Lasers at 50: *The History of Lasers at Stanford*

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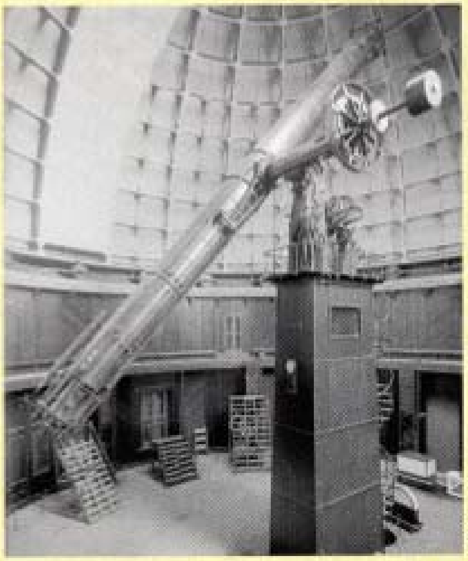
Abstract

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 at Stanford 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.

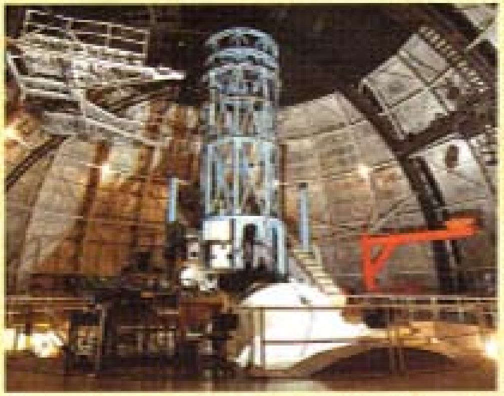
Stanford Historical Society
34th Annual Meeting & Reception
May 25, 2010

California – Leader in advanced telescopes for astronomy



Special Collections Research Center, University of Chicago Library

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



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

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

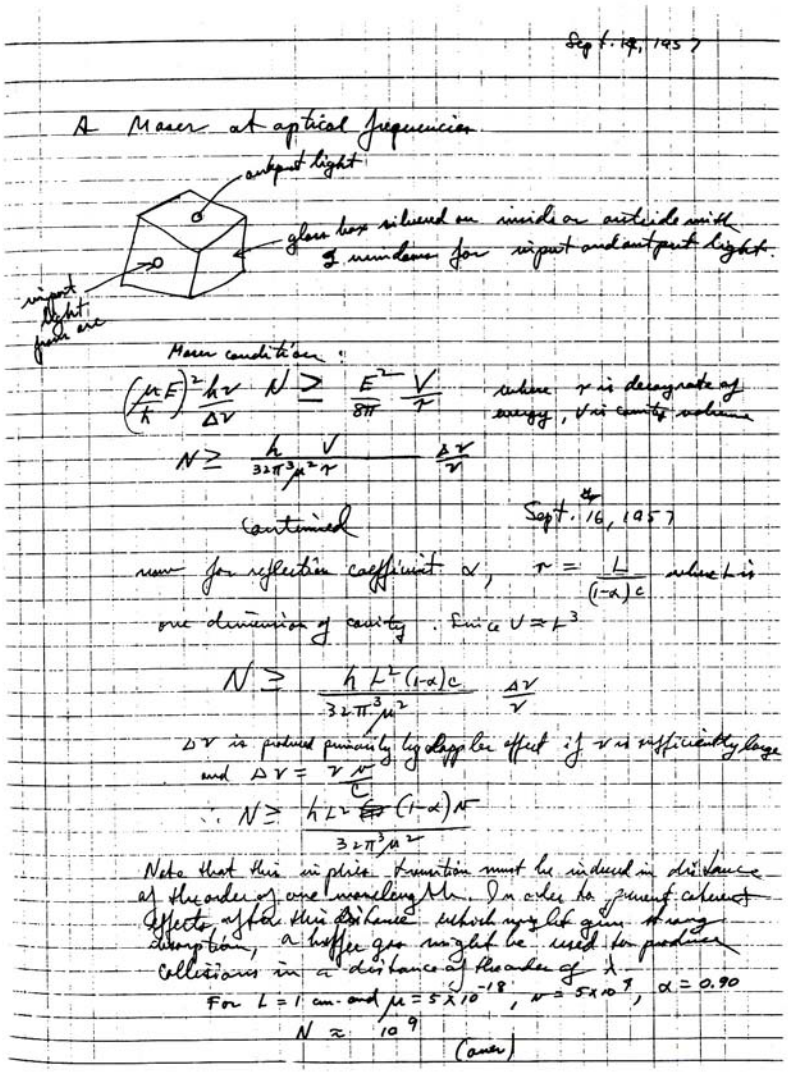
The massive Hale 200-inch telescope was under construction for 21 years. George Ellery Hale, who secured the funding for the 200-inch, passed away in 1938. Almost 1,000 people attended the 1948 dedication of the Hale 200-inch reflector.

Lick 36 inch refractor
1888

The Mount Wilson 100 inch
1917

The Palomar 200 inch
1948

6 A. L. Schawlow


Sept. 14, 1957

A Maser at optical frequencies

output light

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

input light from arc

Maser condition:

$\left(\frac{\mu E}{h}\right)^2 \frac{h\nu}{\Delta\nu} N \geq \frac{E^2}{8\pi} \frac{V}{\tau}$ where τ is decay rate of energy, V is cavity volume

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

continued Sept. 16, 1957

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

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

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

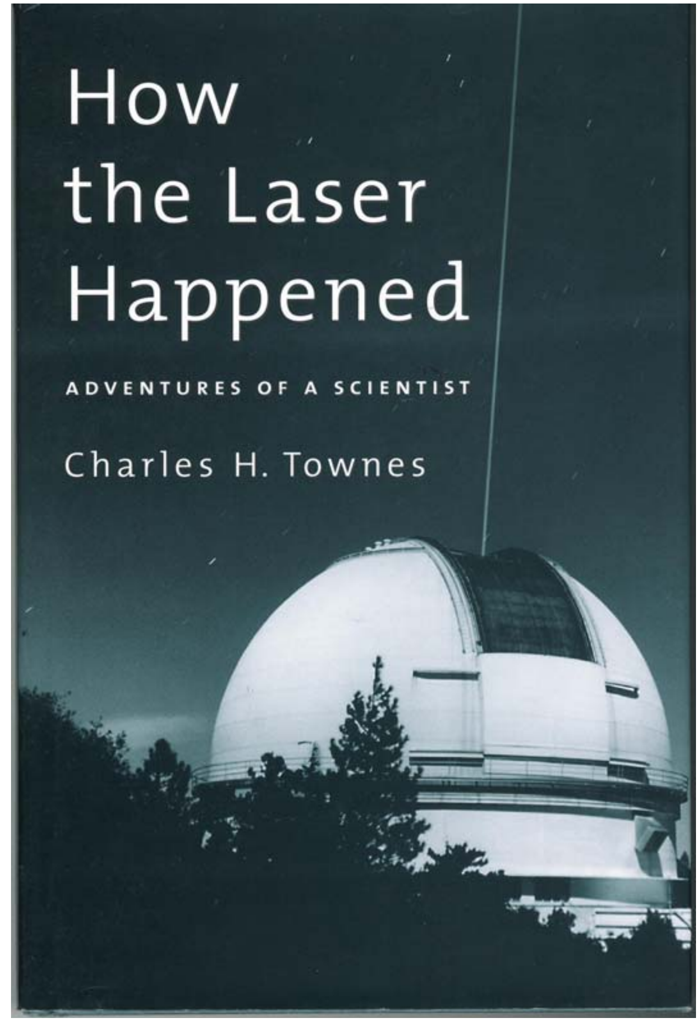
$\therefore N \geq \frac{h L^2 (1-\alpha) v}{32\pi^3 \mu^2}$

Note that this in phase transition must be induced in distance of the order of one wavelength. In order to prevent coherent effects after this distance which might give strong absorption, a buffer gas might be used to produce collisions in a distance of the order of λ.

For $L = 1$ cm and $\mu = 5 \times 10^{-18}$, $v = 5 \times 10^4$, $\alpha = 0.90$

$N \approx 10^9$

(over)



Early advances in lasers ---
2009 a Special Year

Concept of Optical Maser	Schawlow & Townes	1958
Ruby Laser	Ted Maiman	1960

Nobel Prize awarded in 1964 Townes, Prokhorov and Basov

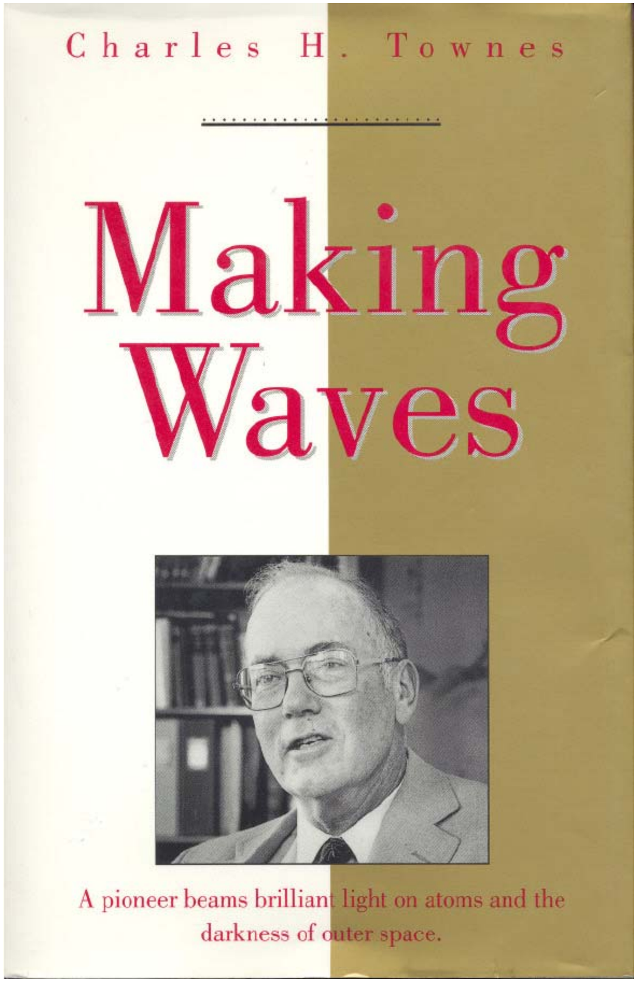
Hg+ Ion Laser	Earl Bell	1965
Argon Ion Laser	Bill Bridges	
Tunable cw parametric Laser	Harris	1968
Diode bar 1Watt Laser	Scifres	1978
Diode Pumped Nd:YAG (NPRO)	Byer	1984

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

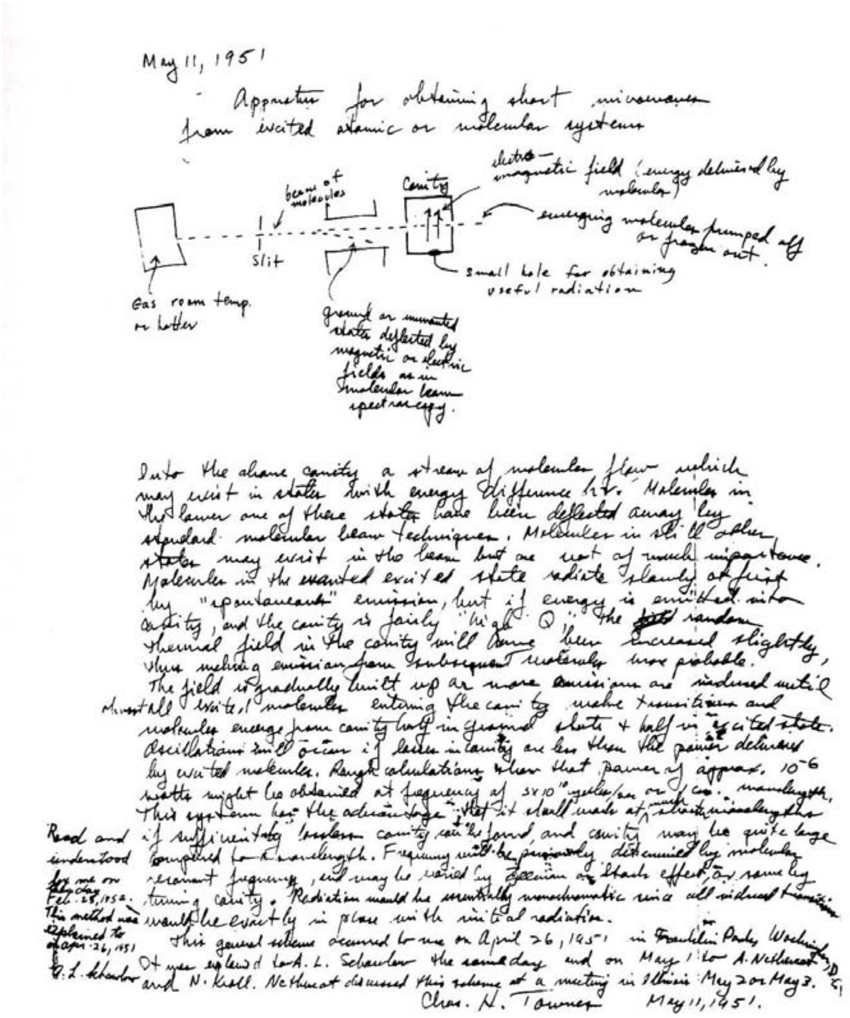
Lightwaves



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

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

Concept for the MASER, May 11, 1951



May 11, 1951

Apparatus for obtaining short microwaves from excited atomic or molecular systems

Into the above cavity a stream of molecules flow which may exist in states with energy difference hν. Molecules in the lower one of these states have been deflected away by standard molecular beam techniques. Molecules in still other states may exist in the beam but are not of much importance. Molecules in the wanted excited state radiate slowly at first by "spontaneous" emission, but if energy is emitted into cavity, and the cavity is fairly "high Q", the random thermal field in the cavity will have been increased slightly, thus making emission from subsequent molecules more probable. The field is gradually built up as more emissions are induced until almost all excited molecules entering the cavity make transitions and molecules emerge from cavity half in ground state + half in excited state. Oscillations will occur if losses in cavity are less than the power delivered by excited molecules. Rough calculations show that power of approx. 10^{-6} watts might be obtained at frequency of 5×10^{11} cycles/sec or ½ cm. wavelength. This system has the advantage that it should work at much shorter wavelengths if sufficiently lossless cavity can be found, and cavity may be quite large compared to a wavelength. Frequency will be precisely determined by molecular resonant frequency, and may be varied by Zeeman or Stark effect, or some by tuning cavity. Radiation would be essentially monochromatic since all induced transitions would be exactly in phase with the initial radiation.

This general scheme occurred to me on April 26, 1951 in Franklin Park, Washington, D.C. It was explained to A. L. Schawlow the same day and on May 1 to A. Nethercot and N. Kroll. Nethercot discussed this scheme at a meeting in Illinois May 2 or May 3.

Chas. H. Townes May 11, 1951.

Read and understood by me on Feb. 23, 1952. This method was explained to me Apr. 26, 1951 A. L. Schawlow

Charles Townes & Jim Gordon

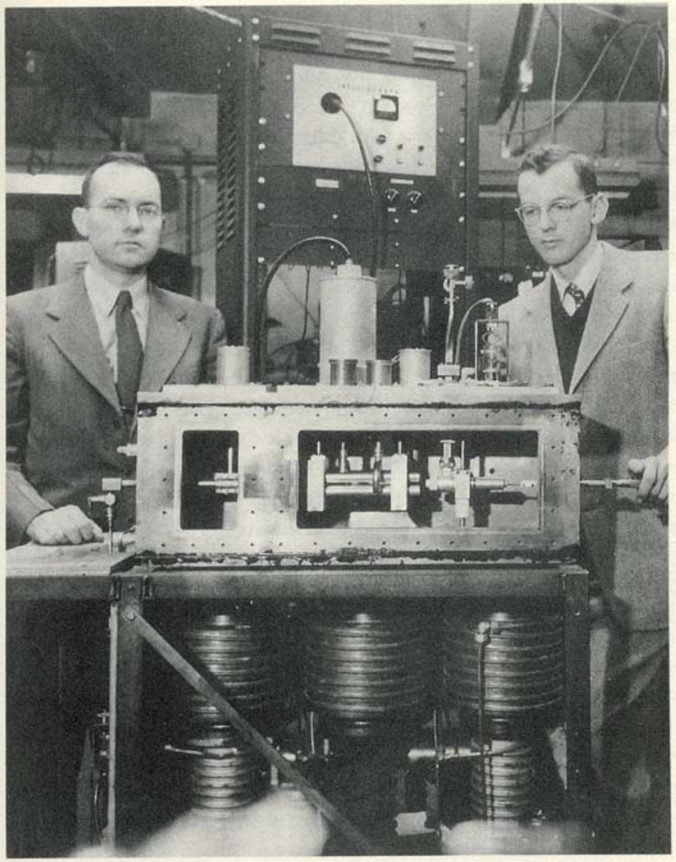
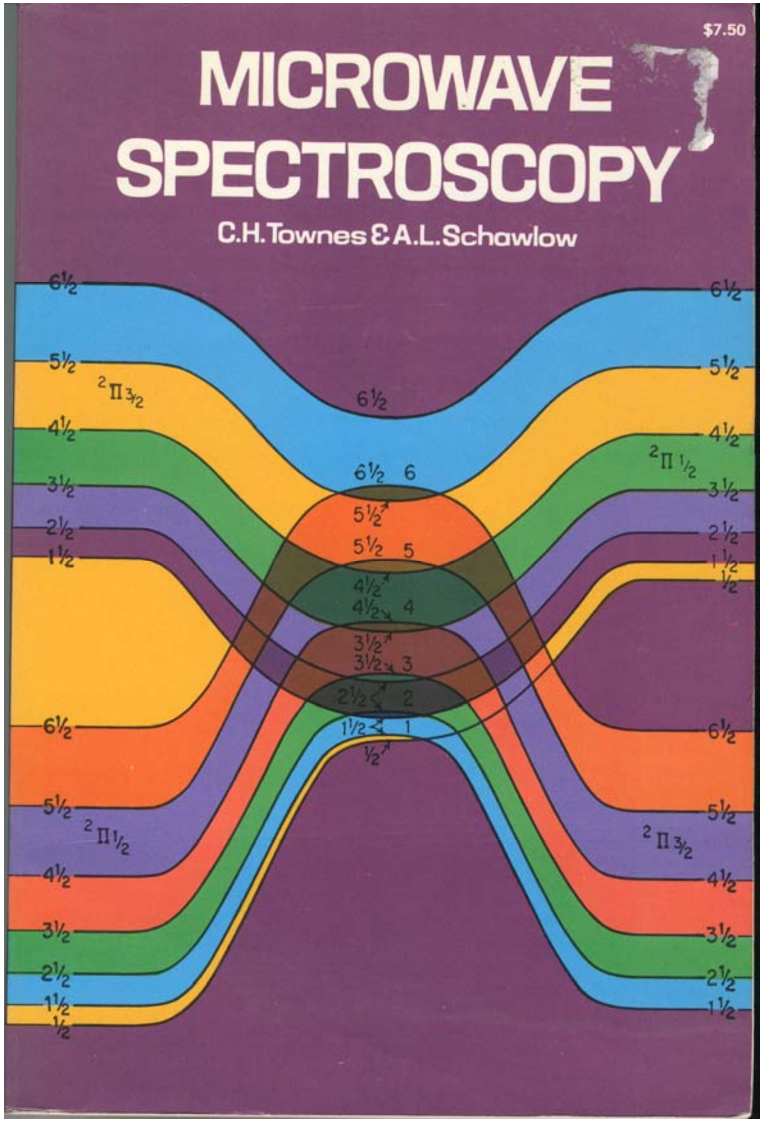


Figure 9. James Gordon (at right) and I were photographed with the second maser at Columbia University. The normally evacuated metal box where maser action occurred is opened up to show the four rods (quadrupole focuser) which sent excited molecules into a resonant cavity (the small cylinder to the right of the four rods). The microwaves that were generated emerged through the vertical copper waveguide near my hand. This second maser was essentially a duplicate of the first operating one, and it was built to examine the purity of maser signals, by allowing the two to beat together, thus producing a pure audio signal.

From Radar to Fundamental Science



Published in 1955,

Microwave Spectroscopy
by
C. H. Townes and A. L. Schawlow

illustrated
how new sources of coherent radiation could open the field of precision molecular spectroscopy.

Hail Stanford Hail - Microwaves

The Ruby Laser

Art Schawlow with Mickey Mouse Balloon and Ruby Laser

Retinal Attachment

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

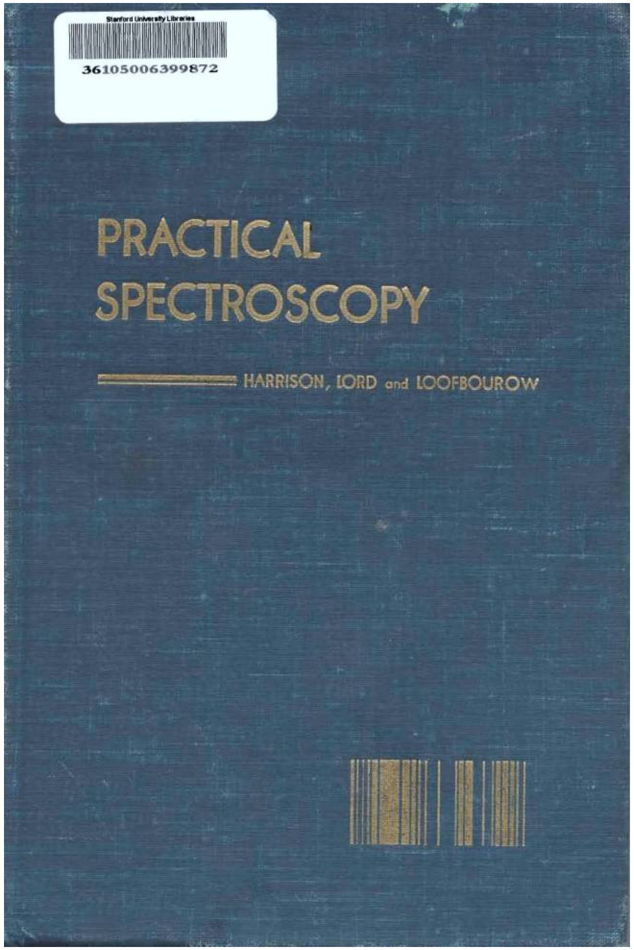
Laser Eraser

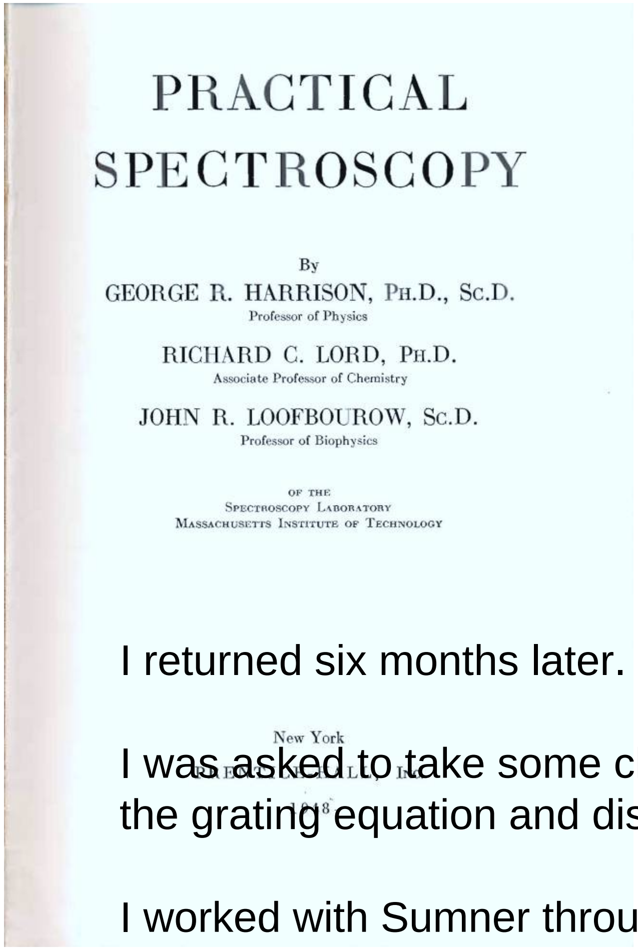
"The "Laser Eraser" may not find any near term application, but it is interesting."

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

Arrived in Berkeley Autumn 1960

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





PRACTICAL SPECTROSCOPY

By

GEORGE R. HARRISON, Ph.D., Sc.D.
Professor of Physics

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

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

of the
Spectroscopy Laboratory
Massachusetts Institute of Technology

New York

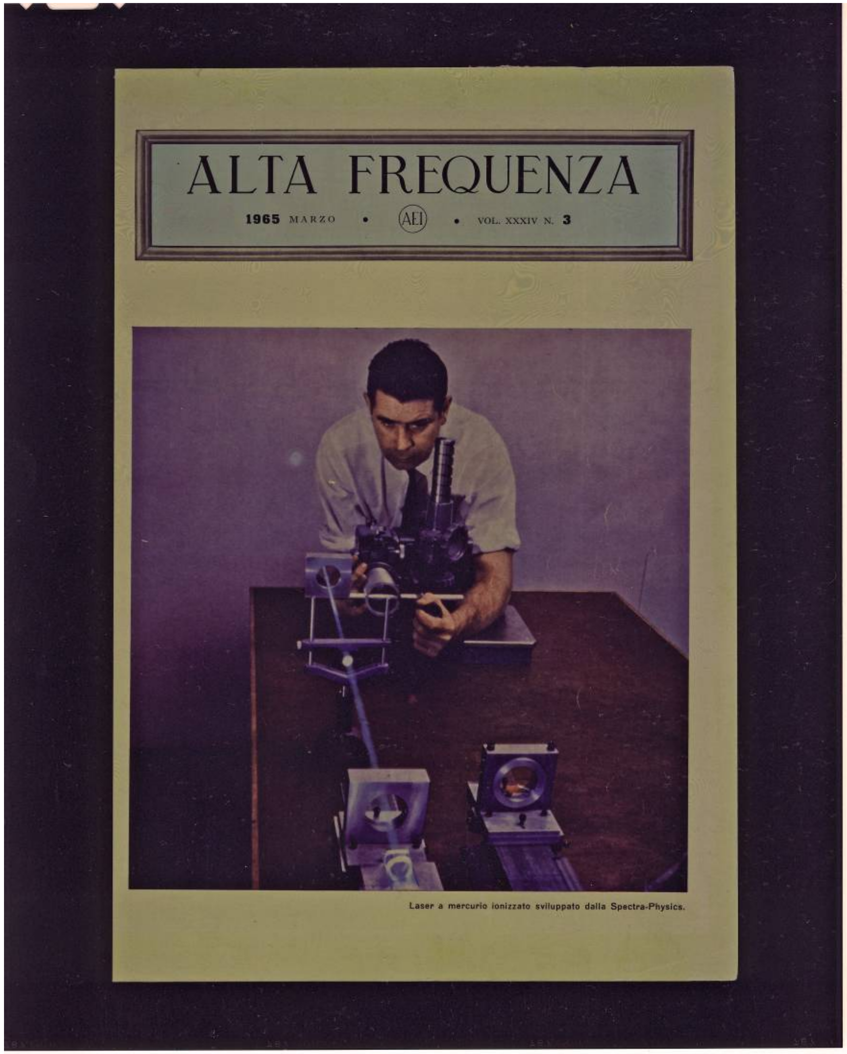
Sumner P. Davis

I returned six months later.

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

I worked with Sumner through my senior year.

Spectra Physics – the ion laser


ALTA FREQUENZA

1965 MARZO • AEI • VOL. XXXIV N. 3

Laser a mercurio ionizzato sviluppato dalla Spectra-Physics.

Earl Bell 1965 Mercury Ion Laser

I arrived at a small company in Mountain View, CA for an interview.

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

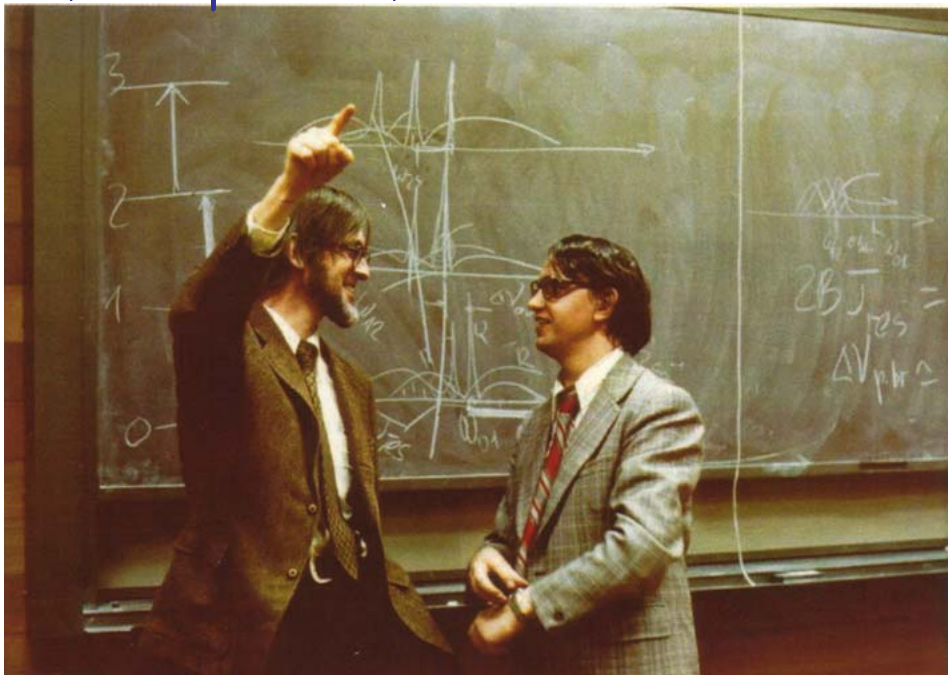
Earl Bell had just operated the first Ion laser that generated orange light.

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

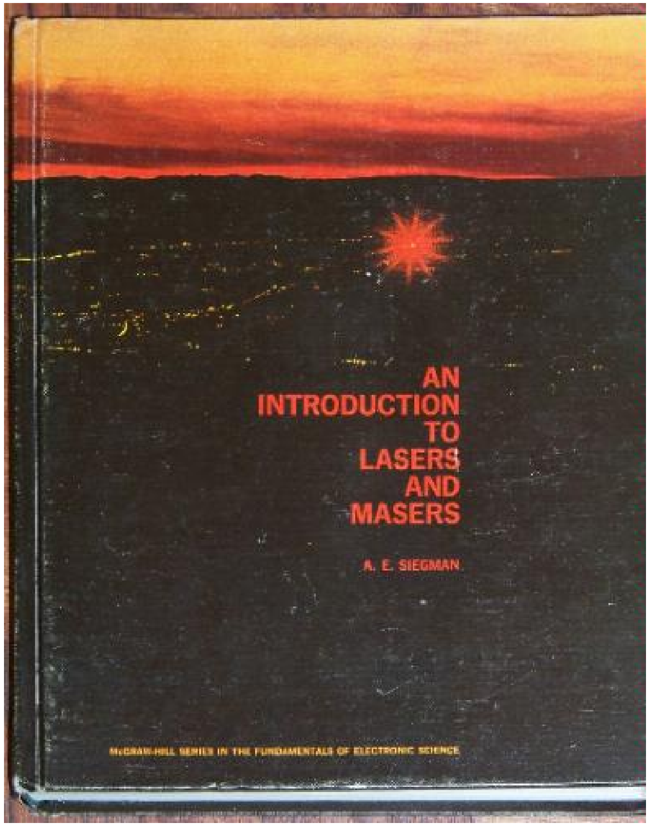
"If a laser can operate at 5% efficiency, it can do real work." Earl Bell 1965

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

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



Tony Siegman and Professor Letokov at Stanford



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

I joined the Steve Harris Lab in 1965

Stanford research 1965 – 1969 - The Harris Lab

- Larry Osterink and the FM argon ion laser
- Ken Oshman – OPO pumped by yellow Krypton Ion Laser
- Bob Byer and Jim Young
  - Modelocked pumped $LiNbO_3$ OPO
  - Materials development (Bob Feigelson)
  - *Parametric Fluorescence
  - *CW OPO pumped by Argon Ion Laser

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

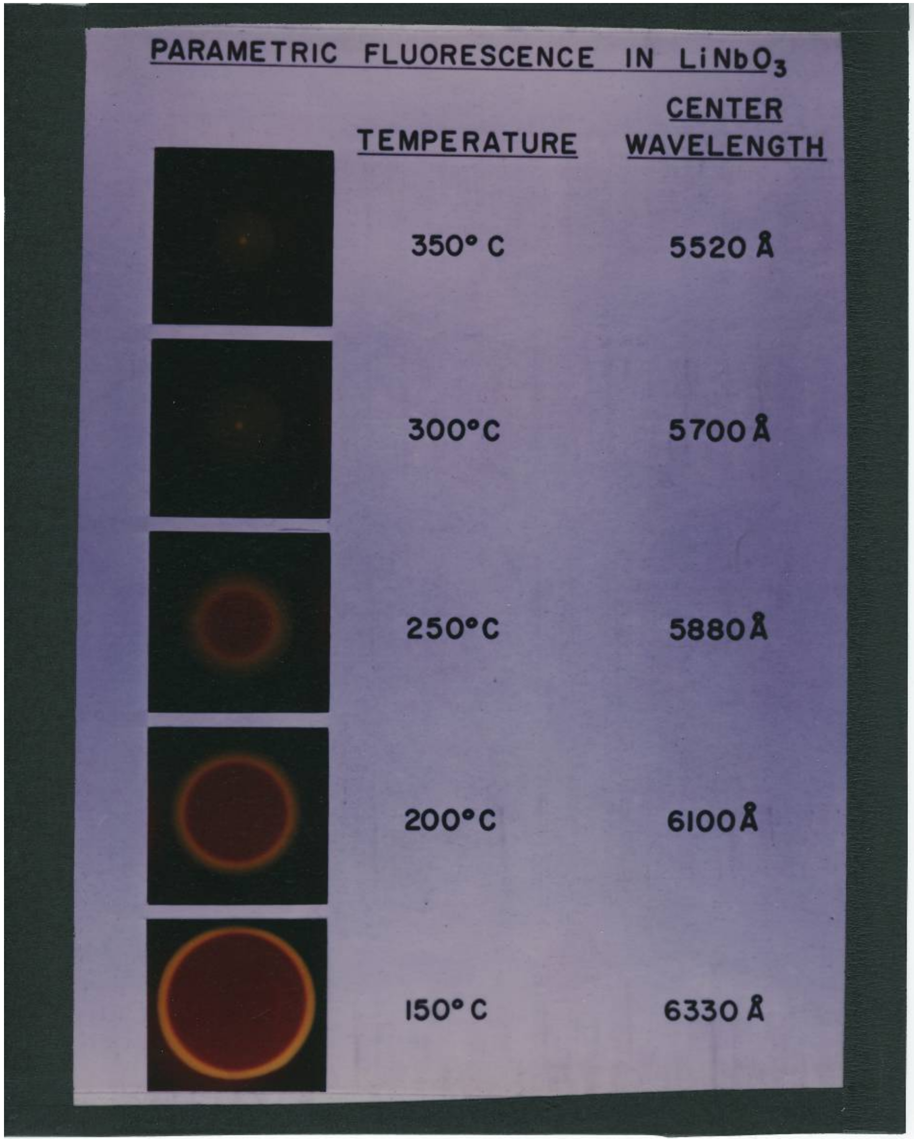
OPO technology transferred to Chromatix - 1970

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

Stephen E. Harris
~1963
Stanford University

Kodachrome images of Parametric Fluorescence in $LiNbO_3$

Byer Group



Measured nonlinear coefficient

Derived parametric gain

Measured tuning curve

Confirmed quality of the Crystal

Observed Parametric Amplifier Quantum Noise by eye!

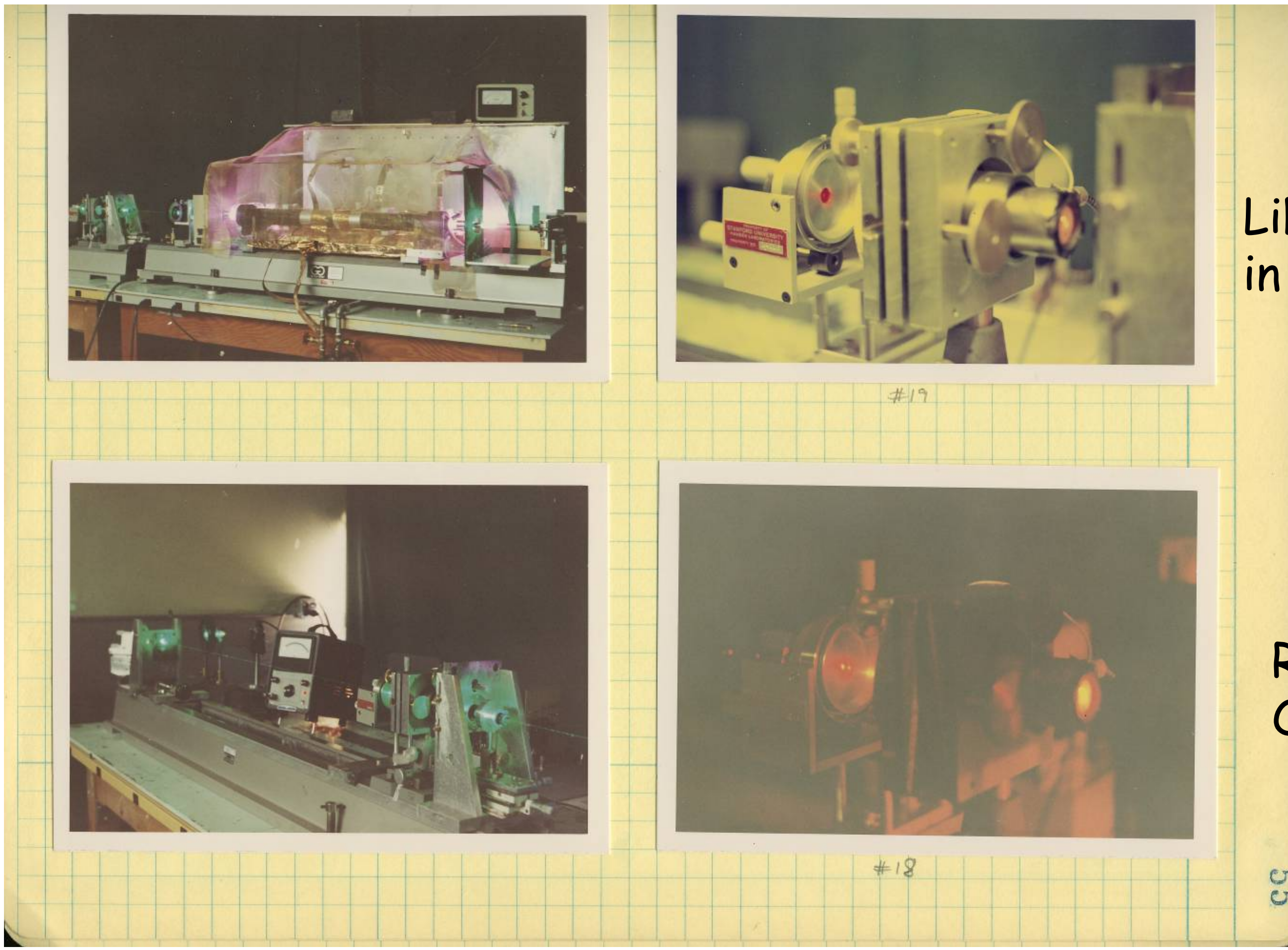
Visible Tunable Parametric Oscillator in $LiNbO_3$

Byer Group

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

Argon Ion Laser pump

$LiNbO_3$ crystal in the oven



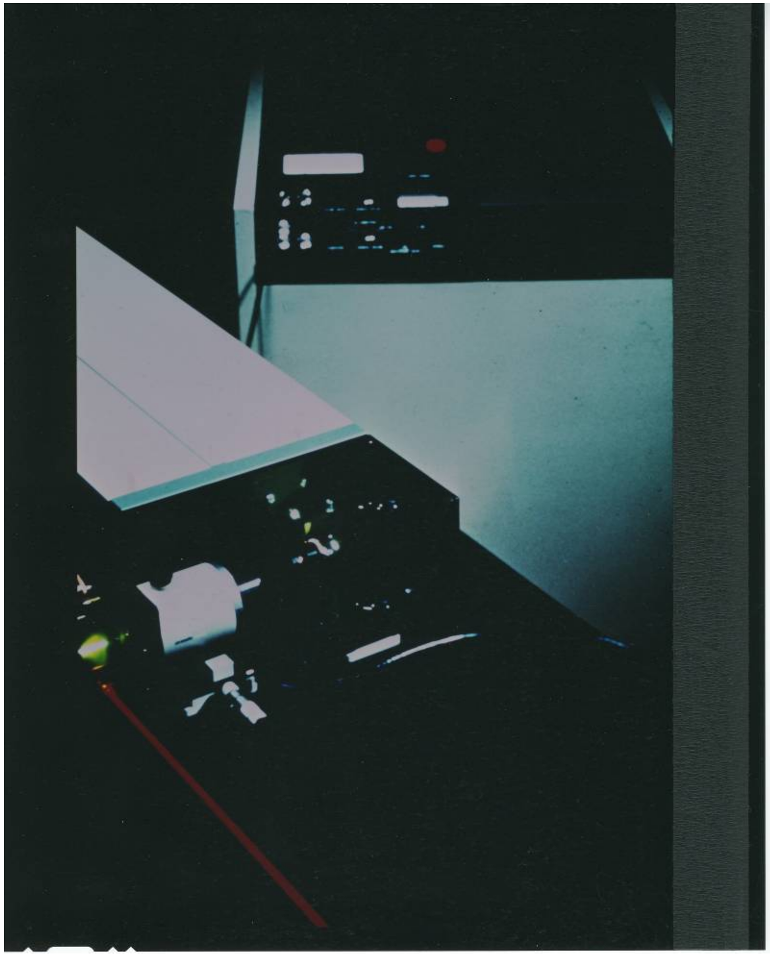
OPO cavity

Red tunable Output ~1mW

Threshold 430mW. Available power at 514.5nm 470mW

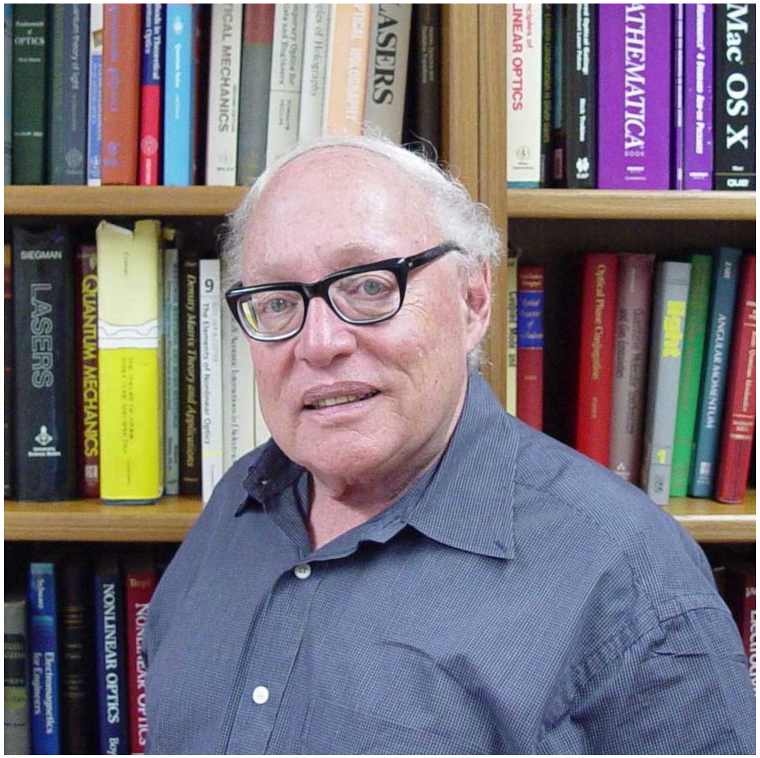
Chromatix Nd:YAG Laser and Tunable OPO ~1970

Richard Wallace with Q-switched Chromatix Nd:YAG Laser



Doubled YAG pumped $LiNbO_3$ OPO
First tunable laser product

Optical Parametric Oscillators



Stephen E. Harris – Stanford University

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

Motivation: Scientific Applications of Lasers

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

Scientific Applications of Lasers

Atmospheric Remote Sensing

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

Global Wind Sensing

Diode pumped Nd:YAG
Frequency stable local oscillator - NPRO

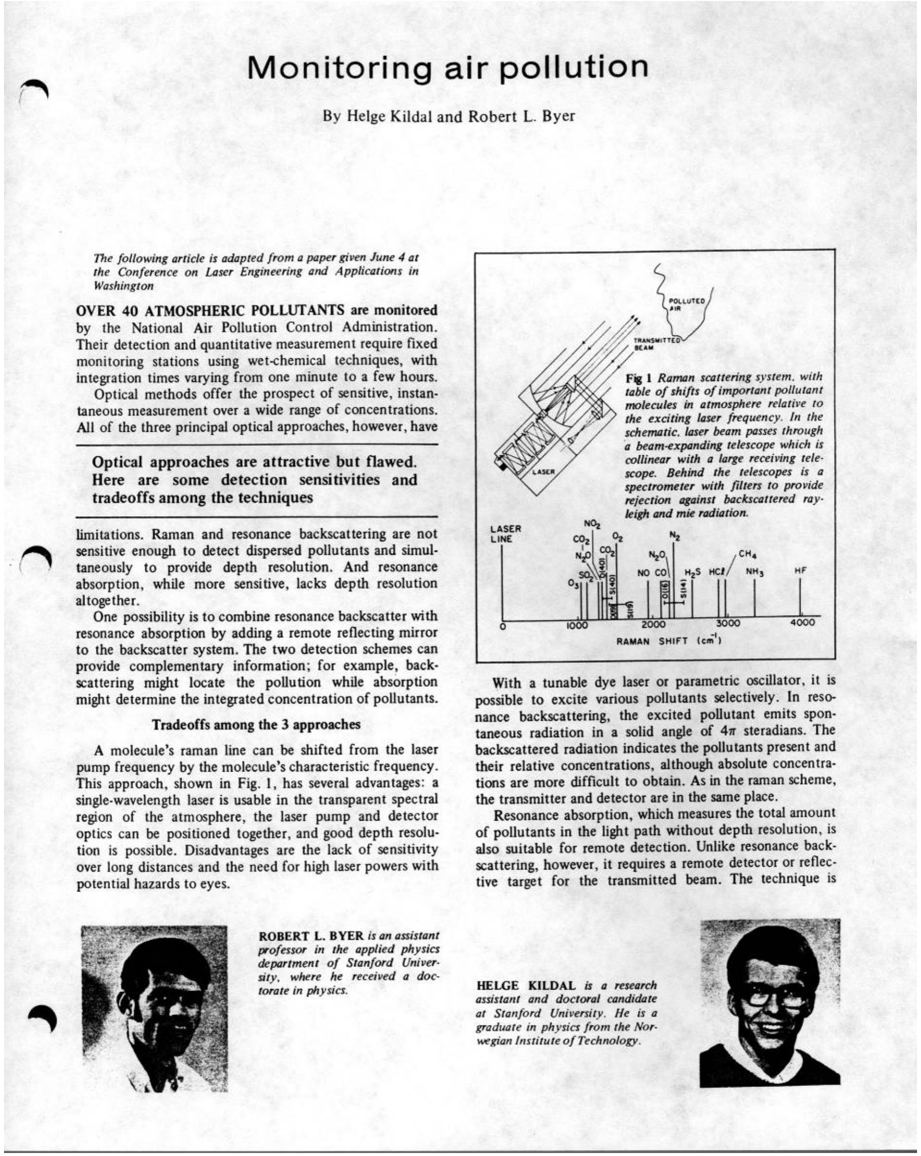
Search for Gravitational Waves

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

Laser Accelerators and Coherent X-rays

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

Monitoring Air Pollution



Monitoring air pollution

By Helge Kildal and Robert L. Byer

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

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

Optical methods offer the prospect of sensitive, instantaneous measurement over a wide range of concentrations. All of the three principal optical approaches, however, have

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.

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

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

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

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

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

Helge Kildal and R. L. Byer

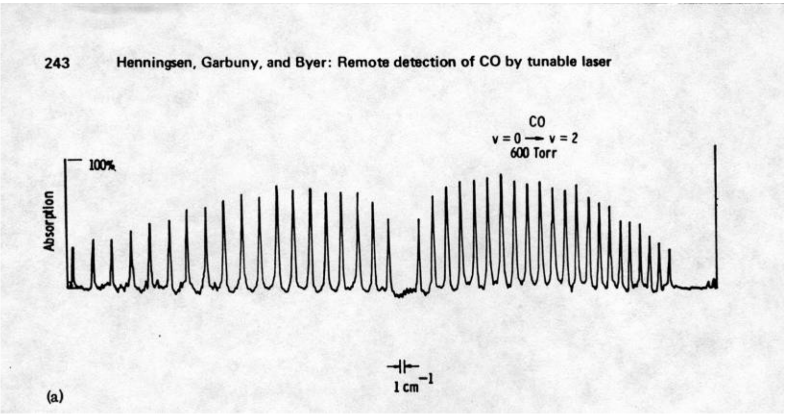
"Comparison of Laser Methods for The Remote Detection of Atmospheric Pollutants"

Proc. IEEE 59,1644 1971 (invited)

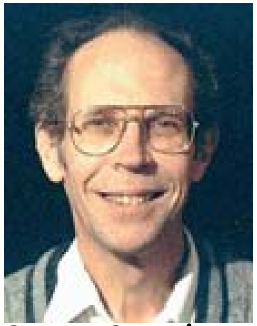
Henningsen, Garbuny and Byer - 1974

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

(Chromatix Nd:YAG pumped $LiNbO_3$ OPO Product introduced as product in 1969)



Motivation for tunable lasers at Stanford



Sune Svanberg

Atmospheric Remote sensing beginning in 1971

Unstable resonator Nd:YAG -- Quanta Ray Laser

1.4 - 4.4 micron tunable $LiNbO_3$ OPO -- computer controlled

Remote sensing of CH_4, SO_2 and H_2O and temperature

Humio Inaba

Early Remote Sensing 1960 - 1975

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

Herbert Walther

1.4 to 4.3 micron Computer Tuned $LiNbO_3$ OPO

Byer Group

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

Papers

Optical Parametric Oscillator Threshold and Linewidth Studies

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

(*Invited Paper*)

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

I. INTRODUCTION

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

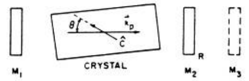


Fig. 1. Simplified OPO schematic. Mirror M_1 is highly reflecting between 1.4–2.1 μm. Output coupler M_2 has signal reflectance R. For DSRO operation, pump high reflector M_3 may be used.

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

Stephen J. Brosnan, R. L. Byer

"Optical Parametric Oscillator Threshold and Linewidth Studies"

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

122 R. L. BYER

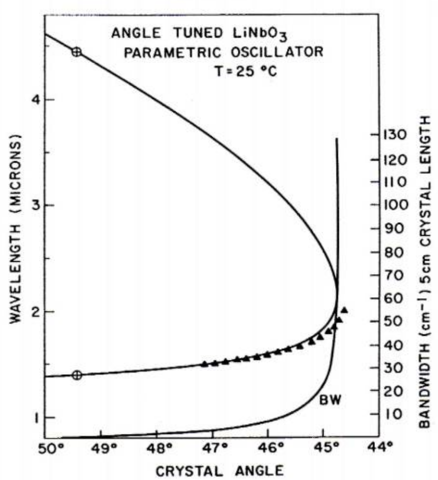


FIG. 19. Tuning curve and bandwidth for the 1.06 μm pumped angle-tuned $LiNbO_3$ SRO.

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

1.4 – 4.3 microns

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

Unstable Resonator Concept - 1965

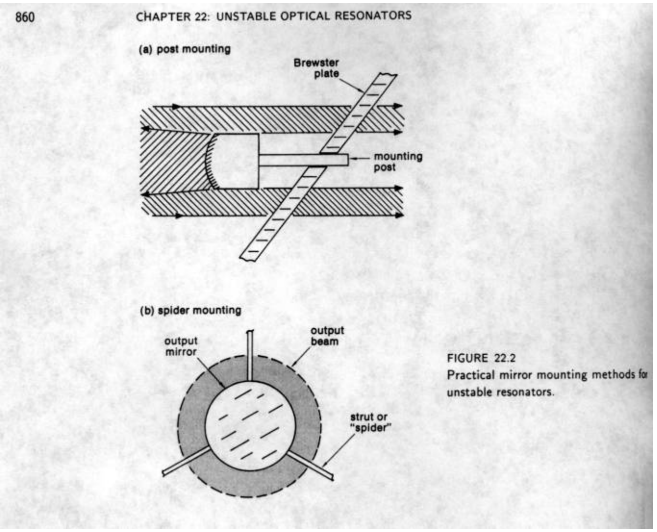
Professor Anthony Siegman received an A.B. degree from Harvard in 1952, an M.S. degree in Applied Physics from UCLA in 1954 (under the Hughes Aircraft Company Cooperative Plan), and a PhD. in Electrical Engineering from Stanford in 1957. Since then he has taught and conducted research in microwave electronics,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

A. E. Siegman

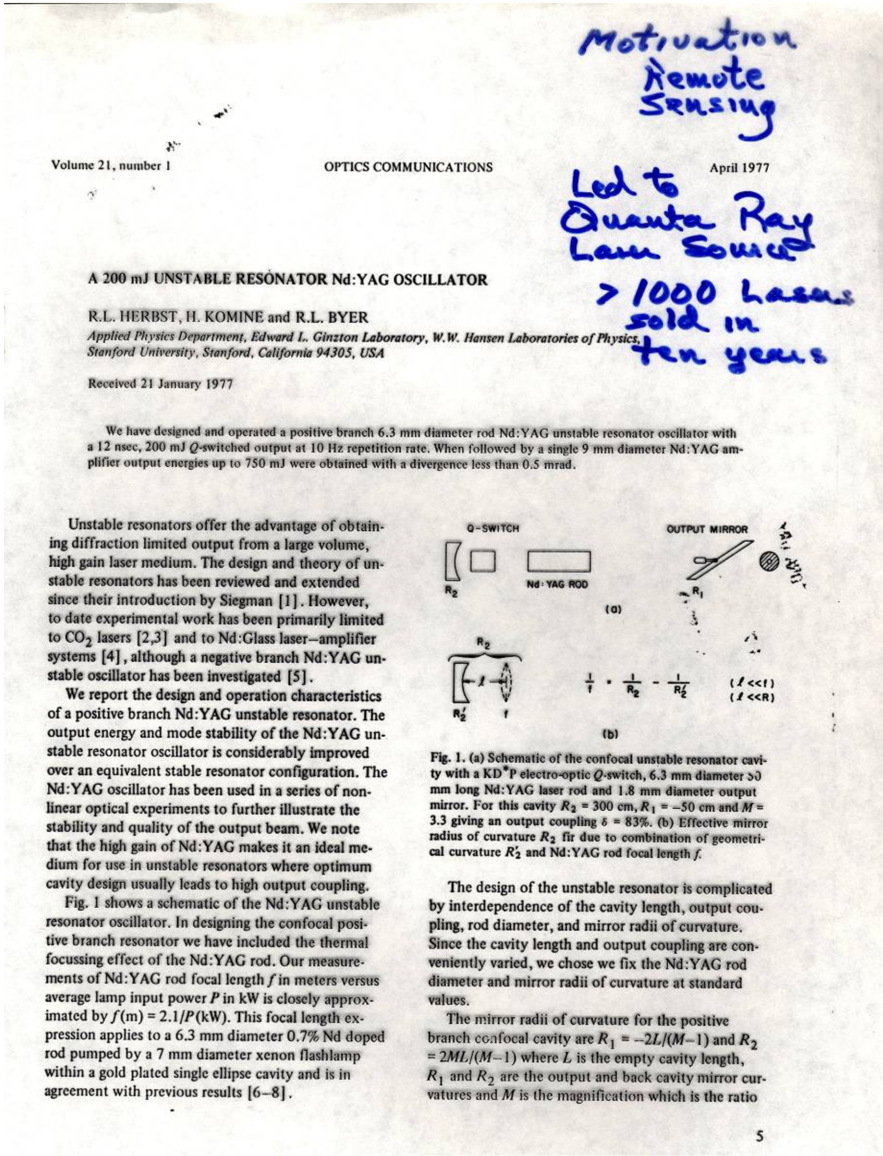
"Unstable optical resonators for laser applications"
Proc. IEEE 53, 277-287, 1965

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

"A 200mJ unstable resonator Nd:YAG Oscillator" Optics Commun. 21, 5, 1977



Unstable Resonator Nd:YAG Oscillator


Motivation Remote Sensing

Led to Quanta Ray Laser Source

> 1000 Lasers sold in ten years

Volume 21, number 1 OPTICS COMMUNICATIONS April 1977

A 200 mJ UNSTABLE RESONATOR Nd:YAG OSCILLATOR

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

Received 21 January 1977

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

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

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

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

Q-SWITCH   Nd:YAG ROD   OUTPUT MIRROR R_2 R_1 (a)

R_2 R'_2 f $\frac{1}{f} + \frac{1}{R_2} = \frac{1}{R'_2}$ ($\ell \ll f$) ($\ell \ll R$)   (b)

Fig. 1. (a) Schematic of the confocal unstable resonator cavity with a KD*P electro-optic *Q*-switch, 6.3 mm diameter 50 mm long Nd:YAG laser rod and 1.8 mm diameter output mirror. For this cavity R_2 = 300 cm, R_1 = –50 cm and M = 3.3 giving an output coupling δ = 83%. (b) Effective mirror radius of curvature R_2 fir due to combination of geometrical curvature R'_2 and Nd:YAG rod focal length f.

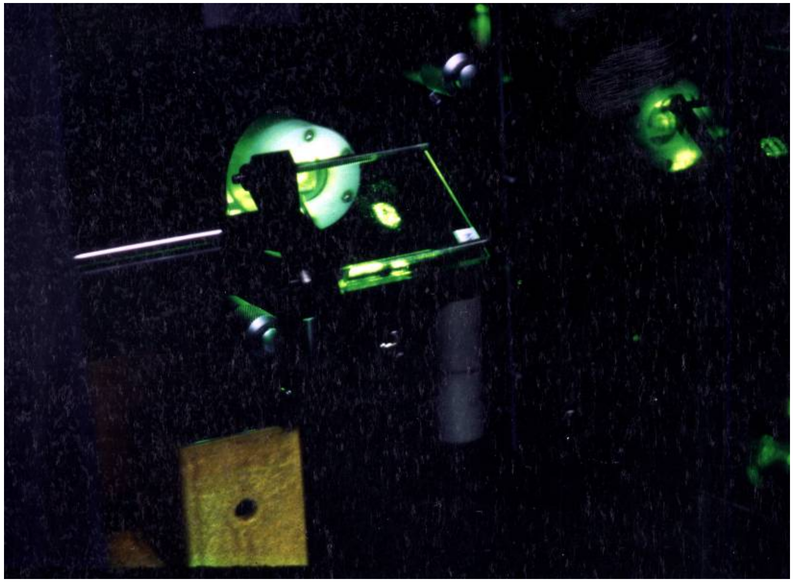
The design of the unstable resonator is complicated by interdependence of the cavity length, output coupling, rod diameter, and mirror radii of curvature. Since the cavity length and output coupling are conveniently varied, we chose we fix the Nd:YAG rod diameter and mirror radii of curvature at standard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

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

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

"A 200mJ Unstable Resonator Nd:YAG Oscillator"

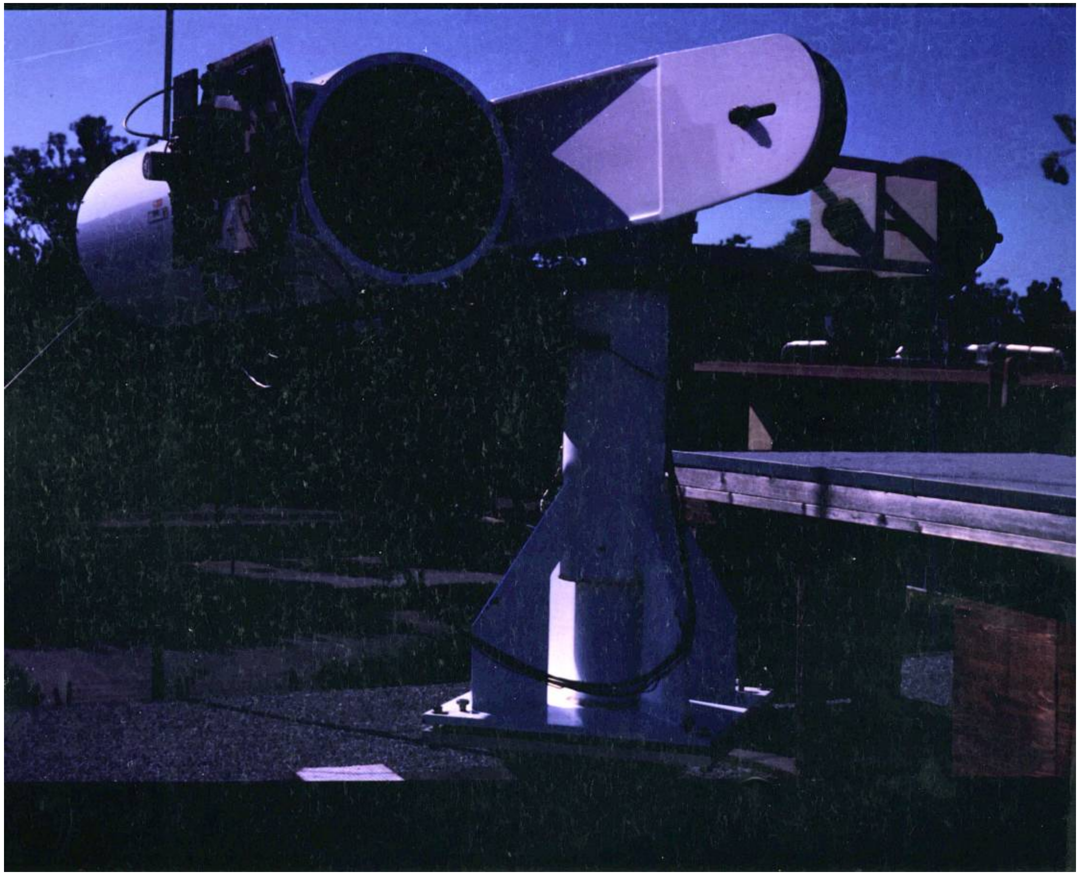
Opt. Commun. 21, 5, 1977



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

Remote Sensing Telescope at Stanford - 1980

Byer Group



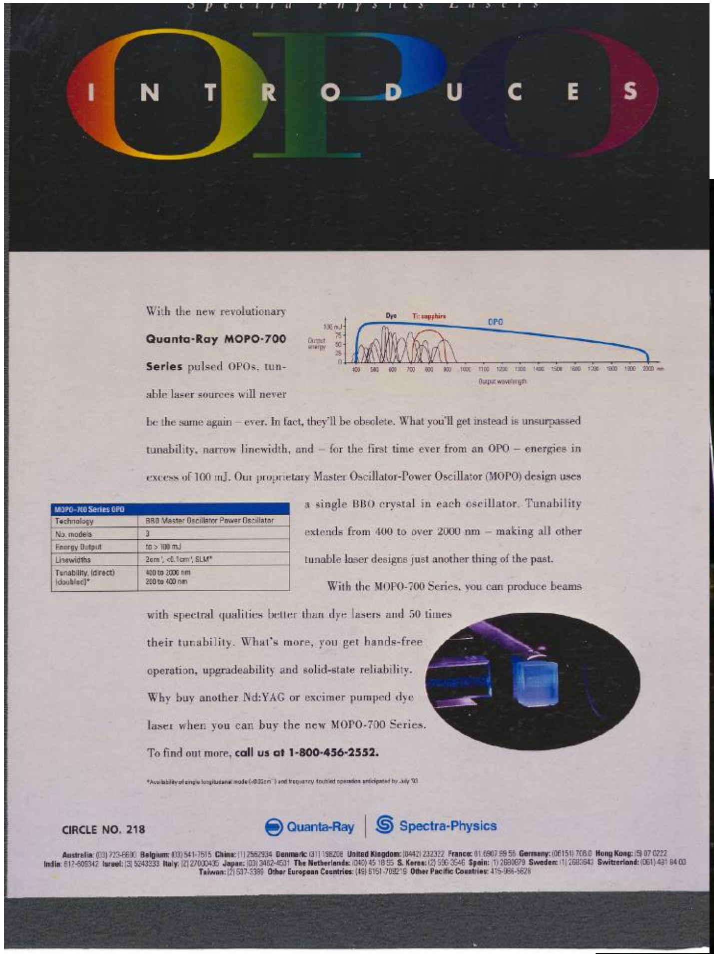
Atmospheric Remote Sensing using a Nd:YAG Pumped $LiNbO_3$ Tunable IR OPO.

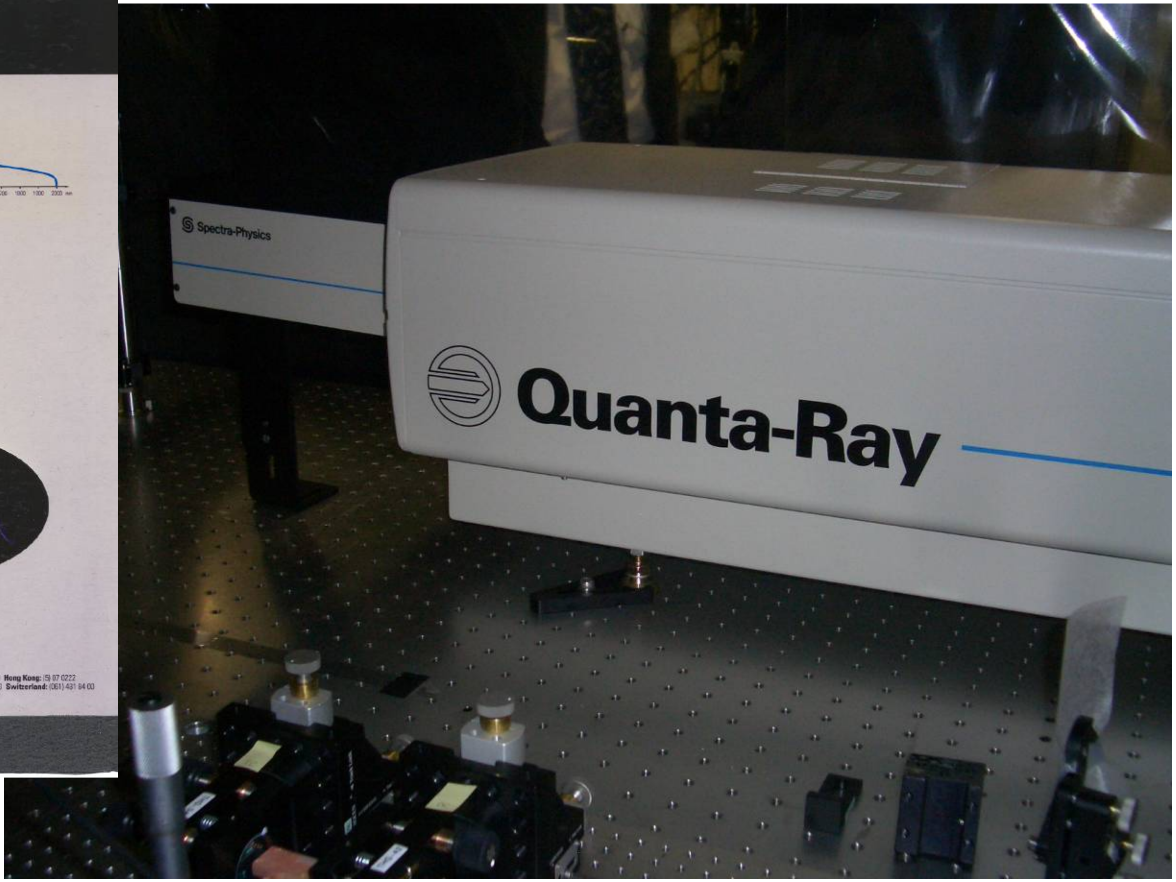
The OPO was tuned under Computer control continuously From 1.4 to 4.3 microns

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

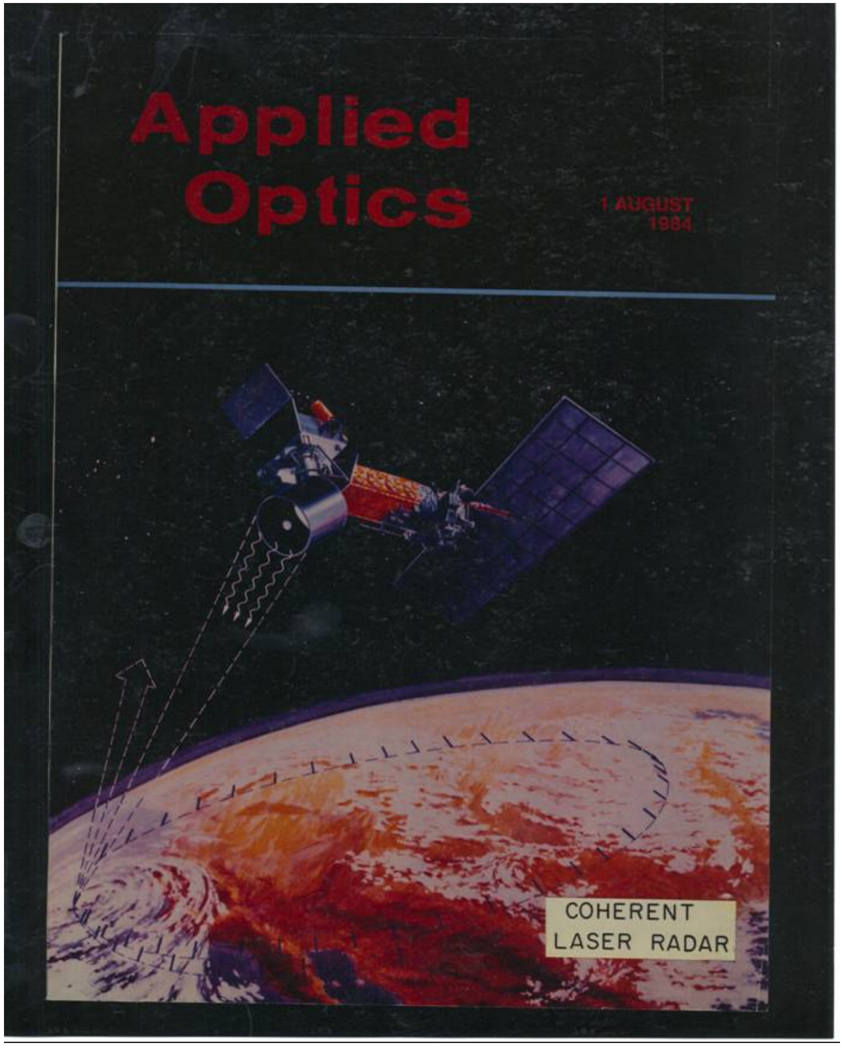
Quanta Ray pumped BBO OPO Spectra Physics





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

Global Wind Concept - Huffaker 1984



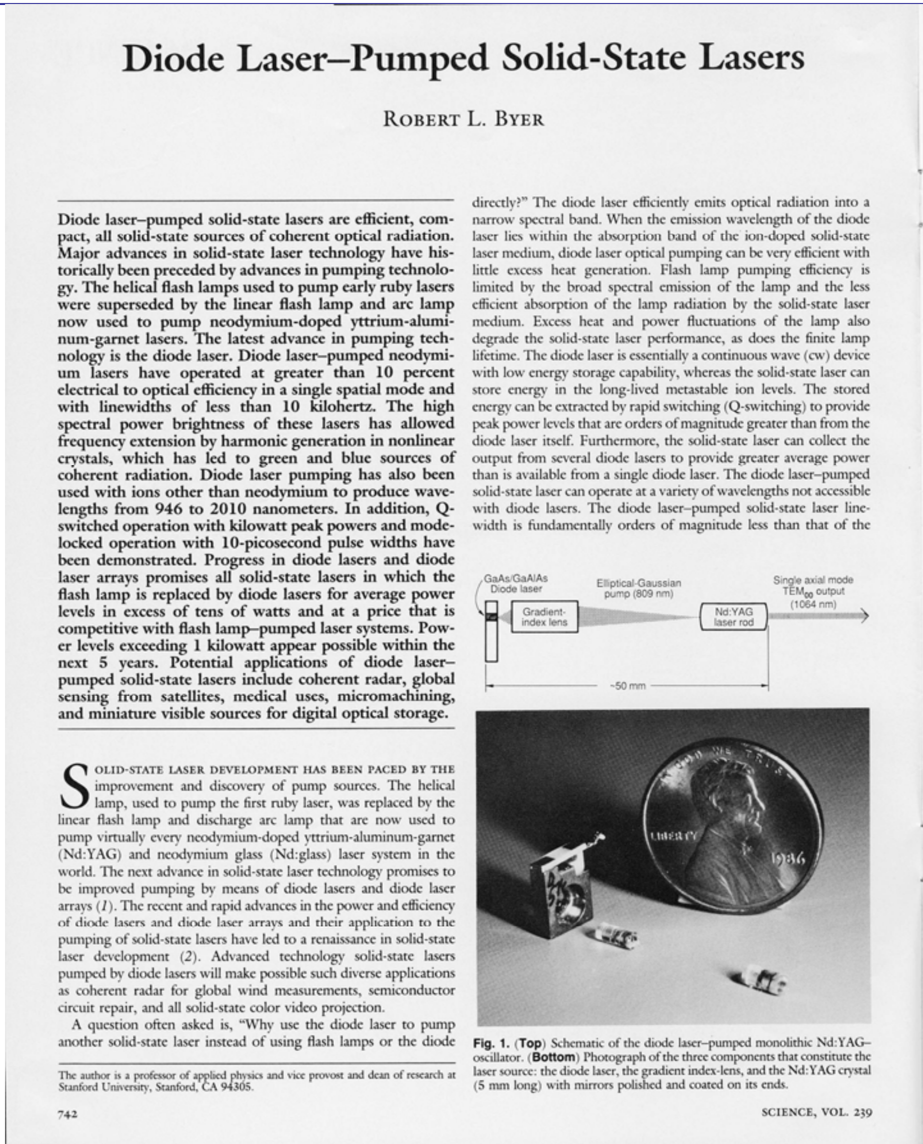
Global wind sensing

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

Applied Optics 22 1984

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

Diode Pumped Solid State Lasers – 1984



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

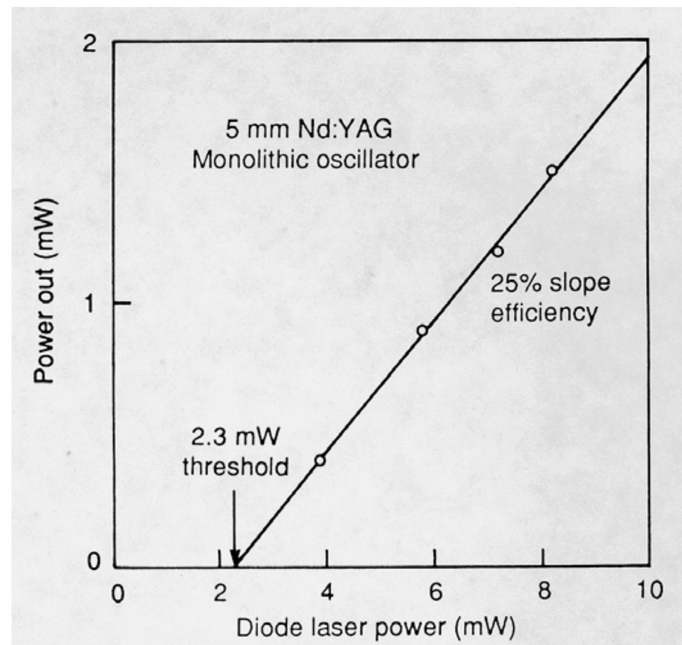
Fig. 1. (**Top**) Schematic of the diode laser–pumped monolithic Nd:YAG–oscillator. (**Bottom**) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

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

1984

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

Δν<10kHz

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 contructed with a standing-wave linear resonator, the threshold of the second axial mode is near that of the first. At the nulls of the standing wave created by the initial axial mode, stimulated emission does not take place, and the gain is not saturated. This spatially modulated gain, termed spatial hole burning, allows other axial modes to reach threshold and oscillate.[2]

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

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

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

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

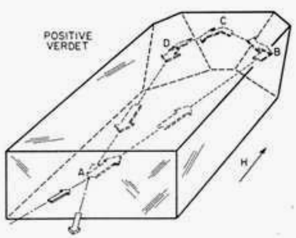


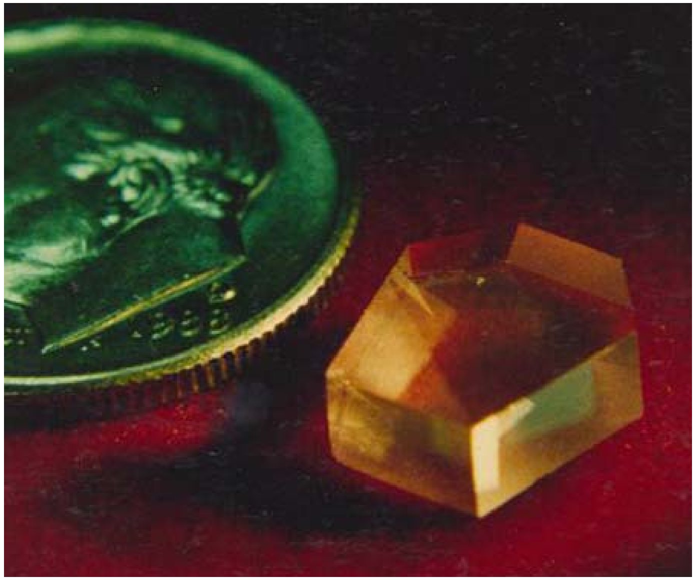
Fig. 1. The MISER laser design. Polarization selection takes place at the curved, partially transmitting face (point A). At points B, C, and D, total internal reflection occurs. A magnetic field *H* is applied to establish unidirectional oscillation. Magnetic rotation takes place along segments *AB*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

0146-9592/85/020065-03$2.00

Tom Kane, R. L. Byer

"Monolithic, unidirectional Single-mode Nd:YAG ring laser"

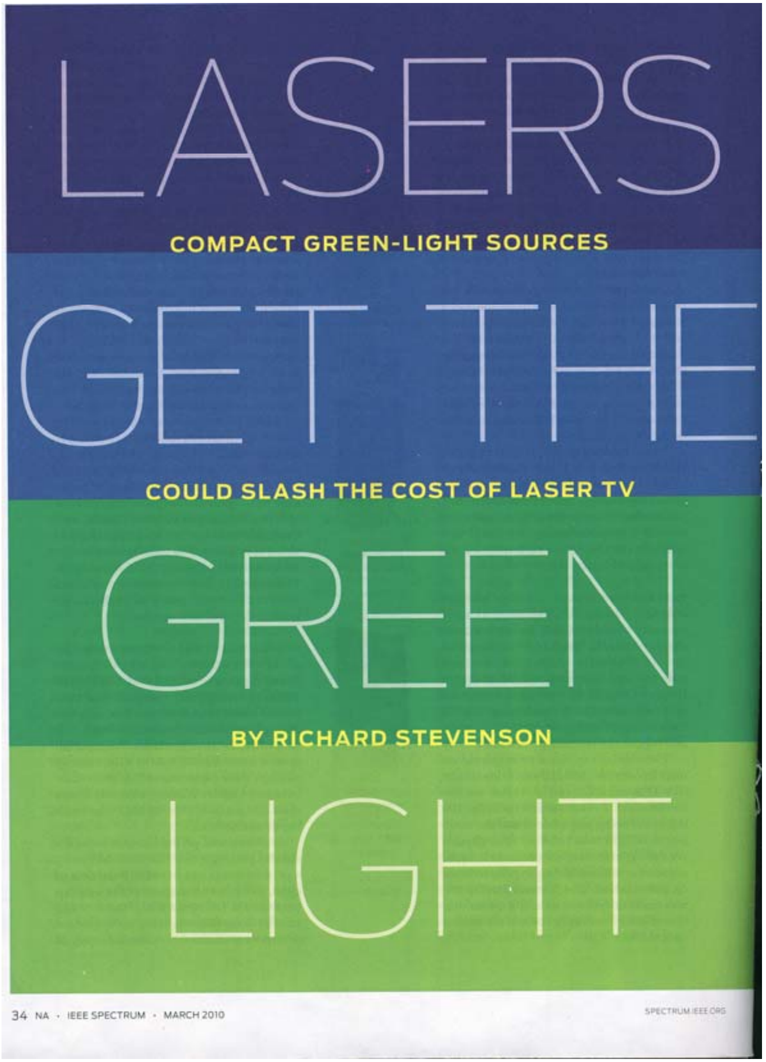
Opt. Lett. 10,65,1985



NonPlanar Ring Oscillator

Single frequency: <10kHz

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



LASERS

COMPACT GREEN-LIGHT SOURCES

GET THE

COULD SLASH THE COST OF LASER TV

GREEN

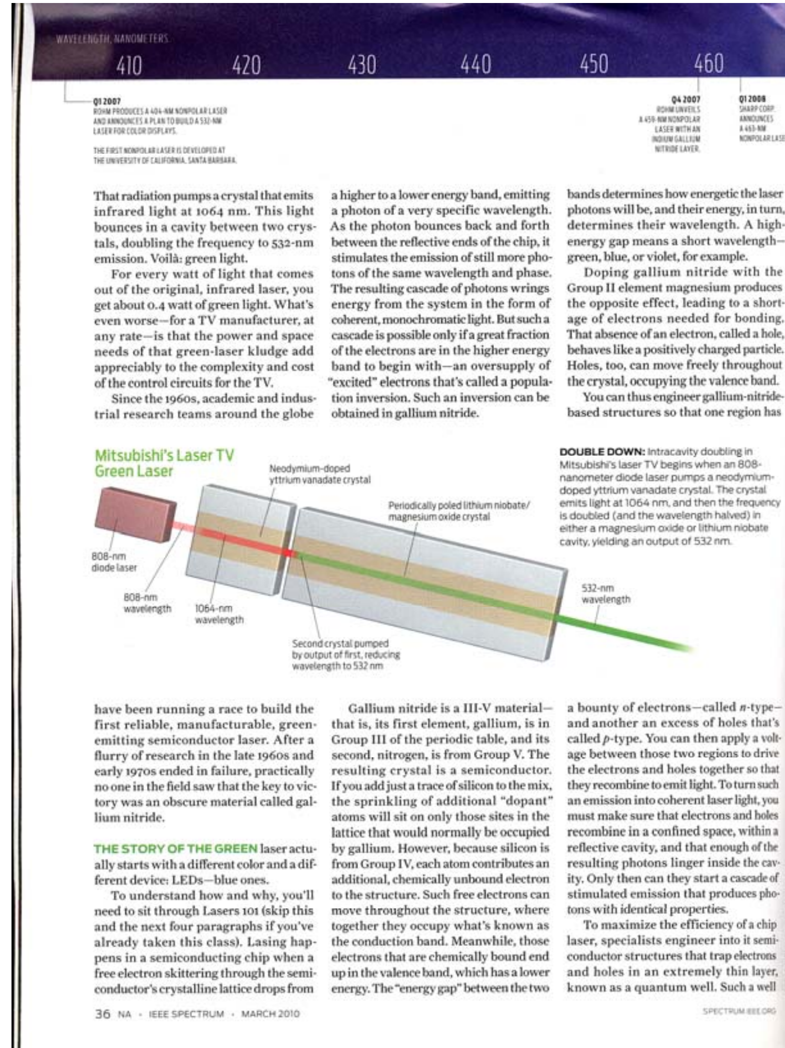
BY RICHARD STEVENSON

LIGHT

34 NA · IEEE SPECTRUM · MARCH 2010

SPECTRUM.IEEE.ORG

IEEE Spectrum March 2010



WAVELENGTH, NANOMETERS

410 420 430 440 450 460

Q1 2007
ROHM PRODUCES A 404-NM NONPOLAR LASER AND ANNOUNCES A PLAN TO BUILD A 532-NM LASER FOR COLOR DISPLAYS.

THE FIRST NONPOLAR LASER IS DEVELOPED AT THE UNIVERSITY OF CALIFORNIA, SANTA BARBARA.

Q4 2007
ROHM UNVEILS A 459-NM NONPOLAR LASER WITH AN INDIUM GALLIUM NITRIDE LAYER.

Q1 2008
SHARP CORP. ANNOUNCES A 463-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 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 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.

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 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 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

Mitsubishi's Laser TV Green Laser

Neodymium-doped yttrium vanadate crystal

Periodically poled lithium niobate/ magnesium oxide crystal

808-nm diode laser

808-nm wavelength

1064-nm wavelength

Second crystal pumped by output of first, reducing wavelength to 532 nm

532-nm wavelength

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.

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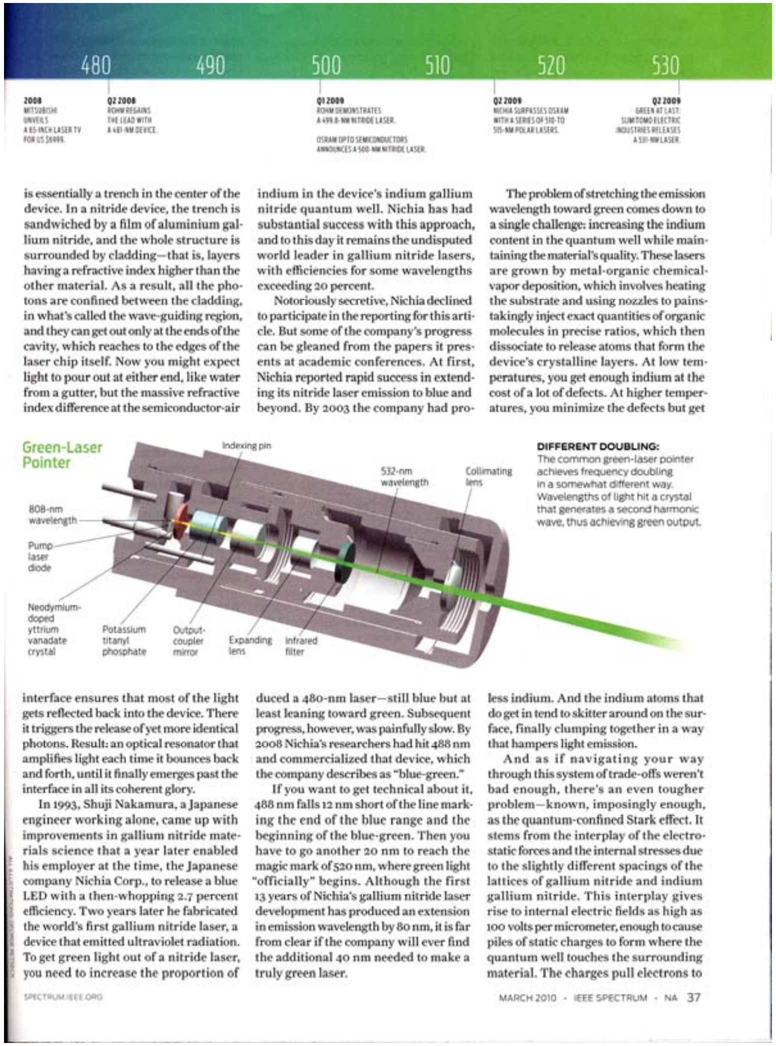
Mitsubishi green laser for TV using PPLN for second harmonic generation



480 490 500 510 520 530

2008 MITSUBISHI UNVEILS A 65-INCH LASER TV FOR US $6999.

Q2 2008 ROHM REGAINS THE LEAD WITH A 481-NM DEVICE.

Q1 2009 ROHM DEMONSTRATES A 499.8-NM NITRIDE LASER.

OSRAM OPTO SEMICONDUCTORS ANNOUNCES A 500-NM NITRIDE LASER.

Q2 2009 NICHIA SURPASSES OSRAM WITH A SERIES OF 510-TO 515-NM POLAR LASERS.

Q2 2009 GREEN AT LAST: SUMITOMO ELECTRIC INDUSTRIES 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 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 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 produced 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.

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 less indium. 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

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.

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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

Hail Stanford Hail – The Laser

Hail Stanford Hail – the Laser

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

Scientific Applications of Lasers

Atmospheric Remote Sensing

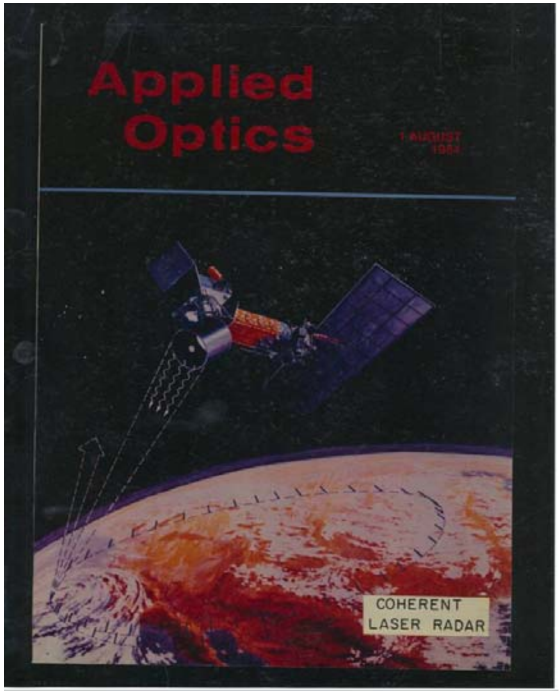
Quanta Ray 1J Unstable resonator
Nd:YAG Laser
1.4 to 4.3 micron Tunable LiNbO3 OPO

Global Wind Sensing

LD pumped Nd:YAG
Frequency Stabilization

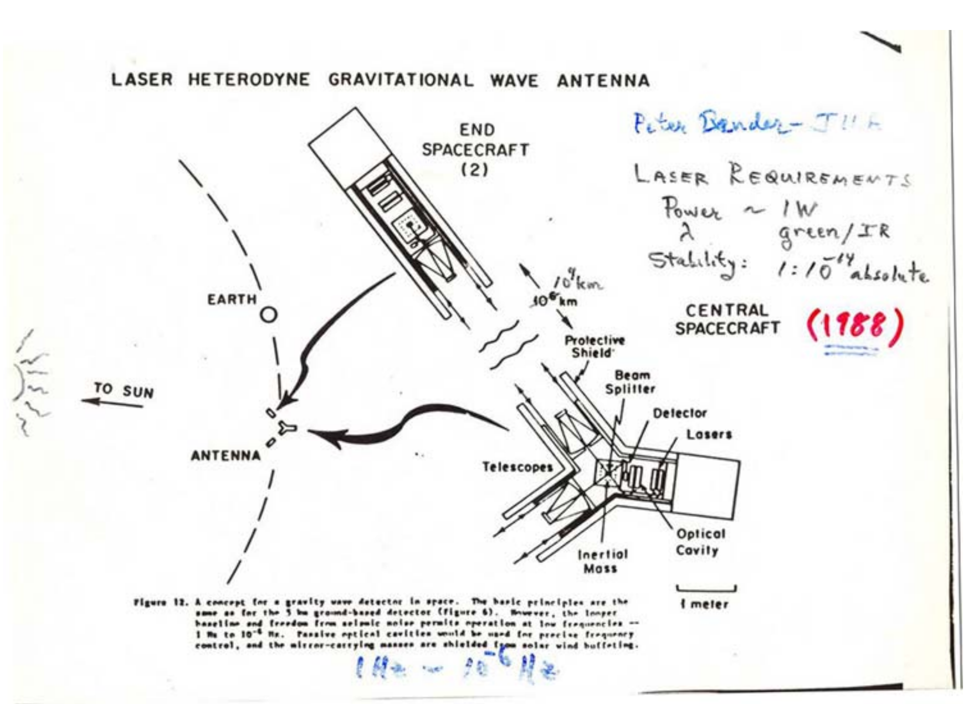
LIGO and LISA & Gravitational Waves

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

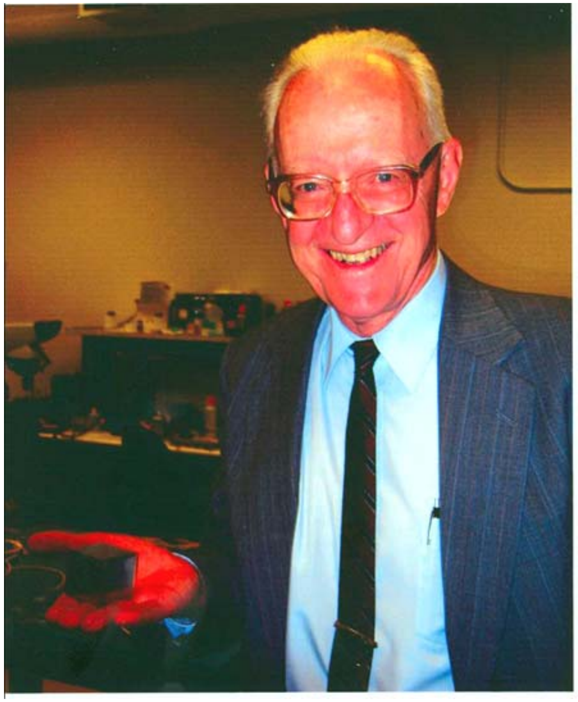


Global remote sensing 1980 – Needed a coherent laser oscillator.

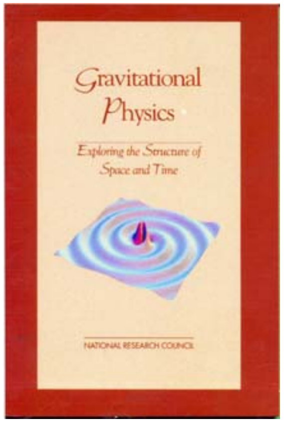
....from Coherent Laser Radar to Gravitational Waves... 1988



Schematic of LISA in 1988



Peter Bender holding 4x4cm Au/Pt cube

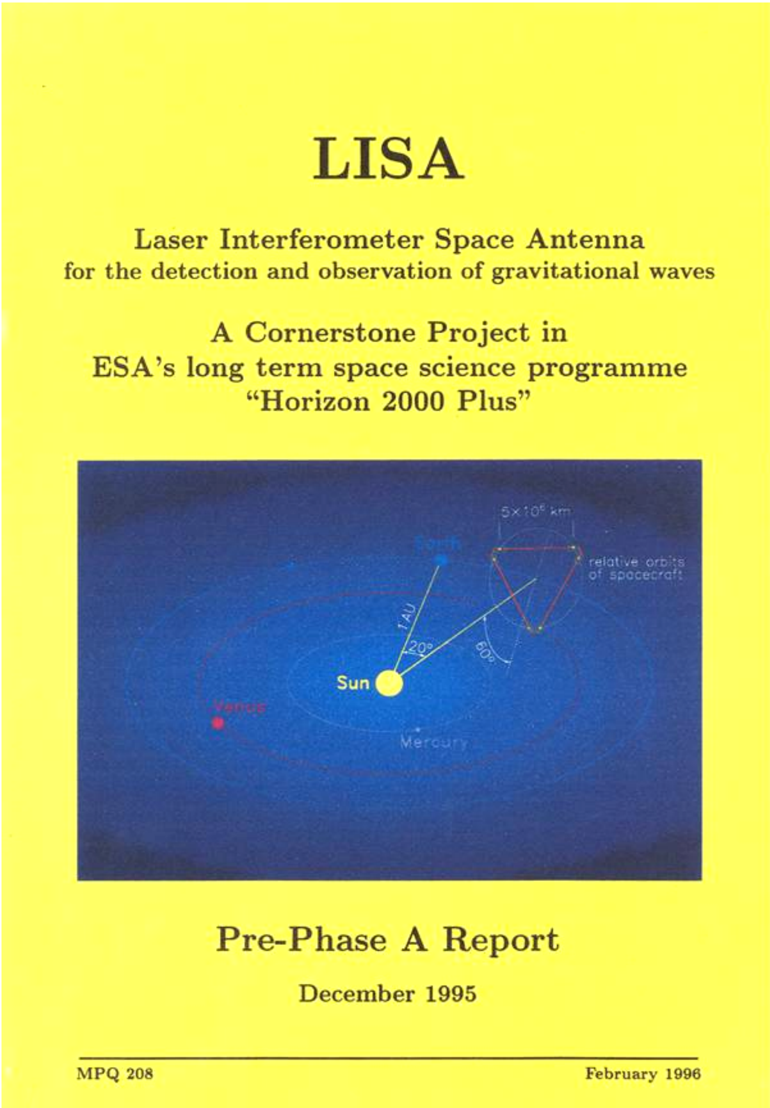


Gravitational waves open a new window on universe

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

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

LISA Mission – Pre Phase A Report - 1995


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

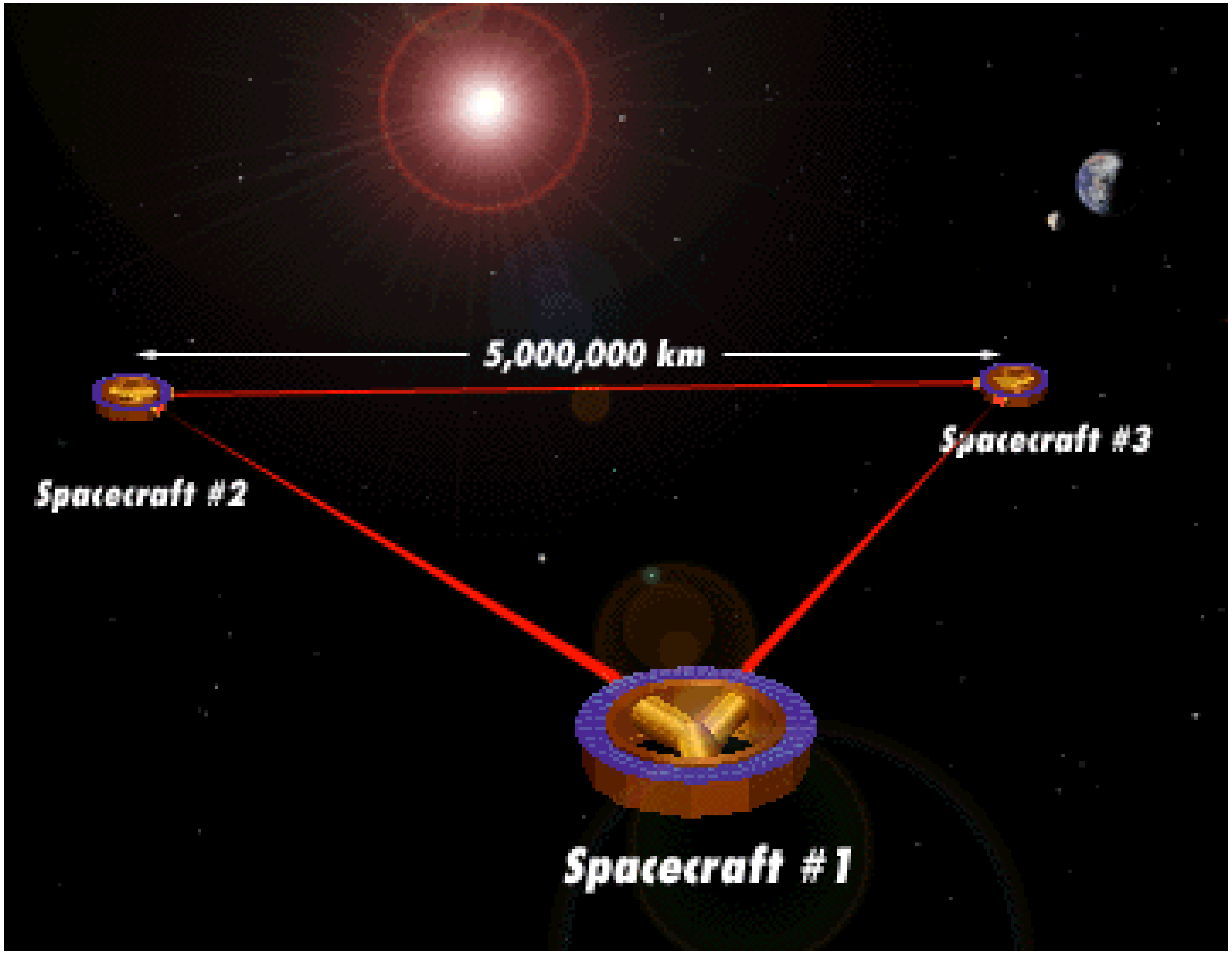
3 satellites in solar orbit
1 W laser - Nd:YAG NPRO
5 million km interferometer path
30 light seconds round trip delay

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

Will detect binary neutron stars in our galaxy

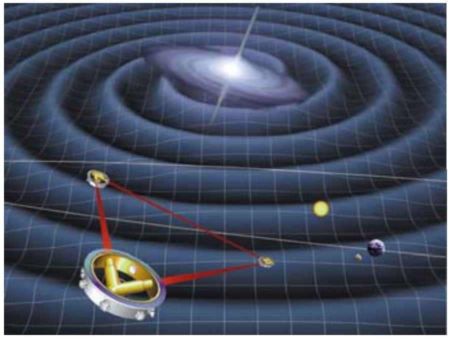
Will detect massive binary Black Holes at Cores of most galaxies

LISA Interferometer Space Antenna



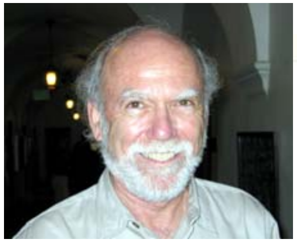
Karsten Danzmann

LISA Pathfinder Technology Mission



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

LIGO Observatory Sites



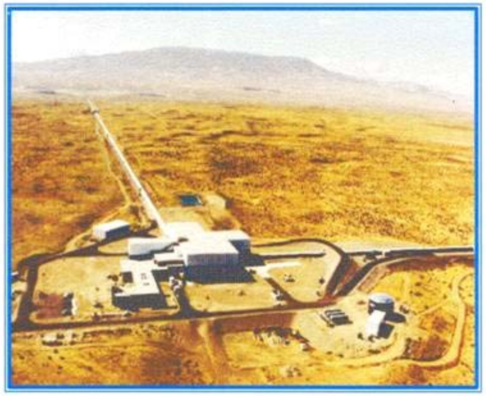
Barry Barish*

LIGO Sites

LIGO-G9900XX-00-M NSF LIGO II Review 5

Rai Weiss
MIT

LIGO sites



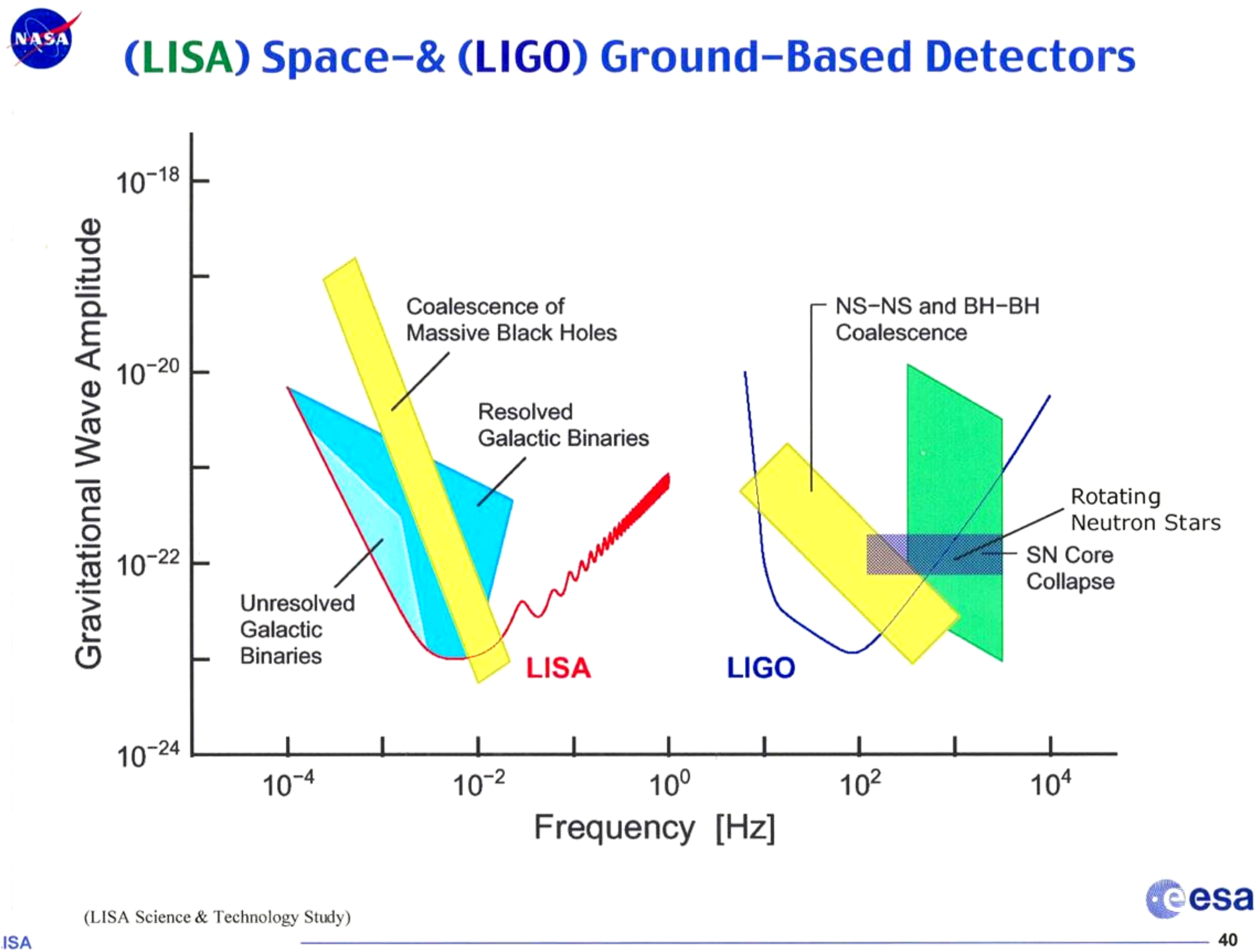
- Hanford Observatory

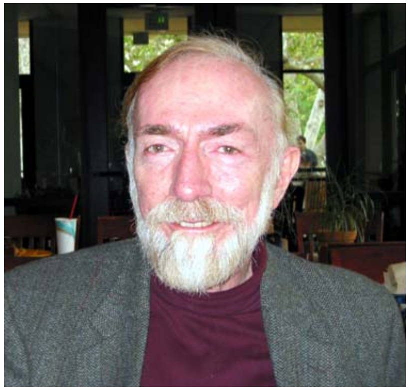
- Livingston Observatory

LIGO-G9900XX-00-M NSF LIGO II Review 12

* Jay Marx joined LIGO as Director – Jan 2006

LISA and LIGO Detection Bands



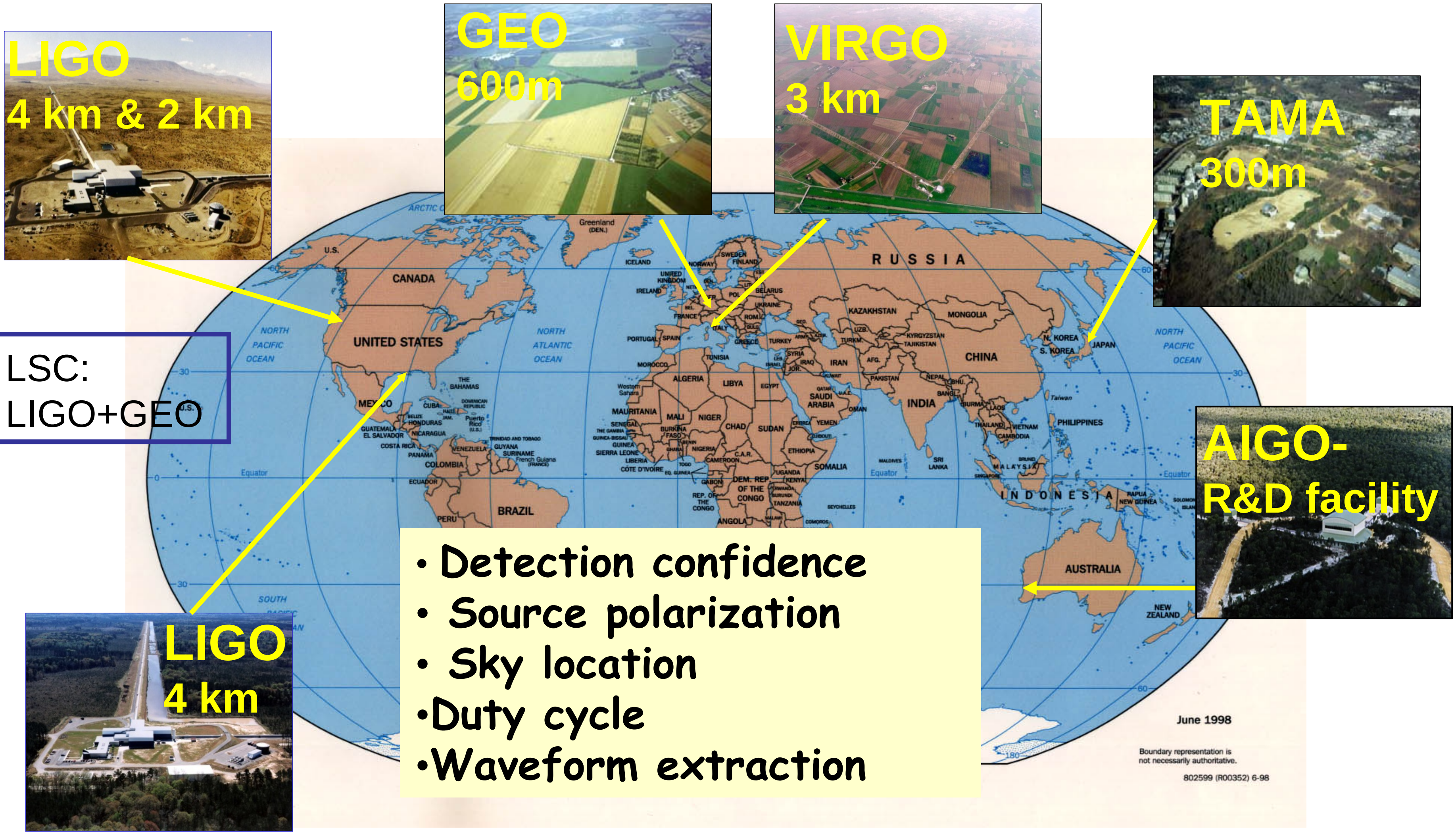


Kip Thorne,
CalTech

&

Rai Weiss
MIT

Global network of interferometers



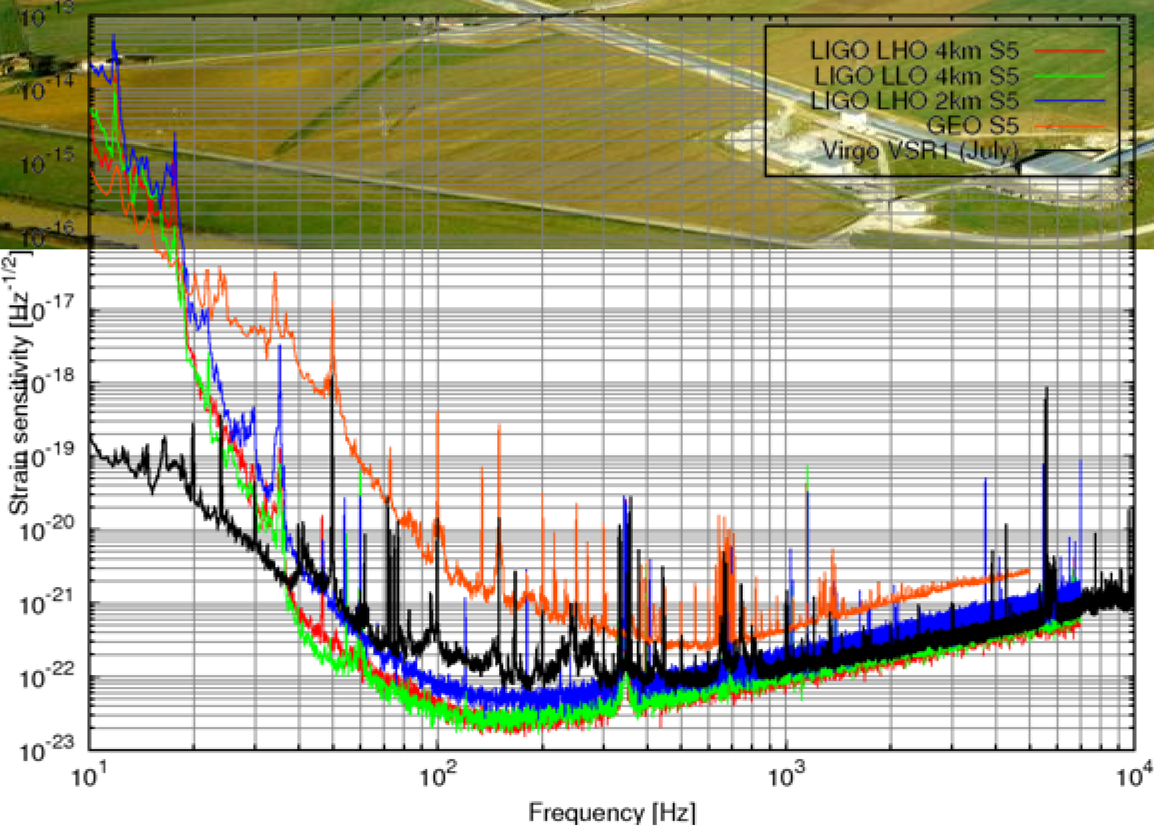
LSC:
LIGO+GEO

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

Virgo 3km detector – Piza, Italy

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 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
- 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 Washington

- What are GW?
  - waves in curvature of space-time
  - a prediction of general relativity
  - produced by acceleration of mass

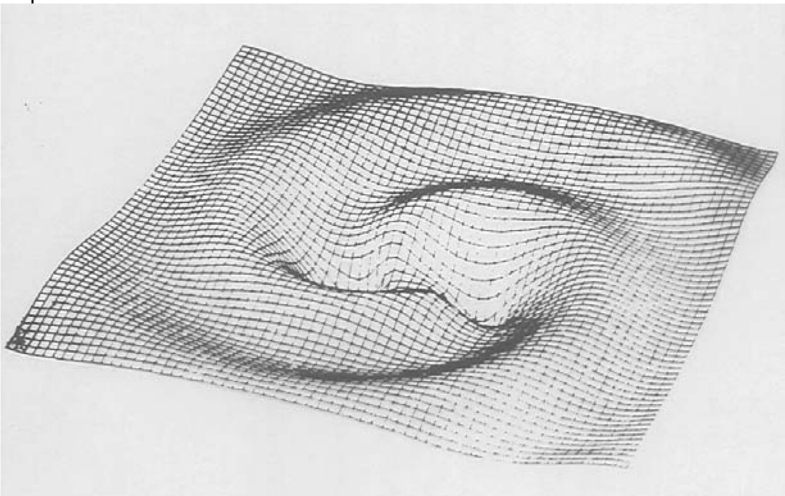
    (c.f. EM waves produced by accelerated charge)
  - travel at speed of light

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!!!!)

1 part in 10^{21} strain

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

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

Strain sensitivity analogous to
10^{-21} x 4 x 10^{16} m = 4 x 10^{-5} m ~ 40 microns!

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

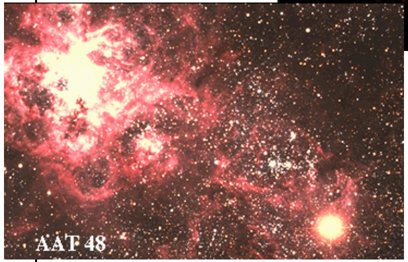
Alpha Centauri
(one of the nearest stars)

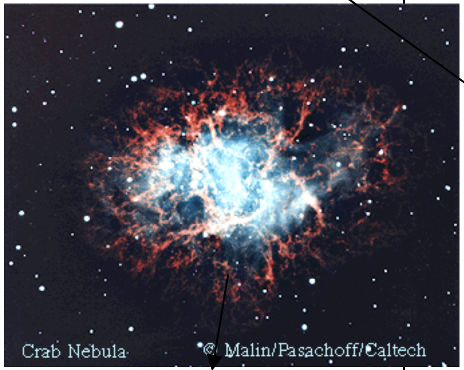
Gravitational Wave Sources

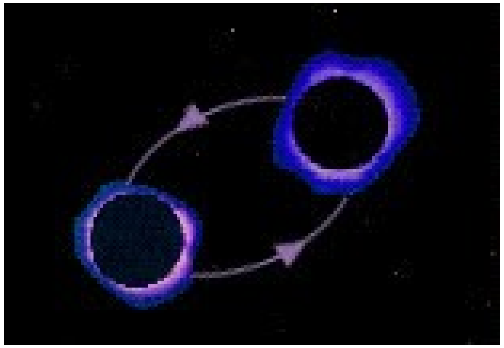
Bver

- ***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
- ***Continuous***
  - pulsars (e.g. Crab)
  (sign up for Einstein@home)
  - low mass X-ray binaries Sco-X1)
- ***Stochastic Background***
  - random background "noise" associated with cosmological processes, e.g. inflation, cosmic strings.....

SN1987a





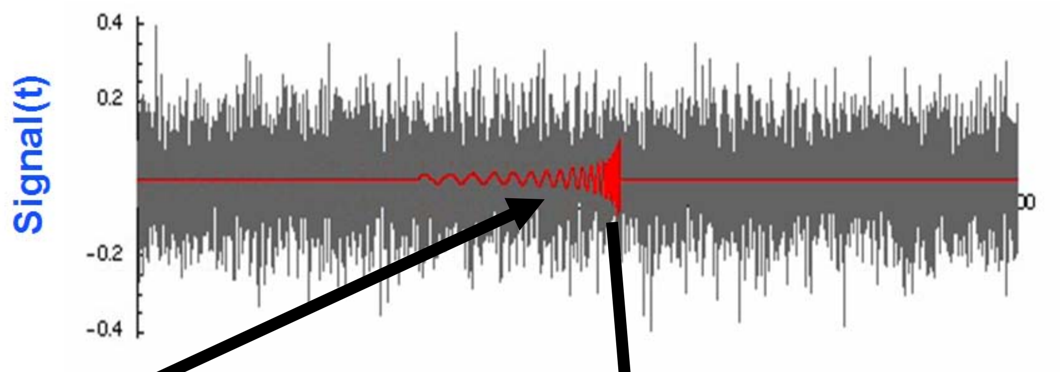


A New Astronomy

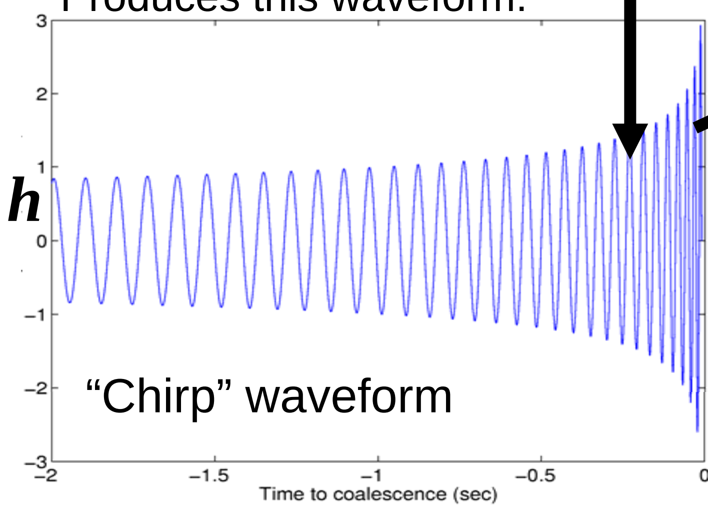
The challenge of LIGO data analysis

This source:

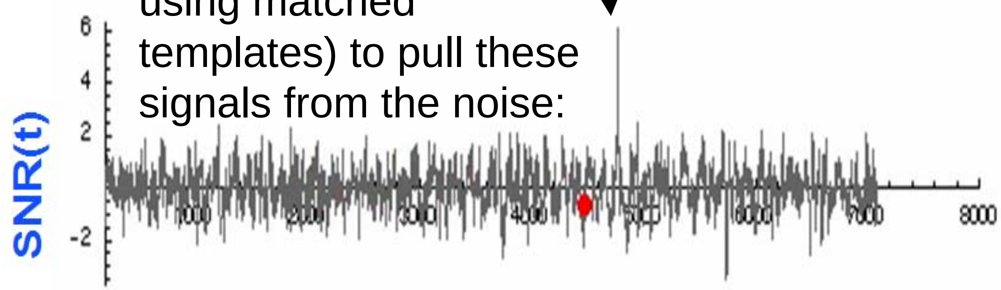
Embedded in this noise stream:



Produces this waveform:



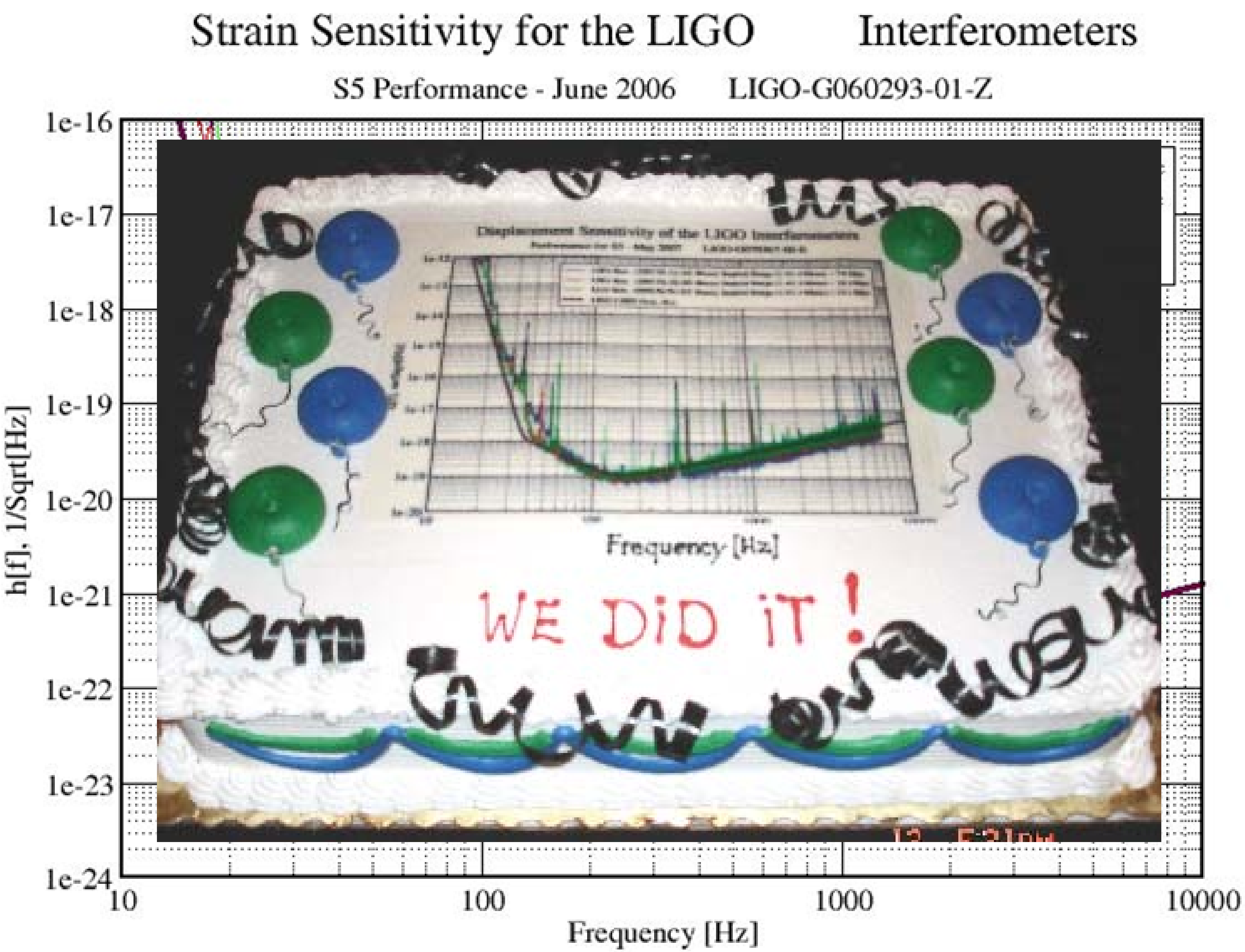
We use different methods (in this case optimal Weiner filtering using matched templates) to pull these signals from the noise:



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

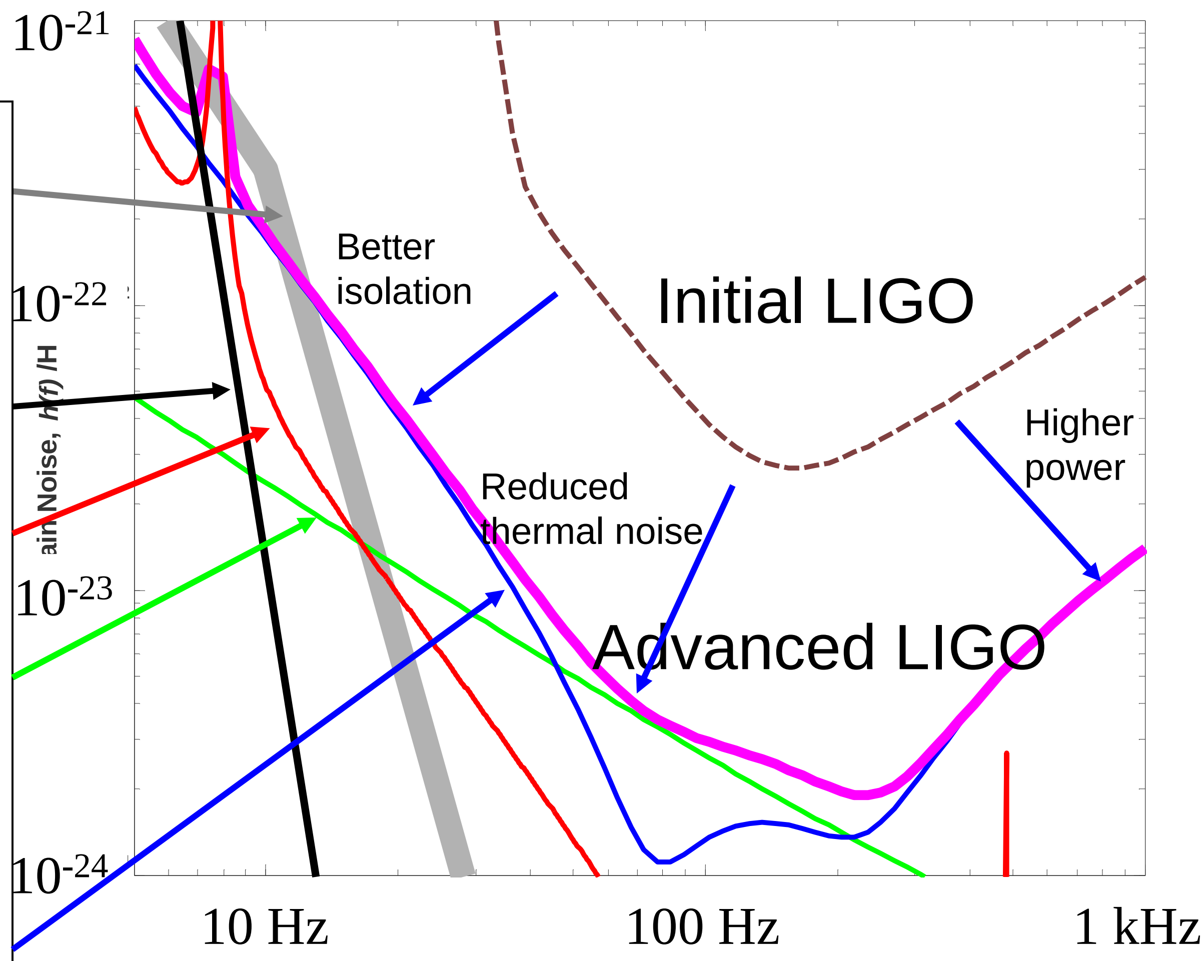
S5 Science Run: LIGO at Design Sensitivity

Byer Group



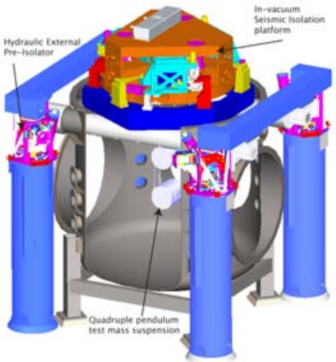
Projected Advanced LIGO performance

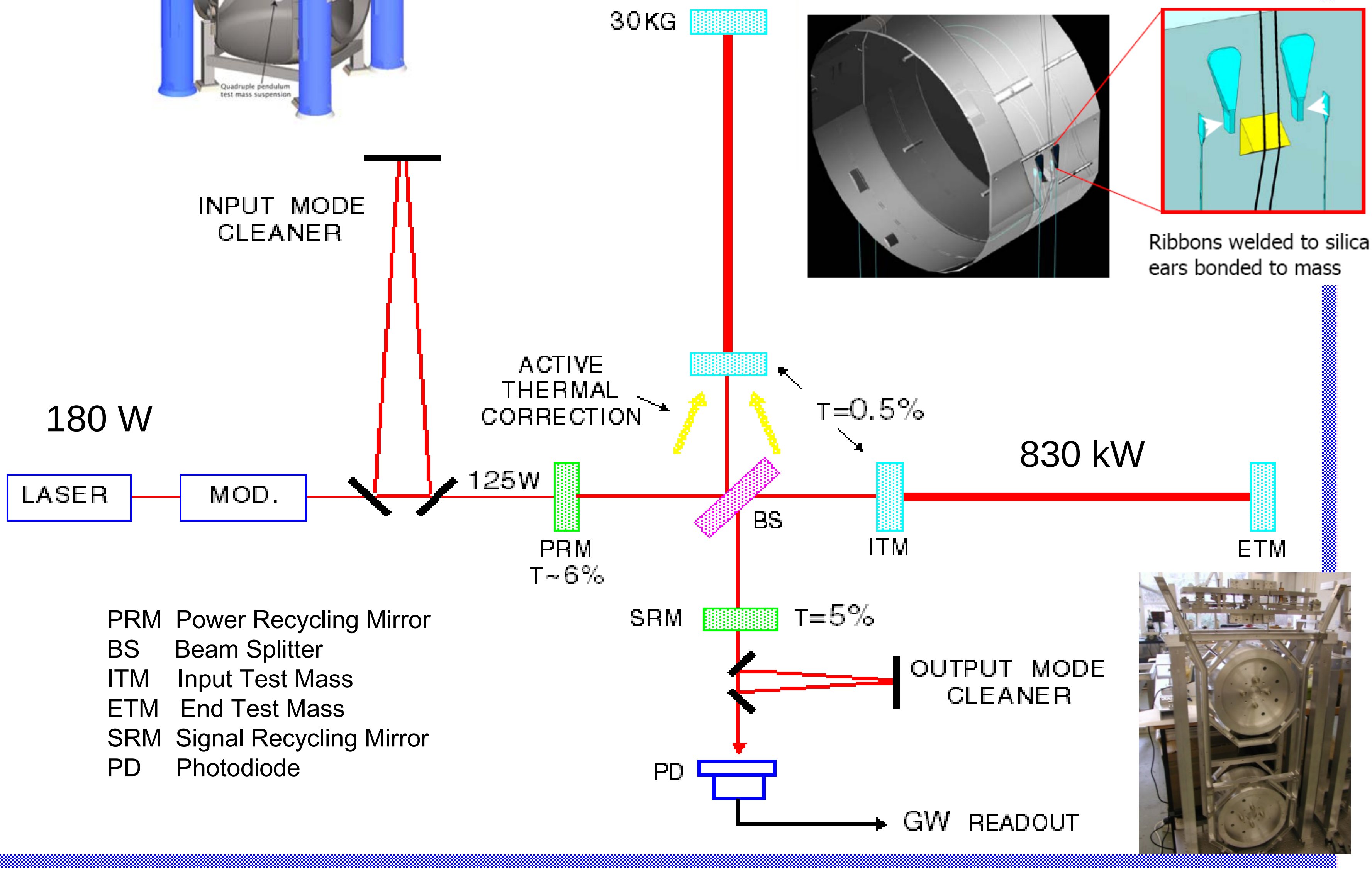
- Newtonian background, estimate for LIGO sites
- Seismic 'cutoff' at 10 Hz
- Suspension thermal noise
- Test mass thermal noise
- Unified quantum noise dominates at most frequencies for full power, broadband tuning



David Shoemaker/adapted

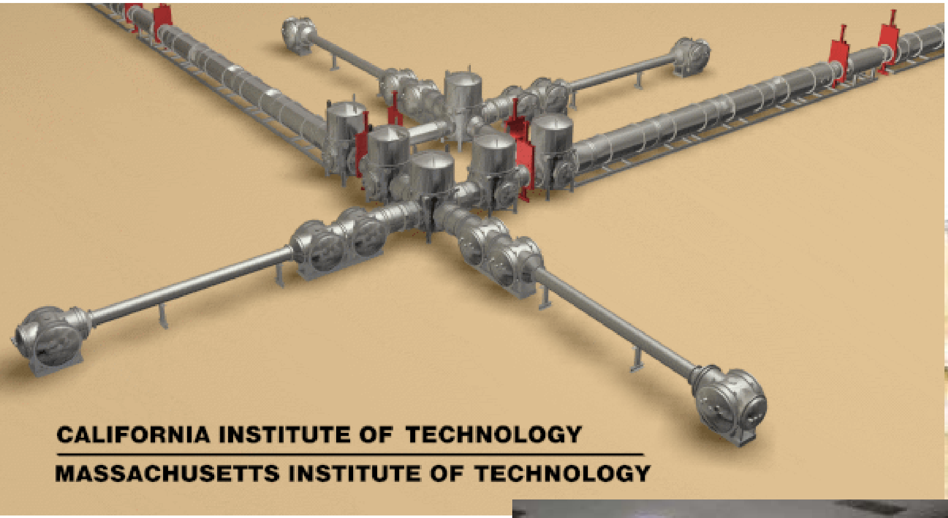
Advanced LIGO





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

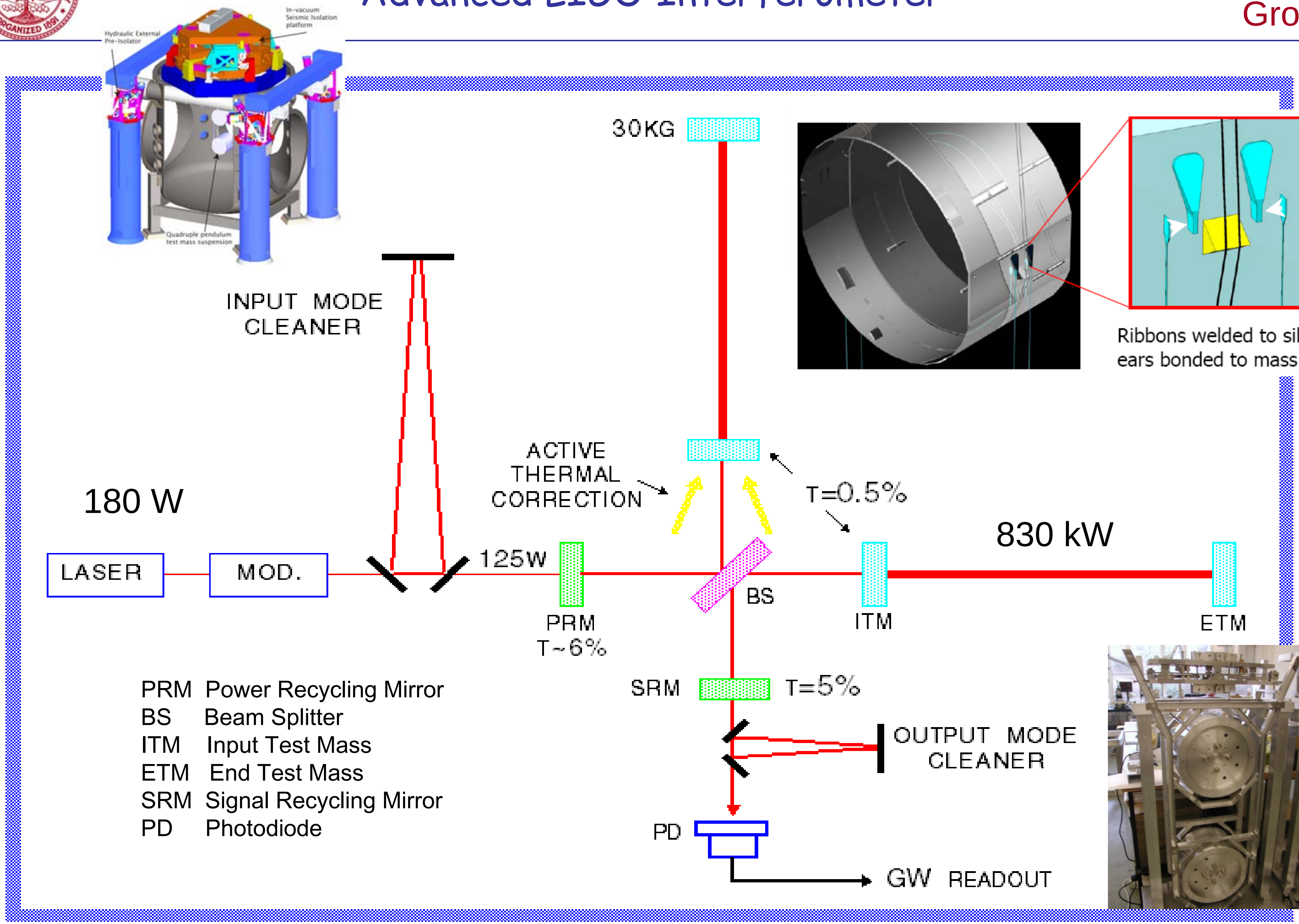
LIGO Vacuum Equipment



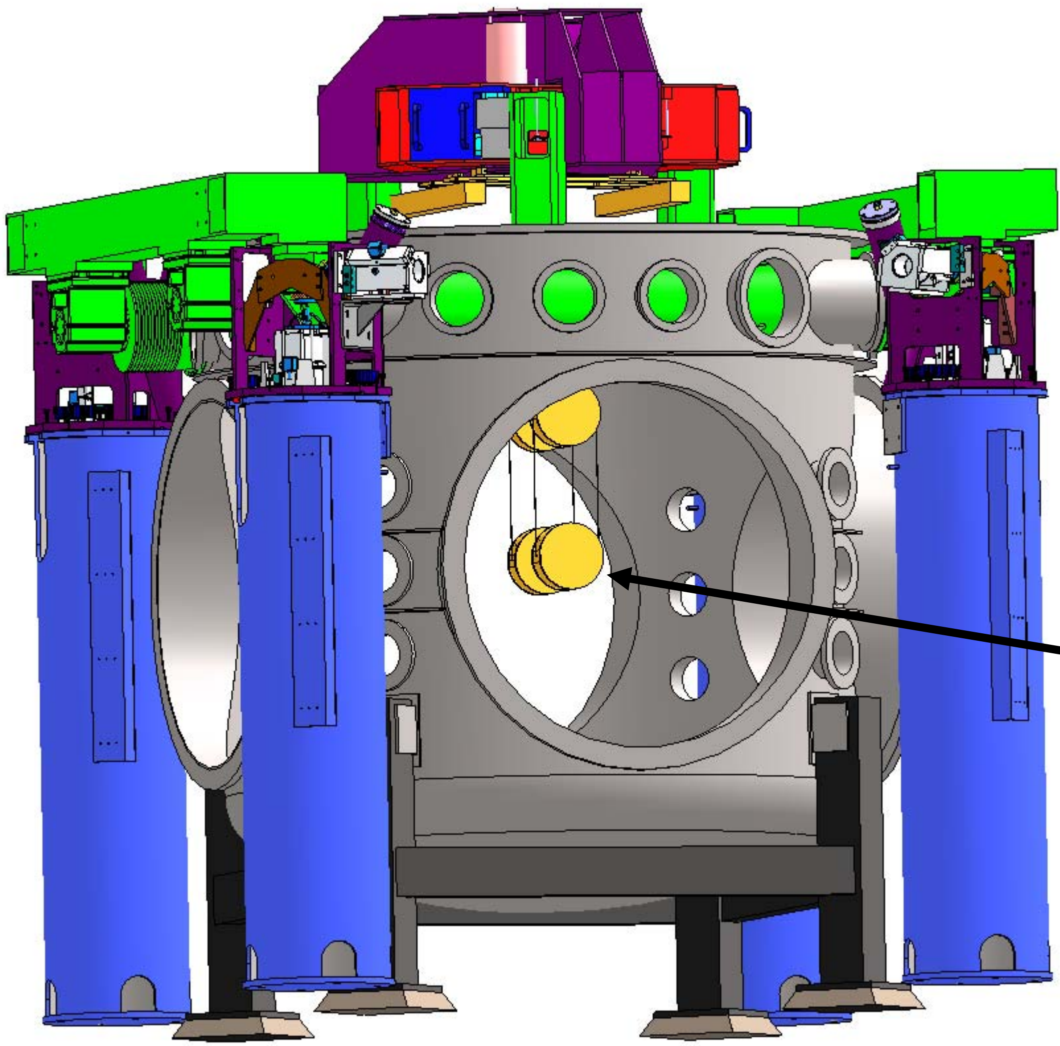
- 1.2 m diameter
- Aligned to a mm
- Total of 16km fabricated with no leaks
- 1 nTorr (!)
- few, remote pumps
- Cover...

Vacuum tube enclosures test

Advanced LIGO Interferometer



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



active isolation platform (Stanford)

Hydraulic pre-isolator (HEPI) (Stanford)

quad pendulum

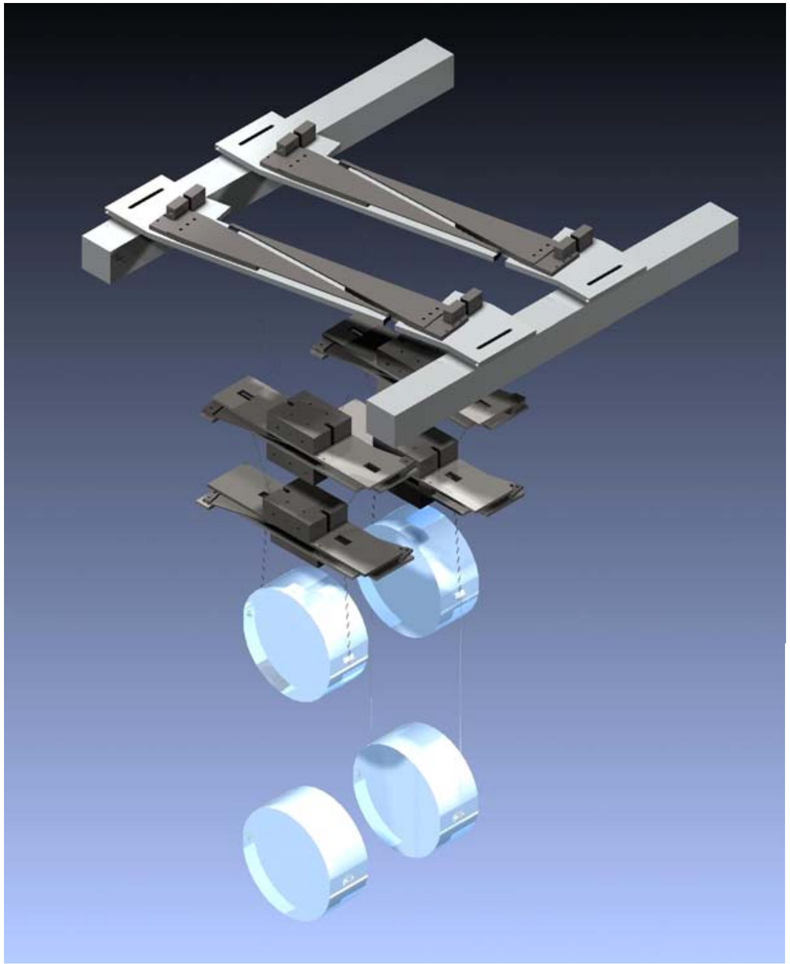
(Glasgow Univ-

Sheila Rowan

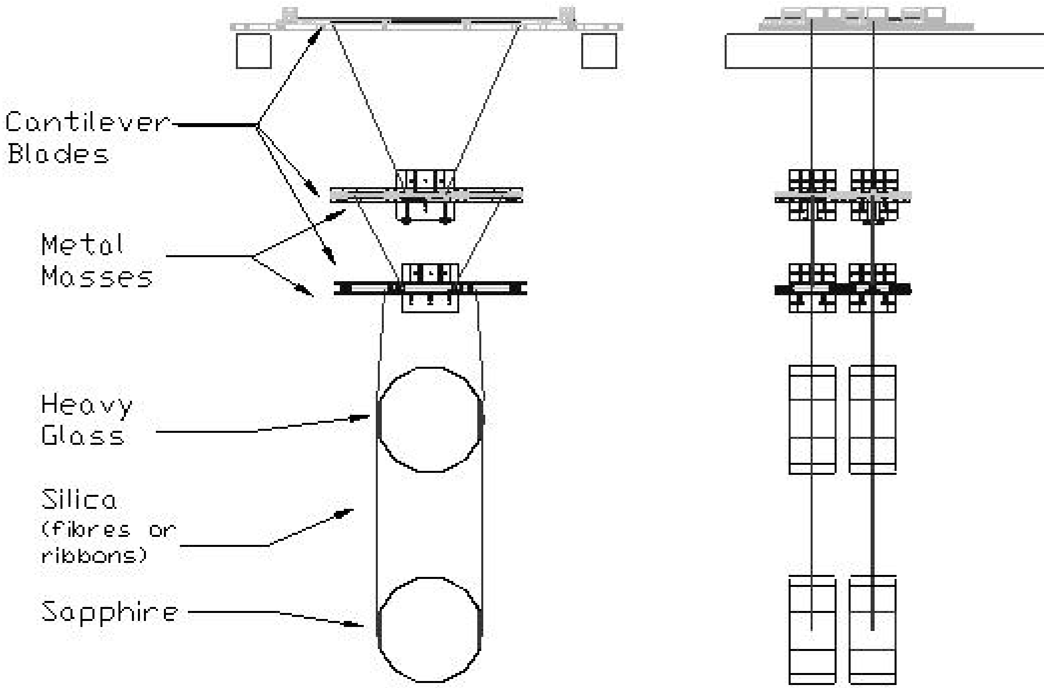
Norna Robertson)

Corwin Hardham

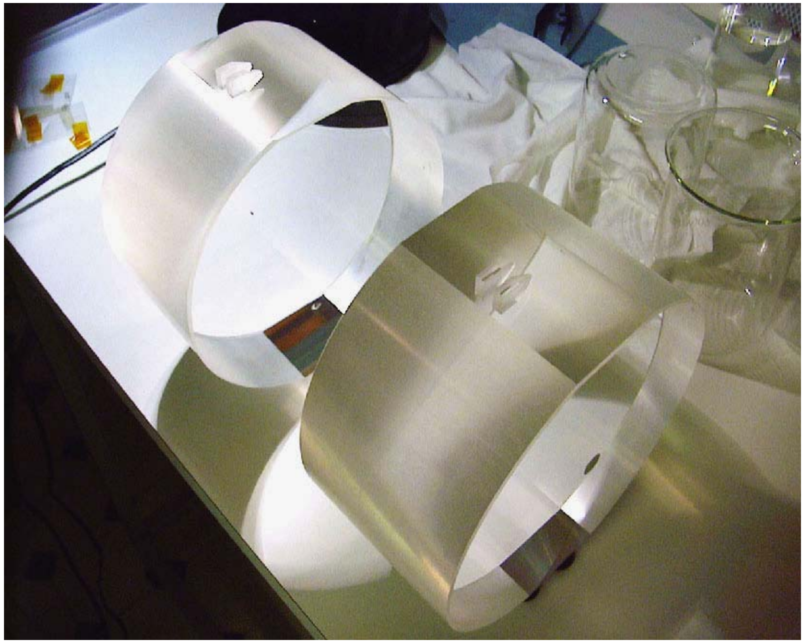
Quadruple Suspension for Advanced LIGO



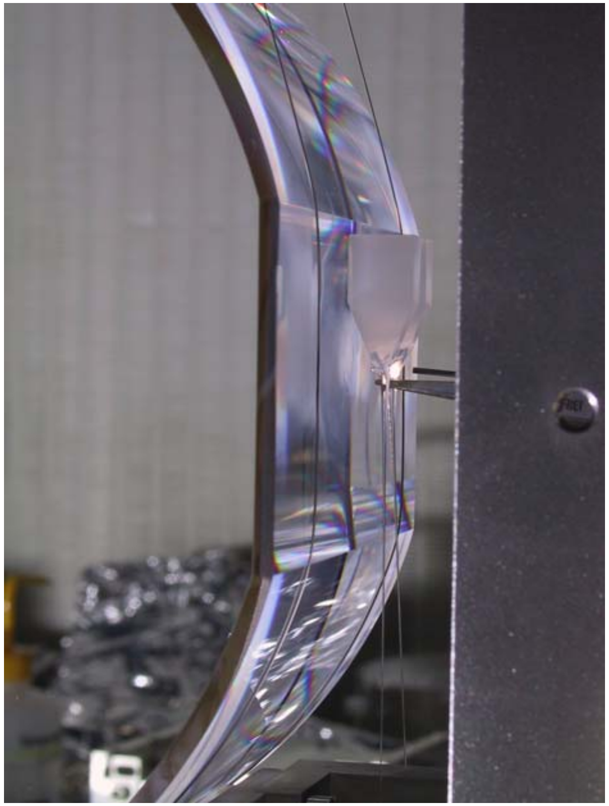
C Torrie, M Perreur-Lloyd, E Elliffe, R Jones



Monolithic Suspension - Assembly

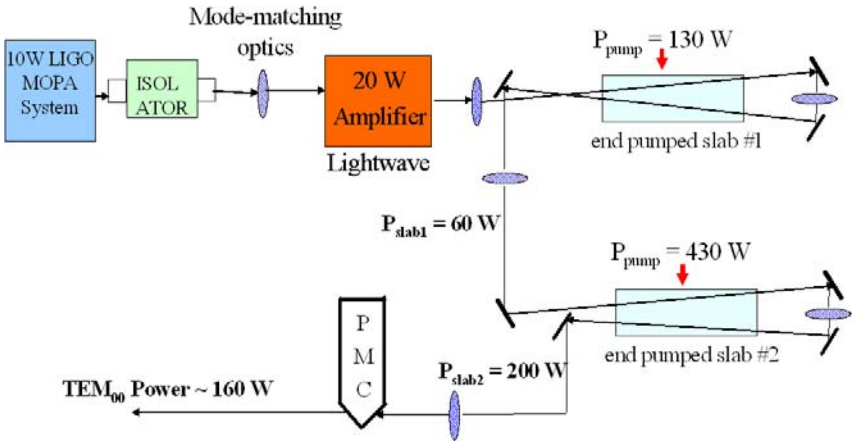


Bonding of ears

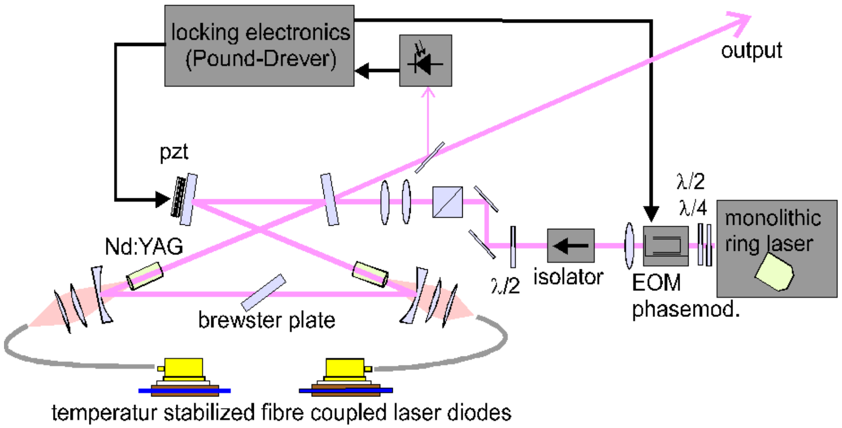


Welding of fibres

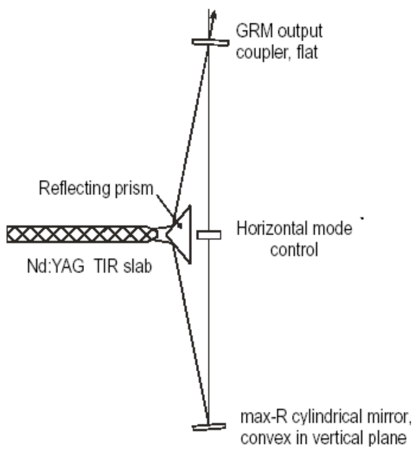
Advanced LIGO 180W Lasers – Benno Wilke, Hannover, Germany



Edge Pumped Nd:YAG slab - Stanford



Injection locked Nd:YAG oscillators Hannover

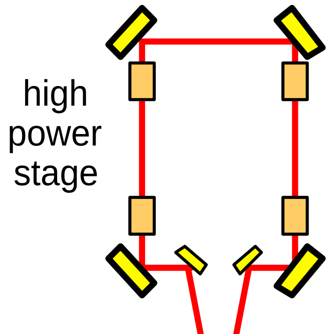
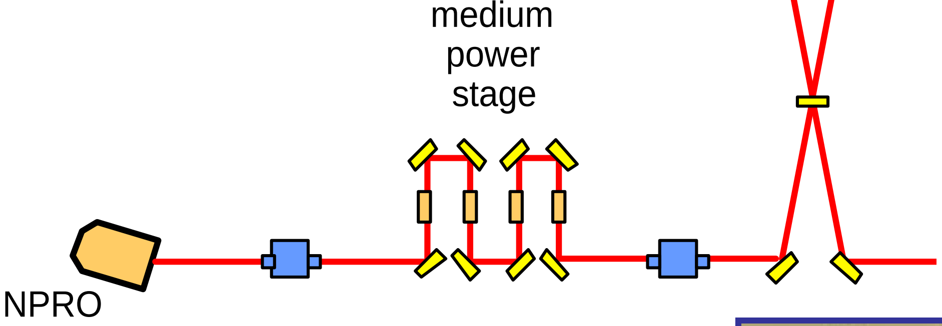


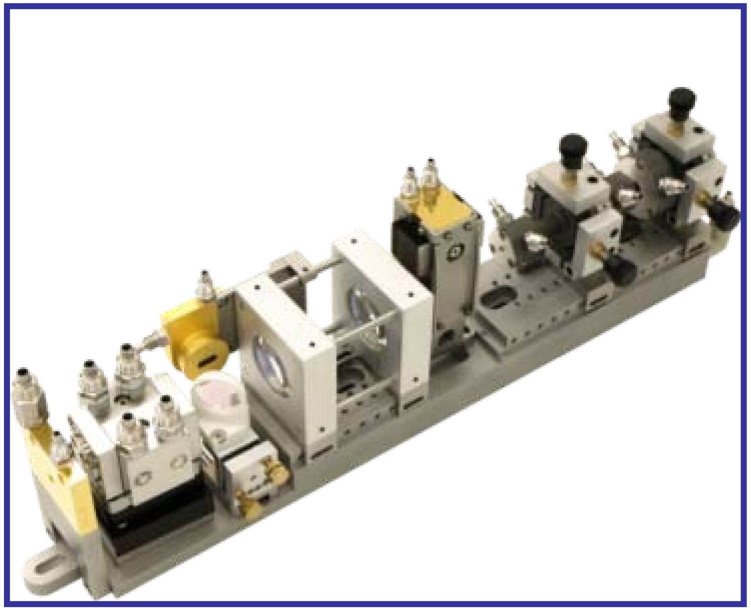
Unstable resonator -- Adelaide

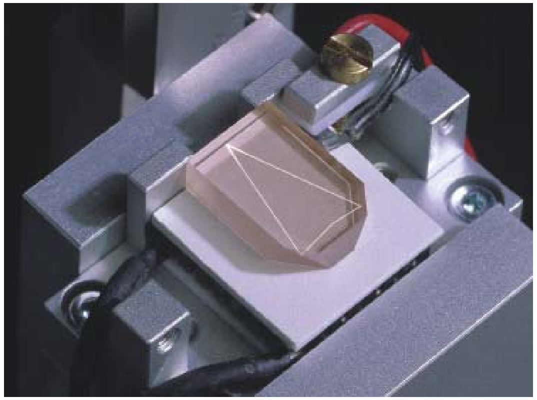
Benno Willke
Hannover

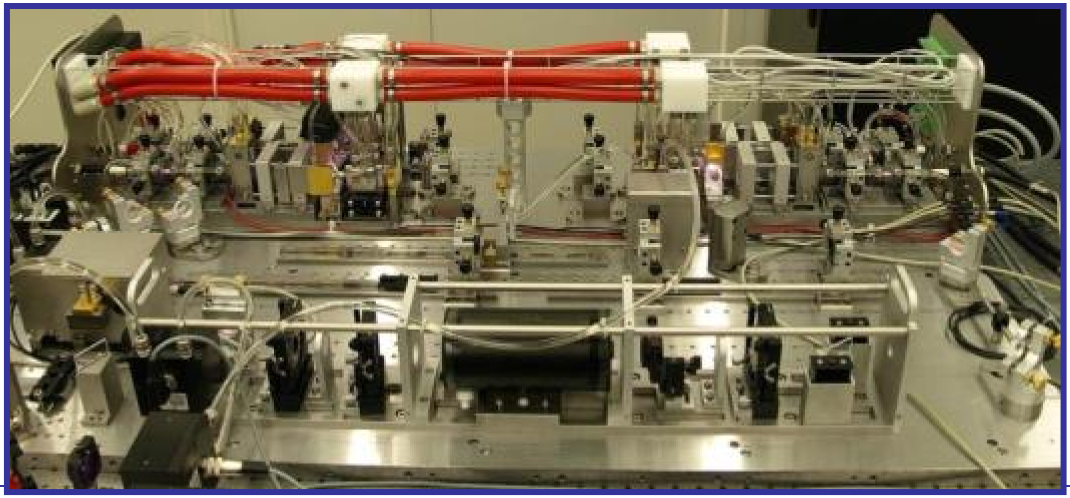
In charge of 180W Laser program for Advanced LIGO

180W prototype - layout



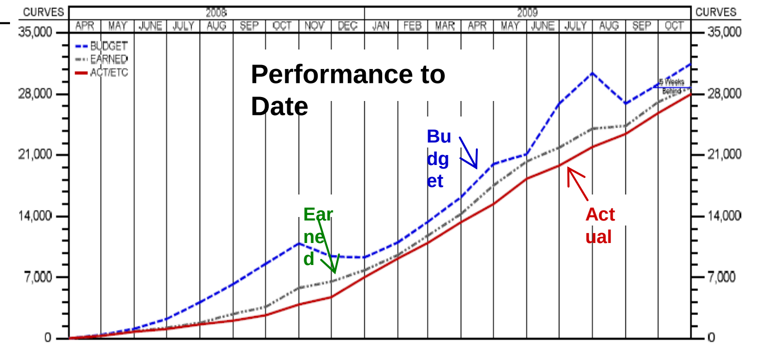




Advanced LIGO is advancing!

David Shoemaker - MIT

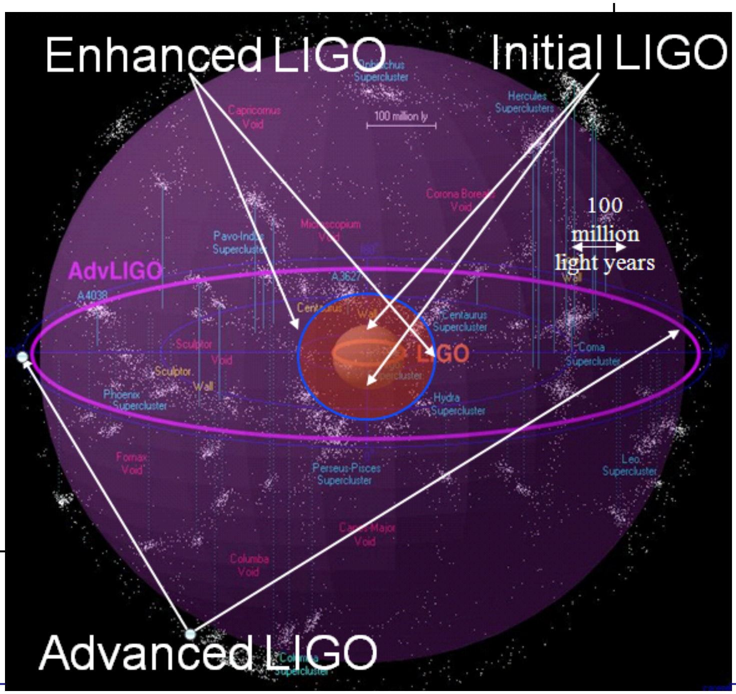
- **Started April 2008, scheduled to wrap up in 2015 with installation of the computing cluster**
- About 1/5 of the way through the Project in terms of 'earned value', pretty close to planned status
- Costs are ok (a little under due to soft economy); allows hiring people to solve problems



(COST IN USD x1,000)	BUDGET	EARNED	ACTUAL	S.V.	C.V.	S.P.I.	C.P.I.		
PREVIOUS PERIODS	29,111	27,067	25,814	-2,044	1,253	0.93	1.05	E.A.C.:	167,789
CURRENT PERIOD	2,383	1,737	2,167	-646	-430	0.73	0.80	SCHED. % COMP.:	18.77
TO DATE	31,494	28,804	27,981	-2,690	823	0.91	1.03	ACTUAL % COMP.:	17.17

BUDGET: 167,789

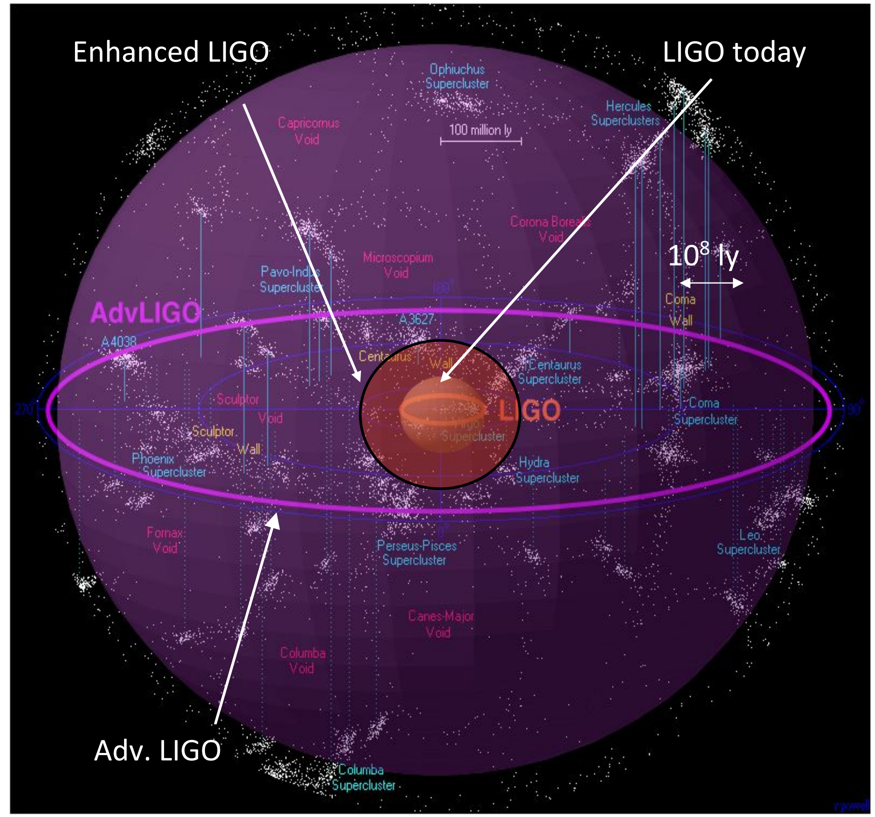
- **No significant new noise sources or problems – should be able to get to that promised factor-of-10 in sensitivity**
- Design is wrapping up; big ticket/long schedule items mostly underway
- Modifications of Observatories for assembly, cleaning, storage complete
- Fabrication is underway of interferometer components



Gravitational Waves: From Discovery to 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

Contents

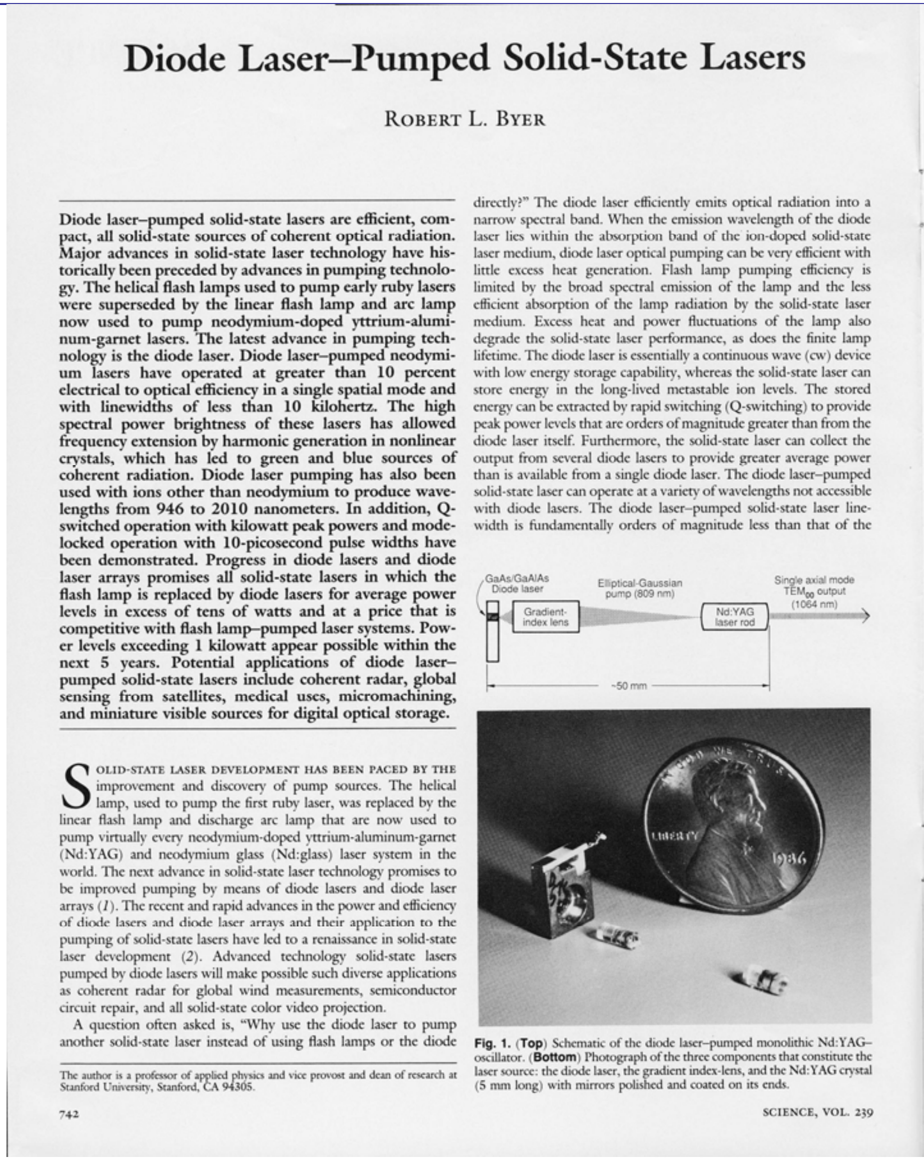
- Introduction *Making Lightwaves*
  - Early laser history and concepts
    - Unstable Resonator
    - Slab Laser – one dimensional cooling
  - Recent Innovations – Solid State Lasers
    - Edge Pumped Slab Laser
    - Transparent 'Ceramic' polycrystalline gain media

    (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 Pumped Solid State Lasers – 1984

Byer
Group



Diode Laser–Pumped Solid-State Lasers

ROBERT L. BYER

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

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

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

GaAs/GaAlAs Diode laser
Gradient-index lens
Elliptical-Gaussian pump (809 nm)
Nd:YAG laser rod
Single axial mode TEM_{00} output (1064 nm)
~50 mm

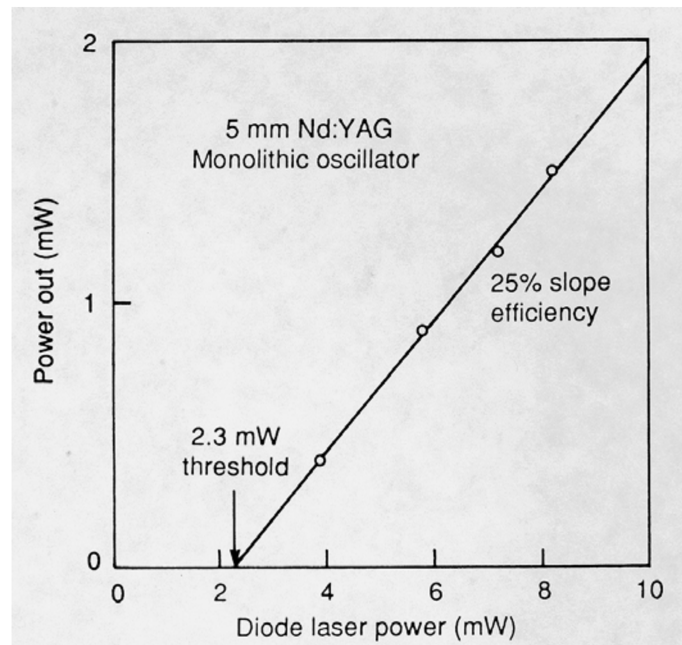
Fig. 1. (**Top**) Schematic of the diode laser–pumped monolithic Nd:YAG–oscillator. (**Bottom**) Photograph of the three components that constitute the laser source: the diode laser, the gradient index-lens, and the Nd:YAG crystal (5 mm long) with mirrors polished and coated on its ends.

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

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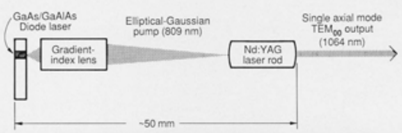

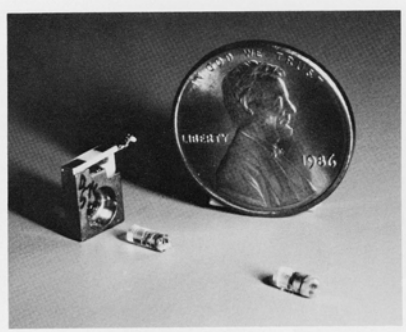

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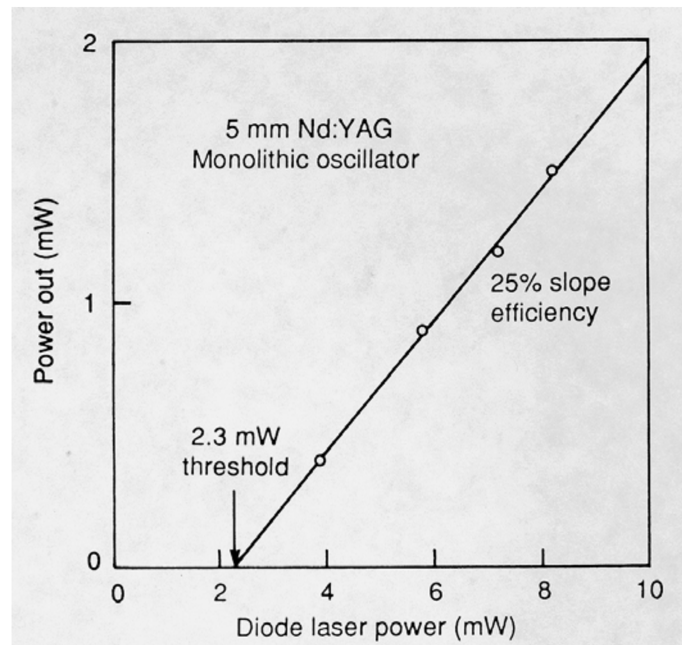
"Efficient, frequency-stable laser-diode-pumped Nd:YAG laser"
Opt. Lett. 10, 62, 1985

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



Innovation: Progress in Laser Diodes - 1978

Phase-locked semiconductor laser array

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

Xerox Palo Alto Research Center, 3333 Coyote Hill Road, Palo Alto, California 94304

(Received 14 August 1978; accepted for publication 6 October 1978)

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

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

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

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

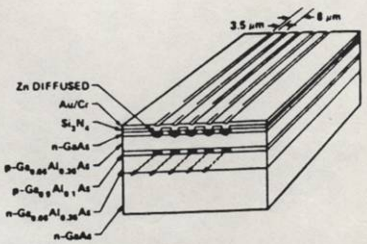


FIG. 1. Schematic diagram of a multiple-stripe phase-locked laser array.

1015 Appl. Phys. Lett. 33(12), 15 December 1978 0003-6951/78/3312-1015$00.50 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,

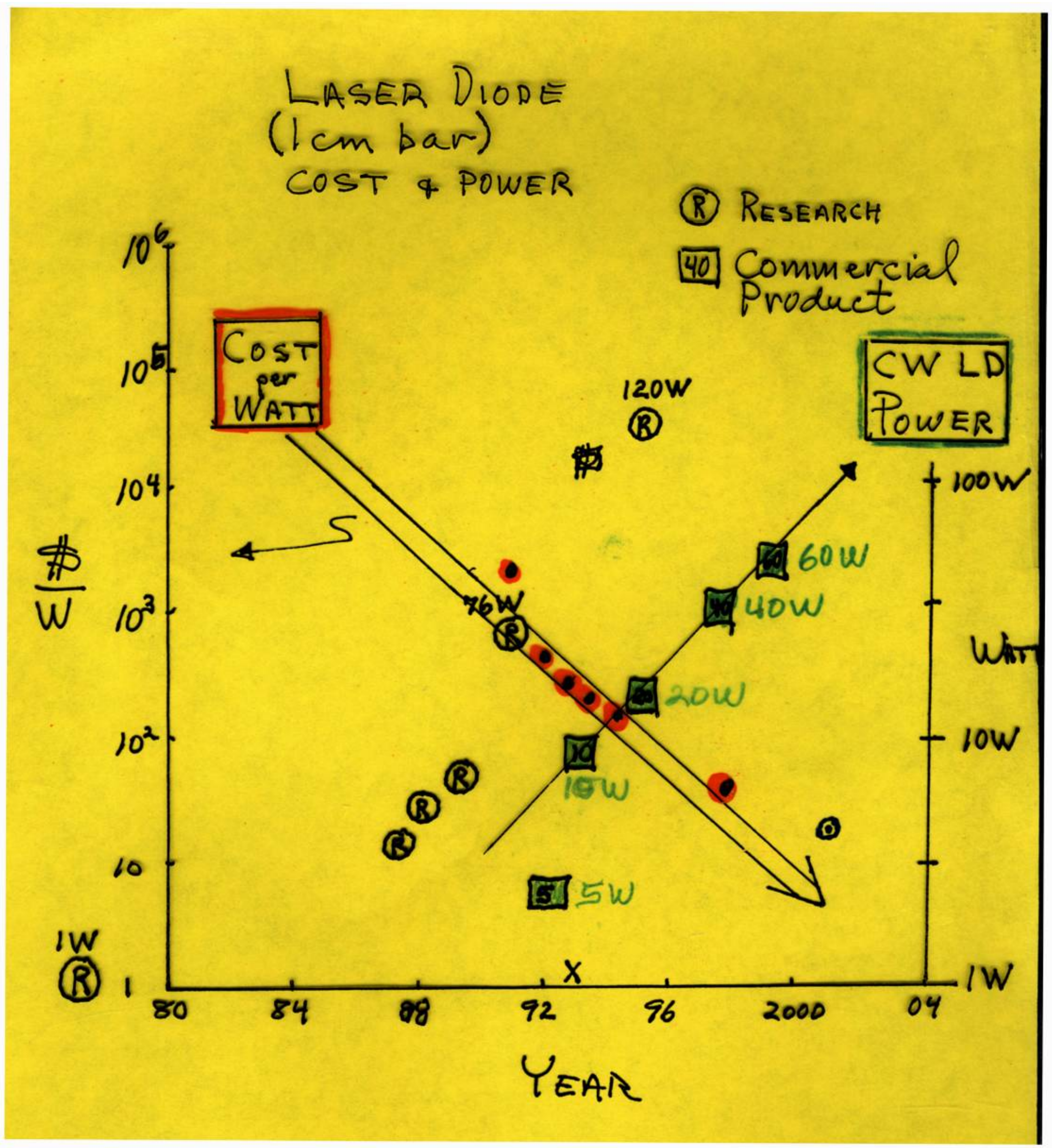
Ralph Burnham, and
Bill Streifer - 1978

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)

Contents

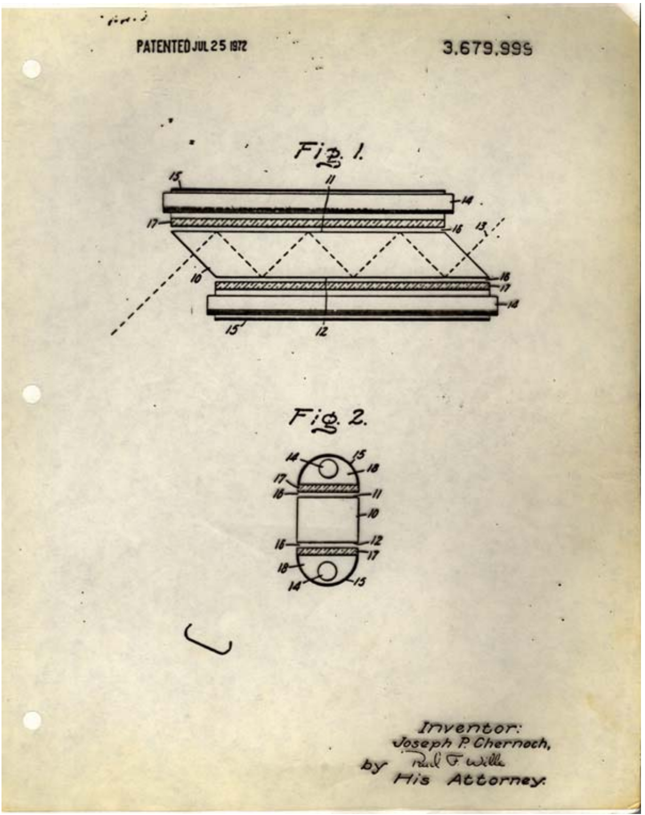
- Introduction *Making Lightwaves*
  - Early laser history and concepts
    - Unstable Resonator
    - Slab Laser – one dimensional cooling
  - Recent Innovations – Solid State Lasers
    - Edge Pumped Slab Laser
    - Transparent 'Ceramic' polycrystalline gain media

    (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**

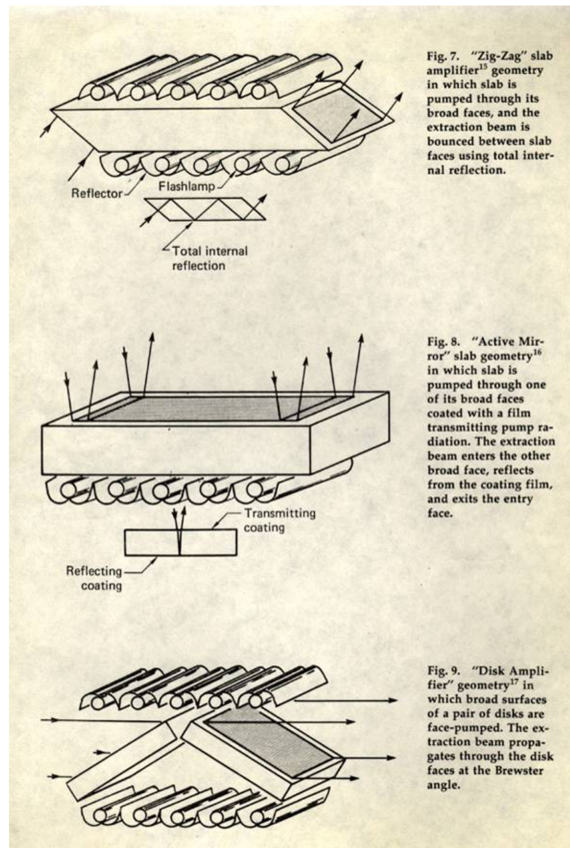
Innovation: Nd:YAG & Nd:Glass Slab Geometry Lasers - 1972



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

The zig-zag slab laser concept

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

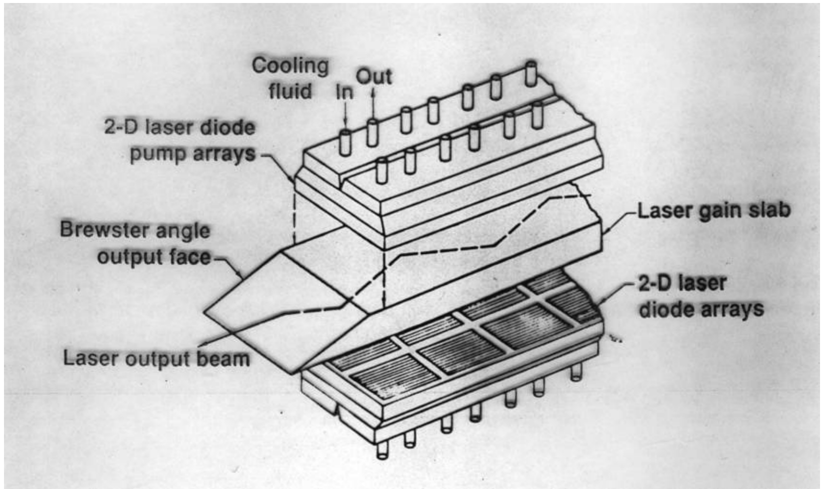


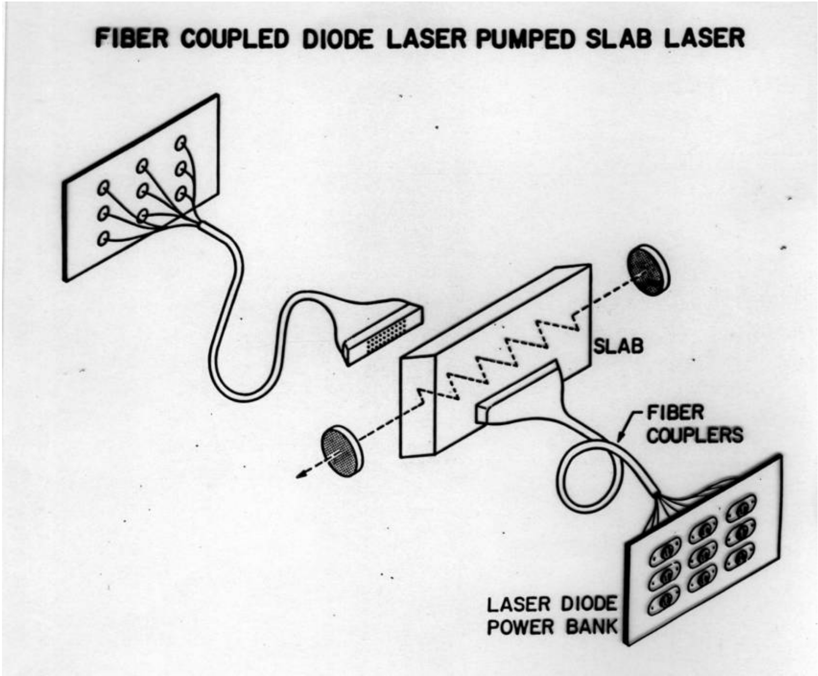
"Zig-Zag" face pumped Slab laser

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

"Disk amplifier" geometry adopted for the NIF Laser

Diode pumped Slab Lasers





TRW DAPKL* Nd:YAG Laser

(1988 - 1993)

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

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

Stanford University

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

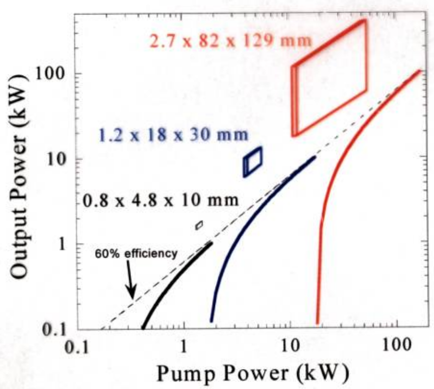
Face pumped, water cooled
25 - 10W fiber coupled laser diodes
250 W pump power
Cost: $280k in 1995

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

T.S. Rutherford, W.M. Tulloch,
E.K. Gustafson, R.L. Byer

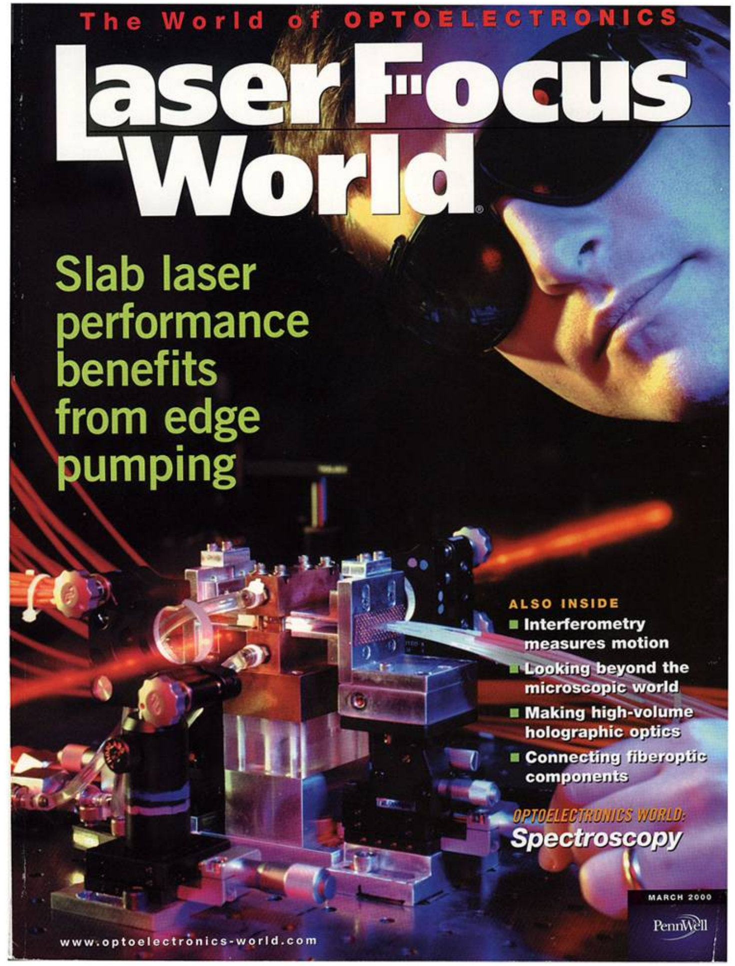
"Edge-Pumped Quasi-Three-Level Slab Lasers: Design and Power Scaling"
IEEE J. Quant. Elec., vol. 36, 2000

Towards a 100 kW DPSSL



	1 kW	10 kW	100 kW	
Pump density	47	27	6	$\frac{kW}{cm^3}$
Doping	2.4	0.8	0.2	% at.
ΔT	108	95	62	°C
Heat Removal	145	130	72	$\frac{W}{cm^2}$
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

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

Ceramic Lasers:
Ready for Action

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

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

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

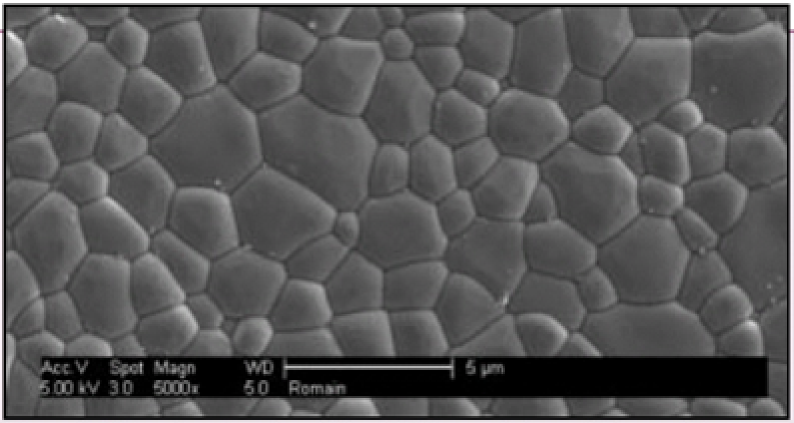


Figure 1. This undoped and unpolished YAG ceramic, imaged by scanning electron microscopy, was fabricated at Stanford University. Courtesy of Romain Gaume.

Professor Kenichi Ueda

New progress in neodymium doped ceramic lasers

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

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

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

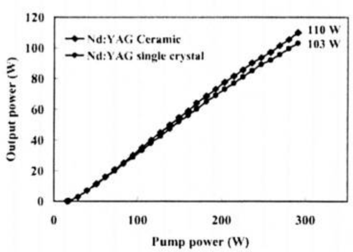
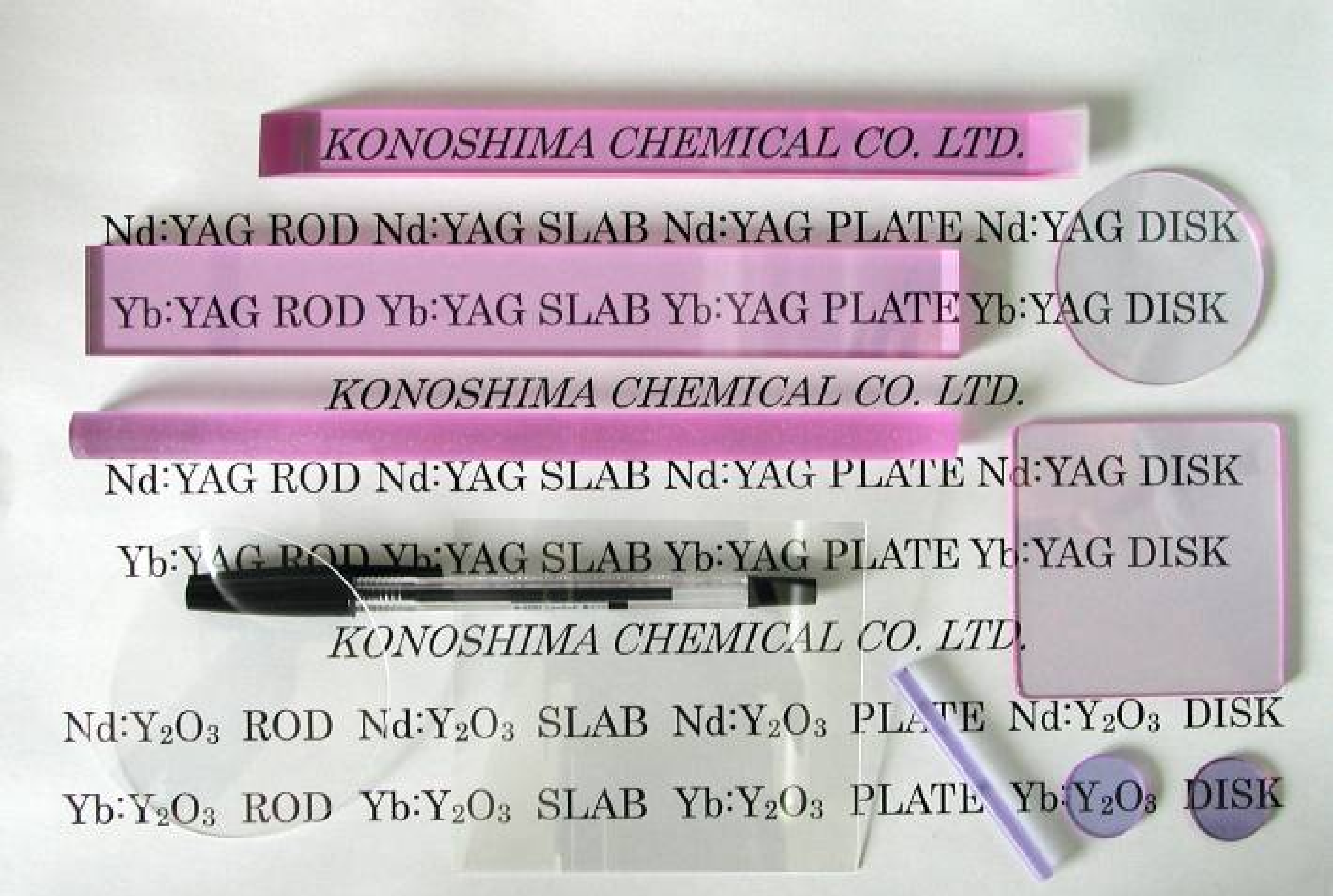


Fig. 1. Input-output dependences of Nd:YAG ceramic and single crystal lasers

Dr. Kenichi Ueda

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

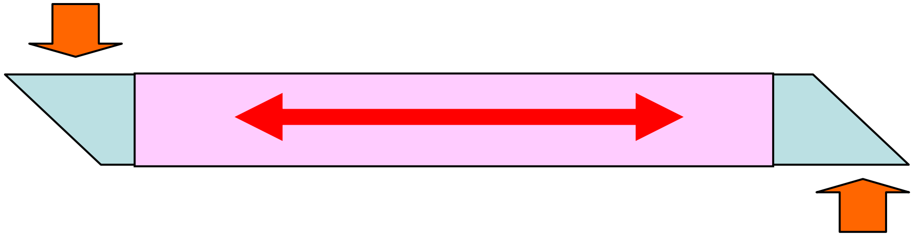
Key result: convinced laser community That Ceramic YAG better than Xtal YAG



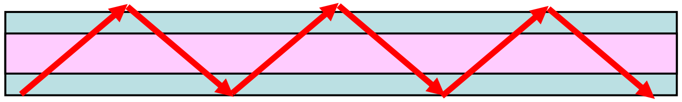
Ceramic gain media can be engineered to optimize laser performance

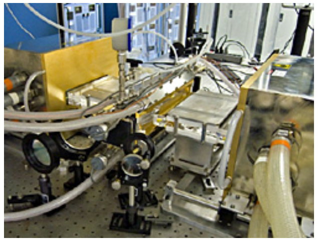
Research in US exceeds 105 kW average power using Diode Pumped Ceramic YAG

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

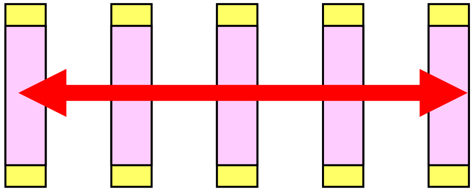


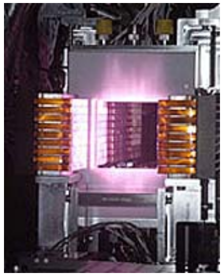
2. Textron: Zigzag Thin Slab Laser: Nd:YAG



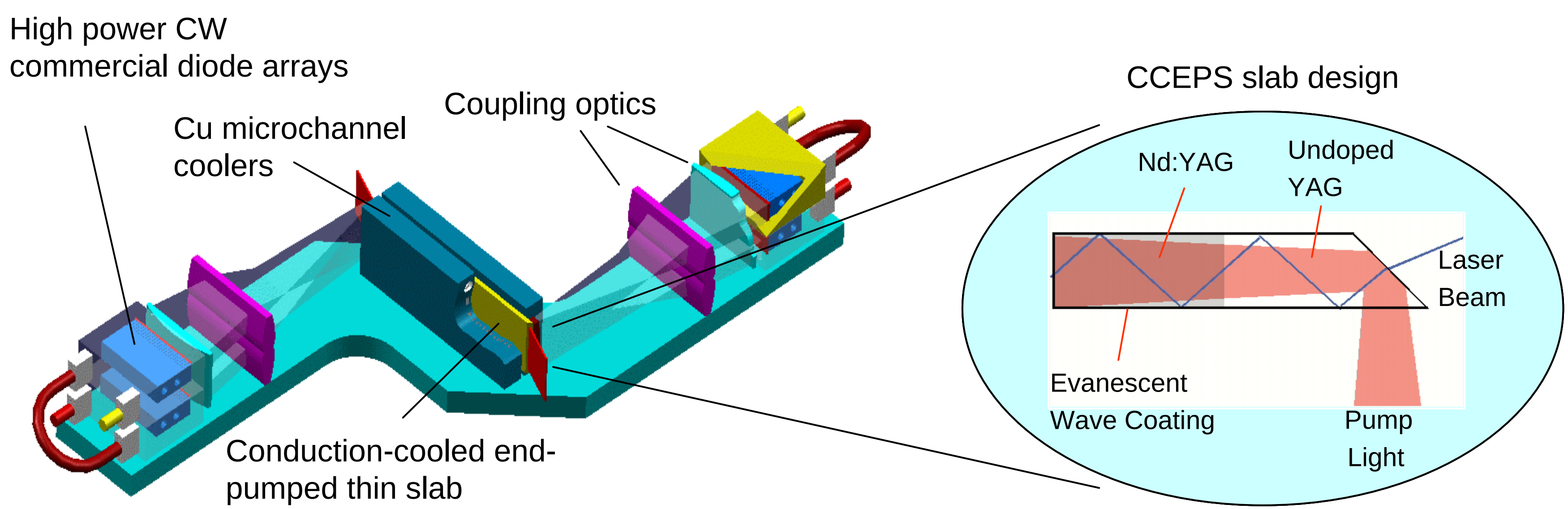


3.LLNL: Thermo Capacity Laser; Nd:Sm:YAG





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

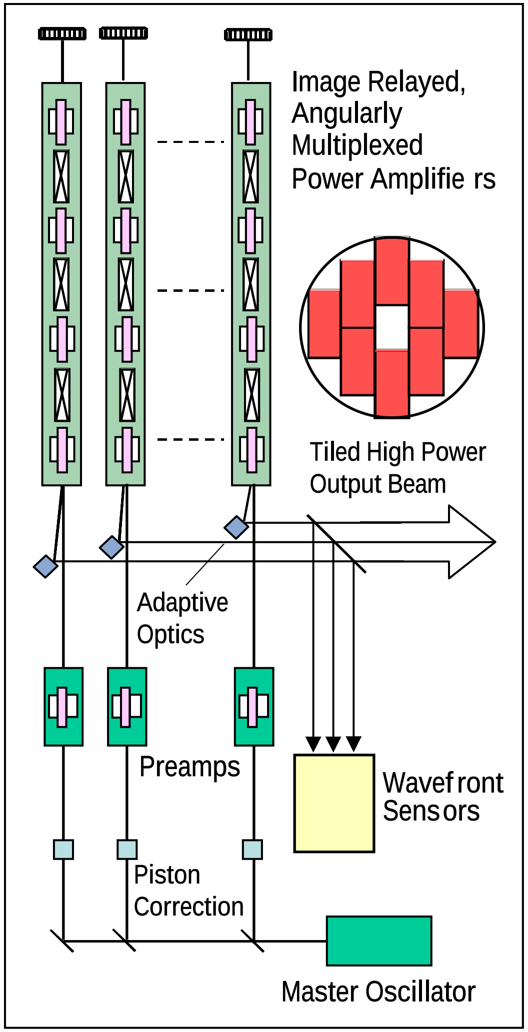


Key elements of CCEPS high power amplifier:

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

NGST JHPSSL Architecture

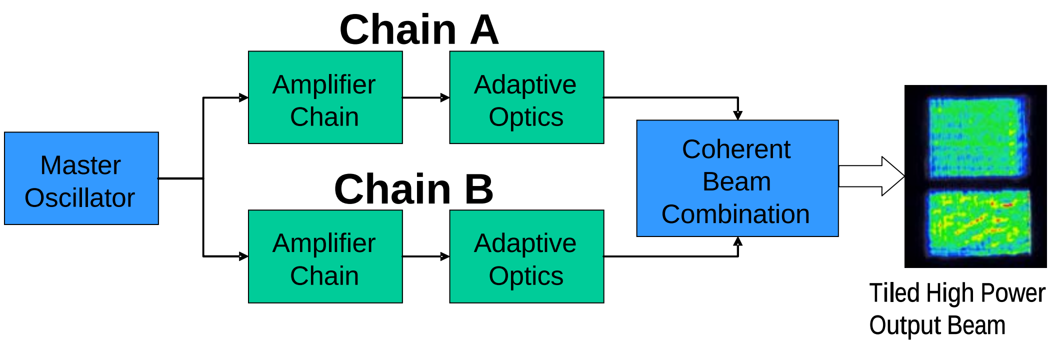
Northrop Grumman Space Technology Joint High Power Solid State Laser



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

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

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



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

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

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-sate laser is available for lethality tests, says Brian Strickland, JHPSSL program 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."

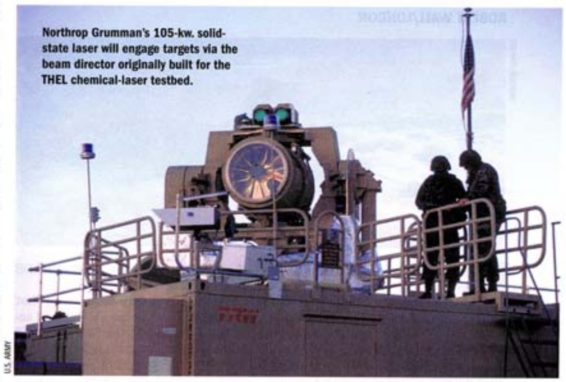
Establishing the effect of atmospheric attenuation on 1.06-micron-wavelength solid-state laser beams is a key task for the new facility. Ringed by mountains and in controlled airspace, the Helstf is able to perform above-the-horizon firing tests. The facility also has a large vacuum chamber into which 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 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.



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

U.S. ARMY

AviationWeek.com/awst

AVIATION WEEK & SPACE TECHNOLOGY/MARCH 8, 2010 53

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

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

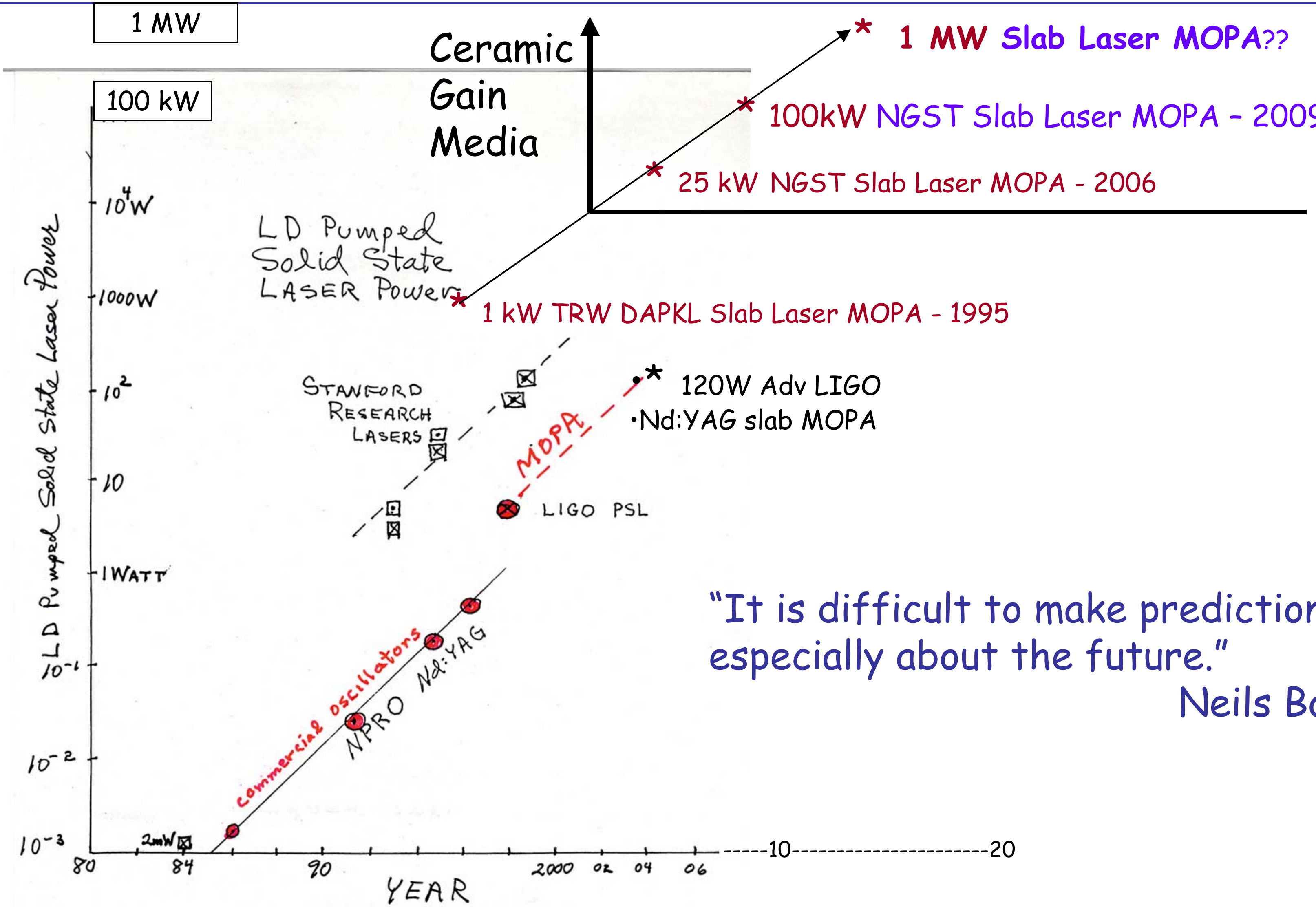
Northrop Grumman diode-pumped Nd:YAG solid state laser

105kw cw output with M^2 ~ 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

Byer Group



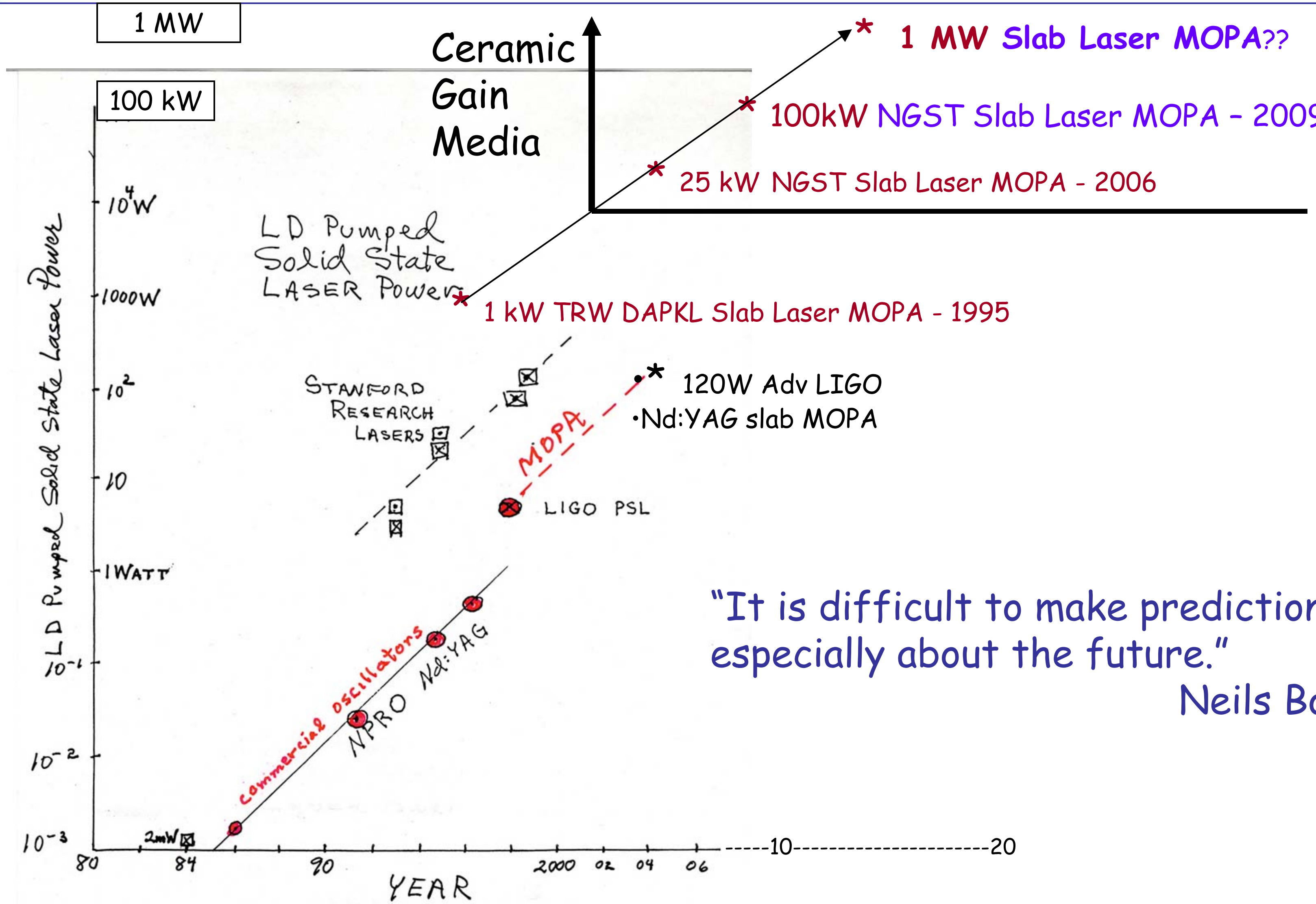
"It is difficult to make predictions, especially about the future."

Neils Bohr

Why the interest in MW average power Lasers?

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

Byer Group

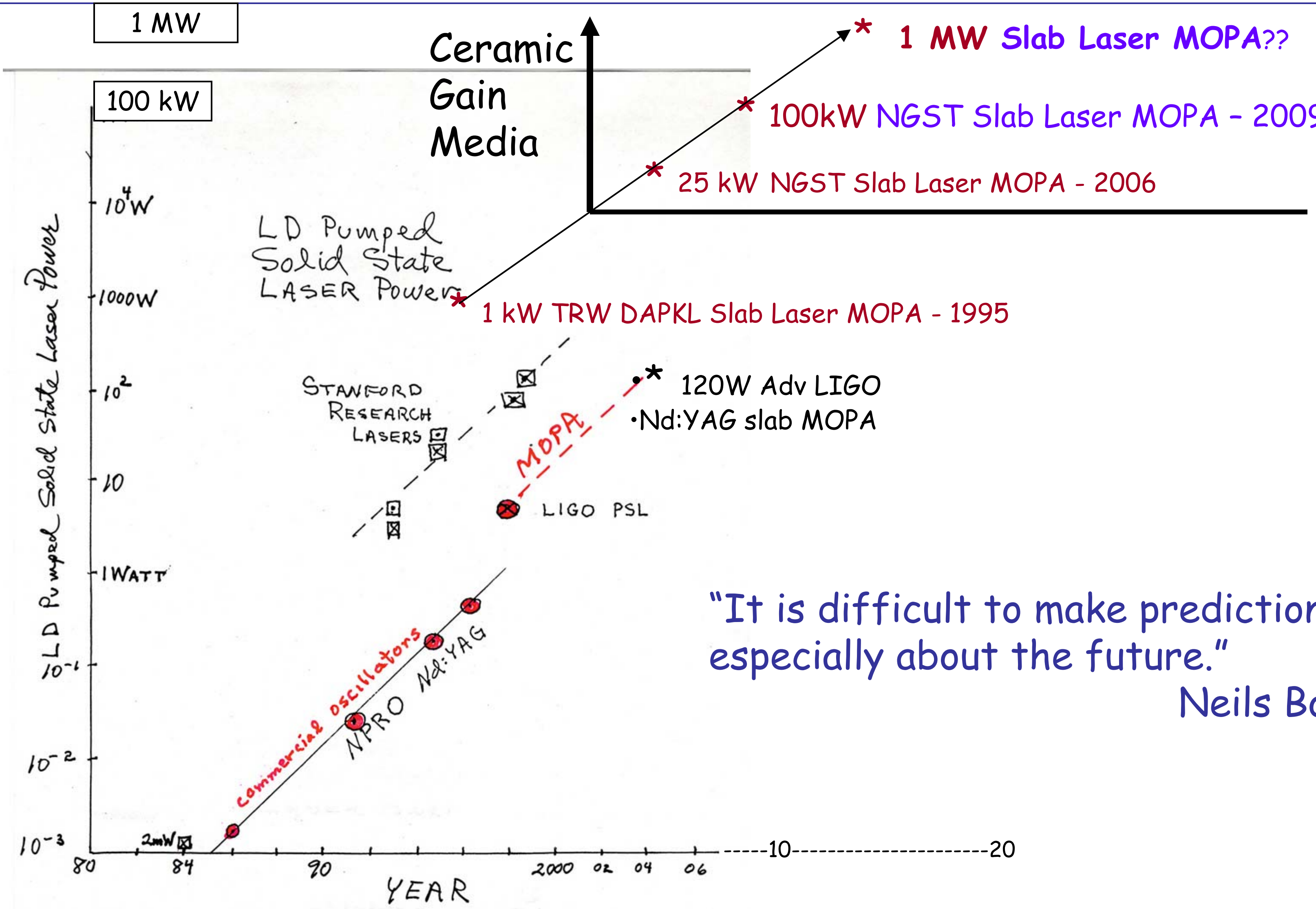


"It is difficult to make predictions, especially about the future."
Neils Bohr

Laser Accelerators for TeV scale physics and coherent X-rays

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

Byer Group



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

And LIFE: Laser Inertial Fusion for Energy Generation

Contents

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- Introduction *Making Lightwaves*
  - Early laser history and concepts
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  - **LIFE - Laser Induced Fusion for Energy**
    - **Fusion/Fission Reactors**

Proposal for Laser Inertial Fusion - 1972

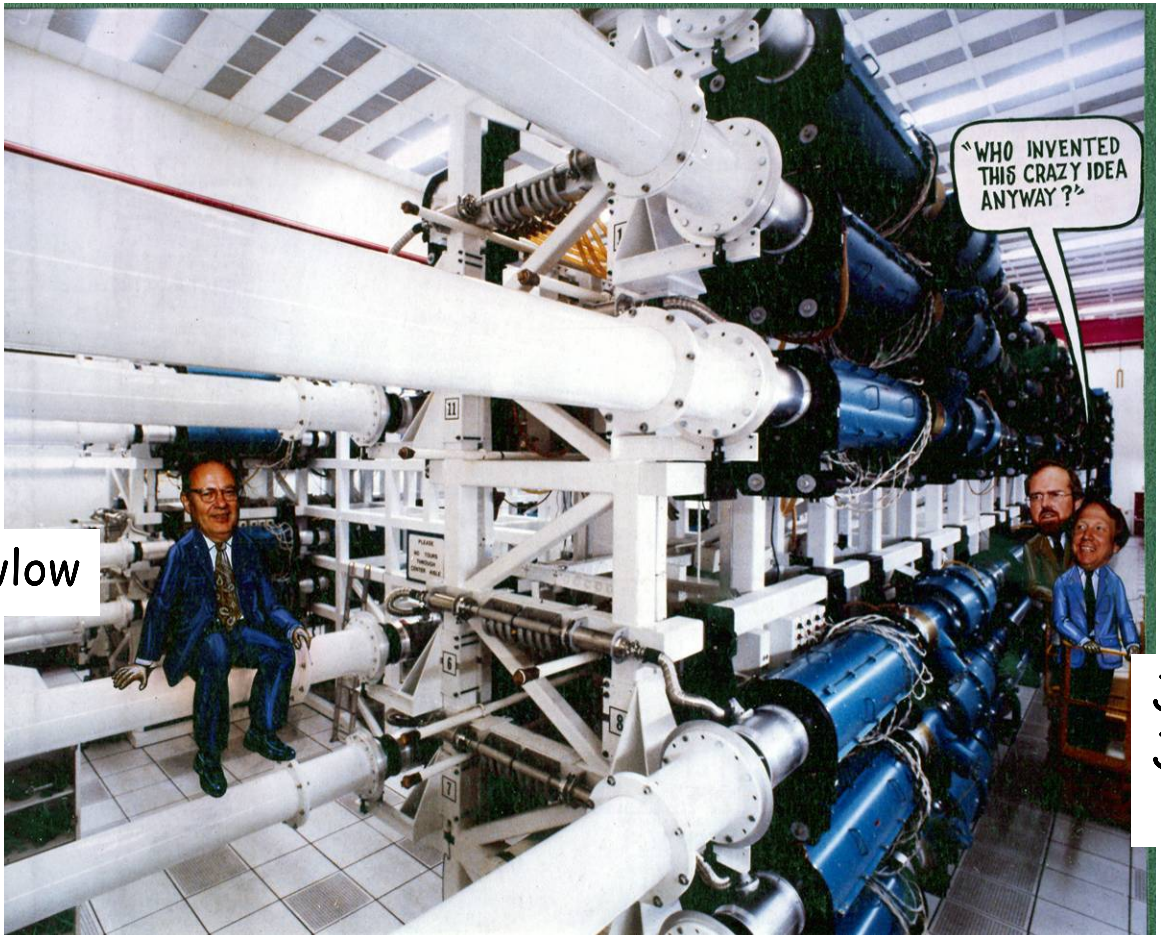
Byer Group

John Emmett

John Nuckols

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 Holzrichter
John Emmett

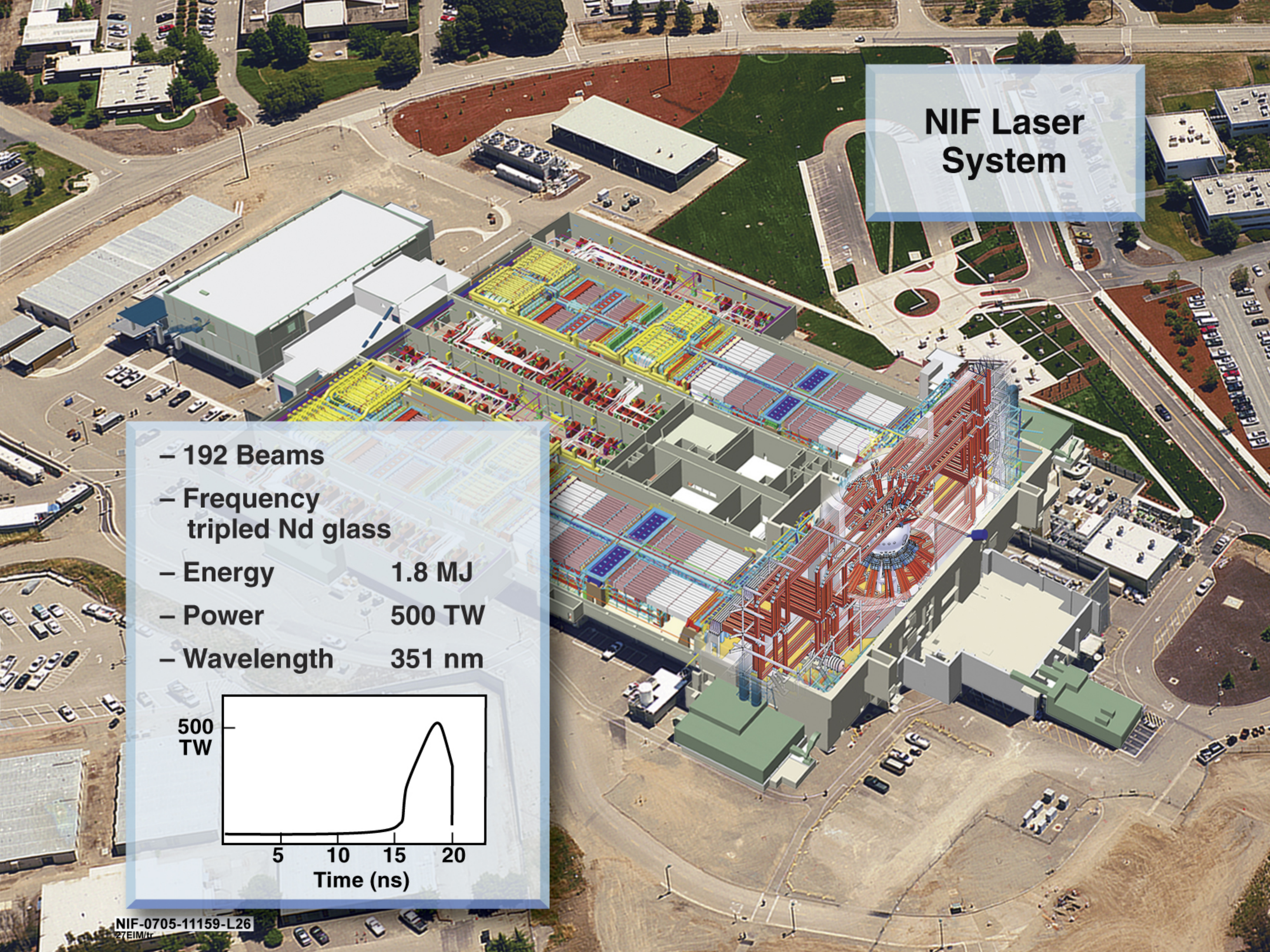
The Shiva Laser, predecessor to the NOVA and NIF Fusion Lasers

The National Ignition Facility

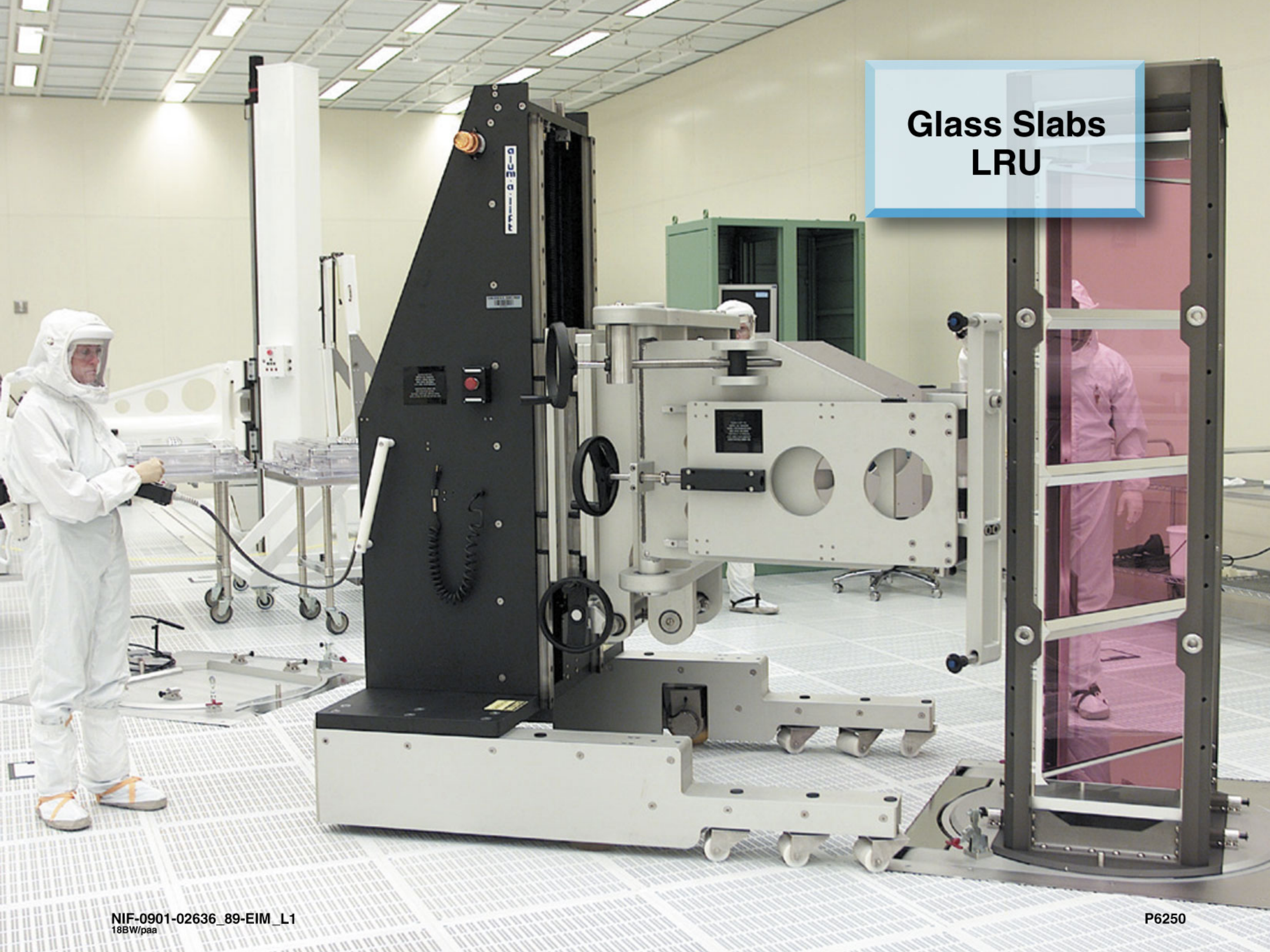
Ed Moses

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
500 TW
5
10
15
20
Time (ns)
NIF-0705-11159-L26
27EIM/tr

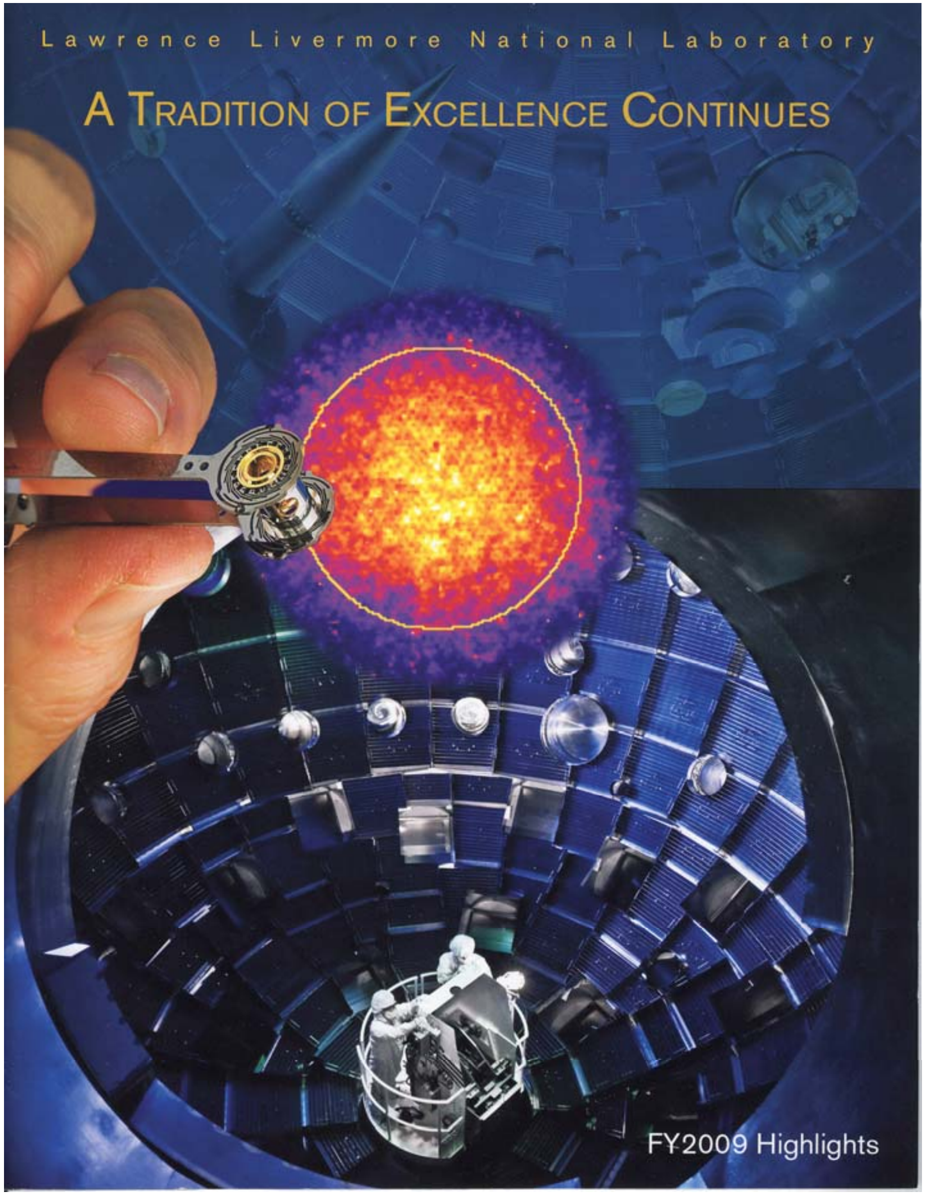
Target Chamber being installed into NIF Facility



NIF-0901-02636_89-EIM_L1
18BW/paa

P6250

NIF 2009 Highlights



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

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

Subject: 1 MJ Barrier Breached at NIF!!!

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

Ladies and Gentlemen!

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

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

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

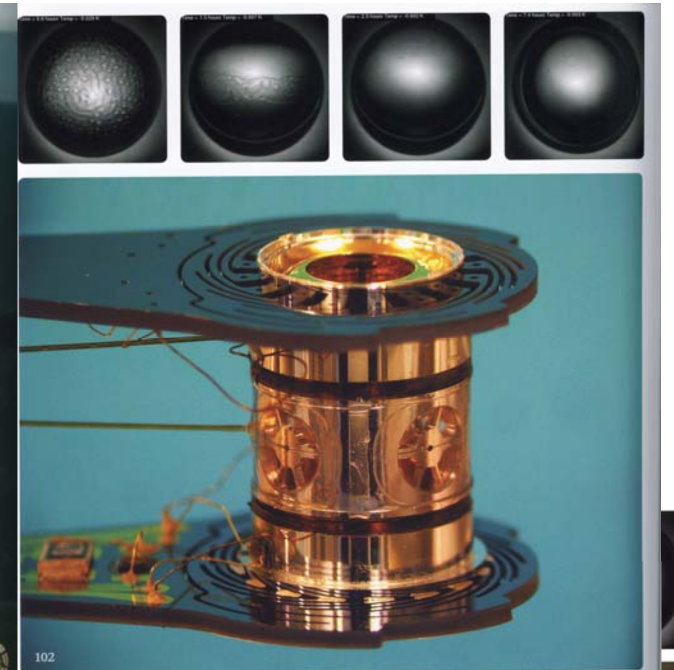
Congratulations to all--On to ignition!

Be Safe, Be Secure,
em

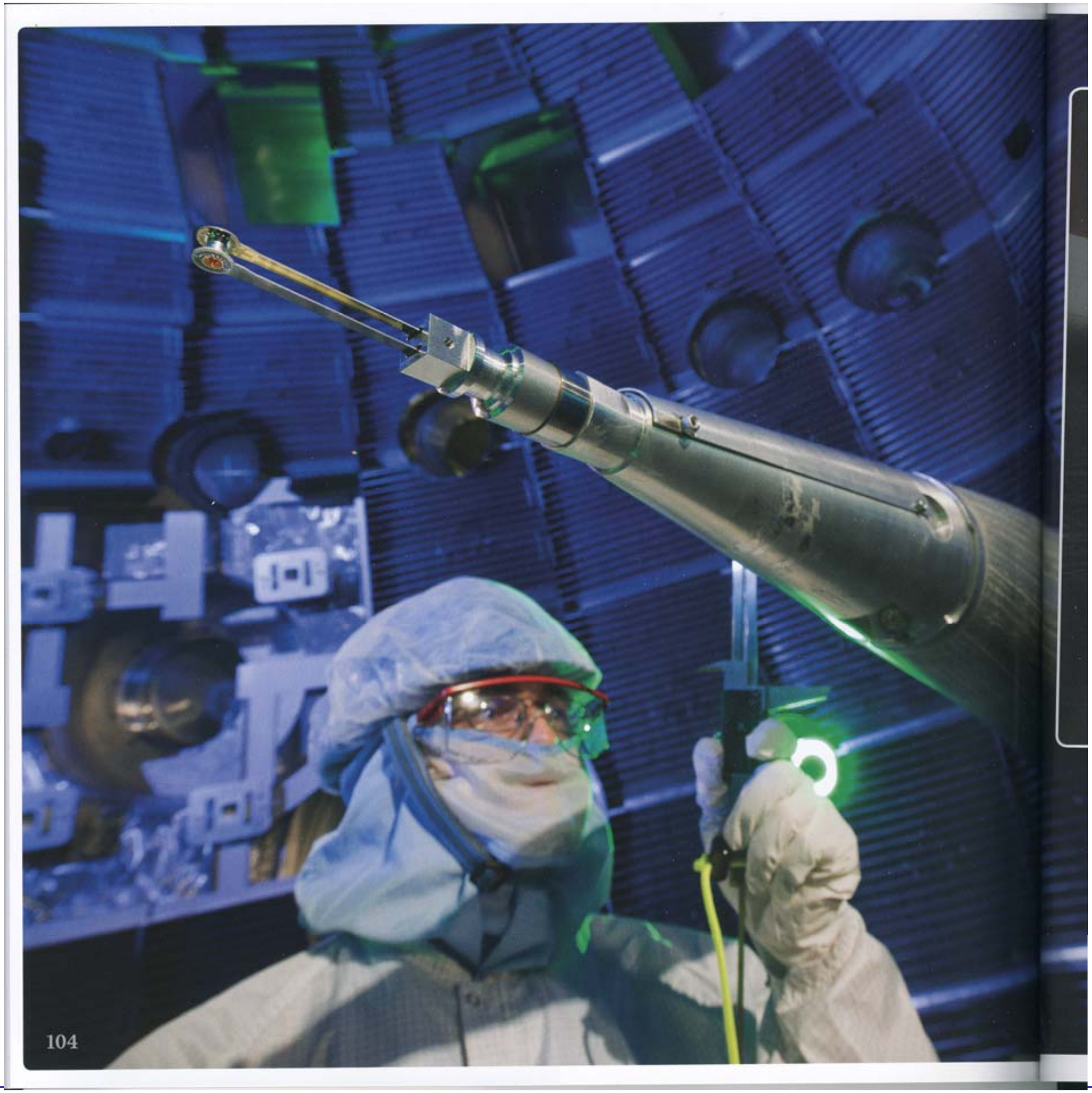
The next steps (**The National Ignition Campaign**) are to study ignition for 18 months culminating in an Ignition shot scheduled for late 2010

NIF Target Holder and Cryo-Target

Byer Group



Cryo holder at Center of Target Chamber



NIF Achieves Implosion Symmetry with Indirect Drive

Science Magazine 5th March 2010 p 1208

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PHYSICS

Controlling Implosion Symmetry Around a Deuterium-Tritium Target

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.

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.

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

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

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

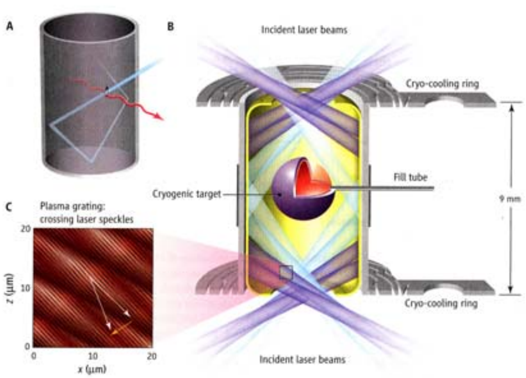
The solution would lie with the concept that light is emitted in packets, or quanta, as pioneered by Max Planck in 1900. His new theory accurately predicted the intensity and the frequency spectra of blackbody radiation as a function of temperature. In doing so, Planck reconciled electromagnetism with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



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).

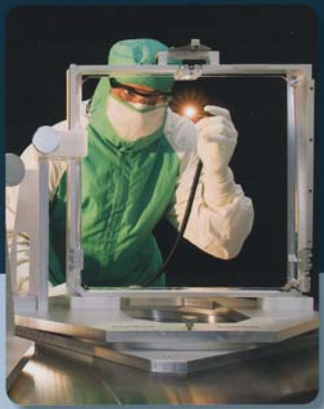
Experiments show that beam control (wavelength and pointing) can shape implosion symmetry

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

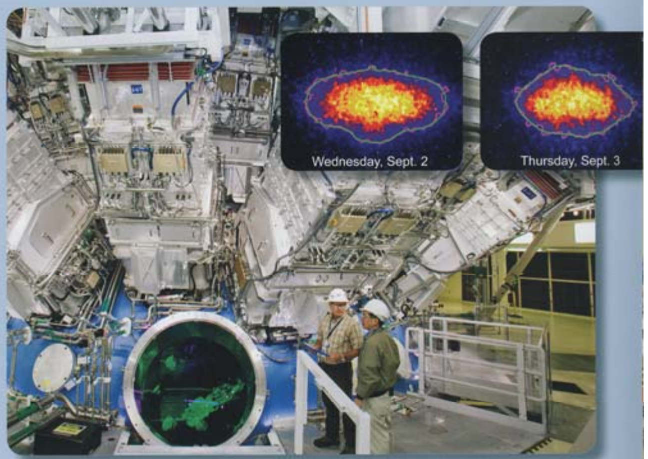
X-ray images of compressed Target Shots
1MJ UV Laser Energy – Sept 2, 3, 4, 5, 2009

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

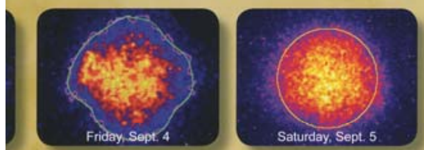
NIF Dedication

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

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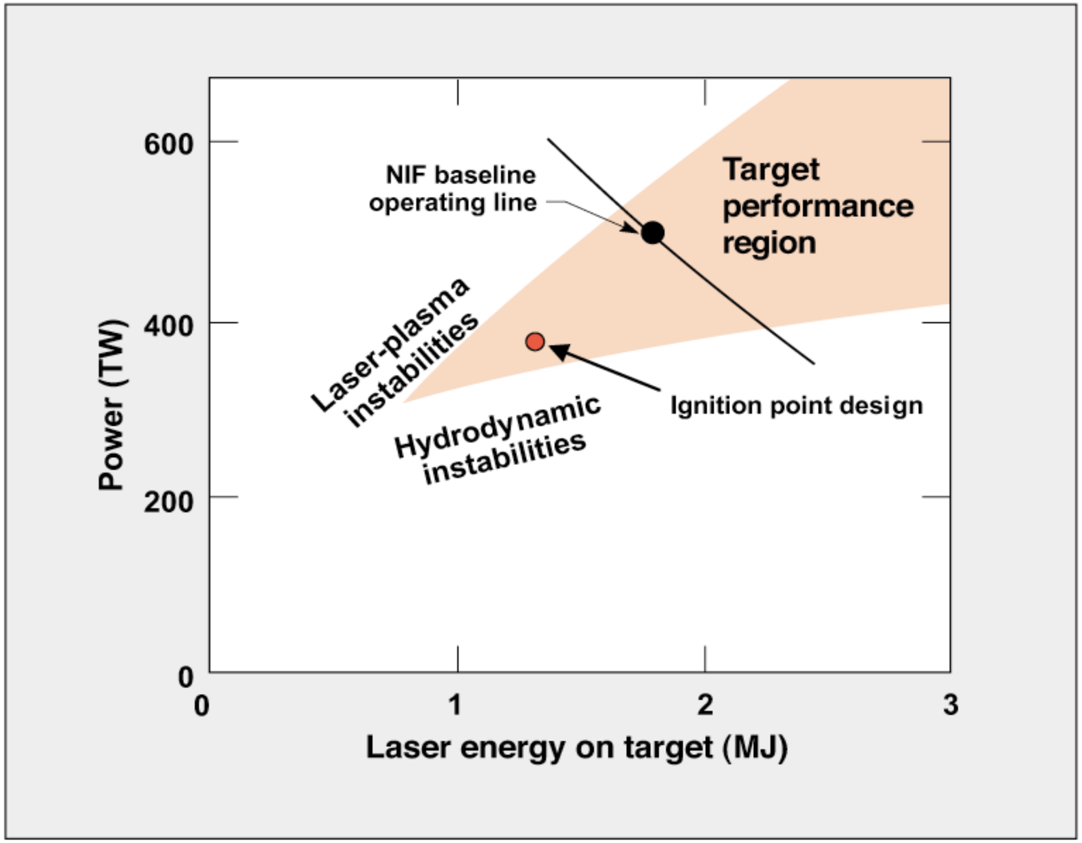
NIF will map out ignition and gain curves for multiple target concepts

The National Ignition Facility



NIF-0201-01704
23GHM/cld

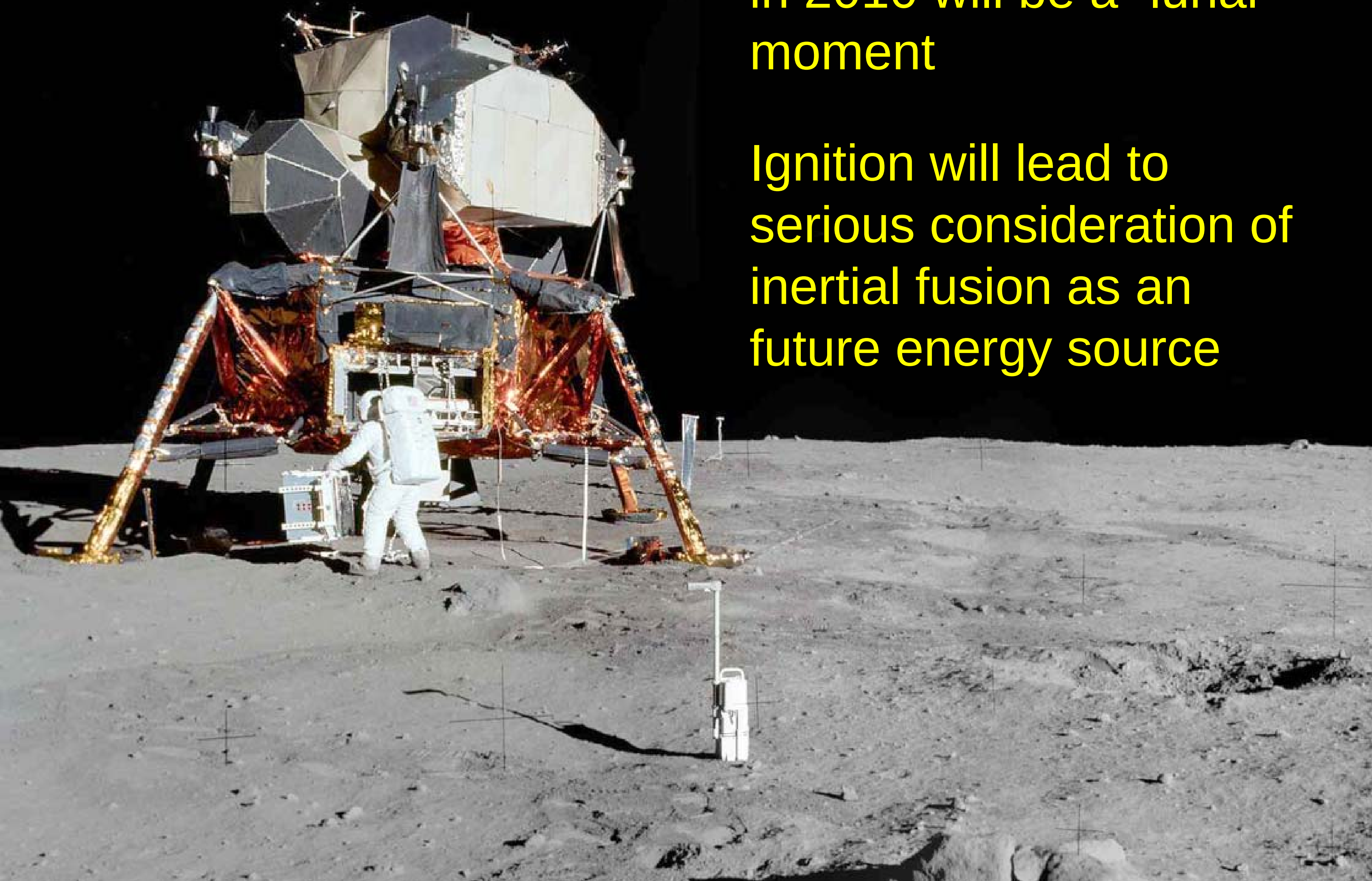
X4187

A series of target compression studies are planned for 2010

Goal: confirm all aspects of target performance prior to a fusion burn shot

Fusion Ignition at the NIF in 2010 will be a “lunar” moment

Ignition will lead to serious consideration of inertial fusion as an future energy source



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

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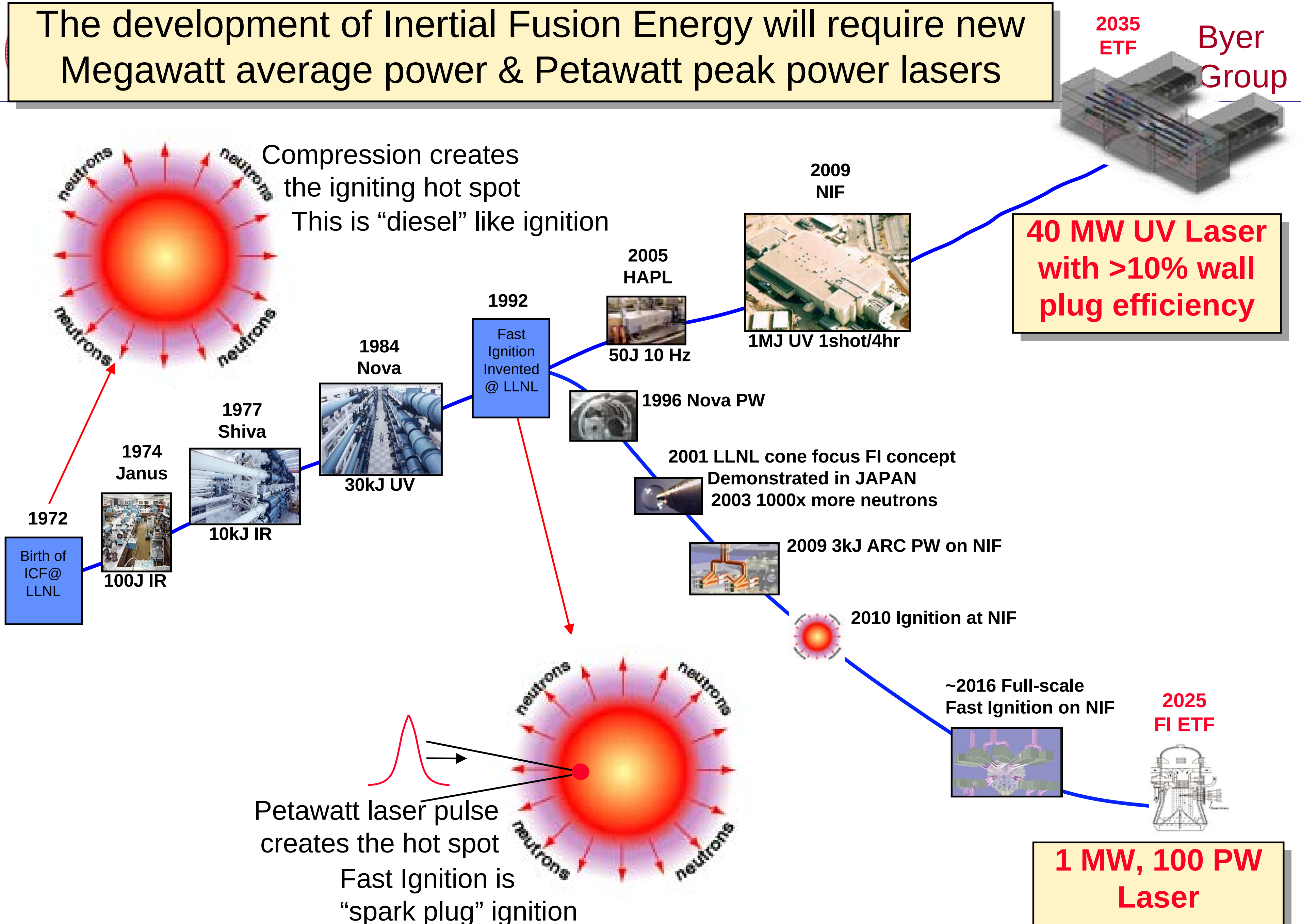
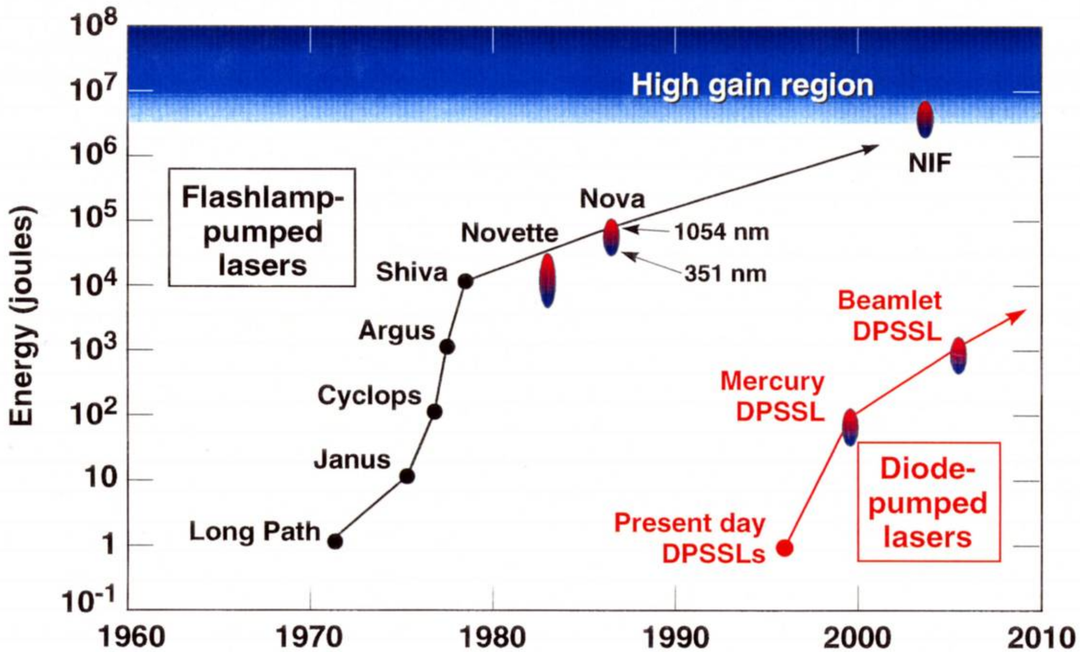


Scaling to IFE drivers for reactor design 1-2 MJ, 16 Hz, 10% efficiency - IFE forum of Japan

Kenichi Ueda – "Temperature Tuned Ceramic Lasers for IFE Drivers"
OSA invited talk FMK1 October 9, 2006

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



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

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

02-15-0388-0678F
CM/skl

5/29/96

Continuous pour of Nd:Glass allowed lower cost for NIF

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

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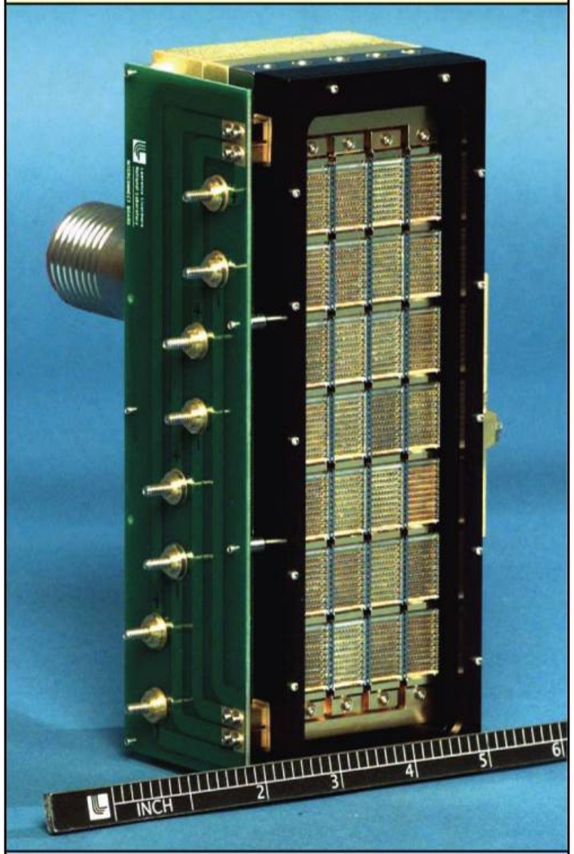
Yb:Ceramic gain media has properties of a crystal but lower cost

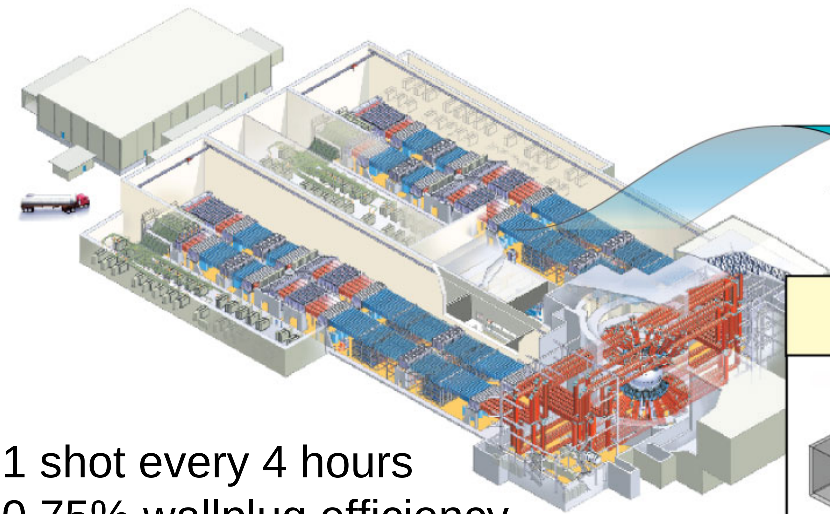
Next Generation Fusion Laser Driver requires
Ceramic gain media for 10 Hz operation

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

Flashlamps	Diodes
	
10% electrical-optical efficiency	60% electrical-optical efficiency

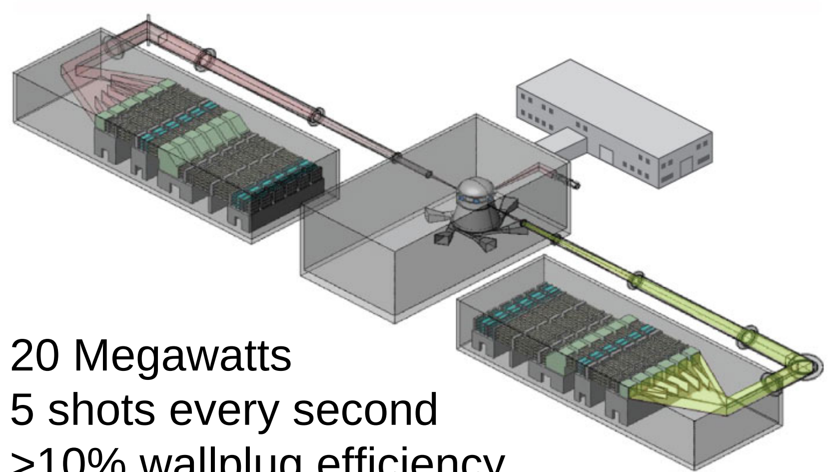
Is NIF/NIC a precursor to an IFE plant?

NIF



1 shot every 4 hours
0.75% wallplug efficiency

LIFE



20 Megawatts
5 shots every second
>10% wallplug efficiency

Laser Inertial Fusion Energy

Total Eclipse of the Sun, July 22, 2009

2010 – APS Session B5: 5 Legacies from the Laser

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

2009 – A Special year in Lasers

Jan - 105kw cw near diff limited Nd:YAG slab laser

Mar - NIF certified as completed - 4MJ IR laser

Apr – LCLS Coherent 8keV X-ray FEL Laser at SLAC

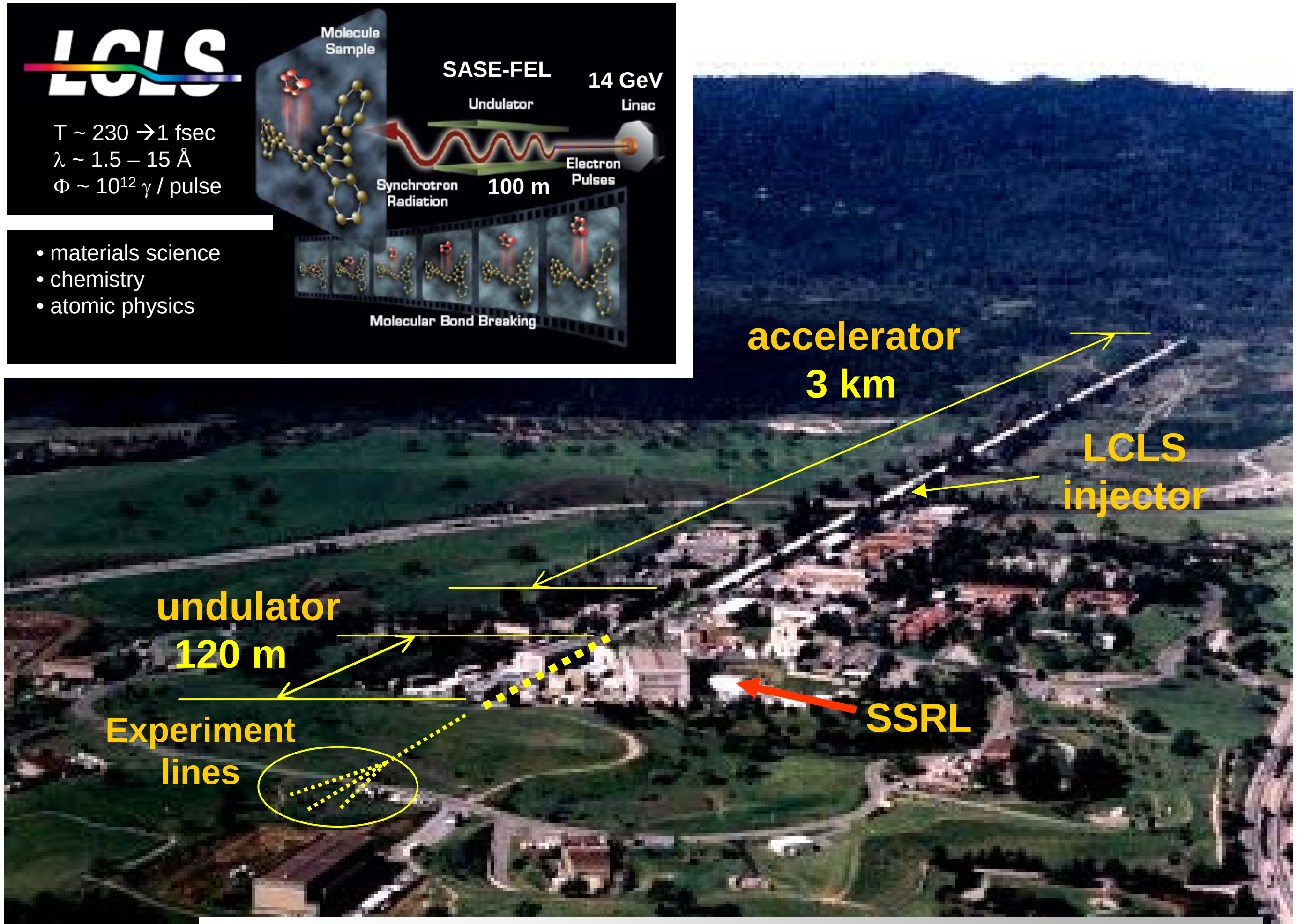
2010 – Successful fusion burn?

2015 – 5Hz 40kJ single arm of LIFE Laser

2025 – 5Hz 2MJ LIFE Laser Engineering Demo

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

RF-accelerator driven SASE FEL at SLAC - April 2009



TTF: Tesla Test Facility; fsec EUV SASE FEL facility

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

LCLS properties

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

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

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

Stanford Photonics Student Group Retreat
April 3 - 4, 2009, Monterey, CA

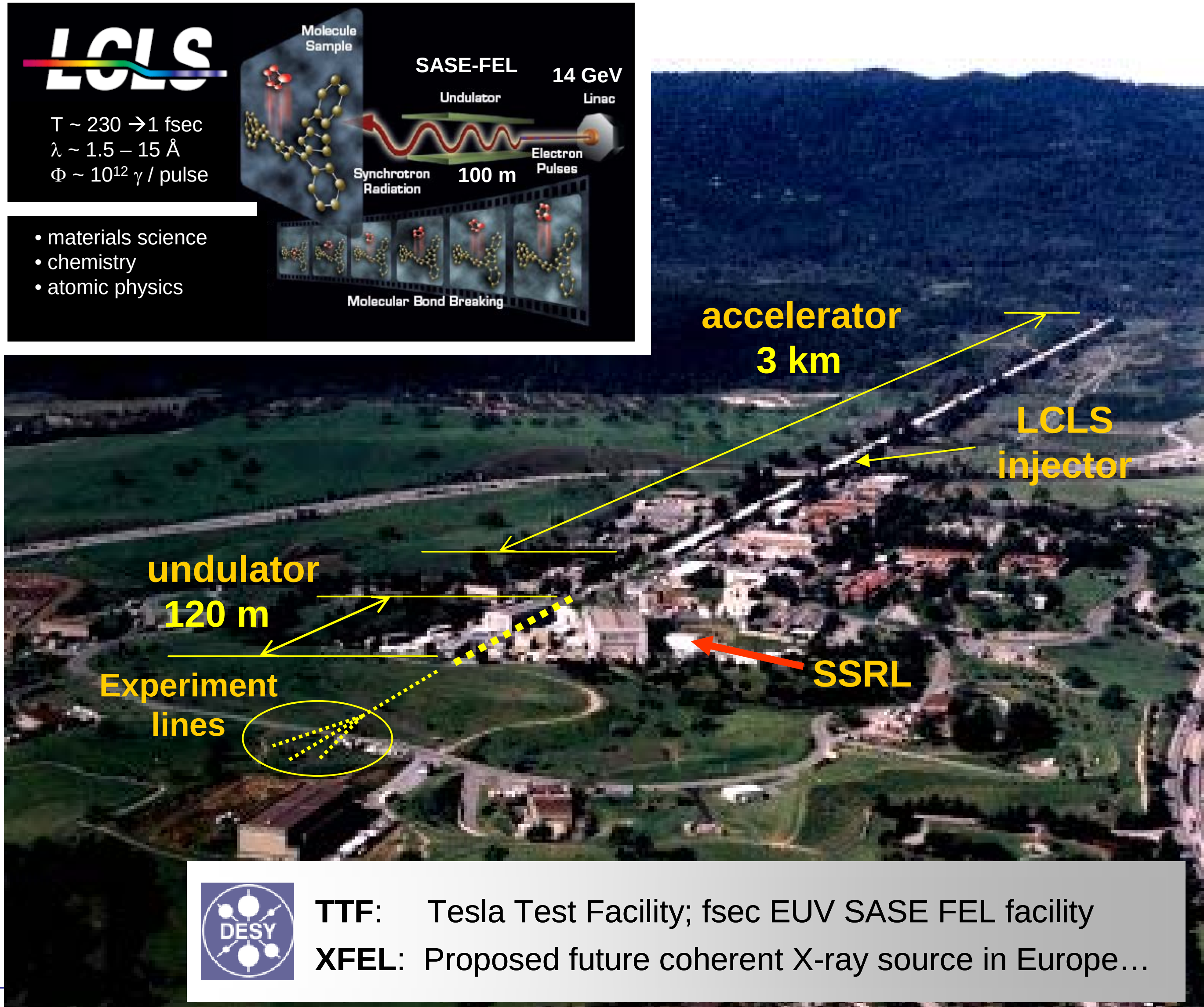
Thanks to my family for allowing me time to pursue my passion

Surfing Ocean Waves – Poipu Beach, Kauai

Contents

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

RF-accelerator driven SASE FEL at SLAC - April 2009



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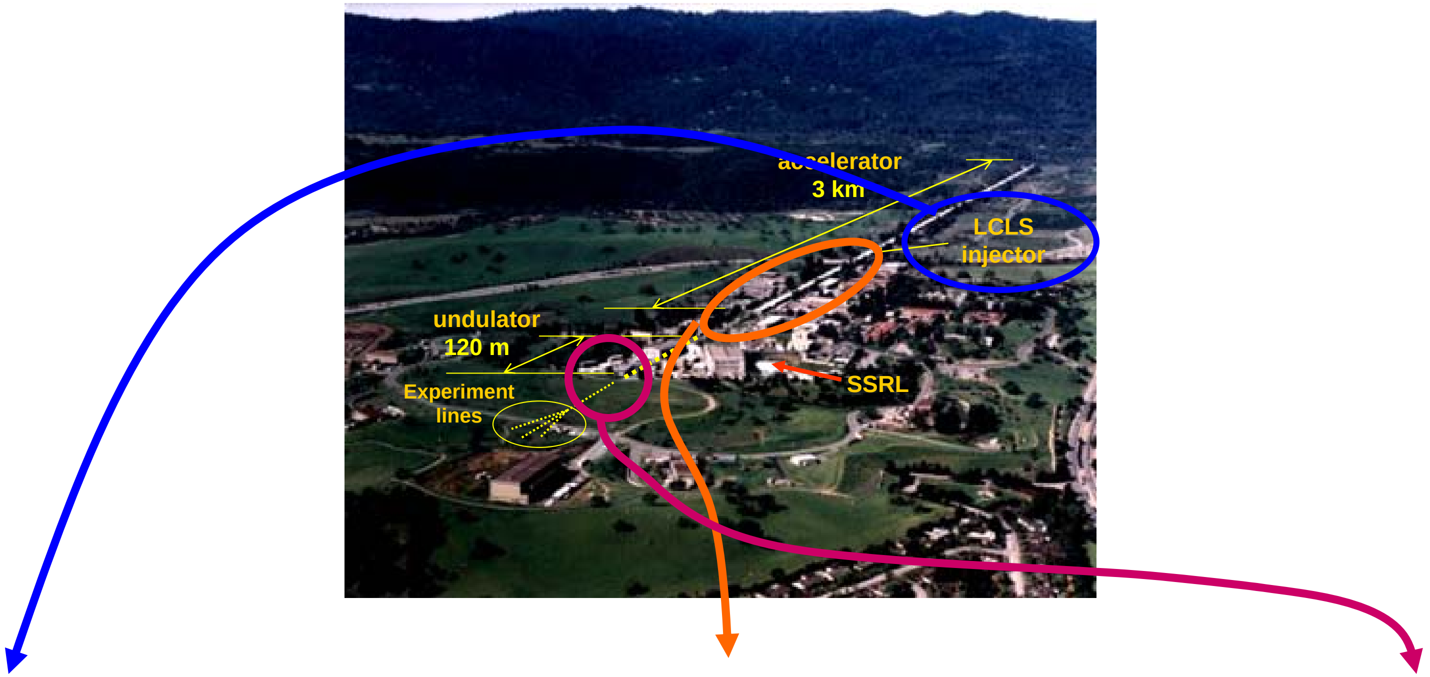
The Key Components of the SASE-FEL architecture

SASE – Self Amplified Spontaneous Emission



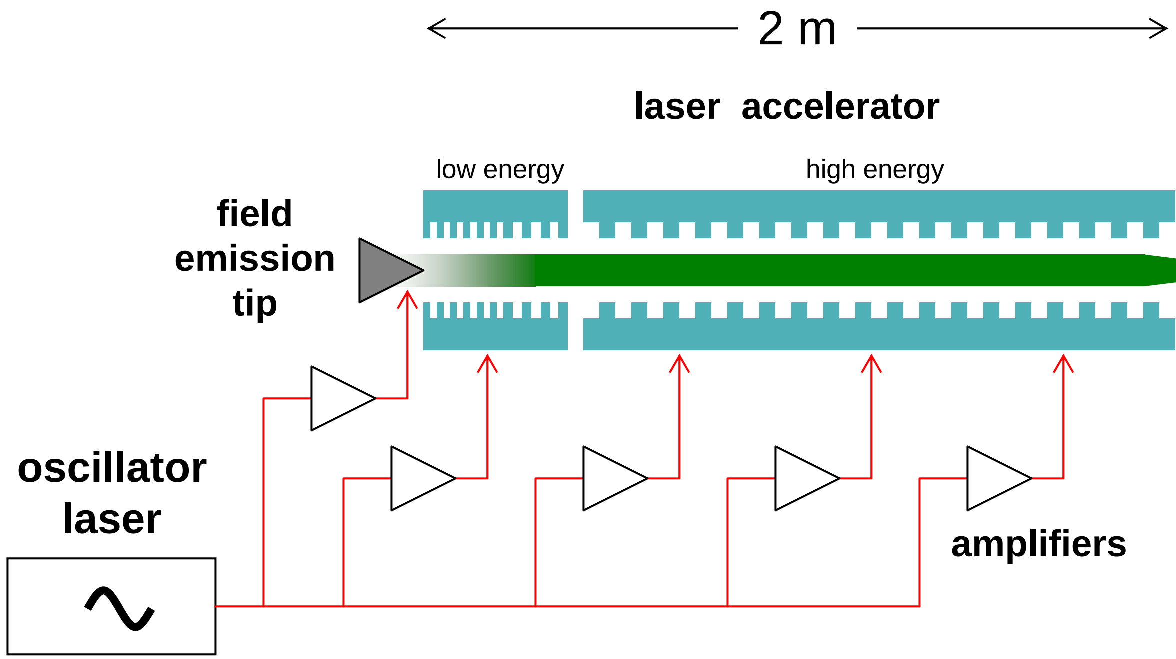
source of free particles → **accelerator section** → **undulator**

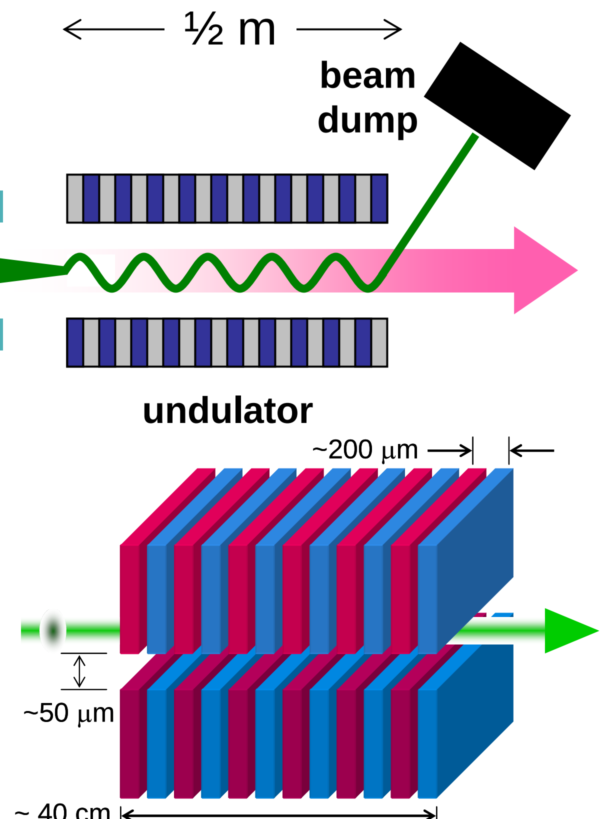
laser-driven
high rep. rate
very compact

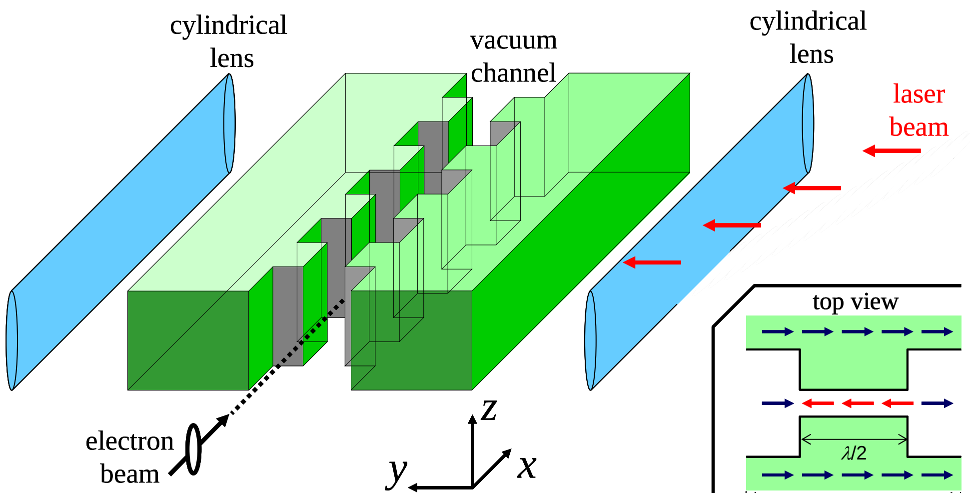
dielectric structure
based laser-driven
particle accelerators

dielectric structure,
laser driven

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



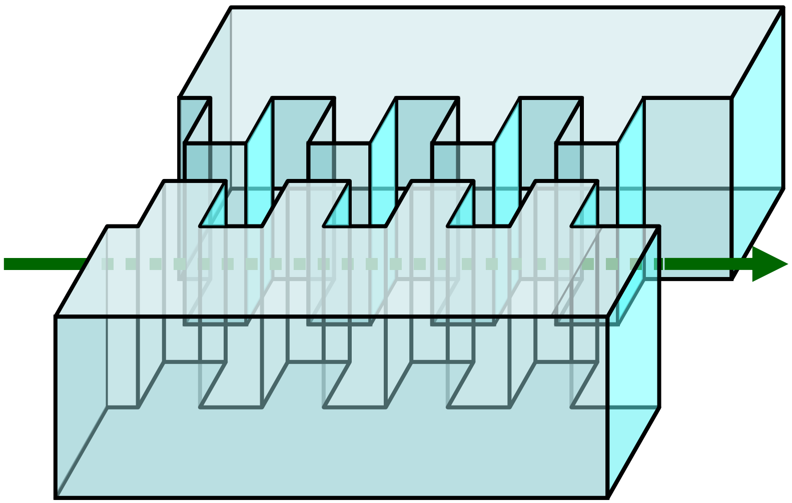


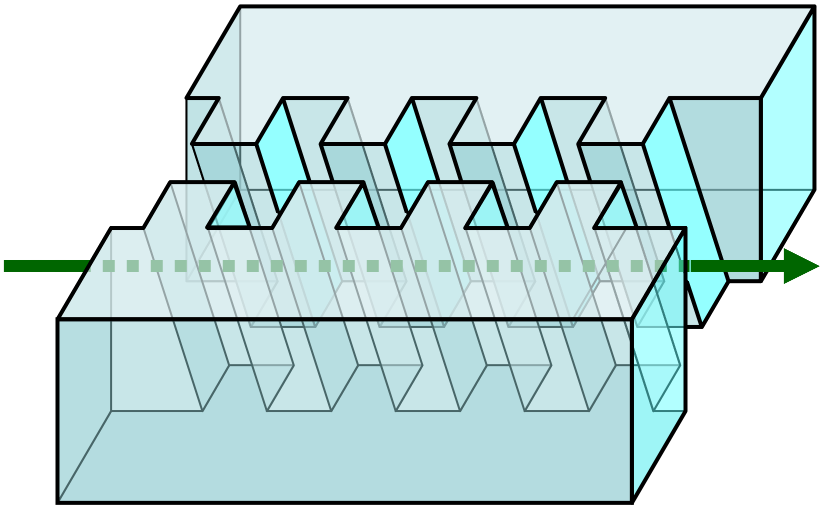


Discouraging! Magnetic Undulator not Matched to attosecond electron bunches

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

New Idea: Laser-Driven Dielectric Undulator for FEL





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

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

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

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

key idea

Extended phase-synchronicity between the EM field and the particle

Use modelocked laser to generate periodic deflection field

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

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

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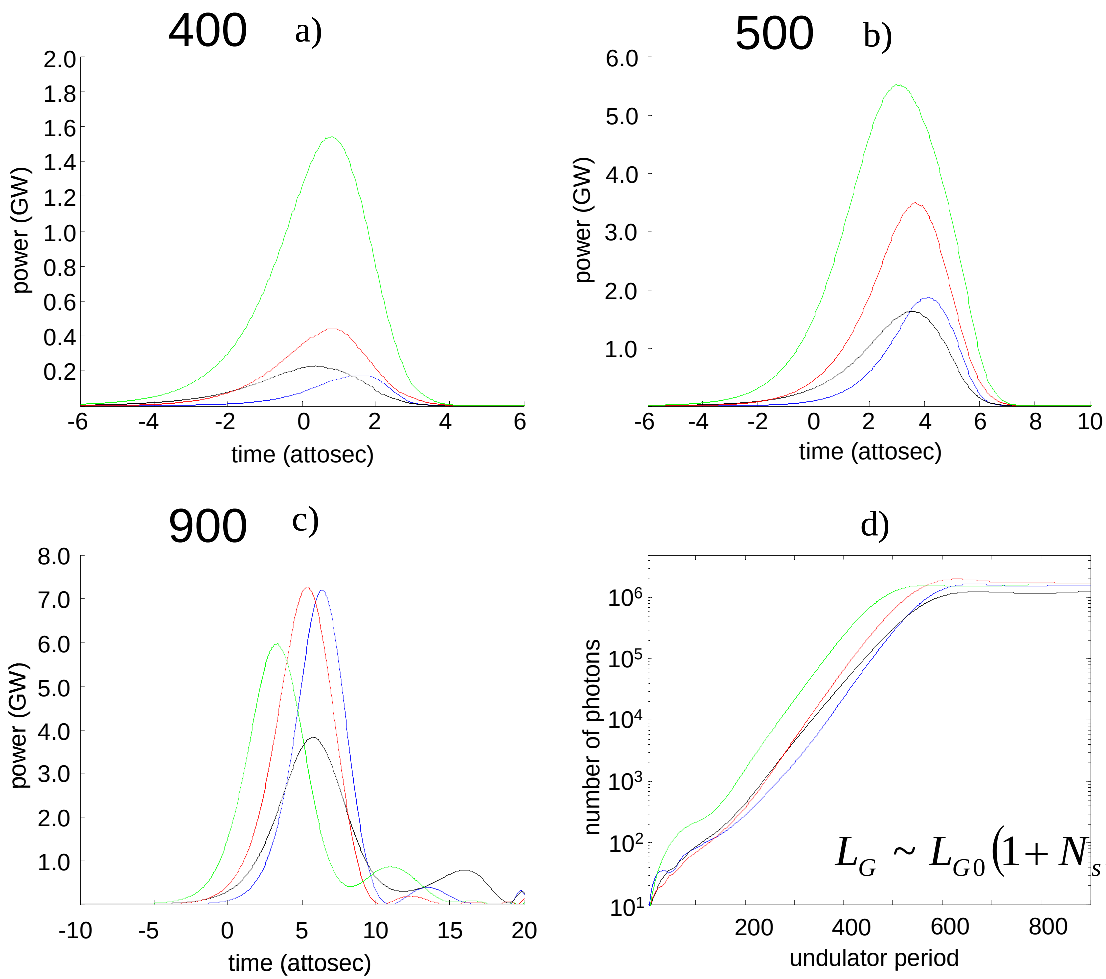


$$U_b = 2\,\text{GeV}$$
$$\varepsilon_N = 10^{-9}\ \text{m-rad}$$
$$Q_b = 20\ \ \text{fC}$$
$$\Delta\gamma/\gamma = 0.1\%$$
$$\sigma_r = 200\,\text{nm}$$
$$\beta^* = 4\ \text{cm}$$

$$L_c \sim 21\lambda_r$$

$$\sigma_b \sim 136\lambda_r$$

$$\sigma_b / L_c \sim 6$$

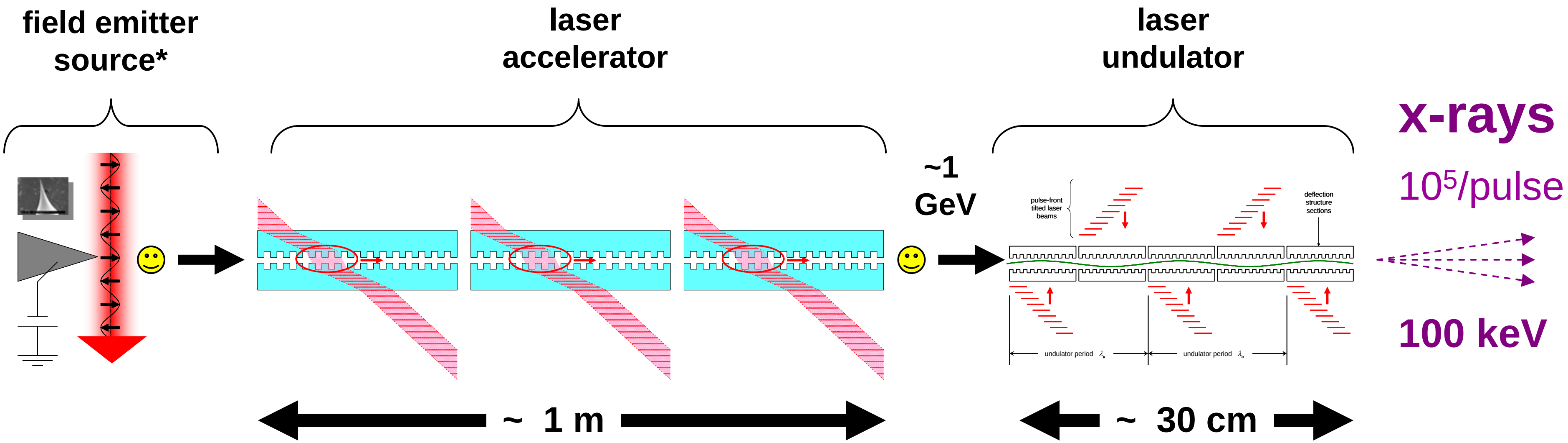
$$L_G \sim L_{G0}\left(1 + N_s \lambda_r / 3\sigma_b\right)$$

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

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

Summary: possible table-top coherent X-ray source

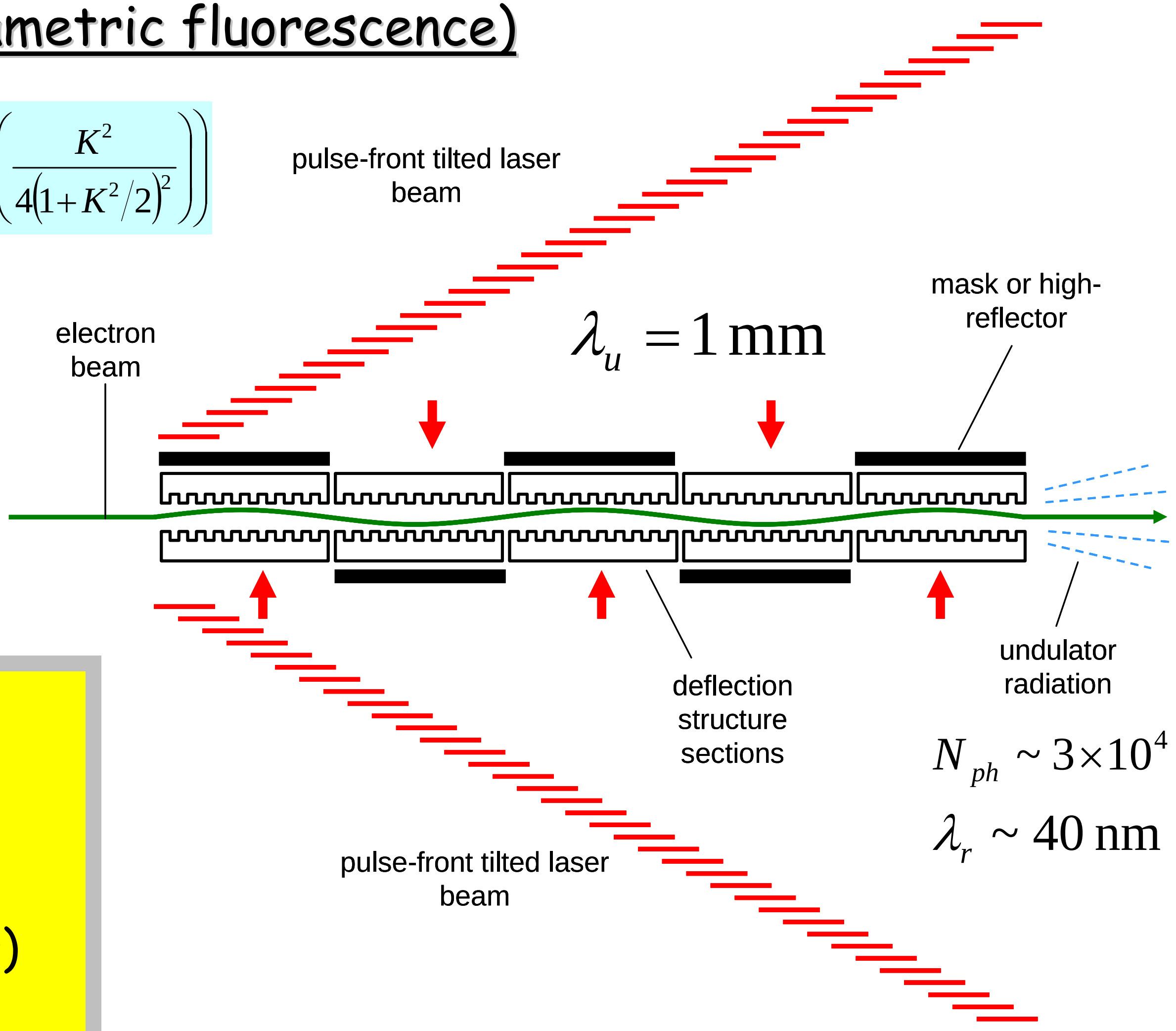
Schematic of the tabletop radiation source



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

Look for undulator radiation (parametric fluorescence)

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



$$\lambda_u = 1\,\mathrm{mm}$$

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

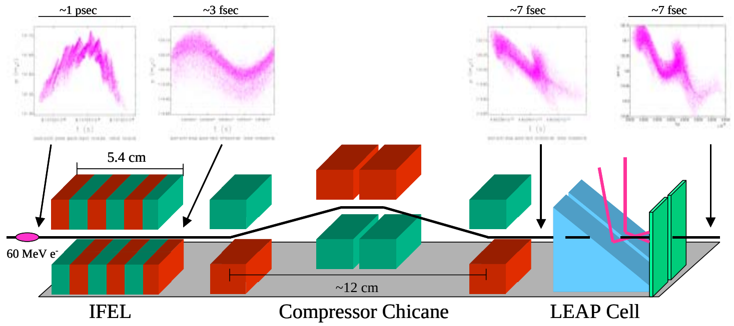
$$\lambda_r \sim 40\ \mathrm{nm}$$

Use periodicity of grating lattice to conserve momentum

(quasiphasematching)

Challenges ahead

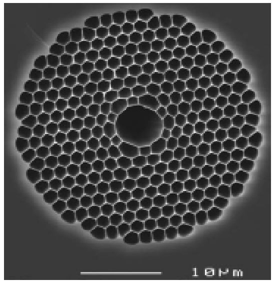
1



Staged acceleration

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

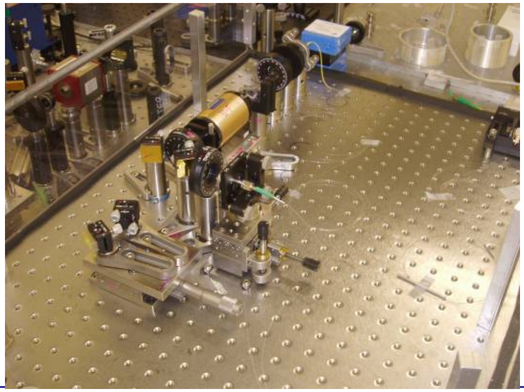
2



Implementation of real accelerator microstructures

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

3

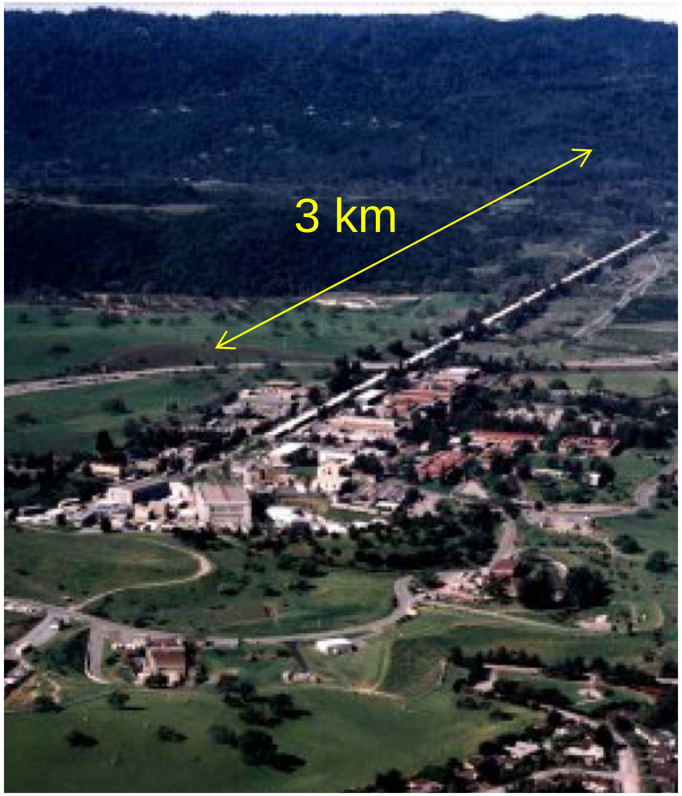


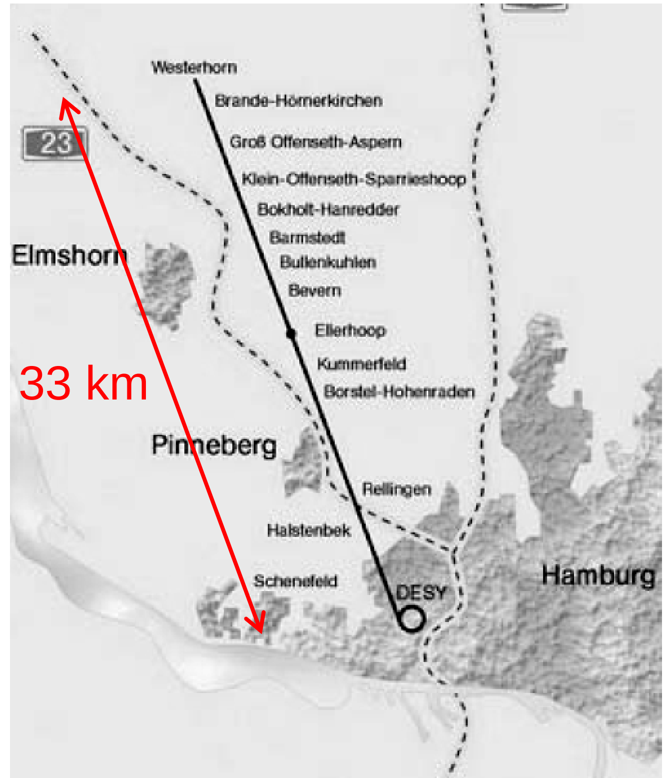
Laser technology

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

- BACK UP SLIDES

Existing and Proposed Linear Accelerators





Existing SLAC – 50 GeV

Proposed ILC Accelerator 1 TeV

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

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

A few rules of the game

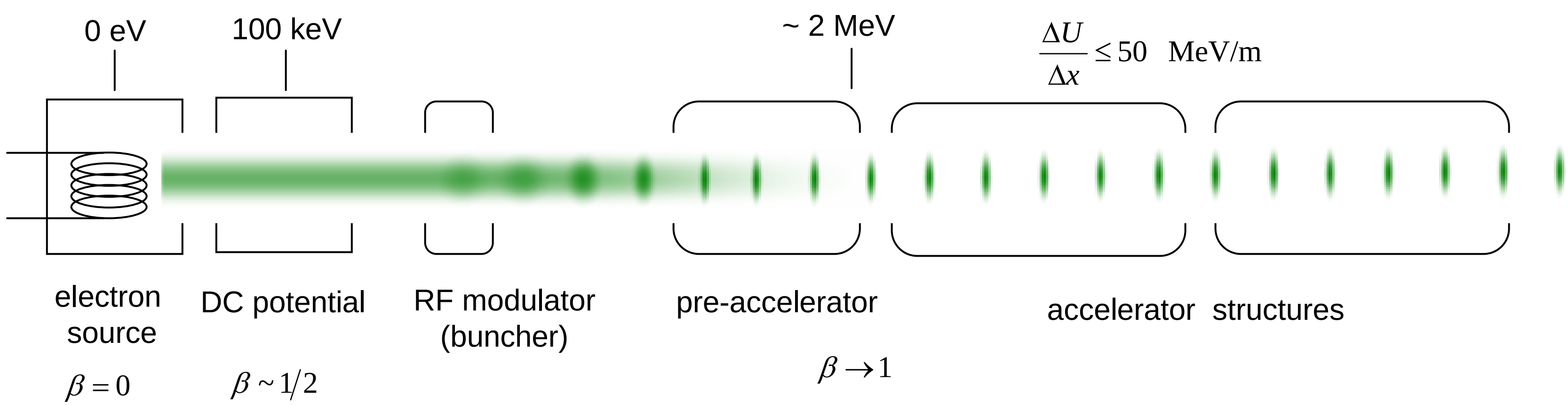
"An accelerator is just a transformer" – Pief Panofsky

"All accelerators operate at the damage limit" - Pief

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

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

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



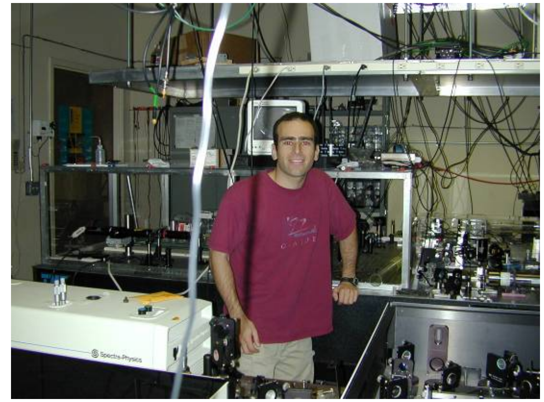
1974 –sabbatical leave, Lund **1994** – SLAC summer school **2004 – Successful 1st Exp**

Participants in the LEAP Experiment
Laser Electron Accelerator Program

Byer Group

Bob Siemann[2]

Chris Sears[2]



Ben Cowan[2]

Jim Spencer[2]

Tomas Plettner[1]

Bob Byer[1]

Eric Colby[2]

New students

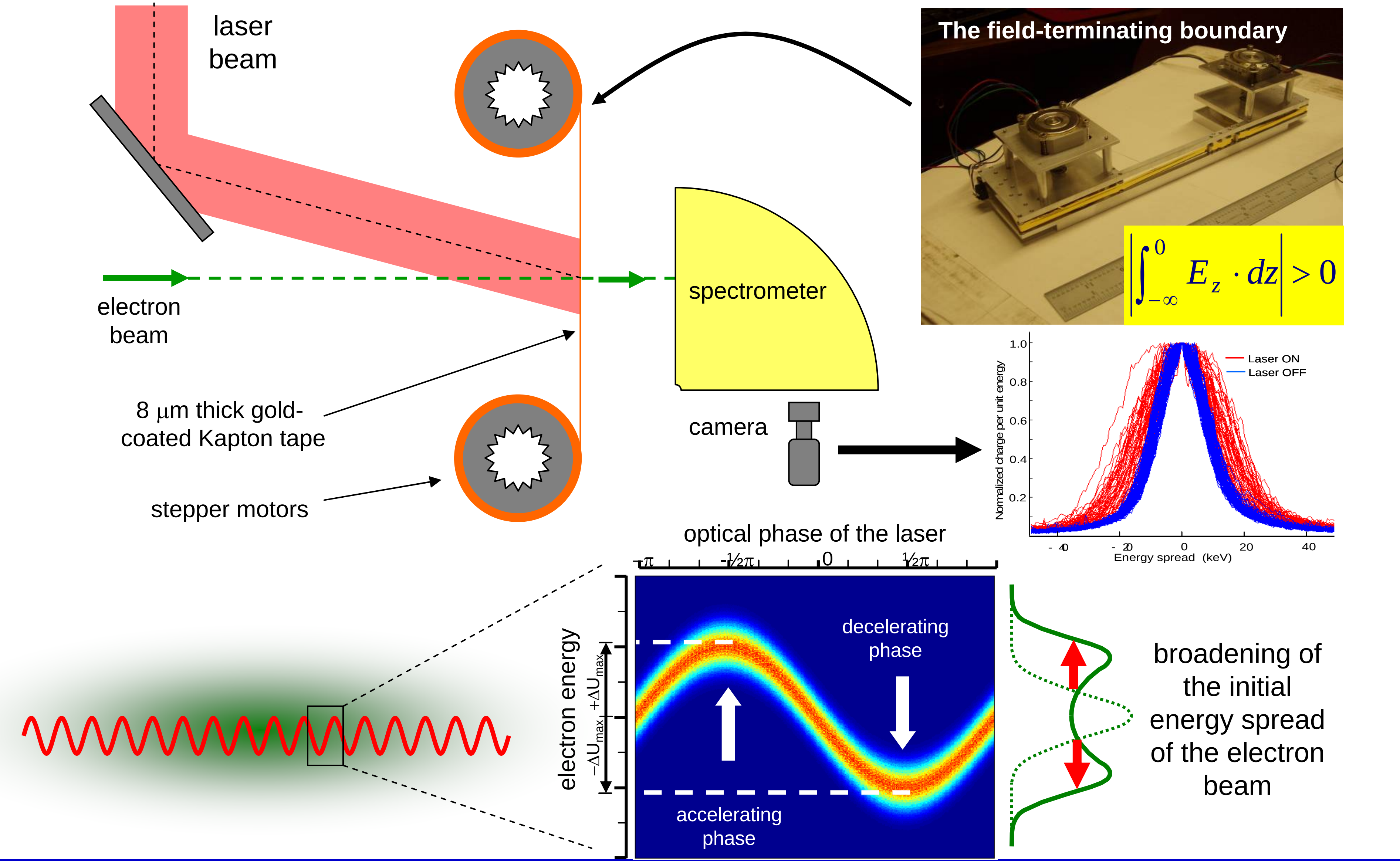
- Chris McGuinness[2]
- Melissa Lincoln[2]
- Patrick Lu[1]

Atomic Physics collaboration

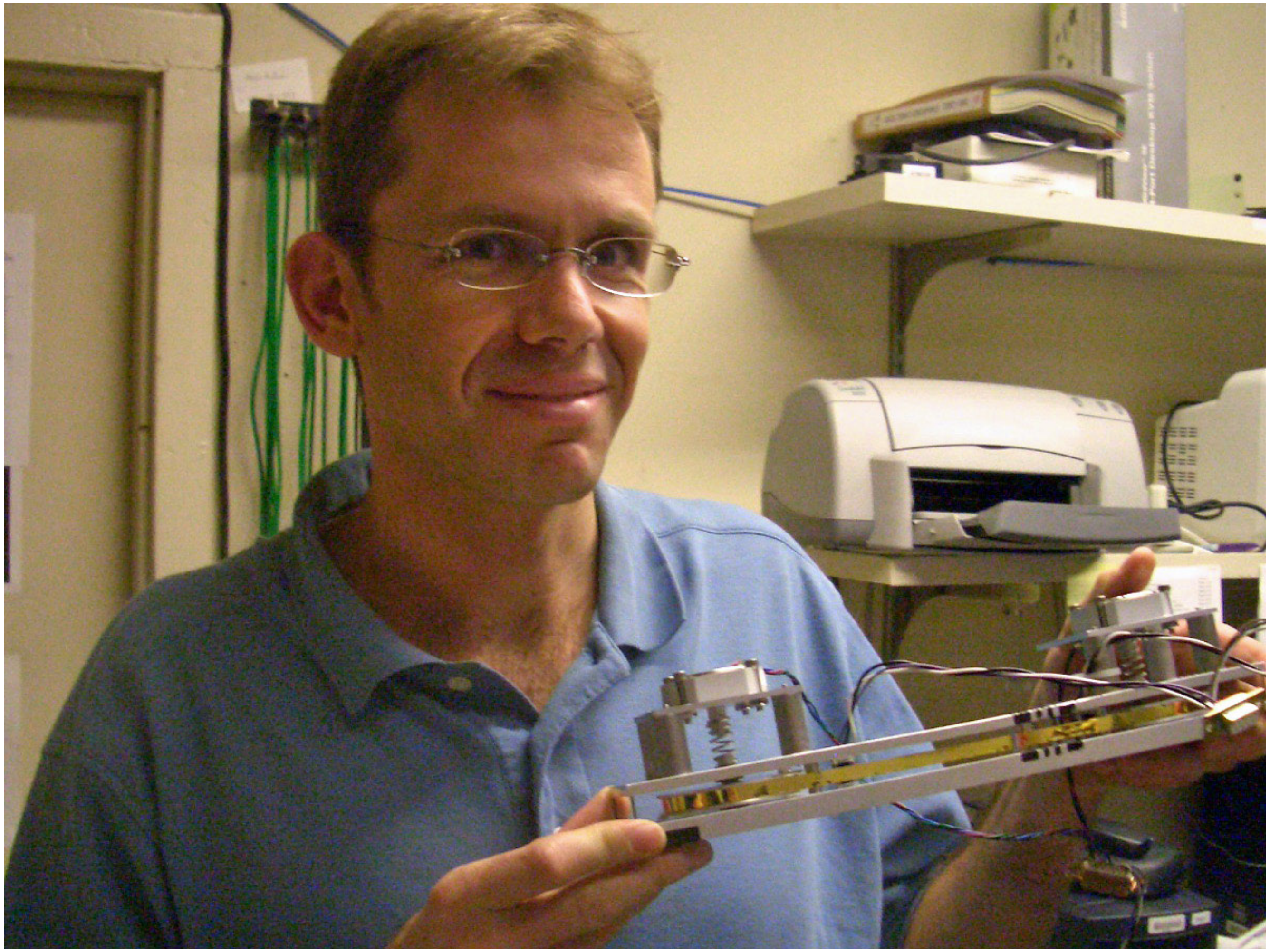
- Mark Kasevich[3]
- Peter Hommelhoff[3]
- Catherine Kealhofer[3]

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

The LEAP experiment
(Laser Electron Accelerator Project)



Tomas Plettner and LEAP Accelerator Cell



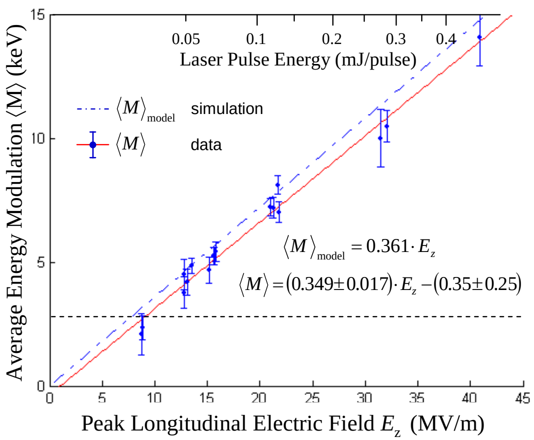
The key was to operate the cell above damage threshold to generate energy modulation in excess of the noise level.

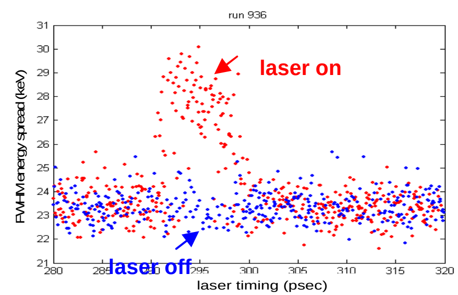
We accelerated electrons with visible light
Phys Rev Letts Sept 2005

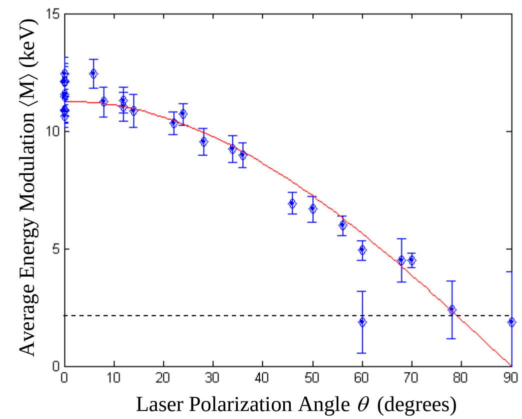
PRL 95, 134801 (2005) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2005

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

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







- confirmation of the Lawson-Woodward Theorem $\int_{-\infty}^{+\infty} E_z dz = 0$
- observation of the linear dependence of energy gain with laser electric field $\Delta U \propto |E_{laser}|$
- observation of the expected polarization dependence $|E_z| \propto |E_{laser}| \cos\rho$

laser-driven linear acceleration in vacuum

Ben Cowan – detailed calculations of Photonic Crystal Accelerator Structures

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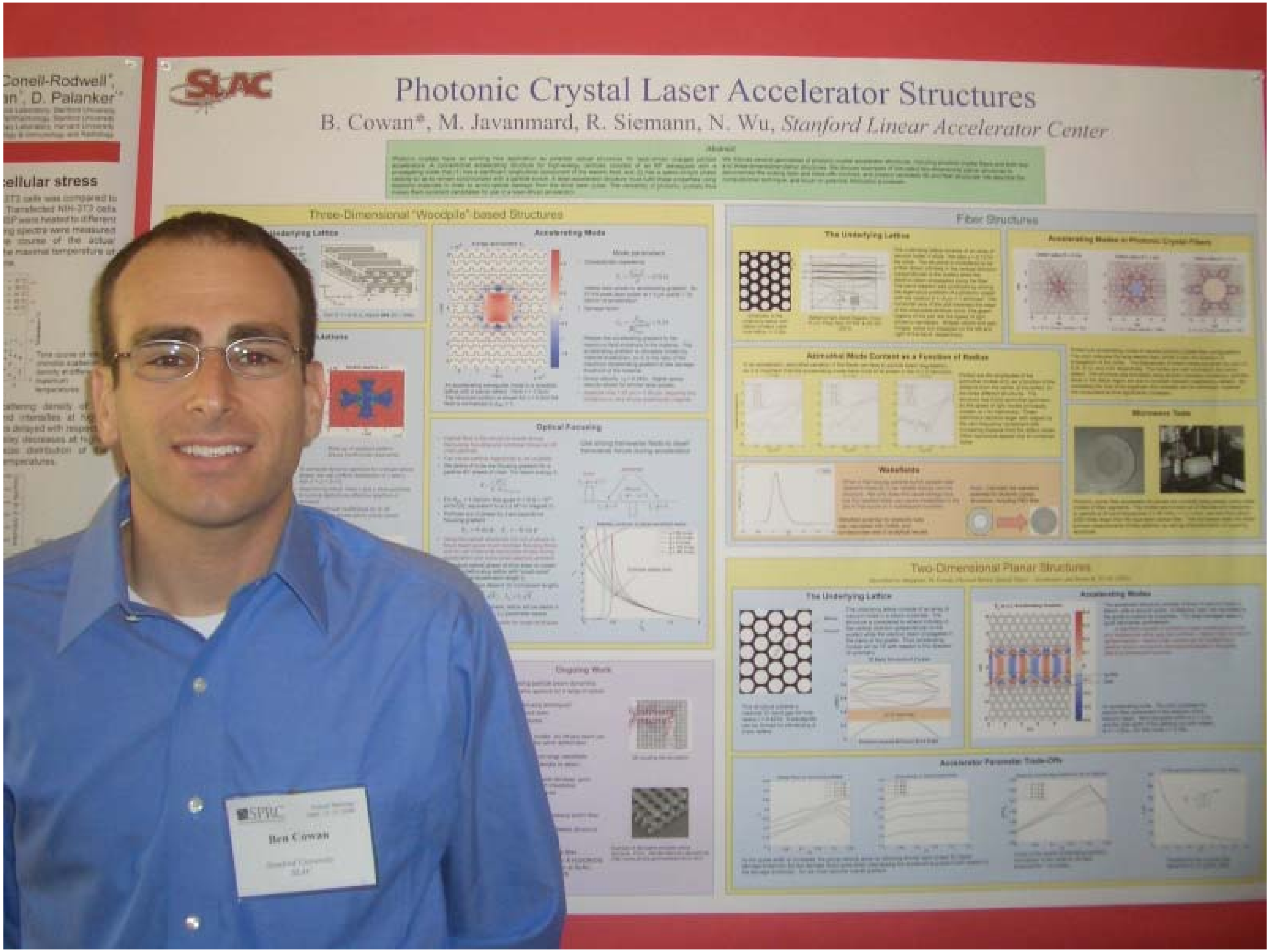
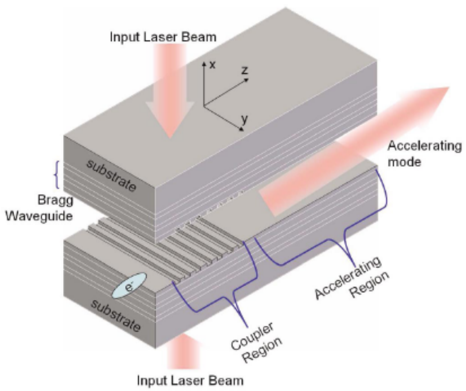
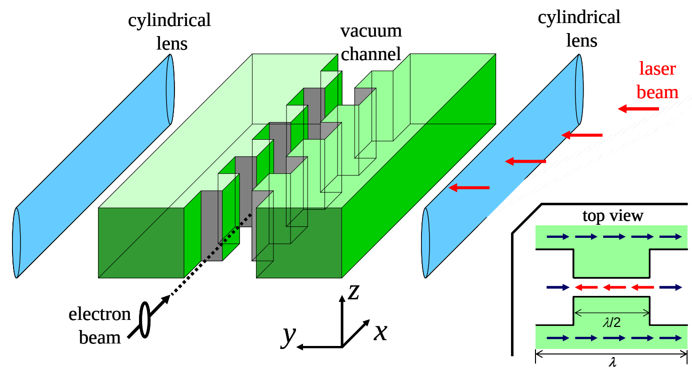


Planar waveguide structures



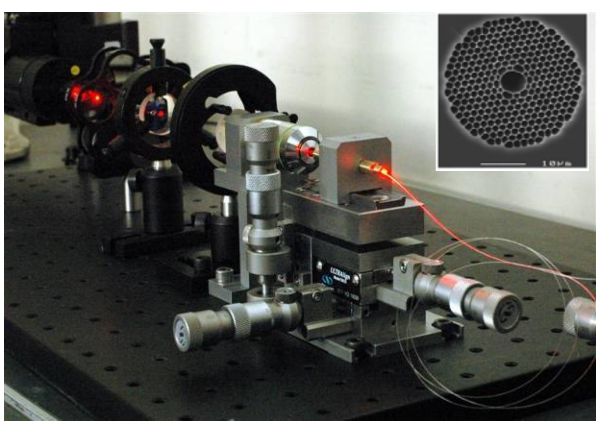
Z. Zhang et al. Phys. Rev. ST AB 8, 071302 (2005)

Periodic phase modulation structures



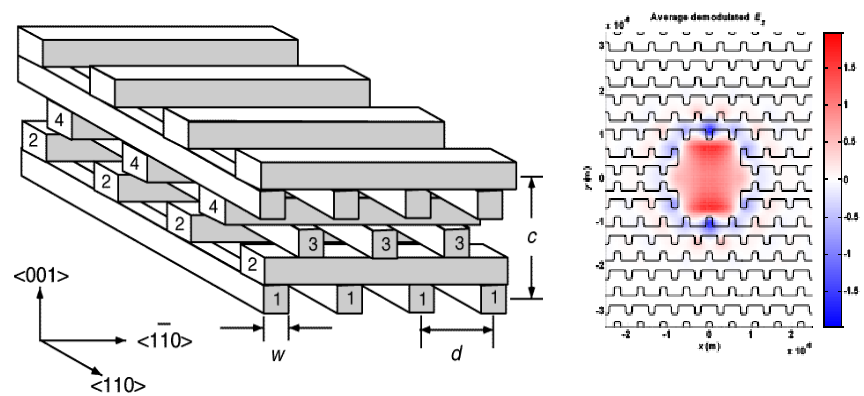
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Hollow core PBG fibers

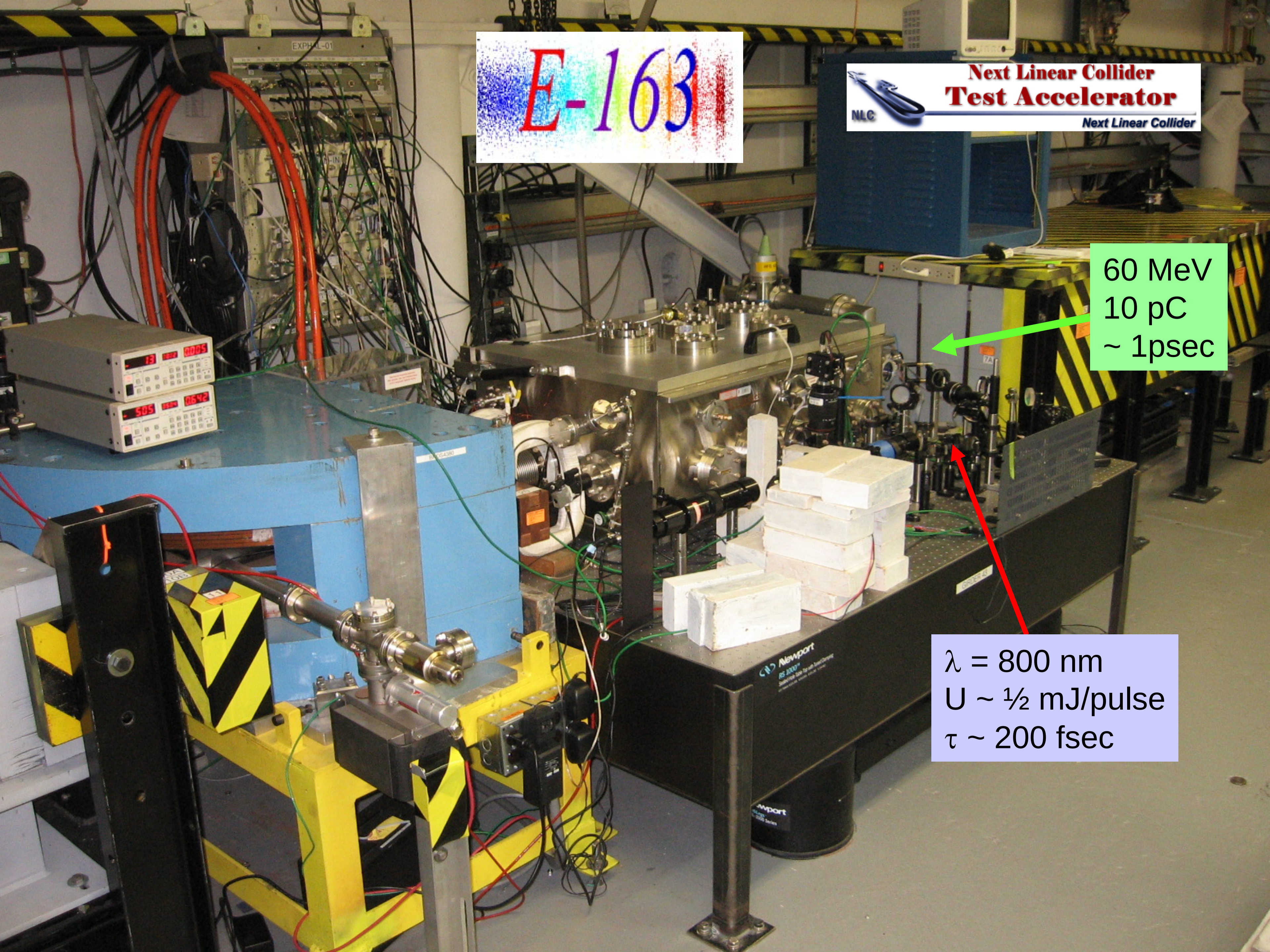


X.E. Lin, Phys. Rev. ST Accel. Beams 4, 051301 (2001)

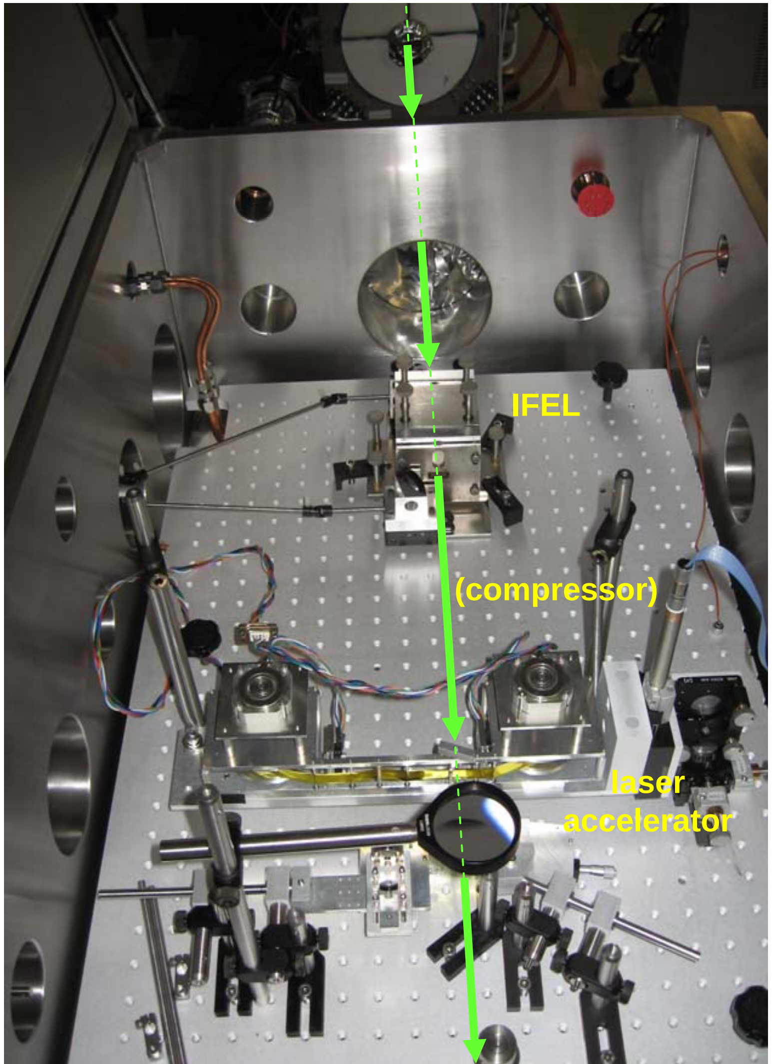
3-D photonic bandgap structures

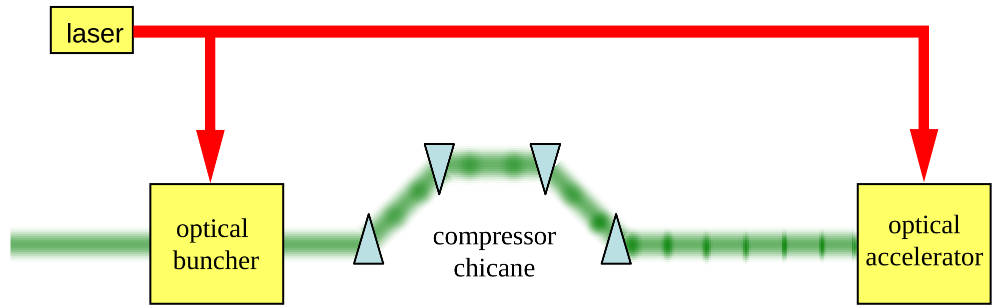


B. M. Cowan, Phys. Rev. ST Accel. Beams , 6, 101301 (2003).

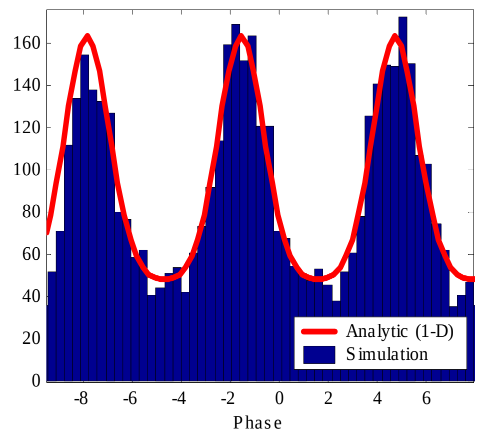

E-163
Next Linear Collider
Test Accelerator
NLC
Next Linear Collider
60 MeV
10 pC
~ 1psec
λ = 800 nm
U ~ ½ mJ/pulse
τ ~ 200 fsec
Newport

We have achieved net acceleration of electrons with attosecond phase control

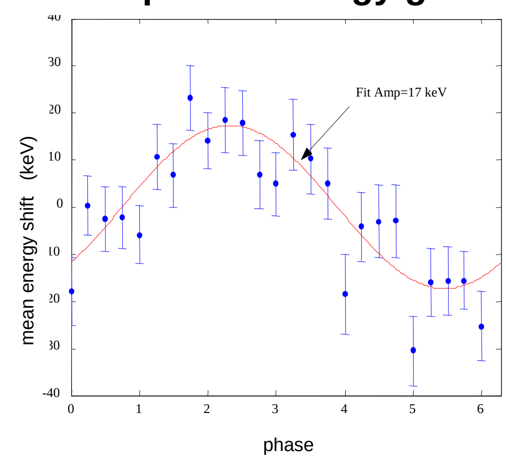




Expected bunching



Expected energy gain



Experiment features

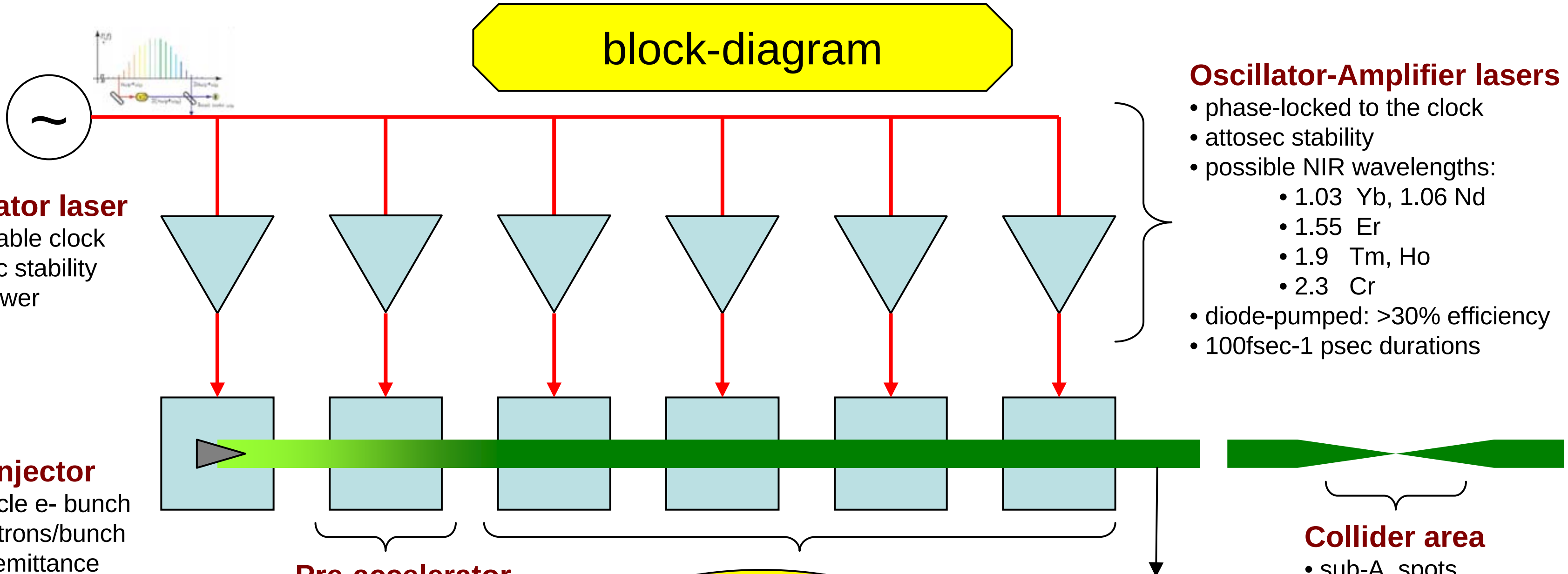
- IFEL modulates energy spread
- electron drift creates optical bunches
- second accelerator → net acceleration

Professor Robert Siemann and Chris Sears

June 15, 2008 – Stanford Graduation Ceremonies

Byer Group

Envisioned 1km long laser-driven TeV scale accelerator



Oscillator laser
- ultrastable clock
- attosec stability
- low power

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

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

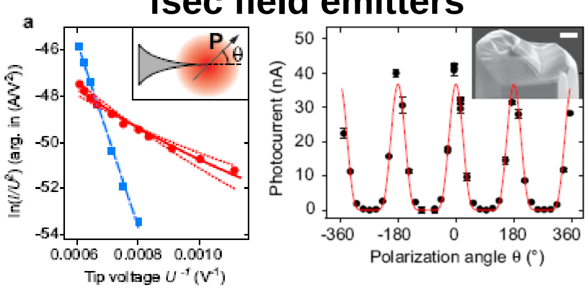
Pre-accelerator
- nonrelativistic
- preserve emittance
- compress bunch

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

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

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

fsec field emitters



P. Hommelhoff et al

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

Order-of-magnitude power estimate
- 1 fC x 10^{10} x 1 TeV → 10^7 W e-beam
- 20% coupling → $2x10^7$ W optical power
- 50% wallplug laser → 10^8 W electricity

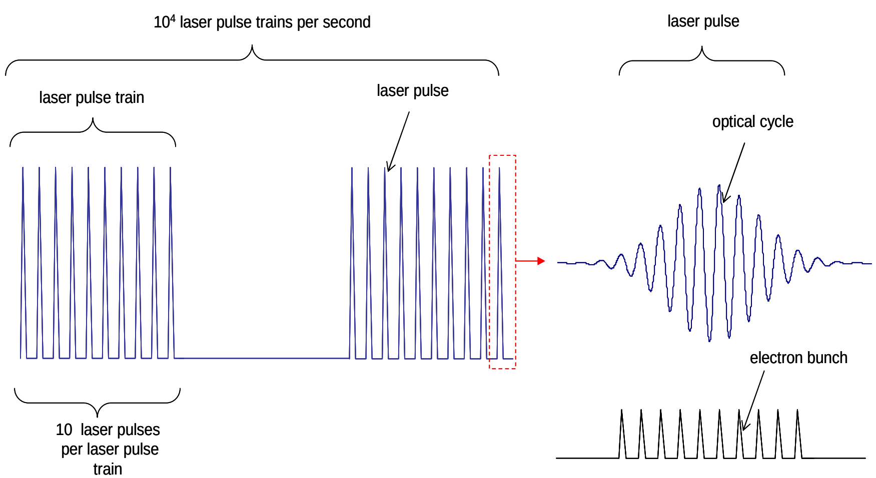
100 MW electricity

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

2. Low bunch charge problem

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

Laser pulse structure that leads to high electron bunch repetition rate



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

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

(~ 10 microjoules in 100fsec per micropulse)

Dramatic increase of

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