11th Advanced Accelerator Concepts Workshop
Stony Brook New York, June 22nd, 2004

Solid-State Laser Technology

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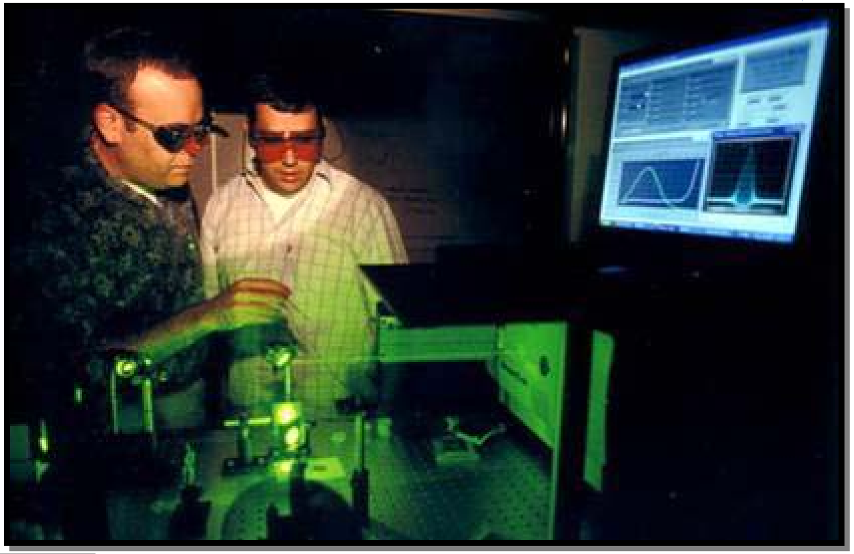
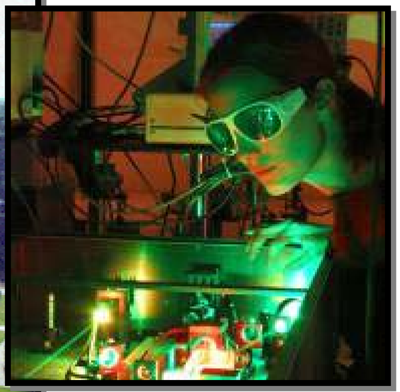
UCF College of Optics & Photonics/CREOL-FPCE





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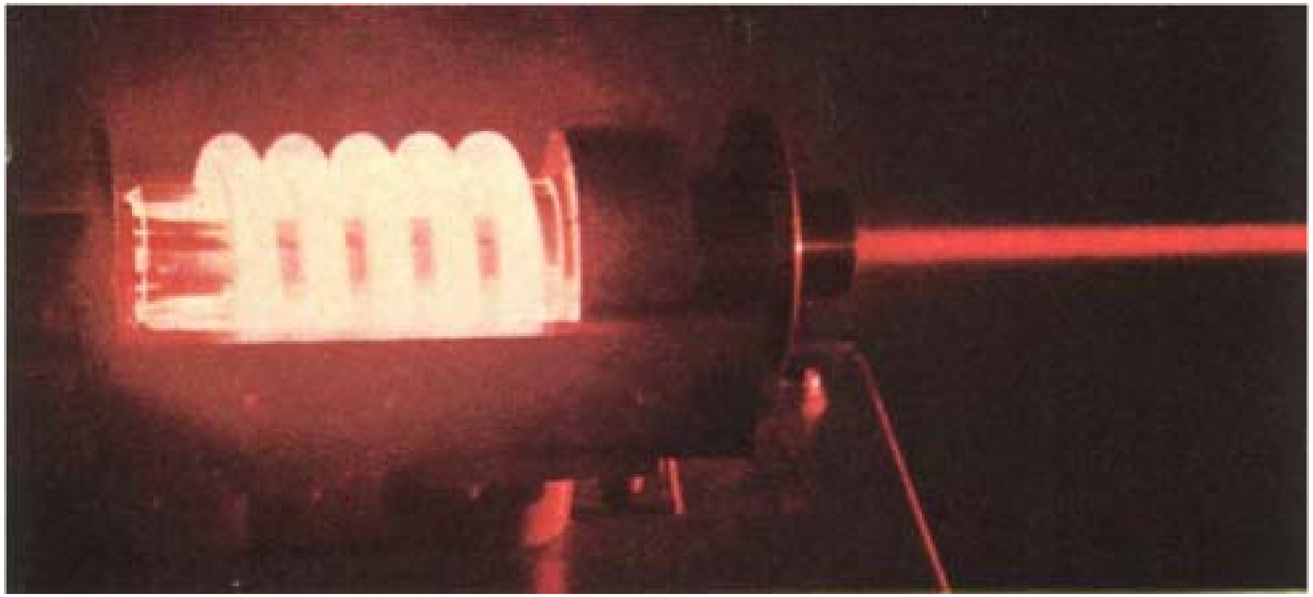
Historical Introduction

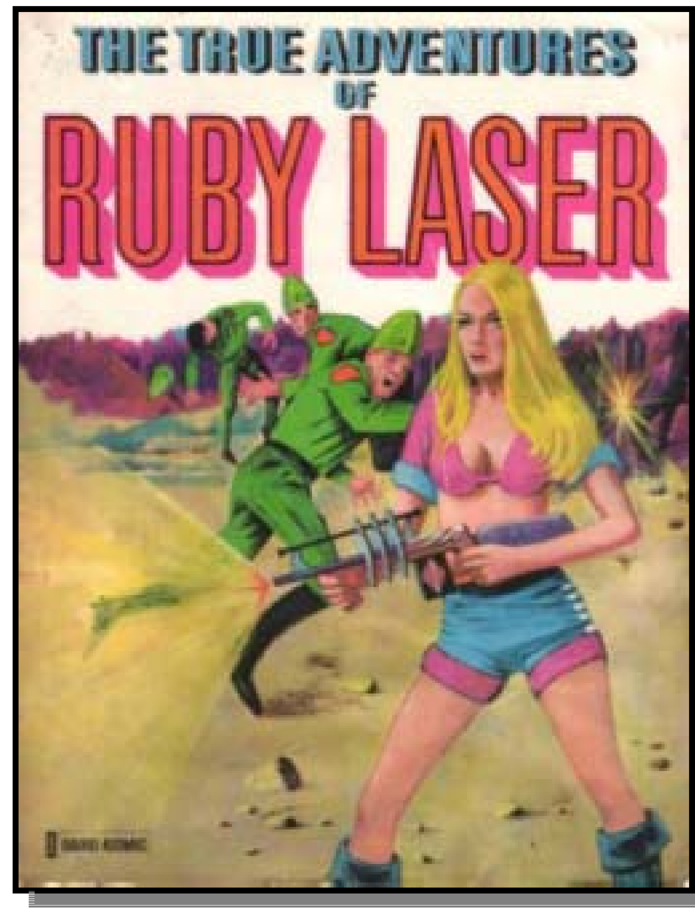
History: The Golden Age of Lasers



May 17, 1960: The Beginning. Ted Maiman's Ruby Laser.
Nature **187**, *493* (August 6, 1960).

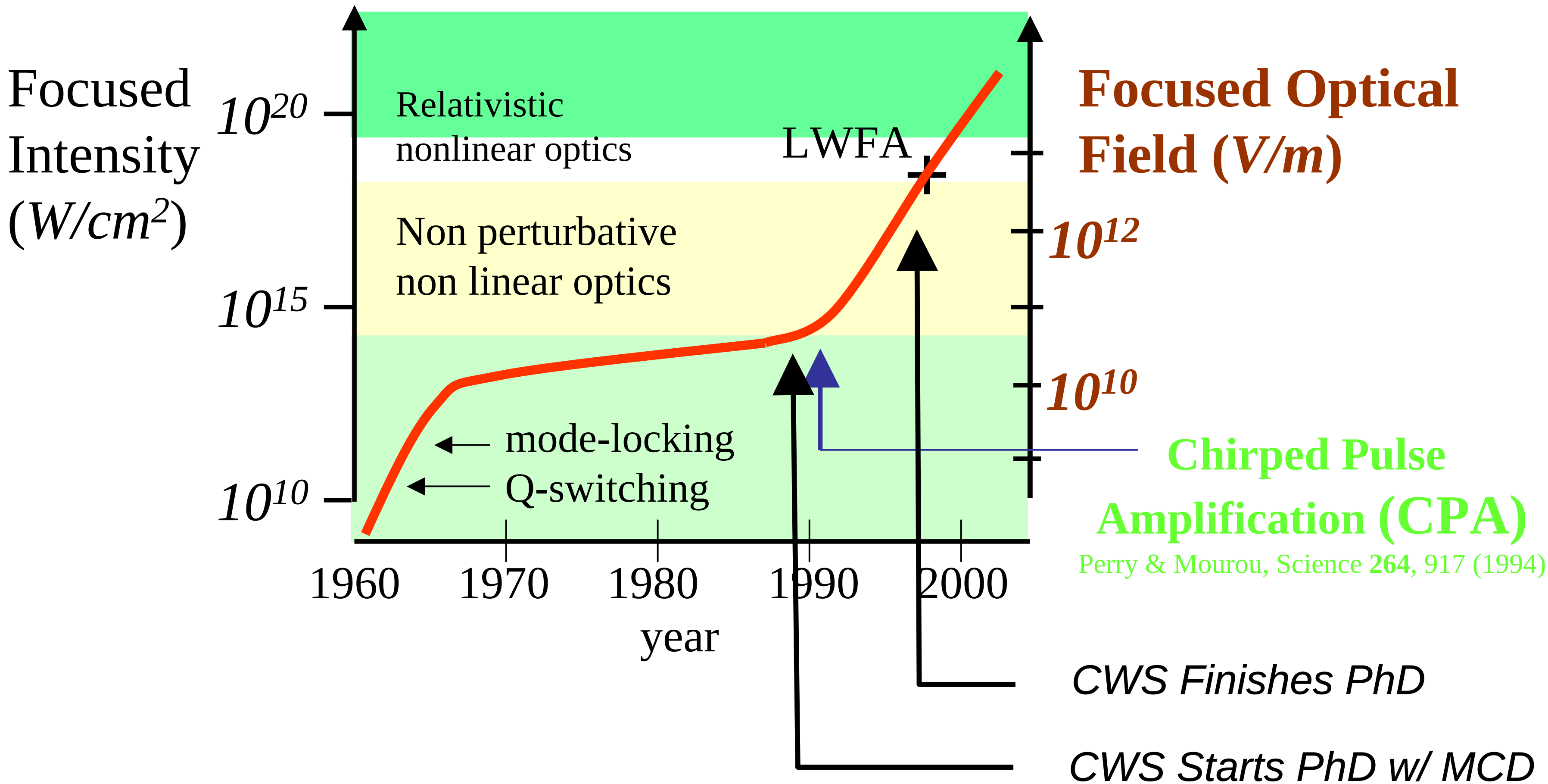
- Nd:glass optical fiber laser: Snitzer, PRL **7**, *444*(1961).
- Q-Switched Laser: Hellwarth, Bull. Am. Phys. Soc. **6**, *414* (1961).
- GaAs laser diode: GE, IBM, Lincoln Labs,1962.
- Modelocking, 1963.
- Nd:YAG laser, 1964.

Early SSL Applications



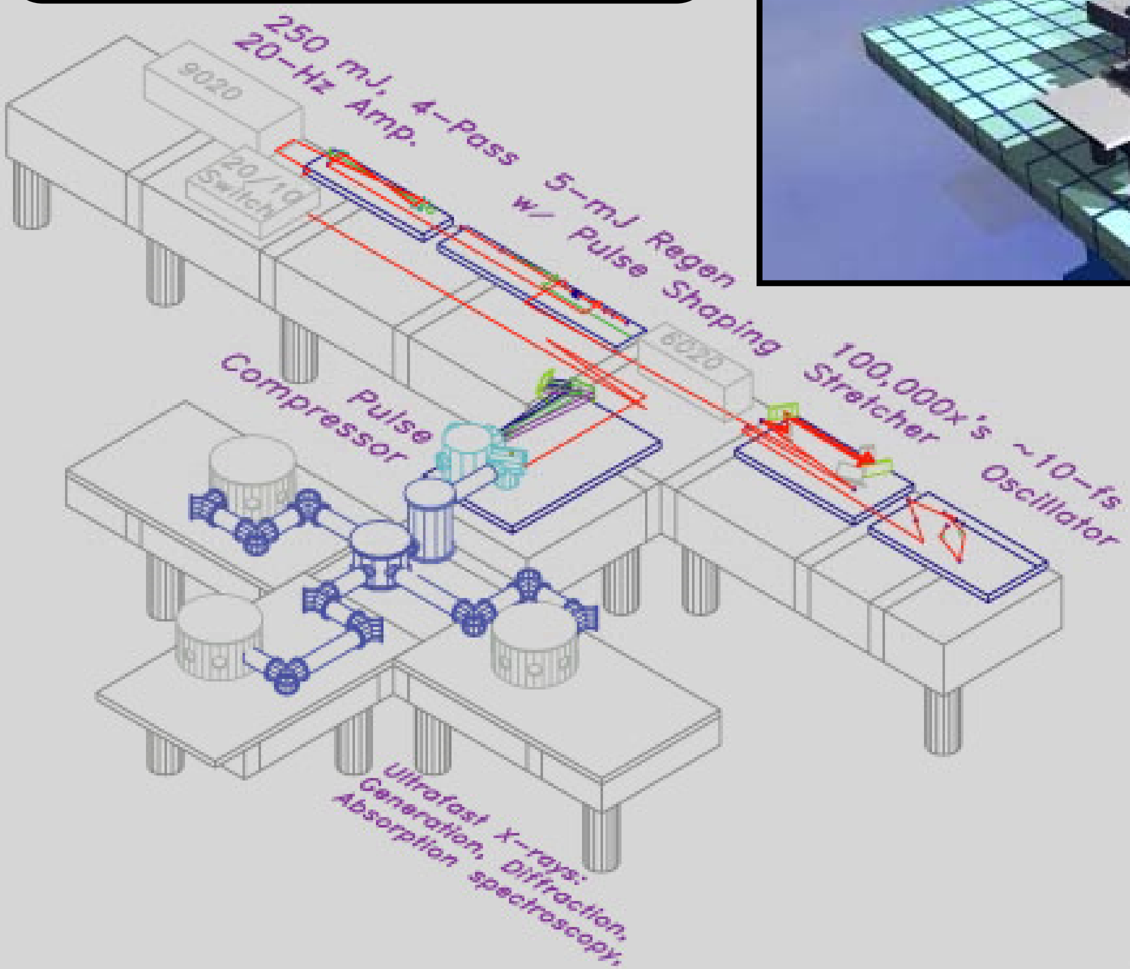
Compliments A. Siegman

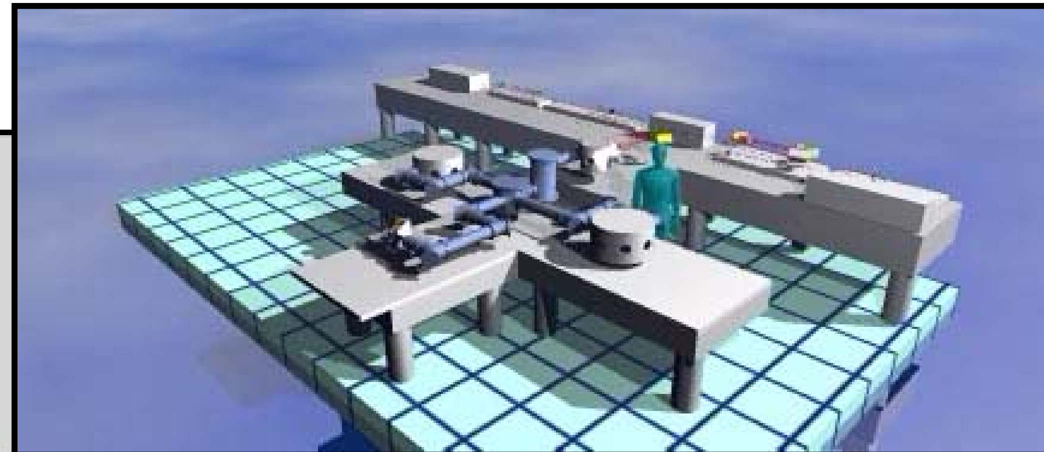
New materials, techniques provide unprecedented laser intensities ...



Chirped Pulse Amplified Laser System

UCSD 20-Hz, 20-fs 5-TW Laser System

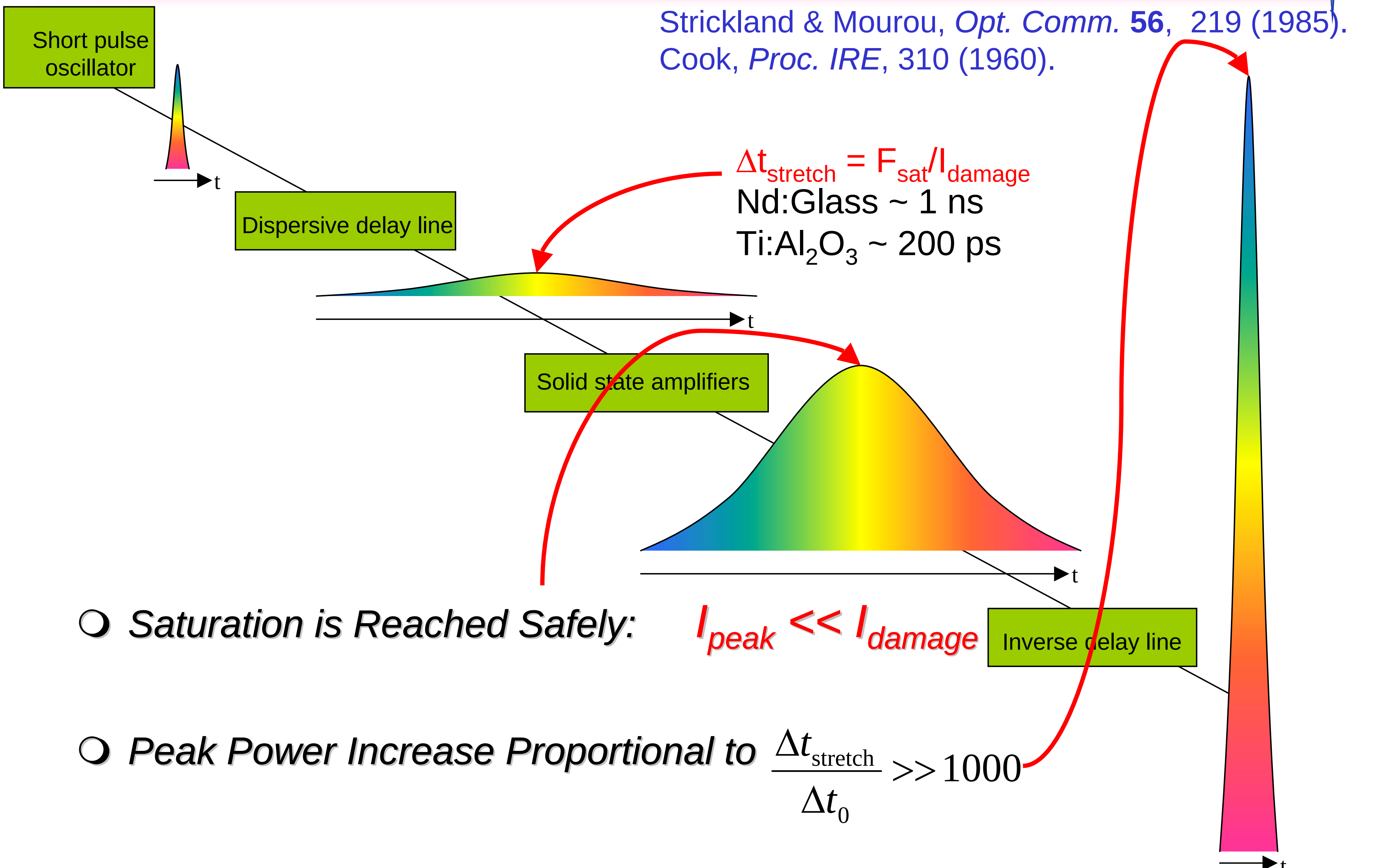




- *Compact*
- *Ultrafast – 20 fs*
- *Ti:Sapphire*
- *Synchronous Pump & Probe*
- *100 mJ @ 20 Hz*

Chirped Pulse Amplification

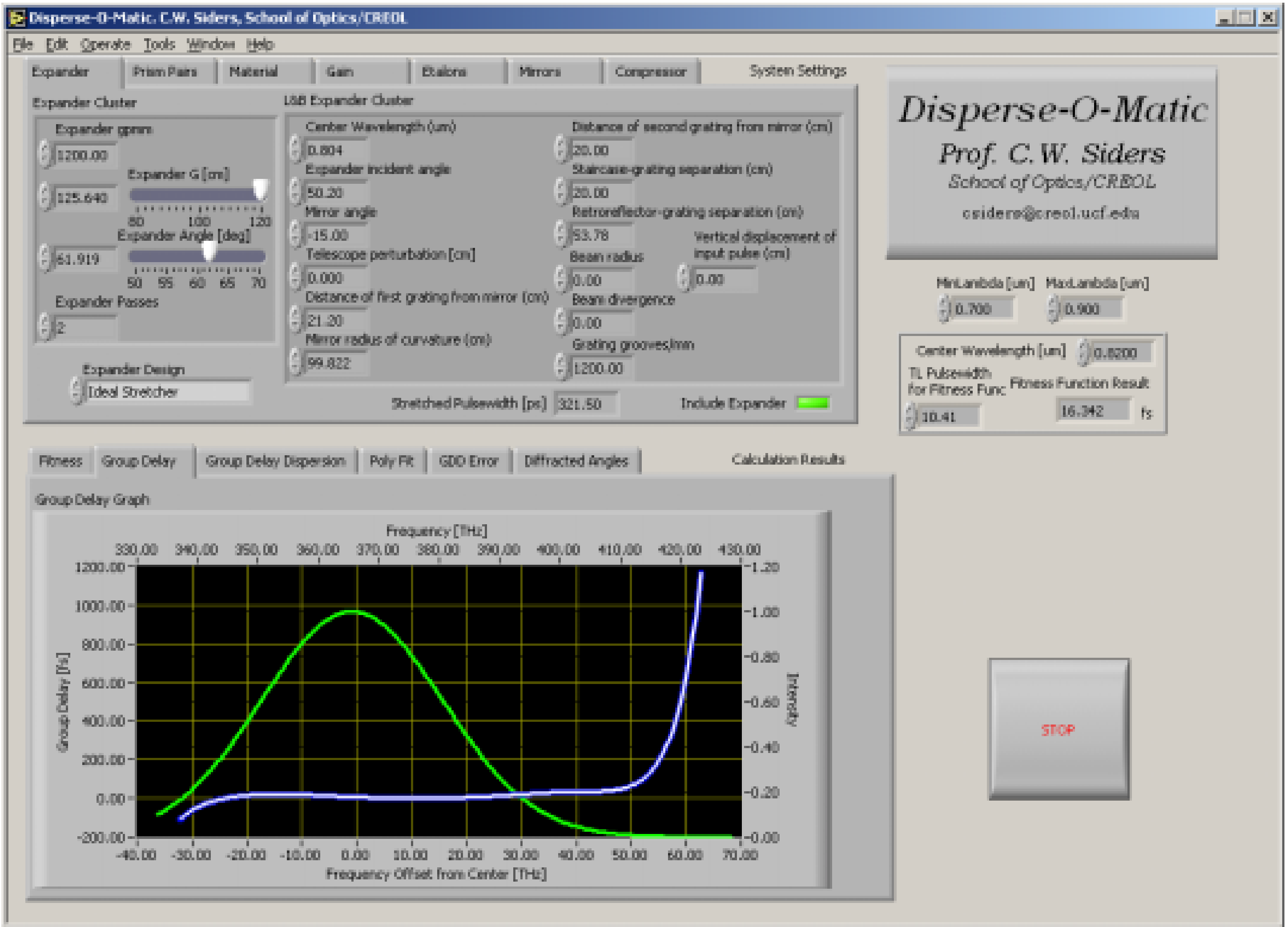
Strickland & Mourou, *Opt. Comm.* **56**, 219 (1985).
Cook, *Proc. IRE*, 310 (1960).



- *Saturation is Reached Safely:* $I_{peak} \ll I_{damage}$
- *Peak Power Increase Proportional to* $\dfrac{\Delta t_{stretch}}{\Delta t_0} \gg 1000$

Disperse-O-Matic Freeware

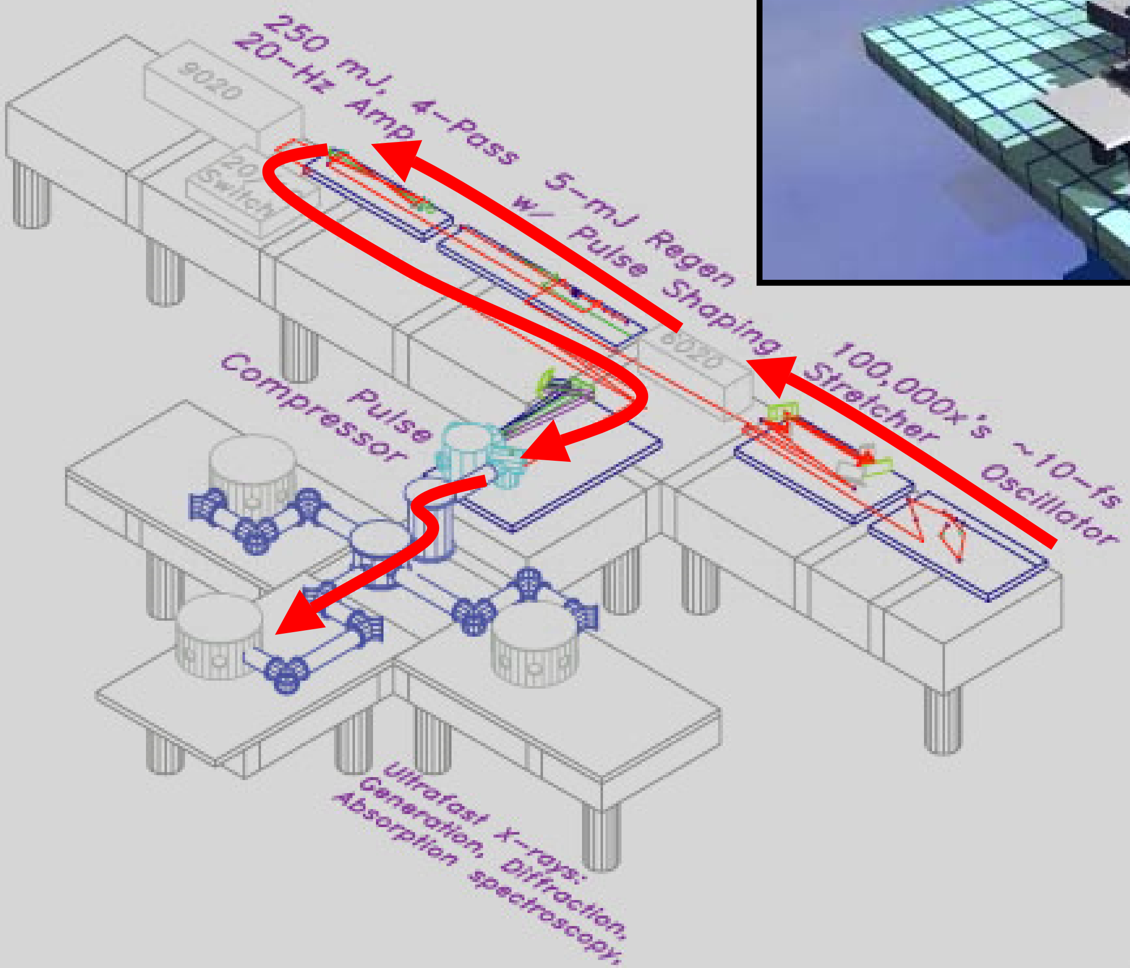
(WARNING: Shameless Self-Promotion)

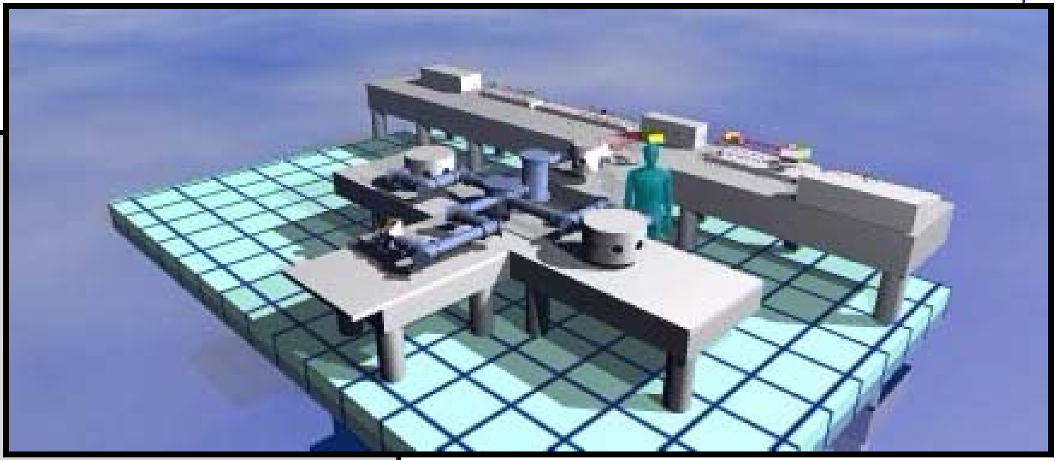


http://dom.creol.ucf.edu/ *http://www.creol.ucf.edu/reu/*

Chirped Pulse Amplified Laser System

UCSD 20-Hz, 20-fs 5-TW Laser System

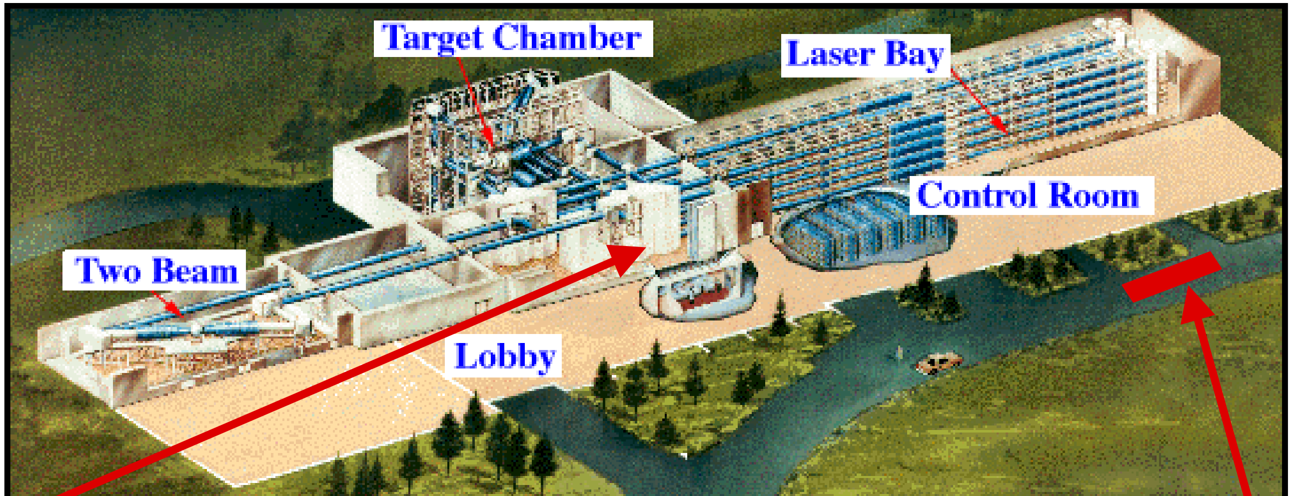




- *Ti:Sapphire*
- *800-nm*
- *100-mJ / pulse*
- *Excellent focusing*
- *10^{18} W/cm^2*

Ultrafast CPA Characteristics

Compactness and high repetition rate



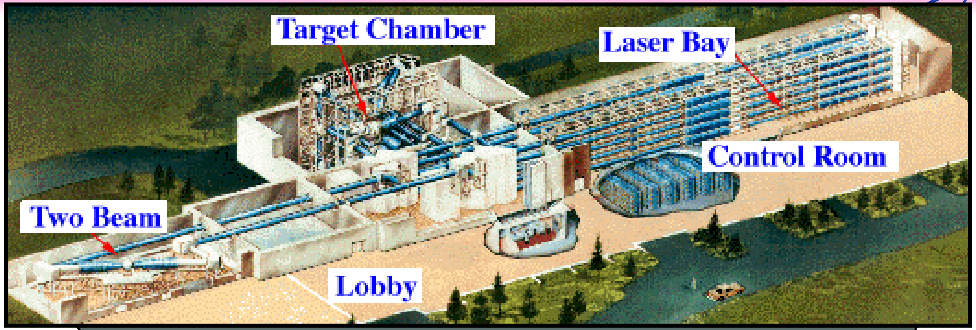
Nova
Pulse duration 1 ns
10 kJ/beam
10 TW/beam
1 shot/hour

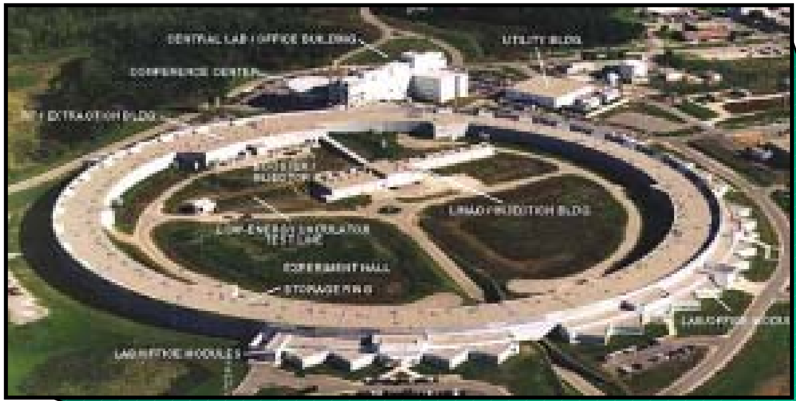
Ultrafast CPA System
Pulse duration 20 fs
100 mJ/beam
5 TW/pulse
72,000 shots/hour

Ultrafast CPA systems allow high experimental "Utility"

- **Signal averaging even at extreme intensities**
- **High average flux of laser-generated x-rays, particles**

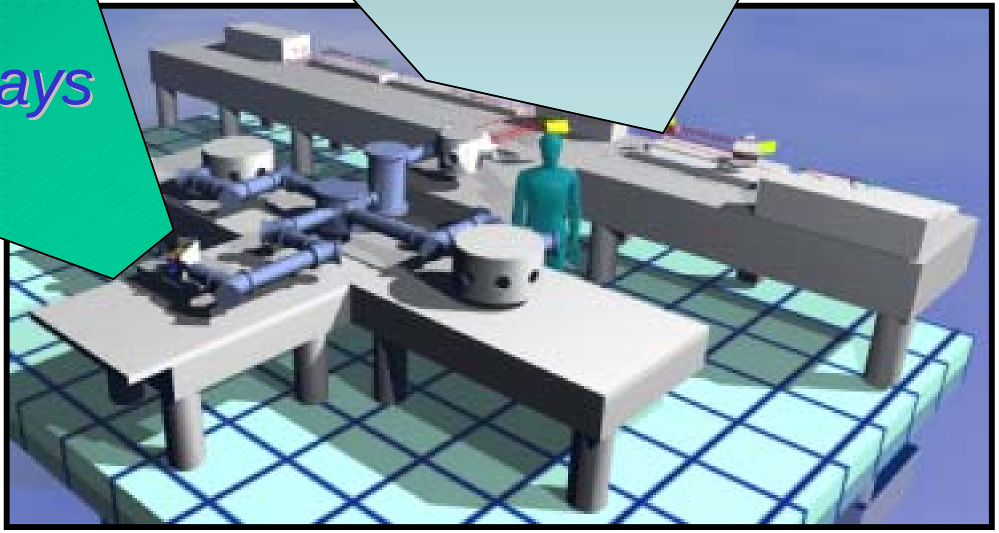
Big Science in the Small Laboratory





High-field
High-rep-rate
Ultrafast lasers

High-flux
~10-keV x-rays



Even Bigger Science in the Big Lab

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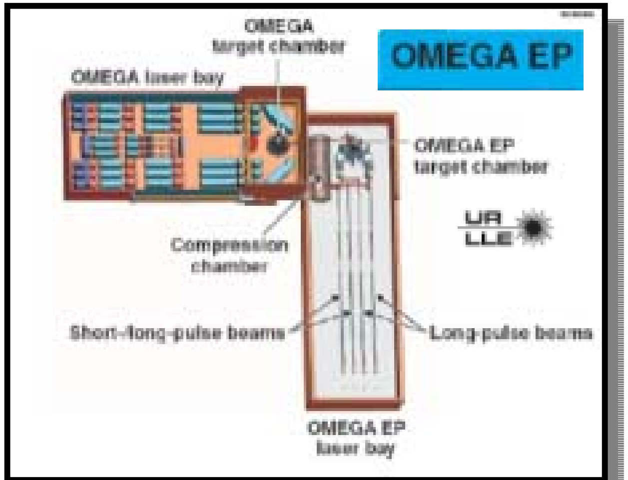
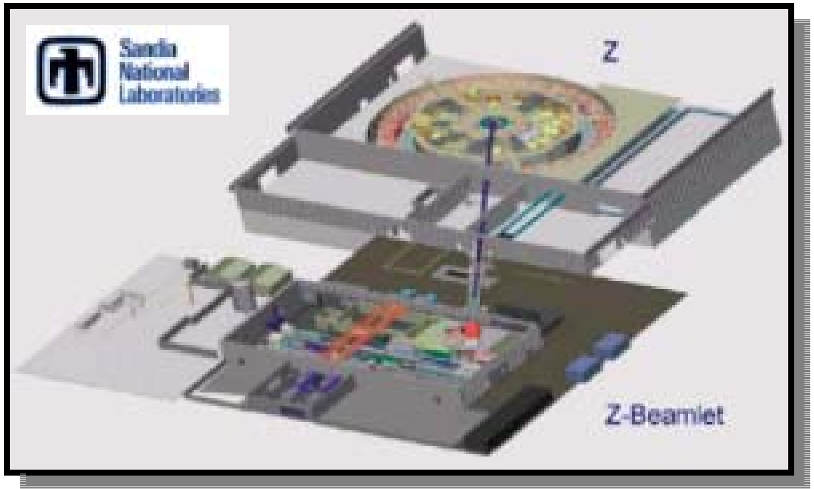
JAERI Petawatt



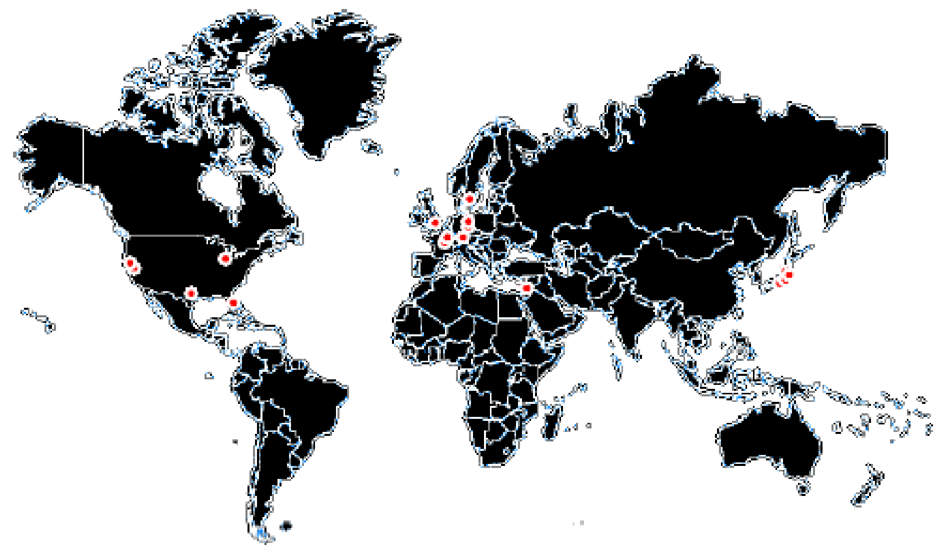


SAUUL Report: >10TW Facilities

Representative list of short pulse laser facilities above 10 TW currently operating world wide

Facility	*Peak Power*	*Type*	*Pulse duration*	*Pulse Energy*
RAL, UK	1 PW	Nd:glass/OPCPA	600 fs	600 J
ILE, Japan	700 TW	Nd:glass/OPCPA	700 fs	350 J
JAERI, Japan	100 TW	Ti:sapphire	20 fs	2 J
MBI, Germany	100 TW	Ti:sapphire	50 fs	5 J
LLNL, USA	100 TW	Ti:sapphire	100 fs	10 J
LULI, France	100 TW	Nd:glass	300 fs	30 J
LOA, France	100 TW	Ti:sapphire	25 fs	2.5 J
ILE, Japan	60 TW	Nd:glass	500 fs	30 J
LLE, Rochester	30 TW	Nd:glass	1 ns	30 kJ
Lund, Sweden	25 TW	Ti:sapphire	35 fs	1.2 J
CUOS, USA	25 TW	Ti:sapphire	30 fs	1 J
Texas, USA	18 TW	Ti:sapphire	40 fs	0.7 J
Jena, Germany	17 TW	Ti:sapphire	60 fs	1 J
Ibaraki, Japan	13 TW	Ti:sapphire	50 fs	0.6 J
CREOL, USA	13 TW	Cr:LiSAF	75 fs	1 J
CUOS, USA	10 TW	Nd:glass	400 fs	4 J
NRL, USA	10 TW	Nd:glass	500 fs	5 J
ILE, Japan	10 TW	Ti:sapphire	100 fs	1 J
LBNL, USA	10 TW	Ti:sapphire	45 fs	0.5 J
RAL, UK	10 TW	Ti:sapphire	50 fs	0.5 J
Soreq, Israel	10 TW	Ti:sapphire	45 fs	0.45 J
Garching, Germany	10 TW	Ti:sapphire	100 fs	1 J

Map of short pulse laser facilities above 10 TW world wide

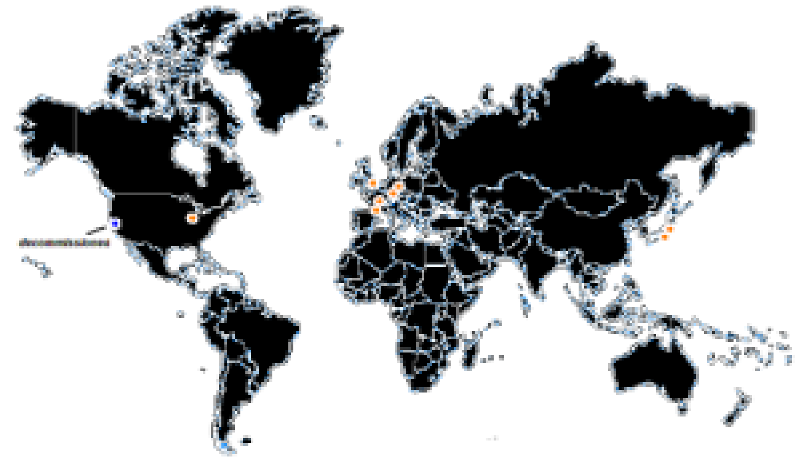


SAUUL Report: PW Facilities

Petawatt laser facilities completed or currently under construction

Facility	Design Peak Power	Type	Pulse duration	Pulse Energy	Status
LLNL, USA	1.25 PW	Nd:glass	400 fs	500 J	Decommissioned
RAL, UK	1 PW	Nd:glass/OPCPA	600 fs	600 J	Operating
ILE, Japan	1 PW	Nd:glass/OPCPA	700 fs	700 J	Operating @ 700 TW
JAERI, Japan	1 PW	Ti:sapphire	20 fs	20 J	Under construction
LULI, France	1 PW	Nd:glass	300 fs	300 J	Under construction
Sandia, USA	1 PW	Nd:glass	500 fs	500 J	Under construction
CELIA+CESTA, France	2 PW	Nd:glass	500 fs	1000 J	Under construction
Jena, Germany	1 PW	Yb:glass	150 fs	150 J	Under construction
GSI, Germany	1 PW	Nd:glass	400 fs	400 J	Under construction
FOCUS Center, USA	1 PW	Ti:sapphire	25 fs	25 J	Under construction
UT Austin	1PW	Nd:glass	160fs	130J	Under Construction

Map of Petawatt laser facilities operating or currently under construction world wide



What We Care About

$$a_0 = \frac{v_{\mathrm{osc}}}{c} \approx 1$$ or $$I \approx 10^{18}\,\mathrm{W/cm^2}$$

Parameter	5 TeV LWFA	NLC γ-γ	Solid St.		CO_2	Units
λ	1–10	1	0.8	1.06	10	μm
E	1	1	0.1	20	15	J
τ	100	1000	20	1000	3000	fs
P_{peak}	10	1	5	20	5	TW
f_{rep}	60	15	50×10^{-3}	10^{-5}	10^{-4}	kHz
P_{avg}	60	15	5×10^{-3}	2×10^{-4}	1.5×10^{-3}	kW
$\eta_{\mathrm{wall-plug}}$	0.1	—	$< 10^{-4}$	$< 10^{-4}$	~ 0.01	

Table 1: Laser Requirements for a 500 stage, 5 TeV LWFA and NLC-based γ-γ collider (85 bunches/macropulse at 180 Hz macropulse rate) and current state of the art for solid-state, i.e. Ti:S (0.8 μm, [3, 4]) or Nd:x (1.06μm, [5]), and CO_2 systems [6]. For the NLC γ-γ collider, current efficiencies are adequate since only one laser system is needed.

Laser Sources WG, AACW '96

Pulse Duration

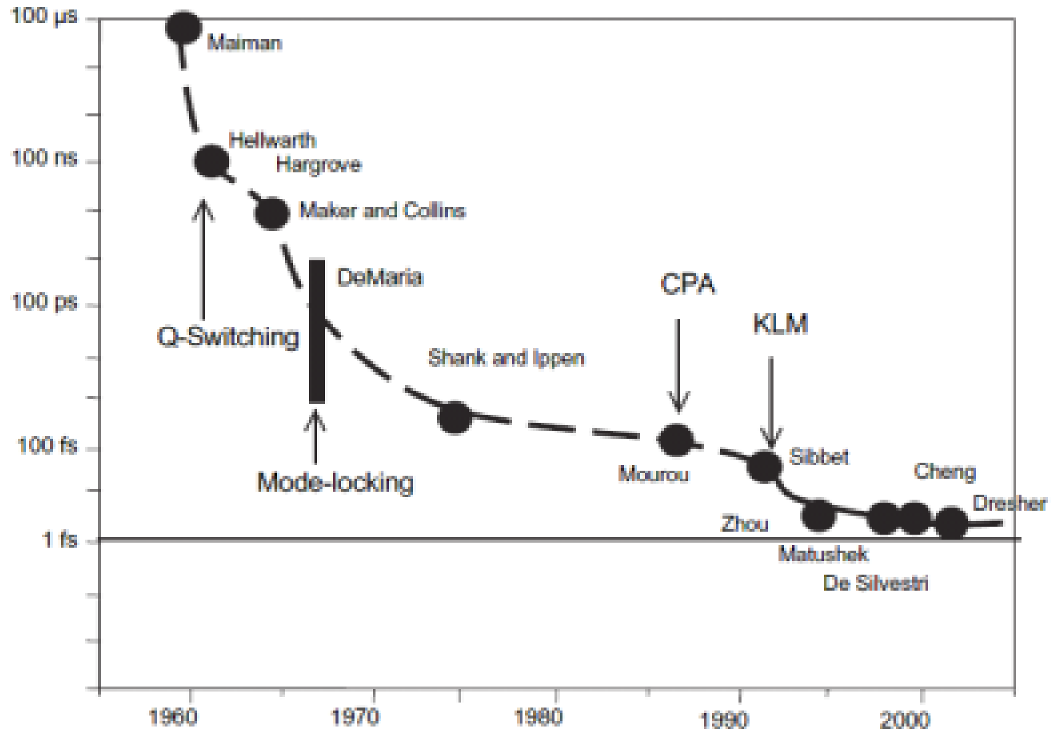


Figure 1. Timeline of the laser pulse length evolution from the free-running laser of Maiman to the recent refinements. A few names and techniques mark the essential steps in this evolution. The existence of a femtosecond barrier is clearly visible on the graph.

Agostini & DiMauro, Rep. Prog. Phys. **67** *813* (2004).

Average Power Challenge

- Traditional USP lasers are limited to watt-level average powers.
- Transitioning of short pulse high-intensity applications require kW-level USP lasers.

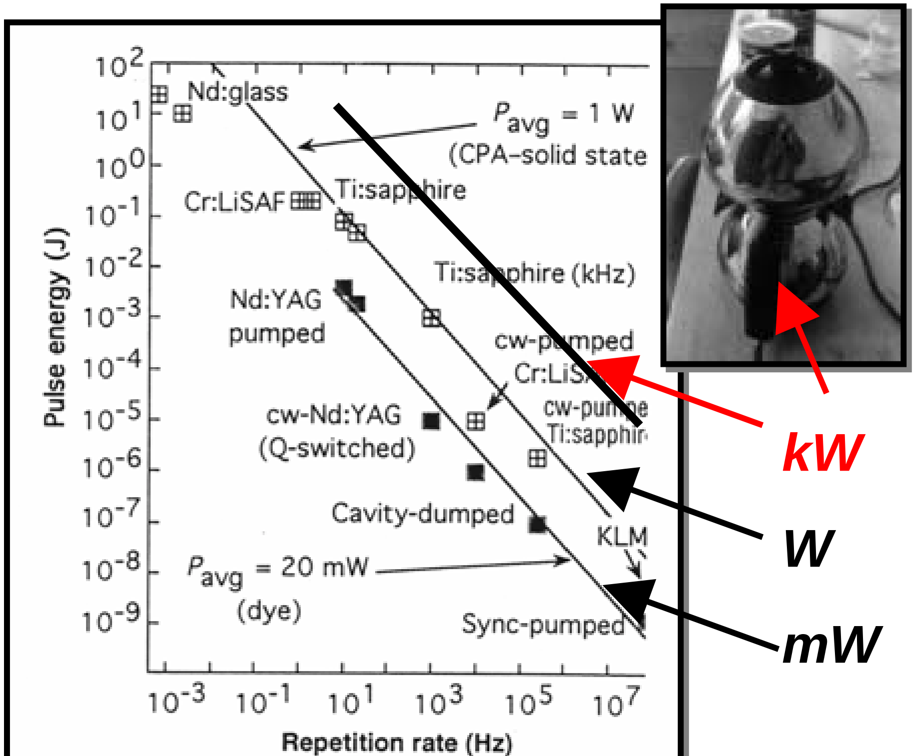
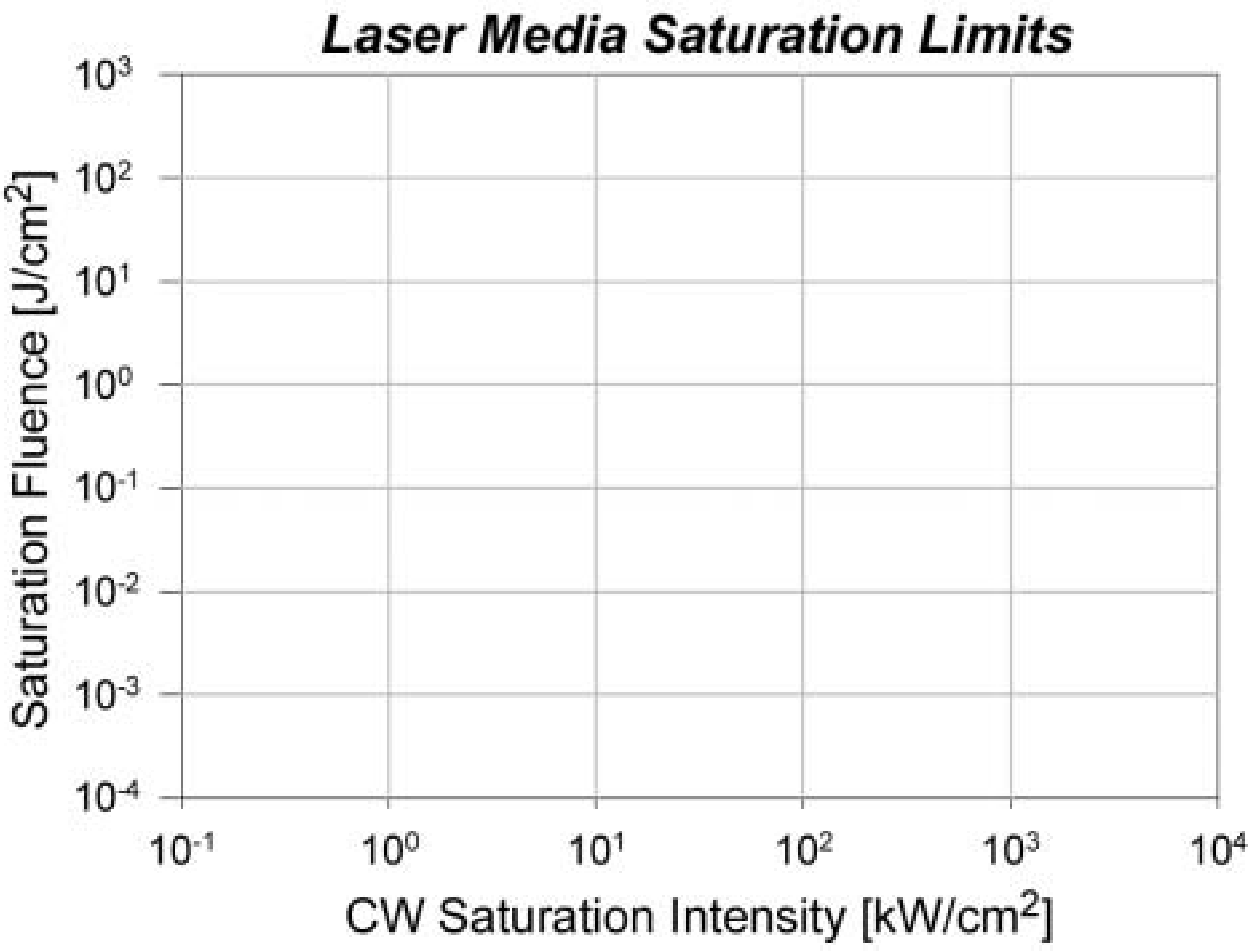
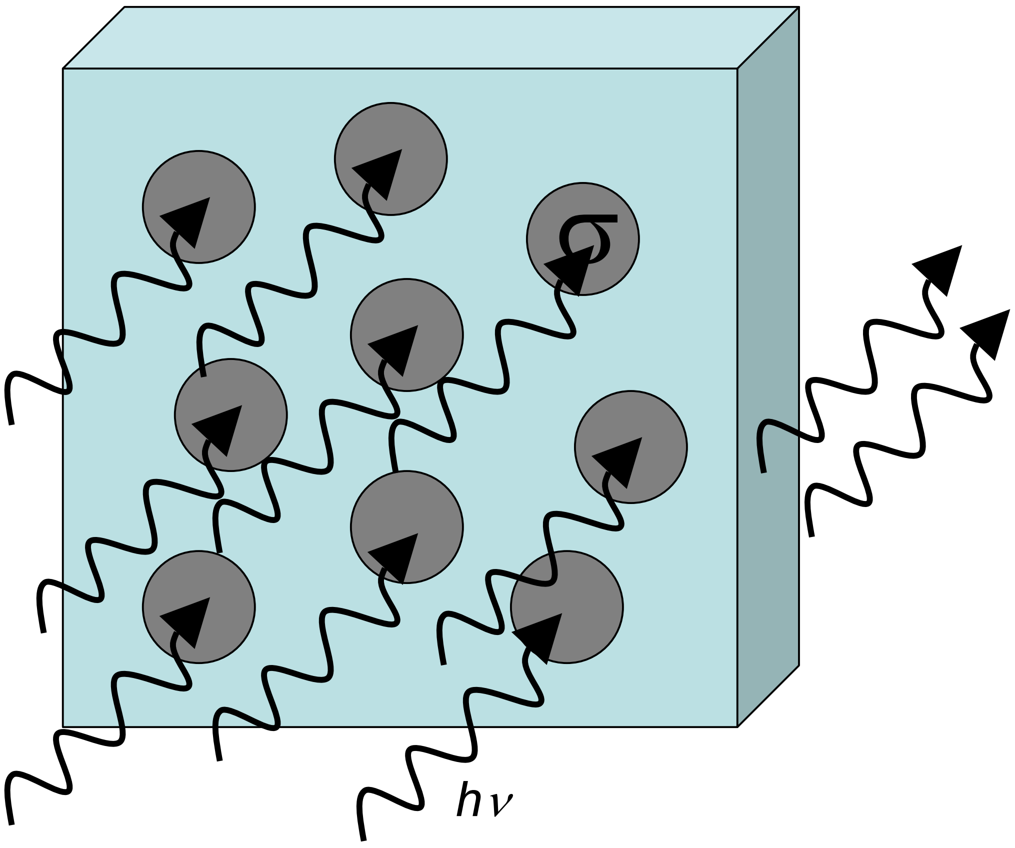


Fig. 2. Current average power (P_{avg}) of femt second lasers (cw, continuous wave; YAG, y trium-aluminum-garnett; KLM, Kerr lens mod locked; Cr:LiSAF, chromium-doped LiSrAlF synch, synchronous).

Efficiency & Saturation Perspective



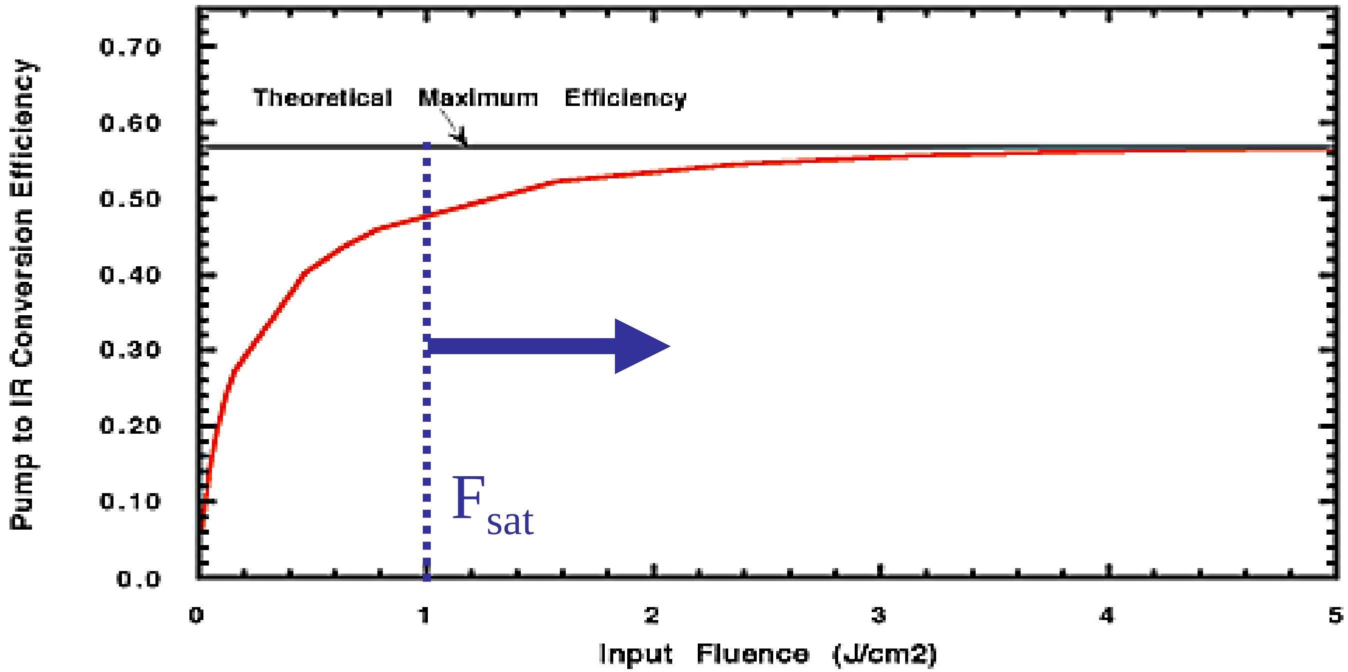
Saturation Fluence



$$F_{sat} = \frac{h\nu}{\sigma}$$

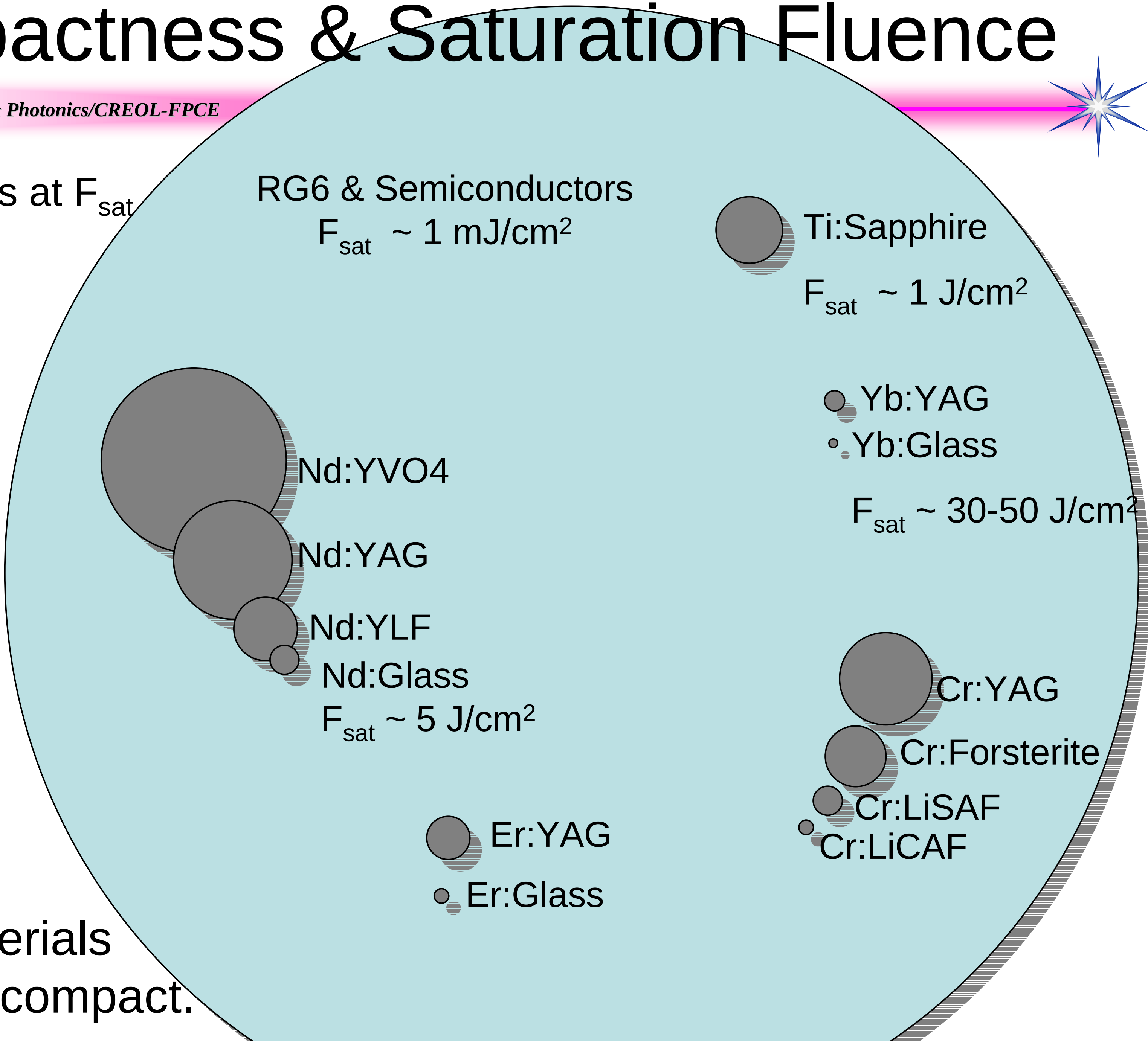
Efficient Solid-State Amplifier

- High Efficiency in Final Amplifier
  - Operate above the saturation fluence



Compactness & Saturation Fluence

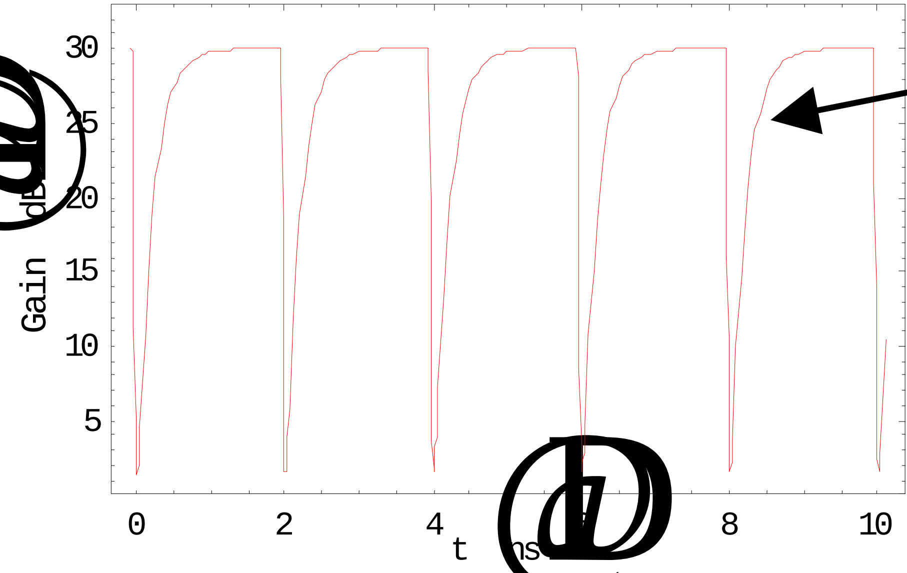
1-J Beam Areas at F_{sat}

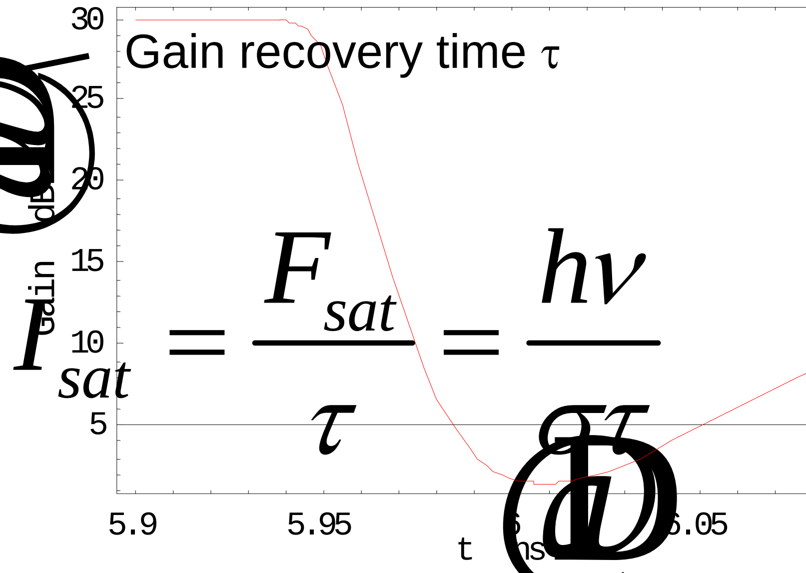


High F_{sat} materials can be more compact.

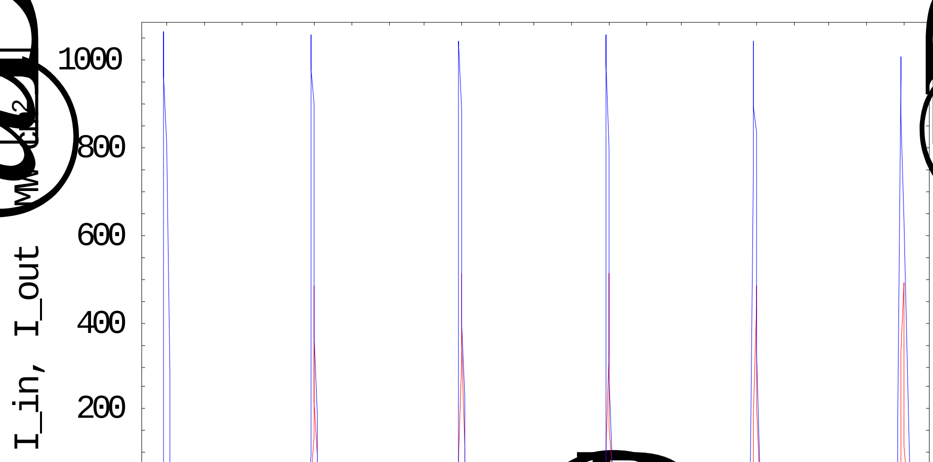
Saturation Intensity

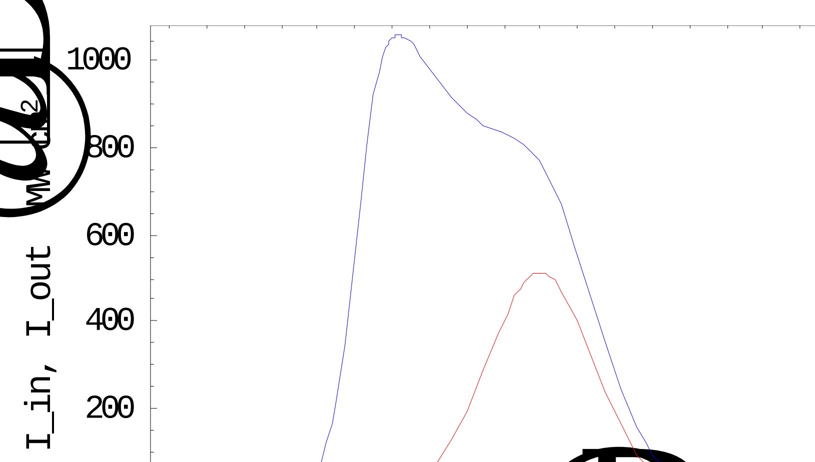
CW-Pumped Pulse Amplifier



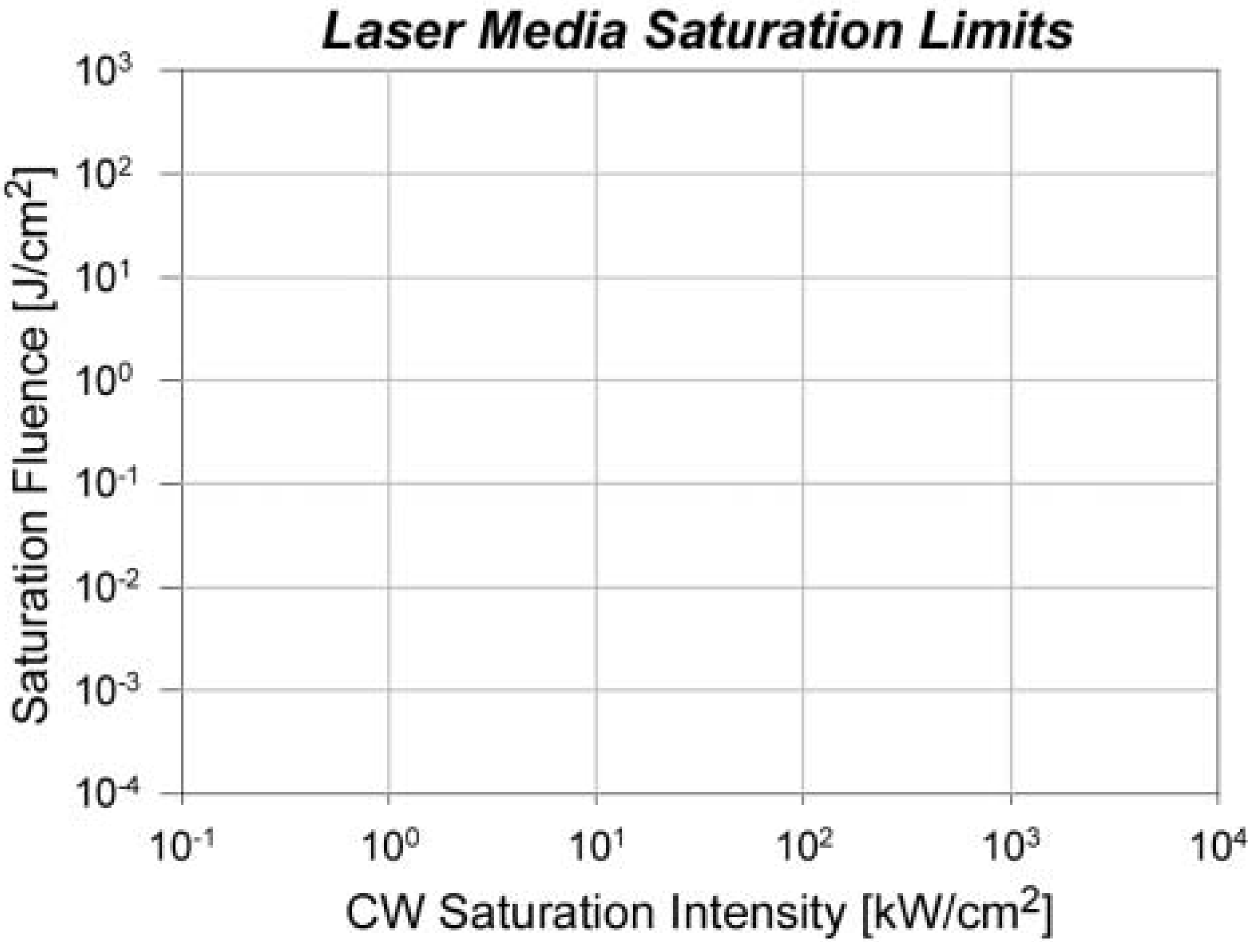


$$I_{sat} = \frac{F_{sat}}{\tau} = \frac{h\nu}{\sigma\tau}$$

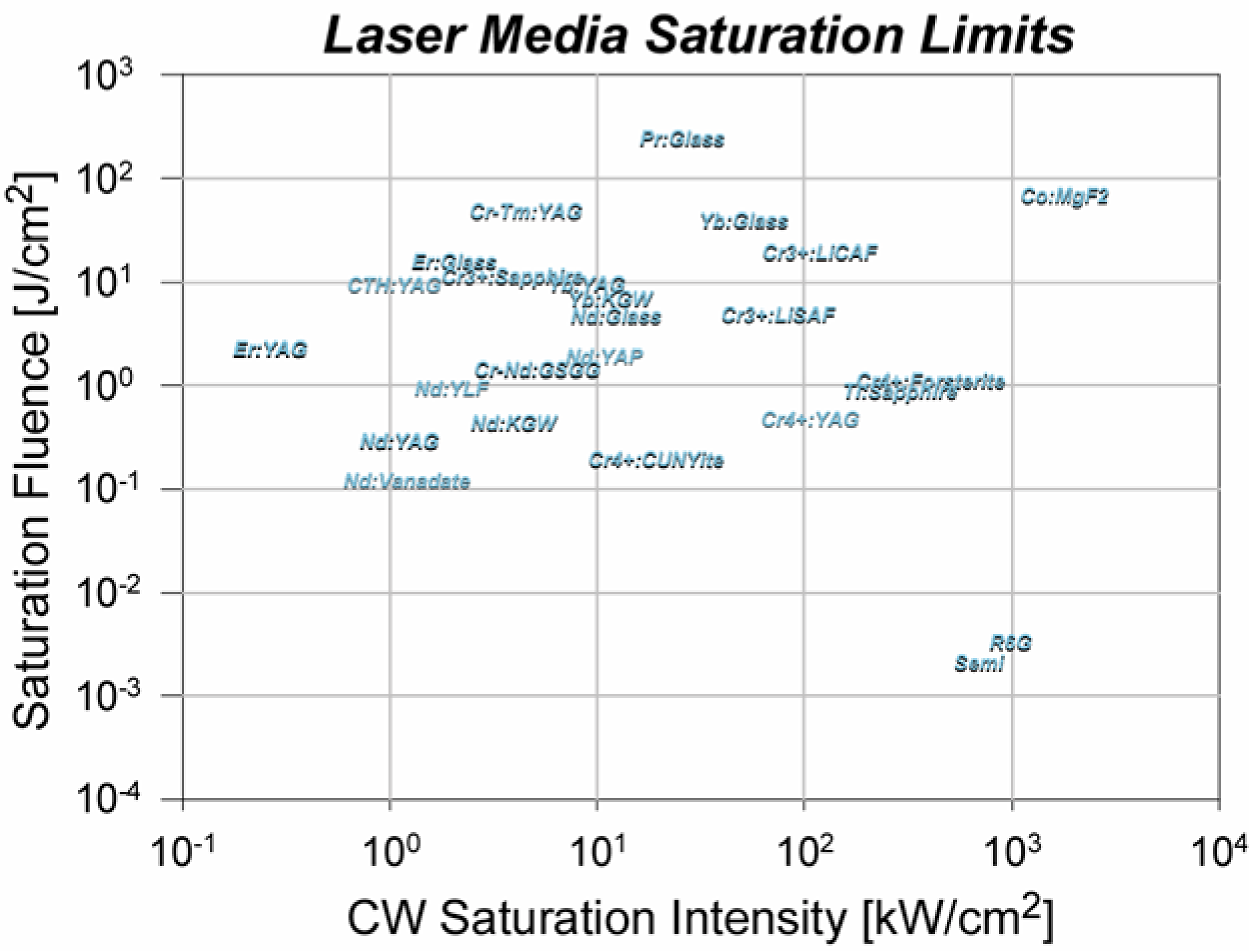




Energy Considerations in USPs



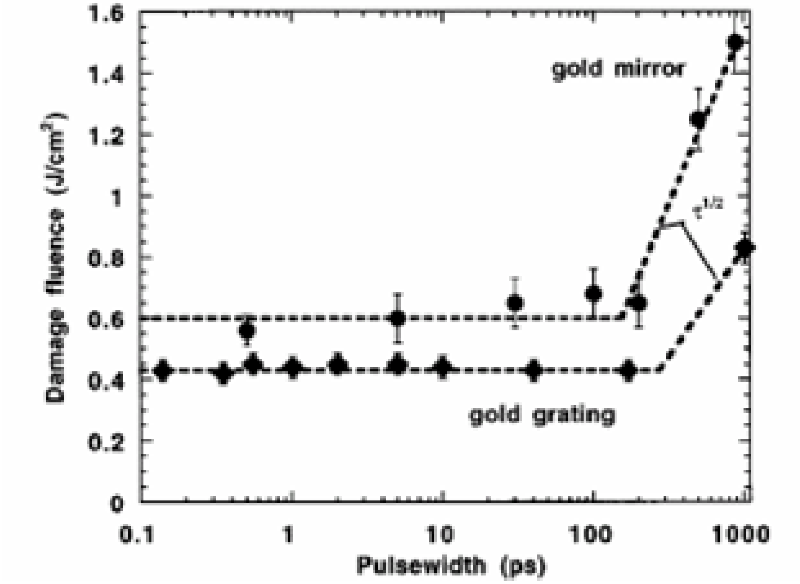
Laser Media


Laser Media Saturation Limits
Saturation Fluence [J/cm2]
CW Saturation Intensity [kW/cm2]
10-4
10-3
10-2
10-1
100
101
102
103
10-1
100
101
102
103
104
Pr:Glass
Co:MgF2
Cr-Tm:YAG
Yb:Glass
Cr3+:LICAF
Er:Glass
CTH:YAG
Cr3+:Sapphire
Yb:YAG
Yb:KGW
Nd:Glass
Cr3+:LISAF
Er:YAG
Nd:YAP
Cr-Nd:GSGG
Nd:YLF
Cr4+:Forsterite
Ti:Sapphire
Cr4+:YAG
Nd:KGW
Nd:YAG
Cr4+:CUNYite
Nd:Vanadate
R6G
Semi

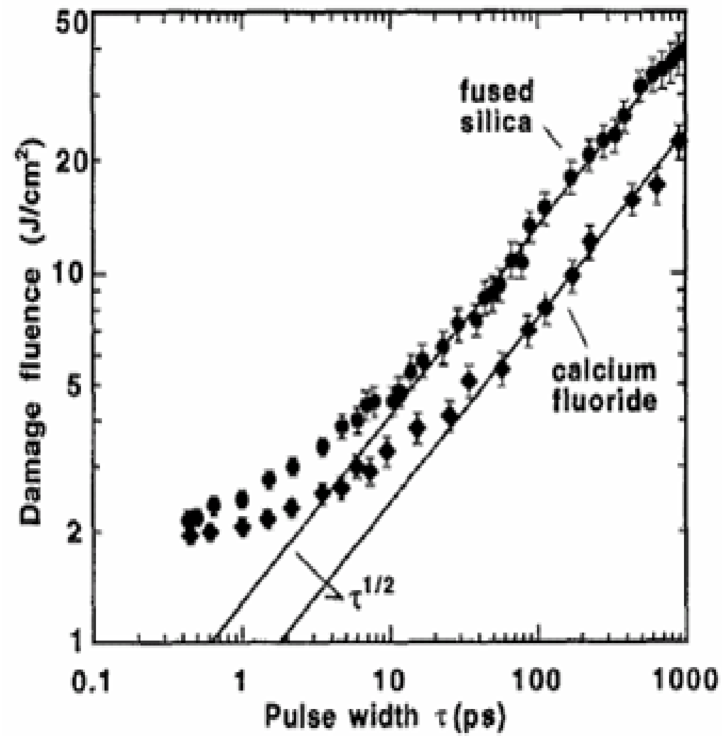
Damage Fluence Limits

Ultrashort-pulse damage thresholds limit usable fluences.

Metals

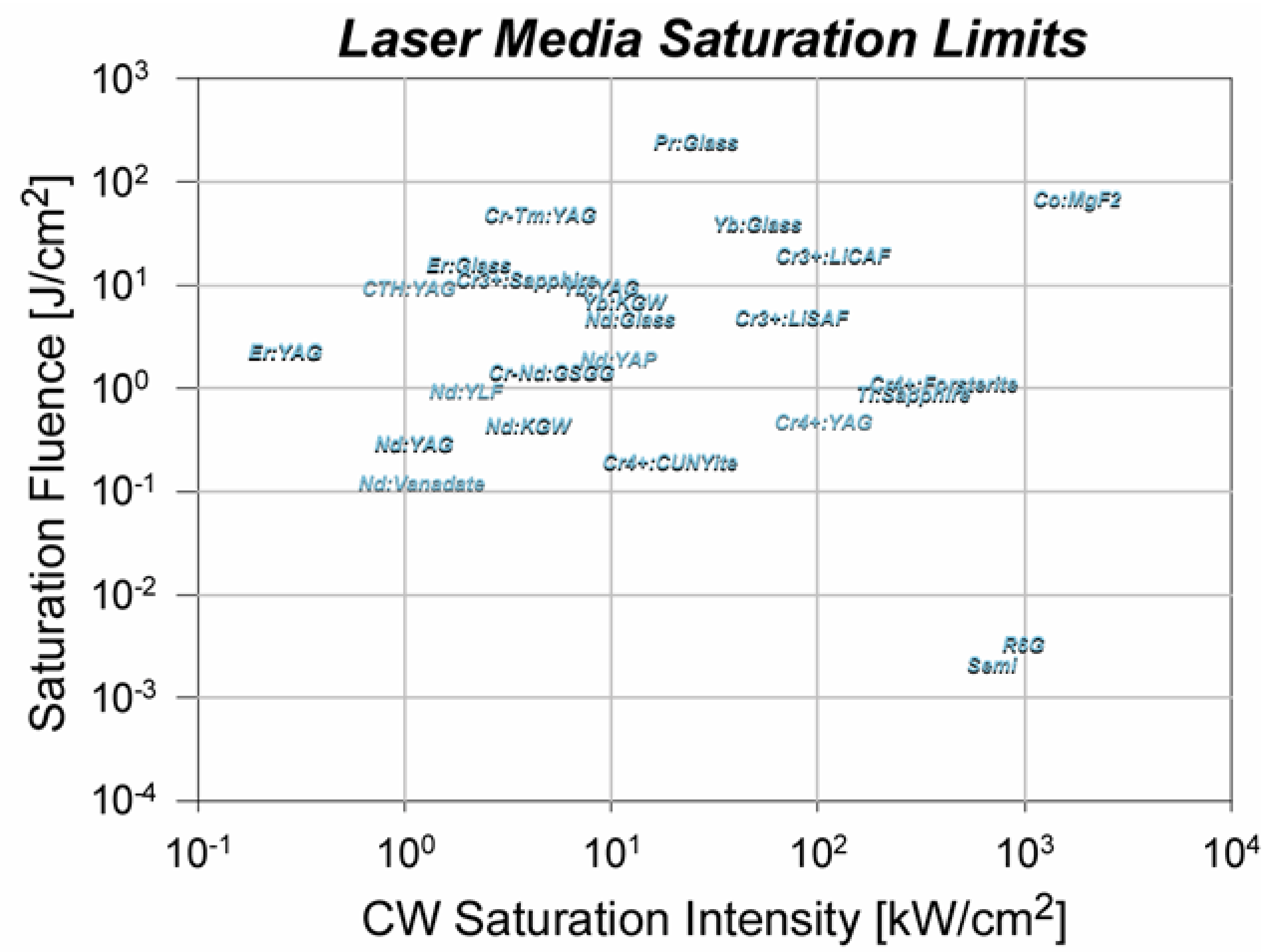


Dielectrics

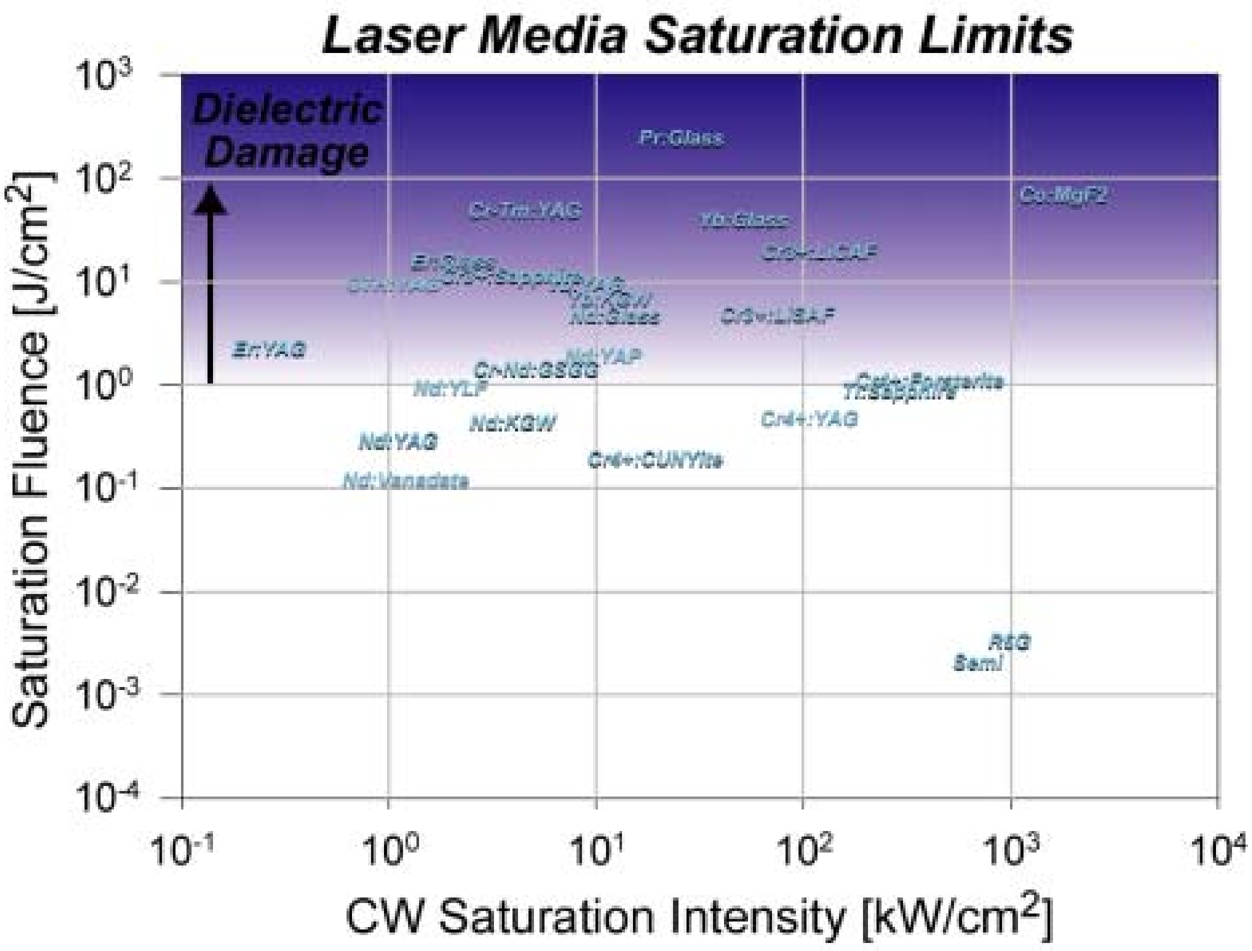


B. Stuart, et al., JOSA B <u>13</u>, 459 (1996);
ibid, PRL 74 (1995).
Pronko, Opt. Comm. <u>114</u>, 106 (1995).

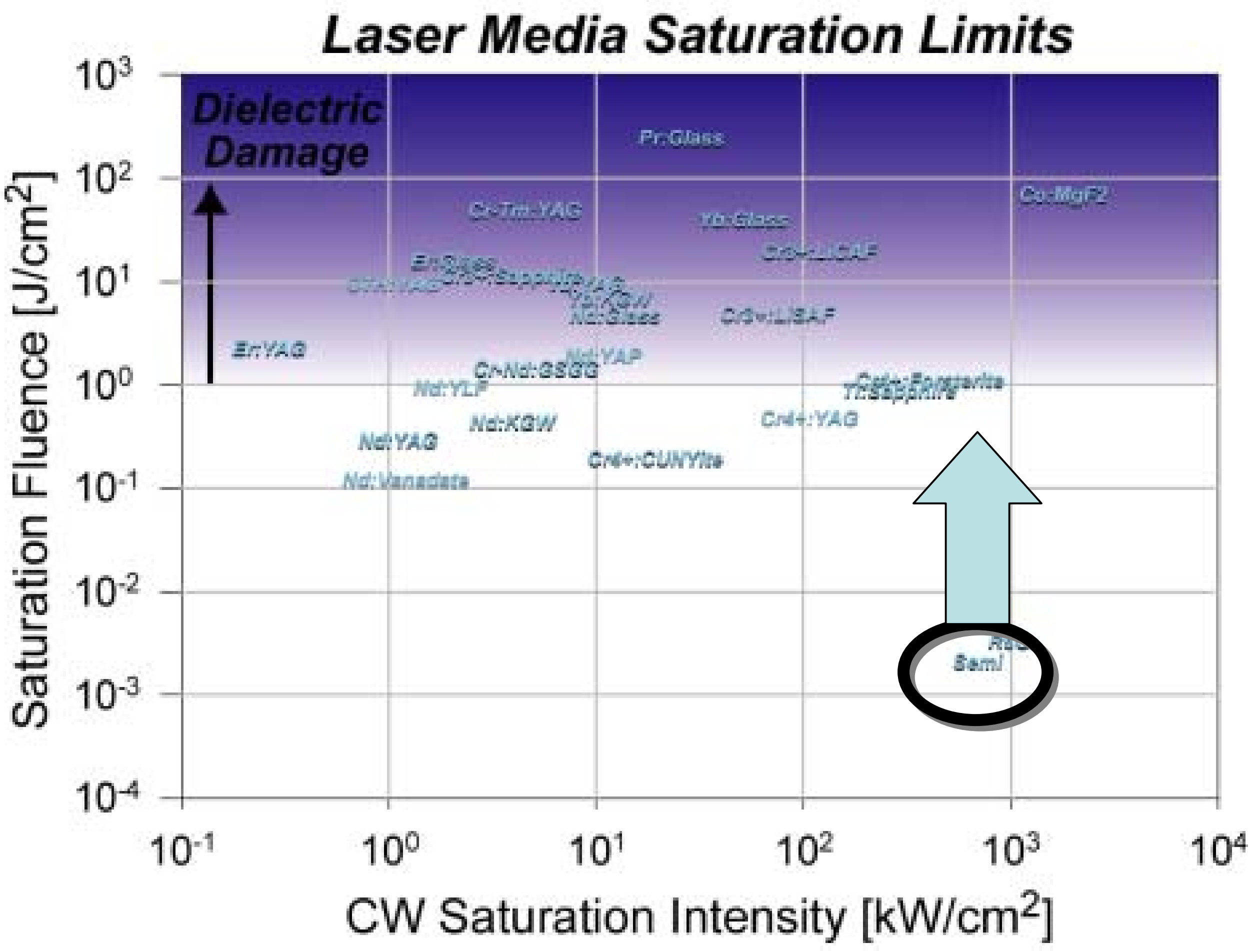
Laser Media


Laser Media Saturation Limits
Saturation Fluence [J/cm2]
CW Saturation Intensity [kW/cm2]
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-3
10^-4
10^4
Pr:Glass
Co:MgF2
Cr-Tm:YAG
Yb:Glass
Cr3+:LICAF
Er:Glass
CTH:YAG
Cr3+:Sapphire
Yb:KGW
Nd:Glass
Cr3+:LISAF
Er:YAG
Nd:YAP
Cr-Nd:GSGG
Nd:YLF
Ti:Sapphire
Cr4+:YAG
Nd:KGW
Nd:YAG
Cr4+:CUNYite
Nd:Vanadate
R6G
Semi

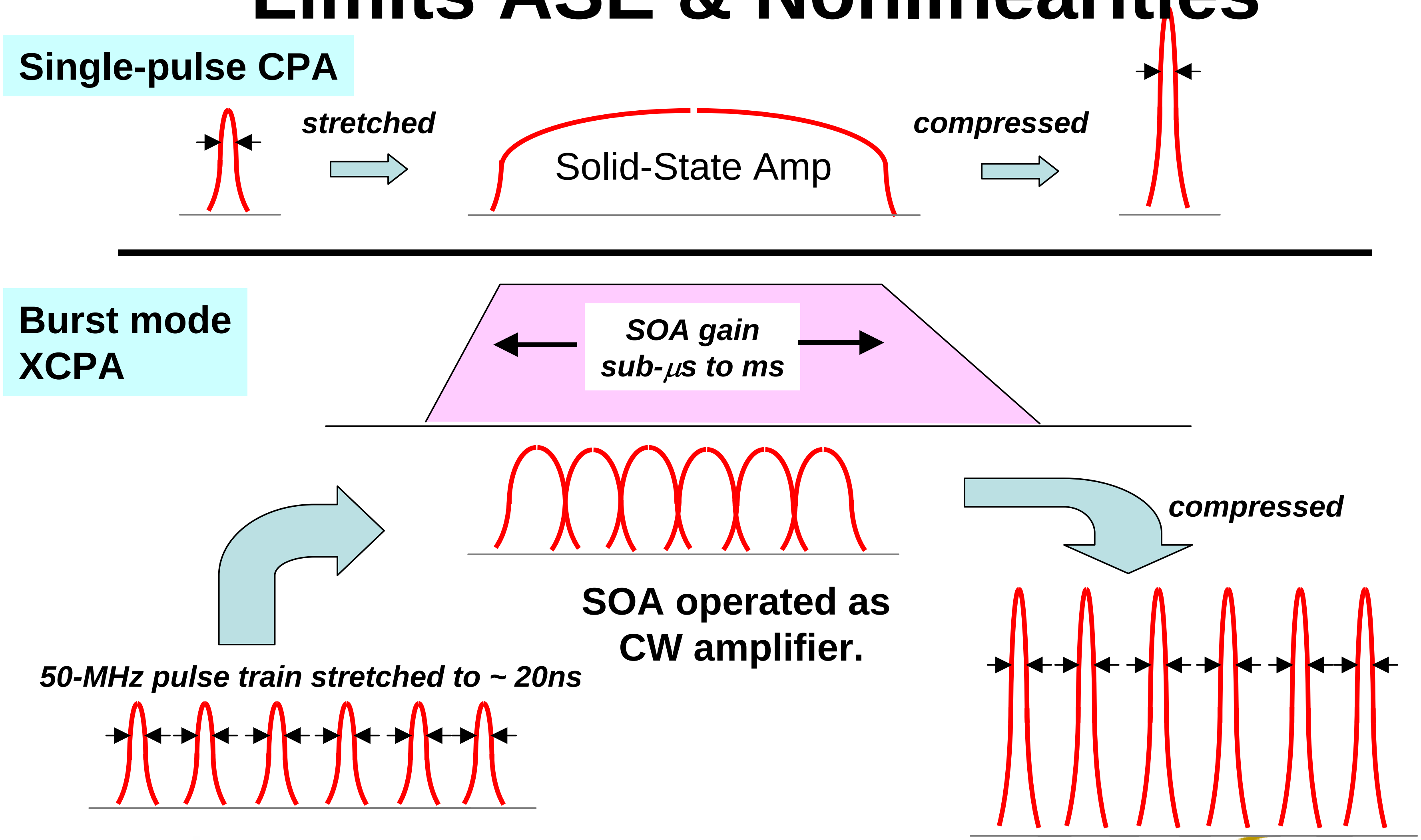
Optical Damage Limits



eXtreme Chirped Pulse Amplification

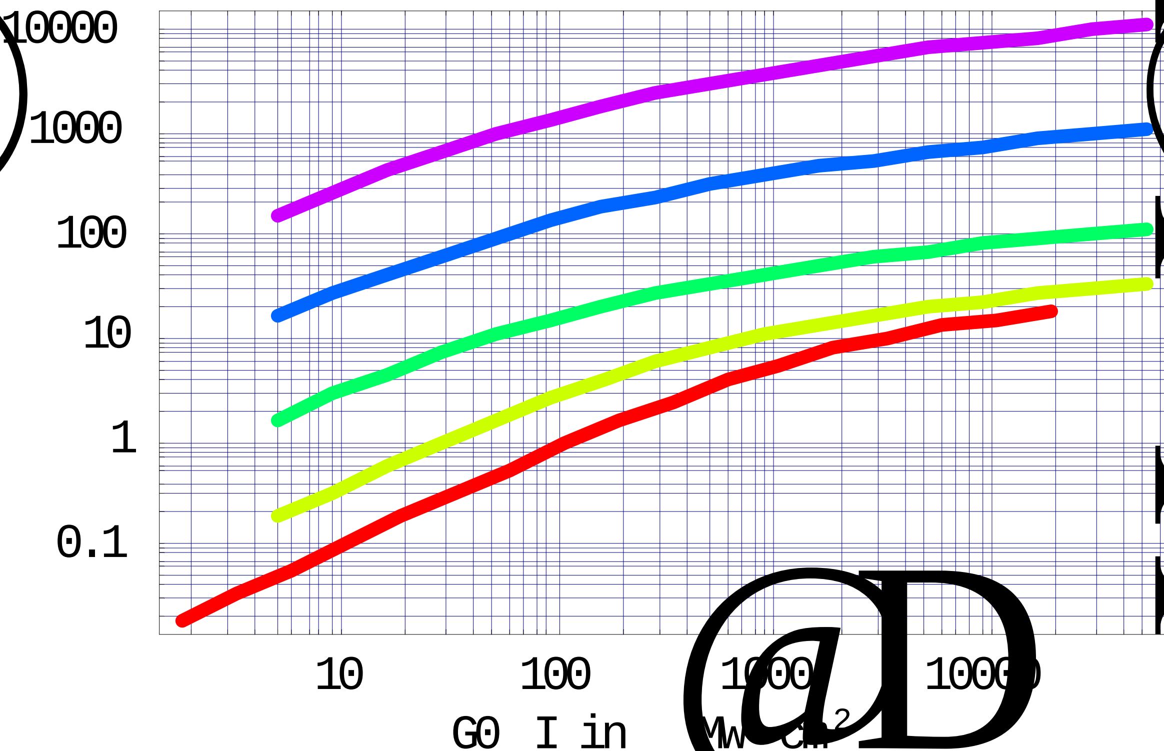


XCPA Semiconductor Amplifier Limits ASE & Nonlinearities



eXtreme CPA

Pulse Durations: 2-ps (red), 20-ps (yellow), 200-ps (green), 2-ns (blue), 20-ns (violet)

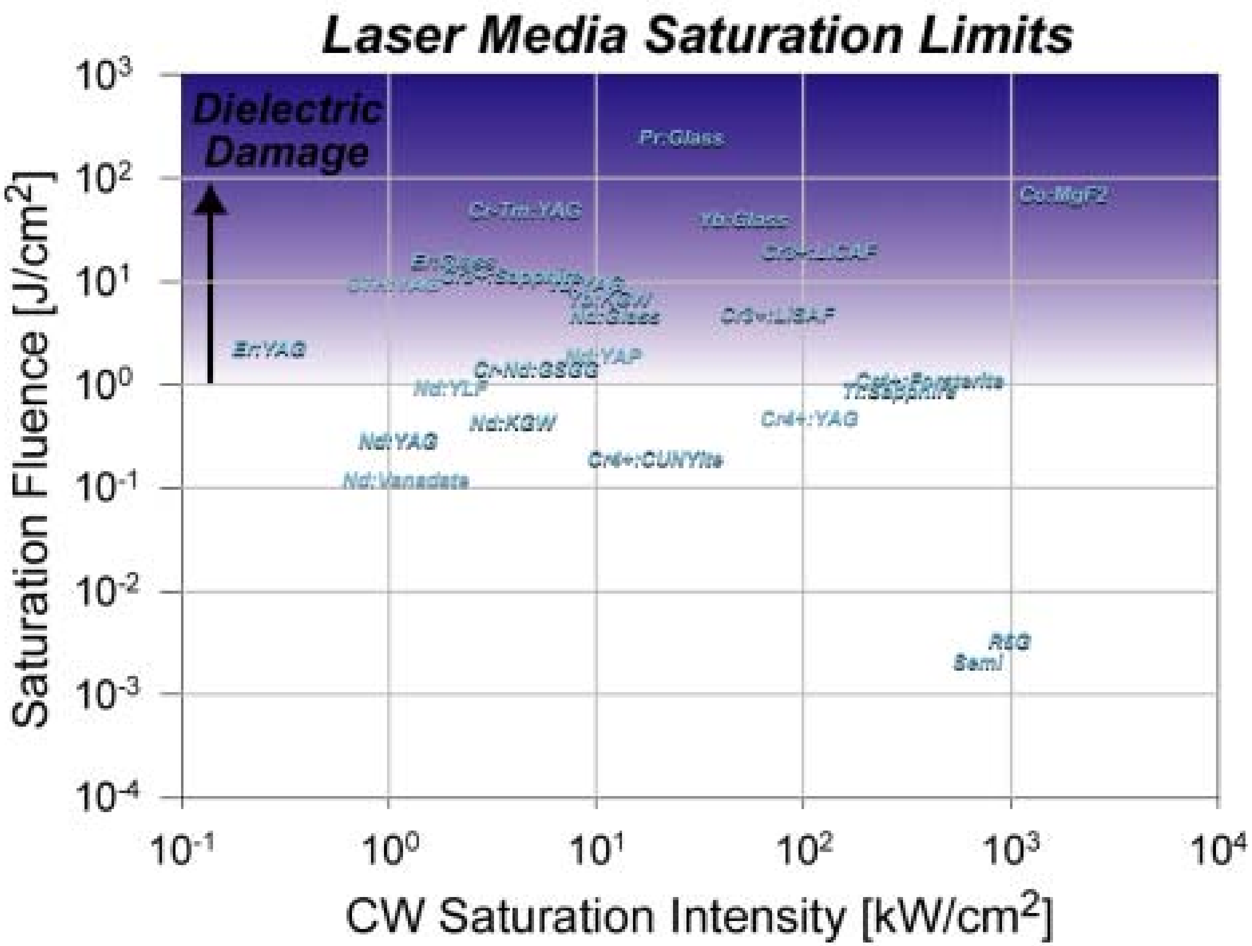


200-ps gain lifetime, 30-dB gain

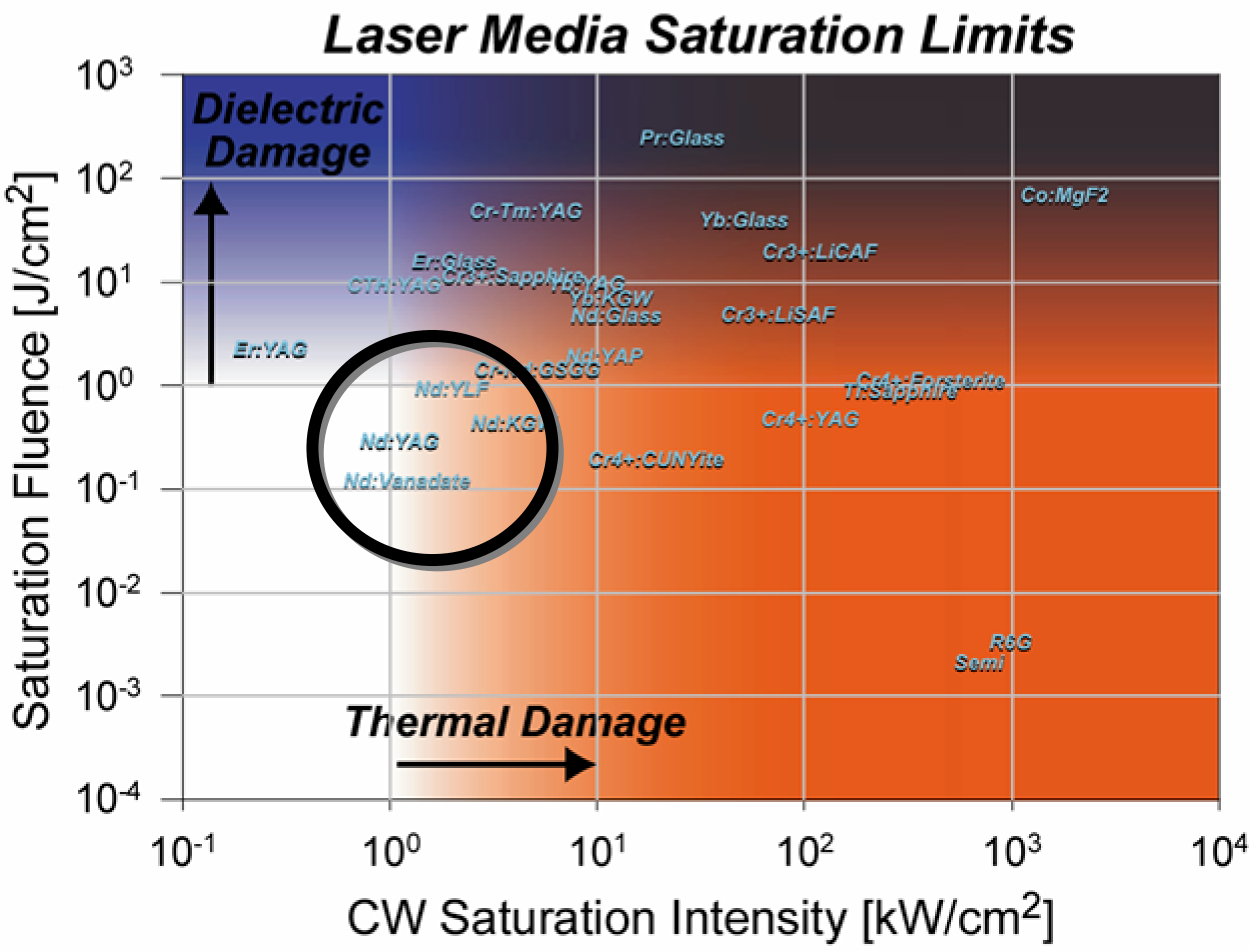
F_{sat} = 1.0-mJ/cm^2; I_{sat} = 5.1 MW/cm^2

λ = 980-nm; σ = 2.5x10^{-16} cm^2

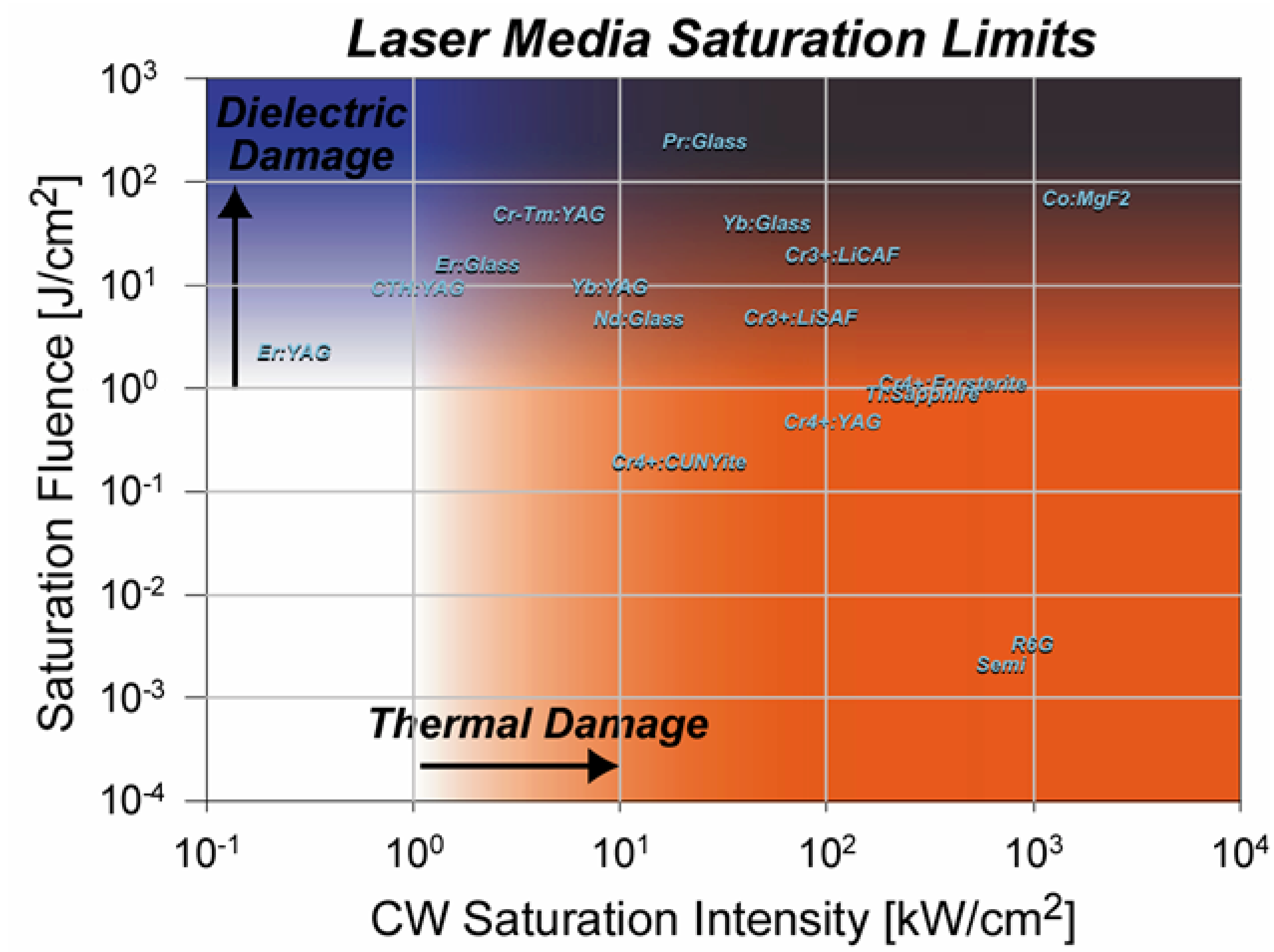
Optical Damage Limits



Thermal Damage Limits

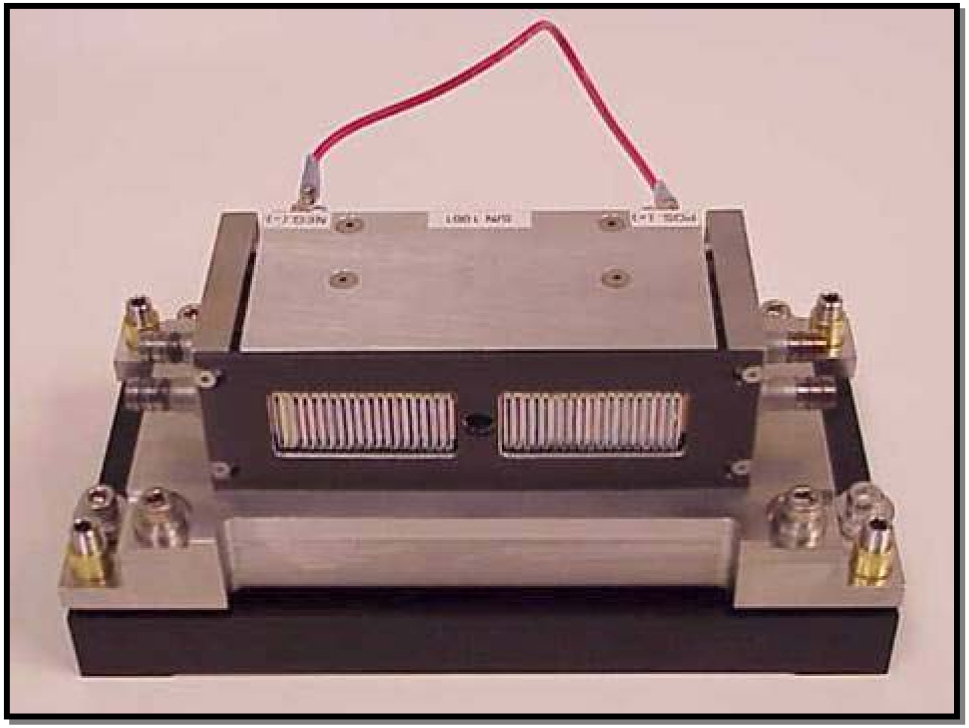


Sub-0.5ps Materials



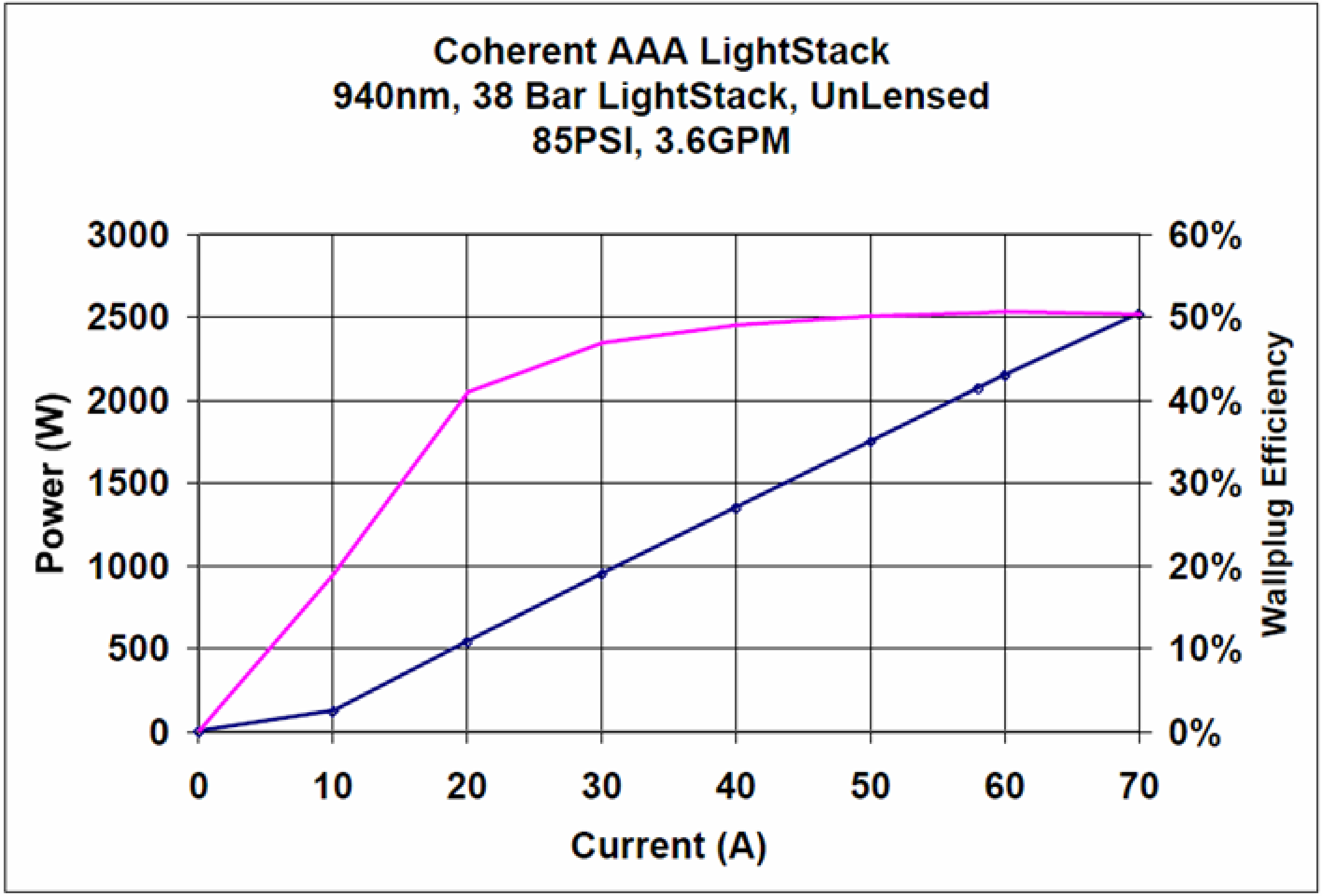
High-power laser diodes

LightStack from Coherent
2-kW @ 940-nm. 50% wallplug efficiency
2 19-bar arrays in series electrically, parallel cooling

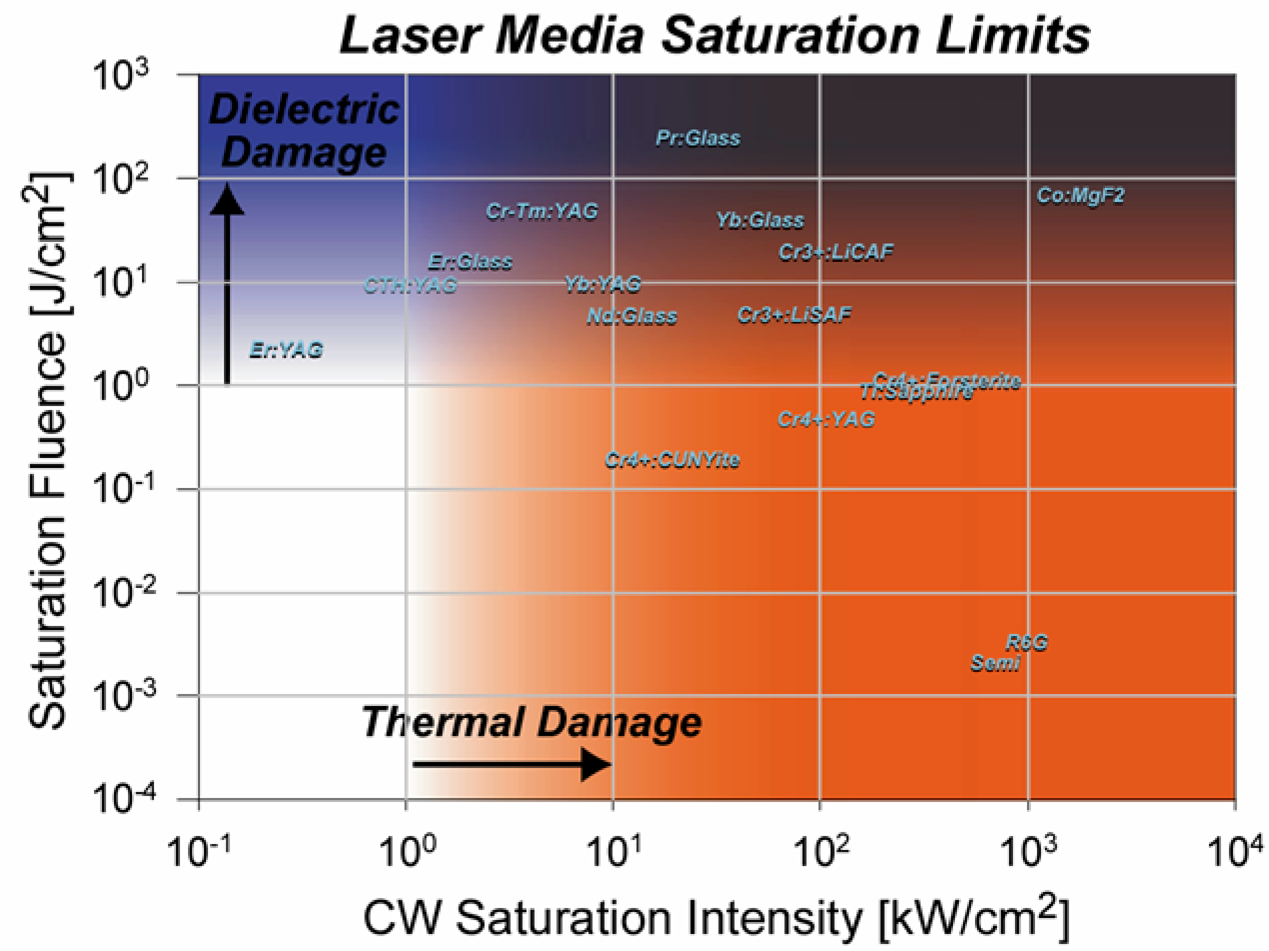


Pump Stack Originally developed for Ytterbium Fiber Pump

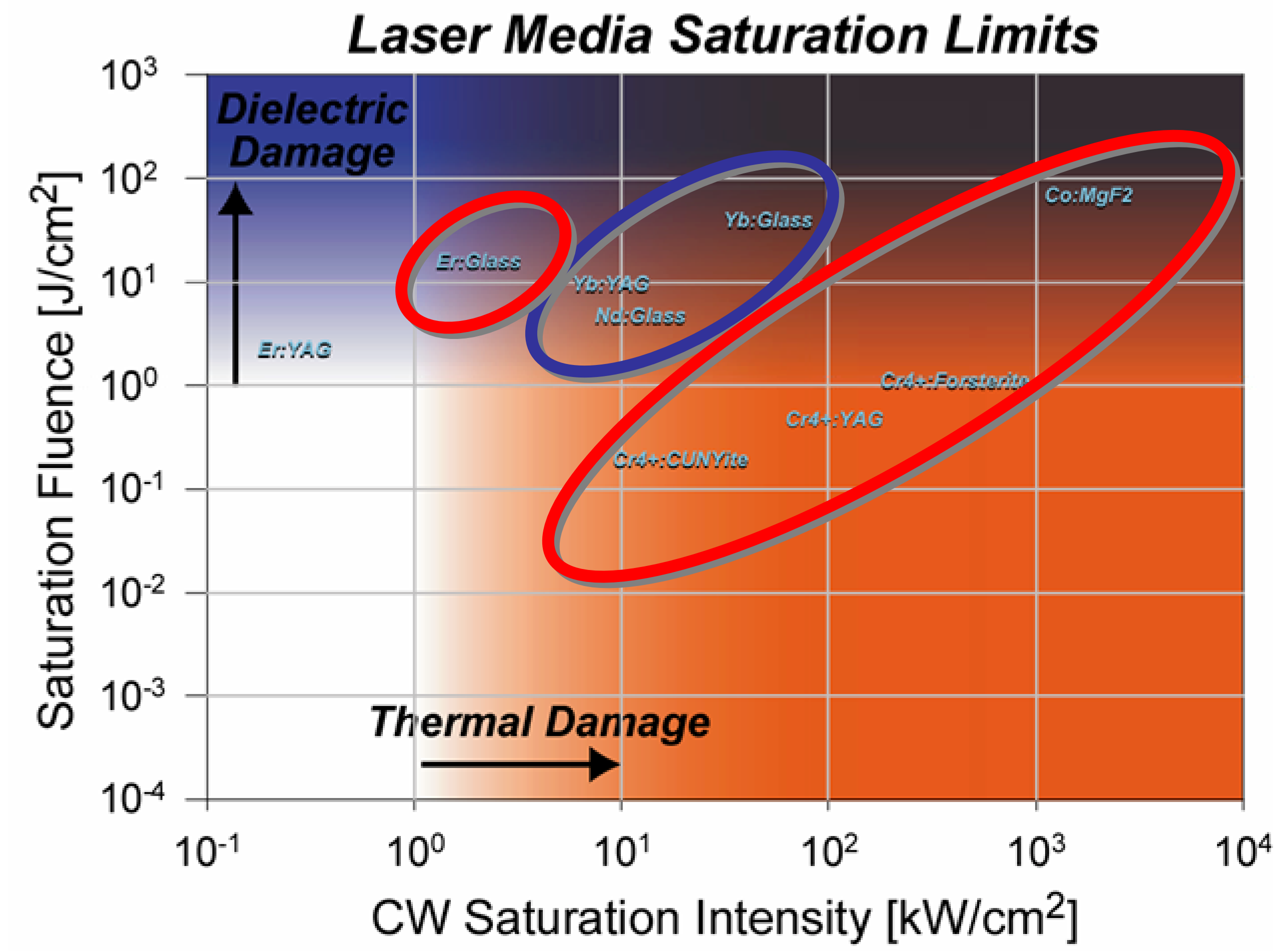
High-power laser diodes



Sub-0.5ps Materials



High-Power Diode Pump-able



What We Care About

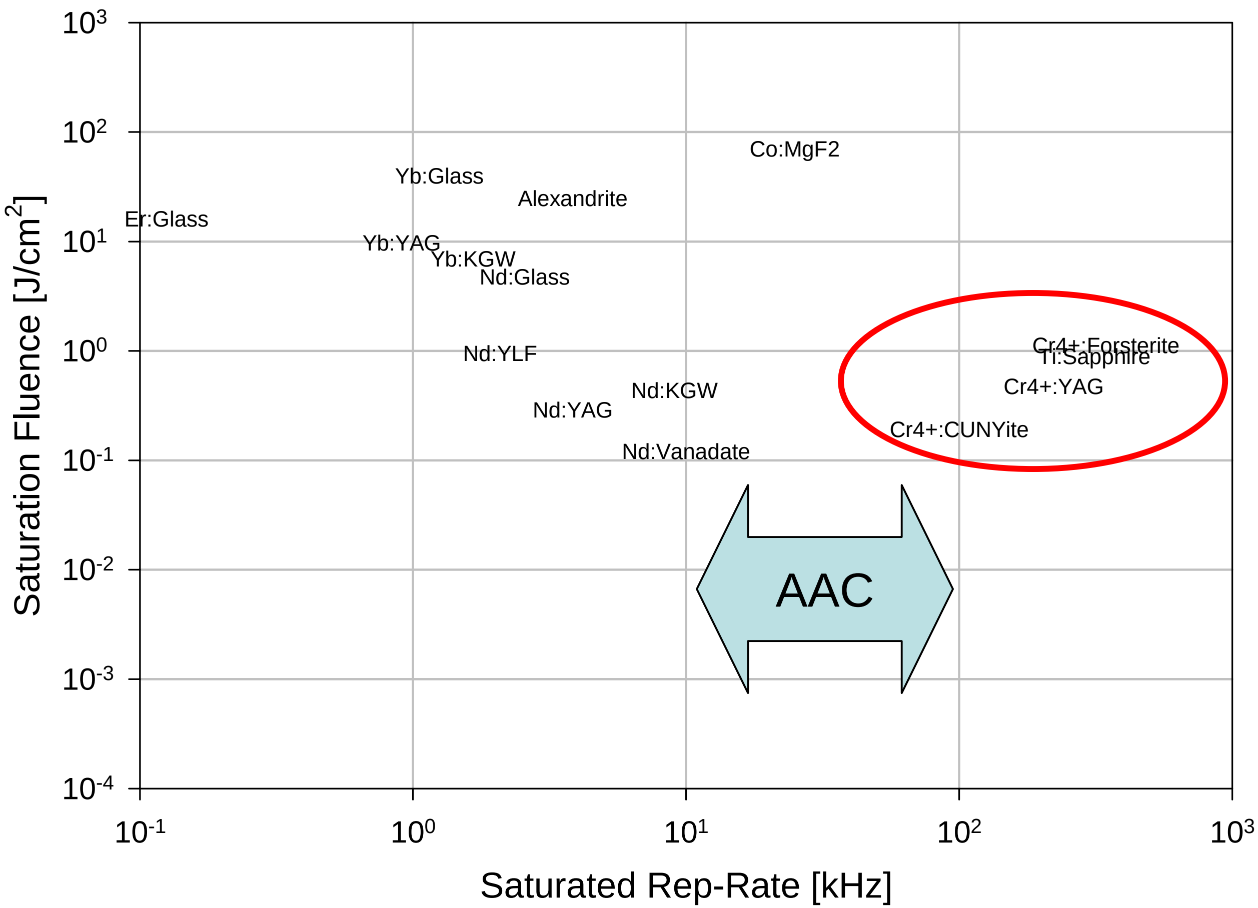
$$a_0 = \frac{v_{\text{osc}}}{c} \approx 1 \quad \text{or} \quad I \approx 10^{18}\,\text{W/cm}^2$$

Parameter	5 TeV LWFA	NLC γ-γ	Solid St.		CO_2	Units
λ	1–10	1	0.8	1.06	10	μm
E	1	1	0.1	20	15	J
τ	100	1000	20	1000	3000	fs
P_{peak}	10	1	5	20	5	TW
f_{rep}	60	15	50×10^{-3}	10^{-5}	10^{-4}	kHz
P_{avg}	60	15	5×10^{-3}	2×10^{-4}	1.5×10^{-3}	kW
$\eta_{wall-plug}$	0.1	—	$< 10^{-4}$	$< 10^{-4}$	~ 0.01	

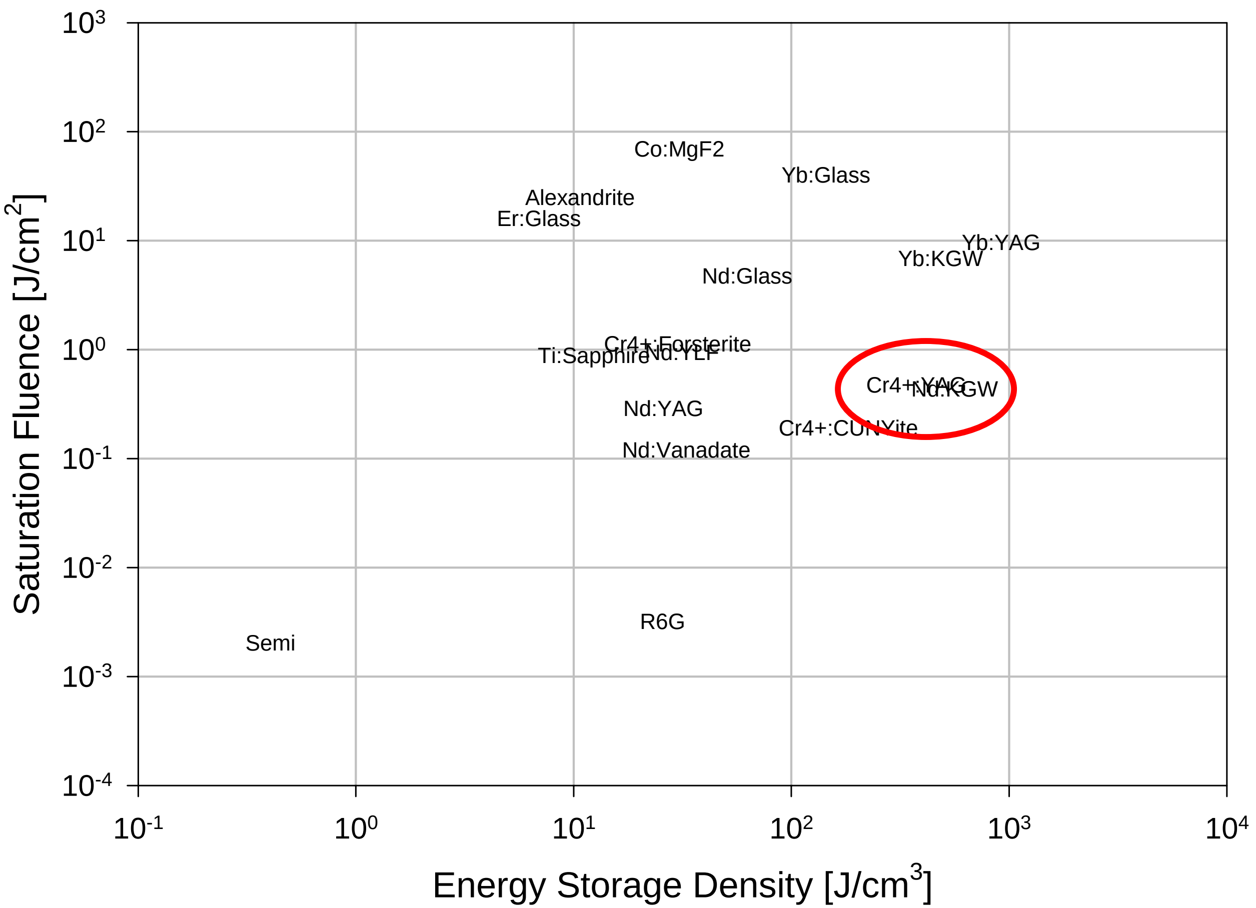
Table 1: Laser Requirements for a 500 stage, 5 TeV LWFA and NLC-based γ-γ collider (85 bunches/macropulse at 180 Hz macropulse rate) and current state of the art for solid-state, i.e. Ti:S (0.8 μm, [3, 4]) or Nd:x (1.06μm, [5]), and CO_2 systems [6]. For the NLC γ-γ collider, current efficiencies are adequate since only one laser system is needed.

Laser Sources WG, AACW '96

Systems Which Access AAC-Relevant Rep-Rates



Energy Storage Density

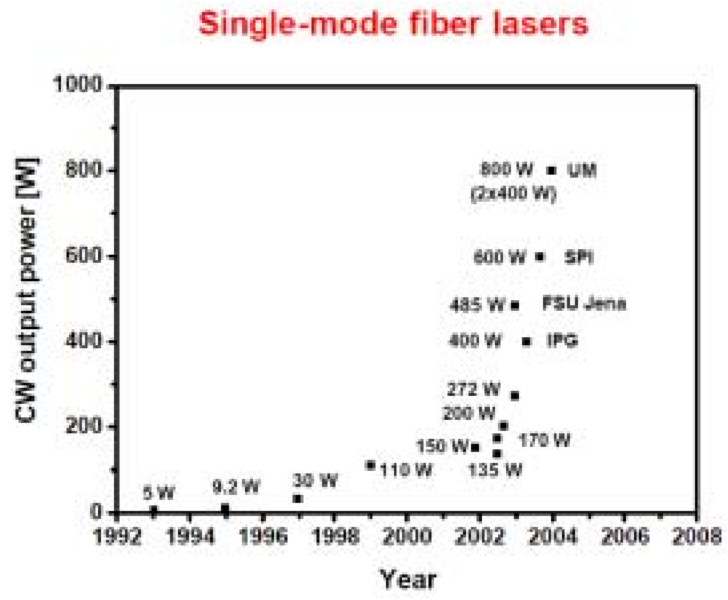


Nd:Glass

- Energy storage good
  - $F_{sat} = 7\ J/cm^2$
- Pumping straightforward
  - 400 microsecond lifetime easily flashlamp pumpable
- Dispersion control easier
  - Picosecond pulses require only GDD and maybe cubic compensation
- Repetition limited
  - Thermal loading a problem. Must wait to re-equilibrate
- Pulse duration limited to around a picosecond
  - Typically 300 fs to 1 ps
- First PW Laser – LLNL/NOVA PW
- Majority of planned PW's are Nd:Glass

Yb:Glass

- High energy storage
  - F_{sat} = 30-50 J/cm^2
  - Damage is a major issue in efficiency and robustness
- Diode pumpable
  - Very long lifetime (840 μs) and absorption at diode wavelengths (915nm, 980nm). Not optimal for 10-100kHz rep-rate applications.
- Shorter pulses possible
  - Fluoresence bandwidth should support ~100 fs
- Stretching requirements difficult - CFBG?
  - Δt = 6ns to reach one times saturation safely
- Can be easily implemented in Fiber geometry
  - >kW CW average powers, 65% slope efficiency demonstrated (Limpert CLEO '04)
  - 0.6-mJ, 1.6-kHz, 800-ps stretched, 400-fs compressed (Limpert CLEO '04)
- Yb:glass PW's under construction
- Yb:SFAP - Mercury Laser @ LLNL. 100J, 10 Hz, ns.


Single-mode fiber lasers
CW output power [W]
Year
800 W UM
(2x400 W)
600 W SPI
485 W FSU Jena
400 W IPG
272 W
200 W
150 W
170 W
135 W
110 W
30 W
9.2 W
5 W
0
200
400
600
800
1000
1992
1994
1996
1998
2000
2002
2004
2006
2008

Ti:Sapphire

- Sapphire great optical quality, high damage threshold
  - Also superior thermal material. Sapphire is often used as transparent heat sink
- Ideal saturation fluence
  - $F_{sat} = 1\ J/cm^2$ yields a stretching requirement of only 200 ps
  - Just below damage threshold
- Huge bandwidth
  - Theoretically could support 3-fs pulses
- Short lifetime
  - 3 us requires laser pumping or heroic flashlamp circuitry
- SHG-Nd pumping. No high-power green laser diodes.
- Widely implemented for 1-100 TW class systems.
- PW's: JAERI, FOCUS

Cr^{4+}:YAG

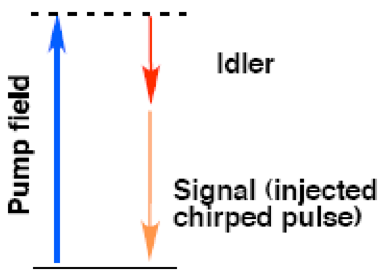
- Versatile Pumping
  - Diode-pumped @ 940-nm, 980-nm
  - Laser-pumped by Nd, Yb lasers
- Operates at telecomm wavelengths (1.3 and 1.5um)
- Excellent optical quality material available (Passive Q-Switch Use)
- Ideal saturation fluence
  - Fsat ~ 0.5 J/cm2 yields a stretching requirement of only 100 ps
  - Just below damage threshold
- Large bandwidth
  - Theoretically could support sub-10 fs pulses
- Short lifetime
  - 4.5 us requires laser pumping
  - High rep-rate pulsed amplifier for 10-100 kHz applications

Er:fiber

- Telecom wavelengths: much hardware available
  - EDFA: The most common telecommunication fiber amplifier
- All diode pumped
- Short pulses
  - 100 fs possible
- Large scale hosts not available so limited energy out
- Reliable source of sub-100-fs pulses at 1550nm.
- Sub-MW peak powers: TW/cm^2 at 10’s MHz rep-rates

OPCPA?

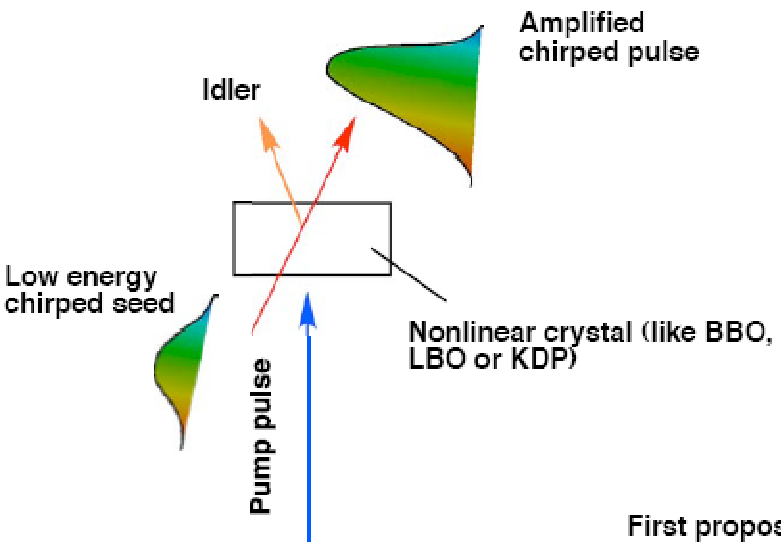
OPCPA is amplification
based on three wave mixing



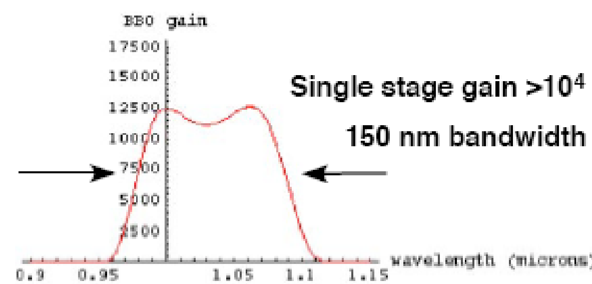
OPCPA

Advantages:
- Very large bandwidth amplificatino possible >100 nm)
- Good thermal properties (because of no heat deposition)
- Very high single stage gain (~10^4 in BBO)
- Lower ASE

Disadvantages:
- Stringent requirements on the pump laser (temporal and spatial quality)
- High nonlinearity leads to unstable performance



Calculated gain at 1053 nm with a co-linear 527 nm pump at 5 x 10^8 W/cm^2



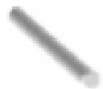
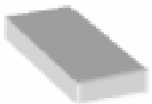
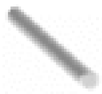
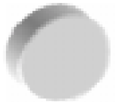
First proposed by the group in RAL: ie I. N. Ross et al. Opt. Comm. 144, 125 (1997)

(T. Ditmire)

Cr:LiSAF

- Flashlamp pumpable and diode pumpable
  - 67 μs lifetime, absorption at diode wavelengths
  - Diode pumped fs oscillators have been made with this material
- Good but not best bandwidth
  - Theoretically around 10 fs
- Inferior material properties
  - Early crystals dissolved in their water cooled housings
  - Easily fractured
- Inferior optical quality

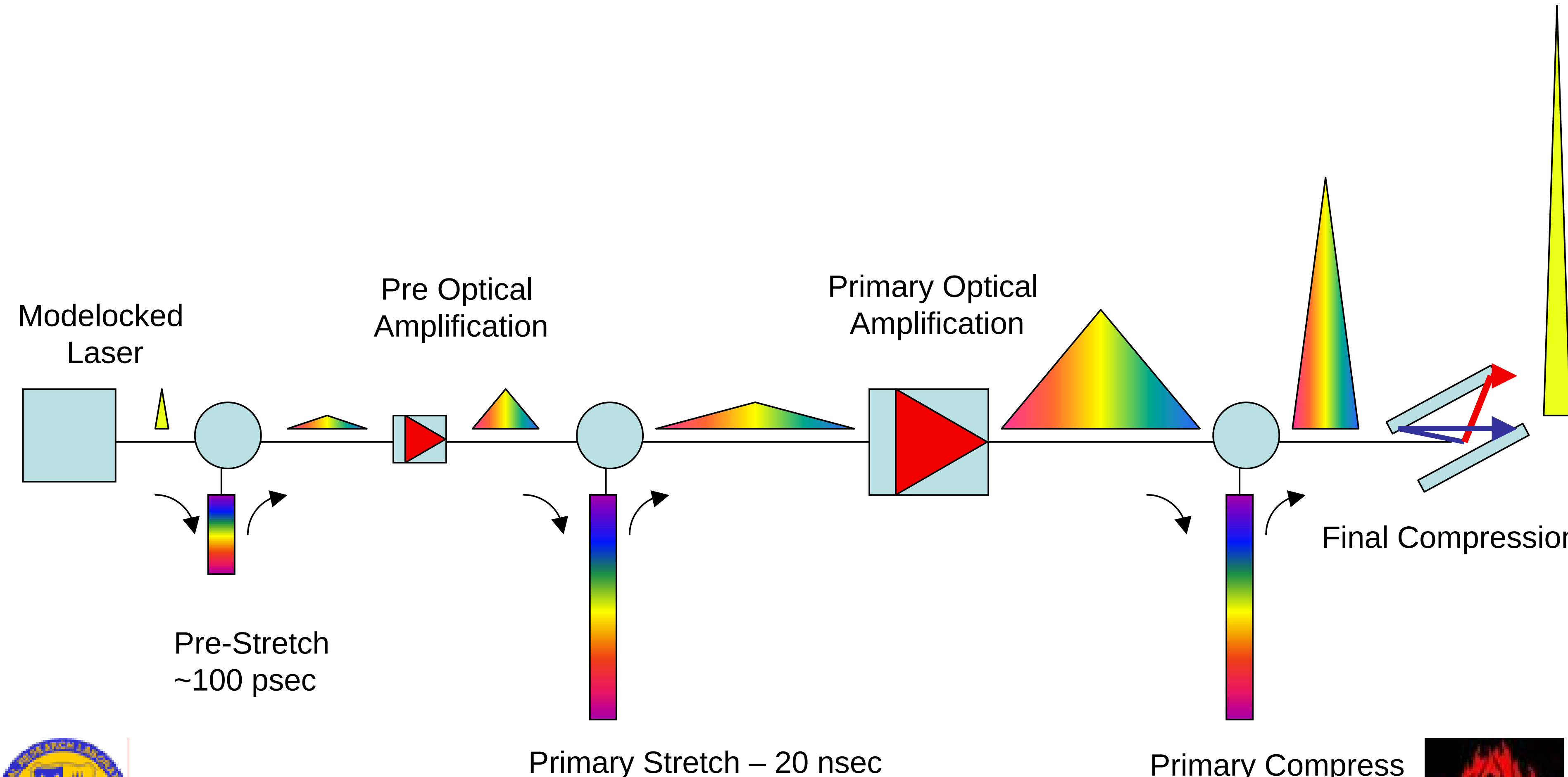
Pros & Cons of Amp Shape

				
	Rod	Zigzag Slab	Fiber	Disk
Thermal Lensing	Significant, but can be dealt with.	None in y-z (zigzag averaging), weak in x-z.	Significant, but can be dealt with.	Minimal due to 1D heat flow.
Stress Birefringence	Significant, but can be dealt with.	None in ideal case.	None for glass fibers.	Minimal due to 1D heat flow.
Mode Control	Good at low power.	Challenging, especially at large aspect ratios.	Good for single mode. More challenging for large mode fibers.	Good
Mode Fill Factor (TEM00)	Up to ~80%	Up to ~80%	~100%	Up to 95%
Best Power with good Beam Qual	500 W, M^2 ~ 1.5	3 kW, M^2 ~ 2.5	1.3 kW, M^2 ~1.3	13 kW, M^2 ~ 4
Key Challenge	Thermal Lensing & Mode	Mode, Mode, and Mode	Aperture limit & beam combining. USP nonlinearities. ASE.	Thermal Distortions

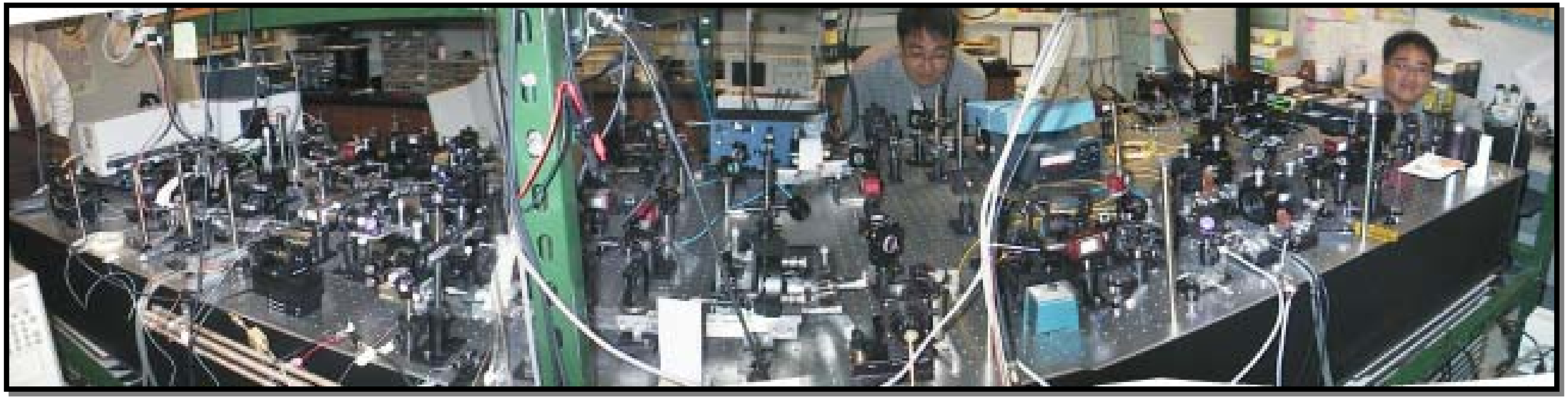
What Does the Future Hold?

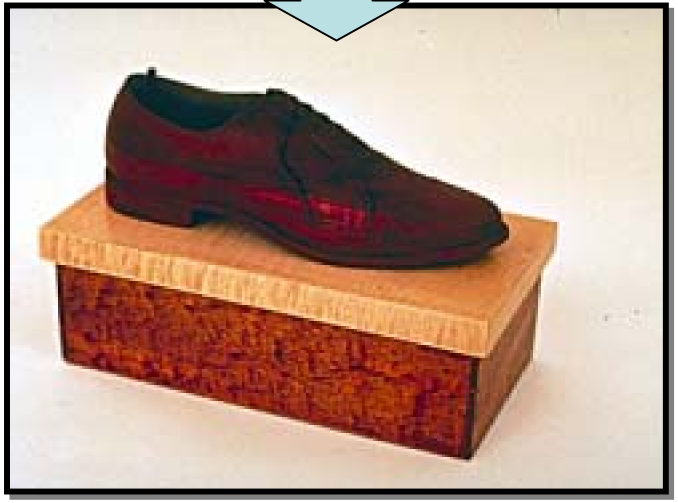
- Diode-pumped Fiber Osc's & Amps:
  - Yb (1um), Er (1.5um)
  - High rep-rates, limited by USP NLO
- Disk Amps: Yb, Cr^{4+}
- X-CPA & SOA's
- Nano-photonics & Integrated Optics
- Dispersion Management
  - Improved Gratings (~J/cm^2 Damage Thresh.)
  - Chirped Fiber Bragg Gratings
  - Compact Free-Space Systems
- Engineered Composite Media
  - Large-area "crystals": ceramic, fused, etc.
  - Thermal Management Improvements (because we must!)
- Multi-kW, Multi-kHz USPs soon!
- GHz GW and MHz TW?

X-CPA *Generic Architecture*



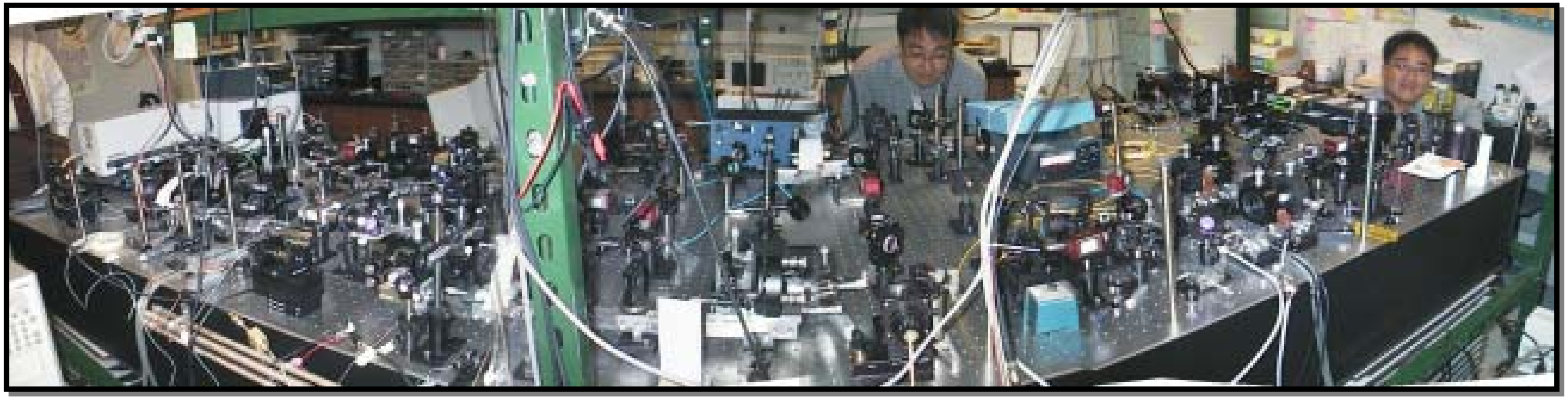
DARPA Challenge

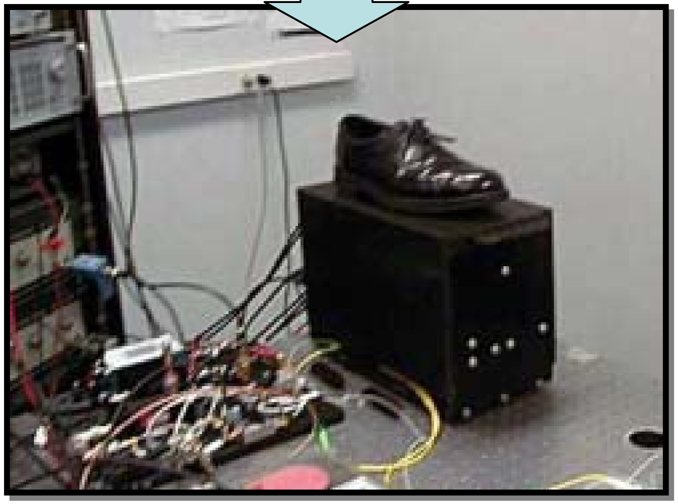




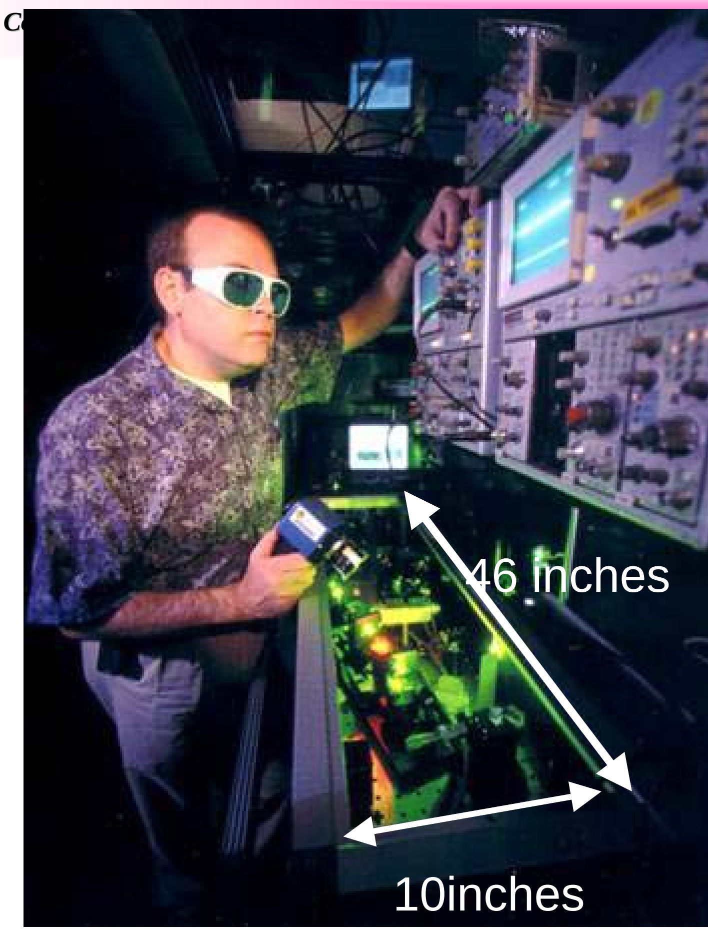
Stu's Shoe

DARPA Challenge



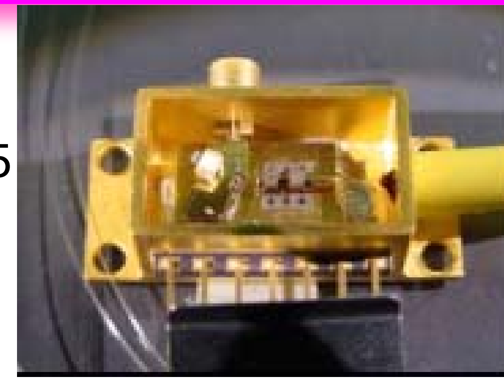


Size Reduction Obtainable from XCPA



Traditional mode locked laser for Ti:Sapphire USPL (KM Labs, Boulder).

0.5



A packaged mode locked laser diode X-CPA USPL

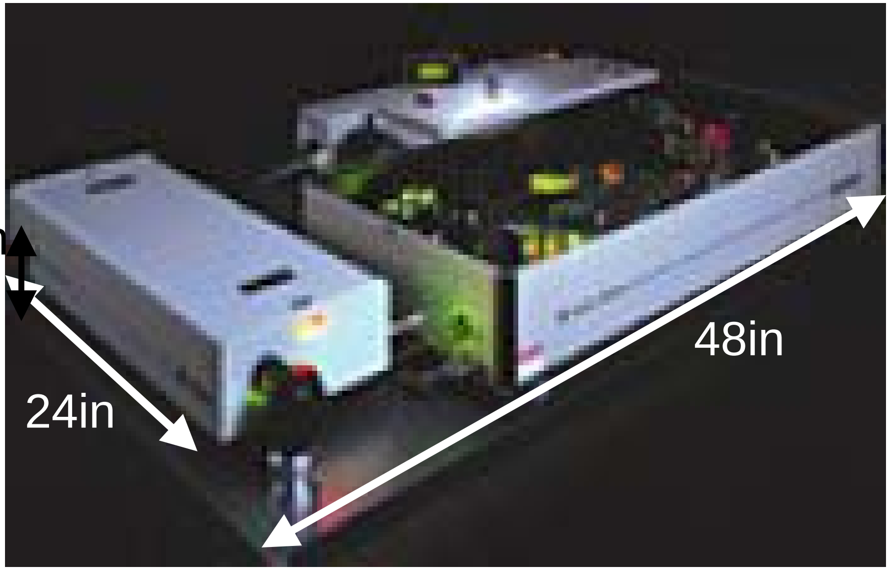
This is the laser diode based Mode locked laser to the same scale as the traditional mode Locked laser for a Ti Sapphire

2760 in^3 for the volume for the traditional Ti Sapphire ML source

0.125 in^3 for the ML source for the X-CPA

22080 time reduction in volume

X-CPA Impact



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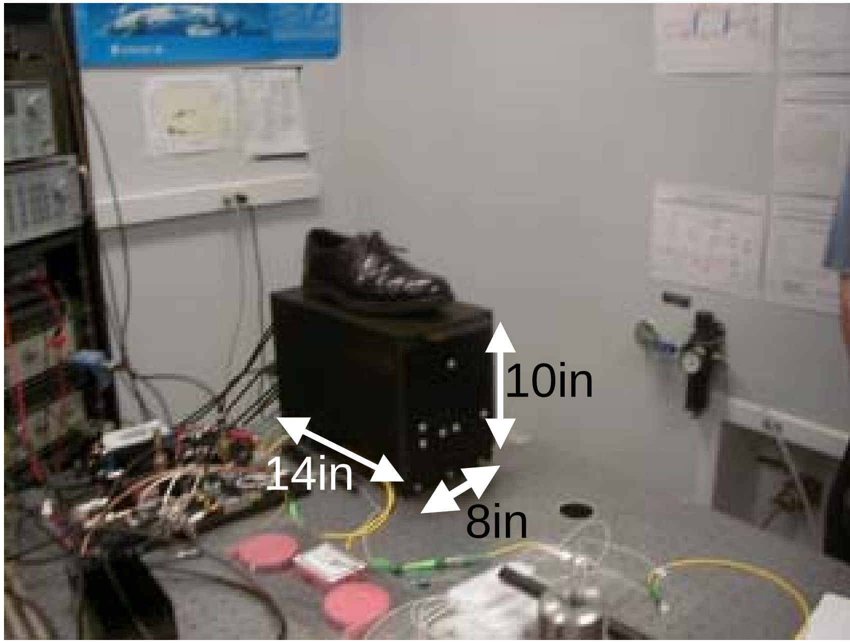

Volume 10368in^3 for a 1 Watt Ave Power Ti:Sapphire Power Supply and Water cooling system are not shown in the photograph

Volume of power supply 3456in^3
Volume of water cool 3000in^3

Volume 1120in^3 for a 0.5 Watt Ave Power XCPA Power Supply not shown.

Volume of power supply ~560in^3
Water Cool Not Required

DARPA

UCF CREOL