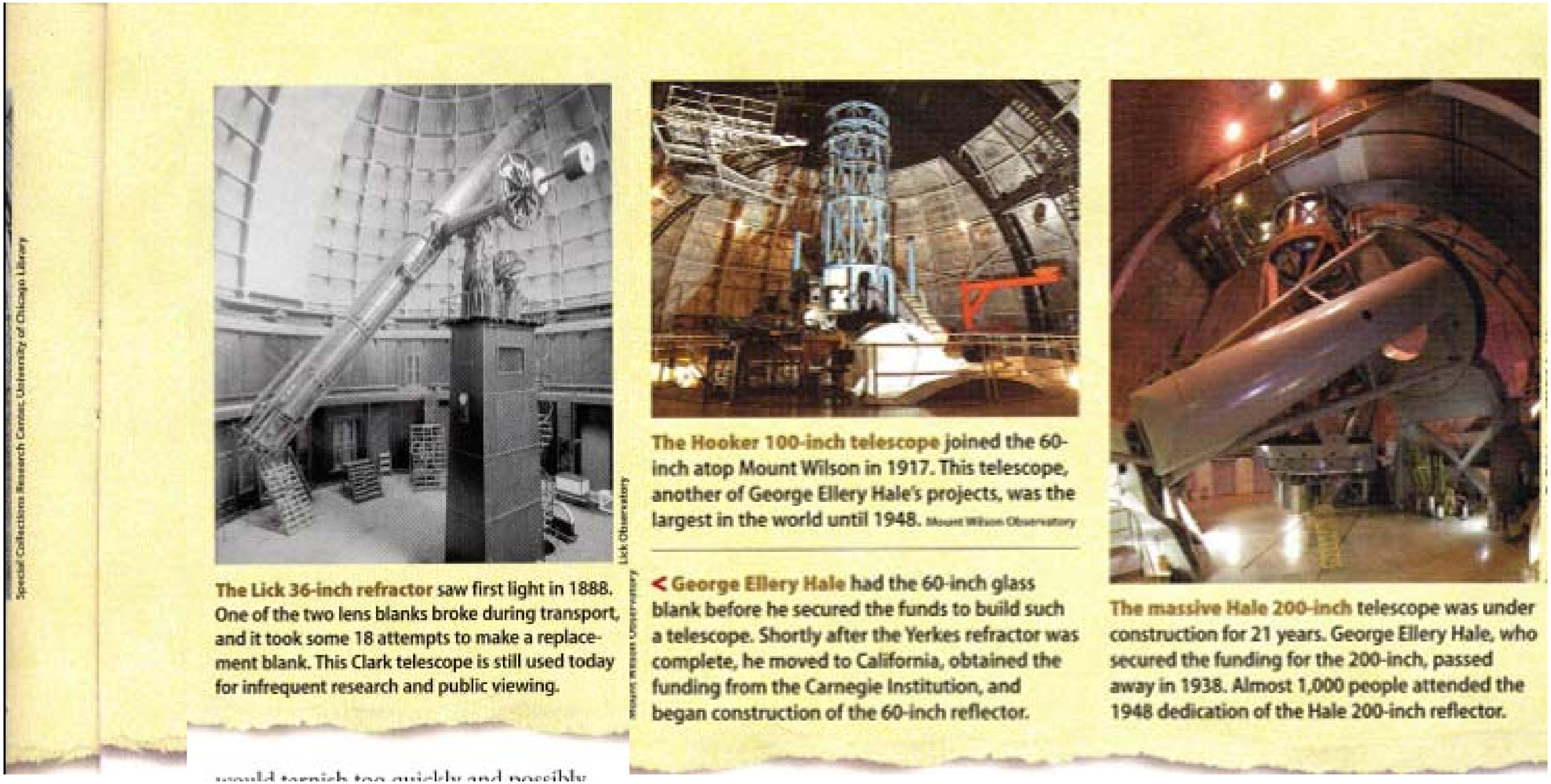
Robert L. Byer
Applied Physics
Stanford University
rlbyer@stanford.edu

Abstract

In the fifty years since the demonstration of the laser, coherent light has changed the way we work, communicate and play. The generation and control of light is critical for meeting important challenges of the 21st century from fundamental science to the generation of energy

Ives Medal Address
Frontiers in Optics
San Jose, CA

California – Leader in advanced telescopes for astronomy



Special Collections Research Center, University of Chicago Library

The Lick 36-inch refractor saw first light in 1888. One of the two lens blanks broke during transport, and it took some 18 attempts to make a replacement blank. This Clark telescope is still used today for infrequent research and public viewing.

Lick Observatory

would tarnish too quickly and possibly

The Hooker 100-inch telescope joined the 60-inch atop Mount Wilson in 1917. This telescope, another of George Ellery Hale's projects, was the largest in the world until 1948. Mount Wilson Observatory

Mount Wilson Observatory

< **George Ellery Hale** had the 60-inch glass blank before he secured the funds to build such a telescope. Shortly after the Yerkes refractor was complete, he moved to California, obtained the funding from the Carnegie Institution, and began construction of the 60-inch reflector.

The massive Hale 200-inch telescope was under construction for 21 years. George Ellery Hale, who secured the funding for the 200-inch, passed away in 1938. Almost 1,000 people attended the 1948 dedication of the Hale 200-inch reflector.

Lick 36 inch refractor
1888

The Mount Wilson 100 inch
1917

The Palomar 200 inch
1948

California – Leader in advanced lasers

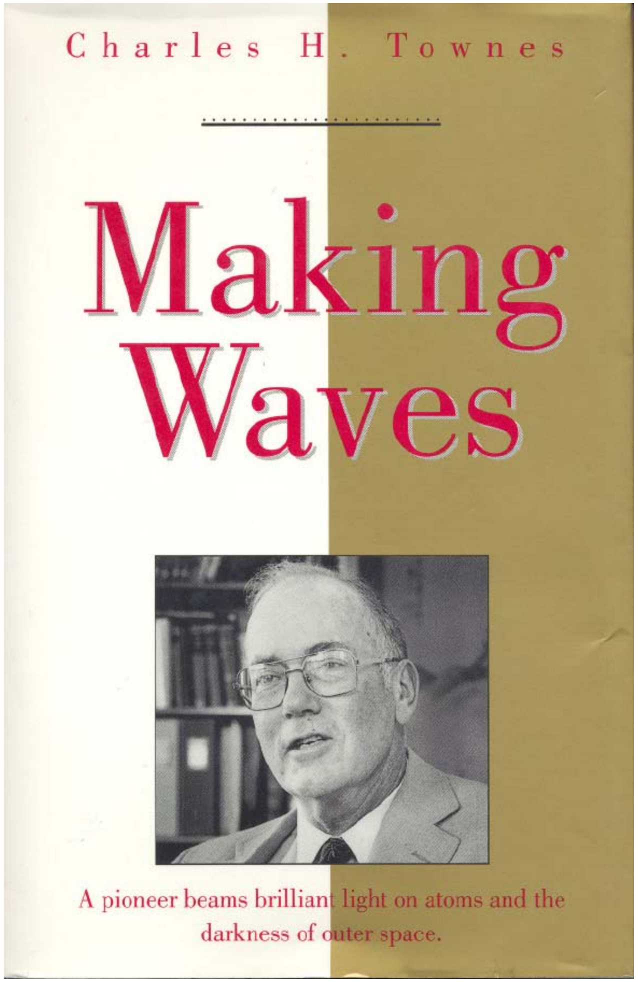
Ruby Laser	Ted Maiman	1960
Hg+ Ion Laser	Earl Bell	1965
Argon Ion Laser	Bill Bridges	
Tunable cw parametric Laser	Harris	1968
Diode bar 1Watt Laser	Scifres	1978
Diode Pumped Nd:YAG (NPRO)	Byer	1984

2009 a special year

105kW cw Nd:YAG Slab Laser	NGST	January
4 MJ IR, 2MJ UV NIF Laser	LLNL	March
1mJ 10Hz 1A Coh Xray Laser	SLAC	April

2010 Laser Fest

Lightwaves



Prelude

Introduction	*Making Lightwaves*
Scientific Applications of Lasers	*Riding Lightwaves*
Future Directions	*Surfing Lightwaves*

Charlie is still contributing to Science at
The University of California at Berkeley

The Ruby Laser

Art Schawlow with Mickey Mouse Balloon and Ruby Laser

Retinal Attachment

"If I had set out to invent a method of re-attaching the retina, I would not have invented the laser"

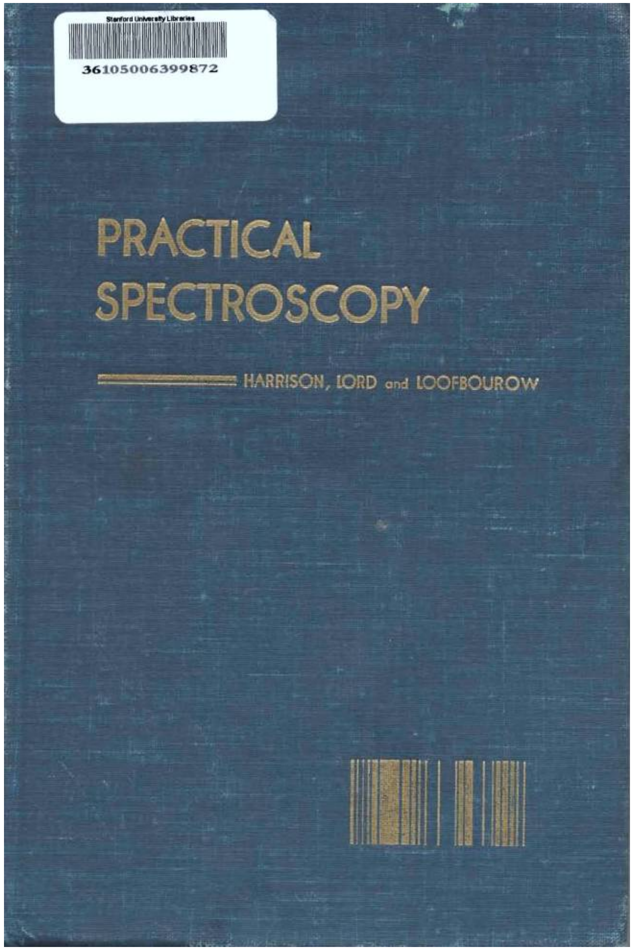
Laser Eraser

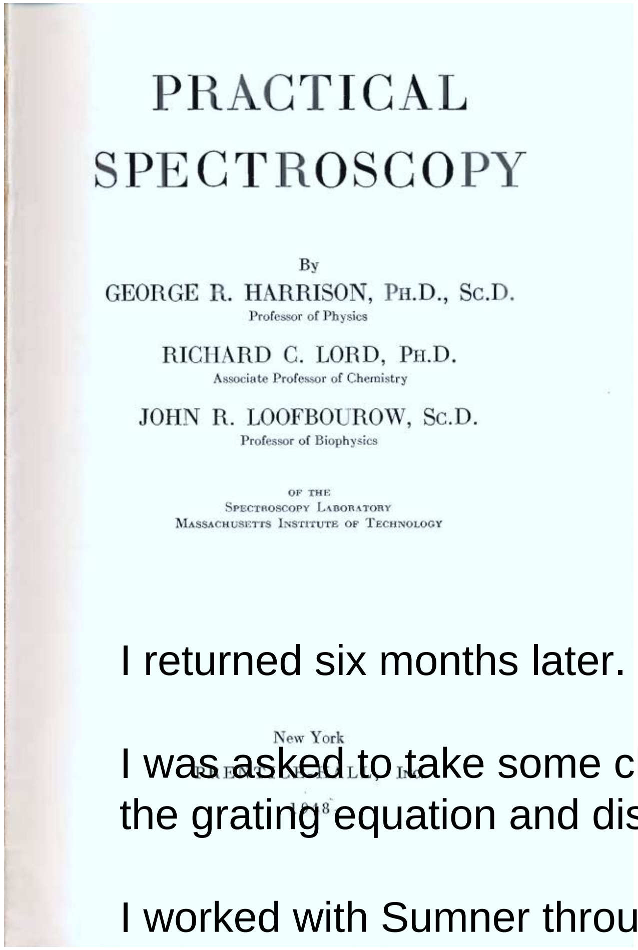
"The "Laser Eraser" may not find any near term application, but it is interesting."

The first Ruby laser was demonstrated in 1960 by Ted Maiman
Hughes Research Labs in Los Angeles

Arrived in Berkeley Autumn 1960

I met with young Assistant Professor Sumner P. Davis and asked if I could work in his laboratory. His reply: "Go read this book and when you understand everything in it, come back and see me."





PRACTICAL
SPECTROSCOPY

By
GEORGE R. HARRISON, PH.D., SC.D.
Professor of Physics

RICHARD C. LORD, PH.D.
Associate Professor of Chemistry

JOHN R. LOOFBOUROW, SC.D.
Professor of Biophysics

OF THE
SPECTROSCOPY LABORATORY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

New York
PRENTICE-HALL, INC.
1948

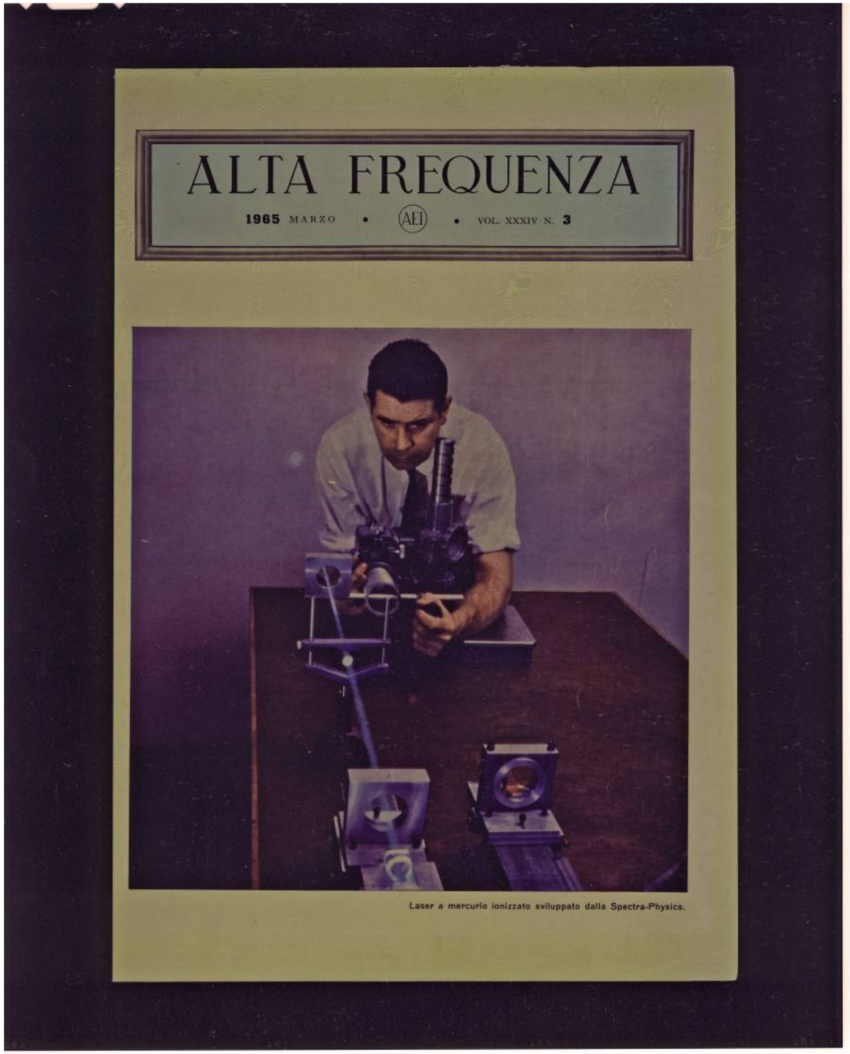
Sumner P. Davis

I returned six months later.

I was asked to take some chalk and derive the grating equation and dispersion relations.

I worked with Sumner through my senior year.

Spectra Physics – the ion laser



ALTA FREQUENZA

1965 MARZO • AEI • VOL. XXXIV N. 3

Laser a mercurio ionizzato sviluppato dalla Spectra-Physics.

Earl Bell 1966 Mercury Ion Laser

With a recommendation from Sumner, I arrived at a small company in Mountain View, CA for an interview.

I waited in the lobby but no one came to say hello. After what seemed like a half an hour I walked into the back where there was loud cheering and celebration.

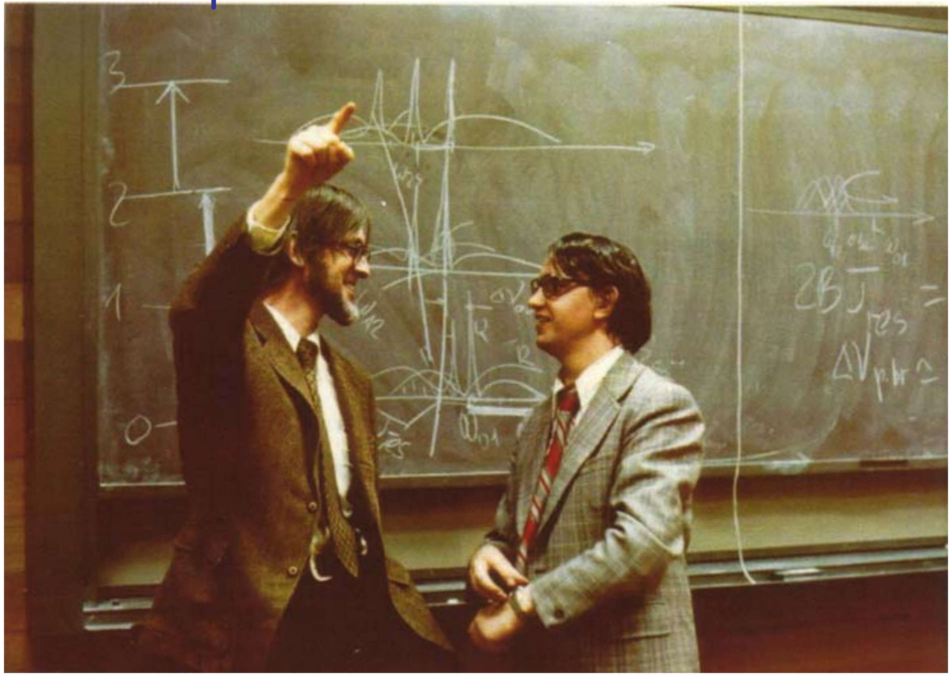
Earl Bell had just operated the first Ion laser that generated orange light.

I took the job at **Spectra Physics** and worked with Earl Bell, Arnold Bloom, Herb Dwight for one year, then….

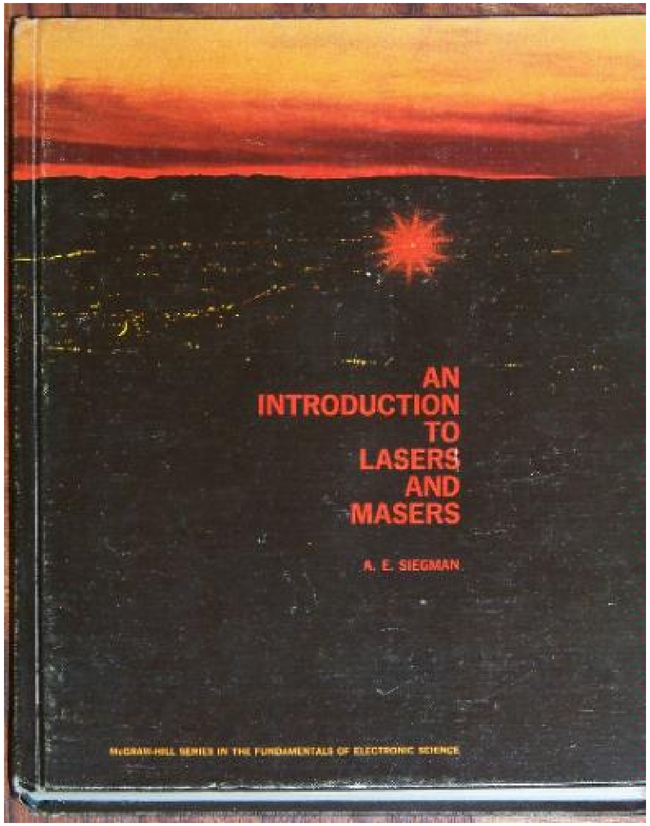
"If a laser can operate at 5% efficiency, it can do real work." Earl Bell 1965

Tony Siegman held brown bag lunches to discuss research topics of interest such as Second Harmonic Generation …

I asked Herb Dwight if I could ride my bicycle to Stanford to attend – yes if I made up the time later.



Tony Siegman and Professor Letokov at Stanford



A Helium Neon laser visible across 'Silicon Valley' from the Lick Observatory on Mount Hamilton

Accepted at Stanford!
Assigned to work with Professor S. E. Harris

Stephen E. Harris
~1963
Stanford University

Optical Parametric Oscillators

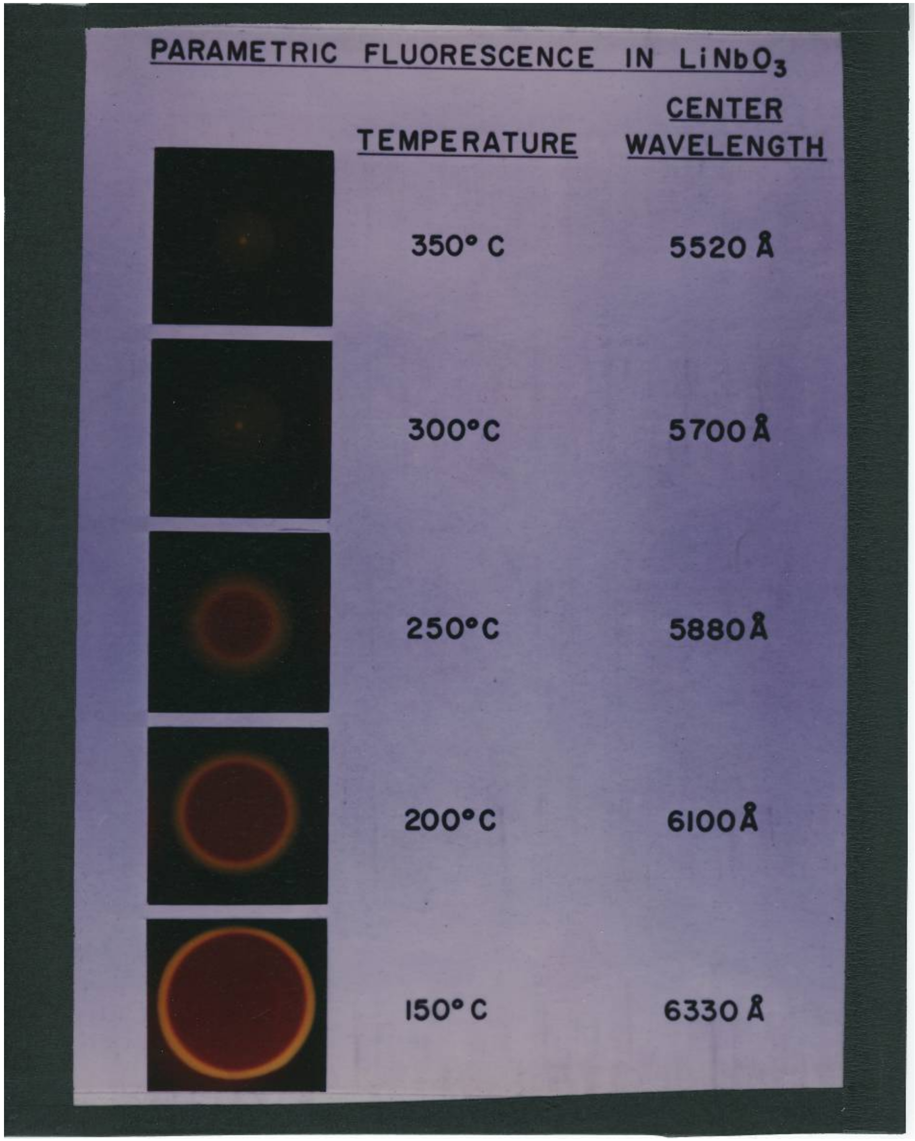
Stanford research 1965 – 1969 - The Harris Lab

Larry Osterink and the FM argon ion laser
Ken Oshman – OPO pumped by yellow Krypton Ion Laser
Bob Byer and Jim Young
    Modelocked pumped LiNbO3 OPO
    Materials development (Bob Feigelson)
    *Parametric Fluorescence
    *CW OPO pumped by Argon Ion Laser

Richard Wallace – studied the AO Q-switched Nd:YAG Laser

OPO technology transferred to Chromatix - 1970

Kodachrome images of Parametric Fluorescence in $LiNbO_3$



PARAMETRIC FLUORESCENCE IN $LiNbO_3$

TEMPERATURE	CENTER WAVELENGTH
350° C	5520 Å
300°C	5700 Å
250°C	5880 Å
200°C	6100 Å
150° C	6330 Å

Measured nonlinear coefficient

Derived parametric gain

Measured tuning curve

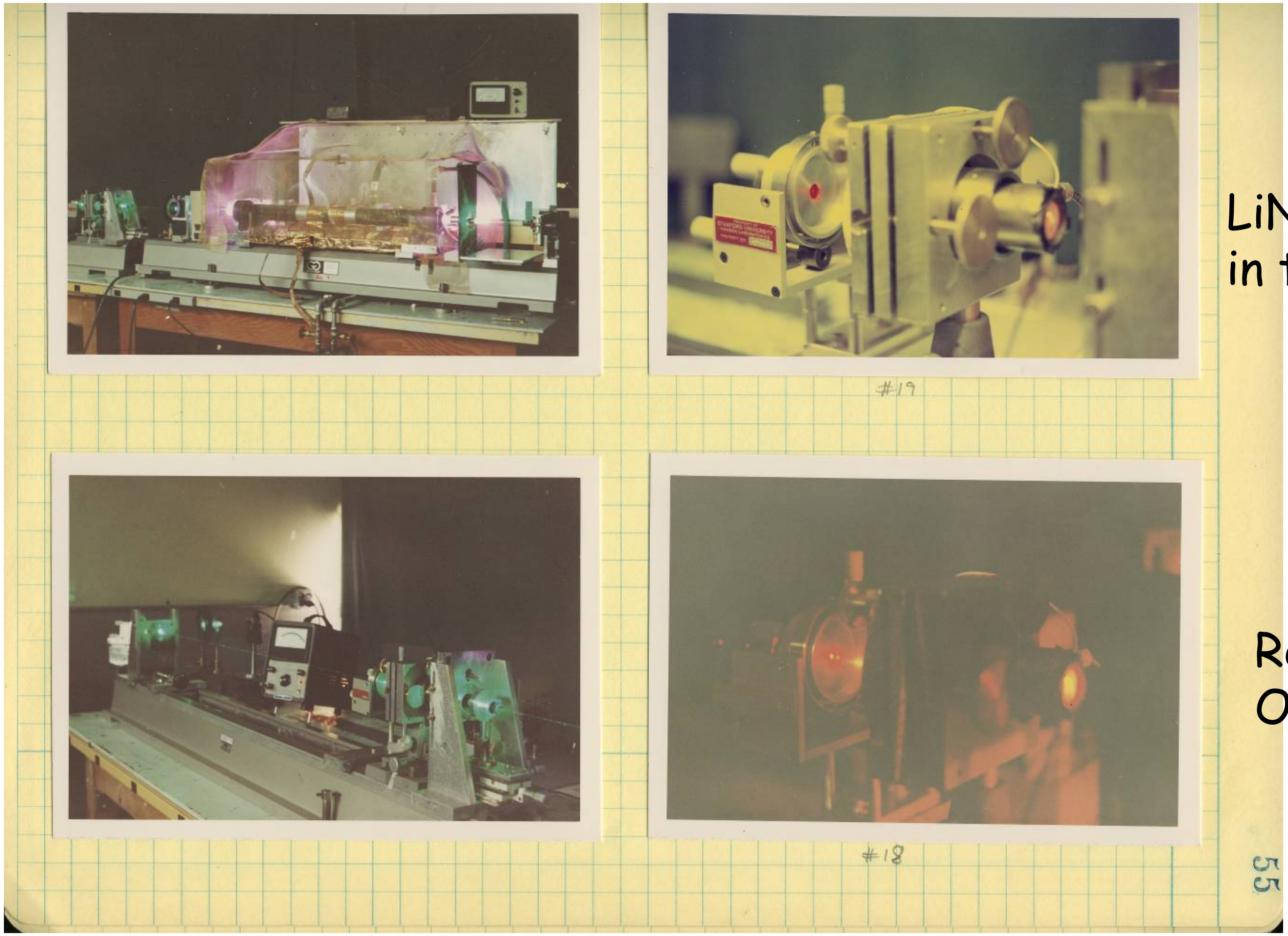
Confirmed quality of the Crystal

Observed Parametric Amplifier Quantum Noise by eye!

"I see red!" Ben Yoshizumi May 11, 1968

Argon Ion
Laser pump

LiNbO$_3$ crystal
in the oven



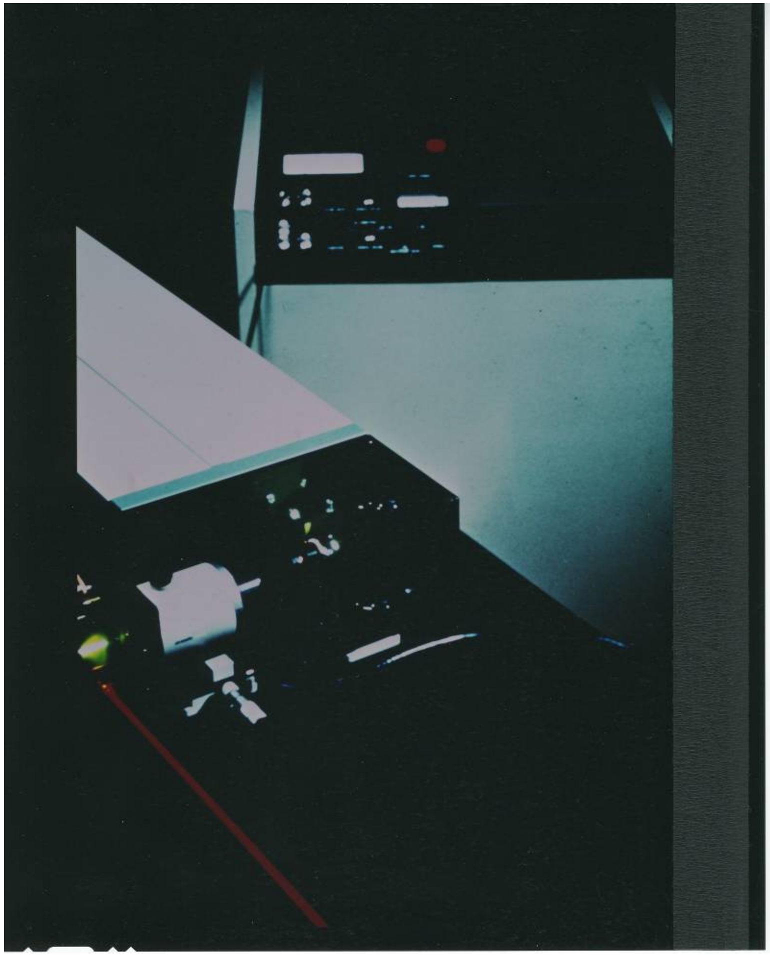
OPO cavity

Red tunable
Output ~1mW

Threshold 430mW. Available power at 514.5nm 470mW

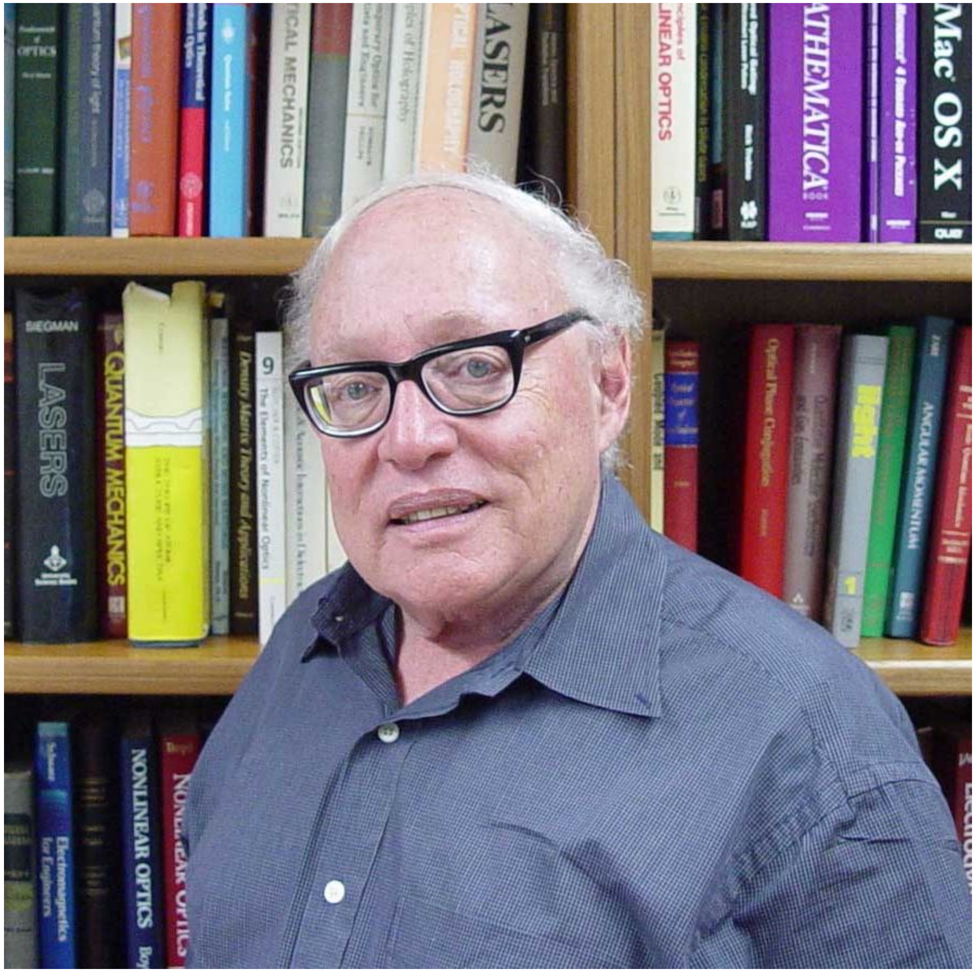
Chromatix Nd:YAG Laser and Tunable OPO ~1970

Richard Wallace with Q-switched Chromatix Nd:YAG Laser



Doubled YAG pumped $LiNbO_3$ OPO First tunable laser product

Stephen E. Harris



HarrisFest – A celebration for Stephen E. Harris – Saturday 16 September 2006 – Stanford University

Contents

- Prelude
- Introduction *Making Lightwaves*
    - Early laser history and concepts
        - Unstable Resonator
        - Slab Laser – one dimensional cooling
    - Recent **Innovations**
        - Large Mode Area Fiber Lasers
        - Edge Pumped Slab Laser
        - Transparent 'Ceramic' polycrystalline gain media
- Scientific Applications of Lasers *Riding Lightwaves*
    - Laser Remote Sensing
    - Global Wind Sensing
    - Observing the Universe with Gravitational Waves
- The Future – continued innovation *Surfing Lightwaves*
    - Exploring TeV scale physics with laser accelerators
        - Coherent X-rays at the Attosecond time scale
    - LIFE - Laser Induced Fusion for Energy
        - Fusion/Fission Reactors

Motivation: Scientific Applications of Lasers

> "Don't undertake a project unless it is manifestly important and nearly impossible." Edwin Land - 1982

Scientific Applications of Lasers

Atmospheric Remote Sensing

- **Quanta Ray Laser** 1J Unstable resonator
- 1.4 to 4.3 micron Tunable $LiNbO_3$ OPO

Global Wind Sensing

- **Diode pumped Nd:YAG**
- Frequency stable local oscillator - NPRO

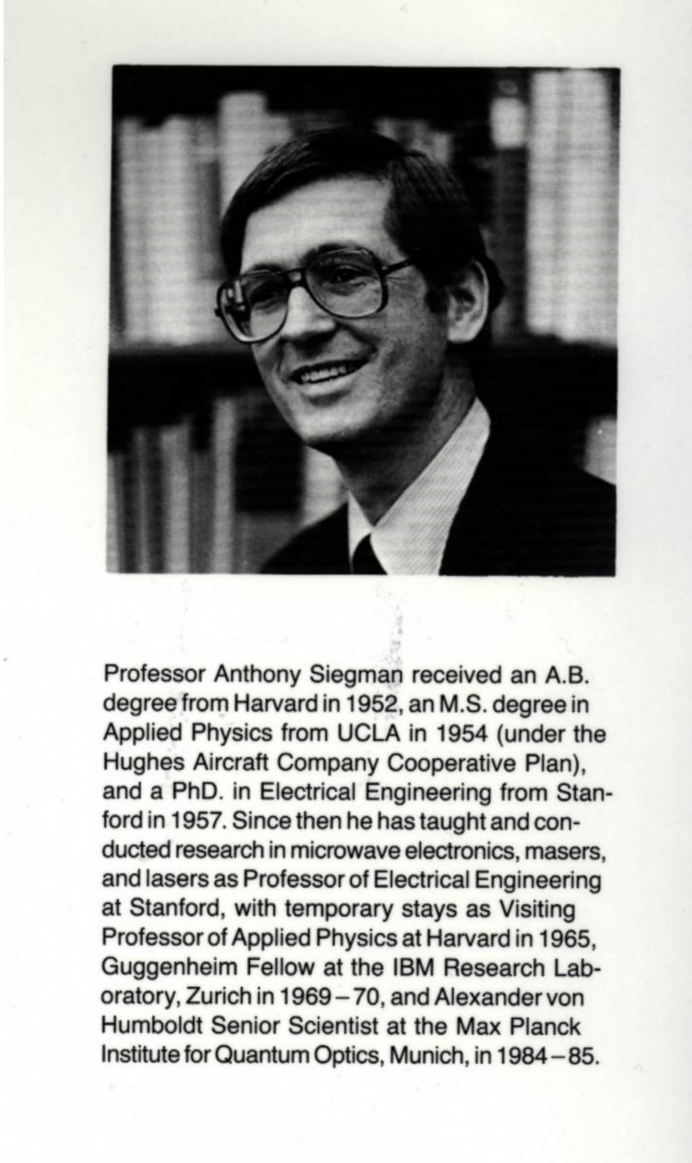
Search for Gravitational Waves

10 W Nd:YAG slab MOPA	**LIGO**
200W fiber laser MOPA	Adv LIGO
1W Iodine Stabilized Nd:YAG	**LISA**

Laser Accelerators and Coherent X-rays

- TeV energy scale particle physics
- Coherent X-rays for attosecond science

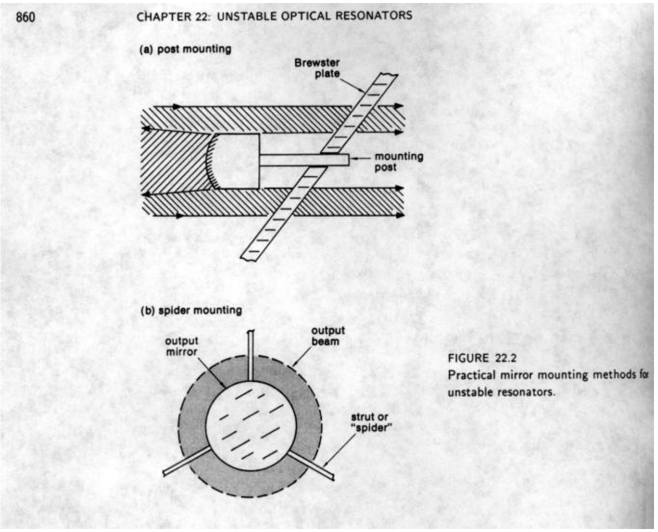
Unstable Resonator Concept - 1965



Professor Anthony Siegman received an A.B. degree from Harvard in 1952, an M.S. degree in Applied Physics from UCLA in 1954 (under the Hughes Aircraft Company Cooperative Plan), and a PhD. in Electrical Engineering from Stanford in 1957. Since then he has taught and conducted research in microwave electronics, masers, and lasers as Professor of Electrical Engineering at Stanford, with temporary stays as Visiting Professor of Applied Physics at Harvard in 1965, Guggenheim Fellow at the IBM Research Laboratory, Zurich in 1969–70, and Alexander von Humboldt Senior Scientist at the Max Planck Institute for Quantum Optics, Munich, in 1984–85.

A. E. Siegman
"Unstable optical resonators for laser applications"
Proc. IEEE 53, 277-287, 1965

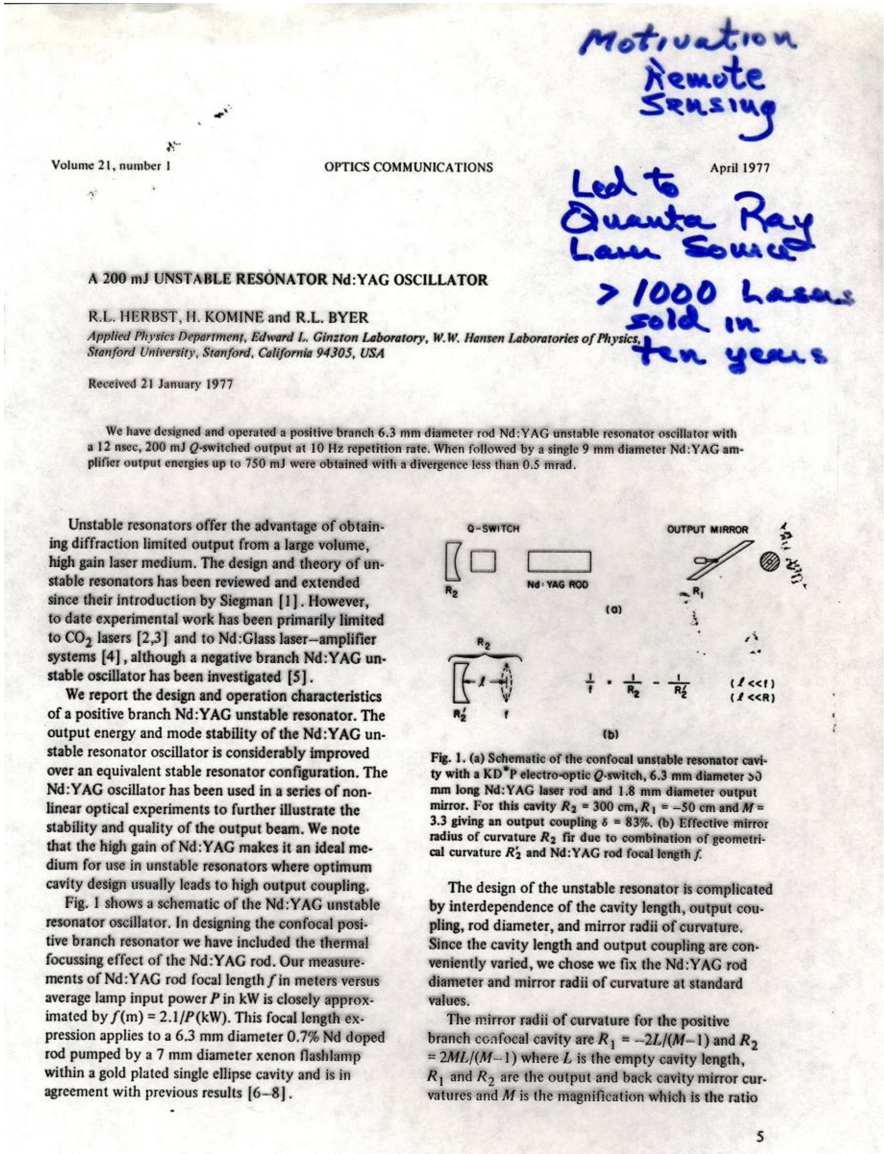
R. L. Herbst, H. Komine, R. L. Byer
"A 200mJ unstable resonator Nd:YAG Oscillator" Optics Commun. 21, 5, 1977



860 CHAPTER 22: UNSTABLE OPTICAL RESONATORS

FIGURE 22.2
Practical mirror mounting methods fo
unstable resonators.

Unstable Resonator Nd:YAG Oscillator



Motivation
Remote
Sensing

Led to
Quanta Ray
Laser Source

> 1000 Lasers
sold in
ten years

Volume 21, number 1 OPTICS COMMUNICATIONS April 1977

A 200 mJ UNSTABLE RESONATOR Nd:YAG OSCILLATOR

R.L. HERBST, H. KOMINE and R.L. BYER
Applied Physics Department, Edward L. Ginzton Laboratory, W.W. Hansen Laboratories of Physics, Stanford University, Stanford, California 94305, USA

Received 21 January 1977

We have designed and operated a positive branch 6.3 mm diameter rod Nd:YAG unstable resonator oscillator with a 12 nsec, 200 mJ Q-switched output at 10 Hz repetition rate. When followed by a single 9 mm diameter Nd:YAG amplifier output energies up to 750 mJ were obtained with a divergence less than 0.5 mrad.

Unstable resonators offer the advantage of obtaining diffraction limited output from a large volume, high gain laser medium. The design and theory of unstable resonators has been reviewed and extended since their introduction by Siegman [1]. However, to date experimental work has been primarily limited to CO_2 lasers [2,3] and to Nd:Glass laser–amplifier systems [4], although a negative branch Nd:YAG unstable oscillator has been investigated [5].

We report the design and operation characteristics of a positive branch Nd:YAG unstable resonator. The output energy and mode stability of the Nd:YAG unstable resonator oscillator is considerably improved over an equivalent stable resonator configuration. The Nd:YAG oscillator has been used in a series of nonlinear optical experiments to further illustrate the stability and quality of the output beam. We note that the high gain of Nd:YAG makes it an ideal medium for use in unstable resonators where optimum cavity design usually leads to high output coupling.

Fig. 1 shows a schematic of the Nd:YAG unstable resonator oscillator. In designing the confocal positive branch resonator we have included the thermal focussing effect of the Nd:YAG rod. Our measurements of Nd:YAG rod focal length f in meters versus average lamp input power P in kW is closely approximated by $f(\mathrm{m}) = 2.1/P(\mathrm{kW})$. This focal length expression applies to a 6.3 mm diameter 0.7% Nd doped rod pumped by a 7 mm diameter xenon flashlamp within a gold plated single ellipse cavity and is in agreement with previous results [6–8].

Fig. 1. (a) Schematic of the confocal unstable resonator cavity with a KD*P electro-optic Q-switch, 6.3 mm diameter 50 mm long Nd:YAG laser rod and 1.8 mm diameter output mirror. For this cavity R_2 = 300 cm, R_1 = –50 cm and M = 3.3 giving an output coupling δ = 83%. (b) Effective mirror radius of curvature R_2 fir due to combination of geometrical curvature R_2' and Nd:YAG rod focal length f.

The design of the unstable resonator is complicated by interdependence of the cavity length, output coupling, rod diameter, and mirror radii of curvature. Since the cavity length and output coupling are conveniently varied, we chose we fix the Nd:YAG rod diameter and mirror radii of curvature at standard values.

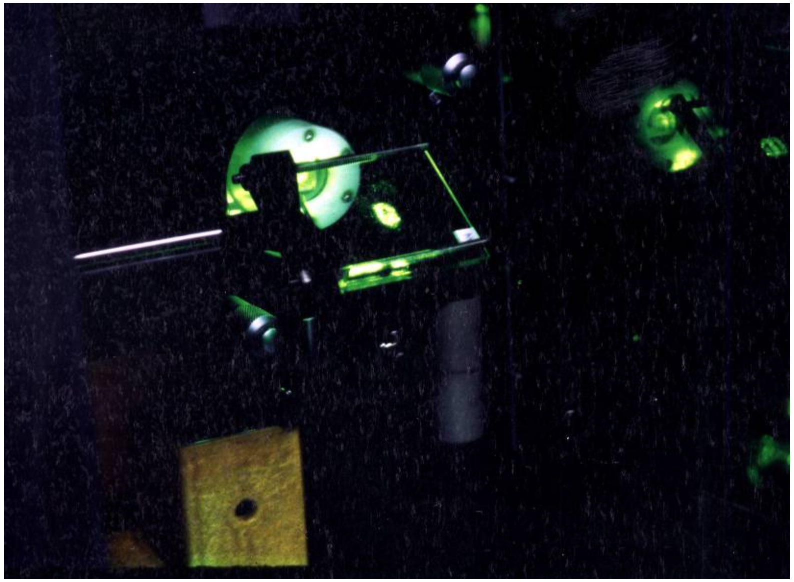
The mirror radii of curvature for the positive branch confocal cavity are $R_1 = -2L/(M-1)$ and $R_2 = 2ML/(M-1)$ where L is the empty cavity length, R_1 and R_2 are the output and back cavity mirror curvatures and M is the magnification which is the ratio

5

R. L. Herbst, H. Komine, and R. L. Byer

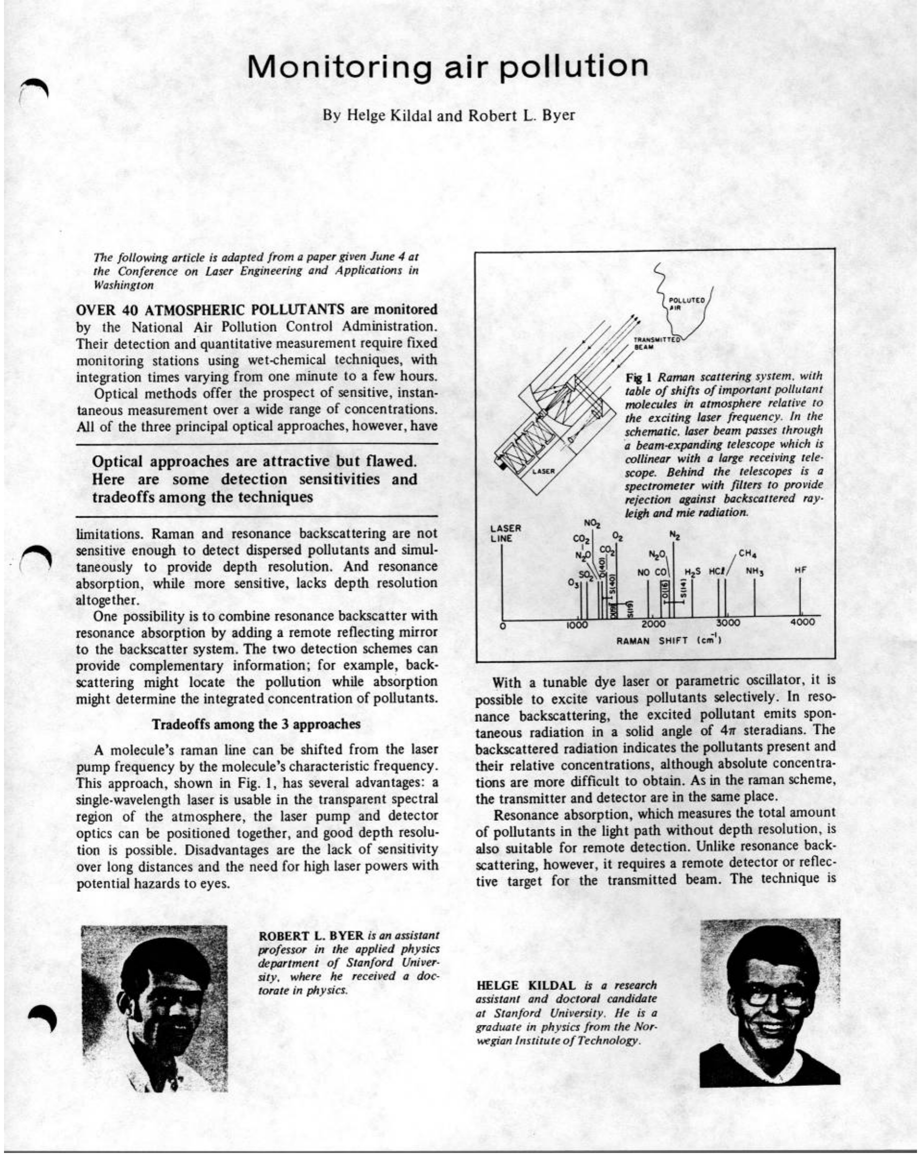
"A 200mJ Unstable Resonator Nd:YAG Oscillator"

Opt. Commun. 21, 5, 1977



Quanta Ray 532nm output after SHG in KD*P crystal. Note "hole" in beam.

Monitoring Air Pollution



Monitoring air pollution

By Helge Kildal and Robert L. Byer

The following article is adapted from a paper given June 4 at the Conference on Laser Engineering and Applications in Washington

OVER 40 ATMOSPHERIC POLLUTANTS are monitored by the National Air Pollution Control Administration. Their detection and quantitative measurement require fixed monitoring stations using wet-chemical techniques, with integration times varying from one minute to a few hours.

Optical methods offer the prospect of sensitive, instantaneous measurement over a wide range of concentrations. All of the three principal optical approaches, however, have limitations. Raman and resonance backscattering are not sensitive enough to detect dispersed pollutants and simultaneously to provide depth resolution. And resonance absorption, while more sensitive, lacks depth resolution altogether.

Optical approaches are attractive but flawed. Here are some detection sensitivities and tradeoffs among the techniques

One possibility is to combine resonance backscatter with resonance absorption by adding a remote reflecting mirror to the backscatter system. The two detection schemes can provide complementary information; for example, backscattering might locate the pollution while absorption might determine the integrated concentration of pollutants.

Tradeoffs among the 3 approaches

A molecule's raman line can be shifted from the laser pump frequency by the molecule's characteristic frequency. This approach, shown in Fig. 1, has several advantages: a single-wavelength laser is usable in the transparent spectral region of the atmosphere, the laser pump and detector optics can be positioned together, and good depth resolution is possible. Disadvantages are the lack of sensitivity over long distances and the need for high laser powers with potential hazards to eyes.

Fig 1 *Raman scattering system, with table of shifts of important pollutant molecules in atmosphere relative to the exciting laser frequency. In the schematic, laser beam passes through a beam-expanding telescope which is collinear with a large receiving telescope. Behind the telescopes is a spectrometer with filters to provide rejection against backscattered rayleigh and mie radiation.*

With a tunable dye laser or parametric oscillator, it is possible to excite various pollutants selectively. In resonance backscattering, the excited pollutant emits spontaneous radiation in a solid angle of 4π steradians. The backscattered radiation indicates the pollutants present and their relative concentrations, although absolute concentrations are more difficult to obtain. As in the raman scheme, the transmitter and detector are in the same place.

Resonance absorption, which measures the total amount of pollutants in the light path without depth resolution, is also suitable for remote detection. Unlike resonance backscattering, however, it requires a remote detector or reflective target for the transmitted beam. The technique is

ROBERT L. BYER *is an assistant professor in the applied physics department of Stanford University, where he received a doctorate in physics.*

HELGE KILDAL *is a research assistant and doctoral candidate at Stanford University. He is a graduate in physics from the Norwegian Institute of Technology.*

Helge Kildal and R. L. Byer

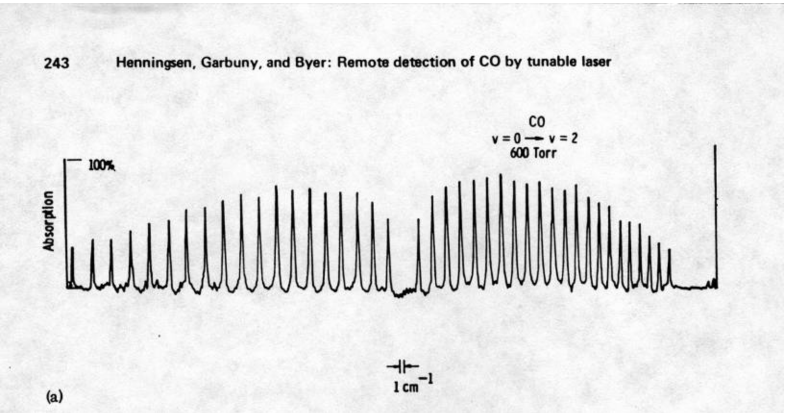
"Comparison of Laser Methods for The Remote Detection of Atmospheric Pollutants"

Proc. IEEE 59,1644 1971 (invited)

Henningsen, Garbuny and Byer - 1974

Vibrational-Rotational overtone spectrum of Carbon Monoxide by tunable OPO.

(Chromatix Nd:YAG pumped LiNbO$_3$ OPO Product introduced as product in 1969)



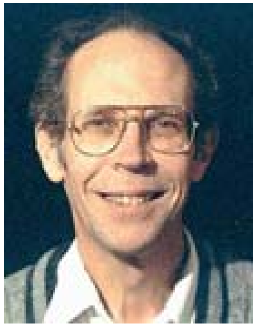
243 Henningsen, Garbuny, and Byer: Remote detection of CO by tunable laser

Atmospheric Remote Sensing

Motivation for tunable lasers at Stanford

Atmospheric Remote sensing beginning in 1971

Unstable resonator Nd:YAG -- Quanta Ray Laser
1.4 - 4.4 micron tunable $LiNbO_3$ OPO -- computer controlled
Remote sensing of CH_4, SO_2 and H_2O and temperature

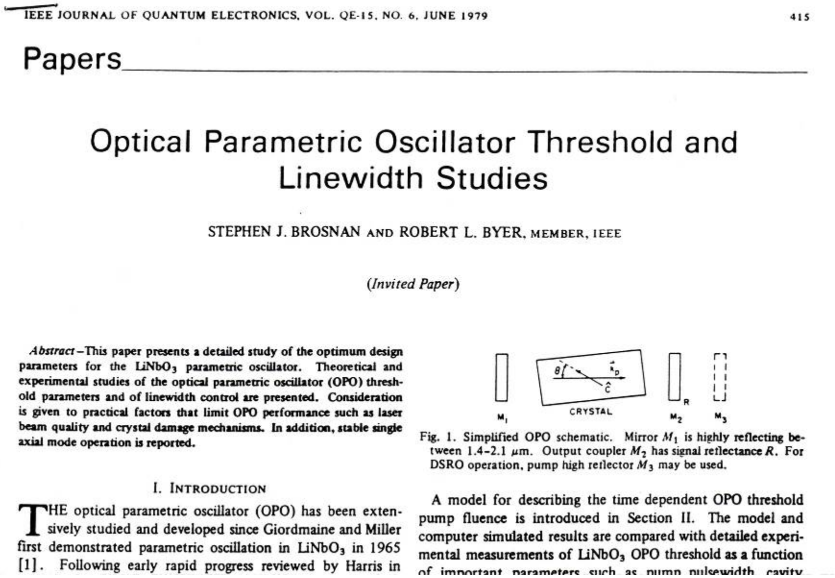

Sune Svanberg


Humio Inaba

Early Remote Sensing	1960 - 1975
LIDAR	Laser Detection and Ranging
Inaba, Kobayashi	Detection of Molecules
Kidal and Byer	Comparison of Detection Methods
DIAL	Differential Absorption Lidar
Menzies	CO_2 laser Direct and Coherent Detection
Walther & Rothe	Remote sensing of pollutants
Svanberg	Remote sensing pollution monitoring


Herbert Walther

1.4 to 4.3 micron Computer Tuned $LiNbO_3$ OPO



IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. QE-15, NO. 6, JUNE 1979 415

Papers

Optical Parametric Oscillator Threshold and Linewidth Studies

STEPHEN J. BROSNAN AND ROBERT L. BYER, MEMBER, IEEE

(*Invited Paper*)

Abstract–This paper presents a detailed study of the optimum design parameters for the $LiNbO_3$ parametric oscillator. Theoretical and experimental studies of the optical parametric oscillator (OPO) threshold parameters and of linewidth control are presented. Consideration is given to practical factors that limit OPO performance such as laser beam quality and crystal damage mechanisms. In addition, stable single axial mode operation is reported.

I. INTRODUCTION

THE optical parametric oscillator (OPO) has been extensively studied and developed since Giordmaine and Miller first demonstrated parametric oscillation in $LiNbO_3$ in 1965 [1]. Following early rapid progress reviewed by Harris in

Fig. 1. Simplified OPO schematic. Mirror M_1 is highly reflecting between 1.4–2.1 μm. Output coupler M_2 has signal reflectance R. For DSRO operation, pump high reflector M_3 may be used.

A model for describing the time dependent OPO threshold pump fluence is introduced in Section II. The model and computer simulated results are compared with detailed experimental measurements of $LiNbO_3$ OPO threshold as a function of important parameters such as pump pulsewidth, cavity

Stephen J. Brosnan, R. L. Byer

"Optical Parametric Oscillator Threshold and Linewidth Studies"

Proc. IEEE J. Quant. Electr. QE-15,415,1979

Steve Brosnan observing atmospheric spectrum with OPO tuning under PDP-11 computer control

122 R. L. BYER

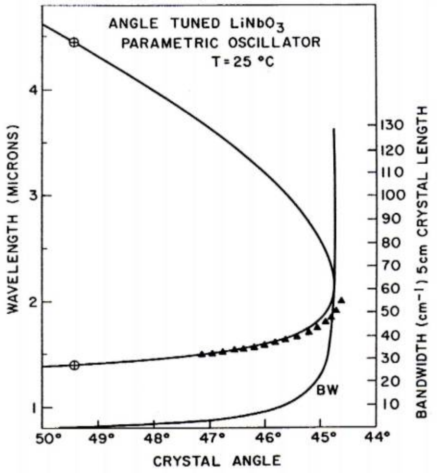
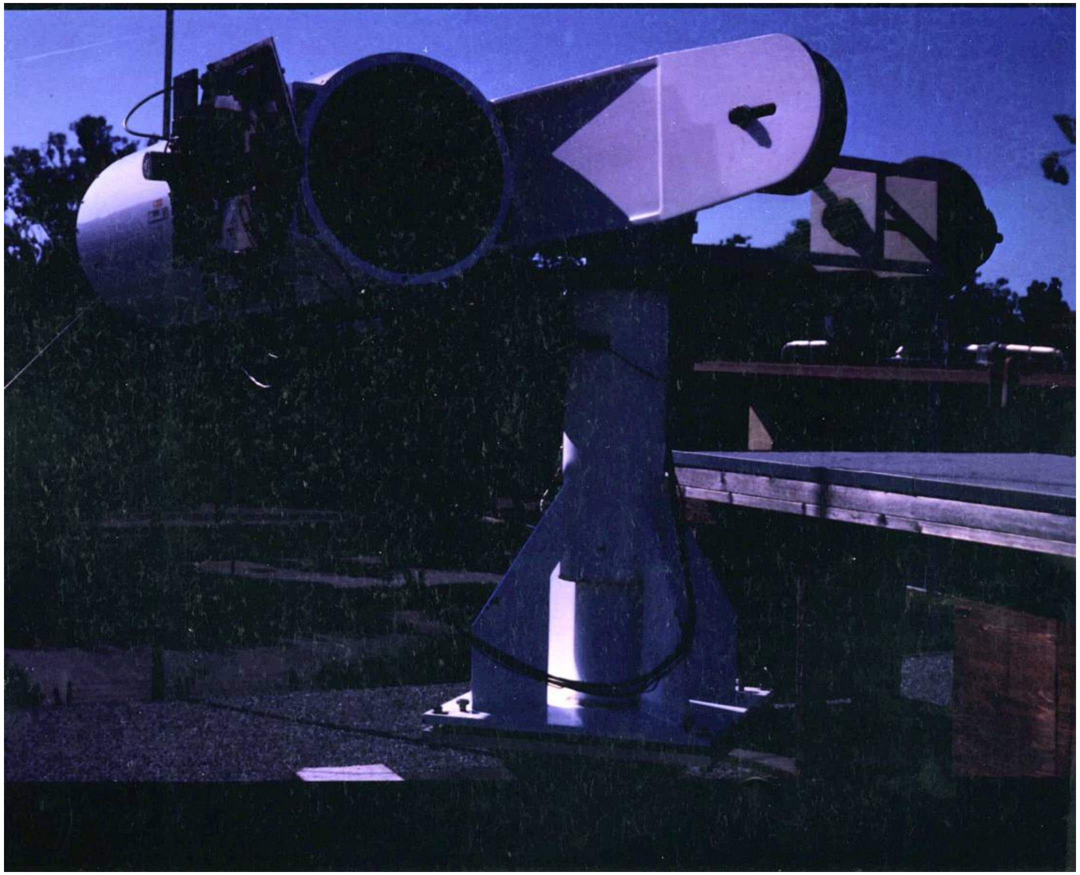


FIG. 19. Tuning curve and bandwidth for the 1.06 μm pumped angle-tuned $LiNbO_3$ SRO.

Fig 19.
$LiNbO_3$ OPO
Angle
Tuning curve
(45-50 deg)

1.4 – 4.3 microns

Remote Sensing Telescope at Stanford - 1980



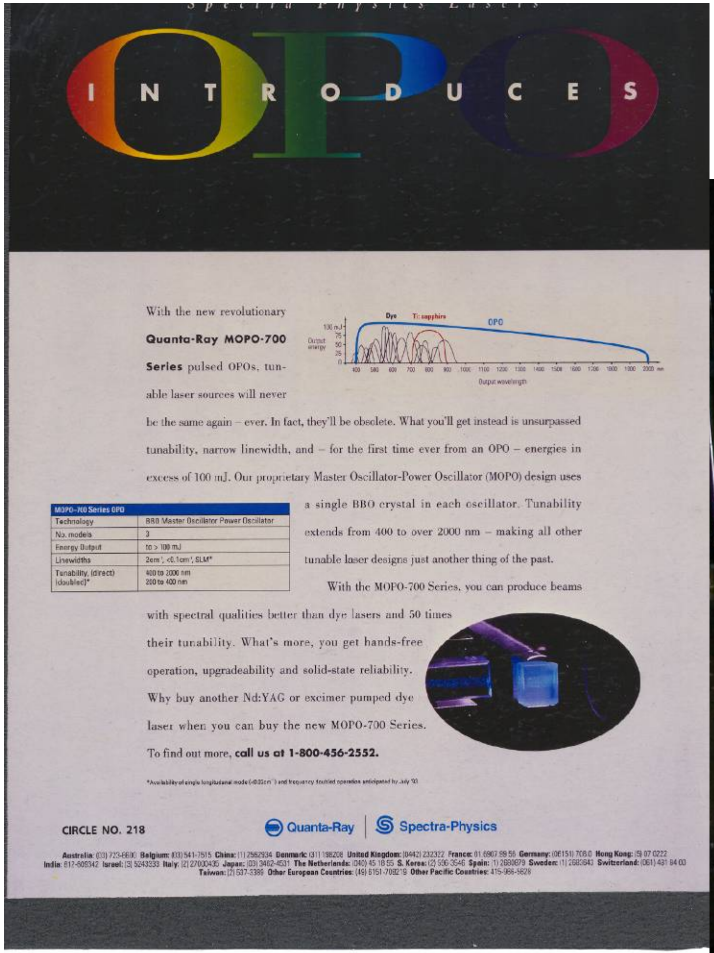
Atmospheric Remote Sensing using a Nd:YAG Pumped $LiNbO_3$ Tunable IR OPO.

The OPO was tuned under Computer control continuously From 1.4 to 4.3 microns

Atmospheric measurements Were made of CO_2, SO_2, CH_4, H_2O and Temperature.

Sixteen inch diameter telescope on the roof of the Ginzton Laboratory, Stanford

Quanta Ray pumped BBO OPO Spectra Physics



Spectra-Physics Lasers

OPO

INTRODUCES

With the new revolutionary **Quanta-Ray MOPO-700 Series** pulsed OPOs, tunable laser sources will never be the same again – ever. In fact, they'll be obsolete. What you'll get instead is unsurpassed tunability, narrow linewidth, and – for the first time ever from an OPO – energies in excess of 100 mJ. Our proprietary Master Oscillator-Power Oscillator (MOPO) design uses a single BBO crystal in each oscillator. Tunability extends from 400 to over 2000 nm – making all other tunable laser designs just another thing of the past.

With the MOPO-700 Series, you can produce beams with spectral qualities better than dye lasers and 50 times their tunability. What's more, you get hands-free operation, upgradeability and solid-state reliability. Why buy another Nd:YAG or excimer pumped dye laser when you can buy the new MOPO-700 Series.

To find out more, **call us at 1-800-456-2552.**

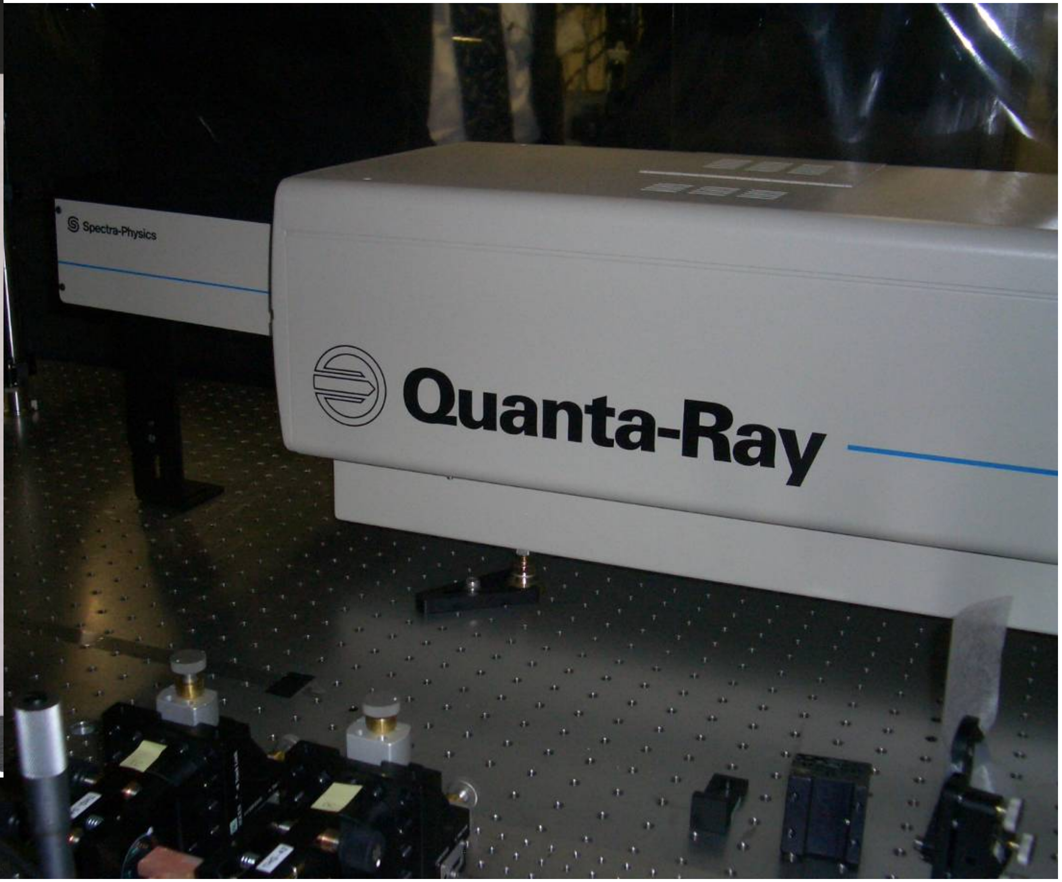
MOPO-700 Series OPO	
Technology	BBO Master Oscillator Power Oscillator
No. models	3
Energy Output	to > 100 mJ
Linewidths	2cm^{-1}, <0.1cm^{-1}, SLM*
Tunability, (direct) (doubled)*	400 to 2000 nm 200 to 400 nm

*Availability of single longitudinal mode (<0.03cm^{-1}) and frequency doubled operation anticipated by July '93

CIRCLE NO. 218

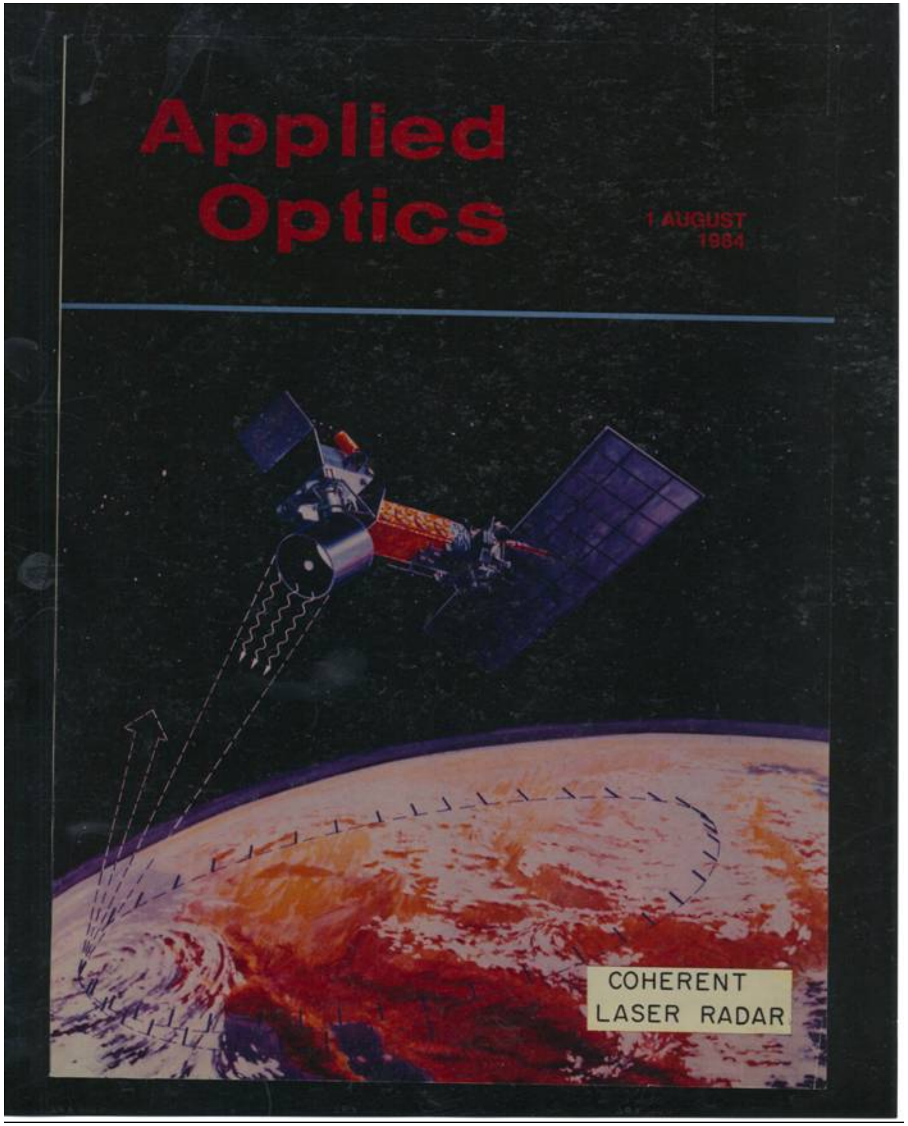
Quanta-Ray | Spectra-Physics

Australia: (03) 723-6600 **Belgium:** (03) 541-7515 **China:** (1) 2562934 **Denmark:** (31) 198208 **United Kingdom:** (0442) 232322 **France:** 01.6907.99.56 **Germany:** (06151) 708.0 **Hong Kong:** (5) 07 0222
India: 812-609342 **Israel:** (3) 5243333 **Italy:** (2) 27000435 **Japan:** (03) 3462-4531 **The Netherlands:** (040) 45 18 55 **S. Korea:** (2) 596-3546 **Spain:** (1) 2680879 **Sweden:** (1) 2683643 **Switzerland:** (061) 431 84 00
Taiwan: (2) 537-3386 **Other European Countries:** (49) 6151-708219 **Other Pacific Countries:** 415-966-5628



My 'optimistic' projection in 1975 was a total market of about 75 lasers.
More than 10,000 Quanta Ray Lasers sold to date.

Global Wind Concept - Huffaker 1984



Global wind sensing

Milton Huffaker proposed coherent detection of wind using eye-safe lasers.

Applied Optics 22 1984

Coherent Laser Radar

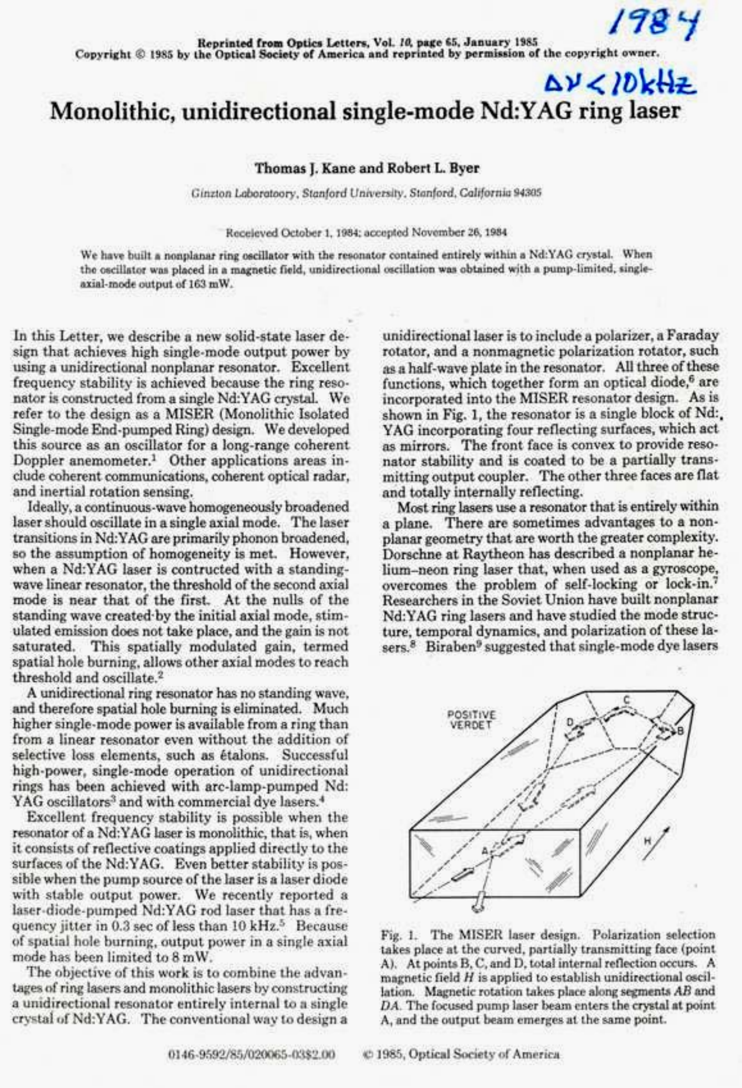
Local Oscillator
- Invention of the Nonplanar Ring Oscillator

Power Amplifier
- Multipass 60 dB gain slab amplifier

Heterodyne Receiver
- Fiber coupled heterodyne detection

Goal: wind sensing from the laboratory using a coherent Nd:YAG laser transmitter-receiver

The Non-Planar Ring Oscillator - 1984



1984

Reprinted from Optics Letters, Vol. 10, page 65, January 1985

$\Delta\nu < 10$kHz

Monolithic, unidirectional single-mode Nd:YAG ring laser

Thomas J. Kane and Robert L. Byer

Ginzton Laboratoory, Stanford University, Stanford, California 94305

Receieved October 1, 1984; accepted November 26, 1984

We have built a nonplanar ring oscillator with the resonator contained entirely within a Nd:YAG crystal. When the oscillator was placed in a magnetic field, unidirectional oscillation was obtained with a pump-limited, single-axial-mode output of 163 mW.

In this Letter, we describe a new solid-state laser design that achieves high single-mode output power by using a unidirectional nonplanar resonator. Excellent frequency stability is achieved because the ring resonator is constructed from a single Nd:YAG crystal. We refer to the design as a MISER (Monolithic Isolated Single-mode End-pumped Ring) design. We developed this source as an oscillator for a long-range coherent Doppler anemometer.[1] Other applications areas include coherent communications, coherent optical radar, and inertial rotation sensing.

Ideally, a continuous-wave homogeneously broadened laser should oscillate in a single axial mode. The laser transitions in Nd:YAG are primarily phonon broadened, so the assumption of homogeneity is met. However, when a Nd:YAG laser is contructed with a standing-wave linear resonator, the threshold of the second axial mode is near that of the first. At the nulls of the standing wave created by the initial axial mode, stimulated emission does not take place, and the gain is not saturated. This spatially modulated gain, termed spatial hole burning, allows other axial modes to reach threshold and oscillate.[2]

A unidirectional ring resonator has no standing wave, and therefore spatial hole burning is eliminated. Much higher single-mode power is available from a ring than from a linear resonator even without the addition of selective loss elements, such as étalons. Successful high-power, single-mode operation of unidirectional rings has been achieved with arc-lamp-pumped Nd:YAG oscillators[3] and with commercial dye lasers.[4]

Excellent frequency stability is possible when the resonator of a Nd:YAG laser is monolithic, that is, when it consists of reflective coatings applied directly to the surfaces of the Nd:YAG. Even better stability is possible when the pump source of the laser is a laser diode with stable output power. We recently reported a laser-diode-pumped Nd:YAG rod laser that has a frequency jitter in 0.3 sec of less than 10 kHz.[5] Because of spatial hole burning, output power in a single axial mode has been limited to 8 mW.

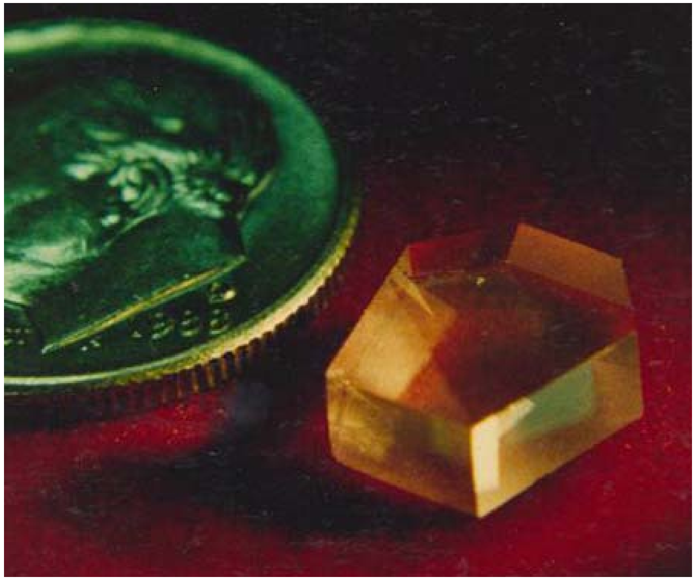
The objective of this work is to combine the advantages of ring lasers and monolithic lasers by constructing a unidirectional resonator entirely internal to a single crystal of Nd:YAG. The conventional way to design a unidirectional laser is to include a polarizer, a Faraday rotator, and a nonmagnetic polarization rotator, such as a half-wave plate in the resonator. All three of these functions, which together form an optical diode,[6] are incorporated into the MISER resonator design. As is shown in Fig. 1, the resonator is a single block of Nd:YAG incorporating four reflecting surfaces, which act as mirrors. The front face is convex to provide resonator stability and is coated to be a partially transmitting output coupler. The other three faces are flat and totally internally reflecting.

Most ring lasers use a resonator that is entirely within a plane. There are sometimes advantages to a nonplanar geometry that are worth the greater complexity. Dorschne at Raytheon has described a nonplanar helium–neon ring laser that, when used as a gyroscope, overcomes the problem of self-locking or lock-in.[7] Researchers in the Soviet Union have built nonplanar Nd:YAG ring lasers and have studied the mode structure, temporal dynamics, and polarization of these lasers.[8] Biraben[9] suggested that single-mode dye lasers

Fig. 1. The MISER laser design. Polarization selection takes place at the curved, partially transmitting face (point A). At points B, C, and D, total internal reflection occurs. A magnetic field *H* is applied to establish unidirectional oscillation. Magnetic rotation takes place along segments *AB* and *DA*. The focused pump laser beam enters the crystal at point A, and the output beam emerges at the same point.

0146-9592/85/020065-03$2.00

Tom Kane, R. L. Byer
"Monolithic, unidirectional
Single-mode Nd:YAG ring laser"
Opt. Lett. 10,65,1985



NonPlanar Ring Oscillator
Single frequency: <10kHz

Diode Pumped Solid State Lasers – 1984

Byer
Group

Diode Laser–Pumped Solid-State Lasers

ROBERT L. BYER

Diode laser–pumped solid-state lasers are efficient, compact, all solid-state sources of coherent optical radiation. Major advances in solid-state laser technology have historically been preceded by advances in pumping technology. The helical flash lamps used to pump early ruby lasers were superseded by the linear flash lamp and arc lamp now used to pump neodymium-doped yttrium-aluminum-garnet lasers. The latest advance in pumping technology is the diode laser. Diode laser–pumped neodymium lasers have operated at greater than 10 percent electrical to optical efficiency in a single spatial mode and with linewidths of less than 10 kilohertz. The high spectral power brightness of these lasers has allowed frequency extension by harmonic generation in nonlinear crystals, which has led to green and blue sources of coherent radiation. Diode laser pumping has also been used with ions other than neodymium to produce wavelengths from 946 to 2010 nanometers. In addition, Q-switched operation with kilowatt peak powers and mode-locked operation with 10-picosecond pulse widths have been demonstrated. Progress in diode lasers and diode laser arrays promises all solid-state lasers in which the flash lamp is replaced by diode lasers for average power levels in excess of tens of watts and at a price that is competitive with flash lamp–pumped laser systems. Power levels exceeding 1 kilowatt appear possible within the next 5 years. Potential applications of diode laser–pumped solid-state lasers include coherent radar, global sensing from satellites, medical uses, micromachining, and miniature visible sources for digital optical storage.

SOLID-STATE LASER DEVELOPMENT HAS BEEN PACED BY THE improvement and discovery of pump sources. The helical lamp, used to pump the first ruby laser, was replaced by the linear flash lamp and discharge arc lamp that are now used to pump virtually every neodymium-doped yttrium-aluminum-garnet (Nd:YAG) and neodymium glass (Nd:glass) laser system in the world. The next advance in solid-state laser technology promises to be improved pumping by means of diode lasers and diode laser arrays (*1*). The recent and rapid advances in the power and efficiency of diode lasers and diode laser arrays and their application to the pumping of solid-state lasers have led to a renaissance in solid-state laser development (*2*). Advanced technology solid-state lasers pumped by diode lasers will make possible such diverse applications as coherent radar for global wind measurements, semiconductor circuit repair, and all solid-state color video projection.

A question often asked is, “Why use the diode laser to pump another solid-state laser instead of using flash lamps or the diode directly?” The diode laser efficiently emits optical radiation into a narrow spectral band. When the emission wavelength of the diode laser lies within the absorption band of the ion-doped solid-state laser medium, diode laser optical pumping can be very efficient with little excess heat generation. Flash lamp pumping efficiency is limited by the broad spectral emission of the lamp and the less efficient absorption of the lamp radiation by the solid-state laser medium. Excess heat and power fluctuations of the lamp also degrade the solid-state laser performance, as does the finite lamp lifetime. The diode laser is essentially a continuous wave (cw) device with low energy storage capability, whereas the solid-state laser can store energy in the long-lived metastable ion levels. The stored energy can be extracted by rapid switching (Q-switching) to provide peak power levels that are orders of magnitude greater than from the diode laser itself. Furthermore, the solid-state laser can collect the output from several diode lasers to provide greater average power than is available from a single diode laser. The diode laser–pumped solid-state laser can operate at a variety of wavelengths not accessible with diode lasers. The diode laser–pumped solid-state laser linewidth is fundamentally orders of magnitude less than that of the

Fig. 1. (**Top**) Schematic of the diode laser–pumped monolithic Nd:YAG–oscillator. (**Bottom**) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

The author is a professor of applied physics and vice provost and dean of research at Stanford University, Stanford, CA 94305.

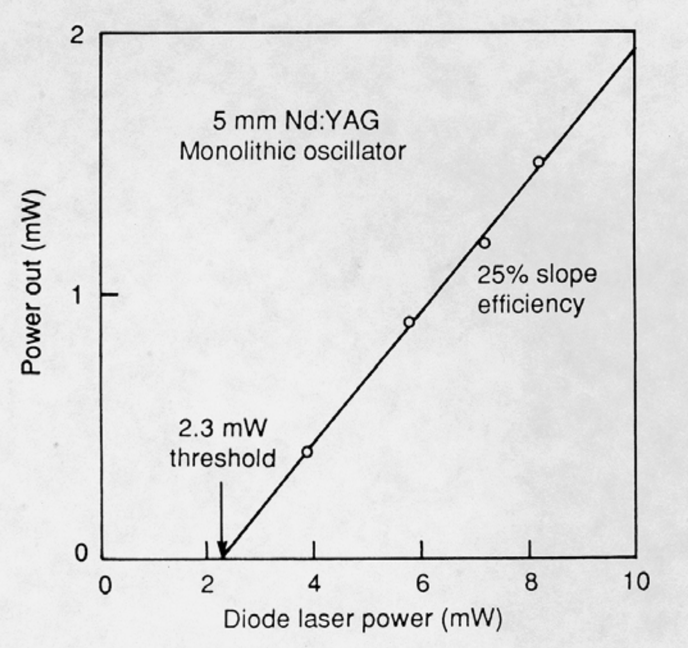
742

SCIENCE, VOL. 239

Laser Diode Pumped Nd:YAG - 1984

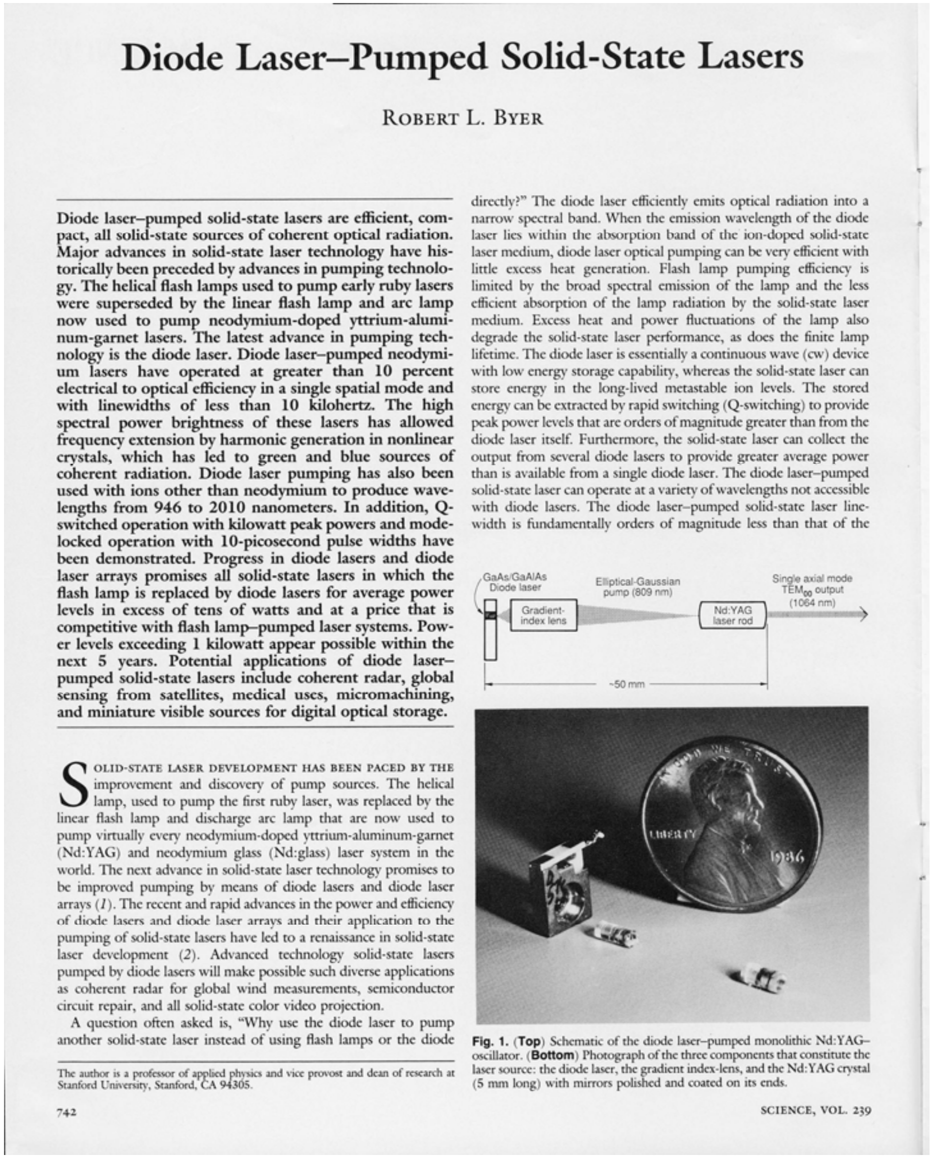
Binkun Zhou, **Tom Kane, Jeff Dixon and R. L. Byer**
"Efficient, frequency-stable laser-diode-pumped Nd:YAG laser"
Opt. Lett. 10, 62, 1985

5mm Nd:YAG Monolithic Oscillator
< 2mW output power for 8mw Pump
25% slope efficiency



Nd;YAG < 2mW at 25% slope efficiency - 1984

How did we progress from 2mW in 1984 to > 100kW in 2009?
Where are we going in the future?



Diode Laser–Pumped Solid-State Lasers

Robert L. Byer

Diode laser–pumped solid-state lasers are efficient, compact, all solid-state sources of coherent optical radiation. Major advances in solid-state laser technology have historically been preceded by advances in pumping technology. The helical flash lamps used to pump early ruby lasers were superseded by the linear flash lamp and arc lamp now used to pump neodymium-doped yttrium-aluminum-garnet lasers. The latest advance in pumping technology is the diode laser. Diode laser–pumped neodymium lasers have operated at greater than 10 percent electrical to optical efficiency in a single spatial mode and with linewidths of less than 10 kilohertz. The high spectral power brightness of these lasers has allowed frequency extension by harmonic generation in nonlinear crystals, which has led to green and blue sources of coherent radiation. Diode laser pumping has also been used with ions other than neodymium to produce wavelengths from 946 to 2010 nanometers. In addition, Q-switched operation with kilowatt peak powers and mode-locked operation with 10-picosecond pulse widths have been demonstrated. Progress in diode lasers and diode laser arrays promises all solid-state lasers in which the flash lamp is replaced by diode lasers for average power levels in excess of tens of watts and at a price that is competitive with flash lamp–pumped laser systems. Power levels exceeding 1 kilowatt appear possible within the next 5 years. Potential applications of diode laser–pumped solid-state lasers include coherent radar, global sensing from satellites, medical uses, micromachining, and miniature visible sources for digital optical storage.

SOLID-STATE LASER DEVELOPMENT HAS BEEN PACED BY THE improvement and discovery of pump sources. The helical lamp, used to pump the first ruby laser, was replaced by the linear flash lamp and discharge arc lamp that are now used to pump virtually every neodymium-doped yttrium-aluminum-garnet (Nd:YAG) and neodymium glass (Nd:glass) laser system in the world. The next advance in solid-state laser technology promises to be improved pumping by means of diode lasers and diode laser arrays (*1*). The recent and rapid advances in the power and efficiency of diode lasers and diode laser arrays and their application to the pumping of solid-state lasers have led to a renaissance in solid-state laser development (*2*). Advanced technology solid-state lasers pumped by diode lasers will make possible such diverse applications as coherent radar for global wind measurements, semiconductor circuit repair, and all solid-state color video projection.

A question often asked is, "Why use the diode laser to pump another solid-state laser instead of using flash lamps or the diode directly?" The diode laser efficiently emits optical radiation into a narrow spectral band. When the emission wavelength of the diode laser lies within the absorption band of the ion-doped solid-state laser medium, diode laser optical pumping can be very efficient with little excess heat generation. Flash lamp pumping efficiency is limited by the broad spectral emission of the lamp and the less efficient absorption of the lamp radiation by the solid-state laser medium. Excess heat and power fluctuations of the lamp also degrade the solid-state laser performance, as does the finite lamp lifetime. The diode laser is essentially a continuous wave (cw) device with low energy storage capability, whereas the solid-state laser can store energy in the long-lived metastable ion levels. The stored energy can be extracted by rapid switching (Q-switching) to provide peak power levels that are orders of magnitude greater than from the diode laser itself. Furthermore, the solid-state laser can collect the output from several diode lasers to provide greater average power than is available from a single diode laser. The diode laser–pumped solid-state laser can operate at a variety of wavelengths not accessible with diode lasers. The diode laser–pumped solid-state laser linewidth is fundamentally orders of magnitude less than that of the

Fig. 1. (**Top**) Schematic of the diode laser–pumped monolithic Nd:YAG–oscillator. (**Bottom**) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

The author is a professor of applied physics and vice provost and dean of research at Stanford University, Stanford, CA 94305.

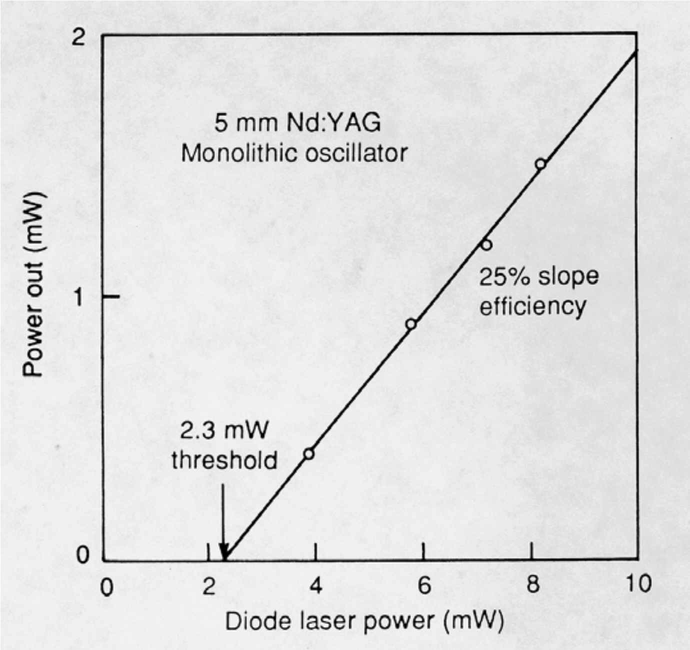
742

SCIENCE, VOL. 239

Laser Diode Pumped Nd:YAG - 1984

Binkun Zhou, Tom Kane, Jeff Dixon and R. L. Byer
"Efficient, frequency-stable laser-diode-pumped Nd:YAG laser"
Opt. Lett. 10, 62, 1985

5mm Nd:YAG Monolithic Oscillator
< 2mW output power for 8mw Pump
25% slope efficiency



How did we progress from 2mW in 1984 to > 100kW in 2009?
Where are we going in the future?

Diode Laser–Pumped Solid-State Lasers

Robert L. Byer

Diode laser–pumped solid-state lasers are efficient, compact, all solid-state sources of coherent optical radiation. Major advances in solid-state laser technology have historically been preceded by advances in pumping technology. The helical flash lamps used to pump early ruby lasers were superseded by the linear flash lamp and arc lamp now used to pump neodymium-doped yttrium-aluminum-garnet lasers. The latest advance in pumping technology is the diode laser. Diode laser–pumped neodymium lasers have operated at greater than 10 percent electrical to optical efficiency in a single spatial mode and with linewidths of less than 10 kilohertz. The high spectral power brightness of these lasers has allowed frequency extension by harmonic generation in nonlinear crystals, which has led to green and blue sources of coherent radiation. Diode laser pumping has also been used with ions other than neodymium to produce wavelengths from 946 to 2010 nanometers. In addition, Q-switched operation with kilowatt peak powers and mode-locked operation with 10-picosecond pulse widths have been demonstrated. Progress in diode lasers and diode laser arrays promises all solid-state lasers in which the flash lamp is replaced by diode lasers for average power levels in excess of tens of watts and at a price that is competitive with flash lamp–pumped laser systems. Power levels exceeding 1 kilowatt appear possible within the next 5 years. Potential applications of diode laser–pumped solid-state lasers include coherent radar, global sensing from satellites, medical uses, micromachining, and miniature visible sources for digital optical storage.

SOLID-STATE LASER DEVELOPMENT HAS BEEN PACED BY THE improvement and discovery of pump sources. The helical lamp, used to pump the first ruby laser, was replaced by the linear flash lamp and discharge arc lamp that are now used to pump virtually every neodymium-doped yttrium-aluminum-garnet (Nd:YAG) and neodymium glass (Nd:glass) laser system in the world. The next advance in solid-state laser technology promises to be improved pumping by means of diode lasers and diode laser arrays (*1*). The recent and rapid advances in the power and efficiency of diode lasers and diode laser arrays and their application to the pumping of solid-state lasers have led to a renaissance in solid-state laser development (*2*). Advanced technology solid-state lasers pumped by diode lasers will make possible such diverse applications as coherent radar for global wind measurements, semiconductor circuit repair, and all solid-state color video projection.

A question often asked is, "Why use the diode laser to pump another solid-state laser instead of using flash lamps or the diode directly?" The diode laser efficiently emits optical radiation into a narrow spectral band. When the emission wavelength of the diode laser lies within the absorption band of the ion-doped solid-state laser medium, diode laser optical pumping can be very efficient with little excess heat generation. Flash lamp pumping efficiency is limited by the broad spectral emission of the lamp and the less efficient absorption of the lamp radiation by the solid-state laser medium. Excess heat and power fluctuations of the lamp also degrade the solid-state laser performance, as does the finite lamp lifetime. The diode laser is essentially a continuous wave (cw) device with low energy storage capability, whereas the solid-state laser can store energy in the long-lived metastable ion levels. The stored energy can be extracted by rapid switching (Q-switching) to provide peak power levels that are orders of magnitude greater than from the diode laser itself. Furthermore, the solid-state laser can collect the output from several diode lasers to provide greater average power than is available from a single diode laser. The diode laser–pumped solid-state laser can operate at a variety of wavelengths not accessible with diode lasers. The diode laser–pumped solid-state laser linewidth is fundamentally orders of magnitude less than that of the

Fig. 1. (**Top**) Schematic of the diode laser–pumped monolithic Nd:YAG–oscillator. (**Bottom**) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

The author is a professor of applied physics and vice provost and dean of research at Stanford University, Stanford, CA 94305.

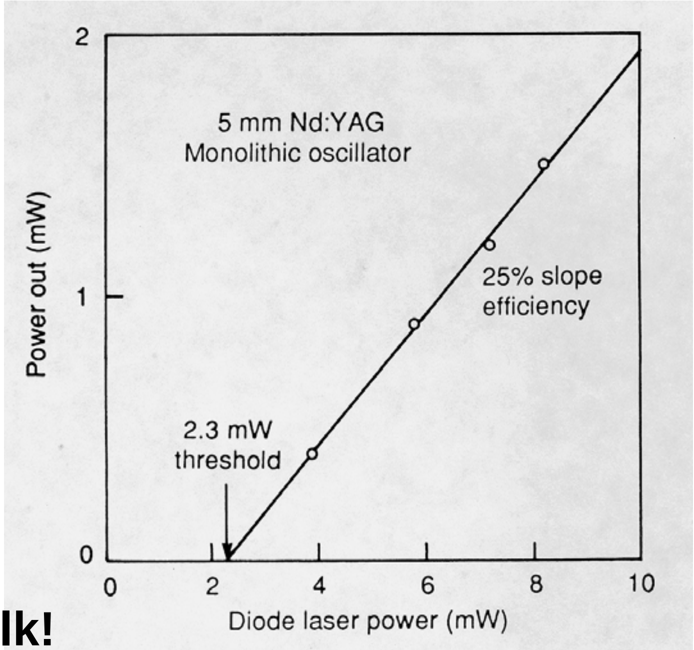
742

SCIENCE, VOL. 239

Laser Diode Pumped Nd:YAG - 1984

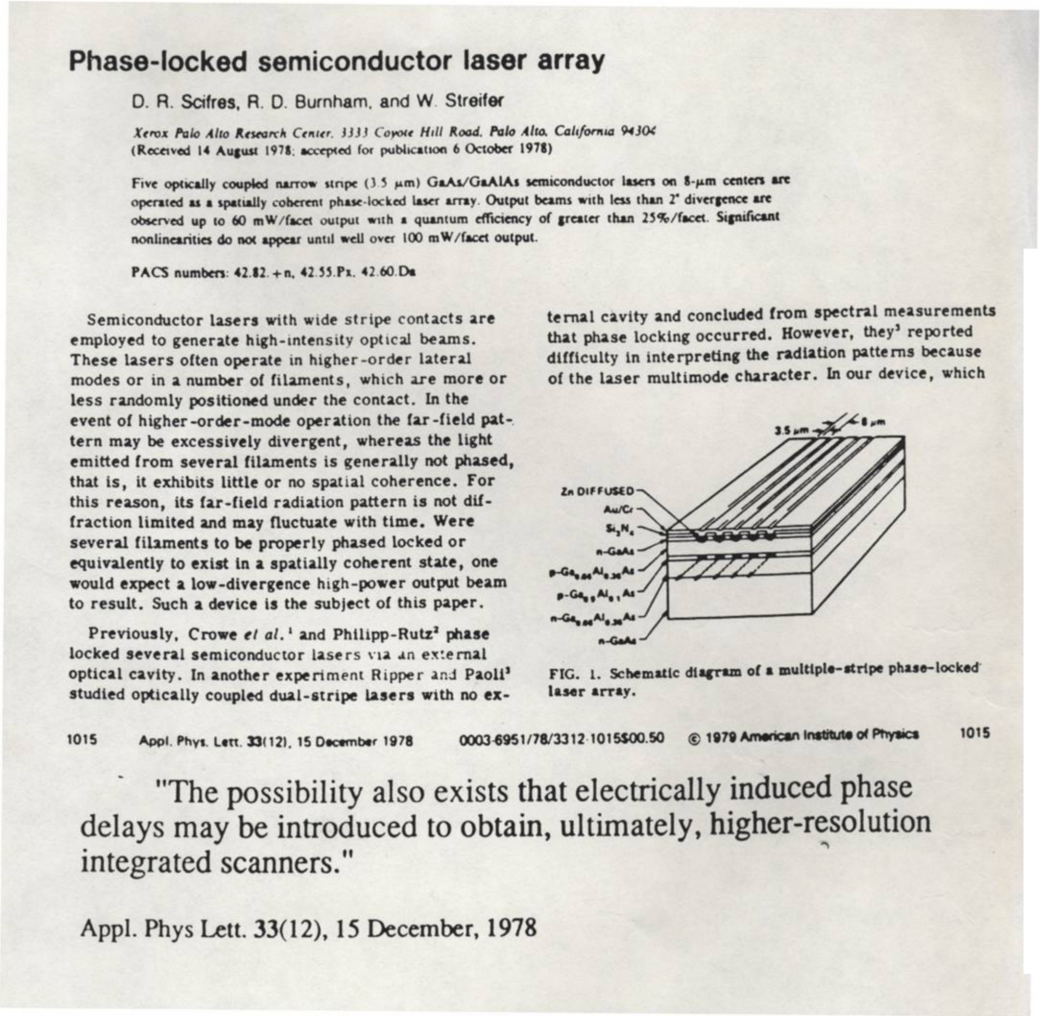
Binkun Zhou, Tom Kane, Jeff Dixon and R. L. Byer
"Efficient, frequency-stable laser-diode-pumped Nd:YAG laser"
Opt. Lett. 10, 62, 1985

5mm Nd:YAG Monolithic Oscillator
< 2mW output power for 8mw Pump
25% slope efficiency



Not by a direct path, but more like a random walk!

Innovation: Progress in Laser Diodes - 1978



Phase-locked semiconductor laser array

D. R. Scifres, R. D. Burnham, and W. Streifer

Xerox Palo Alto Research Center, 3333 Coyote Hill Road, Palo Alto, California 94304
(Received 14 August 1978; accepted for publication 6 October 1978)

Five optically coupled narrow stripe (3.5 μm) GaAs/GaAlAs semiconductor lasers on 8-μm centers are operated as a spatially coherent phase-locked laser array. Output beams with less than 2° divergence are observed up to 60 mW/facet output with a quantum efficiency of greater than 25%/facet. Significant nonlinearities do not appear until well over 100 mW/facet output.

PACS numbers: 42.82.+n, 42.55.Px, 42.60.Da

Semiconductor lasers with wide stripe contacts are employed to generate high-intensity optical beams. These lasers often operate in higher-order lateral modes or in a number of filaments, which are more or less randomly positioned under the contact. In the event of higher-order-mode operation the far-field pattern may be excessively divergent, whereas the light emitted from several filaments is generally not phased, that is, it exhibits little or no spatial coherence. For this reason, its far-field radiation pattern is not diffraction limited and may fluctuate with time. Were several filaments to be properly phased locked or equivalently to exist in a spatially coherent state, one would expect a low-divergence high-power output beam to result. Such a device is the subject of this paper.

Previously, Crowe *et al.*[1] and Philipp-Rutz[2] phase locked several semiconductor lasers via an external optical cavity. In another experiment Ripper and Paoli[3] studied optically coupled dual-stripe lasers with no external cavity and concluded from spectral measurements that phase locking occurred. However, they[3] reported difficulty in interpreting the radiation patterns because of the laser multimode character. In our device, which

FIG. 1. Schematic diagram of a multiple-stripe phase-locked laser array.

"The possibility also exists that electrically induced phase delays may be introduced to obtain, ultimately, higher-resolution integrated scanners."

Appl. Phys Lett. 33(12), 15 December, 1978

Don Scifres,

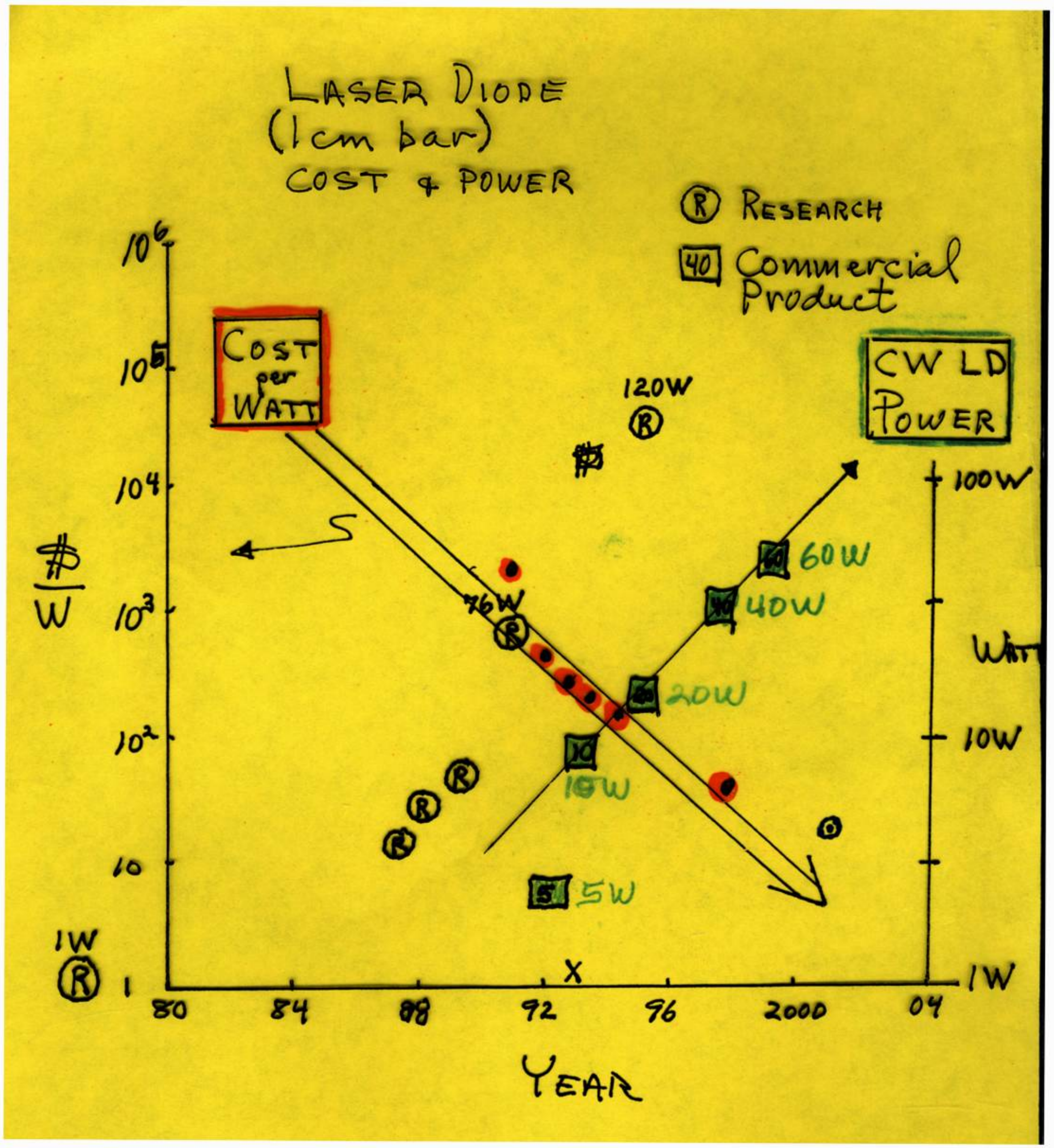
Ralph Burnham, and
Bill Streifer - 1978

This was the first Watt level power output from a linear Laser Diode Array.

Within one decade the output power would increase to greater than 100W from a one centimeter LD bar.

1 Watt at 25% efficiency – 1cm bar

Laser Diode Cost & Output Power vs Year
Moore's Law applied to Solid State Lasers



Moore noted that the number of transistors per chip was doubling every 18 months. He attributed this to experience and learning from improved production.

The corollary was that the cost decreased as market size and production volume grew.

Moore's Law was born.

Byer's version of Moore's Law
(1988 – 2004)

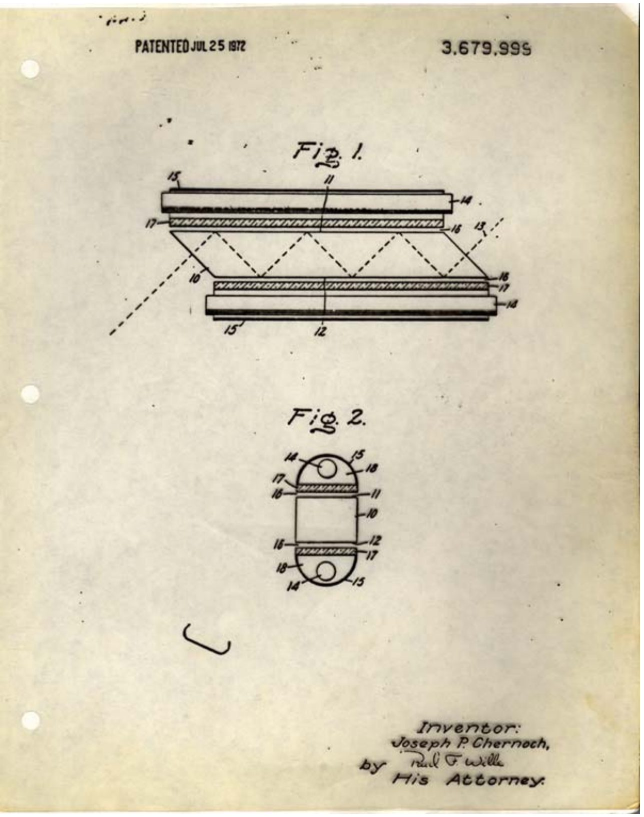
Predicted $1/Watt in 2004
Delayed by 2 years –
by Telecom boom and bust

(Today diode bars cost $0.1/W)

Contents

- Prelude
- Introduction *Making Lightwaves*
    - Early laser history and concepts
        - Unstable Resonator
        - **Slab Laser** – one dimensional cooling
    - Recent **Innovations**
        - Large Mode Area Fiber Lasers
        - **Edge Pumped Slab Laser**
        - **Transparent 'Ceramic' polycrystalline gain media**
- Scientific Applications of Lasers *Riding Lightwaves*
    - Laser Remote Sensing
    - Global Wind Sensing
    - Observing the Universe with Gravitational Waves
- The Future – continued innovation *Surfing Lightwaves*
    - Exploring TeV scale physics with laser accelerators
        - Coherent X-rays at the Attosecond time scale
    - LIFE - Laser Induced Fusion for Energy
        - Fusion/Fission Reactors

Innovation: Nd:YAG & Nd:Glass Slab Geometry Lasers - 1972



PATENTED JUL 25 1972

3,679,999

Inventor:
Joseph P. Chernoch,
by Paul F. Wille
His Attorney.

The zig-zag slab laser concept

Cancels thermal focusing to first order
Power scales as slab area
Retains linear polarization

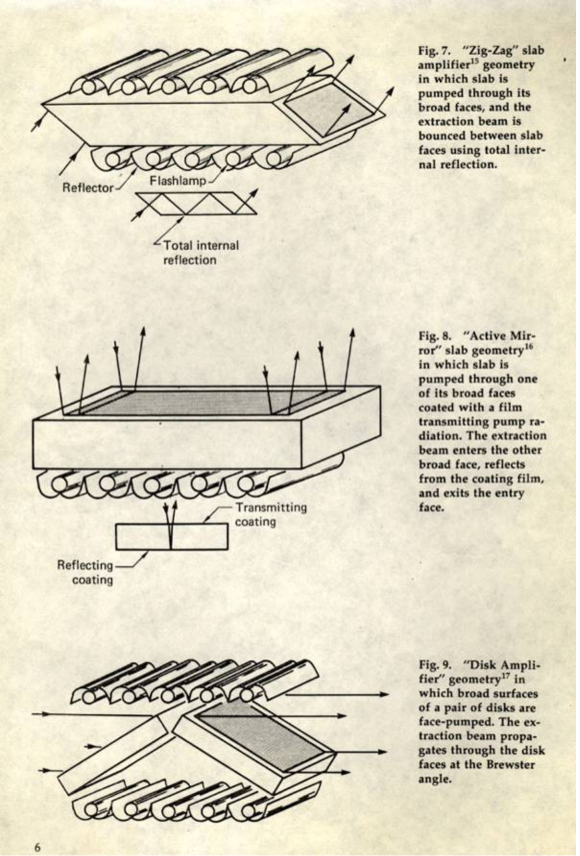


Fig. 7. "Zig-Zag" slab amplifier[15] geometry in which slab is pumped through its broad faces, and the extraction beam is bounced between slab faces using total internal reflection.

Fig. 8. "Active Mirror" slab geometry[16] in which slab is pumped through one of its broad faces coated with a film transmitting pump radiation. The extraction beam enters the other broad face, reflects from the coating film, and exits the entry face.

Fig. 9. "Disk Amplifier" geometry[17] in which broad surfaces of a pair of disks are face-pumped. The extraction beam propagates through the disk faces at the Brewster angle.

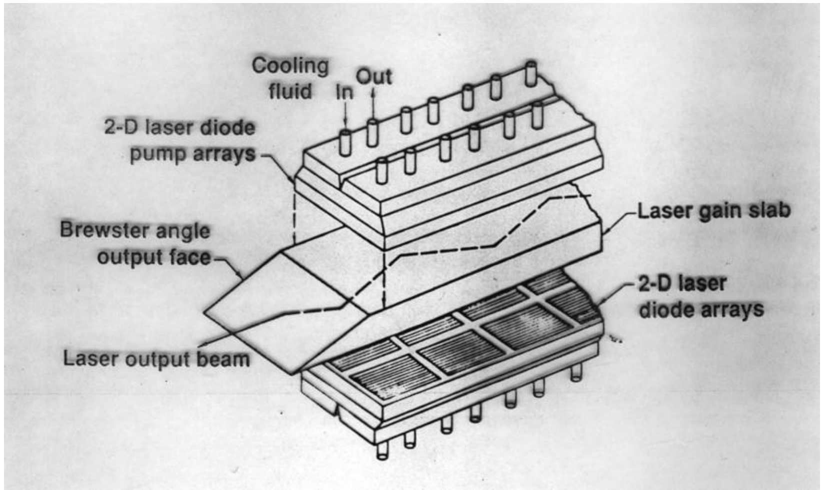
"Zig-Zag" face pumped
Slab laser

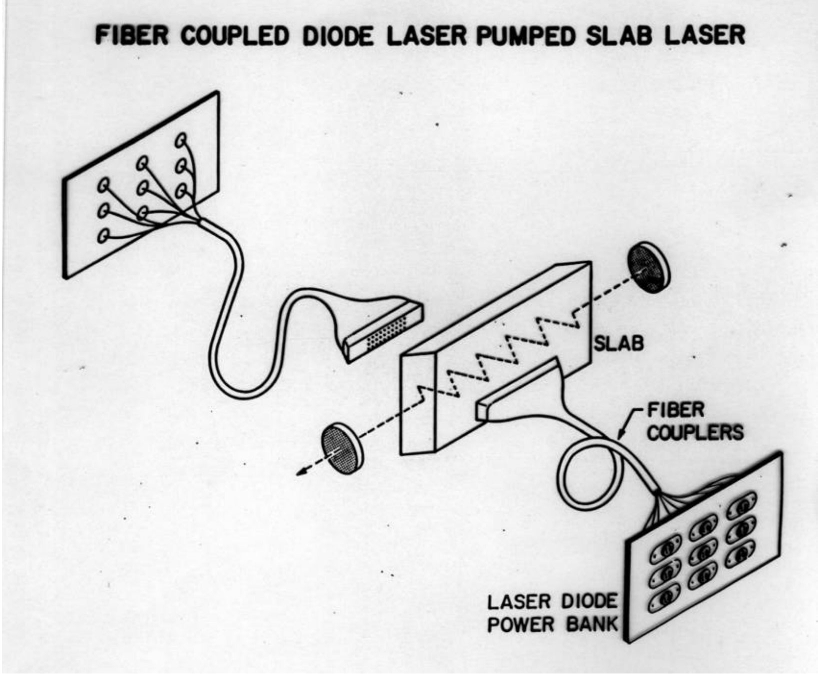
"Active mirror" or also
known as the
"thin disk" laser.

"Disk amplifier" geometry
adopted for the NIF
Laser

Joe Chernoch Invention
Patent # 3,679,999
July 25, 1972
Engineer at
General Electric Corp

Diode pumped Slab Lasers





TRW DAPKL* Nd:YAG Laser

(1988 - 1993)

Three stage MOPA with Phase Conjugation
10 J Q-switched pulses at 100 Hz
1 kW near diffraction limited laser
SHG to green

*Diode Array Pumped Kilowatt Laser
1 kW of average power –a 1st step.

Stanford University

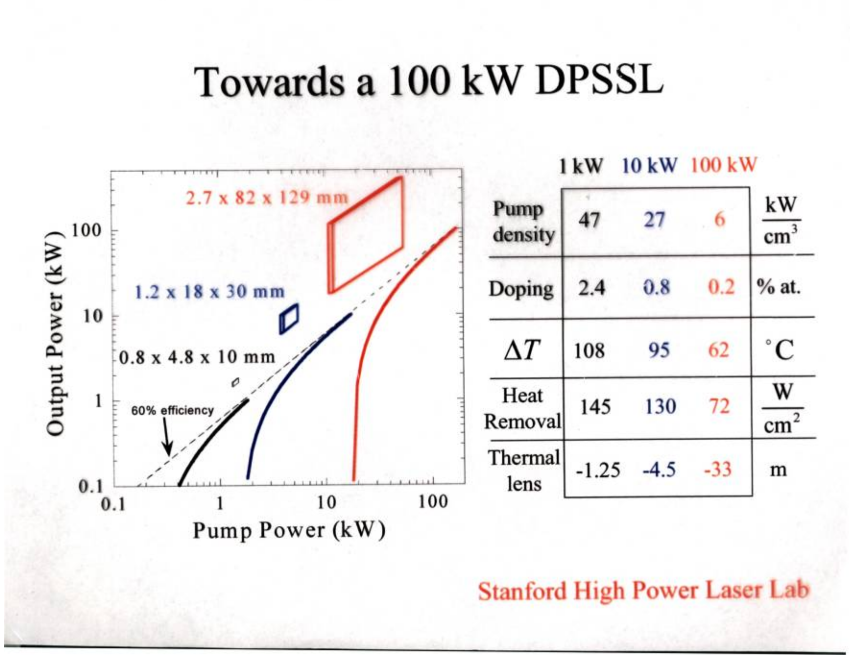
R. J. Shine, A. J. Alfrey, R. L. Byer
"40W cw, TEMoo-mode,
Diode-laser-pumped, Nd:YAG miniature
Slab laser" Opt. Lett. 20, 459, 1995

Face pumped, water cooled
25 - 10W fiber coupled laser diodes
250 W pump power
Cost: $280k in 1995

Innovation: Edge-Pumped, Conduction Cooled Slab Laser – 2000 (Predicted Power scaling to >100 kW with High Coherence)

Conduction cooled, low doping, TIR guided pump, power scaling as Area

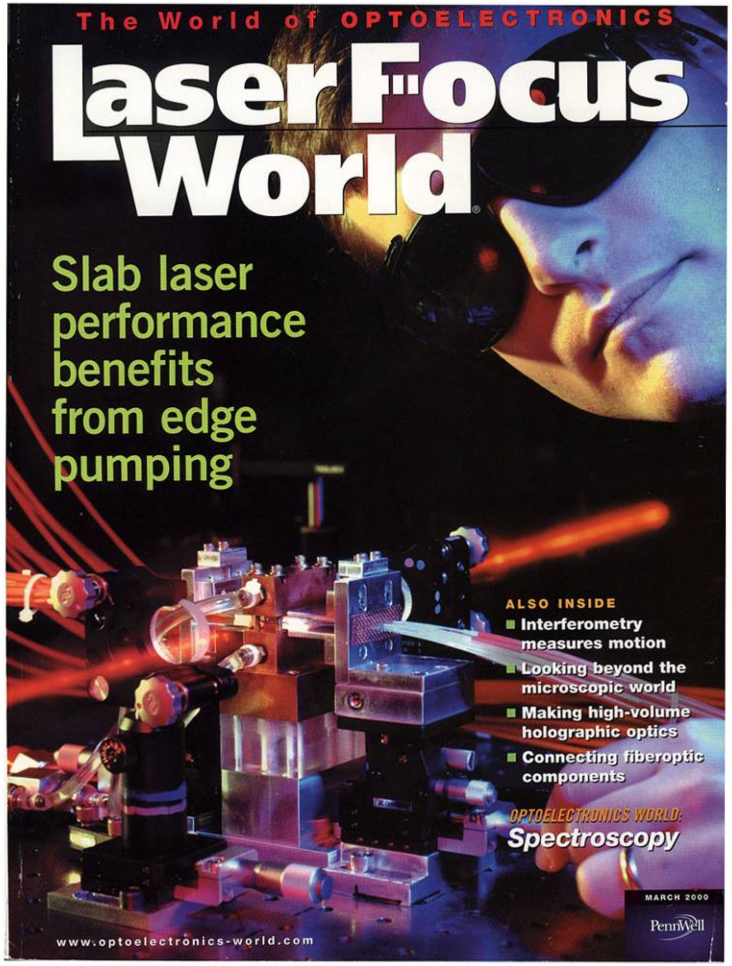
T.S. Rutherford, W.M. Tulloch,
E.K. Gustafson, R.L. Byer
"Edge-Pumped Quasi-Three-Level
Slab Lasers: Design and Power Scaling"
IEEE J. Quant. Elec., vol. 36, 2000



Towards a 100 kW DPSSL

	1 kW	10 kW	100 kW	
Pump density	47	27	6	kW/cm^3
Doping	2.4	0.8	0.2	% at.
ΔT	108	95	62	°C
Heat Removal	145	130	72	W/cm^2
Thermal lens	-1.25	-4.5	-33	m

Stanford High Power Laser Lab



The World of OPTOELECTRONICS

Laser Focus World

Slab laser performance benefits from edge pumping

ALSO INSIDE
- Interferometry measures motion
- Looking beyond the microscopic world
- Making high-volume holographic optics
- Connecting fiberoptic components

OPTOELECTRONICS WORLD: Spectroscopy

MARCH 2000

PennWell

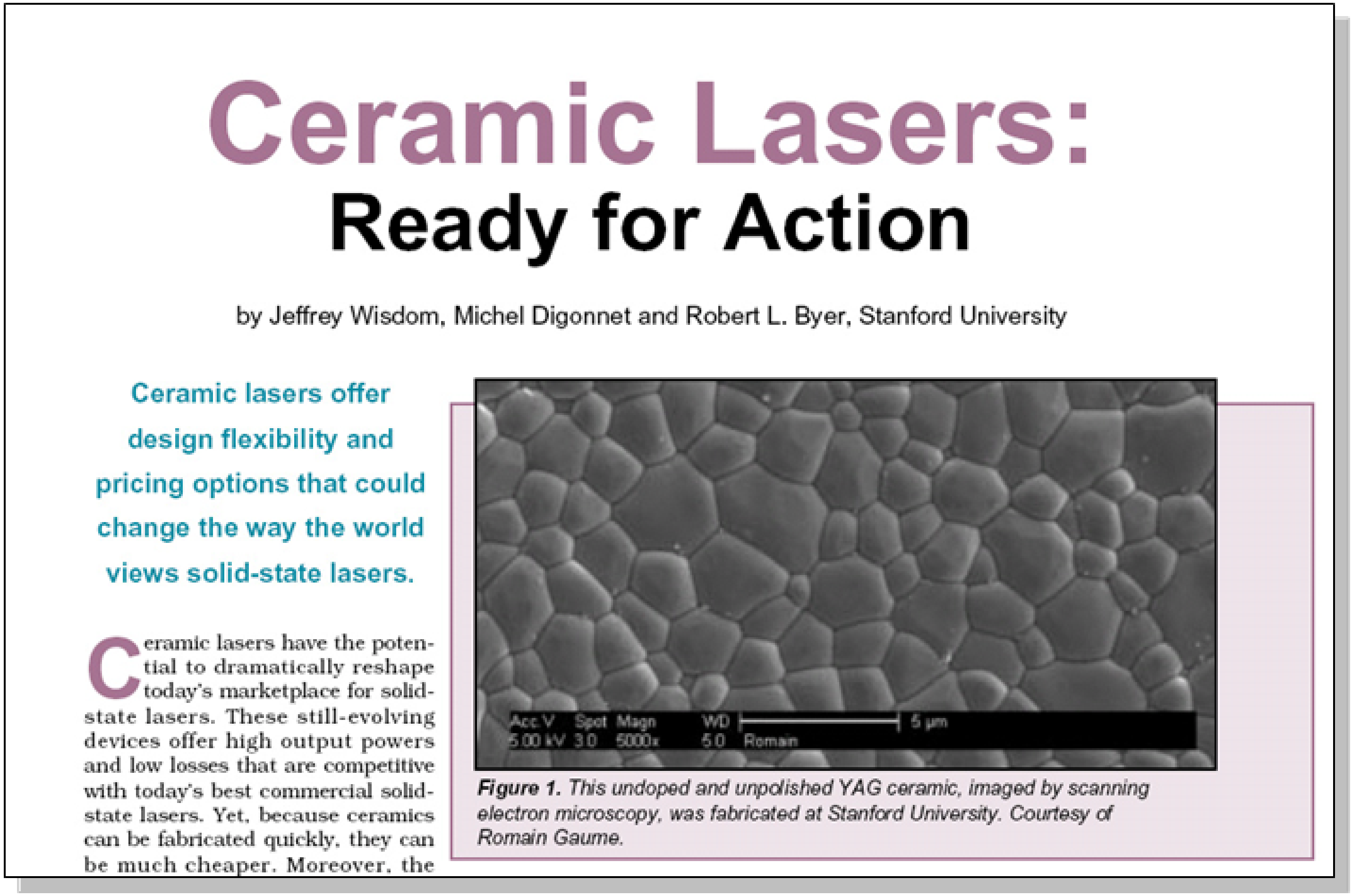
www.optoelectronics-world.com

Predicted 100kW output based on single crystal Yb:YAG – need sizes > 20 cm
Difficult with single xtals, but possible with polycrystalline ceramic YAG!

Innovation: Polycrystalline “Ceramic” Laser Gain Media

Challenge the traditional single crystal approach

In late 2003, ceramics offered equivalent performance to single crystals.
Can ceramics offer improved performance?



Ceramic Lasers:

Ready for Action

by Jeffrey Wisdom, Michel Digonnet and Robert L. Byer, Stanford University

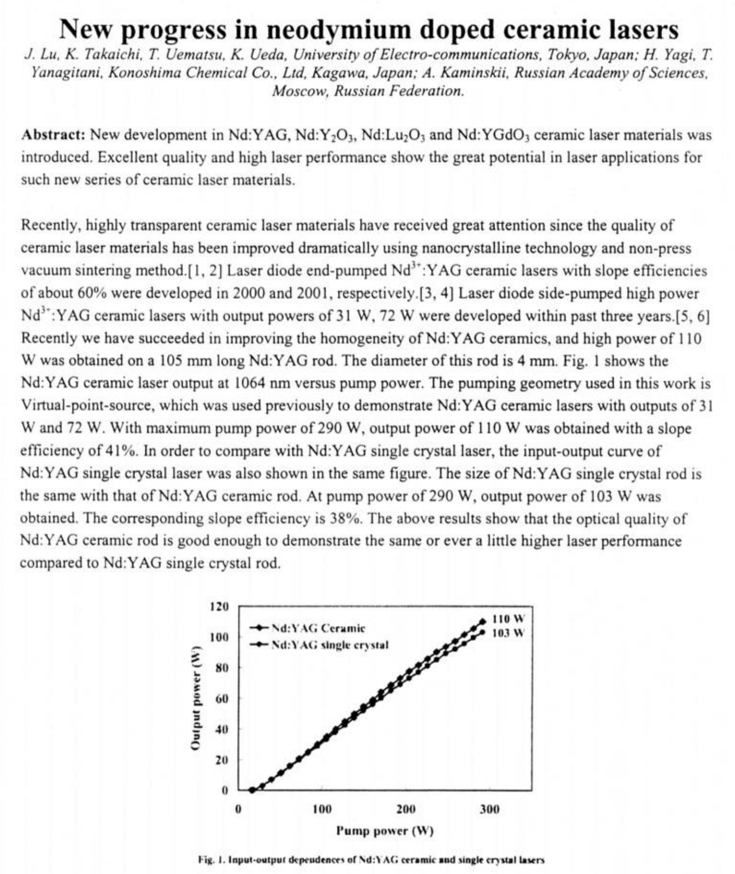
Ceramic lasers offer design flexibility and pricing options that could change the way the world views solid-state lasers.

Ceramic lasers have the potential to dramatically reshape today’s marketplace for solid-state lasers. These still-evolving devices offer high output powers and low losses that are competitive with today’s best commercial solid-state lasers. Yet, because ceramics can be fabricated quickly, they can be much cheaper. Moreover, the

Figure 1. *This undoped and unpolished YAG ceramic, imaged by scanning electron microscopy, was fabricated at Stanford University. Courtesy of Romain Gaume.*

Innovation: Power scaling of Neodymium Doped Ceramic Lasers

Professor Kenichi Ueda



New progress in neodymium doped ceramic lasers

J. Lu, K. Takaichi, T. Uematsu, K. Ueda, University of Electro-communications, Tokyo, Japan; H. Yagi, T. Yanagitani, Konoshima Chemical Co., Ltd, Kagawa, Japan; A. Kaminskii, Russian Academy of Sciences, Moscow, Russian Federation.

Abstract: New development in Nd:YAG, Nd:Y_2O_3, Nd:Lu_2O_3 and Nd:$YGdO_3$ ceramic laser materials was introduced. Excellent quality and high laser performance show the great potential in laser applications for such new series of ceramic laser materials.

Recently, highly transparent ceramic laser materials have received great attention since the quality of ceramic laser materials has been improved dramatically using nanocrystalline technology and non-press vacuum sintering method.[1, 2] Laser diode end-pumped Nd^{3+}:YAG ceramic lasers with slope efficiencies of about 60% were developed in 2000 and 2001, respectively.[3, 4] Laser diode side-pumped high power Nd^{3+}:YAG ceramic lasers with output powers of 31 W, 72 W were developed within past three years.[5, 6] Recently we have succeeded in improving the homogeneity of Nd:YAG ceramics, and high power of 110 W was obtained on a 105 mm long Nd:YAG rod. The diameter of this rod is 4 mm. Fig. 1 shows the Nd:YAG ceramic laser output at 1064 nm versus pump power. The pumping geometry used in this work is Virtual-point-source, which was used previously to demonstrate Nd:YAG ceramic lasers with outputs of 31 W and 72 W. With maximum pump power of 290 W, output power of 110 W was obtained with a slope efficiency of 41%. In order to compare with Nd:YAG single crystal laser, the input-output curve of Nd:YAG single crystal laser was also shown in the same figure. The size of Nd:YAG single crystal rod is the same with that of Nd:YAG ceramic rod. At pump power of 290 W, output power of 103 W was obtained. The corresponding slope efficiency is 38%. The above results show that the optical quality of Nd:YAG ceramic rod is good enough to demonstrate the same or ever a little higher laser performance compared to Nd:YAG single crystal rod.

Fig. 1. Input-output dependences of Nd:YAG ceramic and single crystal lasers

Dr. Kenichi Ueda

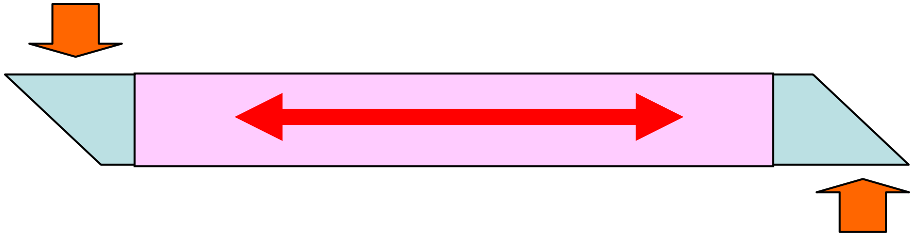
Nd:YAG ceramic laser performance
equals that of Nd:YAG single crystal

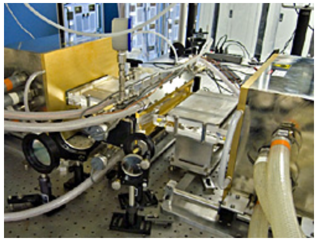
Key result: convinced laser community
That Ceramic YAG better than Xtal YAG

Ceramic gain media can be engineered to optimize laser performance

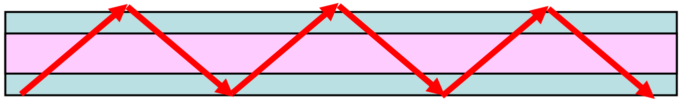
Research in US exceeds 105 kW average power using Diode Pumped Ceramic YAG

1. Northrop Grumman: End-pumped Slab: Yb:YAG

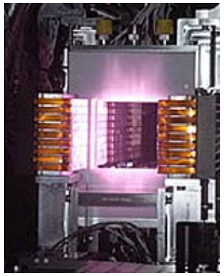


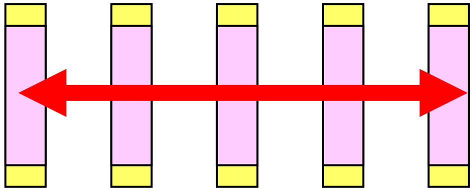


2. Textron: Zigzag Thin Slab Laser: Nd:YAG

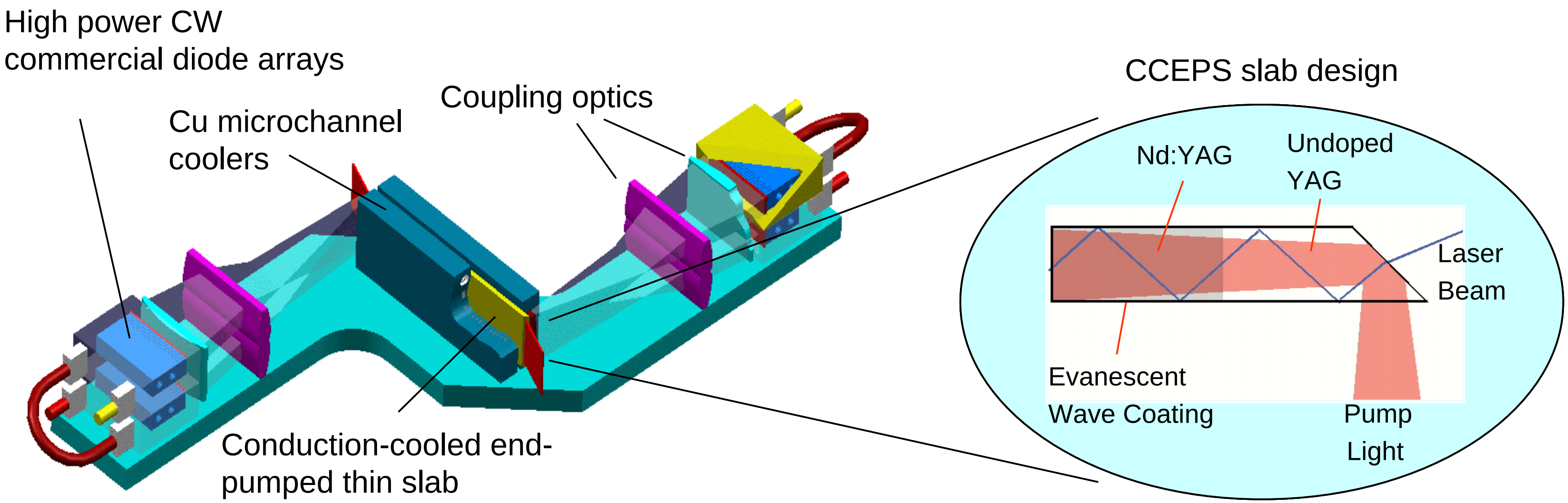


3.LLNL: Thermo Capacity Laser; Nd:Sm:YAG





High Power Amplifiers Based on Conduction-Cooled End-Pumped Slab (CCEPS)



High power CW
commercial diode arrays

Cu microchannel
coolers

Coupling optics

Conduction-cooled end-pumped thin slab

CCEPS slab design

Nd:YAG

Undoped
YAG

Laser
Beam

Evanescent
Wave Coating

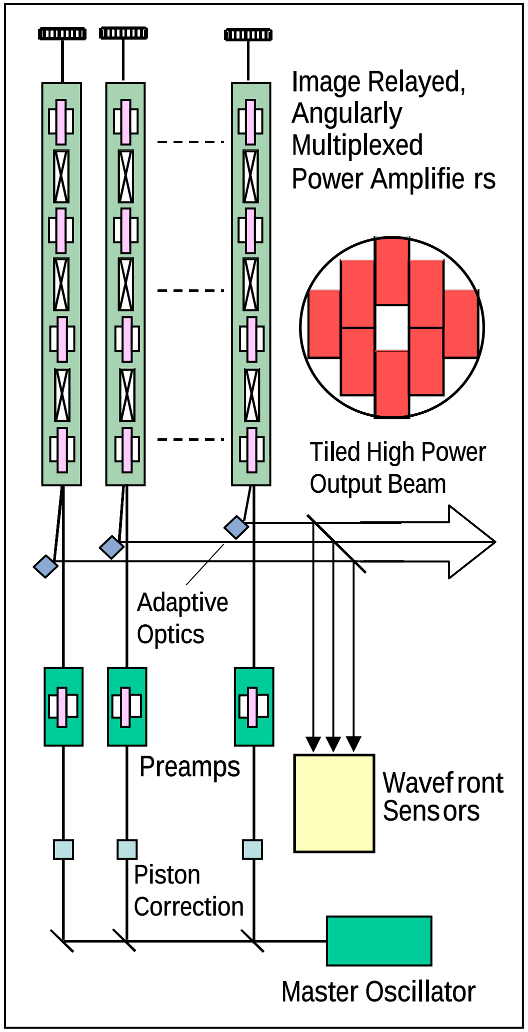
Pump
Light

Key elements of CCEPS high power amplifier:

- Composite Nd:YAG slab with undoped YAG endcaps
- Copper microchannel coolers for conductive heat removal
- Uniform & efficient end pumping
- Evanescent coating on cooled faces
- Zig-zag extraction

NGST JHPSSL Architecture

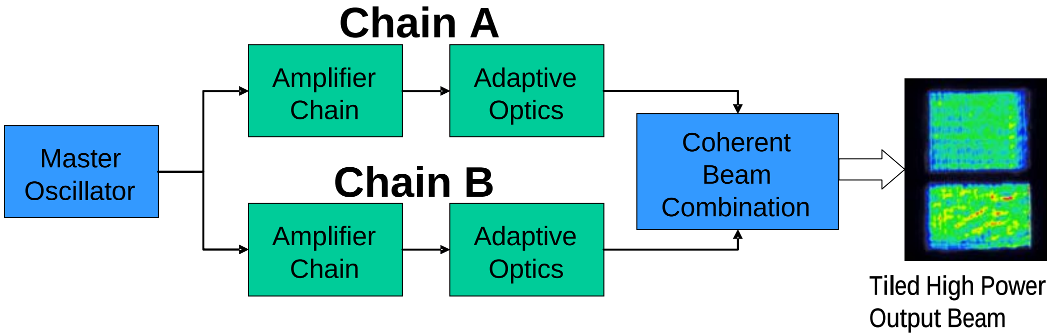
Northrop Grumman Space Technology Joint High Power Solid State Laser



(H. Injeyan et al, CLEO/QELS 2005, CMJ3)

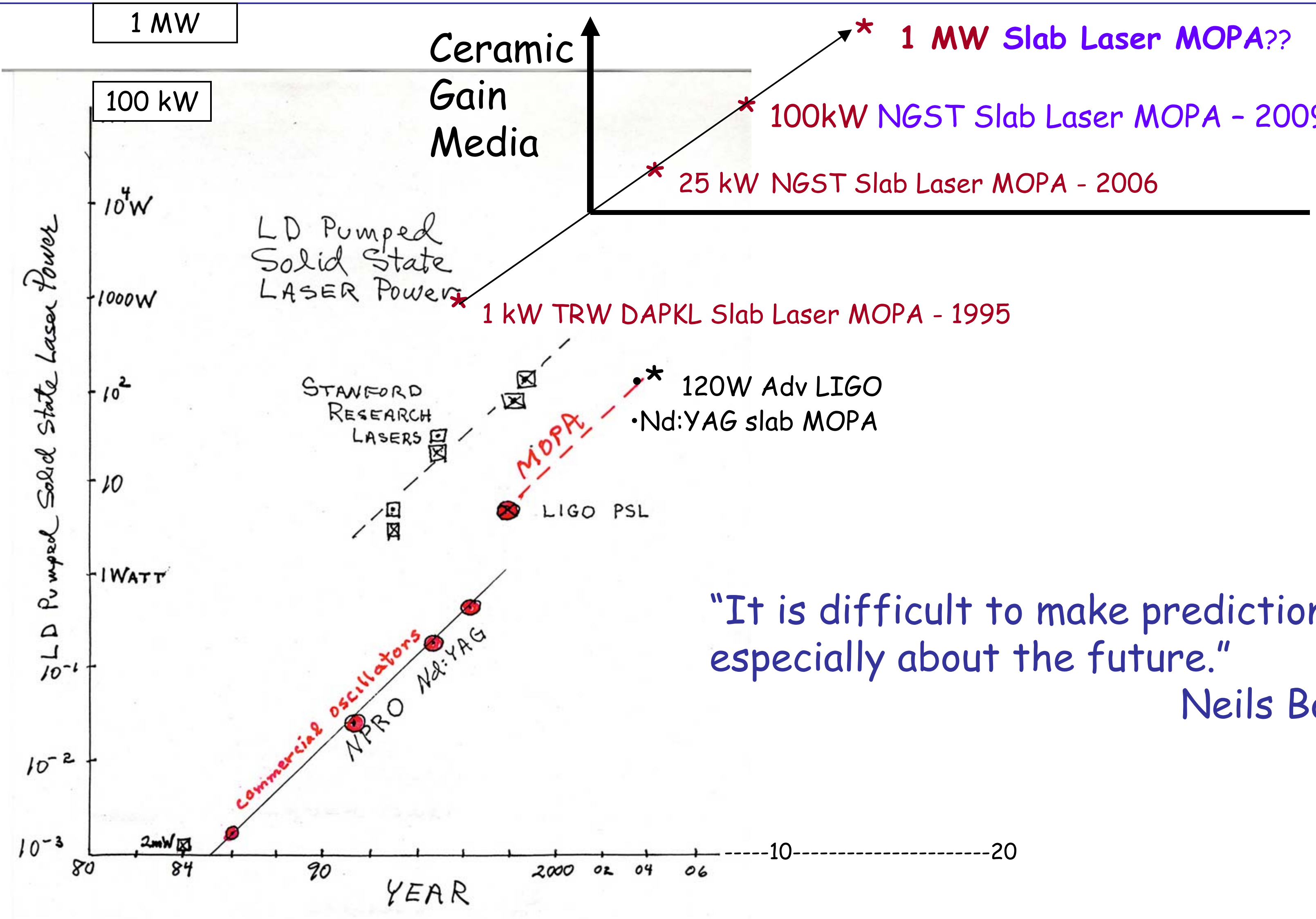
- A single low power master oscillator injects multiple amplifier chains
- The MOPA outputs are wavefront corrected, coherently combined, and stacked side-by-side to form a common beam
- JHPSSL Phase 2 used two chains to demonstrate 25 kW output:

(G. Goodno et al, Advanced Solid State Photonics 2006, MA2)



NGST: Northrop Grumman Space Technology
JPHSSL: Joint High Power Solid State Laser

Realized & Projected Laser Power "Livingston Plot" for Diode pumped Solid State Lasers



1 MW

100 kW

Ceramic Gain Media

1 MW Slab Laser MOPA??

100kW NGST Slab Laser MOPA – 2009

25 kW NGST Slab Laser MOPA - 2006

1 kW TRW DAPKL Slab Laser MOPA - 1995

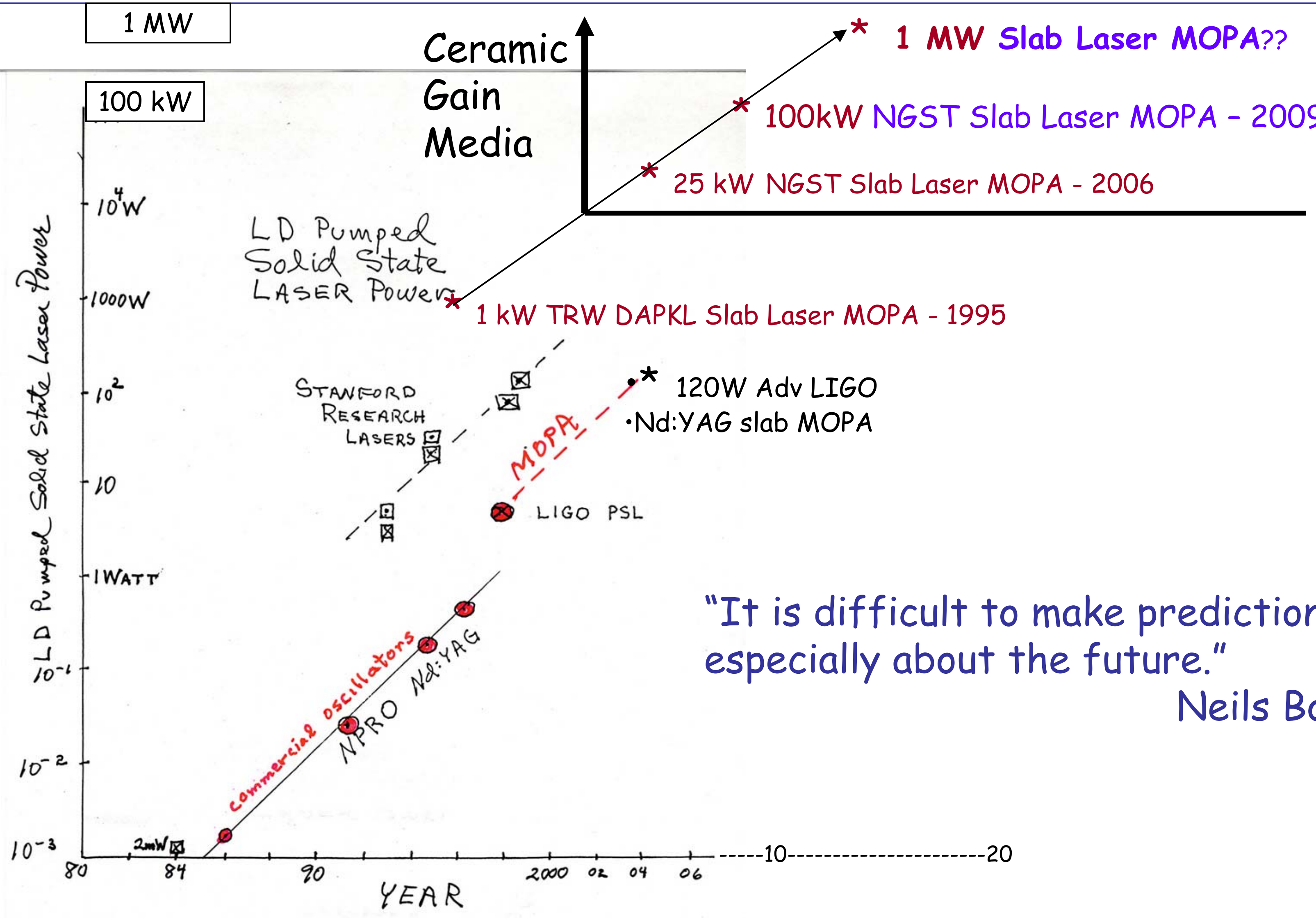
120W Adv LIGO

- Nd:YAG slab MOPA

"It is difficult to make predictions, especially about the future."
Neils Bohr

Why and interest in MW average power Lasers?

Realized & Projected Laser Power "Livingston Plot" for Diode pumped Solid State Lasers

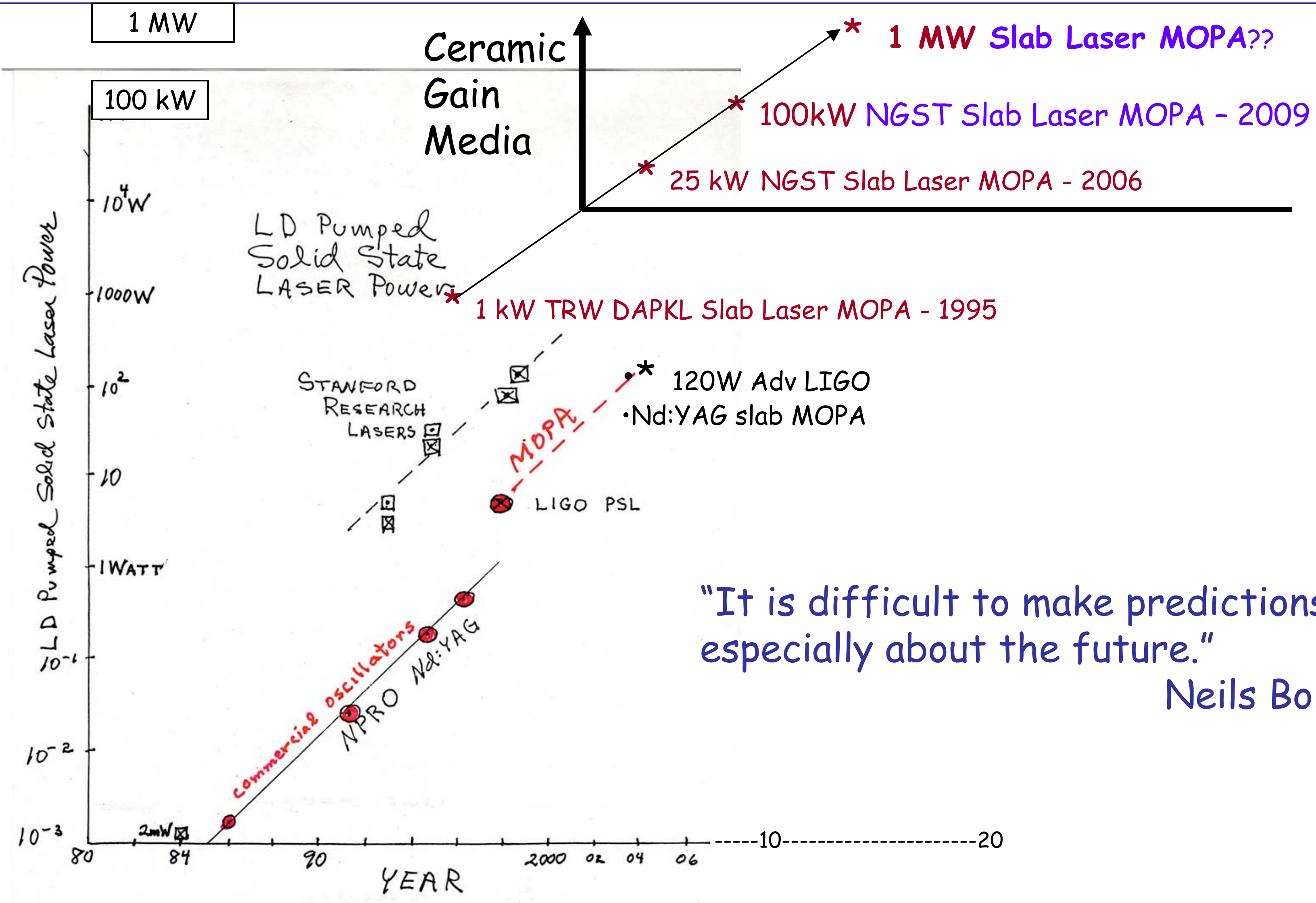


"It is difficult to make predictions, especially about the future."
Neils Bohr

Laser Accelerators for TeV scale physics and coherent X-rays

Realized & Projected Laser Power "Livingston Plot" for Diode pumped Solid State Lasers

Byer
Group



"It is difficult to make predictions, especially about the future."
Neils Bohr

And LIFE: Laser Inertial Fusion for Energy Generation

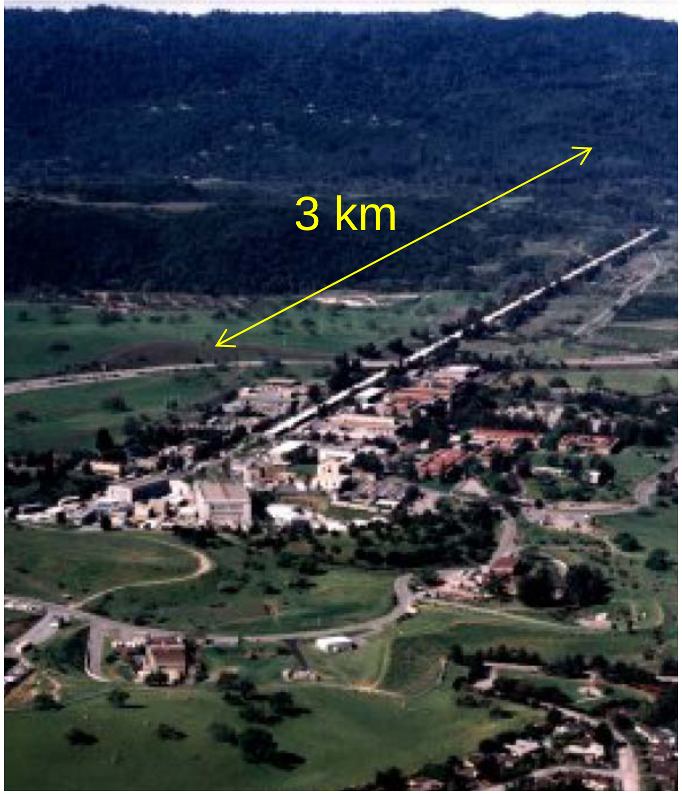
Contents

- Prelude
- Introduction *Making Lightwaves*
  - Early laser history and concepts
    - Unstable Resonator
    - Slab Laser – one dimensional cooling
  - Recent Innovations
    - Large Mode Area Fiber Lasers
    - Edge Pumped Slab Laser
    - Transparent 'Ceramic' polycrystalline gain media

- Scientific Applications of Lasers *Riding Lightwaves*
  - Laser Remote Sensing
  - Global Wind Sensing
  - Observing the Universe with Gravitational Waves
    (Special Session this afternoon and tomorrow morning)

- The Future – continued innovation *Surfing Lightwaves*
  - Exploring TeV scale physics with laser accelerators
    - Coherent X-rays at the Attosecond time scale
  - LIFE - Laser Induced Fusion for Energy
    - Fusion/Fission Reactors

Existing and Proposed Linear Accelerators



Existing SLAC – 50 GeV **Proposed ILC Accelerator 1 TeV**

The **goal** of the Laser Electron Accelerator Program – LEAP - is to invent a new approach that will allow TeV physics on the SLAC site.

To achieve the goal we need an acceleration gradient of 1 GeV per meter.

A few rules of the game

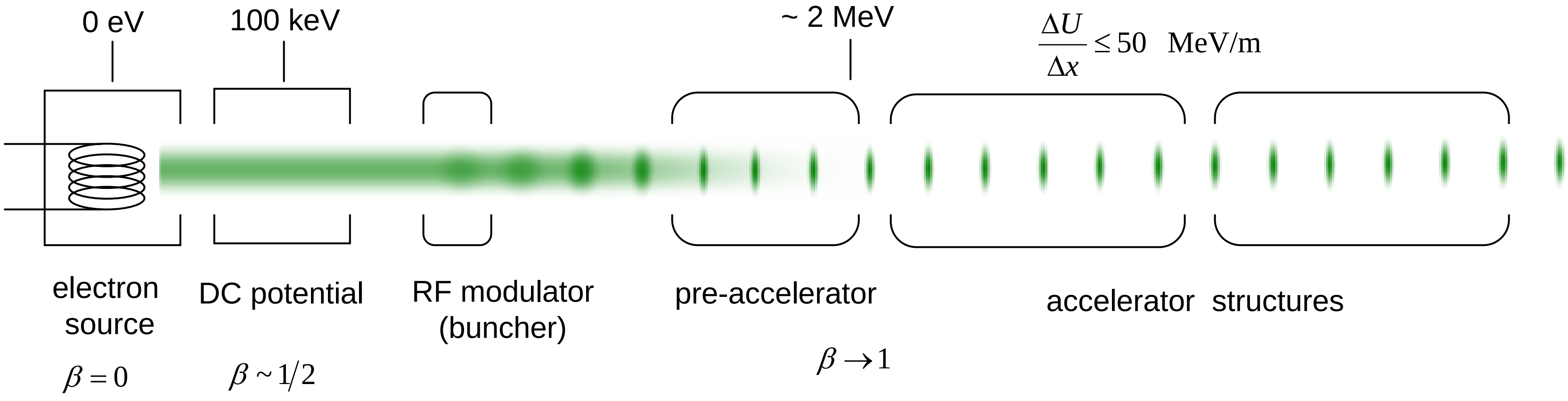
"An accelerator is just a transformer" – Pief Panofsky

"All accelerators operate at the damage limit" - Pief

"To be efficient, the accelerator must operate in reverse"
- Ron Ruth, SLAC

" It is not possible to accelerate electrons in a vacuum"
Lawson - Woodward theorem

"An accelerator requires structured matter – a waveguide - to efficiently couple the field to the electrons"   Bob Siemann

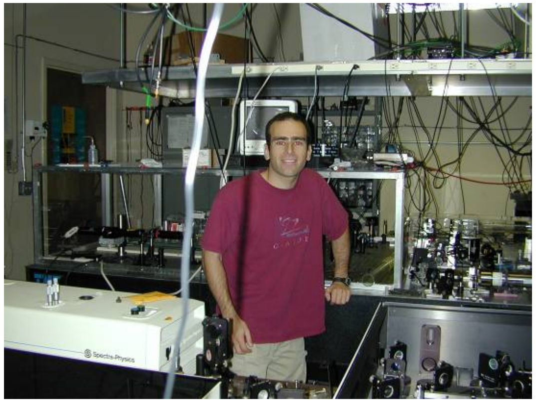


1974 –sabbatical leave, Lund   **1994** – SLAC summer school   **2004 – Successful 1st Exp**

Participants in the LEAP Experiment
Laser Electron Accelerator Program

Bob Siemann[2]

Chris Sears[2]



Ben Cowan[2]

Jim Spencer[2]

Tomas Plettner[1]

Bob Byer[1]

Eric Colby[2]

New students

- **Chris McGuinness[2]**
- **Melissa Lincoln[2]**
- **Patrick Lu[1]**

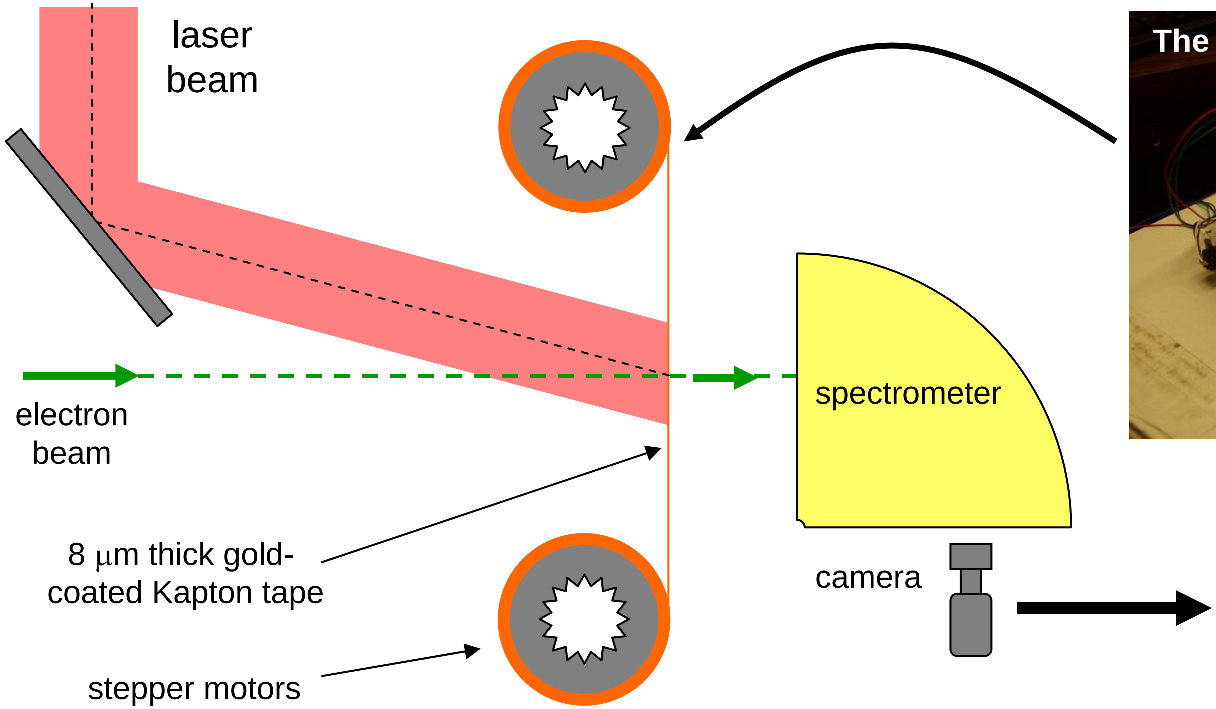
Atomic Physics collaboration

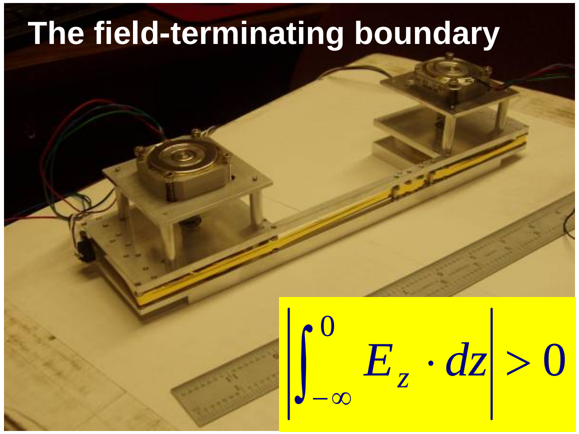
- **Mark Kasevich[3]**
- **Peter Hommelhoff[3]**
- **Catherine Kealhofer[3]**

1 E.L. Ginzton Laboratories, Stanford University
2 Stanford Linear Accelerator Center (SLAC)
3 Department of Physics, Stanford University

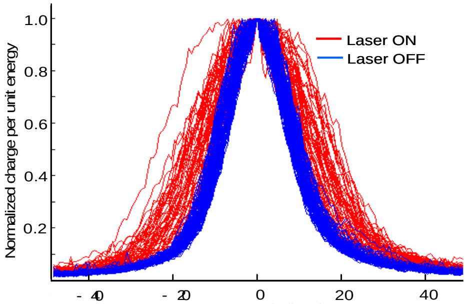
The LEAP experiment
(Laser Electron Accelerator Project)

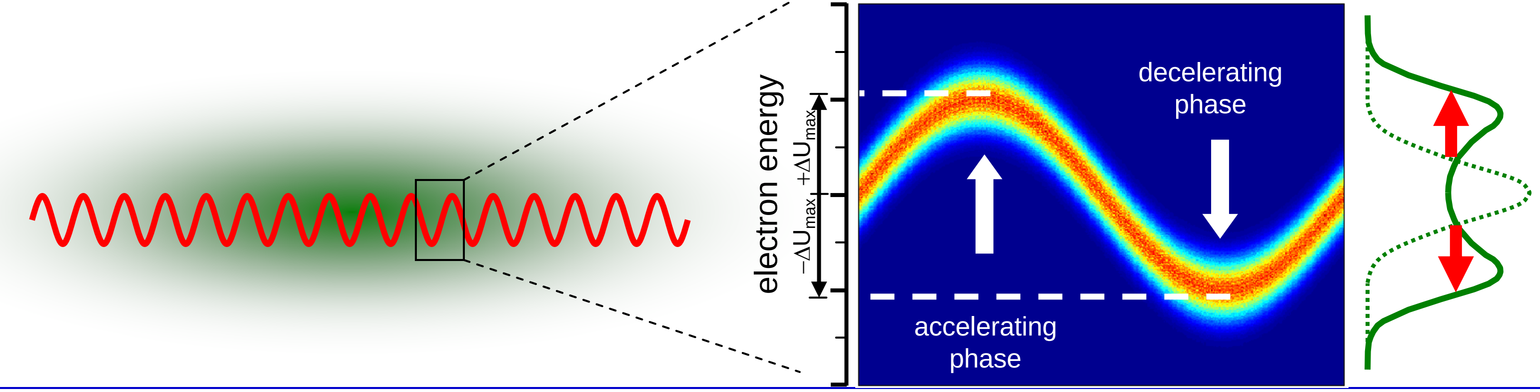
Byer Group




The field-terminating boundary

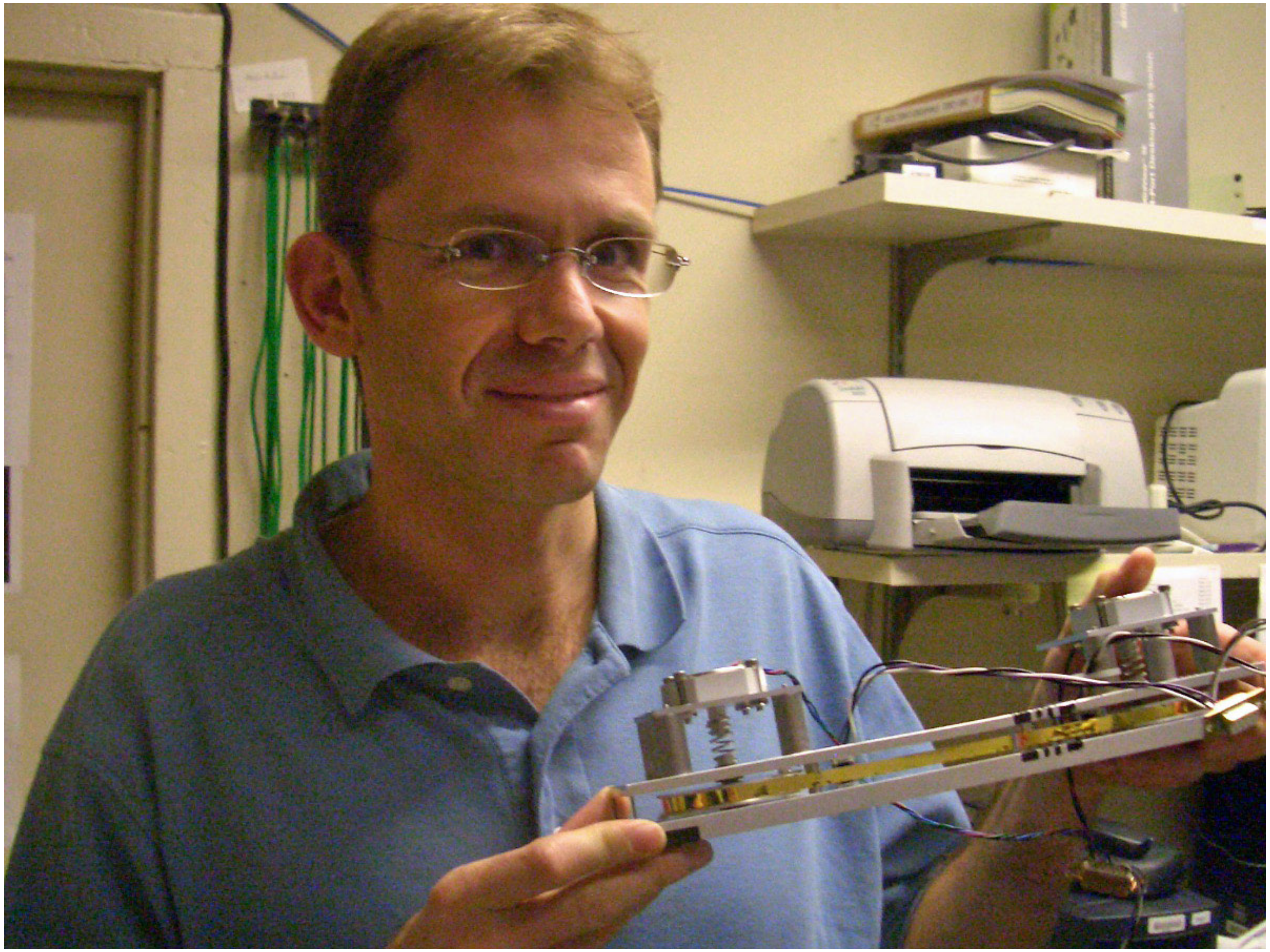
$$\left|\int_{-\infty}^{0} E_z \cdot dz\right| > 0$$





broadening of the initial energy spread of the electron beam

Tomas Plettner and LEAP Accelerator Cell



The key was to operate the cell <u>above</u> damage threshold to generate energy modulation in excess of the noise level.

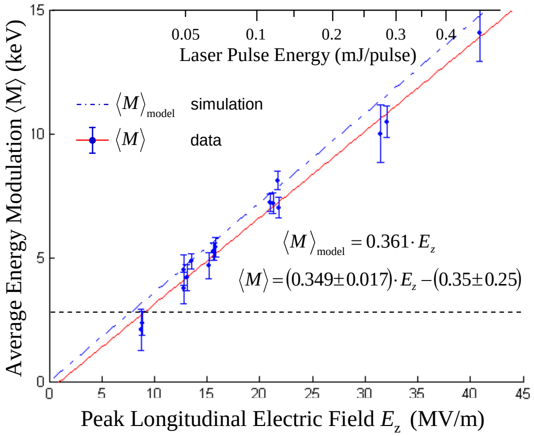
We accelerated electrons with visible light
Phys Rev Letts Sept 2005

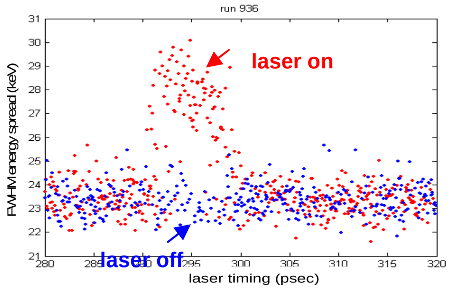
Byer
Group

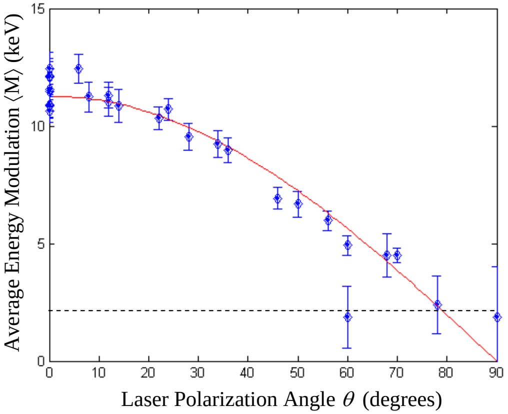
PRL **95,** 134801 (2005) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2005

Visible-Laser Acceleration of Relativistic Electrons in a Semi-Infinite Vacuum

T. Plettner and R. L. Byer
Stanford University, Stanford, California 94305, USA
Colby, B. Cowan, C. M. S. Sears, J. E. Spencer, and R. H. Siemann
SLAC, Menlo Park, California 94025, USA
(Received 19 April 2005; published 22 September 2005)







- confirmation of the Lawson-Woodward Theorem

$$\int_{-\infty}^{+\infty} E_z dz = 0$$

- observation of the linear dependence of energy gain with laser electric field

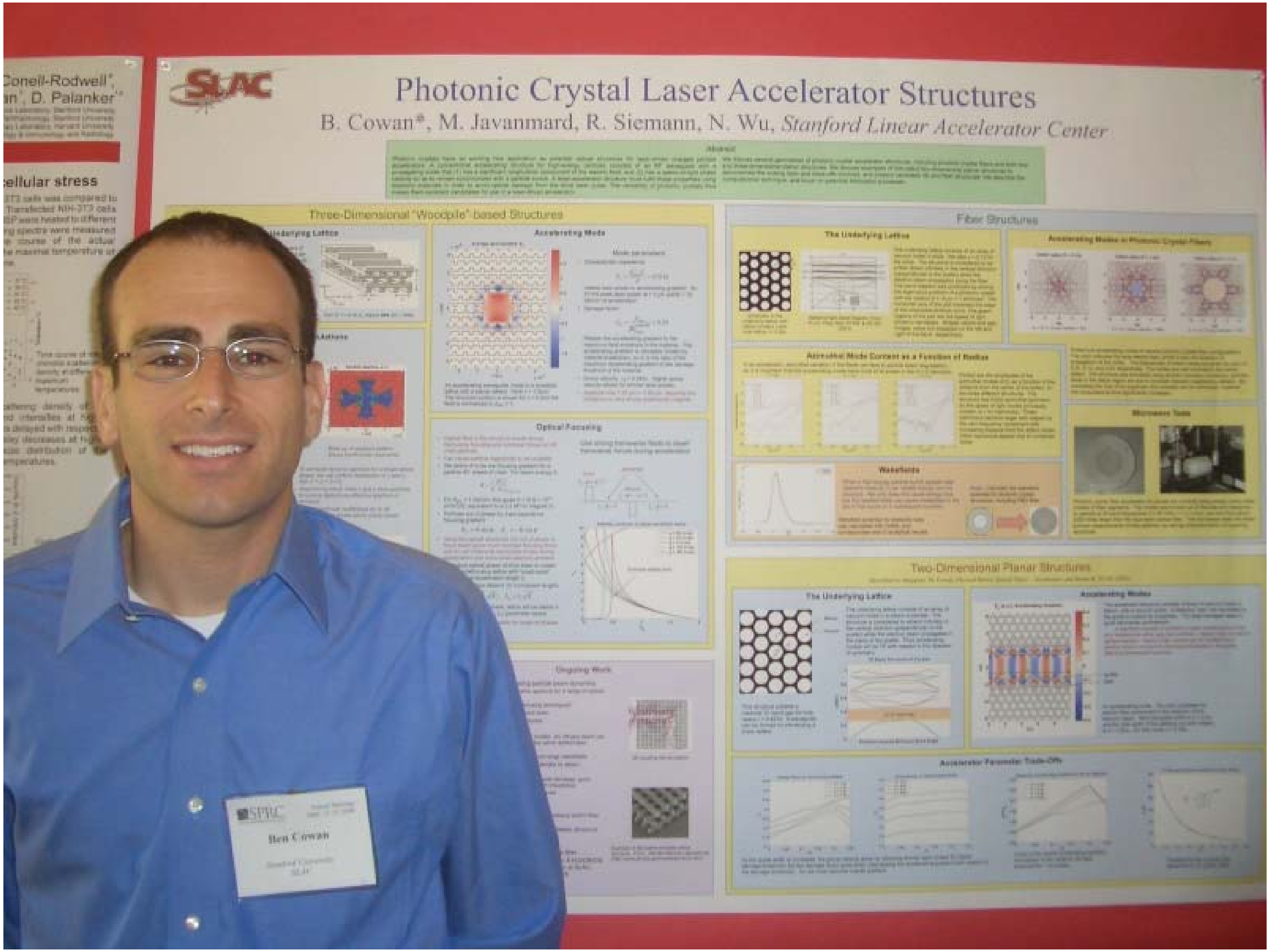
$$\Delta U \propto |E_{laser}|$$

- observation of the expected polarization dependence

$$|E_z| \propto |E_{laser}| \cos\rho$$

laser-driven
linear
acceleration in
vacuum

Ben Cowan – detailed calculations of Photonic Crystal Accelerator Structures



SLAC

Photonic Crystal Laser Accelerator Structures

B. Cowan*, M. Javanmard, R. Siemann, N. Wu, *Stanford Linear Accelerator Center*

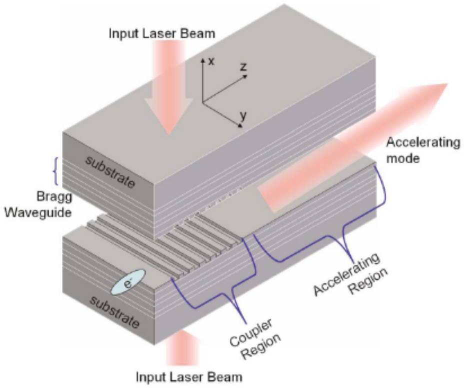
Three-Dimensional "Woodpile"-based Structures

Fiber Structures

Two-Dimensional Planar Structures

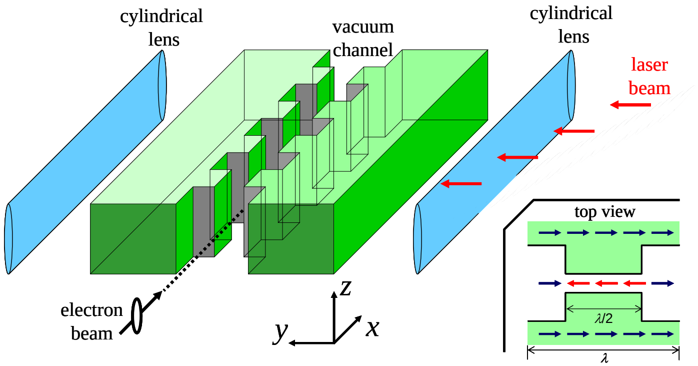
Goal: Invent and Test Dielectric Accelerator Microstructures
KEY: Impedance match field to electrons using Photonic Xtal structures

Planar waveguide structures



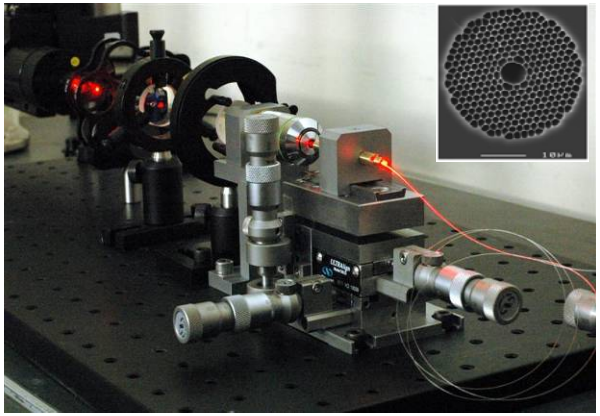
Z. Zhang et al. Phys. Rev. ST AB 8, 071302 (2005)

Periodic phase modulation structures



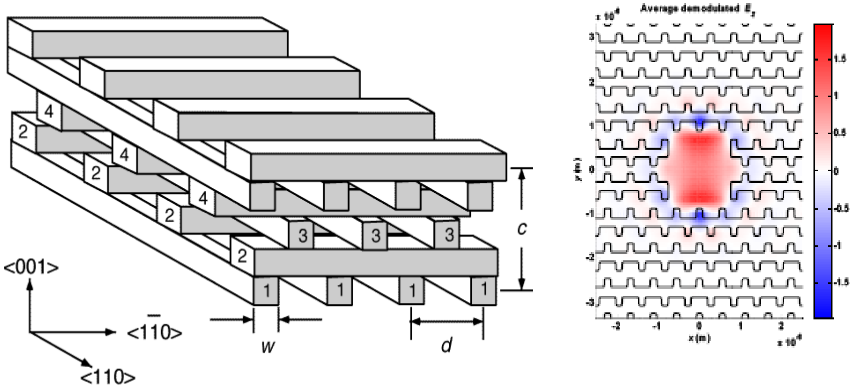
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Hollow core PBG fibers



X.E. Lin, Phys. Rev. ST Accel. Beams 4, 051301 (2001)

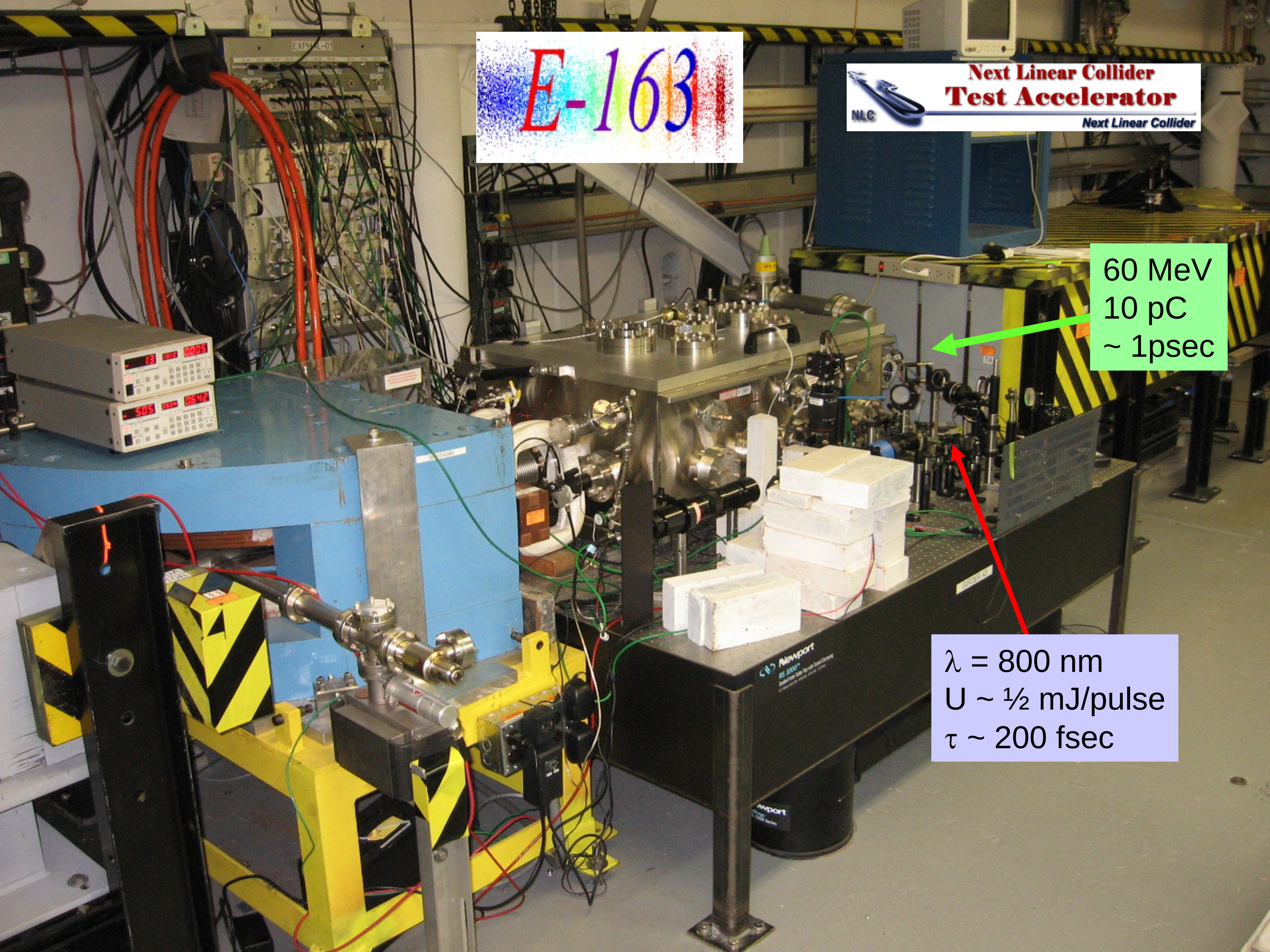
3-D photonic bandgap structures



B. M. Cowan, Phys. Rev. ST Accel. Beams , 6, 101301 (2003).

E-163

Next Linear Collider
Test Accelerator
NLC
Next Linear Collider



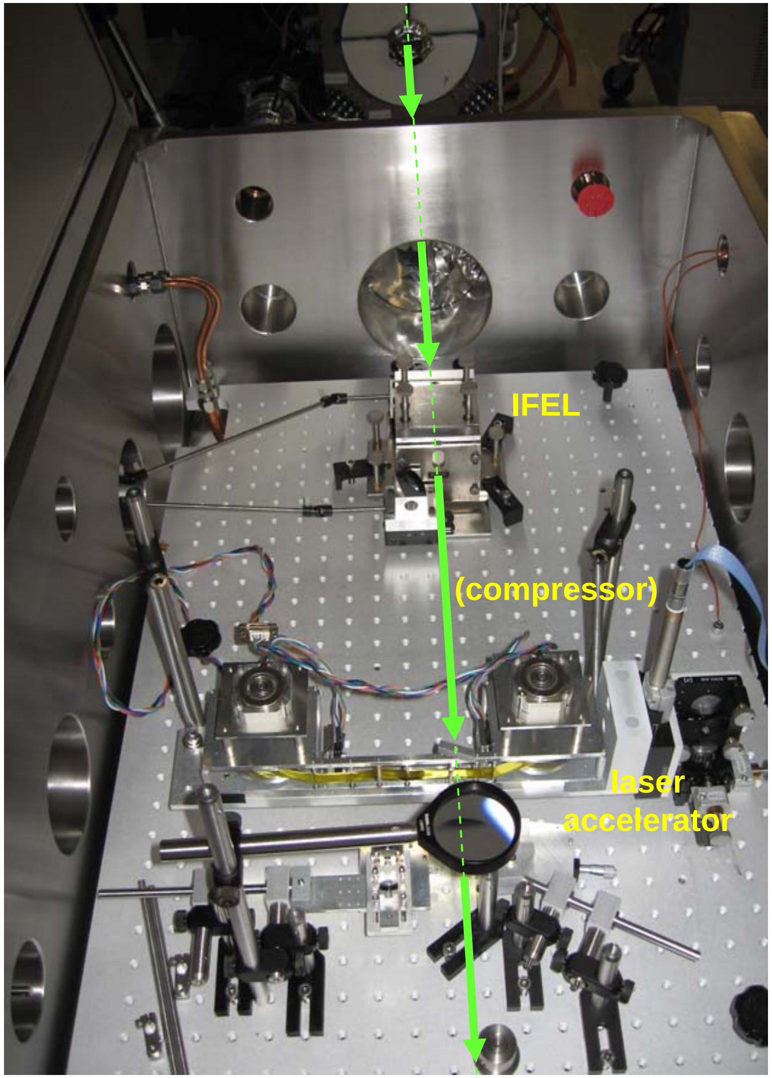
60 MeV
10 pC
~ 1psec

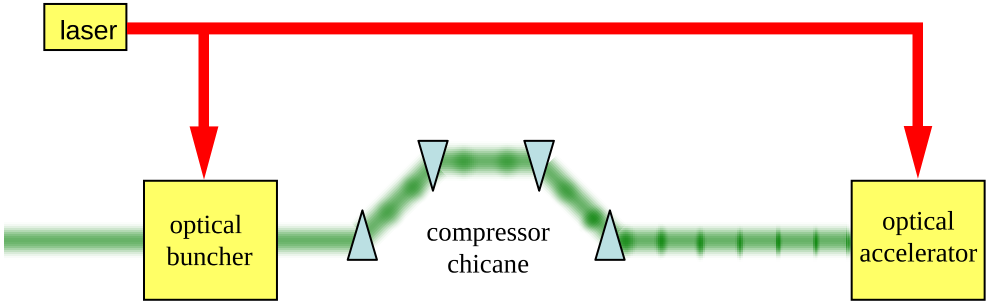
λ = 800 nm
U ~ ½ mJ/pulse
τ ~ 200 fsec

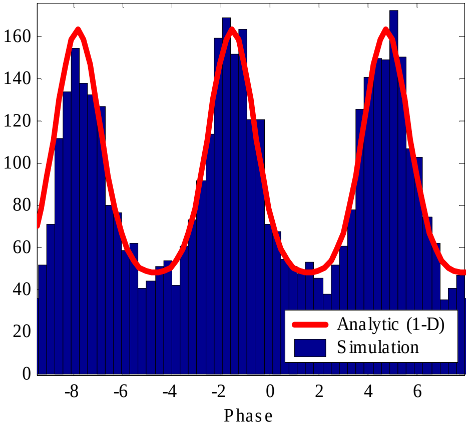
<500 attosecond electron compression in Inverse FEL

(Chris. M. Sears, PhD thesis SLAC June 2008**)**

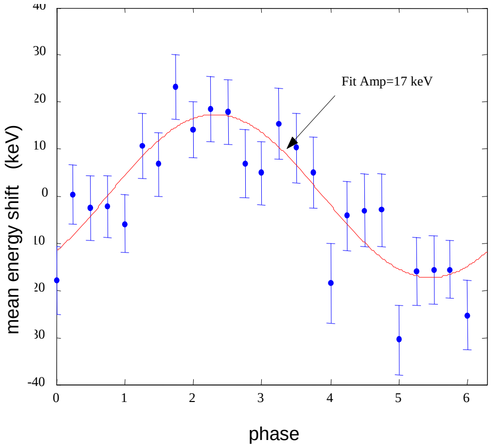
We have achieved net acceleration of electrons with attosecond phase control







Expected bunching



Expected energy gain

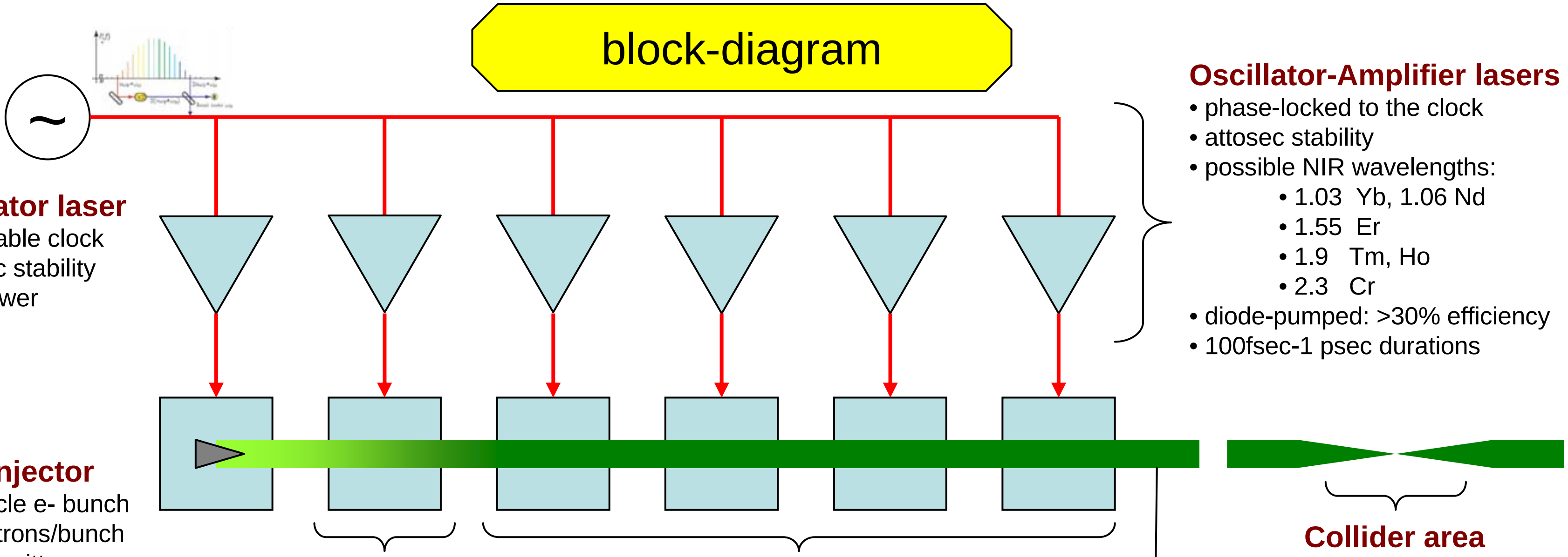
Experiment features

- IFEL modulates energy spread
- electron drift creates optical bunches
- second accelerator → net acceleration

Professor Robert Siemann and Chris Sears

June 15, 2008 – Stanford Graduation Ceremonies

Envisioned 1km long laser-driven TeV scale accelerator



Oscillator laser
- ultrastable clock
- attosec stability
- low power

Oscillator-Amplifier lasers
- phase-locked to the clock
- attosec stability
- possible NIR wavelengths:
  - 1.03 Yb, 1.06 Nd
  - 1.55 Er
  - 1.9 Tm, Ho
  - 2.3 Cr
- diode-pumped: >30% efficiency
- 100fsec-1 psec durations

Optical Injector
- optical cycle e- bunch
- ~10^4 electrons/bunch
- ultra low emittance
- laser-driven field emitters

Pre-accelerator
- nonrelativistic
- preserve emittance
- compress bunch

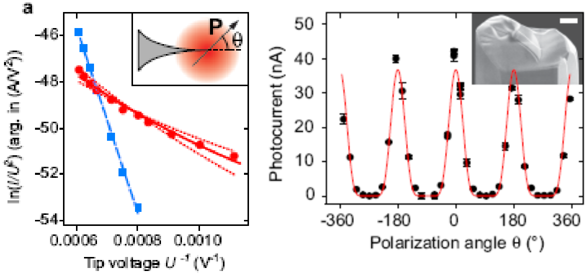
Accelerator sections
- relativistic
- preserve emittance
- periodic focusing
- alignment and stabilization

Electron beam
- 1 fC/bunch
- sub μm spot size
- ~10^{10} bunches/sec

Collider area
- sub-A spots
- multi-MHz rep-rate

LIGO vibration isolation in ES3 at Stanford

fsec field emitters



P. Hommelhoff et al

Initial focus of our research
- success of proof-of-principle exp.
- research on dielectric structures

Order-of-magnitude power estimate
- 1 fC x 10^{10} x 1 TeV → 10^7 W e-beam
- 20% coupling → $2\text{x}10^7$ W optical power
- 50% wallplug laser → 10^8 W electricity

100 MW electricity

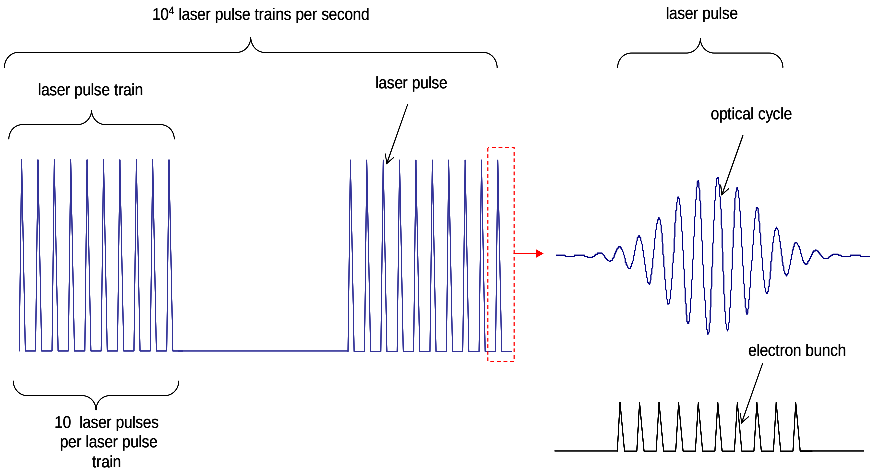
Laser beam parameters for TeV scale accelerator

1 GeV/meter – 1 kilometer accelerator – 10MW laser power

2. Low bunch charge problem

- Take advantage of high laser repetition rate
- Multiple accelerator array architecture

Laser pulse structure that leads to high electron bunch repetition rate



	SLC	NLC	SCA-FEL	TESLA	laser-accelerator
f_{RF} (GHz)	2.856	11.424	1.3	1.3	3×10^{4}
f_m (Hz)	120	120	10	4	10^{4}
N_b	1	95	10^{4}	4886	10
Δt_b (nsec)	-	2.8	84.7	176	3×10^{-6}
f_b (Hz)	1.2×10^{2}	1.1×10^{4}	1×10^{5}	1.6×10^{4}	3×10^{6}
N_e	3.5×10^{10}	8×10^{9}	3.1×10^{7}	1.4×10^{10}	10^{4}
I_e (sec^{-1})	4×10^{12}	9×10^{13}	3×10^{12}	2×10^{19}	3×10^{10}

Requires 10kW/meter or 10MW/km and ~30% efficiency Laser Source!

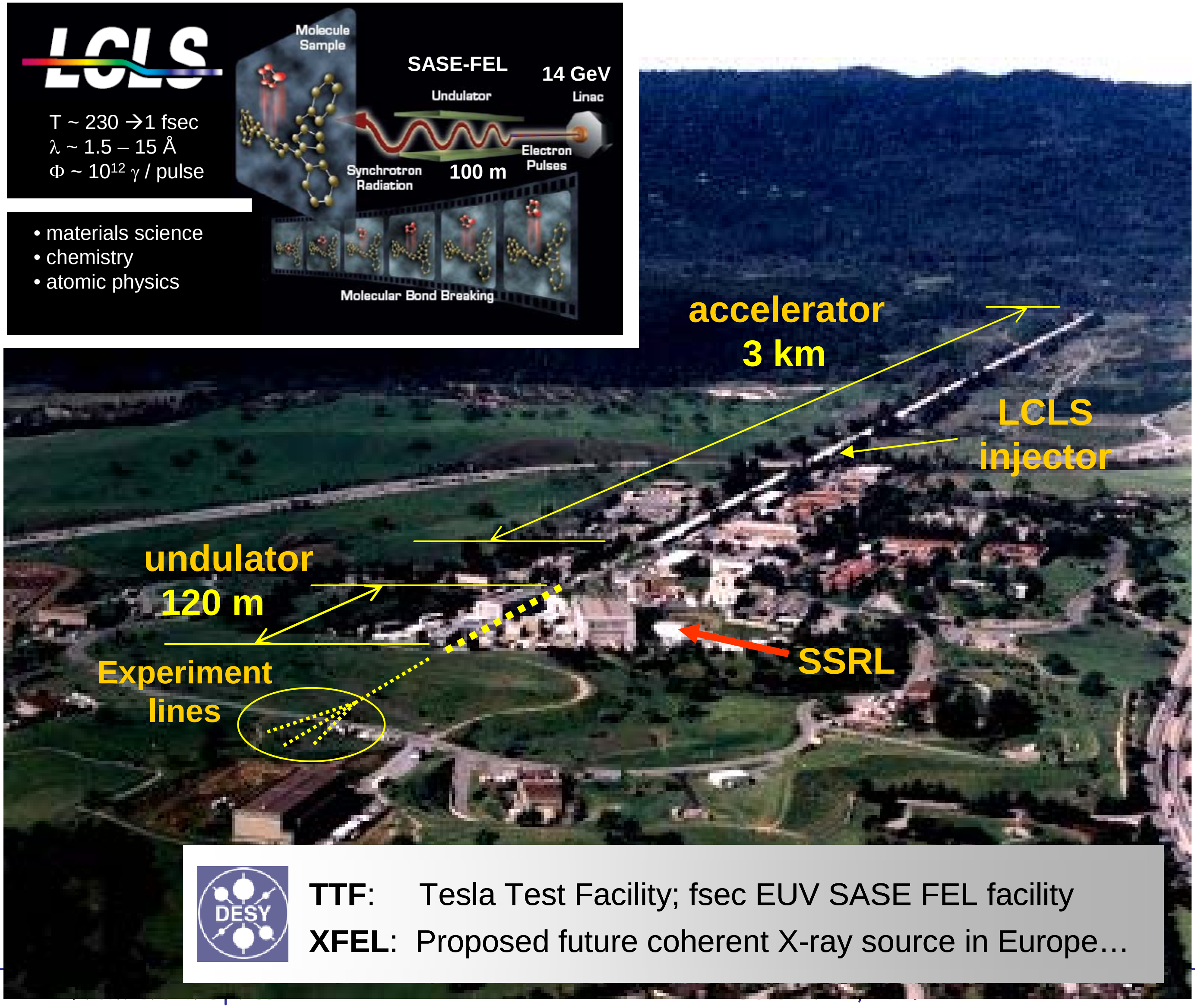
(~ 10 microjoules in 100fsec per micropulse)

Dramatic increase of

- electric field cycle frequency ~10^{14} Hz
- macro pulse repetition rate ~1GHz

April 2009 - LCLS: Coherent 8KeV X-ray source- 1mJ at 10Hz !!

RF-accelerator driven SASE FEL at SLAC - April 2009



TTF: Tesla Test Facility; fsec EUV SASE FEL facility

XFEL: Proposed future coherent X-ray source in Europe…

LCLS properties

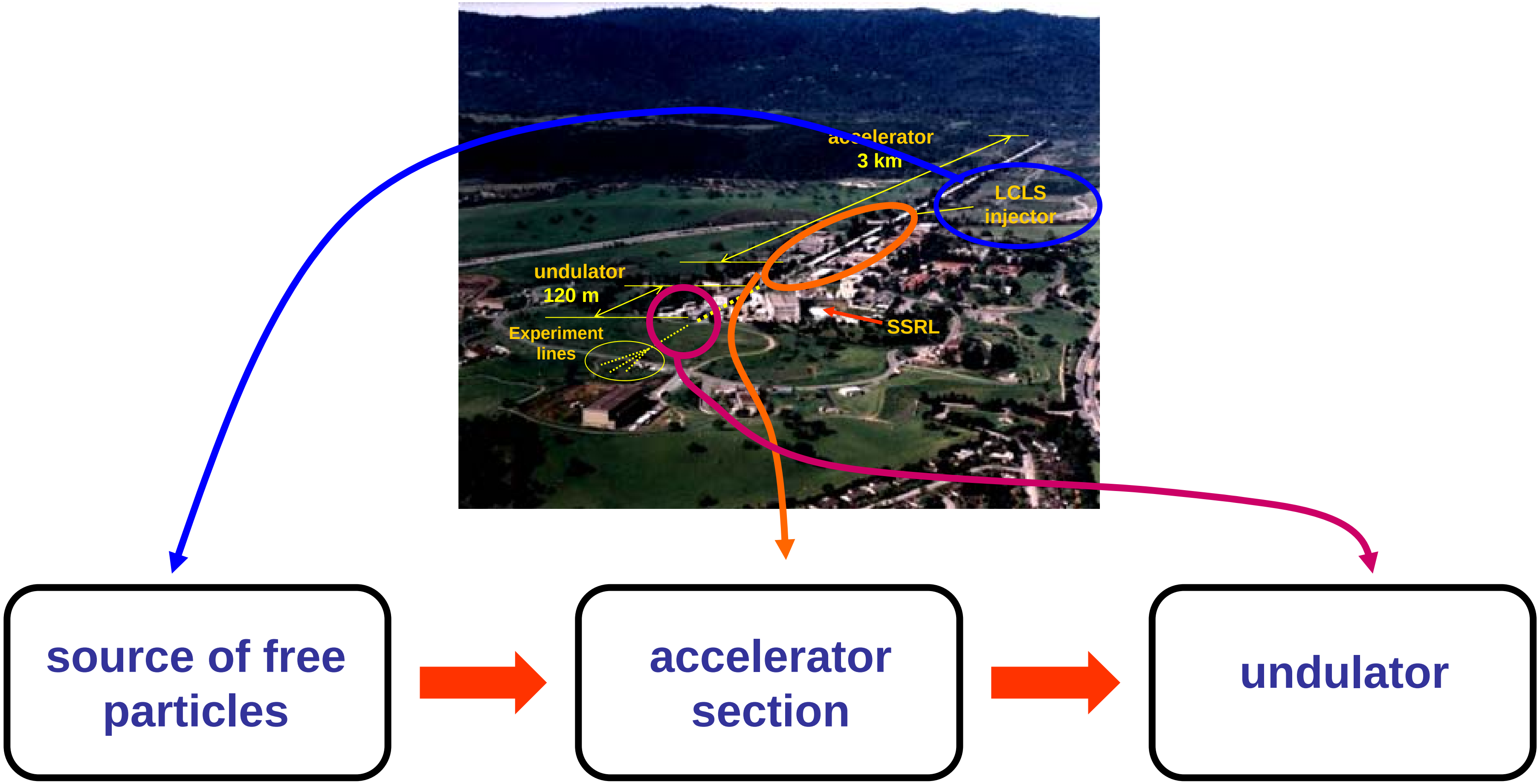
- 1 km-size facility
- microwave accelerator
- λ_{RF} ~ 10 cm
- 4-14 GeV e-beam

- 120 m undulator
- 23 cm period
- 15-1.5 A radiation
- 0.8-8 keV photons
- 10^{14} photons/sec
- ~77 fsec

- **SUCCESS – April 09**
- **1mJ per pulse**
- **10 Hz**
- **8 keV X-ray photons**

The Key Components of the SASE-FEL architecture

SASE – Self Amplified Spontaneous Emission



source of free particles → **accelerator section** → **undulator**

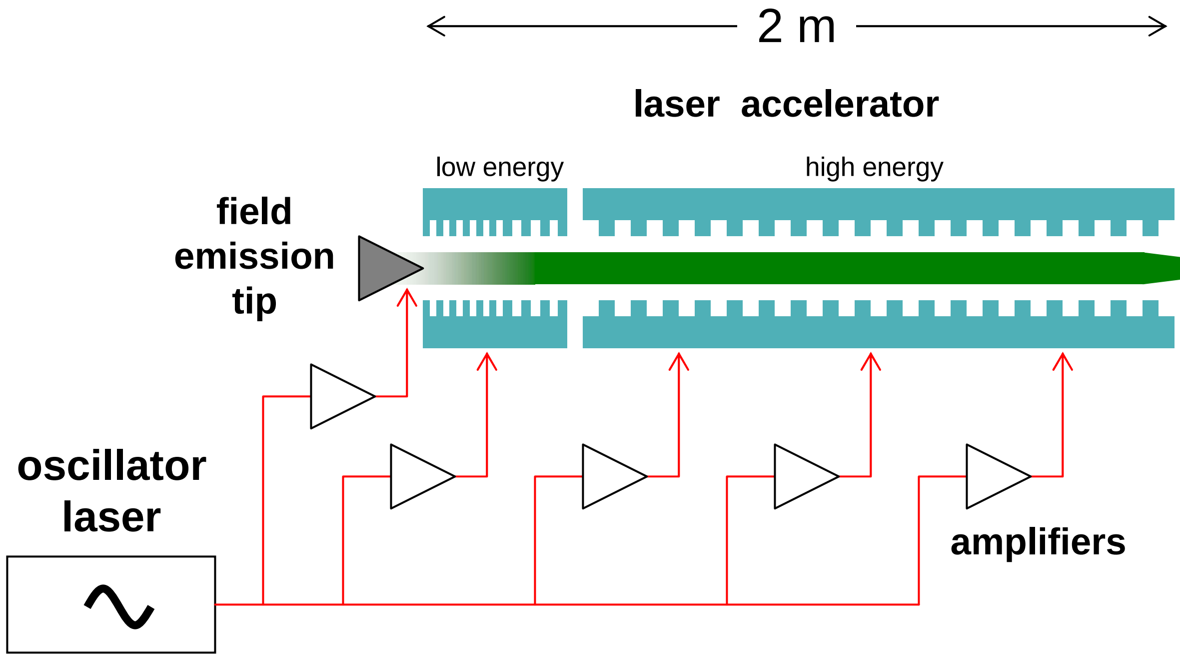
laser-driven
high rep. rate
very compact

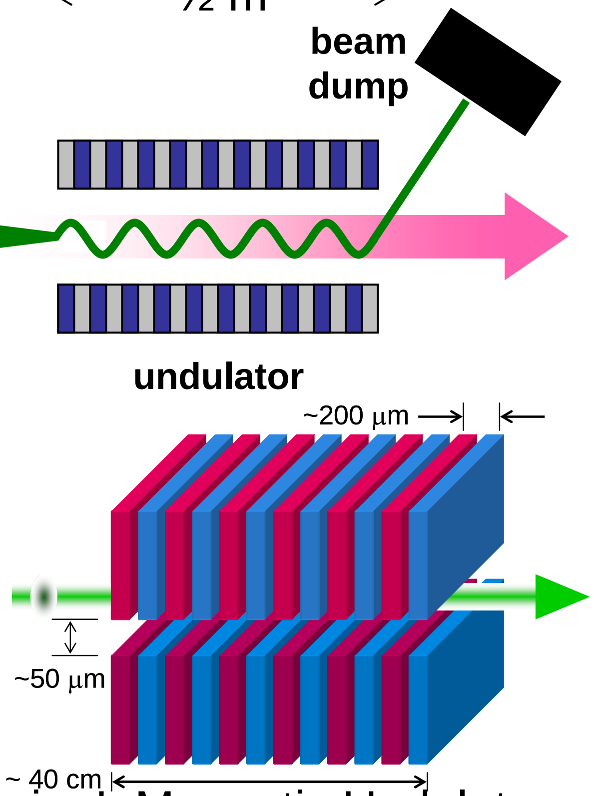
dielectric structure
based laser-driven
particle accelerators

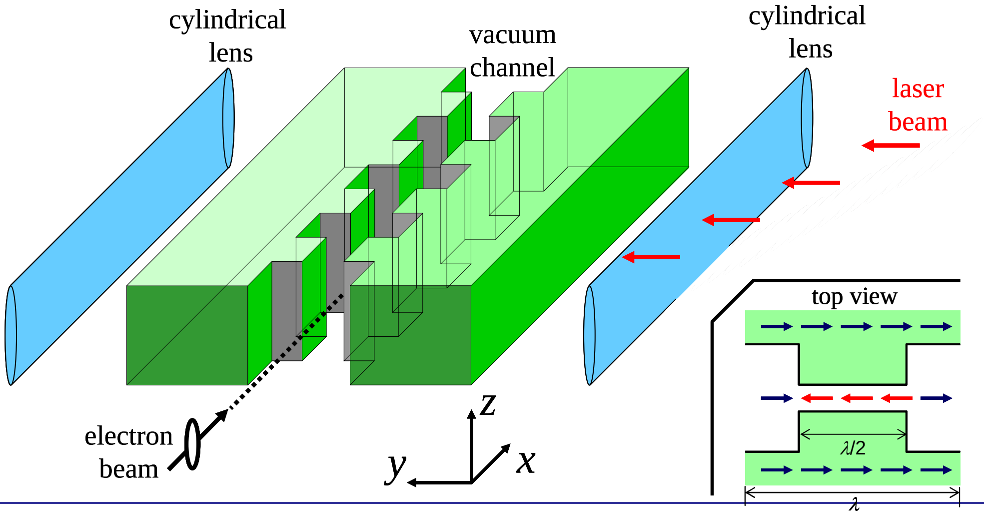
dielectric structure,
laser driven

Proposed parameters for laser driven SASE-FEL

(Theoretical Study of FEL operation – summer 2008)







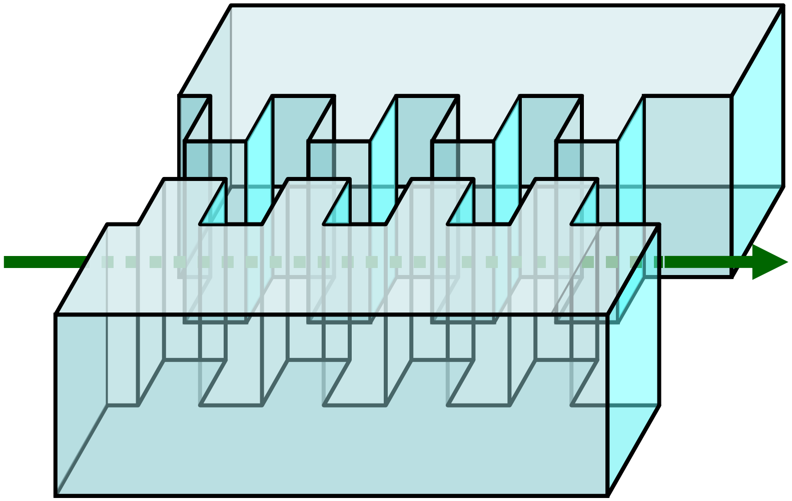
Discouraging! Magnetic Undulator not Matched to attosecond electron bunches

1 pC,
2 GeV,
λu = 200 μm,
Lu = 40 cm
rb ~ 200 nm
B ~ 1 T

End of Story? NO! Plettner went away and thought real hard -

New Idea: Laser-Driven **Dielectric Undulator** for FEL

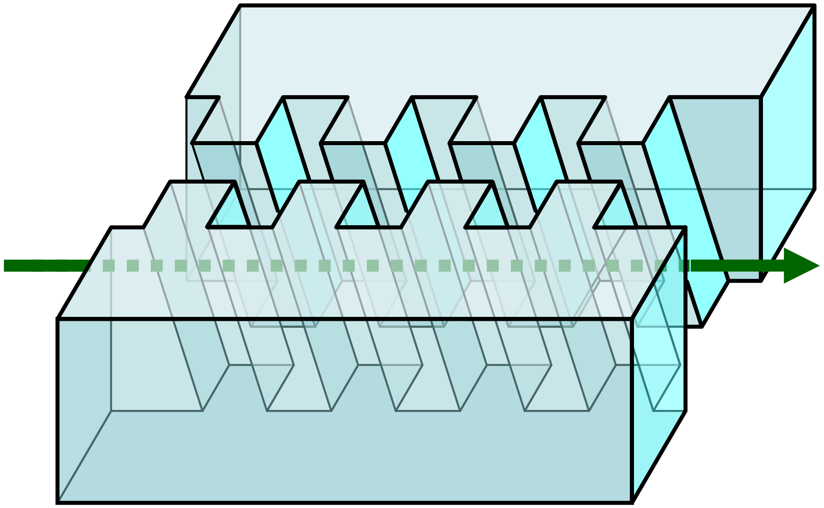
accelerator structure



$$\left\langle \vec{E}_\perp + \left(\vec{v}\times\vec{B}\right)_\perp \right\rangle = 0$$

$$\left\langle \vec{E}_\parallel \right\rangle \sim \tfrac{1}{2} E_{laser} \rightarrow \sim 4\,\mathrm{GeV/m}$$

deflection structure



$$\left\langle \vec{E}_\perp + \left(\vec{v}\times\vec{B}\right)_\perp \right\rangle \neq 0$$

$$\left\langle \vec{F}_\perp / q \right\rangle \sim \tfrac{1}{5} E_{laser} \rightarrow \sim 2\,\mathrm{GeV/m}$$

key idea

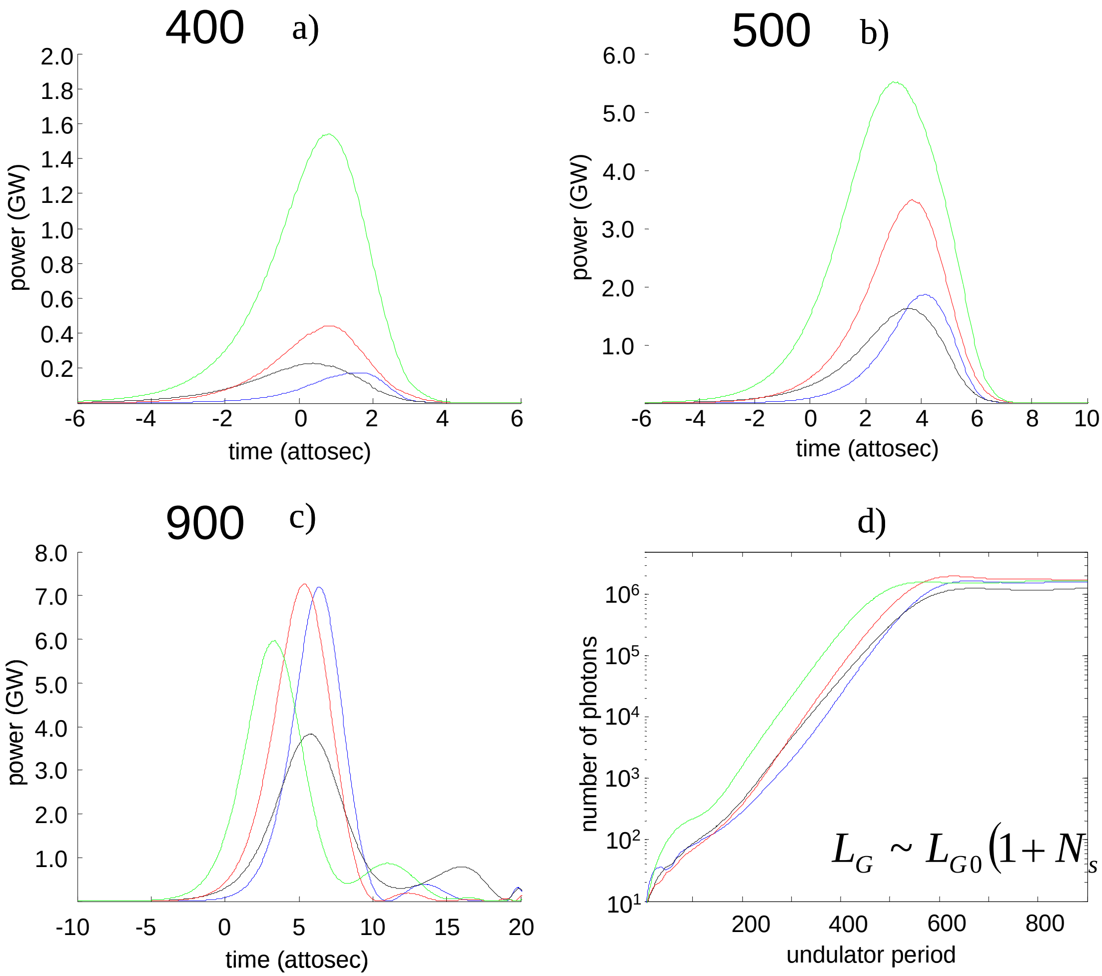
Extended phase-synchronicity between the EM field and the particle

Use modelocked laser to generate periodic deflection field

T. Plettner, *“Phase-synchronicity conditions from pulse-front tilted laser beams on one-dimensional periodic structures and proposed laser-driven deflection”*, submitted to Phys. Rev. ST AB

Calculated FEL Performance – 0.1 Angstrom X-rays (Pulse duration of X-rays – 5 attoseconds)

Byer Group



$$U_b = 2\,\text{GeV}$$

$$\varepsilon_N = 10^{-9}\ \text{m-rad}$$

$$Q_b = 20\ \ \text{fC}$$

$$\Delta\gamma/\gamma = 0.1\%$$

$$\sigma_r = 200\,\text{nm}$$

$$\beta^* = 4\ \text{cm}$$

$$L_c \sim 21\lambda_r$$

$$\sigma_b \sim 136\lambda_r$$

$$\sigma_b / L_c \sim 6$$

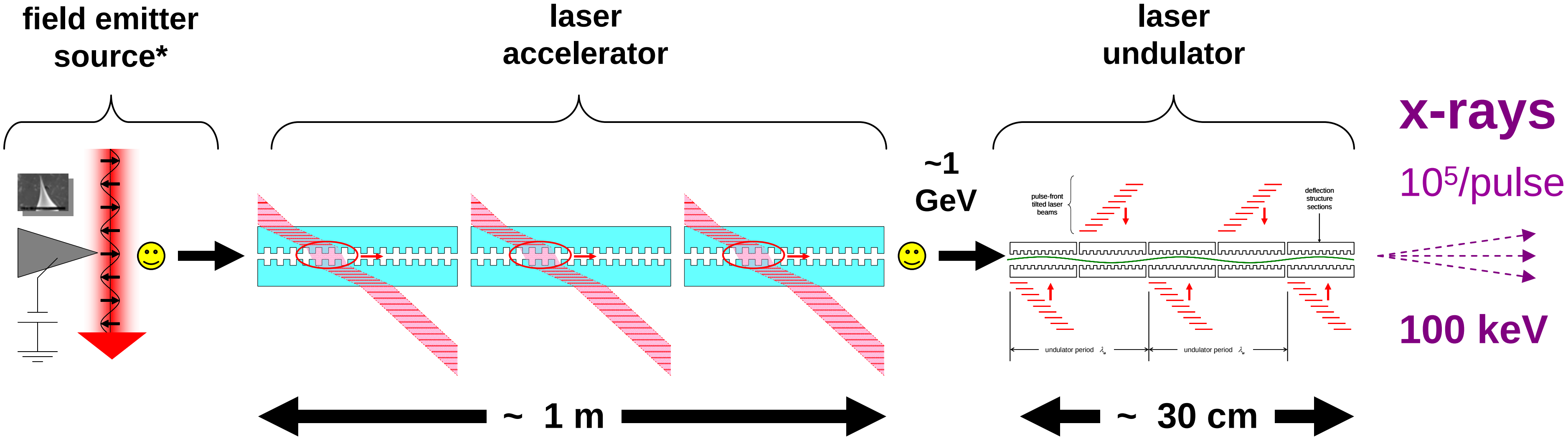
$$L_G \sim L_{G0}\left(1 + N_s \lambda_r / 3\sigma_b\right)$$

$$\rho_{eff} = U_{FEL} / U_{beam} \sim 5\times10^{-4}$$

G. Dattoli, L. Giannessi, P.L. Ottaviani, C. Ronsivalle, J. Appl. Phys. 95, 3206 (2004)

Summary: possible table-top coherent X-ray source

Schematic of the tabletop radiation source



field emitter source*

laser accelerator

~1 GeV

laser undulator

x-rays

10^5/pulse

100 keV

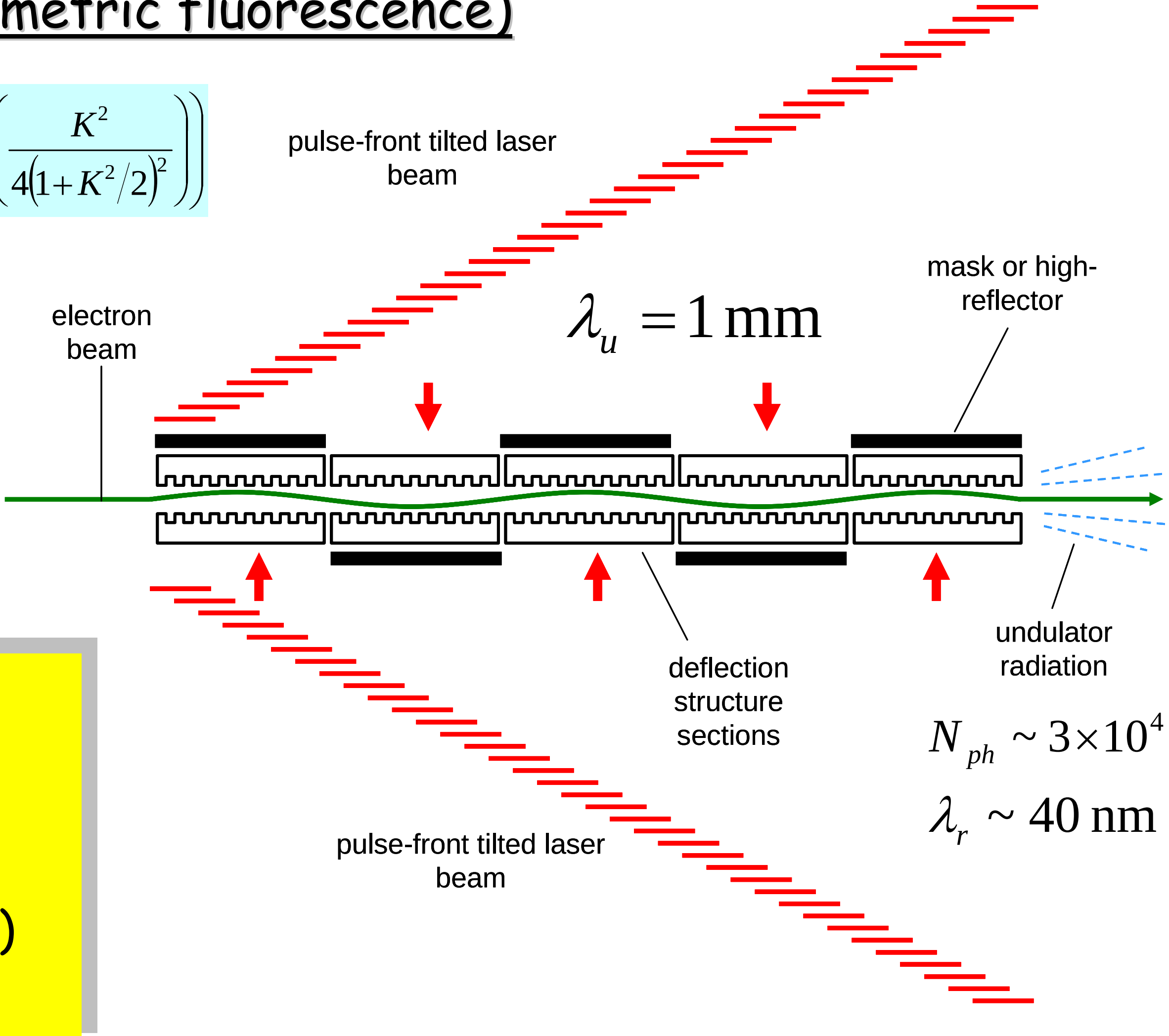
~ 1 m

~ 30 cm

There is a path forward based on a modelocked laser driven dielectric structure

Look for undulator radiation
(parametric fluorescence)

$$N_{ph} = \pi\alpha \frac{K^2}{\left(1+K^2/2\right)^2}\left(J_1\left(\frac{K^2}{4\left(1+K^2/2\right)^2}\right) - J_0\left(\frac{K^2}{4\left(1+K^2/2\right)^2}\right)\right)$$



$N_{ph} \sim 3\times10^4$

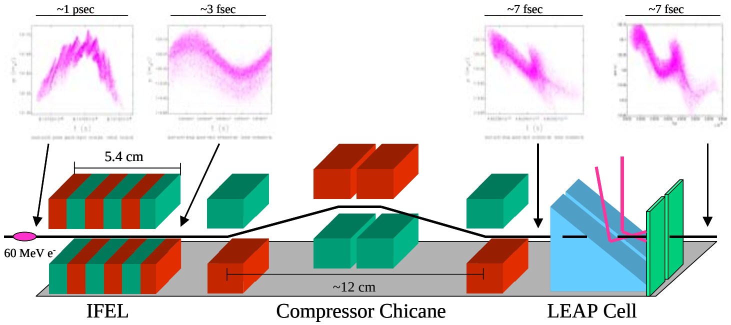
$\lambda_r \sim 40\ \mathrm{nm}$

Use periodicity of grating lattice to conserve momentum

(quasiphasematching)

Challenges ahead

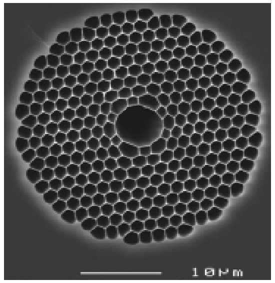
1



Staged acceleration

- precise control of optical phase
- control of focusing and steering of the electron beam

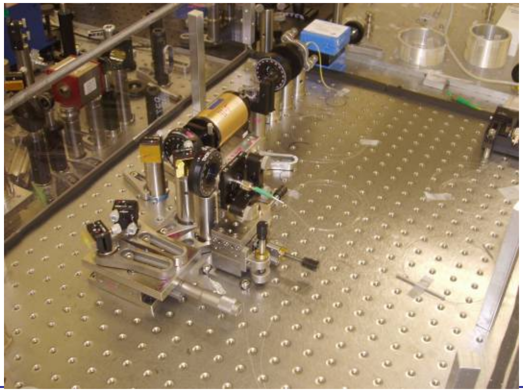
2



Implementation of real accelerator microstructures

- fabrication
- coupling of the laser
- electron beam transmission
- survival of the radiation environment
- heat removal

3



Laser technology

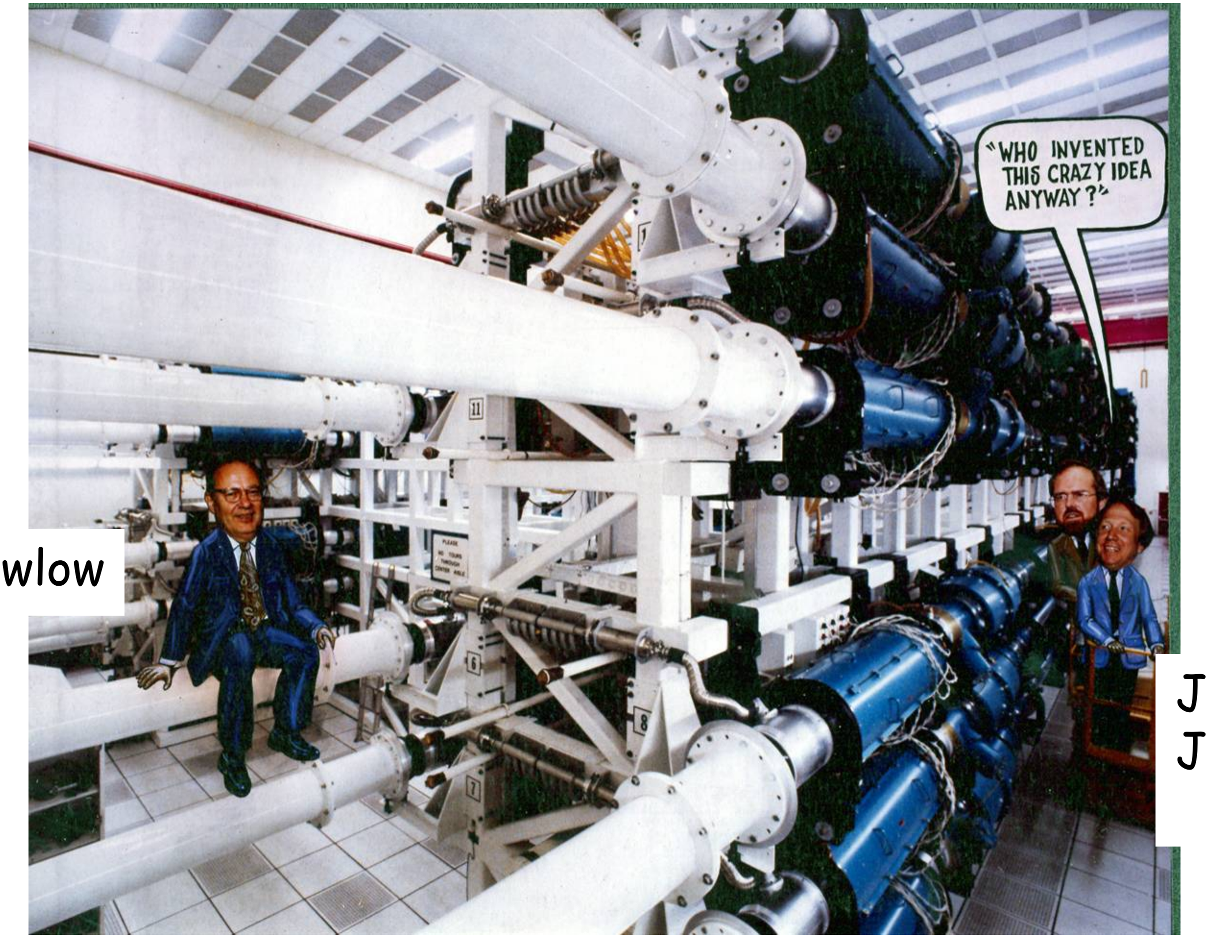
- wavelength 2 μm
- optical phase control
- wallplug efficiency
- lifetime

Contents

- Prelude
- Introduction *Making Lightwaves*
  - Early laser history and concepts
    - Unstable Resonator
    - Slab Laser – one dimensional cooling
  - Recent Innovations
    - Large Mode Area Fiber Lasers
    - Edge Pumped Slab Laser
    - Transparent 'Ceramic' polycrystalline gain media
- Scientific Applications of Lasers *Riding Lightwaves*
  - Laser Remote Sensing
  - Global Wind Sensing
  - Observing the Universe with Gravitational Waves
    - (Special Session this afternoon and tomorrow morning)
- The Future – continued innovation *Surfing Lightwaves*
  - Exploring TeV scale physics with laser accelerators
    - Coherent X-rays at the Attosecond time scale
  - **LIFE - Laser Induced Fusion for Energy**
    - **Fusion/Fission Reactors**

Who Invented This Crazy Idea, Anyway?

Shortly after the demonstration of the Ruby laser in 1960 John Nuckolls at Livermore Labs suggested that lasers could drive matter to extreme density and temperature and achieve a **fusion burn** in the laboratory.



Art Schawlow

John Holzrichter
John Emmett

The Shiva Laser, predecessor to the NOVA and NIF Fusion Lasers

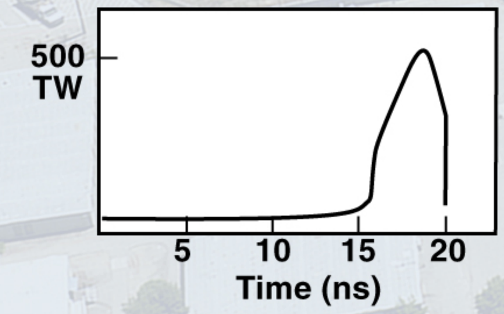
The National Ignition Facility

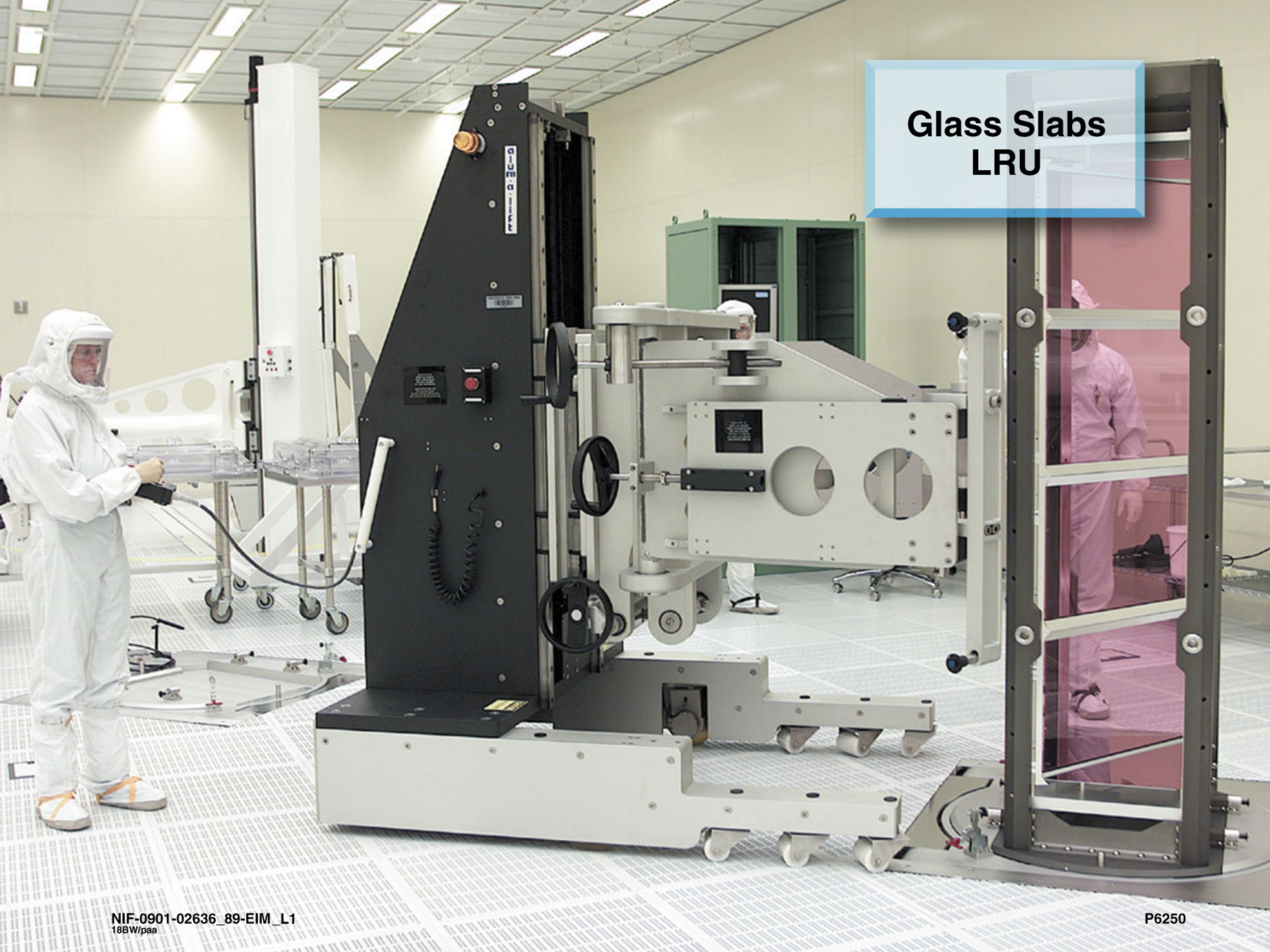
Ed Moses

Project Manager

NIF Laser System

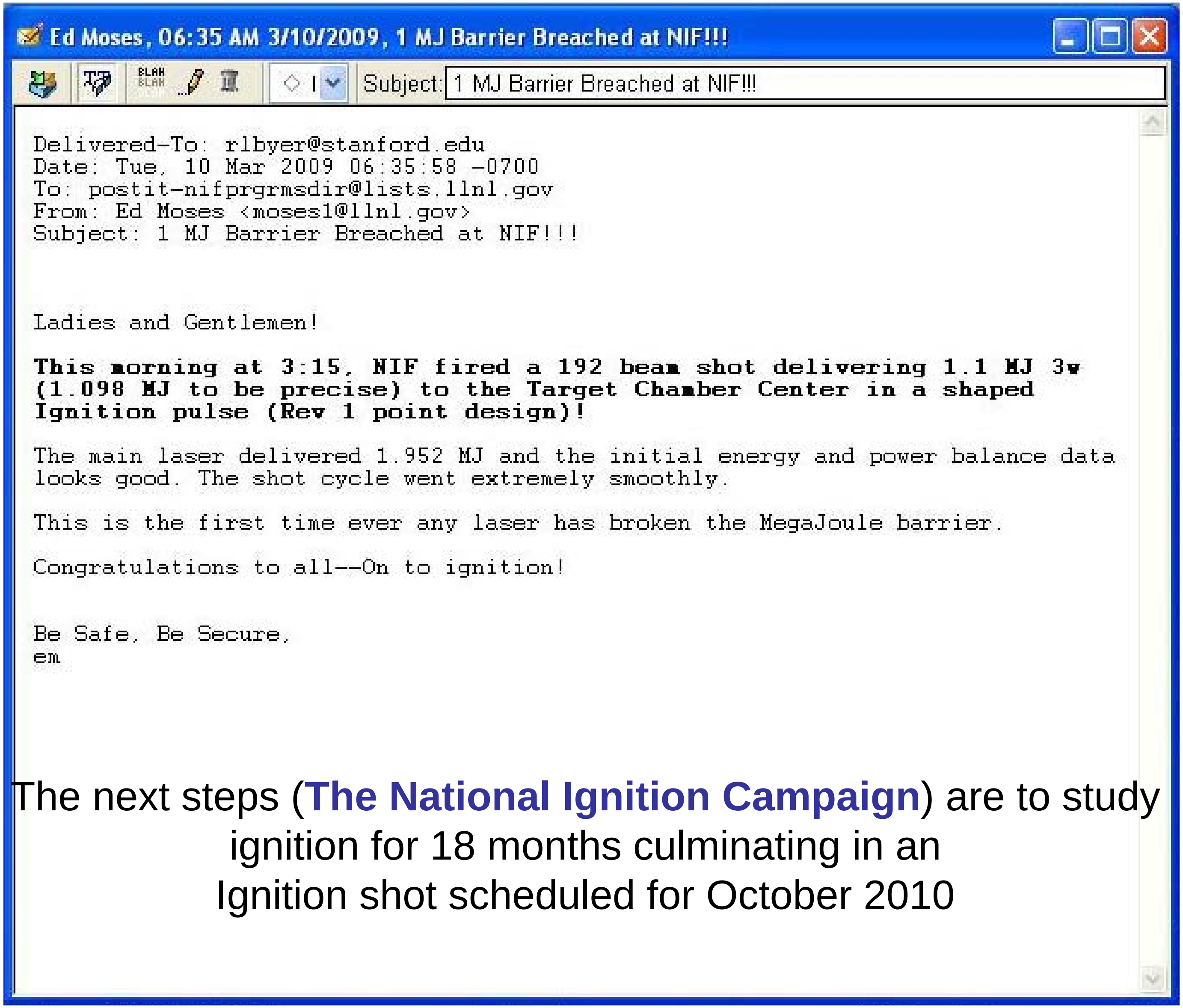
- 192 Beams
- Frequency tripled Nd glass
- Energy 1.8 MJ
- Power 500 TW
- Wavelength 351 nm





Glass Slabs
LRU

On March 15, 2009 the NIF Laser is Certified as Complete



Ed Moses, 06:35 AM 3/10/2009, 1 MJ Barrier Breached at NIF!!!

Subject: 1 MJ Barrier Breached at NIF!!!

Delivered-To: rlbyer@stanford.edu
Date: Tue, 10 Mar 2009 06:35:58 -0700
To: postit-nifprgrmsdir@lists.llnl.gov
From: Ed Moses <moses1@llnl.gov>
Subject: 1 MJ Barrier Breached at NIF!!!

Ladies and Gentlemen!

This morning at 3:15, NIF fired a 192 beam shot delivering 1.1 MJ 3w (1.098 MJ to be precise) to the Target Chamber Center in a shaped Ignition pulse (Rev 1 point design)!

The main laser delivered 1.952 MJ and the initial energy and power balance data looks good. The shot cycle went extremely smoothly.

This is the first time ever any laser has broken the MegaJoule barrier.

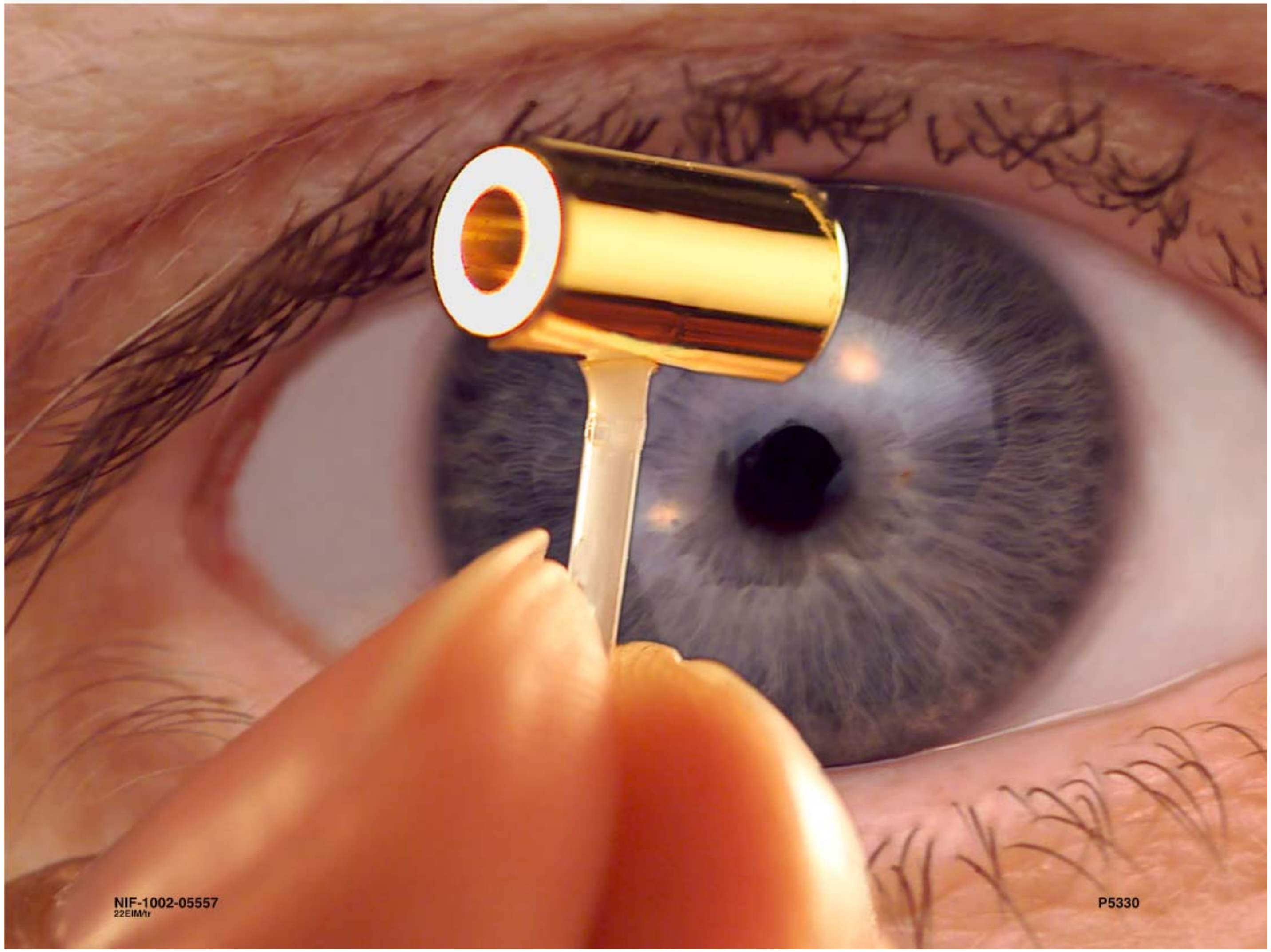
Congratulations to all--On to ignition!

Be Safe, Be Secure,
em

The next steps (**The National Ignition Campaign**) are to study ignition for 18 months culminating in an Ignition shot scheduled for October 2010

NIF Holhraum Target for generation of X-rays

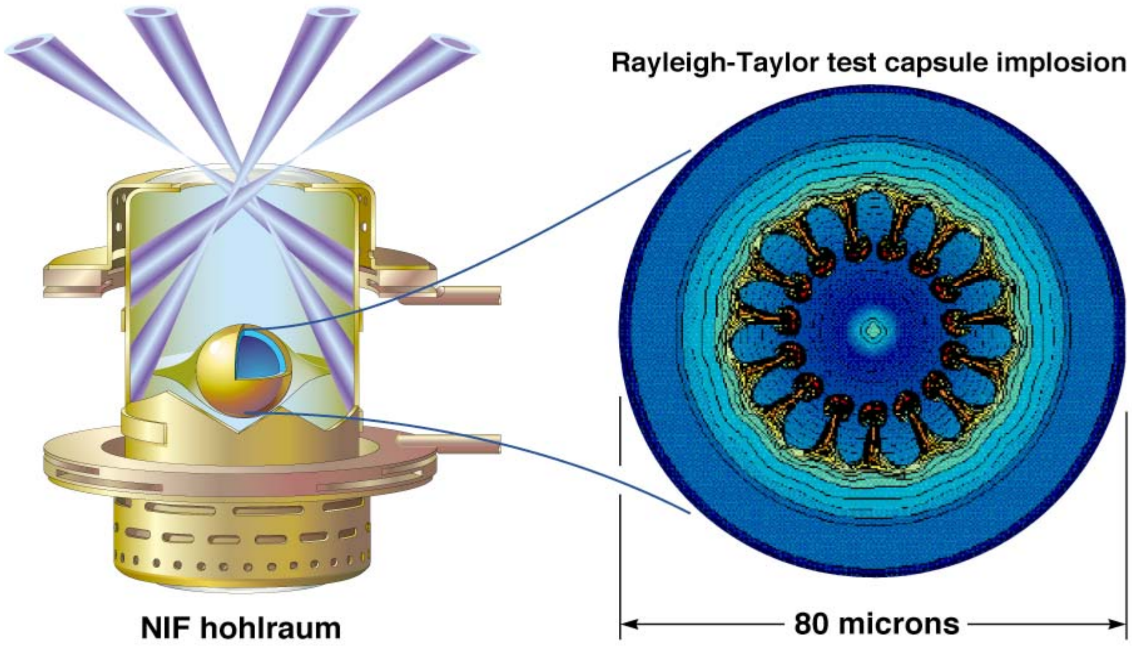
Byer
Group



NIF Hohlraum and Target - Plasma Instabilities

Rayleigh-Taylor instabilities leading to turbulence in collapsing supernovae can be simulated on NIF

The National Ignition Facility

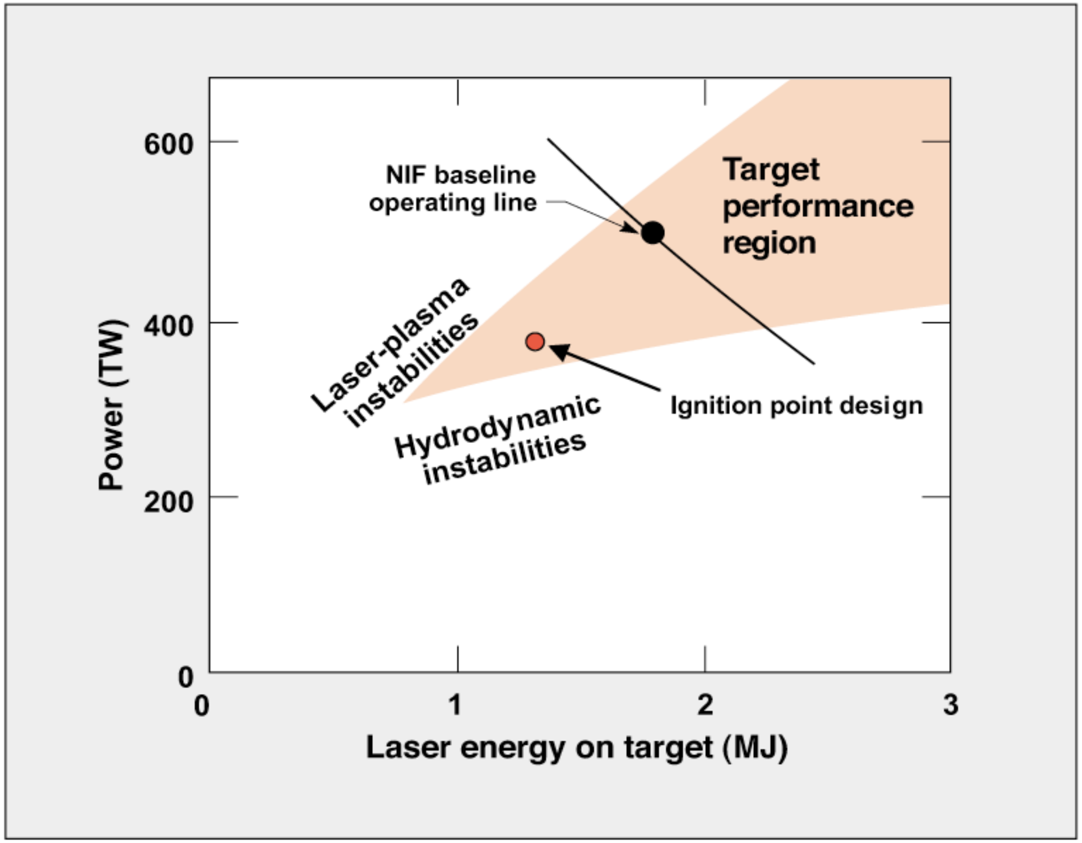


NIF-0201-00286rev1

2 MegaJoules of UV Energy exceeds Ignition Point by 2x

NIF will map out ignition and gain curves for multiple target concepts

The National Ignition Facility

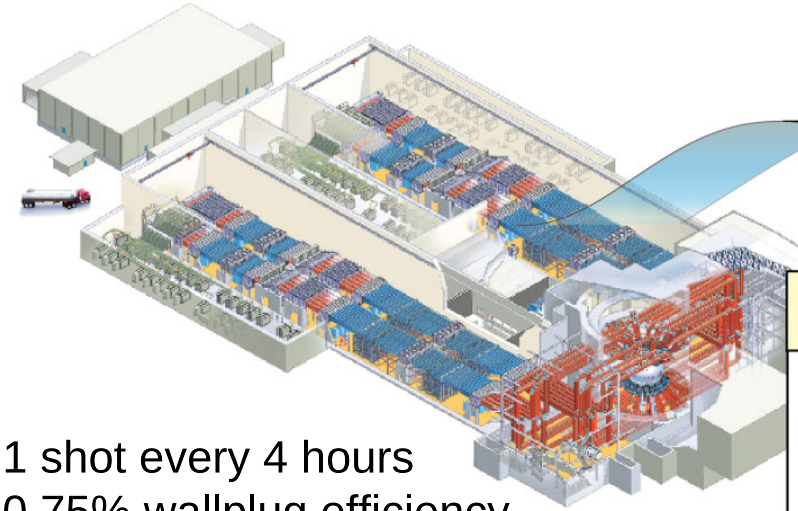


NIF-0201-01704
23GHM/cld

X4187

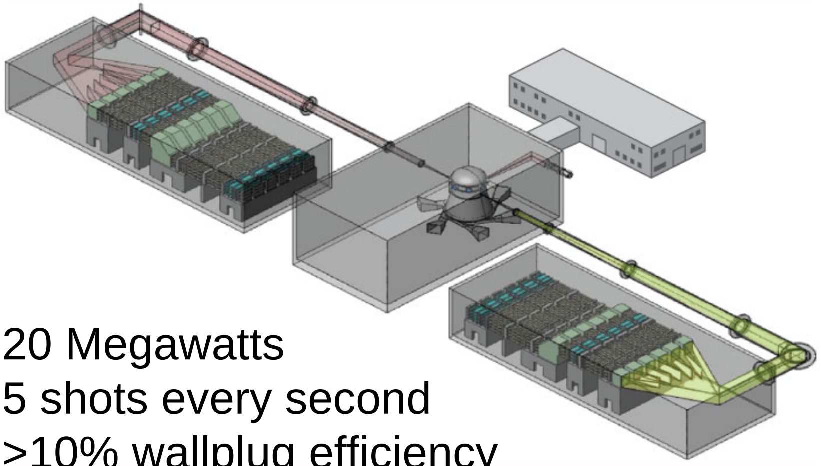
Is NIF/NIC a precursor to an IFE plant?

NIF



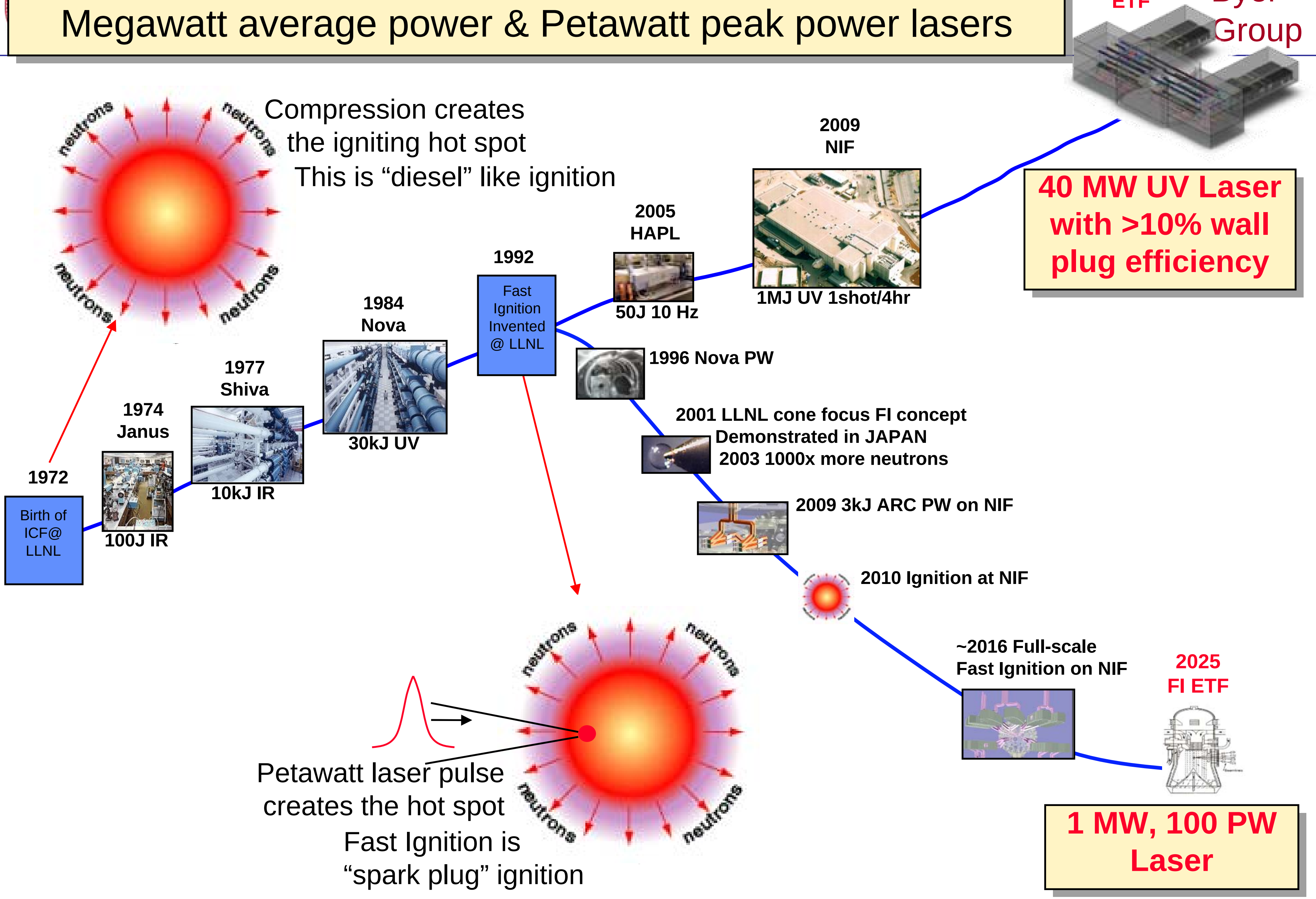
1 shot every 4 hours
0.75% wallplug efficiency

LIFE



20 Megawatts
5 shots every second
>10% wallplug efficiency

The development of Inertial Fusion Energy will require new Megawatt average power & Petawatt peak power lasers



Compression creates the igniting hot spot

This is “diesel” like ignition

1972

Birth of ICF@ LLNL

1974 Janus

100J IR

1977 Shiva

10kJ IR

1984 Nova

30kJ UV

1992

Fast Ignition Invented @ LLNL

2005 HAPL

50J 10 Hz

2009 NIF

1MJ UV 1shot/4hr

2035 ETF

40 MW UV Laser with >10% wall plug efficiency

1996 Nova PW

2001 LLNL cone focus FI concept
Demonstrated in JAPAN
2003 1000x more neutrons

2009 3kJ ARC PW on NIF

2010 Ignition at NIF

~2016 Full-scale Fast Ignition on NIF

2025 FI ETF

1 MW, 100 PW Laser

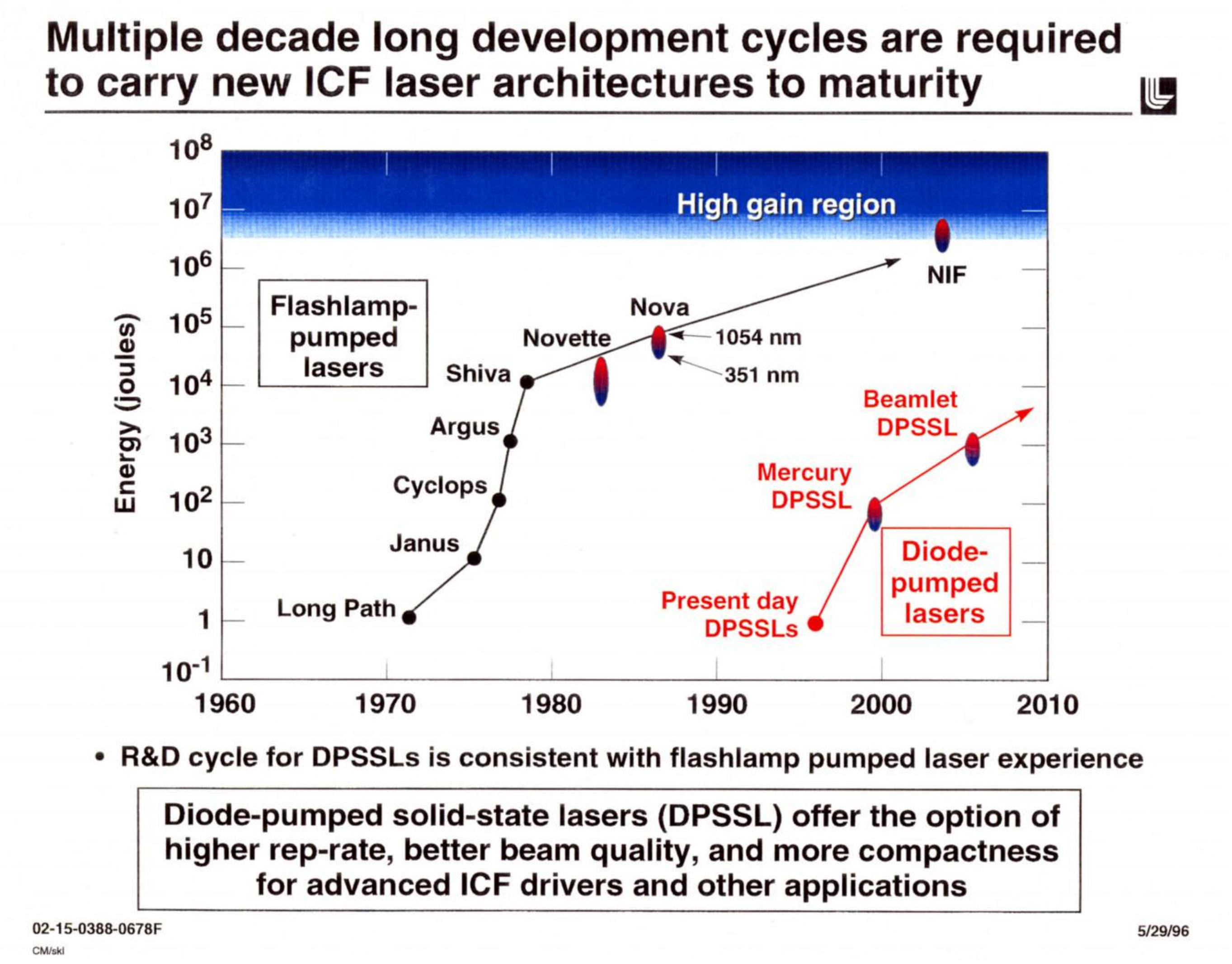
Petawatt laser pulse creates the hot spot

Fast Ignition is “spark plug” ignition

Scaling to IFE drivers for reactor design 1-2 MJ, 16 Hz, 10% efficiency - IFE forum of Japan

Kenichi Ueda – "Temperature Tuned Ceramic Lasers for IFE Drivers"

OSA invited talk FMK1 October 9, 2006



Multiple decade long development cycles are required to carry new ICF laser architectures to maturity

- R&D cycle for DPSSLs is consistent with flashlamp pumped laser experience

Diode-pumped solid-state lasers (DPSSL) offer the option of higher rep-rate, better beam quality, and more compactness for advanced ICF drivers and other applications

02-15-0388-0678F
CM/ski

5/29/96

Continuous pour of Nd:Glass allowed lower cost for NIF

(However, low **thermal conductivity** of glass limits average power)

Yb:Ceramic gain media has properties of a crystal but lower cost

Next Generation Fusion Laser Driver requires
Ceramic gain media for 10 Hz operation

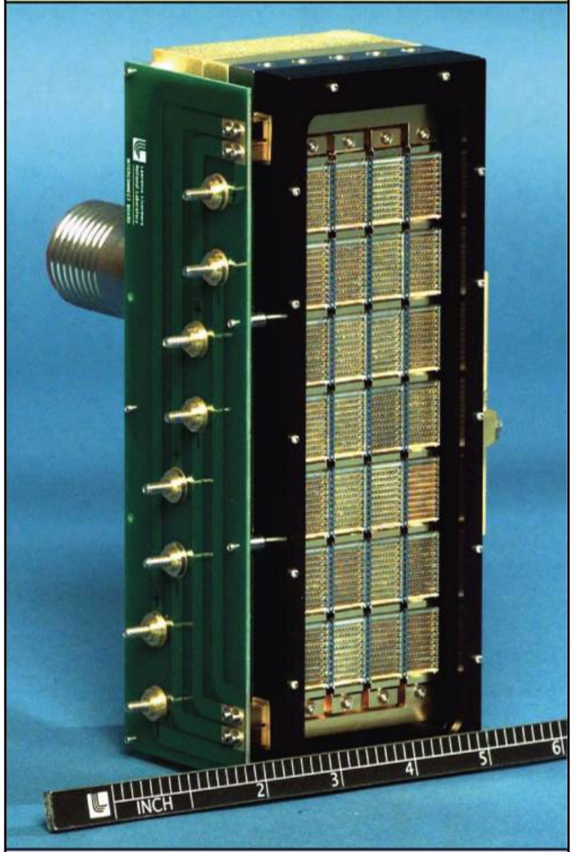
LLNL’s diode laser array technology is the key to increased laser repetition rate and efficiency

The National Ignition Facility

Flashlamps

10% electrical-optical efficiency

Diodes



60% electrical-optical efficiency

Total Eclipse of the Sun, July 22, 2009

After nearly 50 years of determined effort,

we should see a “sun” in the laboratory for ~10 psec duration in October 2010

2009 – A Special Year for Lasers

- Introduction
- Recent Innovations — *Making Lightwaves*
- Scientific Applications of Lasers — *Riding Lightwaves*
- The Future – continued innovation — *Surfing Lightwaves*

2009 – A Special year in Lasers

Jan - 105kw cw near diff limited Nd:YAG slab laser
Mar - NIF certified as completed - 4MJ IR laser
Apr – LCLS Coherent 8keV X-ray FEL Laser at SLAC

2010 – Successful fusion burn?
2015 – 5Hz 40kJ single arm of LIFE Laser
2025 – 5Hz 2MJ LIFE Laser Engineering Demo

Post Script - Hello from the **S**tanford **P**hotonics **R**esearch **C**enter (**SPRC**)

Stanford Student OSA Group Retreat

April 3 - 4, 2009, Monterey, CA

Thanks to my family for allowing me time to pursue my passion

Surfing Ocean Waves – Poipu Beach, Kauai