



Lasers at 50: *Meeting the Grand Challenges for the 21st Century*

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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.

A look back at the early days of the laser will be contrasted to the recent breakthroughs in solid state lasers and the applications to fundamental science of gravitational wave detection, remote sensing, and laser induced fusion for energy production.

Session B5: Five Legacies from the Laser
Portland, Oregon
March 15, 2010



From Maser to Laser - stimulated emission at optical frequencies proposed in 1958 - A. Schawlow and C. H. Townes

6 A. L. Schawlow

Sept. 14, 1957

A Maser at optical frequencies.

input light from one side

output light

glass box silvered on inside or outside with 2 mirrors for input and output light.

Maser conditions:

$$\left(\frac{\mu E}{h}\right)^2 \frac{h\nu}{\Delta\nu} N \geq \frac{E^2}{8\pi} \frac{V}{\tau}$$

where τ is decay rate of energy, V is cavity volume

$$N \geq \frac{h}{32\pi^3 \mu^2 \tau} \frac{\Delta\nu}{\nu^2}$$

continued

now for reflection coefficient α , $\tau = \frac{L}{(1-\alpha)c}$ where L is one dimension of cavity. Since $V \approx L^3$

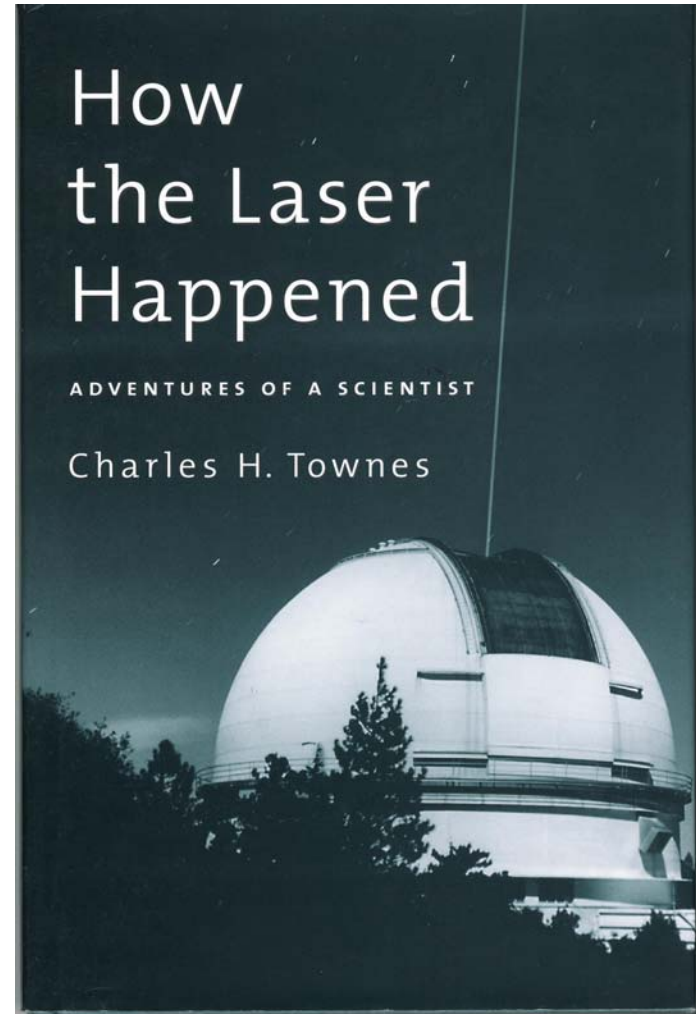
$$N \geq \frac{h L^2 (1-\alpha)c}{32\pi^3 \mu^2} \frac{\Delta\nu}{\nu^2}$$

$\Delta\nu$ is perturbed primarily by Doppler effect if ν is sufficiently large and $\Delta\nu = \nu \frac{v}{c}$

$$\therefore N \geq \frac{h L^2 (1-\alpha) \nu}{32\pi^3 \mu^2 c}$$

Note that this in precise formulation must be increased in distance at the order of one wavelength λ . In order to prevent coherent effects after this distance which would give strong absorption, a buffer gas might be used for producing collisions in a distance of the order of λ .

For $L = 1$ cm. and $\mu = 5 \times 10^{-18}$, $\nu = 5 \times 10^9$, $\alpha = 0.90$

$$N \approx 10^9 \quad (\text{answer})$$




Early advances in lasers --- 2009 a Special Year

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Concept of Optical Maser	Schawlow & Townes	1958
Ruby Laser	Ted Maiman	1960
Nobel Prize awarded in 1964 Townes, Prokhorov and Basov		
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 X-ray Laser	SLAC	April

2010 LaserFest



Charles H. Townes

Making Waves



A pioneer beams brilliant light on atoms and the
darkness of outer space.

Prelude

Introduction

Scientific Applications of Lasers

Future Directions

Making Lightwaves

Riding Lightwaves

Surfing Lightwaves

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



The Ruby Laser

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Retinal Attachment

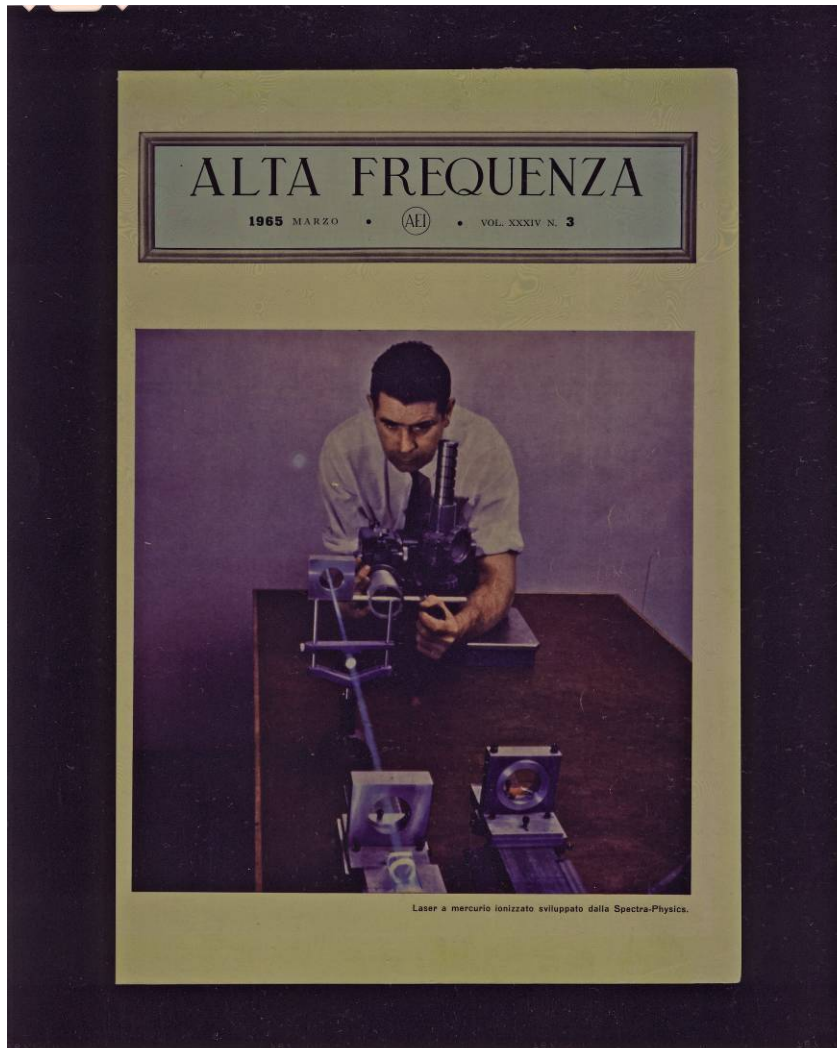
"If I had set out to invent a method of re-attaching the retina, I would not have invented the laser"

Laser Eraser

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

Art Schawlow with Mickey Mouse Balloon and Ruby Laser

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



Earl Bell 1965 Mercury Ion Laser

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

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....

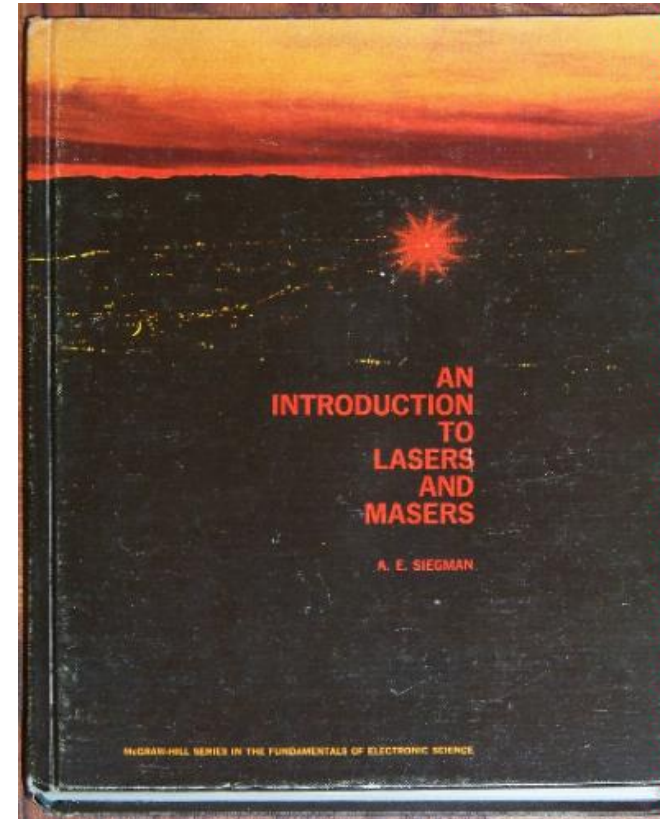


Tony Siegman held brown bag lunches to discuss research topics of interest such as Second Harmonic Generation ...

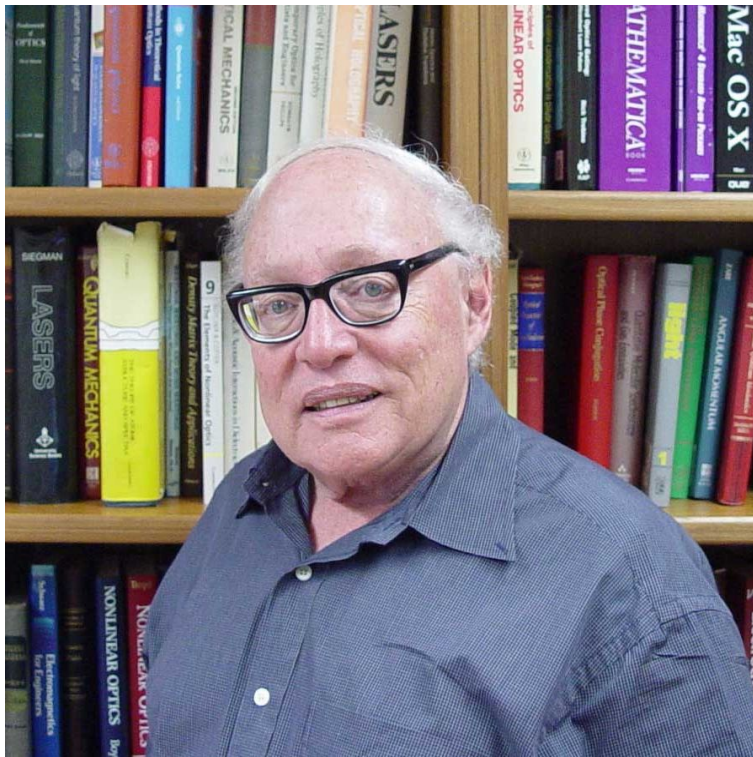
I asked Herb Dwight if I could ride my bicycle to Stanford to attend - yes if I made up the time later.



Tony Siegman and Professor Letokov at Stanford



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



Stanford research 1965 - 1969 - The Harris Lab
Larry Osterink and the FM argon ion laser
Ken Oshman - OPO pumped by yellow 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

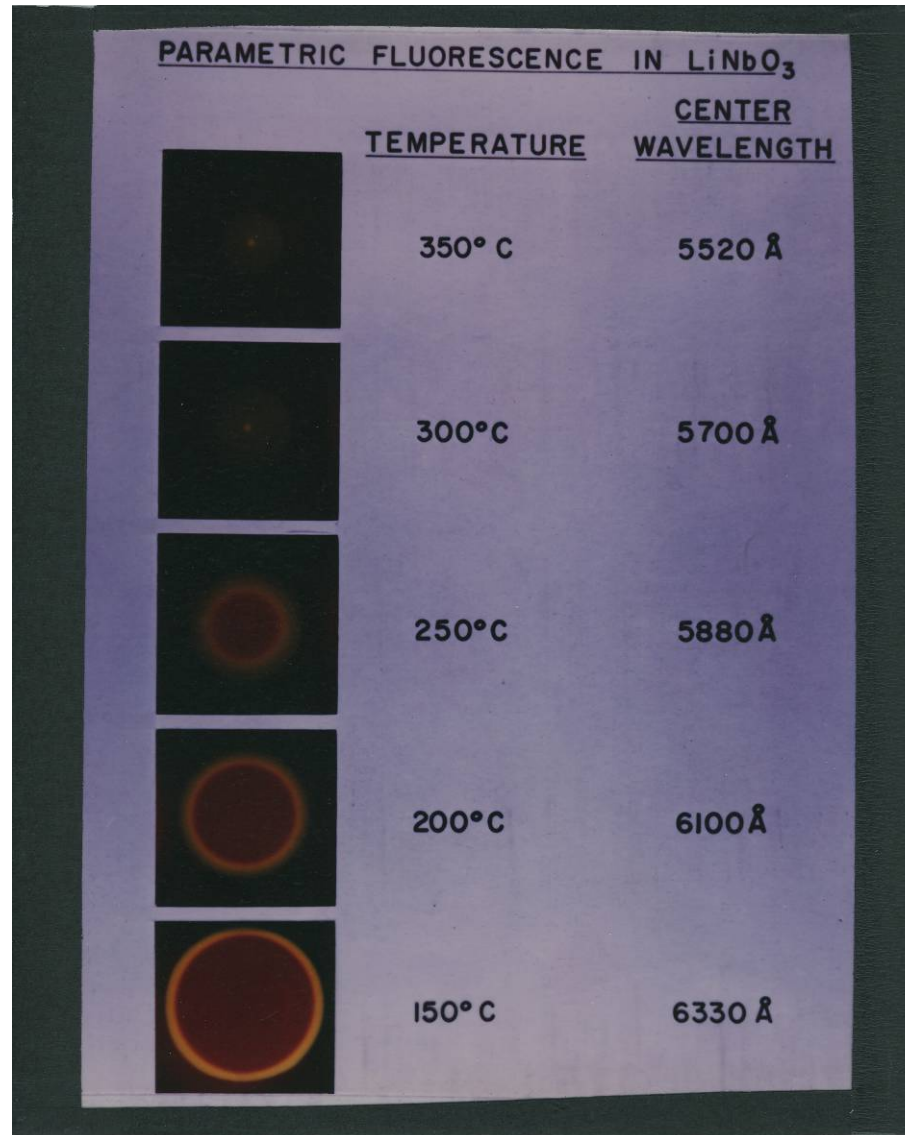
OPO technology transferred to Chromatix - 1970

Stephen E. Harris - Stanford University



Kodachrome images of Parametric Fluorescence in LiNbO_3

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Measured nonlinear coefficient

Derived parametric gain

Measured tuning curve

Confirmed quality of the Crystal

Observed Parametric Amplifier
Quantum Noise by eye!

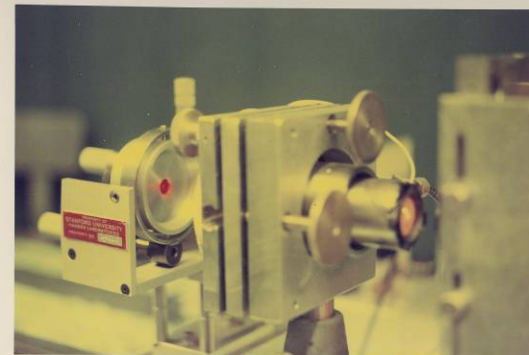
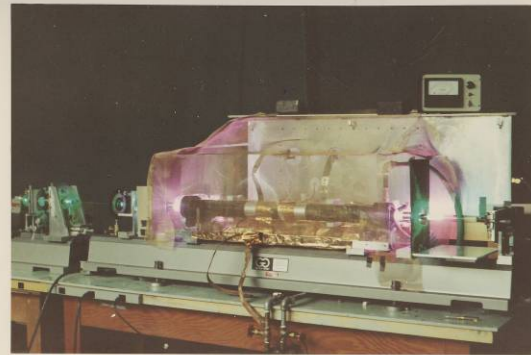


Visible Tunable Parametric Oscillator in LiNbO_3

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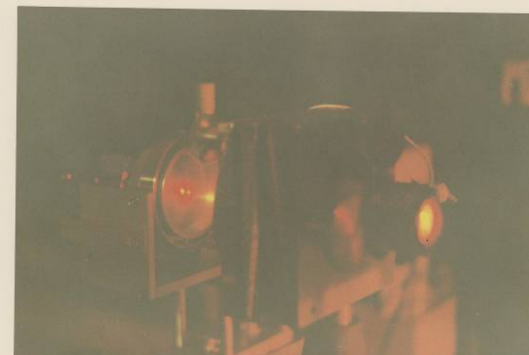
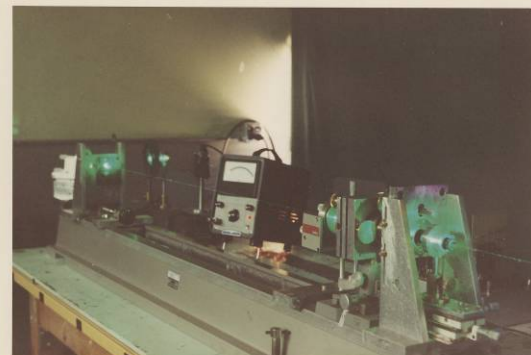
"I see red!" Ben Yoshizumi May 11, 1968

Argon Ion
Laser pump



LiNbO_3 crystal
in the oven

OPO cavity



Red tunable
Output $\sim 1\text{mW}$

Threshold 430mW. Available power at 514.5nm 470mW



"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 LiNbO₃ 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



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

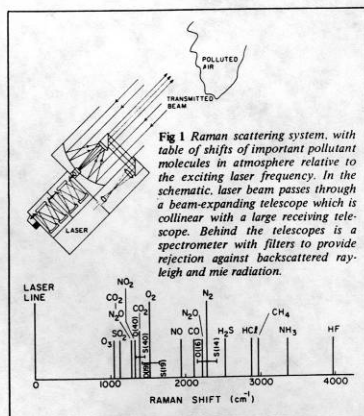
Optical approaches are attractive but flawed. Here are some detection sensitivities and tradeoffs among the techniques

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.

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.



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.

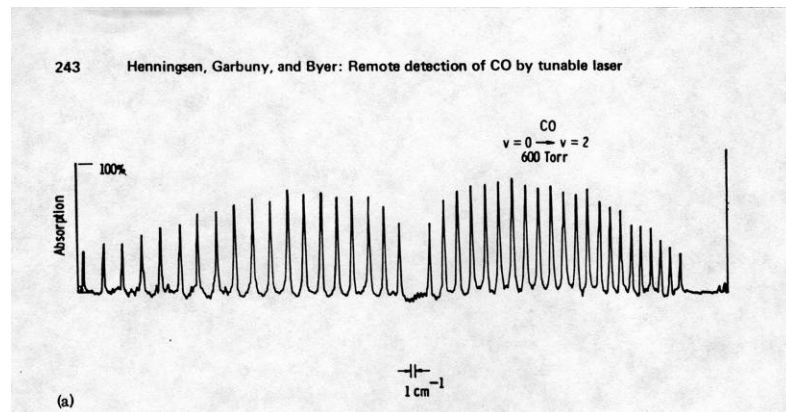
Helge Kildal and R. L. Byer "Comparison of Laser Methods for The Remote Detection of Atmospheric Pollutants"

Proc. IEEE 59,1644 1971 (invited)

Henningesen, Garbuny and Byer - 1974

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

(Chromatix Nd:YAG pumped LiNbO₃ OPO
Product introduced as product in 1969)





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 LiNbO₃ OPO -- computer controlled
Remote sensing of CH₄, SO₂ and H₂O and temperature



Sune Svanberg

Early Remote Sensing



Humio Inaba

LIDAR
Inaba, Kobayashi
Kidai and Byer
DIAL
Menzies
Walther & Rothe
Svanberg

1960 - 1975

Laser Detection and Ranging
Detection of Molecules
Comparison of Detection Methods
Differential Absorption Lidar
CO₂ laser Direct and Coherent Detection
Remote sensing of pollutants
Remote sensing pollution monitoring



Herbert Walther



1.4 to 4.3 micron Computer Tuned LiNbO₃ OPO

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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 LiNbO₃ 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.

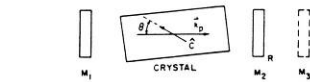


Fig. 1. Simplified OPO schematic. Mirror M_1 is highly reflecting between 1.4–2.1 μm . Output coupler M_2 has signal reflectance R . For DSRO operation, pump high reflector M_3 may be used.

I. INTRODUCTION

THE optical parametric oscillator (OPO) has been extensively studied and developed since Giordmaine and Miller first demonstrated parametric oscillation in LiNbO₃ in 1965 [1]. Following early rapid progress reviewed by Harris in

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 LiNbO₃ OPO threshold as a function of important parameters such as pump linewidth, cavity

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R. L. BYER

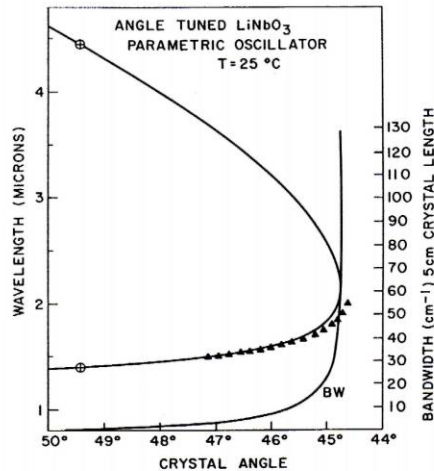


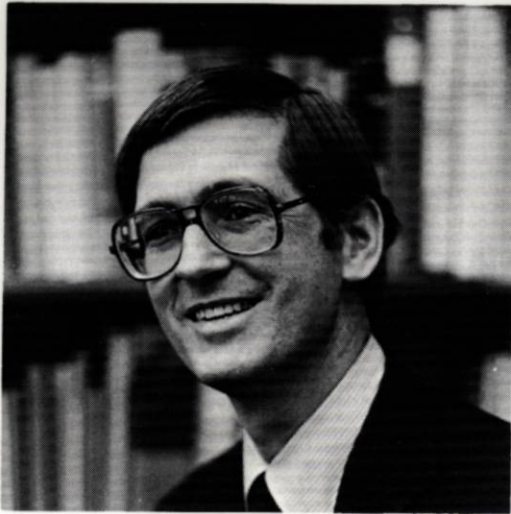
Fig. 19. Tuning curve and bandwidth for the 1.06 μm pumped angle-tuned LiNbO₃ SRO.

Fig 19. LiNbO₃ OPO Angle Tuning curve (45-50 deg) 1.4 - 4.3 microns

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

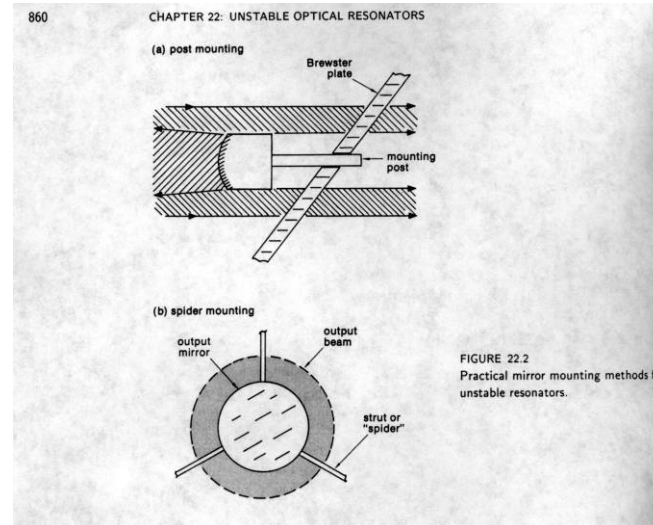




Professor Anthony Siegman received an A.B. degree from Harvard in 1952, an M.S. degree in Applied Physics from UCLA in 1954 (under the Hughes Aircraft Company Cooperative Plan), and a PhD. in Electrical Engineering from Stanford in 1957. Since then he has taught and conducted research in microwave electronics, 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



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

"A 200mJ Unstable Resonator Nd:YAG Oscillator"

Opt. Commun. 21, 5, 1977

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 CO₂ 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 $f(m) = 2.1/P(kW)$. 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].

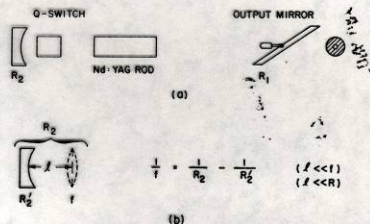
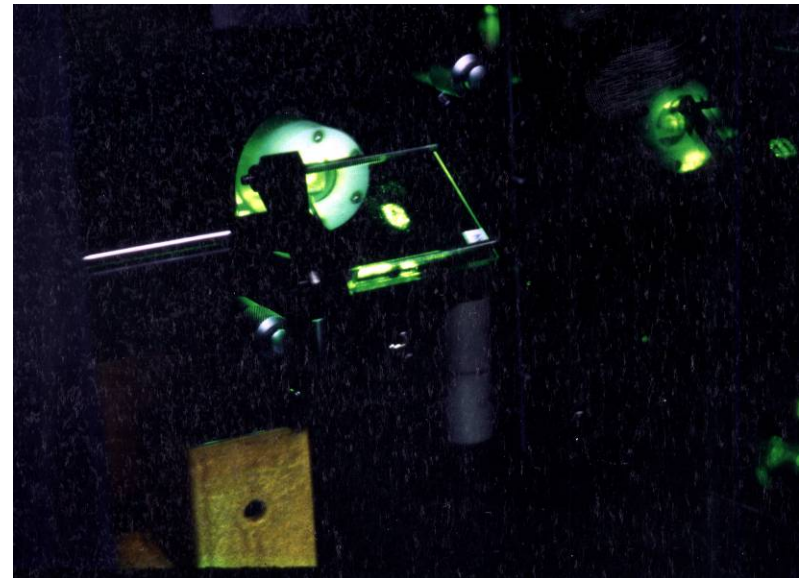


Fig. 1. (a) Schematic of the confocal unstable resonator cavity with a KD*P electro-optic Q-switch, 6.3 mm diameter 50 mm long Nd:YAG laser rod and 1.8 mm diameter output mirror. For this cavity $R_2 = 300$ cm, $R_1 = -50$ cm and $M = 3.3$ giving an output coupling $\delta = 83\%$. (b) Effective mirror radius of curvature R_2 for 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

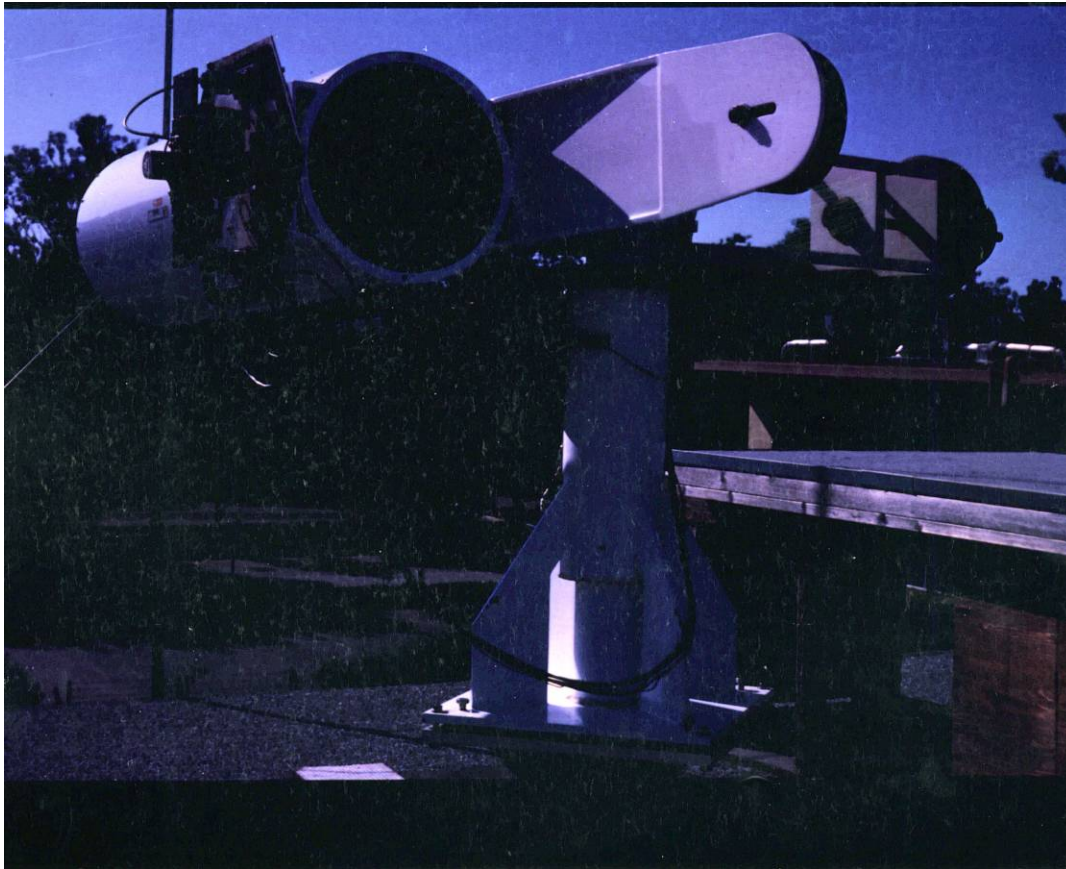


Quanta Ray 532nm output after SHG in KD*P crystal. Note "hole" in beam.



Remote Sensing Telescope at Stanford - 1980

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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

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Spectra-Physics Lasers

I N T R O D U C E S

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.

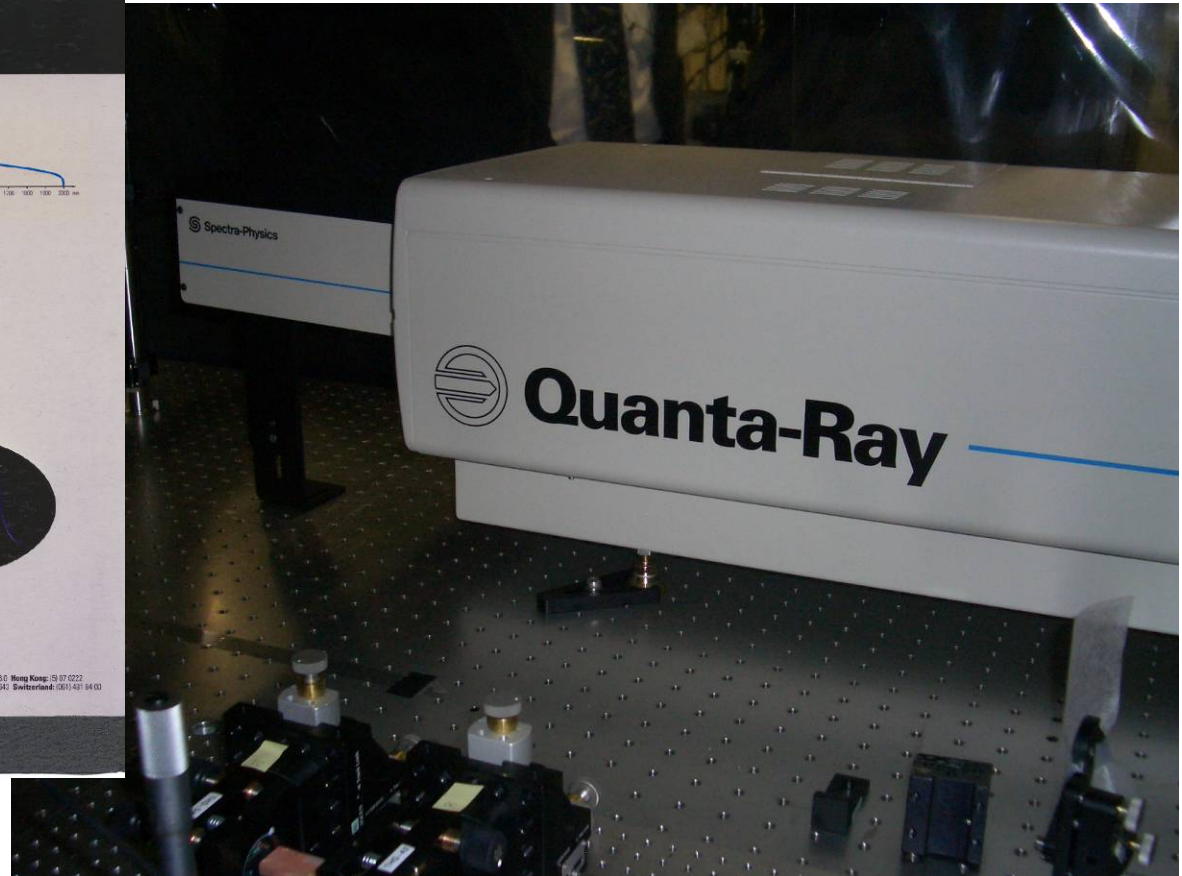
With the MOPO-700 Series, you can produce beams with spectral qualities better than dye lasers and 50 times their tunability. What's more, you get hands-free operation, upgradeability and solid-state reliability. Why buy another Nd:YAG or excimer pumped dye laser when you can buy the new MOPO-700 Series. To find out more, call us at **1-800-456-2552**.

*Availability of single longitudinal mode (SLM) and frequency locked operation anticipated by July '91

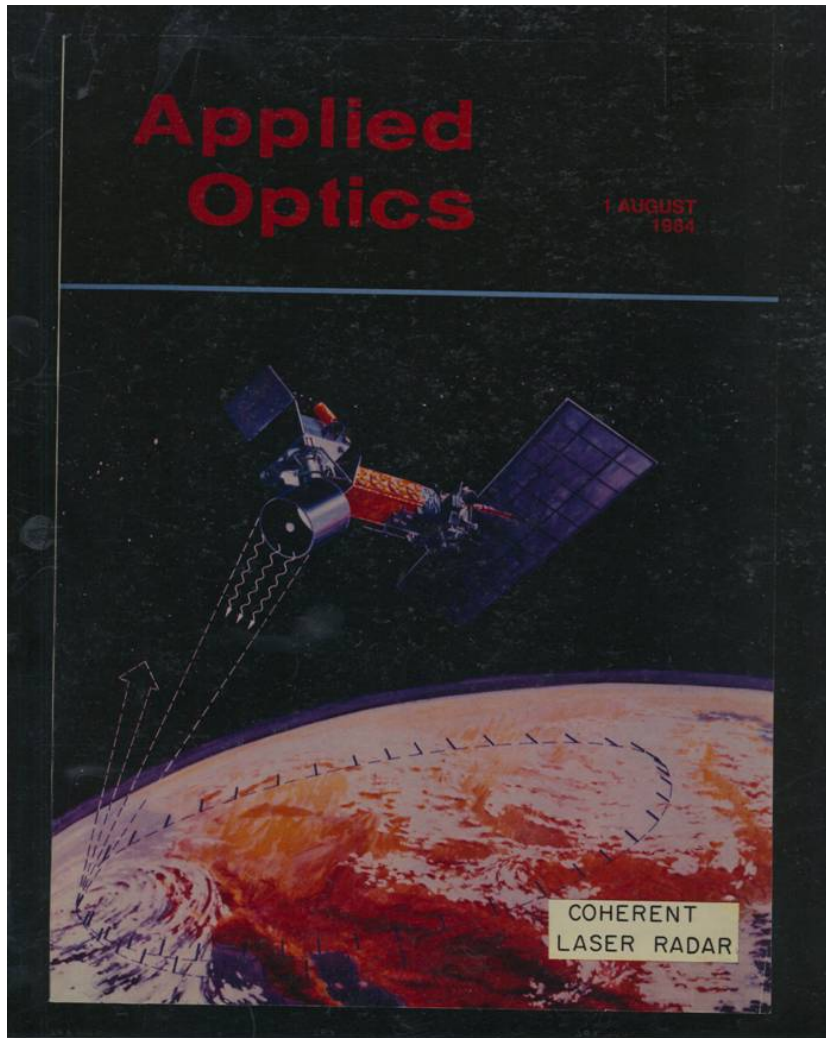
MOPO-700 Series OPO	
Technology	BBO Master Oscillator Power Oscillator
No. modes	2
Energy Output	10 to 100 mJ
Linewidths	2cm ⁻¹ , <0.5nm ² SLM*
Tunability (Direct/Doublet)*	400 to 2000 nm 200 to 400 nm

CIRCLE NO. 218

Australia: (01) 723-6687; Belgium: (03) 541-7815; China: (11) 256234; Denmark: (0) 11 9820; United Kingdom: (0442) 23232; France: (0) 1967 58 55; Germany: (0) 510 708 0; Hong Kong: (9) 07 0222; India: (01) 600542; Israel: (0) 543533; Italy: (0) 270044; Japan: (0) 3962-6231; The Netherlands: (0) 45 1815; & Korea: (0) 08-2545; Spain: (1) 300079; Sweden: (1) 430843; Switzerland: (0) 437 84 03; Taiwan: (0) 537-3385; Other European Countries: (81) 819-7092; Other Pacific Countries: 415-868-8628



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 sensing

Milton Huffaker

proposed coherent
detection of wind using
eye-safe lasers.

Applied Optics 22 1984



Led to diode pumped solid state laser studies to meet laser in space requirements

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

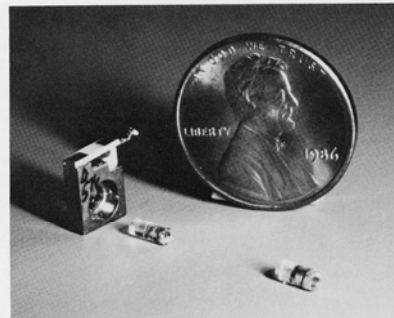
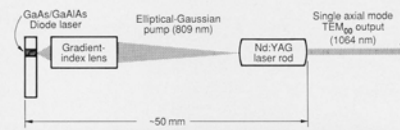


Fig. 1. (Top) Schematic of the diode laser-pumped monolithic Nd:YAG-oscillator. (Bottom) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

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

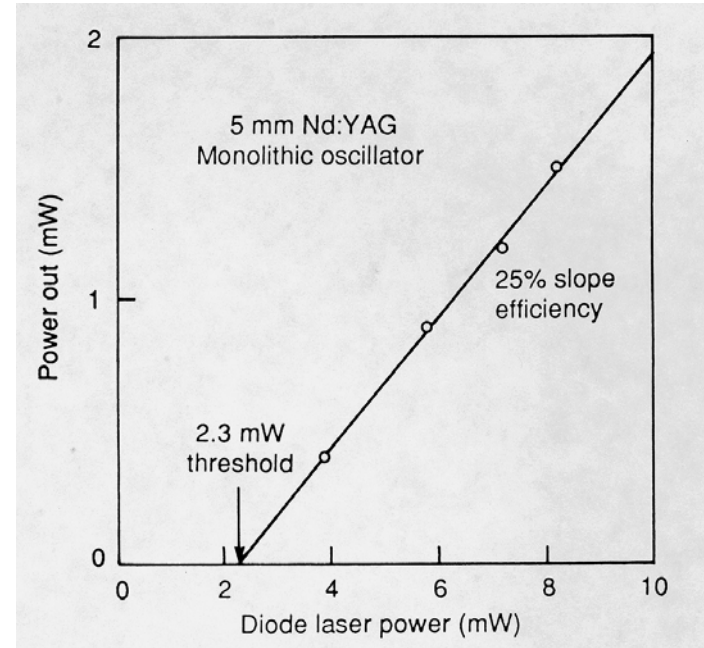
Laser Diode Pumped Nd:YAG - 1984

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



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

Byer Group

Single axial mode, narrow linewidth, Nd:YAG local oscillator

Reprinted from Optics Letters, Vol. 10, page 65, January 1985
Copyright © 1985 by the Optical Society of America and reprinted by permission of the copyright owner.

1984

$\Delta\nu < 10\text{kHz}$

Monolithic, unidirectional single-mode Nd:YAG ring laser

Thomas J. Kane and Robert L. Byer

Ginzton Laboratory, Stanford University, Stanford, California 94305

Received 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 constructed 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 oscillators³ 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. Dorsche 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 Biraben⁹ suggested that single-mode dye lasers

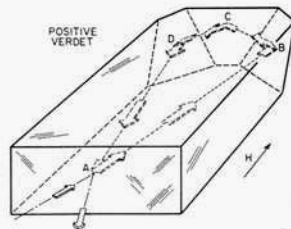
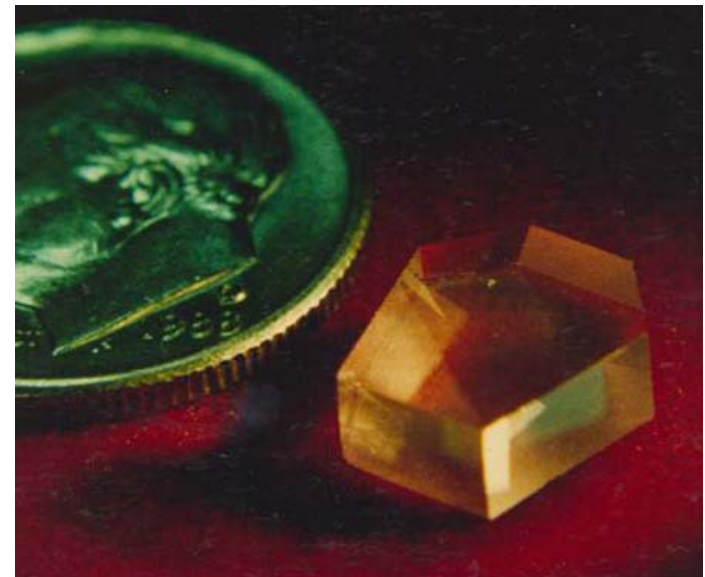


Fig. 1. The MISER laser design. Polarization selection takes place at the curved, partially transmitting face (point A). At points B, C, and D, total internal reflection occurs. A magnetic field H is applied to establish unidirectional oscillation. Magnetic rotation takes place along segments AD and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



NonPlanar Ring Oscillator Single frequency: <10kHz

0146-9592/85/020065-03\$2.00

© 1985, Optical Society of America



From Concept (Bloembergen 1962) To Demonstration in the Lab (Stanford 1988) To Green Laser Pointers and Laser TV (2005 - 2010)

Byer
Group

LASERS
COMPACT GREEN-LIGHT SOURCES

GET THE GREEN LIGHT

COULD SLASH THE COST OF LASER TV

BY RICHARD STEVENSON

34 NA • IEEE SPECTRUM • MARCH 2010

IEEE Spectrum March 2010

Five Legacies from the Laser

WAVELENGTH, NANOMETERS
410 420 430 440 450 460

Q1 2007
RHM PRODUCES A 404-NM NONPOLAR LASER AND ANNOUNCES A PLAN TO BUILD A 510-NM LASER FOR COLOR DISPLAYS.
THE FIRST NONPOLAR LASER IS DEVELOPED AT THE UNIVERSITY OF CALIFORNIA, SANTA BARBARA.

Q4 2007
RHM UNVEILS A 450-NM NONPOLAR LASER WITH AN INDIUM GALLIUM NITRIDE LAYER.

Q1 2008
SAPPH CORP. ANNOUNCES A 440-NM NONPOLAR LASER.

That radiation pumps a crystal that emits infrared light at 1064 nm. This light bounces in a cavity between two crystals, doubling the frequency to 532-nm emission. Voilà, green light.

For every watt of light that comes out of the original, infrared laser, you get about 0.4 watt of green light. What's even worse—for a TV manufacturer, at any rate—is that the power and space needs of that green-laser kludge add appreciably to the complexity and cost of the control circuits for the TV.

Since the 1960s, academic and industrial research teams around the globe

a higher to a lower energy band, emitting a photon of a very specific wavelength. As the photon bounces back and forth between the reflective ends of the chip, it stimulates the emission of still more photons of the same wavelength and phase. The resulting cascade of photons wrings energy from the system in the form of coherent, monochromatic light. But such a cascade is possible only if a great fraction of the electrons are in the higher energy band to begin with—an oversupply of "excited" electrons that's called a population inversion. Such an inversion can be obtained in gallium nitride.

bands determines how energetic the laser photons will be, and their energy, in turn, determines their wavelength. A high-energy gap means a short wavelength—green, blue, or violet, for example.

Doping gallium nitride with the Group II element magnesium produces the opposite effect, leading to a shortage of electrons needed for bonding. That absence of an electron, called a hole, behaves like a positively charged particle. Holes, too, can move freely throughout the crystal, occupying the valence band.

You can thus engineer gallium-nitride-based structures so that one region has

DOUBLE DOWN: Intracavity doubling in Mitsubishi's laser TV begins when an 808-nanometer diode laser pumps a neodymium-doped yttrium vanadate crystal. The crystal emits light at 1064 nm, and then the frequency is doubled (and the wavelength halved) in either a magnesium oxide or lithium niobate cavity, yielding an output of 532 nm.

Mitsubishi's Laser TV Green Laser

808-nm diode laser
808-nm wavelength
1064-nm wavelength
Neodymium-doped yttrium vanadate crystal
Periodically poled lithium niobate/magnesium oxide crystal
532-nm wavelength
Second crystal pumped by output of first, reducing wavelength to 532 nm

have been running a race to build the first reliable, manufacturable, green-emitting semiconductor laser. After a flurry of research in the late 1960s and early 1970s ended in failure, practically no one in the field saw that the key to victory was an obscure material called gallium nitride.

THE STORY OF THE GREEN laser actually starts with a different color and a different device: LEDs—blue ones.

To understand how and why, you'll need to sit through Lasers 101 (skip this and the next four paragraphs if you've already taken this class). Lasing happens in a semiconducting chip when a free electron skittering through the semiconductor's crystalline lattice drops from the

Gallium nitride is a III-V material—that is, its first element, gallium, is in Group III of the periodic table, and its second, nitrogen, is from Group V. The resulting crystal is a semiconductor. If you add just a trace of silicon to the mix, the sprinkling of additional "dopant" atoms will sit on only those sites in the lattice that would normally be occupied by gallium. However, because silicon is from Group IV, each atom contributes an additional, chemically unbound electron to the structure. Such free electrons can move throughout the structure, where together they occupy what's known as the conduction band. Meanwhile, those electrons that are chemically bound end up in the valence band, which has a lower energy. The "energy gap" between the two

a bounty of electrons—called *n*-type—and another an excess of holes that's called *p*-type. You can then apply a voltage between those two regions to drive the electrons and holes together so that they recombine to emit light. To turn such an emission into coherent laser light, you must make sure that electrons and holes recombine in a confined space, within a reflective cavity, and that enough of the resulting photons linger inside the cavity. Only then can they start a cascade of stimulated emission that produces photons with identical properties.

To maximize the efficiency of a chip laser, specialists engineer into it semiconductor structures that trap electrons and holes in an extremely thin layer, known as a quantum well. Such a well

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Mitsubishi green laser for TV using PPLN for second harmonic generation

March 15 2010

APS March Meeting 2010



Green Laser Pointer - from a question in class to invention and patent (1984)

Byer
Group

480 490 500 510 520 530

2008 MITSUBISHI UNIVELS UNVEILS A RED INGaAs LASER TV FOR US SALES.

Q2 2008 OSRAM POSSESSES THE LEAD WITH A 480-NM LASER.

Q1 2008 OSRAM DEMONSTRATES A 488-NM NITRIDE LASER. OSRAM OPTO SEMICONDUCTORS ANNOUNCES A 500-NM NITRIDE LASER.

Q2 2008 NICHIA SURPASSES OSRAM WITH A SERIES OF 510- TO 515-NM PICO-POWER LASERS.

Q3 2009 GREEN AT LAST: SUNTOMO ELECTRIC INTRODUCES RELEASES A 531-NM LASER.

is essentially a trench in the center of the device. In a nitride device, the trench is sandwiched by a film of aluminium gallium nitride, and the whole structure is surrounded by cladding—that is, layers having a refractive index higher than the other material. As a result, all the photons are confined between the cladding, in what's called the wave-guiding region, and they can get out only at the ends of the cavity, which reaches to the edges of the laser chip itself. Now you might expect light to pour out at either end, like water from a gutter, but the massive refractive index difference at the semiconductor-air

indium in the device's indium gallium nitride quantum well. Nichia has had substantial success with this approach, and to this day it remains the undisputed world leader in gallium nitride lasers, with efficiencies for some wavelengths exceeding 20 percent.

Notoriously secretive, Nichia declined to participate in the reporting for this article. But some of the company's progress can be gleaned from the papers it presents at academic conferences. At first, Nichia reported rapid success in extending its nitride laser emission to blue and beyond. By 2003 the company had pro-

The problem of stretching the emission wavelength toward green comes down to a single challenge: increasing the indium content in the quantum well while maintaining the material's quality. These lasers are grown by metal-organic chemical-vapor deposition, which involves heating the substrate and using nozzles to painstakingly inject exact quantities of organic molecules in precise ratios, which then dissociate to release atoms that form the device's crystalline layers. At low temperatures, you get enough indium at the cost of a lot of defects. At higher temperatures, you minimize the defects but get

Green-Laser Pointer

DIFFERENT DOUBLING: The common green-laser pointer achieves frequency doubling in a somewhat different way. Wavelengths of light hit a crystal that generates a second harmonic wave, thus achieving green output.

interface ensures that most of the light gets reflected back into the device. There it triggers the release of yet more identical photons. Result: an optical resonator that amplifies light each time it bounces back and forth, until it finally emerges past the interface in all its coherent glory.

In 1993, Shuji Nakamura, a Japanese engineer working alone, came up with improvements in gallium nitride materials science that a year later enabled his employer at the time, the Japanese company Nichia Corp., to release a blue LED with a then-whopping 2.7 percent efficiency. Two years later he fabricated the world's first gallium nitride laser, a device that emitted ultraviolet radiation. To get green light out of a nitride laser, you need to increase the proportion of

duced a 480-nm laser—still blue but at least leaning toward green. Subsequent progress, however, was painfully slow. By 2008 Nichia's researchers had hit 488 nm and commercialized that device, which the company describes as "blue-green."

If you want to get technical about it, 488 nm falls 12 nm short of the line marking the end of the blue range and the beginning of the blue-green. Then you have to go another 20 nm to reach the magic mark of 520 nm, where green light "officially" begins. Although the first 13 years of Nichia's gallium nitride laser development has produced an extension in emission wavelength by 80 nm, it is far from clear if the company will ever find the additional 40 nm needed to make a truly green laser.

And the indium atoms that do get in tend to skitter around on the surface, finally clumping together in a way that hampers light emission.

And as if navigating your way through this system of trade-offs weren't bad enough, there's an even tougher problem—known, imposingly enough, as the quantum-confined Stark effect. It stems from the interplay of the electrostatic forces and the internal stresses due to the slightly different spacings of the lattices of gallium nitride and indium gallium nitride. This interplay gives rise to internal electric fields as high as 100 volts per micrometer, enough to cause piles of static charges to form where the quantum well touches the surrounding material. The charges pull electrons to

SPECTRUM IEEE.ORG MARCH 2010 • IEEE SPECTRUM • NA 37

Question in class from Jeff Dixon:
Professor Byer, can we frequency double the cw diode pumped Nd:YAG laser with good efficiency?

Answer: *I don't know. If you do the calculations, I will do them as well and we can discuss the possibility of a green laser at class on Tuesday.*

Result: Demonstration of internal SHG of a diode pumped Nd:YAG laser with cw 532nm green output.
(Patent issued in 1986 to Stanford)

- Applications:**
- Lecture pointer (for color challenged males)
 - Green laser pointer for astronomy
 - Rescue flare for sailors at sea
 - Green laser for color TV

My favorite invention and laser legacy because of widespread use by amateur astronomers



"One thing leads to another.." (Brad Parkinson) Scientific Applications of Lasers

Byer
Group

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

Scientific Applications of Lasers

Atmospheric Remote Sensing

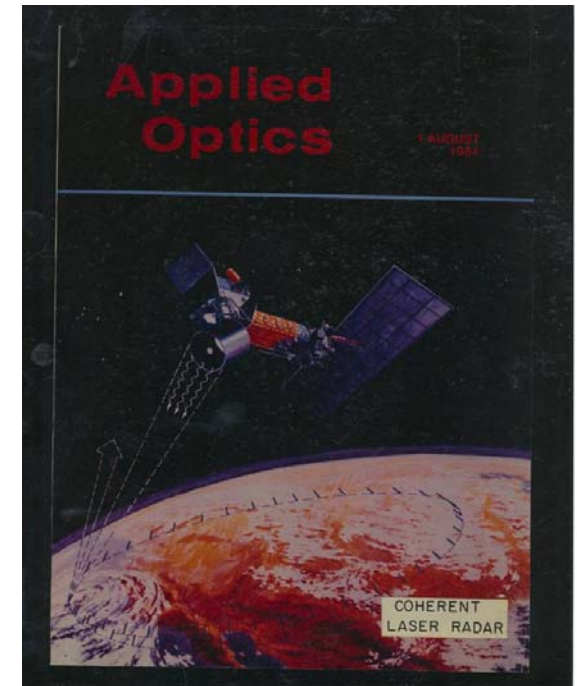
Quanta Ray 1J Unstable resonator
Nd:YAG Laser
1.4 to 4.3 micron Tunable LiNbO3 OPO

Global Wind Sensing

LD pumped Nd:YAG
Frequency Stabilization

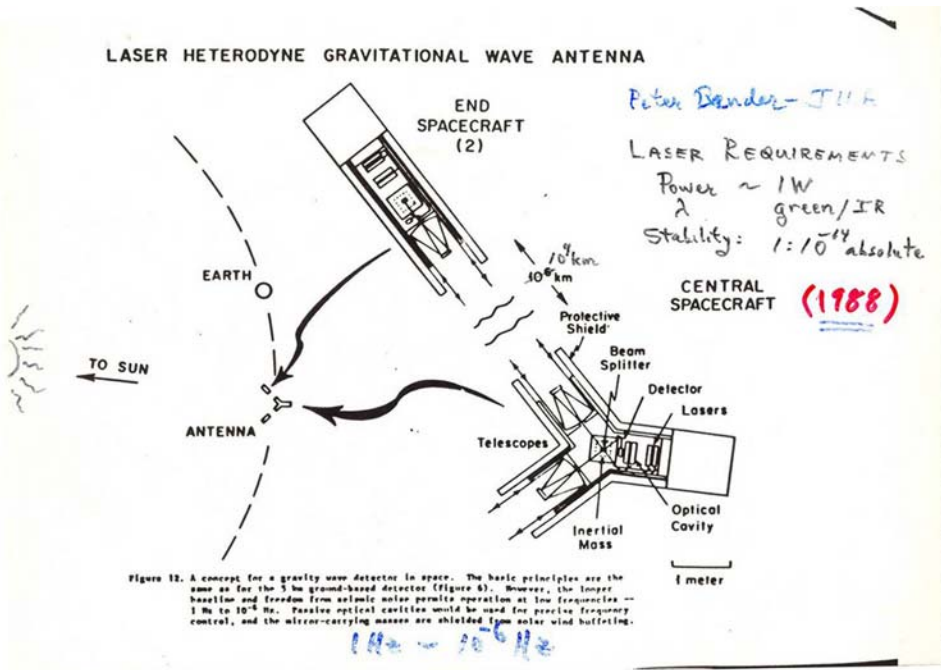
LIGO and LISA & Gravitational Waves

10 W Nd:YAG slab MOPA for LIGO
200W fiber laser MOPA Adv LIGO
1W Iodine Stabilized Nd:YAG LISA
Optical Clock for SMEX mission STAR



Global remote sensing 1980 -
Needed a coherent laser oscillator.

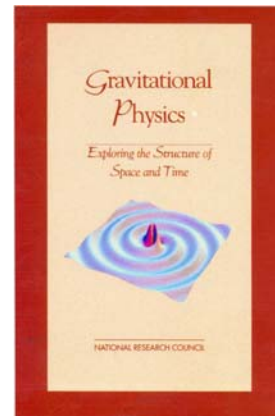
...from Coherent Laser Radar to Gravitational Waves... 1988



Peter Bender holding 4x4cm Au/Pt cube

Schematic of LISA in 1988

- Expected Launch date of 1998 (now 2015)
- Laser power 1W
- Laser stability extremely high
- Laser reliability > 5 years



Gravitational waves open a new window on universe

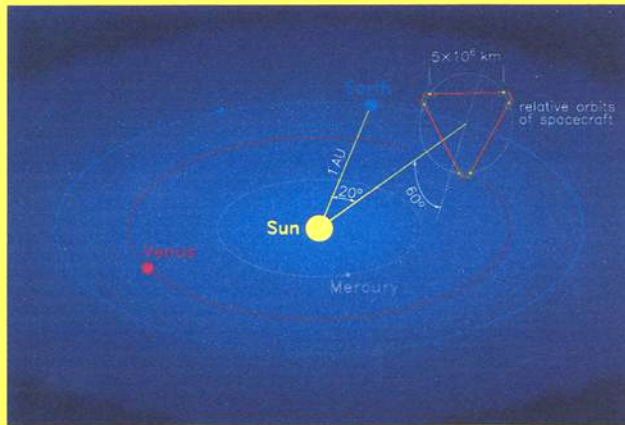
Detect amplitude and phase of gravitational waves with sensitivity to detect back the era of galaxy formation.



LISA

Laser Interferometer Space Antenna
for the detection and observation of gravitational waves

A Cornerstone Project in
ESA's long term space science programme
"Horizon 2000 Plus"



Pre-Phase A Report

December 1995

MPQ 208

February 1996

LISA - Laser Interferometer Space Antenna

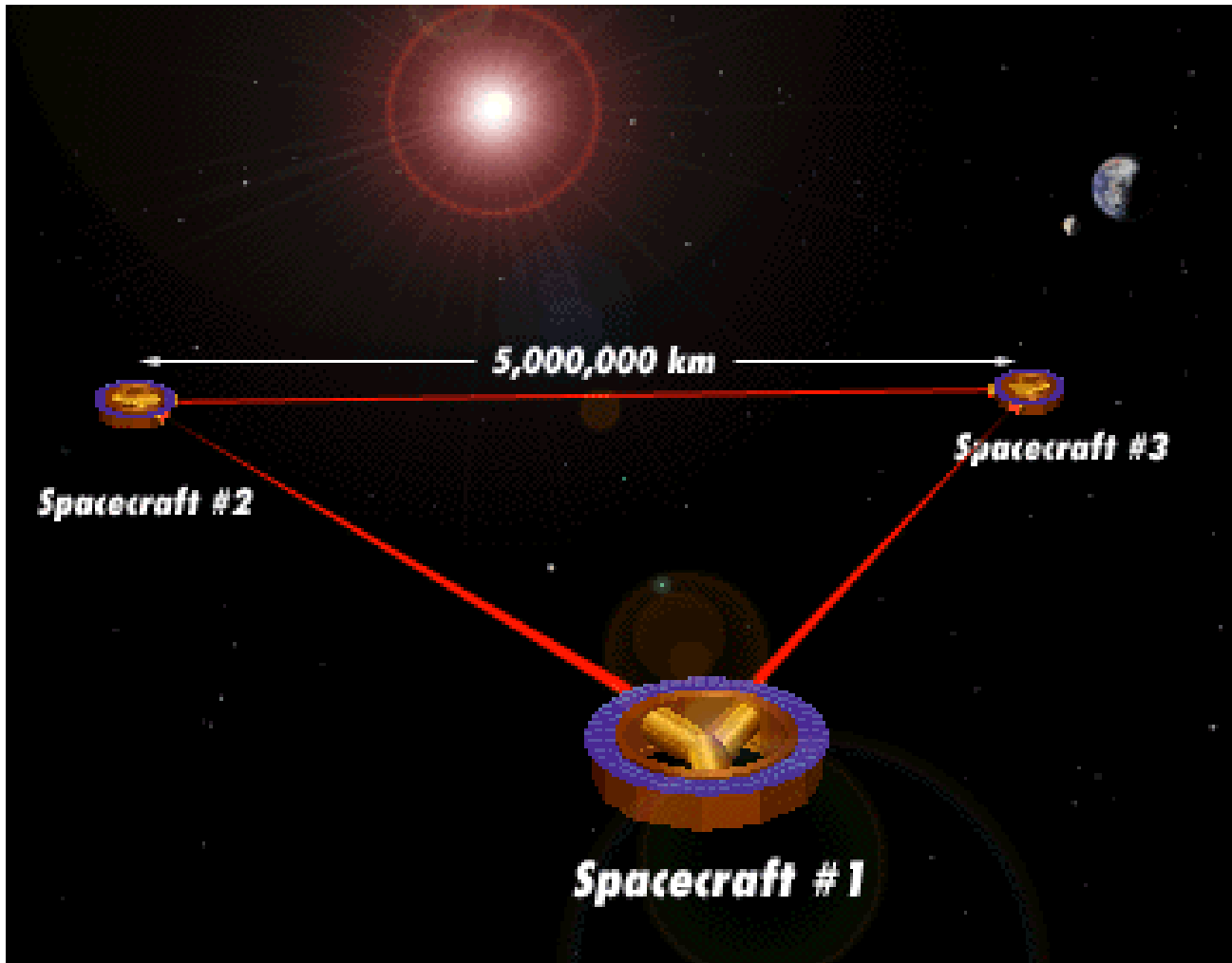
Phase A Study - 1995
Joint mission NASA and ESA

3 satellites in solar orbit
1 W laser - Nd:YAG NPRO
5 million km interferometer path
30 light seconds round trip delay

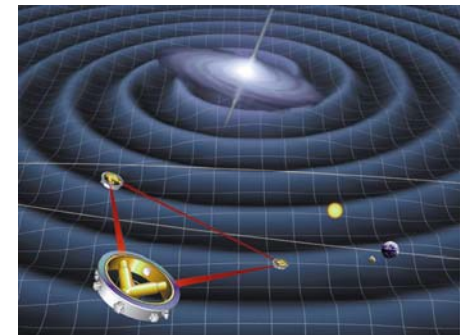
Scheduled for launch in 2020
1 year to station, 5 year mission

Will detect binary neutron stars in our galaxy

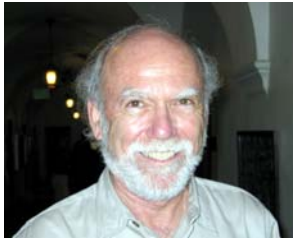
Will detect massive binary Black Holes at
Cores of most galaxies



Karsten Danzmann
LISA Pathfinder
Technology Mission



LISA will detect *Gravitational Waves*(amplitude and phase) from massive binary black holes



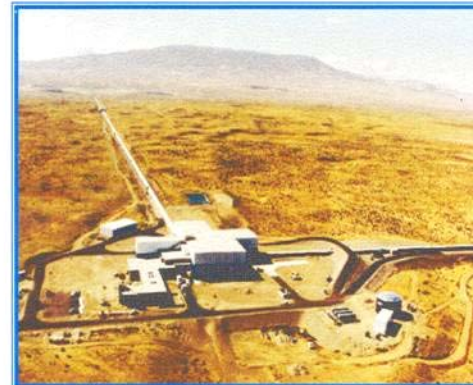
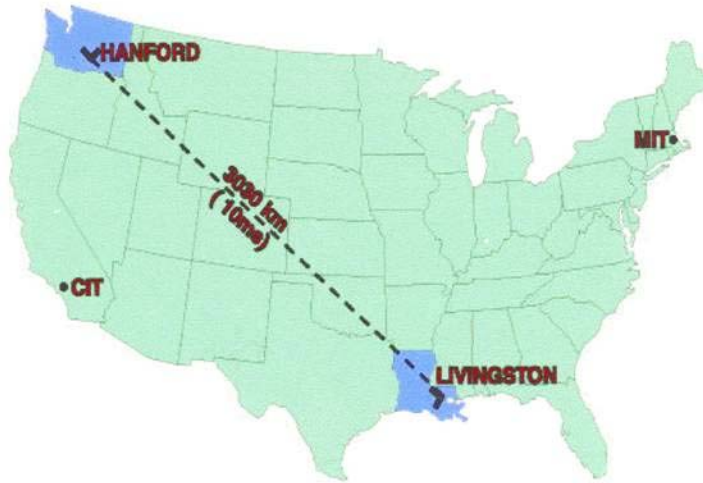
Barry Barish*

LIGO Sites



Rai Weiss
MIT

LIGO sites



• Hanford Observatory

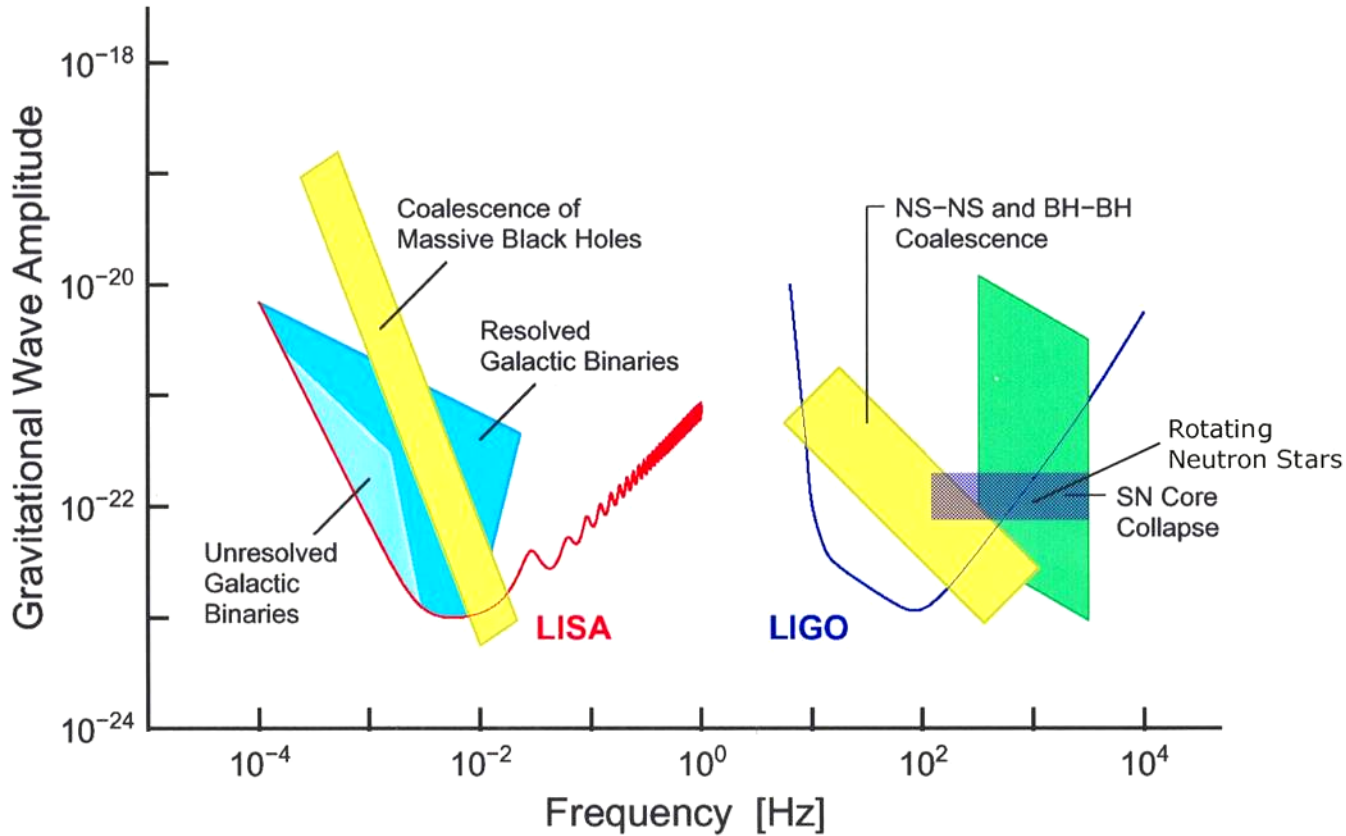


• Livingston Observatory

* Jay Marx joined LIGO as Director - Jan 2006



(LISA) Space- & (LIGO) Ground-Based Detectors



(LISA Science & Technology Study)



Kip Thorne,
CalTech

&

Rai Weiss
MIT



Global network of interferometers



LSC:
LIGO+GEO



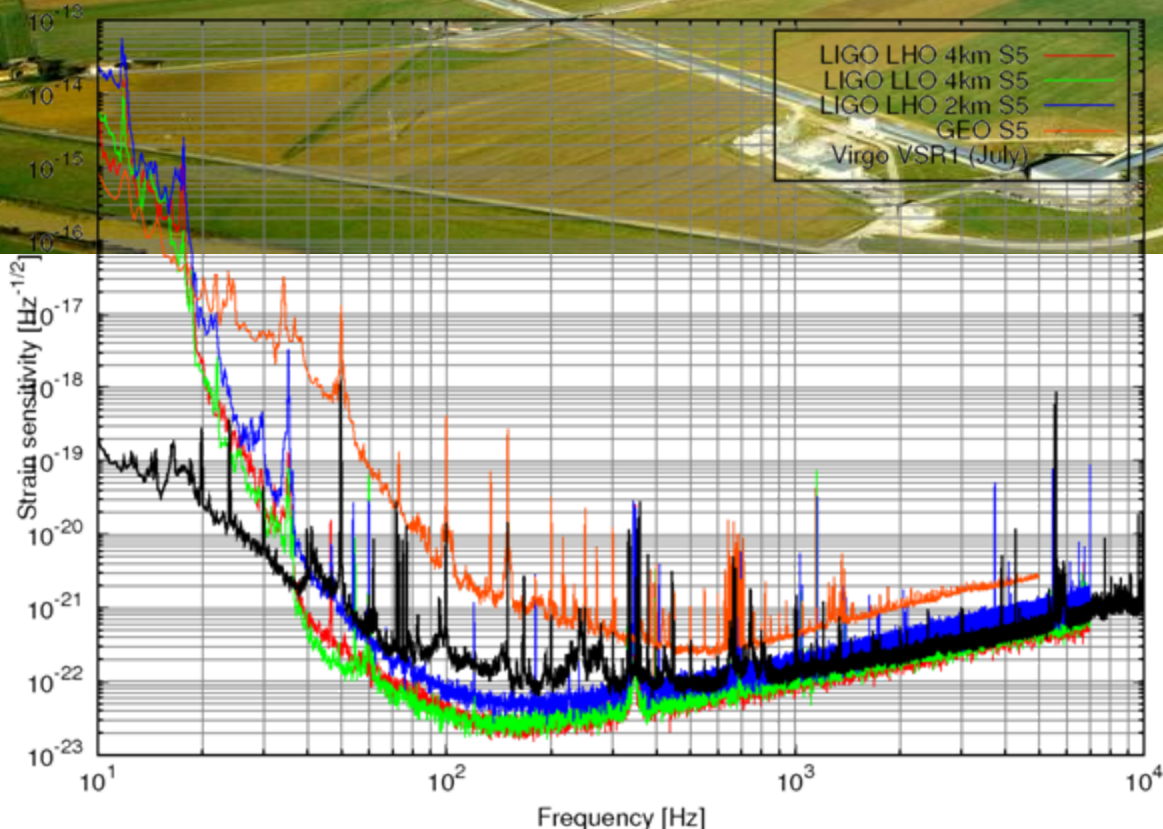
- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Waveform extraction



June 1998
Boundary representation is not necessarily authoritative.
802599 (R00352) 6-98

French-Italian project, located near Pisa, Italy; 3 km arms

Joint data-sharing agreement with the LSC, started 2007



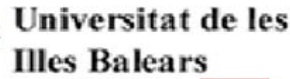
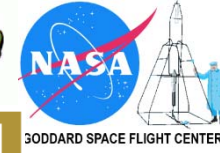
LIGO, GEO, Virgo,
July 2007

LIGO

LIGO Scientific Collaboration



- Australian Consortium for Interferometric Gravitational Astronomy
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Stuart Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland



Universität Hannover



- Max Planck Institute for Gravitational Physics
- University of Michigan
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Southampton

15 2010



• What are *GW*?

- waves in curvature of space-time
- a prediction of general relativity
- produced by acceleration of mass

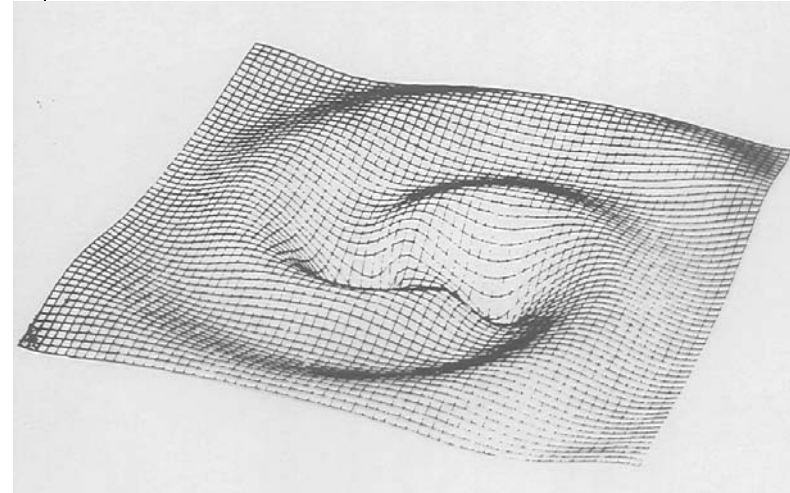
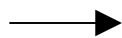
(c.f. EM waves produced by accelerated charge)

- travel at speed of light

BUT

- gravitational interactions are very weak
- no dipole radiation (due to conservation of momentum and mass of only one "sign")

To produce significant flux requires asymmetric accelerations of large masses



Astrophysical Sources



How Precise must LIGO/LISA be? (Answer: Very, very Precise!!!!)

Byer
Group

1 part in 10^{21} strain

$10^{21} = 1,000,000,000,000,000,000,000$

Alpha Centauri: 4.4 light years = 4×10^{16} meters

Strain sensitivity analogous to
 $10^{-21} \times 4 \times 10^{16} \text{ m} = 4 \times 10^{-5} \text{ m} \sim 40 \text{ microns!}$

**Like measuring the distance to a nearby
star to the diameter of a human hair !
(~100 microns)**



Alpha Centauri
(one of the nearest
stars)

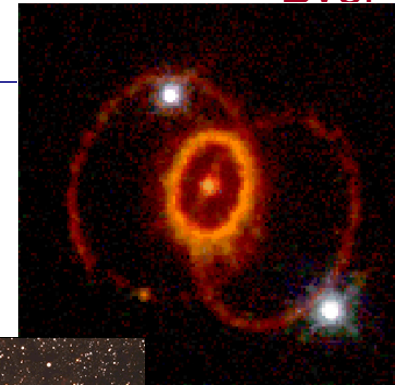


Gravitational Wave Sources

Bver

- **Bursts**

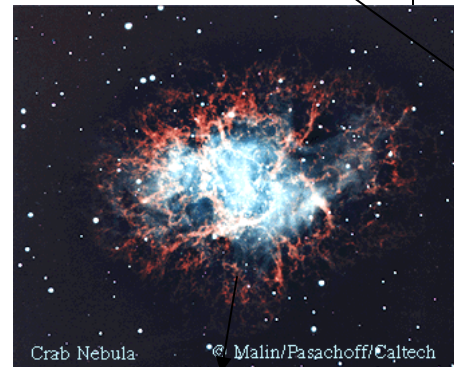
- catastrophic stellar collapse to form black holes or neutron stars
- final inspiral and coalescence of neutron star or black hole binary systems - possibly associated with gamma ray bursts



SN1987a

- **Continuous**

- pulsars (e.g. Crab) (sign up for Einstein@home)
- low mass X-ray binaries (Sco-X1)



Crab Nebula © Malin/Pasachoff/Caltech

- **Stochastic Background**

- random background "noise" associated with cosmological processes, e.g. inflation, cosmic strings.....

A New Astronomy

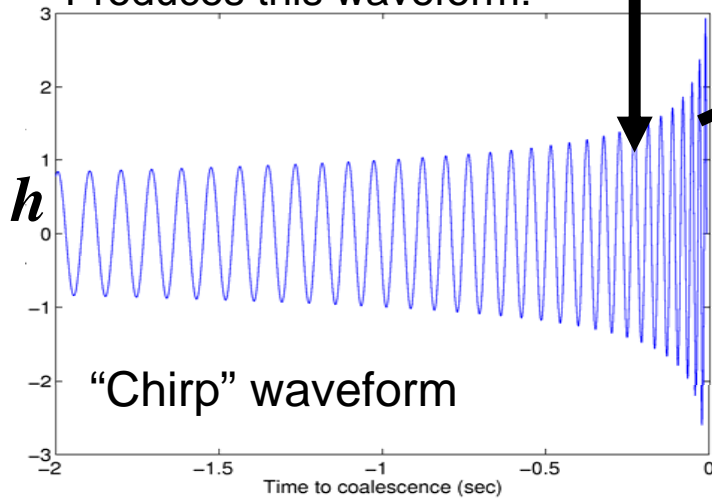


The challenge of LIGO data analysis

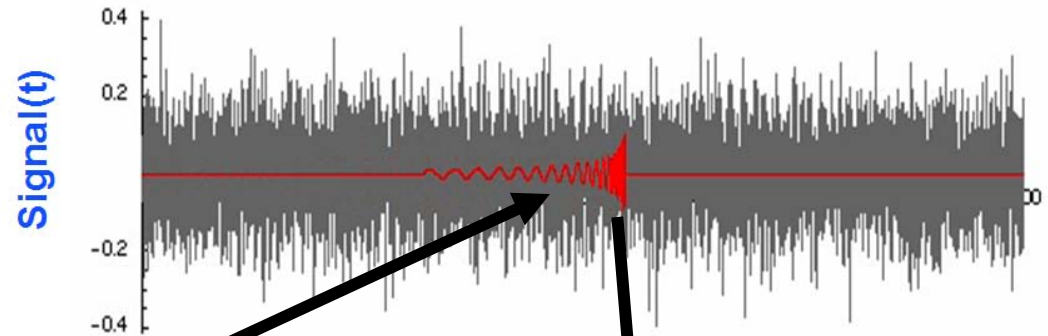
This source:



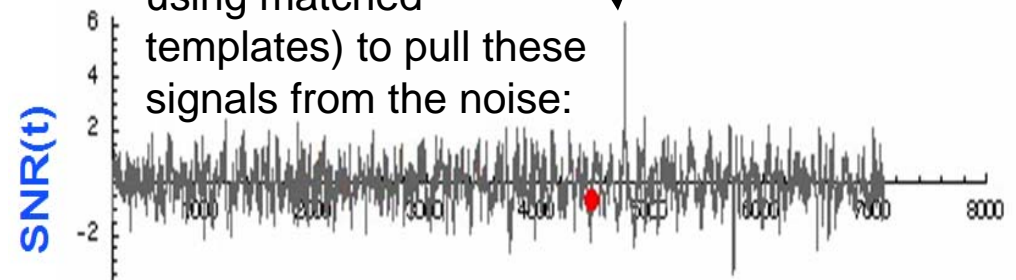
Produces this waveform:



Embedded in this noise stream:



We use different methods (in this case optimal Weiner filtering using matched templates) to pull these signals from the noise:



The problem is that non-astronomical sources also produce signals (false positives)



S5 Science Run: LIGO at Design Sensitivity

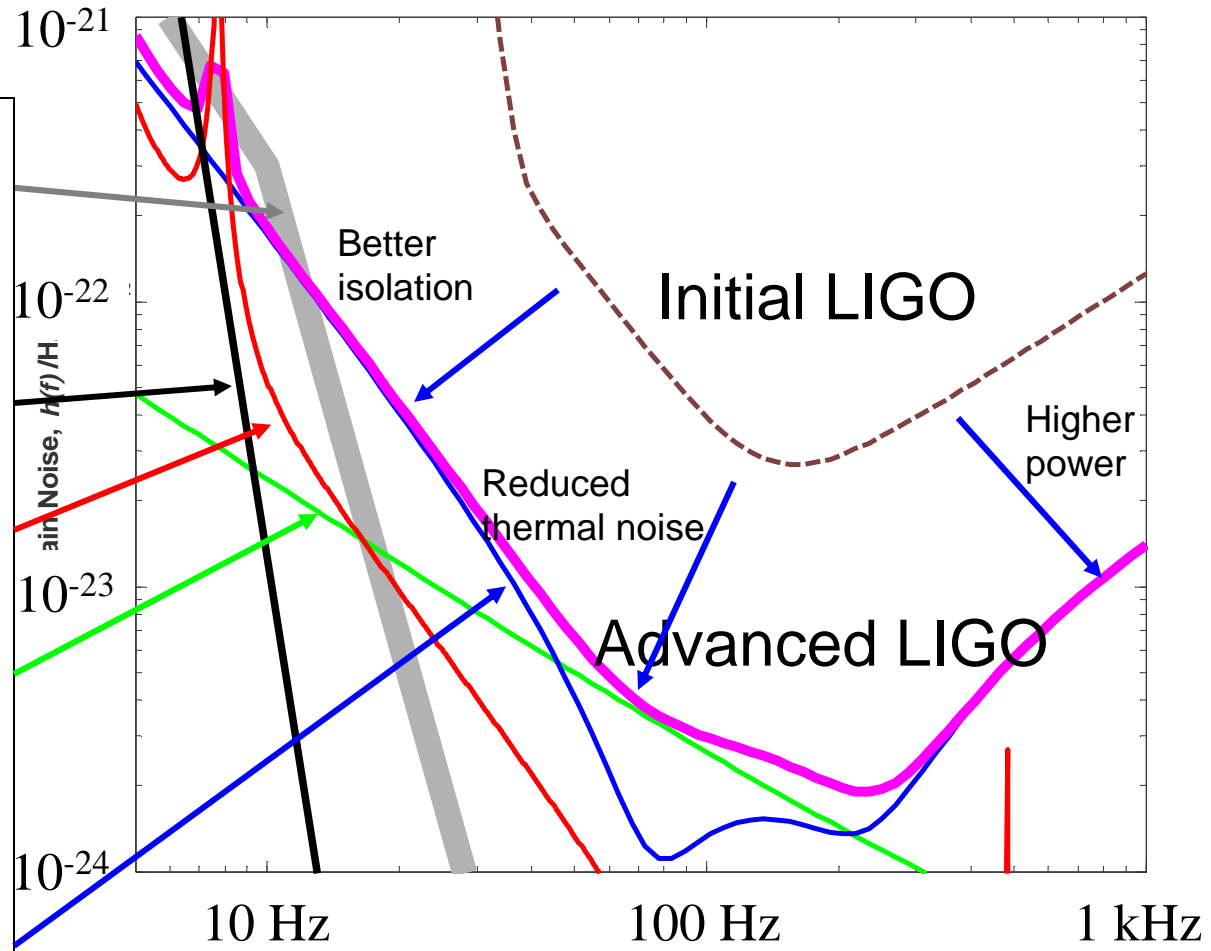
Strain Sensitivity for the LIGO Interferometers

S5 Performance - June 2006 LIGO-G060293-01-Z





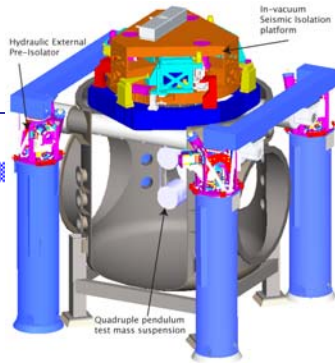
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



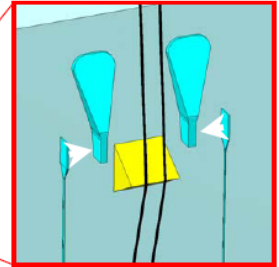
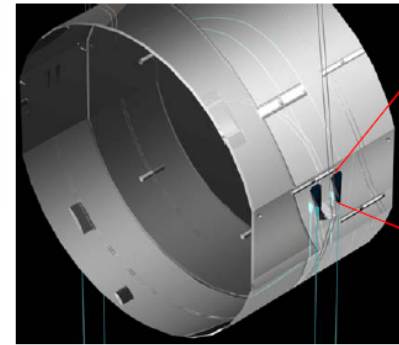
David Shoemaker/adapted



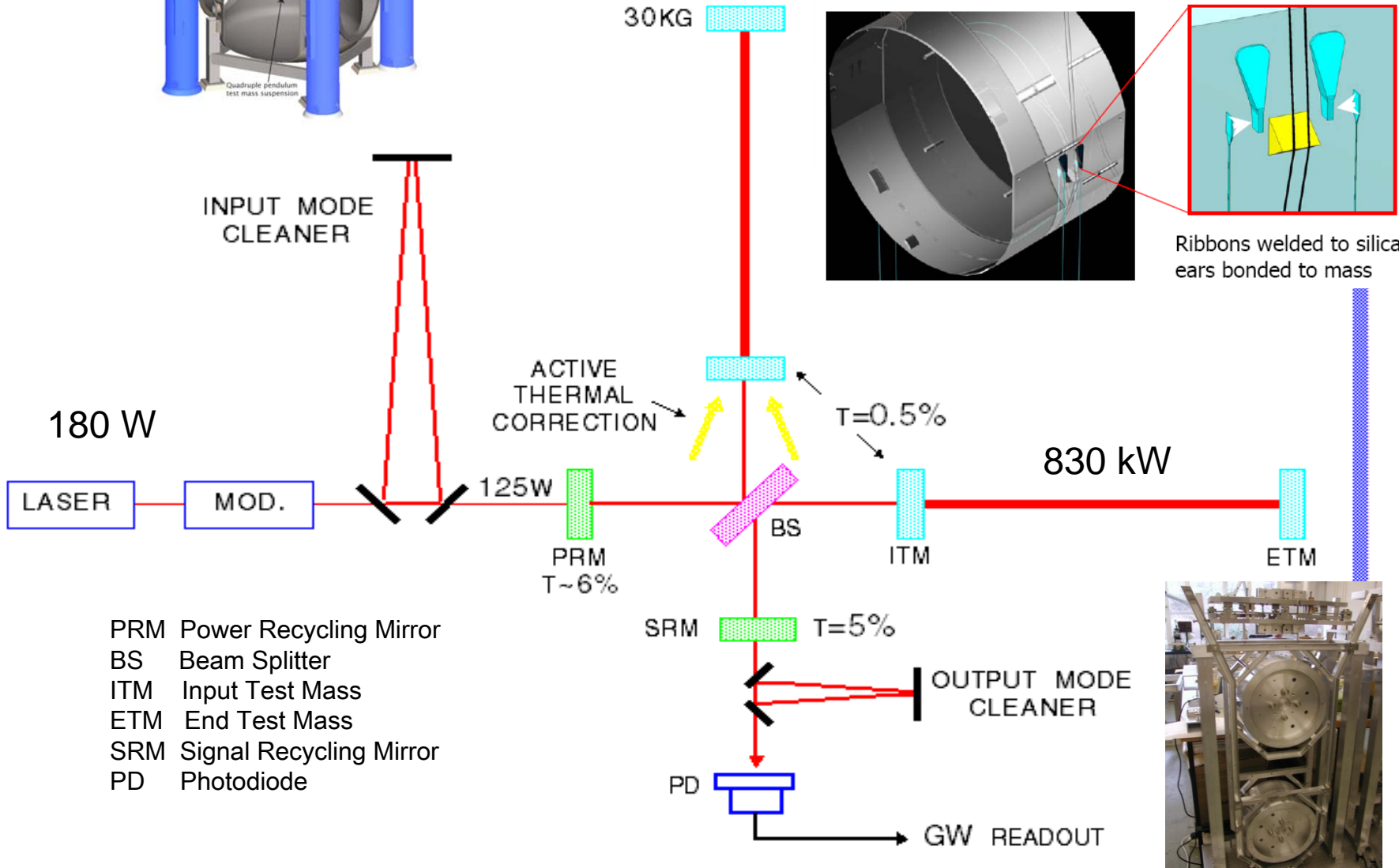
Advanced LIGO



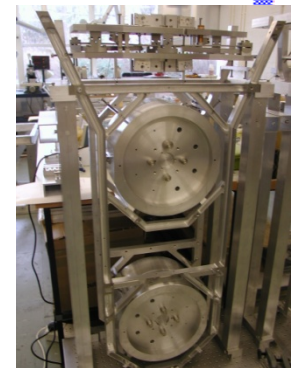
30 KG



Ribbons welded to silica ears bonded to mass



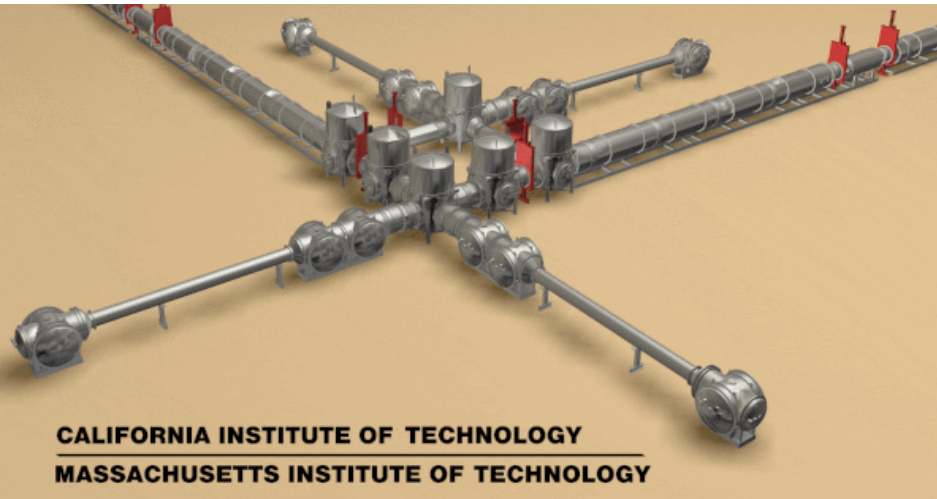
- PRM Power Recycling Mirror
- BS Beam Splitter
- ITM Input Test Mass
- ETM End Test Mass
- SRM Signal Recycling Mirror
- PD Photodiode





LIGO Vacuum Equipment

Byer
Group



CALIFORNIA INSTITUTE OF TECHNOLOGY
MASSACHUSETTS INSTITUTE OF TECHNOLOGY



- 1.2 m diameter
- Aligned to a mm
- Total of 16km fabricated with no leaks
- 1 nTorr (!)
- few, remote pumps
- Cover...





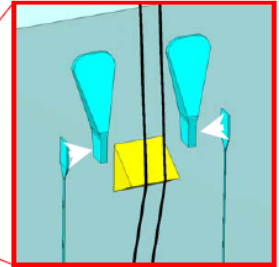
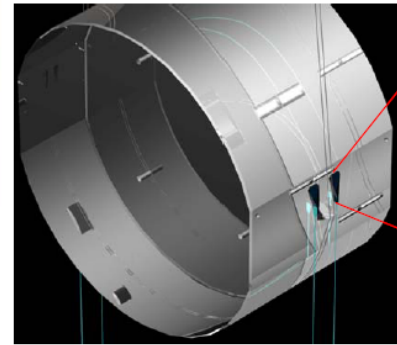
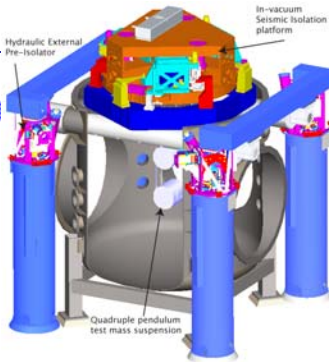
Vacuum tube enclosures test

Byer
Group

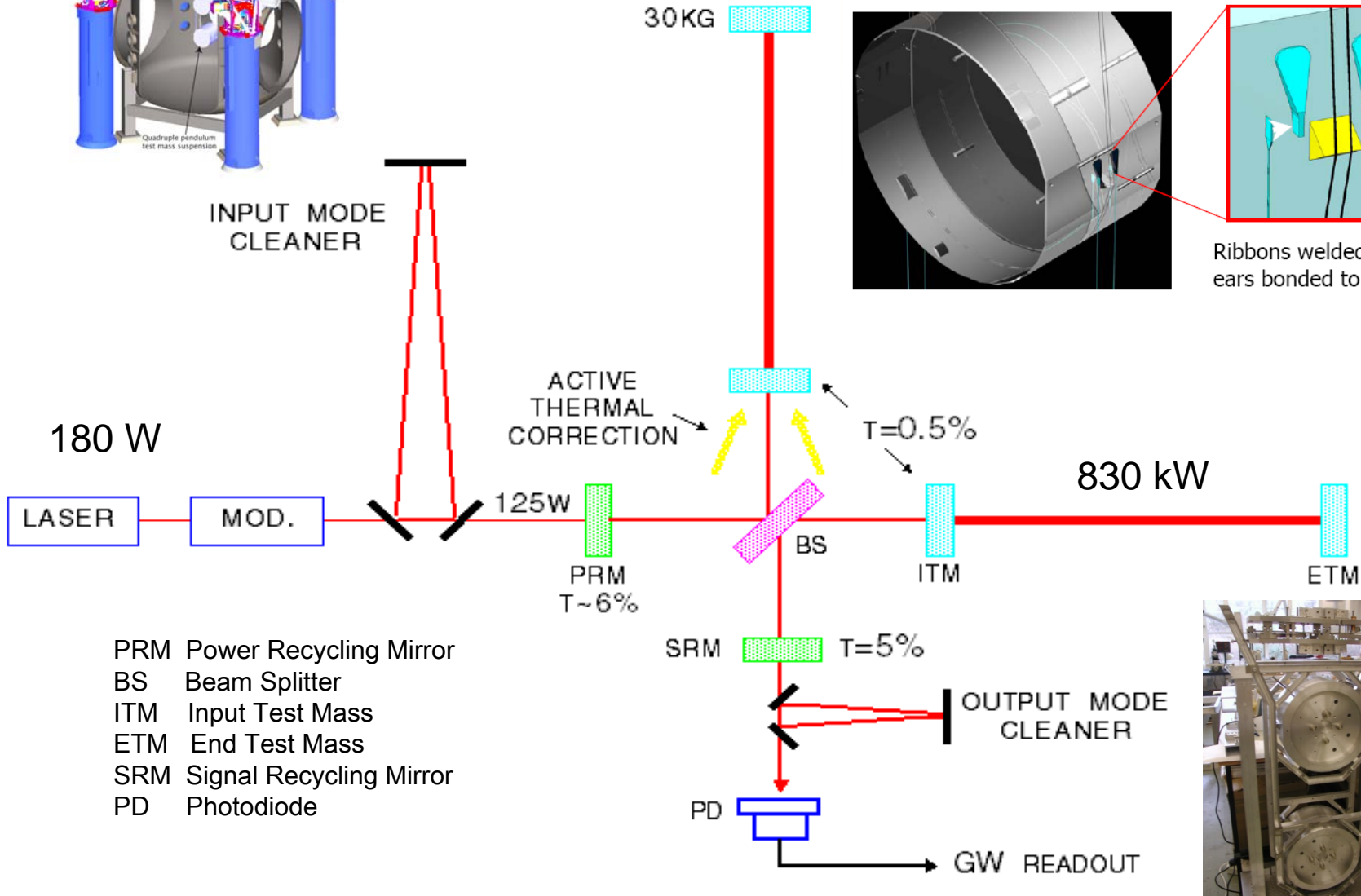




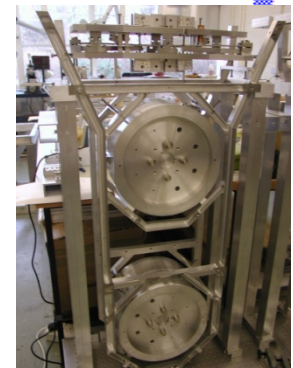
Advanced LIGO Interferometer



Ribbons welded to silica ears bonded to mass



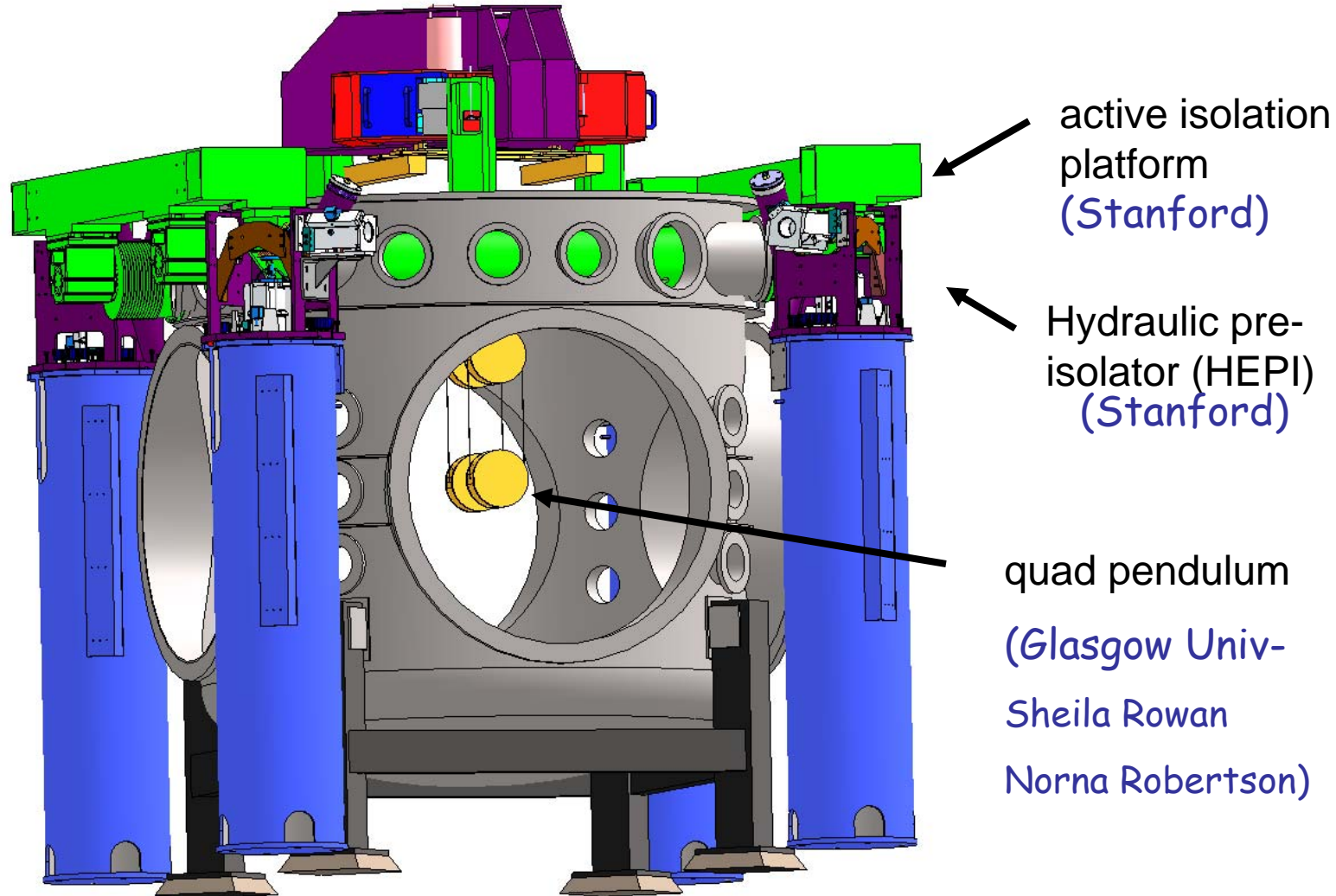
- PRM Power Recycling Mirror
- BS Beam Splitter
- ITM Input Test Mass
- ETM End Test Mass
- SRM Signal Recycling Mirror
- PD Photodiode





Advanced LIGO Suspension + Isolation (Dan DeBra and Brian Lantz)

Byer
Group



active isolation
platform
(Stanford)

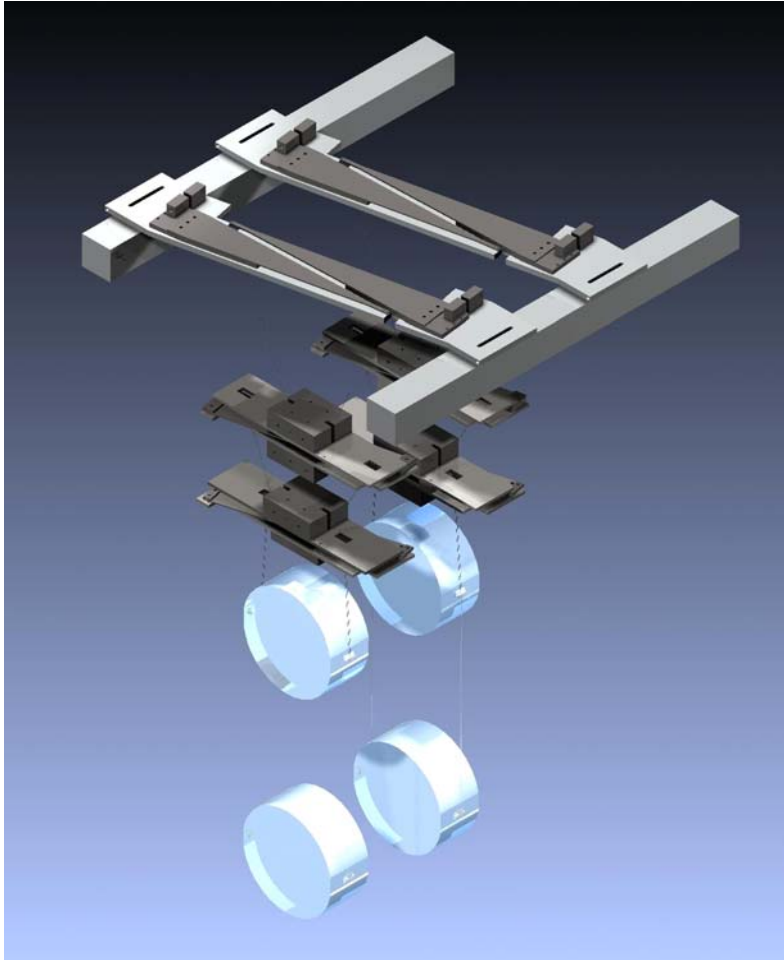
Hydraulic pre-
isolator (HEPI)
(Stanford)

quad pendulum
(Glasgow Univ-
Sheila Rowan
Norna Robertson)

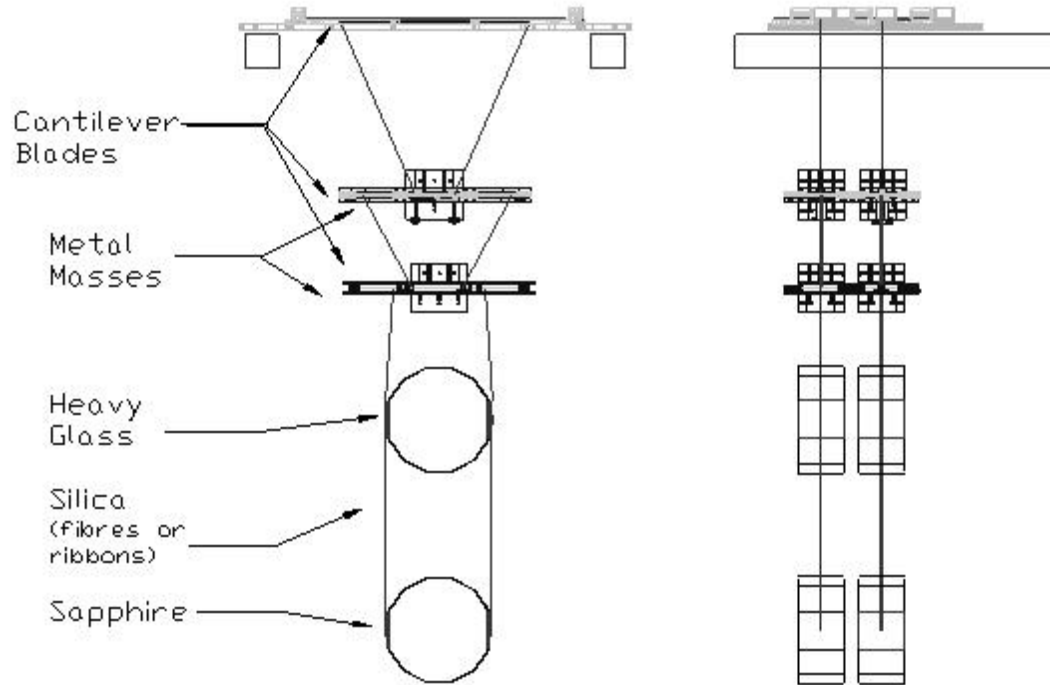
Corwin Hardham



Quadruple Suspension for Advanced LIGO



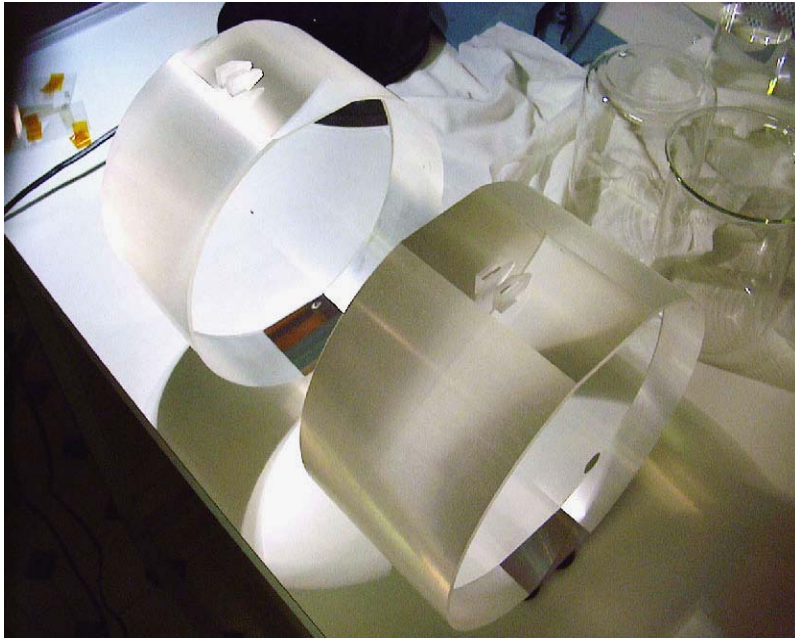
C Torrie, M Perreur-Lloyd, E Elliffe, R Jones



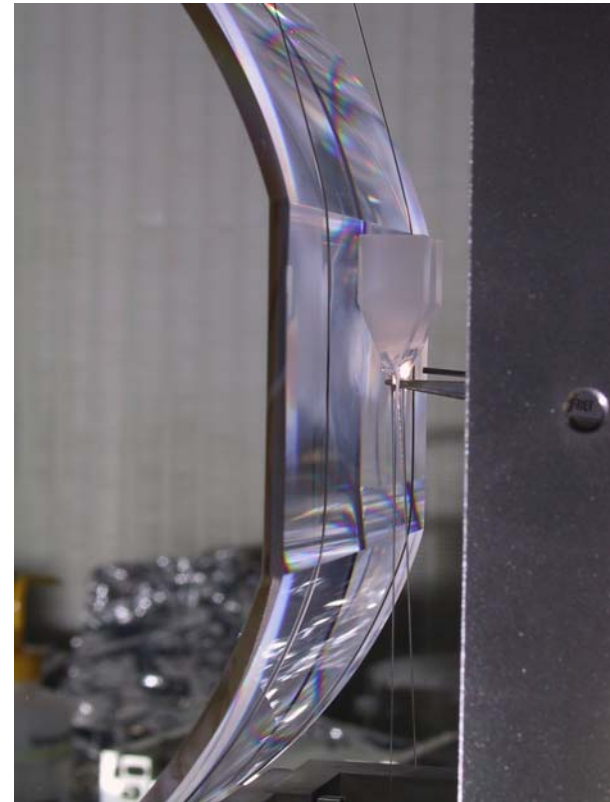


Monolithic Suspension - Assembly

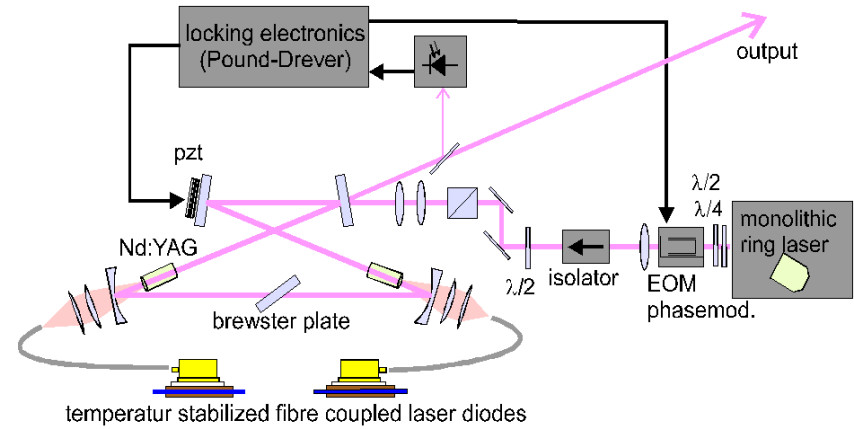
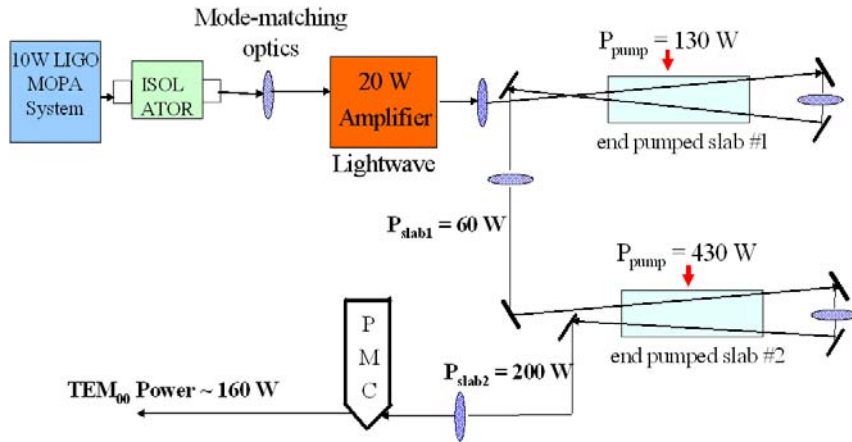
Byer
Group



Bonding of ears

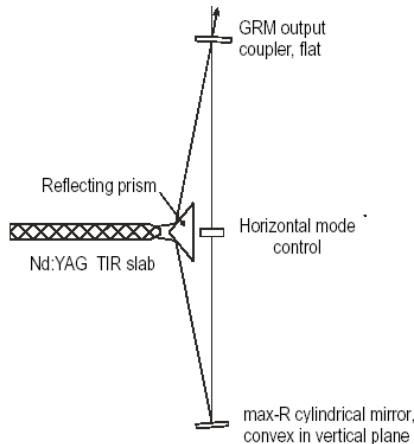


Welding of fibres



Edge Pumped Nd:YAG slab - Stanford

Injection locked Nd:YAG oscillators Hannover

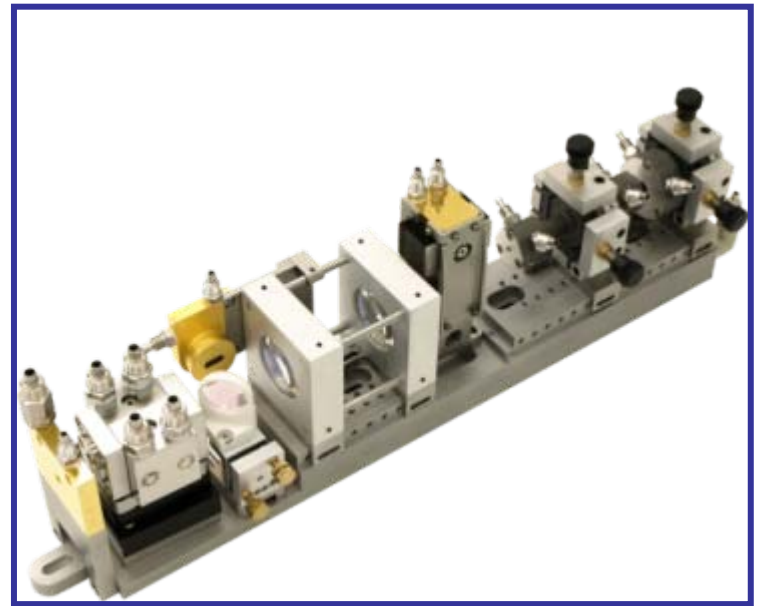
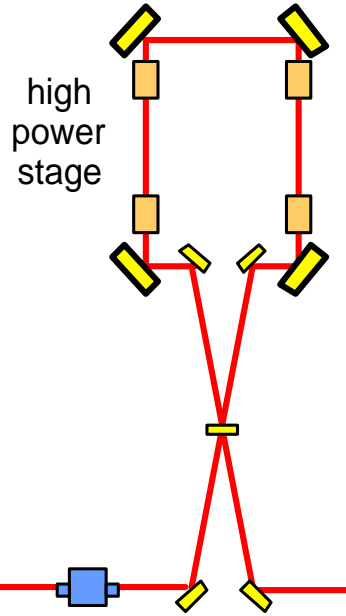
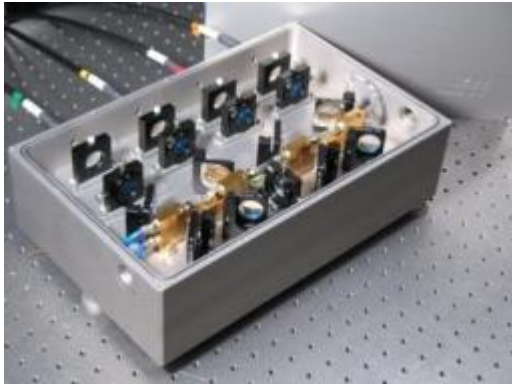


Unstable resonator -- Adelaide



Benno Wilke
Hannover

In charge of 180W
Laser program for
Advanced LIGO



Five Legacies from the Laser



Marc

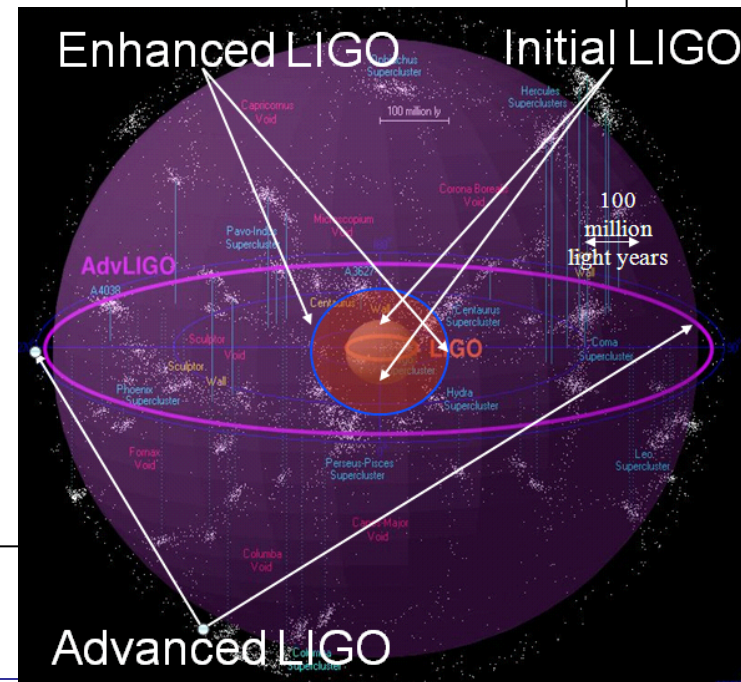
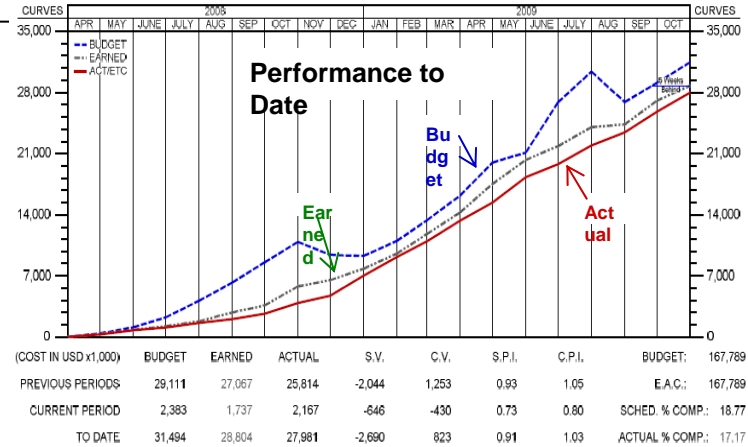


Advanced LIGO is advancing!

Byer Group

David Shoemaker - MIT

- Started April 2008, scheduled to wrap up in 2015 with installation of the computing cluster
- About 1/5 of the way through the Project in terms of 'earned value', pretty close to planned status
- Costs are ok (a little under due to soft economy); allows hiring people to solve problems
- No significant new noise sources or problems - should be able to get to that promised factor-of-10 in sensitivity
- Design is wrapping up; big ticket/long schedule items mostly underway
- Modifications of Observatories for assembly, cleaning, storage complete
- Fabrication is underway of interferometer components

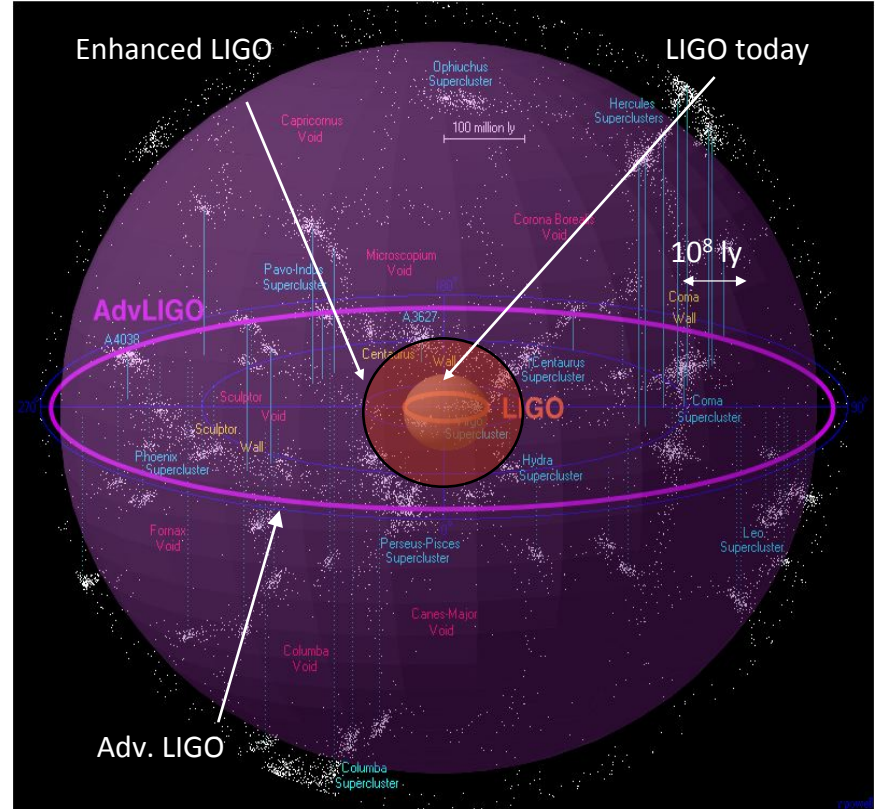




Astronomy

2nd generation:
Advanced LIGO

GOAL:
sensitivity 10x better →
look 10x further →
Detection rate 1000x larger



Credit: R.Powell, B.Berger

Legacy from the laser: gravitational wave astronomy later this decade



- **Introduction** *Making Lightwaves*
 - Early laser history and concepts
 - Unstable Resonator
 - Slab Laser - one dimensional cooling
 - Recent Innovations - Solid State Lasers**
 - Edge Pumped Slab Laser
 - Transparent 'Ceramic' polycrystalline gain media
 - ** (Path to MegaWatt Solid State Lasers - cutting metal at a distance)****
- **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**

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

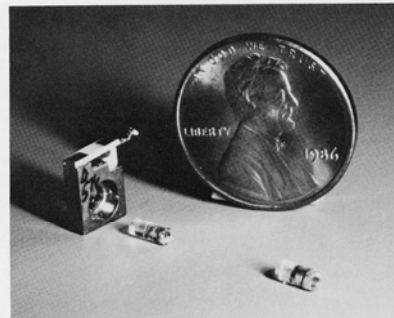
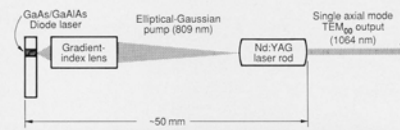


Fig. 1. (Top) Schematic of the diode laser-pumped monolithic Nd:YAG-oscillator. (Bottom) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

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

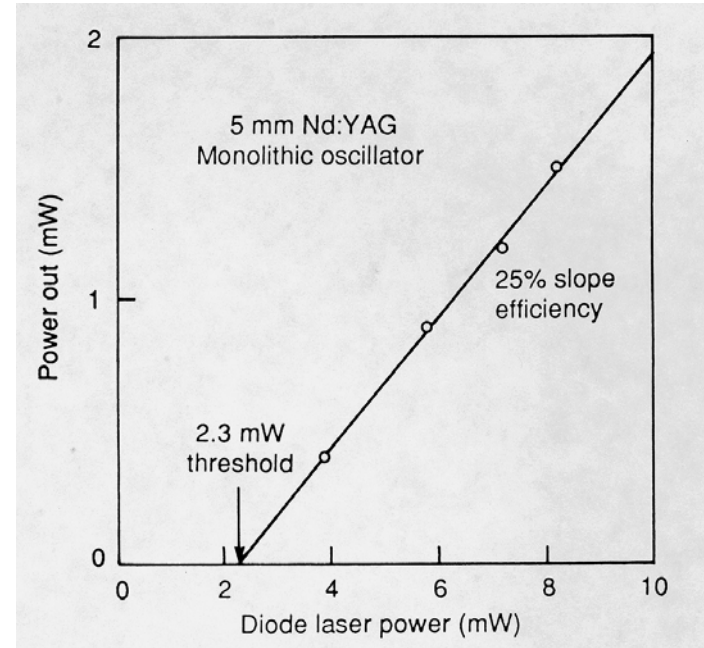
Laser Diode Pumped Nd:YAG - 1984

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?

Byer
Group

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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.

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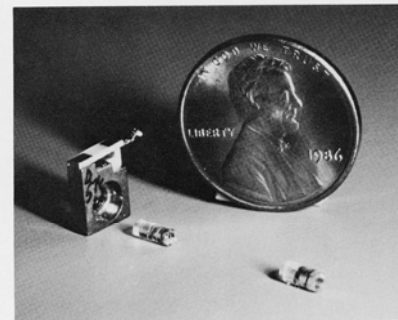
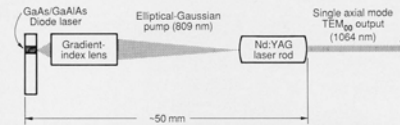


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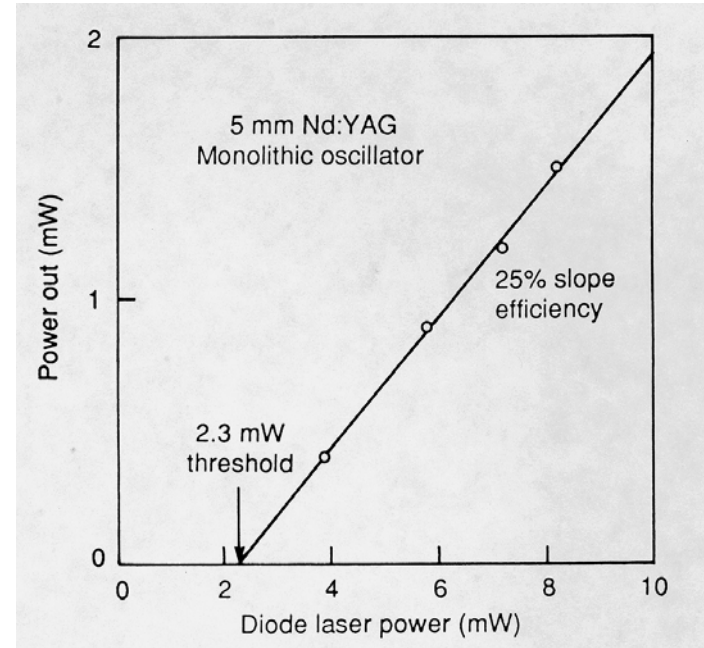
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Binkun Zhou, Tom Kane, Jeff Dixon
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"Efficient, frequency-stable laser-diode-pumped Nd:YAG laser"

Opt. Lett. 10, 62, 1985

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





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-Rutz² phase locked several semiconductor lasers via an external optical cavity. In another experiment Ripper and Paoli³ studied optically coupled dual-stripe lasers with no ex-

ternal cavity and concluded from spectral measurements that phase locking occurred. However, they³ reported difficulty in interpreting the radiation patterns because of the laser multimode character. In our device, which

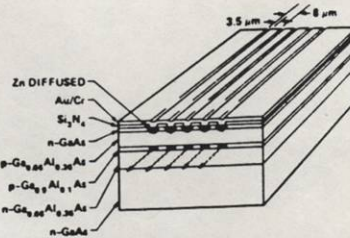


FIG. 1. Schematic diagram of a multiple-stripe phase-locked laser array.

1015 Appl. Phys. Lett. 33(12), 15 December 1978 0003-6951/78/3312-1015\$00.50 © 1978 American Institute of Physics 1015

"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.

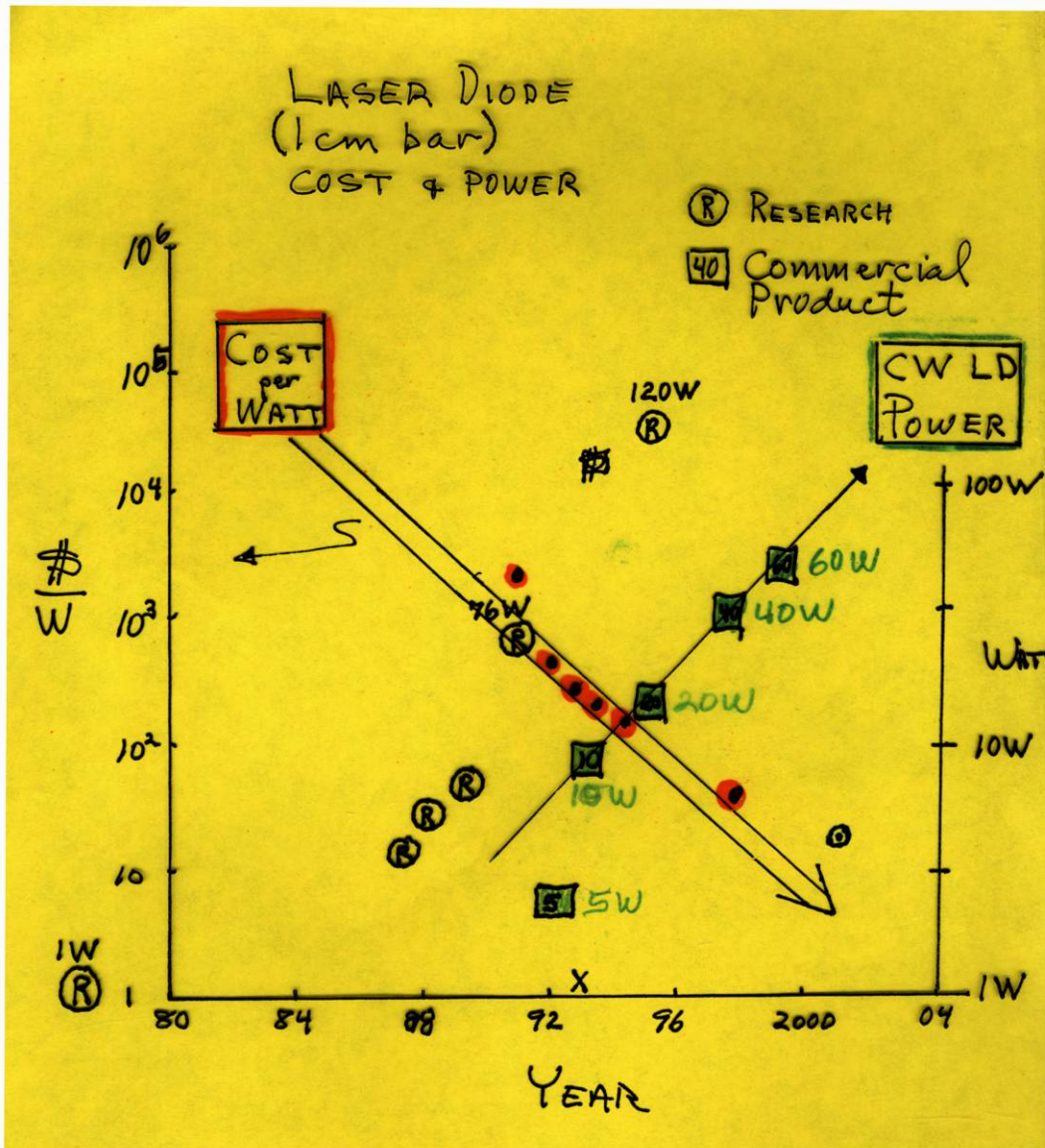
Within one decade the output power would increase to greater than 100W from a one centimeter LD bar.

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)

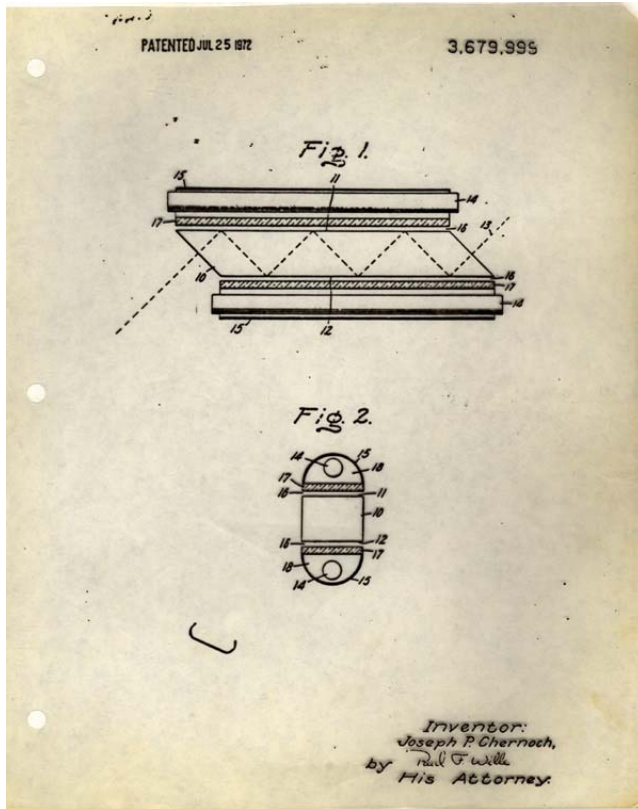


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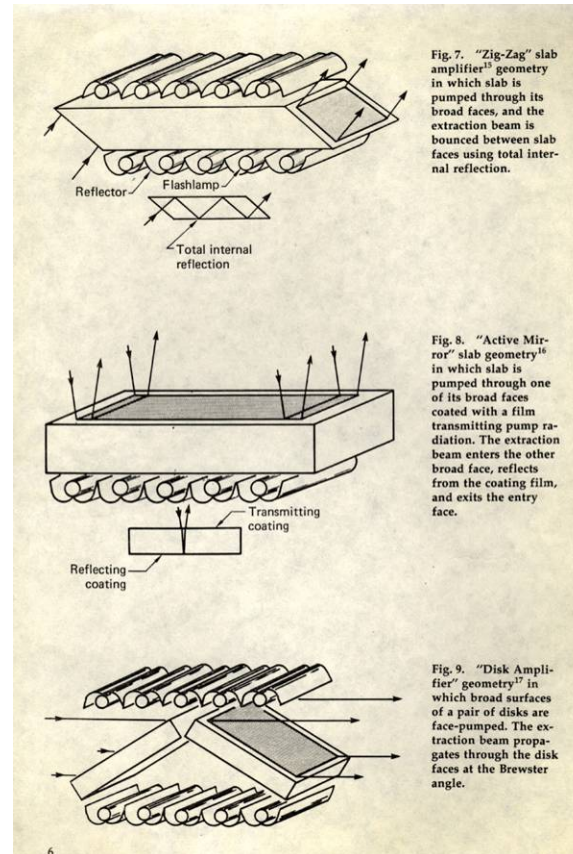


The zig-zag slab laser concept

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



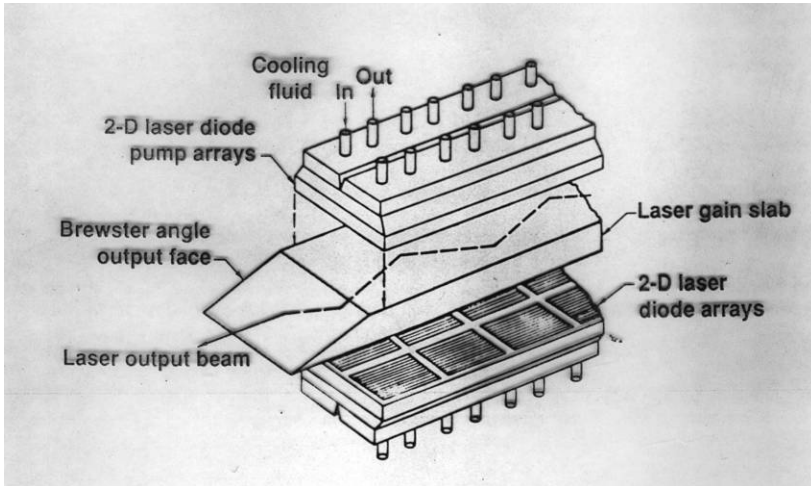
Joe Chernoch Invention
Patent # 3,679,999
July 25, 1972
Engineer at
General Electric Corp



"Zig-Zag" face pumped
Slab laser

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

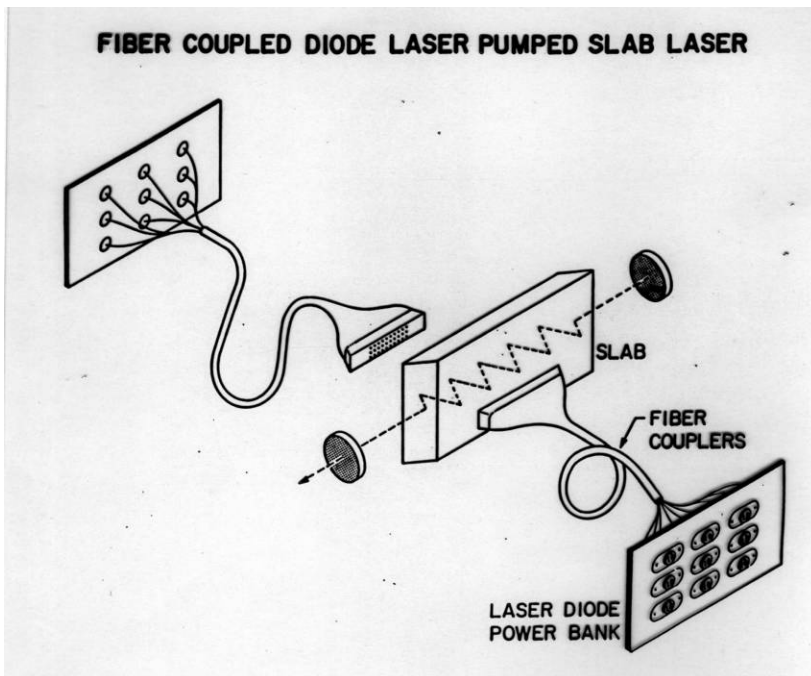
"Disk amplifier" geometry
adopted for the NIF
Laser



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, TEM₀₀-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



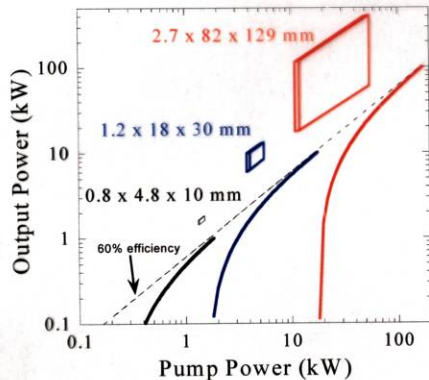
Innovation: Edge-Pumped, Conduction Cooled Slab Laser - 2000 (Predicted Power scaling to >100 kW with High Coherence)

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

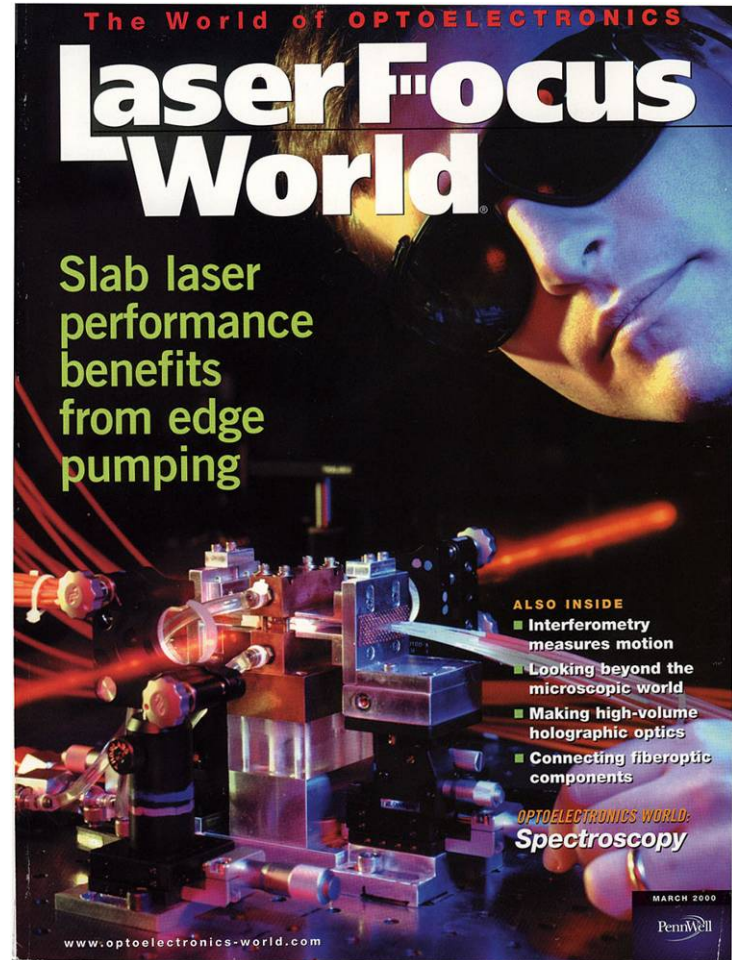
T.S. Rutherford, W.M. Tulloch,
E.K. Gustafson, R.L. Byer
*"Edge-Pumped Quasi-Three-Level
Slab Lasers: Design and Power Scaling"*
IEEE J. Quant. Elec., vol. 36, 2000

Towards a 100 kW DPSSL



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

Stanford High Power Laser Lab



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

Byer
Group

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

Ceramic Lasers: Ready for Action

by Jeffrey Wisdom, Michel Dignonnet 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

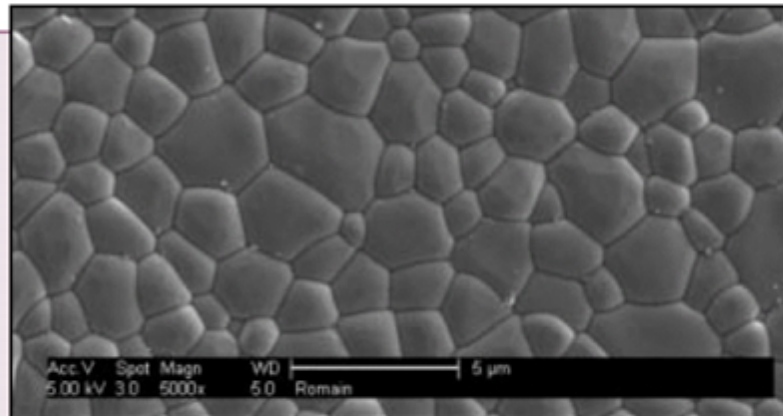


Figure 1. This undoped and unpolished YAG ceramic, imaged by scanning electron microscopy, was fabricated at Stanford University. Courtesy of Romain Gaume.



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:Y₂O₃, Nd:Lu₂O₃ and Nd:YGD₃ 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-pressure vacuum sintering method.[1, 2] Laser diode end-pumped Nd³⁺:YAG ceramic lasers with slope efficiencies of about 60% were developed in 2000 and 2001, respectively.[3, 4] Laser diode side-pumped high power Nd³⁺: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 even a little higher laser performance compared to Nd:YAG single crystal rod.

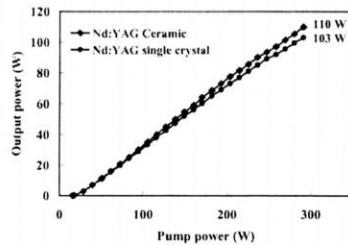


Fig. 1. Input-output dependences of Nd:YAG ceramic and single crystal lasers



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

KONOSHIMA CHEMICAL CO. LTD.

Nd:YAG ROD Nd:YAG SLAB Nd:YAG PLATE Nd:YAG DISK

Yb:YAG ROD Yb:YAG SLAB Yb:YAG PLATE Yb:YAG DISK

KONOSHIMA CHEMICAL CO. LTD.

Nd:YAG ROD Nd:YAG SLAB Nd:YAG PLATE Nd:YAG DISK

Yb:YAG ROD Yb:YAG SLAB Yb:YAG PLATE Yb:YAG DISK

KONOSHIMA CHEMICAL CO. LTD.

Nd:Y₂O₃ ROD Nd:Y₂O₃ SLAB Nd:Y₂O₃ PLATE Nd:Y₂O₃ DISK

Yb:Y₂O₃ ROD Yb:Y₂O₃ SLAB Yb:Y₂O₃ PLATE Yb:Y₂O₃ DISK

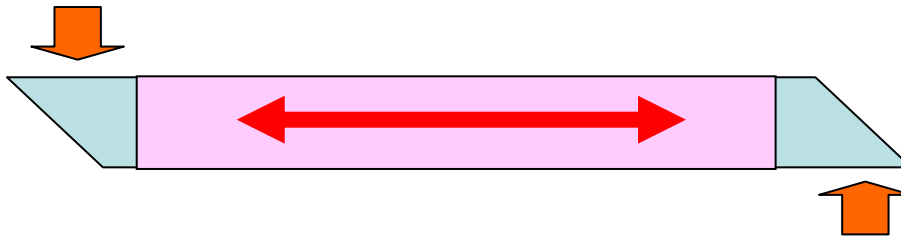
Ceramic gain media can be engineered to optimize laser performance



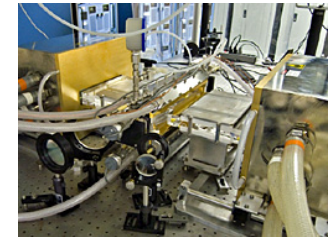
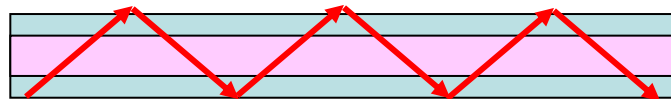
Research in US exceeds 105 kW average power using Diode Pumped Ceramic YAG

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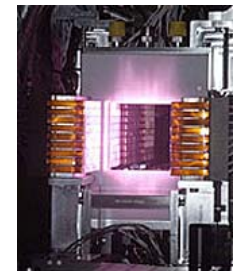
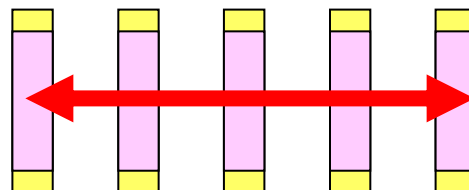
1. Northrop Grumman: End-pumped Slab: Yb:YAG



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

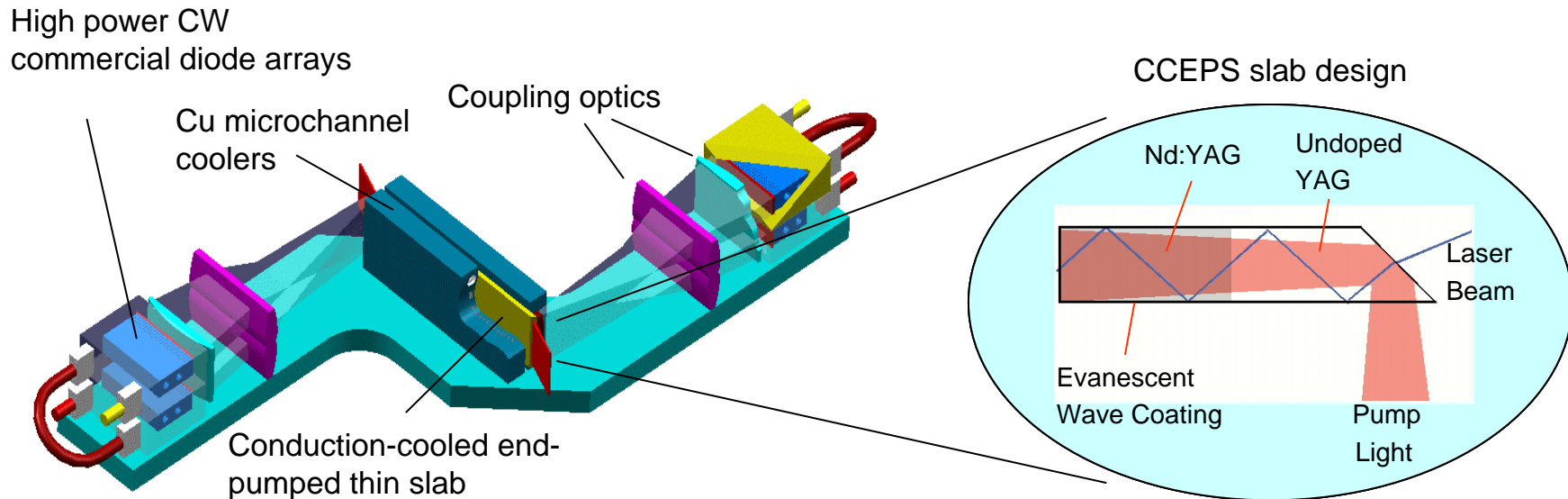


3. LLNL: Thermo Capacity Laser; Nd:Sm:YAG





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



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

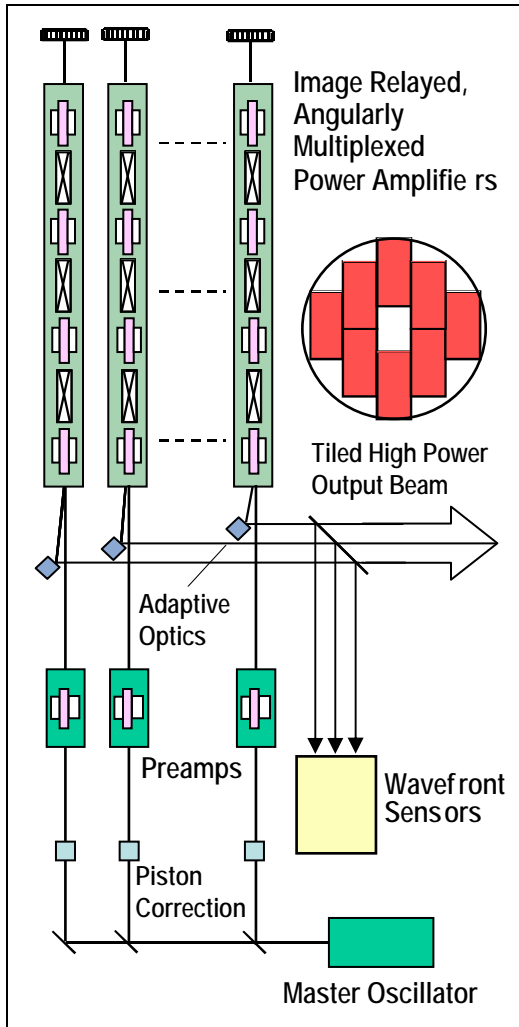


NGST JHPSSL Architecture

Northrop Grumman Space Technology

Joint High Power Solid State Laser

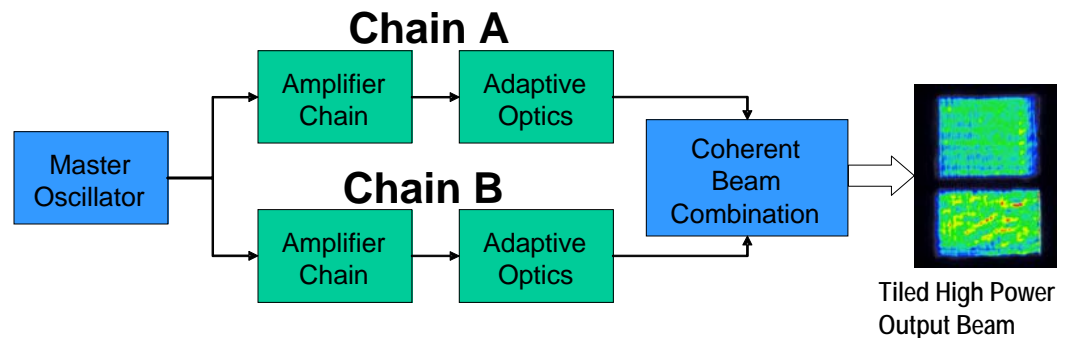
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(H. Injeyan et al, CLEO/QELS 2005, CMJ3)

- 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



105 kW Nd:YAG laser to be demonstrated at DoD High Energy Laser Systems Test Facility (Helstf)

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RESEARCH & DEVELOPMENT

Lasers on Lethal

Electric lasers near field trials as Pentagon upgrades test capability

GRAHAM WARWICK/WASHINGTON

Directed-energy weapons are to take a major step forward with creation of the first test facility enabling open-air firings of high-power solid-state lasers against rockets, mortars, unmanned aircraft and other targets.

Upgrading the U.S. Defense Dept.'s High-Energy Laser Systems Test Facility (Helstf) will help generate data needed to establish operational requirements for electric laser weapons, seen as more practical than the cumbersome chemical lasers now in flight-test.

Located on White Sands Missile Range in New Mexico, the Helstf became operational in 1985 with the megawatt-class Mid-Infrared Advanced Chemical Laser, which was test-fired against rocket stages, unmanned aircraft and an orbiting satellite. This led in the early 2000s to development of the smaller Tactical High Energy Laser (THEL), which shot down Katyusha rockets, mortar rounds and artillery shells in tests.

Chemical lasers can generate hundreds of kilowatts of beam power, enough to shoot down a ballistic missile, but the fuel is toxic and the number of shots limited. Electric lasers promise to provide the same surgical accuracy, but keep shooting for as long as power and cooling is available, making them more practical for installation in aircraft and vehicles.

The Solid-State Laser Test Experiment (SSLTE) is to be set up by relocating to the Helstf the 105-kw. prototype demonstrated by Northrop Grumman under the Pentagon's Joint High-Power Solid-State Laser (JHPSSL) program. There the laser will be connected to the pointer-tracker system originally built for the THEL and now being modified to operate at the electric laser's different wavelength.

Establishing the SSLTE is a "monumental event, [and] pretty expensive," says Col. James Jaworski, Helstf director. "But solid-state lasers are the way of the future. They will eventually generate megawatts."

Transferring the JHPSSL laser to the test facility from Northrop Grumman's laboratory in El Segundo, Calif., is expected to take about six months, with open-air live-fire tests against dynamic

targets slated to begin "within a year from now," he says.

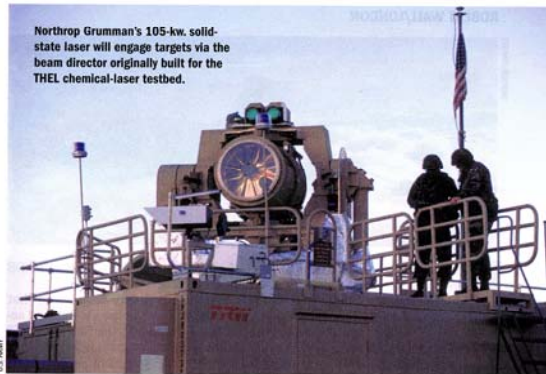
In the face of lingering doubts about their effectiveness as weapons, the upgraded facility's goal is to "remove the giggle factor from lasers, and prove they are capable systems," Jaworski says.

This will be the first time a 100-kw. solid-state laser is available for lethality tests, says Brian Strickland, JHPSSL program

and in controlled airspace, the Helstf is able to perform above-the-horizon firing tests. The facility also has a large vacuum chamber into which the beam can be directed to simulate firing the laser into low Earth orbit, Jaworski says.

Tests will begin with indoor shots against material coupons and advance to open-air firings against static and dynamic targets on the ground and in the air. "We hope to shoot down mortars with the SSLTE," he says.

Counter rocket, artillery and mortar (C-RAM) is one of the key early missions seen for high-power lasers, and is behind U.S. Army plans to test the mobile High-Energy Laser Technology Demonstrator (HEL TD) in the 2013-15 timeframe. Boeing is building the truck-mounted beam director for the HEL TD and this is set



Northrop Grumman's 105-kw. solid-state laser will engage targets via the beam director originally built for the THEL chemical-laser testbed.

manager at U.S. Army Space and Missile Defense Command. "Before that we had lower power and different wavelengths. We think we know how they scale, but it's better to have results."

"Building the first high-power solid-state laser testbed capable of addressing targets is a huge step toward fielding systems," says Dan Wildt, Northrop Grumman's vice president of directed-energy systems. "We will be able to fully understand the effectiveness of the laser and use that to establish operational requirements. It's an important step forward in transitioning the technology from the laboratory to the warfighter."

Establishing the effect of atmospheric attenuation on 1.06-micron-wavelength solid-state laser beams is a key task for the new facility. Ringed by mountains

for delivery to the Helstf "in about a year," says Jaworski. Once in place, the SSLTE laser will be hooked up to the HEL TD beam control for firing tests.

Northrop Grumman was the first of two contractors to exceed the 100-kw. power, beam-quality and run-time goals set for Phase 3 of the \$100-million JHPSSL program, and its laser was selected for the SSLTE in part because it is more easily relocated. "Northrop's laser is in a box; Textron's is still on an optical bench," says Strickland.

Northrop Grumman achieved a power level of 105 kw. in March last year by optically combining the beams from seven slab-laser chains. The company has since accumulated more than 4-hr. run time at over 100 kw, demonstrating its reliability, says Wildt.

Solid State Laser Test Experiment (SSLTE) to be set up in 2011

Establishing the SSLTE is a "monumental event" says Col James Jaworski, Helstf Director. "But solid-state lasers are the way of the future. They will eventually generate megawatts."

Northrop Grumman diode-pumped Nd:YAG solid state laser

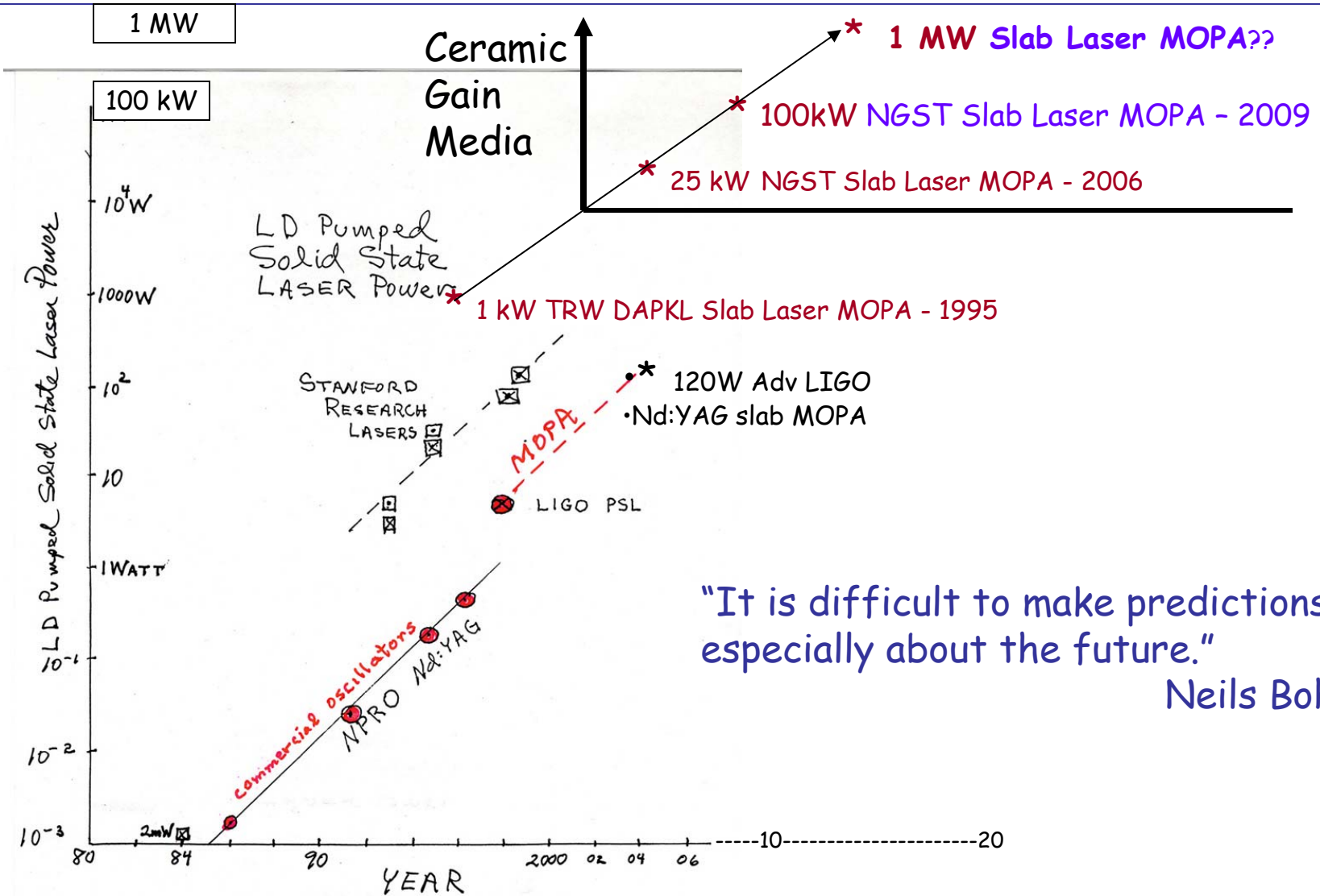
- 105kw cw output with $M^2 \sim 1.5$
- >4 hr operation to date
- ~ 20% electrical efficiency
- Adaptive Optics enabled coh beams
- < 1 sec turn-on time
- MOPA architecture for power scaling

Solid State Lasers - a path to megawatt power with high efficiency



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

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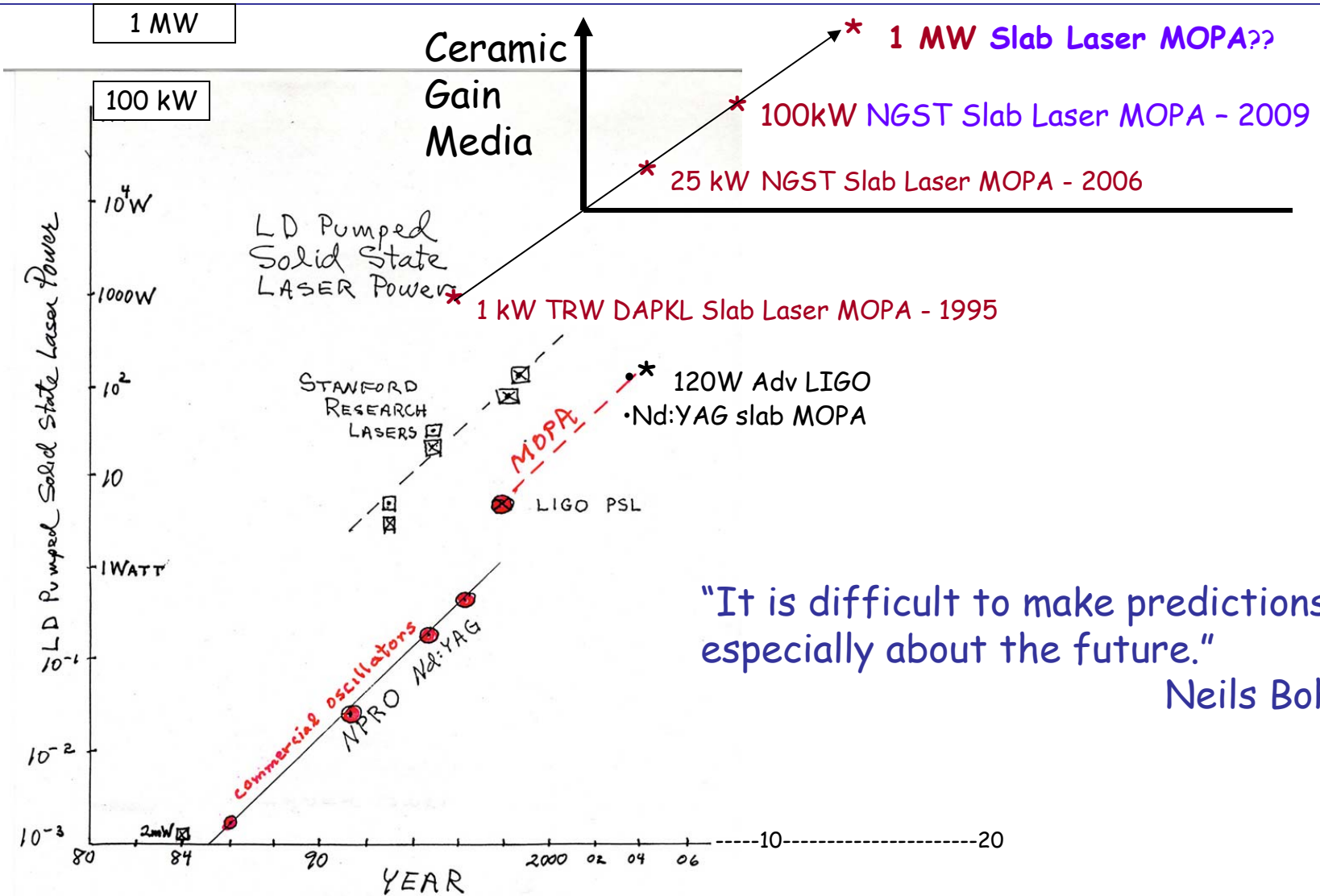
"It is difficult to make predictions, especially about the future."
Neils Bohr

Why the interest in MW average power Lasers?



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

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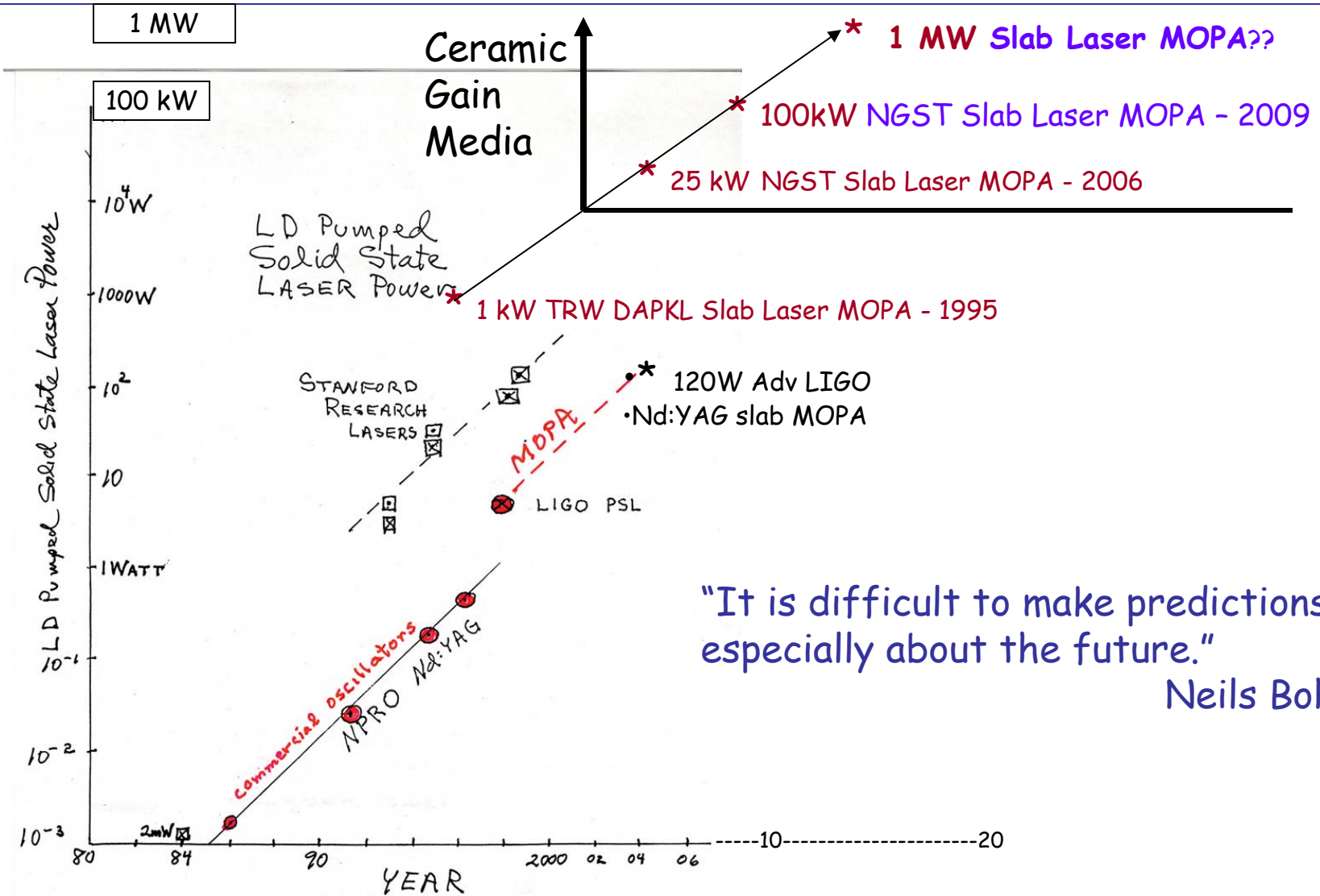
"It is difficult to make predictions, especially about the future."
Neils Bohr

Laser Accelerators for TeV scale physics and coherent X-rays



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

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

And LIFE: Laser Inertial Fusion for Energy Generation



- 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**



Proposal for Laser Inertial Fusion - 1972

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John Emmett



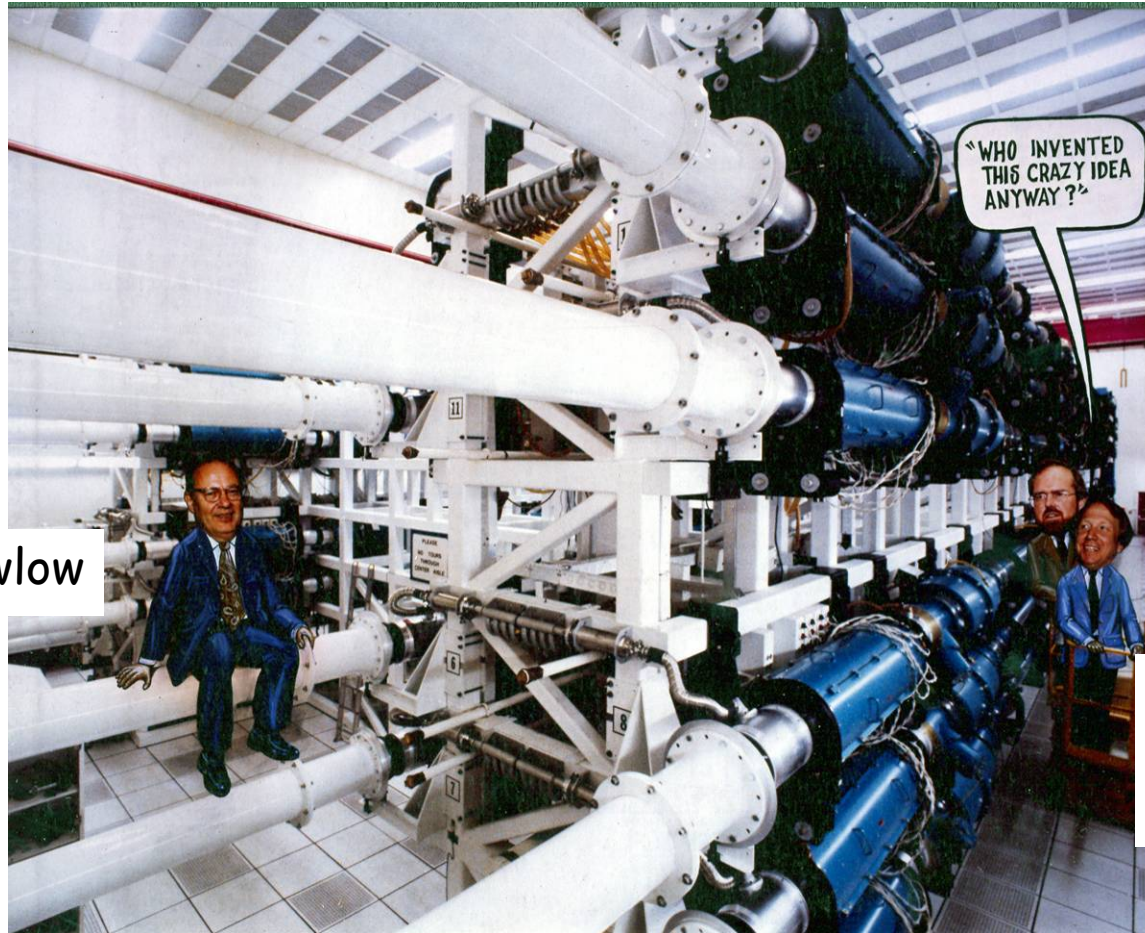
John Nuckols

10



Who Invented This Crazy Idea, Anyway?

Shortly after the demonstration of the Ruby laser John Nuckols 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 Holzhrichter
John Emmett

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

The National Ignition Facility

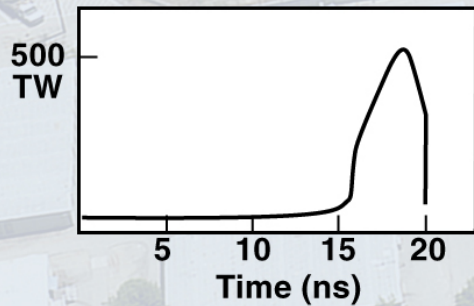
Ed Moses
Project Manager



NIF-0302-05920
03EIM/tr

NIF Laser System

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





Target Chamber being installed into NIF Facility

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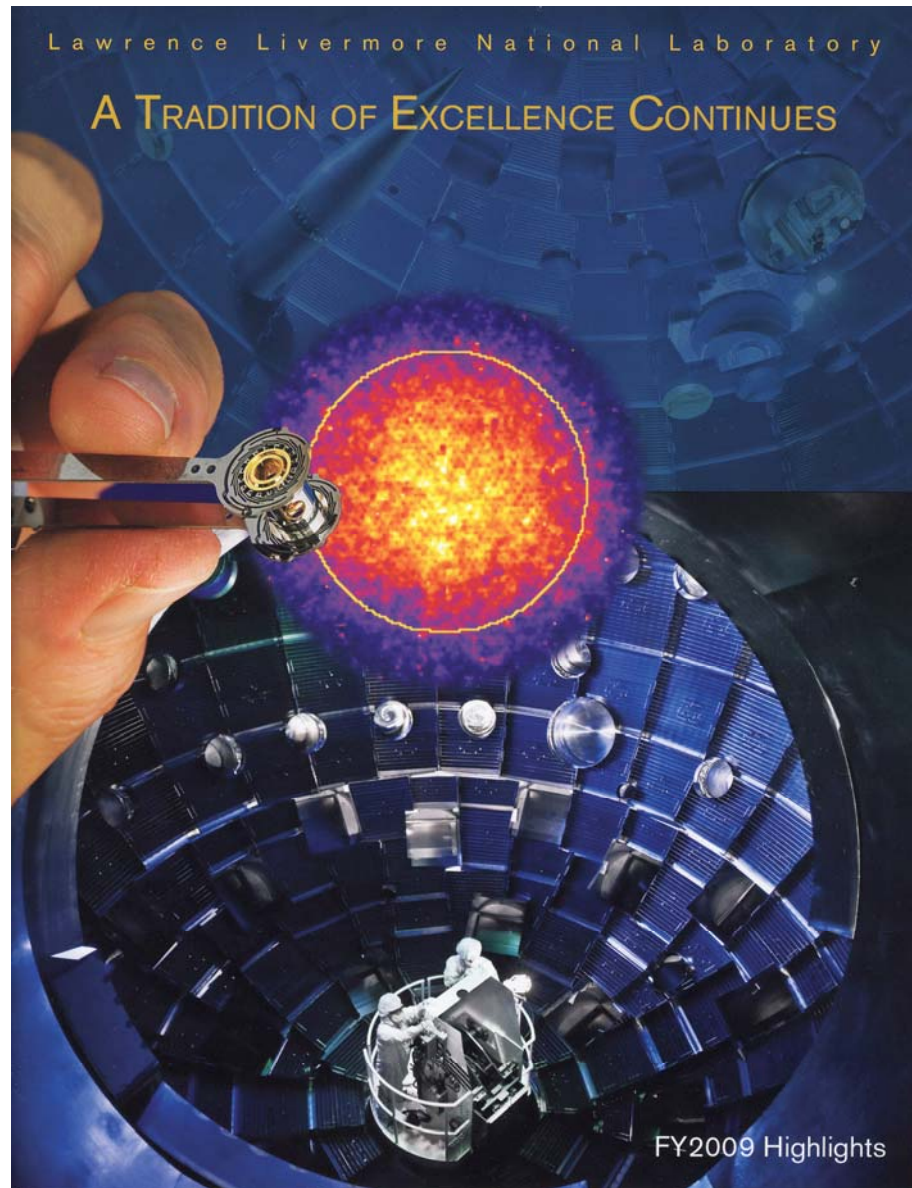
Glass Slabs LRU





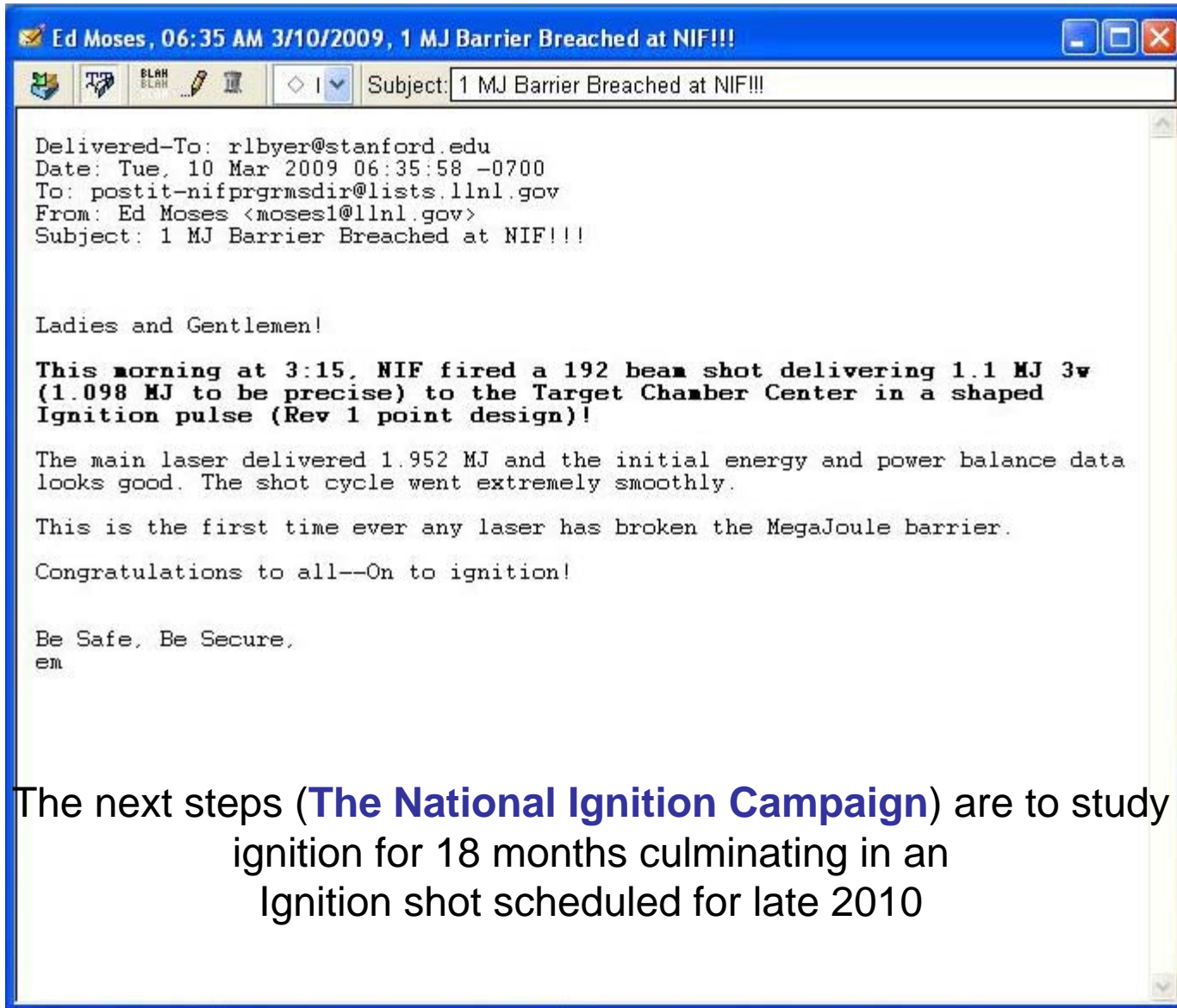
NIF 2009 Highlights

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

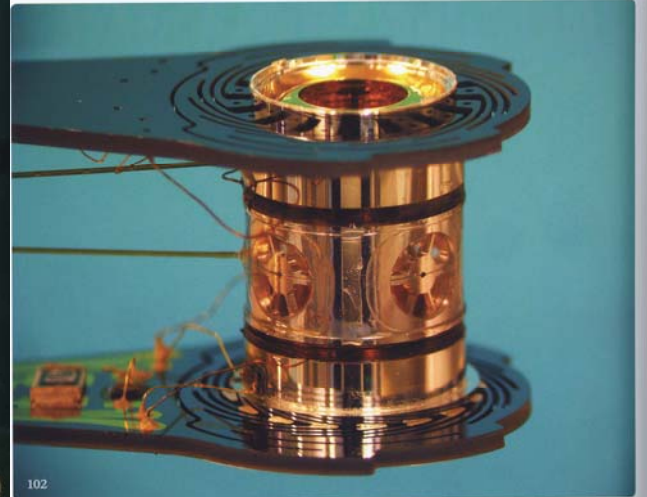
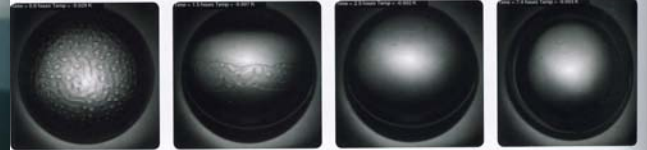



The next steps (**The National Ignition Campaign**) are to study ignition for 18 months culminating in an Ignition shot scheduled for late 2010



NIF Target Holder and Cryo-Target

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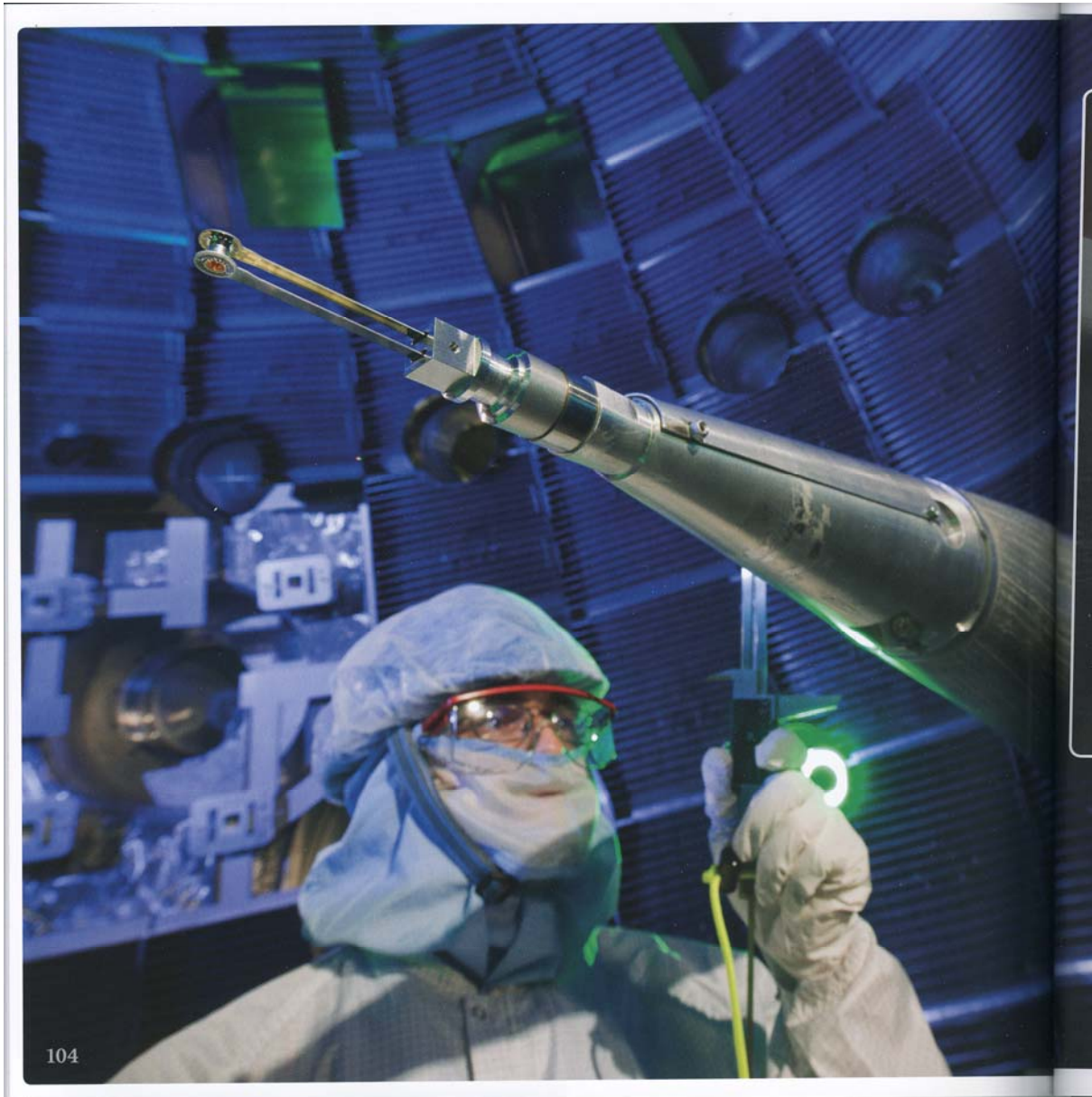


 Above: A NIF target contains a polished capsule about 2 millimeters in diameter, filled with cryogenic hydrogen fuel. (opposite page) A metallic case called a hohlraum holds the fuel capsule for NIF experiments. (top row, from left) This sequence of x-ray images shows hydrogen (the deuterium-tritium fuel) inside the capsule during the freezing and smoothing process. The final temperature is about 18 kelvins (-427 degrees Fahrenheit).



Cryo holder at Center of Target Chamber

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PHYSICS

Controlling Implosion Symmetry Around a Deuterium-Tritium Target

Peter A. Norreys

One of the goals of 21st-century physics—controlling the implosion of a target and initiating nuclear fusion—has its origins in one of the puzzles of 19th-century physics. The understanding of thermal radiation emitted from a cavity (“blackbody radiation”), which is an important component of the fusion problem, began by abandoning classical physics and adopting the revolutionary idea of energy quantization. Thermal

radiation has reappeared in the fusion problem because the powerful megajoule-class lasers do not implode their targets directly—instead, they create intense radiation pressure within a cavity. On pages 1231 and 1228 of this issue, Li *et al.* (1) and Glenzer *et al.* (2) show that the distribution of radiation inside a cavity can be accurately controlled to create a symmetrical implosion, thereby removing major obstacles to the realization of fusion energy in the laboratory. These new insights promise another revolution in physics in the near future, one that provides access to new states of matter with unprecedented energy densities.

Fusion power is a step closer with the demonstration of control over the extreme thermal radiation pressure created by high-power laser beams within a cavity.

The ideal limit of a thermal emitter, a “black body,” absorbs all incoming radiation. In practice, the best black body to study is a small hole in an enclosed cavity; almost all incoming light will be absorbed on its walls before finding a reflecting pathway back out (see the figure, panel A). Classical physics accounted for thermal emission from an object as a continuous process resulting from accelerating electrical charges and predicted that more radiation would be emitted as the wavelength of light decreased. The classical theory not only failed to account for the intensity of thermal emission peaking at some frequency, but also suffered from the “ultraviolet catastrophe”—a

Central Laser Facility, Science and Technology Facilities Council (STFC) Rutherford Appleton Laboratory, Didcot, Oxfordshire OX11 0QX, UK, and Blackett Laboratory, Imperial College London, Prince Consort Road, London SW7 2BZ, UK. E-mail: peter.norreys@stfc.ac.uk

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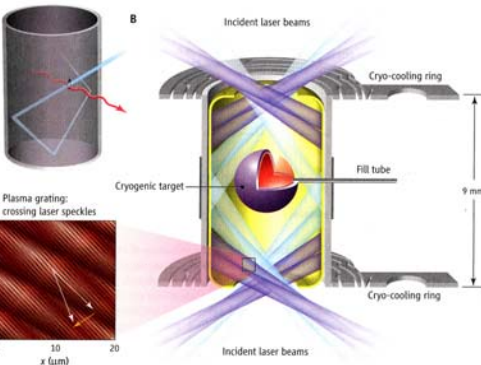
PERSPECTIVES

black body, or any other object with a temperature, would emit an infinite amount of energy.

The solution would lie with the concept that light is emitted in packets, or quanta, as pioneered by Max Planck in 1900. His new theory accurately predicted the intensity and the frequency spectra of blackbody radiation as a function of temperature. In doing so, Planck reconciled electromagnetism with statistical mechanics, which describes the energy distribution of a gas in thermal equilibrium.

Unlike molecules in a gas, radiation in a cavity does not come to equilibrium by experiencing collisions in the middle of the box. Energy can shift from one frequency mode to another by charge oscillations induced in the wall material. Energy can then be transferred to other charges in the wall, and these will oscillate and radiate at different frequencies. Eventually, the radiation inside the box comes to thermal equilibrium, which can be measured when it eventually escapes the cavity through the hole.

This old problem received a new lease on life with the invention of lasers in the second half of the 20th century. It was quickly realized that these devices can deliver immense energy densities to a small target. If that energy could be captured and enclosed in a cavity similar to Planck’s black box, called a hohlraum, then the resulting blackbody radiation would have its maximum at frequencies in the soft x-ray regime, which corresponds to cavity temperatures of millions of kelvin. This value is many orders of magnitude more powerful than anything that Planck considered. Indeed, this blackbody radiation is so powerful that it can then be used to implode a small shell of material containing fusion fuel (deuterium and tritium, the isotopes of hydrogen) to



Thermal radiation, then and now. (A) The classical blackbody source is a hole in a blackened cavity. Light coming in (shown in blue) will absorb as it bounces around; the emission (red) is thermal radiation from the cavity walls. (B) A schematic illustration of the radiation cavity, or hohlraum, containing the shell that has a layer of deuterium-tritium fusion target frozen on its inner surface. The cavity is kept at cryogenic temperatures by two cooling rings at the top and bottom; laser radiation will increase the temperature above 3 million kelvin. The 192 laser beams of the National Ignition Facility enter the hohlraum from both the top and bottom of the chamber. They are arranged in four cones of beams. The radiation symmetry is controlled by adjusting the wavelength of the two inner cones with respect to the outer two cones. (C) An expanded view of the overlap point of the beams, which combine to form a plasma diffraction grating. The arrows depict how the wave vectors of the beams (long arrows) combine to generate the wave vector of the grating (short arrow).

must converge at the center of the pellet at peak compression, must be timed accurately. Finally, hydrodynamic instabilities that are seeded by imperfections (residual mass perturbations in the original shell) must be controlled (4, 5).

The radiation temperature needed for fusion is at least 3 million kelvin, which would require nearly a megajoule of laser energy delivered in several nanoseconds, corresponding to peak powers of 500 TW. Given that the entire world’s electricity generation output is

thermore, striations previously observed with direct laser illumination of shell targets are absent with the soft x-ray drive (7).

The worry is that these structures could affect both the energy absorption (via laser beam scattering or self-focusing) and parametric instability growth in the larger targets needed for fusion energy gain that will be used at the National Ignition Facility (8). Fortunately, this is not the case. Indeed, Glenzer *et al.* demonstrate greater than 90% energy coupling to the hohlraum (see the figure,

Experiments show that beam control (wavelength and pointing) can shape implosion symmetry

Targets illuminated by 192 beams at 355nm in UV with > 1MJ of energy

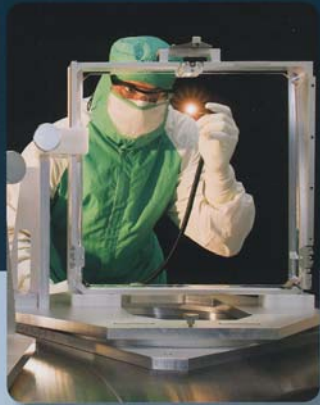


X-ray images of compressed Target Shots 1MJ UV Laser Energy - Sept 2, 3, 4, 5, 2009

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NATIONAL IGNITION FACILITY

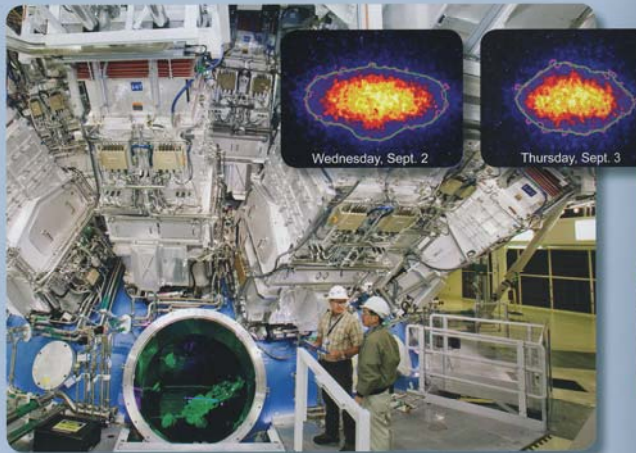
Completing the NIF project and beginning the campaign to achieve fusion ignition



NIF is the most energetic laser system in the world and the only facility capable of creating the conditions necessary for fusion ignition and burn in a laboratory setting. NIF epitomizes the kind of versatile "big science" that has been a hallmark of the Laboratory for more than 50 years. It is a critical experimental facility for stockpile stewardship and an important international scientific resource. Experiments at NIF will help resolve key issues about nuclear weapons

performance; provide a unique experimental platform to study how materials behave under extreme temperatures and pressures; and demonstrate the potential of laser fusion as a clean, sustainable energy source for the future.

A technician examines a slab of laser glass for minute defects (above). National Ignition Facility engineers inspect the exterior of the target chamber (right). First results from hohlraum experiments demonstrated the use of wavelength tuning to adjust the shape of the implosion from asymmetric to spherical (inset images).



2009 HIGHLIGHTS

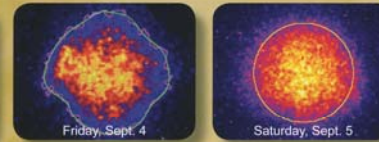
NIF Dedication

NIF was formally dedicated on May 29, 2009, exactly 12 years to the day after its groundbreaking. More than 3,500 guests attended the ceremony, including California Governor Arnold Schwarzenegger; California Senator Dianne Feinstein; local Congressional Representatives Ellen Tauscher, Jerry McNerney, and Zoe Lofgren; University of California President Mark Yudof; LLNS Board of Governors Chairman Norm Pattiz; DOE Under Secretary of Science Steve Koonin; and NNSA Administrator Tom D'Agostino. Charles Townes, the inventor of the laser, also attended, along with many former LLNL directors and laser and fusion leaders from around the world. The event attracted national media attention, with portions aired live on network television.

Two months earlier, on March 31, 2009, DOE certified the completion of the NIF construction project. At that occasion, D'Agostino stated, "Completion of NIF is a true milestone that will make America safer and energy independent by opening new avenues of scientific advancement and discovery."

Breaking the Megajoule Barrier

At 3:15 a.m. on March 10, 2009, NIF became the first laser facility in the world to break the megajoule barrier. The shot, which was designed to last only a few nanoseconds, delivered 1.1 megajoules of ultraviolet energy to the center of the target chamber. The energy and power balance met expectations, and,



the pulse shape precisely matched that required for ignition. NIF is systematically ramping up to deliver its design specification of 1.8 megajoules of ultraviolet energy.

Progress toward Ignition

Early results from the National Ignition Campaign (NIC) and the opportunity to tour NIF were highlights for the 600 researchers from around the world who attended the Sixth International Conference on Inertial Fusion Sciences and Applications, which was held in San Francisco in September 2009. By conference time, the first 11 experimental shots using 192 beams had been performed, all at an ultraviolet energy of approximately



500 kilojoules. The last four shots were fired into cryogenically cooled targets and provided excellent data; these were the first experiments with neutron yield.

One of the most talked-about conference presentations featured the first results from NIC hohlraum experiments in which a technique called wavelength tuning was used to greatly improve implosion symmetry. An initially asymmetric implosion with a "pancake" shape was formed into a spherical one by changing only the wavelength of some of the laser beams. These results confirmed our prediction that the wavelength tuning technique would work. This prediction was based on the results of high-fidelity three-dimensional simulations of the complex laser-plasma interaction processes, which were published in *Physical Review Letters*.

LIFE for Future Energy Security

At the National Energy Summit and International Dialogue, which was held this September in Washington, D.C., Director George Miller asserted that given sufficient funding, a prototype Laser Inertial Fusion Engine (LIFE) power plant could be brought into operation within 15 years. LIFE builds on the anticipated achievement of fusion with NIF and holds considerable promise as a sustainable carbon-free source of energy. The baseline concept is a pure fusion machine. LIFE could also be developed as a fusion-fission combination to meet other missions, such as destroying excess weapons-grade materials or disposing of spent nuclear fuel from today's light-water reactors, while generating copious amounts of electrical energy.

Creating a MEGaRAY

Laboratory researchers made important progress toward developing an intense, tunable source of mono-energetic gamma rays, called MEGaRAY. The concept is based on the interaction of a laser and an electron beam to generate a tunable laser-beam-like photon source in the mega-electron-volt spectral range that is 15 orders of magnitude brighter than any other source. MEGaRAY efficiently excites the nucleus through a process called nuclear resonance fluorescence (NRF), which provides a unique fingerprint of the target's isotopic content. Similar to the way lasers have greatly advanced the study of atoms and molecules, this technology has the potential to revolutionize the study of the nucleus, creating applications in such areas as the detection of special nuclear material. In FY2009, we demonstrated the NRF technique for identifying a material using our first-generation tunable gamma-ray source and began development of an improved laser system for the next-generation MEGaRAY.

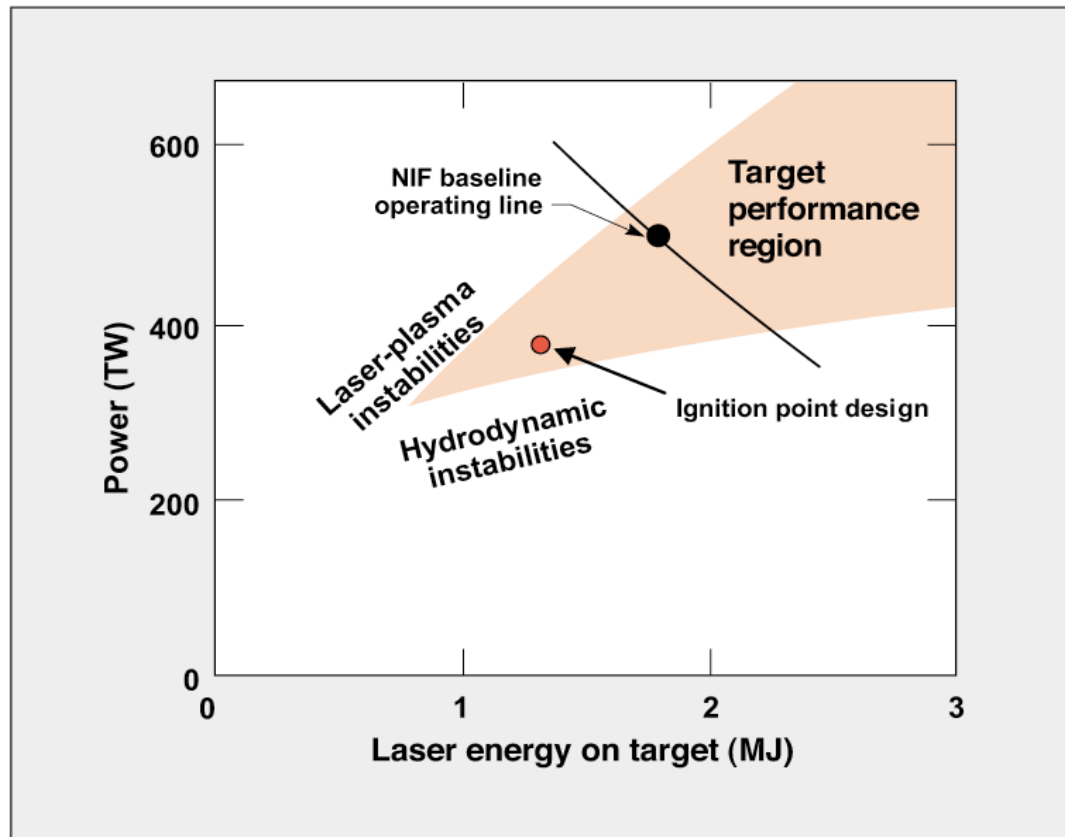


1.8 MegaJoules of UV Energy exceeds Ignition Point by 2x

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



The National Ignition Facility



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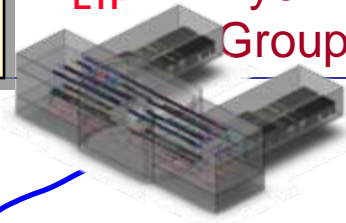
X4187

A series of target compression studies are planned for 2010
Goal: confirm all aspects of target performance prior to a fusion burn shot

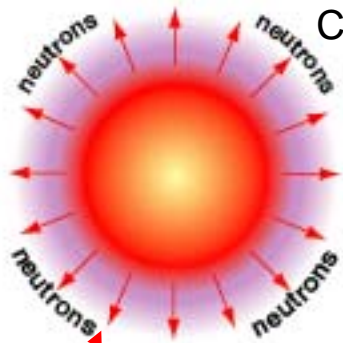
The development of Inertial Fusion Energy will require new Megawatt average power & Petawatt peak power lasers

2035
ETF

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**40 MW UV Laser
with >10% wall
plug efficiency**



Compression creates the igniting hot spot
This is "diesel" like ignition

2009
NIF



1MJ UV 1shot/4hr

2005
HAPL



50J 10 Hz

1992

Fast Ignition
Invented
@ LLNL

1984
Nova



30kJ UV

1977
Shiva



10kJ IR

1974
Janus



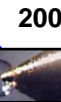
100J IR

1972

Birth of
ICF@
LLNL



1996 Nova PW



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



2009 3kJ ARC PW on NIF

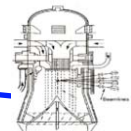
2010 Ignition at NIF



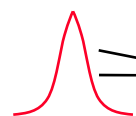
~2016 Full-scale
Fast Ignition on NIF



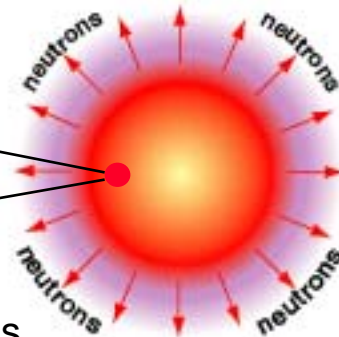
2025
FI ETF



**1 MW, 100 PW
Laser**



Petawatt laser pulse
creates the hot spot
Fast Ignition is
"spark plug" ignition



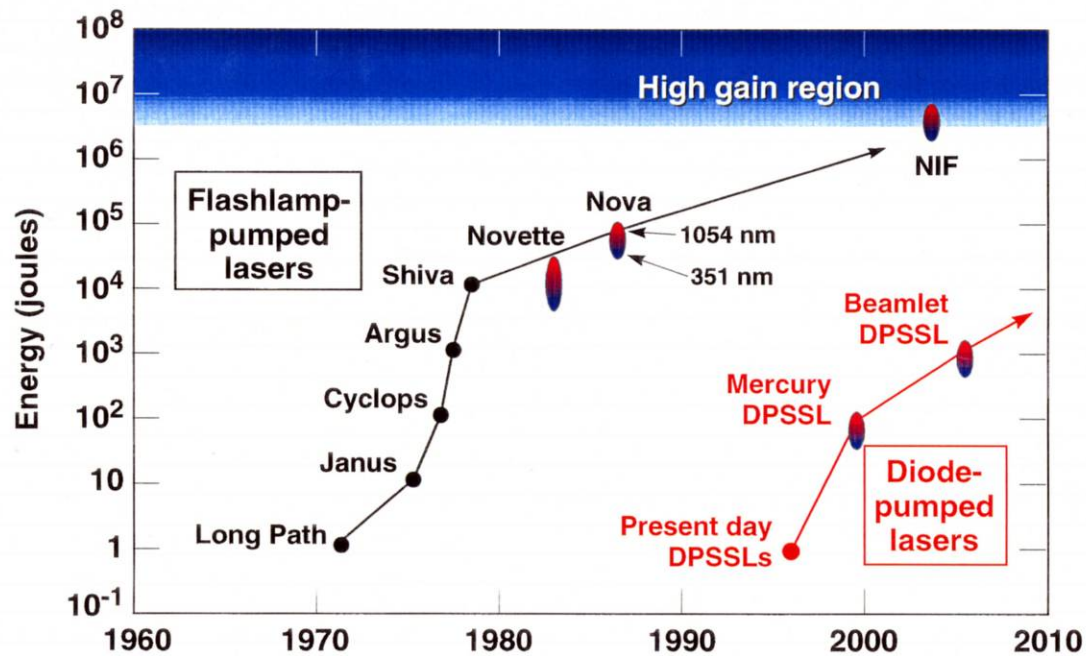


Scaling to IFE drivers for reactor design 1-2 MJ, 16 Hz, 10% efficiency - IFE forum of Japan

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



Continuous pour of Nd:Glass allowed lower cost for NIF (However, low thermal conductivity of glass limits average power)

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Group



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

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Group



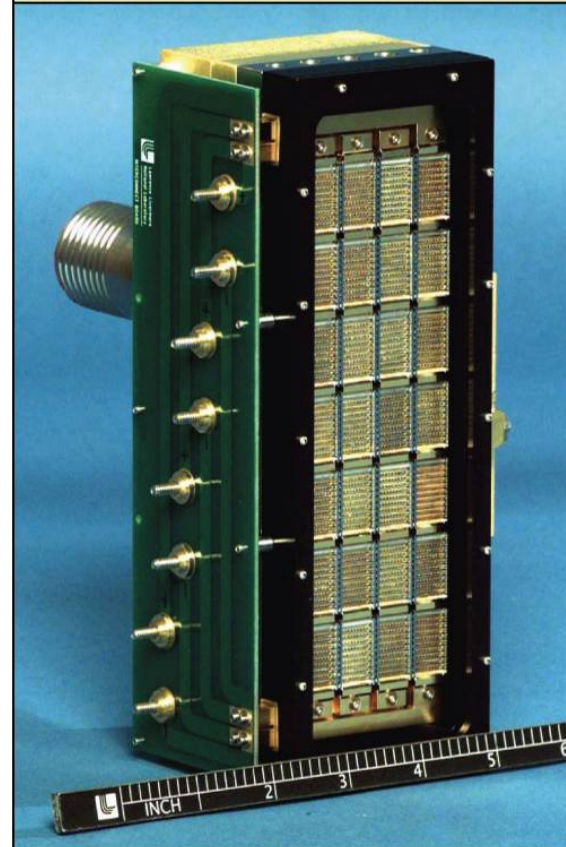
The National Ignition Facility

Flashlamps



10% electrical-optical efficiency

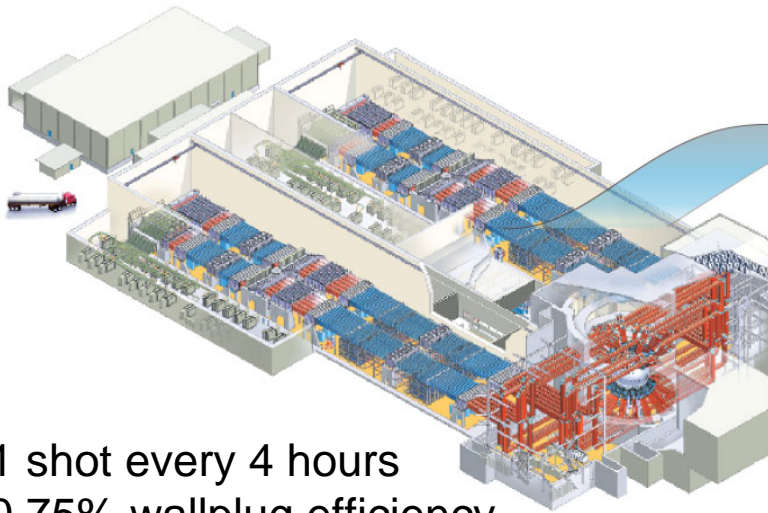
Diodes



60% electrical-optical efficiency

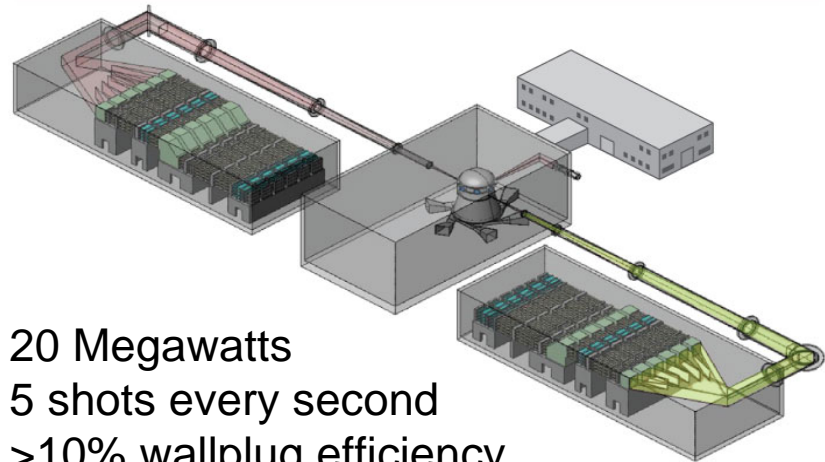
Is NIF/NIC a precursor to an IFE plant?

NIF



1 shot every 4 hours
0.75% wallplug efficiency

LIFE



20 Megawatts
5 shots every second
>10% wallplug efficiency



Laser Inertial Fusion Energy

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Group





Total Eclipse of the Sun, July 22, 2009

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After nearly 50 years of determined effort,
we should see a “sun” in the laboratory for ~ 10 psec duration in 2011



- 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?

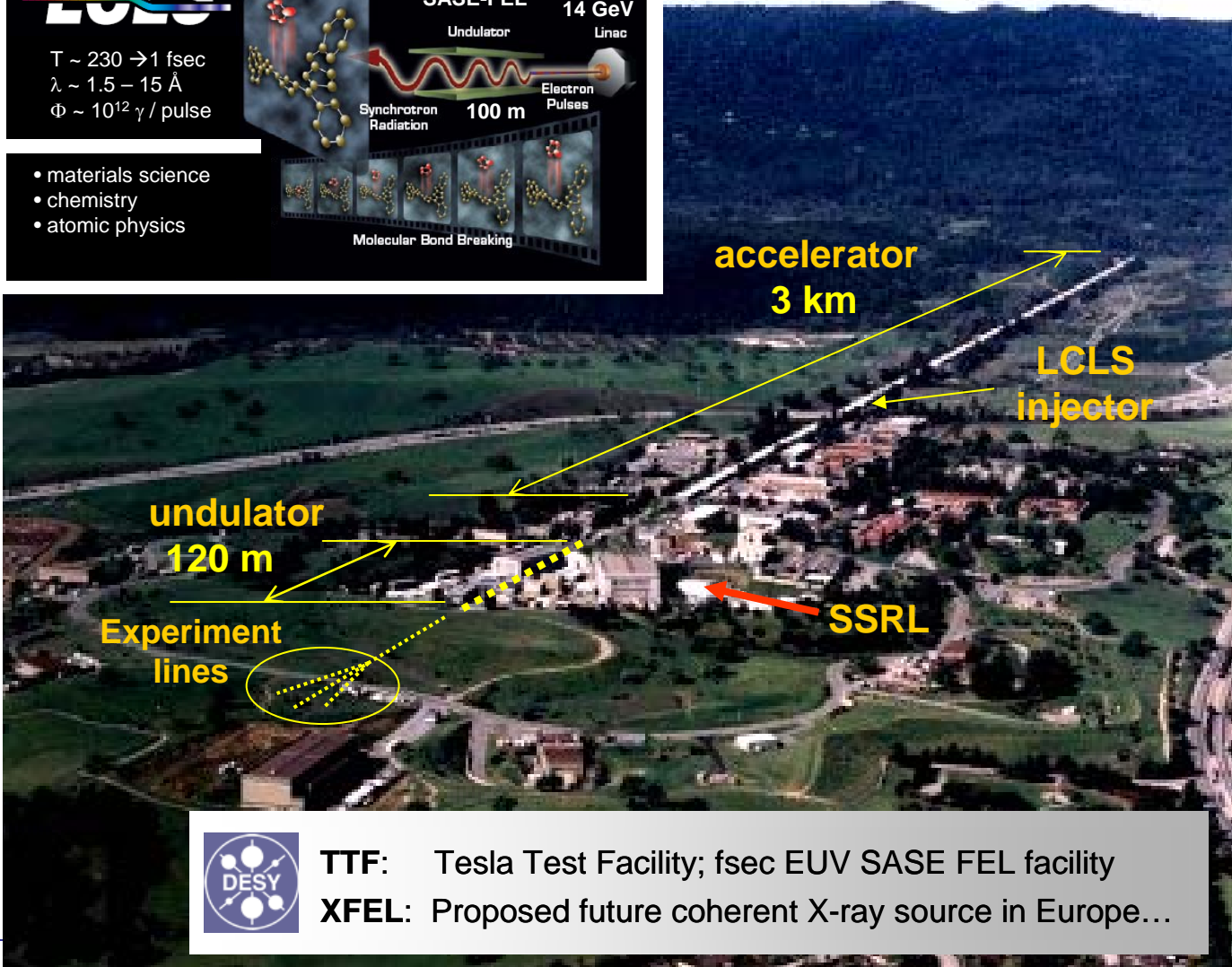
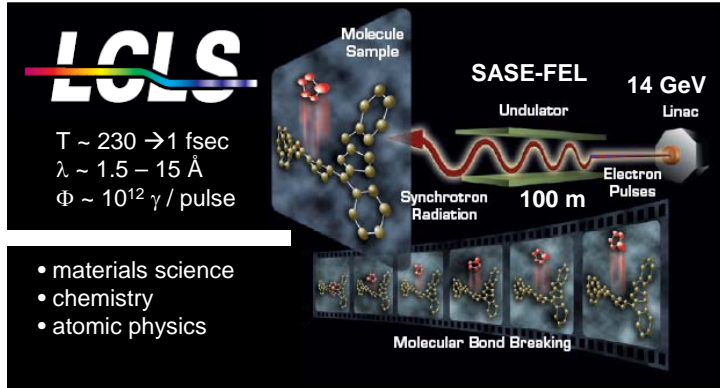
2015 – 5Hz 40kJ single arm of LIFE Laser

2025 – 5Hz 2MJ LIFE Laser Engineering Demo

Post Script - Hello from the **Stanford Photonics Research Center (SPRC)**



RF-accelerator driven SASE FEL at SLAC - April 2009



LCLS properties

- 1 km-size facility
- microwave accelerator
- $\lambda_{RF} \sim 10 \text{ cm}$
- 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**



TTF: Tesla Test Facility; fsec EUV SASE FEL facility
XFEL: Proposed future coherent X-ray source in Europe...



Stanford Photonics Student Group Retreat

April 3 - 4, 2009, Monterey, CA

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Surfing Ocean Waves - Poipu Beach, Kauai

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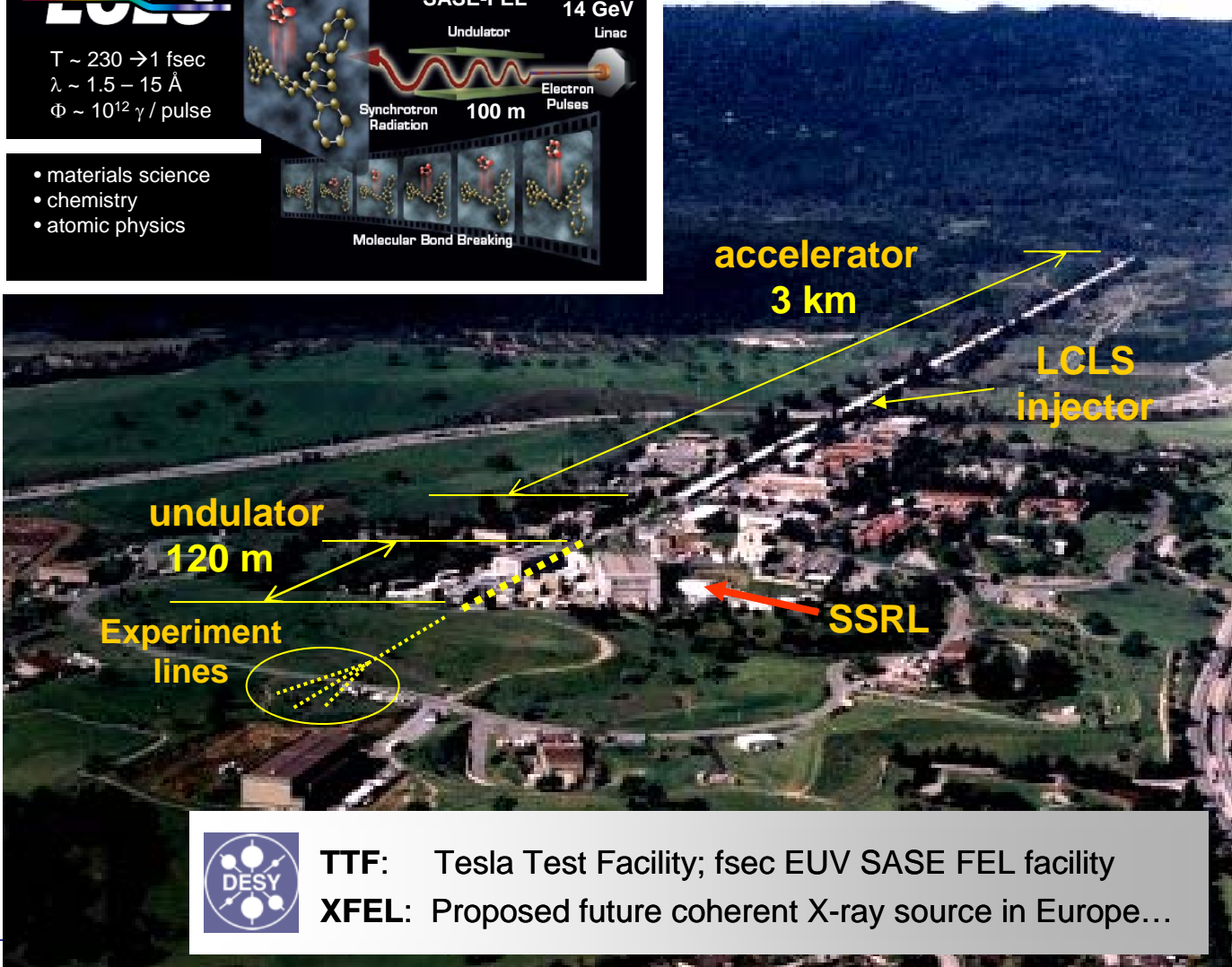
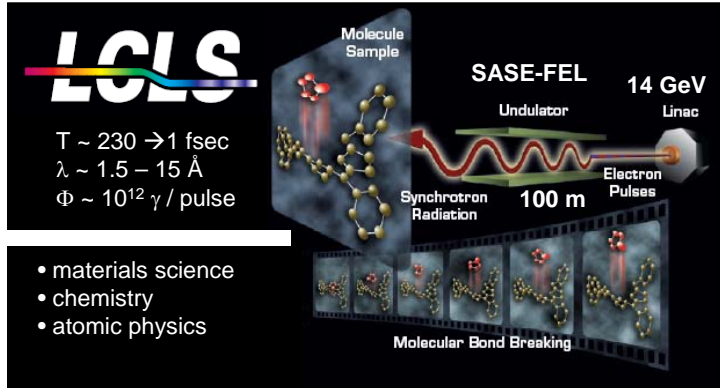




- Prelude
- Introduction *Making Lightwaves*
 - Early laser history and concepts
 - Unstable Resonator
 - Slab Laser - one dimensional cooling
 - Recent Innovations
 - Large Mode Area Fiber Lasers
 - Edge Pumped Slab Laser
 - Transparent 'Ceramic' polycrystalline gain media
- Scientific Applications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



RF-accelerator driven SASE FEL at SLAC - April 2009



LCLS properties

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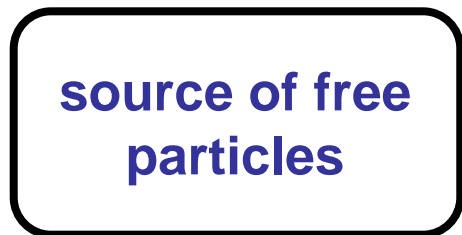
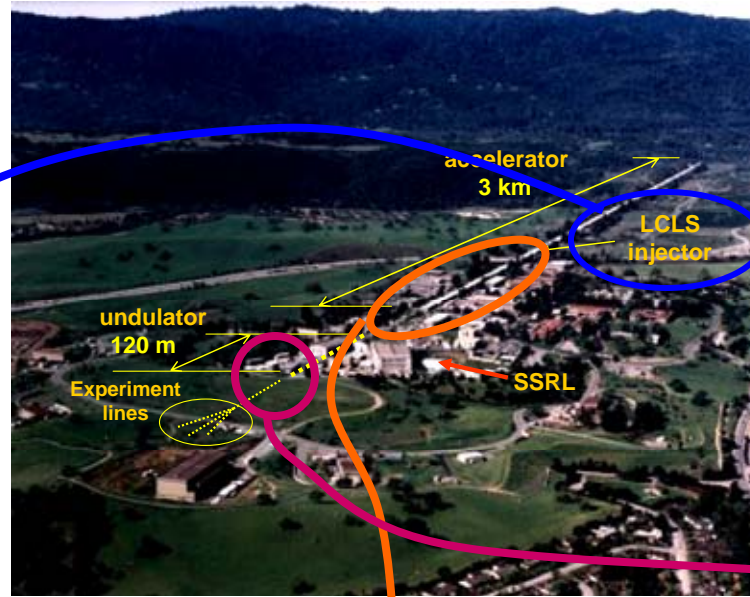


TTF: Tesla Test Facility; fsec EUV SASE FEL facility
XFEL: Proposed future coherent X-ray source in Europe...



The Key Components of the SASE-FEL architecture

SASE - Self Amplified Spontaneous Emission



laser-driven
high rep. rate
very compact



dielectric structure
based laser-driven
particle accelerators

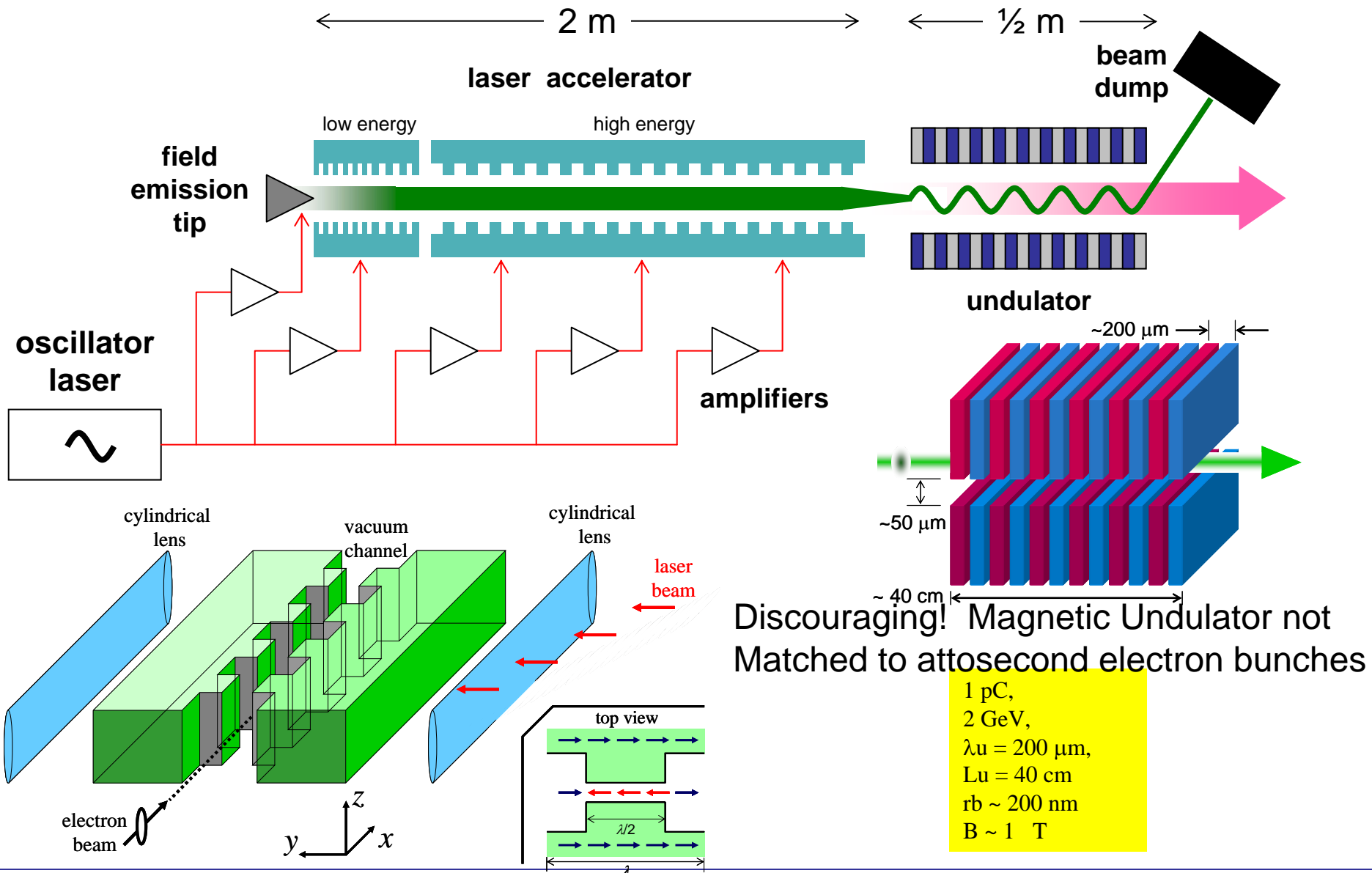


dielectric structure,
laser driven



Proposed parameters for laser driven SASE-FEL (Theoretical Study of FEL operation - summer 2008)

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Group



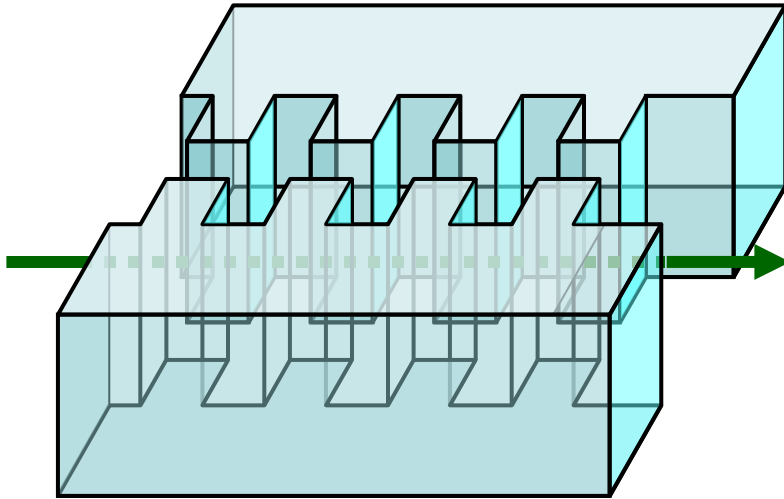


End of Story? NO! Plettner went away and thought real hard -

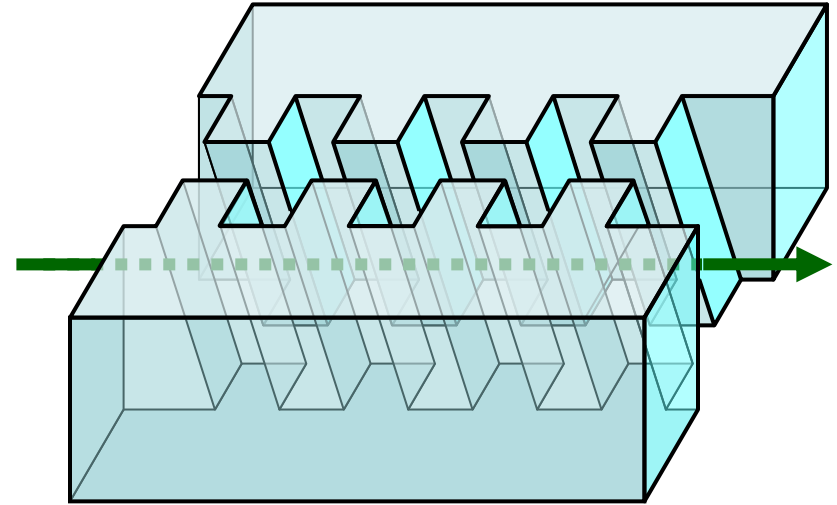
Byer Group

New Idea: Laser-Driven Dielectric Undulator for FEL

accelerator structure



deflection structure



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

$$\langle \vec{E}_\parallel \rangle \sim \frac{1}{2} E_{laser} \rightarrow \sim 4 \text{ GeV/m}$$

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

$$\langle \vec{F}_\perp / q \rangle \sim \frac{1}{5} E_{laser} \rightarrow \sim 2 \text{ GeV/m}$$

key idea

Extended phase-synchronicity between the EM field and the particle

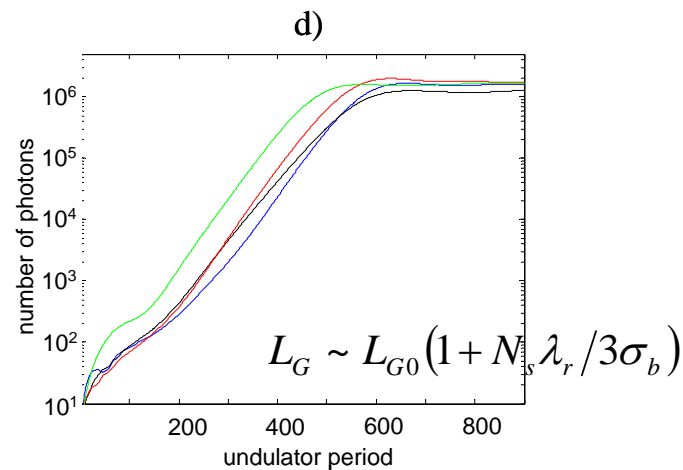
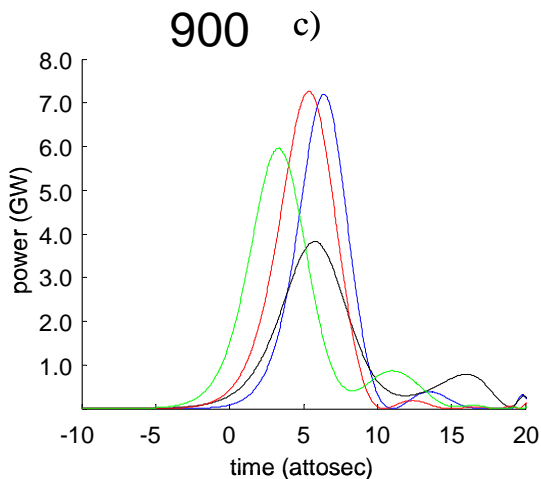
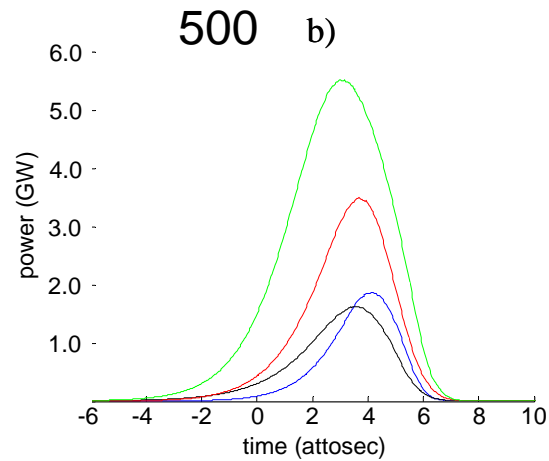
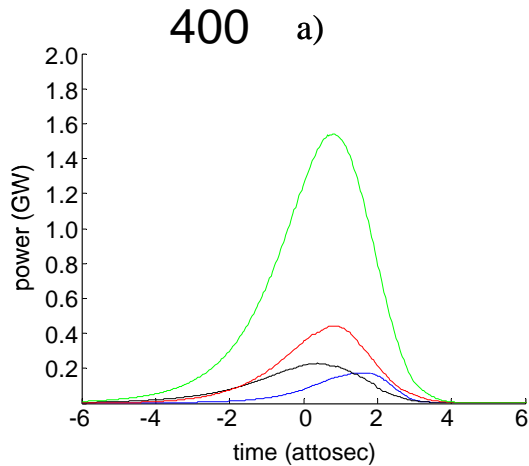
Use modelocked laser to generate periodic deflection field

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)

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$$\rho_{\text{eff}} = U_{\text{FEL}} / U_{\text{beam}} \sim 5 \times 10^{-4}$$

$$\begin{aligned} U_b &= 2 \text{ GeV} \\ \varepsilon_N &= 10^{-9} \text{ m-rad} \\ Q_b &= 20 \text{ fC} \\ \Delta\gamma/\gamma &= 0.1\% \\ \sigma_r &= 200 \text{ nm} \\ \beta^* &= 4 \text{ cm} \end{aligned}$$

$$L_c \sim 21\lambda_r$$

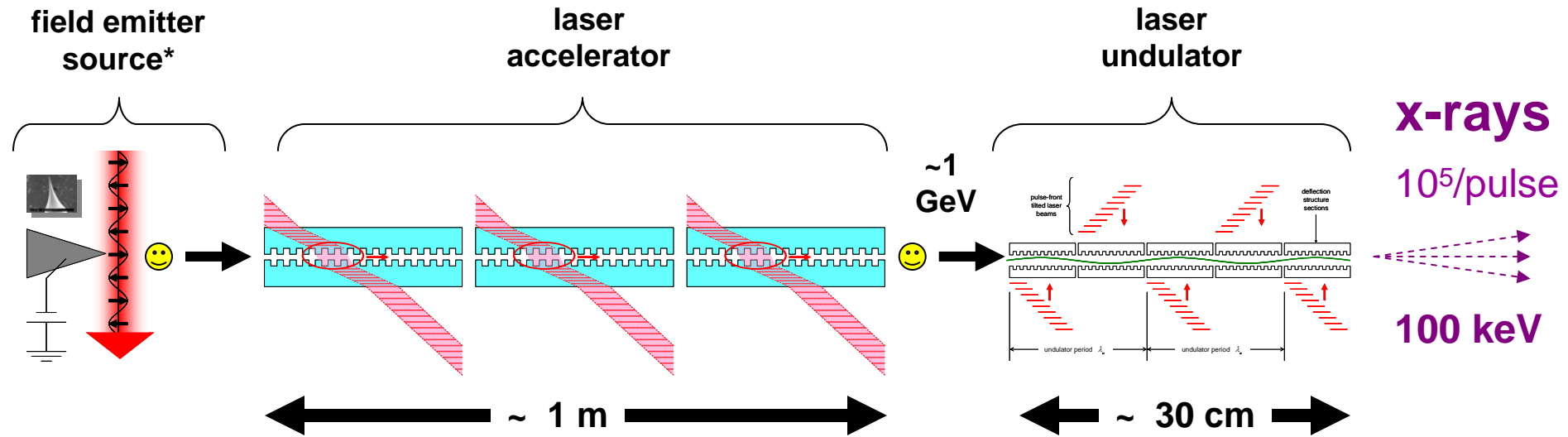
$$\sigma_b \sim 136\lambda_r$$



$$\sigma_b / L_c \sim 6$$

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

Schematic of the tabletop radiation source



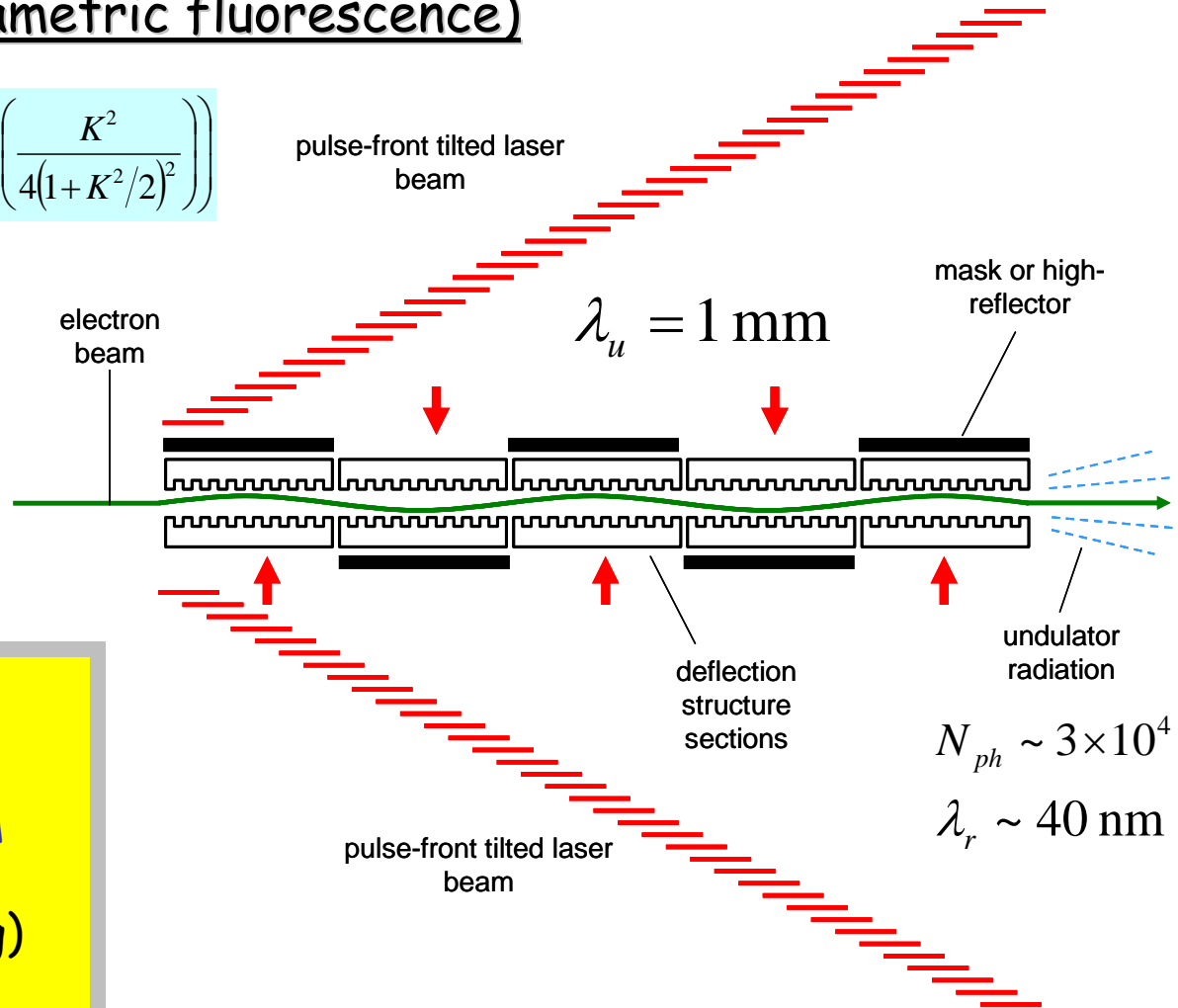
There is a path forward based on a modelocked laser driven dielectric structure





Look for undulator radiation (parametric fluorescence)

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

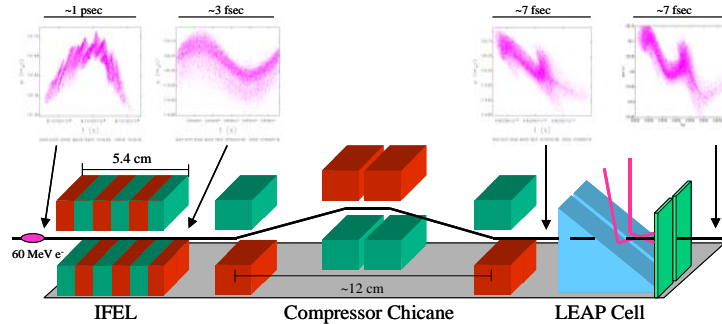


$$N_{ph} \sim 3 \times 10^4$$

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

Use periodicity of grating lattice to conserve momentum
(quasiphasematching)

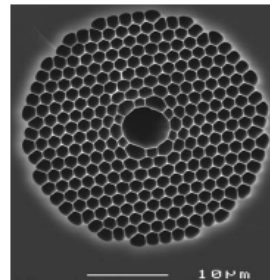
1



Staged acceleration

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

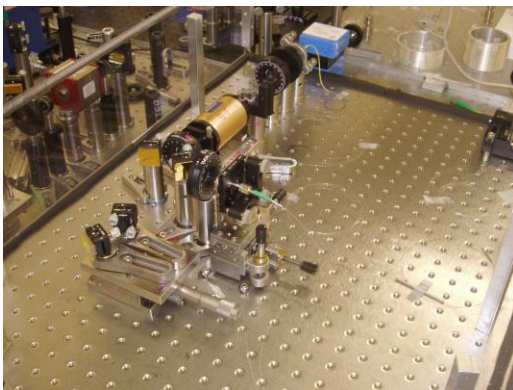
2



Implementation of real accelerator microstructures

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

3

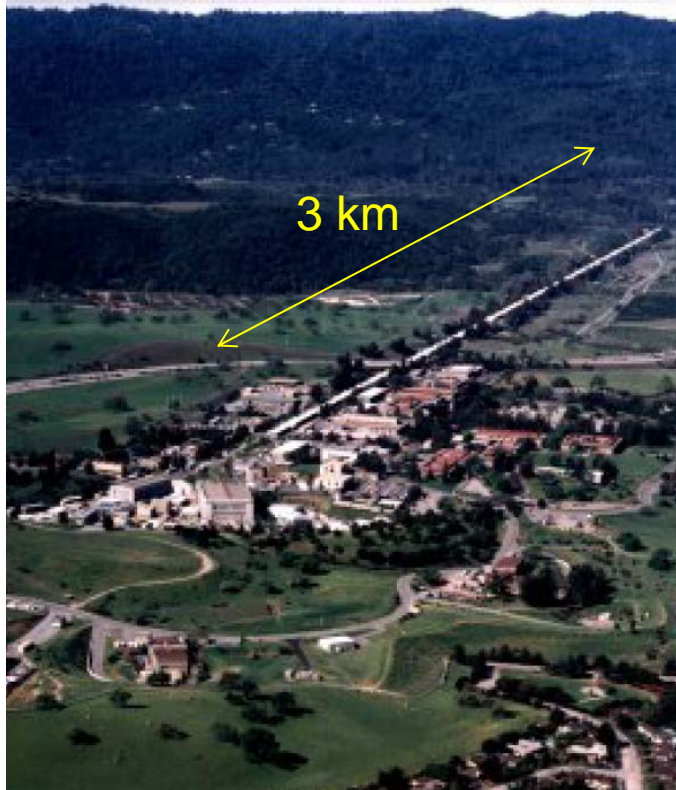


Laser technology

- wavelength $2 \mu\text{m}$
- optical phase control
- wallplug efficiency
- lifetime



- **BACK UP SLIDES**



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

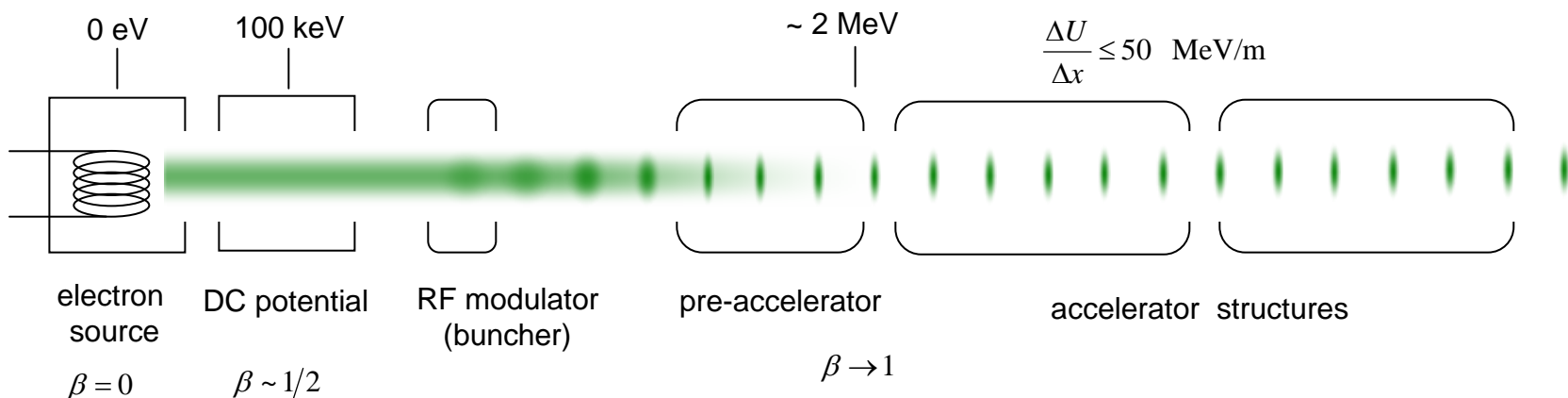
"To be efficient, the accelerator must operate in reverse"

- 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

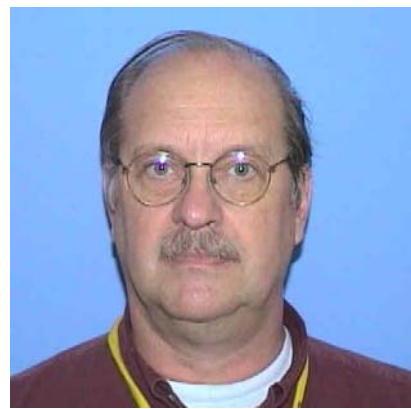
1994 - SLAC summer school

2004 - Successful 1st Exp

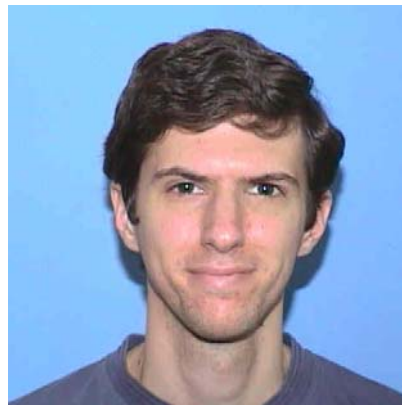


Participants in the LEAP Experiment Laser Electron Accelerator Program

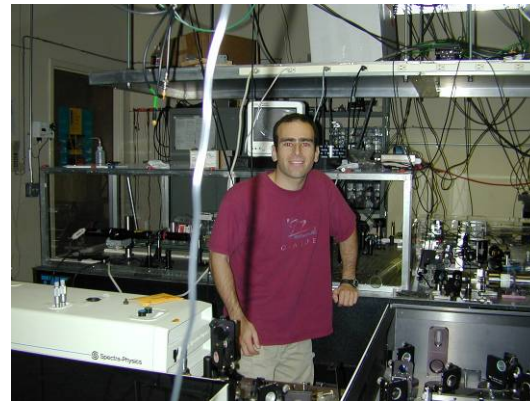
Byer
Group



Bob Siemann²



Chris Sears²



Ben Cowan²



Jim Spencer²



Tomas Plettner¹



Bob Byer¹



Eric Colby²

New students

- Chris McGuinness²
- Melissa Lincoln²
- Patrick Lu¹

Atomic Physics collaboration

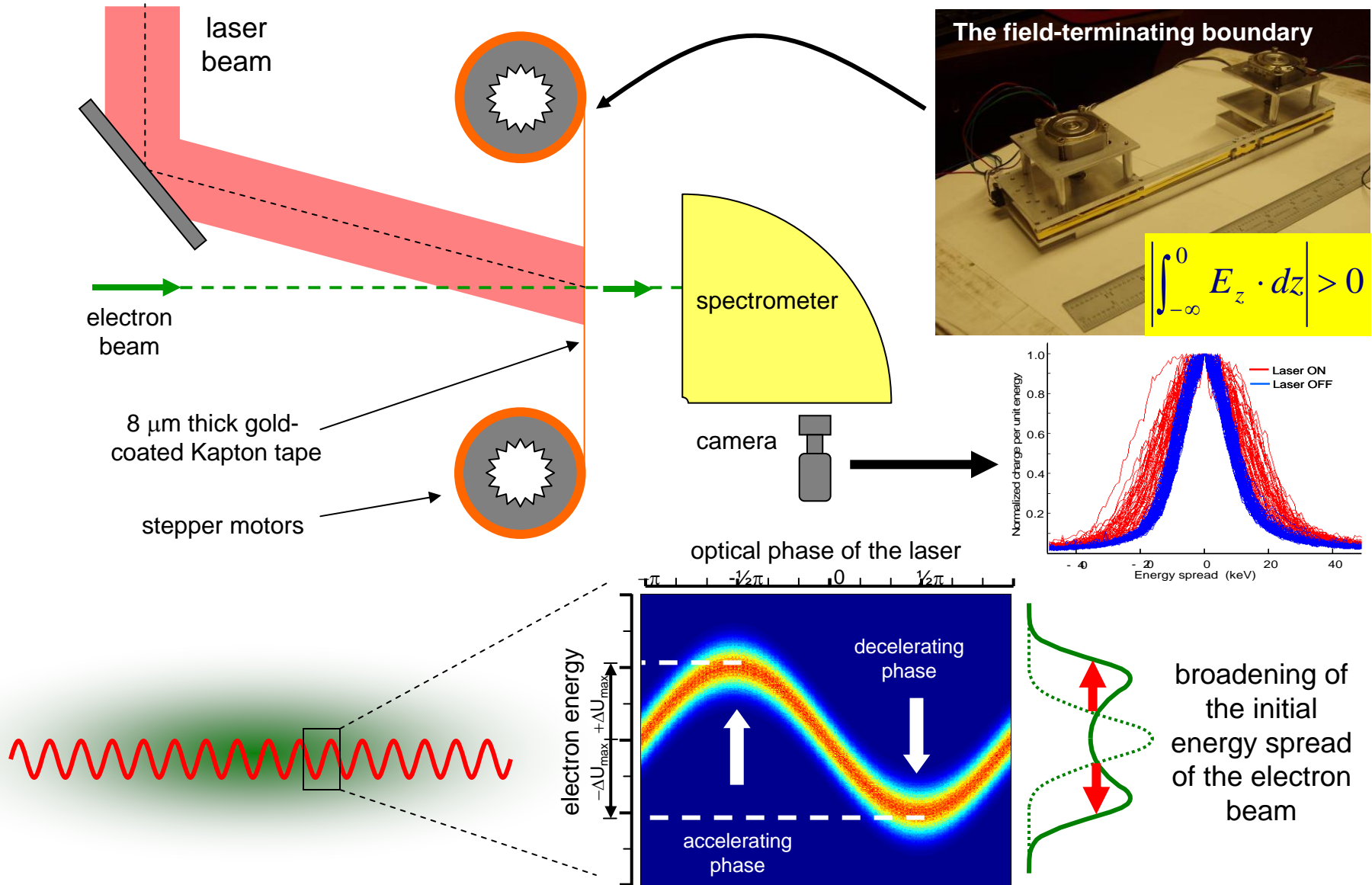
- Mark Kasevich³
- Peter Hommelhoff³
- Catherine Kealhofer³

- 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)

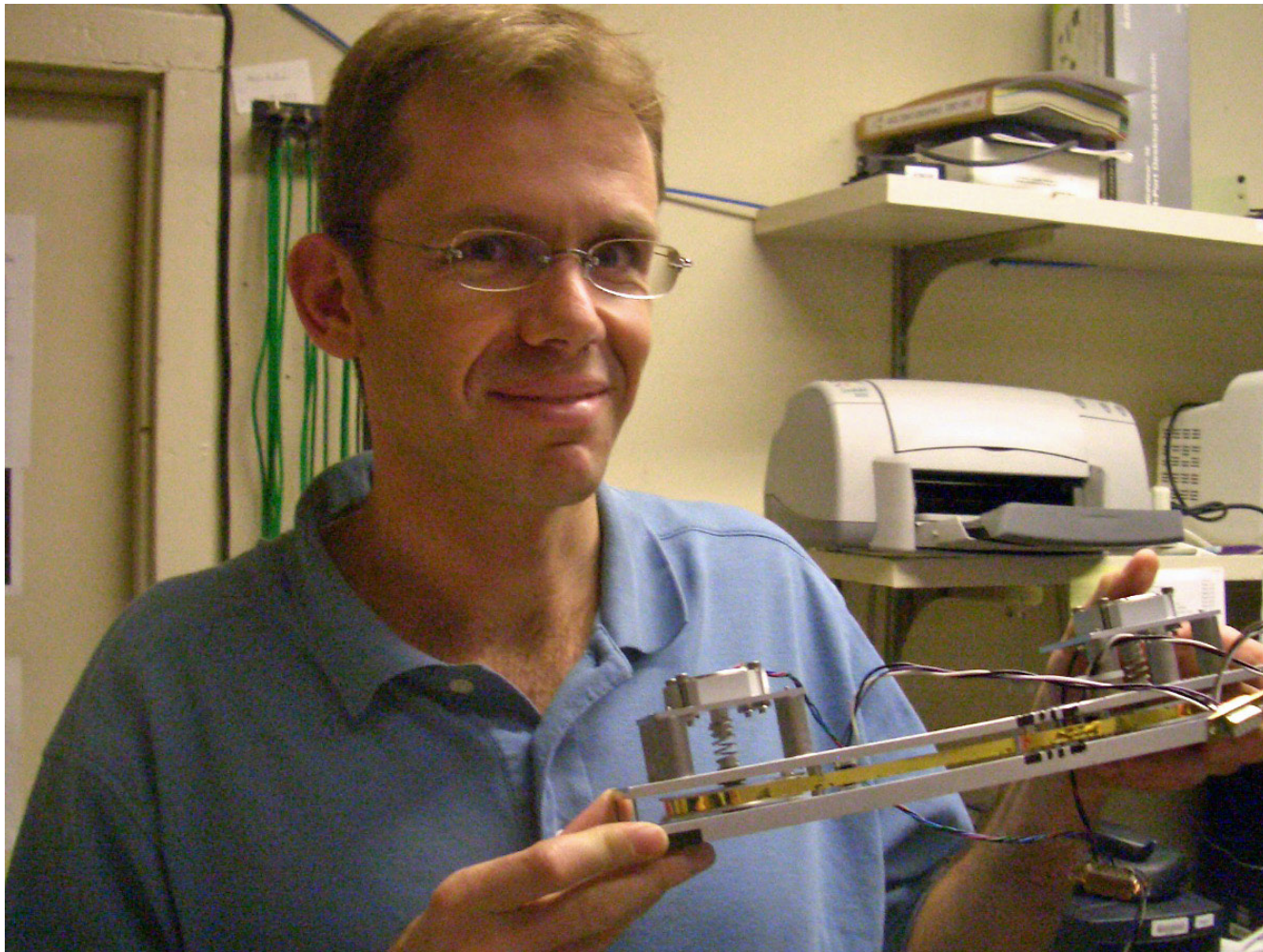
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Tomas Plettner and LEAP Accelerator Cell

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Group



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



We accelerated electrons with visible light

Phys Rev Letts Sept 2005

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Group

PRL 95, 134801 (2005)

PHYSICAL REVIEW LETTERS

week ending
23 SEPTEMBER 2005

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

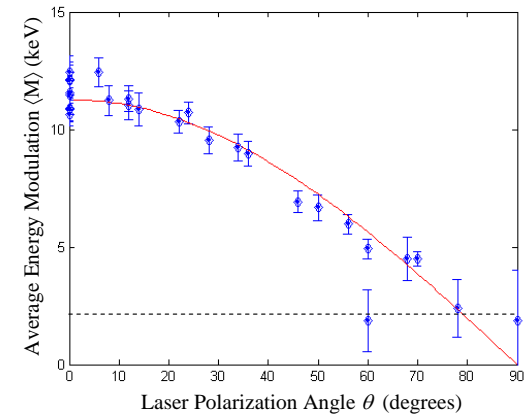
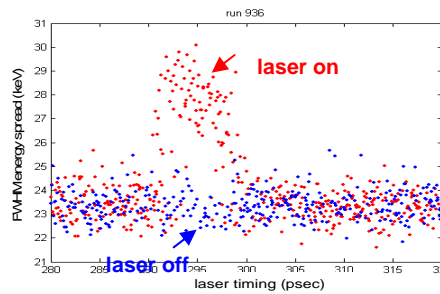
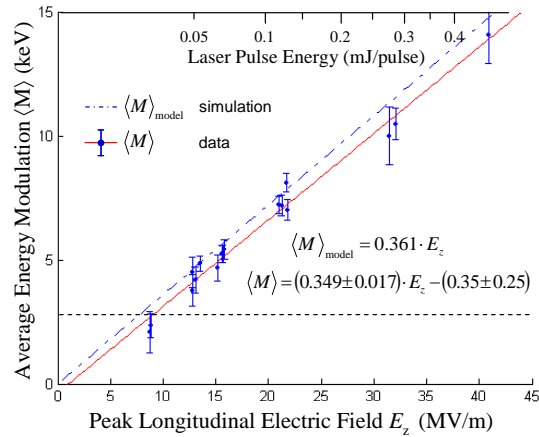
T. Plettner and R. L. Byer

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

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

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

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

laser-driven
linear
acceleration in
vacuum



Ben Cowan - detailed calculations of Photonic Crystal Accelerator Structures

Byer Group

SLAC

Photonic Crystal Laser Accelerator Structures

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

Abstract

Photonic crystal laser structures are promising for high-energy particle acceleration. A photonic crystal structure is a periodic lattice of dielectric material with a periodicity on the order of the wavelength of light. The structure is designed to have a photonic band structure that allows light to propagate in a direction perpendicular to the plane of the lattice. The structure is designed to have a photonic band structure that allows light to propagate in a direction perpendicular to the plane of the lattice.

Three-Dimensional "Woodpile"-based Structures

The Underlying Lattice

Accelerating Modes

Optical Focusing

Dispersing Modes

Fiber Structures

The Underlying Lattice

Accelerating Modes in Photonic Crystal Fibers

Accelerator Mode Content as a Function of Radius

Waveforms

Microscope Tools

Two-Dimensional Planar Structures

The Underlying Lattice

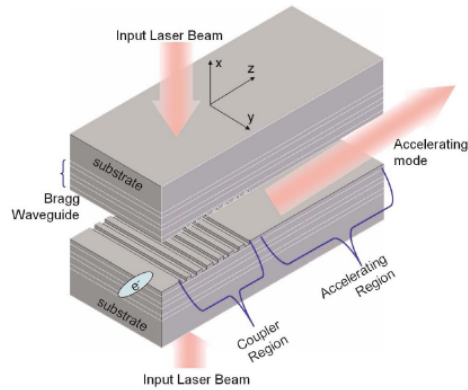
Accelerating Modes

Accelerator Parameter Trade-Offs

Ben Cowan
Stanford University
SLAC

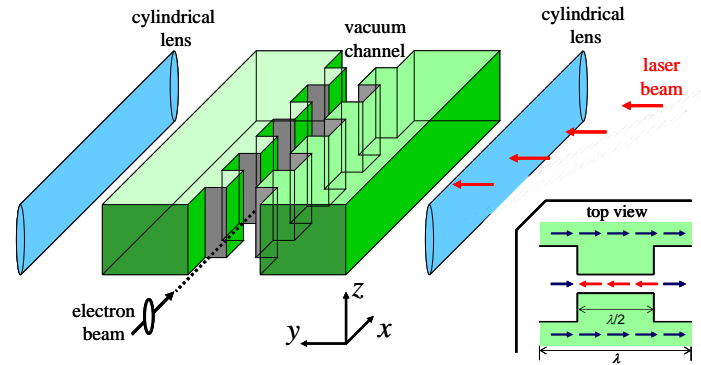


Planar waveguide structures



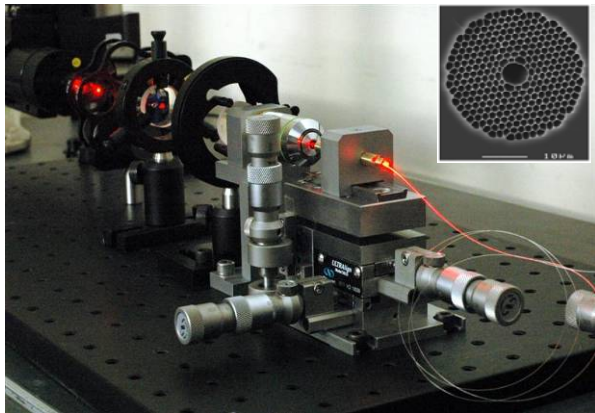
Z. Zhang et al. Phys. Rev. ST AB 8, 071302 (2005)

Periodic phase modulation structures



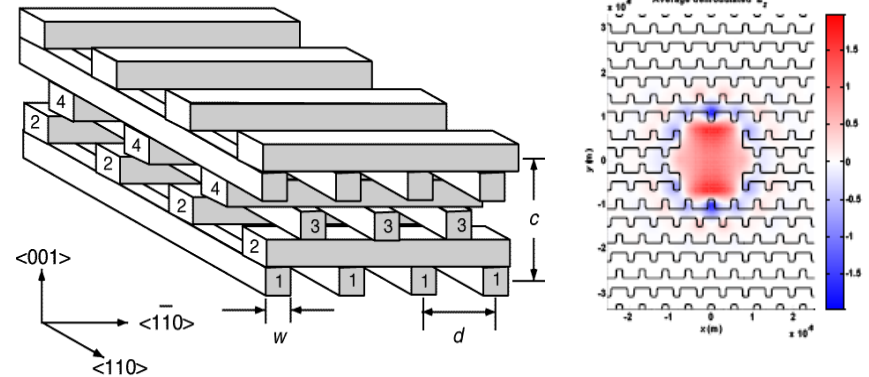
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Hollow core PBG fibers



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

3-D photonic bandgap structures



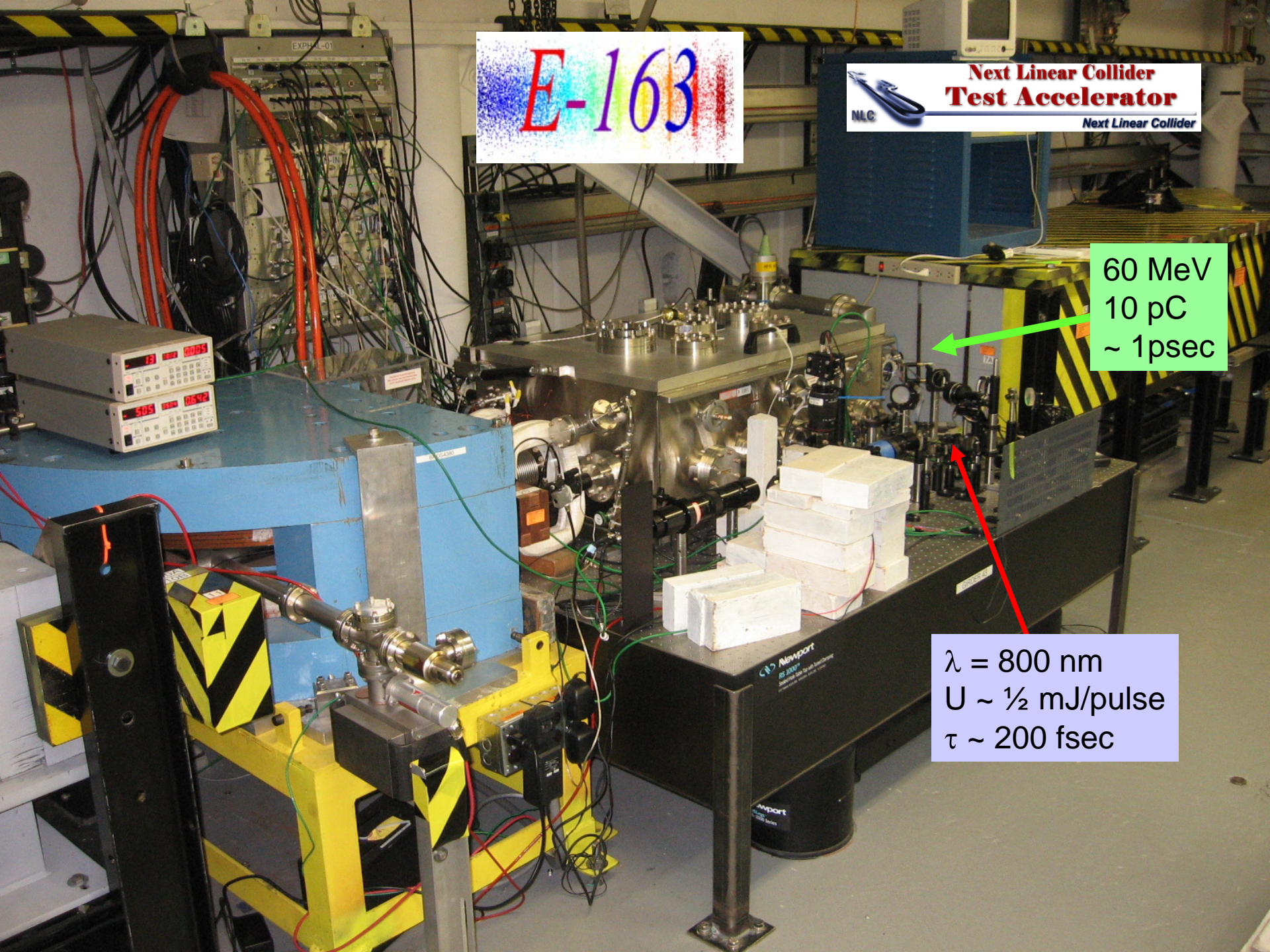
B. M. Cowan, Phys. Rev. ST Accel. Beams, 6, 101301 (2003).

E-163

Next Linear Collider
Test Accelerator
NLC
Next Linear Collider

60 MeV
10 pC
~ 1psec

$\lambda = 800 \text{ nm}$
 $U \sim \frac{1}{2} \text{ mJ/pulse}$
 $\tau \sim 200 \text{ fsec}$

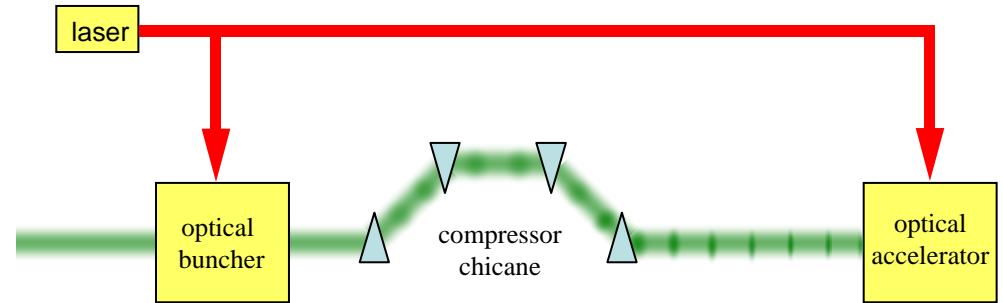
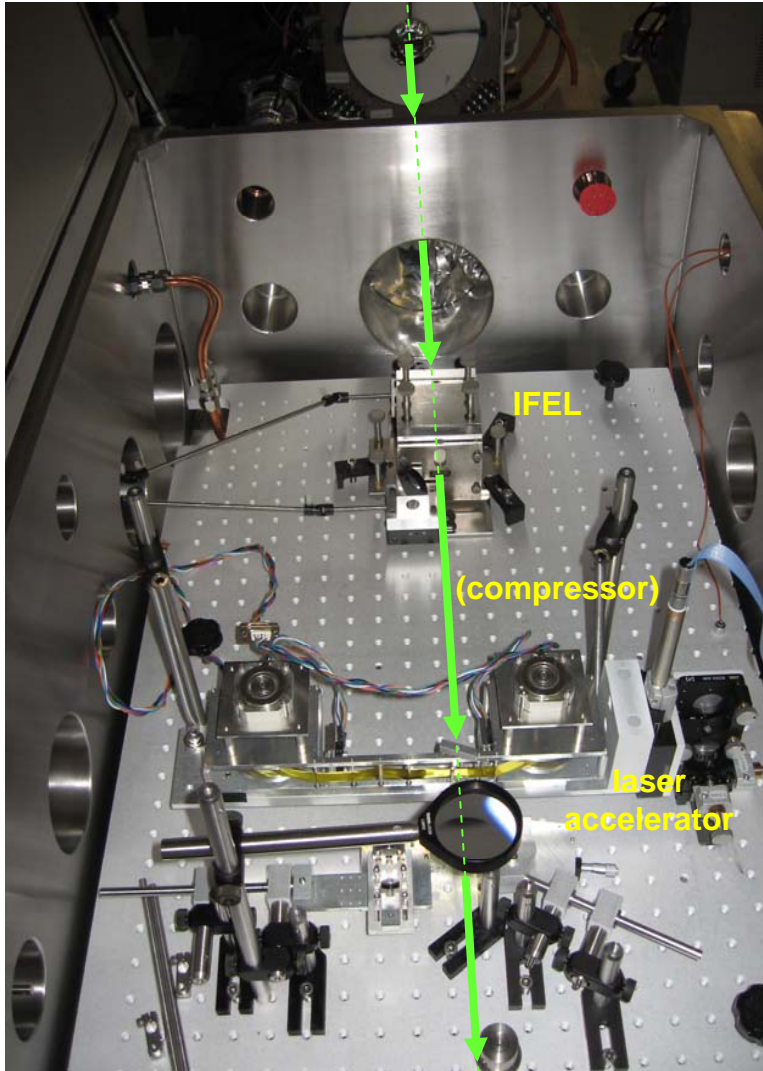




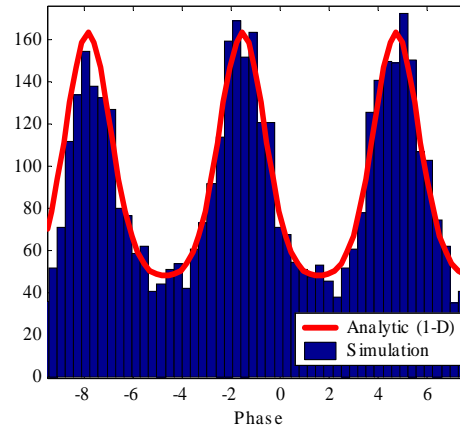
<500 attosecond electron compression in Inverse FEL (Chris. M. Sears, PhD thesis SLAC June 2008)



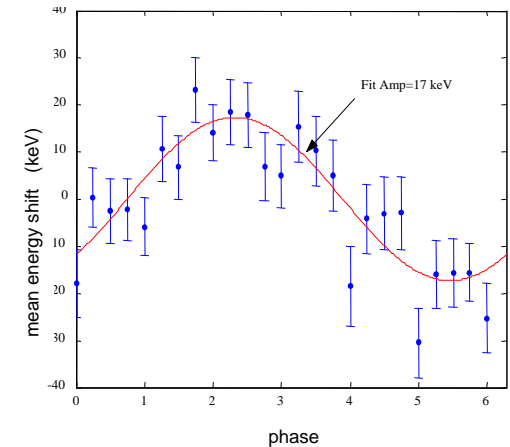
We have achieved net acceleration of electrons with attosecond phase control



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

E-163 Byer Group



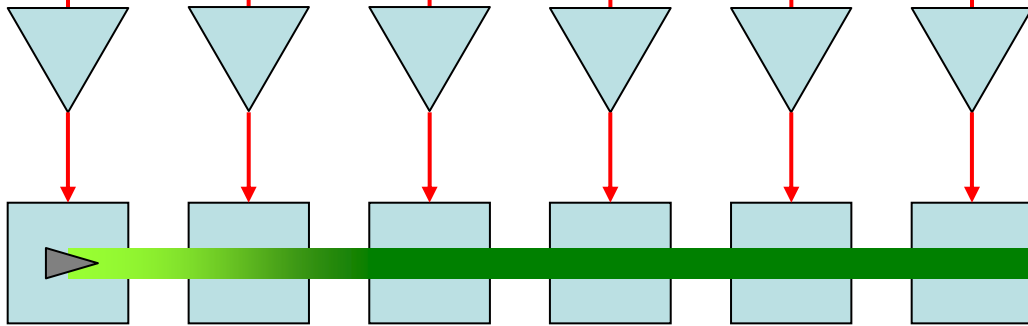
block-diagram

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

Oscillator laser

- ultrastable clock
- attosec stability
- low power



Pre-accelerator

- nonrelativistic
- preserve emittance
- compress bunch

Accelerator sections

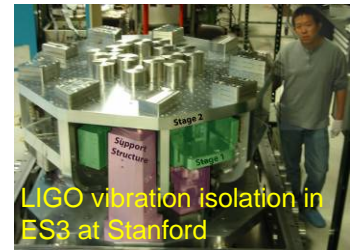
- relativistic
- preserve emittance
- periodic focusing
- alignment and stabilization

Electron beam

- 1 fC/bunch
- sub μm spot size
- $\sim 10^{10}$ bunches/sec

Collider area

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



Order-of-magnitude power estimate

- 1 fC x 10^{10} x 1 TeV $\rightarrow 10^7$ W e-beam
- 20% coupling $\rightarrow 2 \times 10^7$ W optical power
- 50% wallplug laser $\rightarrow 10^8$ W electricity

100 MW electricity

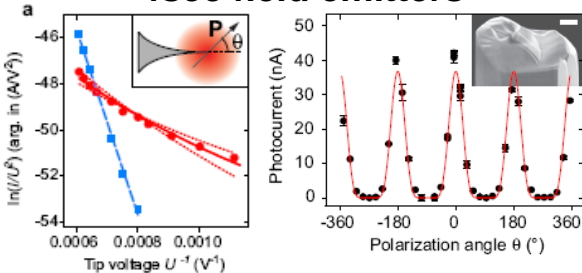
Initial focus of our research

- success of proof-of-principle exp.
- research on dielectric structures

Optical Injector

- optical cycle e- bunch
- $\sim 10^4$ electrons/bunch
- ultra low emittance
- laser-driven field emitters

fsec field emitters



P. Hommelhoff et al

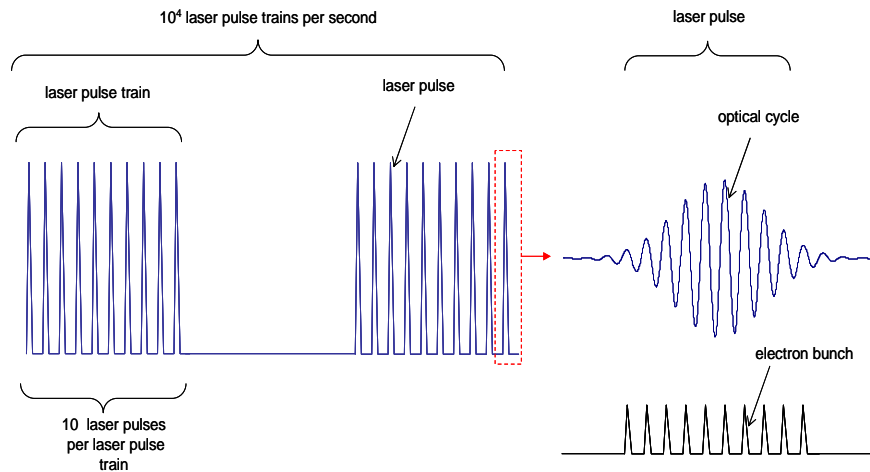


Laser beam parameters for TeV scale accelerator 1 GeV/meter - 1 kilometer accelerator - 10MW laser power

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 $\sim 10^{14}$ Hz
- macro pulse repetition rate ~ 1 GHz



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

Byer
Group

