Drive Laser State-of-the-art:
Performance, Stability and Programmable Repetition Rate
The Jefferson Lab Experience

Michelle Shinn

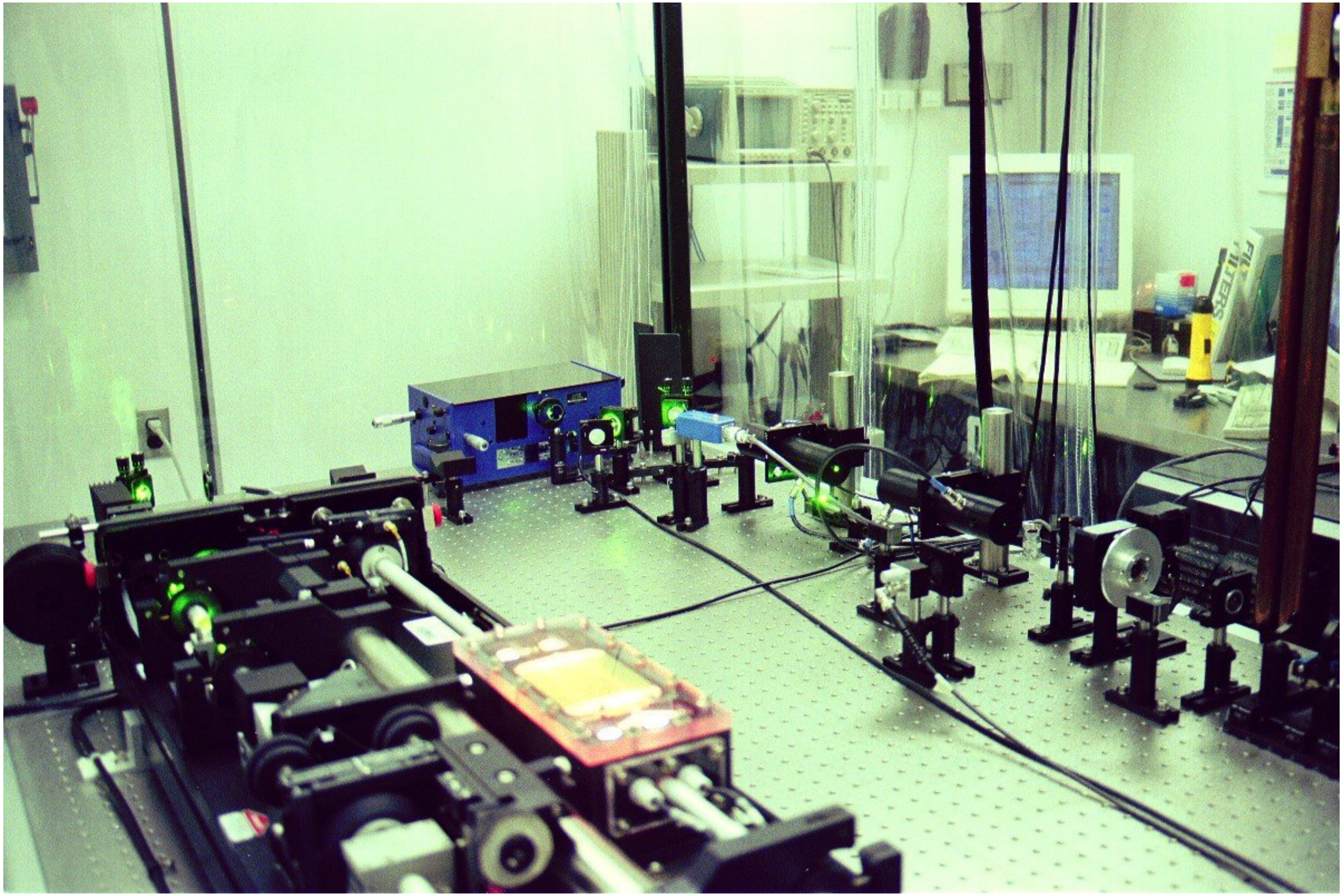
ERL Workshop
Jefferson Lab
March 22, 2005

Work supported by, the Joint Technology Office, the Office of Naval Research, the Air Force Research Laboratory, the Commonwealth of Virginia, U.S. Dept. of Energy under contract DE-AC05-84-ER40150 and the Laser Processing Consortium

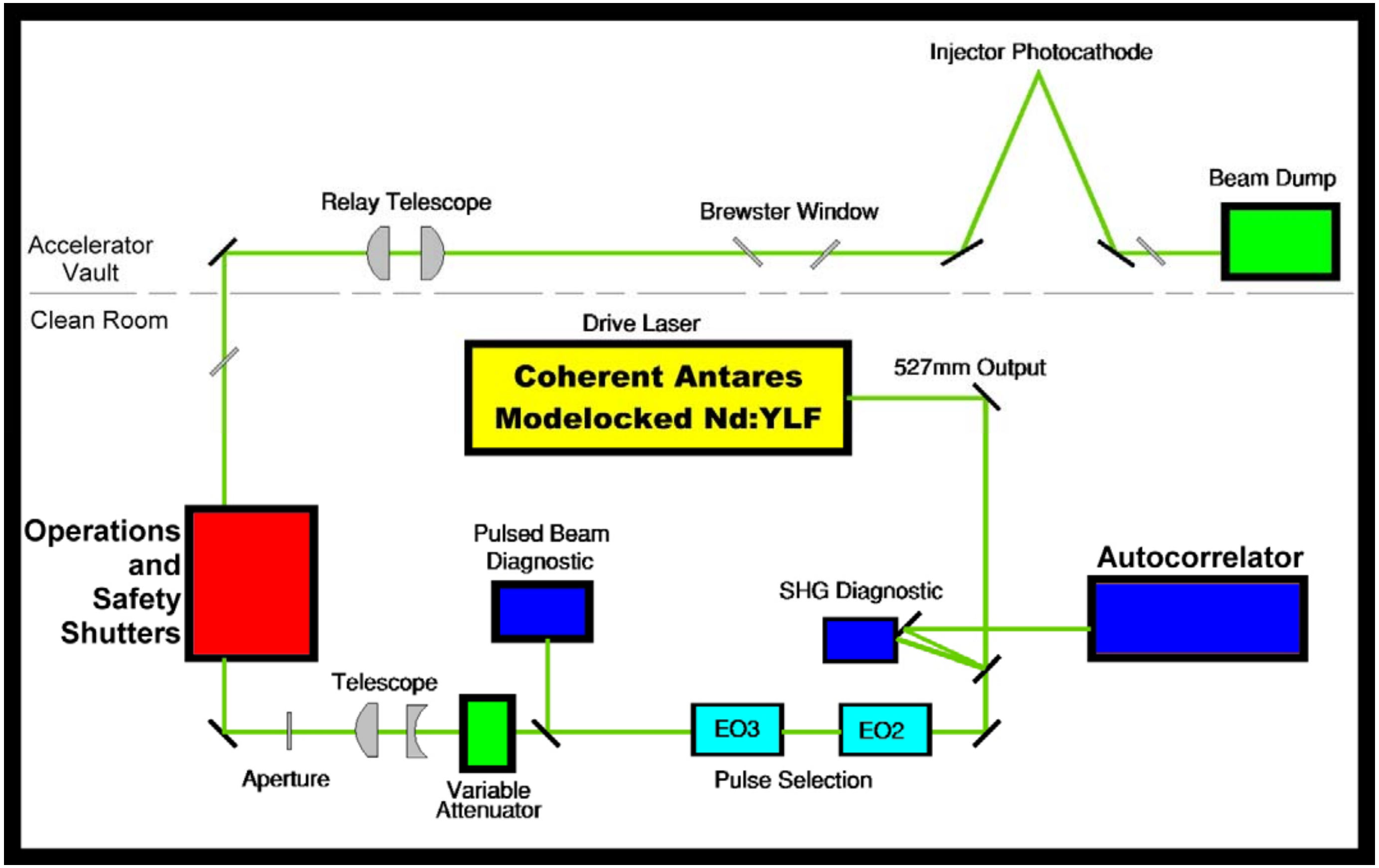
OUTLINE

- The current drive laser system for the IR Upgrade FEL
  - Performance
- The advanced drive laser
  - Possible approaches
  - Status of the chosen approach
- What is the state-of-the-art?
- Conclusions

FEL DRIVE LASER



DRIVE LASER SYSTEM & TRANSPORT



- Most of the hardware is in a Class 10000 clean room
  - Essential for long term stability
  - Contains drive laser, diagnostics, beam conditioning and pulse selection
  - Transport ~ 20 m in evacuable beam pipe to injector light box

DRIVE LASER DIAGNOSTICS

- We have refined our laser diagnostics over the last decade of operation.
  - We continuously monitor:
    - Overall health of the laser (*e.g*. water temp, water conductivity)
    - IR & visible power (1 Hz sampling rate)
    - Pulsewidth (using autocorrelation)
    - Contrast ratio of macropulses and micropulses (‘scope display)
    - Phase noise wrt MO
    - PLL parameters
  - Monitor beam profile (transverse mode quality) in a nonintercepting way:
    - In the drive laser clean room.
    - At a distance corresponding to the cathode position.

FEL DRIVE LASER PERFORMANCE

- Normally produces 4 W of 527 nm light at 74.85 MHz, ~ 50 ps FWHM .
  - Produces over 7 W with new (less than 5 khrs) laser rod.
  - SHG scaleable to ~ 12 W (longer crystal, external cavity).
  - Uptime > 99.5% over 9 years.

Parameter	**Specification**
PRF (MHz)	74.85 MHz
IR output wavelength	1053 nm
IR output Power	~ 14 W (max ~ 25 W)
SHG output wavelength	526.5 nm
SHG output power	≥ 4 W
SHG amplitude stability	~2 % p-p
Timing stability	≤ 0.5 ps (10 – 10 kHz)
Beam quality	Better than 2x diffraction-limited
Pointing stability	< 20 μrad
Beam profile	Elliptical (~25% ellipticity) Flat-top @ cathode

OUR DRIVE LASER EXPERIENCE

- Over time, we have created a drive laser system that is rarely the cause of downtime.
- Arc lamp pumping causes more amplitude jitter than diode pumping.
- Power delivered to photocathode only 25% of that launched.
- Use of an aperture to set transverse profile greatly increases amplitude jitter.
  - Due to laser beam wander (pointing stability).
- Optical transport needs periodic (~ once a day) check of alignment to minimize halo and amplitude jitter.

JLAB ADVANCED DRIVE LASER-DERIVED SPECS

- Both high current (> 100 mA) ERLs and high average power FELs (≥100 kW) need higher output drive lasers.
  - Since we are funded to plan for the next generation of FELs, we concentrate on the latter system.
- Simulations indicate this requires ~80 pC charge/bunch, or 60 mA average current.
- To achieve this current, we need a laser with these specs:
- Power: ~ 30 W, 748.5 MHz, 532 nm
  - Assumes NEA GaAs with 1% QE @ 532 nm
- Pulsewidth: ~30 ps FWHM
- Amplitude jitter < 0.5% p-p
- Timing jitter < 1 ps rms wrt RF master oscillator

HOW TO ACHIEVE THESE SPECS?

- Given that the SHG conversion efficiency lies somewhere between 35-55%
  - THG or FHG is of order 15-25%
- Therefore, IR power must be in the range of 60-90 W.
- The PRF should be high (≥ 500 MHz) commesurate with the linac RF frequency.

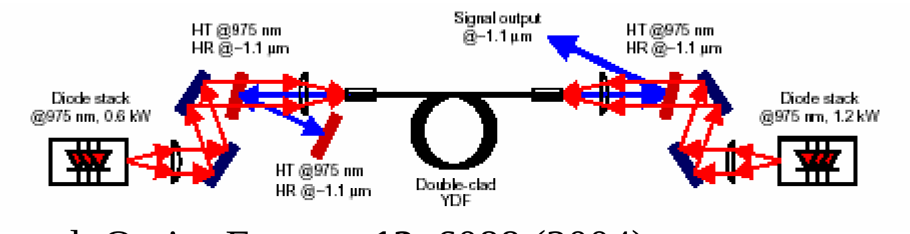
- To achieve the power goal
- Active ions are limited to Nd^{3+} and Yb^{3+}
- Lasing media could be slabs, thin disks, or fibers
- System architectures could be oscillators or MOPAs (Master Oscillator Power Amplifier)

OSCILLATOR OPTIONS

- High average power, mode-locked oscillators must have high beam quality (for efficient conversion from the IR)
  - Architecture is evolving from zig-zag slabs to thin disk geometry
  - Power of order 100 W with excellent beam quality achieved in lab
    - Time-Bandwidth Products produces Fortis (50 W @ 1030 nm, 60 MHz)
      - Based on Yb:YAG, passively mode-locked
      - Won't operate at very high PRF when passively mode-locked.
        - Energy/pulse too low to saturate the absorber.
  - Passive mode-locking eliminates low gain laser materials like Nd:YLF or Yb:YAG for use at high PRFs.
    - Harmonic mode-locking may work (must manage irradiance to avoid damage).

MOPA OPTION #1 - DIODE-PUMPED FIBER LASERS

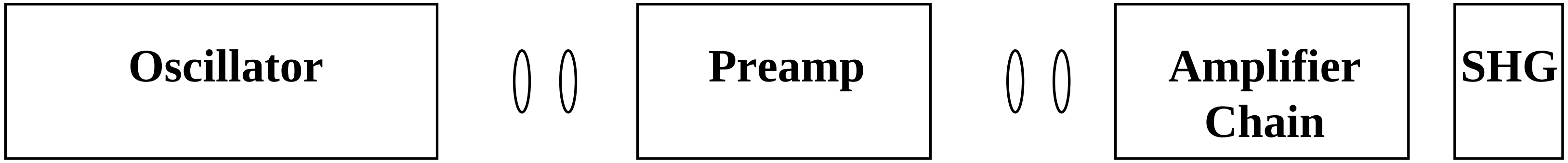
- The recent discovery (~2000 that one can trivially produce single-mode output from a multimode, double-clad fiber has led to impressive cw powers with very good beam quality:
  - J. Nillson et al (Southampton Photonics 2003) :
    - 270 W @ 1080 nm (Yb^{3+}-doped fiber)
    - 100 W @ 1565 nm (Er^{3+}, Yb^{3+}-doped fiber)
  - Y. Jeong et al (Univ. of Southampton Dec 2004)
    - 1.36 kW @ 1100 nm (12 m long Yb^{3+}-doped fiber)



Y. Jeong et al, Optics Express **12**, 6088 (2004)

- Aculight recently (July 2004) produced 60 W of SHG (540 nm) in ns pulses @ 10MHz
  - Used diode pumped fiber preamp.
  - Pulseshape when propagating ps pulses? Opportunities to do shaping?
- This is definitely an exciting area, but needs development.

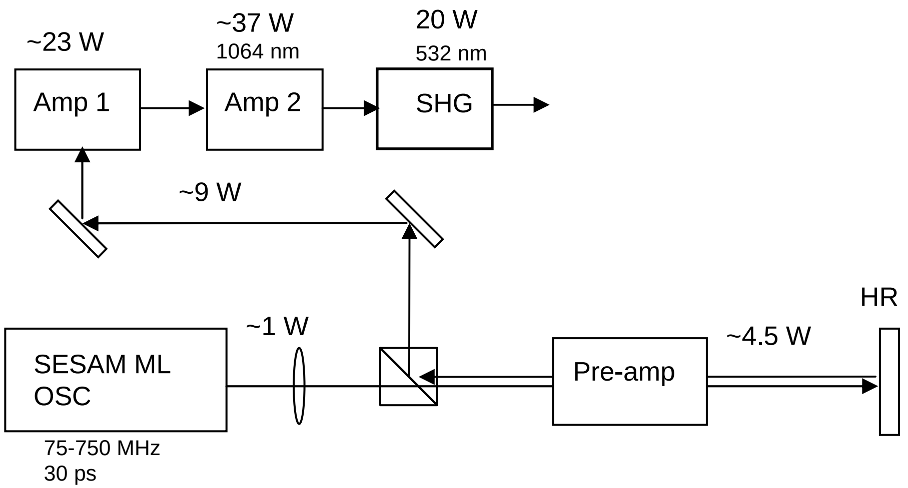
MOPA OPTION #2 - DIODE-PUMPED SLABS



- In the last 4 years, several companies introduced mode-locked lasers of this type (**e.g**., Spectra-Physics Vanguard, Time-Bandwidth Cougar, etc)
- Passively mode-locked oscillator
- Multipass amplifiers with $YVO_4:Nd^{3+}$ gain media
- This is the architecture we chose, as it minimized risk
  - Oscillator operates at either 74.85 MHz or 748.5 MHz

Parameter	**Specification**
IR output wavelength	1064 nm
IR output Power	~ 70 W
SHG output wavelength	532 nm
SHG output power	≥ 25 W
SHG amplitude stability	≤ +/- 0.5 %
Timing stability	≤ 1 ps
Beam quality	Better than 3x diffraction-limited
Pointing stability	< 20 μrad
Beam profile	Circular (up to 25% ellipticity permitted)

NEW DRIVE LASER PERFORMANCE - NOV 2004



CLEO 2005 Paper CMJ4, "**High-Average-Power Picosecond Drive Source for Photocathode Injectors",** A. Dergachev **et al**

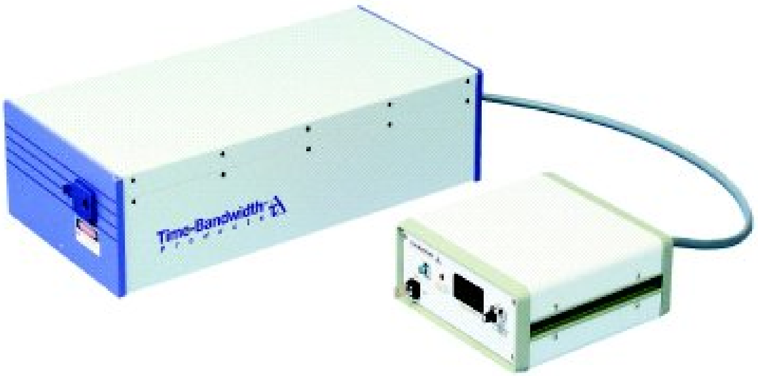
- Performance degraded by high loss (~ 5%/pass) in amplifier host material.
  - Some slabs had problems with poor coatings, producing parasitic oscillation.
  - Vendor had provided excellent material the past 7 years.
- Since last November, using material that meets spec, preamp delivers 15 W, output/amp is ~15 W.
  - SHG conversion efficiency with 30 ps pulses exceeds 50% (@74.85 MHz PRF)
  - One preamp and three amplifiers should give us > 25 W at 532 nm.
  - One can continue adding amplifiers to achieve higher powers.

ADVANCED DRIVE LASER OSCILLATOR

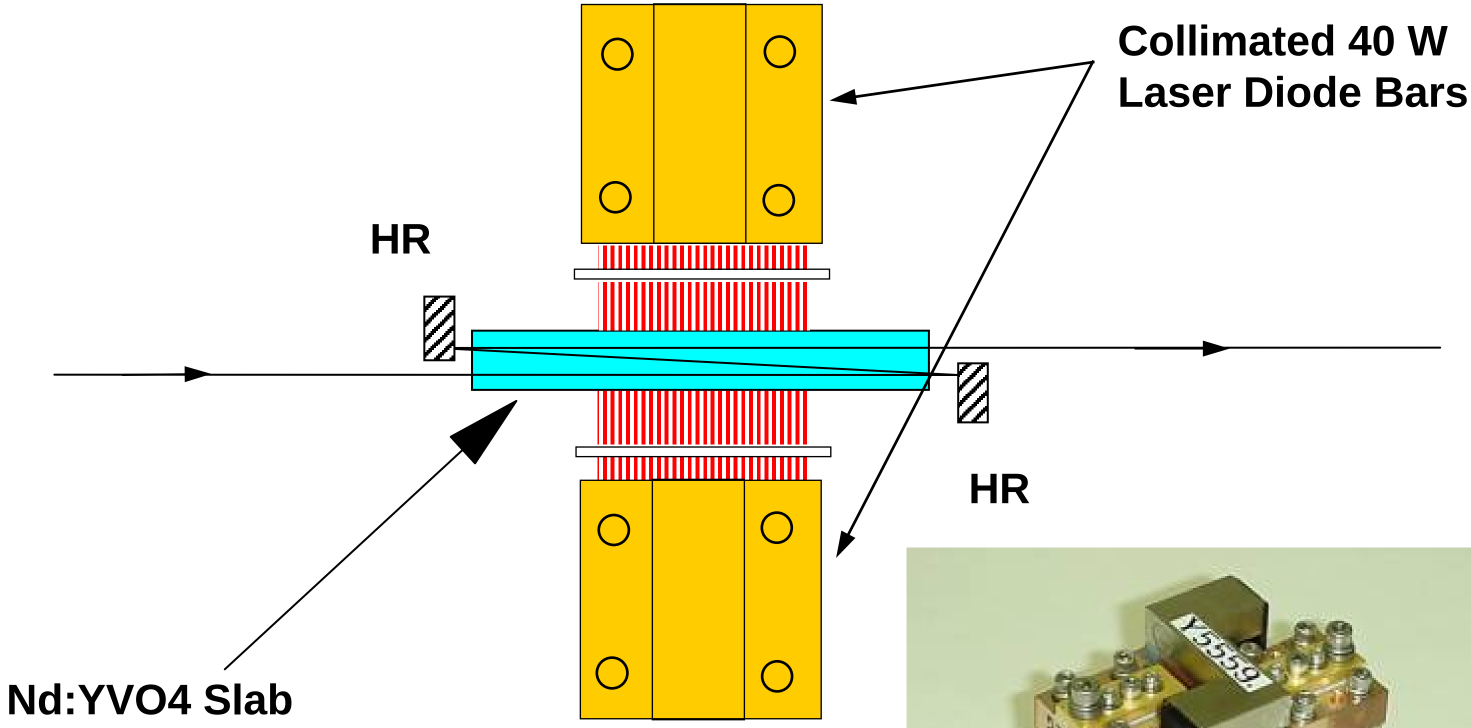
Quantity	Spec	Achieved @ 74.85 MHz	Achieved @ 748.5 MHz
Power	≥ 0.5 W	1 W	1.05 W
Pulselength	30-50 ps	29 ps	27 ps
Ampl. Jitter	< 1 % p-p	0.8 % p-p	0.8 % p-p
Timing Jitter	< 1 ps	0.4 ps	0.2 ps*
Beam Quality	2 x D. L.	< 2 x D.L	< 2 x D.L
Pointing Stability	20 μrad	5 μrad	5 μrad
Ellipticity	1.25	1.9**	1.6**

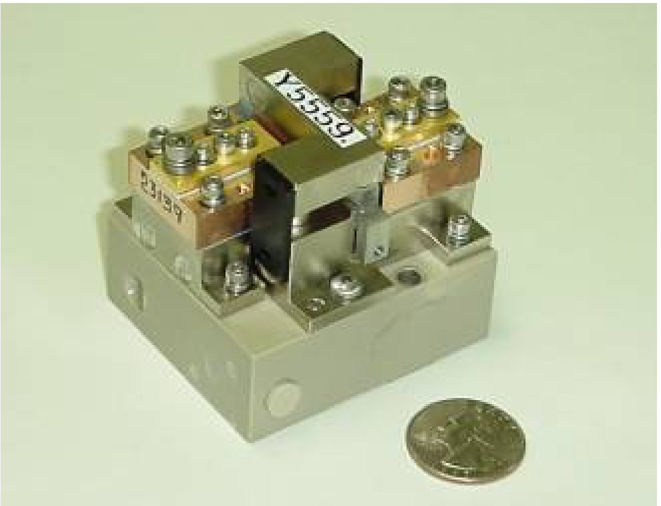
* At lower limit of measurement

** Circularizing optics remove ellipticity



THE Q-Peak LASER AMPLIFIER IS COMPACT





IMPROVED DRIVE LASER TRANSPORT

- One of our largest sources of loss is the pulse selection.
  - Two EO modulators, each with ~ 90% transmission.
- We will replace this with one EO cell, located before the SHG crystal

- The hard aperture transmits 63% of the input
- We will replace this with an aspheric beam shaper of our own design.

- Uncoated wedge too lossy, will replace with optimized version.

WHAT IS THE STATE-OF-THE-ART?

- For systems operating in the 10s of ps, a fiber laser solution appears ideal:
  - *If the dispersive effects in the fiber amplifier are tractable.*
  - Power in the infrared looks fine.
  - Use of a laser diode as the seed means the PRF can be whatever you wish it to be.
  - No EO modulators
  - Laser system alignment is maintained.
    - Simple optical transport system, laser can sit very close to the gun.
  - Doubling Er^{3+}-doped fiber gives you plenty of power for a polarized electron source.
- For fs systems, the choice is far less clear.
  - Dispersive effects must be carefully managed, no matter what system you chose.

CONCLUSIONS

- Drive laser systems can be a reliable component of an accelerator.
- Economics (telecom & material processing) are driving the state-of-the-art in the right direction to provide sources for 100 mA ERLs
  - We are taking receipt of a system that will do this.
  - Will likely need to stay in the ps time regime.
- These systems will probably never be catalog items.
  - PRFs not really interesting to major laser manufactures.
    - However, “boutique” laser vendors proably can provide what’s needed.

ACKNOWLEDGEMENTS

- FEL Group, esp Optics and Inst. & Control
- A. Brown, Aculight
- M.Poelker, Injector Source Group, JLab.

AS A GENERAL RULE

"A laser working for one shift/day is just paying for itself; if working for two shifts/day it is distinctly profitable, if it is working three shifts/day you will probably find the owner in the Bahamas or some such place."

W. Steen, Laser Materials Processing (2nd ed, 1998) pg 186