Lawrence Livermore National Laboratory

Design work for the photon collider laser

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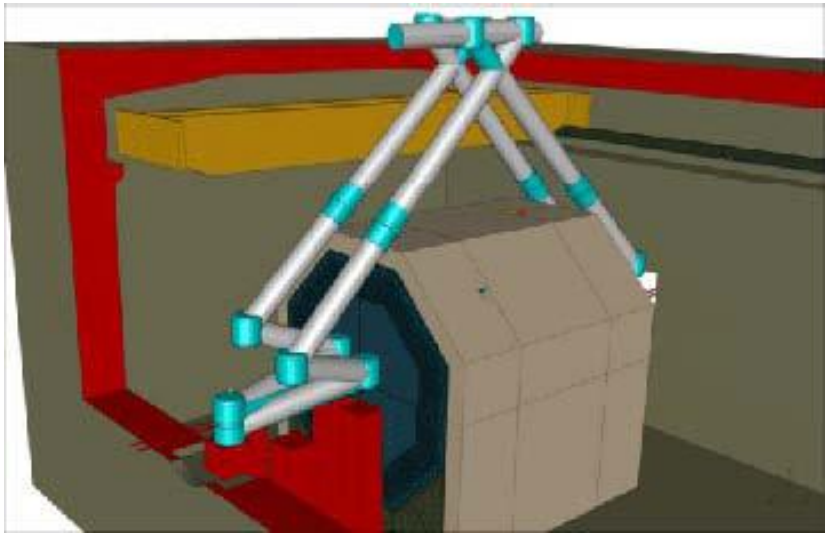
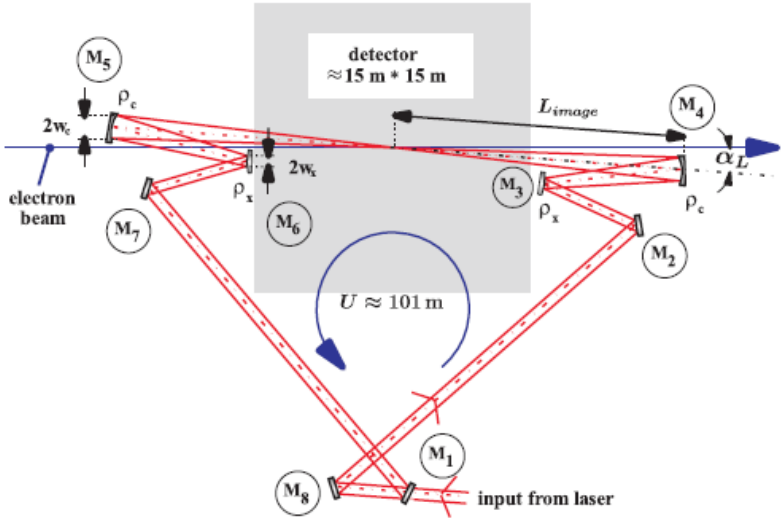
UCRL-XXXX-12345

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)



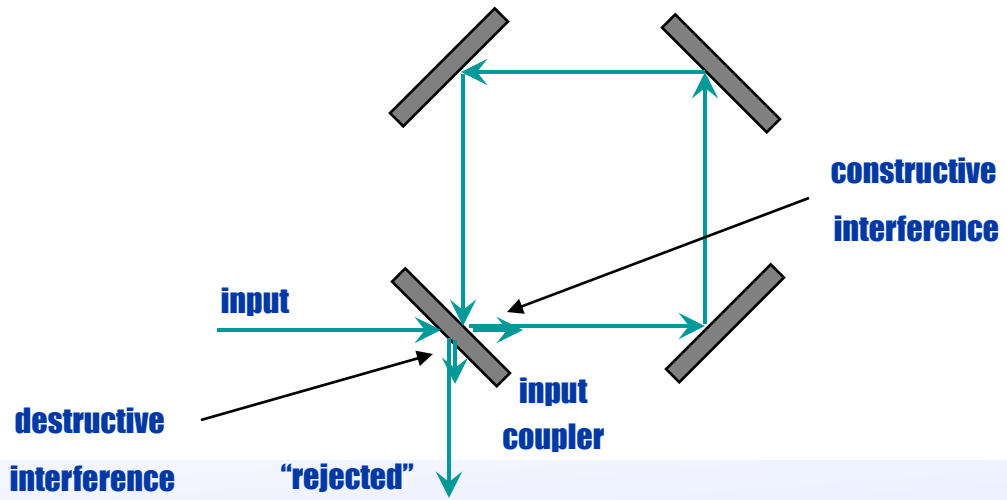


* I.Will, T. Quast, H. Redlin andW. Sander, "A Laser System For The TESLA Photon Collider Based On An External Ring Resonator", *Nucl. Instrum. Meth.* A 472 (2001) 79.

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.

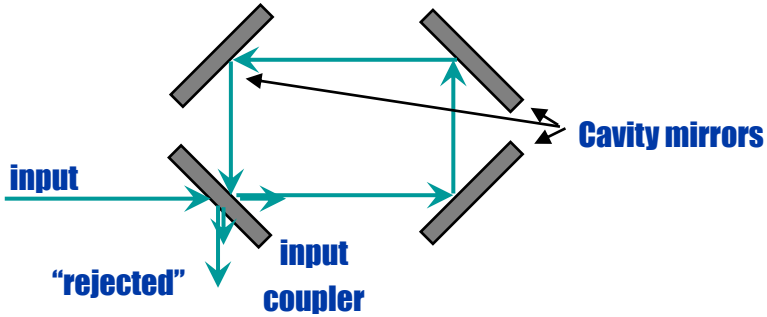
A resonant stacking cavity greatly reduces the required laser average power

- 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)

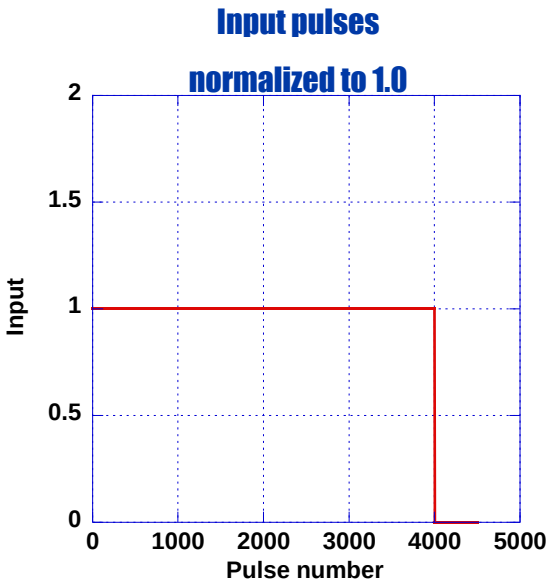


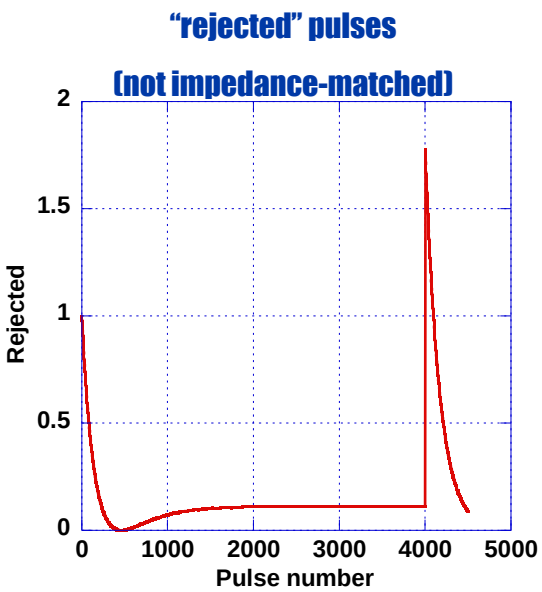
Resonant stacking cavity

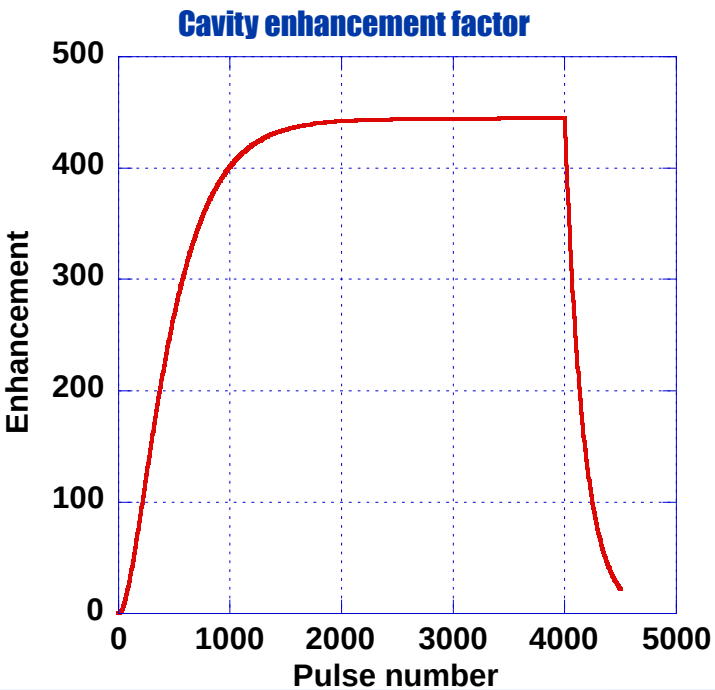
- Baseline case: input coupler R=0.996, cavity mirrors R=0.998



Cavity round-trip lifetime ≈ 225 pulses

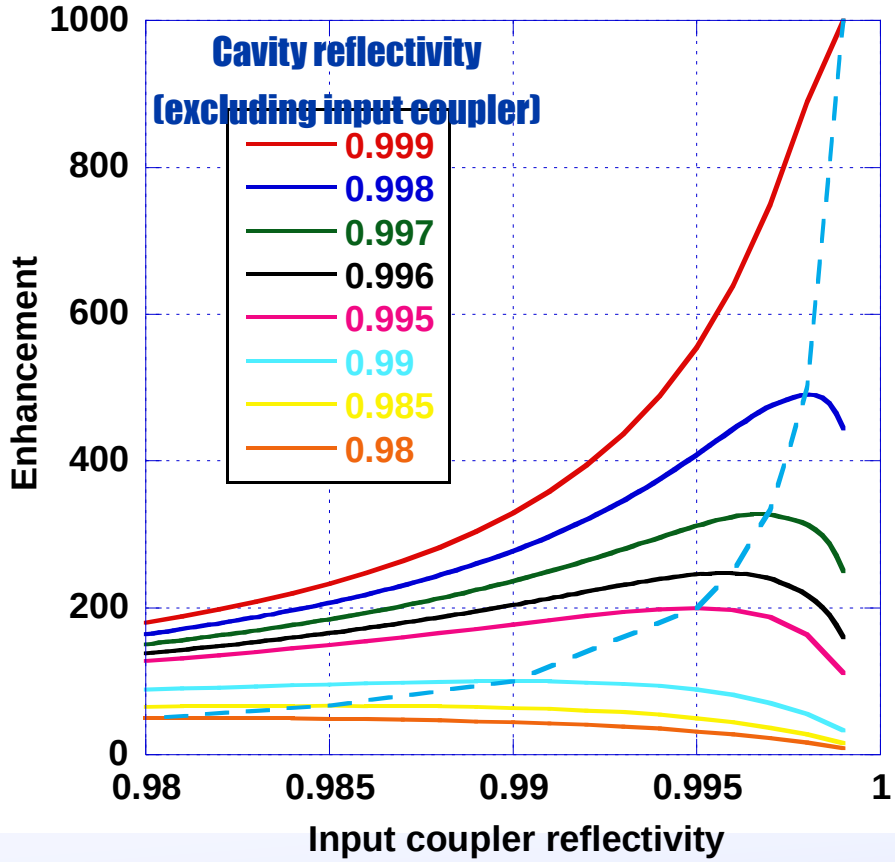






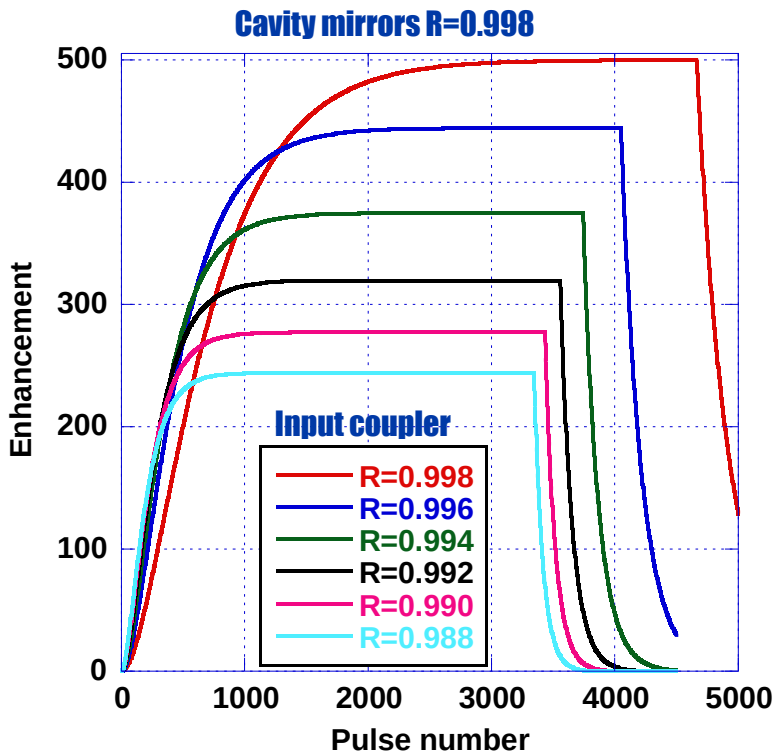
Enhancement as a function of mirror reflectivities

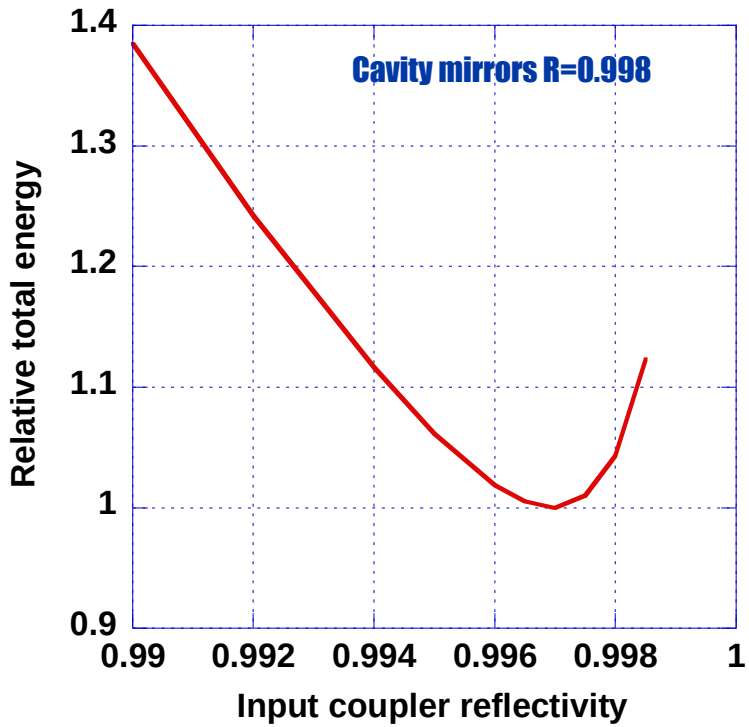
- Impedance-matched cavity (equal cavity and input coupler reflectivity) gives greatest enhancement for given cavity reflectivity
- For given input coupler, increasing cavity reflectivity increases enhancement



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





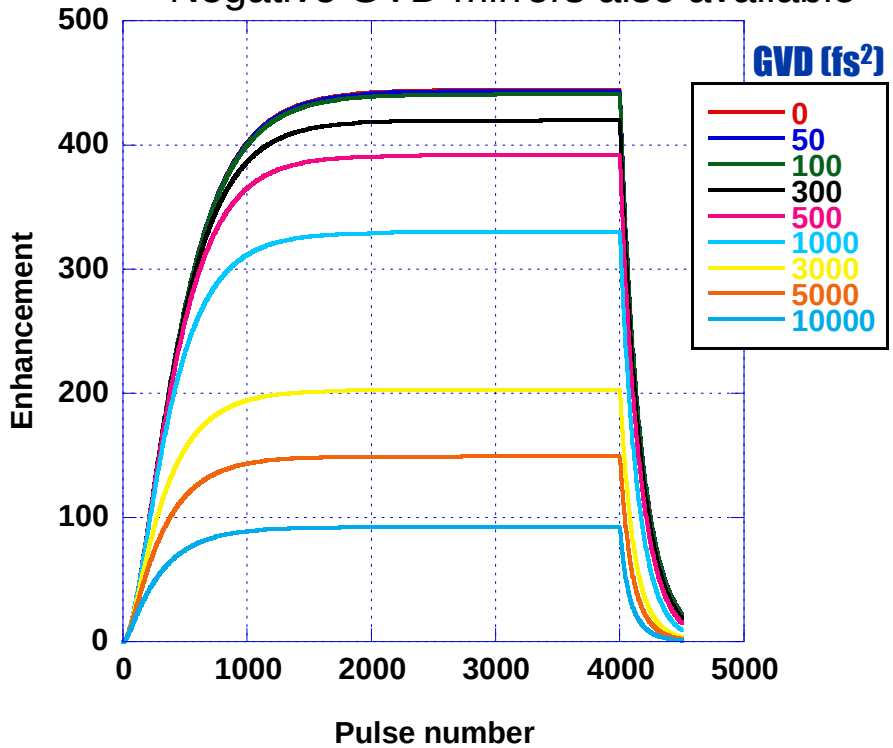
Resonant cavity enhancement puts stringent requirements on the laser and optics

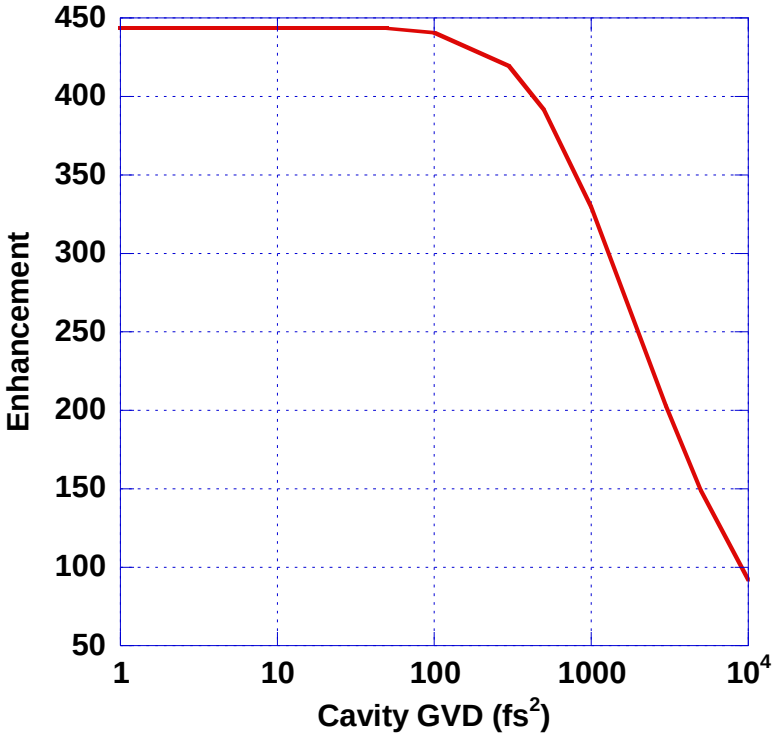
- Dispersion in resonant cavity
- Phase noise
- Cavity length/laser repetition frequency
- Amplitude noise
- Thermal changes to refractive index in amplifiers/optics
- Pointing stability

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

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

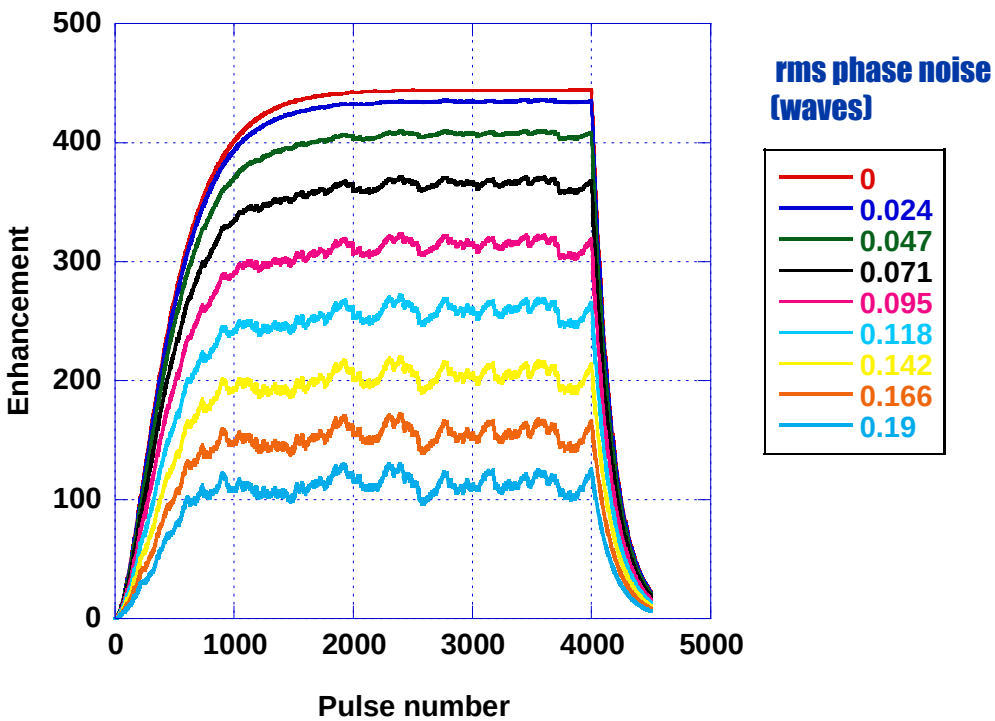
- Low-dispersion mirrors can be manufactured with < 10 fs^2 GVD
  - Negative GVD mirrors also available

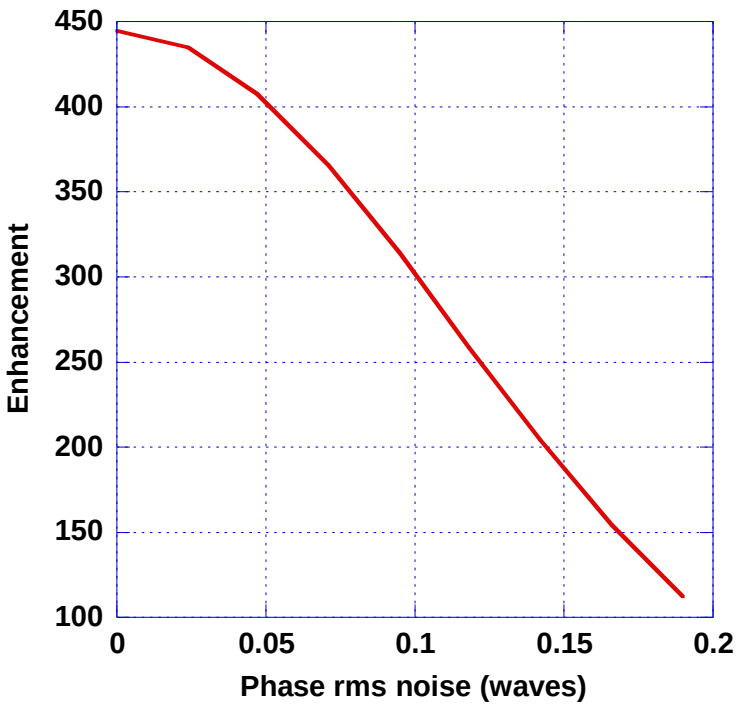




1 ps (FWHM) transform-limited input pulses

Phase noise





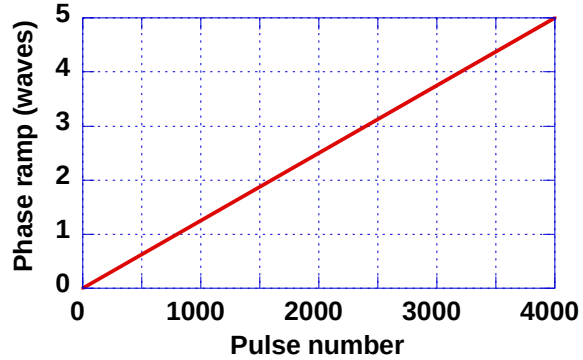
- 0.10 wave (650 mrad) achieved in CEP stabilized Ti:Sapphire system (1.4 mJ @ 1 kHz)*
- 0.03 wave (171 mrad) achieved with single amplifier (21 nJ, 75 MHz)**

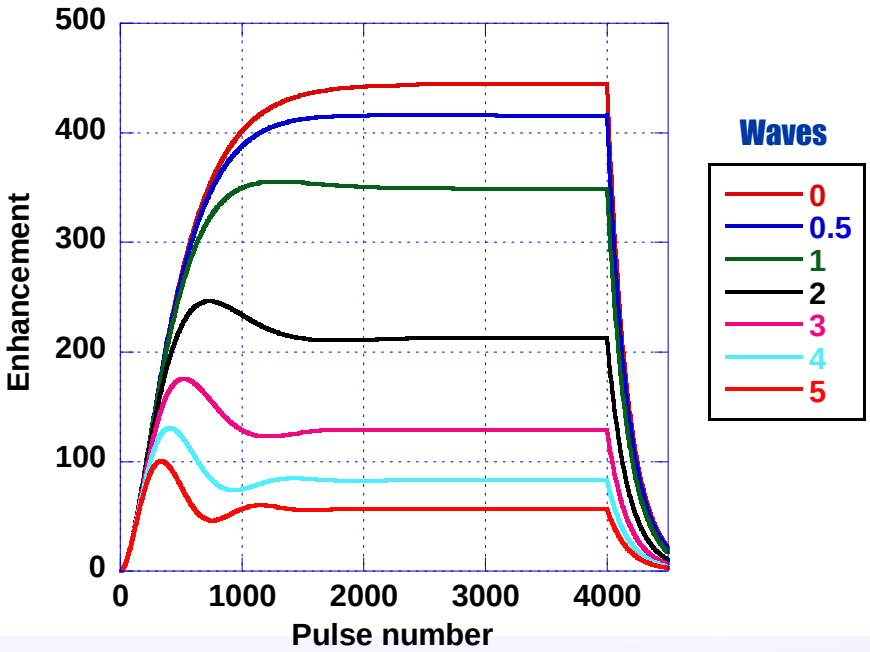
* E. Gagnon, et al., Opt. Lett. 31, 1866 (2006)

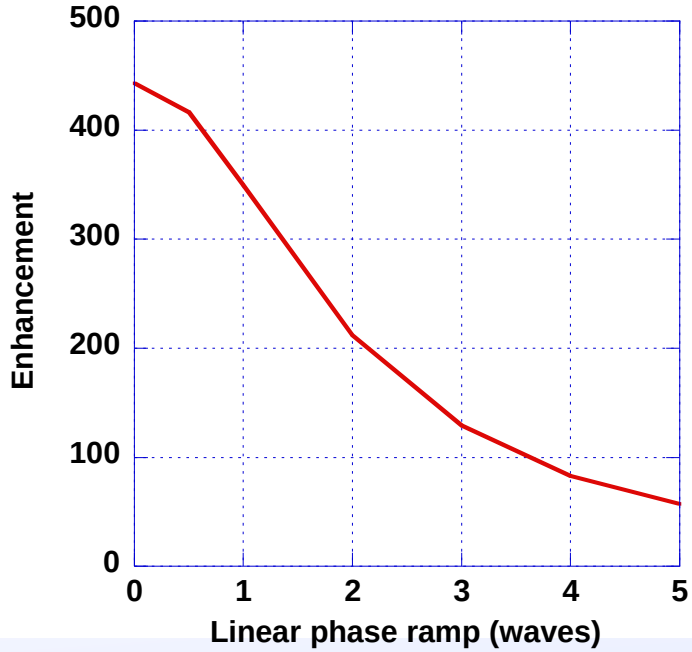
** A. Ozawa, et al., New J. Phys. 11, 083029 (2009)

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

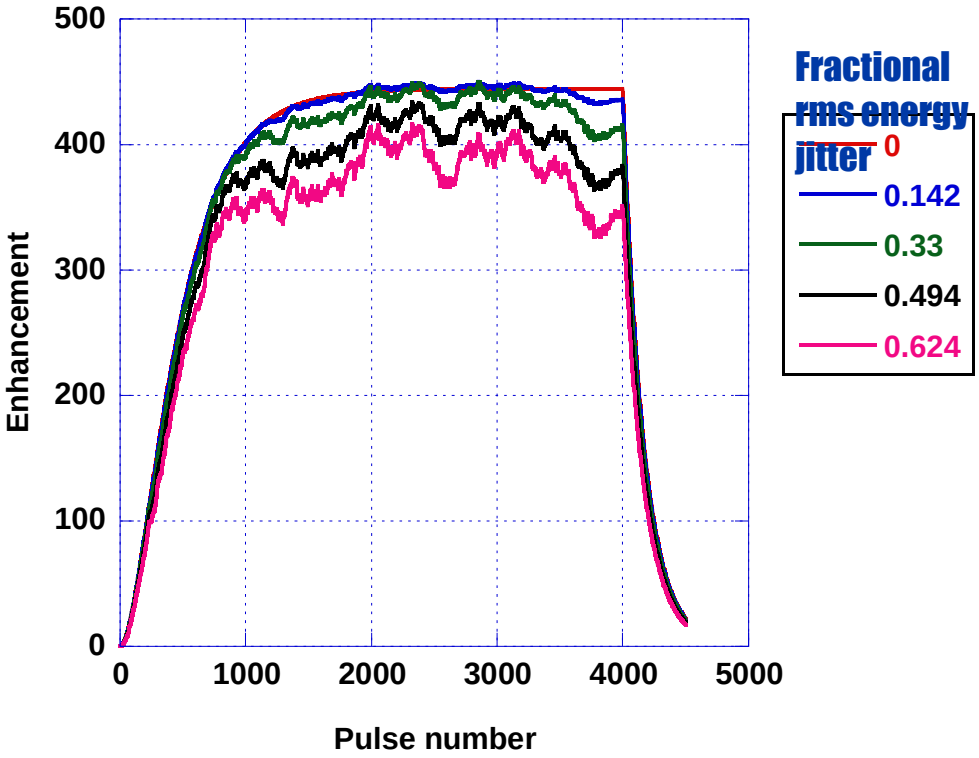


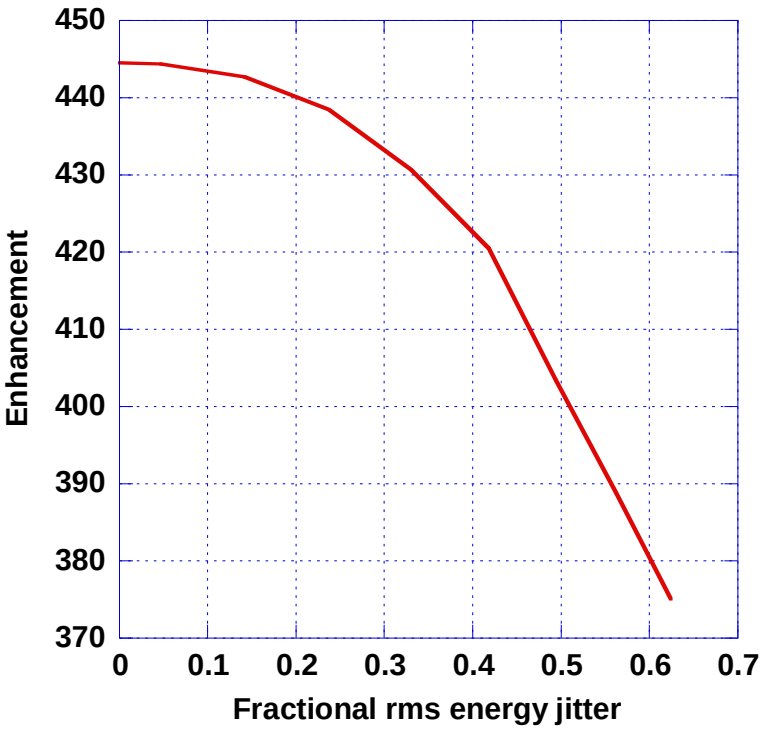




Energy jitter

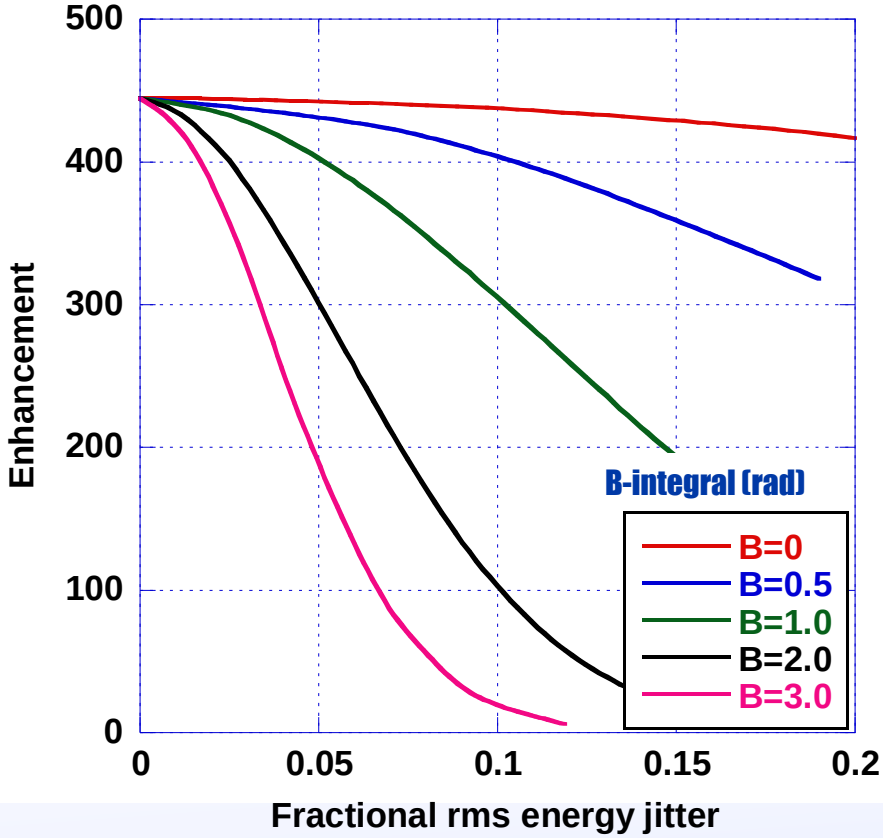
- Large jitter acceptable with no B-integral (phase) variation





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



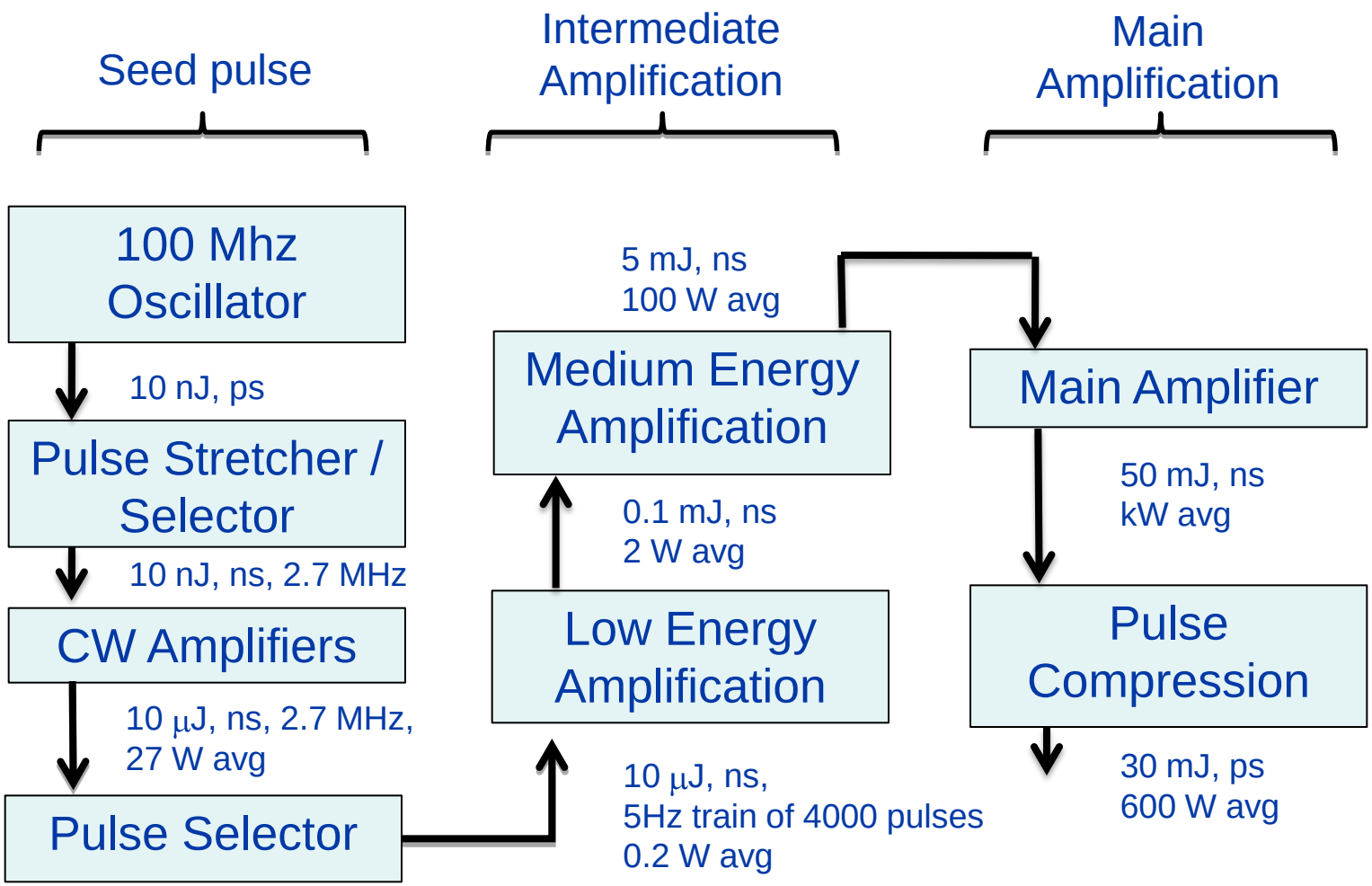
Phase:

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

B-integral (nonlinear phase accumulation):

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

Laser system concept



Pulse injection

100 MHz Oscillator

↓ 10 nJ, ps

Pulse Stretcher / Selector

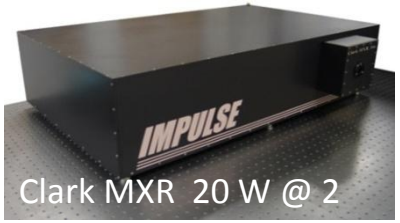
↓ 100 nJ, ns, 2.7 MHz

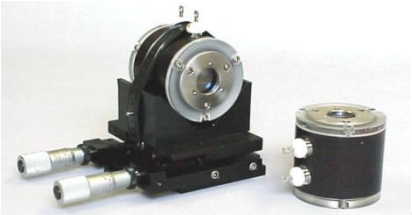
CW Amplifier

↓ 10 μJ, ns, 2.7 MHz
27 W avg

Pulse Selector

KM Labs pulse stretcher/compressor





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

↓

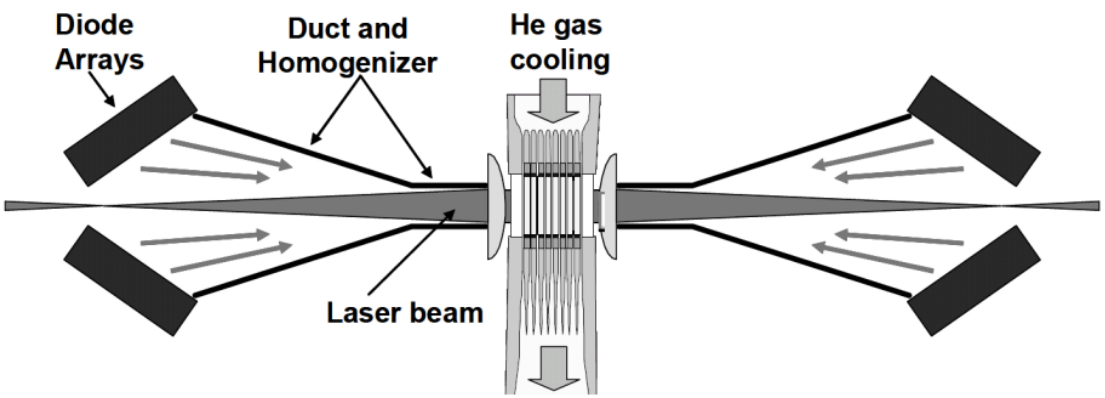
Main Amplifier

↓

50 mJ, ns
1 kW avg

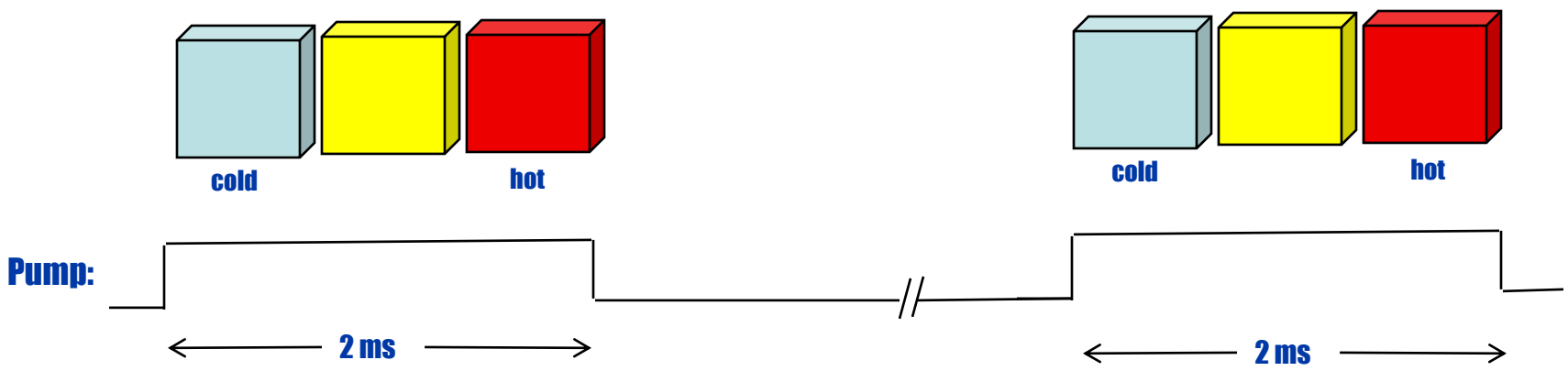
- Not commercially available
- Basic enabling technologies exist:
  - Pulsed diode pumping
  - Thermal management
- Must be adapted to ILC pulse format

LLNL Mercury He gas cooling



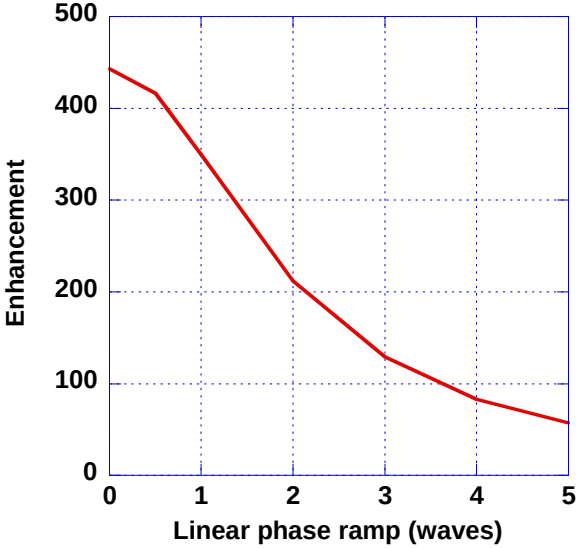
Final amplifier design must balance energetics with heat removal

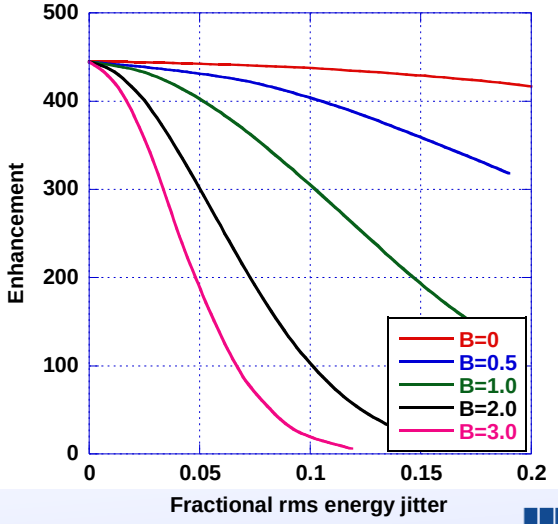
- Would like to maintain spatially uniform temperature profile through pulse train
- Would like to remove all heat before next train
  - High thermal conductivity and low heat capacity for gain medium
- Thermal effects may drive choice of flat-top vs. Gaussian beam shape in amplifiers
- Need gain of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



Uniformity of the pulse gains will be important

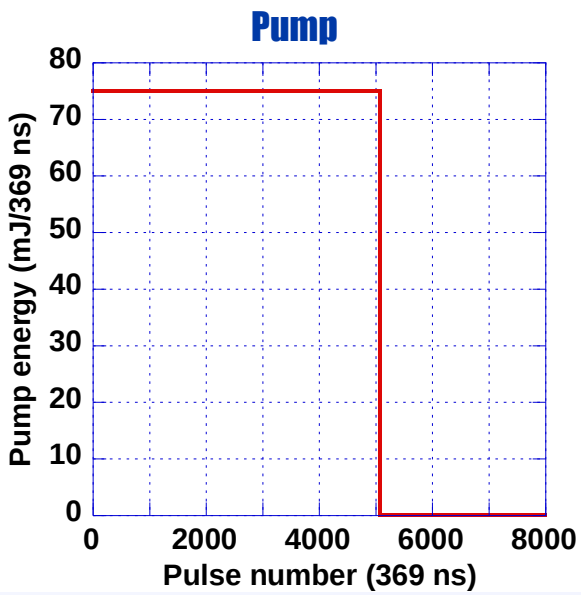
- Heating of the amplifier crystal over the train will create a linear phase ramp
- Pulse to pulse energy jitter will induce phase jitter and will make linear phase ramp more difficult to correct
- We have been evaluating various amplifier media to determine a good choice for creating a uniform output

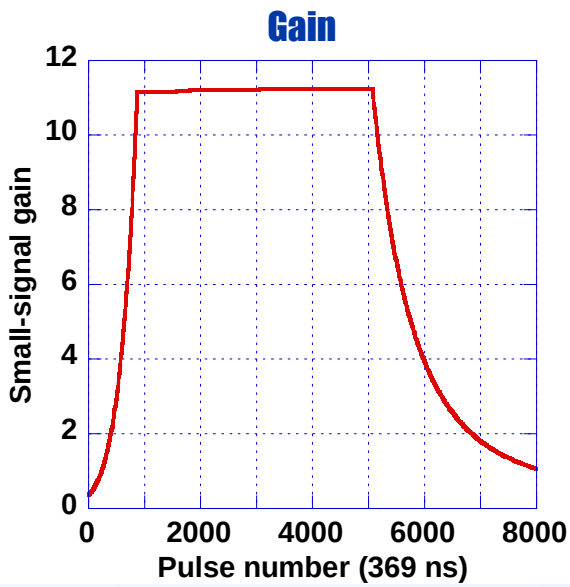


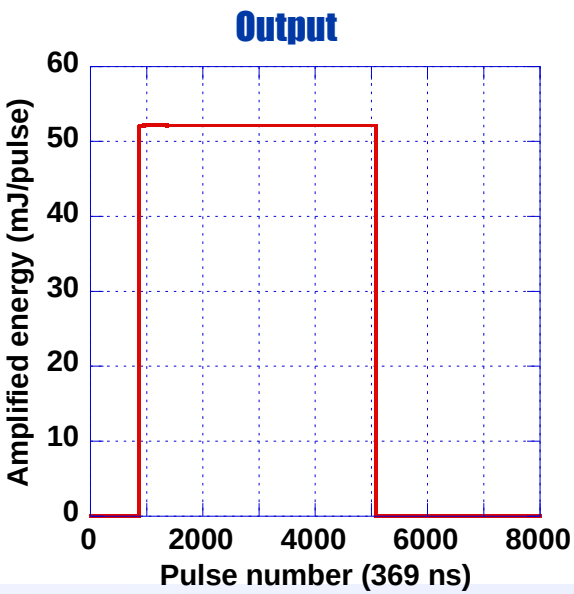


Yb:YAG is an attractive gain medium for the photon collider laser

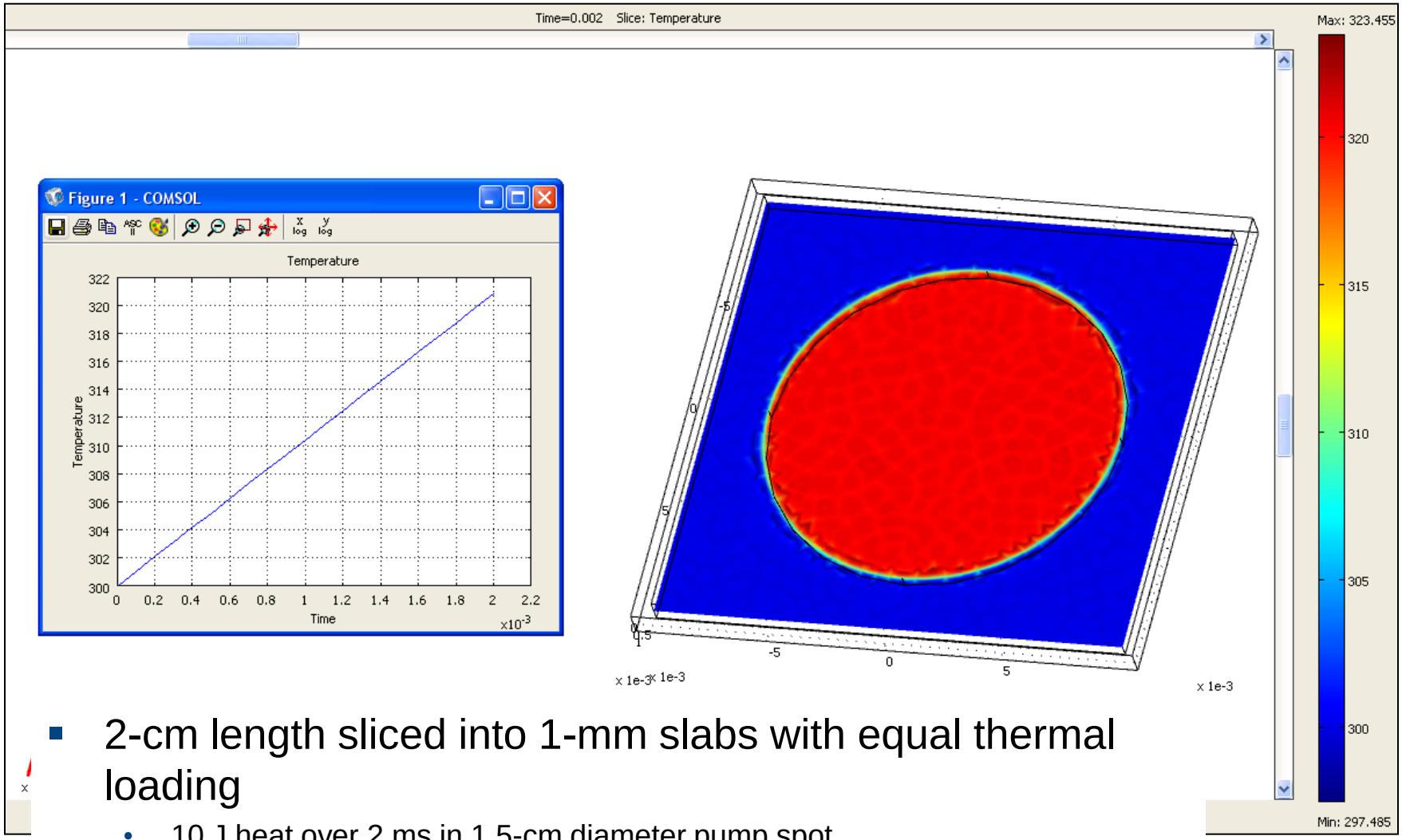
- Can achieve a gain of 1000 with bandwidth (1.5 nm) to support 1 ps pulses
  - Three stages with G≈10 to boost 50-μJ fiber output to 50 mJ
- Reduced thermal effects with pump at 940 nm, lasing at 1030 nm
- Other Yb hosts also possible: S-FAP, KYW, Sc_2O_3
- Basic three-level energetics model for final stage gives 50-mJ pulse train:
  - $\sigma_a = 0.76\times10^{-20}$ cm^2, $\sigma_s = 3.3\times10^{-20}$ cm^2, τ=0.95 ms, 5-mJ input, room temperature
  - 2-cm long crystal, 1.5-cm diameter beams (flat-top)







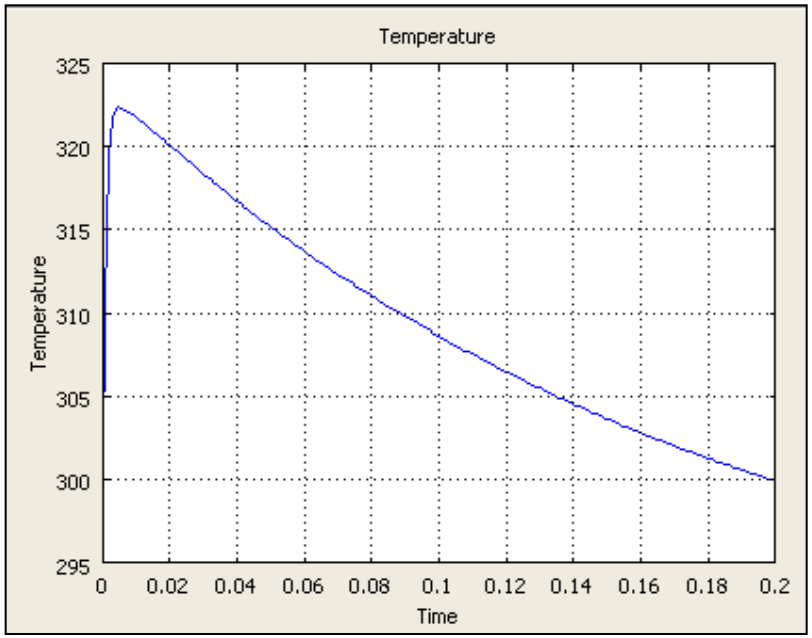
A 1-mm slice of Yb:YAG increases ≈22°K during the 2-ms pulse train



- 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

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

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:

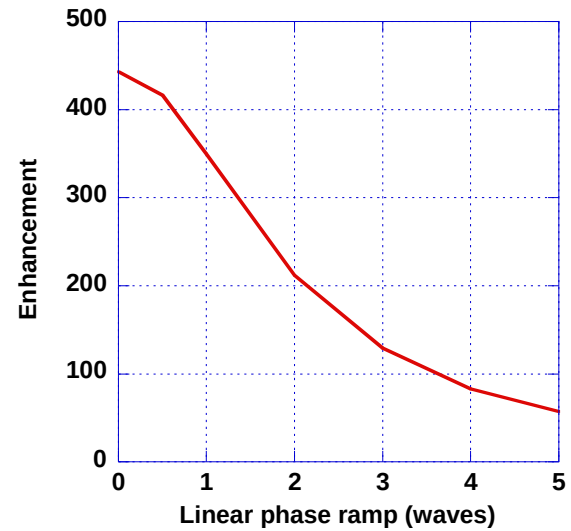
$dn/dT \approx 7\times10^{-6}$ /°K , L = 6 cm (three pass)

1 λ (2π rad) -> ΔT = 2.4 °K

Heating Yb:YAG with 200 J/bunch:

ΔT=200 J/((0.59 J/gK)(4.56 g/cm^3)(3.4 cm^3))

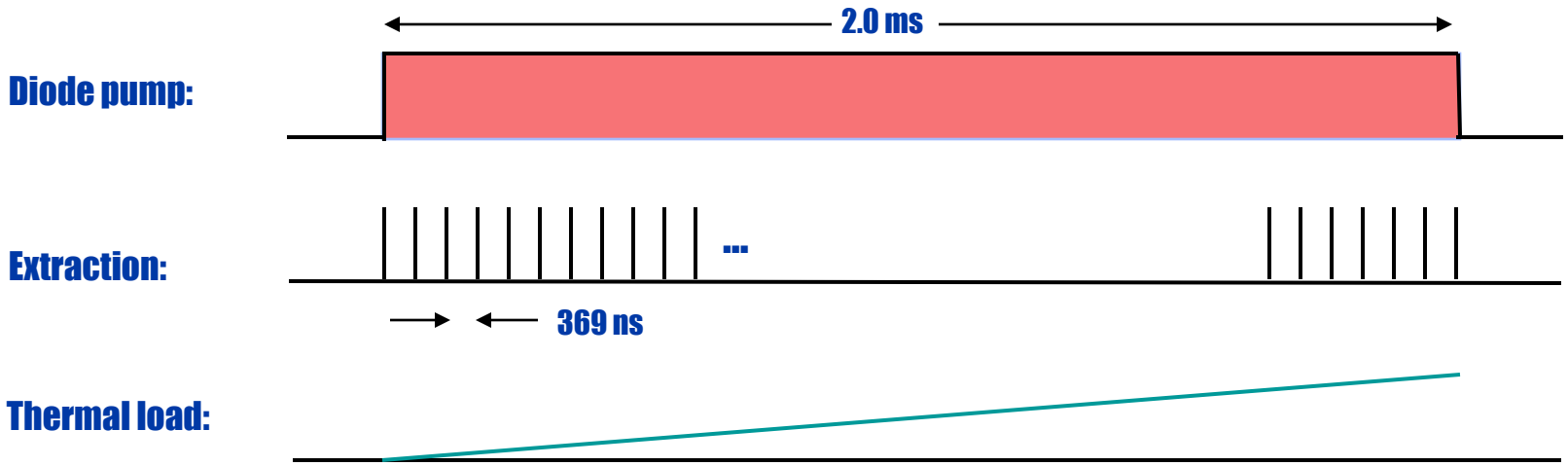
ΔT = 22 °K (9 λ)



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

Pulsed diode pumping will be required for the bulk amplifiers



Diodes:

75 mJ/369 ns = 204 kW peak $\Rightarrow$ 40% eff. 510 kW peak

at $5/peak W $\Rightarrow$ $2.5 M for diodes/drivers

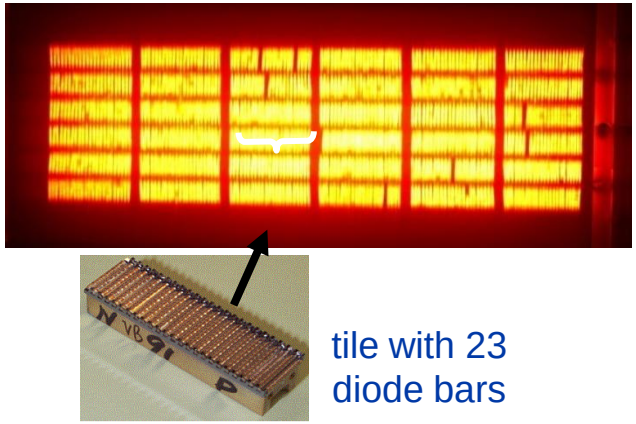
$\sim$ 5100 bars at 100 W/bar

Lifetime $\approx$ 5×10^9 shots = 31.7 years @ 5 Hz

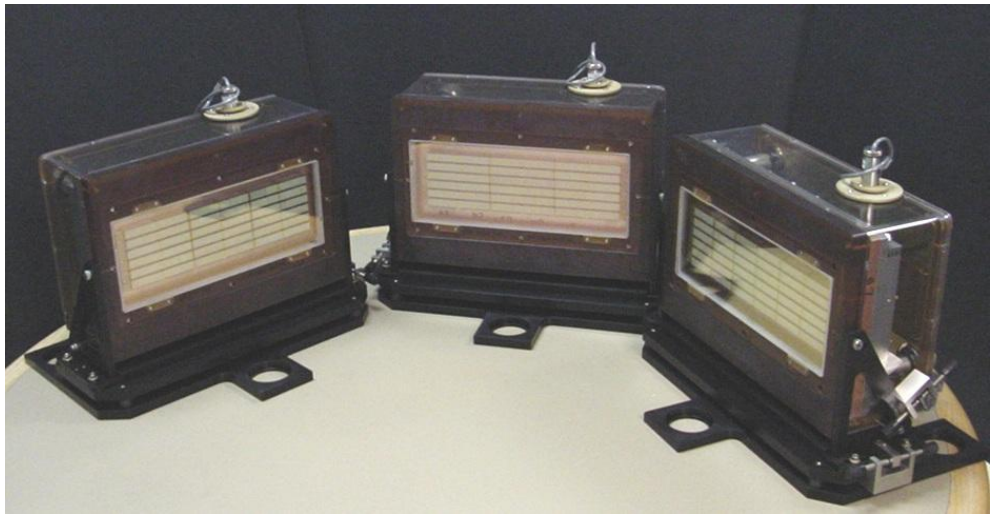
The Mercury laser at LLNL uses four 80 kW diode arrays for a total of 320 kW of peak diode power

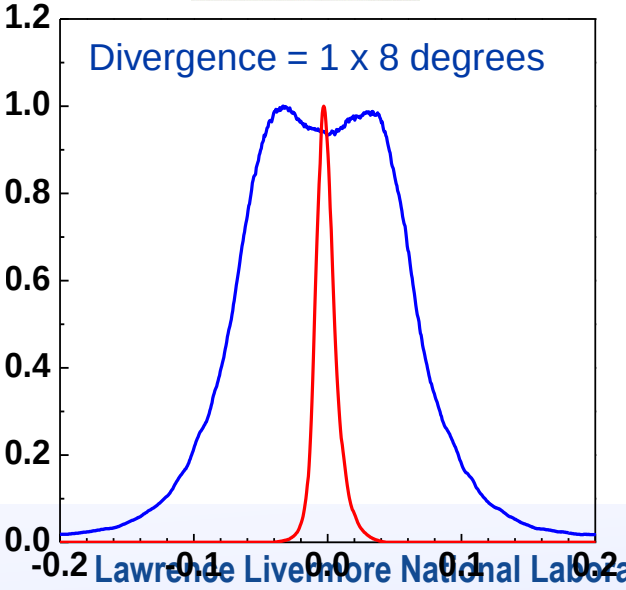
Operated at:

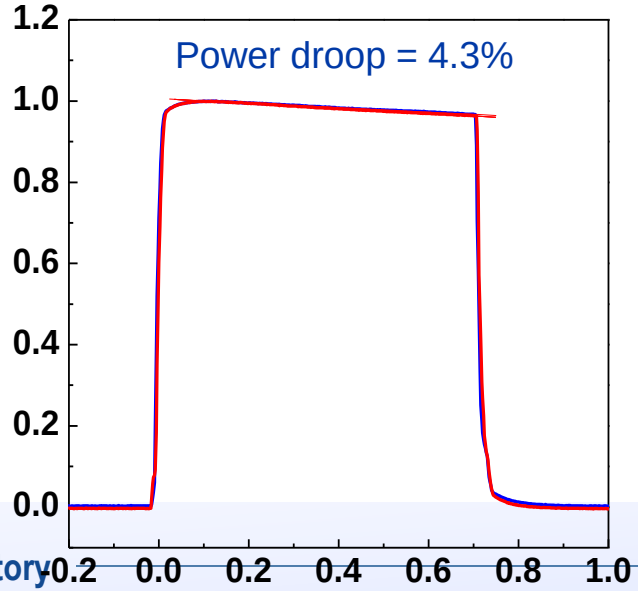
- 120 W/bar at 10 Hz

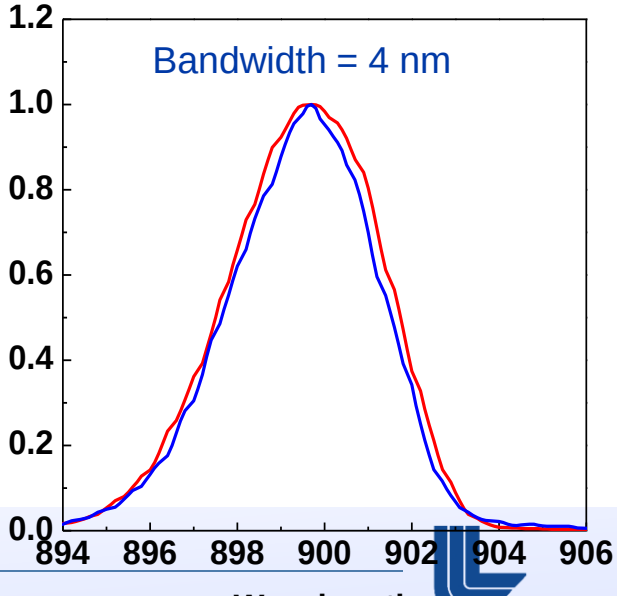


tile with 23 diode bars



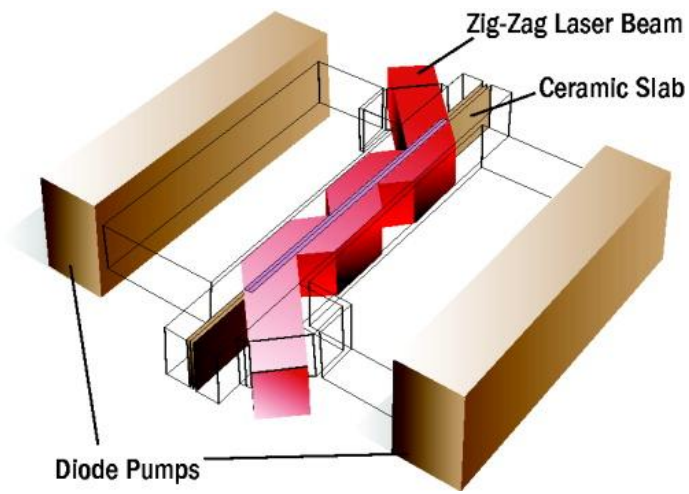




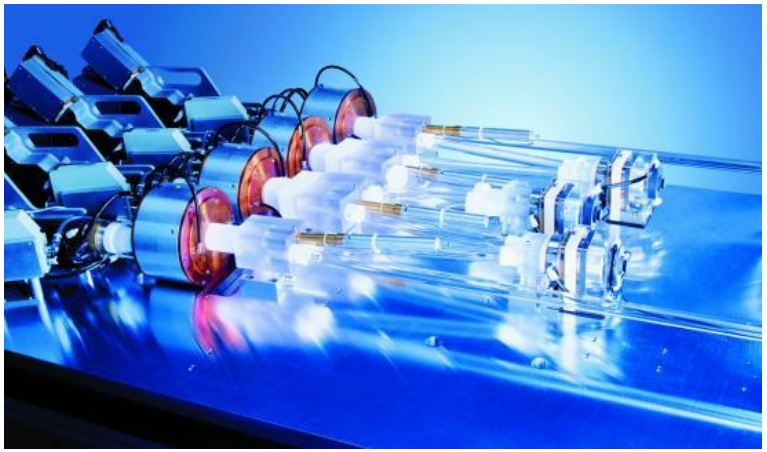


Several current amplifier designs allow aggressive cooling of thin (~mm) slabs in kW-class systems

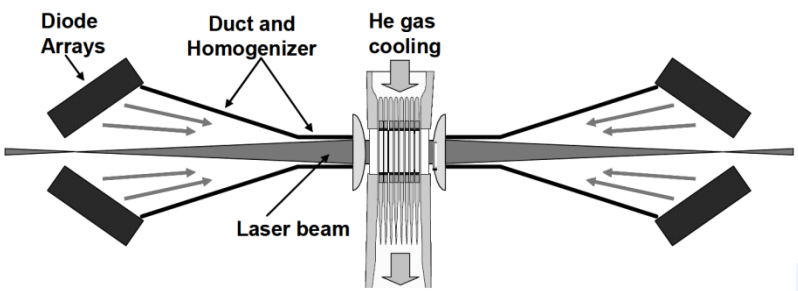
Textron ThinZag® amplifier



TRUMPF thin-disk laser



LLNL Mercury He gas cooling



EdgeWave INNOSLAB laser

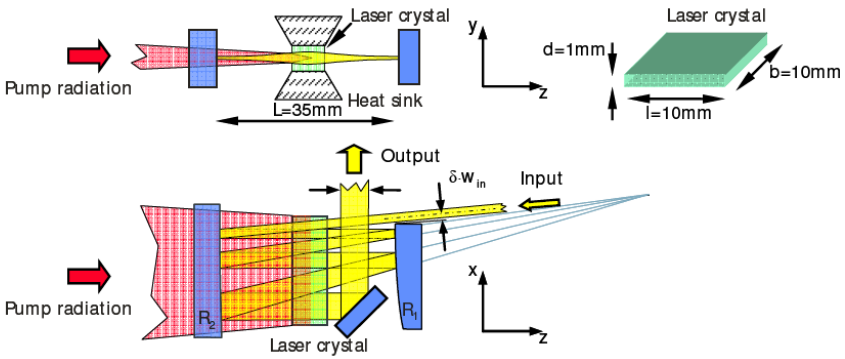


Fig. 2. Schematic setup of an Innoslab amplifier

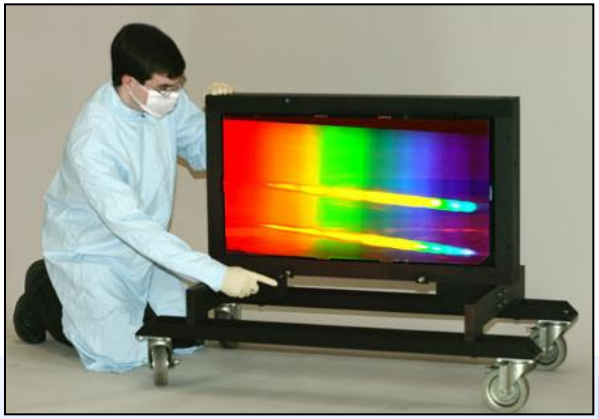
Pulse Compression

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)



Status and Outlook

- This activity is coming to an end
  - Completing thermal simulations
  - Producing documentation

- Conclusion is that generating a pulse train that can maintain the gain of the cavity is possible with available technology but maintaining phase stability is nontrivial
  - Will require prototyping and demonstration at some point

- Probably next steps should be to revisit the design of the MBI/Zeuthen cavity and layout the feedback and control system building on experience gained with Hiroshima and LAL 4-mirror cavities