Designing and Characterizing the laser system

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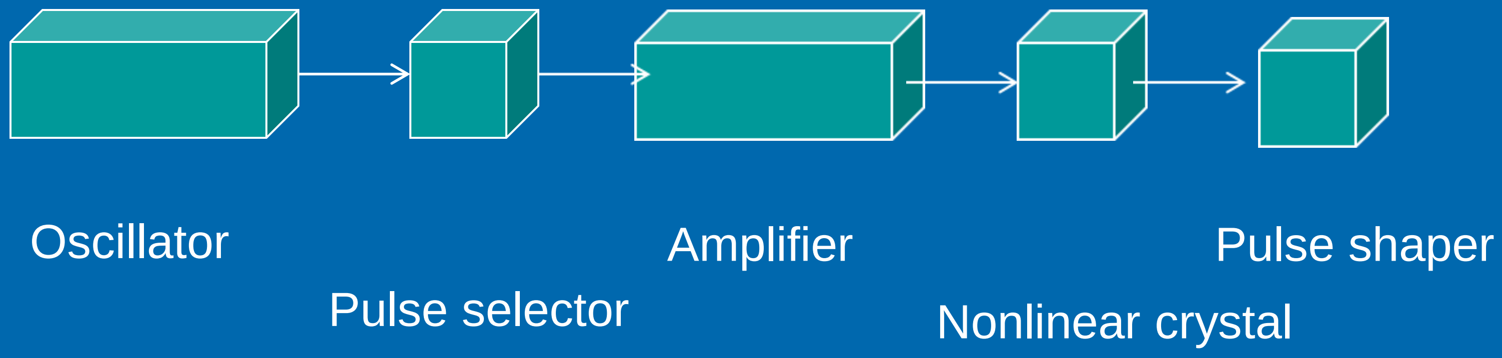
First things first

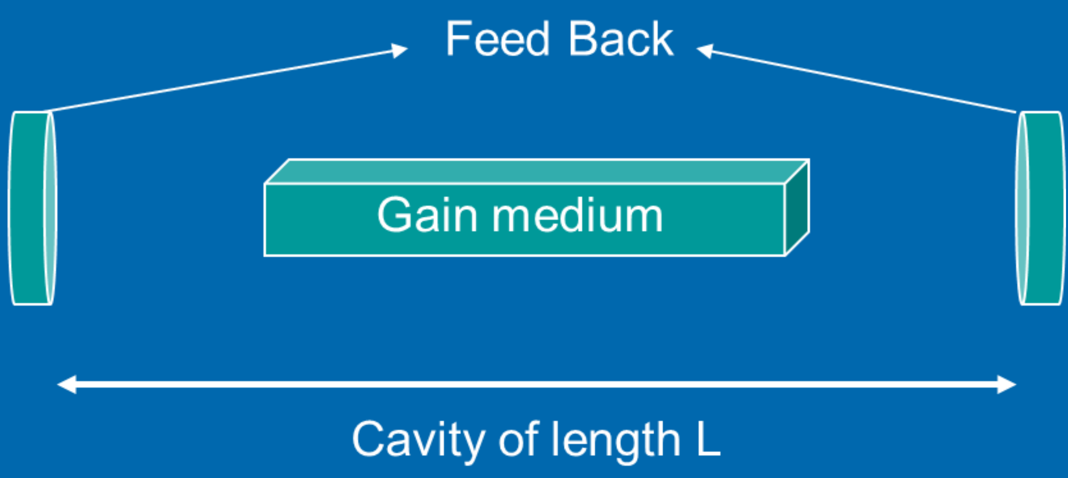
- Determine the operating parameters:
  - Wavelength
  - Pulse duration
  - Energy/power
  - Pulse structure
  - Synchronization
  - Beam quality
  - Polarization
  - Stability
    - Energy
    - Pulse duration
    - Timing
    - Direction
  - Pre/post pulse energy
- Safety
- Infra-structure
  - Power
  - Water
  - Temperature control
  - Humidity control
  - Particulate control
  - Vibration
- Data collection
- Parameter control

Typical Laser System



Based on Requirements, each of these components (+ a few others) have to be defined

Laser Oscillator



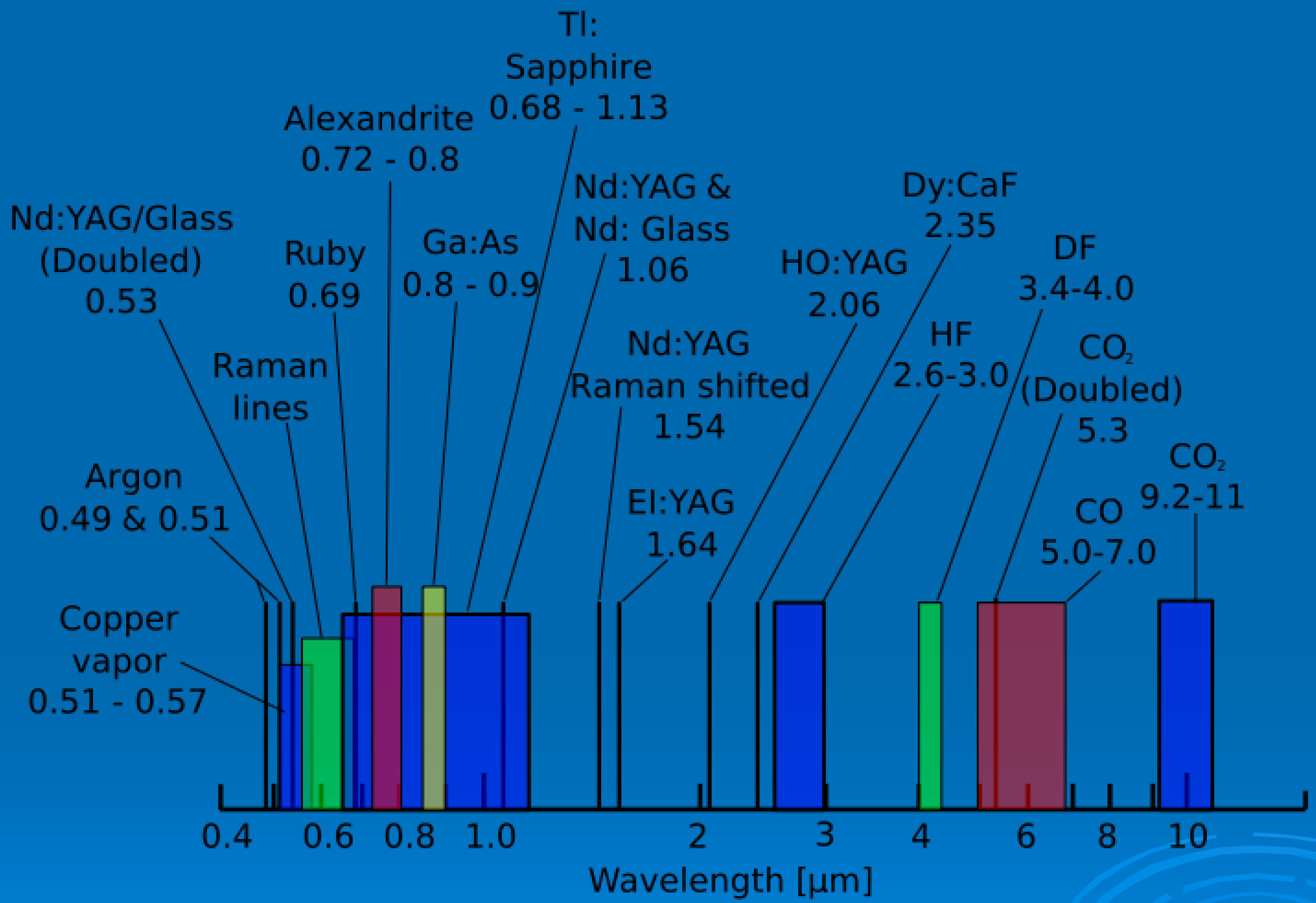
Gain medium determines:
Fundamental wavelength
Minimum pulse duration
Maximum storable energy

Cavity configuration determines:
Repetition rate
Synchronism
Max extractable power
Pulse duration
Transverse parameters
Maximum extractable energy

Consists of
Gain medium-Energized by pumping source
Cavity mirrors
Synchronizing elements

Pump Source determines:
Pulse repetition rate
Maximum stored energy

Wavelength



Most Commonly used: Nd family, Ti: Sapphire, CO_2

Properties of most common Bulk Solid State Laser Gain Media

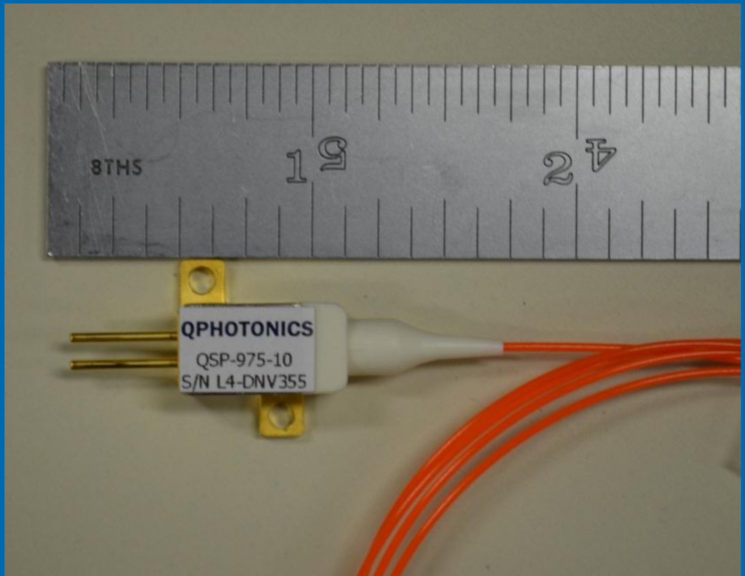
Host	Dopant	Wavelength (μm)	Band Width (nm)	Gain Cross Section ($\times 10^{-20}$ cm^2)	Upper State Lifetime (μs)
YAG	Nd	1.064	0.6	33	230
YLF	Nd	1.047-1.0530	1.2	18	480
Vanadate	Nd		0.8	300	100
Phosphate Glass	Nd	1.0535-1.054	24.3	4.5	323
KGW	Yb	1.026	25	2.8	250
YAG	Yb	1.030	6.3	2.0	950
Phosphate Glass	Yb	1.06-1.12	62	0.049	1 300
Sapphire	Ti	0.790	230	41	3.2

Pulse duration

E. Wolf, Ed., *Progress in Optics*, Vol. 34, Amsterdam: Elsevier Science, 2004

Pump Sources

- Arc Lamp-CW laser
- Flash lamp-Pulsed laser
- Electron beam
- Electric discharge
- Diode-CW and pulsed
  - High efficiency
  - Current or voltage modulation
  - Scalable to high energy/power
  - Compact
  - Fiber coupled

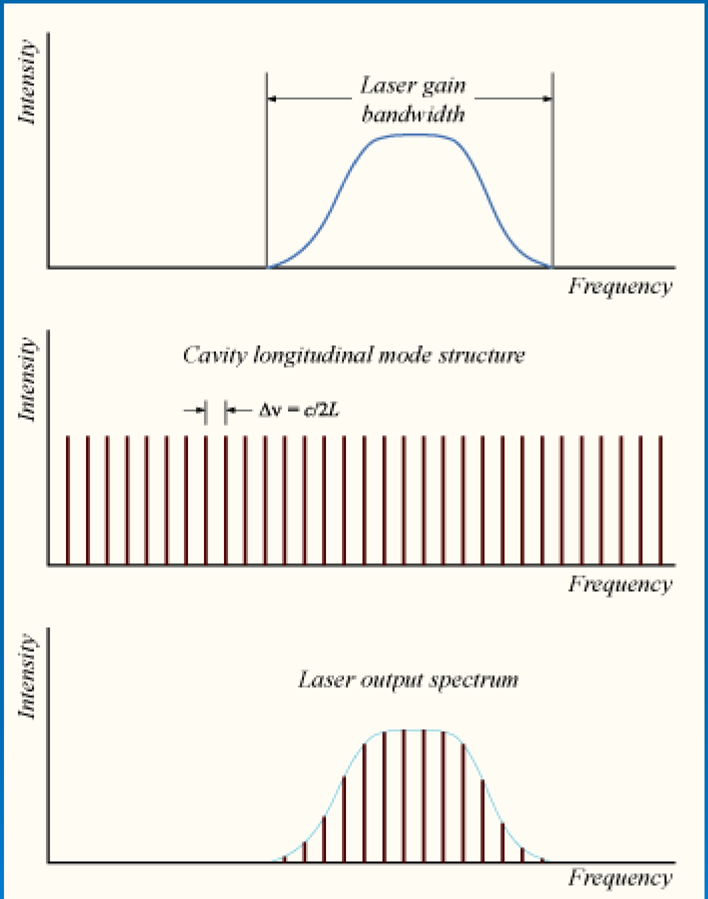


10 W diode laser

How to get pulses?

- Change the Q of the cavity:
  - Sudden change in gain
    - Pulse pumping (Flash lamp, e beam, electric discharge)
  - Sudden change in loss
    - Q switching
    - Mode-locking
      - Active mode-locking - AO/EO modulator
      - Passive mode locking- Saturable absorber(intensity dependent absorption), Kerr lens (Intensity dependent focusing)
- Modulating the pump laser diode pump

Mode locking

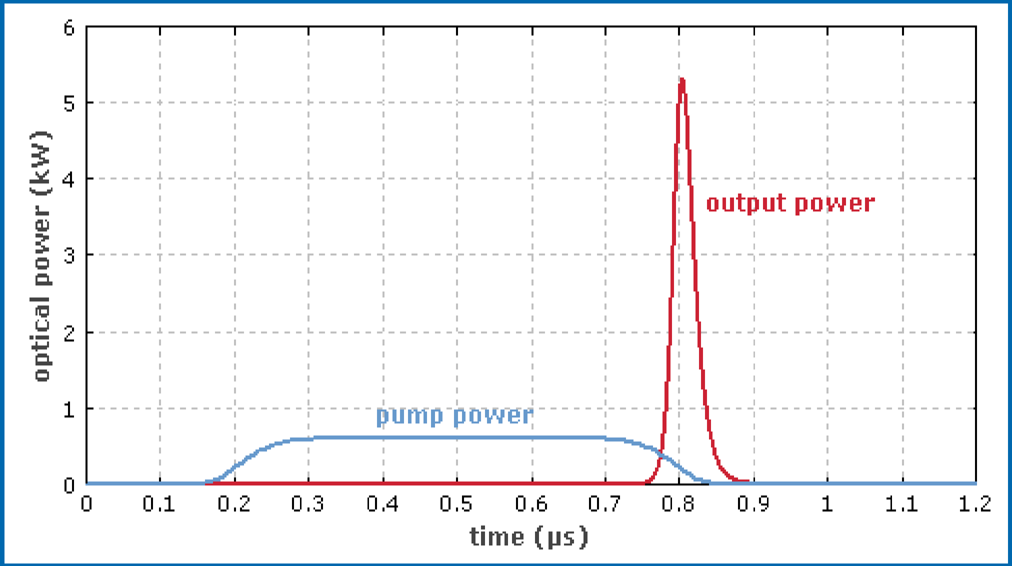


Youtube video:
Principles of mode-locking-
passively mode-locked lasers

http://www.youtube.com/watch?v=efxFduO2Yl8

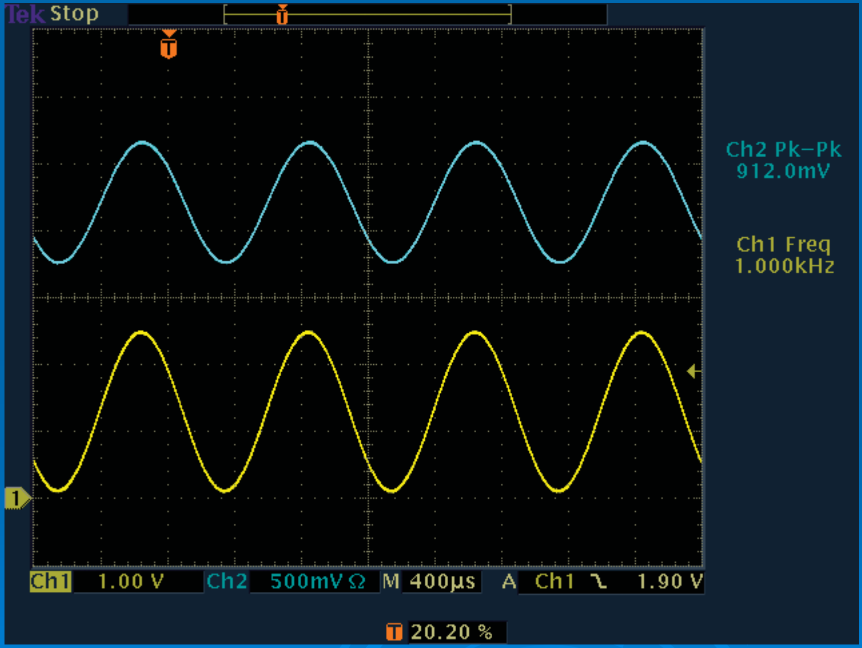
http://upload.wikimedia.org/wikipedia/commons/c/ca/Modelock-1.png

Gain switching in diode laser



http://www.rp-photonics.com/gain_switching.html

http://www.ilxlightwave.com/appnotes/AN%2022%20REV01%20Modulating%20Laser%20Diodes.pdf



Current modulation of the power supply

Amplifier

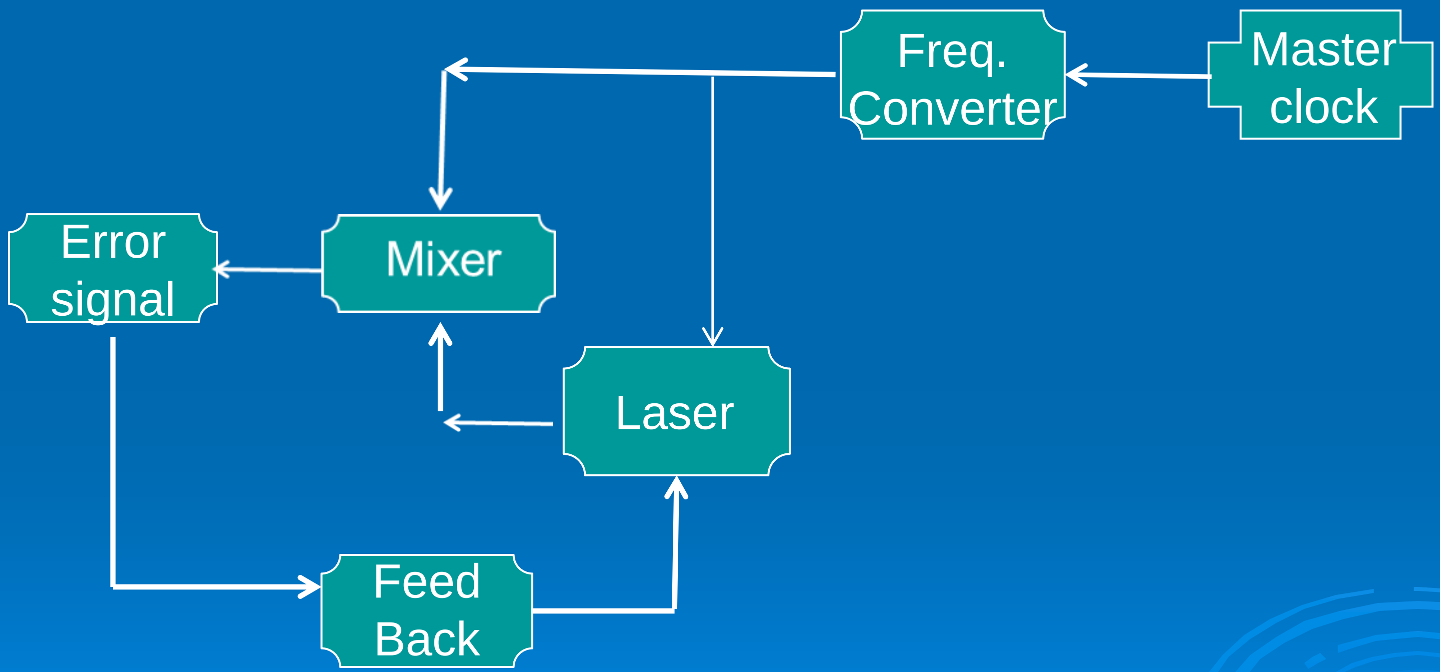
- Determine Number of stages
  - Required amplification
  - S/N Ratio
- Determine amplifier configuration:
  - Regenerative
    - Good transverse mode quality, Multiple passes
    - Higher noise, optical damage
  - Multipass
    - Scalable, higher energy/power
    - Poor mode quality, larger fluctuation

Pulse selection

- Choose the process
  - (eg. Pockell's cell)
- Choose the hardware
  - S/N
  - Damage threshold
  - Operating conditions (temp. etc)
- Choose the location
  - After oscillator, amplifier, harmonic crystals

Synchronization

Need to synchronize laser pulse to other pulses: electron, RF, other lasers etc.



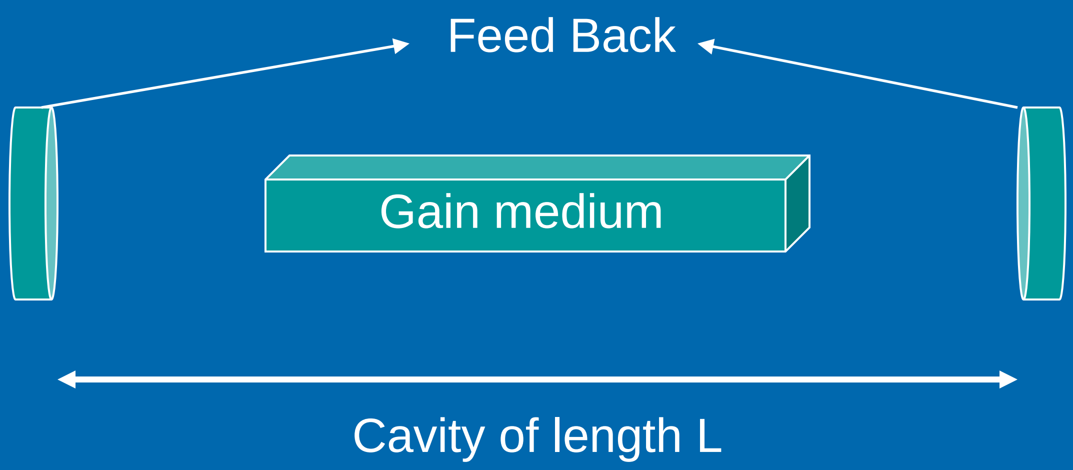
Diagnostics

Energy, Power

- Energy, Power: energy meter, power meter
- Pulse to Pulse Stability: Photodiode
- Online Monitoring: Calibrated photodiode
- Droop correction: Calibrated photodiode+ feedback/feed forward

Spatial distribution

- Profile
- Spot size
- stability



Cavity supports transverse (spatial profile) and longitudinal (frequency spectrum) modes

The electric field E is given by

$$\vec{E}(r,z,t) = \vec{E}(r,t)e^{i(k\vec{n}\bullet\vec{r}-\omega t)}$$

Time averaged Energy flux S is given by

$$S = \frac{c}{8\pi}\sqrt{\frac{\varepsilon}{\mu}}\left|E\right|^2\vec{n}$$

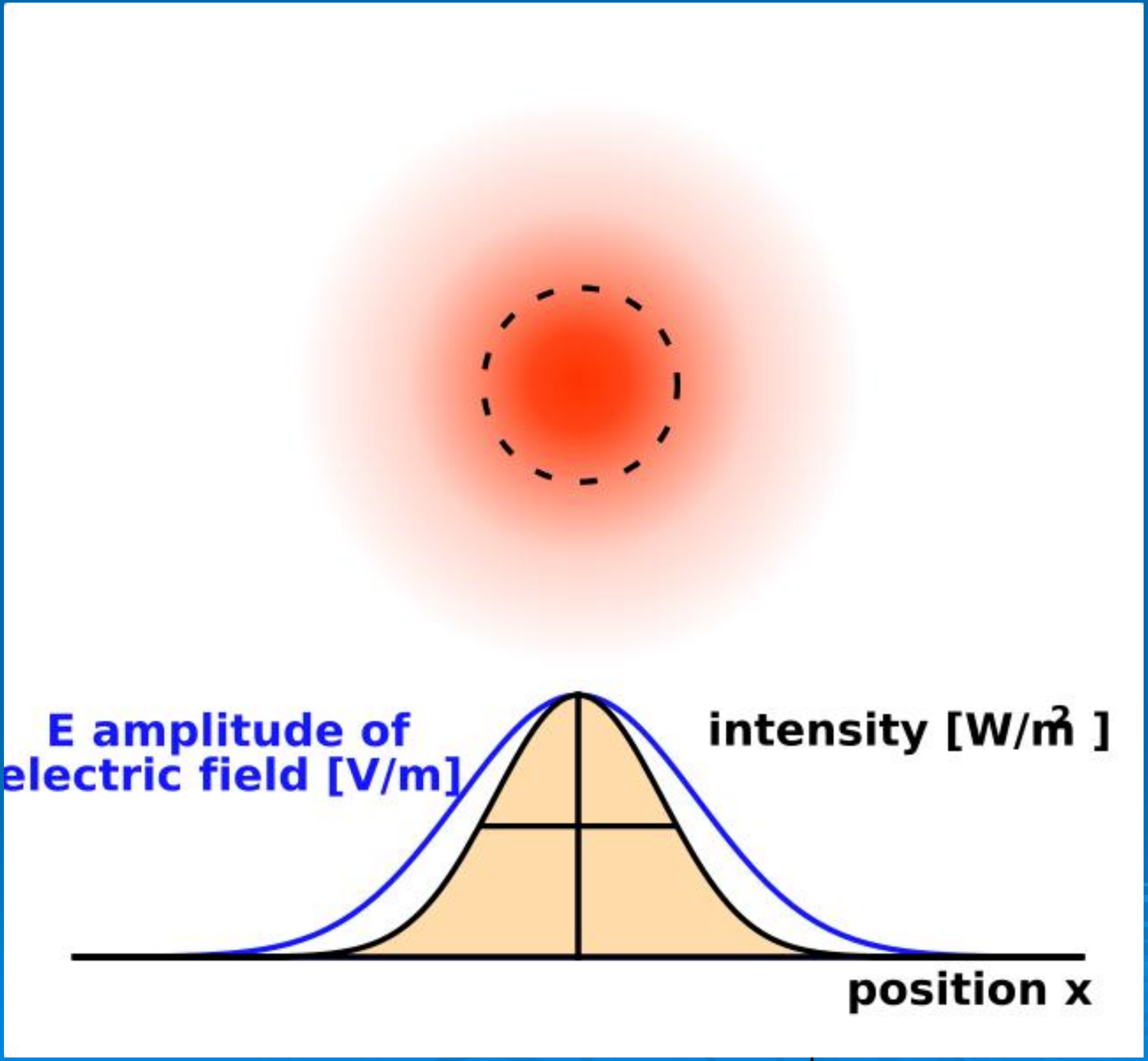
Transverse Profile E(r)

Limiting to lowest order mode,

$$E(r) = E_0 e^{-\left(\frac{r}{w}\right)^2}$$

$$I(r) = I_0 e^{-\left(\frac{2r^2}{w^2}\right)}$$

Gaussian Intensity profile!



E amplitude of electric field [V/m]
intensity [W/m 2]
position x

Important Parameters/Equations of Gaussian Beam

- The parameter w is called the beam radius within which 86.5% of the total power of the Gaussian beam is contained.
- The spot size at any axial distance z from beam waist w_0 can be calculated using

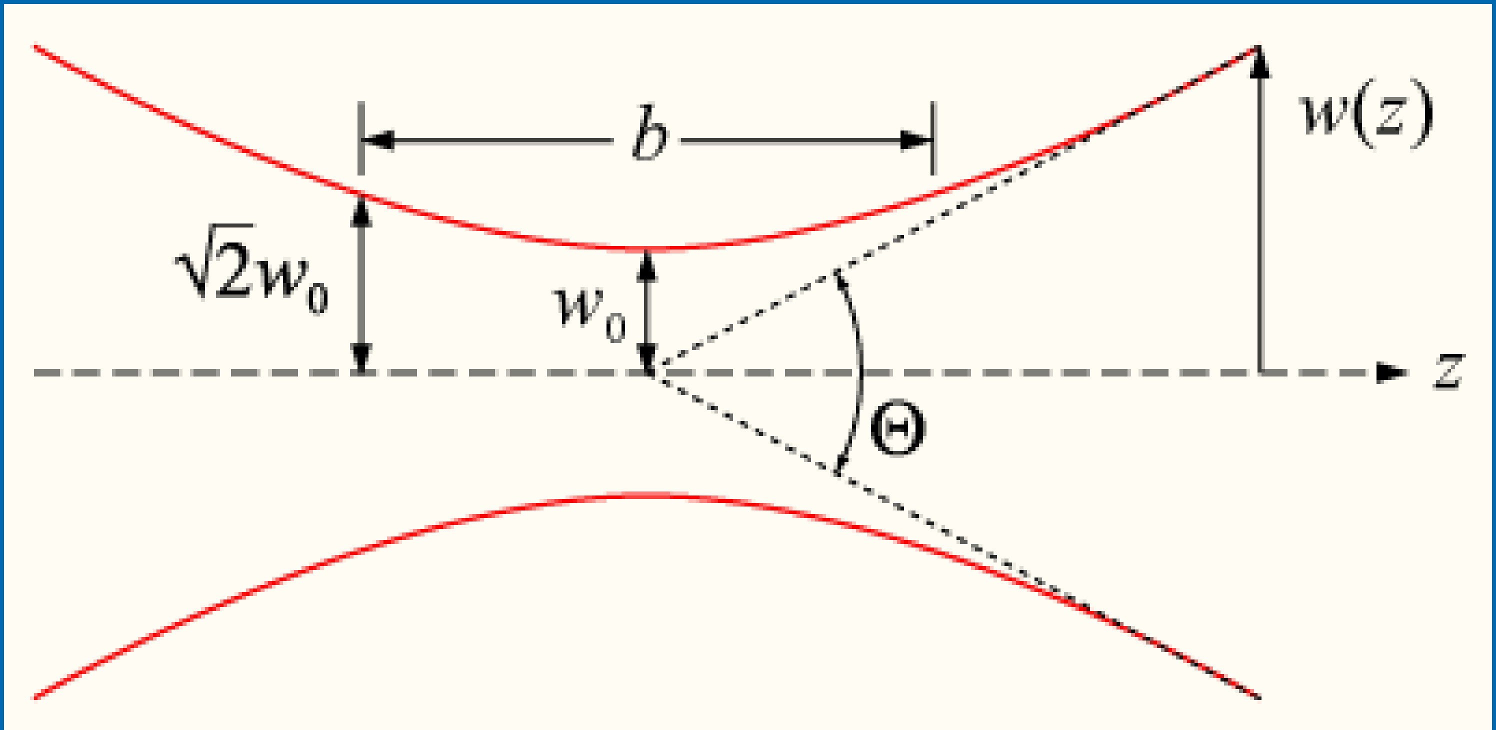
$$w(z) = w_0 \left\{ 1 + \left(\frac{\lambda z}{\pi w_0} \right)^2 \right\}^{\frac{1}{2}}$$

- The full divergence angle θ is given by

$$\theta = 1.27 \frac{\lambda}{(2w_0)}$$

- The confocal parameter b, the distance between points on either side of the beam waist for which the spot size $w(z) = \sqrt{2} w_0$ and the region over which the phase front is nearly planar, is given by

$$b = \frac{2\pi w_0^2}{\lambda}$$

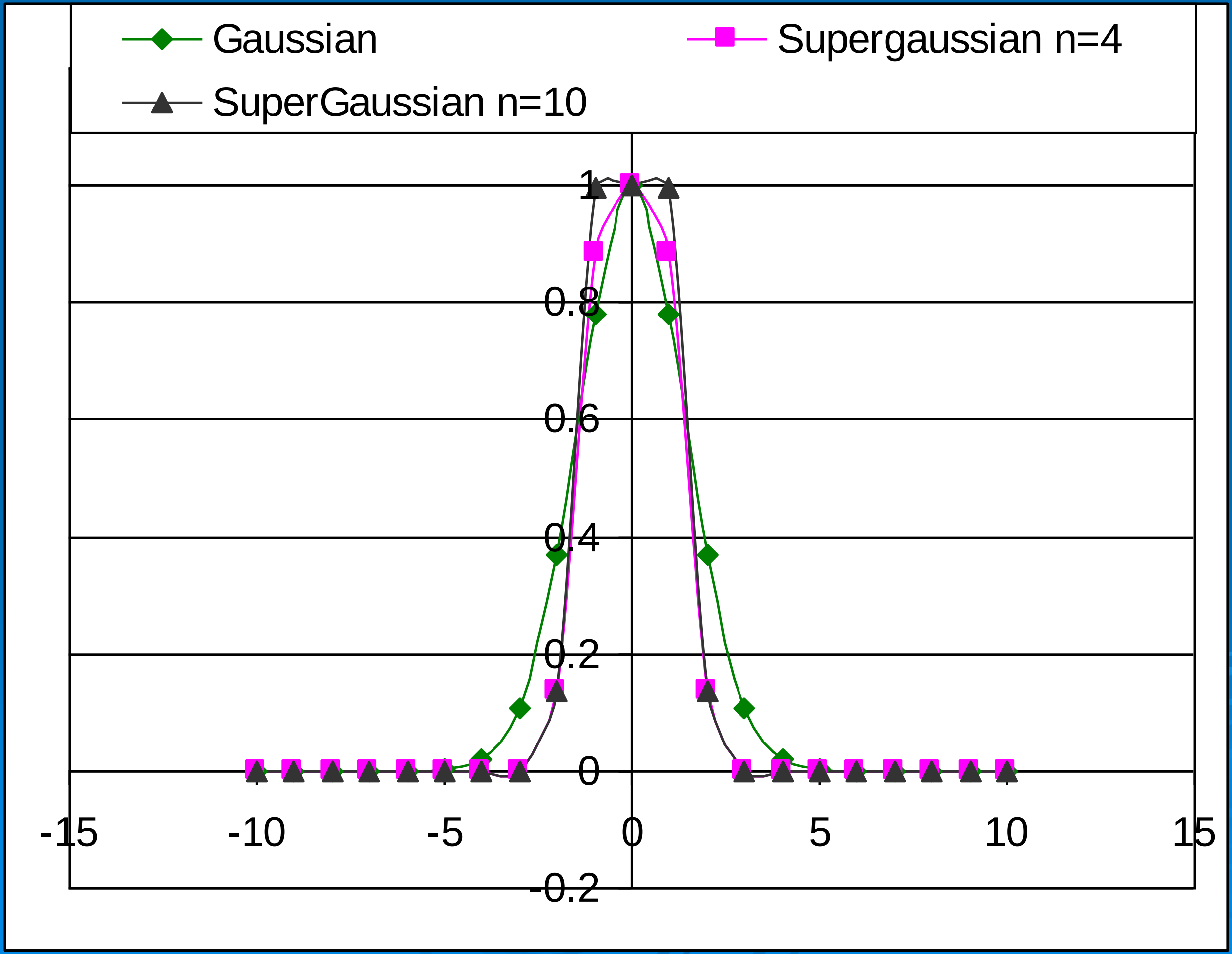


Typical commercial lasers have outputs that are nearly Gaussian, but not exactly. The extent to which they approach Gaussian is given by the *m* parameter

$$m = w_{laser}/w_{gaussian}$$

Supergaussian (Flat Top) Intensity Profile

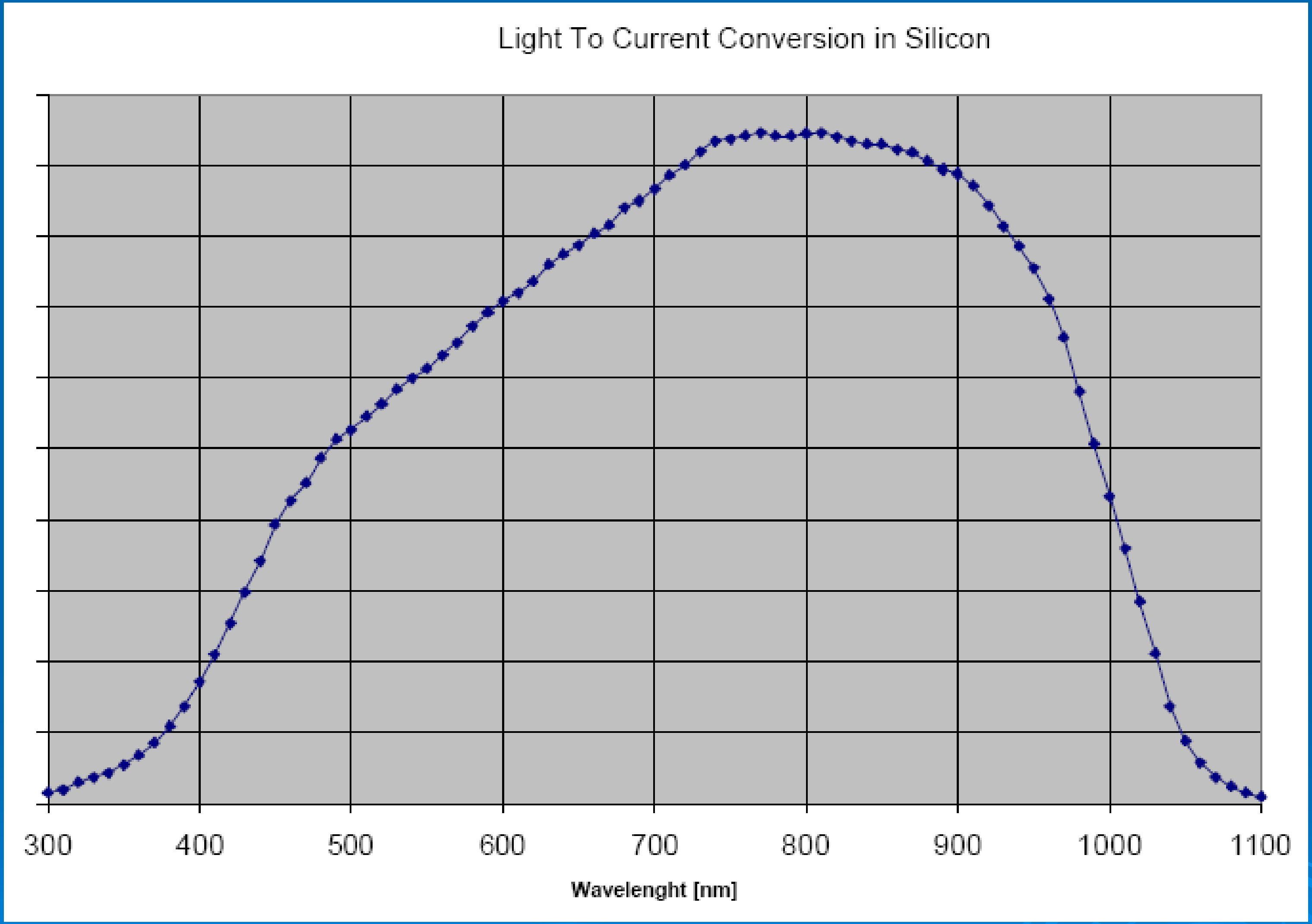
- $$I(r) = I_0 e^{-2\left(\frac{r}{w}\right)^n}$$ **n>2**



Measurement Techniques for Transverse Profile

Technique	Advantage	Disadvant.	Application
CCD	Direct Ease of measurements w/algorithms Good resolution	Dynamic range Long/short wavelength sensitivity	On line beam diagnostics
Slit scan	Inexpensive	Poor resolution Multi-shot Data analysis	Low cost beam diagnostics
Video camera	Multiple displays Inexpensive	Poor resolution Data analysis	Monitoring, aligning

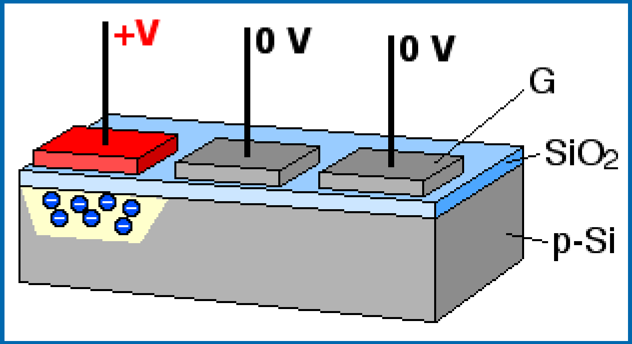
Photosensitive material



IR: Ge response curve 0.8-1.8 micron. HgCdT 1-12 micron (Cryo cooled)

UV: Fluorescence

Principle of CCD



Video

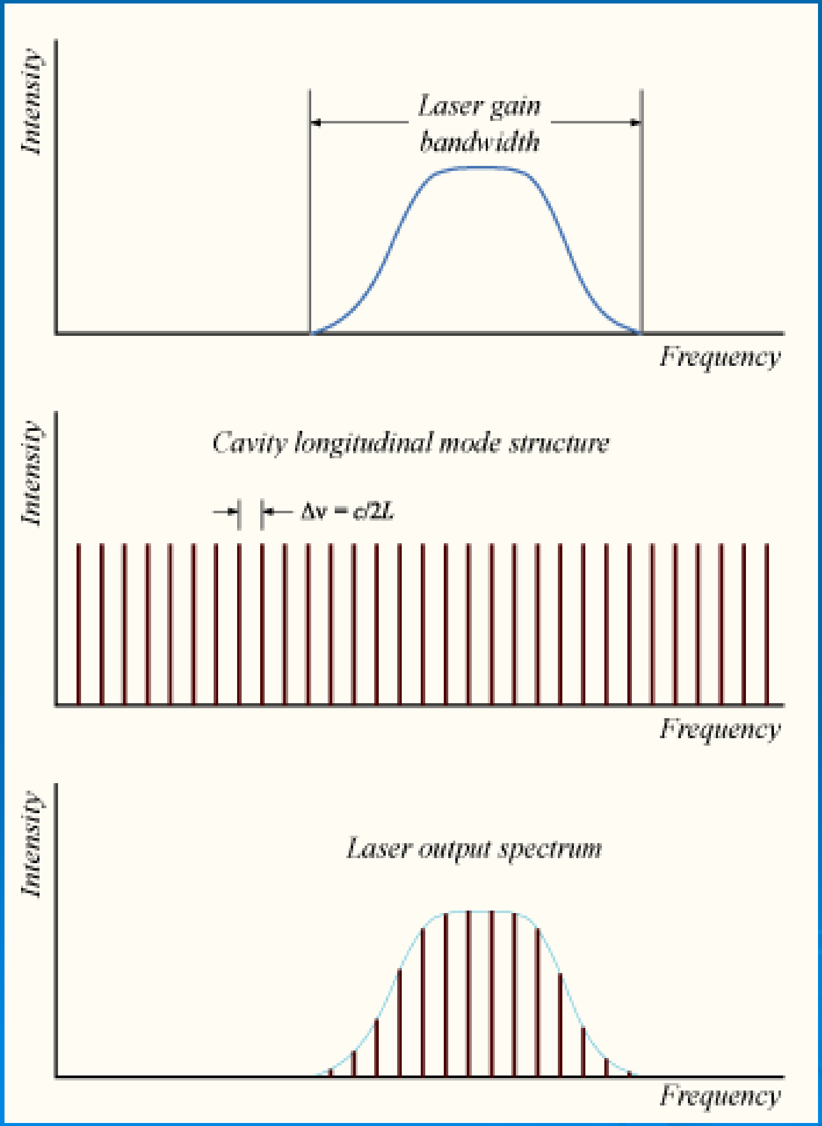
http://nofilmschool.com/2012/06/ever-wondered-how-a-ccd-sensor-works/

http://en.wikipedia.org/wiki/Charge-coupled_device

Selection Criteria

- Sensor and array:
  - Wavelength
  - Size and resolution
  - Dynamic Range
- Software:
  - Parameters required
  - Theory behind software

Longitudinal modes-Spectral Content, Pulse Duration



The pulse duration of the laser beam is dictated by a number of factors

- Storage time (upper state life time) of the lasing medium
- Bandwidth of the lasing line
- Pump duration
- Design of the cavity elements, their linear and nonlinear dispersion

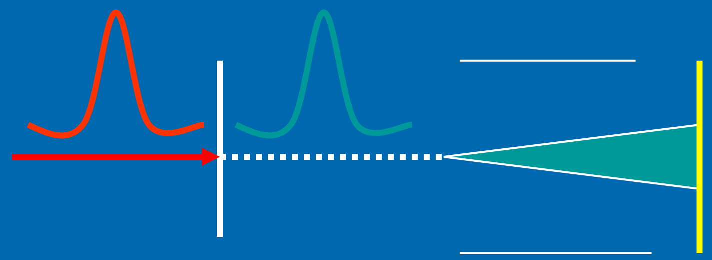
Minimum Pulse duration for Gaussian profile is

$$\Delta t = \frac{0.44}{N \Delta \nu}.$$

Measurement Techniques for Longitudinal (temporal) profile

Technique	Advantage	Disadvant.	Application
Photodiode, phototube	Direct Inexpensive Sensitive Linear simple	Bandwidth limited	ns, subns pulses
Streak camera	Direct Vis-UV	Expensive Complicated	Few ps
Auto/cross correlator Single, multi shot	Moderately inexpensive	Indirect Insensitive to assymmetry	ps, fs
Spectral domain measurements	Complete characterization	Complicated	fs

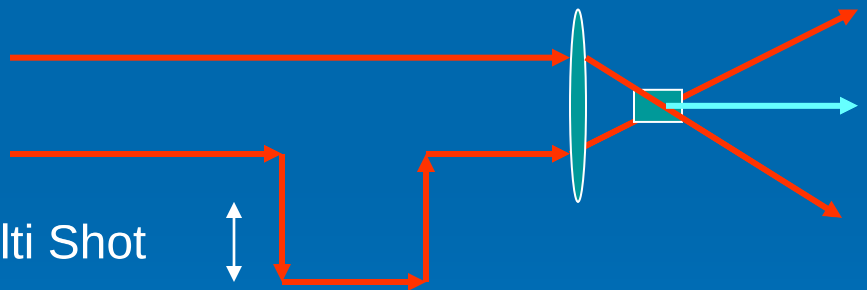
Streak Camera Principle



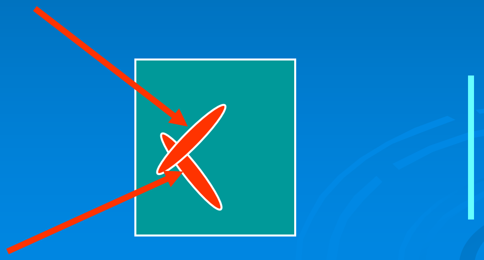
Laser spot size, intensity: Space charge Vs s/n

Synchronization

Autocorrelator Principle

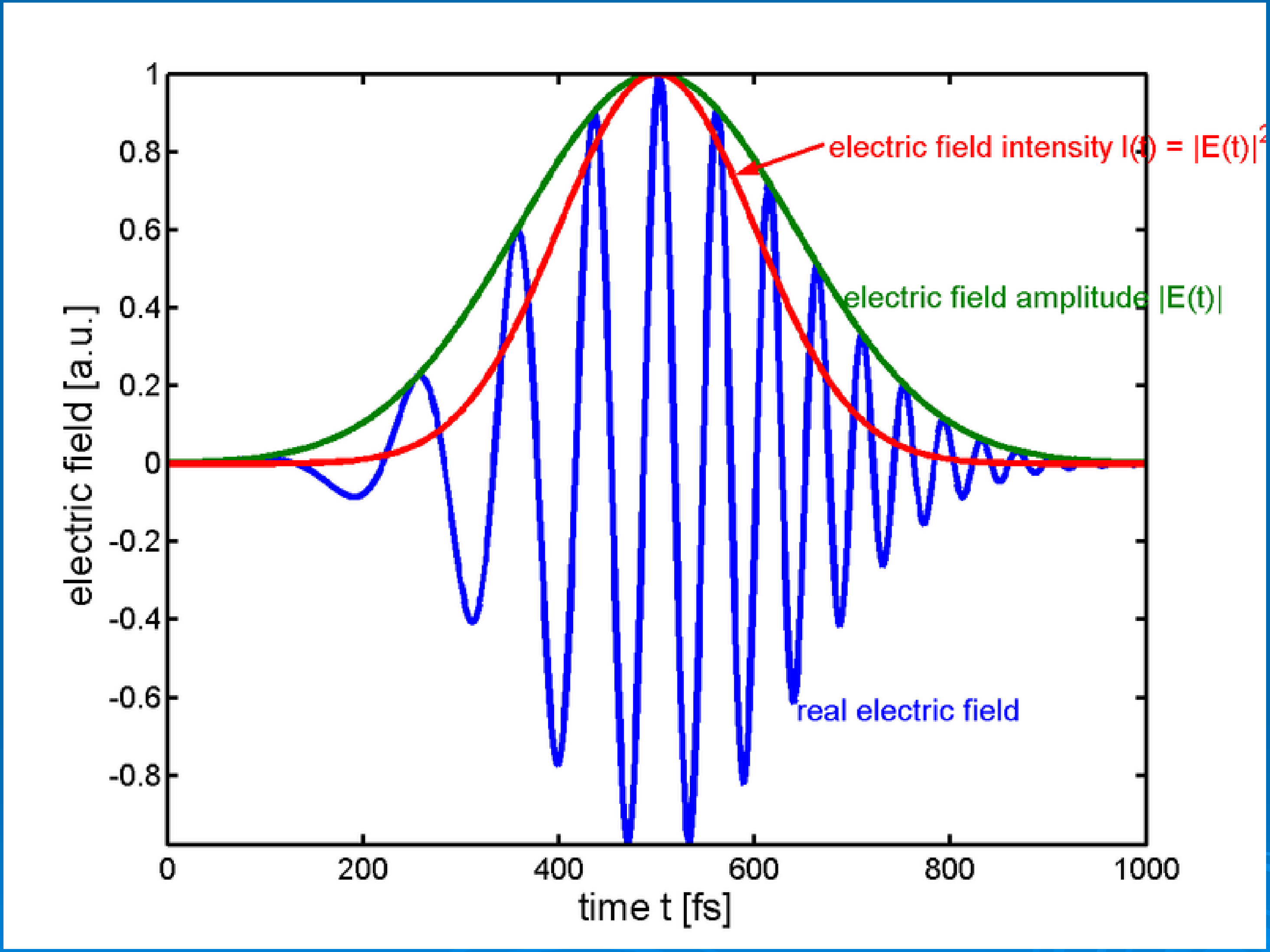


Multi Shot



Single shot

Ultra short pulses may not be transform limited: Need to measure amplitude and phase simultaneously



$E(t) = \sqrt{I(t)}e^{i\omega_0 t}e^{i\psi(t)}$

$E(\omega) = \mathcal{F}(E(t))$

$E(\omega) = \sqrt{S(\omega)}e^{i\phi(\omega)}$

Ψ(t): Phase function

*Φ(ω):*spectral phase

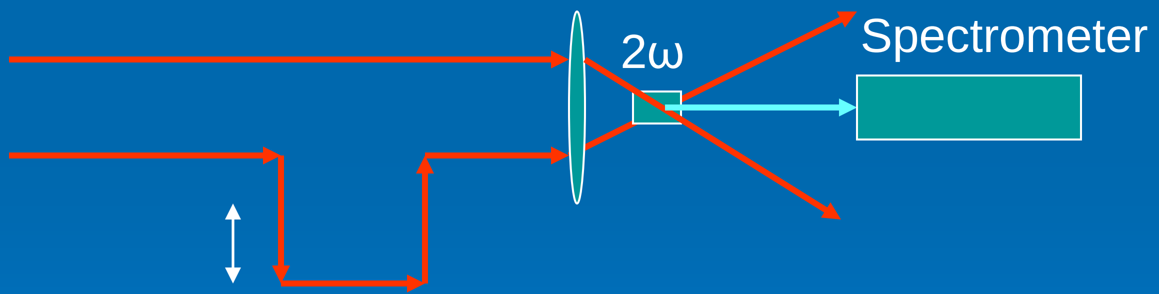
Characterizing fs pulses

$$E(t) = \sqrt{I(t)}e^{i\omega_0 t}e^{i\psi(t)}$$

$$E(\omega) = \sqrt{S(\omega)}e^{i\phi(\omega)}$$

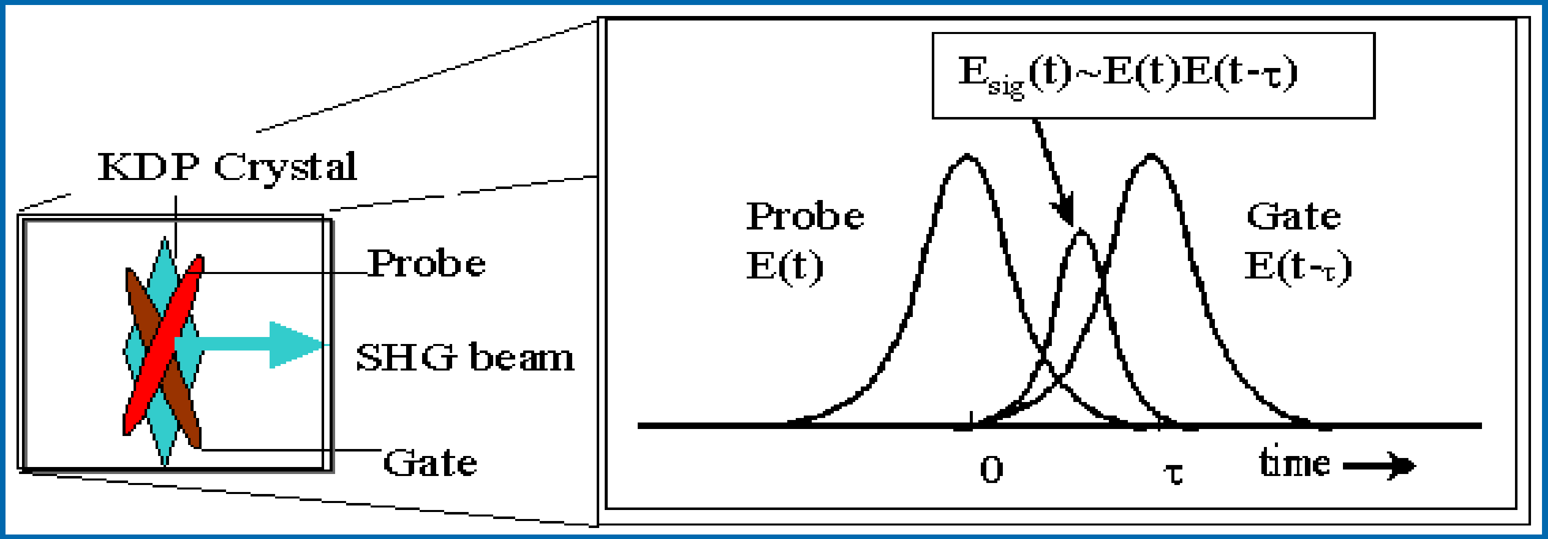
Need to measure both spectrum and spectral phase simultaneously

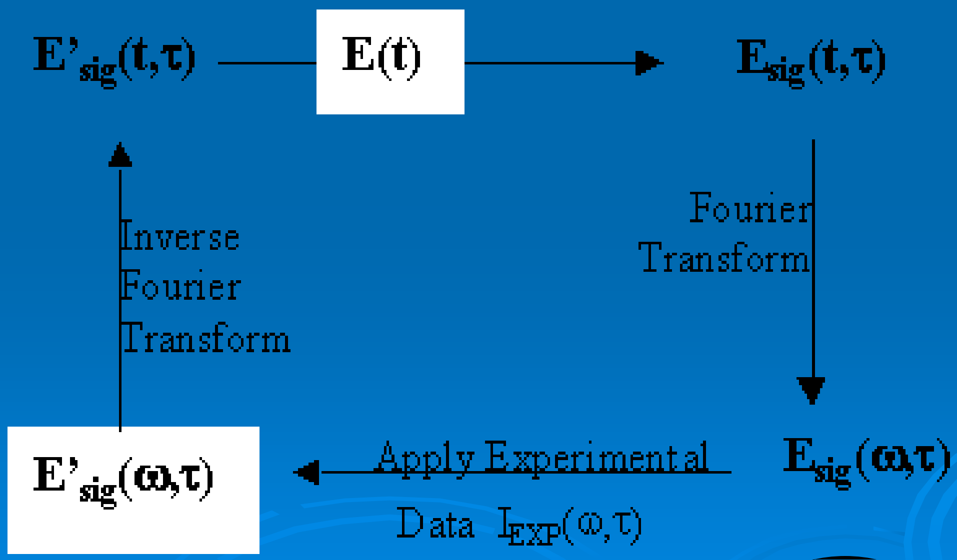
FROG: Frequency Resolved Optical Gating



Most commonly used technique

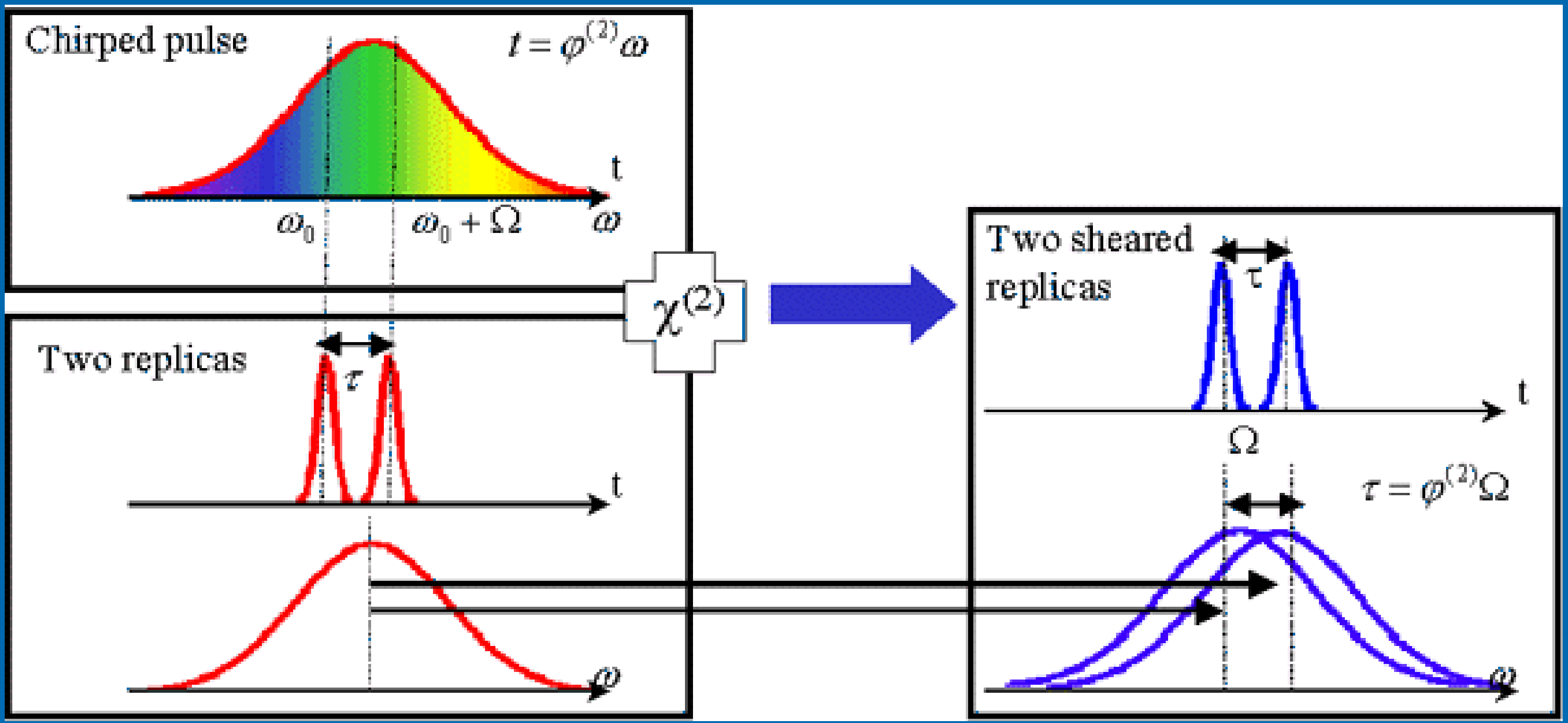
GRENOUILLE: (Grating eliminated no-nonsense Observation of Ultrafast laser light e-fields) simplified device based on SHG FROG-Thick SHG crystal for 2ω and spectrometer, Fresnel biprism for beam splitter, delay line and beam recombination

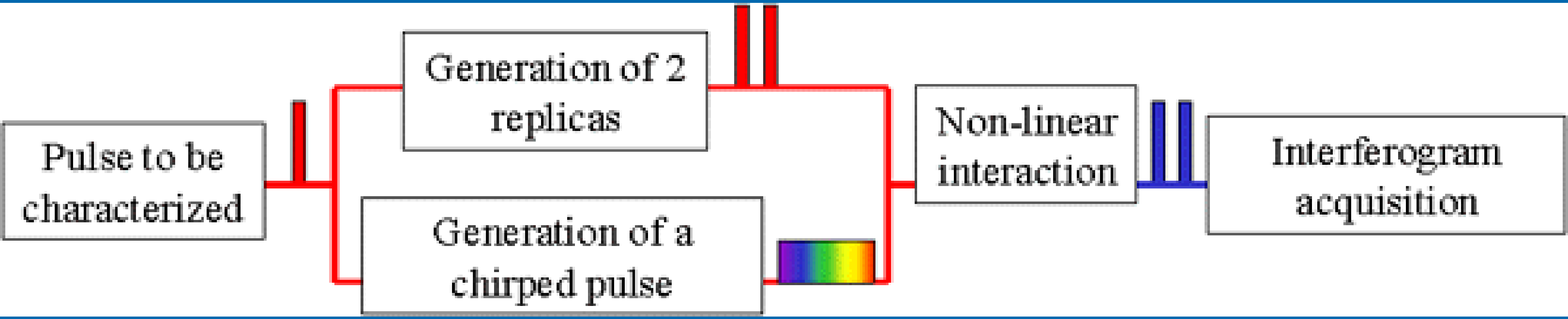




Courtesy: http://www.phys.ufl.edu/reu/1999/reports/mei/mei.htm

SPIDER: Spectral Phase Interferometry for Direct Electric field Reconstruction





The interference of the two fields is given by

$$\tilde{S}(\omega) = \tilde{I}(\omega) + \tilde{I}(\omega + \Omega) + 2\sqrt{\tilde{I}(\omega)}\sqrt{\tilde{I}(\omega + \Omega)}\cos(\phi(\omega) - \phi(\omega + \Omega))$$

where $\tilde{E}(\omega) = \sqrt{\tilde{I}(\omega)}e^{i\phi(\omega)}$

Use Algorithms to extract the phase information

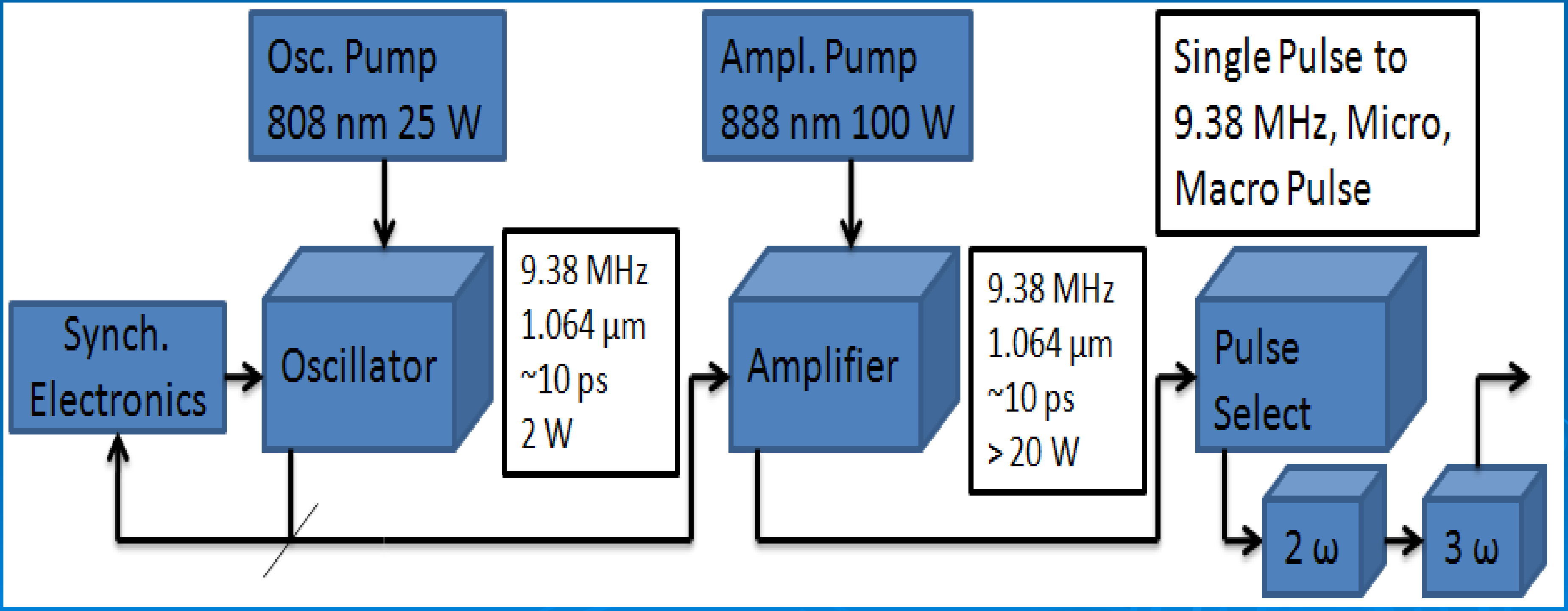
http://ultrafast.physics.ox.ac.uk/spider/tech.html

Other Design Criteria

- Beam transport from laser to interaction region
  - Simulation codes (eg., Zemax)
  - Remote manipulation, vacuum transport
  - Radiation considerations (fiber transport)
- Computer system and platform
  - Data collection
  - Parameter control
- Environmental control
  - Temperature
  - Humidity
  - Dust
- Safety
  - Interlock, entry

Example

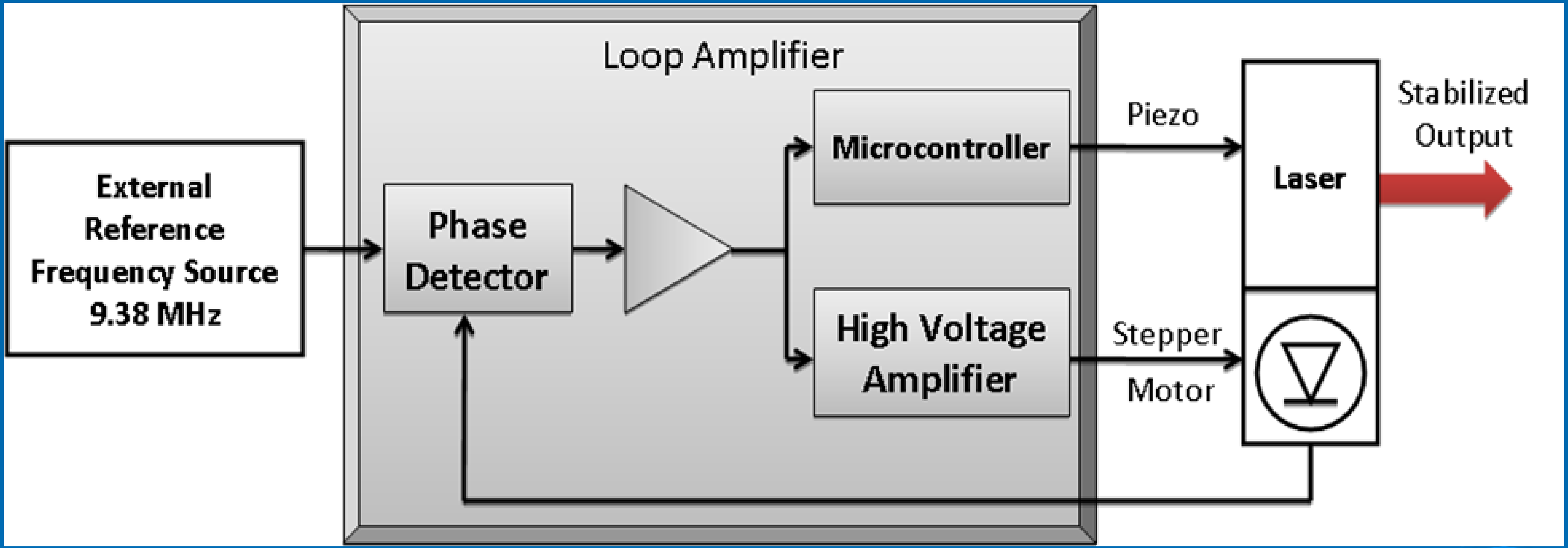
- BNL ERL laser: Commercial, custom unit from Lumera for illuminating photocathode



Oscillator

- Gain medium: Nd vanadate
- Pump: 18 W fiber coupled 808 nm diode laser
- Mode-Locking: Passive Saturable absorber
- Cavity: Folded cavity w/ resonator length of 16 m
- Synchronization: Piezo-driven mirror in cavity

Synchronization



Amplifier

- Gain Medium: Nd: vanadate
- Pump: 100 W diode laser at 888 nm (lower absorption, uniform longitudinal pumping)
- # of passes: 2, polarization rotation between passes
- Entire pulse train amplified

Pulse selector

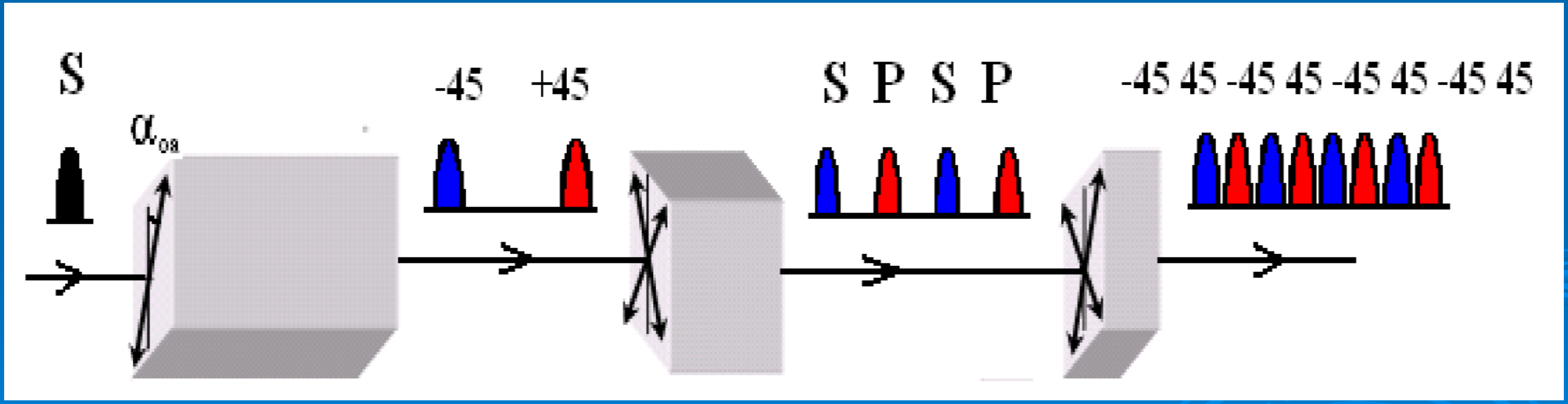
- Method: Pockel's cell, pulse picked when voltage on
- Material: BBO
- Pulse train structure: Micro and macro pulse,
  - macro pulse length adjustable from tens of ns to 100 μs,
  - PRF from on demand to 10 kHz
  - # of pulses in macro pulse adjustable from 1 to CW

Harmonic Crystal

- 1064 nm to 532 nm:
  - LBO, non-critically phase matched, 150 C
  - 50 % efficiency- 10 W
- To 355 nm:
  - LBO, non-critically phase matched, 40 C
  - Green to UV efficiency 50 %- 5W

Pulse Shaping

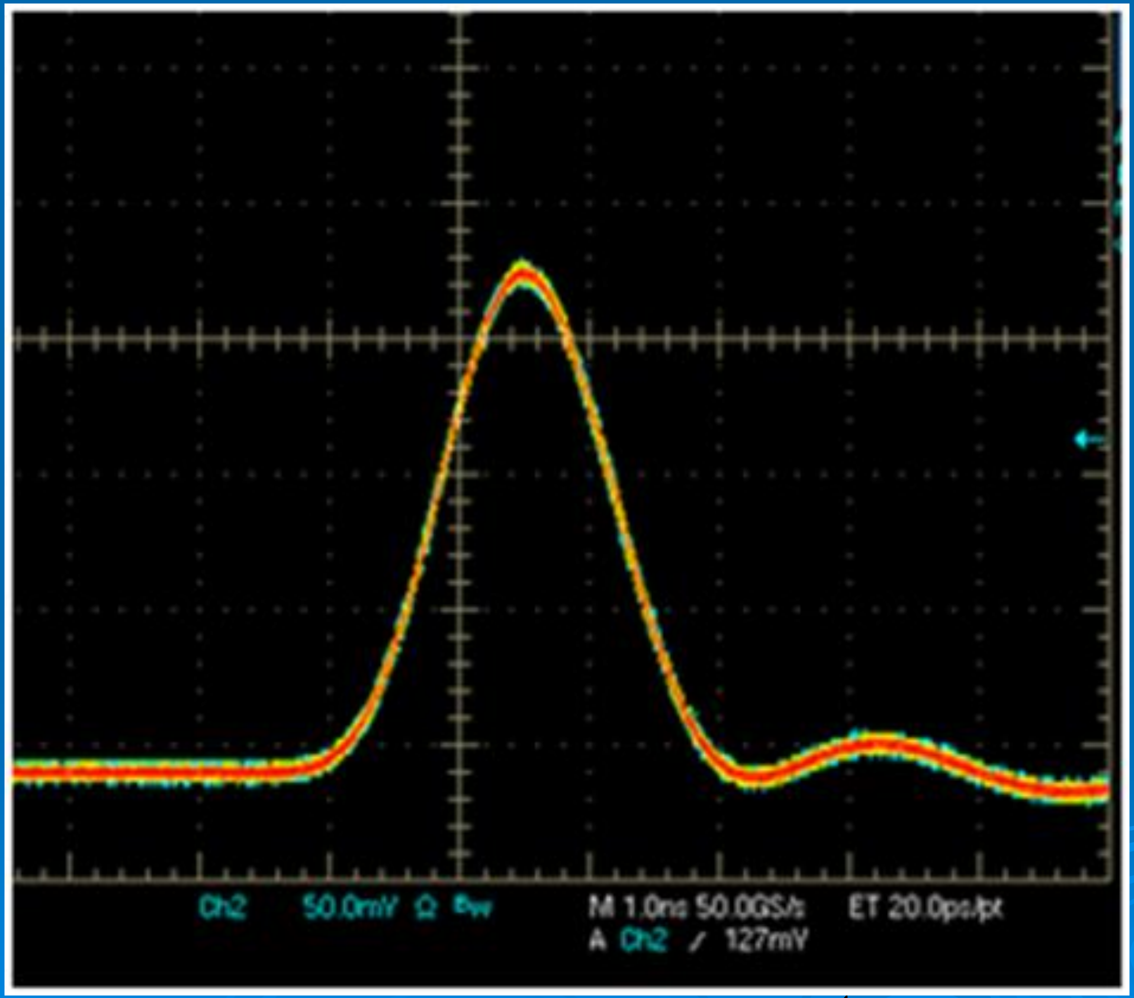
- Spatial: Commercial pi shaper
- Temporal: Beam stacking
  - 3 YVO_4 crystals of length 6, 12 and 24 mm



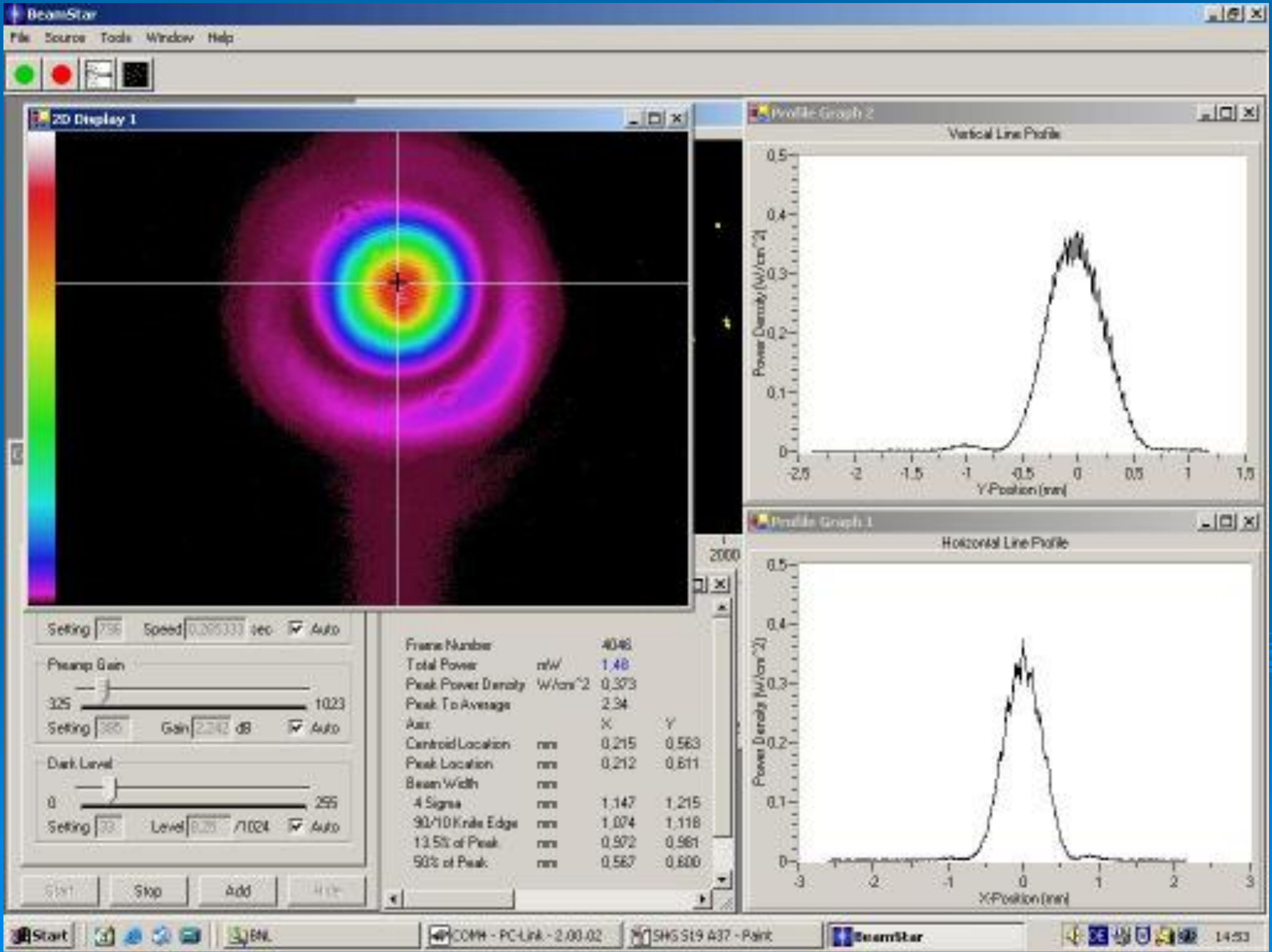
Diagnostics

- On-line:
  - Pulse energy and stability-Calibrated Photodiode
  - Beam profile-Video camera
  - Pointing stability-Video camera
- Performance:
  - Pulse energy: energy meter
  - Beam profile, pointing stability: CCD
  - Pulse duration in IR: Autocorrelator
  - Pulse picker, S/N: Photodiode

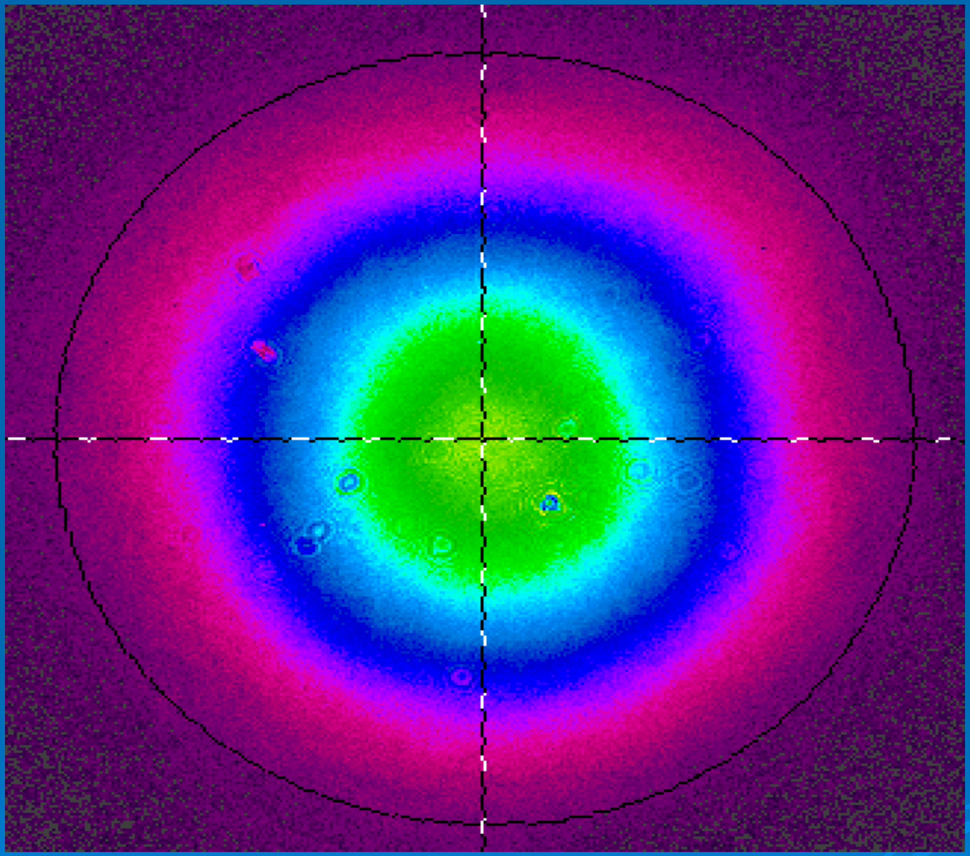
Energy and energy stability



IR image

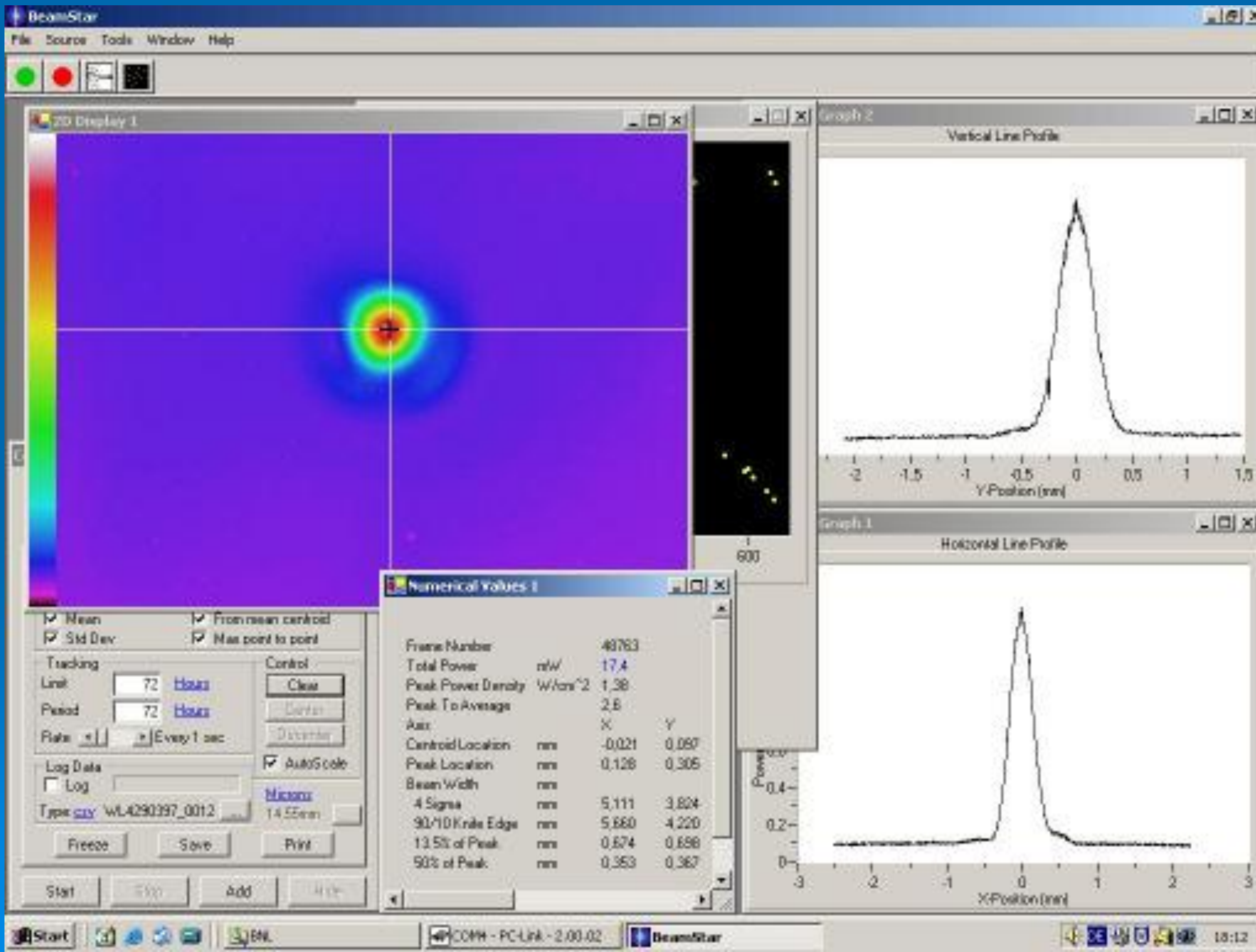

BeamStar
File Source Tools Window Help
2D Display 1
Profile Graph 2
Vertical Line Profile
Power Density [W/cm^2]
Y-Position [mm]
Profile Graph 1
Horizontal Line Profile
X-Position [mm]
Setting Speed sec Auto
Preamp Gain
325 1023
Setting Gain dB Auto
Dark Level
0 255
Setting Level /1024 Auto
Start Stop Add
Frame Number 4048
Total Power mW 1.48
Peak Power Density W/cm^2 0.373
Peak To Average 2.34
Axis X Y
Centroid Location mm 0.215 0.563
Peak Location mm 0.212 0.611
Beam Width mm
4 Sigma mm 1.147 1.215
90/10 Knife Edge mm 1.074 1.118
13.5% of Peak mm 0.972 0.981
50% of Peak mm 0.567 0.600
Start
BNL
COMM - PC-Link - 2.00.02
BeamStar
14:53

IR image Core



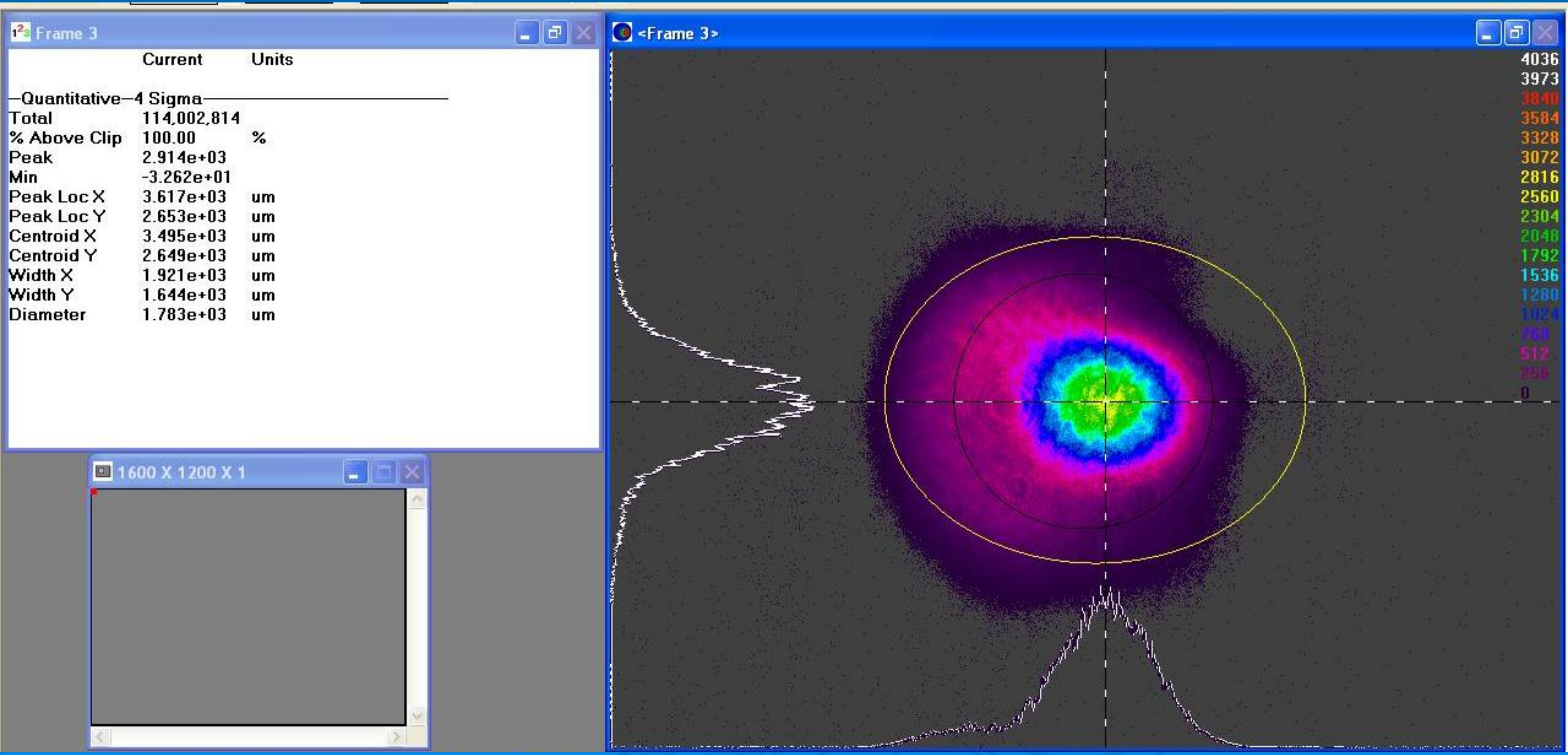
Gaussian beam

Green Image

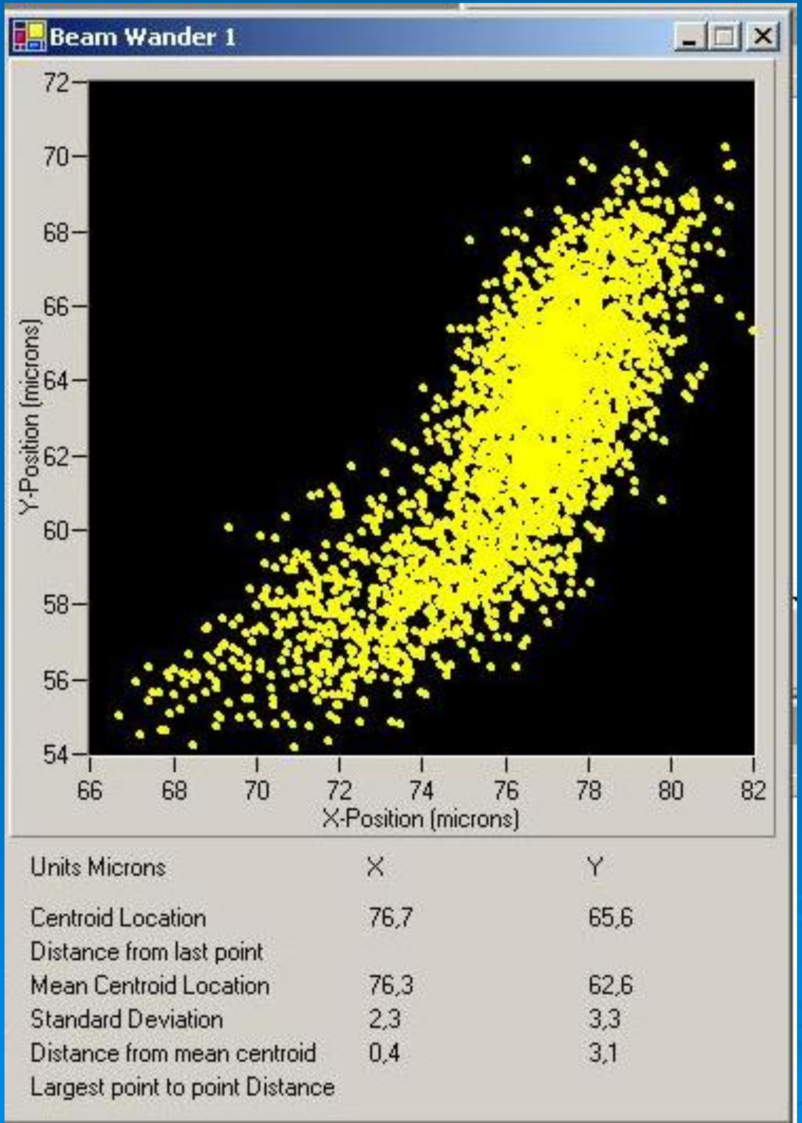


BeamStar
File Source Tools Window Help
2D Display 1
Graph 2
Vertical Line Profile
Y-Position (mm)
Graph 1
Horizontal Line Profile
X-Position (mm)
Numerical Values 1
Frame Number 48763
Total Power mW 17,4
Peak Power Density W/cm^2 1,38
Peak To Average 2,6
Axis X Y
Centroid Location mm -0,021 0,087
Peak Location mm 0,128 0,305
Beam Width mm
4 Sigma mm 5,111 3,824
90/10 Knife Edge mm 5,660 4,220
13.5% of Peak mm 0,674 0,698
50% of Peak mm 0,353 0,367
Mean
Std Dev
From mean centroid
Max point to point
Tracking
Limit 72 Hours
Period 72 Hours
Control
Clear
Log Data
Log
AutoScale
Microns
Freeze
Save
Print
Start
Add
COM4 - PC-Link - 2.00.02
18:12

UV image
Nonlinear process distorts the profile
Ellipticity and nonuniformity



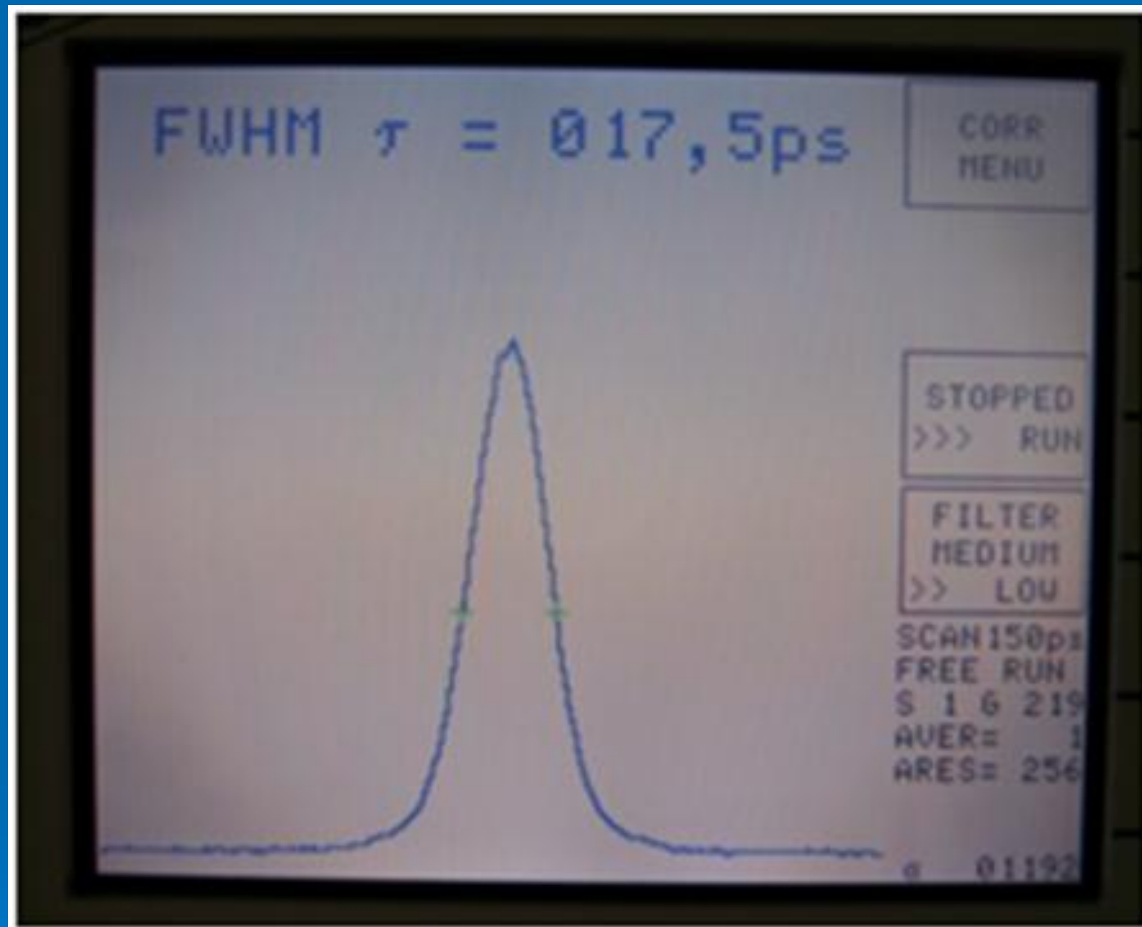
Pointing Stability



Centroid deviation: 3.3 and 2.3 µm in x and y respectively at 1 m from laser

Corresponds to 3.3 and 2.3 µrad angular deviation

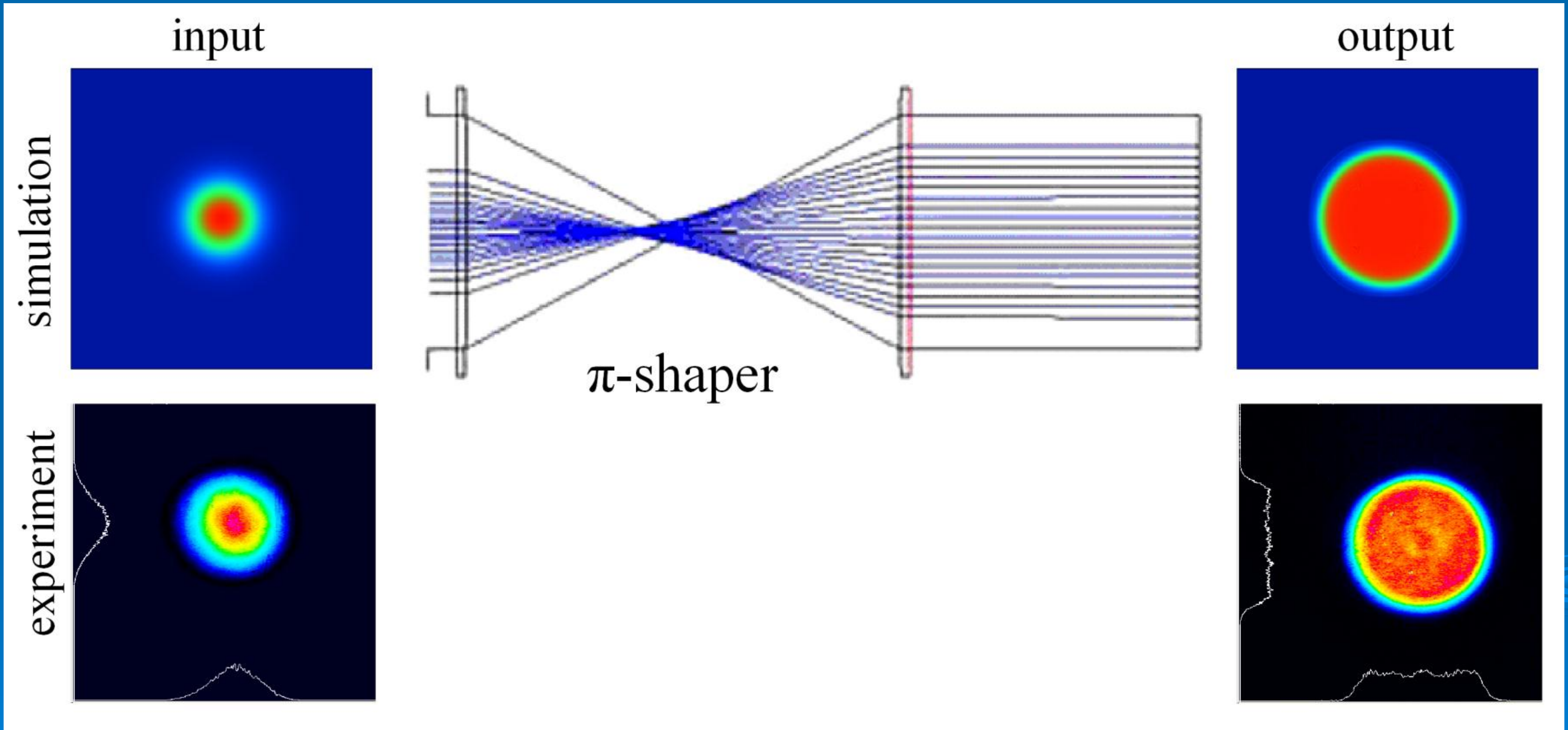
Pulse Duration in IR



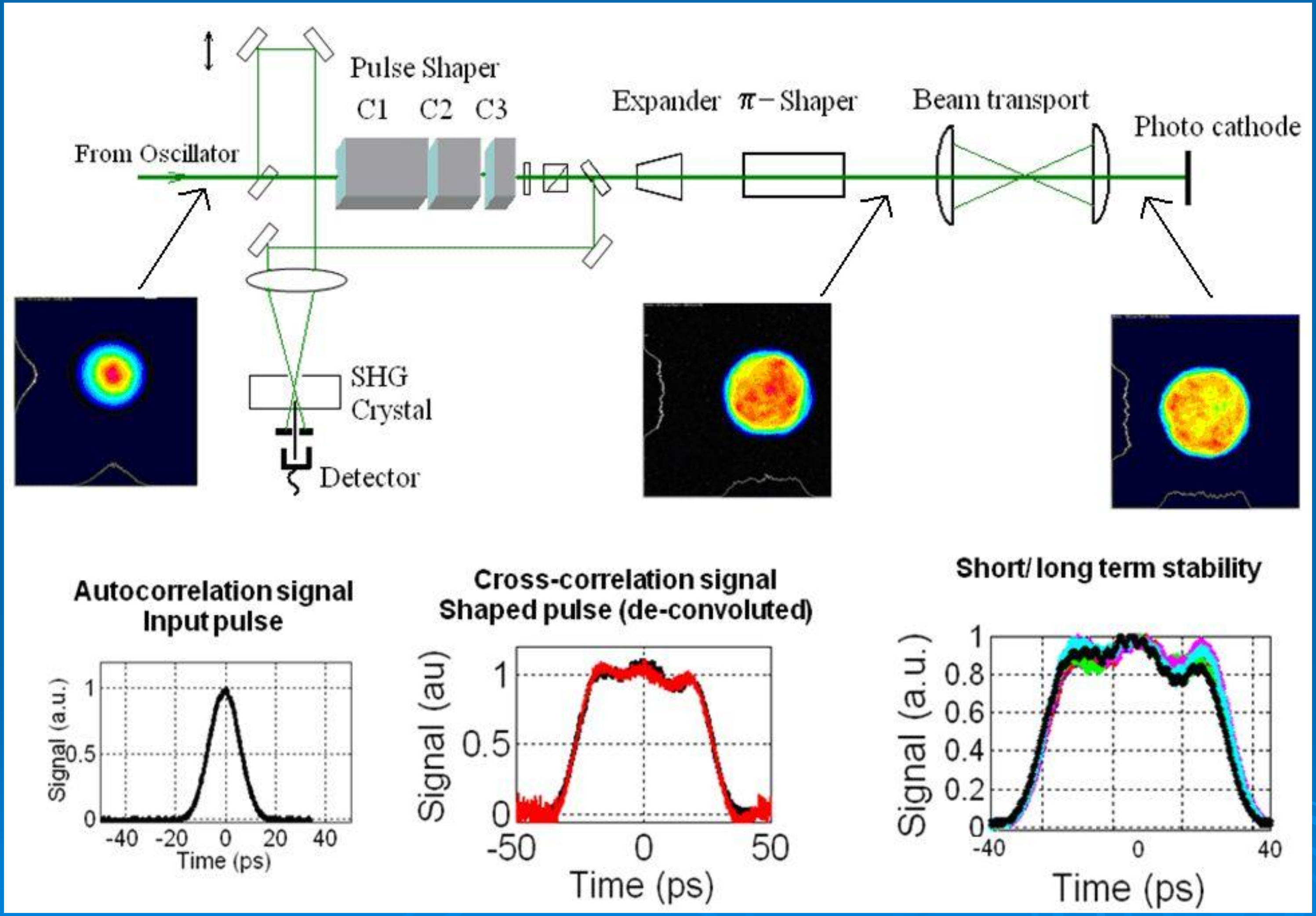
FWHM of autocorrelator trace =17.5 ps

Corresponding FWHM for Gaussian laser pulse = 12 ps

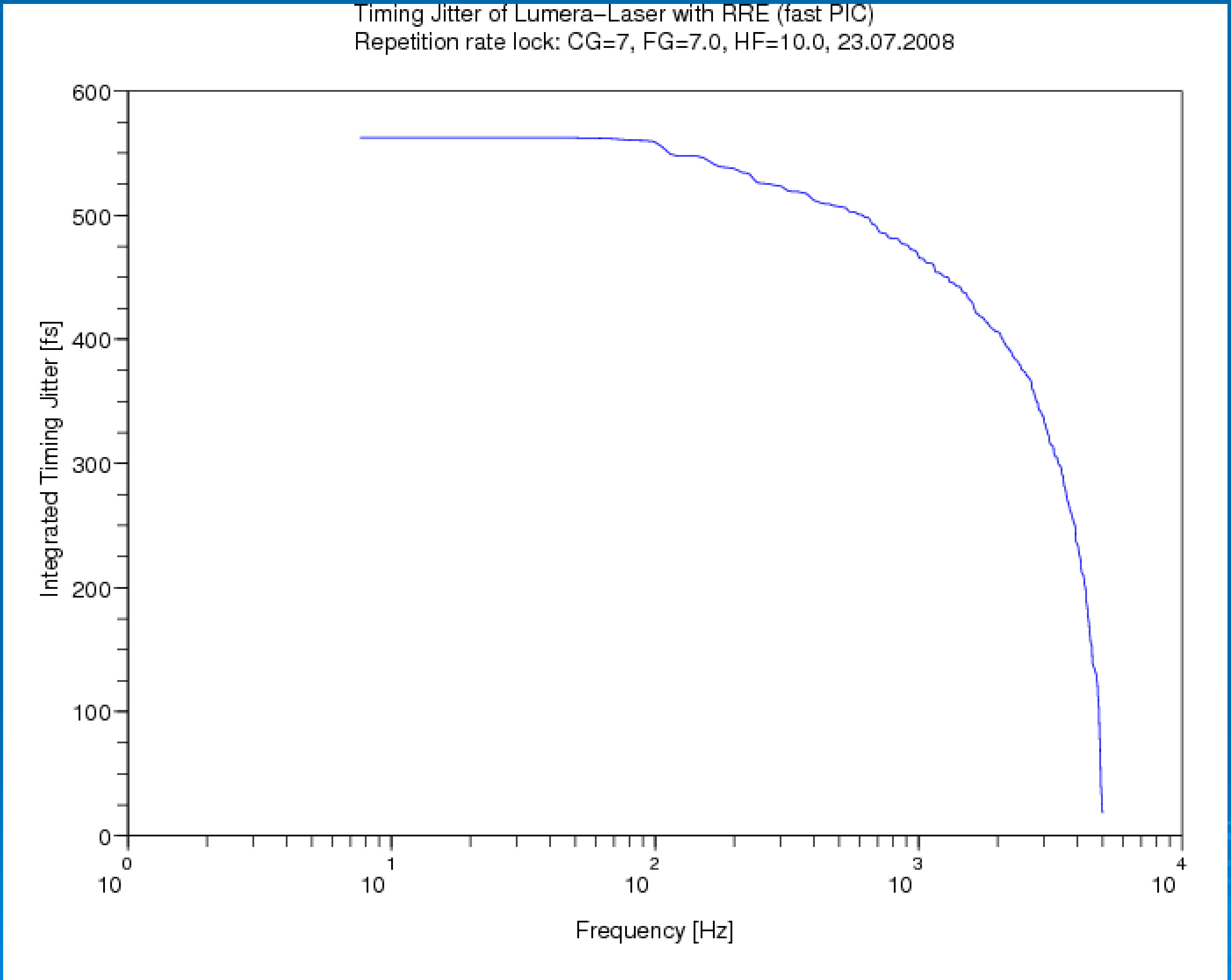
Spatial shaping



Temporal and Spatial Shaping @ 532 nm



Timing Jitter



Pulse Selection