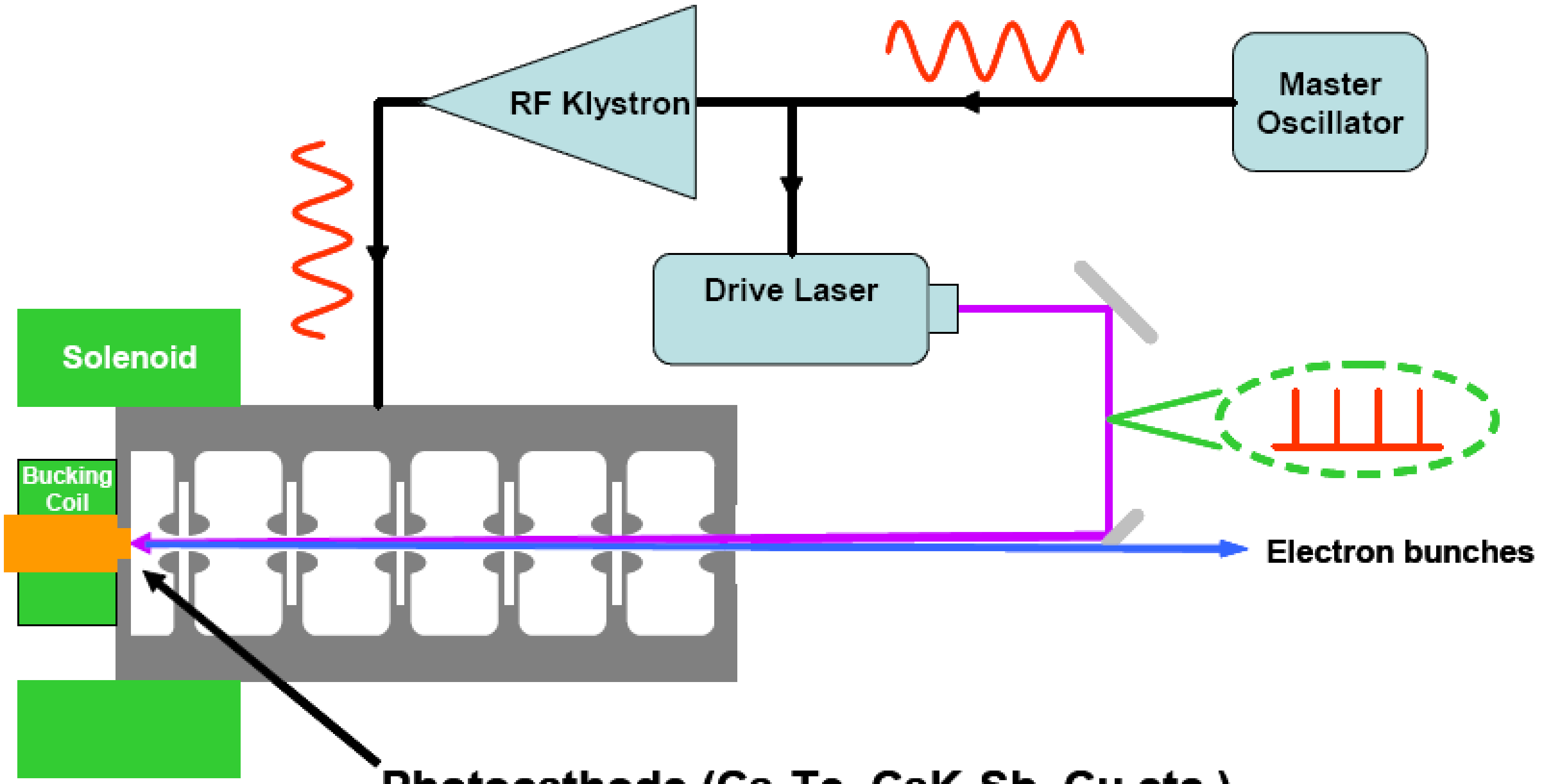
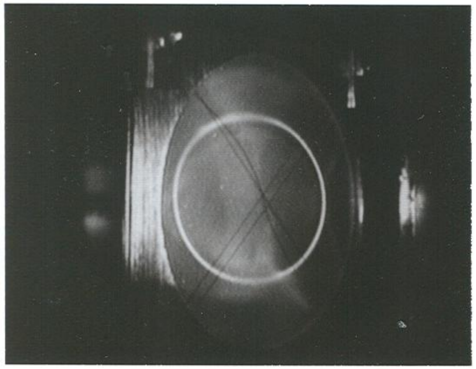
Photoinjector

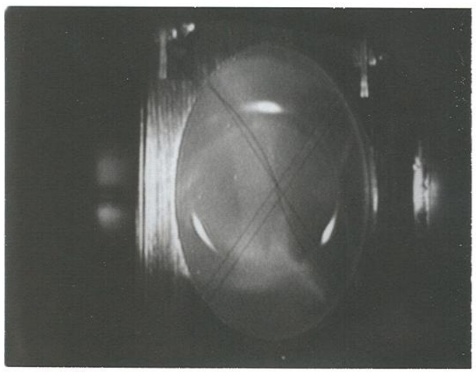


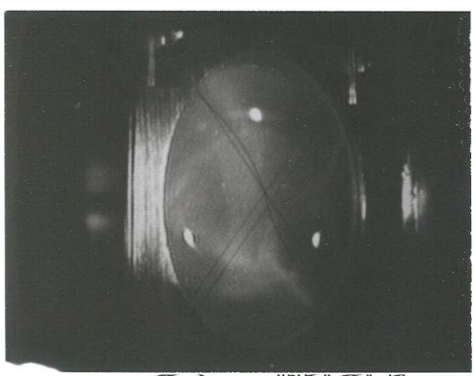
Photocathode (Cs_2Te, CsK_2Sb, Cu etc.)

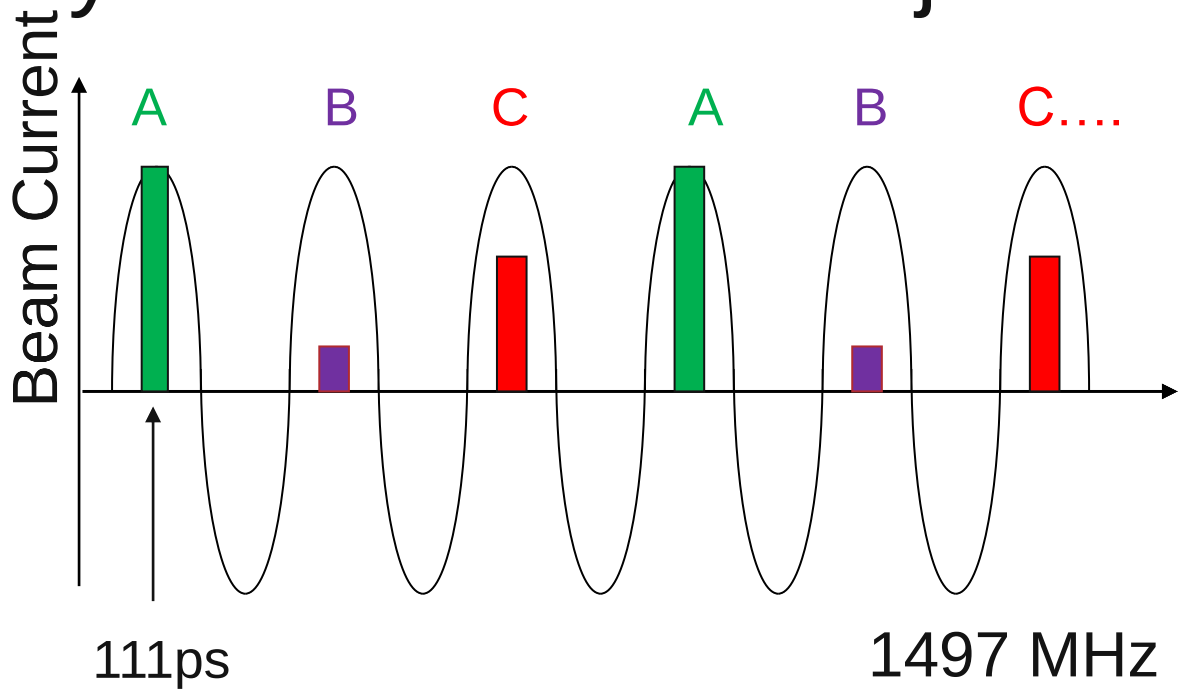
Slide compliments of P. O'Shea, UMd

Synchronous Photoinjection

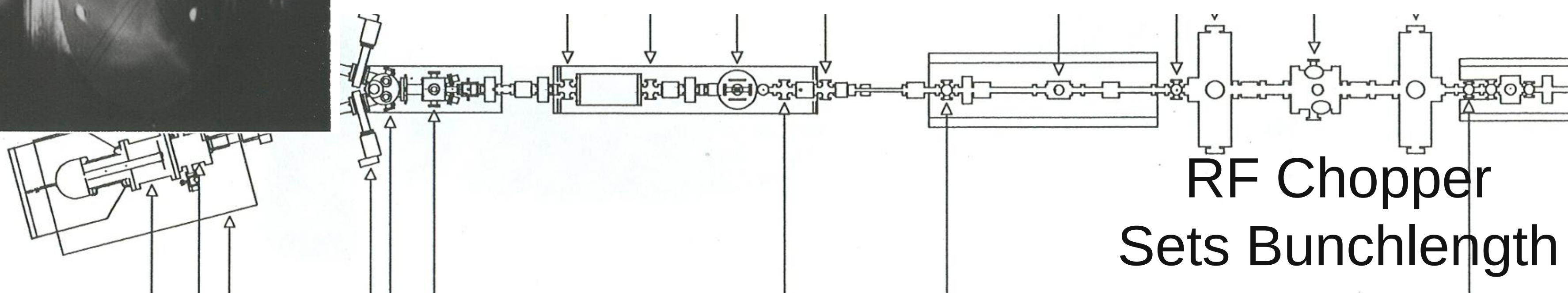








Extracting DC beam, very wasteful, most of the beam dumped at chopper. Need ~ 2mA from gun to provide 100uA to one hall. Gun lifetime not good enough.....yet.



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... for a brighter future

Laser applications for accelerators

Laser Basics

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U.S. Department of Energy

UChicago Argonne LLC

Office of Science U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory managed by UChicago Argonne, LLC

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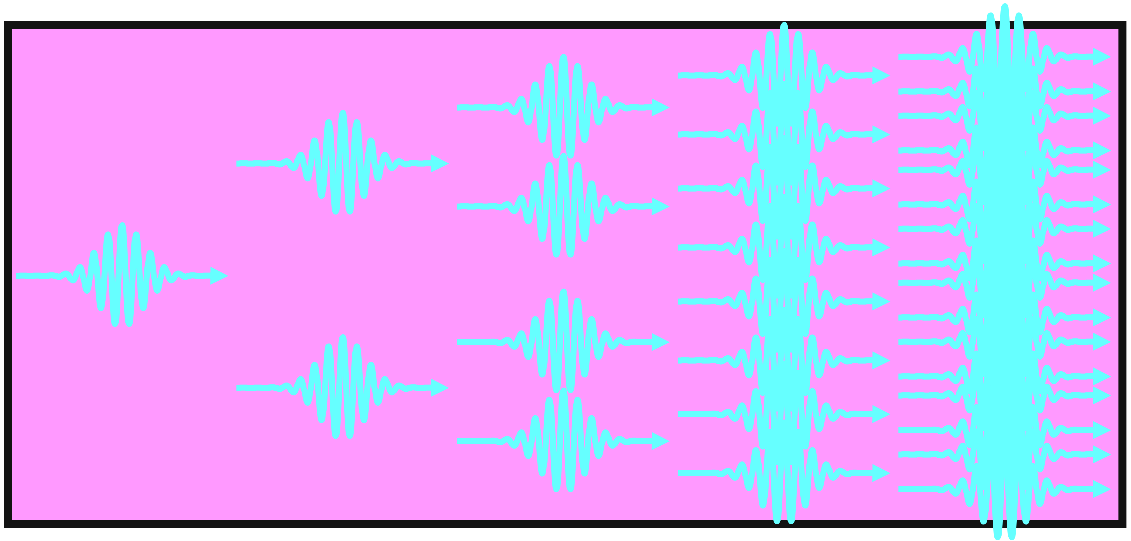
Laser

Light Amplification by Stimulated Emission of Radiation

If a medium has many excited molecules, one photon can become many.

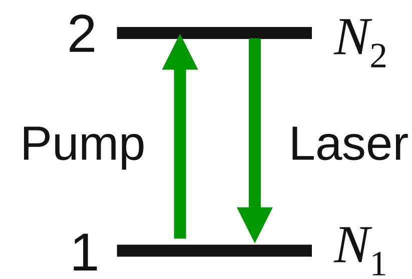
Excited medium



This is the essence of the laser. The factor by which an input beam is amplified by a medium is called the gain and is represented by G.

Credit: R. Trebino

Rate equations for a two-level system



Rate equations for the densities of the two states:

Absorption — Stimulated emission — Spontaneous emission

$$\frac{dN_2}{dt} = BI(N_1 - N_2) - AN_2$$

Pump intensity

$$\frac{dN_1}{dt} = BI(N_2 - N_1) + AN_2$$

If the total number of molecules is N:

$$N \equiv N_1 + N_2$$

$$\Delta N \equiv N_1 - N_2$$

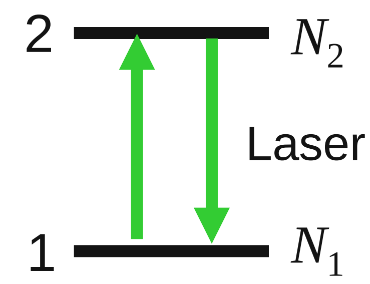
$$\Rightarrow \quad \frac{d\Delta N}{dt} = -2BI\Delta N + 2AN_2$$

$$2N_2 = (N_1 + N_2) - (N_1 - N_2) = N - \Delta N$$

$$\Rightarrow \quad \frac{d\Delta N}{dt} = -2BI\Delta N + AN - A\Delta N$$

Credit: R. Trebino

Why inversion is impossible in a two-level system



$$\frac{d\Delta N}{dt} = -2BI\,\Delta N + AN - A\Delta N$$

In steady-state: $$0 = -2BI\,\Delta N + AN - A\Delta N$$

$$\Rightarrow (A + 2BI)\Delta N = AN$$

$$\Rightarrow \Delta N = AN/(A + 2BI)$$

$$\Rightarrow \Delta N = N/(1 + 2BI/A)$$

$$\Rightarrow \boxed{\Delta N = \frac{N}{1 + I/I_{sat}}}$$

where: $I_{sat} = A/2B$

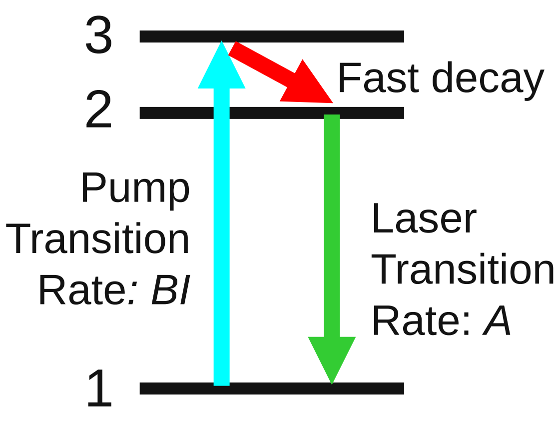
I_{sat} is the **saturation intensity**.

ΔN is always positive, no matter how high I is!

It's impossible to achieve an inversion in a two-level system!

Credit: R. Trebino

A 3-level system



Assume we pump to a state 3 that rapidly decays to level 2.

Spontaneous emission

$$\frac{dN_2}{dt} = BIN_1 - AN_2$$

Absorption

$$\frac{dN_1}{dt} = -BIN_1 + AN_2$$

The total number of molecules is N:

$$N \equiv N_1 + N_2$$

$$\Delta N \equiv N_1 - N_2$$

Level 3 decays fast and so is zero.

$$\frac{d\Delta N}{dt} = -2BIN_1 + 2AN_2$$

$$2N_2 = N - \Delta N$$

$$2N_1 = N + \Delta N$$

$$\Rightarrow \frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

Credit: R. Trebino

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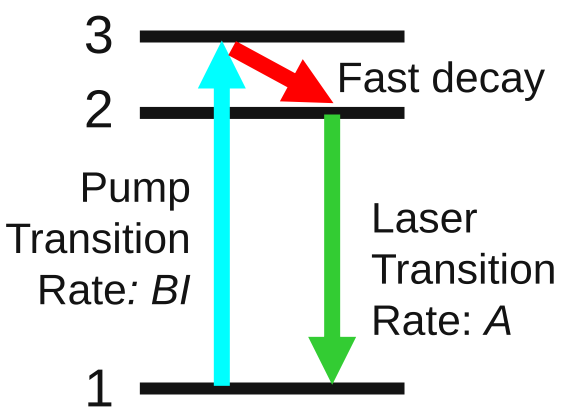
Population inversion, 3 level system



$$\frac{d\Delta N}{dt} = -BIN - BI\Delta N + AN - A\Delta N$$

In steady-state: $0 = -BIN - BI\Delta N + AN - A\Delta N$

$$\Rightarrow (A + BI)\Delta N = (A - BI)N$$

$$\Rightarrow \Delta N = N(A - BI)/(A + BI)$$

$$\Rightarrow \boxed{\Delta N = N\,\frac{1 - I/I_{sat}}{1 + I/I_{sat}}}$$

where: $I_{sat} = A/B$

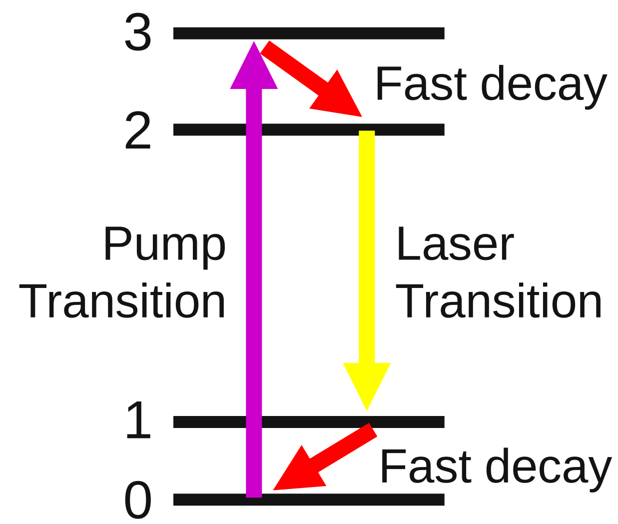
I_{sat} is the **saturation intensity**.

Now if $I > I_{sat}$, ΔN is negative!

Gain: $g \propto -\sigma\Delta N$

Credit: R. Trebino

Rate equations for a four-level system



Now assume the lower laser level 1 also rapidly decays to a ground level 0.

As before: $$\frac{dN_2}{dt} = BIN_0 - AN_2$$

The total number of molecules is N:

$$N \equiv N_0 + N_2$$

$$N_0 = N - N_2$$

$$\frac{dN_2}{dt} = BI(N - N_2) - AN_2$$

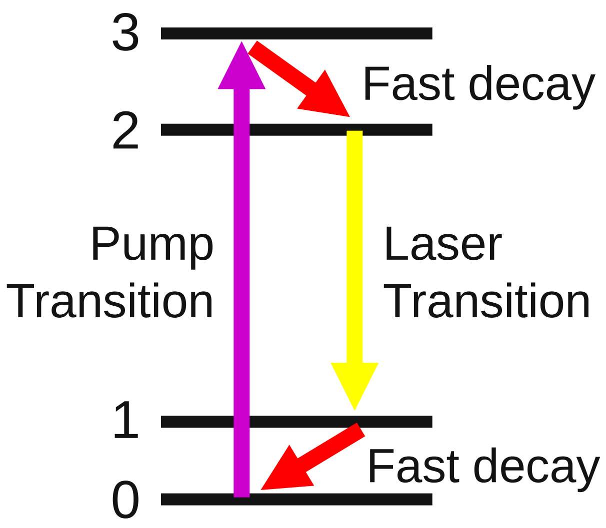
Because $N_1 \approx 0$, $\Delta N \approx -N_2$

$$-\frac{d\Delta N}{dt} = BIN + BI\Delta N + A\Delta N$$

At steady state: $$0 = BIN + BI\Delta N + A\Delta N$$

Credit: R. Trebino

Population inversion in a four-level system (cont'd)



$$0 = BIN + BI\Delta N + A\Delta N$$

$$\Rightarrow \quad (A + BI)\Delta N = -BIN$$

$$\Rightarrow \quad \Delta N = -BIN/(A + BI)$$

$$\Rightarrow \quad \Delta N = -(BIN/A)/(1 + BI/A)$$

$$\Rightarrow \quad \boxed{\Delta N = -N \frac{I/I_{sat}}{1 + I/I_{sat}}}$$

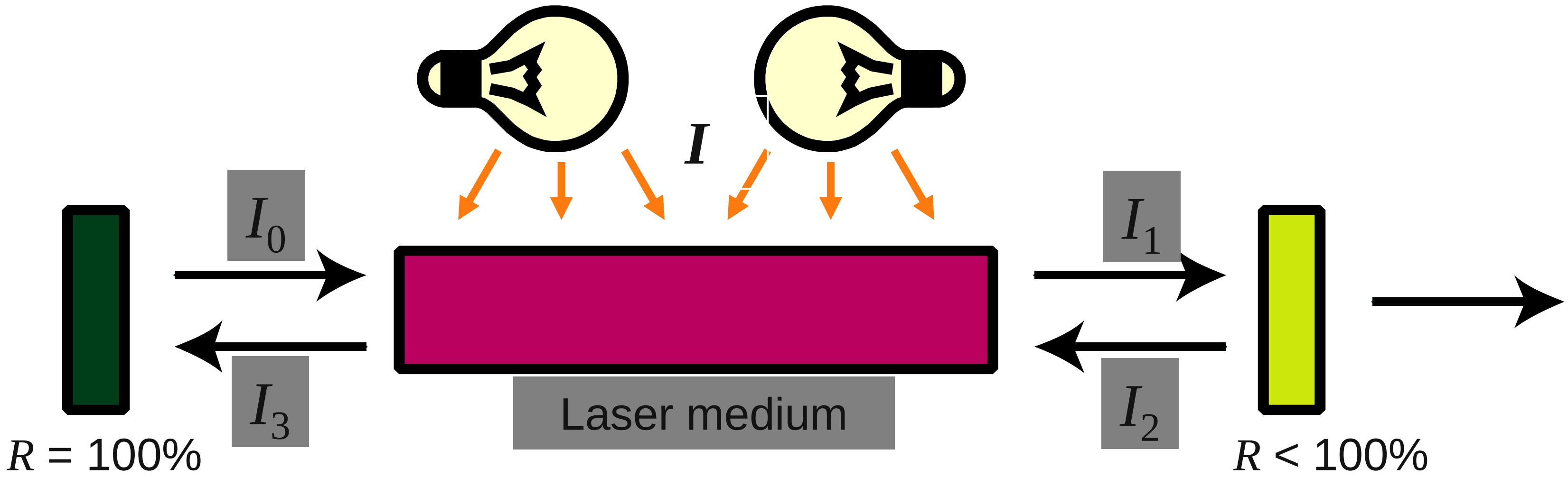
where: $I_{sat} = A/B$

I_{sat} is the **saturation intensity**.

Now, ΔN is negative—always!

Credit: R. Trebino

How to build a laser



- Laser medium
  - Depends on wavelength, pulse duration, power
- Pump it: ASE
  - Multimode in time and space
- Add resonator: laser oscillation
  - Mode selection

Credit: R. Trebino

Gaussian optics: summary

- Gaussian distribution is the solution of paraxial Helmholtz equation
- TM00 mode

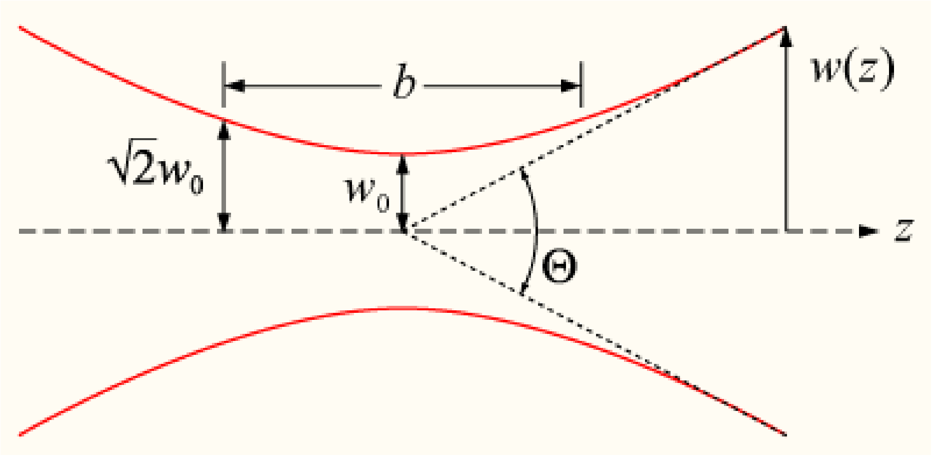
$$E(r,z) = E_0 \frac{w_0}{w(z)} \exp\left(-\frac{r^2}{w^2(z)}\right),$$

$$w(z) = w_0 \sqrt{1 + \left(\frac{z}{z_0}\right)^2},$$

$$z_0 = \frac{\pi w_0^2}{\lambda},$$

$$w_0 = \frac{2\lambda}{\pi\Theta},$$

$$b = 2z_0.$$

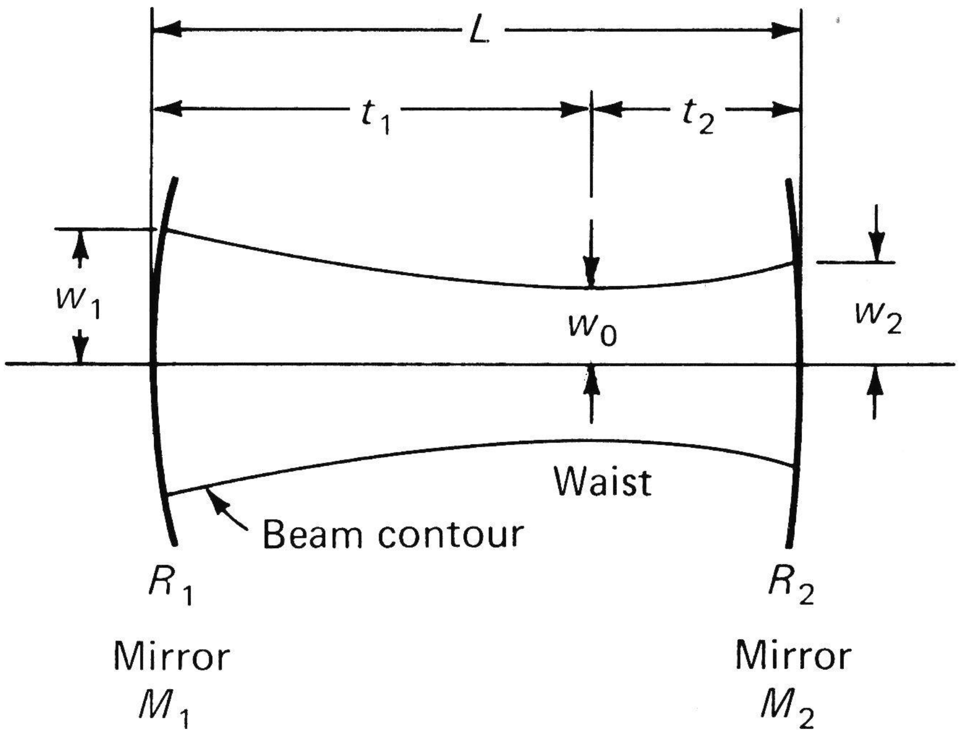


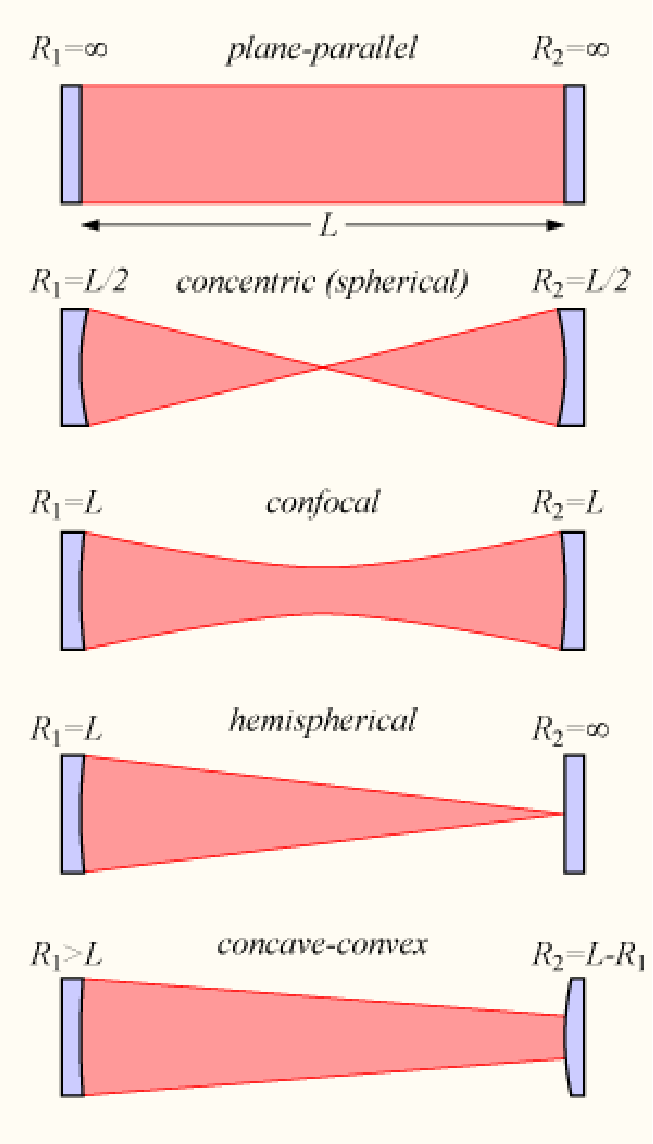
w_0: beam waist

z_0: Rayleigh range

b: confocal parameter

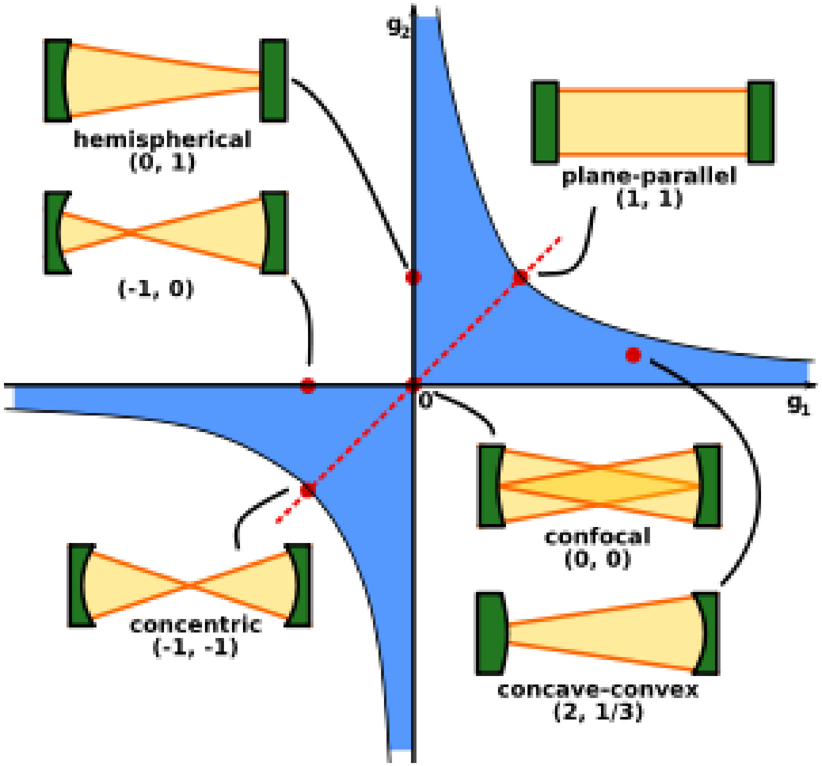
Cavity: Optical resonators

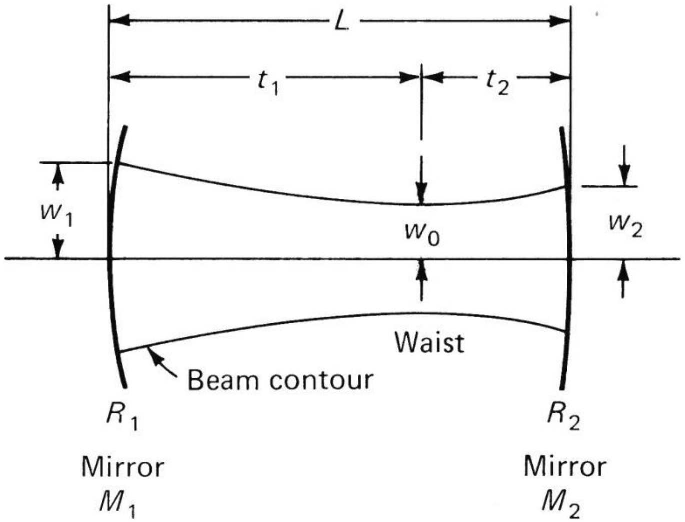




Credit: W. Koechner: Solid State Laser engineering,
Credit: Wekipedia

Stability of laser resonators





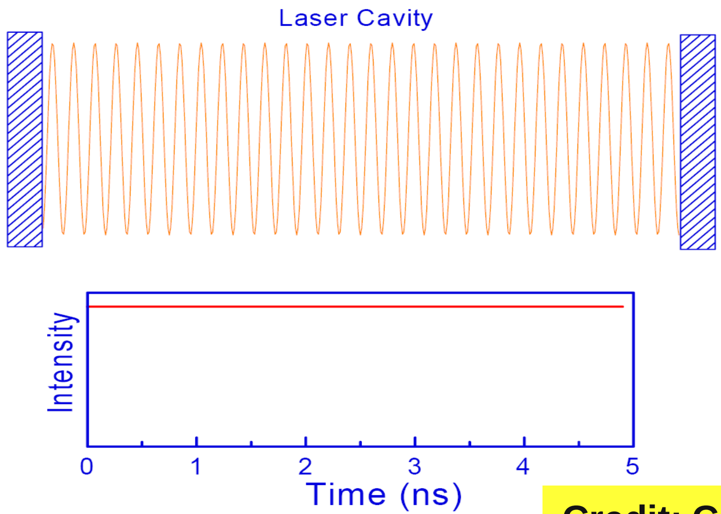
$$0 < \left(1 - \frac{L}{R_1}\right)\left(1 - \frac{L}{R_2}\right) < 2,$$

$$g_1 = 1 - \frac{L}{R_1},$$

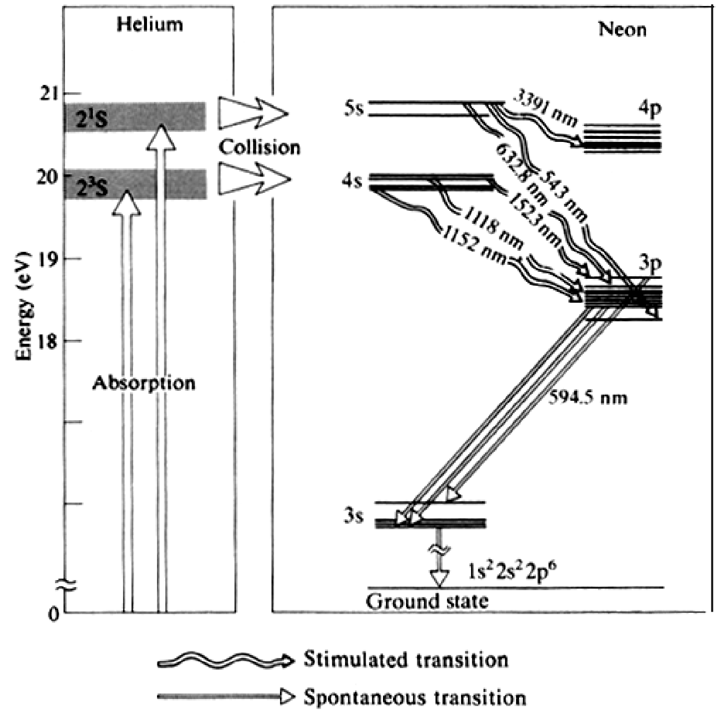
$$g_2 = 1 - \frac{L}{R_2}.$$

Credit: W. Koechner: Solid State Laser engineering,
Credit: Wekipedia

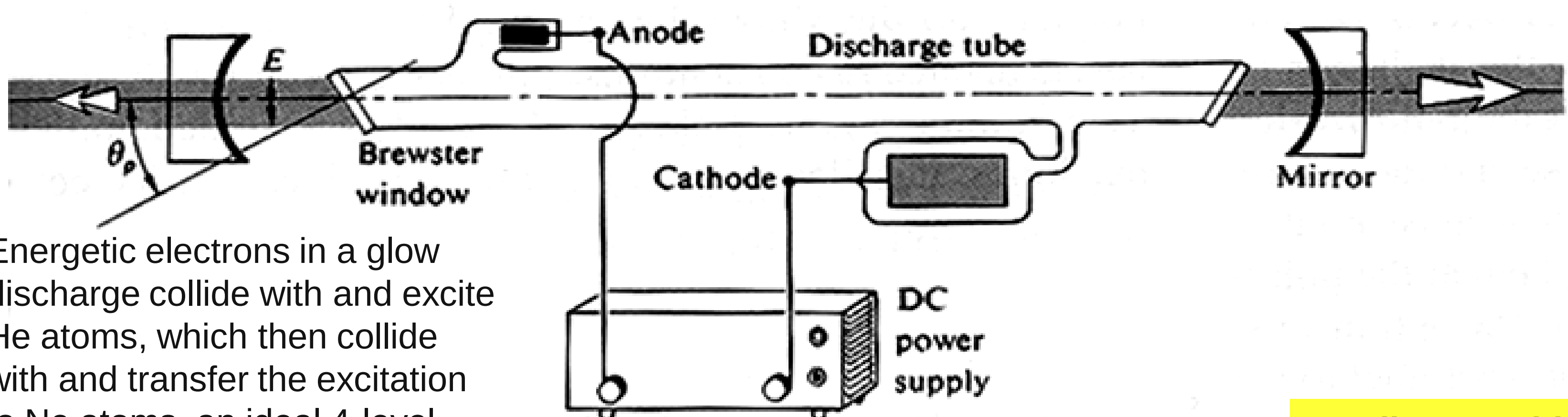
A cavity and laser oscillator



Credit: Cundiff, UCB



Resonant condition for cavity: L=nλ



Energetic electrons in a glow discharge collide with and excite He atoms, which then collide with and transfer the excitation to Ne atoms, an ideal 4-level system.

Credit: R. Trebino

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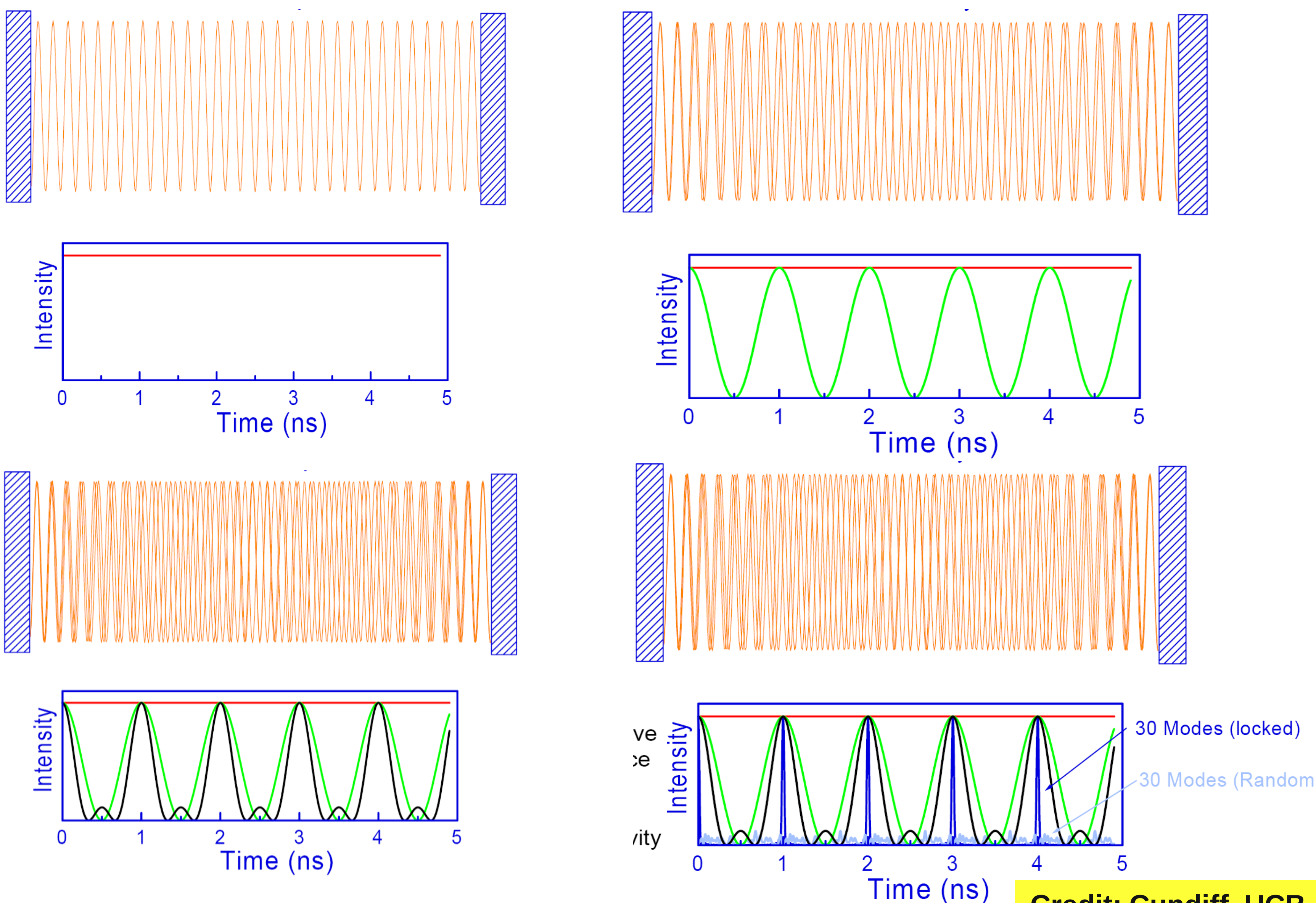
Mode locking: what



Credit: Cundiff, UCB

Mode locking: how

Introduce amplitude or phase modulation/control

Active mode locking

- Acousto-optic modulator, driven by RF

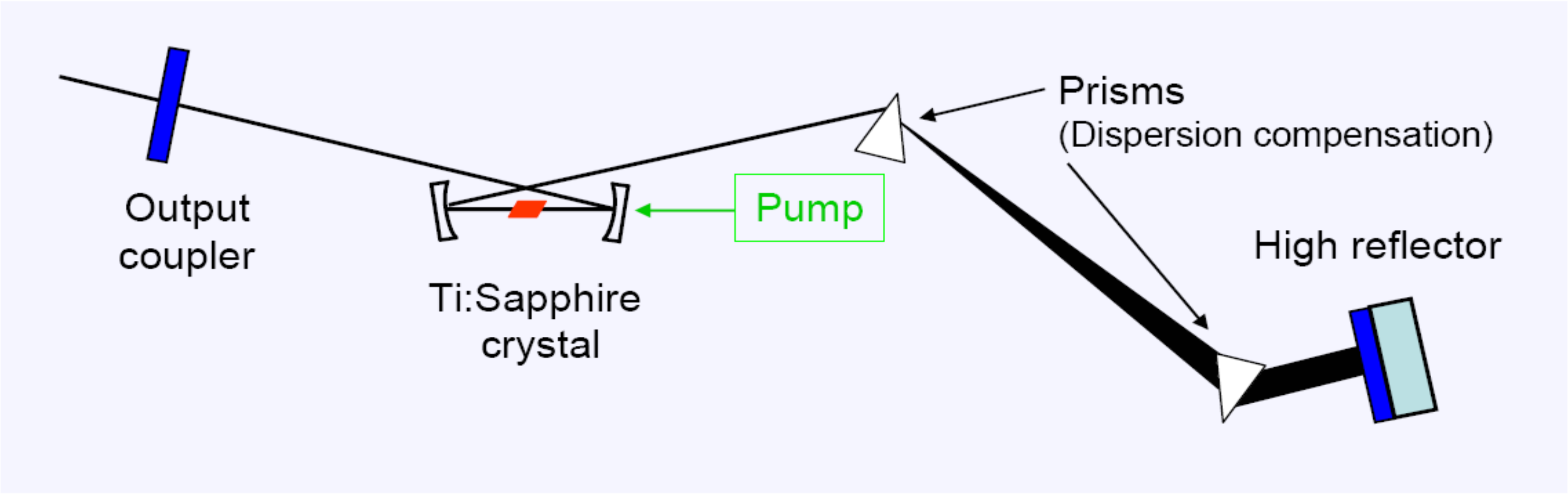
Passive mode locking

- Saturable absorption
- Nonlinear lensing + aperture
- Nonlinear polarization rotation + polarizer

Mode locking: result

- Shorter pulse, high intensity, larger bandwidth
- Single mode
- Accurate timing at round trip time

Ti: Sapphire oscillator: an example



M.T. Asaki, et al, Opt. Lett. 18, 977 (1993)

Femtolasers: Fusion

(28”x12”x3”)

Pulse duration	< 10 fs
Bandwidth (FWHM) @ 800 nm	> 100 nm
Mode locked output power (av.)	150 - 500 mW
Output energy @ 75 MHz	2 - 6.5 nJ
Peak power @ 75 MHz	200 - 650 kW

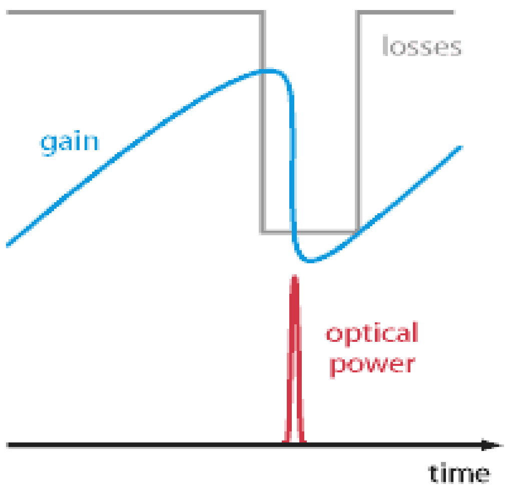
Q-switch

Q factor of a resonator

$$Q = \nu T \frac{2\pi}{L}$$

T: round trip time; ν: optical frequency;
l: fraction power loss per round trip

Q switch: reducing the loss

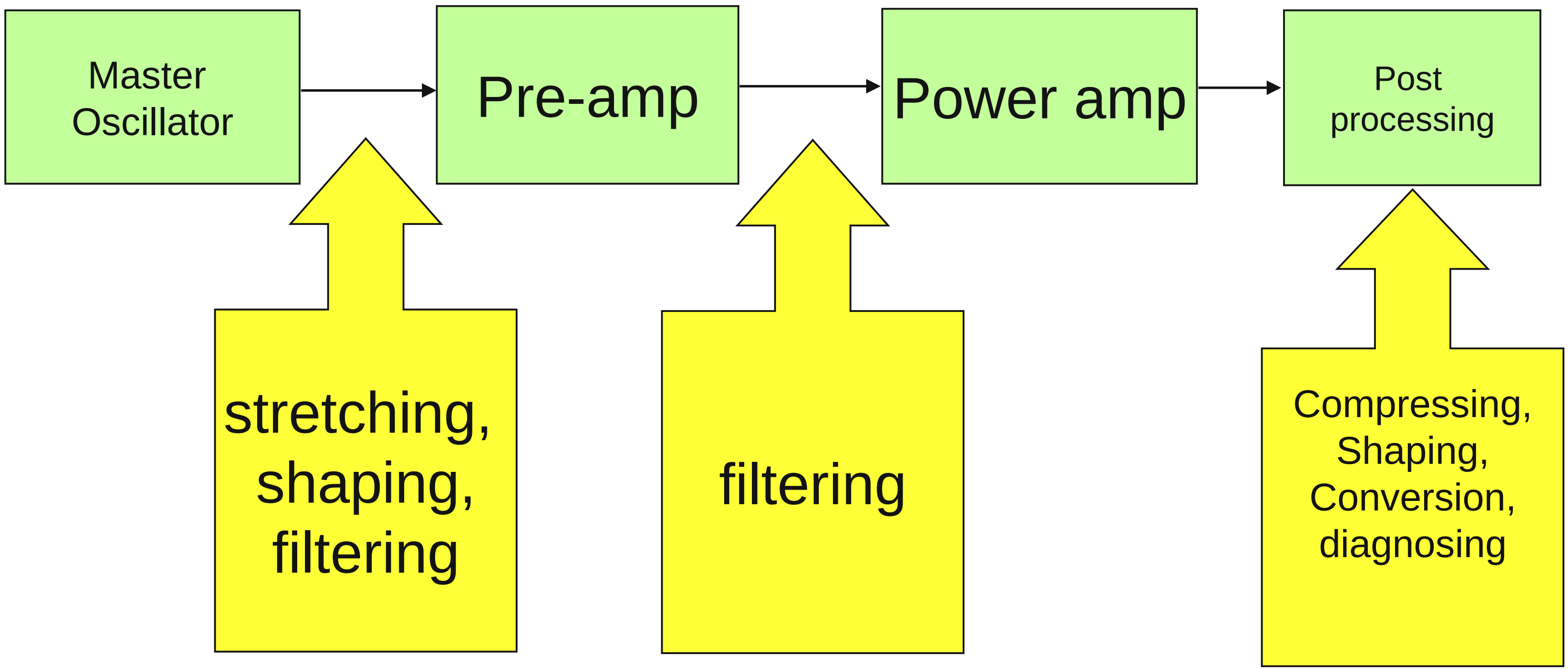


Active: accousto-optical, electro-optical, and mechanical

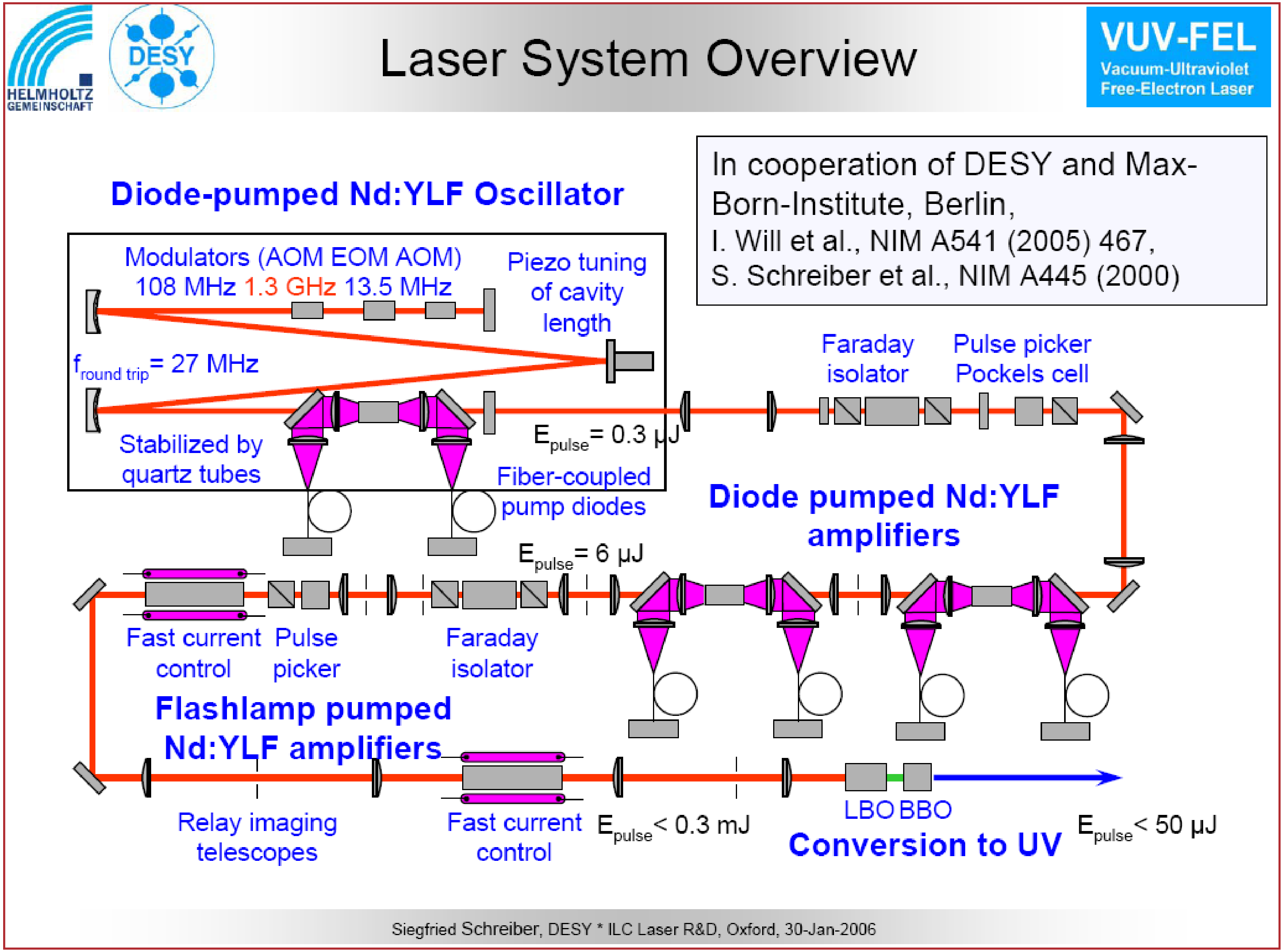
Passive: saturable absorbers

A MOPA system
Master Oscillator – Power Amplifier

- An oscillator usually does not have enough energy, thus needs amplification
- A MOPA is expected to carry over the characteristics of an OSC
- Pulse duration is limited at 10 ps due to damage



A MOPA example: Flash lamp drive laser



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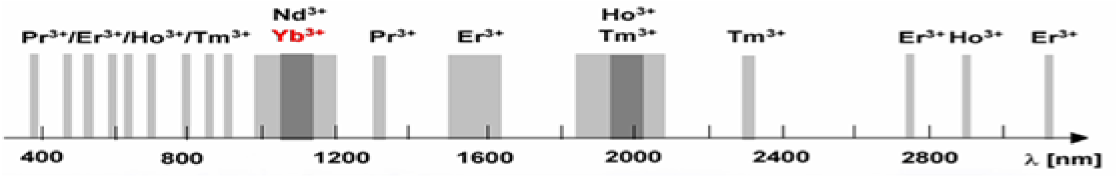
Laser materials

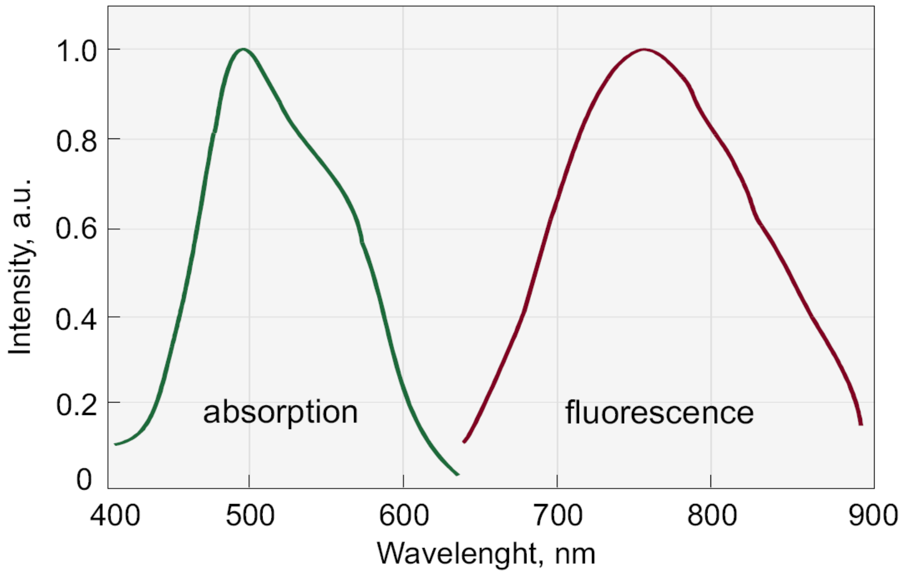
- What we care
  - Lasing mechanism: four-level systems is always preferred
  - Lasing wavelength: tunable is better
  - Lasing bandwidth: bigger is better but not always
  - Pump requirement: visible preferred
  - Gain lifetime: longer is better
  - Damage threshold: higher is better
  - Saturation flux: higher is better
  - Heat conductivity: as high as possible
  - Thermal stability: as small as possible
  - Form: solid is always preferred

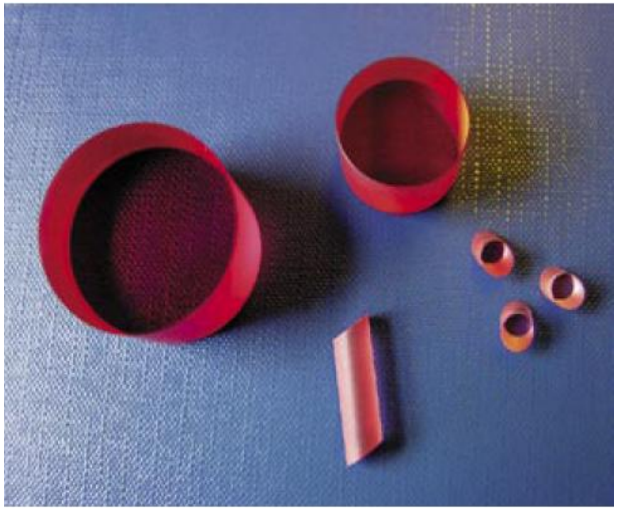
Laser materials

- Host + active ions
- Host
  - Crystalline solids (Sapphire, Garnets, Fluoride, Aluminate, etc.)
    - *Difficult to grow to large size*
    - *Narrow line width thus lower lasing threshold, and narrow absorption band*
    - *Good thermal conductivity*
  - Glass (property varies by make, and processing)
    - *Easy to make in large size and large quantities*
    - *No well defined bonding field thus larger line width and higher lasing threshold, large absorption band*
    - *Lower thermal conductivity thus severe thermal birefringence and thermal lensing, lower duty cycle*
- Active ions
  - Rare earth ions: No. 58-71, most importantly, Nd^{3+}, Er^{3+}…
  - Transition metals: Ti^{3+}, Cr^{3+},



Laser material: Ti: Saaphire ($Al_2O_3:Ti^{3+}$)



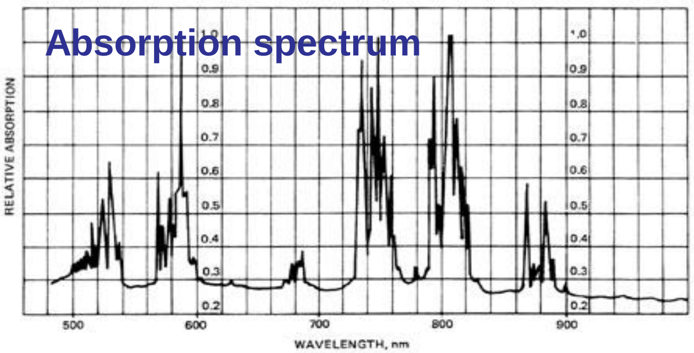


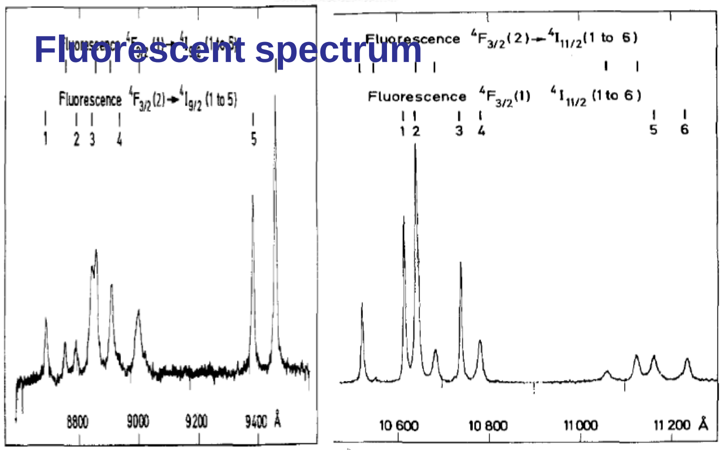
MATERIAL PHYSICAL AND LASER PROPERTIES

Chemical formula	$Ti^{3+}:Al_2O_3$
Crystal structure	Hexagonal
Lattice constants	a=4.748, c=12.957
Density	3.98 g/cm^3
Mohs hardness	9
Thermal conductivity	0.11 cal/(°C×sec×cm)
Specific heat	0.10 cal/g
Melting point	2050 °C
Laser action	4-Level Vibronic
Fluorescence lifetime	3.2 μsec (T=300K)
Tuning range	660–1050 nm
Absorbtion range	400–600 nm
Emission peak	795 nm
Absorption peak	488 nm
Refractive index	1.76 @ 800 nm

- Giving shortest pulse so far
- Wonderful tunability
- Good thermal properties
- Short gain lifetime (has to be pumped by a ns-pulsed green laser)

Laser material (Nd:YAG)





PROPERTIES OF 1.0% Nd:YAG AT 25°C

Formula	$Y_{2.97}Nd_{0.03}Al_5O_{12}$
Crystal structure	Cubic
Density	4.55 g/cm^3
Melting point	1970 °C
Mohs hardness	8.5
Transition	$^4F_{3/2} \rightarrow {}^4I_{11/2}$ @ 1064 nm
Fluorescence lifetime	230 μs for 1064 nm
Thermal conductivity	0.14 Wcm^{-1}K^{-1}
Specific heat	0.59 Jg^{-1}K^{-1}
Thermal expansion	6.9×10^{-6} °C^{-1}
∂n/∂t	7.3×10^{-6} °C^{-1}
Young's modulus	3.17×10^4 Kg/mm^{-2}
Poisson ratio	0.25
Thermal shock resistance	790 Wm^{-1}
Refractive index	1.818 @ 1064 nm

- High saturation flux
- Narrow bandwidth (0.15 nm), thus long pulse (>10 ps), high gain
- Good thermal properties
- Long gain lifetime (diode pump)

Laser material: (Nd:Glass)

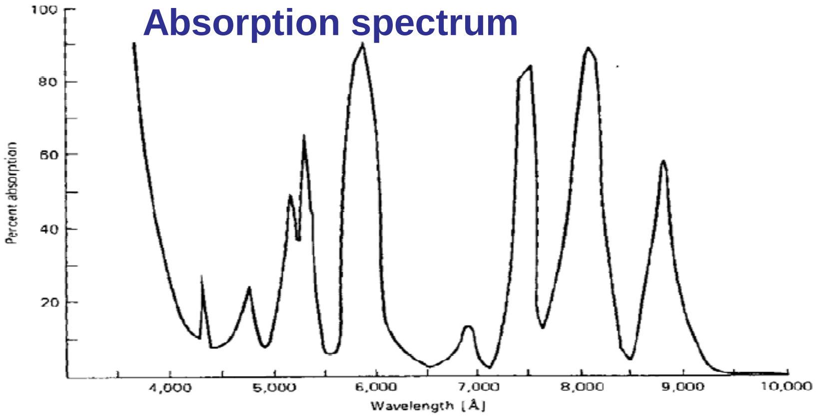
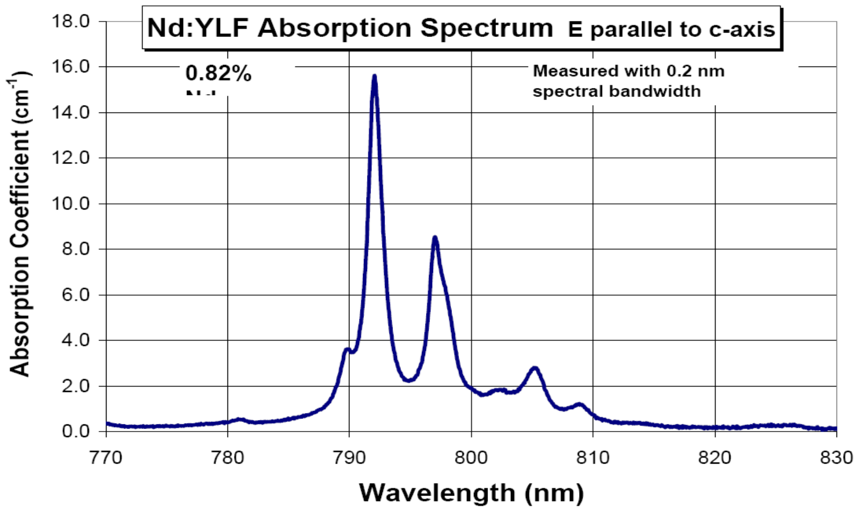


Fig. 2.9. Absorption versus wavelength of Nd: glass. (Material: ED-2; thickness: 6.3 mm)

Chemical formula	$Nd:Y_3Al_5O_{12}$
Weight % Nd	0.725
Atomic % Nd	1.0
Nd atoms/cm^3	1.38×10^{20}
Melting point	1970 C
Knoop hardness	1215
Density	4.56 g/cm^3
Rupture stress	$1.3–2.6 \times 10^3$ kg/cm^3
Modulus of elasticity	3×10^3 kg/cm^2
Thermal expansion coefficient	
[100] orientation	8.2×10^{-6} C^{-1}, 0–250 C
[110] orientation	7.7×10^{-6} C^{-1}, 10–250 C
[111] orientation	7.8×10^{-6} C^{-1}, 0–250 C
Linewidth	4.5 Å
Stimulated emission cross section	
$R_2 - Y_3$	$\sigma_{21} = 6.5 \times 10^{-19}$ cm^2
$4F_{3/2} - {}^4I_{11/2}$	$\sigma_{21} = 2.8 \times 10^{-19}$ cm^2
Spontaneous fluorescence lifetime	230 μs
Photon energy at 1.06 μm	$h\nu = 1.86 \times 10^{-19}$ J
Index of refraction	1.82 (at 1.0 μm)
Scatter losses	$\alpha_{sc} \approx 0.002$ cm^{-1}

- High saturation flux
- large bandwidth (20 nm), thus short pulse (<1 ps),
- Poor thermal
- Long gain lifetime (diode pump)
- Only for big lasers now (PW or MJ)

Laser Material: Nd:YLF



- High saturation flux
- Narrow bandwidth (0.15 nm), thus long pulse (>10 ps), high gain
- Good thermal properties
- Long gain lifetime (diode pump)
- Difficult to handle

Physical Properties	
Chemical Formula	$LiY_{1.0-x}Nd_xF_4$
Lattice Parameters	a=5.16Å b=10.85Å
Crystal Structure	Tetragonal
Space Group	$I4_1/a$
Nd atoms/cm3	1.40×10^{20} atoms/cm^3 for 1% Nd doping,
Mohs Hardness	4 ~ 5
Melting Point	819℃
Density	3.99 g/cm^3
Modulus of Elasticity	85 GPa
Thermal Expansion Coefficient	8.3×10^{-6}/k ⊥c, ac=13.3×10^{-6}/k ||c
Thermal Conductivity Coefficient	0.063 W/cm K
Specific Heat	0.79 J/g K
Optical Properties	
Transparency Region	180nm to 6.7μm
Peak Simulation Emission Cross Section	1.8×10^{-19}cm^2 (E || c) at 1.047μm 1.2×10^{-19}cm^2 (E ⊥ c) at 1.053μm
Spontaneous Fluorescence Lifetime	485μs for 1% Nd doping
Scatter Losses	<0.2% / cm
Peak Absorption Coefficient	α=10.8cm^{-1} (792.0 nm E || c) α=3.59cm^{-1} (797.0 nm E ⊥ c)
Refractive Indices	Wavelength (nm) / n_e / n_e 262 / 1.485 / 1.511 350 / 1.473 / 1.491 525 / 1.456 / 1.479 1050 / 1.448 / 1.470 2065 / 1.442 / 1.464
Sellmeier Equations	$n_i^2(\lambda) = A + B\lambda^2/(\lambda^2-C) - D\lambda^2/(\lambda^2-E)$ A / B / C / D / E n_o 3.38757 0.70757 0.00931 0.18849 50.99741 n_2 1.31021 0.84903 0.00876 0.53607 134.9566

Laser materials: summary

	Ti:Sa Al_2O_3:Ti	Nd:YAG $Y_{3.0-x}Nd_xAL_5O_{12}$	Nd:Glass (Kigre Q-88) $Y_3Al_5O_{12}$:Nd	Nd:YLF $LiY_{1.0-x}Nd_xF_4$
Fluorescence life time (μs)	3.2	230	330	485
Peak wavelength (nm)	780	1064	1054	1047,1053
Line width (nm)	220	0.15	22	1
Emission cross section (10^{-19} cm^2)	3	6.5	0.4	1.8
Saturation flux (J/cm^2)	0.9	0.6	4.5	.43
Thermal conductivity ($w\ cm^{-1}\ K^{-1}$)	0.5	0.14	0.0084	0.06
Thermal expansion coef (10^{-6}/°C)		7.5	10	10
n	1.76	1.8	1.55	1.5
dn/dT (10^{-6}/°C)		7.3	-0.5	

Content

- Laser and accelerator history
- Map of laser application in accelerators
- Laser basics
  - Rate equations
  - Laser configurations
  - Gaussian beam optics and ABCD law
  - Laser cavity and laser modes
- Laser configurations
  - Mode-lokcing and q-switch
  - MOPA
  - CPA and dispersion
- Laser materials
- Other lasers
  - Semiconductor lasers
  - Fiber lasers
- Frequency conversion and short wavelength lasers

Semiconductor laser: laser diode

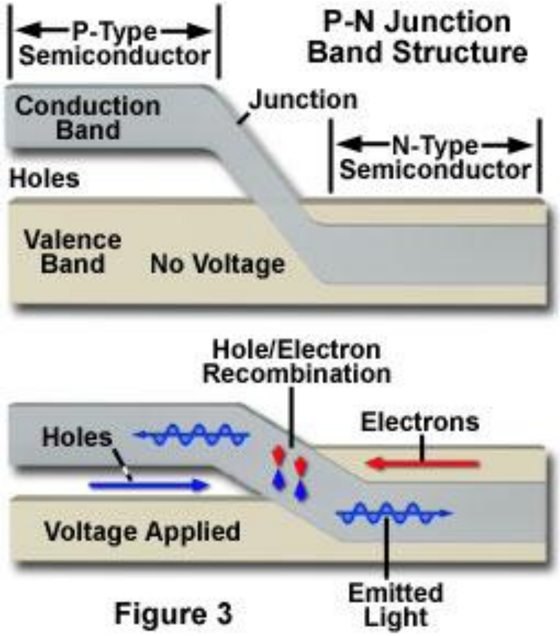


Figure 3

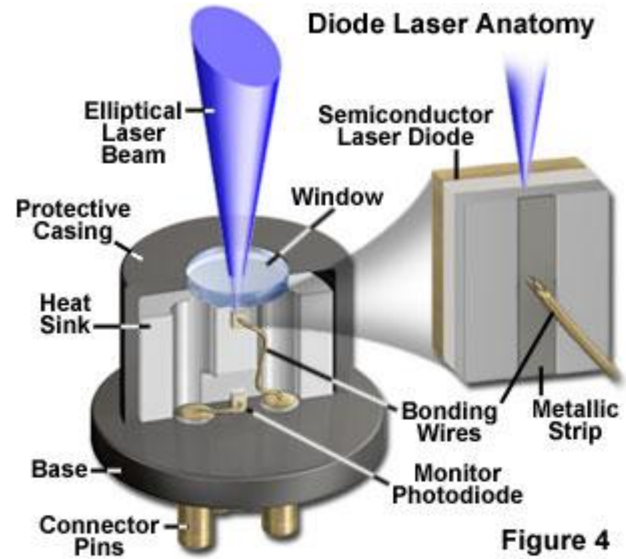
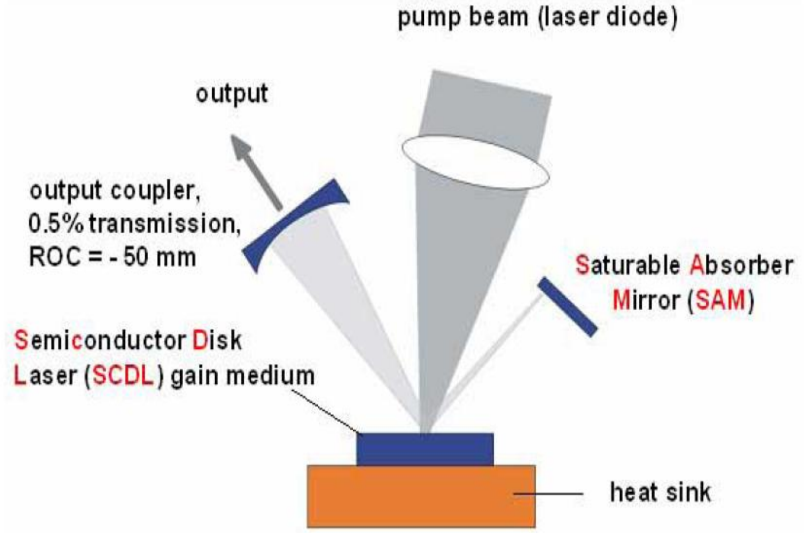


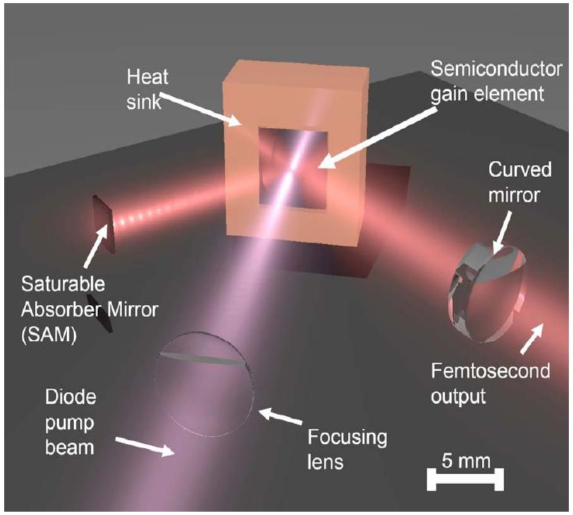
Figure 4

- Convert current into light, can be tuned by junction temperature
- Used mostly for pumping other lasers, also CD and DVD players
- VCSELs and VECSELs (virtical cavity surface emission lasers and virtical exteranl cavity surface emission lasers)
- Also for seeding pulse fiber lasers (next page)

Credit: http://www.olympusmicro.com/

Mode-locked semiconductor lasers: (using V)





$\lambda_{laser} \approx 1040$ nm

$\lambda_{pump} = 840$ nm

290-fs pulses from a semiconductor disk laser

Peter Klopp[1], Florian Saas[1], Martin Zorn[2], Markus Weyers[2], and Uwe Griebner[1*]

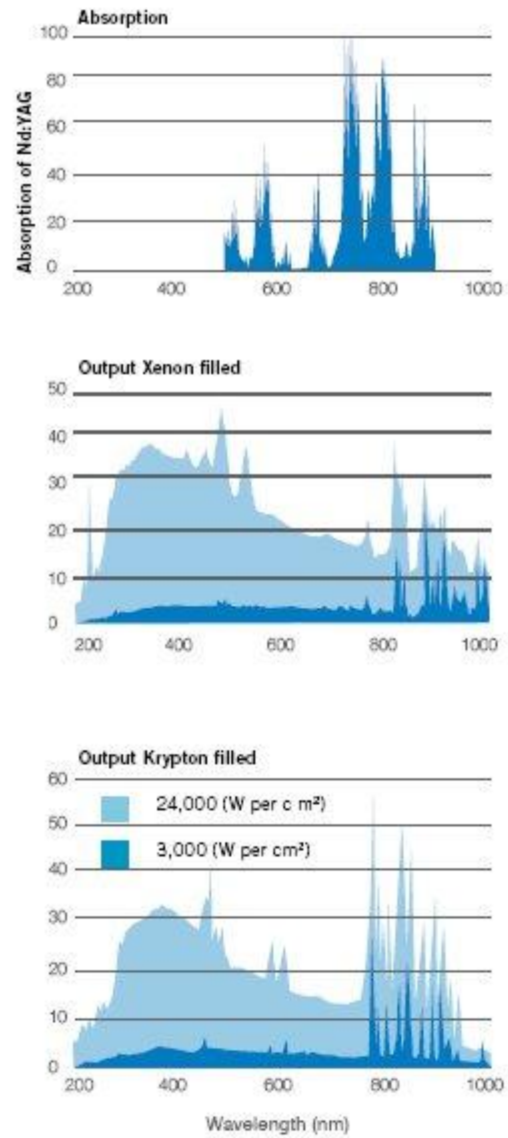
[1]Max-Born-Institute, Max-Born-Strasse 2A, D-12489 Berlin, Germany
[2]Ferdinand-Braun-Institute, Gustav-Kirchhoff-Straße 4, D-12489 Berlin, Germany
**Corresponding author: griebner@mbi-berlin.de*

Opt. Express 16, 5770 (2008)

- Can achieve sub picosecond pulse duration
- 500 mW power
- Widely tunable
- Very high rep rate, up to 100 GHz

Pump for lasers

- Flash lamps:
  - Converts electrical power to light
  - Cheap, low pumping efficiency, and poor stability.
  - Still opted for situations when high energy capacity is the key (NIF), suitable for ruby laser, Nd:Glass, Nd:YAG, Nd:YLF, etc.
- Laser diodes:
  - converts electrical current into light
  - High efficiency, high stability especially in CW mode.
  - Opted now for most off the shelf KHz system and fiber lasers
- Pump lasers (Nd:YAG or Nd: YLF)
  - Both pumped by flash lamps and diodes
  - Normally for Ti: Sapphire system.

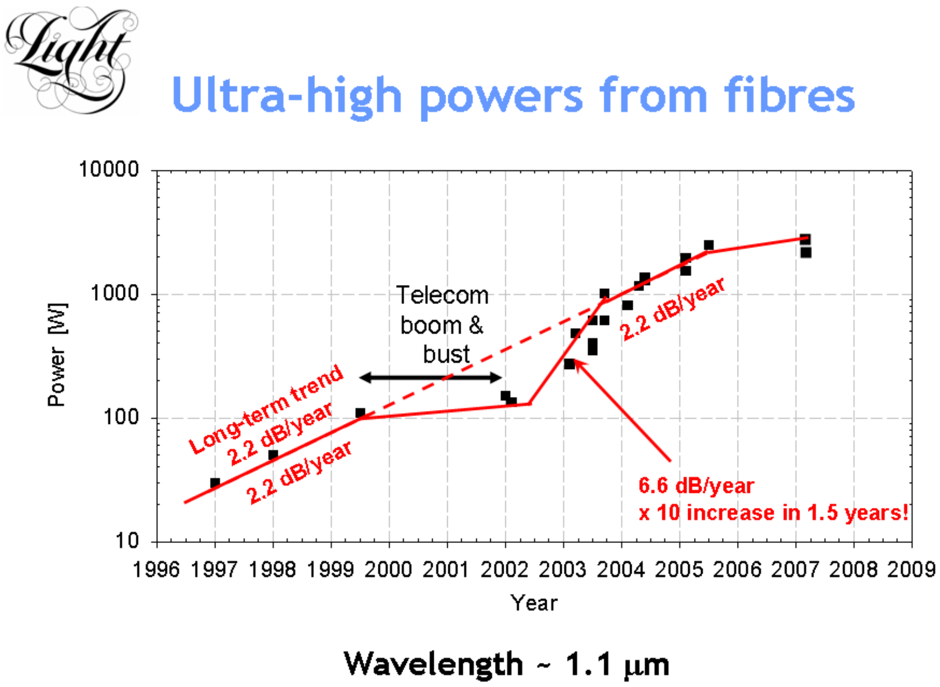


Fiber lasers

Power progress in fiber laser sources

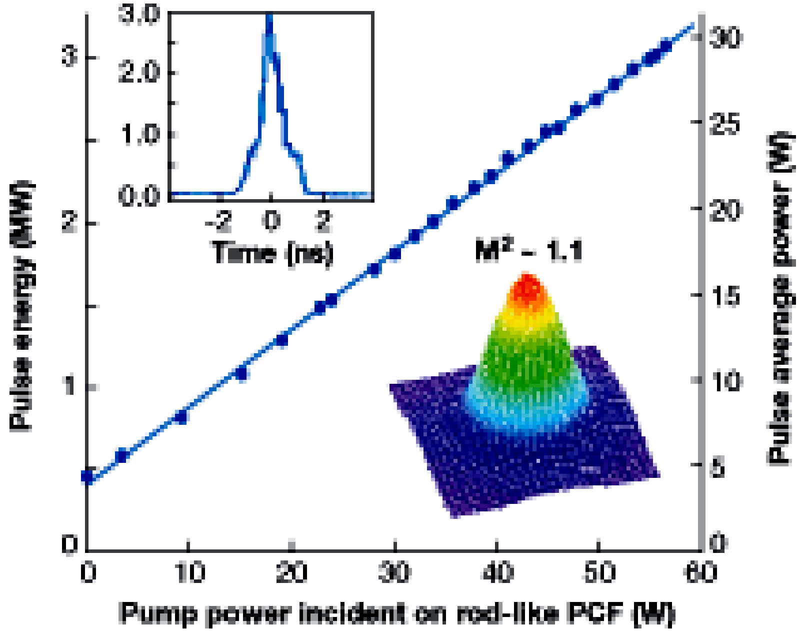
Average power over 2 kW

limited by available pump



Credit: David Richardson

Peak Power over 1 MW



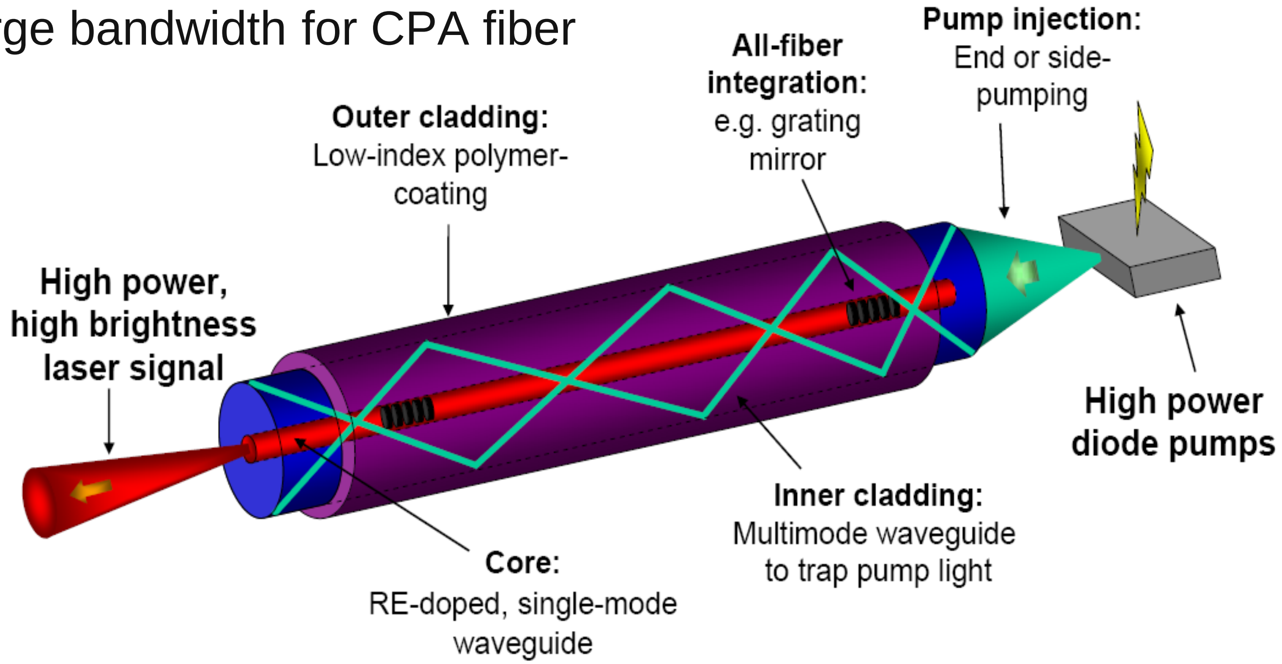
Teodoro et al, Laser Focus World, Nov. 2006

E. Snitzer, "Neodymium glass laser," Proc. of the Third International conference on Solid Lasers, Paris, page 999 (1963).
C.J. Koester and E.Snitzer, "Amplification in a fiber laser," Appl. Opt. 3, 10, 1182 (1964).

Argonne NATIONAL LABORATORY

Laser configuration: Fiber lasers

- Can be a straight MOPA or a CPA
- Low threshold, high efficiency, high rep rate, high power
- No thermal problem, good stability
- Relatively large bandwidth for CPA fiber

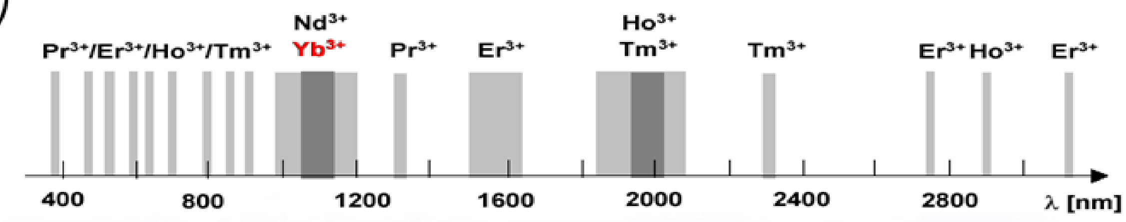


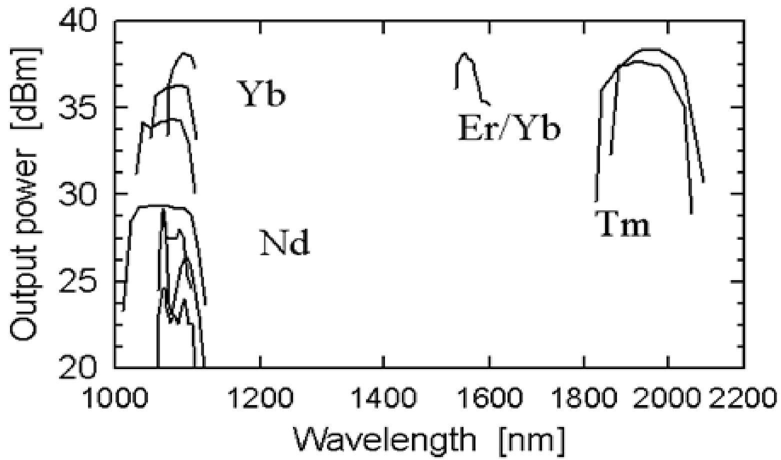
Rare-earth-doped core converts multimode pump energy to high brightness, *diffraction-limited*, signal beam

Credit: David Richardson
J. Limpert et al., 'High-power ultrafast fiber laser systems,' IEEE Xplore 12, 233 (2006).

Fiber laser wavelength

Wavelength Coverage

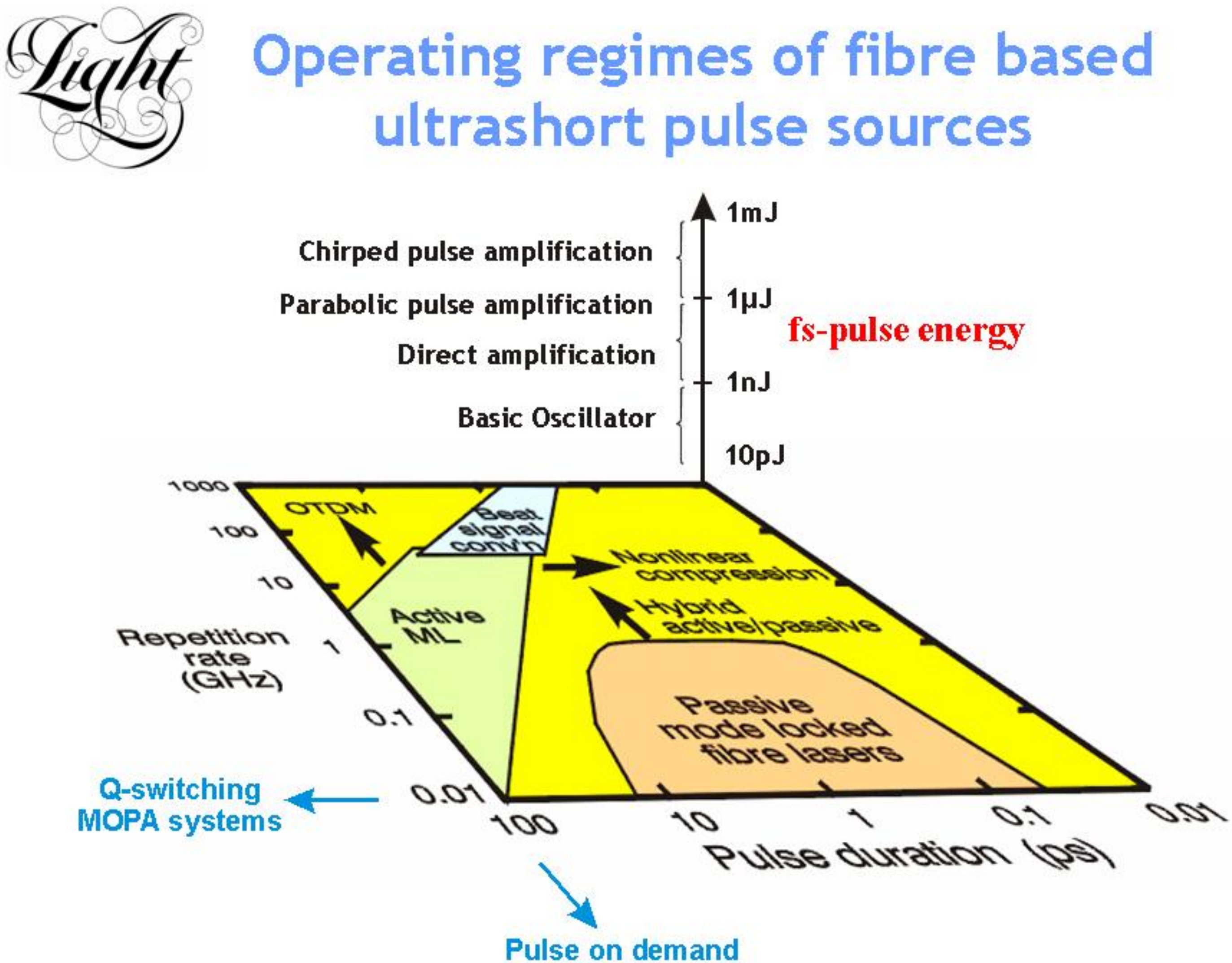




- Many RE transitions but most not good in silica
- Nd, Yb, Er, Tm most attractive for high power operation
- Raman gain for other wavelengths

Credit: David Richardson

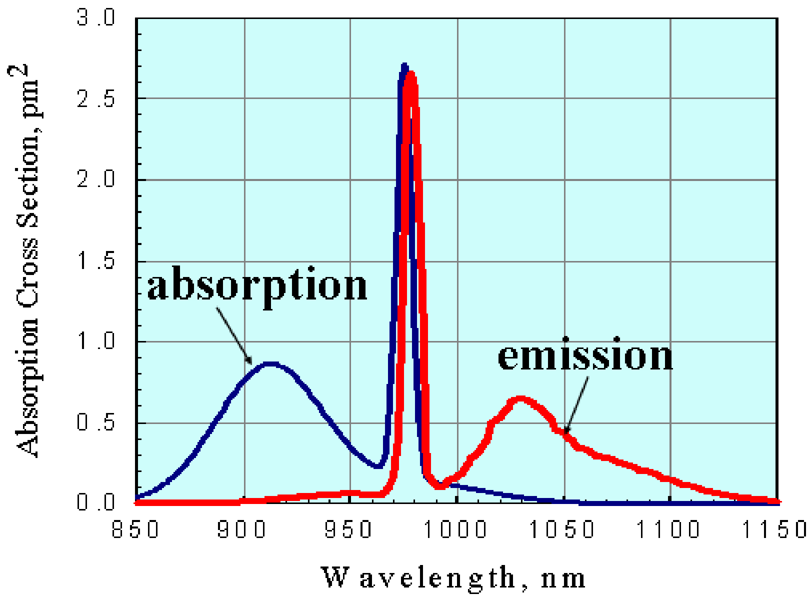
Fiber laser capabilities



Credit: David Richardson

Fiber laser architecture

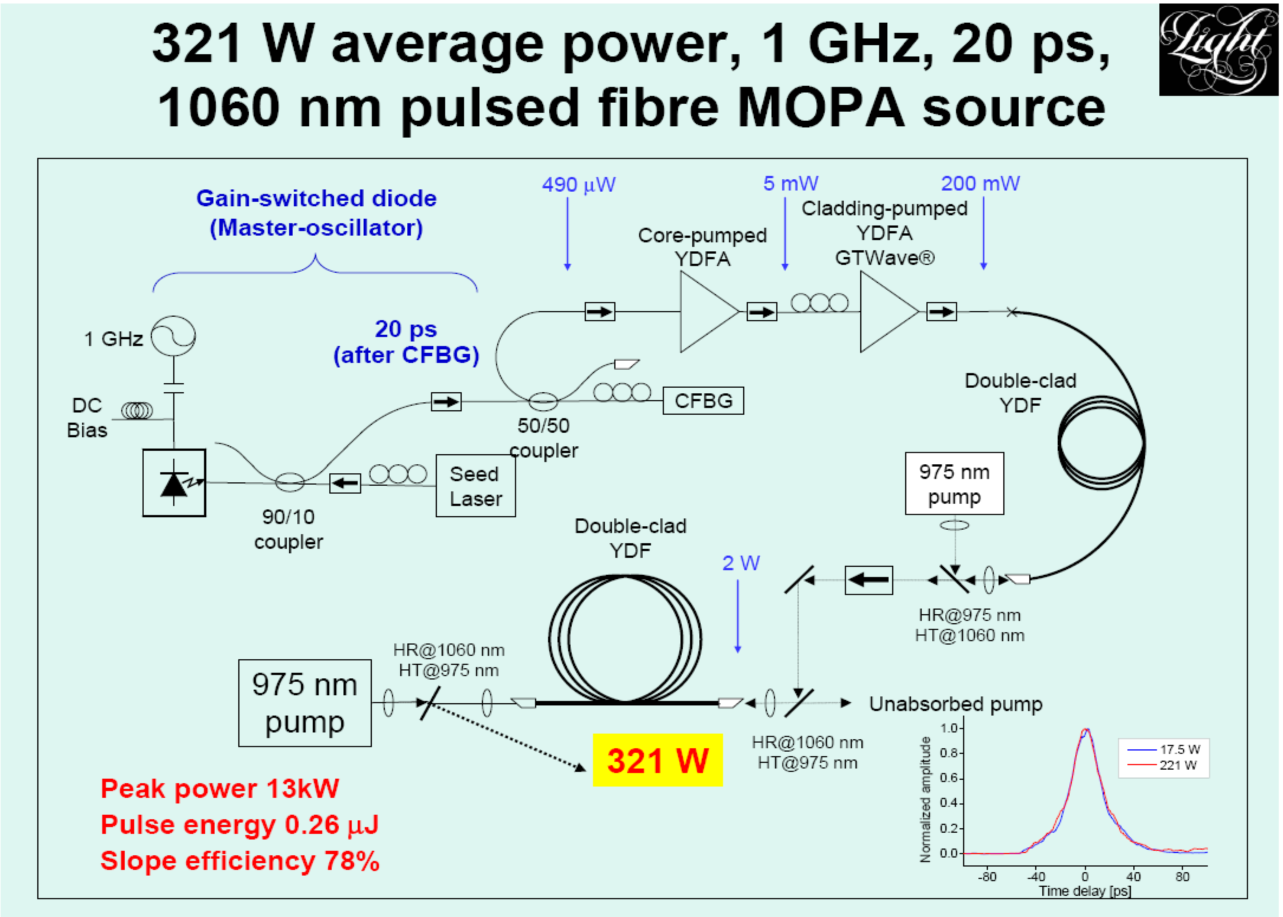
Yb-doped fibres for cladding pumping



- Pump bands at 915nm and 976nm
- Broad gain bandwidths around 1060nm
- Small quantum defect and high efficiency (~85%)

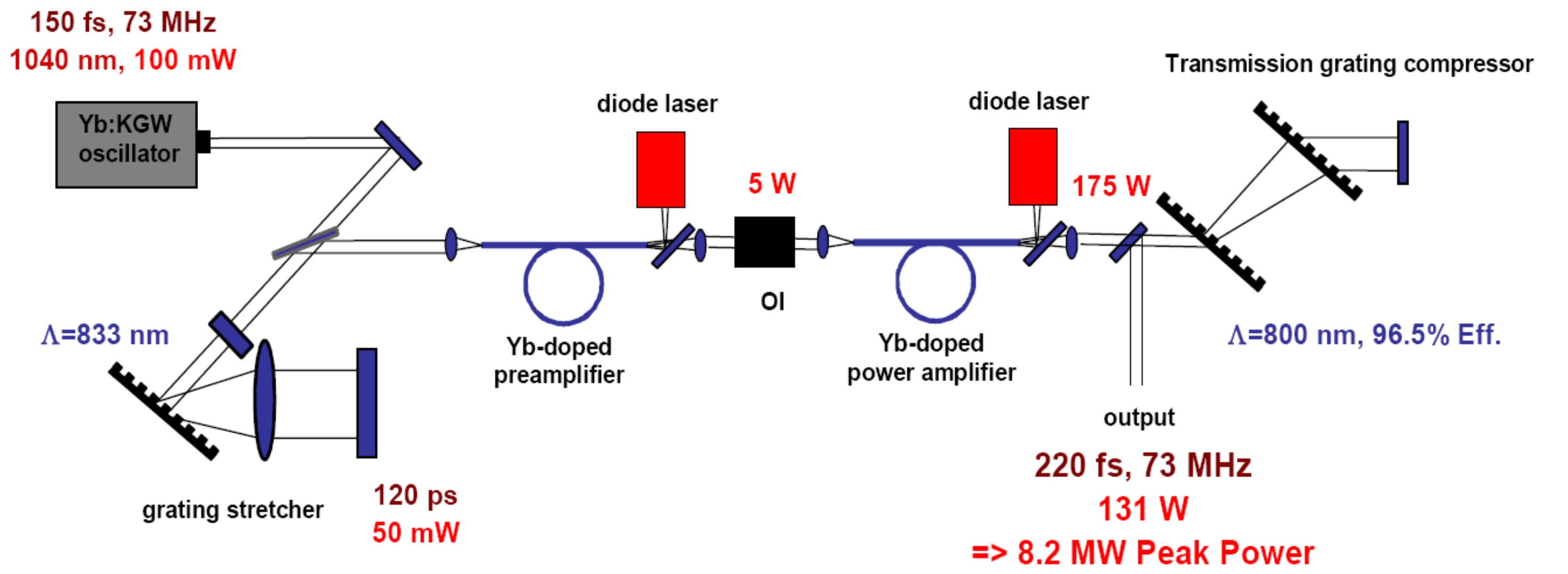
Credit: David Richardson

A short pulse MOPA fiber laser example
1 GHz, 20 ps, 321 W average and 13 kW peak power



Dupriez et al, http://www.ofcnfoec.org/materials/PDP3.pdf

A CPA fiber laser example
73 MHz, 220 fs, 131 W average and 8.2 MW peak power



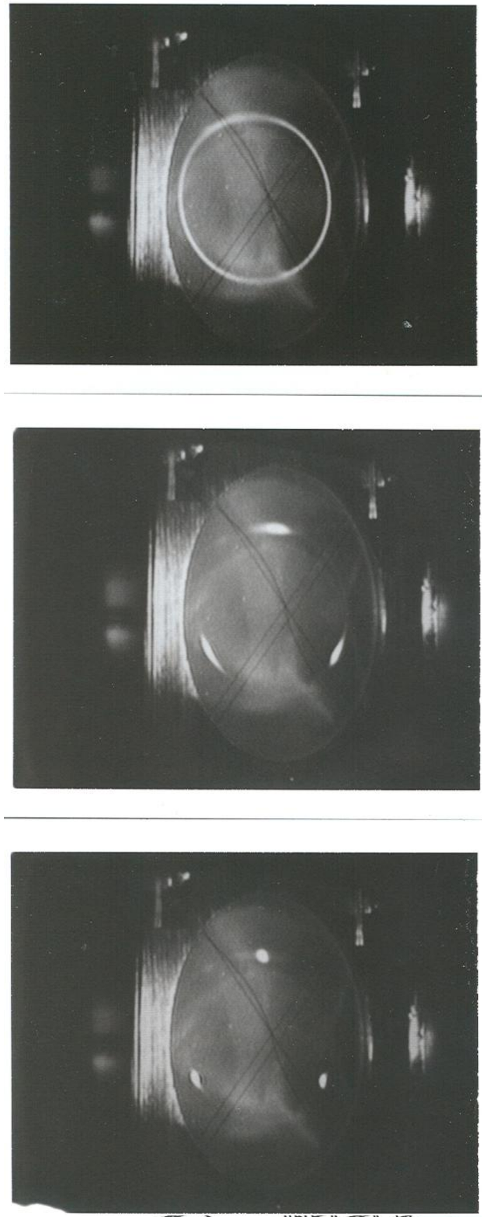
Roeser et al., Opt. Lett. 30, 2754 (2005)

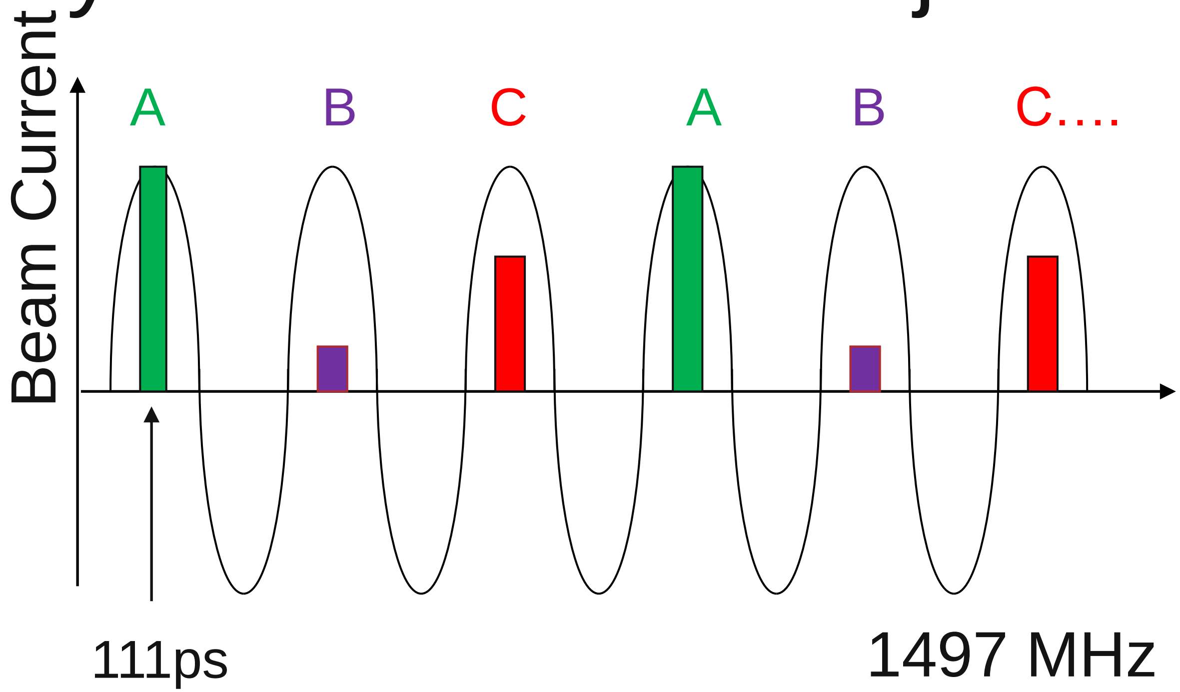
Fig. 9: Schematic setup of the high average power fiber CPA system.

1 μm, 1 mJ, 1 ps, 50 kHz has been achieved, F. Roeser et al, Opt. Lett. 32, 3294 (2007)

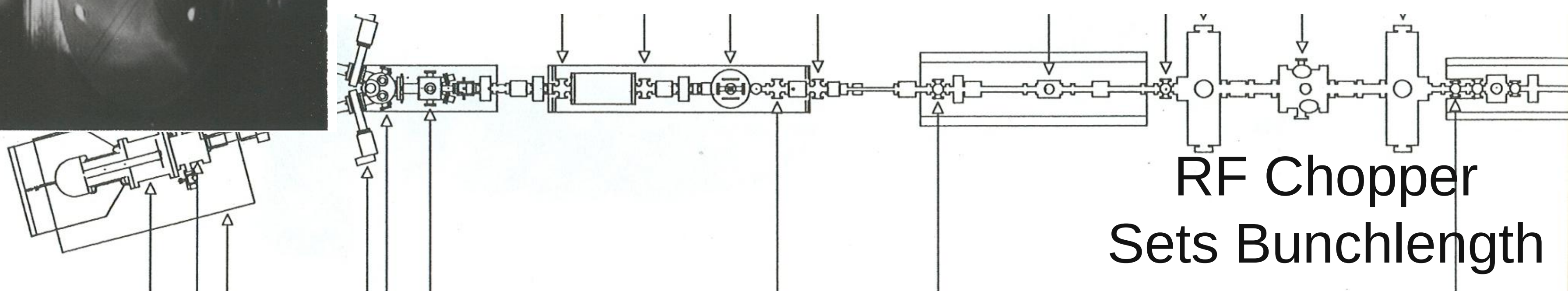
J. Limpert et al., 'High-power ultrafast fiber laser systems,' IEEE Xplore 12, 233 (2006).

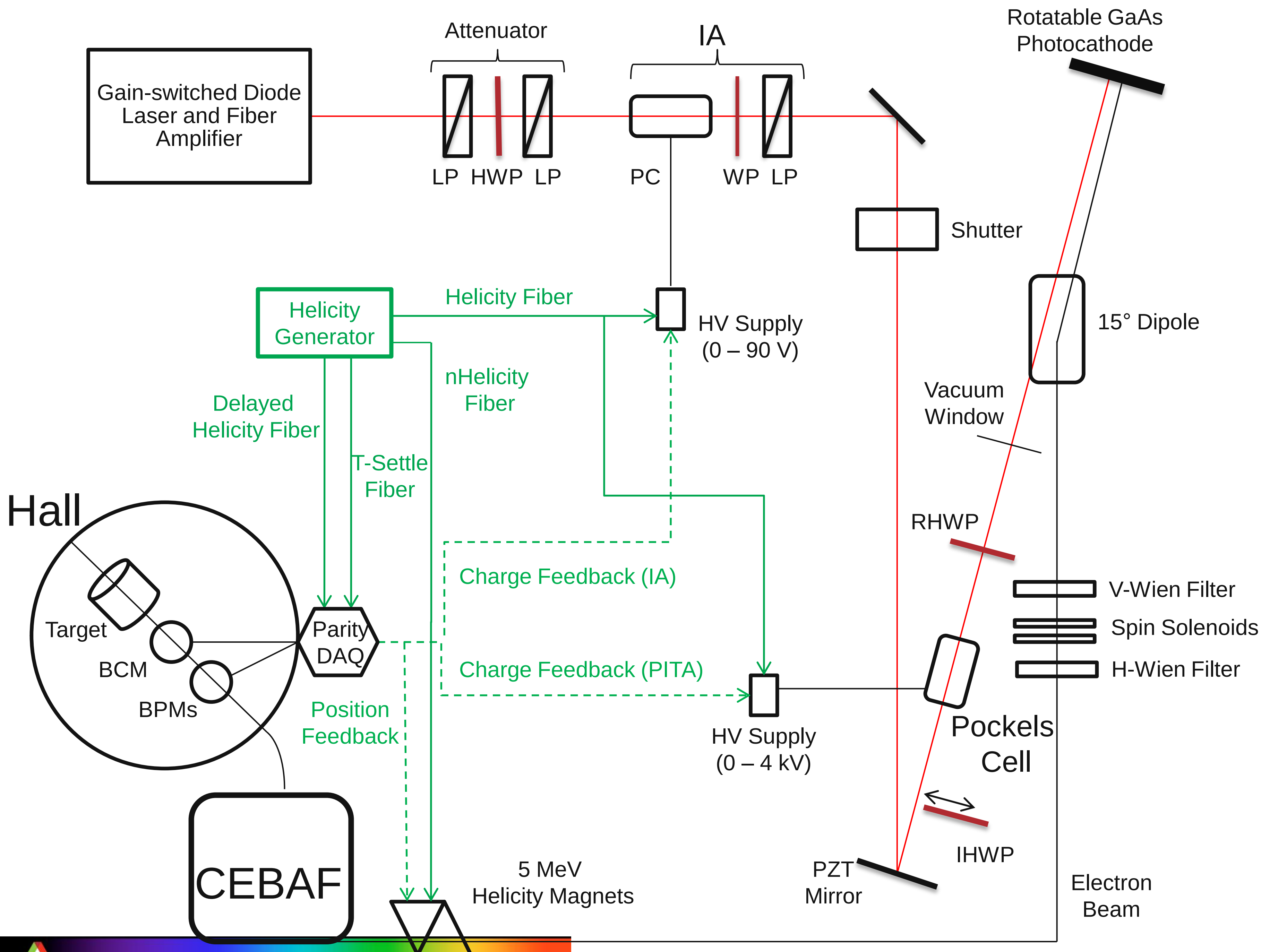
Synchronous Photoinjection



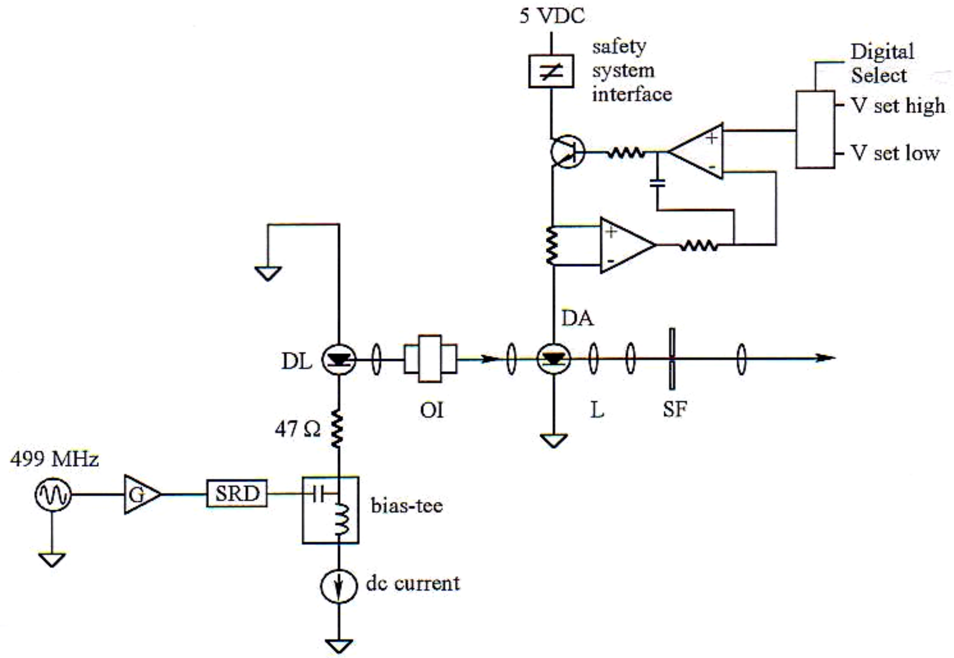


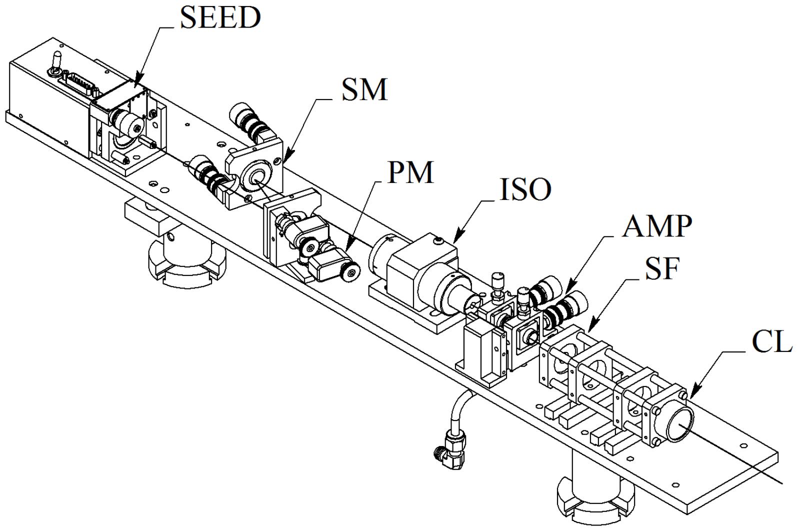
Extracting DC beam, very wasteful, most of the beam dumped at chopper. Need ~ 2mA from gun to provide 100uA to one hall. Gun lifetime not good enough…..yet.

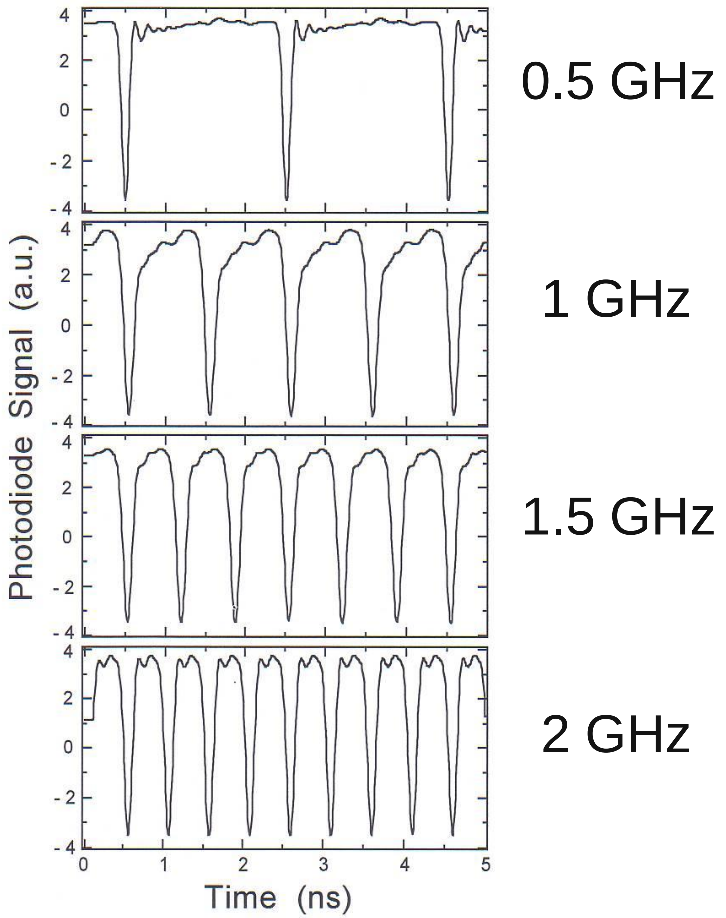



Gain-switched Diode Laser and Fiber Amplifier
Attenuator
LP HWP LP
IA
PC
WP LP
Rotatable GaAs Photocathode
Shutter
Helicity Generator
Helicity Fiber
HV Supply (0 – 90 V)
15° Dipole
nHelicity Fiber
Delayed Helicity Fiber
T-Settle Fiber
Vacuum Window
Hall
RHWP
Charge Feedback (IA)
V-Wien Filter
Target
Parity DAQ
Spin Solenoids
BCM
Charge Feedback (PITA)
H-Wien Filter
BPMs
Position Feedback
HV Supply (0 – 4 kV)
Pockels Cell
IHWP
CEBAF
5 MeV Helicity Magnets
PZT Mirror
Electron Beam

MOPA - with Gain Switched Diode

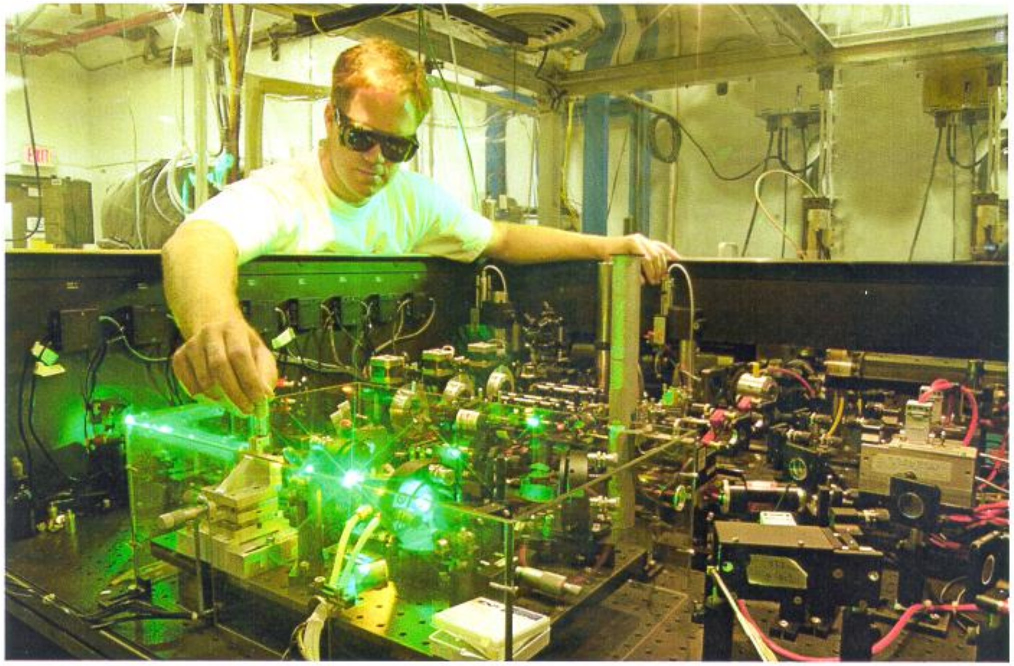






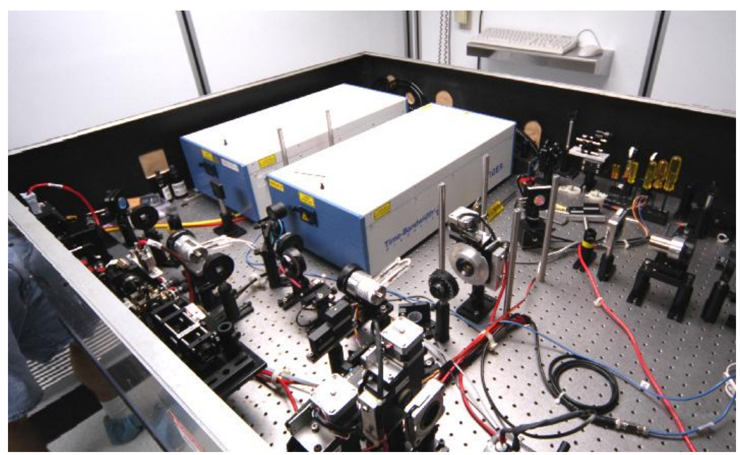
- Easy to phase lock to accelerator
- Components readily available at 780nm and 850nm but…..
- Not easily wavelength tunable and
- Not much power, only ~ 100mW

Ti-Sapphire Lasers at CEBAF



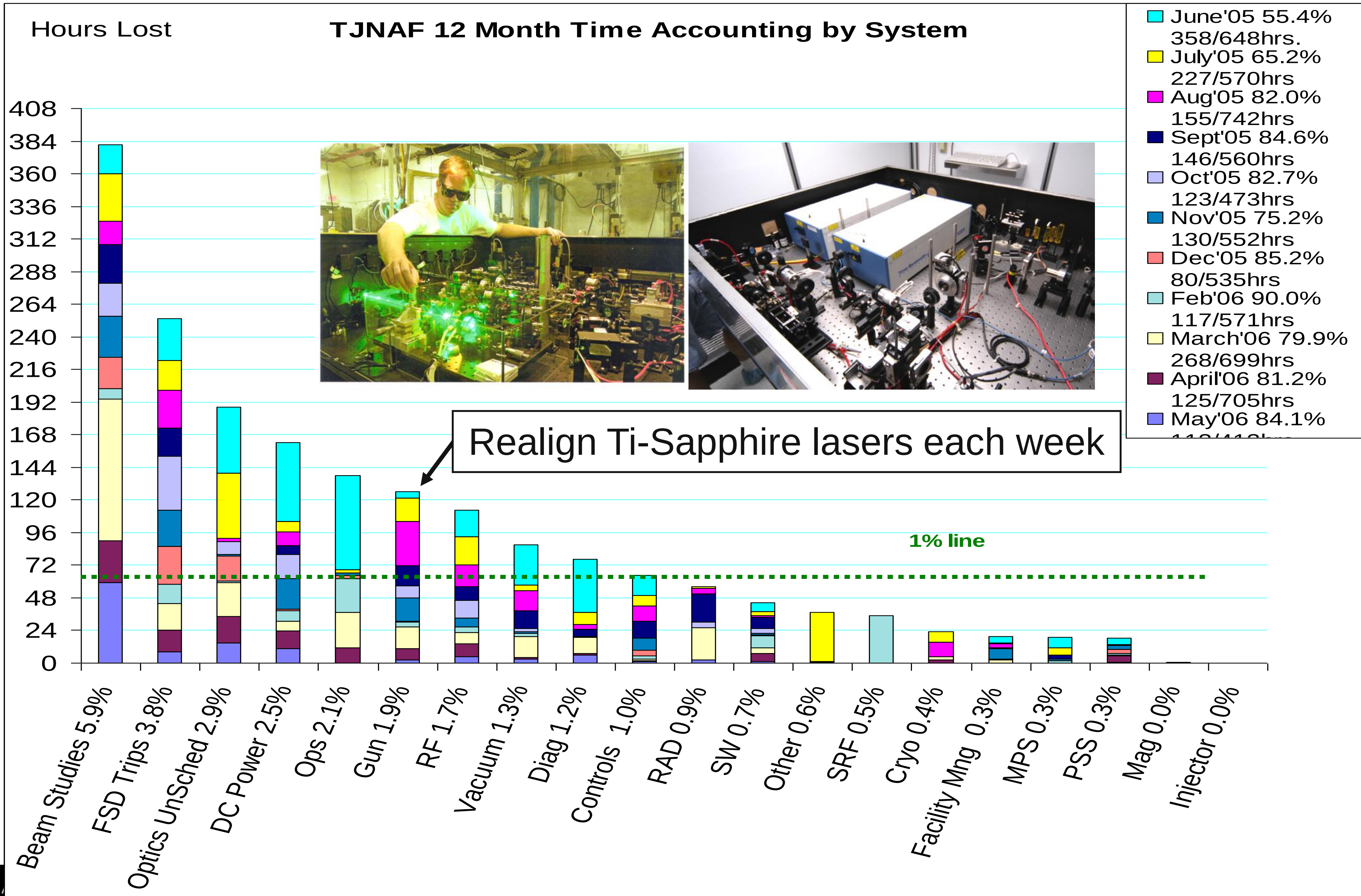
- Needed more laser power for high current experiments
- Diode lasers out, ti-sapphire laser in
- Re-align Ti-Sapphire lasers each week

Homemade harmonic modelocked Ti-Sapphire laser. Seeded with light from gain switched diode. No active cavity length feedback. It was a bit noisy….

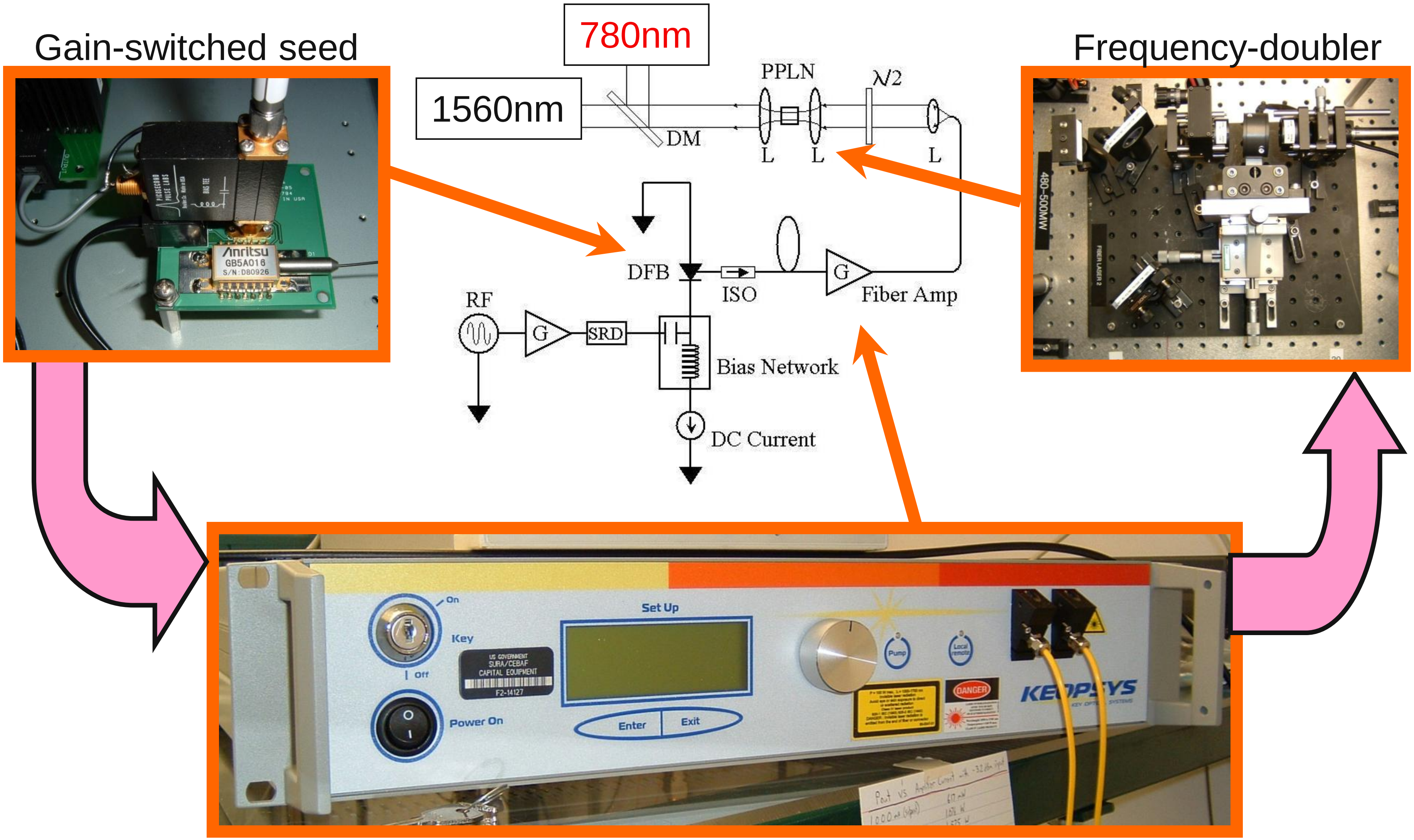


Commercial laser with 499MHz rep rate from Time Bandwidth Products

Accelerator Downtime FY05Q4 – FY06Q3

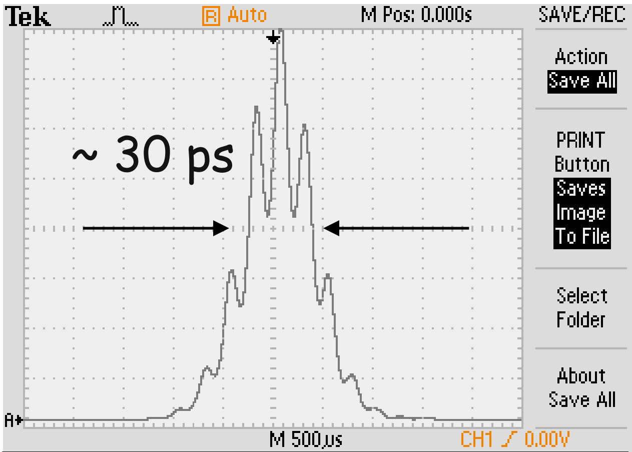


Fiber-Based Drive Laser

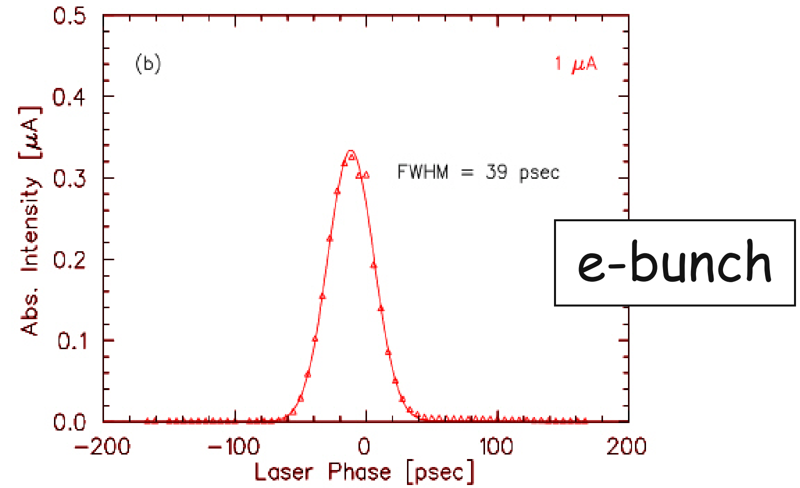


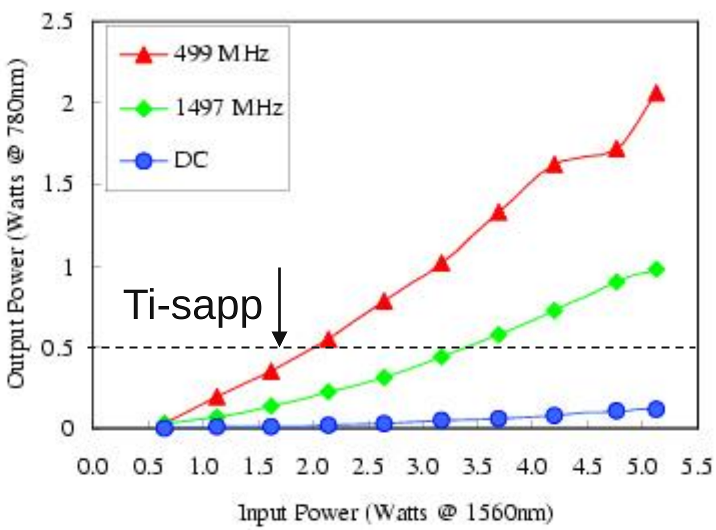
ErYb-doped fiber amplifier

Fiber-Based Drive Laser



autocorrelator trace





- CEBAF's last laser!
- Gain-switching better than modelocking; no phase lock problems, no feedback
- Very high power
- Telecom industry spurs growth, ensures availability
- Useful because of superlattice photocathode (requires 780nm)

Accelerator Downtime FY06Q4 – FY07Q3