Design of a Laser for the Recirculating Cavity

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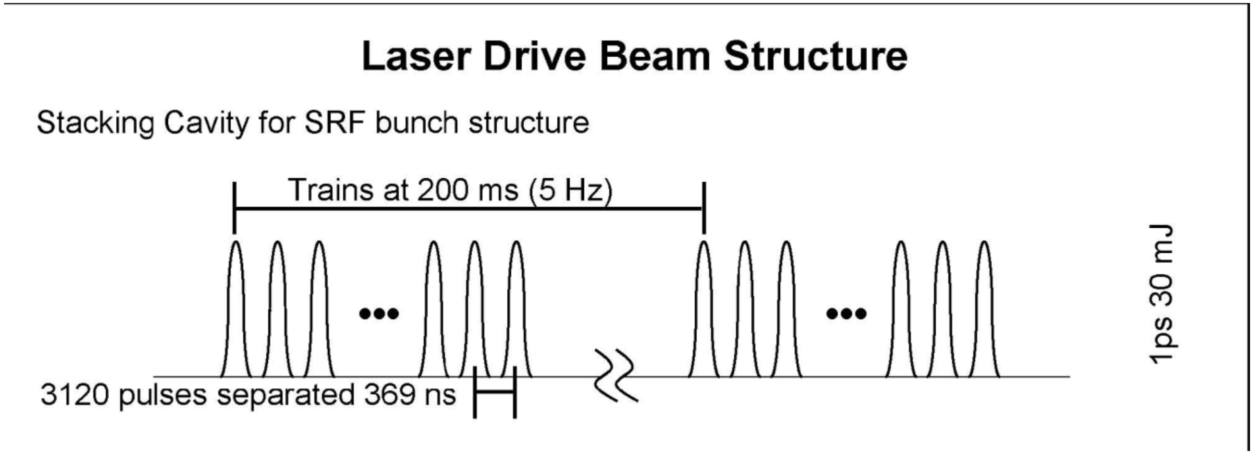
Outline

- Laser requirements
- Resonant cavity
- Sensitivities
- Laser concept

Is it feasible to build the laser?

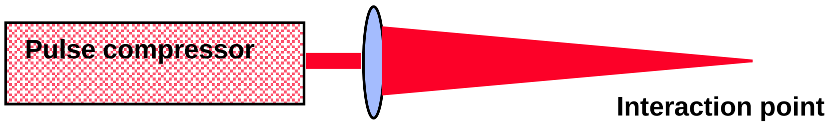
Requirements at interaction point:

- **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**



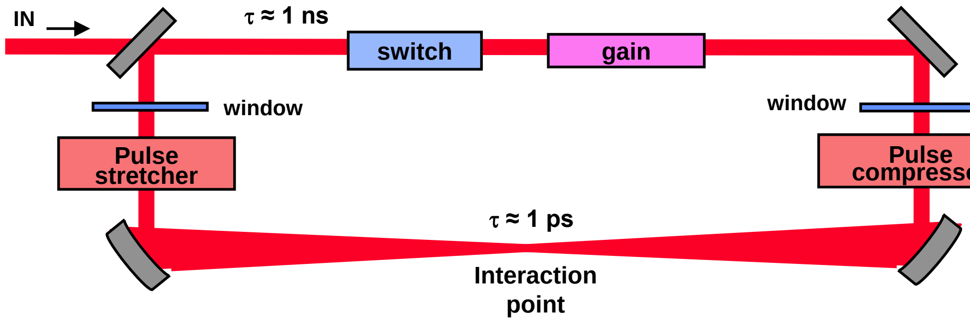
- **5 Hz x 2820 x 10 J ≈ 140 kW average power laser**

Laser requirements depend on interaction configuration



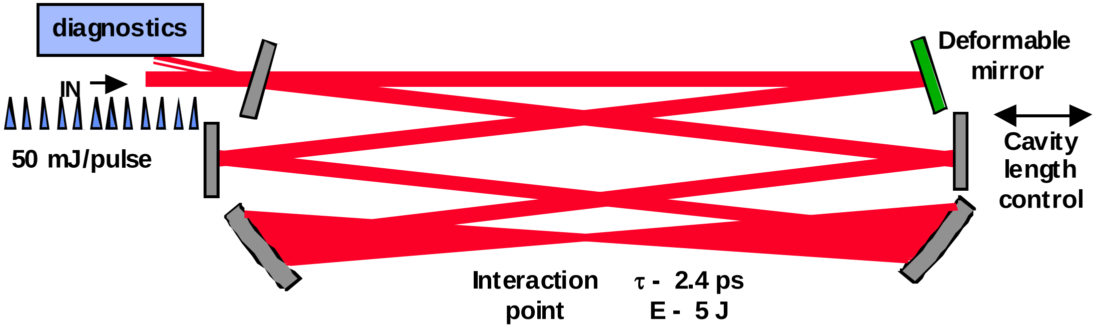
Brute force:

- High average power (>140 kW)



Recirculating cavity:

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

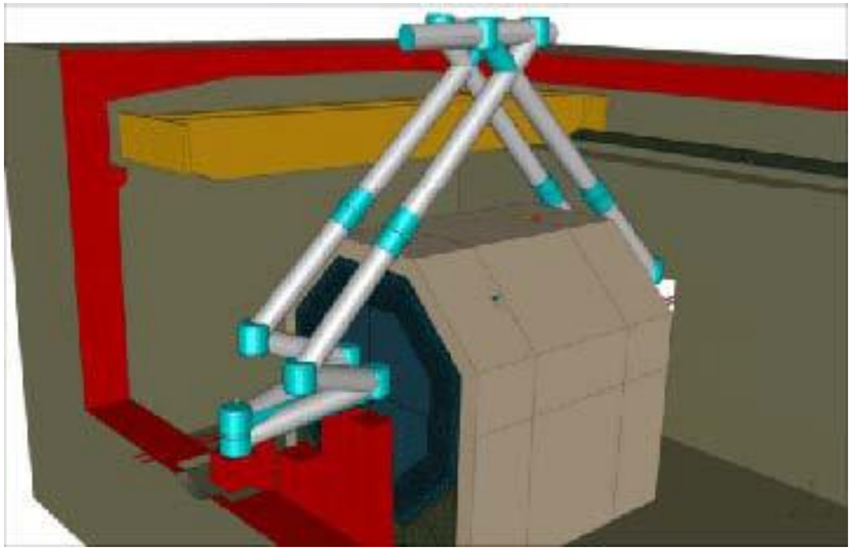


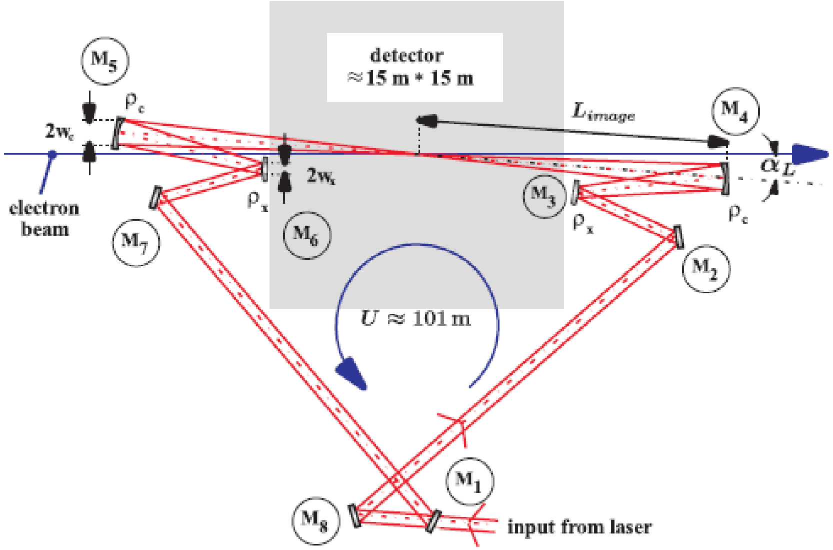
Resonant cavity:

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

A conceptual design for a resonant stacking cavity was done by DESY-Zeuthen and MBI*

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



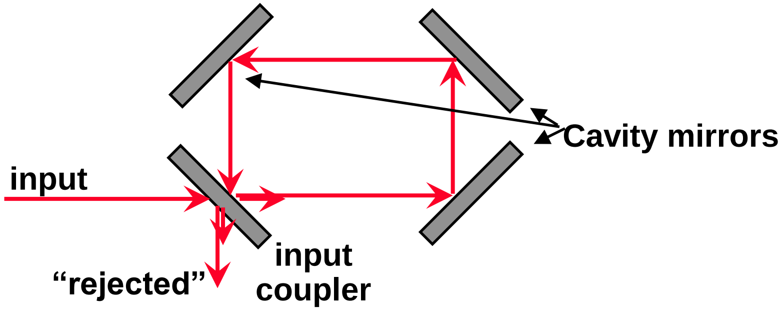


* I.Will, T. Quast, H. Redlin andW. Sander, "A Laser System For The TESLA Photon Collider Based On An External Ring Resonator", *Nucl. Instrum. Meth.* A **472** (2001) 79.

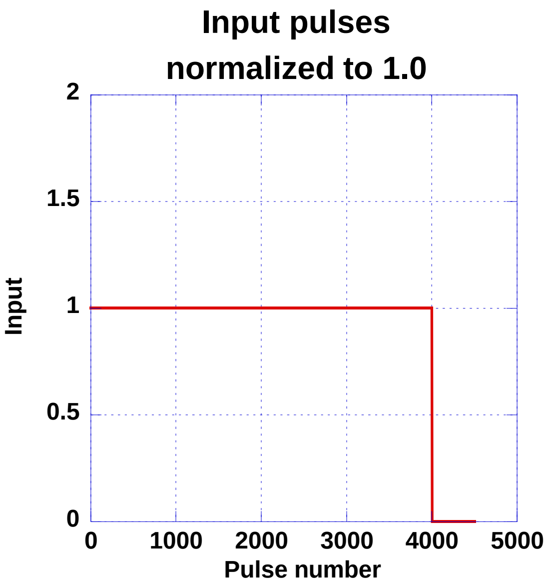
G. Klemz, K. Monig, I. Will, "Design study of an optical cavity for a future photon-collider at ILC", *Nucl. Instrum. Meth.* A **564** (2006) 212.

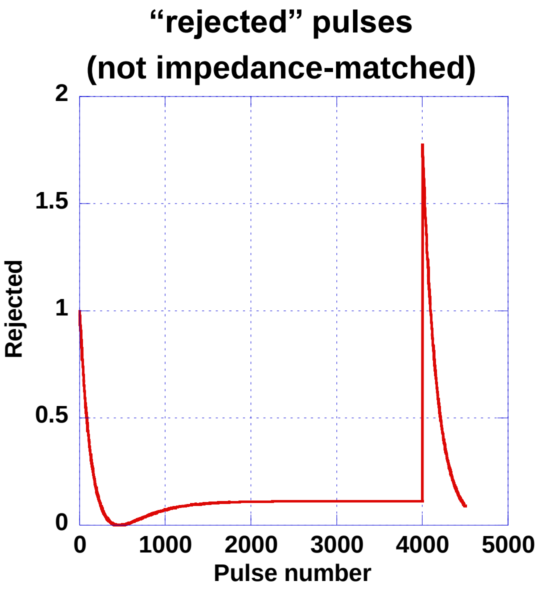
A resonant stacking cavity can enhance the laser interaction intensity by >400 times

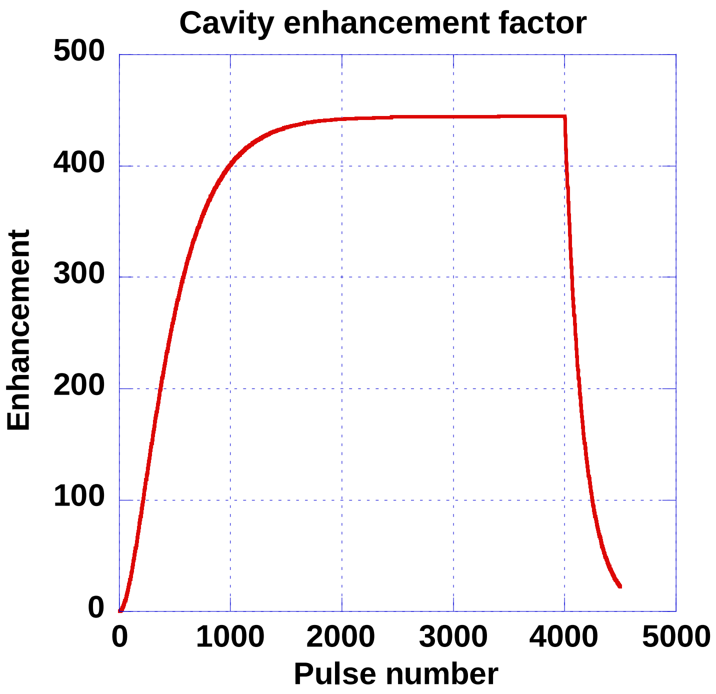
- Only ~10^{-9} of laser energy used in each interaction
- Baseline case: input coupler R=0.996, cavity mirrors R=0.998



Cavity round-trip lifetime ≈ 225 pulses


Input pulses normalized to 1.0


"rejected" pulses (not impedance-matched)


Cavity enhancement factor

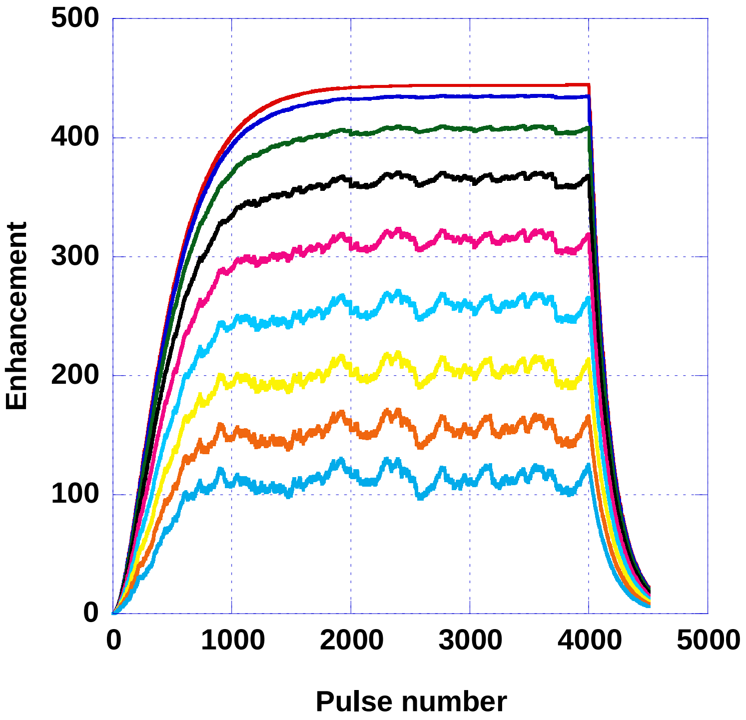
Resonant cavity enhancement puts stringent requirements on the laser and optics

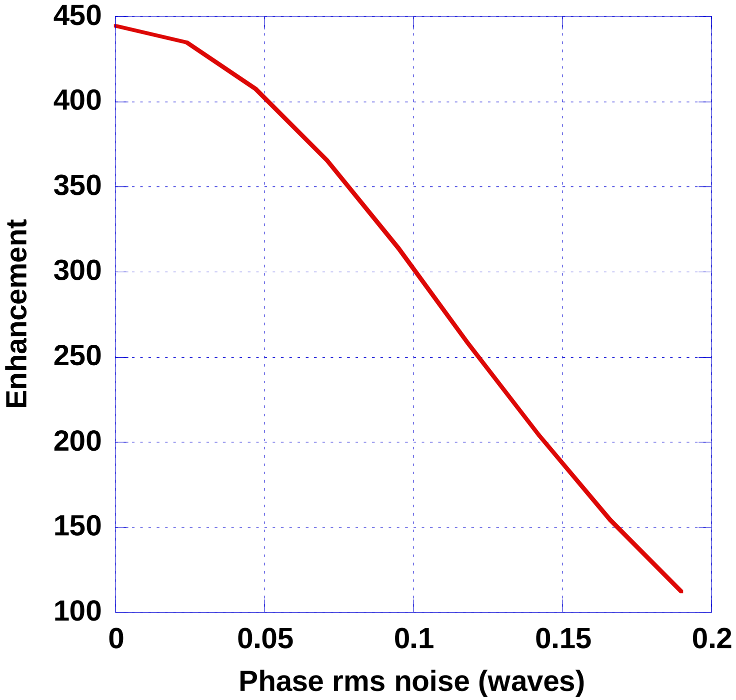
- Dispersion in resonant cavity
- Phase noise
- Cavity length/laser repetition frequency
- Amplitude noise
- Thermal changes to refractive index in amplifiers/optics
- Pointing stability

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

Phase noise >0.02 waves (125 mrad) degrades cavity performance

- **A commercial system (Femtolasers) is now available that produces 5 mJ, 1 kHz, 30-fs pulses at 800 nm with 50 mrad rms phase noise**



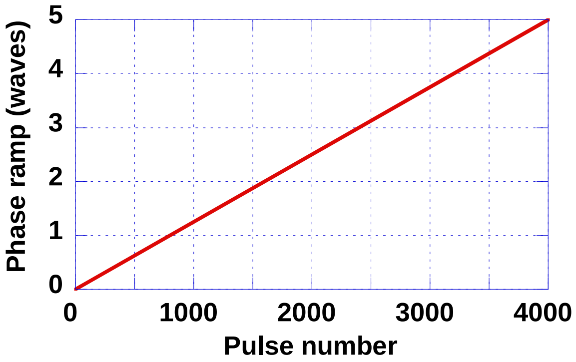


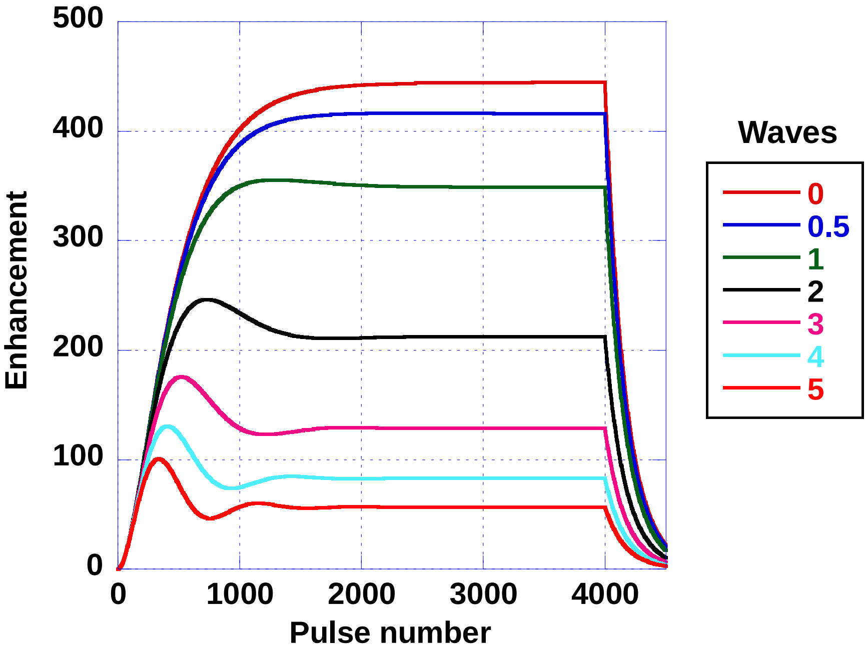
A linear phase ramp through the bunch can be caused by thermal or vibrational effects

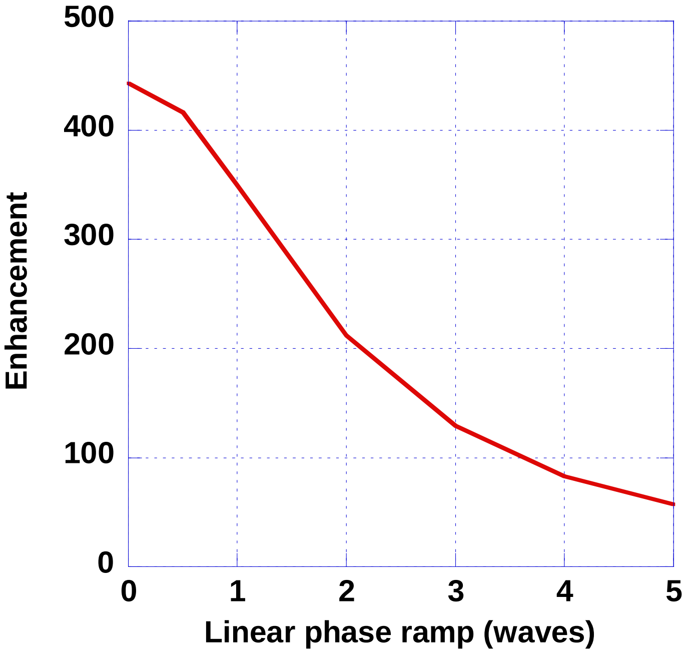
- Would like phase variation <0.2 wave through pulse train
- Can relate to cavity length:

  1 wave ≈ 1 μm

  1 wave/bunch ≈ 0.7 mm/s

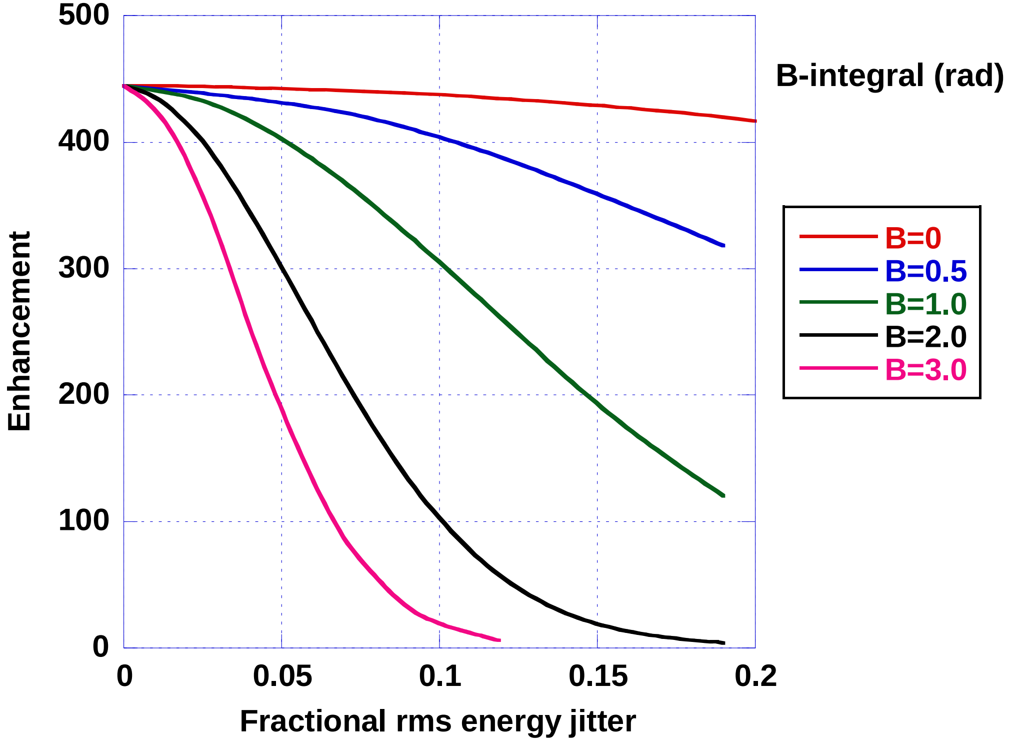




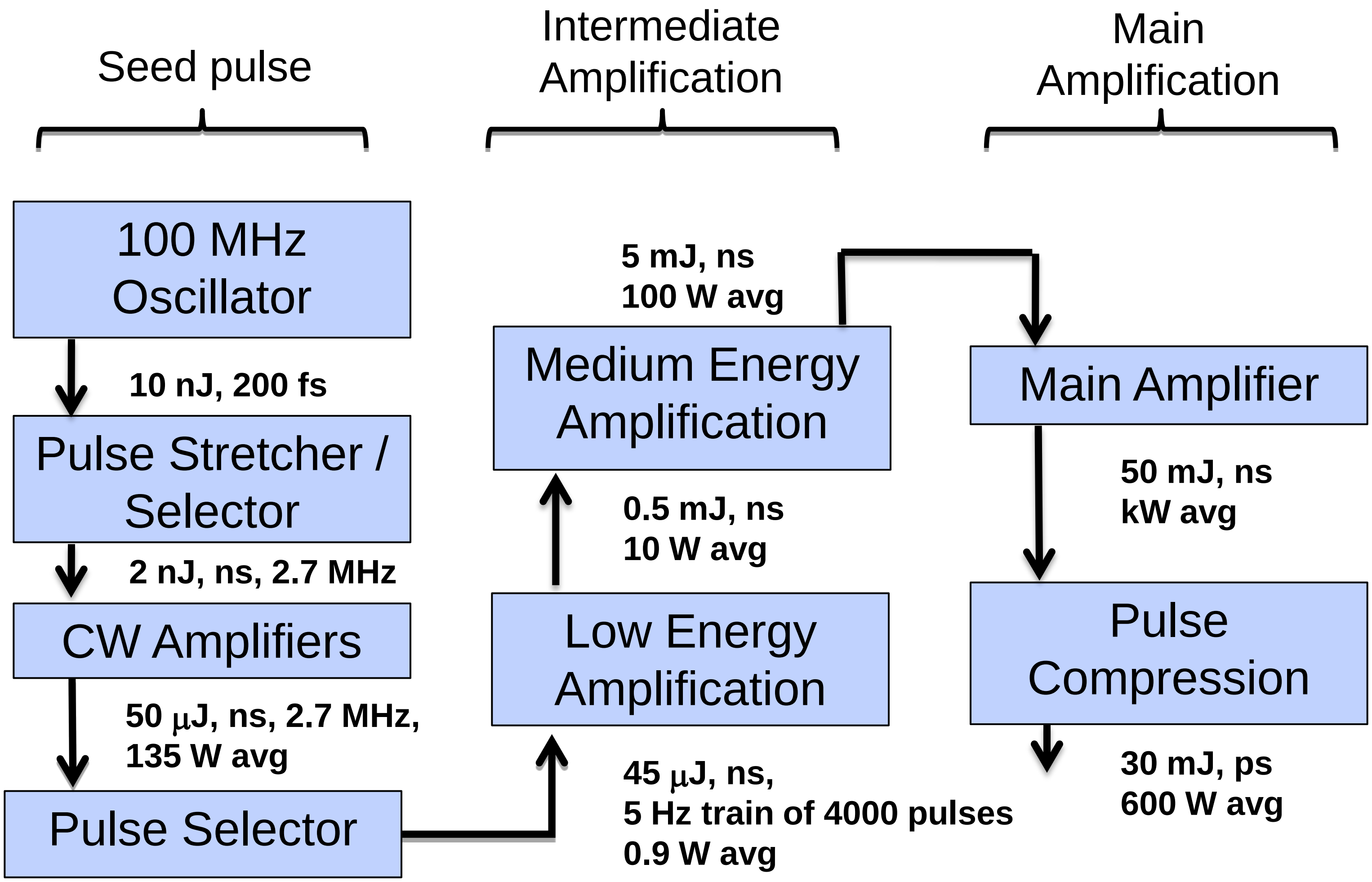


Due to nonlinear effects, the laser energy jitter should be <1% rms

- **The B-integral is a measure of nonlinear phase accumulation**
  - $$B(r,t) = \frac{2\pi}{\lambda}\int \gamma I(r,t)\,dz$$
- **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

Intermediate Amplification

Main Amplification

100 MHz Oscillator

10 nJ, 200 fs

Pulse Stretcher / Selector

2 nJ, ns, 2.7 MHz

CW Amplifiers

50 µJ, ns, 2.7 MHz,
135 W avg

Pulse Selector

45 µJ, ns,
5 Hz train of 4000 pulses
0.9 W avg

Low Energy Amplification

0.5 mJ, ns
10 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

Oscillator

- We must lock the phase of the oscillator to the resonant cavity
  - Would like < 0.02 waves (125 mrad) rms variation

Carrier Envelope Phase (CEP) Locking is now a well-established technique:

- 0.10 wave (650 mrad) achieved in CEP stabilized Ti:Sapphire system (1.4 mJ @ 1 kHz) [1]
- 0.03 wave (171 mrad) achieved with single amplifier (21 nJ, 75 MHz) [2]
- Direct feed-forward method for CEP stabilization has reduced the residual phase noise of a femtosecond oscillator to 45 mrad rms over a 5-second time interval [3]

- A commercial system (Femtolasers) is now available that produces 5 mJ, 1 kHz, 30-fs pulses at 800 nm with 50 mrad rms phase noise

These techniques will need to be adapted to an oscillator operating at 1 μm wavelength

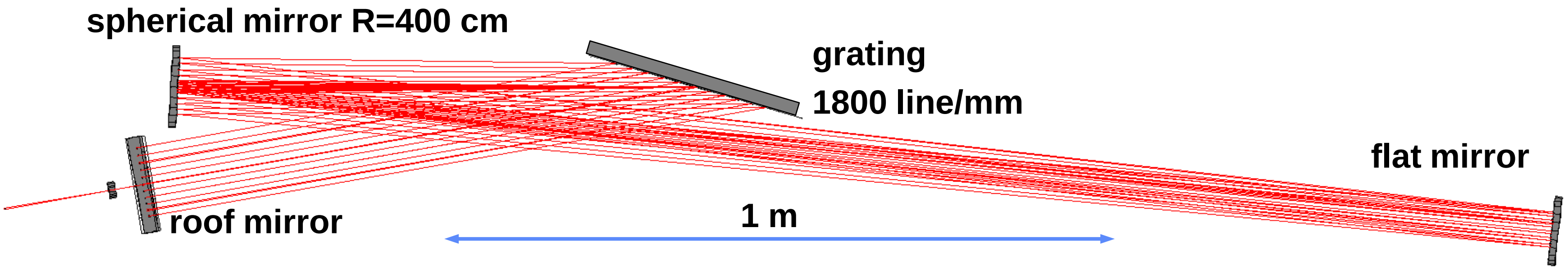
[1] E. Gagnon, et al., Opt. Lett. 31, 1866 (2006)

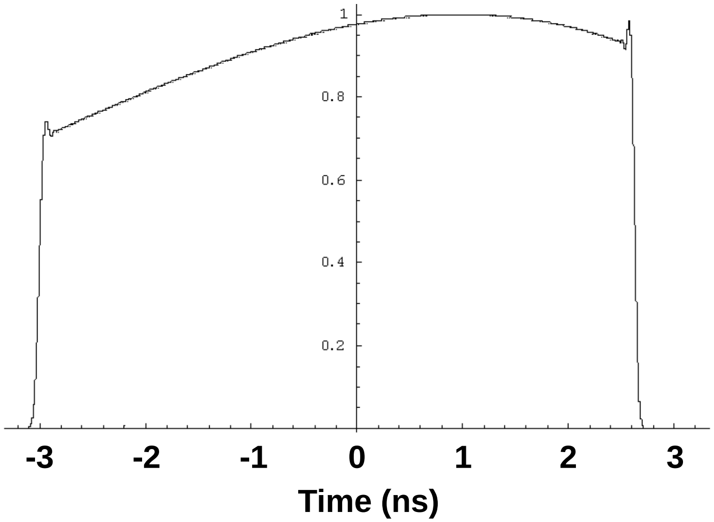
[2] A. Ozawa, et al., New J. Phys. 11, 083029 (2009)

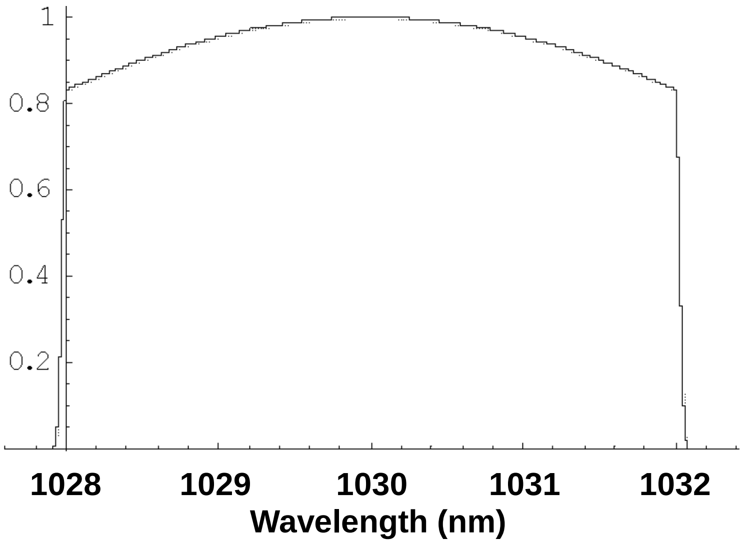
[3] S. Koke, C. Grebing, H. Frei, A. Anderson, A. Assion, G. Steinmeyer, Direct frequency comb synthesis with arbitrary offset and shot-noise-limited phase noise", Nature Photon. 4, 462-465 (2010).

Pulse stretcher

- **Initial 200 fs pulse stretched to 5.6 ns with 4-nm hard-cut bandwidth**







CW amplifiers

- Amplify as far as possible in CW-pumped amplifiers to avoid thermal phase variation caused by pulsed pumping
- Ytterbium (Yb) doped fibers can be used to efficiently amplify the stretched pulses while maintaining the required bandwidth
  - Large-core-diameter step-index or photonic crystal fiber

Recent relevant short-pulse fiber laser results:

- Röser, et al. [1] demonstrated 100-µJ, 500-fs pulses at 0.9 MHz (90 W)
- Zaouter et al. [2] demonstrated 100-µJ, 270-fs pulses at 0.3 MHz (30 W)

- A reasonable target is 135 W average power (50 µJ @ 2.7 MHz)
  - After amplification, slice to 5-Hz, 4000-pulse trains (0.9 W average)

[1] F. Röser, D. Schimpf, O. Schmidt, B. Ortac, K. Rademaker, J. Limpert, A. Tünnermann, “90 W average power 100 µJ energy femtosecond fiber chirped-pulse amplification system”, Opt. Lett. 32, 2230-2232 (2007).

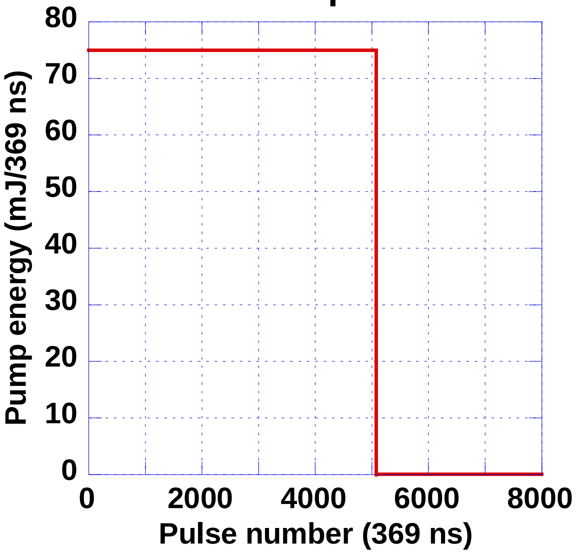
[2] Y. Zaouter, J. Boullet, E. Mottay, E. Cormier, “Generation of high energy and high quality ultrashort pulses in moderately non-linear Fiber Chirped Pulse Amplifier”, Proc. SPIE 7195, 719512-1 (2009).

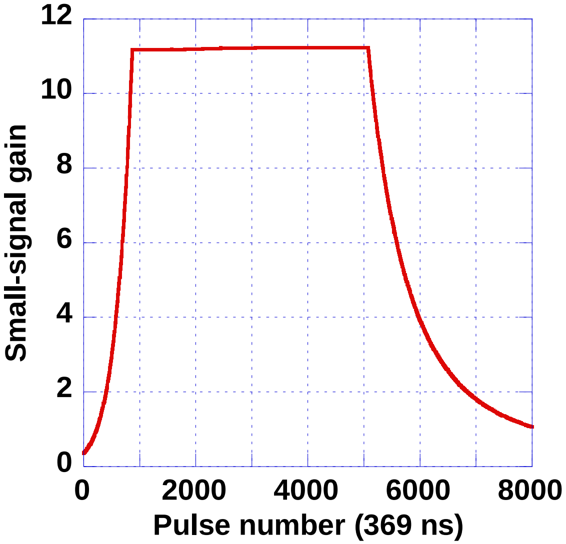
Bulk amplifier design must balance energetics with heat removal

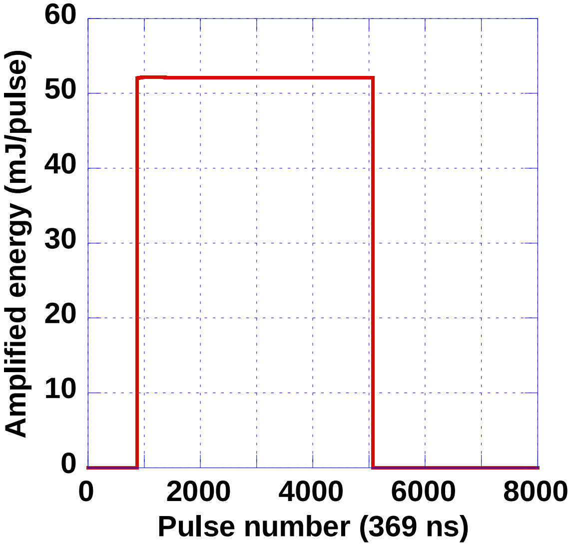
- Need a gain of ≈10 per amplifier for three amplifiers
- Would like to maintain spatially uniform temperature profile through pulse train
- Would like to remove all heat before next train
  - High thermal conductivity and low heat capacity
- Thin slabs or long narrow rods will be necessary for heat extraction

Yb:YAG is an attractive gain medium for the photon collider laser

- Can achieve a gain of 1000 with bandwidth (1.5 nm) to support 1 ps pulses
  - Three stages with G≈10 to boost 50-μJ fiber output to 50 mJ
- Reduced thermal effects with pump at 940 nm, lasing at 1030 nm
- Other Yb hosts also possible: S-FAP, KYW, Sc_2O_3
- Basic three-level energetics model for final stage gives 50-mJ pulse train:
  - $\sigma_a = 0.76 \times 10^{-20}$ cm², $\sigma_s = 3.3 \times 10^{-20}$ cm², τ=0.95 ms, 5-mJ input, room temperature
  - 2-cm long crystal, 1.5-cm diameter beams (flat-top)


Pump


Gain


Output

Thermal effects in the main amplifiers will have to be mitigated

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

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:

$dn/dT \approx 8\times10^{-6}/°K$, $dL/dT \approx 7\times10^{-6}/°K$

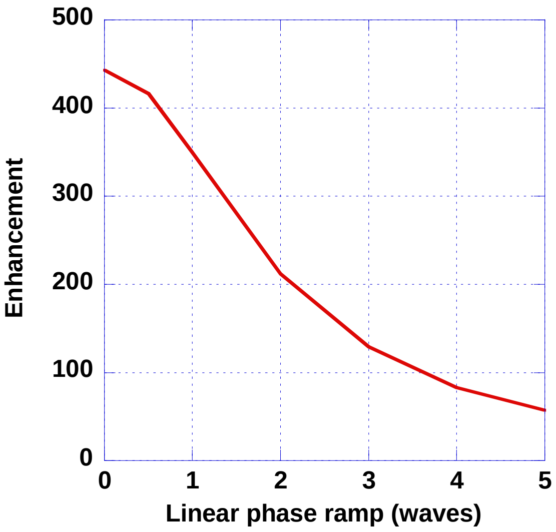
L = 2 cm, n_o=1.82

1 λ (2π rad) -> $\Delta T = 3.6$ °K

Heating Yb:YAG with 200 J/bunch:

ΔT=200 J/((0.59 J/gK)(4.56 g/cm^3)(3.5 cm^3))

ΔT = 21 °K (6 λ)

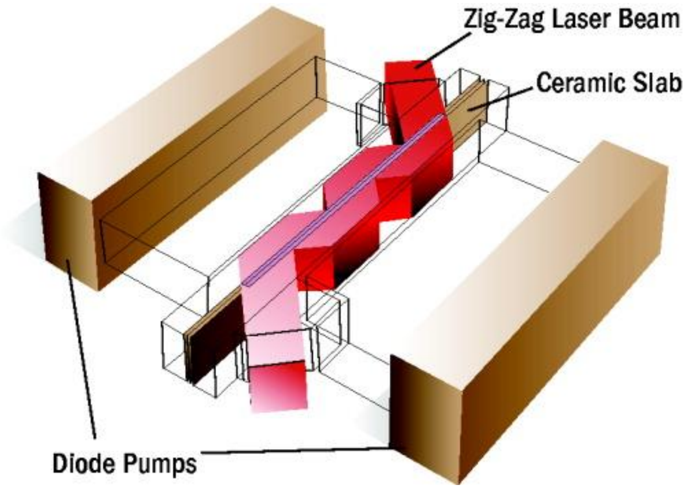


Phase modulator can potentially compensate thermal effects, assuming phase variation is spatially uniform

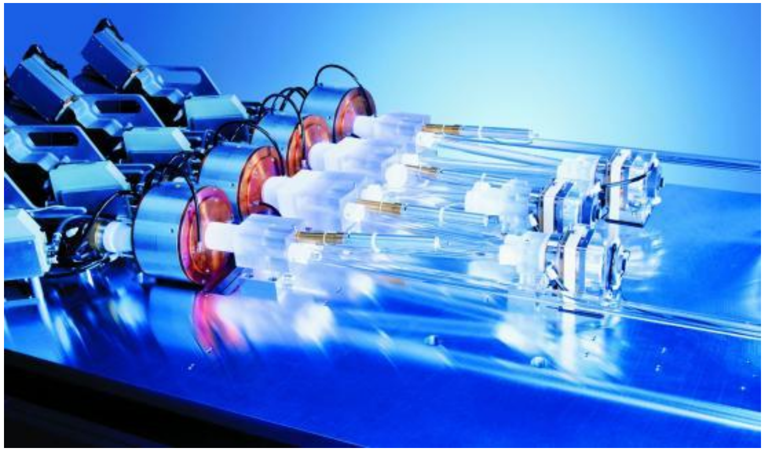
Reducing and compensating for the thermal loading in the final amplifiers will be our main laser challenge

Several current amplifier designs allow aggressive cooling of thin (~mm) slabs in kW-class systems

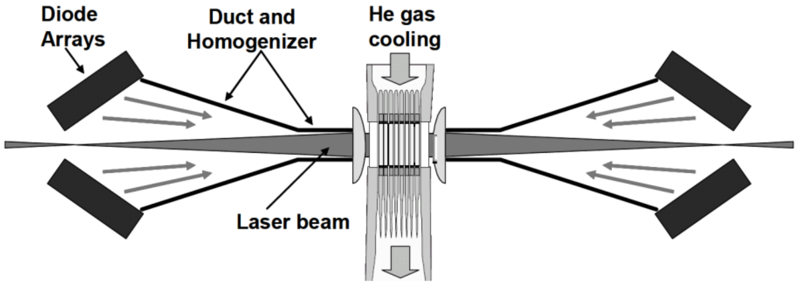
Textron ThinZag® amplifier



TRUMPF thin-disk laser



LLNL Mercury He gas cooling



EdgeWave INNOSLAB laser

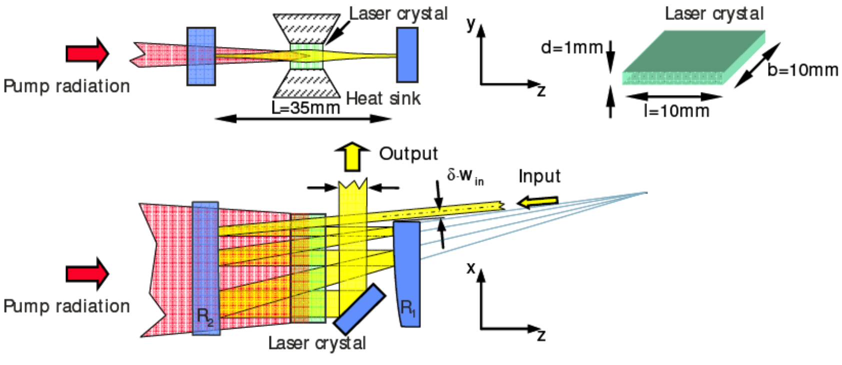
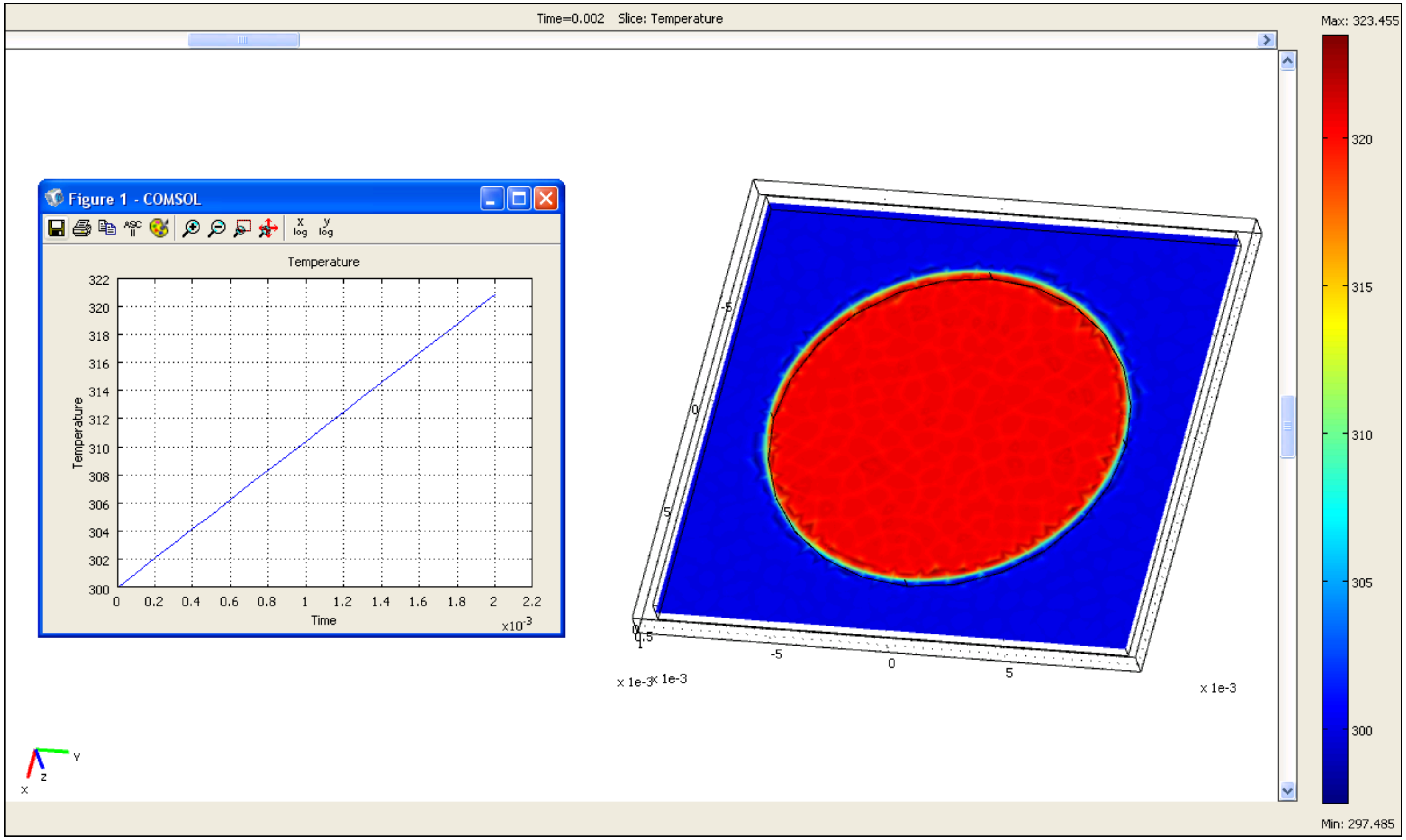


Fig. 2. Schematic setup of an Innoslab amplifier

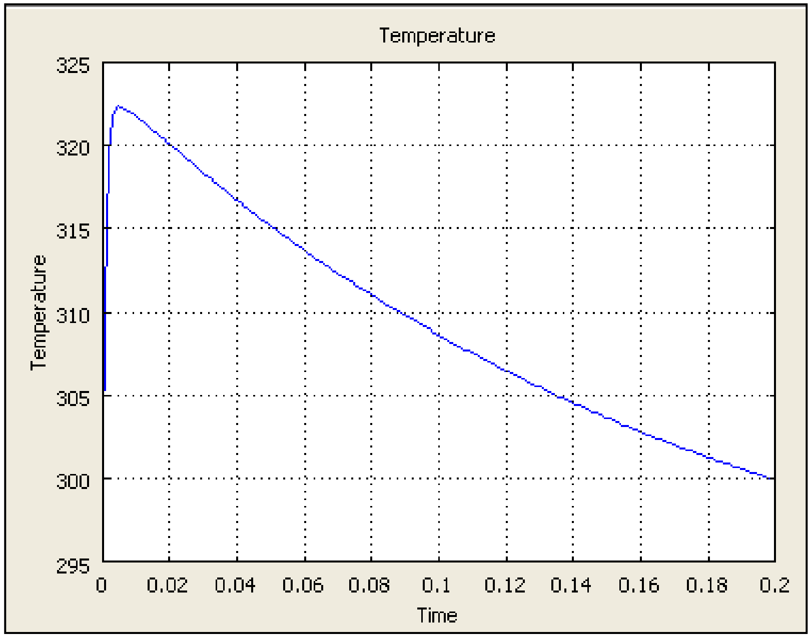
A 1-mm slice of Yb:YAG increases ≈22°K during the 2-ms pulse train

- **2-cm length sliced into 1-mm slabs with equal thermal loading**
  - — **10 J heat over 2 ms in 1.5-cm diameter pump spot**



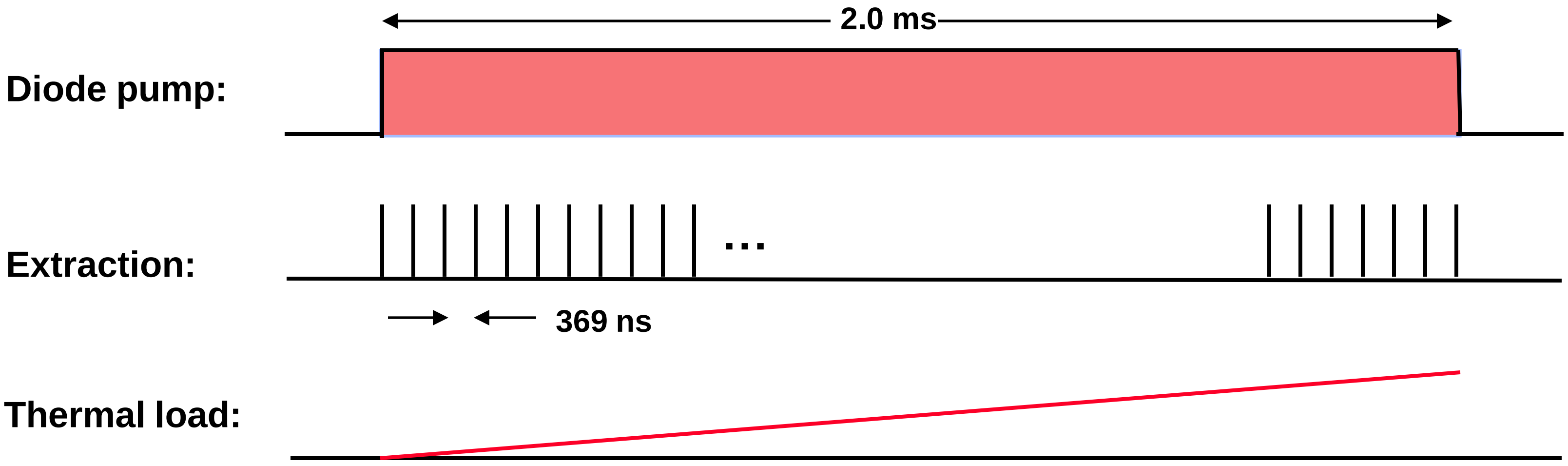
The 1-mm slice can be cooled before the next pulse train

- **Liquid cooling over slab faces with heat transfer coefficient h=1 W/cm^{2}K**
- **Slab temperature equilibrates to 300K between pulses, coolant T=290K**



Radial thermal differences during the pulse train and nonuniformities due to cooling geometry will need to be modeled

Diode pumping of the bulk amplifiers



Diodes:

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

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

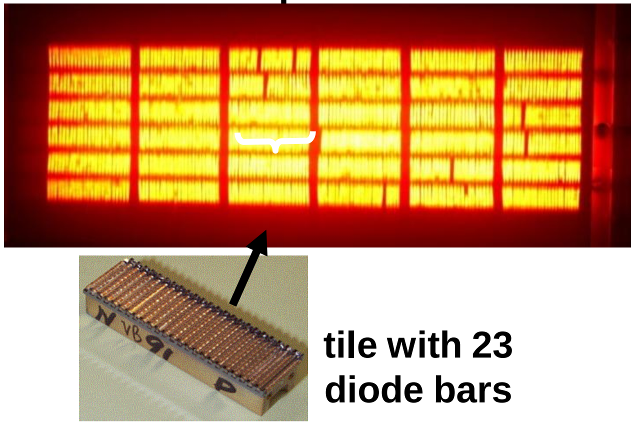
~ 3500 bars at 100 W/bar

Lifetime ≈ 5x10^9 shots = 31.7 years @ 5 Hz

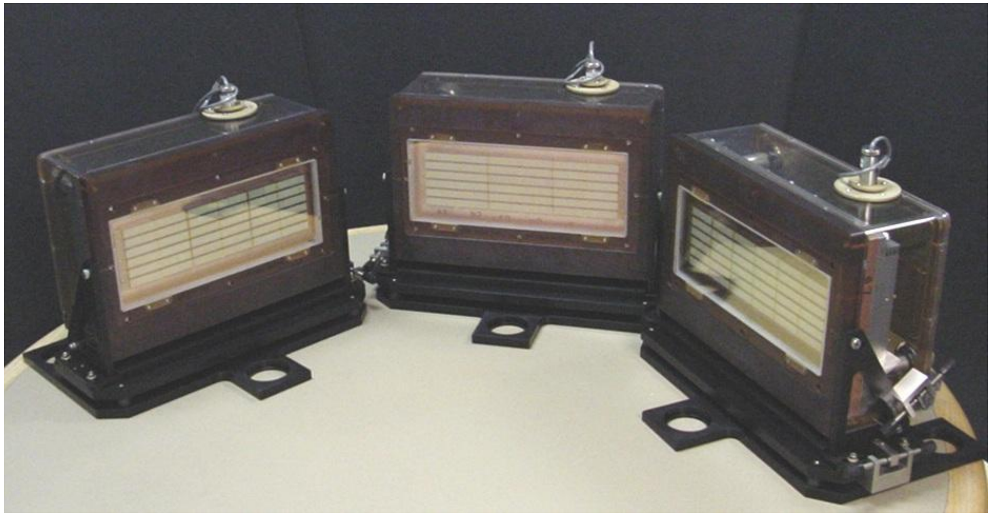
The Mercury laser at LLNL uses four 80 kW diode arrays for a total of 320 kW of peak diode power

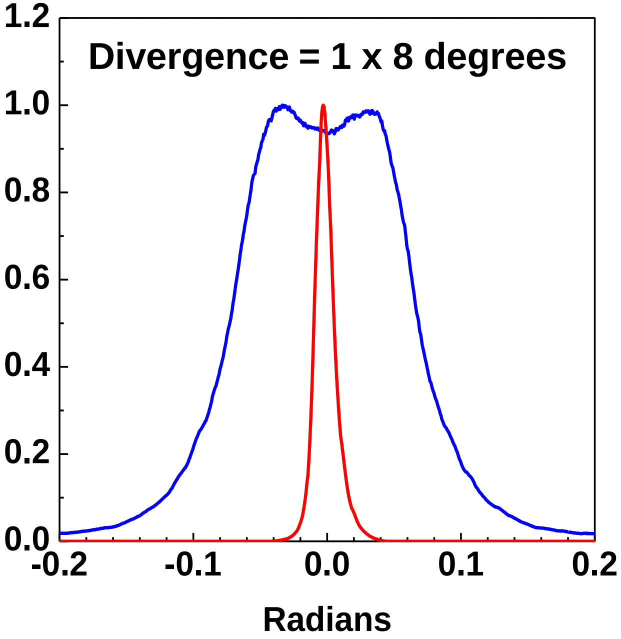
Operated at:

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

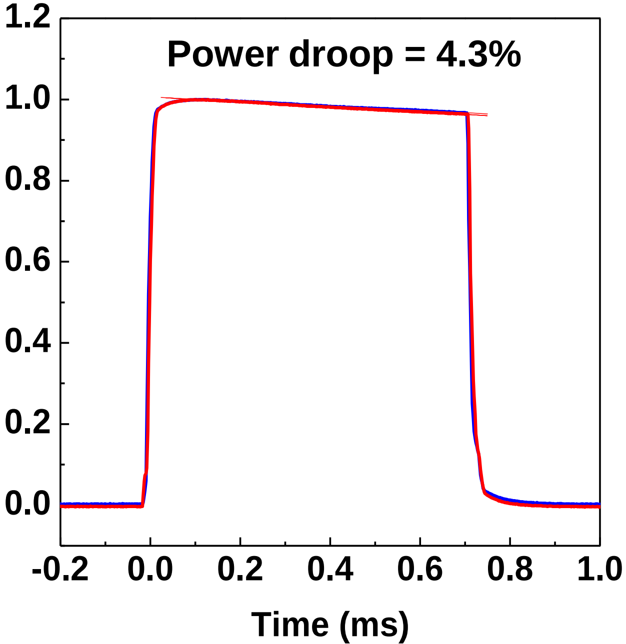


tile with 23 diode bars

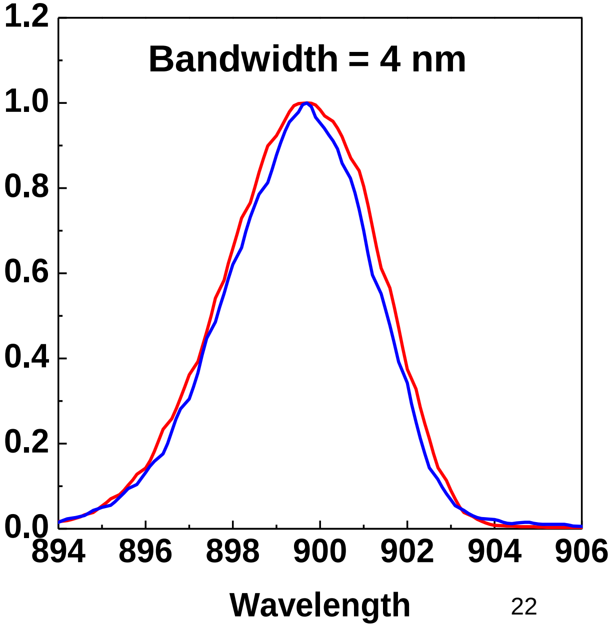




Divergence = 1 x 8 degrees



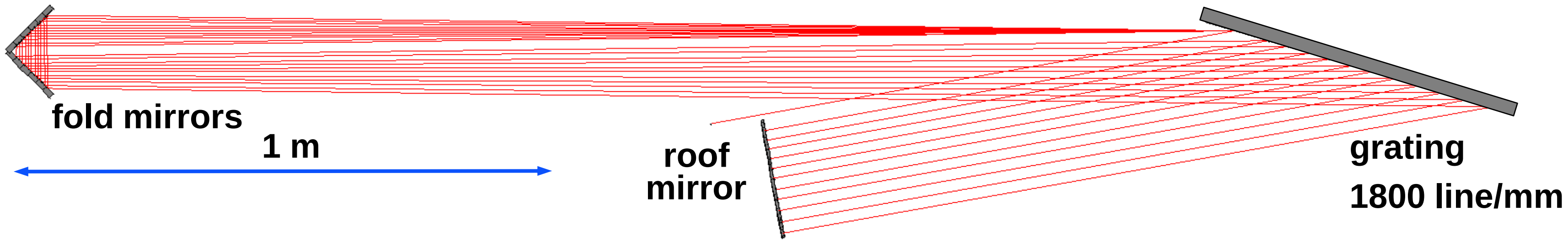
Power droop = 4.3%

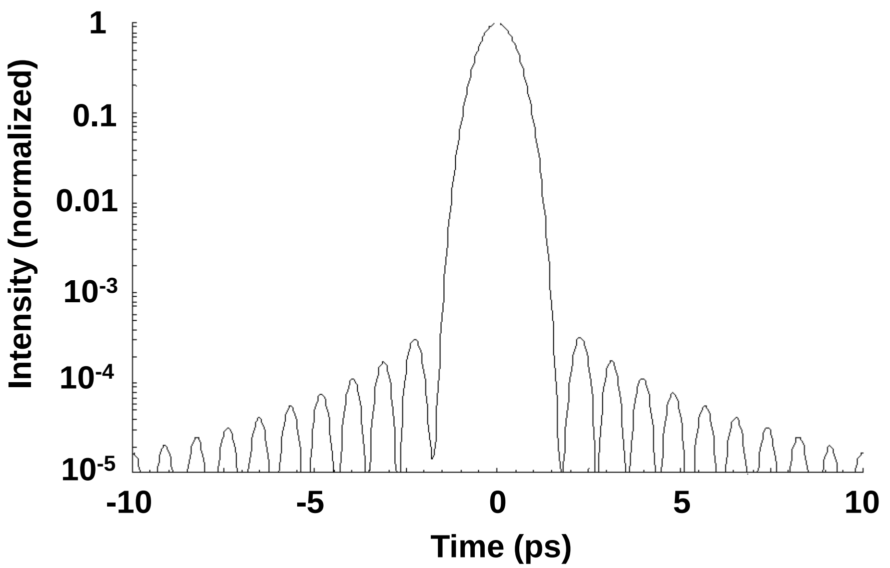


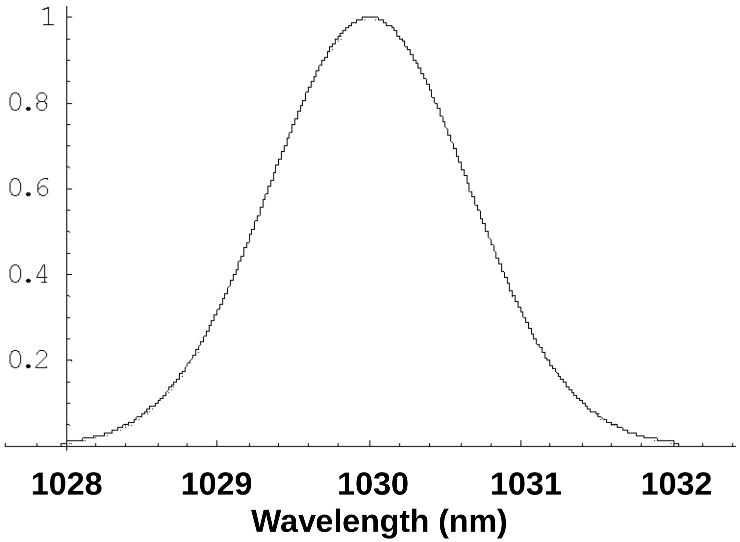
Bandwidth = 4 nm

Pulse compressor

- Amplified spectrum (1.55 nm FWHM) compressed to 1.1 ps FWHM
- 32 mJ in 2-cm diameter (1/e^2 Gaussian) ⇒ 0.02 J/cm^2
  - Well below damage threshold of >2 J/cm^2





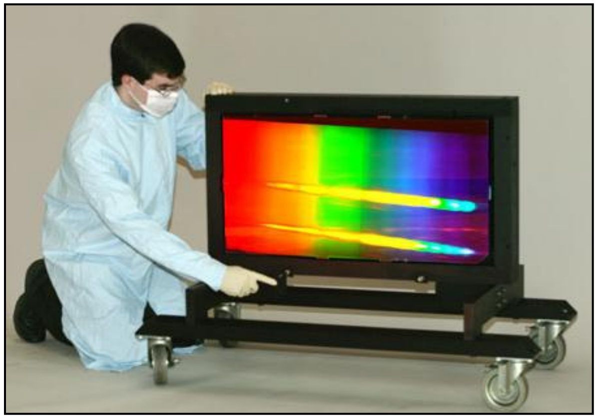


Pulse compressor

- System may be in vacuum after compression
  - Must look at system trades
- Average power density:
  - 1 kW, 2-cm Gaussian ⇒ 640 W/cm^2
- Average power testing of Multi-Layer Dielectric (MLD) gratings:
  - >2 kW/cm^2, no wavefront distortion
  - 100 kW/cm^2 small spot - no damage
- High efficiency (>97%) gratings for linear polarization
  - Waveplate after compressor to make circular polarization

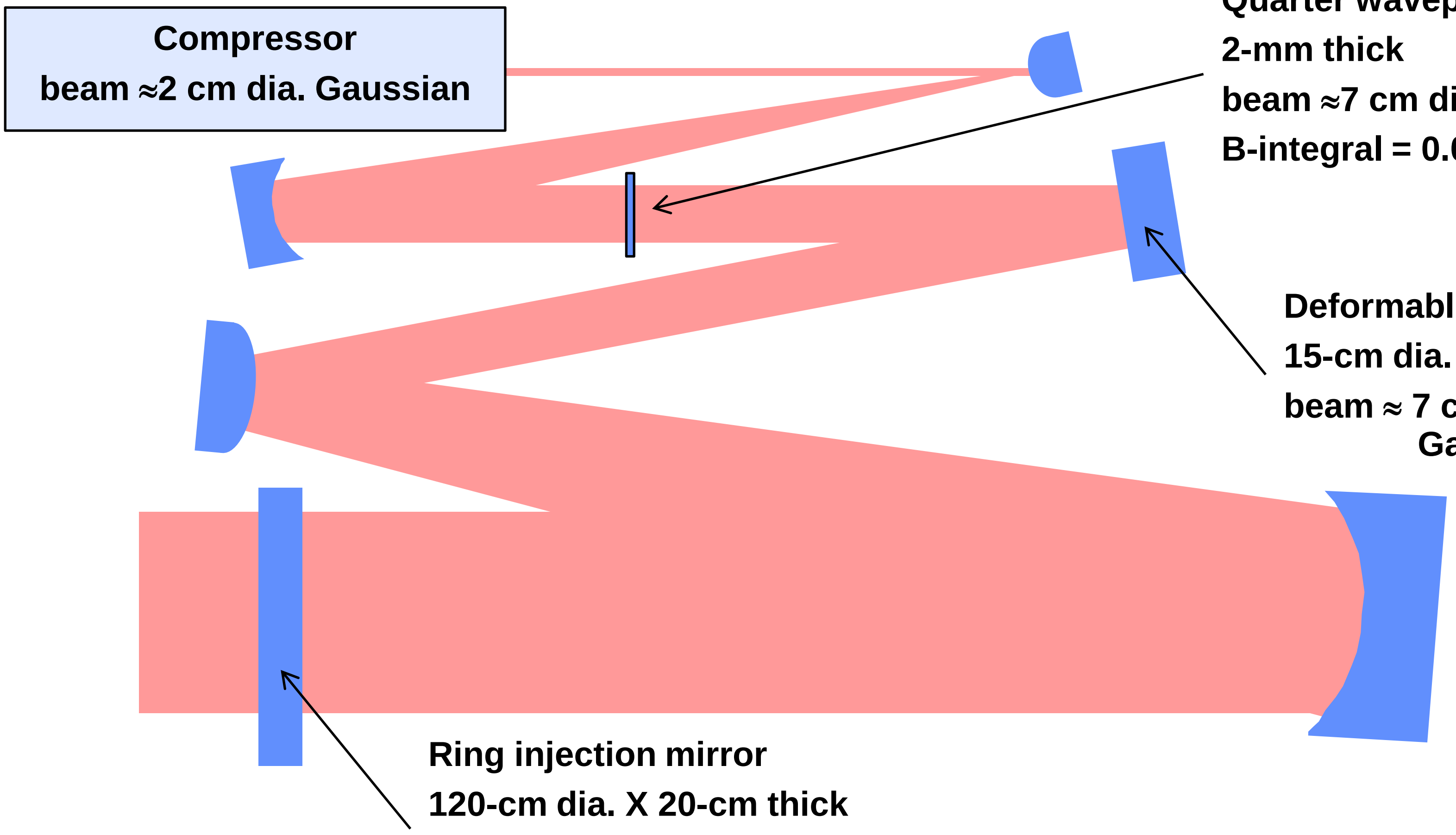
Vacuum compressor (Titan – LLNL)

World's largest dielectric gratings (LLNL)



Pulse transport, polarization, and injection

- **All in controlled environment (vacuum, argon)**



Compressor
beam ≈2 cm dia. Gaussian

Quarter waveplate
2-mm thick
beam ≈7 cm dia. Gaussian
B-integral = 0.01

Deformable mirror
15-cm dia.
beam ≈ 7 cm dia. Gaussian

Ring injection mirror
120-cm dia. X 20-cm thick
beam ≈49 cm dia. Gaussian
B-integral = 0.01

Summary

System will be challenging, but no show-stoppers identified yet

- **Thermal effects in main bulk amplifiers will have to be controlled and compensated**
  - **Needs further design and 4-D modeling**
- **Extensive control system will be necessary to maintain phase coherence in resonant cavity**