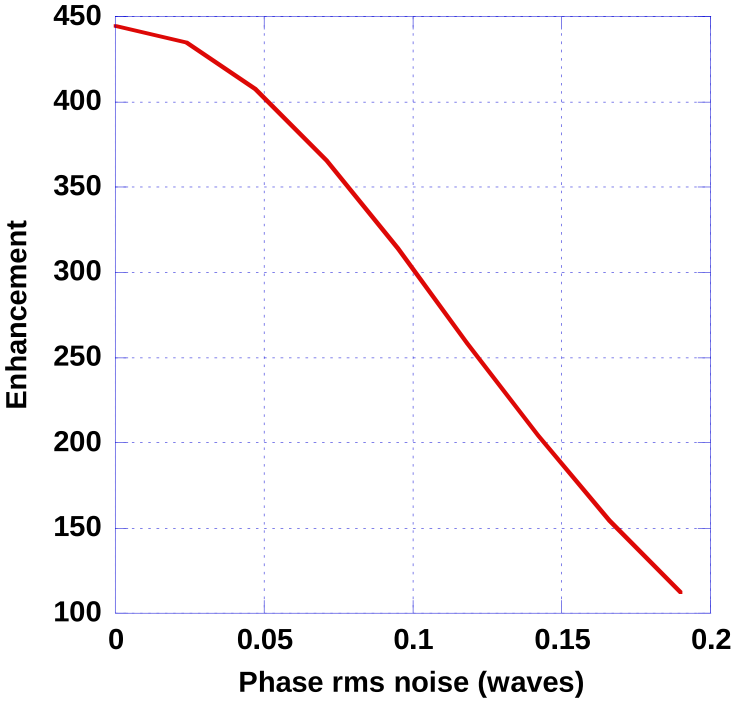


1 ps (FWHM) transform-limited input pulses

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)**





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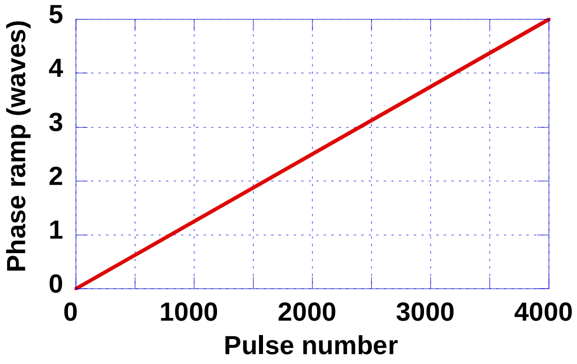
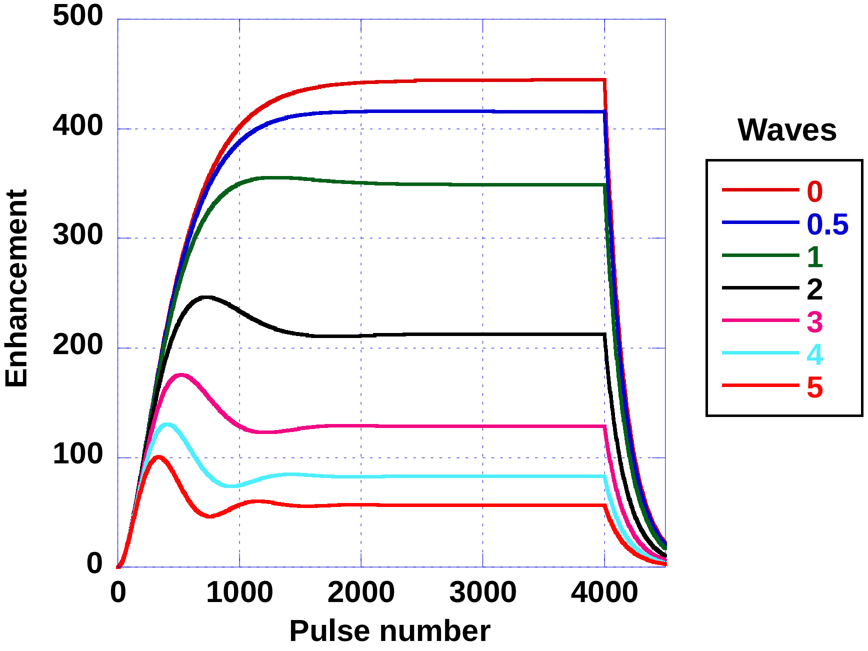
* E. Gagnon, et al., Opt. Lett. 31, 1866 (2006)

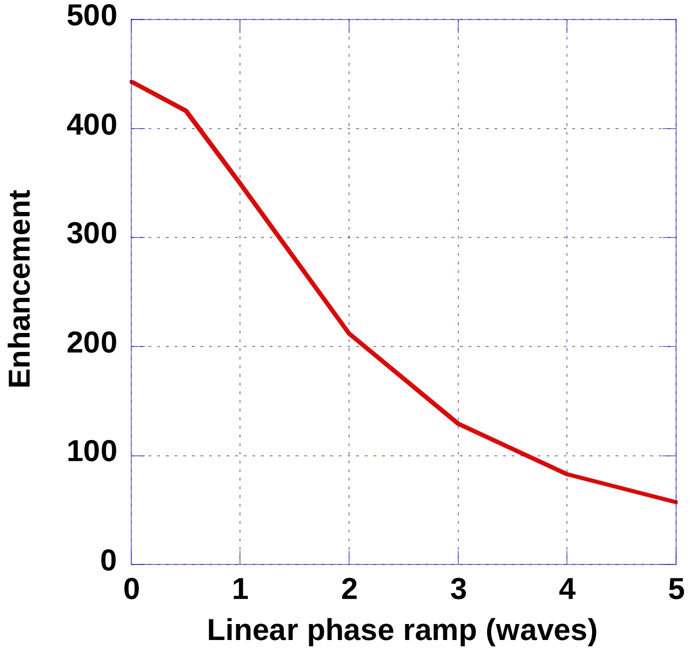
** A. Ozawa, et al., New J. Phys. 11, 083029 (2009)

Linear phase ramp through bunch

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

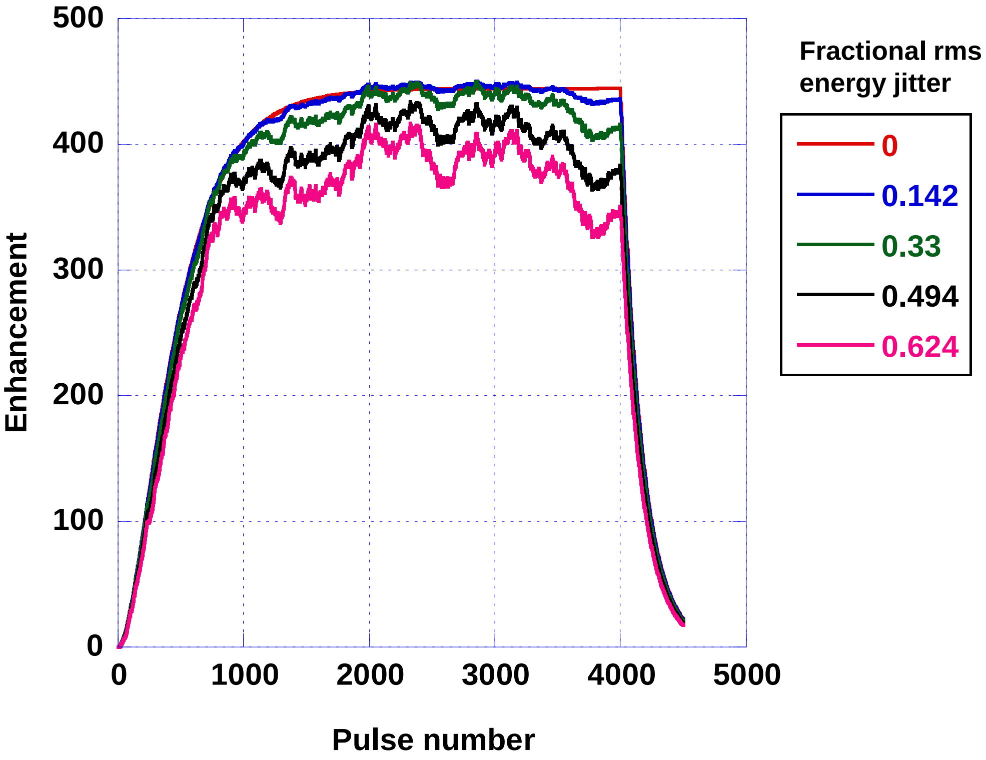


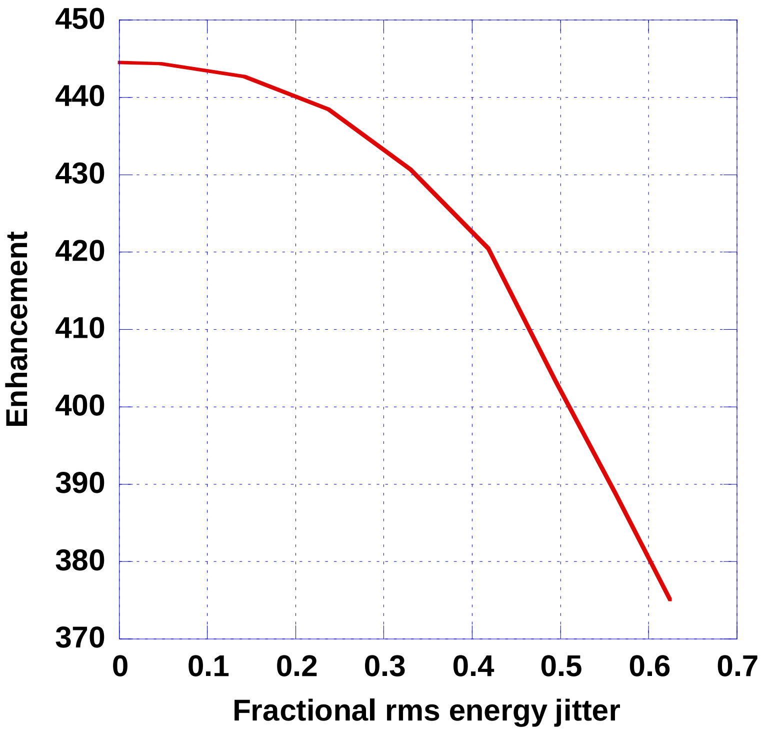




Energy jitter

- **Large jitter acceptable with 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**

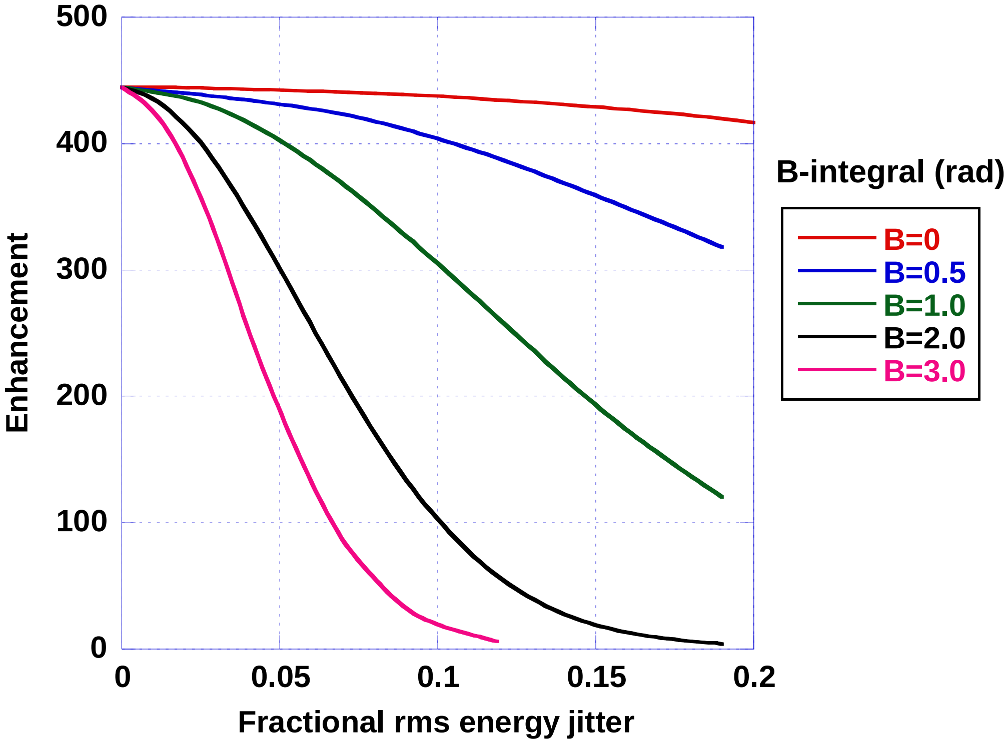
At 1 J/cm^2 and 1064 nm, B=1 radian for:

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

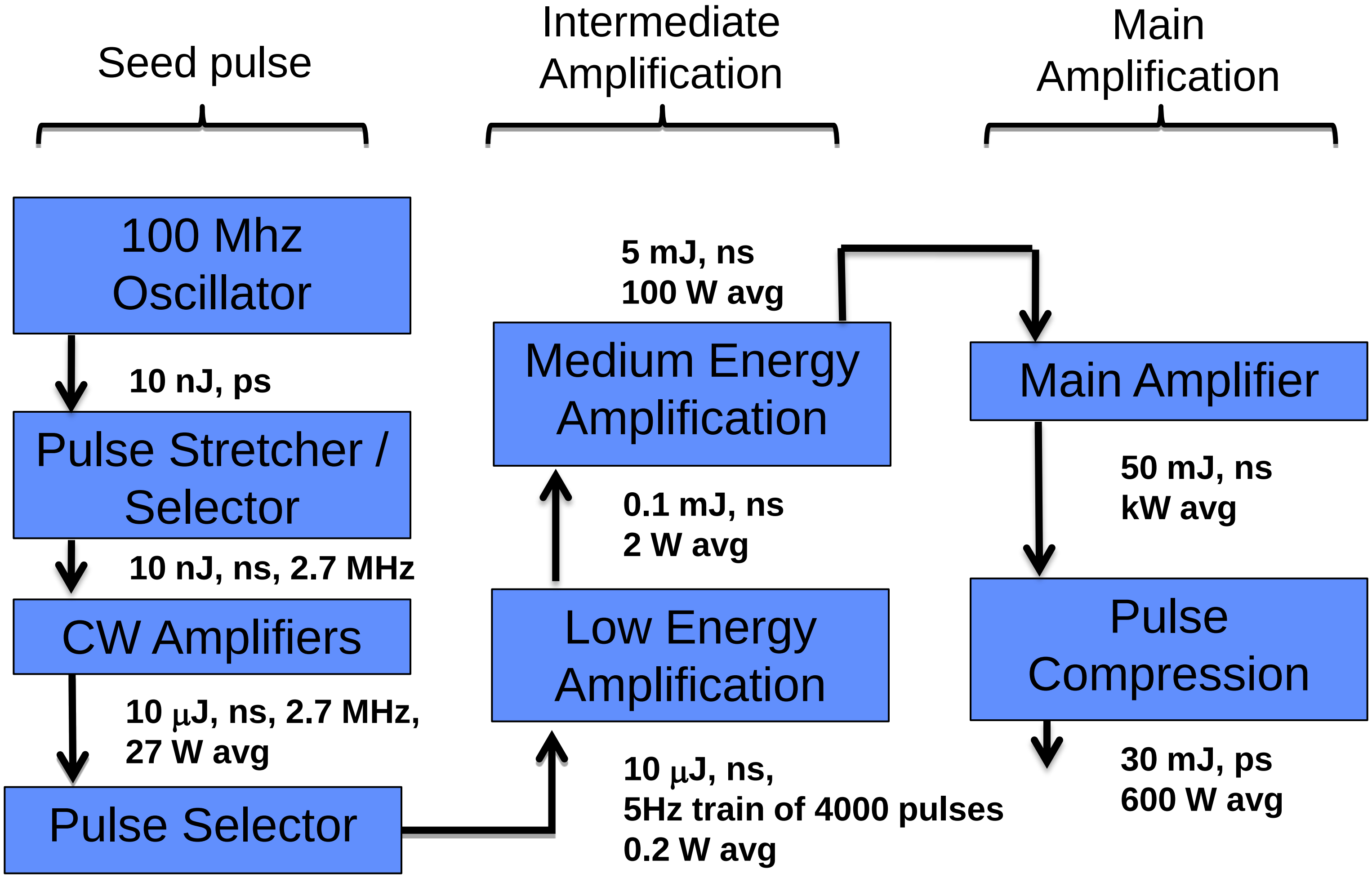
Fused silica:
γ=3x10^{-16} cm^2/W

Energy jitter with B-integral

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



Laser system concept



Seed pulse

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

Intermediate Amplification

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 Amplification

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

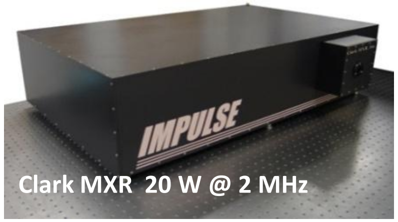
CW Amplifier

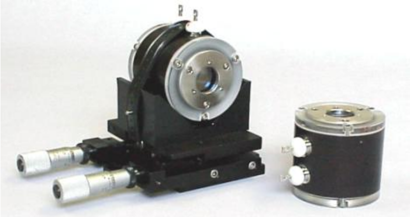
10 μJ, ns, 2.7 MHz
27 W avg

Pulse Selector


High Q Laser femtoTrain

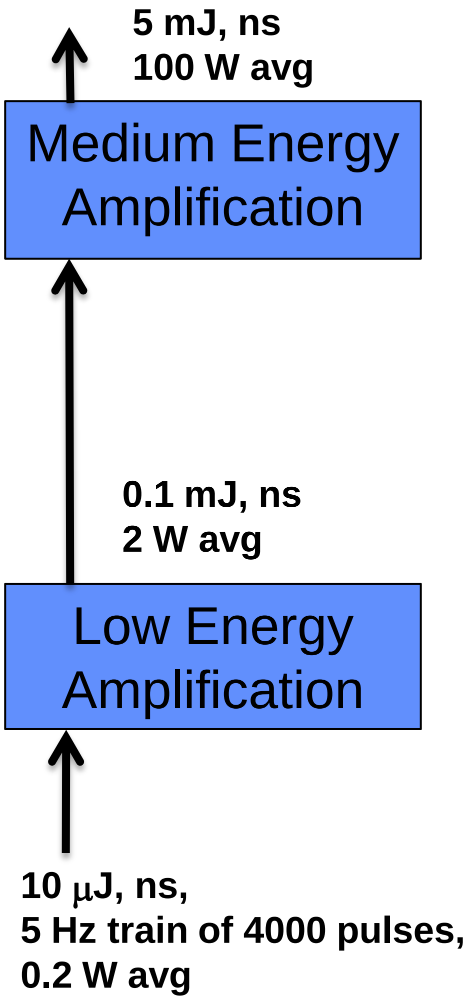

KM Labs pulse stretcher/compressor


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™

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)

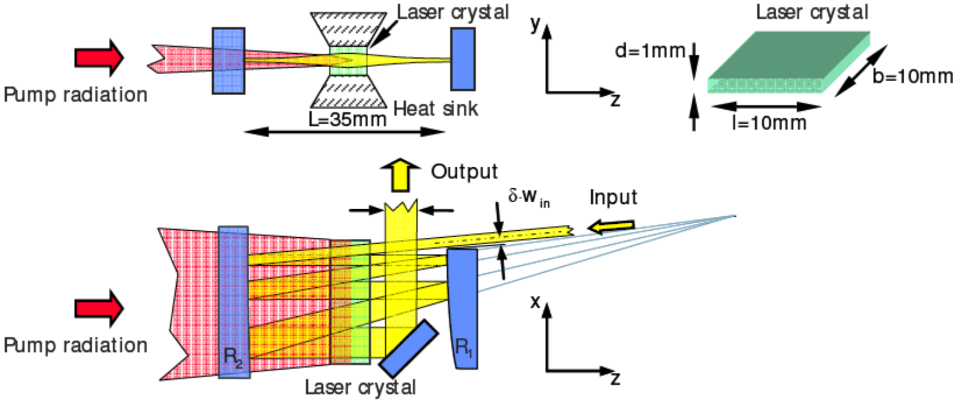
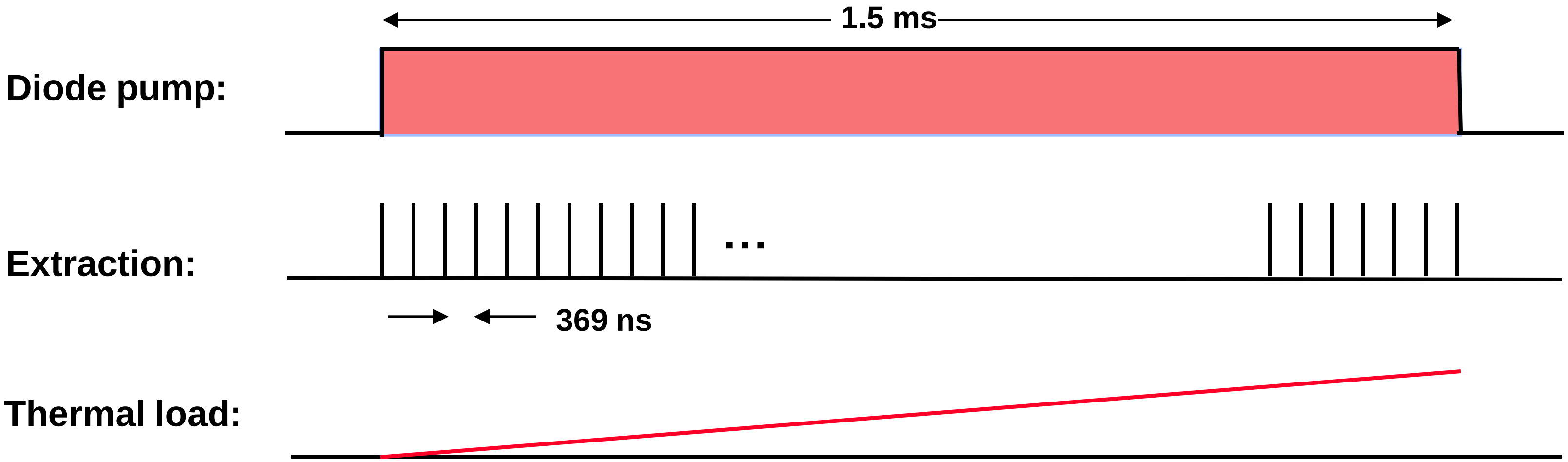


Fig. 2. Schematic setup of an Innoslab amplifier

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

Main amplifier

- **Probably a slab or small-diameter rod configuration**



Diodes:

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

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

~ 3500 bars at 100 W/bar

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:

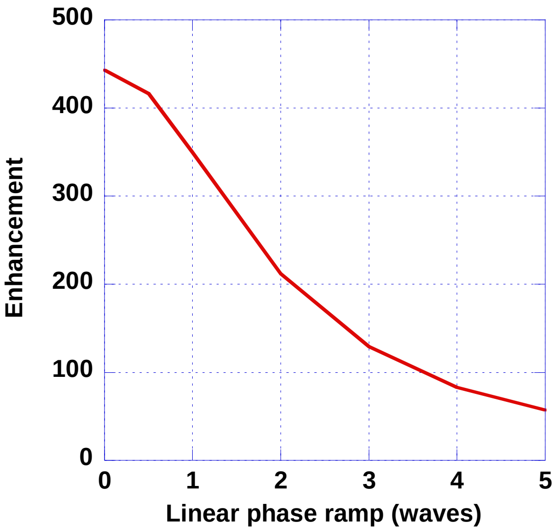
$dn/dT \approx 7\text{x}10^{-6}$ /°K , L = 20 cm

1 λ (2π rad) -> $\Delta T = 0.76$ °K

Heating Yb:YAG with 200 J/bunch:

ΔT=200 J/((0.59 J/gK)(4.56 g/cm^3)(2 cm^3))

ΔT = 37 °K (49 λ)



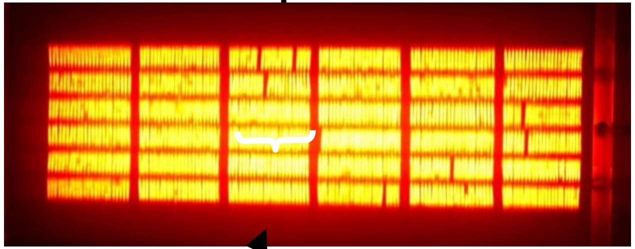
Phase modulator can potentially compensate thermal effects, assuming phase variation is spatially uniform

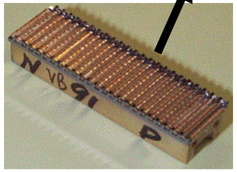
Reducing and compensating for the thermal loading in the final amplifiers will be our main laser challenge

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

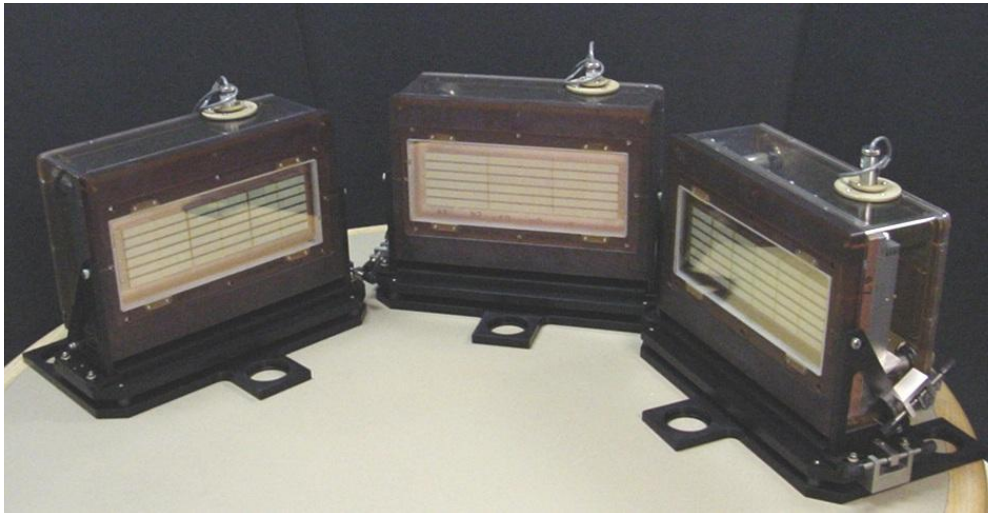
Operated at:

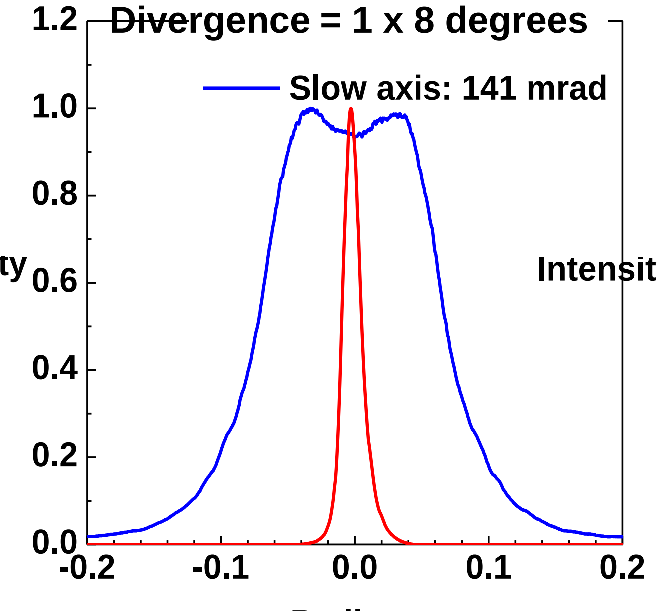
- 120 W/bar at 10 Hz
- 900 ms pulsewidth

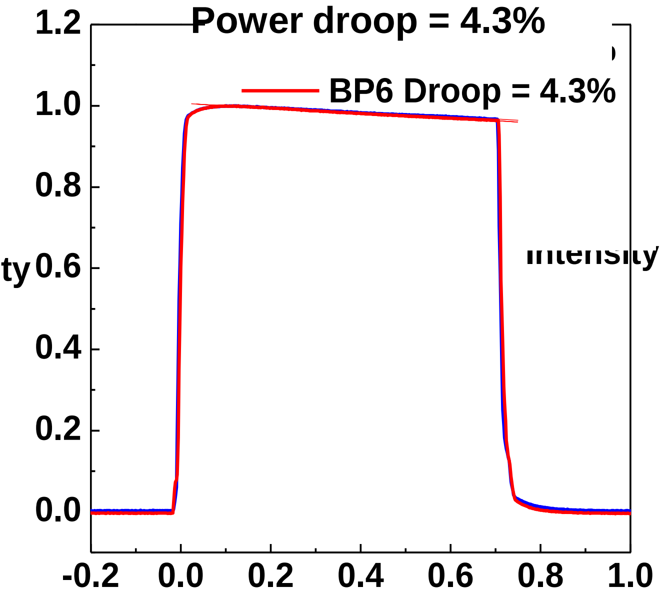


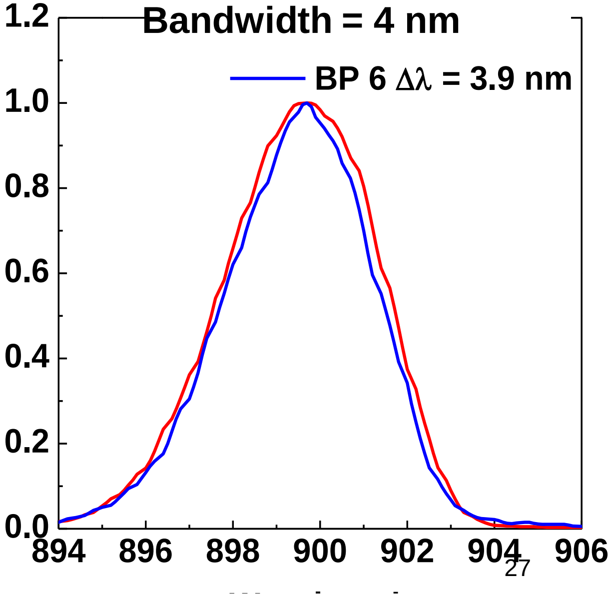


tile with 23 diode bars

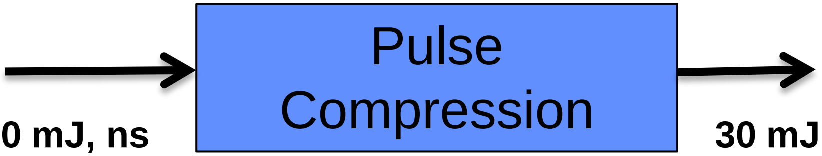








Pulse Compression


Pulse Compression

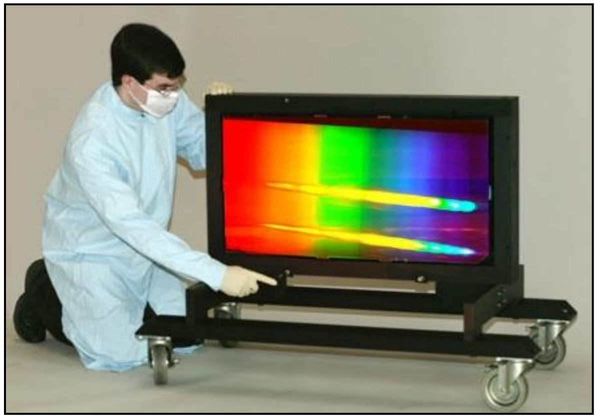
50 mJ, ns

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, but for linear polarization**
  - — **May need to change polarization to circular before compressor**

Vacuum compressor (Titan – LLNL)

World's largest dielectric gratings (LLNL)



Work to be done

- Detailed design of final amplifiers
  - Gain material
  - Pumping/extraction geometry
  - Minimize thermal effects

- Waveplate placement for circular polarization

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

- Conceptual design of laser system

- 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