Lecture 13: Lasers

High Brightness Electron Injectors for Light Sources

January 14-18, 2007

J.F. Schmerge, SLAC

Outline

- Laser Parameters
  - Cathodes
  - Laser and Cathode
- Laser Components
  - Oscillator
  - Amplifier
  - Frequency Conversion
  - Transverse Pulse Shaping
  - Temporal Pulse Shaping
  - Transport Line
  - Diagnostics

Cathodes

Type	QE	Lifetime	Work Function	$\varepsilon_{thermal}$
Metal	$\approx 10^{-4}$	Month	≈ 4 eV	>0.5 μm/mm
Semi-conductor	$\approx 10^{-2}$	Hours	≈ 2 eV	>0.8 μm/mm

Laser Cathode System

- Cathode choice determines laser parameters
- Laser choice determines operation of cathode

Parameters

- QE 5 10^{-5} requires 100 μJ of laser energy to generate 1 nC
- 100 Hz repetition rate requires 10 mW of power but 1 MHz requires 100 W
- 4.5 eV work function requires 275 nm photon but 2.2 eV work function requires 550 nm photons

$$QE = \frac{n_{electrons}}{n_{photons}}$$

$$Q = en_{electrons}$$

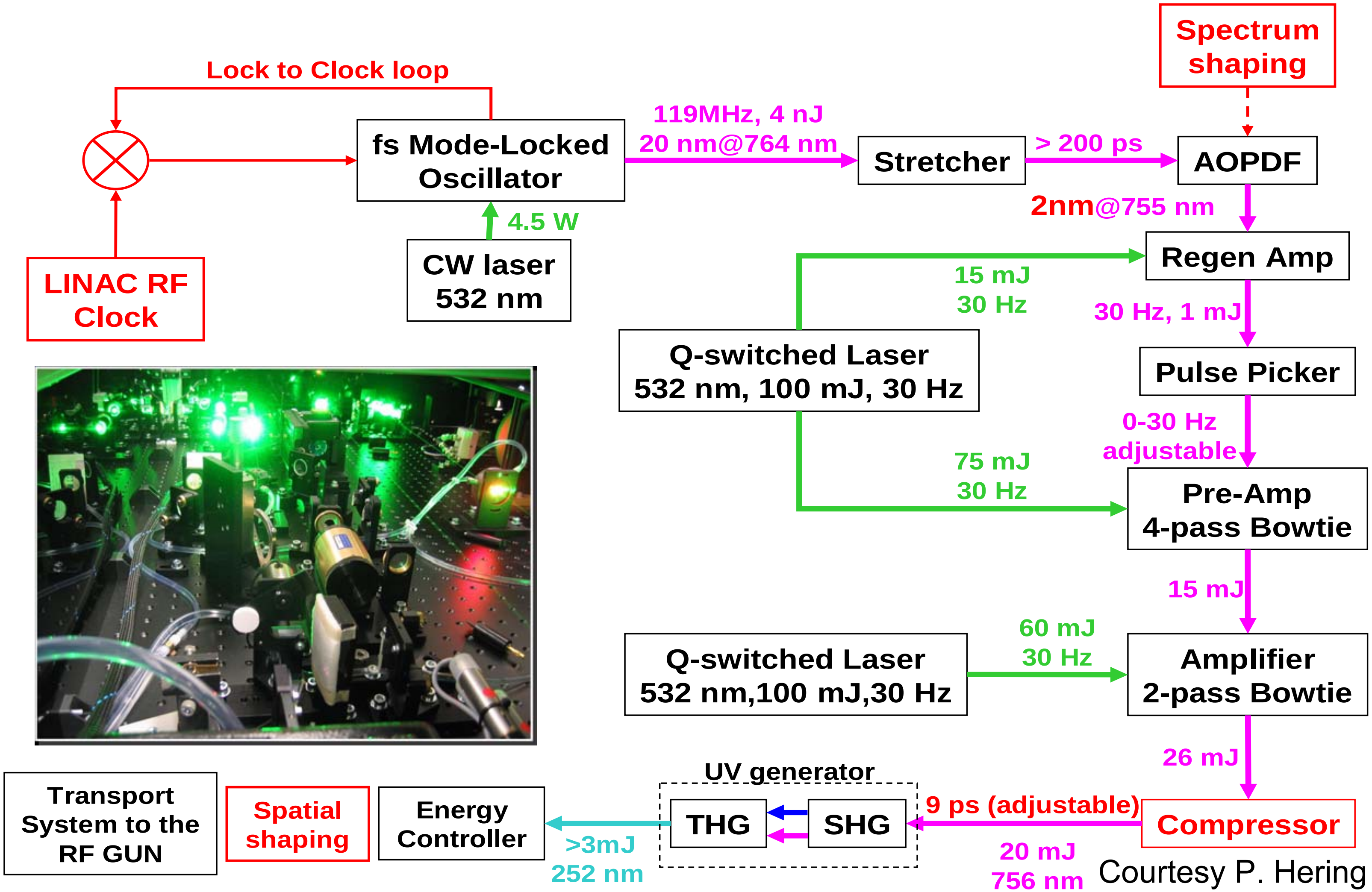
$$E_{laser} = \frac{hc}{\lambda} n_{photons} = \frac{hcQ}{\lambda eQE}$$

$$P_{laser} = RE_{laser} = \frac{hcQR}{\lambda eQE}$$

Specs at the Cathode

- Wavelength
- Energy
- Temporal Pulse Shape
- Beam Size
- Transverse Beam Shape
- Repetition Rate

LCLS Injector Drive Laser



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Oscillator

- Operates at sub-harmonic of RF frequency
  - Typical round trip time is 10 ns
  - ≈100 MHz pulse rate which is 28th sub-harmonic of S-band
- Phase lock laser to RF system
  - Require < 1° of jitter at RF frequency
  - Minimize jitter by locking harmonic rather than the laser fundamental frequency
- Pulse energy roughly 1 nJ
  - Requires significant amplification for injector application
- Oscillator must provide sufficient bandwidth for pulse shaping in later stages
  - Generally produce ≈ 100 fs pulse length

Amplifier

- Total gain required is approximately 7 orders of magnitude
- Use a regenerative amplifier, to amplify to mJ level and external amplifiers for final amplification
- Chirped Pulse Amplification (CPA)
  - Stretch pulse in time
  - Minimizes non-linear effects such as self focussing, self phase modulation
  - Allows increased amplification
  - Pulse is compressed after amplification
- Diode pumped amplifier minimize energy fluctuations
- Thermal effects limit rep rate and energy per pulse

Frequency Conversion

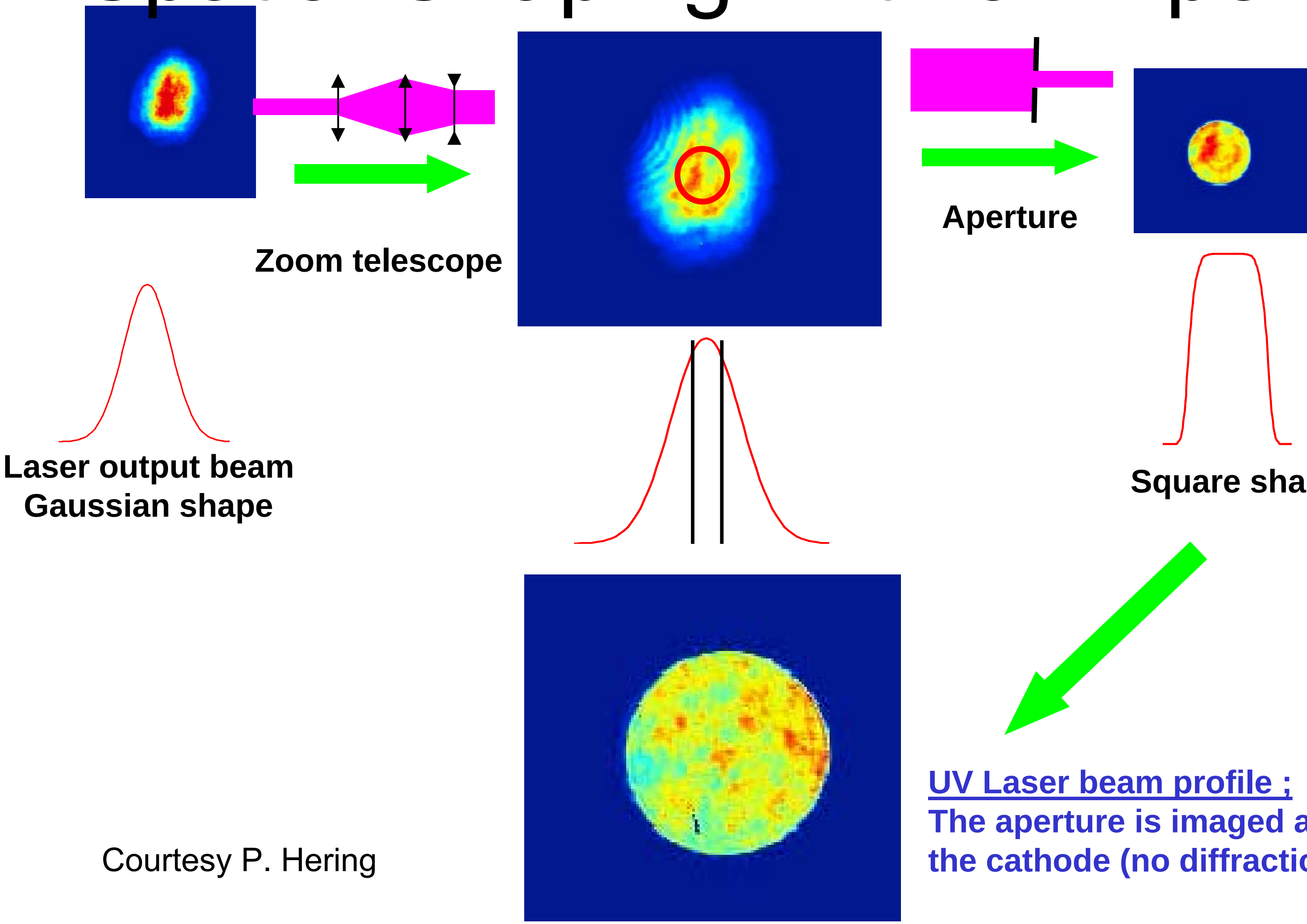
- Non-linear crystal with second order susceptibility
- Process commonly called Second Harmonic Generation (SHG)
- May require multiple stages to reach final photon energy
- Since process depends on E^2 or I, the final pulse length is often smaller than the input pulse length

$$P = \chi_1 E + \chi_2 E^2 + \chi_3 E^3 + \cdots$$

Spatial Shaping

- Transverse shape of the laser is reproduced on the electron beam assuming the QE is independent of position
- Methods
  - Aperture Clipping
  - Aspheric Lens
  - Adaptive Optics

Spatial Shaping With an Aperture



UV Laser beam profile ;
The aperture is imaged and focused on the cathode (no diffraction rings)

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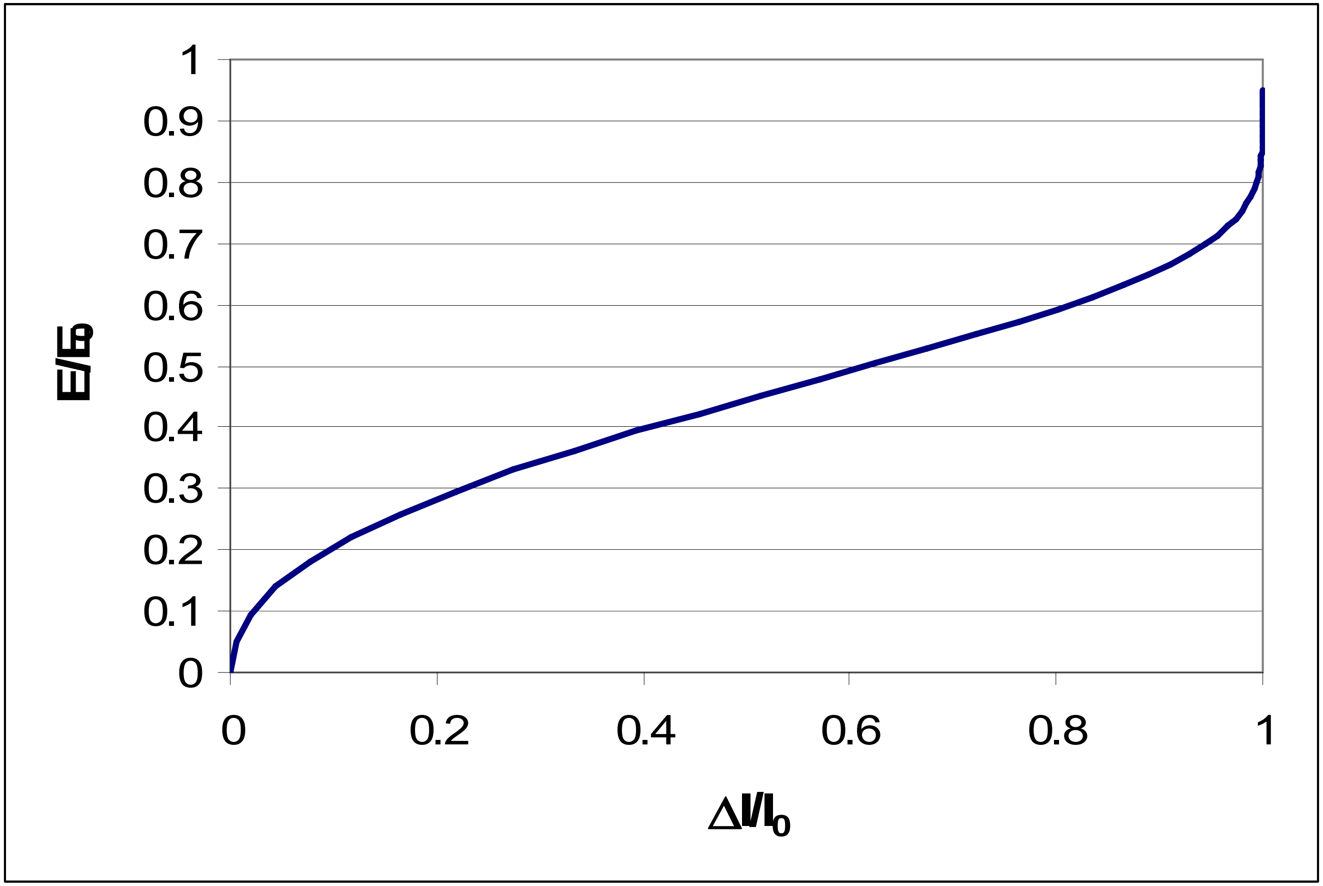
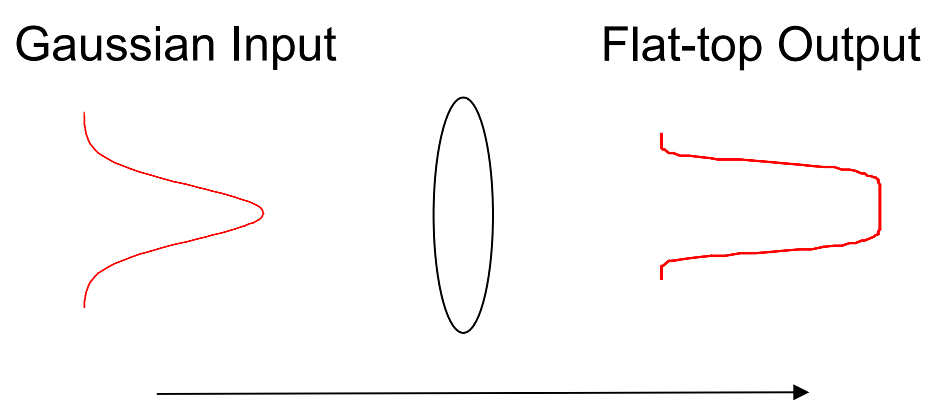
Energy Loss With Aperture Clipping

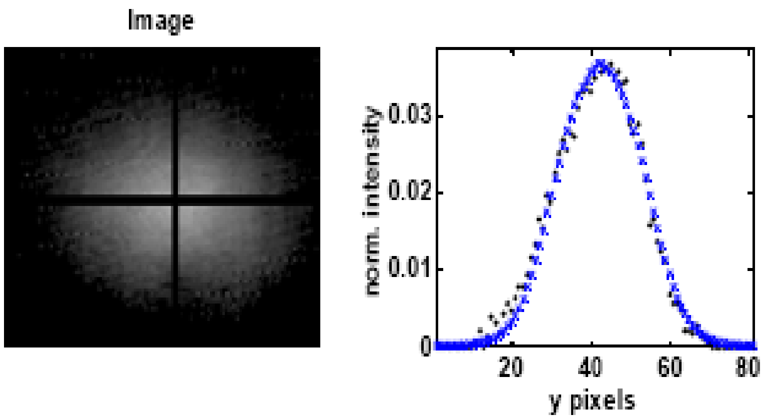


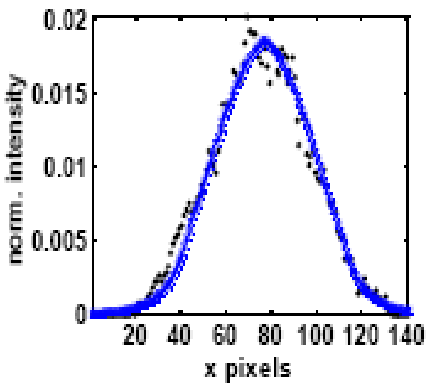
Aspheric Lens

- Lens shaped to produce flat top output for a Gaussian input with a specific beam size
- Transmission near 100%
- Developed by IBM for lithography application
- Now commercially available from Newport



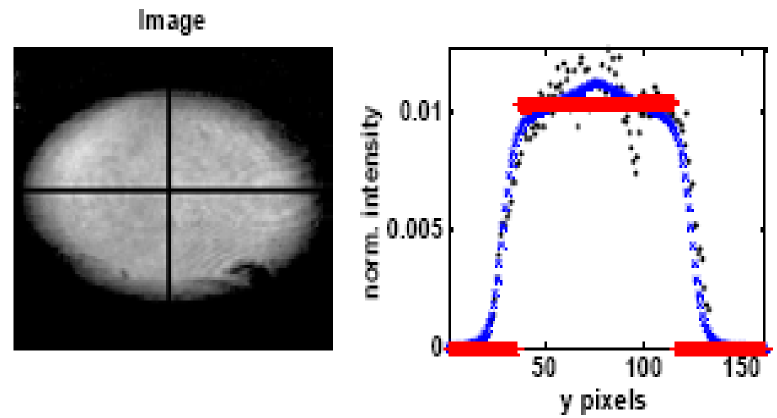
Aspheric Lens Measurement

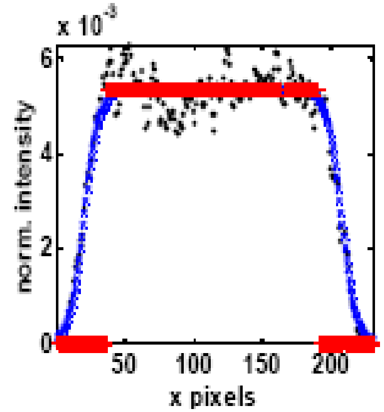




	x	y
centroid, um	2.71e+003	2.98e+003
$1/e^2$ width, um	1.55e+003	1.71e+003
beta	4.41	3.85
F-D err	0.000134	0.000203

Input Gaussian

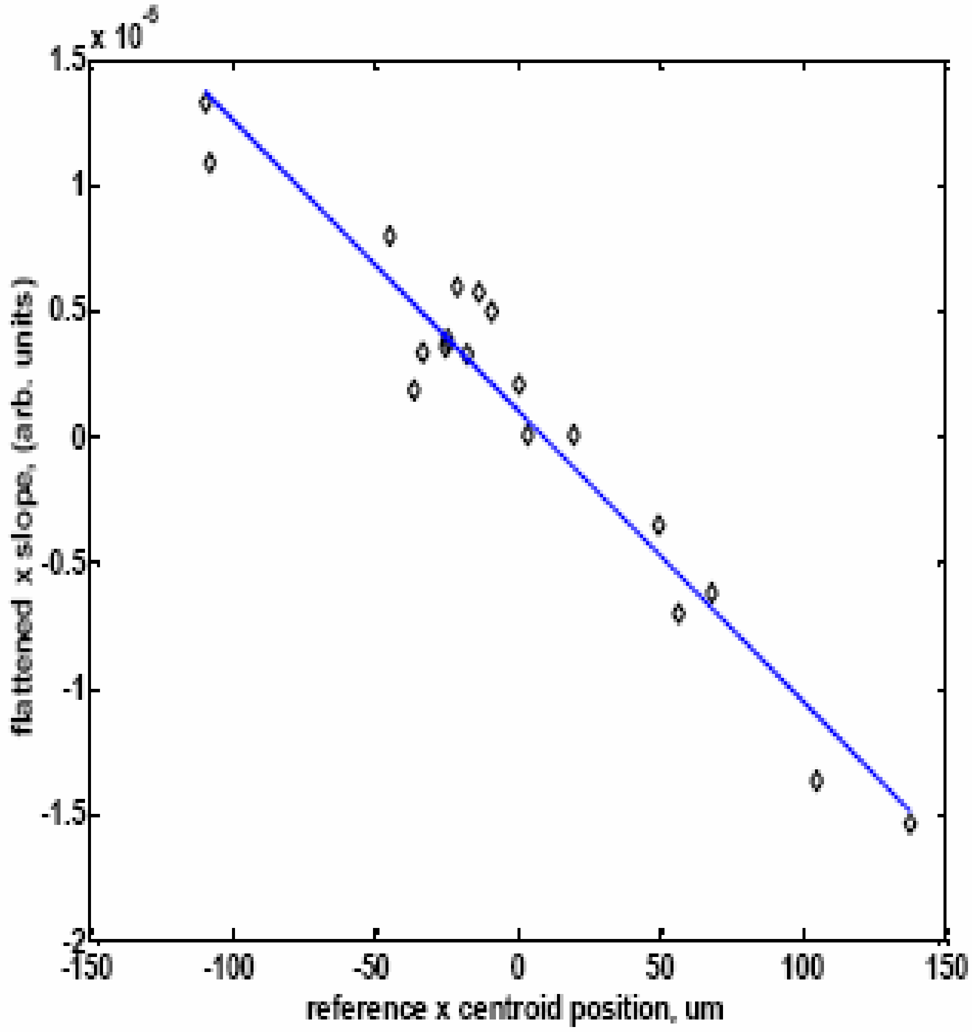




	x	y
centroid, um	4.01e+003	5.28e+003
FWHM, um	3.29e+003	3.03e+003
beta	18	14.2
F-D err	3.62e-005	0.000147
slope	6.77e-008	1.19e-006
lin. err	0.00544	0.0101
min/max	0.998	0.991

Output Flat-top

Effect of Input Position Jitter



Adaptive Optics

- Deformable mirror used to generate nearly arbitrary transverse pulse shape
- In principle could be combined with e-beam transverse shape measurement to compensate for QE spatial variations and generate a flat e-beam transverse shape

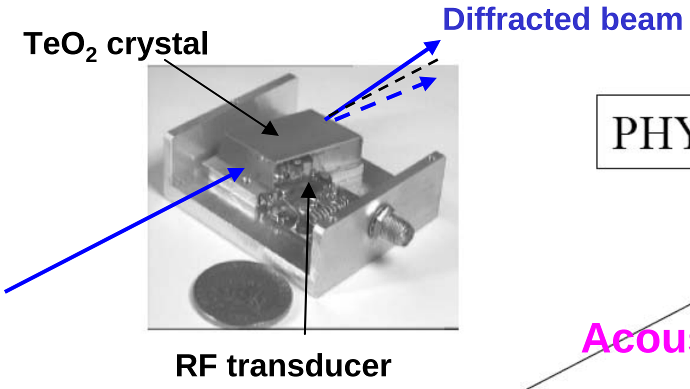
Dazzler

- Acousto-Optic Programmable Dispersive Filter (AOPDF)
- Birefringent TeO_2 Bragg diffracts different wavelengths at different depths
  - Optical path, or phase, is wavelength dependent
  - The phase delay of each wavelength is adjustable
  - Can generate approximate flat-top pulse

Temporal Pulse Shaping

- Dazzler (AOPDF)
- Frequency Domain
- Time Domain

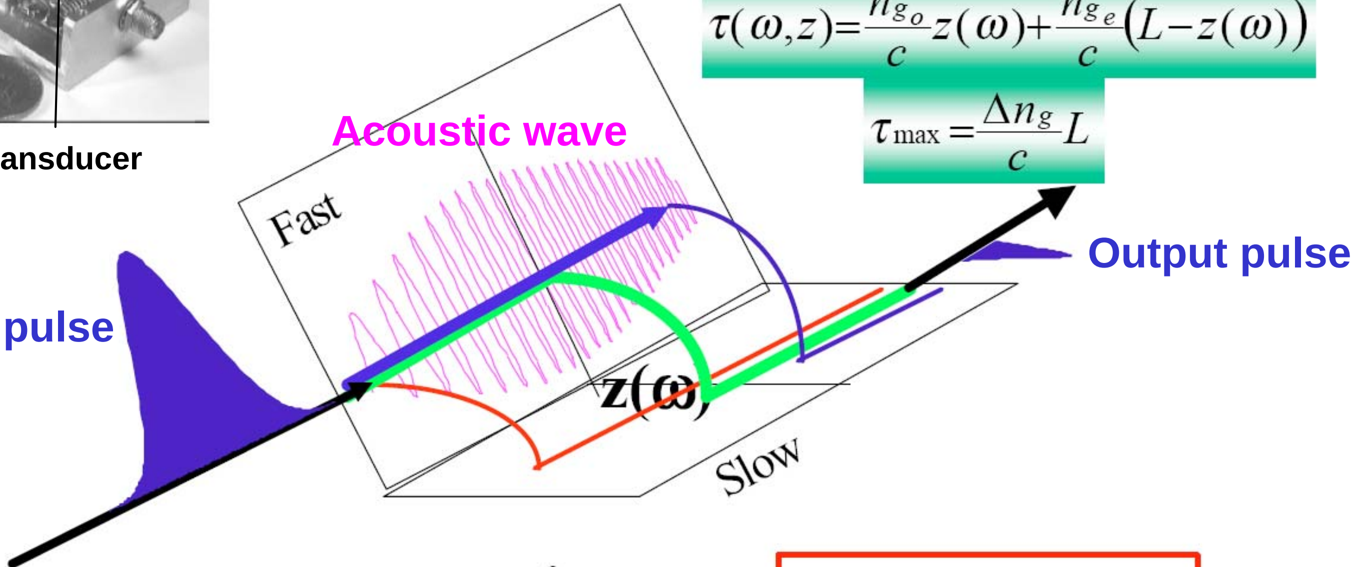
Acousto-Optic Programable Dispersive Filter
Dazzler



PHYSICAL CONCEPT

$$\tau(\omega,z)=\frac{n_{g_o}}{c}z(\omega)+\frac{n_{g_e}}{c}\left(L-z(\omega)\right)$$

$$\tau_{\max}=\frac{\Delta n_g}{c}L$$



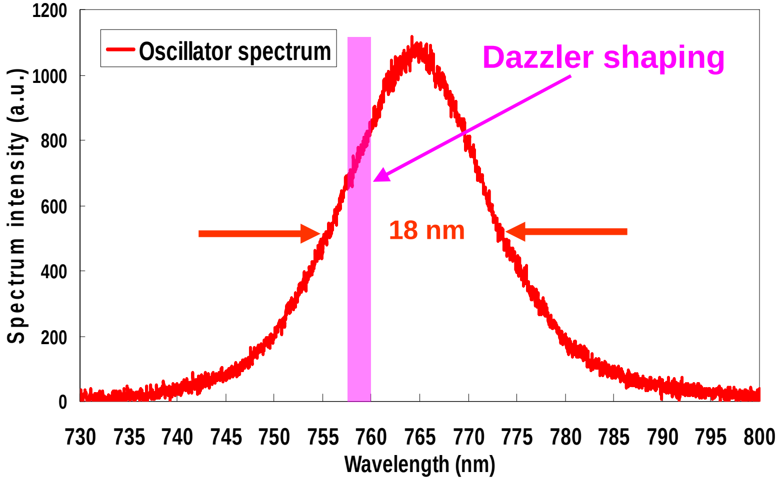
$$E_{out}(t)\propto S(t/\alpha)\otimes E_{in}(t) \quad \text{où} \quad \alpha=\frac{f_{ac}}{f_{opt}}\approx 10^{-7} \Rightarrow \boxed{E_{out}(\omega)\propto S(\alpha\omega)E_{in}(\omega)}$$

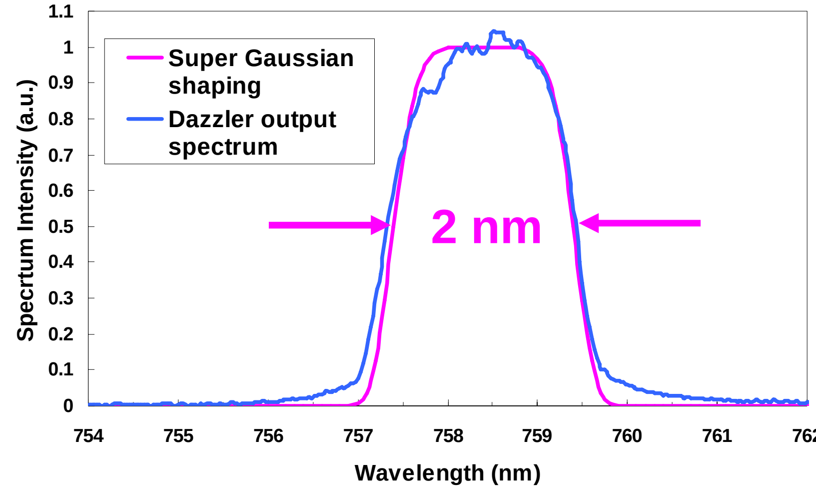
P. Tournois, Opt. Comm. **140**, 245 (1997)

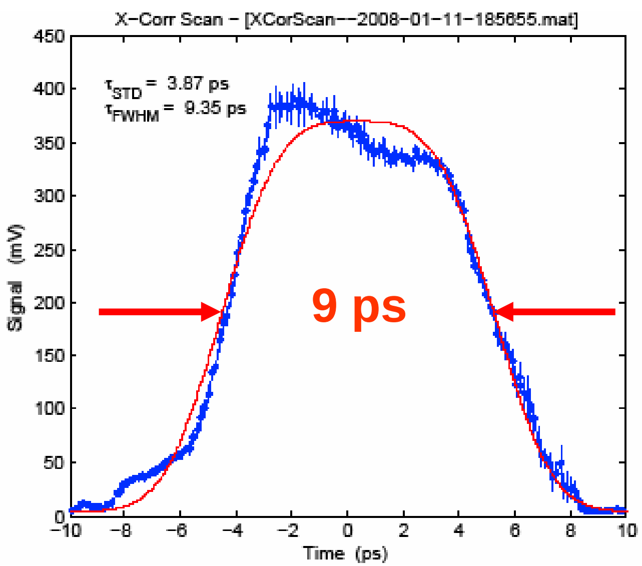
F. Verluise, V. Laude, Z. Cheng, Ch. Spielmann et P. Tournois, Opt. Lett. **25**, 575 (2000)

Courtesy P. Hering

Temporal Shaping with Dazzler







The time shape via the spectrum shape is fixed by the Dazzler

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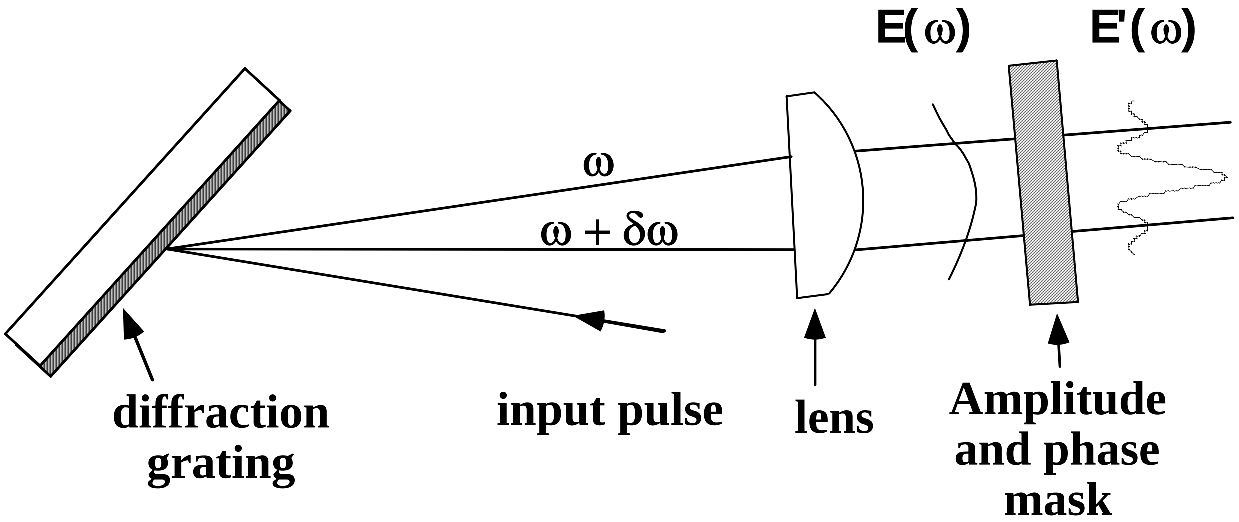
Temporal profile obtained in the UV :
The pulse duration is fixed by the compressor

Frequency Domain Pulse Shaping



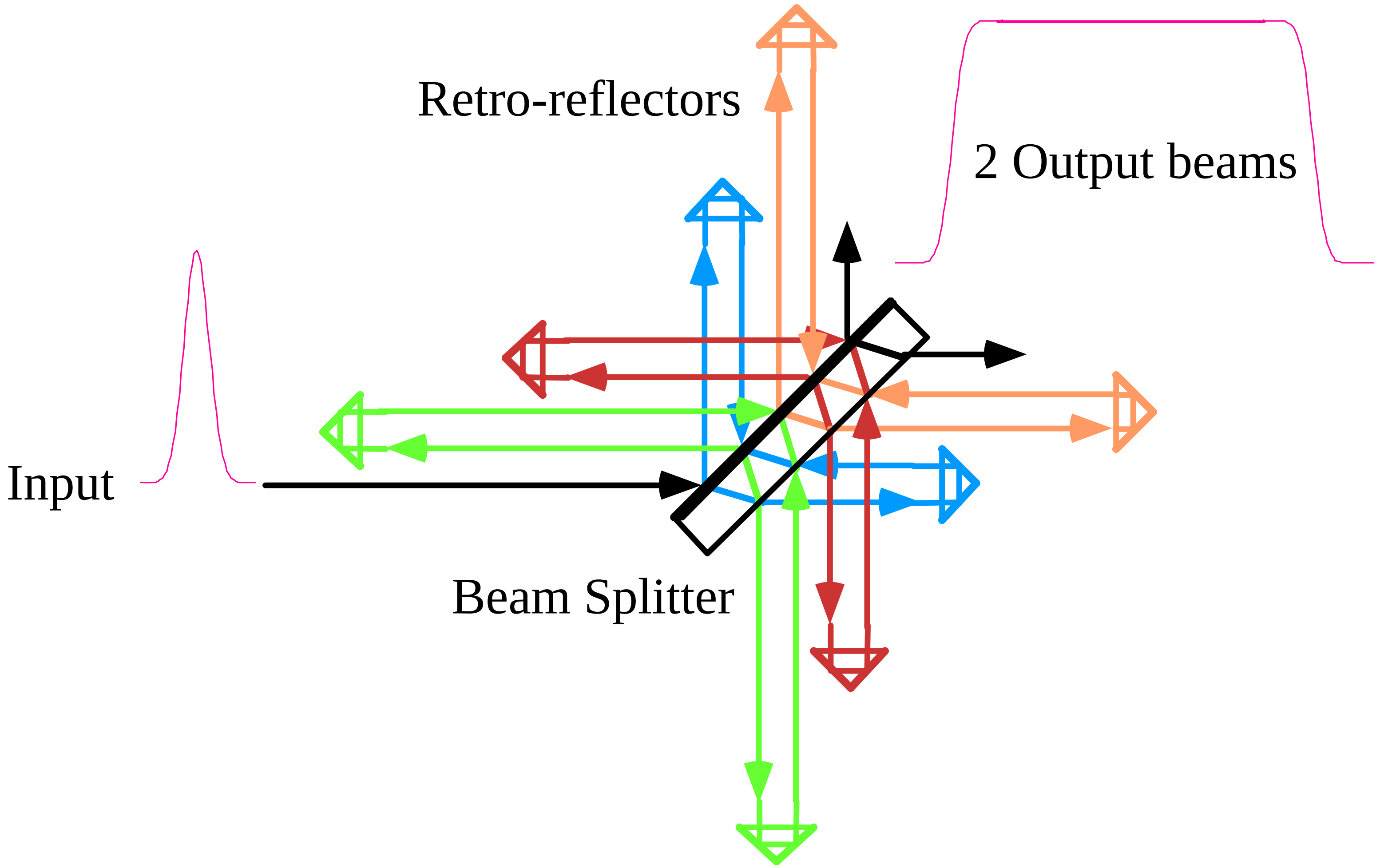
$$E'(\omega) = E(\omega)T(\omega) \qquad I(t) = \left| \int_{-\infty}^{\infty} E'(\omega) e^{-j\omega t} d\omega \right|^2$$

Can generate nearly arbitrary pulse shapes limited by input bandwidth and available masks

Time Domain Pulse Shaping

- Split beam into multiple pulses
- Adjust delay of each pulse and recombine
- Gaussian pulse with delay between pulses approximately equal to the rms width produce approximately flat-top pulse
- Interference between pulses problematic
  - Rotate polarization between pulses minimizes interference
  - Elliptical polarization requires normal incidence due to QE variation with polaration

Time Domain Pulse Shaping



Transport System

- Typically on the order of 10 m between the laser room and the gun
- Transport system must maintain all laser parameters with minimal loss
- Typically relay image the desired plane in the laser room to the cathode
  - Maintains transverse beam shape
  - Minimizes positional jitter
- Some system use a hard aperture a few cm before the cathode to produce a final

Diagnostics

- Monitor Spectrum
- Pulse Length
  - Streak Camera
  - AutoCorrelator
  - Cross Correlator
- Pulse Shape
  - CCD camera at virtual camera location
- Energy per pulse

Losses

- Transmission After Amplifier
  - Compression – 50%
  - Frequency Conversion – 10%
  - Temporal Pulse Shaping – 50%
  - Transverse Pulse Shaping – 25%
  - Transport – 50%
  - Total Transmission – 0.3%
- For 100 μJ at cathode requires 30 mJ from the amplifier

Summary

- Laser System very complex and usually requires dedicated operators
- Laser specs highly dependent on choice of cathode
- Laser is a significant fraction of the cost of the injector