Status of ORION and E163

Robert J. Noble

Accelerator Research Dept. B

On behalf of the ORION and E163 Collaborations:

C. D. Barnes, E. R. Colby, B. M. Cowan, R. J. Noble, D. T. Palmer, R. H. Siemann, J. E. Spencer,
D. R. Walz, R. Assmann, C. D. Barnes, F.-J. Decker, P. Emma, M. J. Hogan, R. Iverson,
P. Krejcik, C. O'Connell, P. Raimondi
Stanford Linear Accelerator Center

R. L. Byer, T. Plettner, J. A.Wisdom, C. Sears, M. Javanmard
Stanford University

C. Joshi, W. Mori, J. Rosenzweig, B. Blue, C. E. Clayton, V. Decyk, C. Huang, J.-N. Leboeuf,
K. A. Marsh, C. Ren, F. Tsung, S. Wang, D. Johnson
UCLA

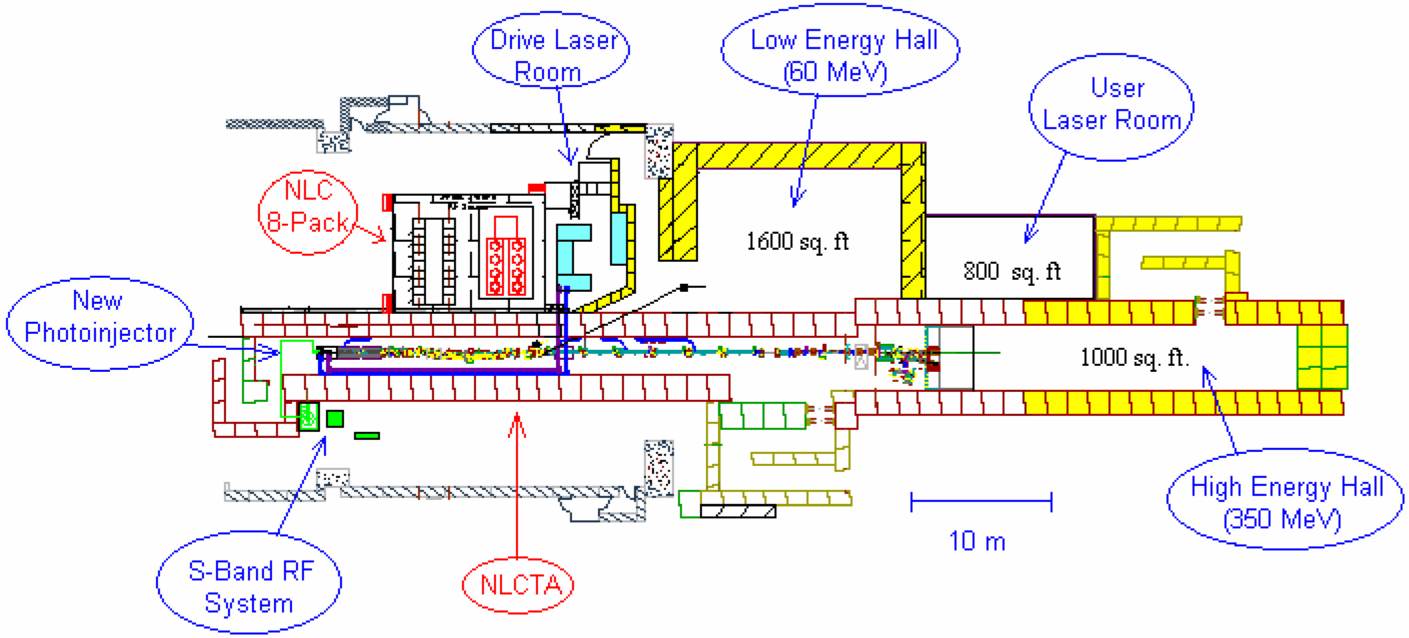
T. Katsouleas, S. Lee, P. Muggli
USC

ORION Facility for Advanced Accelerator and Beam Physics Research

Location: Next Linear Collider Test Accelerator

ORION Facility at the NLCTA

Conceptual Layout



- Feedback received from potential users at the 2nd ORION Workshop, Feb. 18-20, 2003.
- Attended by 85 enthusiastic participants from America, Europe, Asia!
- Working Groups on Beam-Plasma Physics, Laser Acceleration , Particle Sources, and Laboratory Astrophysics suggested many exciting new experiments!

From the Beam-Plasma Working Group, 2nd ORION Workshop

Priority for the Plasma-Beam Physics Working Group: High Quality Acceleration with Narrow ΔE to be achieved through Drive and Witness Bunches

Critical Parameters:

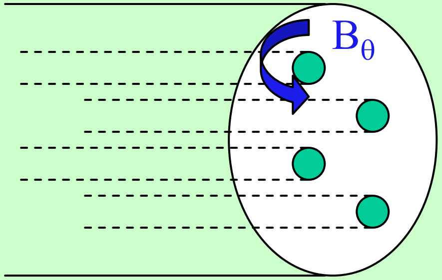
Drive: < 2ps with > 1nC
Witness: 0.2 ps with .1 nC (light beam loading but narrow width limits ΔE)
OR 0.4 ps with .3 nC (beam loading allowing for monoenergetic gain)

Questions:

*** Given the beam optics what will the witness beam look like - σ_z, etc?**
*** We can tolerate high emittance (x10). What charge and bunch length can we get?**

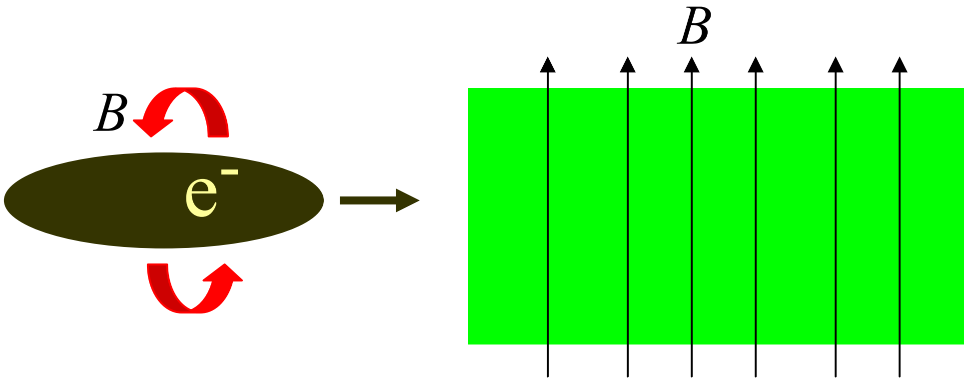
New ORION Experiments:

From the Beam-Plasma Working Group, 2nd ORION Workshop

Experiment	Discussion
Basic Physics	
Heavy Beam Loading	Can give lower energy spread of accelerated particles (via wake flattening) and gives ***high efficiency***.
Beam ionized Sources	Choose parameters such that the incoming beam can ionize the plasma source with tunnel ionization: $\boxed{\left(\frac{Q}{nC}\right) > 1.6\left(\frac{\sigma_r}{20\mu m}\right)\left(\frac{\sigma_z}{.2\,ps}\right)}$
Astrophysics	Weibel/Filamentation Experiment - Basic plasma physics, produces magnetic turbulence leading to synchrotron radiation. A possible model for GRBs. Needs as much charge and as long a pulse as possible & ***LARGE*** (~mm) spot sizes. *Levels:* **1.) 60 MeV:** Detect Filaments on screen **2.) 350 MeV:** Detect Synch. Rad. **3.) 350 MeV + variable witness:** Detect B field Lifetime 

From the Lab Astrophysics Working Group, 2nd ORION Workshop

Cosmic Accelerators in Laboratory (Johnny Ng)



Relativistic charged beam
with strong magnetic fields

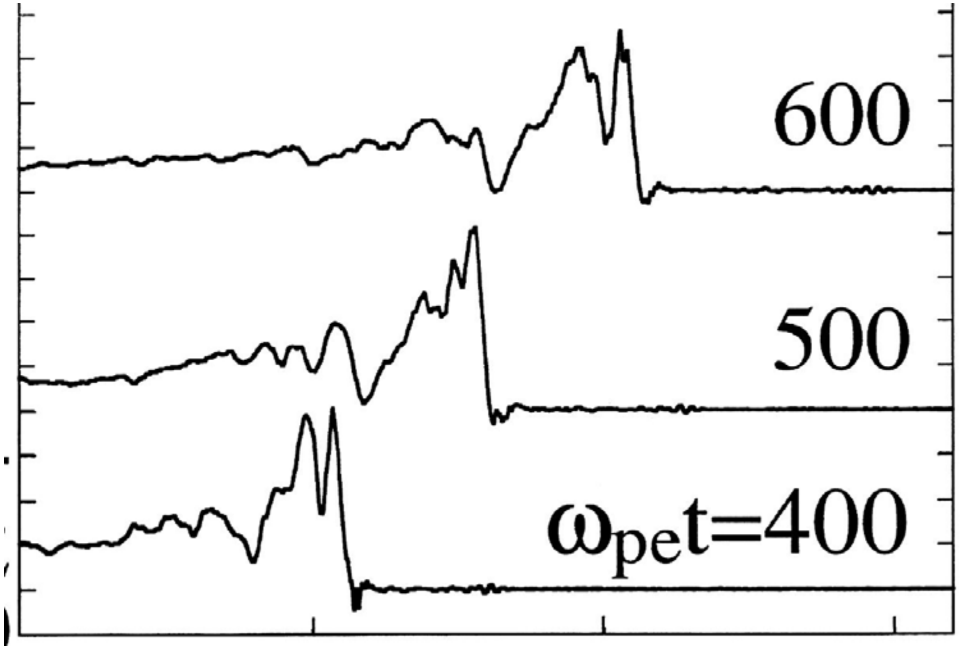
magnetized
ambient plasma

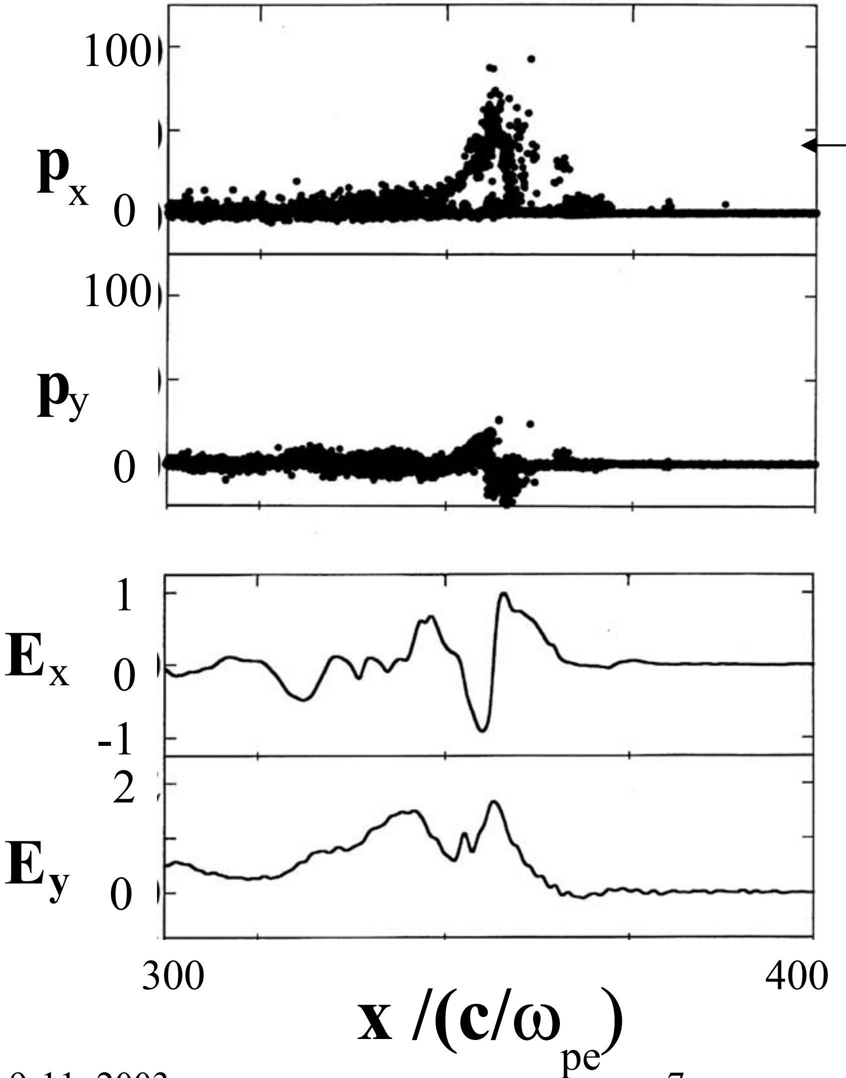
- ➢Efficient way to produce Hybrid modes?
- ➢Possible cosmic electron acceleration
- ➢Relevant for ORION

From the Lab Astrophysics Working Group, 2nd ORION Workshop

Nonlinear Alfven Wave Dynamics: Wave Steepening and Particle Acceleration

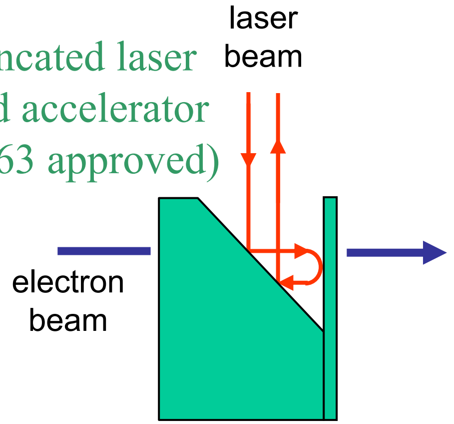
(Rick Sydora, U of Alberta)

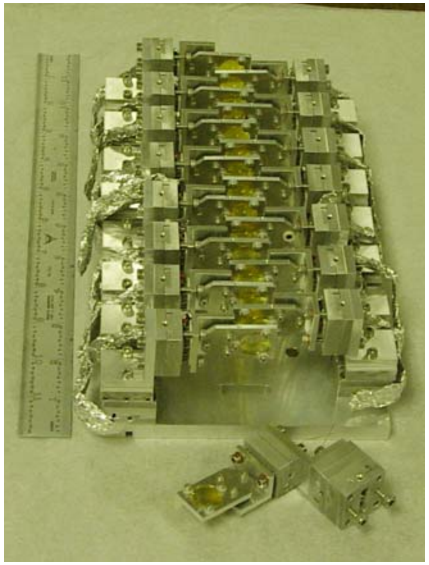




ORION Experiments from Laser Acceleration Working Group, 2nd ORION Workshop

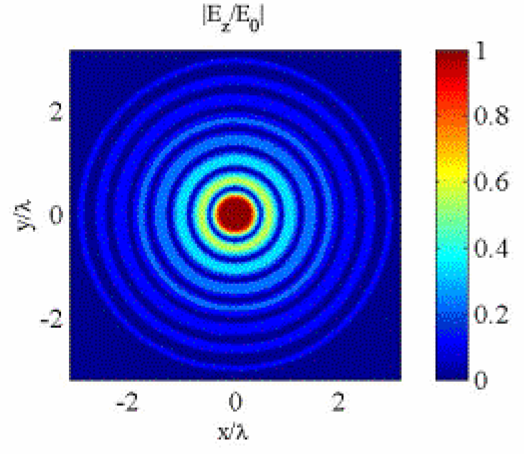
Truncated laser field accelerator (E163 approved)

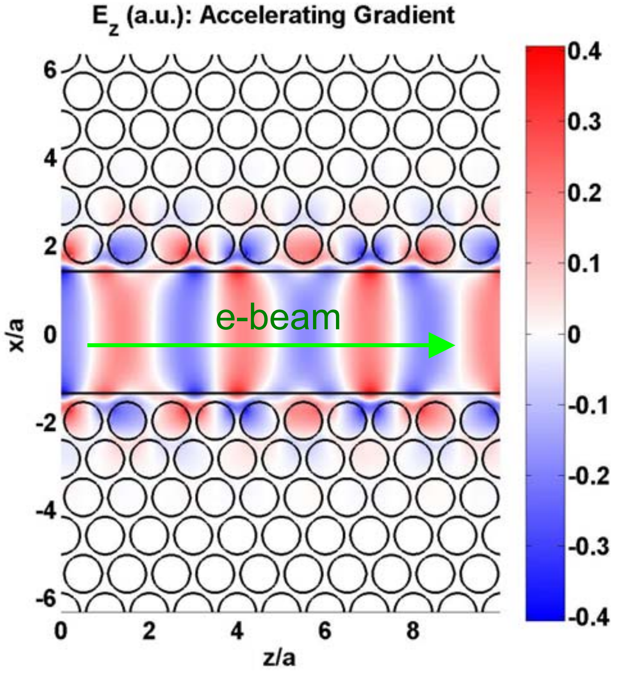




Multi-stage Laser Accelerator (NTHU, Taiwan)

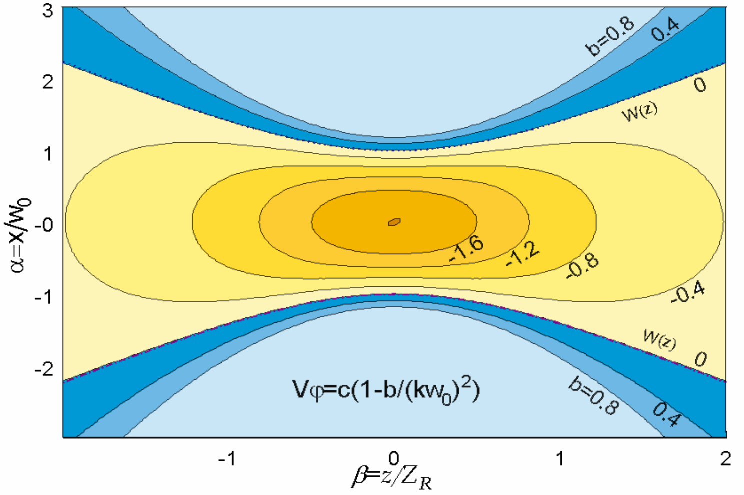
Hollow Fiber Bragg Accelerator





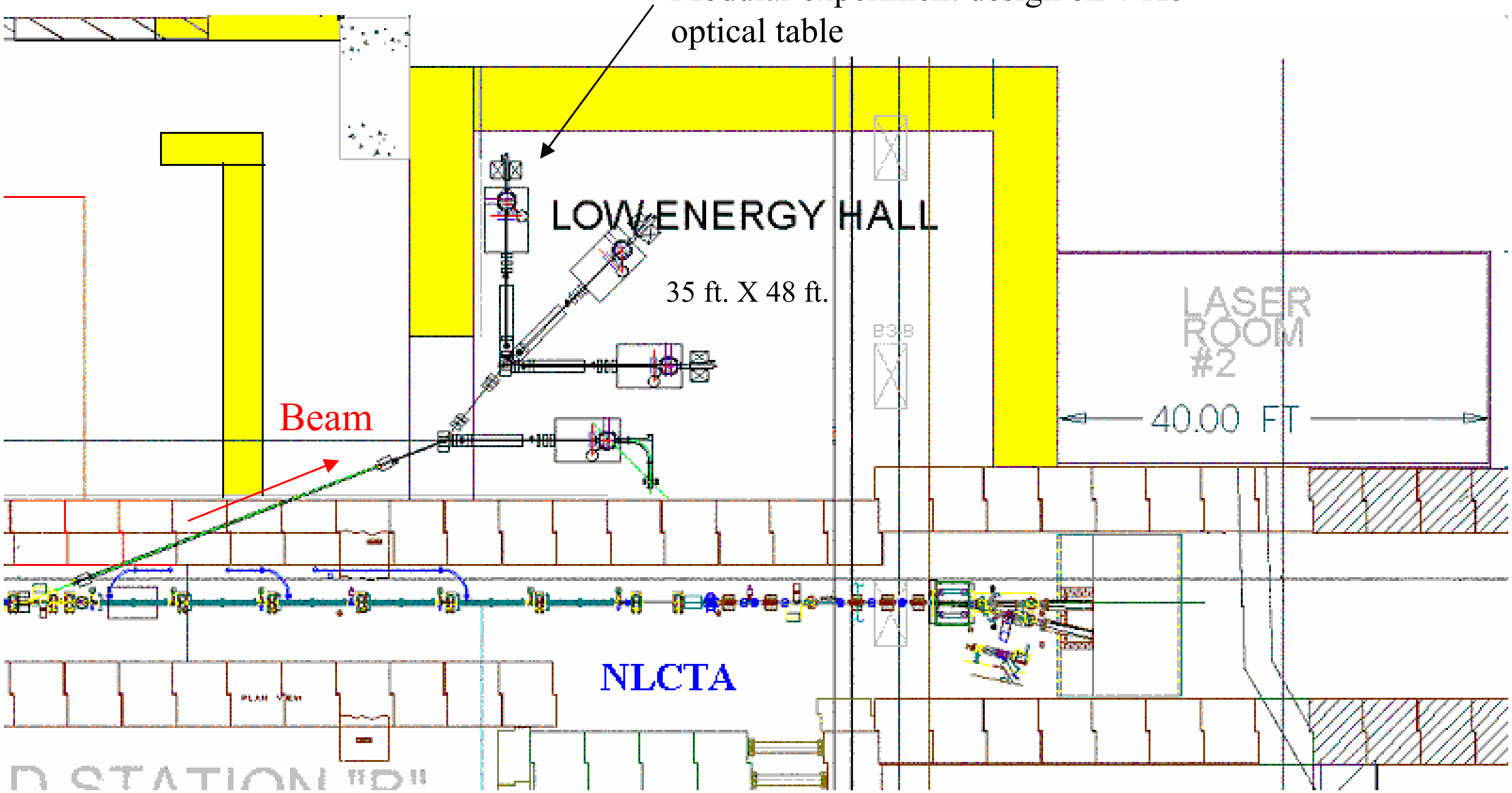
Photonic Crystal Laser Accelerator

Phase-Matched Vacuum Accelerator



ORION Low Energy Hall: A Possible Beamline Layout

Modular experiment design on 4’X8’ optical table

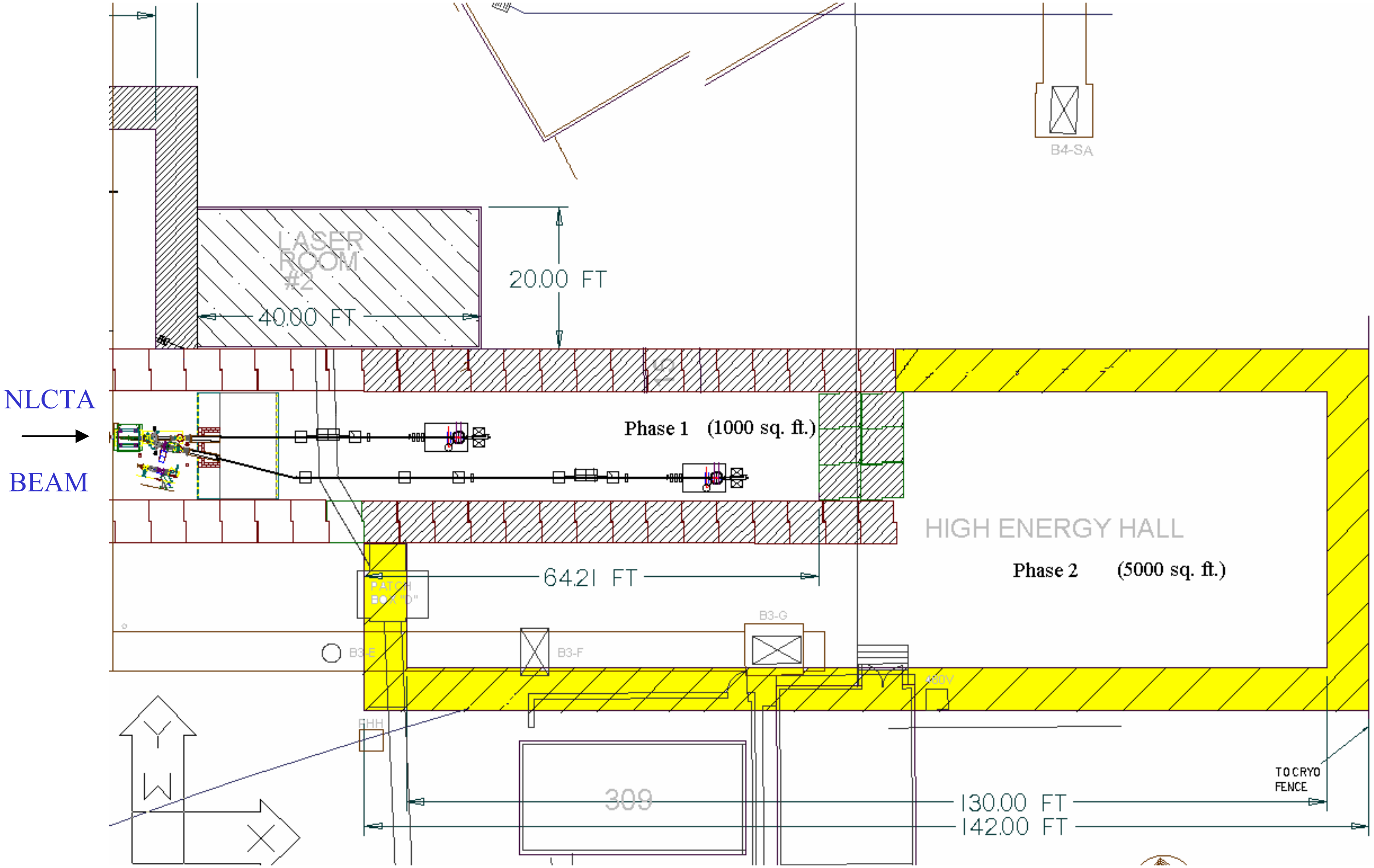


35 ft. X 48 ft.

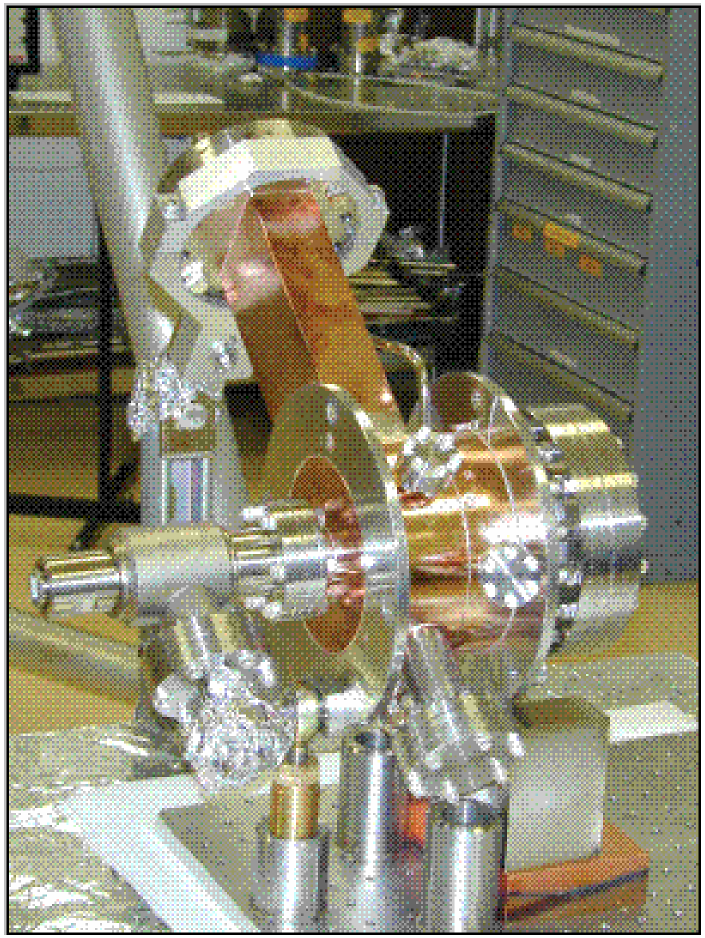
Beam

NLCTA

ORION High Energy Hall: Possible Beamline Layout

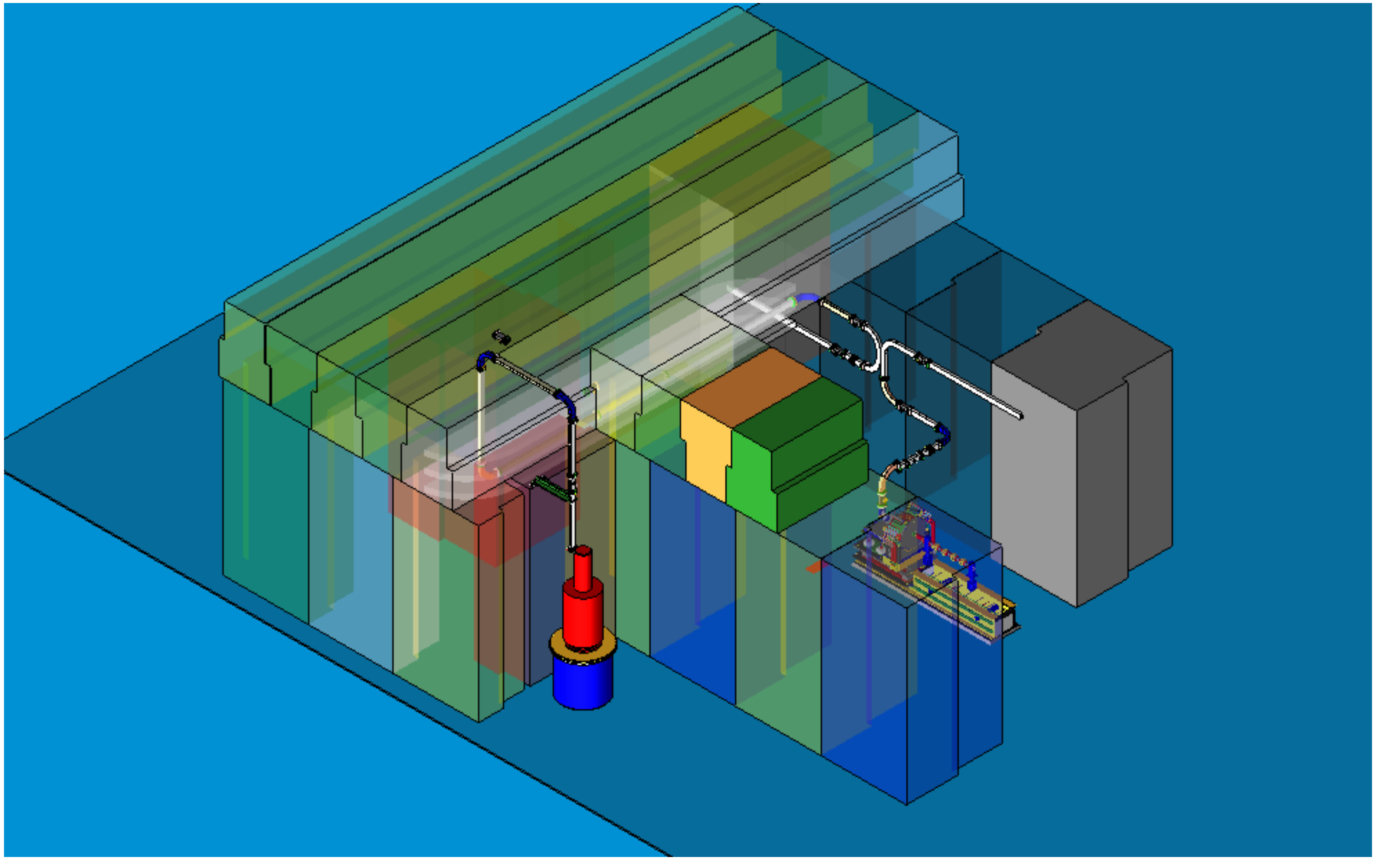


The S-Band RF Photoinjector for ORION/E163 is the same standard design as used at BNL, UCLA, etc.



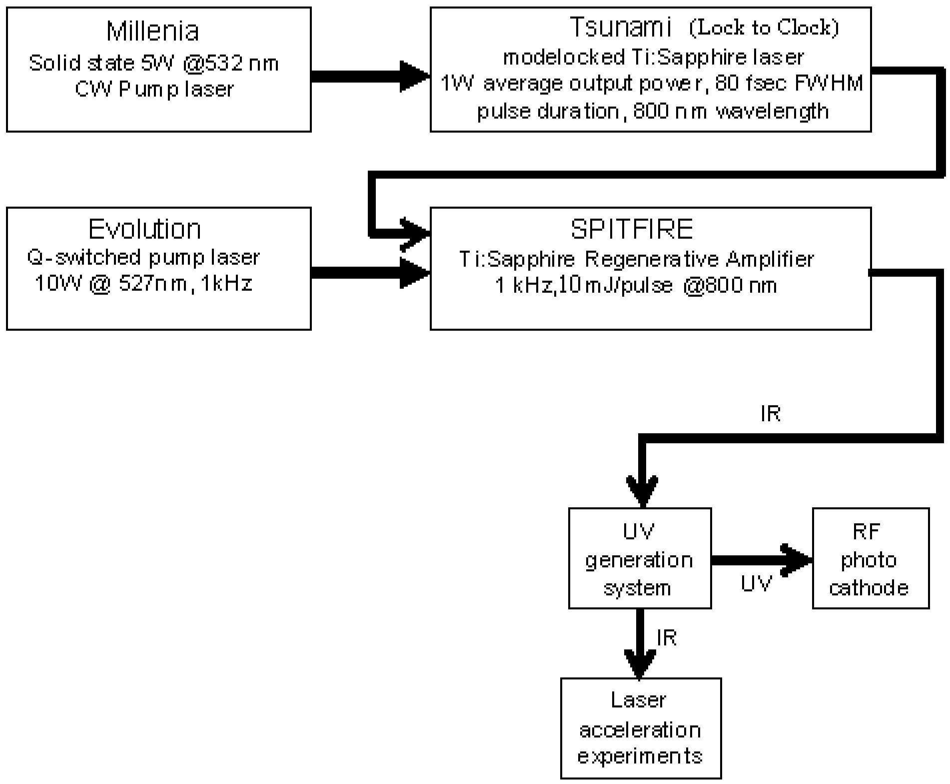
RF gun constructed for E163 (Laser Accel.at NLCTA), brazed and will be high-power tested.

S-Band Klystron and WG Connection to RF Gun



SLAC has committed an S-band klystron, solid-state modulator and waveguide.

Drive Laser for Photoinjector



Millenia
Solid state 5W @532 nm
CW Pump laser

Tsunami (Lock to Clock)
modelocked Ti:Sapphire laser
1W average output power, 80 fsec FWHM
pulse duration, 800 nm wavelength

Evolution
Q-switched pump laser
10W @ 527nm, 1kHz

SPITFIRE
Ti:Sapphire Regenerative Amplifier
1 kHz,10mJ/pulse @800 nm

UV generation system

RF photo cathode

Laser acceleration experiments

←Oscillator is existing SLAC equipment.

←2 mJ amplifier to be purchased as 2003 SLAC cap. equipment. (upgrade for ORION)

1 nC requires about 10 μJ on Mg cathode

E163: Laser Acceleration at the NLCTA

C. D. Barnes, E. R. Colby*, B. M. Cowan, R. J. Noble,
D. T. Palmer, R. H. Siemann, J. E. Spencer, D. R. Walz

Stanford Linear Accelerator Center

R. L. Byer, T. Plettner, J. A.Wisdom, C. Sears

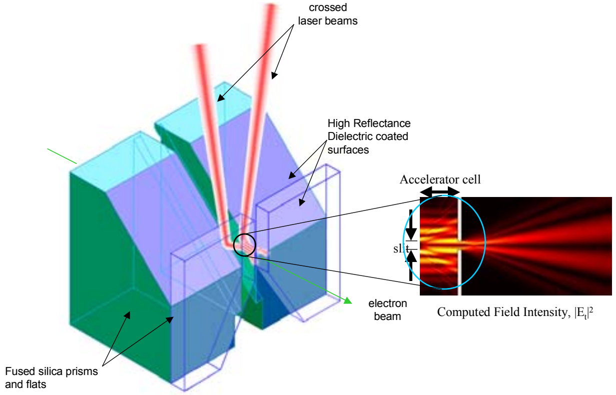
Stanford University

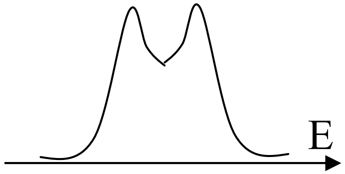
September 24, 2001

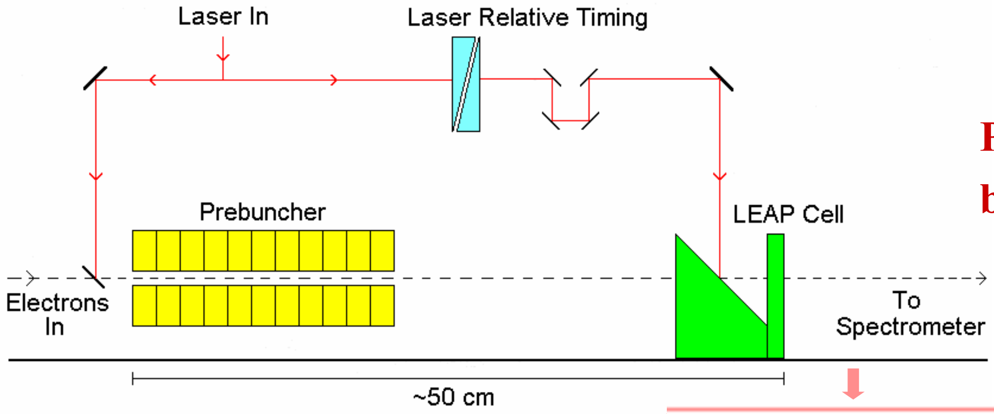
* Spokesman.

E163

Phase I. Characterize laser/electron energy exchange in vacuum

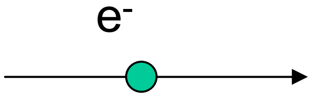


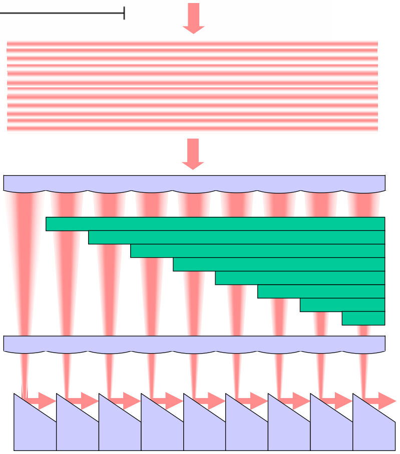




Phase II. Demonstrate optical bunching and acceleration

Phase III. Test multicell lithographically produced structures





Incoming plane waves

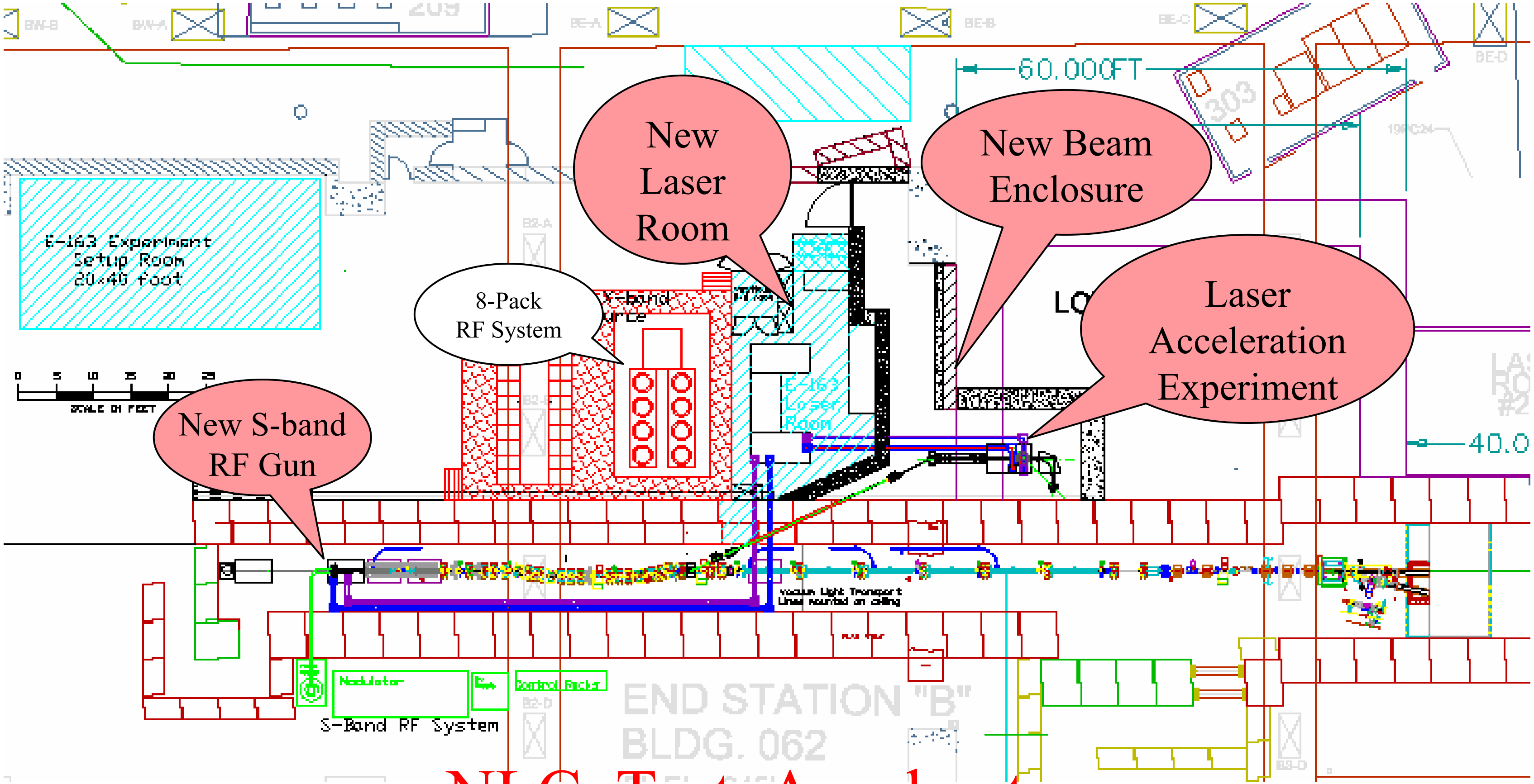
Lenslet Array

Phase Control

Lenslet Array

Electron beam

Laser Acceleration at the NLCTA



New Laser Room

New Beam Enclosure

8-Pack RF System

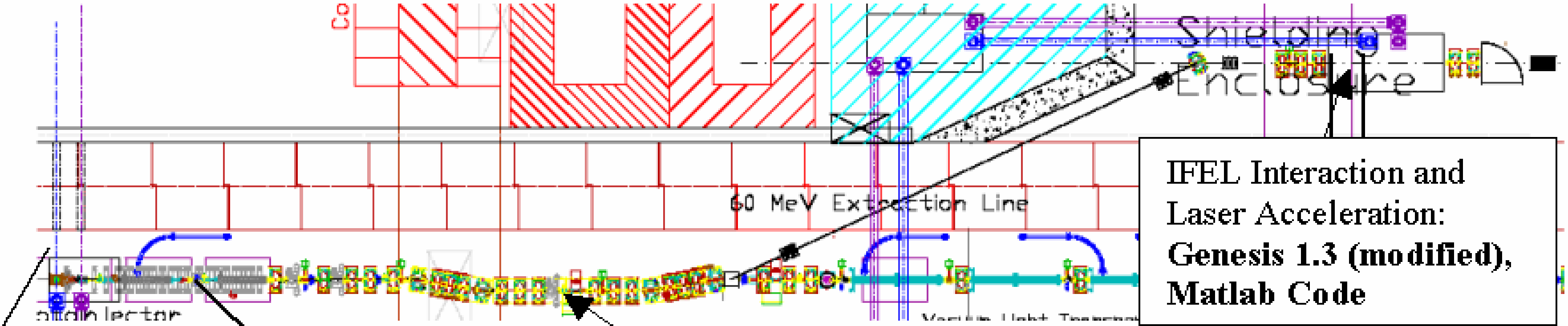
Laser Acceleration Experiment

New S-band RF Gun

NLC Test Accelerator

E163 End-to-End Simulations

Lesson for ORION is that one must understand the interplay between source beam behavior and the experimental signals to be measured.



IFEL Interaction and Laser Acceleration: **Genesis 1.3 (modified), Matlab Code**

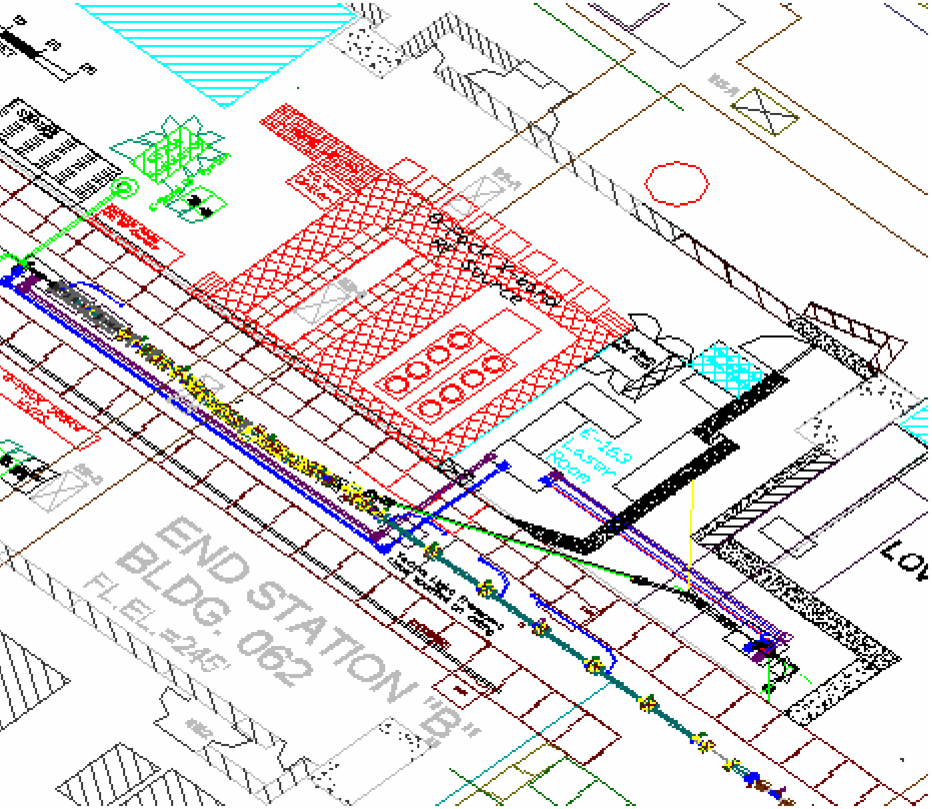
Electron generation and acceleration to 32.5 MeV: **Parmela** (UCLA/SLAC)

Electron transport through 2nd accelerator, chicane, dogleg, energy scraper: **Elegant 14.6β2**, with accelerator structure and collimator wakefields from analytic treatment in the NLC-ZDR, and initial magnet settings from 2nd-Order **Transport** optimization.

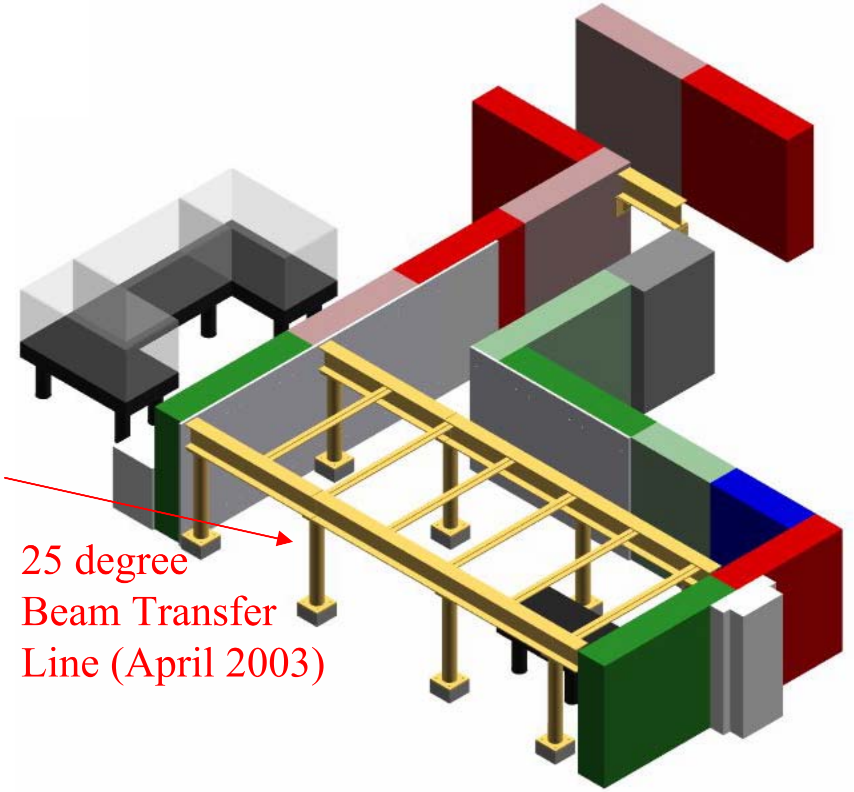
Remainder of Transport: **Elegant 14.6β2**

E163 Enclosure

Construction to start in May 2003

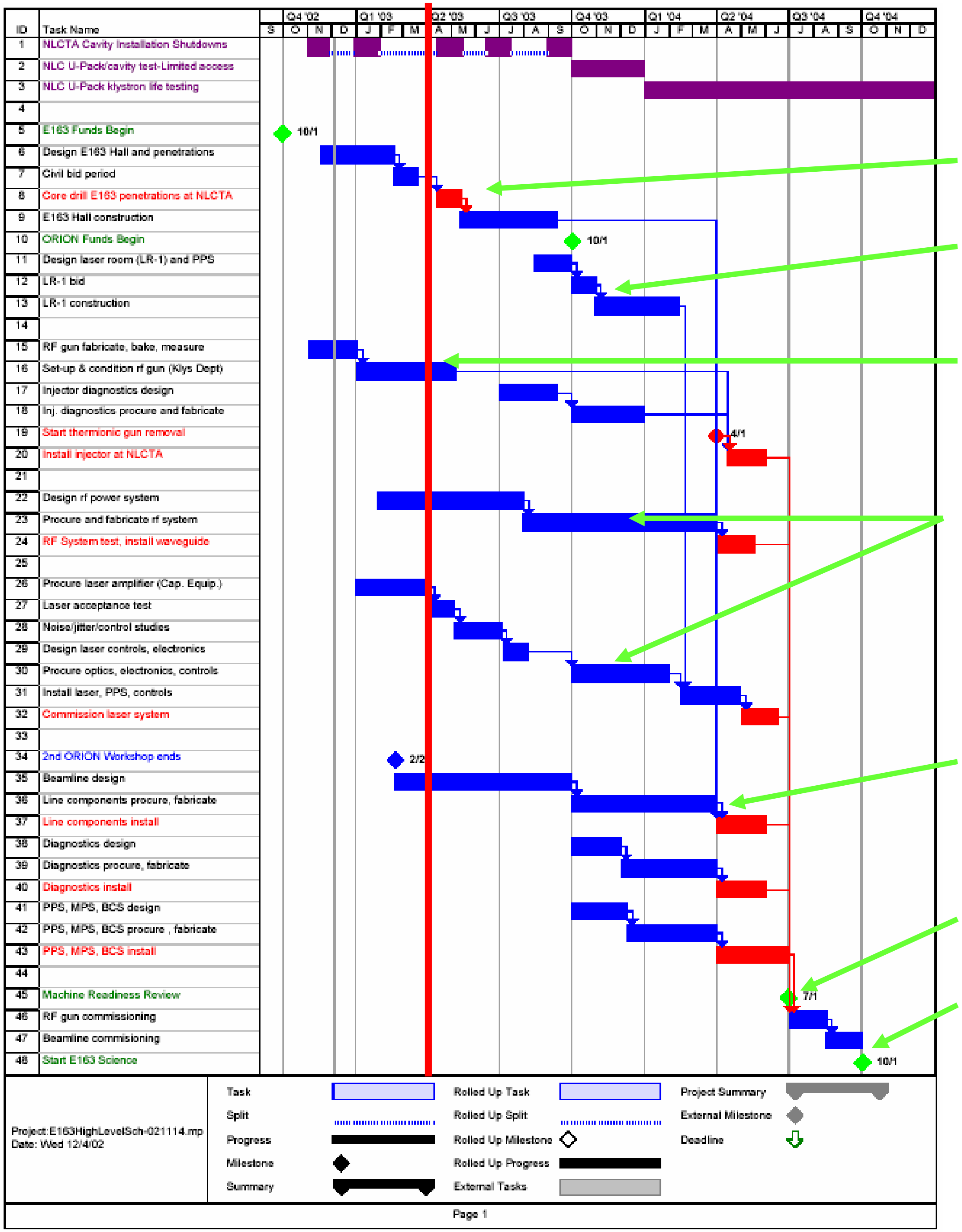


E163 Experimental area, original layout



25 degree
Beam Transfer
Line (April 2003)

E163 Shielded enclosure, as designed



ID	Task Name
1	NLCTA Cavity Installation Shutdowns
2	NLC U-Pack/cavity test-Limited access
3	NLC U-Pack klystron life testing
4	
5	E163 Funds Begin
6	Design E163 Hall and penetrations
7	Civil bid period
8	Core drill E163 penetrations at NLCTA
9	E163 Hall construction
10	ORION Funds Begin
11	Design laser room (LR-1) and PPS
12	LR-1 bid
13	LR-1 construction
14	
15	RF gun fabricate, bake, measure
16	Set-up & condition rf gun (Klys Dept)
17	Injector diagnostics design
18	Inj. diagnostics procure and fabricate
19	Start thermionic gun removal
20	Install injector at NLCTA
21	
22	Design rf power system
23	Procure and fabricate rf system
24	RF System test, install waveguide
25	
26	Procure laser amplifier (Cap. Equip.)
27	Laser acceptance test
28	Noise/jitter/control studies
29	Design laser controls, electronics
30	Procure optics, electronics, controls
31	Install laser, PPS, controls
32	Commission laser system
33	
34	2nd ORION Workshop ends
35	Beamline design
36	Line components procure, fabricate
37	Line components install
38	Diagnostics design
39	Diagnostics procure, fabricate
40	Diagnostics install
41	PPS, MPS, BCS design
42	PPS, MPS, BCS procure , fabricate
43	PPS, MPS, BCS install
44	
45	Machine Readiness Review
46	RF gun commissioning
47	Beamline commisioning
48	Start E163 Science

Project:E163HighLevelSch-021114.mp
Date: Wed 12/4/02

Page 1

Construct E163 Hall CY2003Q2

Laser Room 1 Construction 2003Q4 *

RF Gun Power Conditioning 2003Q2

Construct RF & Laser Systems 2003-04 *

Beamline Installation 2004Q2 *

Commission Beamline 2004Q3 *

Start E163 Physics 2004Q4 *

* Contingent on FY04 ORION construction funds

Summary of Major Steps to Date

1. E163 approved by SLAC Director in July 2002.
2. Brazing of the E163/ORION rf gun, machined at UCLA, is complete.
3. The early GTF solenoid coils, which have been recently replaced with new coils, are to be used for the gun focusing solenoid.
4. Laser oscillator was procured with SLAC 2001 Cap. Equip. funds; 2 mJ amplifier for E163 is being purchased with 2003 Cap. Equip.; still require pump laser.
5. The NLC prototype IGBT modulator has been reserved for use on the E163 rf system; SLAC will contribute an S-band 5045 klystron when needed.
6. Penetrations at NLCTA for E163 beam line, rf waveguide and laser light approved and will be core drilled in mid-April.
7. Surplus shielding blocks/girders identified at Stanford HEPL and on SLAC site which are adequate to build the E163 hall, as well as major parts of the ORION Low Energy Hall and the High Energy Hall in the future.

The Future

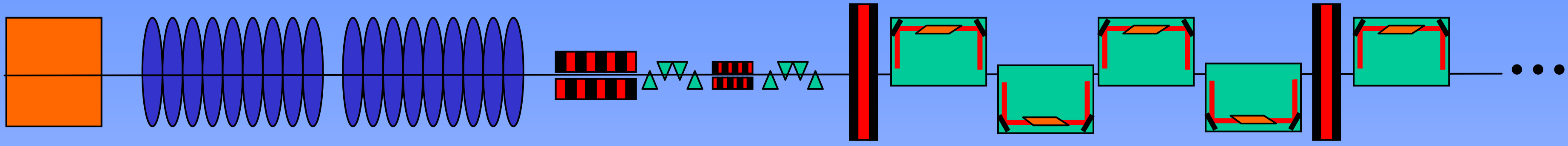
During the next 5 years we anticipate performing path finding research to devise power-efficient lithographic structures with the ultimate goal of realizing an all-optical particle accelerator.

Thanks to the support of DOE and SLAC management, E163 is giving us a major head start on realizing ORION.

We are ready to go when funds arrive.

BACK-UP SLIDES

Laser Linear Collider pre-Concept



CW Injector

Warm rf gun   Cold Preaccelerator   Optical Buncher

433 MHz x 10^5 e^-/macropulse (600 μpulse/macropulse)

$\epsilon_N \sim 10^{-11}$ m (but note $Q/\epsilon_N \sim 1$ μm/nC)

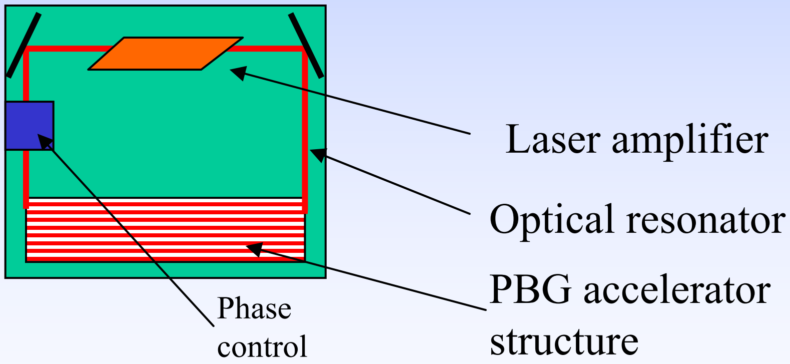
Laser Accelerator

λ=1-2 μ, G~1 GeV/m

Photonic Band Gap Fiber structures embedded in optical resonant rings

Permanent Magnet Quads (B'~1 kT/m)

An Acceleration Unit

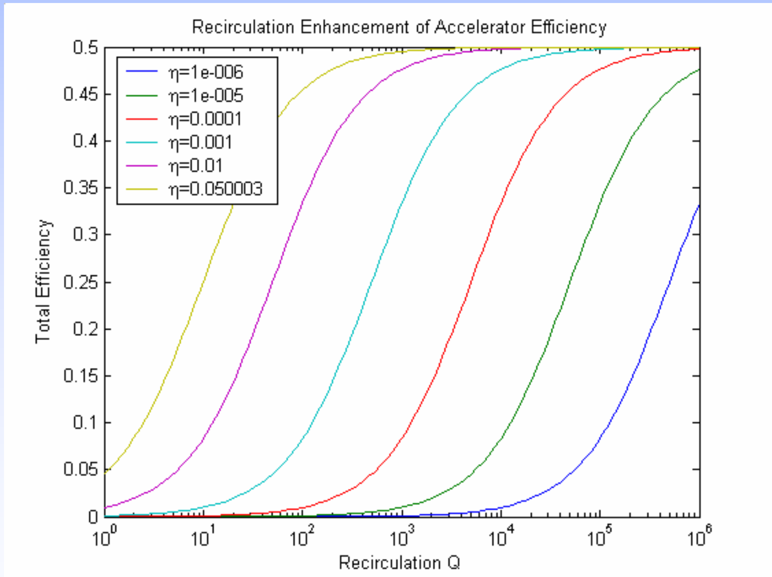


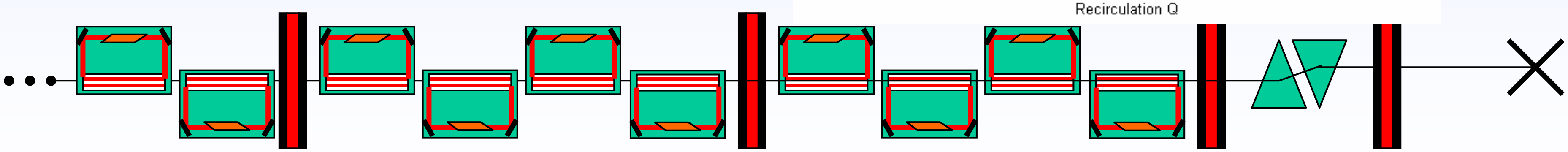
Laser amplifier

Optical resonator

PBG accelerator structure

Phase control





Optical Debuncher

Final Focus **I.P.**

The Promise of Laser Acceleration

Lasers produce unequalled energy densities and electric fields

Very short pulses permit higher surface electric fields without breakdown

Very short wavelengths (compared to microwaves) naturally lead to:

Sub-femtosecond electron bunches → sub-fs radiation pulses

Very short wavelengths require:

Very small emittance beams → radiation sources are truly point-like

Lasers development is strongly driven by industry

Lasers are a $4.8B/year market (worldwide), with laser diodes accounting for 59%, DPSS lasers $0.22B/year, and CO_2 lasers $0.57B/year [1] (in contrast, the domestic microwave power tube market is $0.35B/year, of which power klystrons are just $0.06B/year[2]).

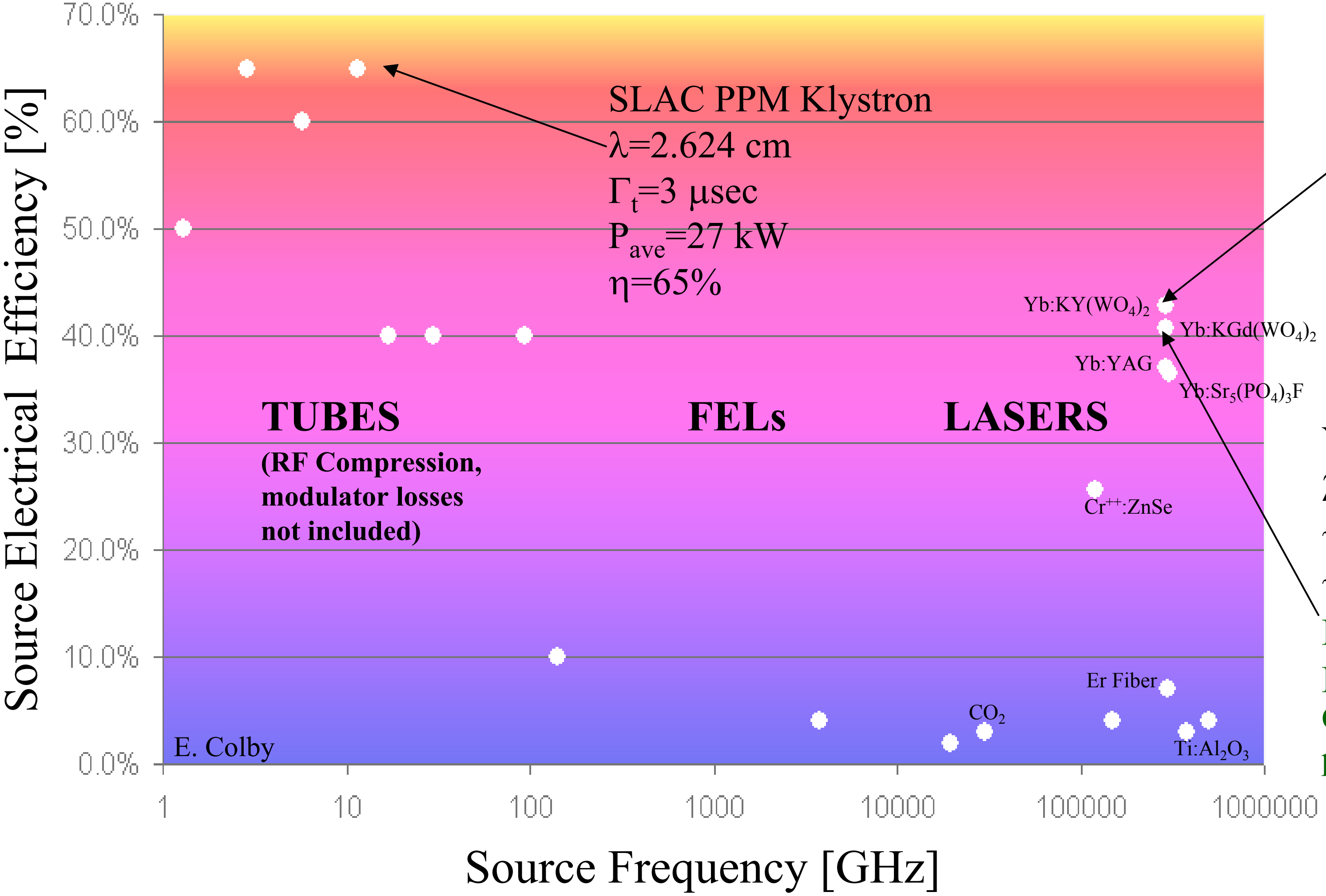
Peak Powers of TW, average powers of kW are readily available from *commercial products*

The market’s needs and accelerator needs **overlap substantially**: Cost, reliability, shot-to-shot energy jitter, coherence, mode quality are common to both.

[1] K. Kincade, “Review and Forecast of the Laser Markets”, Laser Focus World, p. 73, January, (2003).

[2] “Report of Department of Defense Advisory Group on Electron Devices: Special Technology Area Review on Vacuum Electronics Technology for RF Applications”, p. 68, December, (2000).

Electrical Efficiency of Lasers



SLAC PPM Klystron
λ=2.624 cm
Γ_t=3 μsec
P_{ave}=27 kW
η=65%

TUBES

**(RF Compression,
modulator losses
not included)**

FELs

LASERS

$Yb:KY(WO_4)_2$
λ=1.028μ
η_{slope}=86.9%
η_ε=43%
Γ_t=240 fsec
P_{ave}=22.0 W
Opt. Lett., **27** (13), p.1162, July (2002).

$Yb:KGd(WO_4)_2$
λ=1.023μ
η_{slope}=82.7%
η_ε=41%
Γ_t=176 fsec
P_{ave}=1.1 W
Opt. Lett., **25** (15), p.1119, August (2000).

Recent Progress in Optical Materials

High Damage Threshold Materials

- Optical-quality CVD diamond
- ZnSe

High Thermal Stability Materials

- Ultra-high thermal stability optical materials (Photonics Jan 2003, p.158)

(factor of 2 better than Zerodur)

- +ve/-ve material sandwich that has $\beta=(1/n)*dn/dT+\alpha\sim0$ (same article as above)

Lithographically Treatable Materials

- Silicon ($\lambda>1500$nm)
- Optical ceramics

Silica

Nd:YAG

High average power ultra-fast lasers

Existing widespread commercial ultra-fast laser systems: Ti:sapphire

Poor optical efficiency → poor wall-plug efficiency

Low saturation → low power systems (typically few Watts per laser)

Large scale multi-component systems that require water cooling

High costs systems (~100 k$/laser of ~1Watt avg. power)

Requirements for future ultra-fast lasers for particle accelerators

1. Power scalability to hundreds for Watts of average power per laser
2. Wall-plug efficiency > 20%
3. Mass producible, reliable and low-cost
4. Ultra low optical phase noise

Driving Applications

Industry and Basic Research

Materials Processing, ultrafast laser machining, via drilling, medical therapeutics, entertainment, image recording, remote sensing

Defense

Coherent laser radar, remote wind sensing, remote sensing of “smart dust”, trans-canopy ranging, and stand-off coherent laser inspection of laminated-composite aircraft components

Candidate laser host materials for ultra-fast high-power lasers

Monocrystalline materials

→Materials with low quantum defect, excellent slope efficiency, and good thermal conductivity

$Yb:KGd(WO_4)_2$ slope efficiency 82.7% [Opt. Lett., 22 (17) p.1317, Sept. (1997)]
limiting electrical efficiency of 41% (assuming 50% efficient pump diode)

$Yb:KY(WO_4)_2$ slope efficiency 86.9% [Opt. Lett., 22 (17) p.1317, Sept. (1997)]
limiting electrical efficiency of 43% (assuming 50% efficient pump diode)

Polycrystalline materials

Nd:YAG
$Nd: Y_2O_3$
$Cr^{2+}:ZnSe$
$Nd:Y_3Sc_xAl_{(5-x)}O_{12}$

- Better homogeneity of dopant
- Lower fabrication cost
- Possible tailoring of dn/dT
- Single crystal growth still possible

Commercially Available High Efficiency Laser Diode Bars

nLIGHT PHOTONICS

Preliminary Data Sheet | **NL-SAG**

300W, η_e=50%, λ=780-1000 nm

High Power Stacks

nLight Photonics' high power stacked bar module provides state-of-the-art power levels in a compact package. Starting with high power diode 1 cm bars, multiple modules are stacked to provide extremely high output power. These modules are water cooled to maximize output power without sacrificing the lifetime of the diode.

Optical	
Center Wavelength (Range)	780-1000nm
CW Output Power	300W (6 plates)
Center Wavelength Tolerance	±3.0nm
Array Length	1cm

Electrical	
Total Conversion Efficiency	50%
Threshold Current	10A
Operationg Current	60A
Operating Voltage	< 12V
Series Resistance	0.04Ω

Thermal	
Thermal Resistance	0.35°C/W
Operating Temperature	10°C to 40°C
Fluid Flow Rate	300 ml/min/plate
Inlet to Outlet presure drop	30 psi
Deionized Water Resistivity	.5 – 2Mohm-cm
Filter	< 20µm

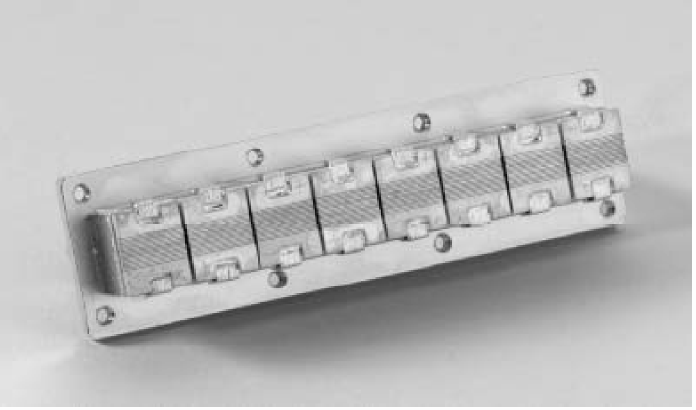
CEO CUTTING EDGE OPTRONICS

3900 W, η_e=40%, λ=792-812 nm

Part Number: ARR04P3900

Z PACKAGE

- Packaged 112 Bar Laser Diode Array
- Other Powers Are Also Available
- Available Wavelengths 785-1064nm



OPTICAL CHARACTERISTICS

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
QCW Peak Power Output	60A, 150 µsec, 1 kHz	3900	---	---	W
Operating Current	3900W at 25°C Heat Sink	---	55	60	A
Threshold Current	25°C Heat Sink	---	13	16	A
Slope Efficiency	25°C Heat Sink	106.4	123.2	---	W/A
Efficiency	3900W at 25°C Heat Sink	35	40	---	%
Number of Emitters	---	---	72 x 112	---	
Emitter Size	---	---	90 x 1	---	µm
Emitter Pitch	---	---	133.3	---	µm
Center Wavelength	3900W at 25°C Heat Sink	792	808	812	nm
Wavelength Tolerance	3900W at 25°C Heat Sink	± 1	± 3	± 4	nm
Spectral Width	3900W at 25°C Heat Sink	---	4.0	5.0	nm
Wavelength Shift	---	0.23	0.25	0.27	nm/°C
Beam Divergence FWHM (1)	---	---	40x10	42x12	° x °
Polarization	---	---	TE	---	---
Degradation Rate (2)	25°C Heat Sink	---	5	---	%/G shots

ELECTRICAL CHARACTERISTICS

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS
Built-In Voltage	25°C Heat Sink	---	179.2	190.4	V
Series Resistance	25°C Heat Sink	---	0.896	1.344	ohms
Operating Voltage	25°C Heat Sink, 3900W	---	224	257.6	V

U.S. Patent Numbers: 5,734,672 5,913,108

NOTES
(1) Lower beam divergence is also available.
(2) Typical degradation rates are 5% in the first 10 million shots and 5% per billion shots thereafter.

Cutting Edge Optronics • 20 Point West Blvd. • St. Charles, MO 63301
636.916.4900 • 636.916.5665 fax • www.ceolaser.com

Laser phase-locking to a microwave reference with great stability has been demonstrated.

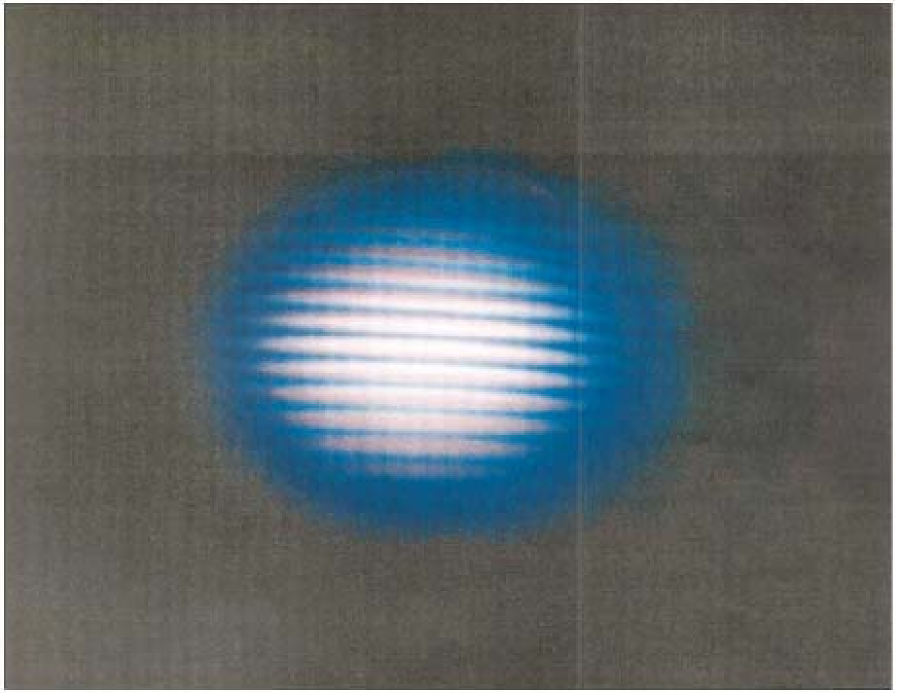


Fig. 2. White-light fringes resulting from the interference of the two continua generated by the two phase-locked IR laser pulses when the relative delay is properly adjusted to zero.

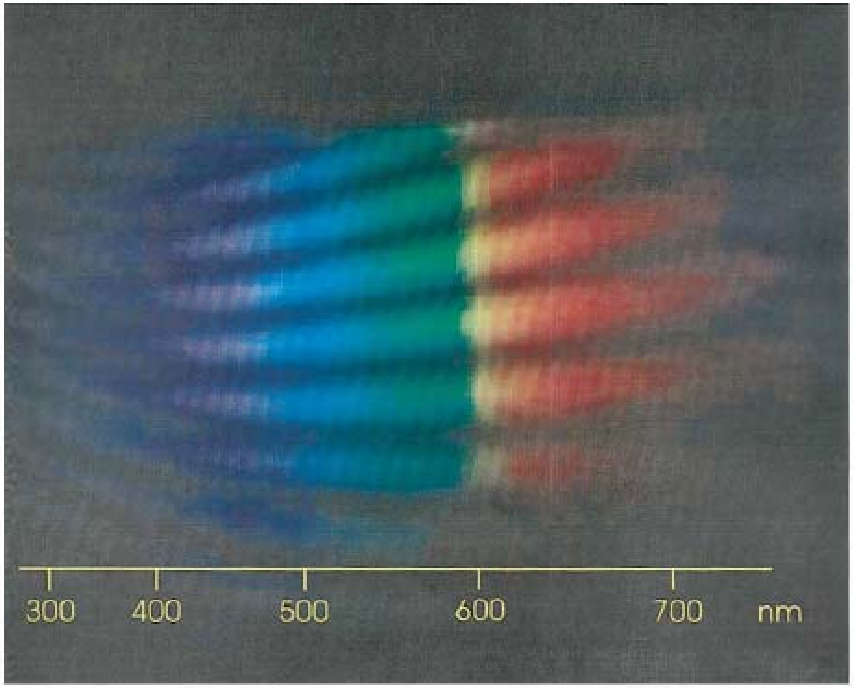
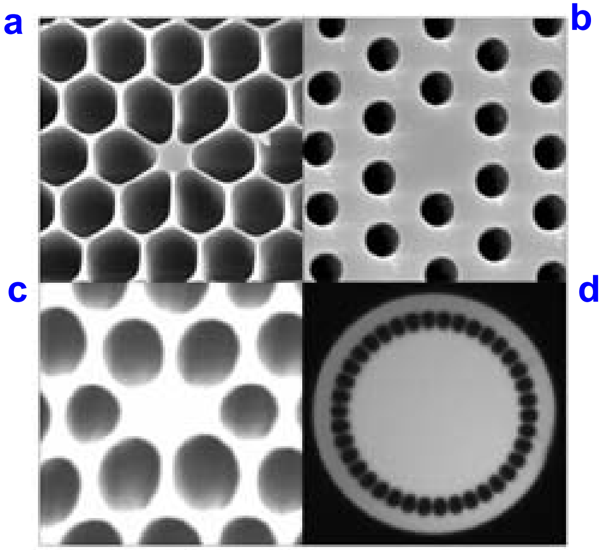


Fig. 3. Spectrally dispersed white-light fringes. Clear and well-defined fringes indicate that a stable phase relationship is conserved across all the generated visible spectrum.

Interference fringes of carrier phase-locked white light continua generated from a Ti:Sapphire laser.

M. Bellini, T Hansch, Optics Letters, **25** (14), p.1049, (2000).

Photonics Trend: Custom Optical Media

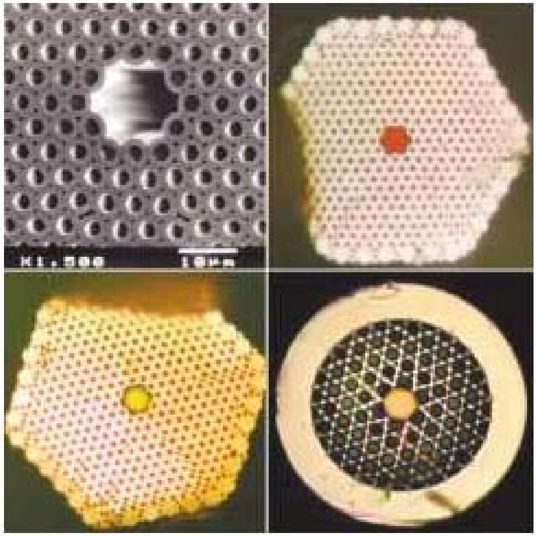


PCF structures vary according to application: (a) highly nonlinear fiber; (b) endlessly single-mode fiber; (c) polarization maintaining fiber; (d) high NA fiber. From René Engel Kristiansen (Crystal Fibre A/S), “Guiding Light with Holey Fibers,” *OE Magazine* June 2002, 25.

- Photonic Crystals allow for tailoring optical properties to specific applications:
  - Nonlinearity: Spectroscopy, wavelength conversion in telecom
  - Dispersion: Telecom signal processing
  - Large mode area: High power applications such as lithography and materials processing
- Custom optics require manufacturing techniques that can meet tight tolerances

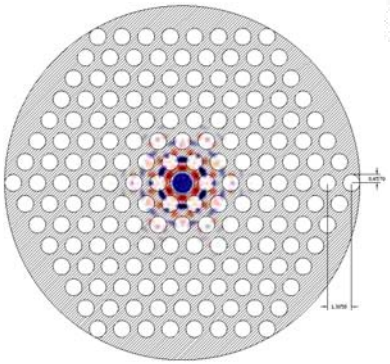
Laser Accelerator Microstructures

Photonic waveguides are the subject of intensive research, and can be designed to propagate only the accelerating mode.



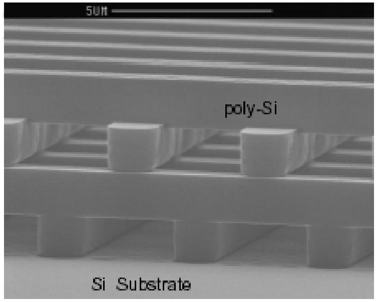
A scanning electron micrograph of guiding hollow-core PCF with core diameter 15 ?m (top left); guided colors are seen in the core when white light was launched into two fibers of slightly different sizes (top right and bottom left); practical recent hollow-core PCF has solid outer cladding (bottom right).

P. Russell, "Holey fiber concept spawns optical-fiber renaissance", *Laser Focus World,* Sept. 2002, p. 77-82.

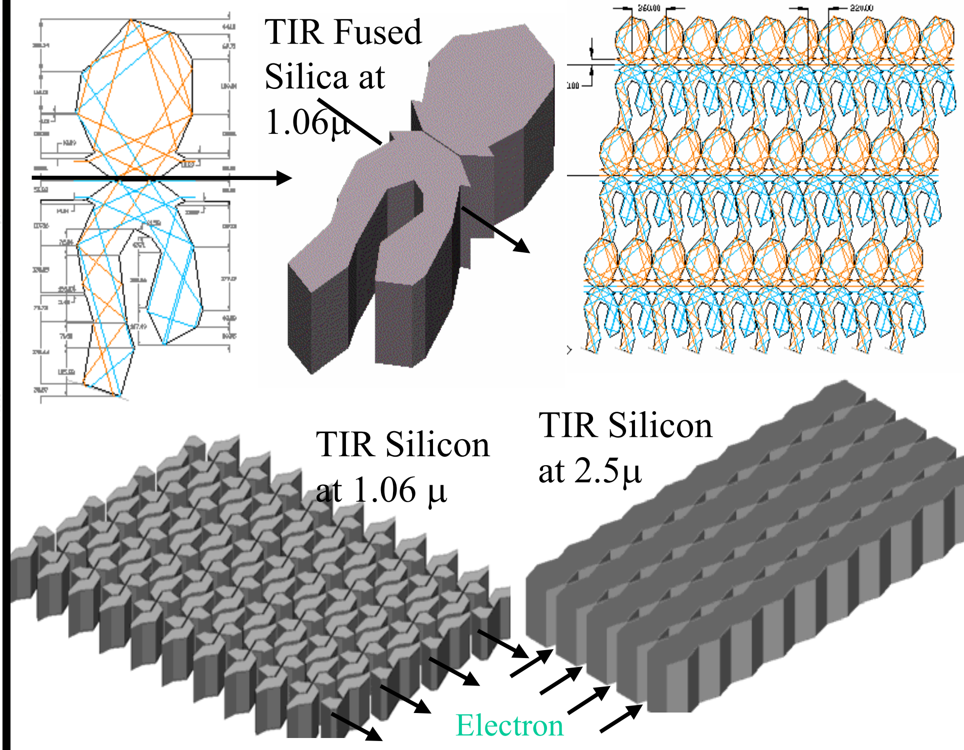


X. Lin, Phys. Rev. ST-AB, **4**, 051301, (2001).

Semiconductor lithography is capable of highly accurate, complex structure production in materials with good damage resistance and at low cost.

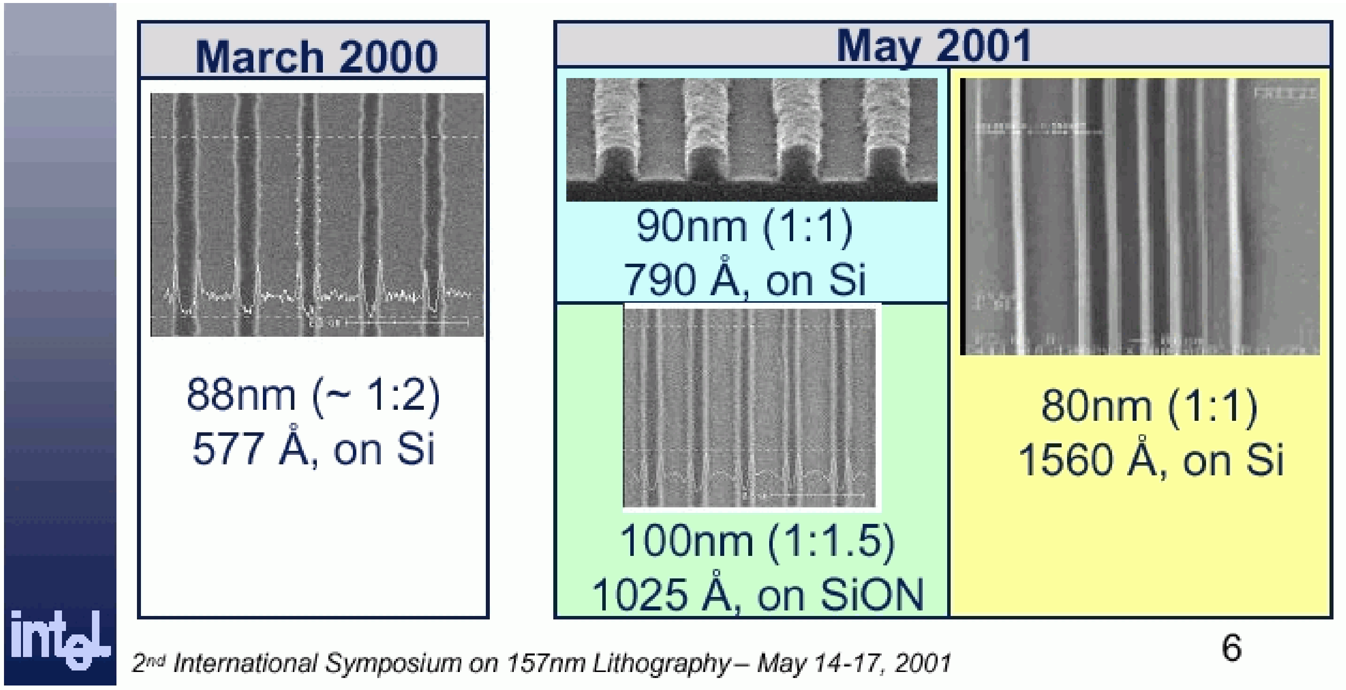


S. Y. Lin *et. al.*, Nature **394**, 251 (1998)



Fabrication Trend: Small Feature Size

- The integrated circuit industry drives development of ever-smaller feature size capability and tolerance
  - DUV, X-ray and e-beam lithography
  - High-aspect-ratio etching using high-density plasma systems
  - Critical Feature size control → 0.5 nm (λ/200) RMS by 2010 ('01 ITRS)



March 2000

88nm (~ 1:2)
577 Å, on Si

May 2001

90nm (1:1)
790 Å, on Si

100nm (1:1.5)
1025 Å, on SiON

80nm (1:1)
1560 Å, on Si

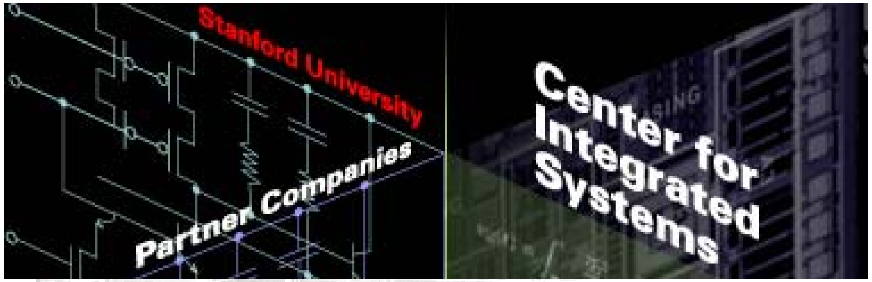
intel

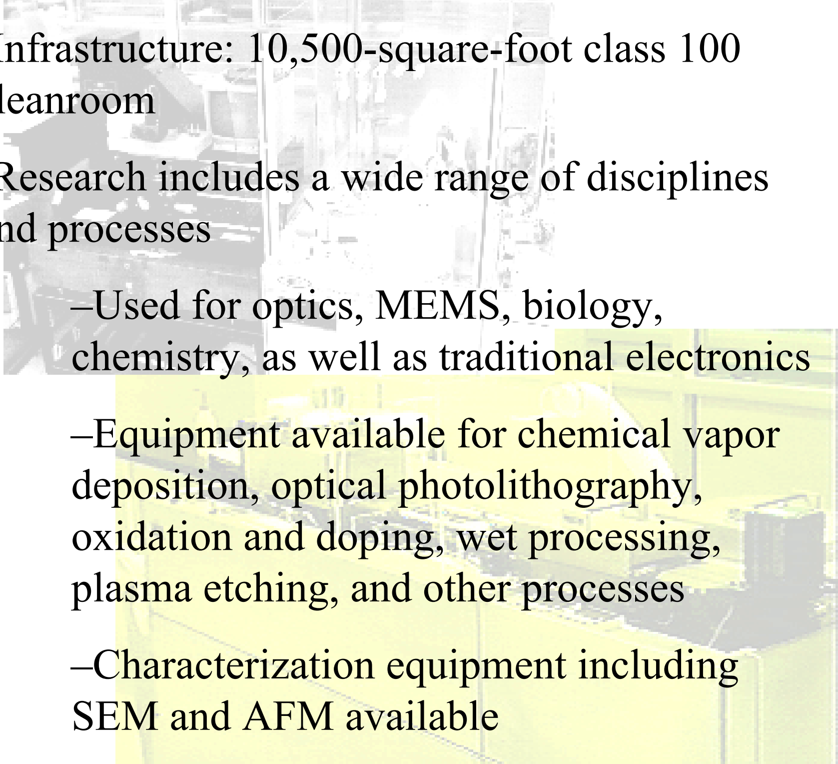
2nd International Symposium on 157nm Lithography – May 14-17, 2001

6

Demonstration of recent progress in lithography

Semiconductor and Advanced Opto-electronics Material Capabilities at Stanford





- Infrastructure: 10,500-square-foot class 100 cleanroom
- Research includes a wide range of disciplines and processes
  - Used for optics, MEMS, biology, chemistry, as well as traditional electronics
  - Equipment available for chemical vapor deposition, optical photolithography, oxidation and doping, wet processing, plasma etching, and other processes
  - Characterization equipment including SEM and AFM available

Stanford Photonics Research Center

incorporating the Center for Novel Optoelectronic Materials (CNOM)

A $60-million dollar 120,000-square-foot photonics laboratory with 20 faculty, 120 doctoral, and 50 postdoctoral researchers, completed in 2004.

Current Research:

Diode Pumped Solid State Lasers

Diode pumped lasers for gravitational wave receivers

Diode pumped Laser Amplfier Studies

Quantum Noise of solid state laser amplifiers

Adaptive Optics for Laser Amplifier beam control

Thermal Modeling of Diode Pumped Nd:YAG lasers

Laser Interferometry for Gravity Wave detection

Sagnac Interferometer for Gravitational Wave Detection

Laser Inteferometer Isolation and Control Studies

Interferometry for Gravitational Wave Detection

Time and Frequency response characteristics of Fabry Perot Int.

GALILEO research program: gravitational wave receivers

Quasiphasematched Nonlinear Devices

Quasi Phasematched $LiNbO_3$ for SHG of diode lasers, cw OPO studies in $LiNbO_3$, and diffusion bonded, GaAs nonlinear materials