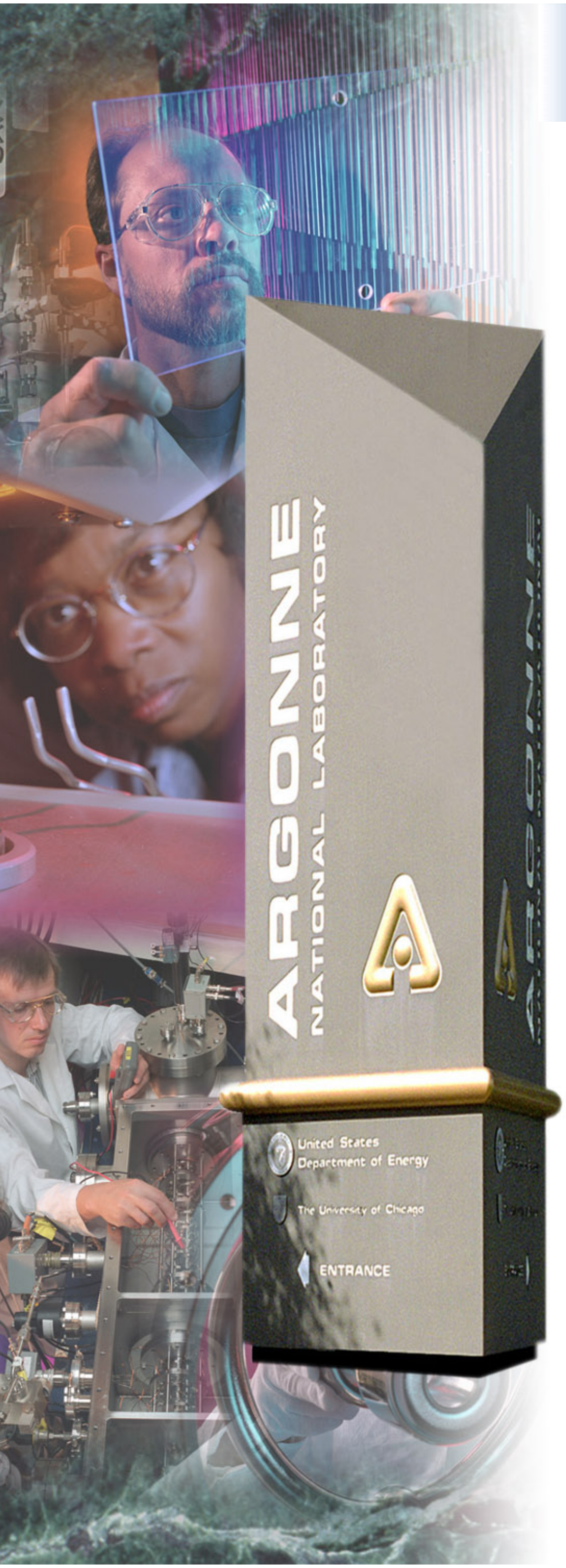


Laser application in accelerators

Laser pulse shaping

Yuelin Li

Accelerator Systems Division

Argonne National Laboratory

THE UNIVERSITY OF CHICAGO

Office of Science U.S. DEPARTMENT OF ENERGY

Argonne National Laboratory is managed by
The University of Chicago for the U.S. Department of Energy

Contents

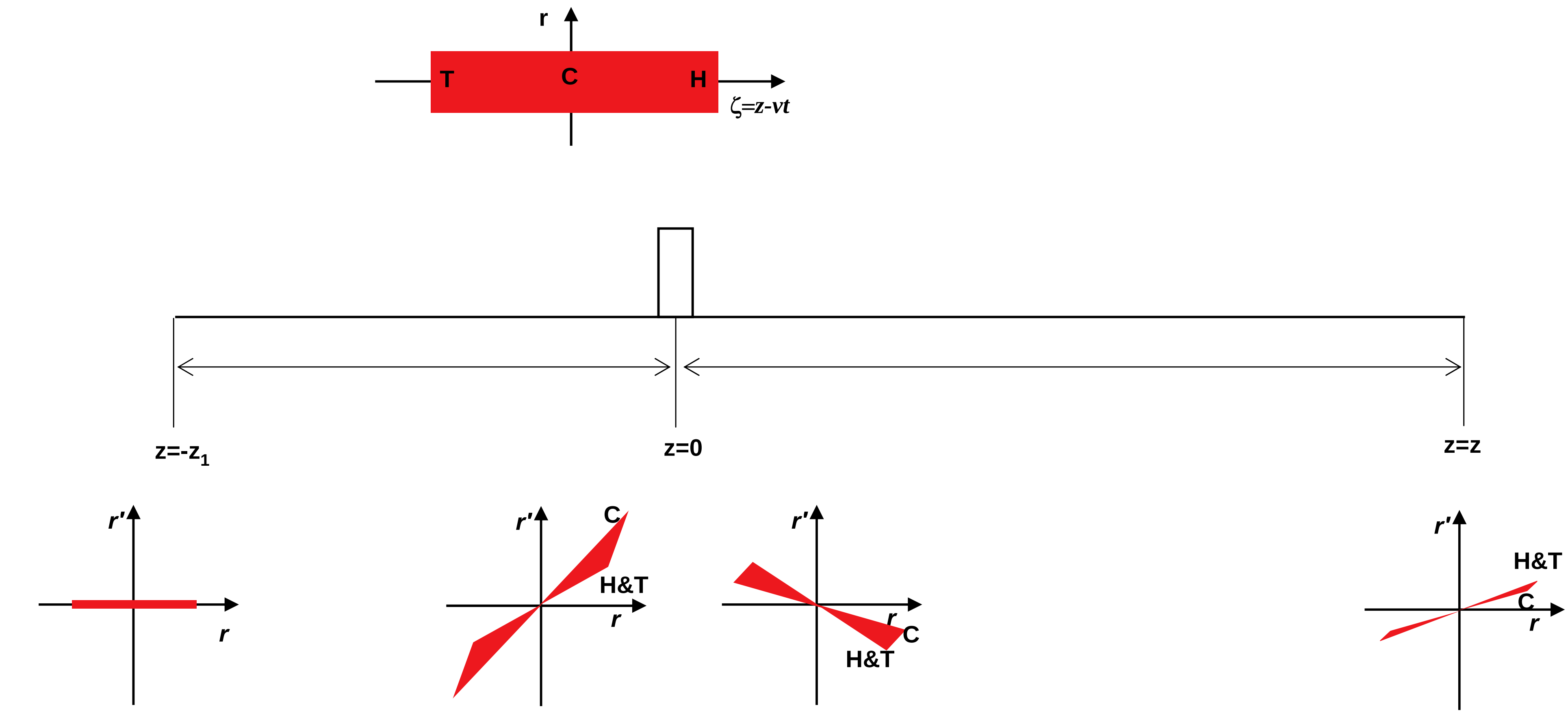
- Emittance compensation
  - Needs for emittance compensation
  - Emittance compensation theory
  - Space charge and beam geometries in emittance compensation
- Laser pulse description and diagnostics (brief refresh)
  - Laser beam: cross/auto-correlation and streak camera
  - Electron beam: rf deflection cavity
- Laser pulse shaping basics
  - Spatial shaping: convert Gaussian to flat-top
  - Temporal shaping: time and frequency domain techniques
  - Odds: man made materials
  - Accelerator examples
- 3D pulse shaping
  - Pulse stacking:
  - Dynamic shaping
  - Phase tailoring and chromatic aberration

Contents

Need for low emittance

- X-ray free electron lasers
  - LCLS: achieved 1 mm mrad
  - Cost saving in beam energy and undulator length
- Energy recovery linacs
  - Better coherence and brightness
- Electron diffraction
  - High S/N

Emittance compensation



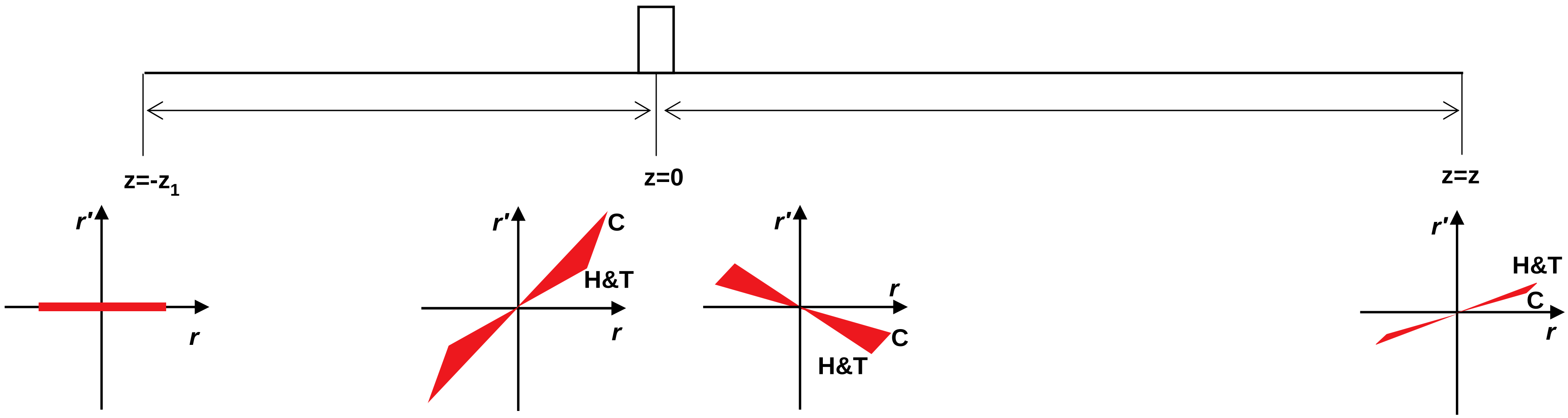
Initial phase space at gun

phase space at a propagation of z_1

phase space rotated by the lens

phase space after some drift after the lens

Emittance compensation



$r(\zeta)$:	r_0	$r_0+\lambda(\zeta)\frac{z_1^2}{2}$	$r_0+\lambda(\zeta)\frac{z_1^2}{2}$	$r_0+\lambda(\zeta)\frac{(z_1+z)^2}{2}-\alpha z\left(r_0+\lambda(\zeta)\frac{z_1^2}{2}\right)$
$r'(\zeta)$:	0	$\lambda(\zeta)z_1$	$\lambda(\zeta)z_1-\alpha\left(r_0+\lambda(\zeta)\frac{z_1^2}{2}\right)$	$\lambda(\zeta)(z_1+z)-\alpha\left(r_0+\lambda(\zeta)\frac{z_1^2}{2}\right)$

Assumptions: laminar beam, transverse linear space charge force

$\lambda(\rho, \zeta)=\rho\lambda(\zeta)/r_0$: space charge force

$1/\alpha$: focal length of solenoid

Let $\alpha = 2\frac{z_1+z}{z^2},\ z=\sqrt{z_1^2+\frac{2r_0}{\lambda}} \Rightarrow$

$$r(\zeta)=0$$
$$r'(\zeta)=0$$

Carlsten, NIMA 285, 313, (1989)

Emittance compensation

- Linearized beam envelope equation (trnasvers space charge force is linear, i.e., E(r)∝r)

$$\sigma'' + \sigma'\frac{\gamma'}{\beta^2\gamma} + K_r\sigma - \frac{\kappa_s}{\sigma\beta^3\gamma^3} - \frac{\varepsilon_n^2}{\sigma^3\beta^2\gamma^2} = 0$$

Transversely linear space charge force

Linear focusing force

σ: rms bema size; γ, β: relativistic factor and normalize velocity;

K_r: strength of a focusing channel;

$\kappa_s = Ig(\zeta)/2I_0$: beam perveance, I_0= 17 kA; g: longitudinal beam profile, $\zeta = z - \beta ct$

Prime denotes the derivative to z

- Normalized emittance

$$\varepsilon_n = \beta\gamma\varepsilon = \frac{\beta\gamma}{2}\sqrt{\langle r^2\rangle\langle r'^2\rangle - \langle rr'\rangle^2}$$

Assumptions:

paraxial approximation ($\sigma' \ll 1$),

cold, monochromatic beam

Linear space charge force

Serafini and Rosenzweig, PRE 55, 7565 (1997)

Envelope equation around equilibrium

- Assuming
  - a coasting beam in a focusing channel: $\gamma'=0$
  - Assuming beam start with zero thermal emittance, $\varepsilon_n=0$
- Envelope equation is now

$$\sigma'' + K_r\sigma - \frac{Ig(\zeta)}{2I_0\sigma\beta^3\gamma^3} = 0$$

- For a slice z at equilibrium, $\sigma''=0$,

$$\sigma_{eq}(g(\zeta)) = \left(\frac{Ig(\zeta)}{2I_0\sigma\beta^3\gamma^3K_r}\right)^{1/2} \rightarrow \quad \sigma'' + K_r\sigma\left(1-\frac{\sigma_{eq}^2}{\sigma^2}\right) = 0$$

- Around the equilibrium, $\sigma=\sigma_{eq}+\delta\sigma$, $\sigma^2=\sigma_{eq}^2(1+2\delta\sigma/\sigma_{eq})$

$$\delta\sigma''(\zeta) + 2K_r\delta\sigma(\zeta) = 0$$

$$\Rightarrow \sigma(z,\zeta) = \sigma_{eq}(g(\zeta)) + [\sigma_0 - \sigma_{eq}(g(\zeta))]\cos(\sqrt{2K_r}z)$$

$$\sigma'(z,\zeta) = \sqrt{2K_r}[\sigma_0 - \sigma_{eq}(g(\zeta))]\sin(\sqrt{2K_r}z)$$

Serafini and Rosenzweig, PRE 55, 7565 (1997)

Emittance oscillation

- Beam emittance

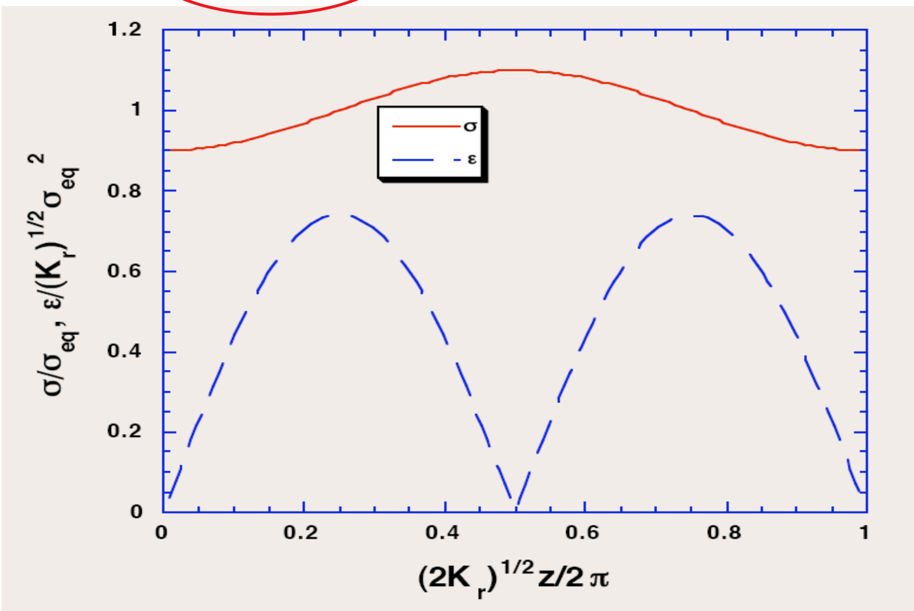
$$\sigma(z,\zeta) = \sigma_{eq}(g(\zeta)) + [\sigma_0 - \sigma_{eq}(g(\zeta))]\cos(\sqrt{2K_r}z)$$

$$\sigma'(z,\zeta) = \sqrt{2K_r}[\sigma_0 - \sigma_{eq}(g(\zeta))]\sin(\sqrt{2K_r}z)$$

$$\Rightarrow \varepsilon(z) = \sqrt{\langle\sigma^2\rangle\langle\sigma'^2\rangle - \langle\sigma\sigma'\rangle^2}$$

$$= \sqrt{2K_r}\sigma_0\sqrt{\langle\sigma_{eq}^2(g(\zeta))\rangle - \langle\sigma_{eq}(g(\zeta))\rangle^2}\left|\sin(\sqrt{2K_r}z)\right|$$

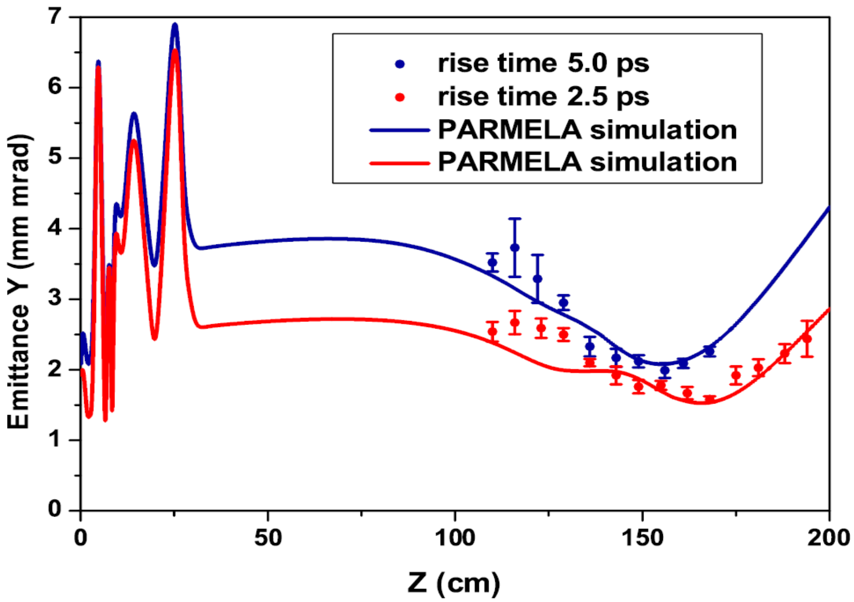
- With proper focusing, emittance due to linear space charge force can always be compensated.



Serafini and Rosenzweig, PRE 55, 7565 (1997)

Emittance oscillation experiment

- Emittance oscillation is real
- Pulse shaping is important: emittance compasation starts with pulse shaping



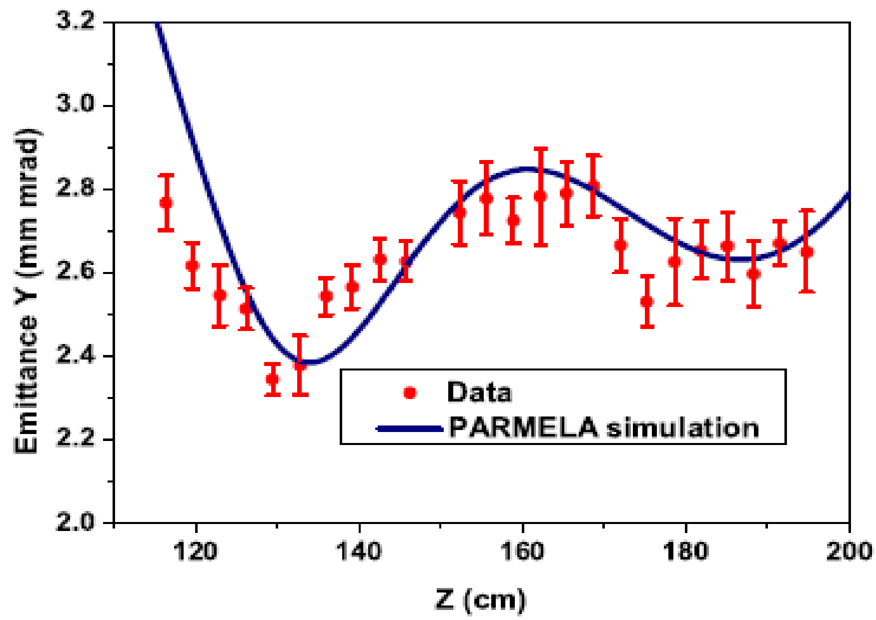
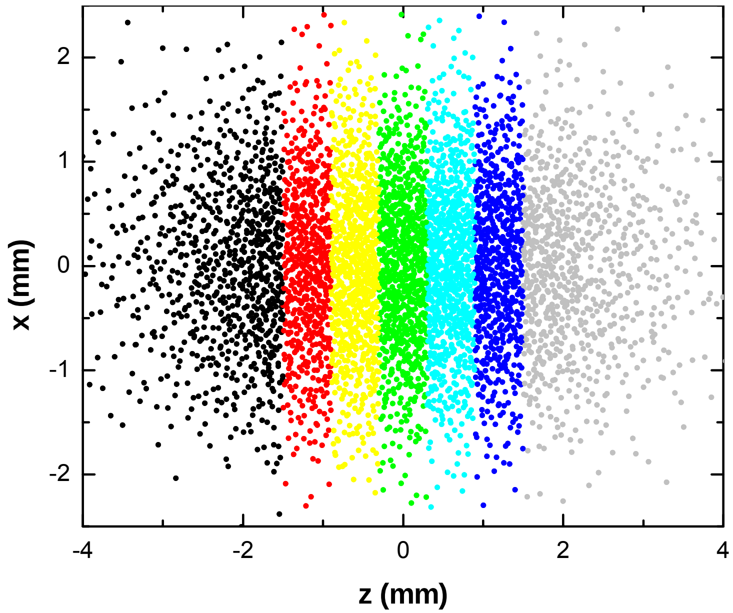


TABLE IV. Parameters of the beam corresponding to the best brightness result.

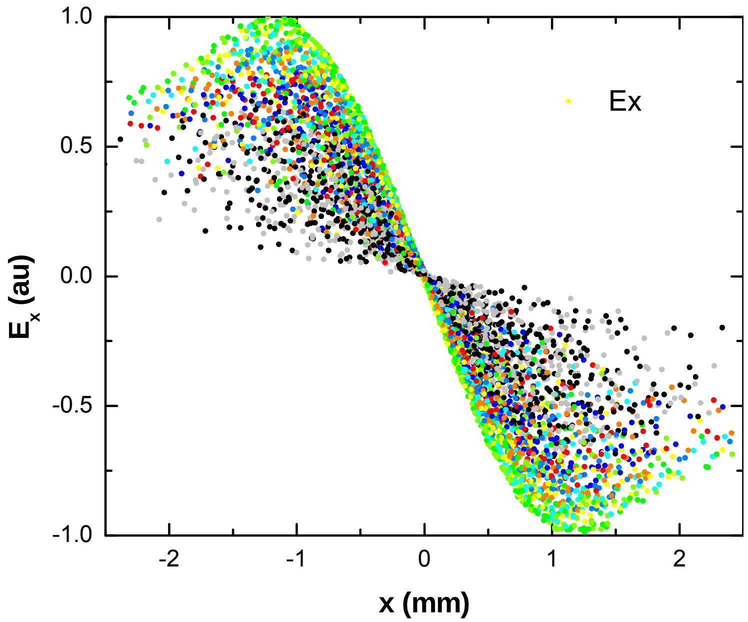
Parameter	Value
Energy	5.65 MeV
Charge	0.83 nC
Laser spot size	360 μm
Laser pulse length	8.9 ps FWHM
Phase ($\varphi - \varphi_{\max}$)	8^0

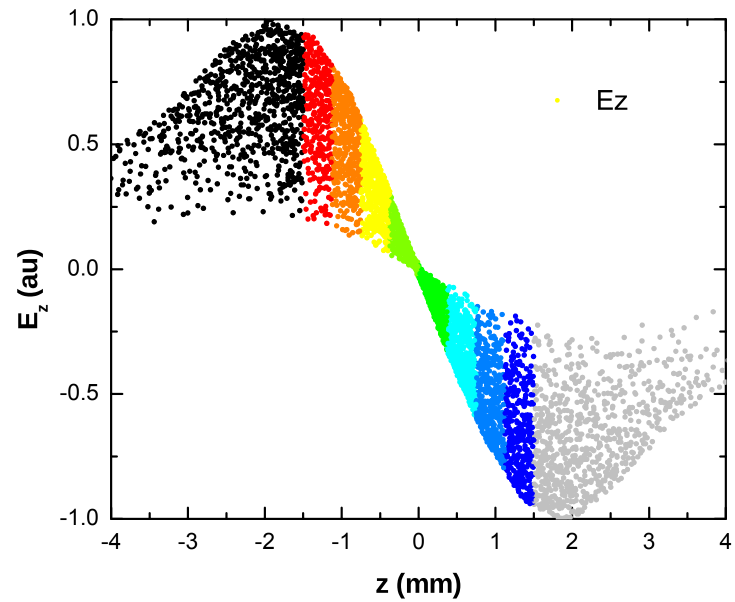
Cianchi et al., PRSTAB 11, 032801 (2008)

Space charge force of different geometries: Gaussian

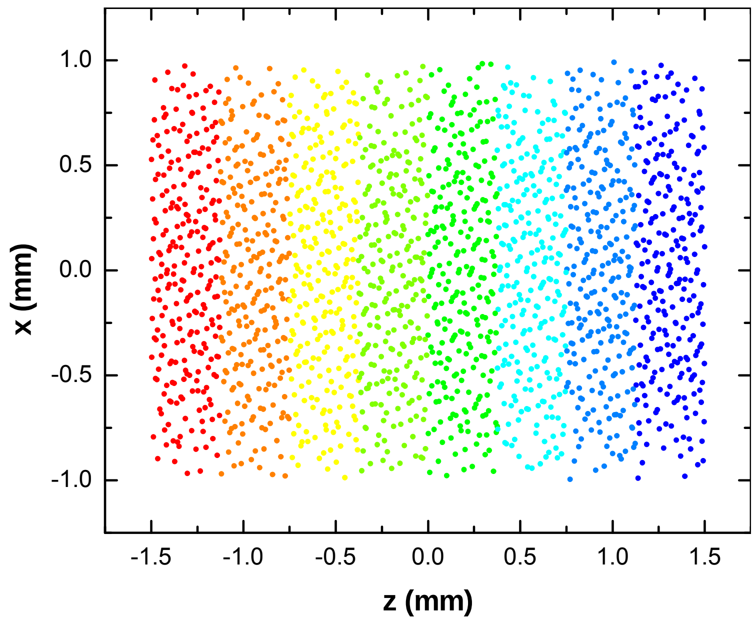


$$\exp\left[-\frac{1}{2}\left(\frac{r}{R}\right)^2-\frac{1}{2}\left(\frac{t}{T}\right)^2\right]$$





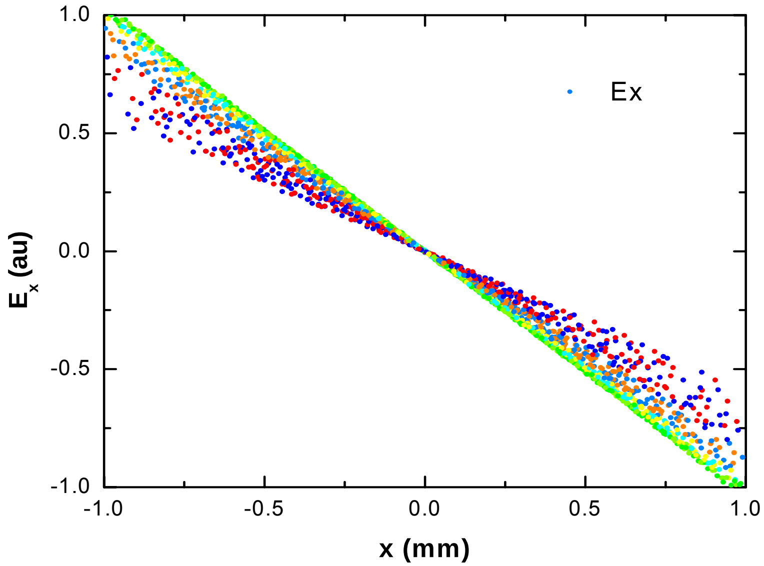
Space charge force of different geometries: Cylinder

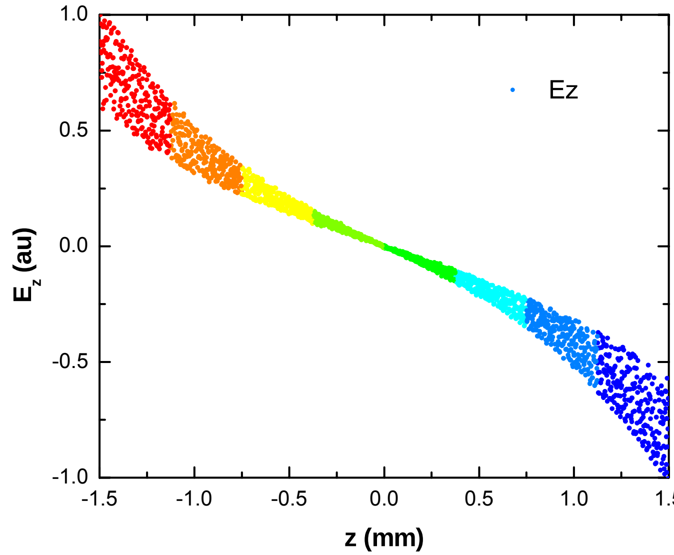


Confining surface

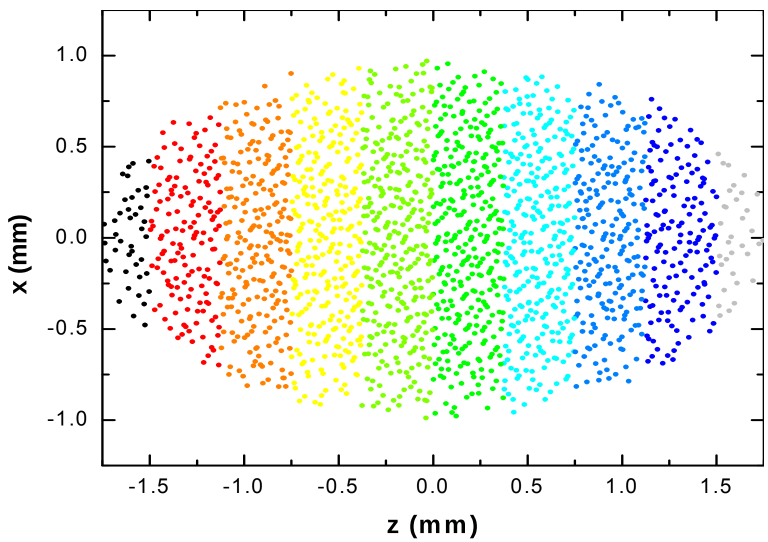
$$-T \leq t \leq T$$

$$r \leq R$$



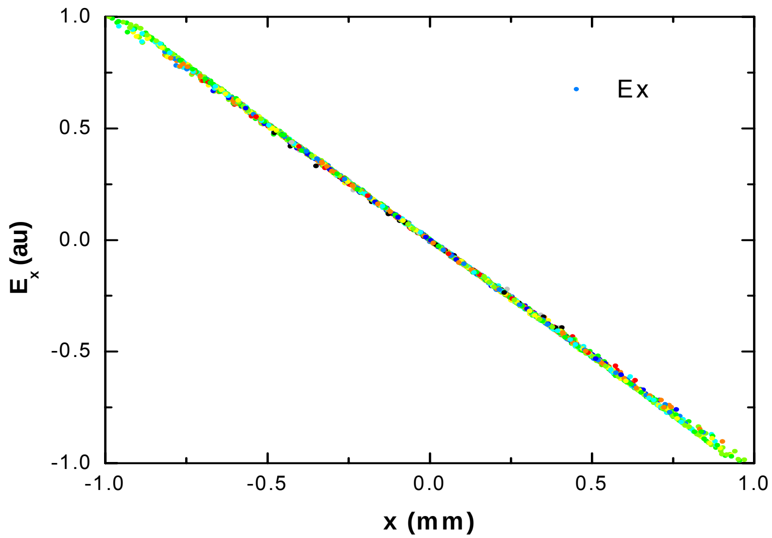


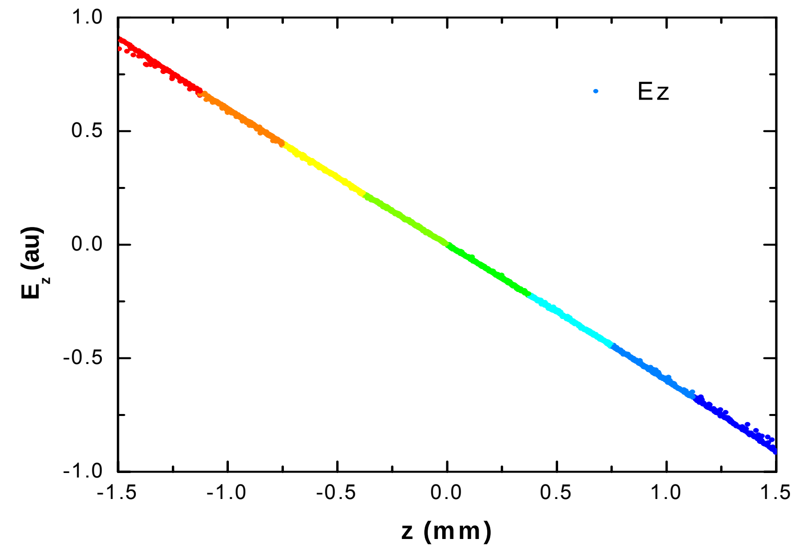
Space charge force of different geometries: Ellipsoid



Confining surface

$$\left(\frac{r}{A}\right)^2 + \left(\frac{z}{C}\right)^2 = 1$$





Space charge force of different geometries: Ellipsoid

- Analytical field expressions
- Linear space charge fields in each direction [Kellogg, Foundation of potential theory, 1929].

$$\vec{\mathbf{E}} = (E_x, E_y, E_z) = \frac{\rho_0}{\varepsilon_0}(M_x x, M_y y, M_z z)$$

- For a spheroid

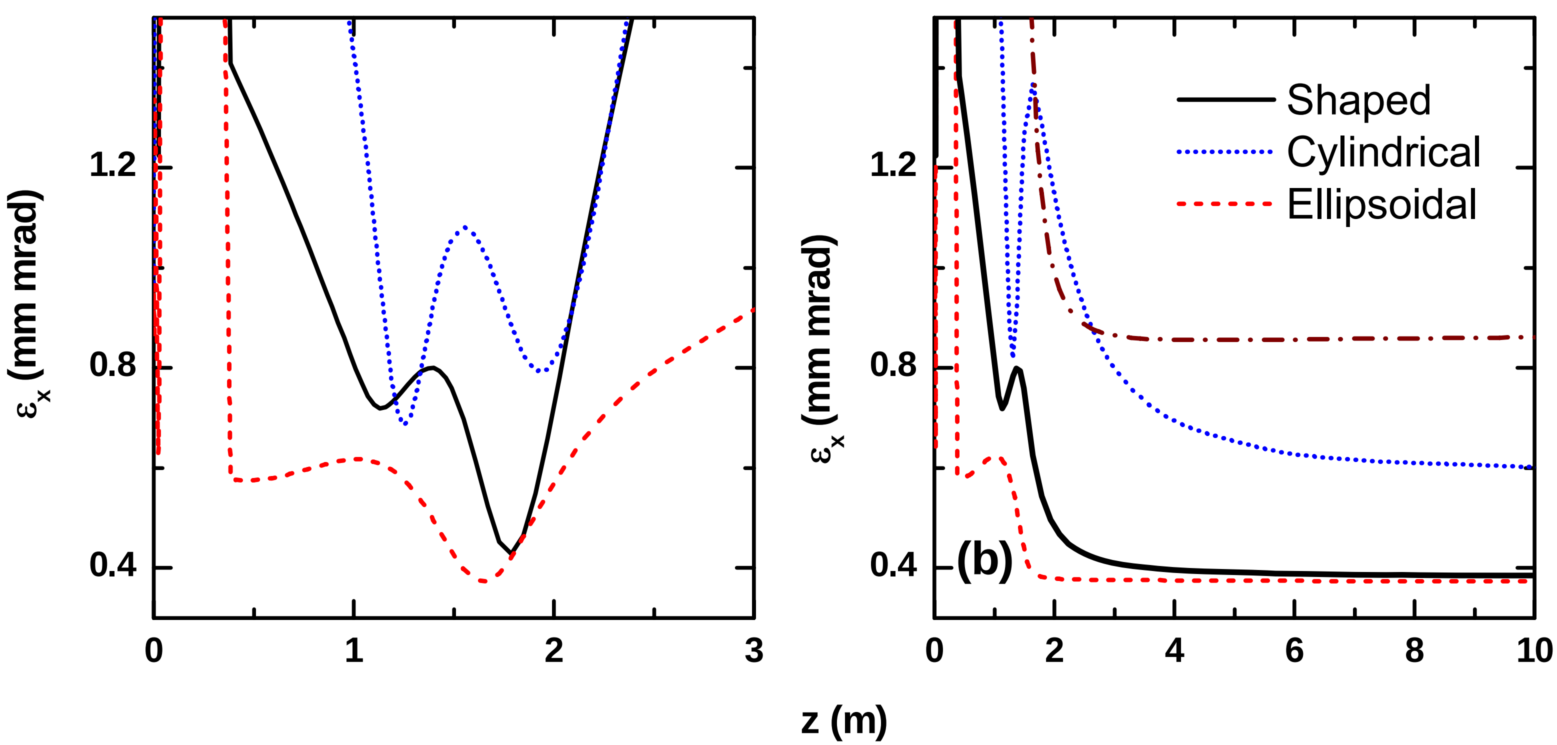
$$M_z = \frac{1+\Gamma}{\Gamma^3}(\Gamma - \arctan(\Gamma)), \qquad M_x = M_y = \tfrac{1}{2}(1-M_z) \qquad \Gamma = \sqrt{A^2/C^2 - 1}$$

$$\left(\frac{r}{A}\right)^2 + \left(\frac{z}{C}\right)^2 = 1$$

An ellipsoidal pulse is the most desirable

- Simulation example using LCLS setup for 1 nC beam
- Emittance oscillation
- Beam geometry matters

(a) No booster **(a)** Plus booster



Li and Lewellen, PRL 100, 074801 (2008)

Emittance compensation starts with Pulse Shaping

- In a photoinjector
  - Beam carries over the laser geometry
    - *Cathode response time issue*
- Emittance compensation requires
  - Linear space charge force, which is dependent on the beam geometry
- Laser pulse geometry is the key
- Other area needs laser pulse shaping
  - bunch train generation
  - Ultrafast electron bunches

Contents

- Emittance compensation
  - Needs for emittance compensation
  - Emittance compensation theory
  - Space charge and beam geometries in emittance compensation
- Laser pulse description and diagnostics (brief refresh)
  - Laser beam: cross/auto-correlation and streak camera
  - Electron beam: rf deflection cavity
- Laser pulse shaping basics
  - Spatial shaping: convert Gaussian to flat-top
  - Temporal shaping: time and frequency domain techniques
  - Odds: man made materials
  - Accelerator examples
- 3D pulse shaping
  - Pulse stacking:
  - Dynamic shaping
  - Phase tailoring and chromatic aberration

Laser pulse description

- Pulse description in time domain

$$E(x,y,t) = A(x,y,t)\exp\big(i\phi(x,y,t)\big)$$
$$\Rightarrow E(r,t) = A(r,t)\exp\big(i\phi(r,t)\big)$$

- Pulse description in frequency domain

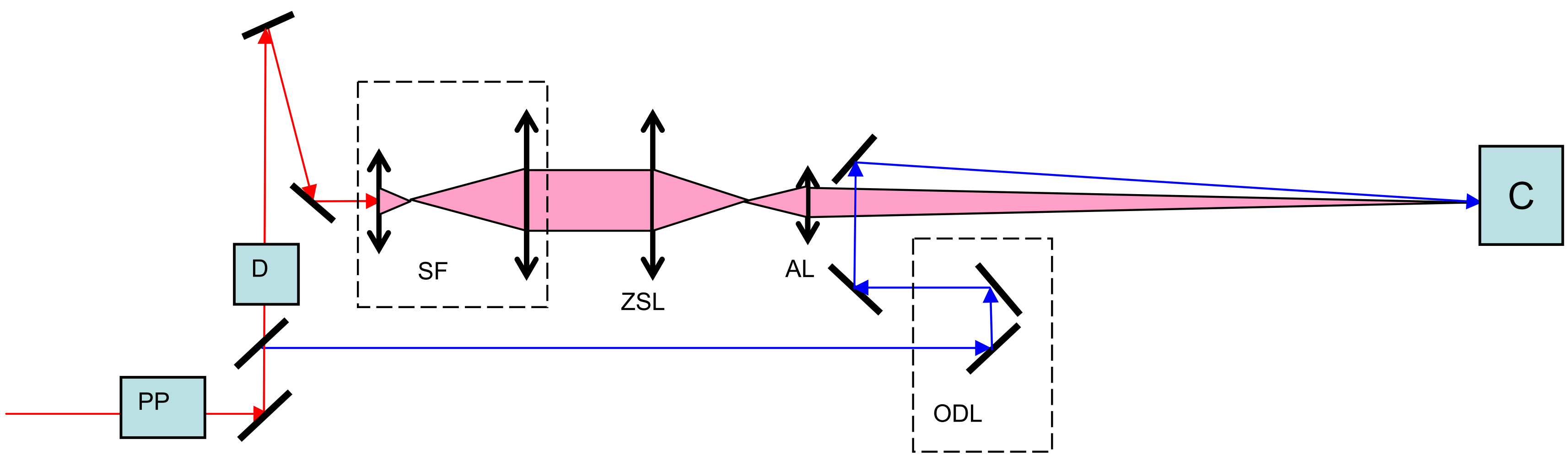
$$E(r,\omega) = A(r,\omega)\exp\big(i\varphi(r,\omega)\big)$$

- An all Gaussian pulse is the most common (TM00 mode)

$$E(r,t) = \exp\left(-\frac{1}{2}\left(\frac{r}{R}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{t}{T}\right)^2\right)\exp\big(i\varphi(r,\omega)\big)$$

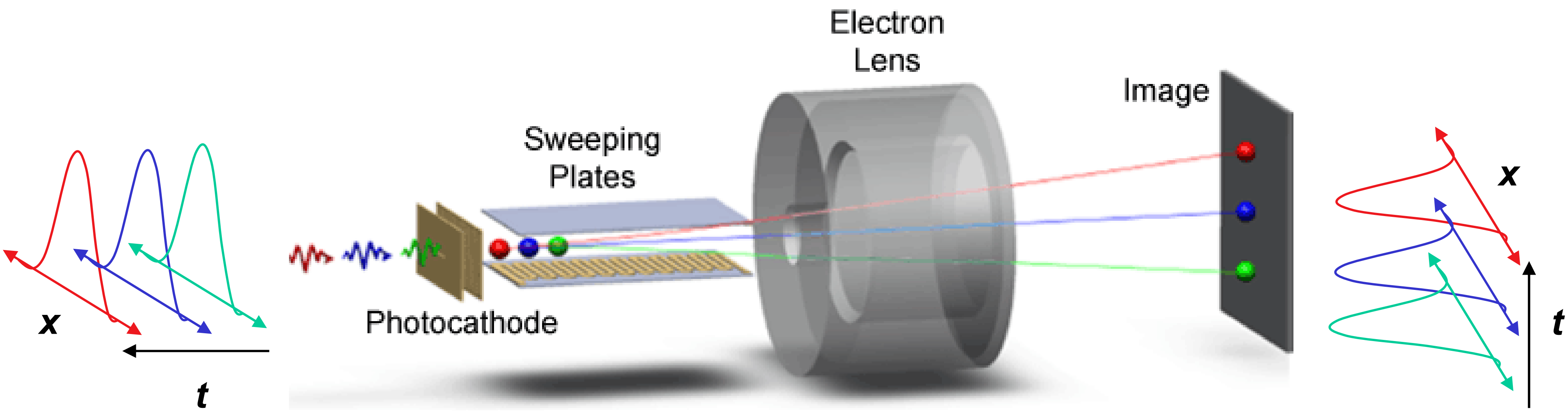
Laser diagnostics, up to 3D

- Cross- correlations
  - Can be accomplished while different interaction mechanisms
    - *Nonlinear interactions: sum or different frequency generation*
    - *Direct interference in time, spatial or frequency domain*
  - Cross a short and long pulse, resolution can be 10 fs
    - *Can be fully 3 D*



Laser and beam diagnostics, up to 3D

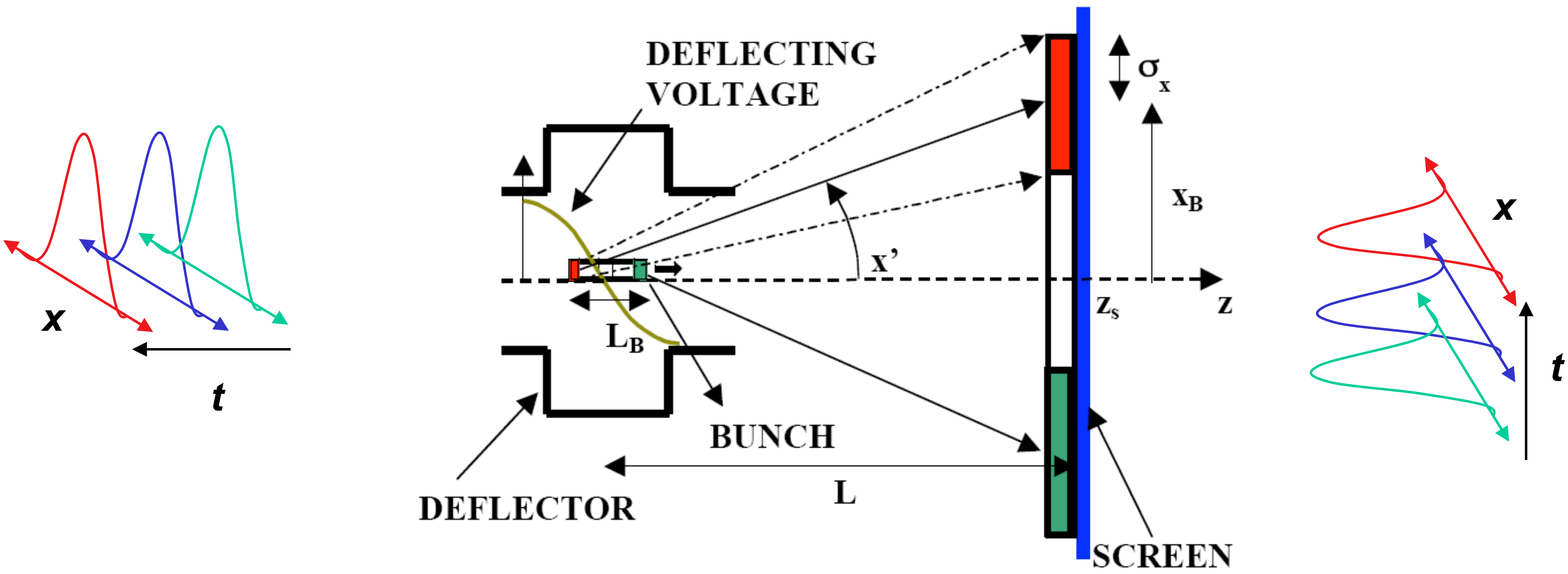
- Streak cameras
  - With proper arrangement can have 2D resolution, ps resolution



http://www-als.lbl.gov/als/science/sci_archive/161streakcamera.html

Beam diagnostics, up to 3D

- Rf-Deflection cavity
  - Similar to a streak camera
  - 50 fs resoltution possible



D. Alesini, C. Vaccarezza, *(INFN/LNF)*, SPARC-BD-03/006

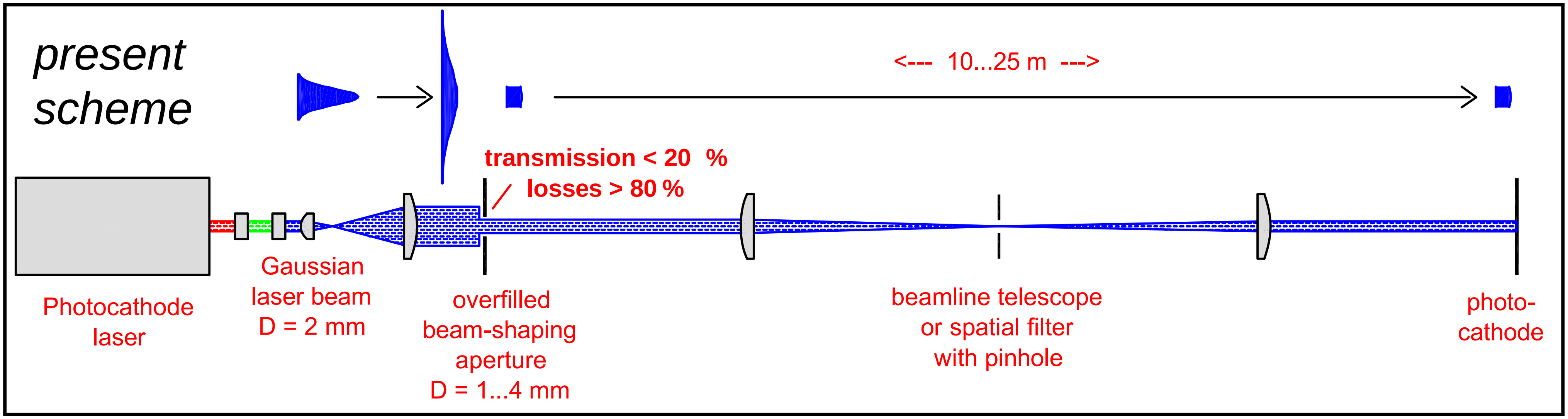
Contents

- Emittance compensation
  - Needs for emittance compensation
  - Emittance compensation theory
  - Space charge and beam geometries in emittance compensation
- Laser pulse description and diagnostics (brief refresh)
  - Laser beam: cross/auto-correlation and streak camera
  - Electron beam: rf deflection cavity
- Laser pulse shaping basics
  - Spatial shaping: convert Gaussian to flat-top
  - Temporal shaping: time and frequency domain techniques
  - Odds: man made materials
  - Accelerator examples
- 3D pulse shaping
  - Pulse stacking:
  - Dynamic shaping
  - Phase tailoring and chromatic aberration

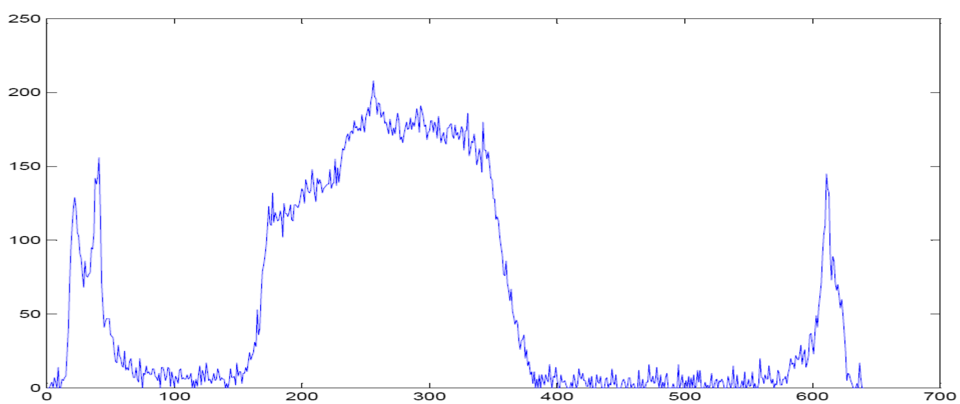
Transverse profile shaping: Conversion to top hat profile

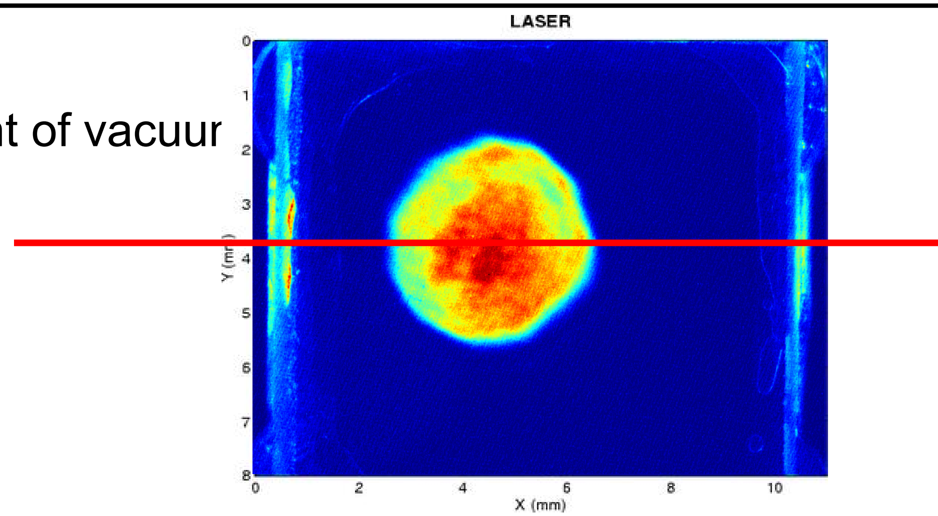
- Purpose: generating cylindrical beam or ellipsoidal beam
  - Top-hat in all dimensions: time and space
- Methods
  - Clipping a Gaussian: self explaining
  - Beam flattener optics
  - Deformable mirrors
  - Spatial light modulators
- Experimental results for injectors
  - None is satisfying

Gaussian to flat top clipping: PITZ and ATF/DESY



- Imaging the overfilled iris on laser table
- Problem: larger pointing jitter than iris in front of vacuur
- Jitter about 0.5 of diameter min/max





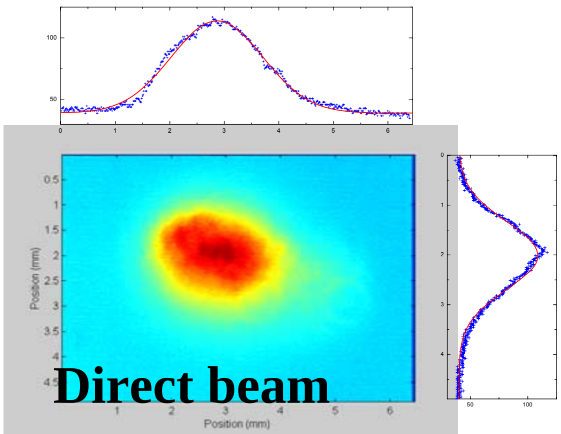
Ingo Will, Max-Born Institute

S. Schreiber, DEZY

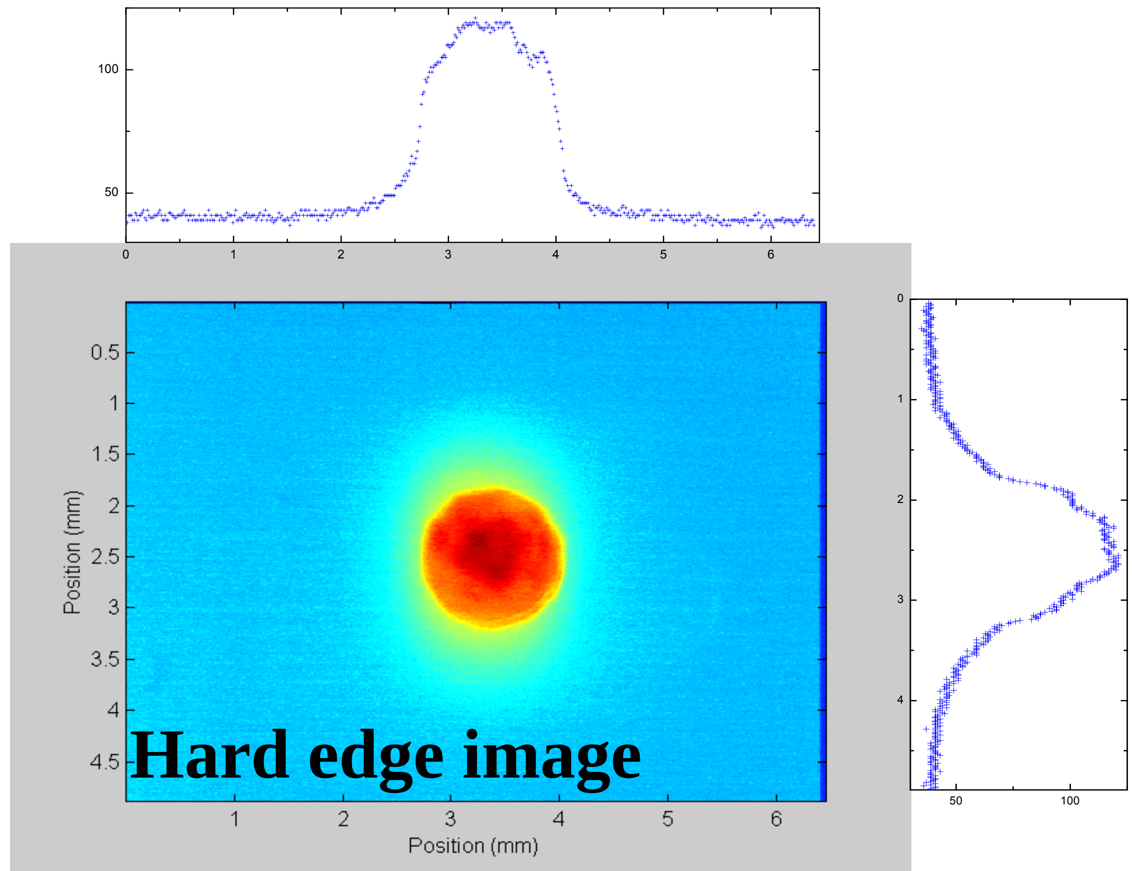
PITZ mini pulse shaping workshop, 2007

Beam clipping

- Slef-explaining but obvious far from perfect and low efficiency



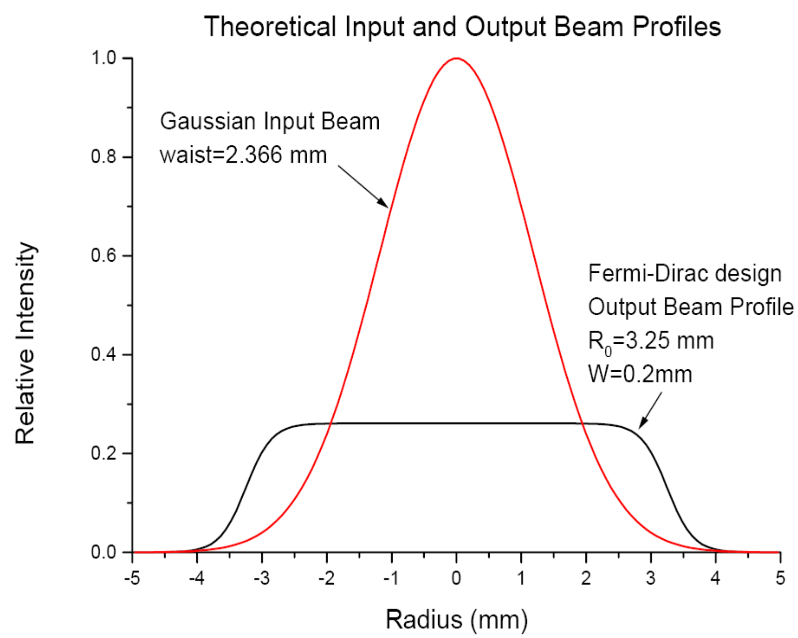
- BNL TTF
- APS PC gun
- LCLS



Y. Li, APS

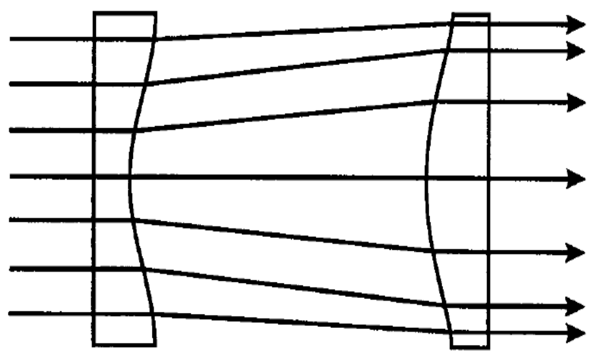
Beam shaper

- The idea is old (B. R. Frieden, "Lossless conversion of a plane laser wave to a plane wave of uniform irradiance," Appl. Opt. **4**, 1400-1403 (1965).)
- Using refraction to redistribute the laser rays, normally from Gaussian to top-hat, match both the phase and the intensity
- Many designs available
- Commercially available from Newport (GBS series) and Mol Tech GmbH (pi-shaper)



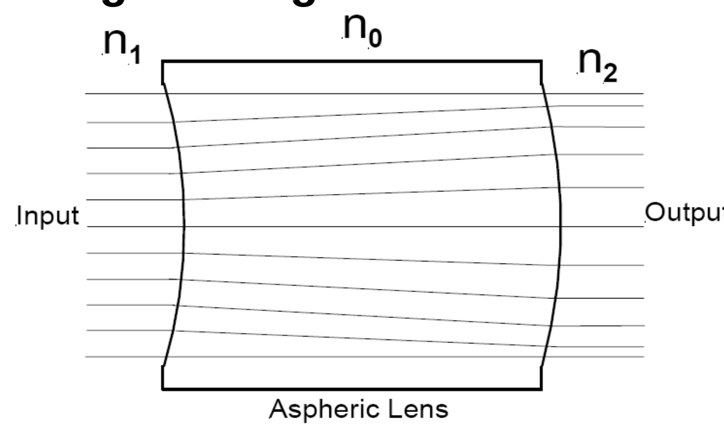
Beam shaper designs

Newport design



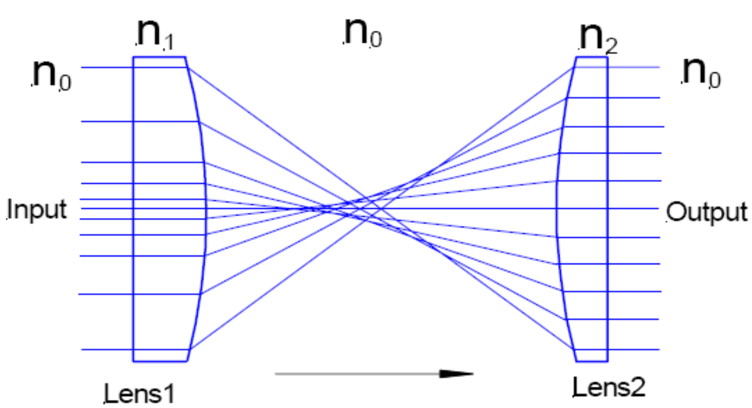
Hoffnagle et al, Apll. Opt. 39, 6488 (2000).

Singlet design 1



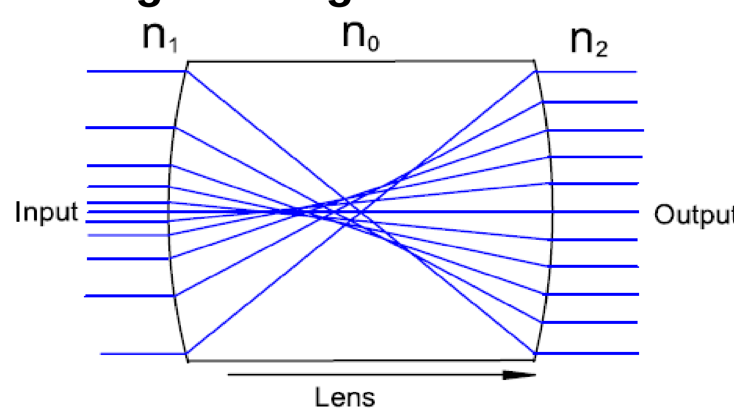
Zhang et al., Opt Express 11, 1942 (2003).

Another 2-lens design



Liu and Zhang et al., Opt. Express 16, 6675 (2008).

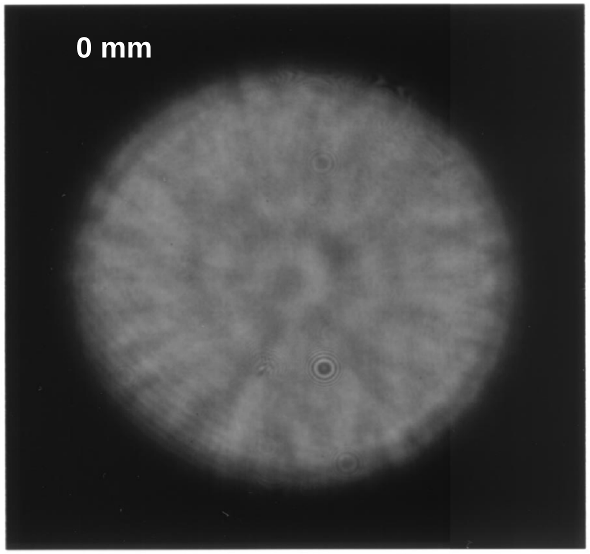
Singlet design 2

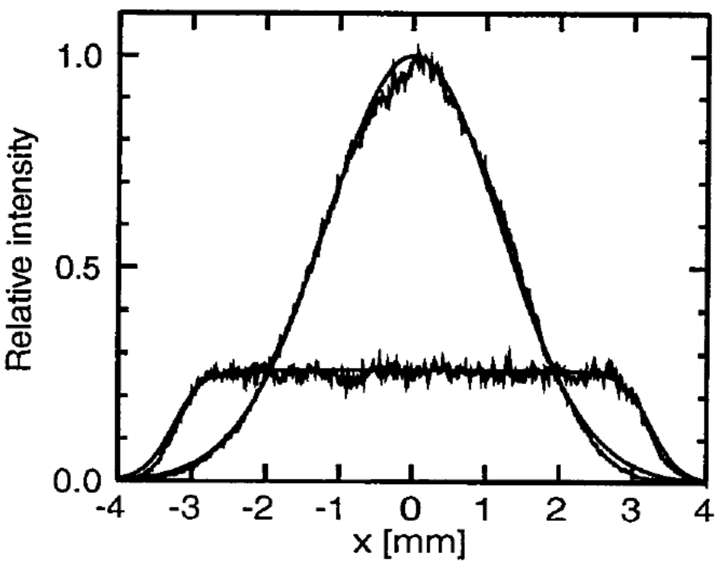


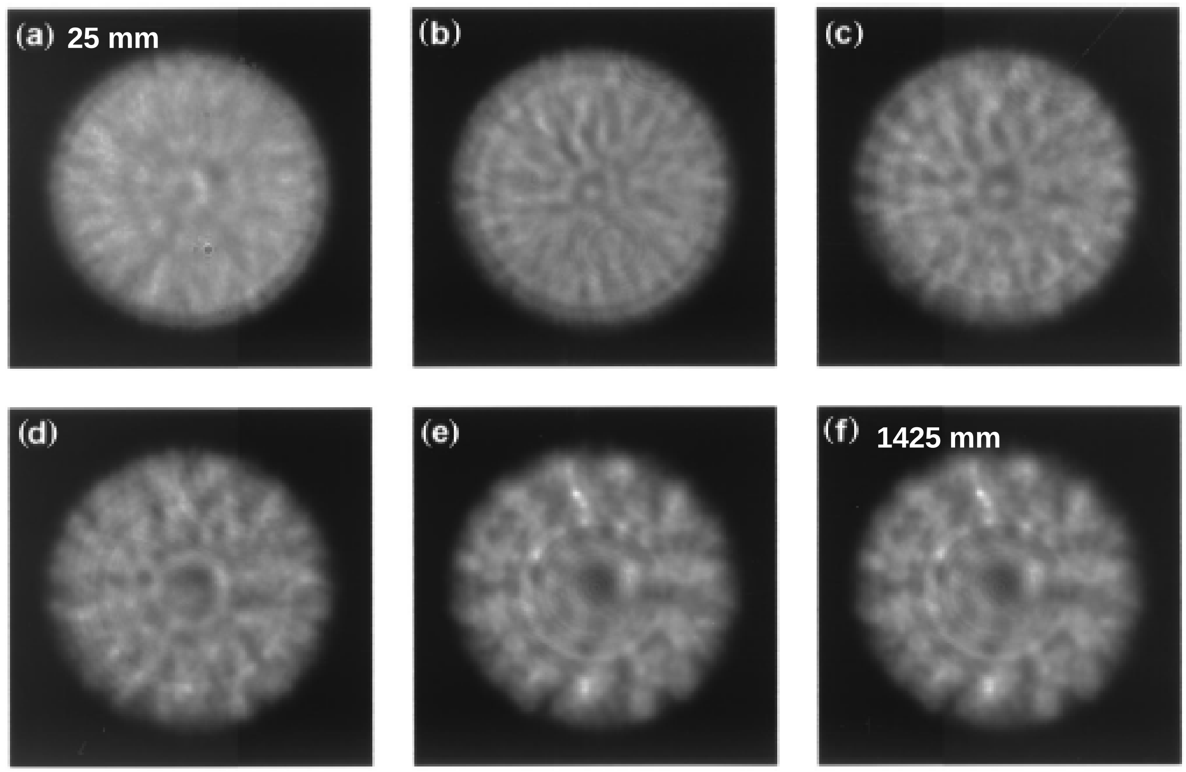
Zhang et al., J. Opt. A9, 945 (2007).

Beam shaper: Newport testing results

Hoffnagle et al, Appl. Opt 39, 6488 (2000).

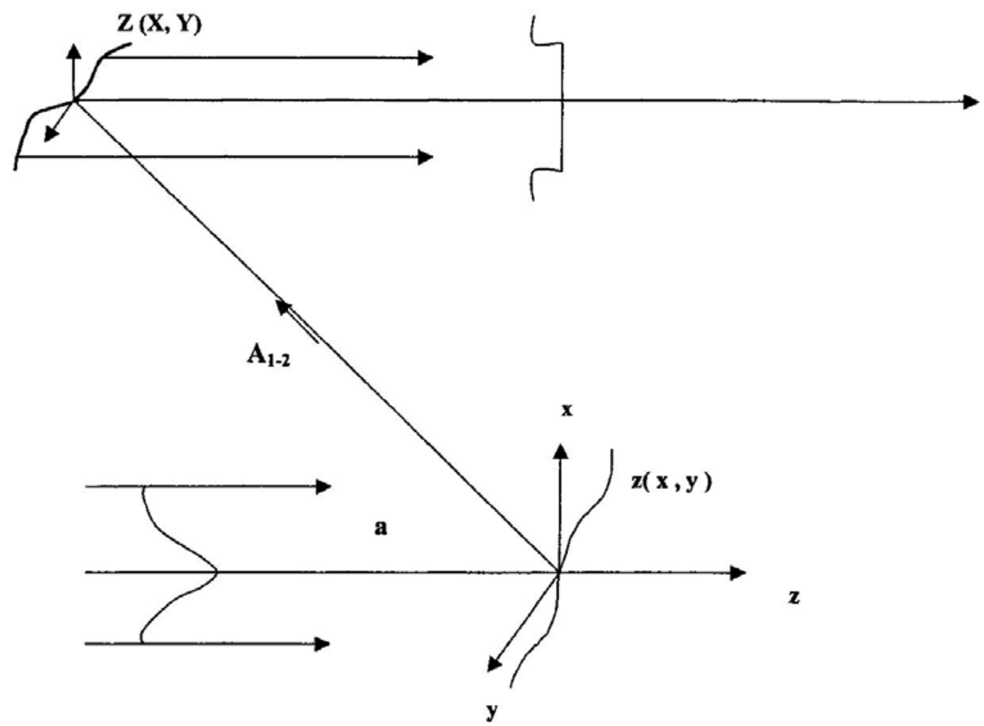






Beam shaper: limitations and hope

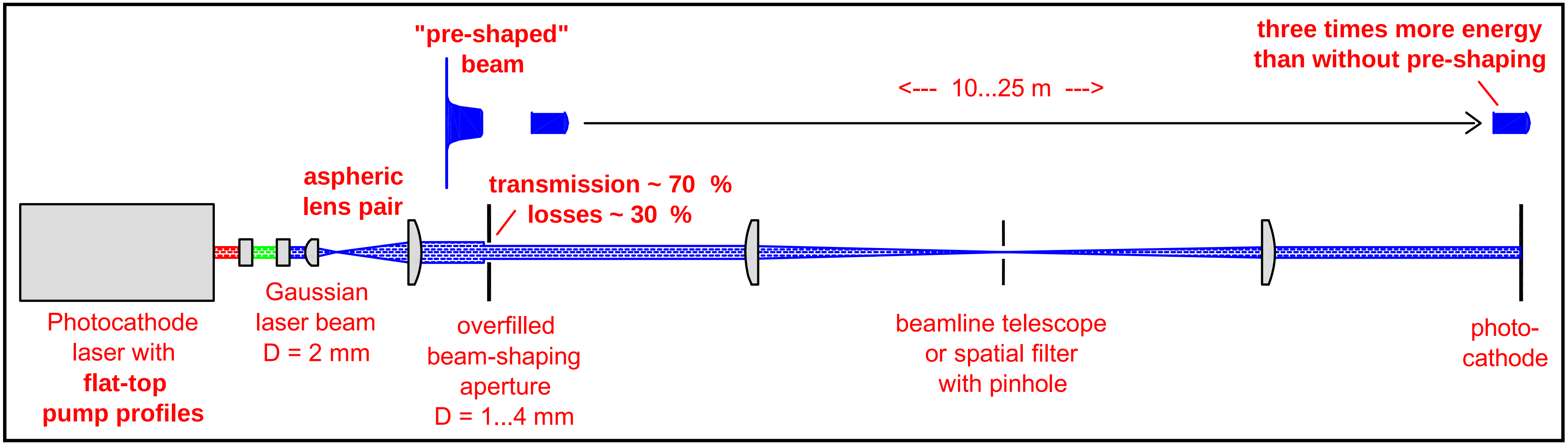
- No test for accelerator is satisfactory (LCLS, SPARC)
- Needs very accurate fabrication, difficult to make
- The beam does not propagate well (Needs image relay)
- Dispersion can be a problem for short pulses
- Reflective design possible



Shealy, in *Laser Beam Shaping* (Marcel Dekker Inc, NY 2000), p. 163

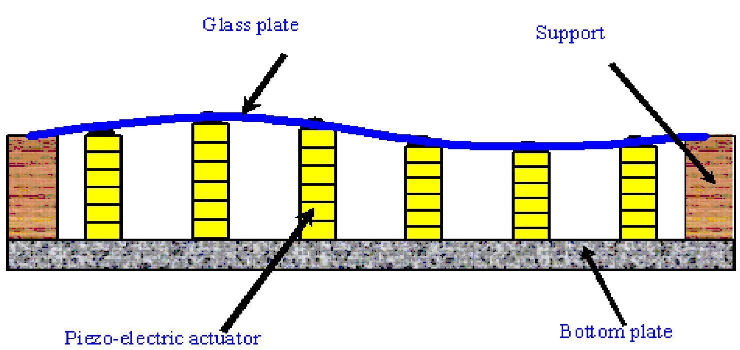
Beam shaper, example

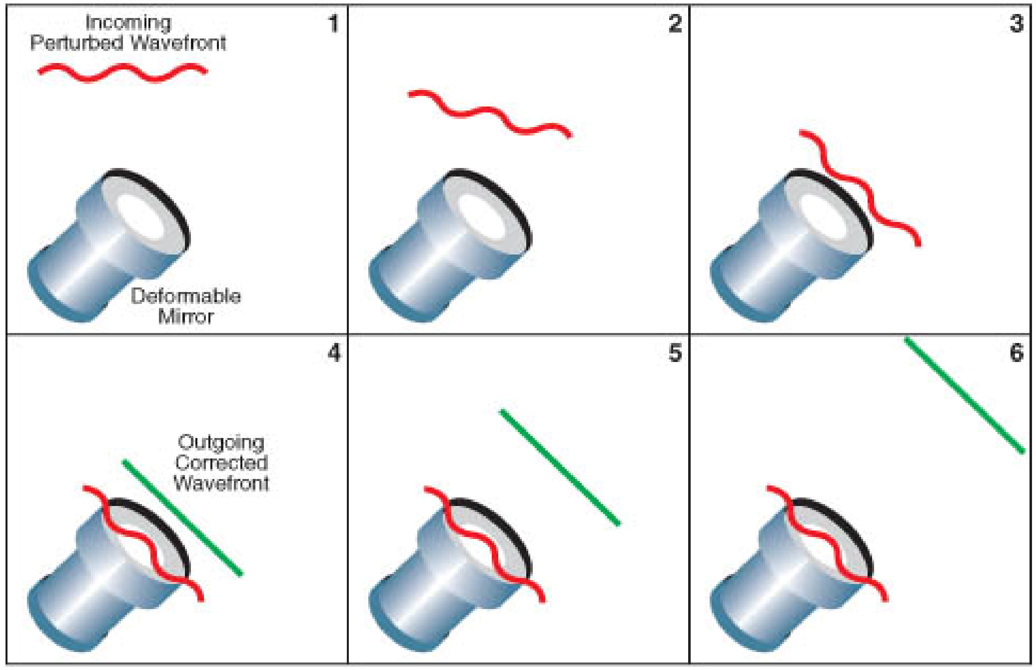
- DESY plan



Deformable mirrors

- For wave front (aberration) correction
- Can be used for minor homogeneity adjustment
- Commercially available, widely
- Many applications
  - Laser beam shaping/correction
  - Large telescopes
  - Microscopes
  - Vision

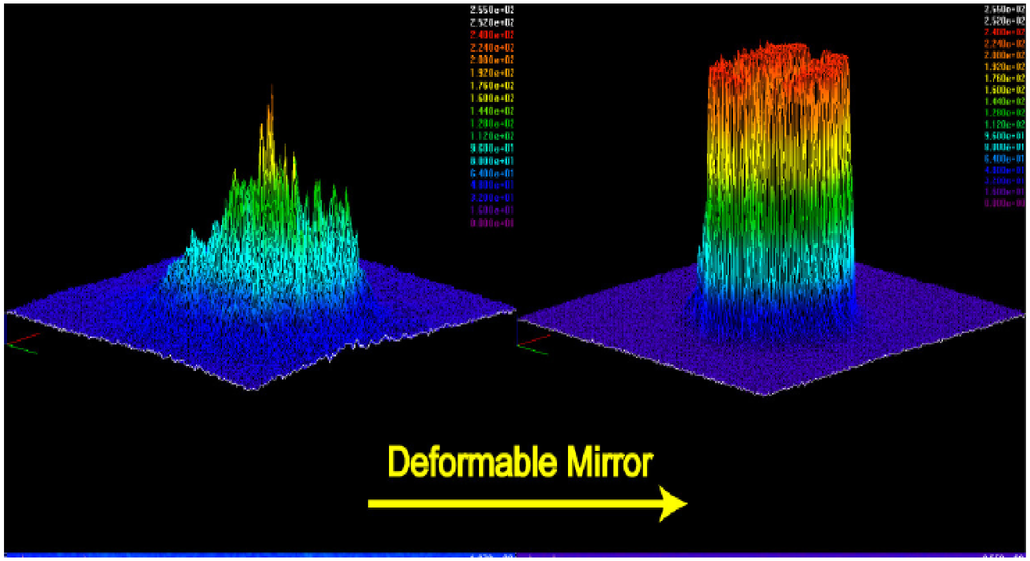


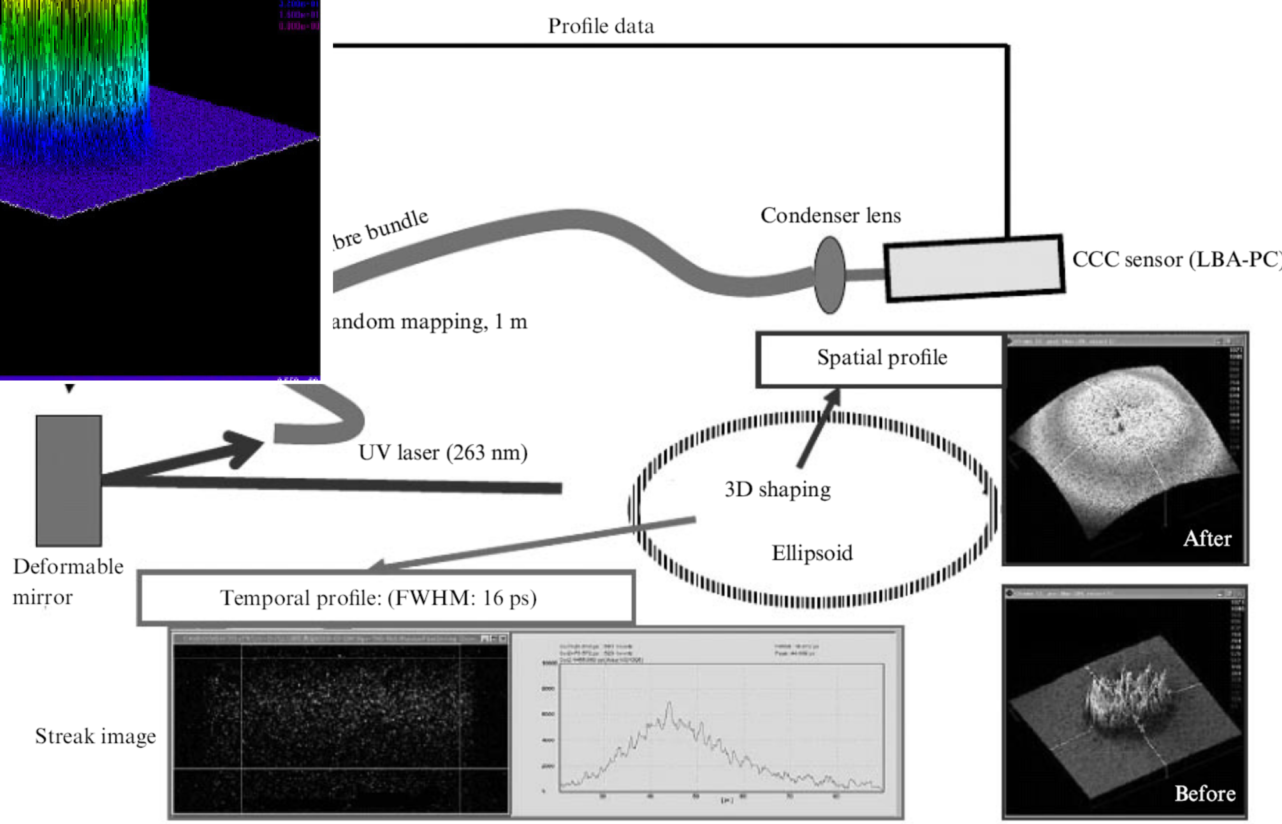


http://www.agiloptics.com

Deformable mirror: testing at Spring8

- A testing for pulse shaping case.

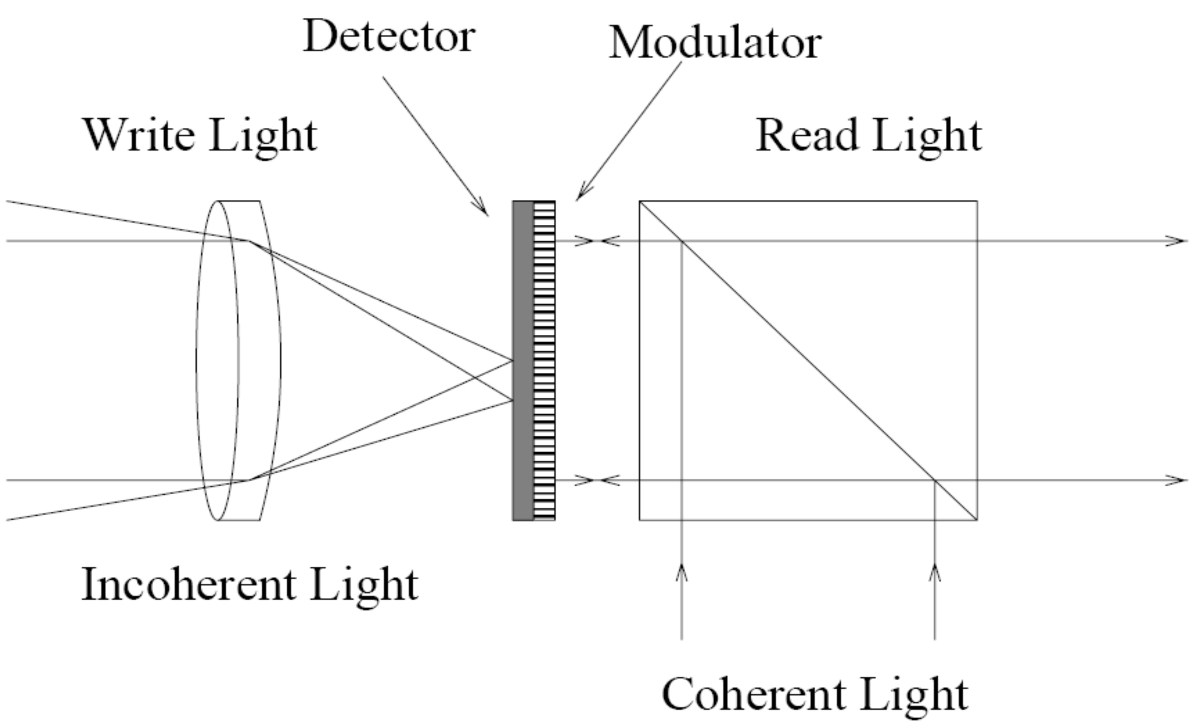




Tomizawa, Quantum Electronics 37, 697 (2007)

Spatial light modulators (SLM)

- Real time or pre-constructed holographic and profile
- Optically or electronically addressable and adaptive
- Commercially available from many, with many implementations
- Many applications (DLP TV is one example of intensity SLM)



http://www.ph.ed.ac.uk/~wjh/teaching/mo/

The idea of using hologram

- The calculated/recorded holography is of the form, where U_o and U_r are the object and reference beam field, where k is a constant

$$U_o = A_o e^{i\phi_o}, U_r = A_r e^{i\phi_r}$$

$$T = K\left|U_o + U_r\right|^2 = K\left(A_o^{\ 2} + A_r^{\ 2} + 2A_o A_r \cos(\phi_o - \phi_r)\right)$$

- During reconstruction, U_r is applied to the hologram, and the reconstructed transmitted/reflected field is thus

$$U' = A_r e^{i\phi_r} K\left(A_o^{\ 2} + A_r^{\ 2} + 2A_o A_r \cos(\phi_o - \phi_r)\right)$$

$$= A_r^{\ 2} e^{i\phi_r} K\left(\frac{A_o^{\ 2}}{A_r} + A_r + A_o e^{i(\phi_o - \phi_r)} + A_o e^{-i(\phi_o - \phi_r)}\right)$$

Back ground

Ref wave

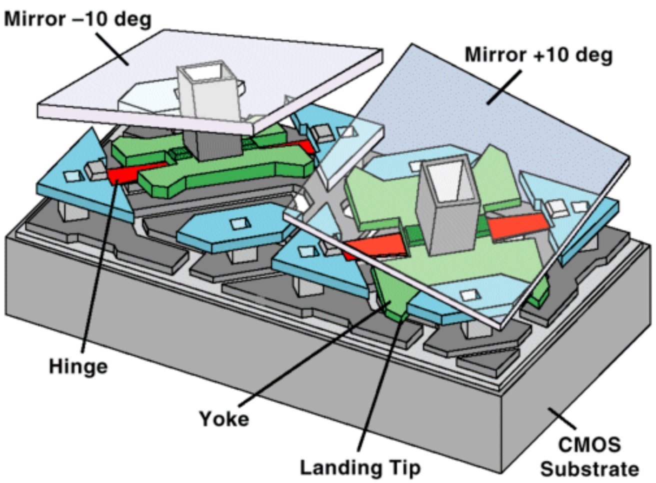
Original wave

Conjugate wave

Either or both can be used!

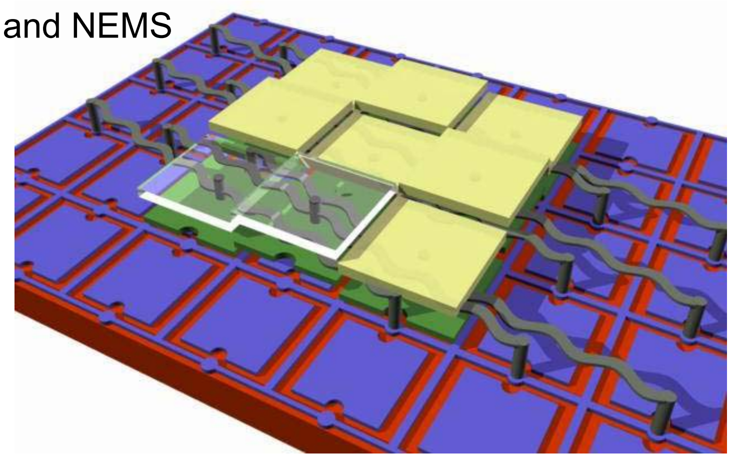
SLM: mechanisms

Texas Instrument DLP unit (intensity)



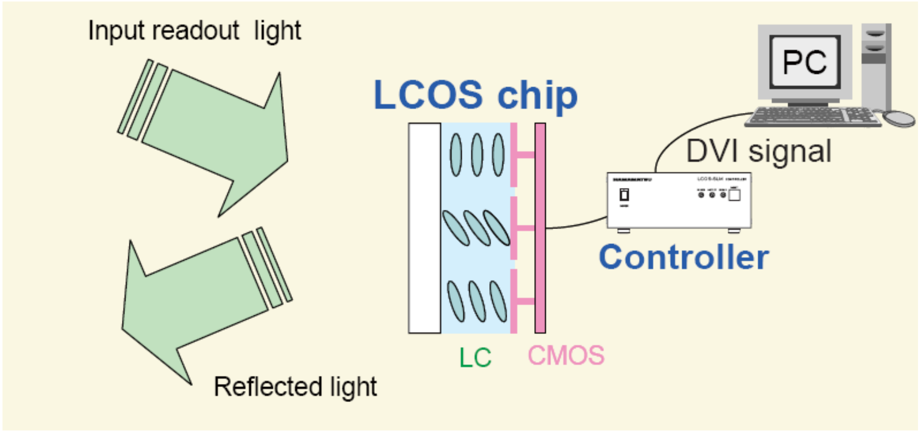
Micro- and nano electronic mechanical systems unit (phase)

MEMS and NEMS



Lopez and Aksyuk, http://spie.org/x16071.xml

Hamamatsu Liquid crystal on silicon (LCOS) (phase)

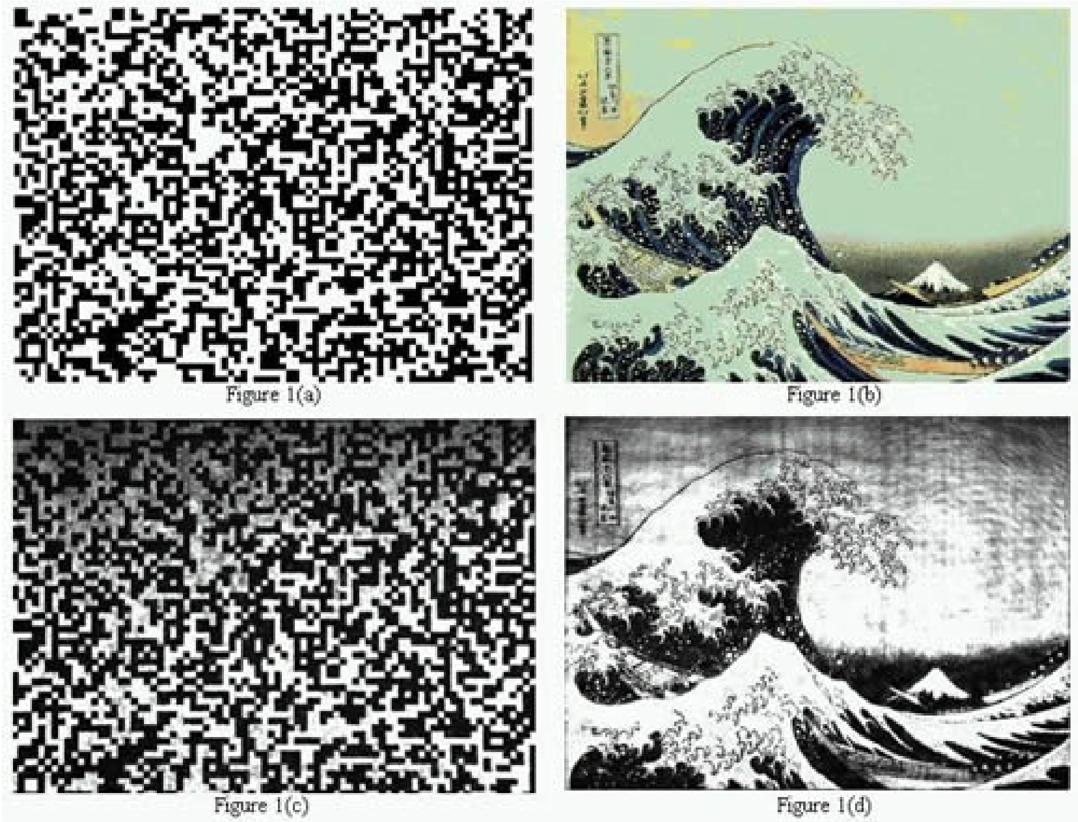


- LCOS: limited in intensity
- MEMS/NEMS very promising

Spatial light modulator: pros and cons

- Adaptive control possible
- Diffraction: many orders, thus low efficiency
- Speckles and hot spots
- Interference between pixels

Figure 1: (a) & (b) Image of data page and analogue image as they appeared on the SLM. (c) & (d) show the reconstructed holographic images which were produced with a combined beam exposure energy of 8 mJ/cm2 using the acrylamide-based photopolymer developed in the IEO. (http://www.ieo.dit.ie)



Temporal shaping: phase space manipulation

- Direct manipulation in time domain is difficult at time scale of less than 1 ns
- Time domain pulse is the inverse Fourier transform of frequency domain pulse
- Frequency domain manipulation can be relatively easy if one can access the Fourier plane.
- In CPA laser, both the stretcher and the compressor present the Fourier plane
- Or one can directly manipulating the phase and amplitude of a pulse via dispersive filters

A. M. Weiner, 'Femtosecond pulse shaping using spatial light modulators,' Rev. Sci. Instrum. 71, 1929 (2000)

Temporal shaping: Fourier transform

$$E(r,t) = \exp\left(-\frac{1}{2}\left(\frac{r}{R}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{t}{T}\right)^2\right)\exp(i\varphi(r,t))$$

$$\Rightarrow E(r,\omega) = \exp\left(-\frac{1}{2}\left(\frac{r}{R}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{\omega}{BW}\right)^2\right)\exp(i\varphi(r,\omega))$$

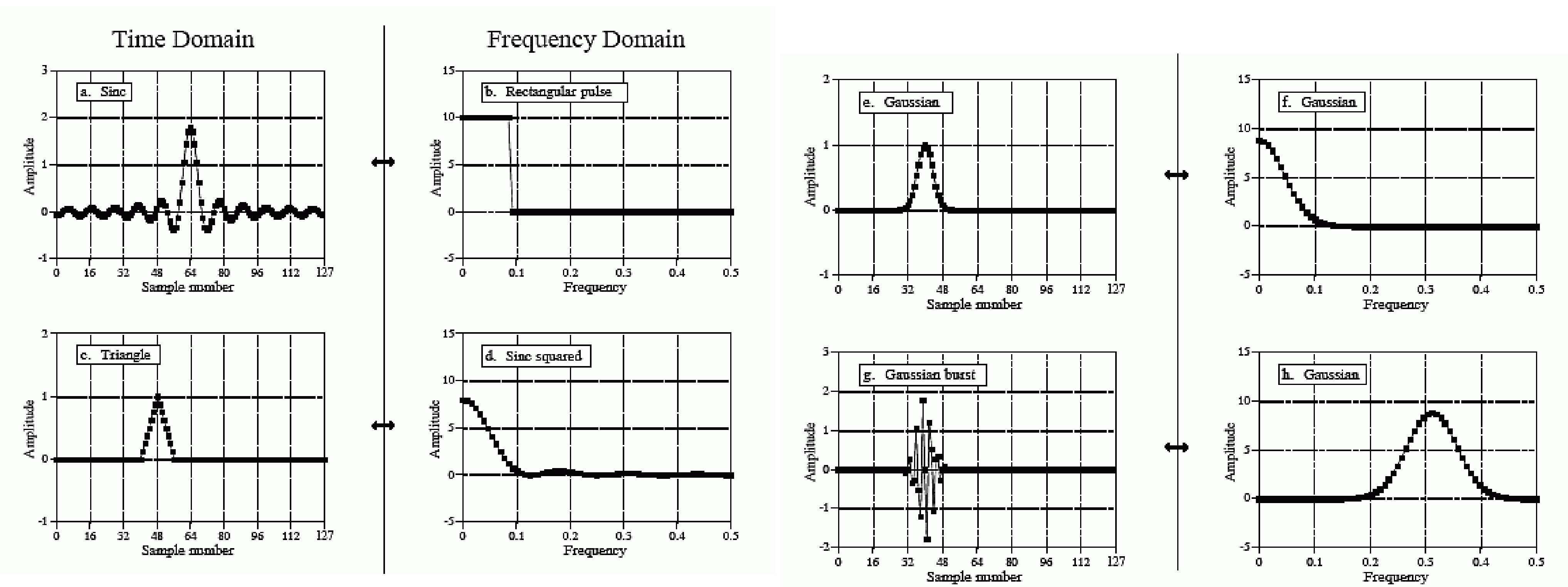
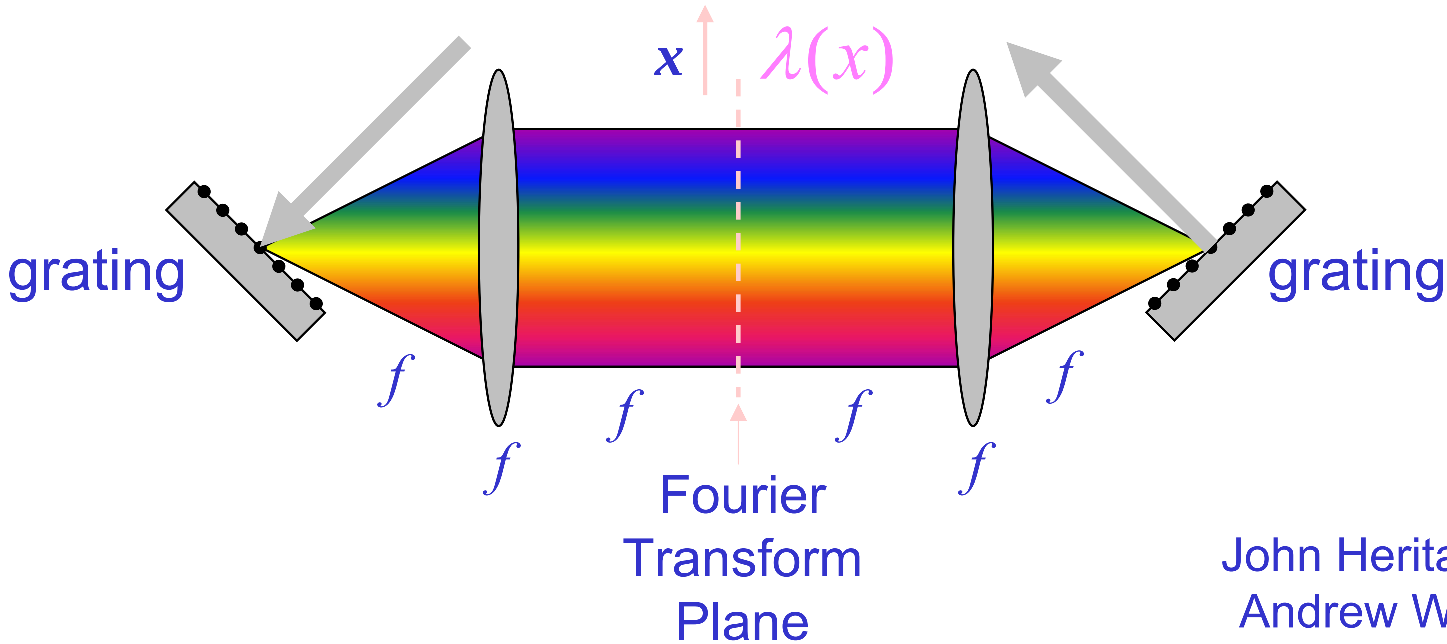


FIGURE 11-5
Common transform pairs.

Optical Fourier transform: zero dispersion stretcher



John Heritage, UC Davis
Andrew Weiner, Purdue

How it works:

The grating disperses the light, mapping color onto angle.

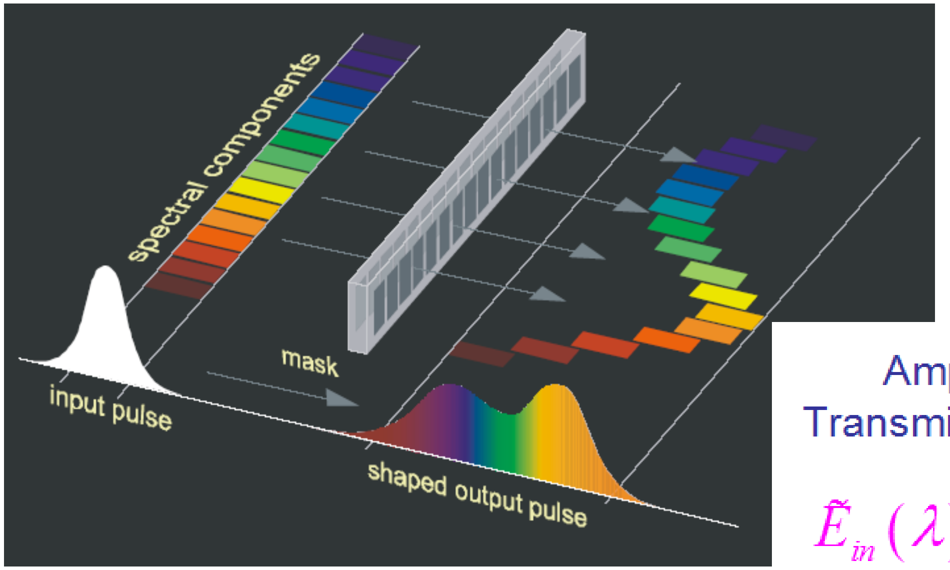
The first lens maps angle (hence wavelength) to position.

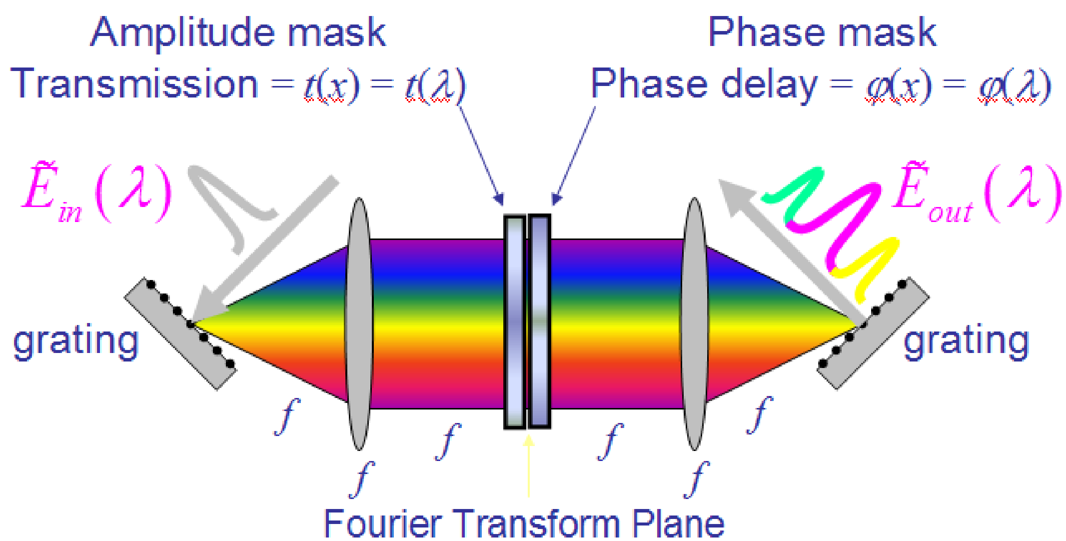
The second lens and grating undo the spatio-temporal distortions.

The trick is to place a mask in the Fourier transform plane.

Credit: R. Trebino

A SLM as the phase/amplitude mask





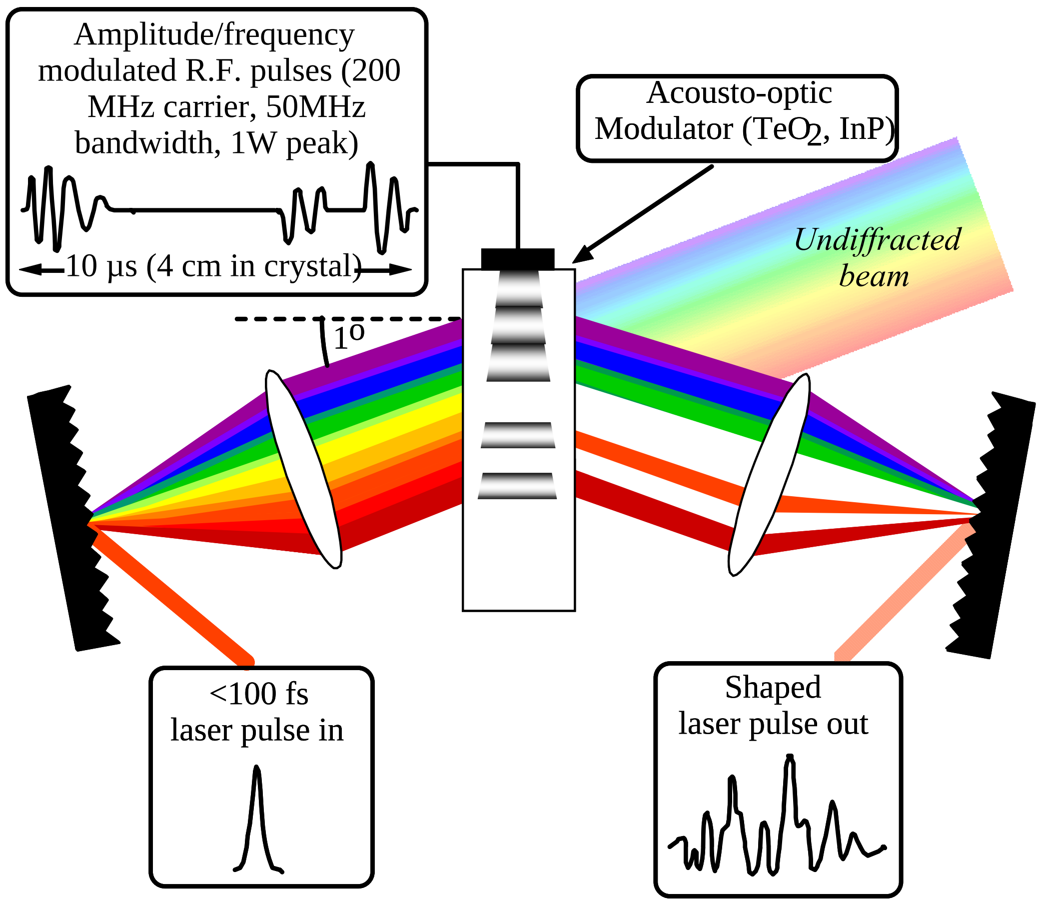
$$H(\lambda) = t(\lambda)\exp[i\varphi(\lambda)]$$

We can control both the amplitude and phase of the pulse. The two masks or "spatial light modulators" together can yield any desired pulse.

Credit: R. Trebino

Acousto-optic light modulator

- AOMs have a very high number of effective “pixels,” the number of sound waves that fit across the aperture of the crystal.
- AOM efficiency is less than other methods since it relies on the diffracted light.



Credit: R. Trebino

Examples or pulse shaping

- Square pulse using a fixed mask

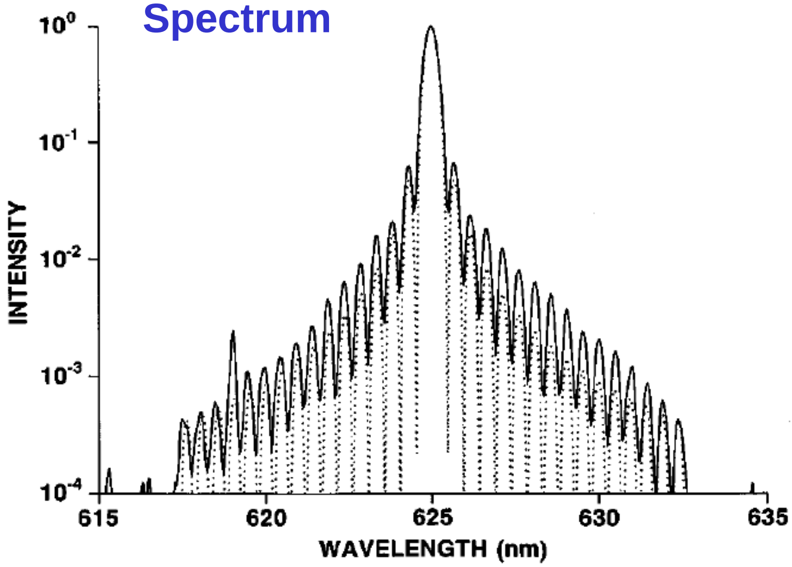


FIG. 4. Semilog plot of power spectrum of an optical square pulse.

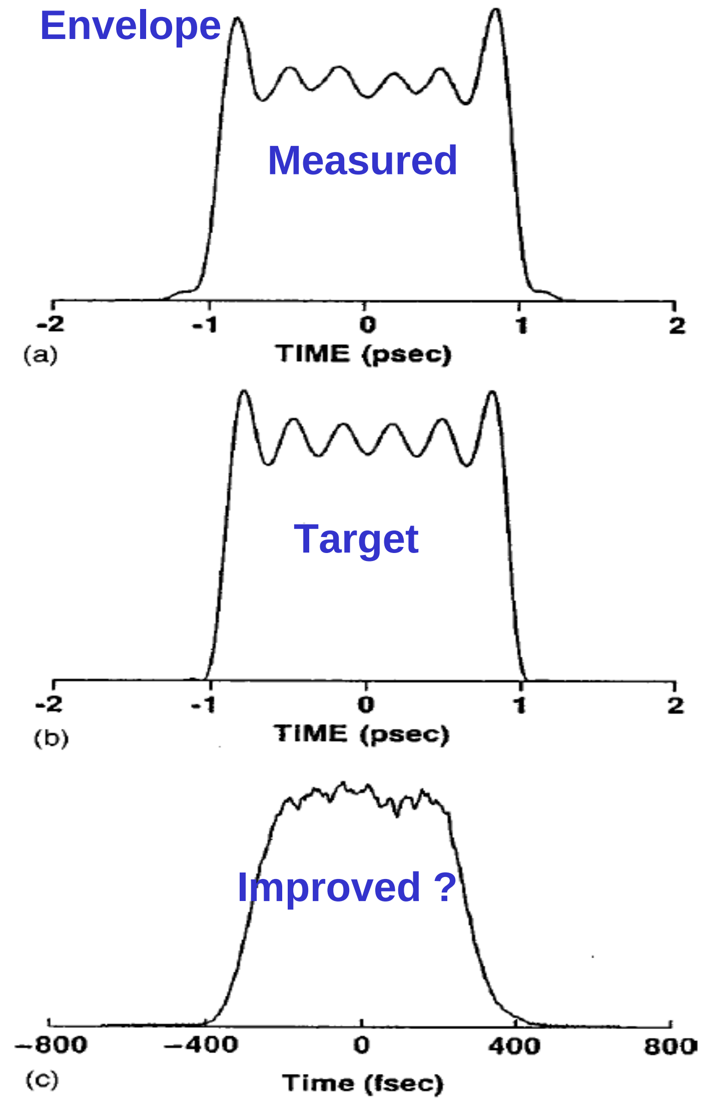
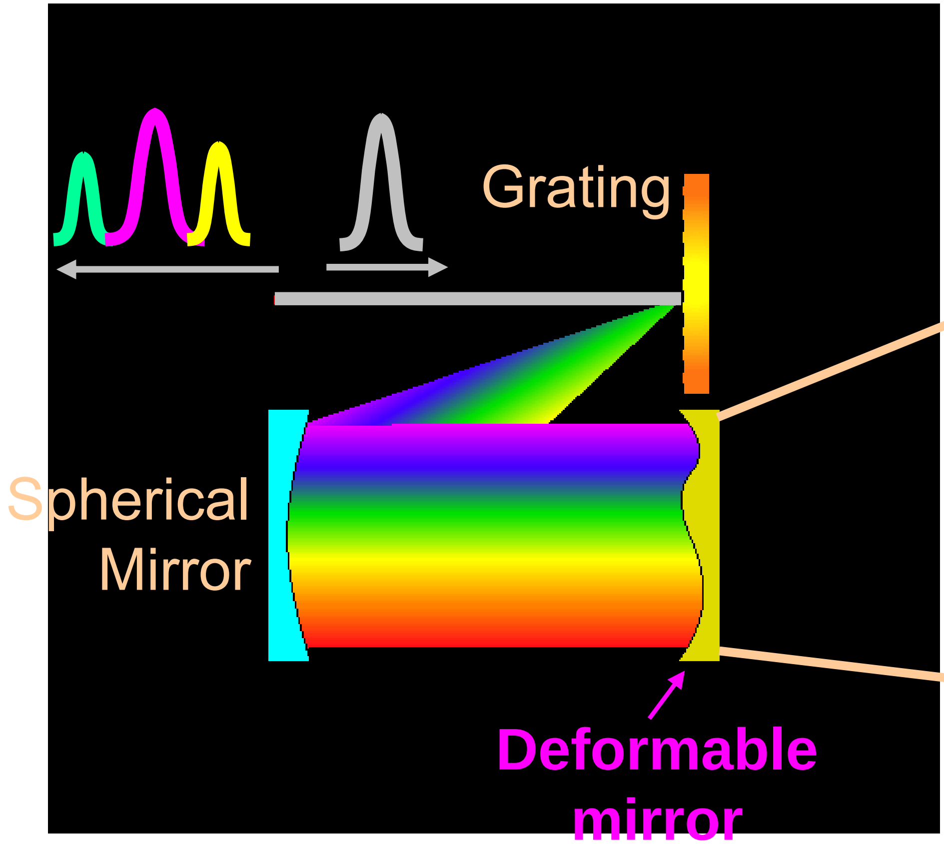
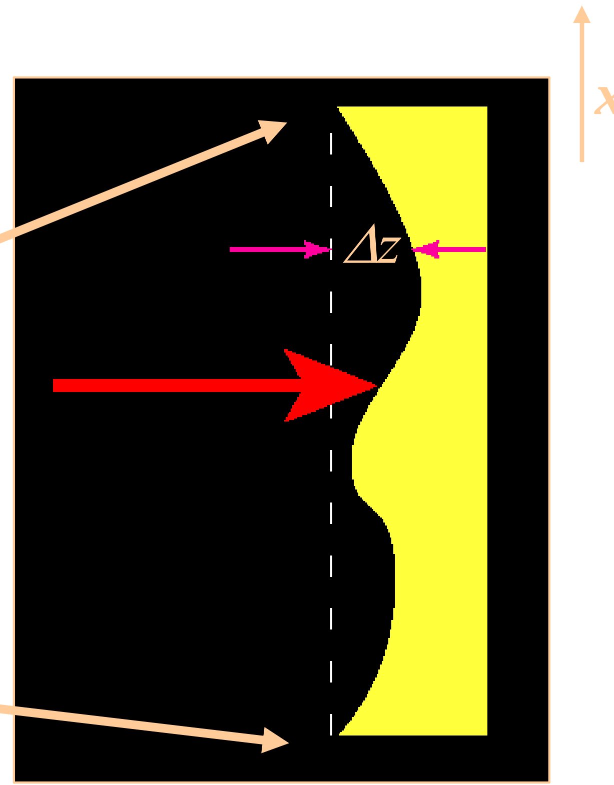


FIG. 5. Optical square pulses. (a) Measurement of a 2 ps optical square pulse. (b) Corresponding theoretical intensity profile. (c) Measurement of a square pulse with reduced ripple.

A. M. Weiner, Rev. Sci. Instrum. 71, 1929 (2000)

Deformable mirror as phase modulator





$$\Delta\varphi(x) = 2\frac{2\pi}{\lambda}\Delta z(x)$$

This modulates the phase but not the amplitude.

A. Efimov, and D. H. Reitze, Proc. SPIE **2701**, 190 (1996)
K. F. Wong, D. Yankelevich, K. C. Chu, J. P. Heritage, and A. Dienes, Opt. Lett. **18**, 558 (1993)

Pulse shaping example

- Using DM to implement a third order phase

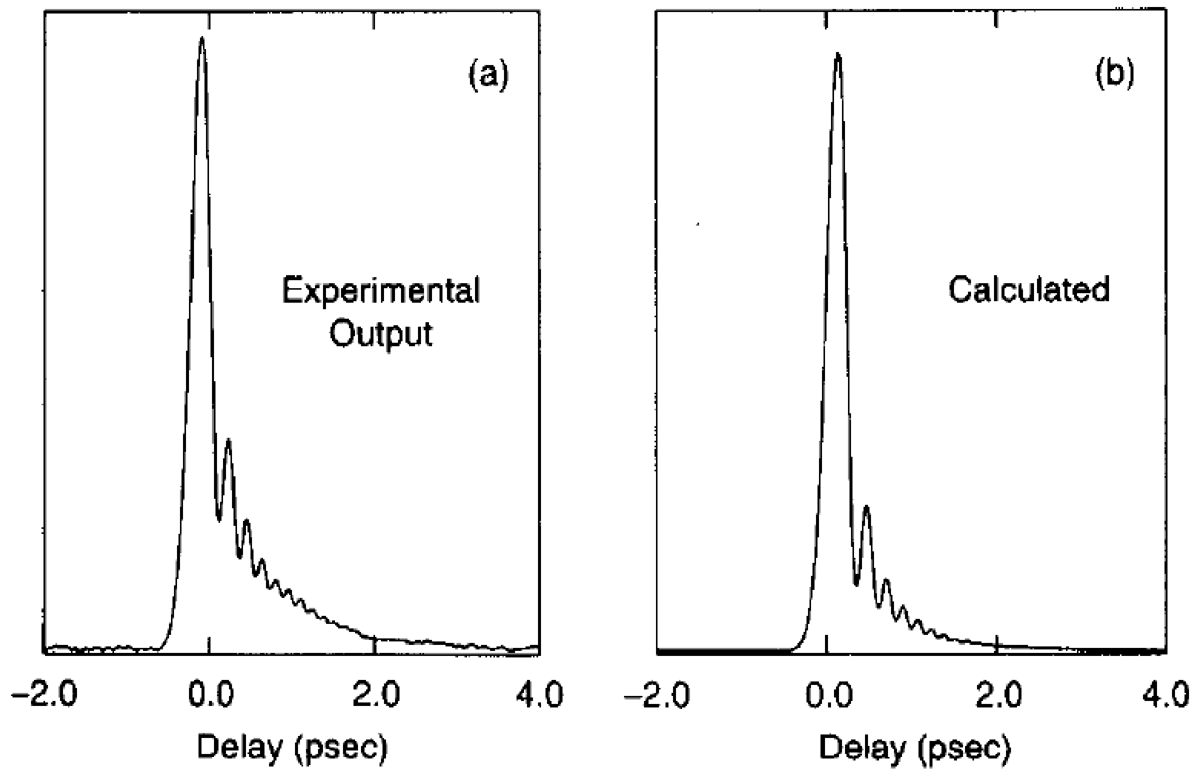
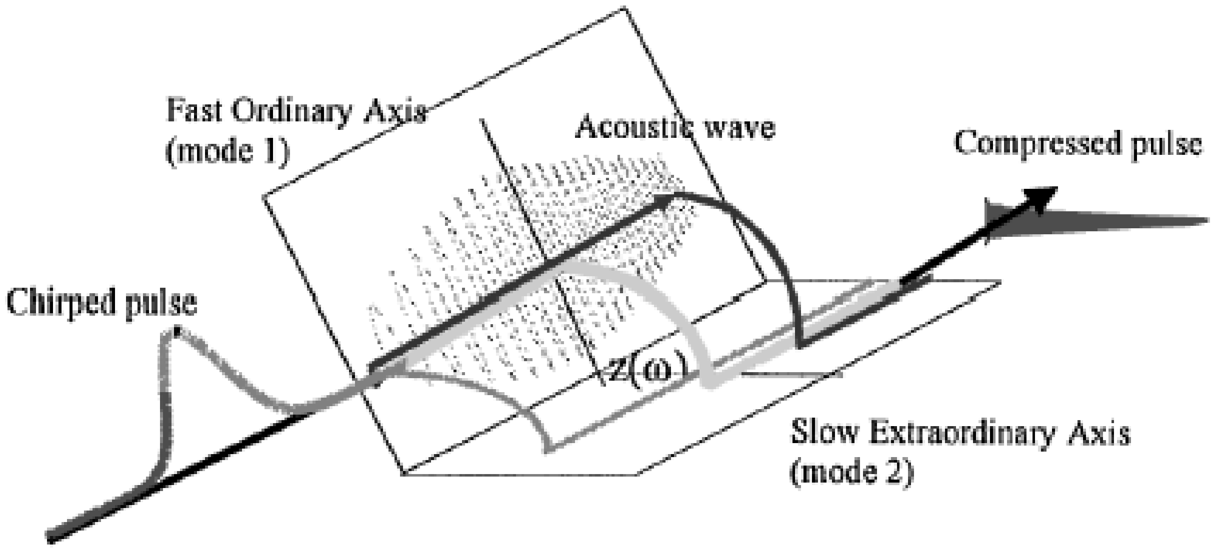


FIG. 19. Experimental (a) and calculated (b) intensity cross-correlation measurements of a 100 fs pulse which has been reshaped by cubic spectral phase modulation. The cubic phase variation was produced by using a deformable mirror.[89]

J. P. Heritage, E. W. Chase, R. N. Thurston and M. Stern, A simple femtosecond optical third-order disperser, *Conference on Lasers and Electro-optics*, p. 74, Optical Society of America, Washington, D.C. (1991).

Acousto-optic Programmable Dispersive filter



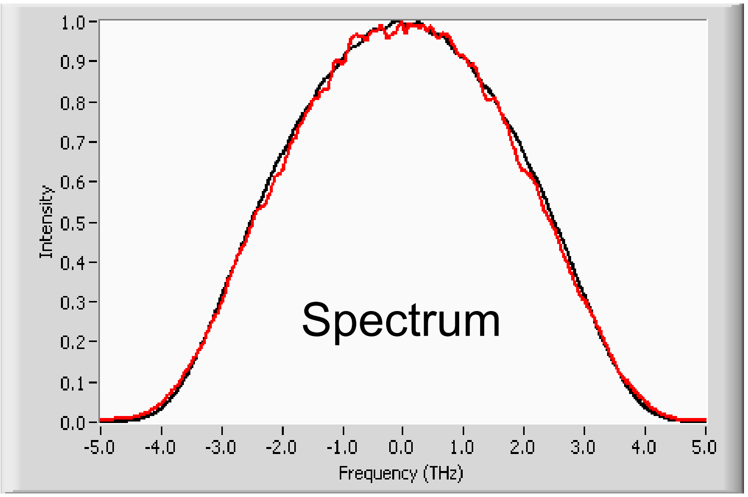
It launches an acoustic wave *along* the beam in a birefringent crystal.

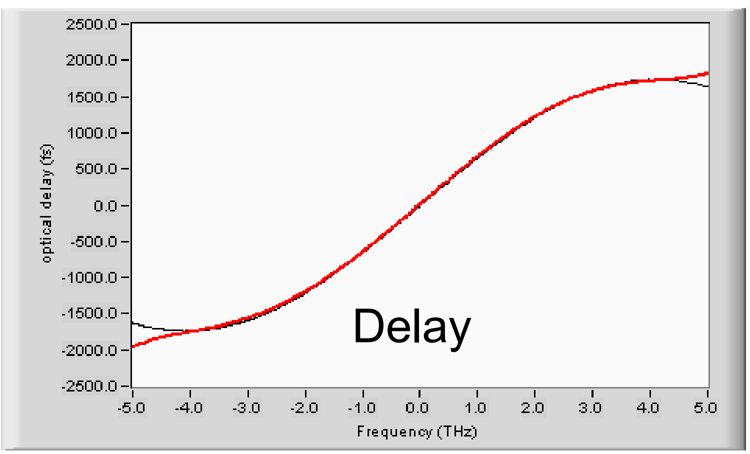
The input polarization is diffracted to the other by the sound wave. The frequency that has its polarization rotated depends on the acoustic-wave frequency. Its relative delay at the crystal exit depends on the relative group velocities of the two polarizations.

Acousto-optic Programmable Dispersive filter AOPDF or DAZZLER

- Test result on temporal top-hat at 266 nm (800/3)

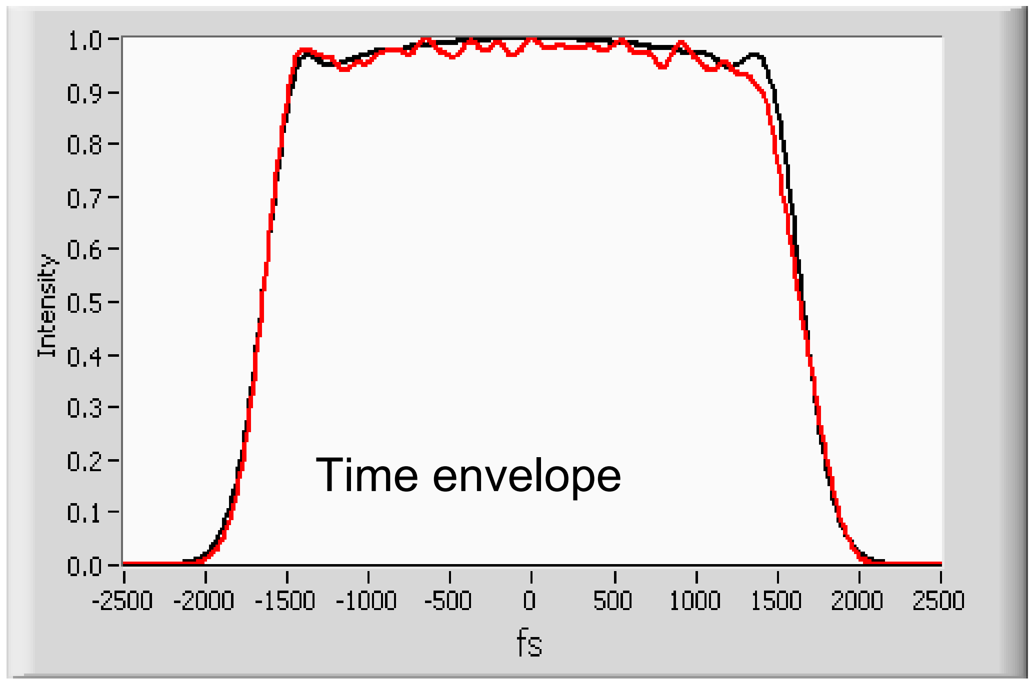
T. Oksenhendler, CLEO 07





Black line: target

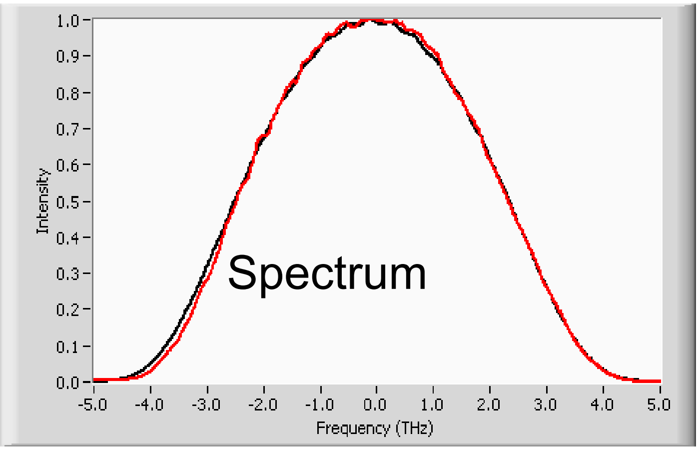
Red line: cross correlation measurement

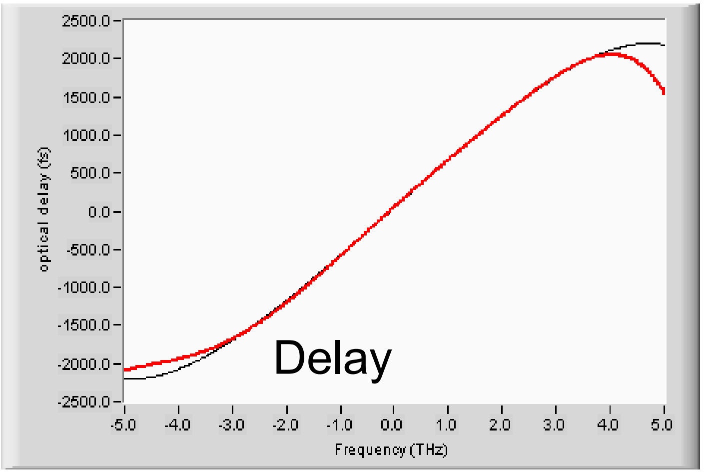


Acousto-optic Programmable Dispersive filter AOPDF or DAZZLER

- Test result on temporal parabolic at 266 nm (800/3)

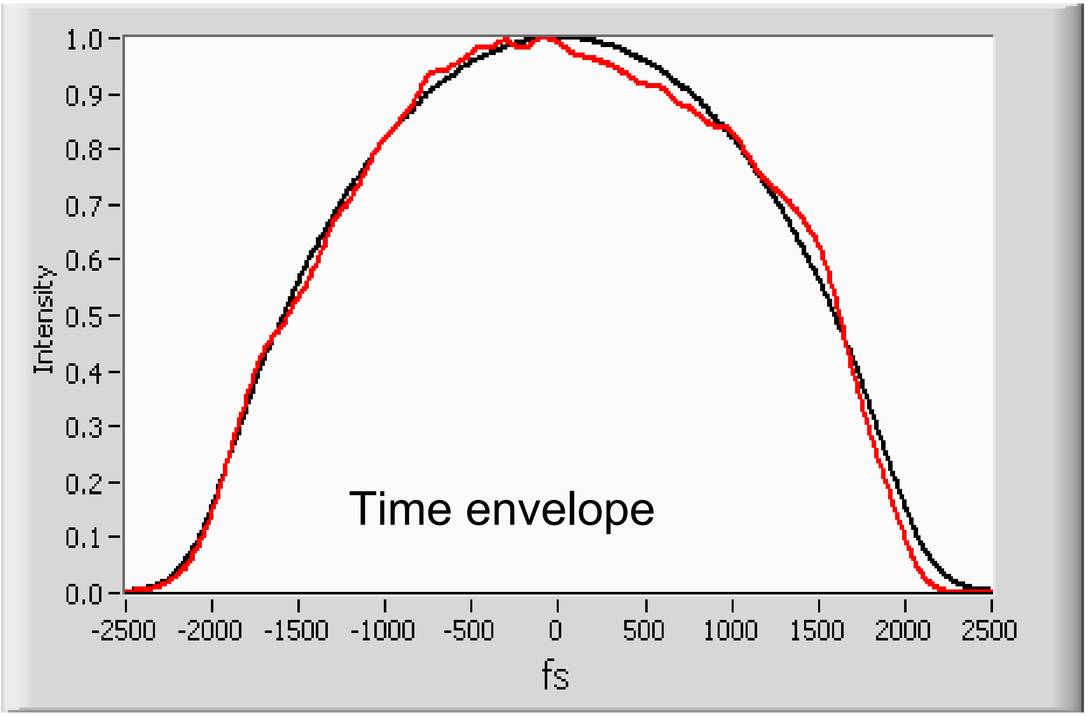
T. Oksenhendler, CLEO 07





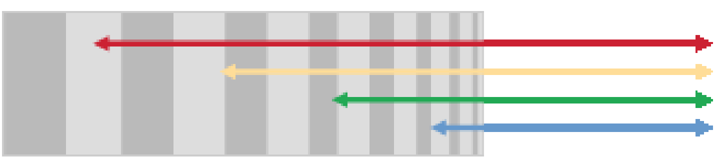
Black line: target

Red line: measurement

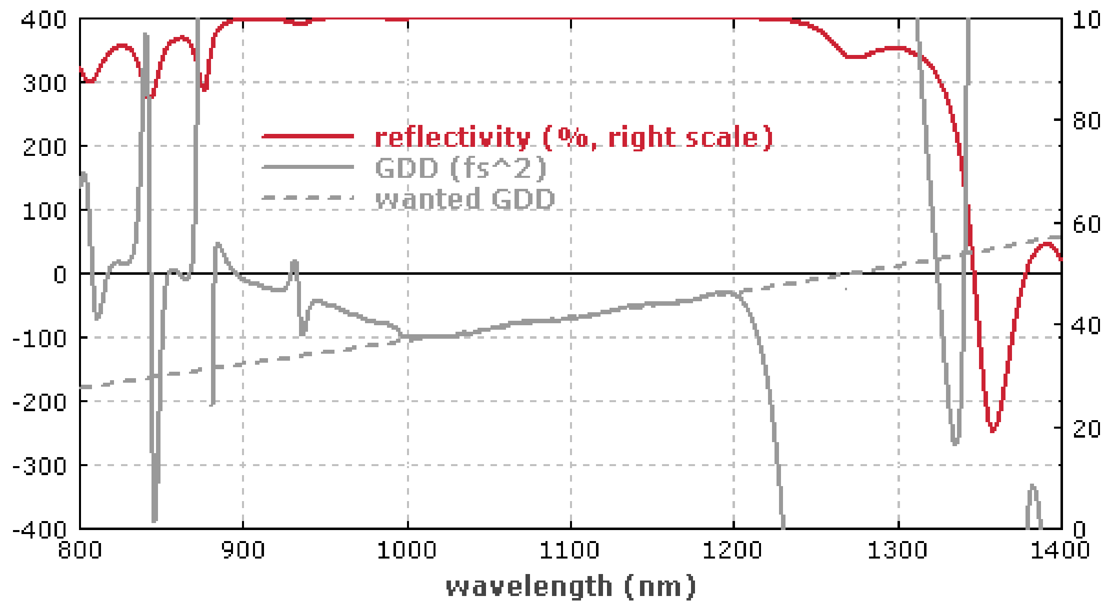


Perspective with man-made materials: chirped mirror

- With designed structure of impose designed features onto a laser pulse
- A very simple example is a chirped mirror



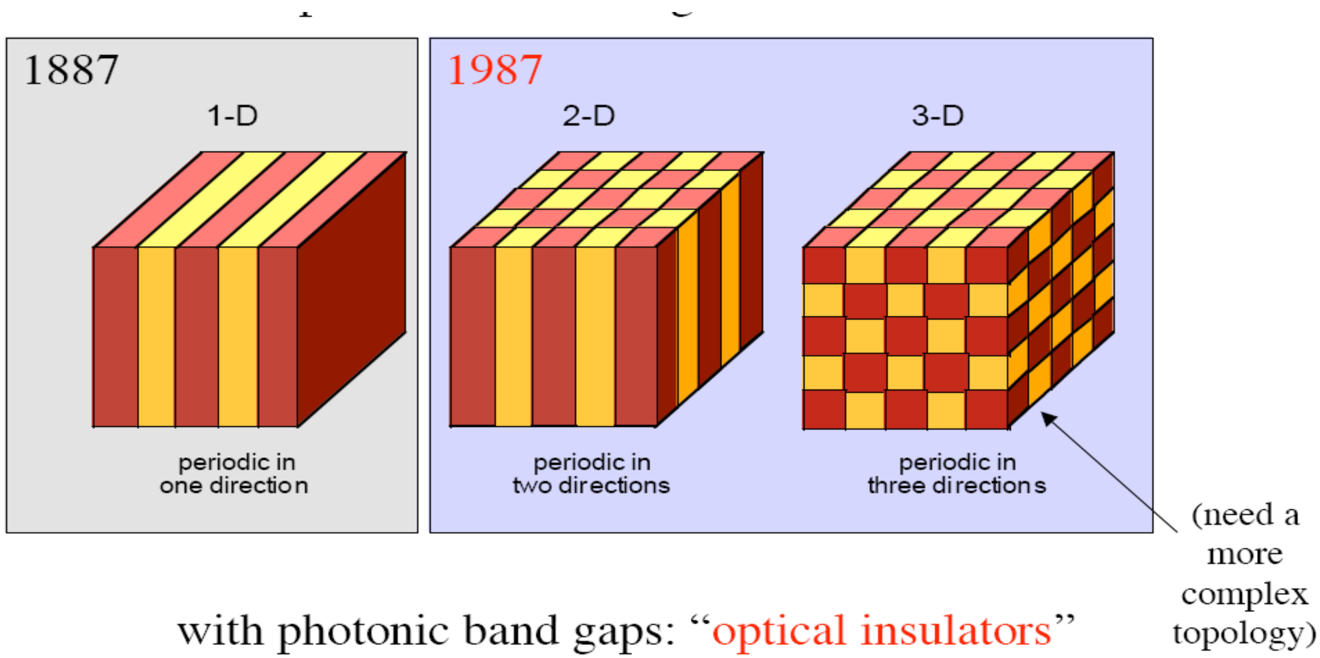
Chirped mirrors use a multilayer periodic structure comprised of dielectric materials to compensate for dispersion of second and higher. This is achieved by designing the mirror stack such that the thickness of the layers gradually decreases.



R. Szipöcs *et al.*, Opt. Lett. 19 (3), 201 (1994).
Encyclopedia of Laser Physics and Technology
http://www.rp-photonics.com

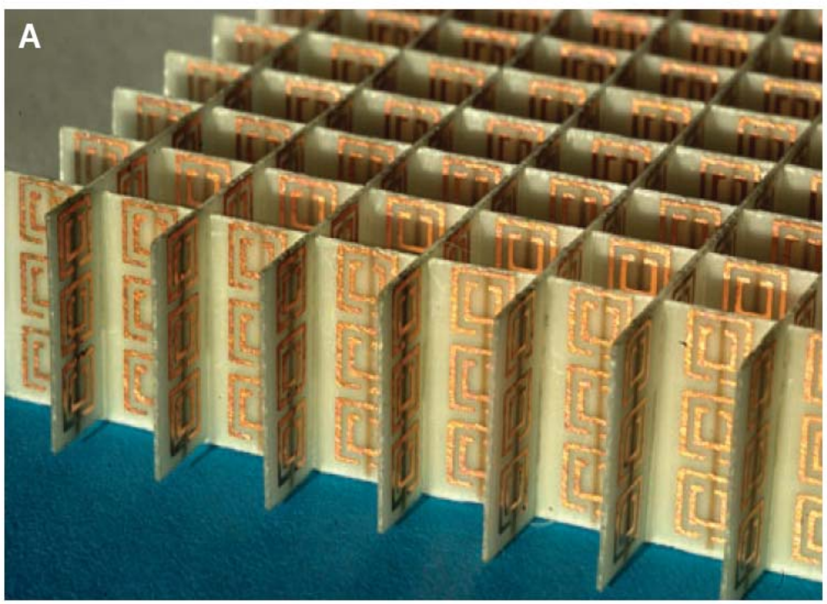
Perspective with man-made materials: photonic crystals

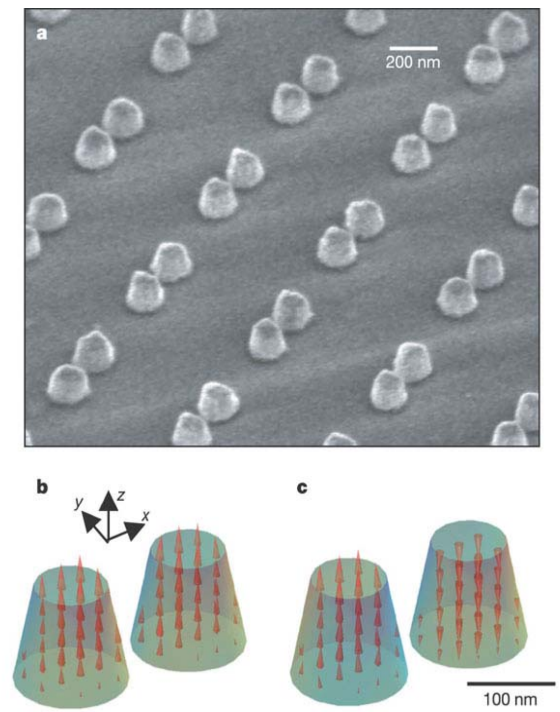
- Tailoring the material properties for desired refractive index
  - Modify the speed of light
  - Control of refractive/reflective properties, etc
  - J. Joannopoulos, R. D. Meade, and J. Winn, *Photonic Crystals* (Princeton University, Princeton, NJ,1995). http://ab-initio.mit.edu/book/photonic-crystals-book.pdf



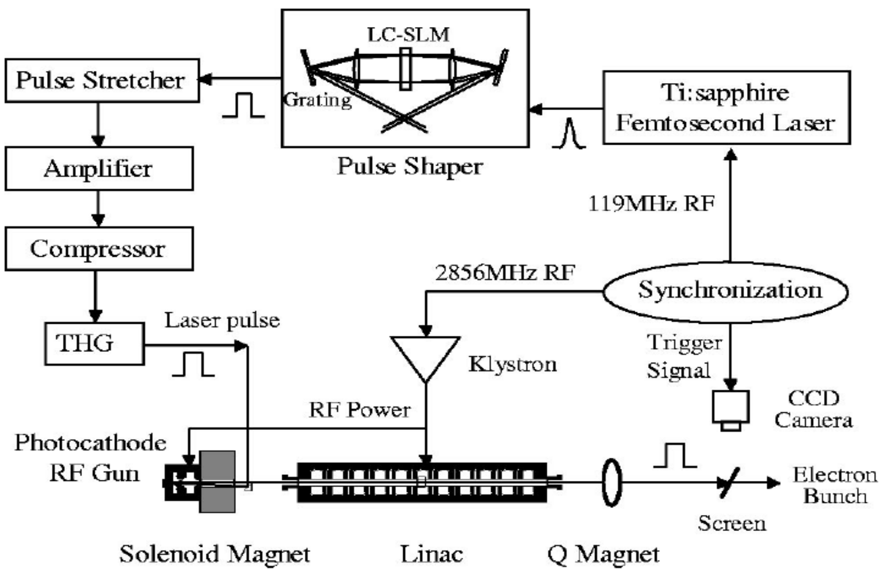
Perspective with man-made materials: metamaterials

- Tailoring the material properties for desired refractive index
  - Negative ref index in microwave; D.R. Smith et al, *Science 305*, 788 (2004); R. Shelby et al, *Science 292*, 77 (2001).
  - Negative ref index at 2 micron; S. Zhang et al., *Phys. Rev. Lett. 95*, 137404 (2005); V. Shalaev et al., *Optics Lett. 30*, 3356 (2005); N. Grigorenko et al., *Nature 438*, 335 (2005).





Some PC gun applications: Sumitomo Heavy Industries



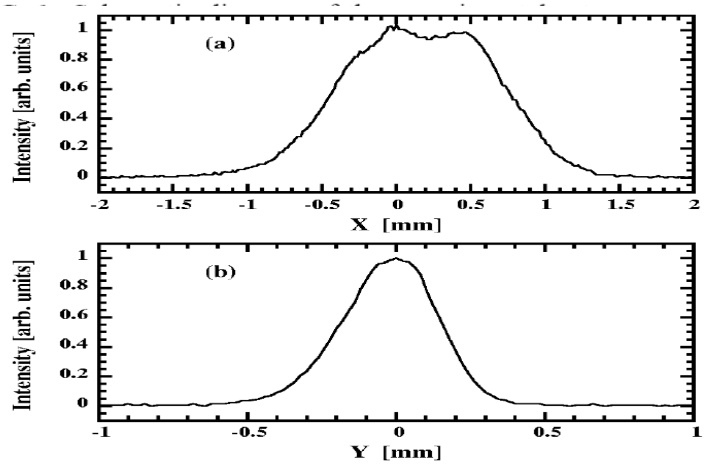
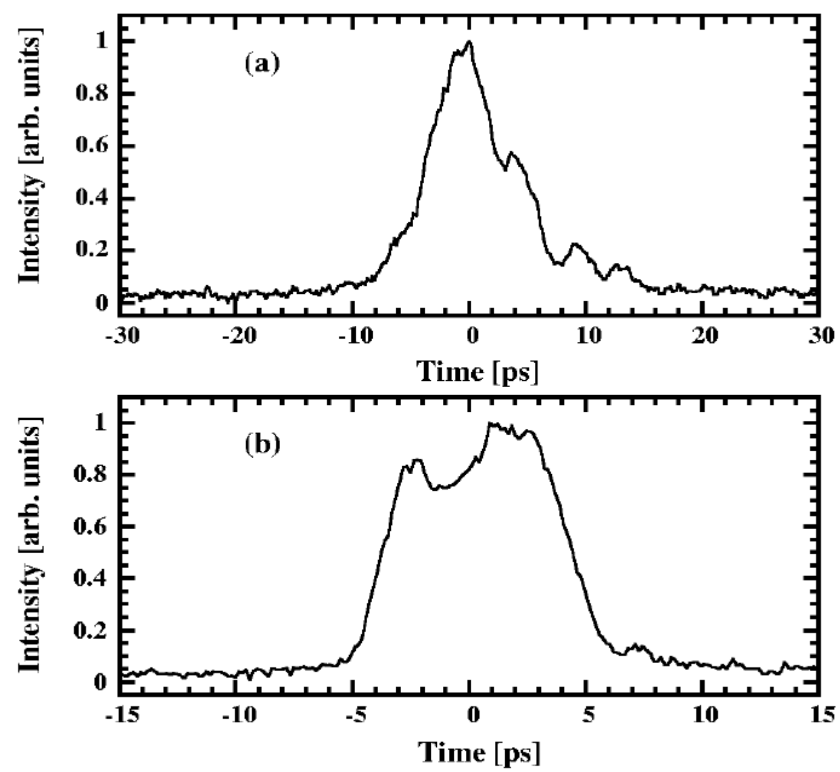


FIG. 3. The spatial distributions of UV laser pulse in horizontal (a) and vertical (b) directions.

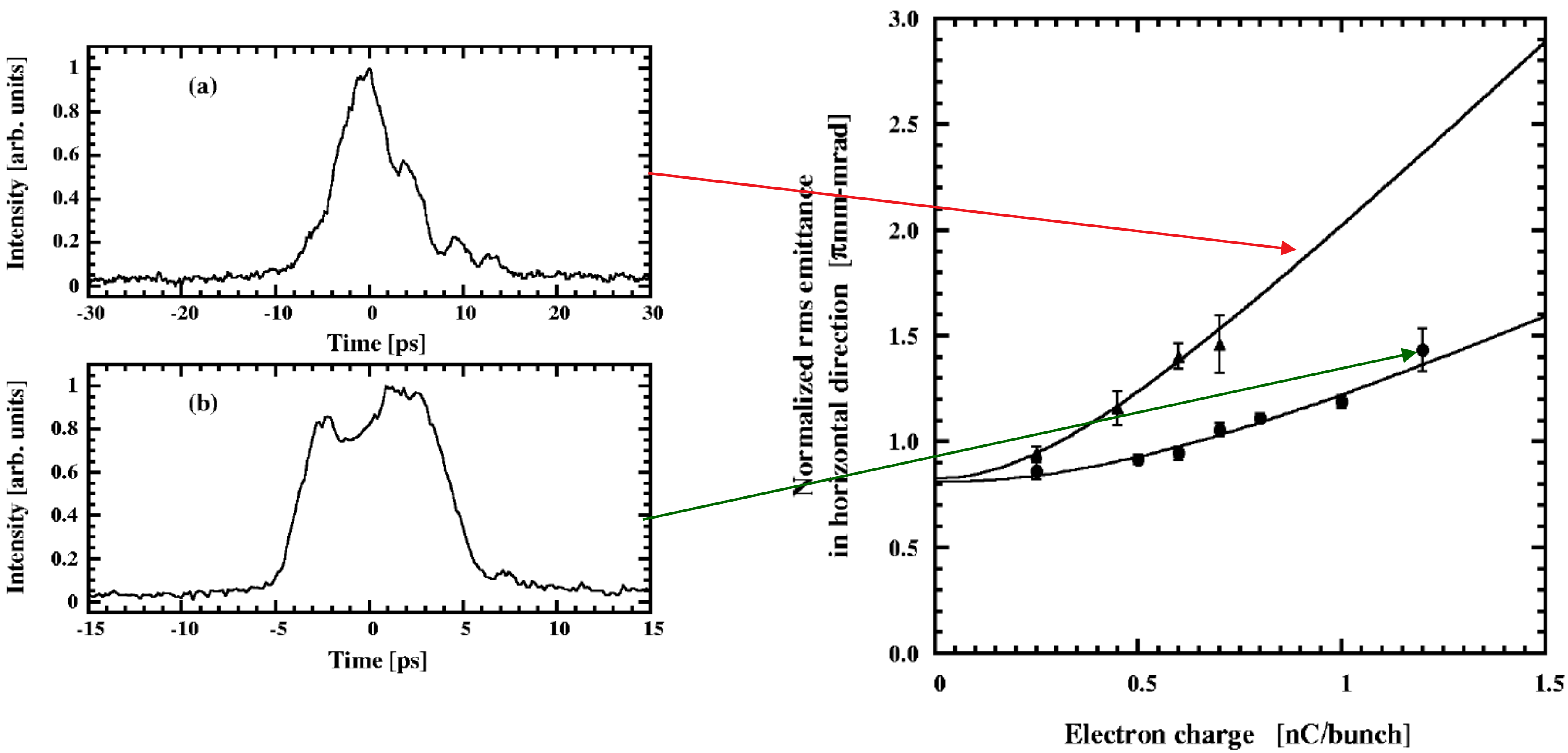
- SLM for pulse shaping
- Significantly improved emittance
- 14 MeV, 1 nC, 9 ps pulse



Yang et al., J. Appl. Phys 92, 1608 (2002)

Some PC gun applications: Sumitomo Heavy Industries

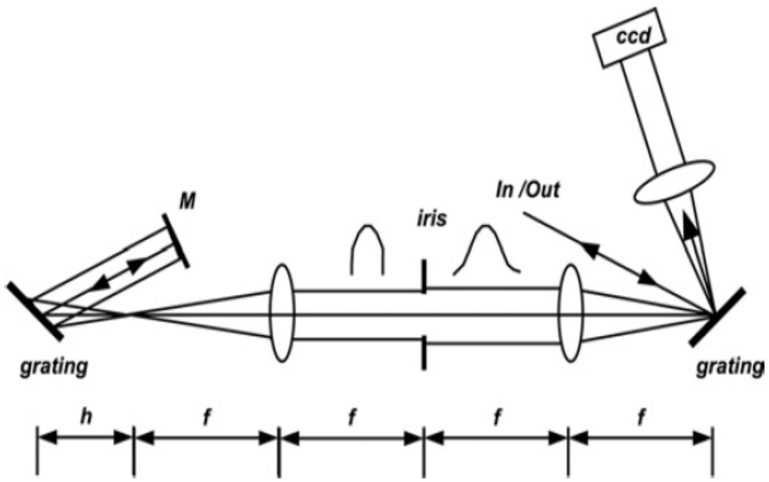
- SLM for pulse shaping
- Significantly improved emittance
- 14 MeV, 1 nC, 9 ps pulse

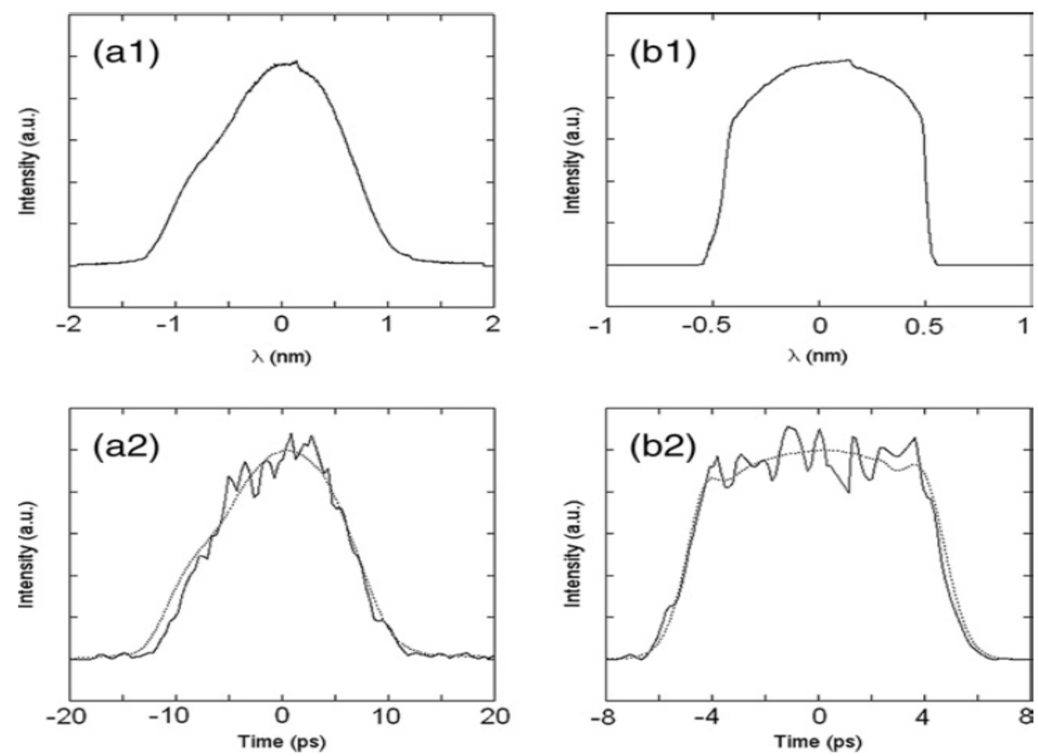


Yang et al., J. Appl. Phys 92, 1608 (2002)

Some PC gun examples: SPARC, SLM variation

- SPARC, SLM iris and chirp of a 100 fs laser system
- Directly in UV

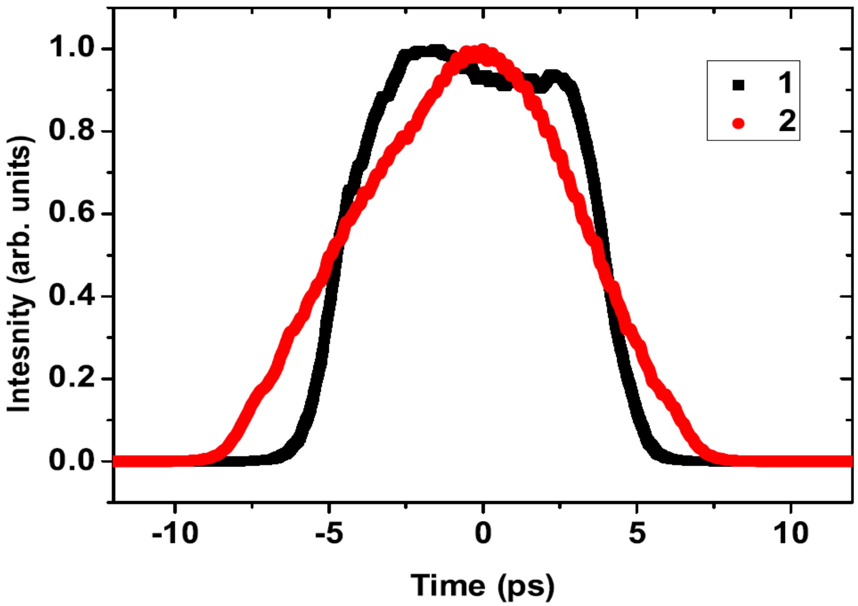




Initial spectrum (a1), spectrum after the mask (b1), and relative measured cross correlations (a2 and b2). The dotted curves represent the theoretical cross correlations obtained, taking into account that the probe pulse used for the measurement is actually 750 fs long.

Cialdi et al, Appl. Opt. 46, 4959 (2007)

Some PC gun examples: SPARC, Continue



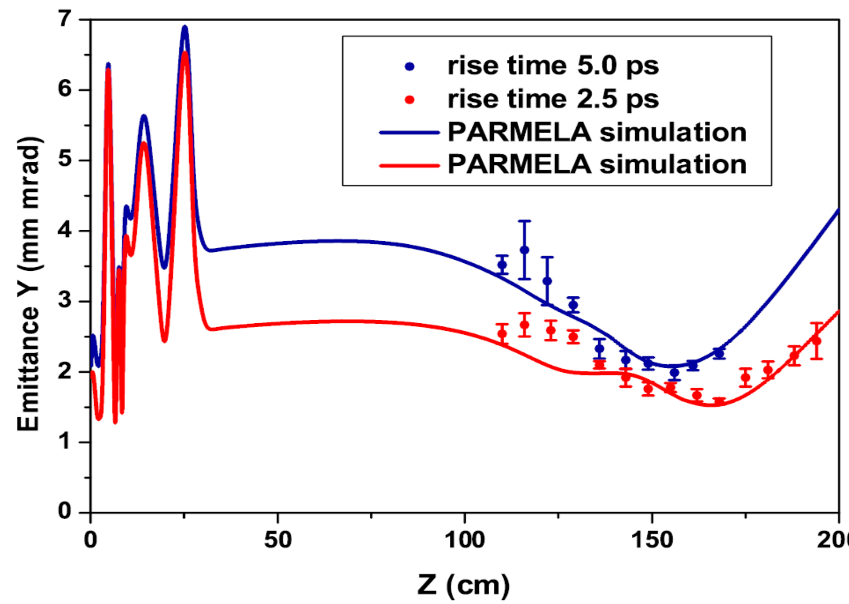


TABLE IV. Parameters of the beam corresponding to the best brightness result.

Parameter	Value
Energy	5.65 MeV
Charge	0.83 nC
Laser spot size	360 μm
Laser pulse length	8.9 ps FWHM
Phase ($\varphi - \varphi_{\max}$)	8^0

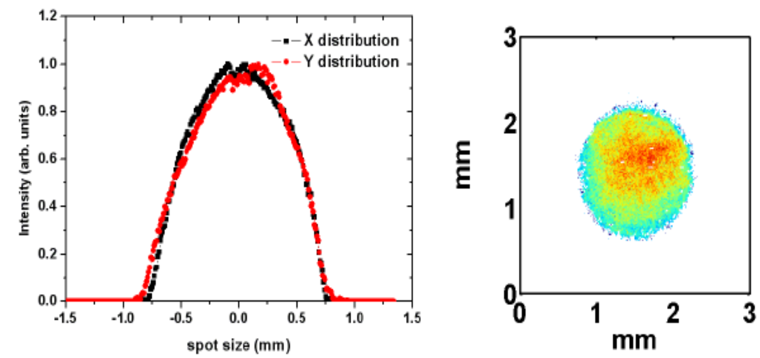


FIG. 10. (Color) Left: Typical projected transverse profile of the laser spot on the virtual cathode. Right: 2D laser spot profile.

Cialdi et al, Appl. Opt. 46, 4959 (2007)

Contents

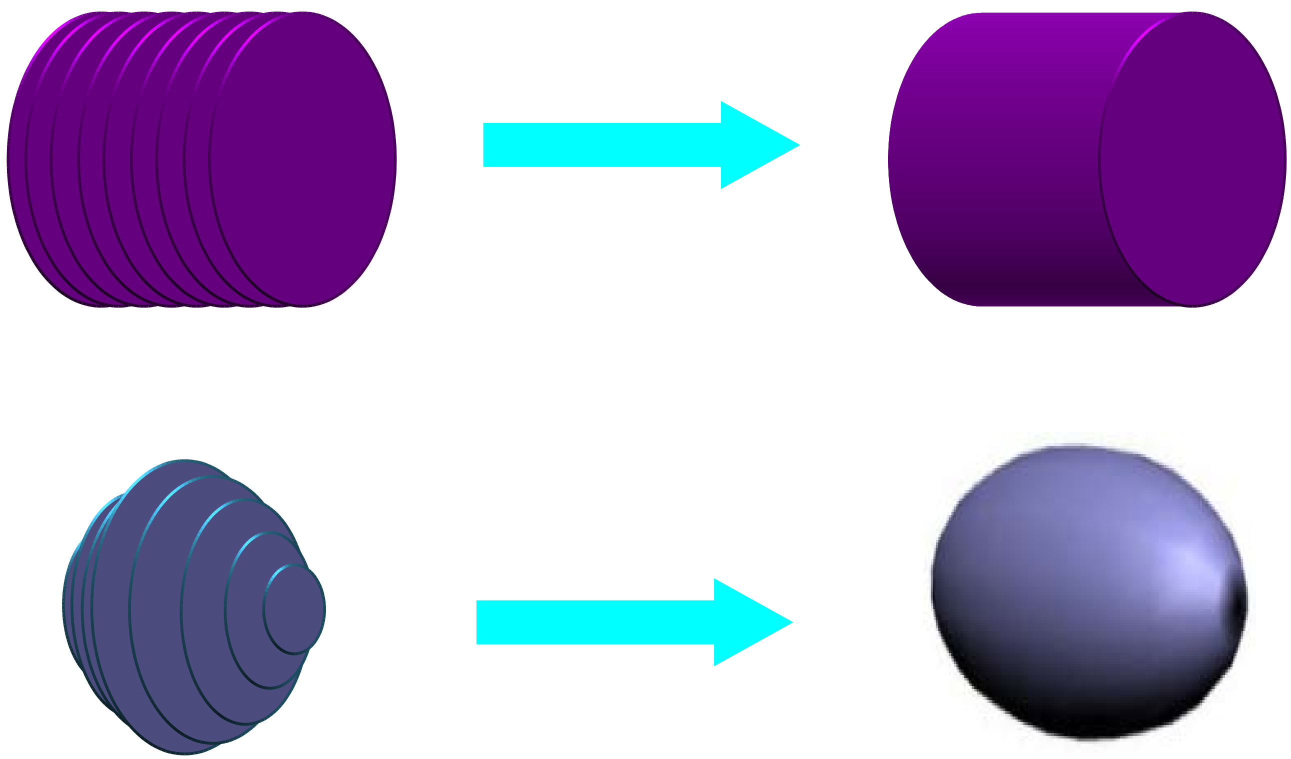
- Emittance compensation
  - Needs for emittance compensation
  - Emittance compensation theory
  - Space charge and beam geometries in emittance compensation
- Laser pulse description and diagnostics (brief refresh)
  - Laser beam: cross/auto-correlation and streak camera
  - Electron beam: rf deflection cavity
- Laser pulse shaping basics
  - Spatial shaping: convert Gaussian to flat-top
  - Temporal shaping: time and frequency domain techniques
  - Odds: man made materials
  - Accelerator examples
- 3D pulse shaping
  - Pulse stacking:
  - Dynamic shaping
  - Phase tailoring and chromatic aberration

Where are we and where do we go

- Pulse shaping independent time and space shaping
  - Temporal shaping: basically successful
  - Spatial shaping: we can do it
  - Combined? Not yet
- Simultaneous time and space
  - Temporal multiplex: pulse stacking
    - *Combination of delay optics*
    - *Birefringence crystal*
    - *Volume holographics*
  - Other novelties
    - *Dynamic shaping*
    - *Shaping via chromaticity*

Pulse stacking

- The idea is simple: volume is a collection of plane
- A series of disc with finite thickness can approach a cylinder or ellipsoid
- Transverse shaping still required
- Temporal rising determined by “seed”



Pulse stacking: time profile

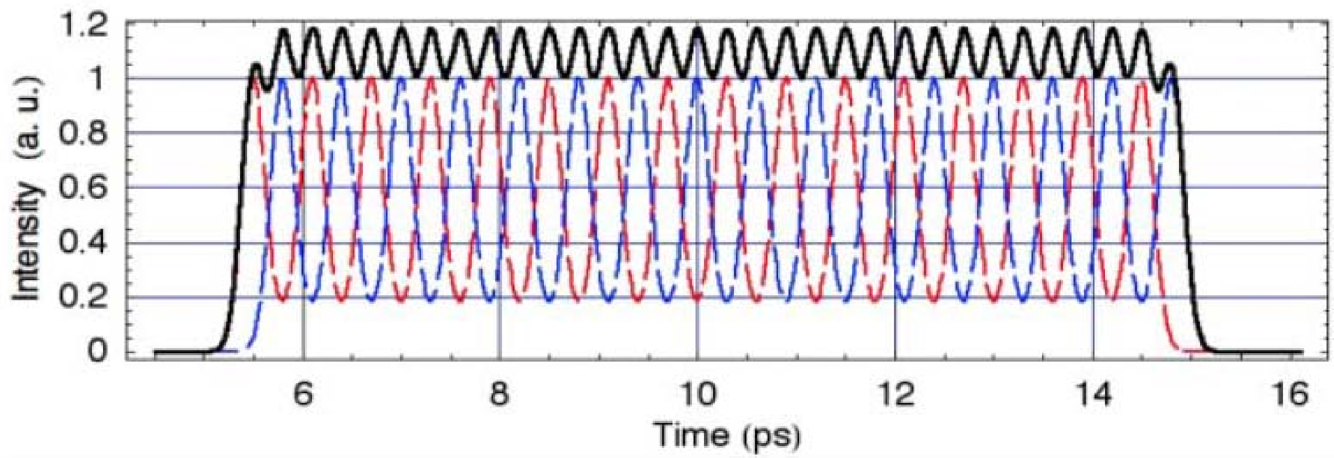


Figure 3: Simulation of the shaped UV pulse after the pulse-stacker. Red and blue dashed lines indicate p and s-polarized pulse trains. The resulting UV pulse on the photocathode is shown by the thick black line. Simulations of the electron beam propagation done in Parmela suggest that the intensity modulation in the resulting laser pulse does not degrade the emittance of the electron bunches.

M. Y. Sheverdin, Proc. PAC07, p. 533 (2007) (LLNL PC gun drive laser)

Pulse stacker inplementation: Michelson interferometer

- Combination of delay stages, mirrors and beam splitters
- Complicated, and difficult to align

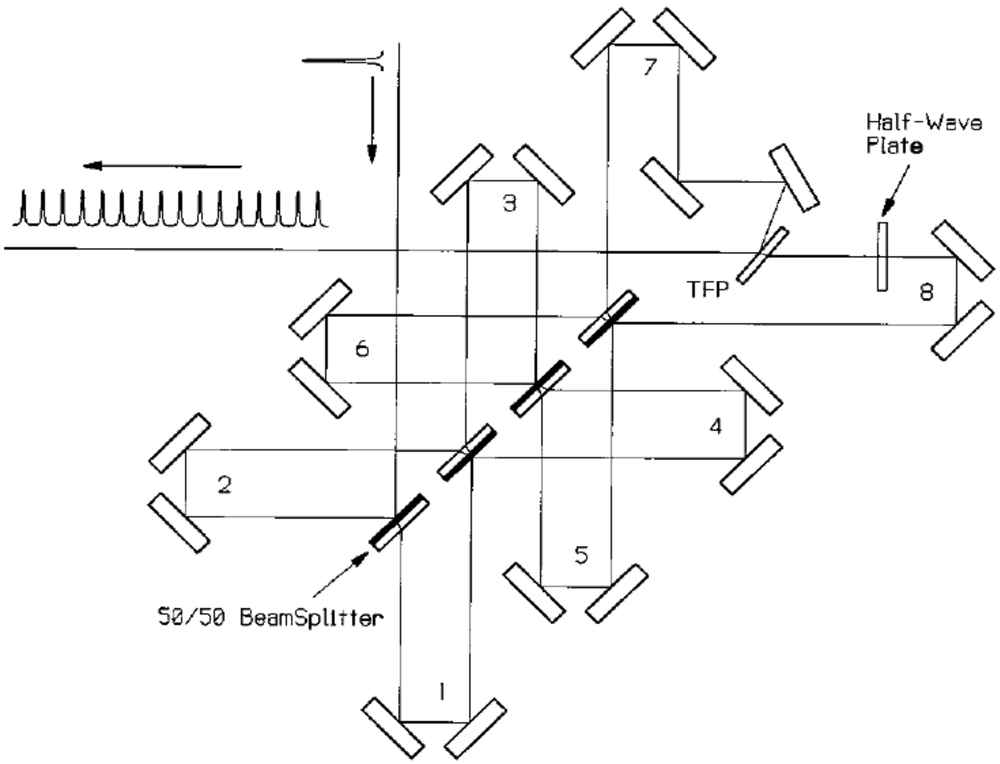
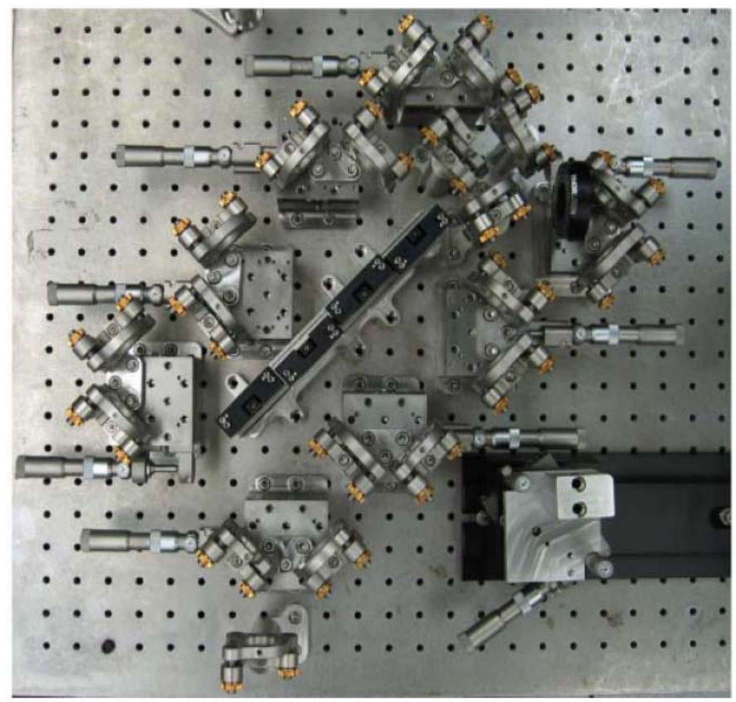


Fig. 1. Interferometer design for generation of a train of 16 pulses. For equally spaced pulses, arm 2 is lengthened by half a unit, arm 3 by one unit, arm 6 by two units, and arm 8 by four units.

C. W. Siders et al., Appl. Opt. 37, 5302 (1998).



M. Y. Sheverdin, Proc. PAC07, p. 533 (2007)
(LLNL PC gun drive laser)

Sample Results for pulse trains and top-hat

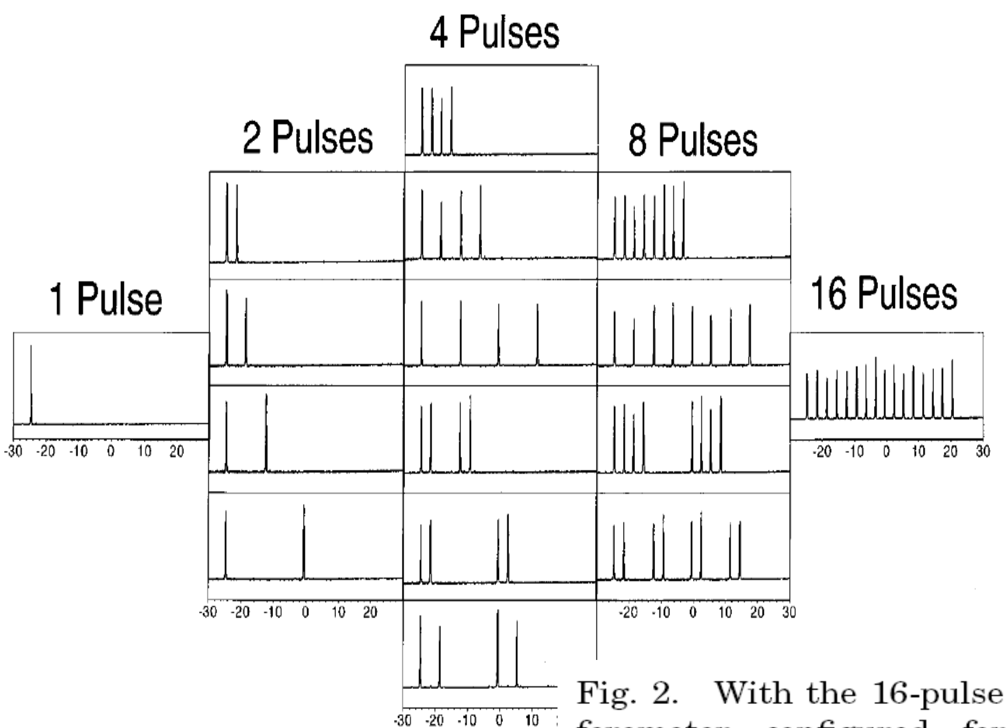


Fig. 2. With the 16-pulse interferometer configured for 3-ps pulse separations, blocking particular arms produces these and similar pulse trains. For these data the output of the interferometer is cross-correlated with a single gate pulse, split off before the interferometer, in a 0.5-mm KDP crystal.

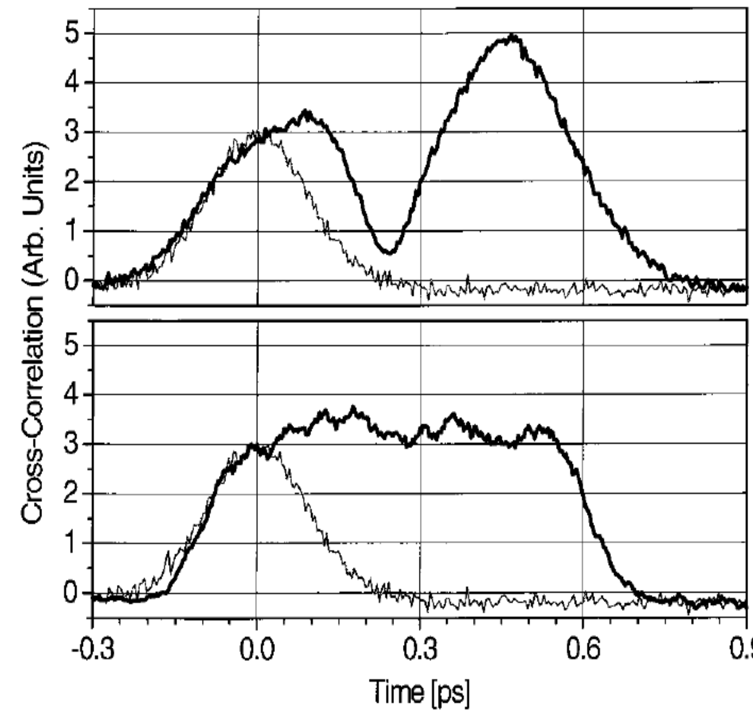
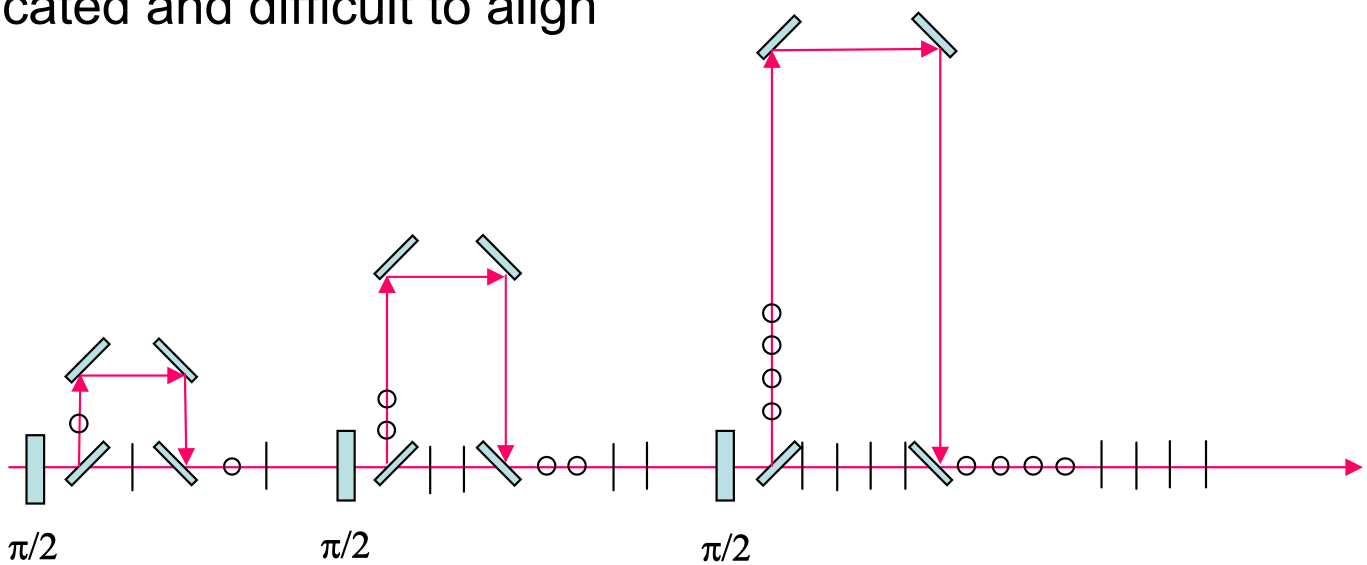


Fig. 4. (Top) Output of the interferometer configured to produce a dark pulse. To produce this output, four pulses separated by 200 fs were stacked together with the second pair of pulses out of phase from the first pair by π. (Bottom) Output of the interferometer configured to produce a super-Gaussian pulse. To produce this output, four pulses separated by 200 fs were stacked together in phase.

C. W. Siders et al., Appl. Opt. 37, 5302 (1998).

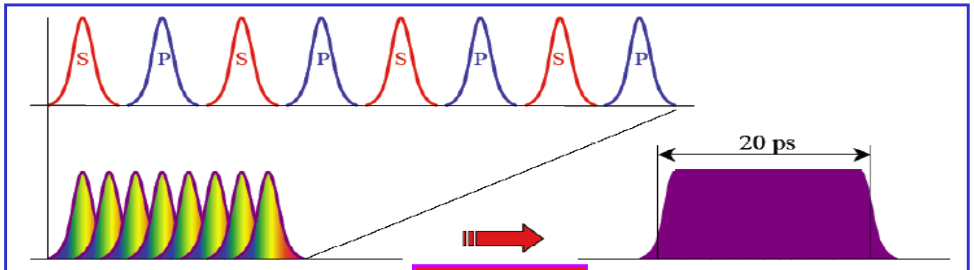
Pulse stacker: delay and polarizers

- Using a combination of quarter wave plates, polarizing beam splitter, and delay lines
- S polarization (parallel to the surface) reflected, P (perpendicular to the surface transmitted)
- 100% efficiency, theoretically
- Complicated and difficult to align

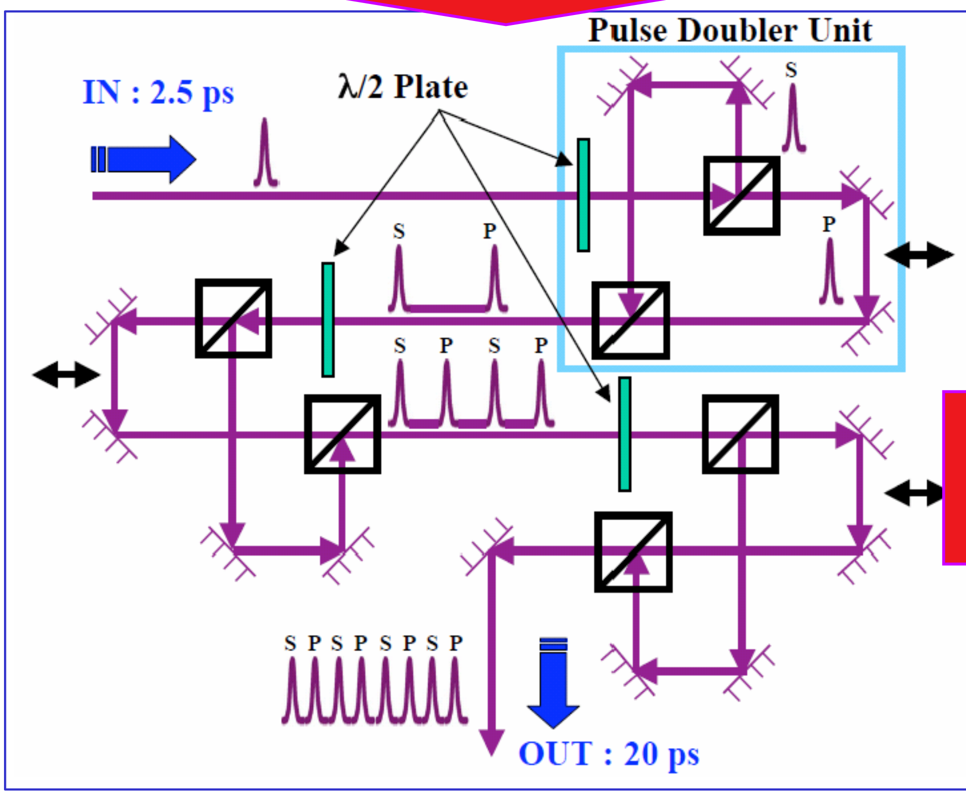


Implementation at Spring8

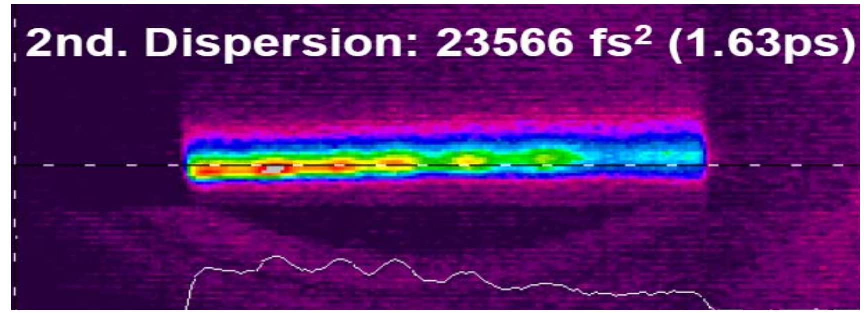
Target

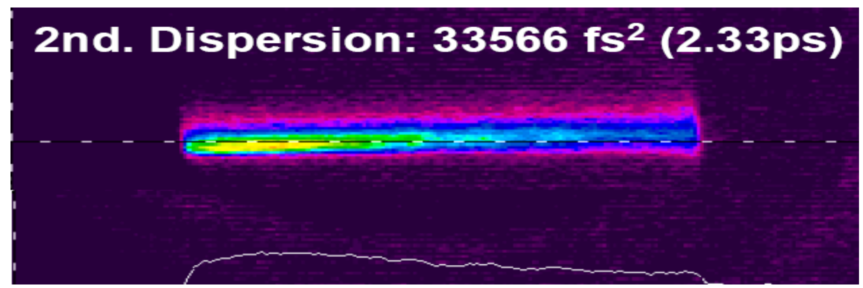


Scheme

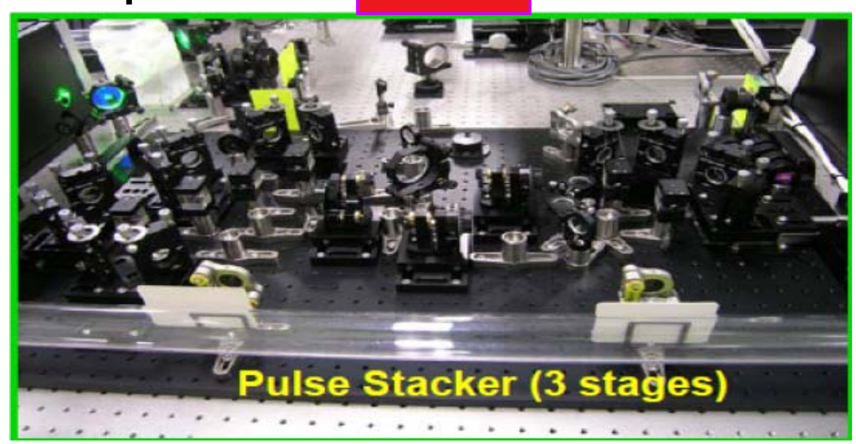


Results



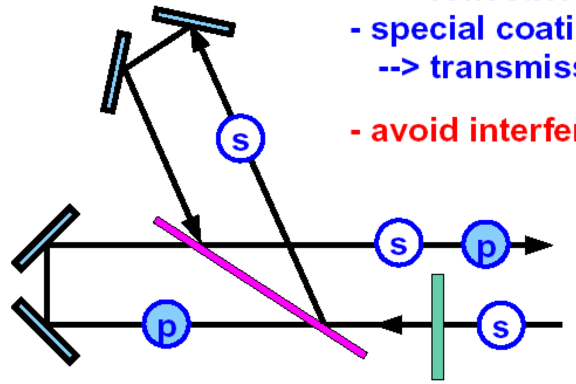


Setup



Tomizawa, Quantum Electronics 37, 697 (2007)

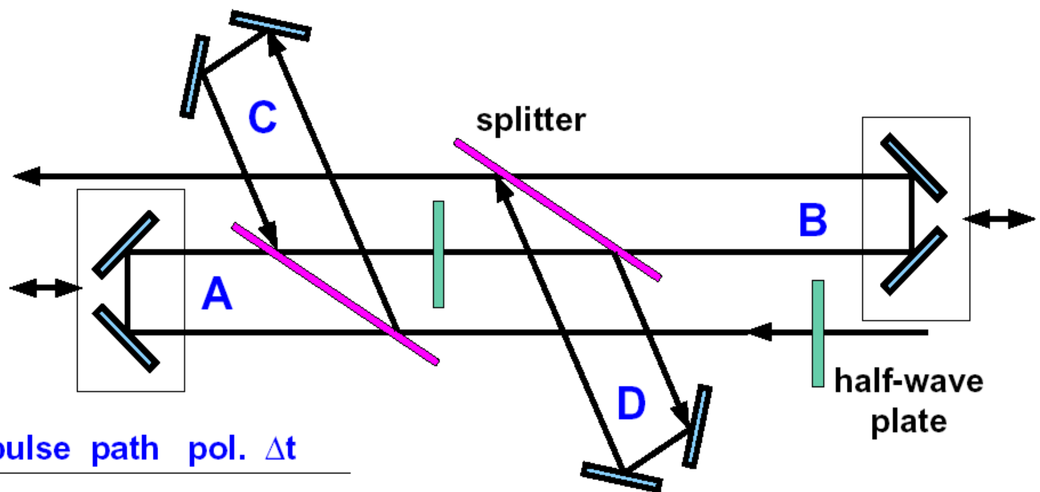
Pulse staking at DESY



- Splitter at Brewster angle (56 dg)
  --> reflectivity for s-pol 100 %
- special coating:
  --> transmission for p-pol close to 100%
- avoid interference by alternating s and p

- incoming beam
  is linear polarized,
  eg. s-pol

- half-wave plate to turn polarisation
  by 45 dg



pulse	path	pol.	Δt
1	A + B	p	
2	A + D	s	D-B
3	C + B	p	(C-A)-(D-B)
4	C + D	s	D-B

condition, to have all Δt equal:

A = C - 2(D-B)

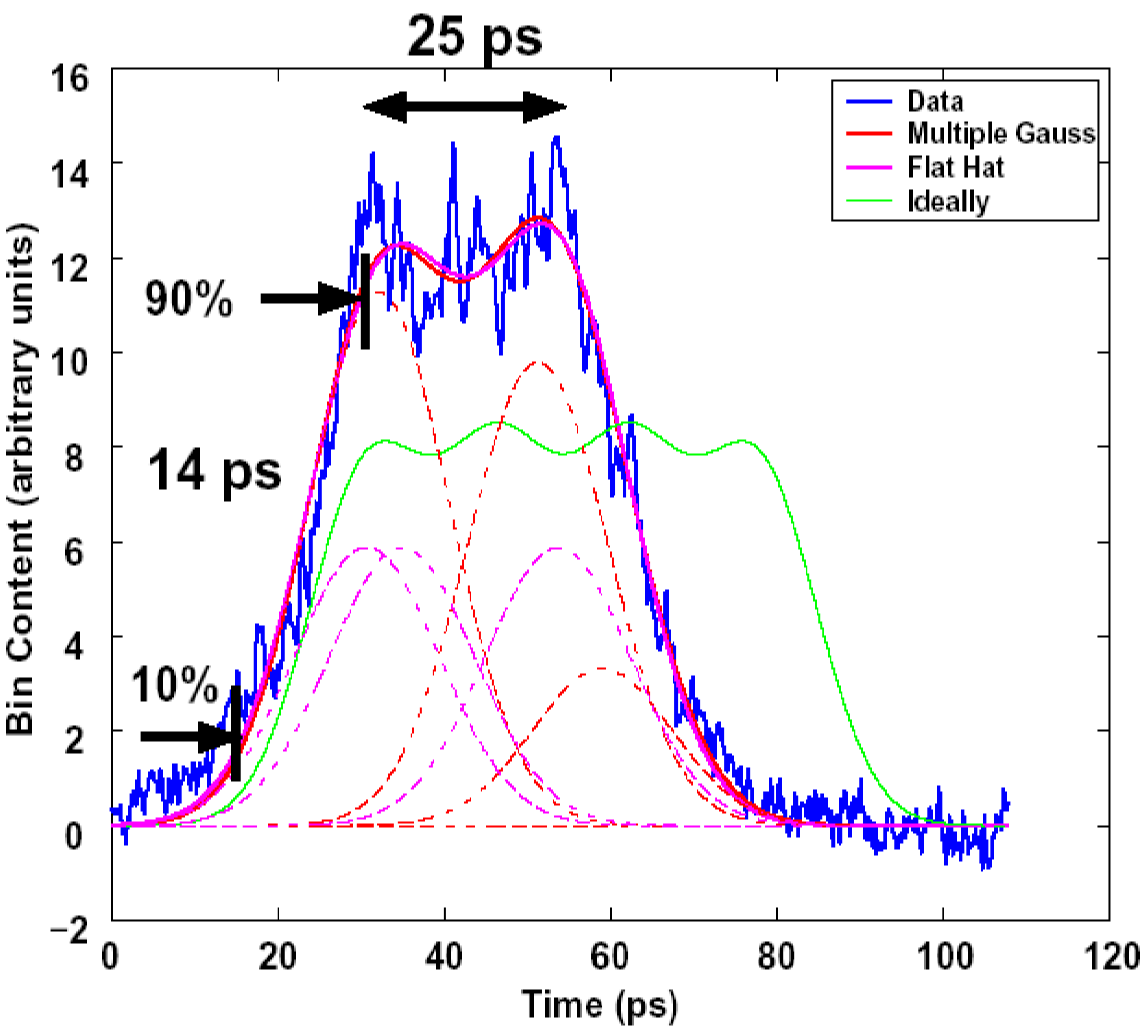
for C=D -> A = 2B-D
and D/2 < B < D

S. Schreiber, DEZY

PITZ mini pulse shaping workshop, 2007

DESY pulse stacking measuremnt

measured with a streak camera



Fits:

1. four gaussians,
   σ same for all 4
2. flat hat
   σ and intensities
   are the for same for all

Ideal profile:

distance of pulses = 2.25 σ

σ = 7 ps

Results:

from flat hat fit:

- rise time = 14.8 ps
- flat top width = 23 ps

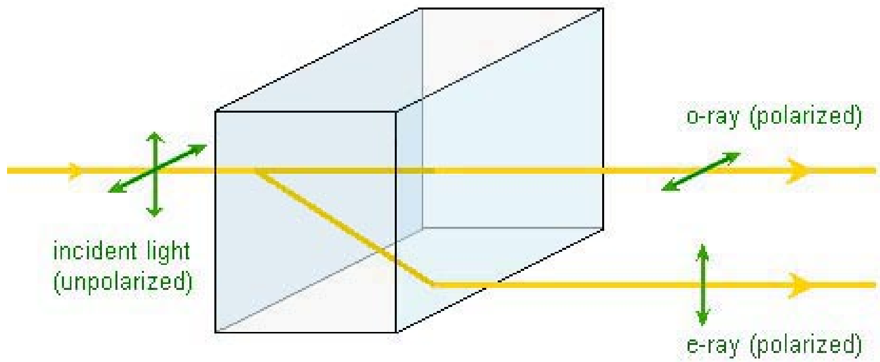
from multiple gauss fit

(same sigma for each gauss):

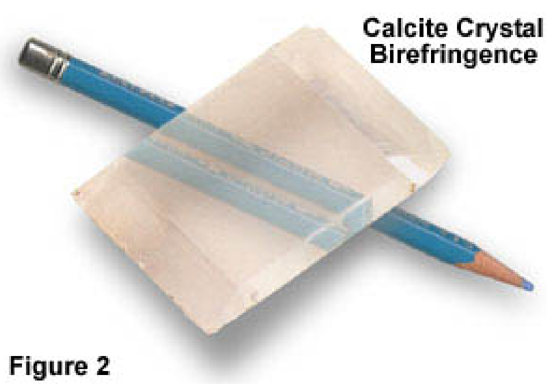
- rise time = 14.2 ps
- flat top width = 27 ps

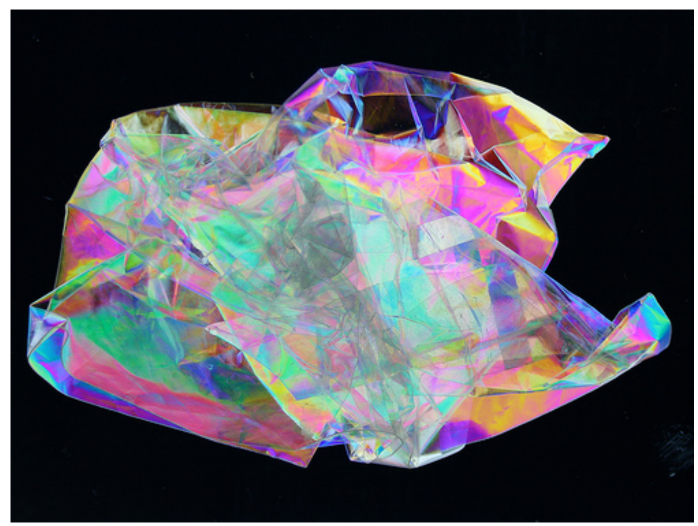
A simpler implementation: birefringence crystals

- Different refractive index for different polarization rays (ordinary and extra ordinary waves), $n_0(\omega),n_e(\omega)$



- Thus
  - Different refraction angles for different waves
  - difference group velocity for different waves





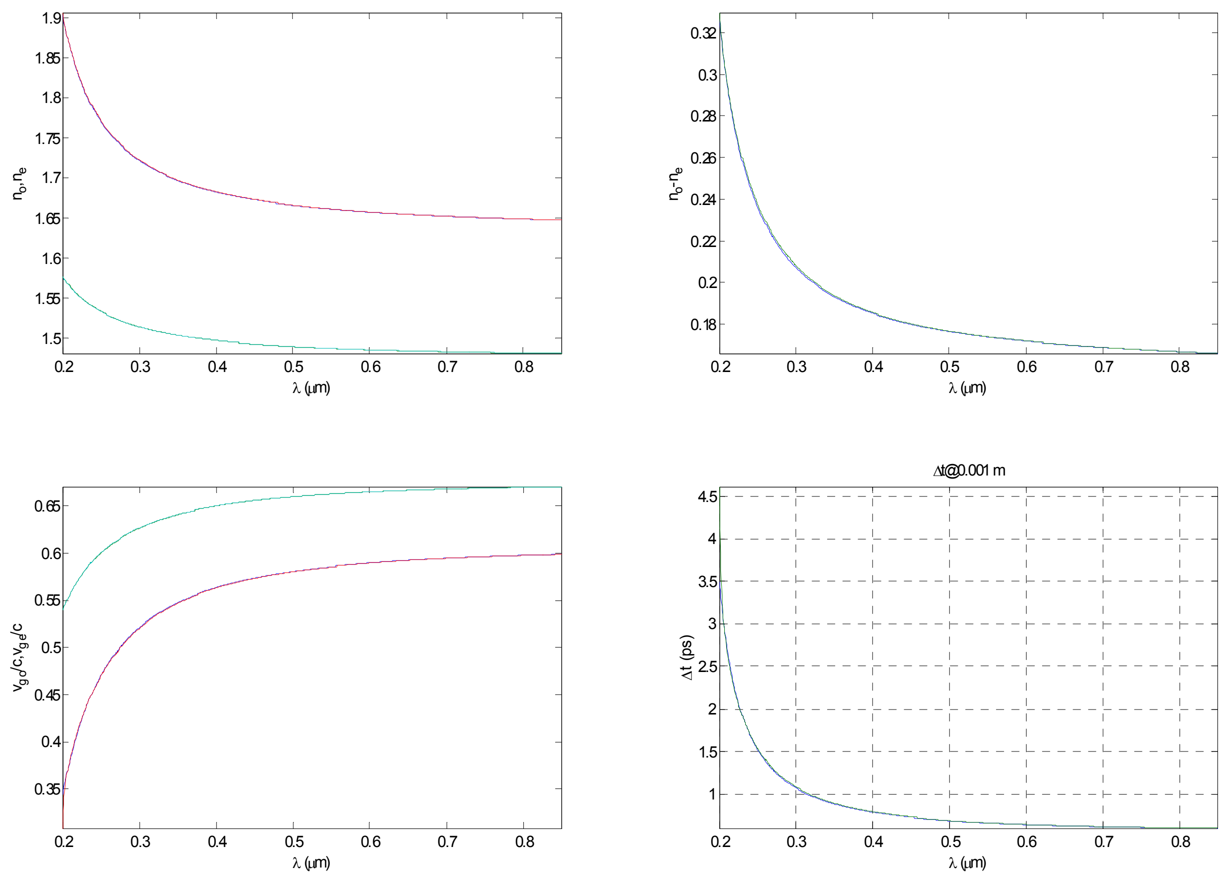
A simpler implementation: birefringence crystals

- Thus difference group velocity for different waves

$$\frac{1}{v_g} = \frac{\partial k}{\partial \omega} = \frac{n}{c}\left(1 + \frac{\omega}{n}\frac{dn}{d\omega}\right).$$

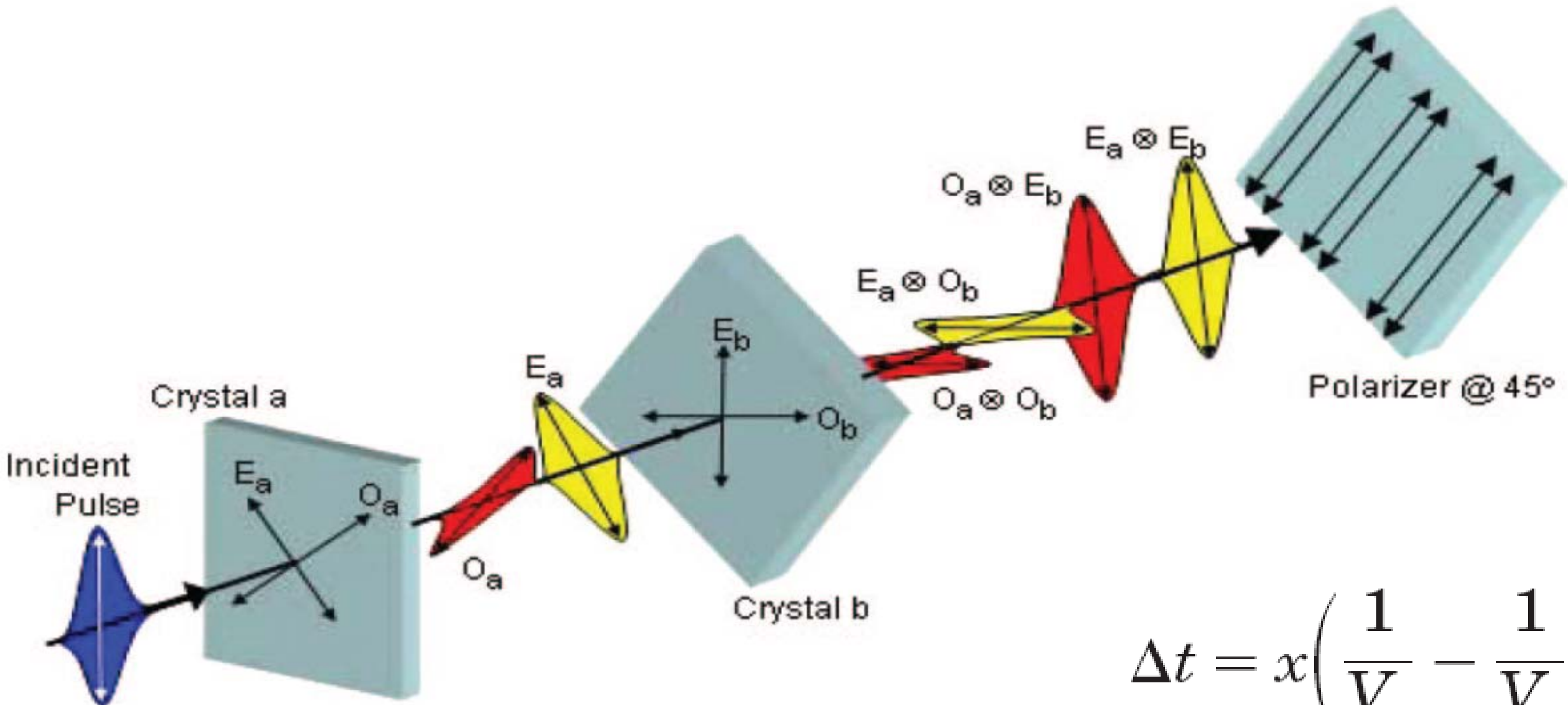
$$\Delta t = x\left(\frac{1}{V_o} - \frac{1}{V_e}\right),$$

Calcite example



A birefringence crystal pulse stacker

- Old idea: H. E. Bates et al., Appl. Opt. 18, 947 (1979)
- Number of pulses= 2^n, n is the number of birefringence crystals



$$\Delta t = x\left(\frac{1}{V_o} - \frac{1}{V_e}\right),$$

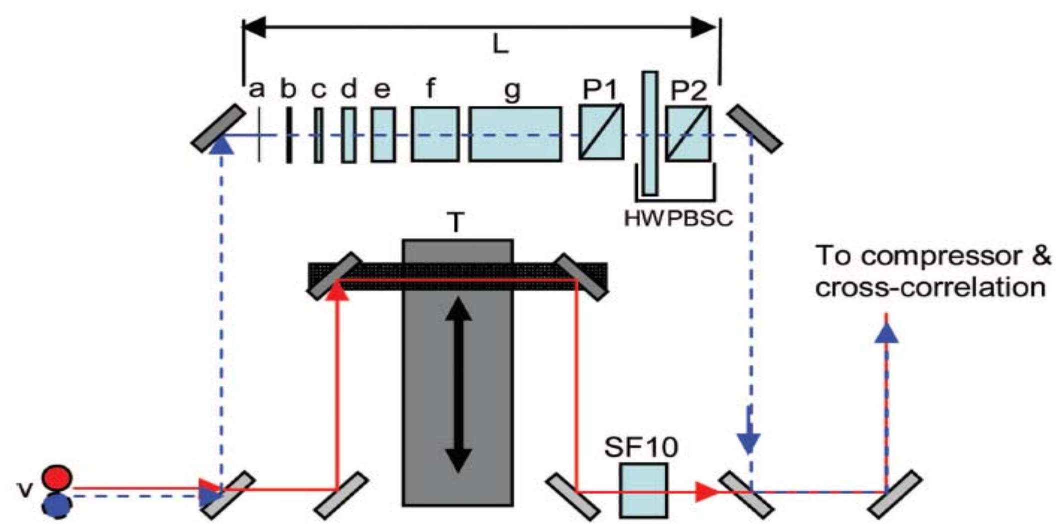
B. Dromey et al., Appl. Opt. 46, 5142 (2007).

The incarnation for 128 pulses

Table 1. Temporal Delay, Δt, for Calcite Crystals of Different Thicknesses x

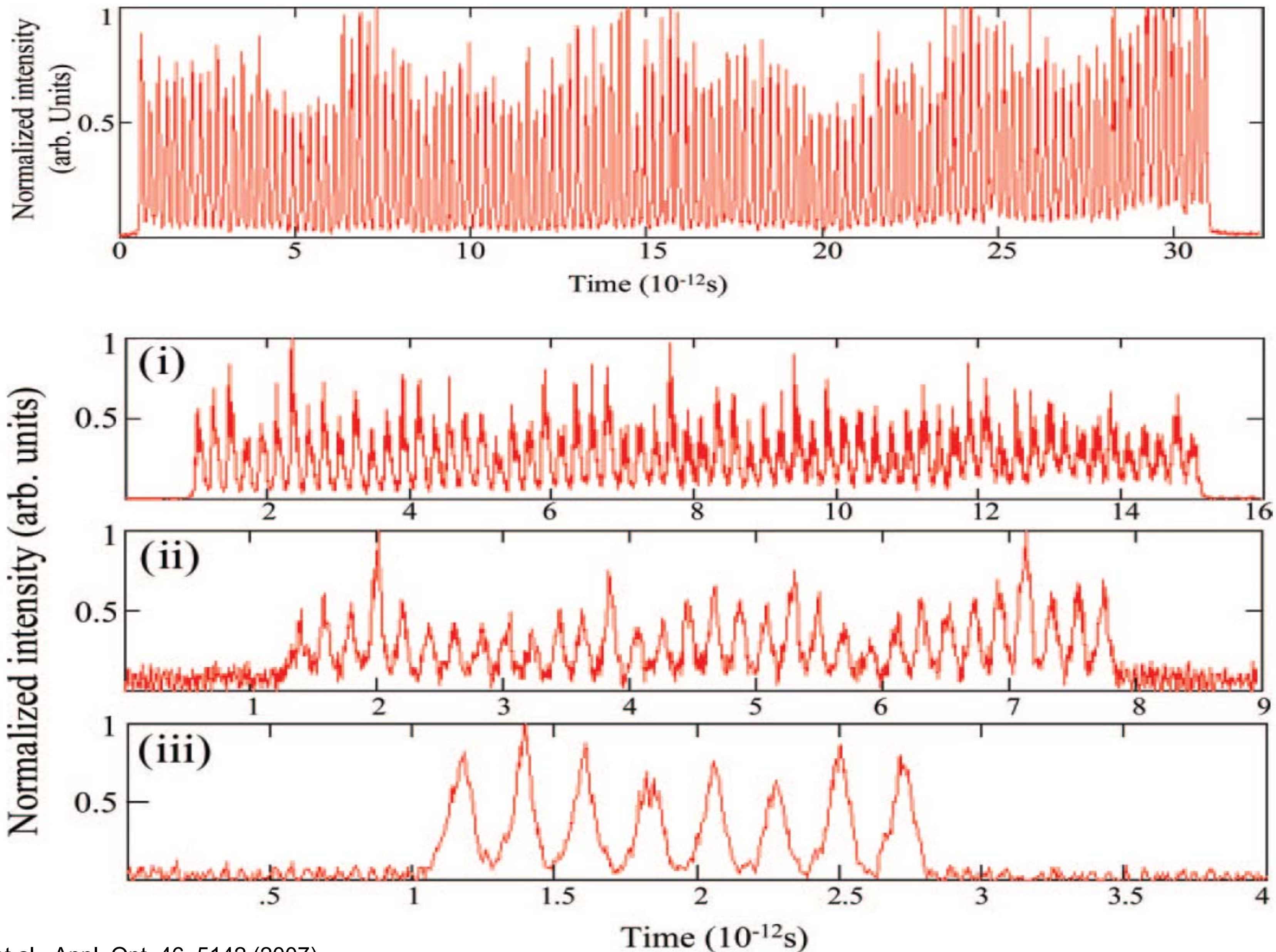
x (mm)	Δt (s)
0.40	2.3×10^{-13}
0.80	4.7×10^{-13}
1.60	9.5×10^{-12}
3.20	1.9×10^{-12}
6.40	3.8×10^{-12}
12.80	7.6×10^{-12}
25.60	1.5×10^{-11}

A 800 nm, 40 fs pulse to start



B. Dromey et al., Appl. Opt. 46, 5142 (2007).

Results, for pulse trains at 800 nm



B. Dromey et al., Appl. Opt. 46, 5142 (2007).

Accelerator testing: Cornell ERL drive laser

- Fiber laser, at 530 nm
- Birefringence pulse stacker for flat top pulses

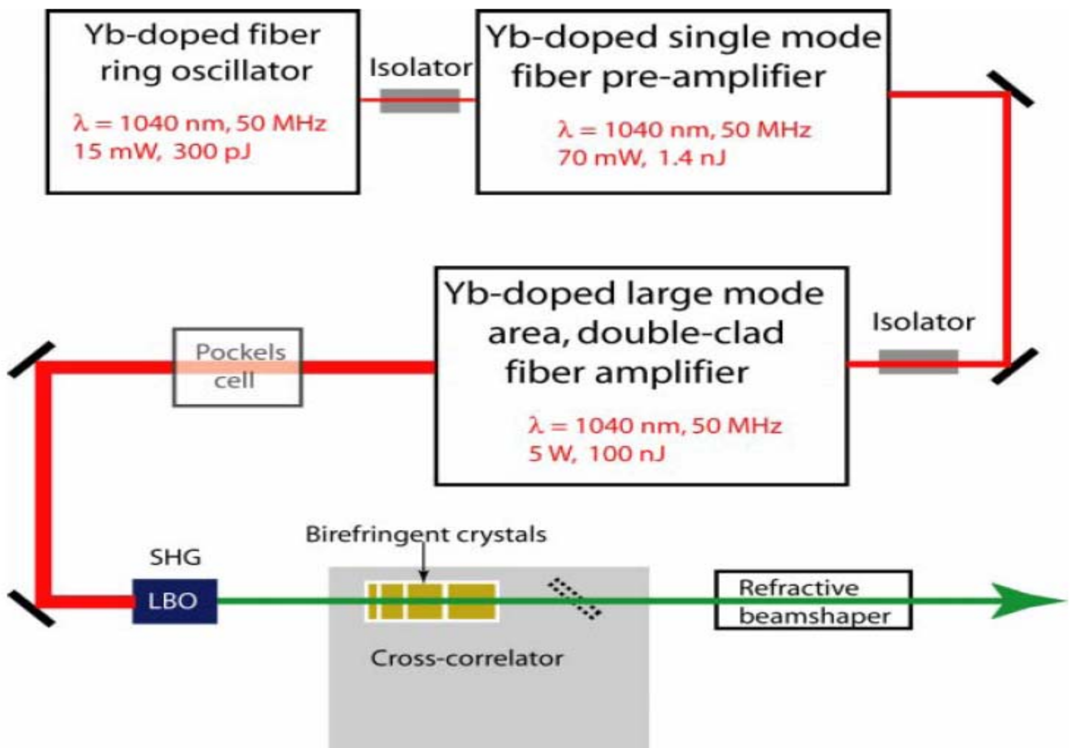


Figure 1. Schematic of the laser system.

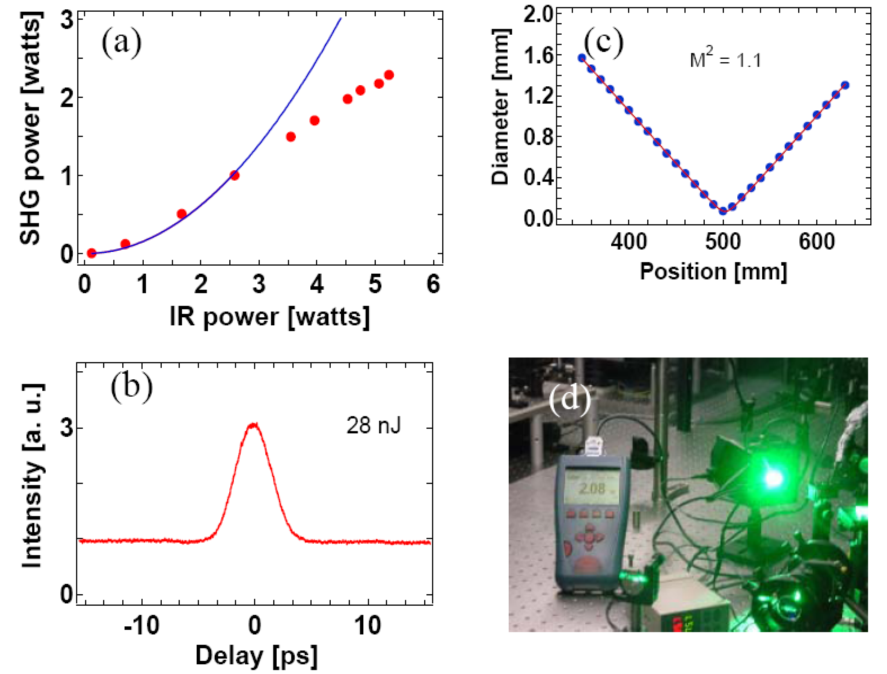
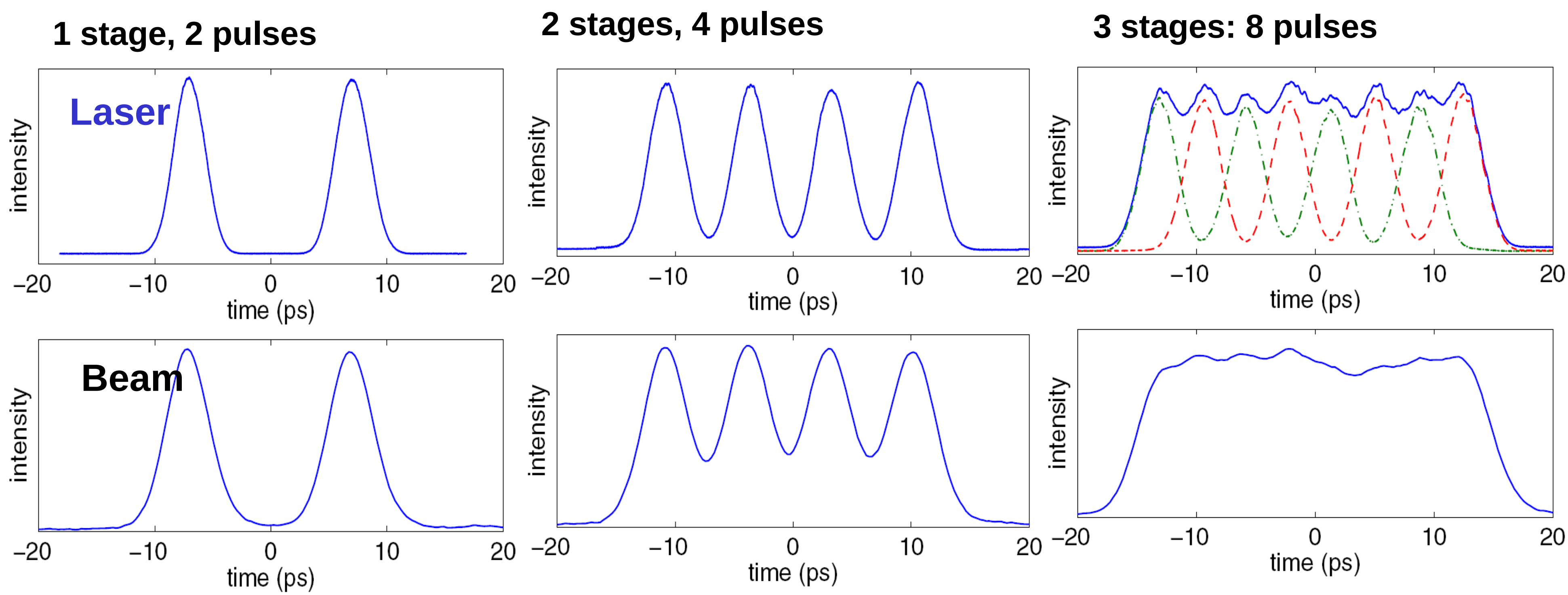


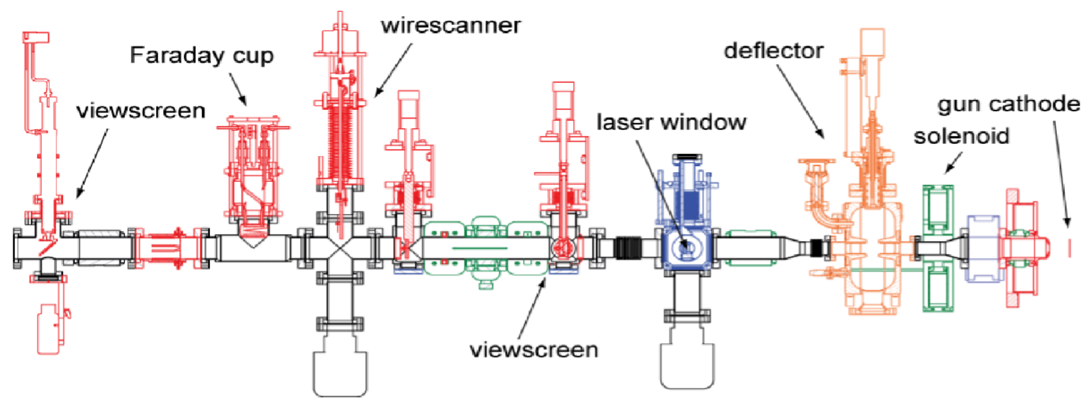
Figure 5. (a) The efficiency of the SHG process. (b) Intensity autocorrelation of a green pulse with pulse energy of 28 nJ. (c) M^2 measurement results for the green beam. (d) SHG generation.

D. G. Quzounov, et al., Proc. PAC07, p. 530 (2007) (Cornell new drive laser)

Cornell test results: Laser and beam profiles



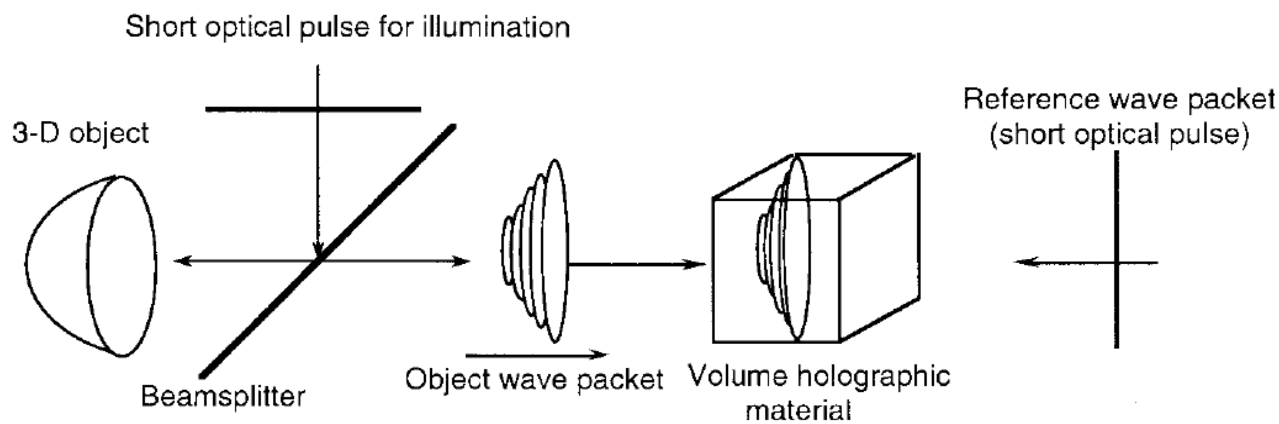
- Laser measured by cross correlation
- Electron beam measured by deflector
- Charge? Energy? Emittance?



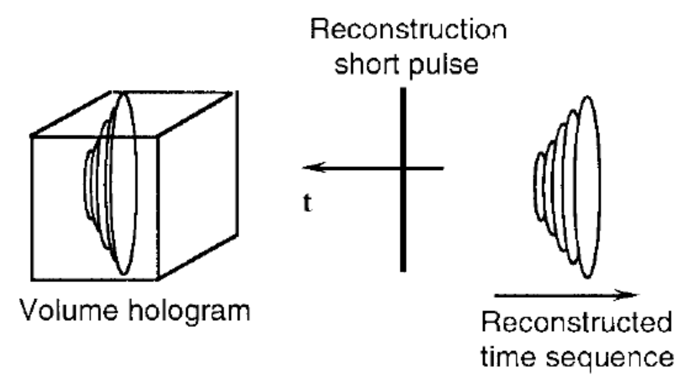
BAZAROV et al. Phys. Rev. ST Accel. Beams 11, 040702 (2008)

Temporal multiplexing via Volume holographic

- Recording of a set of holographic in a volume material
- Originally for optical data storage
- Proposed for many other applications



(a)



Sun Etal., Proc. IEEE 87, 2086 (1999)

Volume holographics: an experiment

- 8 images coded at 1 ps separations
- Image successfully reconstructed

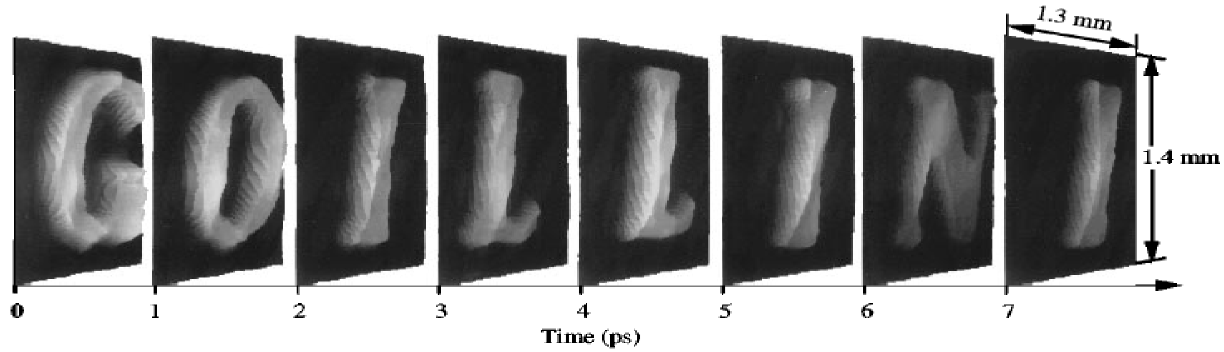
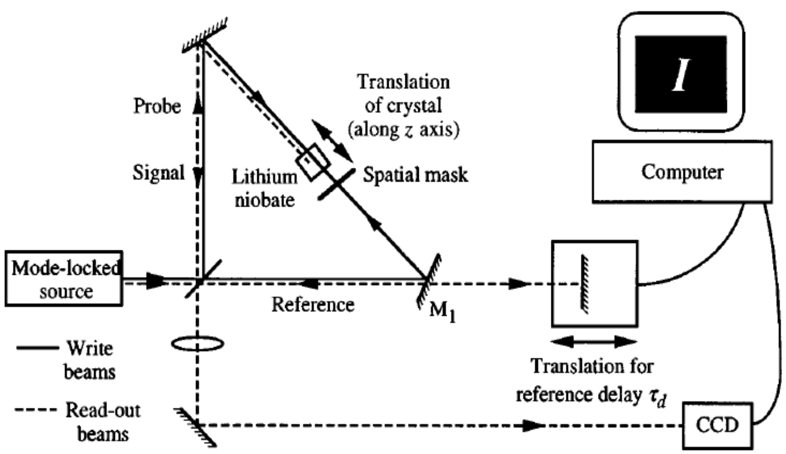
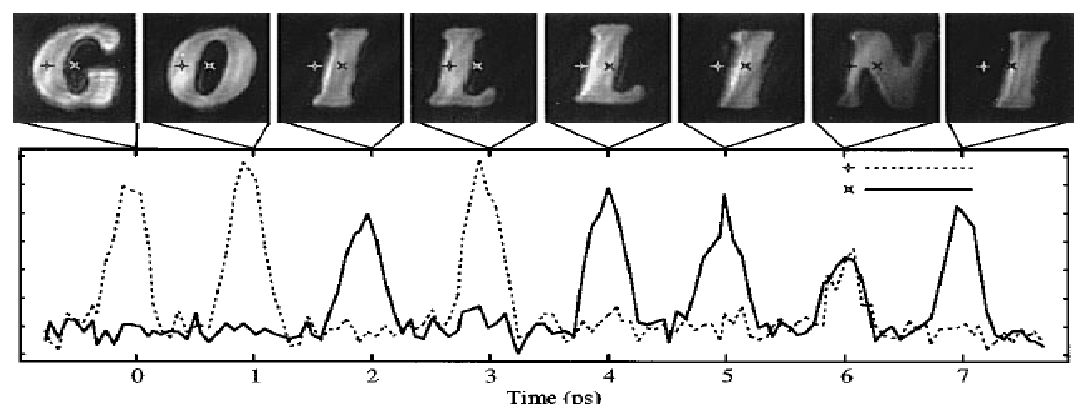


Fig. 2. Surface plots of the pulsed image at 1-ps time intervals.

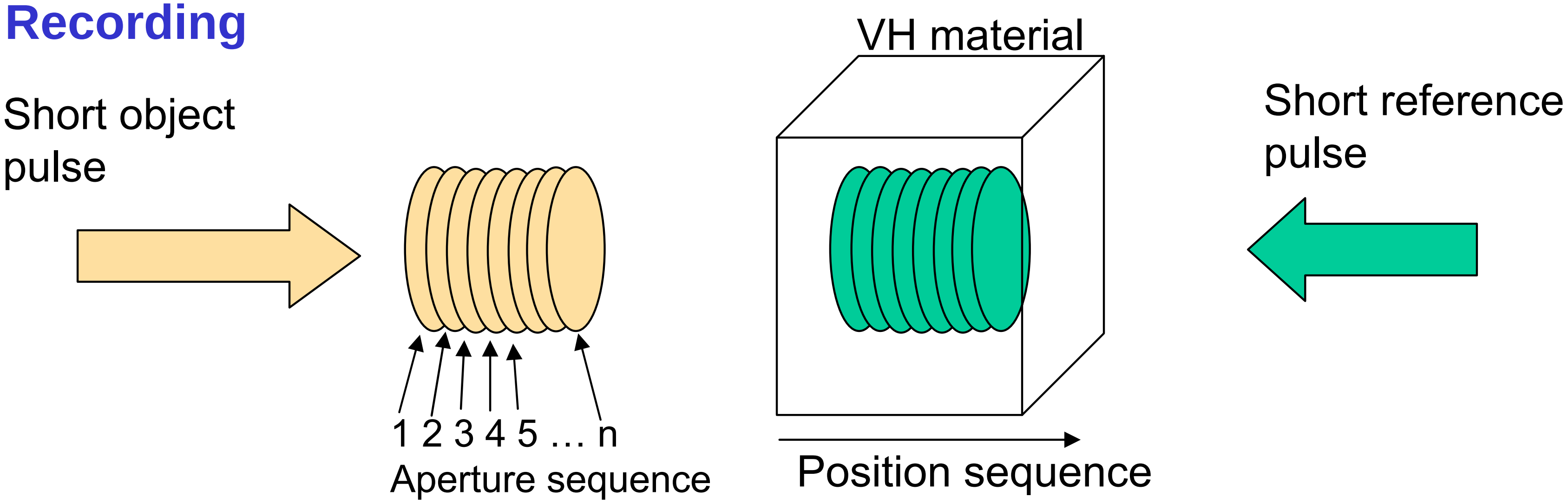




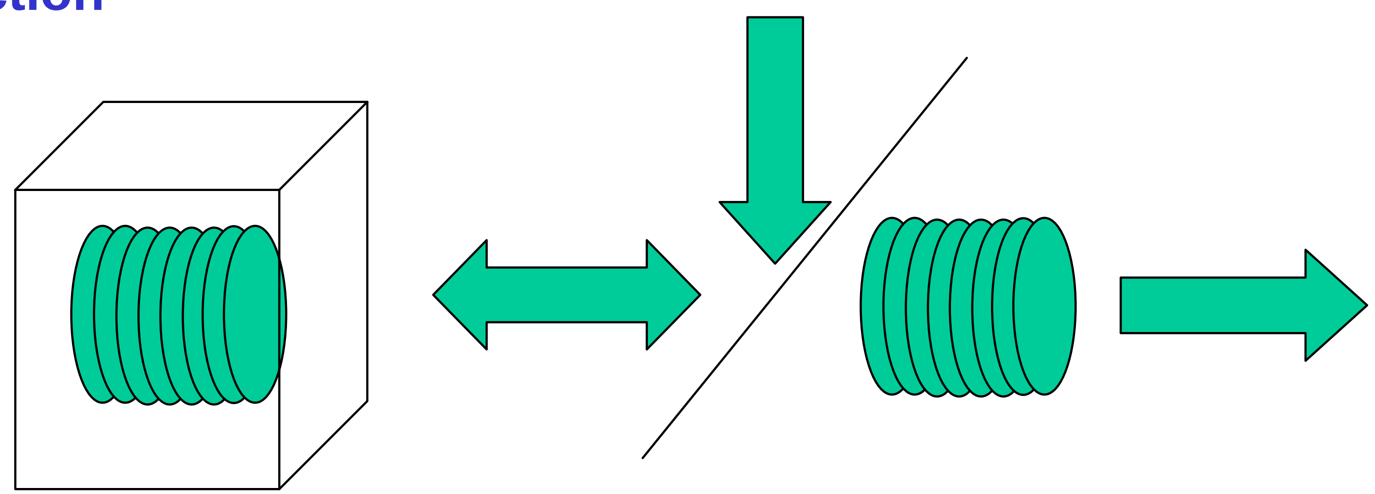
D. Brady and D. Psaltis, Opt. Lett. 15, 1201 (1995).

Volume holographic of a cylindrical beam

Recording

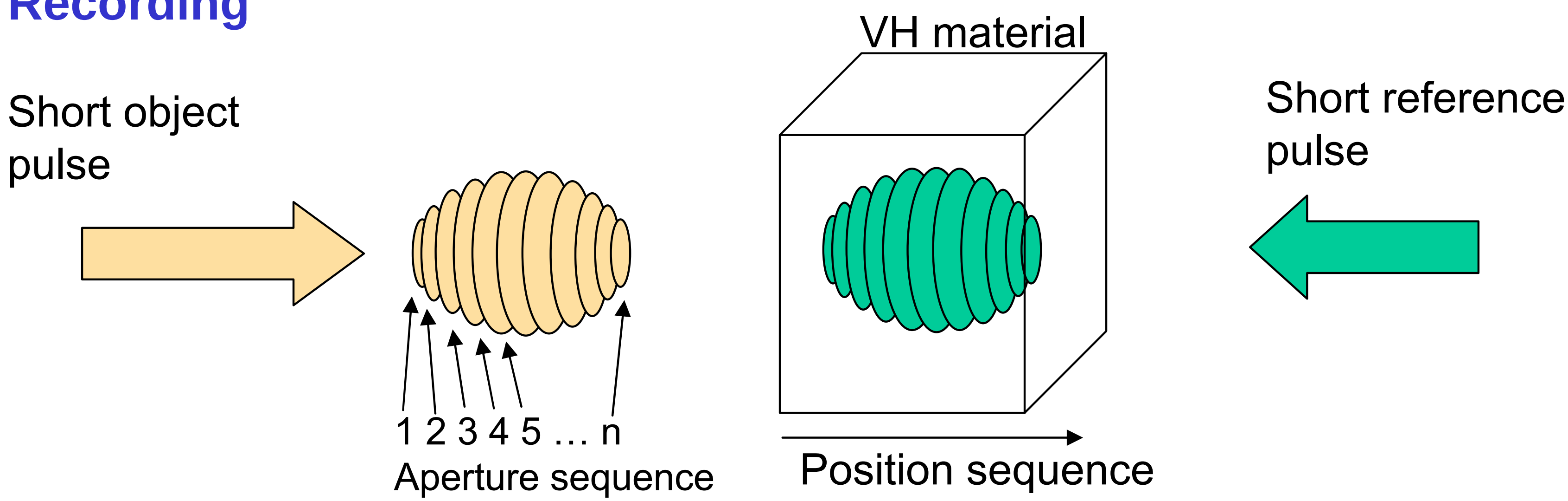


Reconstruction

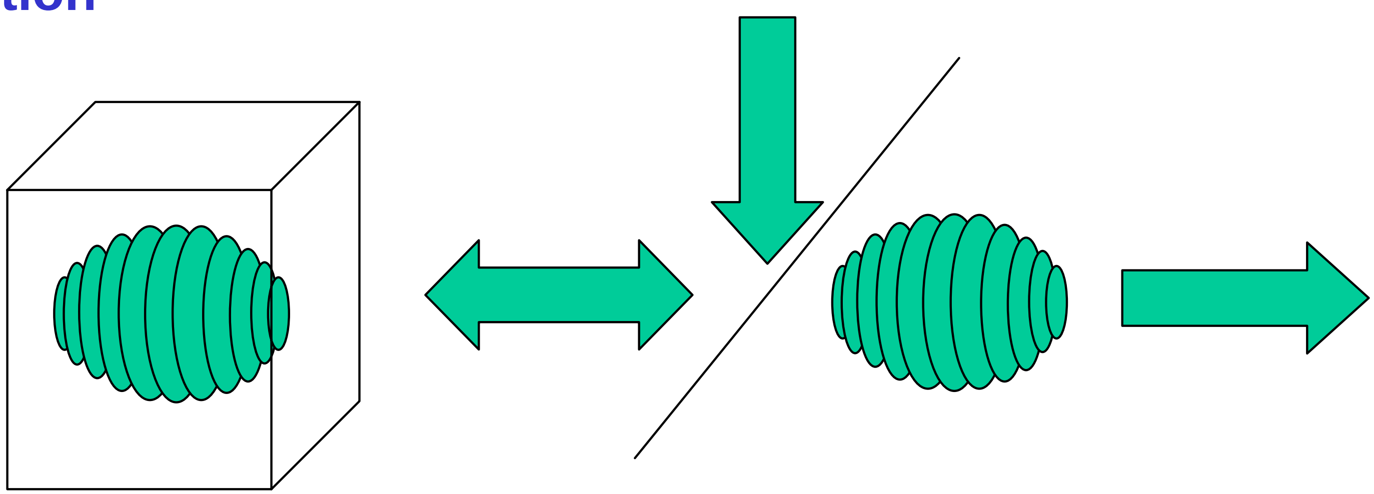


Volume holographic for eliposidal beam

Recording



Reconstruction

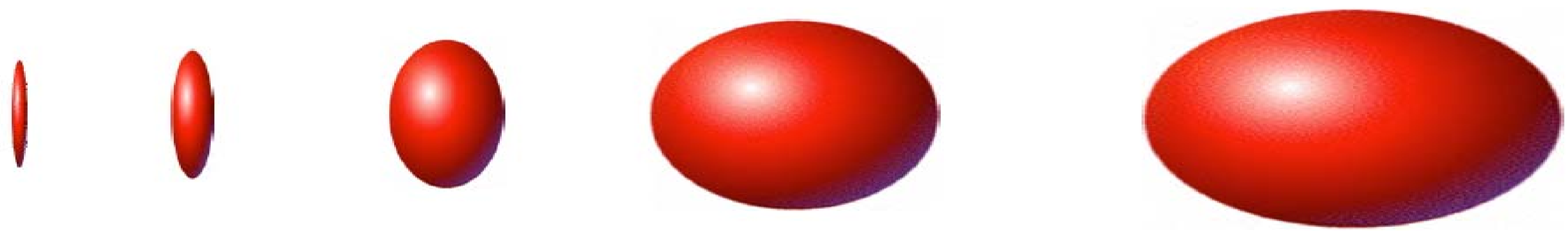


Volume holographic: potential and difficulties

- Advantages envisioned
  - Compact setup for pulse stacking for ellipsoidal pulse!
  - In principle very straight forward
  - Easy to align
- Difficulties exists
  - Material volatility: thermal glass potential solution?
  - Material volatility: better for low energy in visible
  - Material volatility: life time?
  - Efficiency still in question
  - Control?

Novel ideas for ellipsoidal beams: pan cake beam

- Self evolving beams (Pan cake scheme)
  - Expansion driven by space charge force



Waterbag recipe:

• Start with a ***flat ellipsoid*** _ can be ‘cut out’ with 2 intersecting laser beams;
• ***pancake*** _ ***‘half-sphere’*** laser intensity profile;
• ***cigar*** _ ***parabolic*** laser intensity profile;
• **automatic evolution into 3D, uniform ellipsoid.**

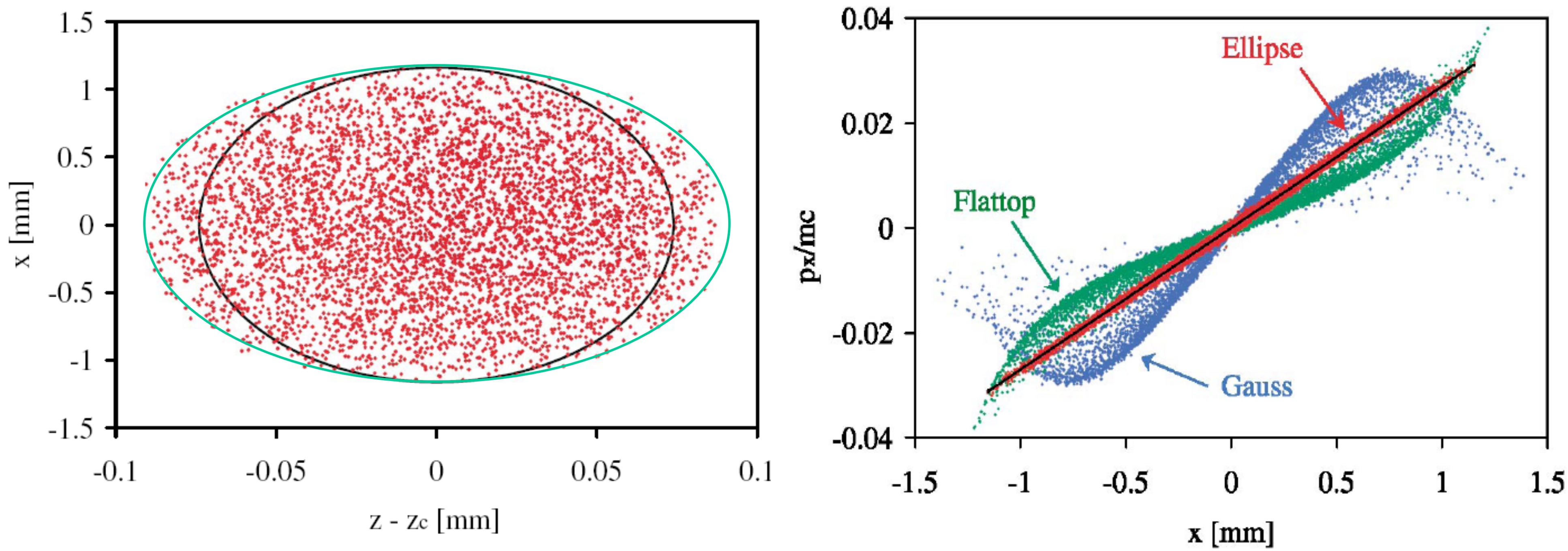
Erice 2005 15

L. Serafini, AIP Conf. Proce. 413, 321 (1997)

O. J. Luiten et al., Phys. Rev. Lett. 93, 094802 (2004).

Pancake beam evolution simulations

- DC of 100 MV/m, 100 pC charge
- Very close to a perfect ellipsoid

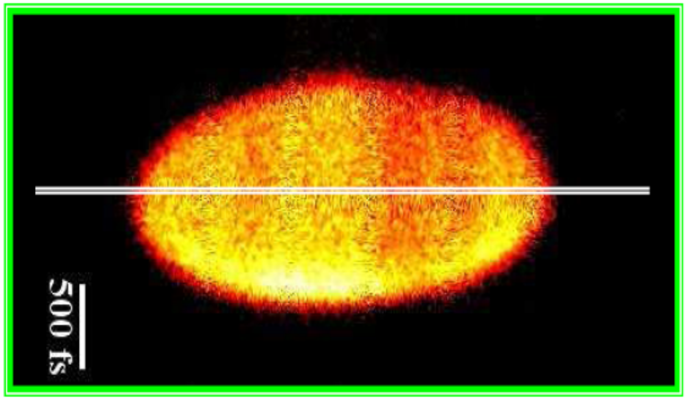


O. J. Luiten et al., Phys. Rev. Lett. 93, 094802 (2004).

Pancake beam: an experiment

- 35 fs laser with 0.1- 1mm spot size, 3-5 MeV beam energy
- Deflecting cavity measurement

Beam homogeneity:



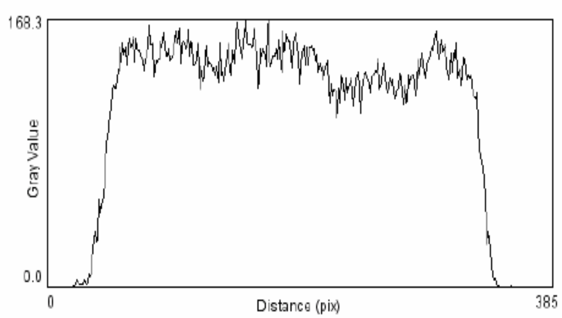
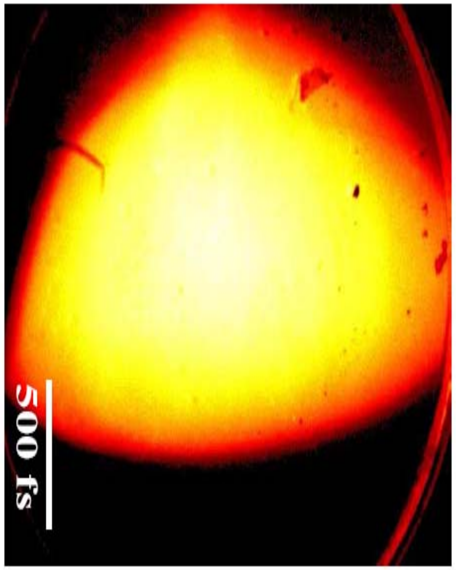
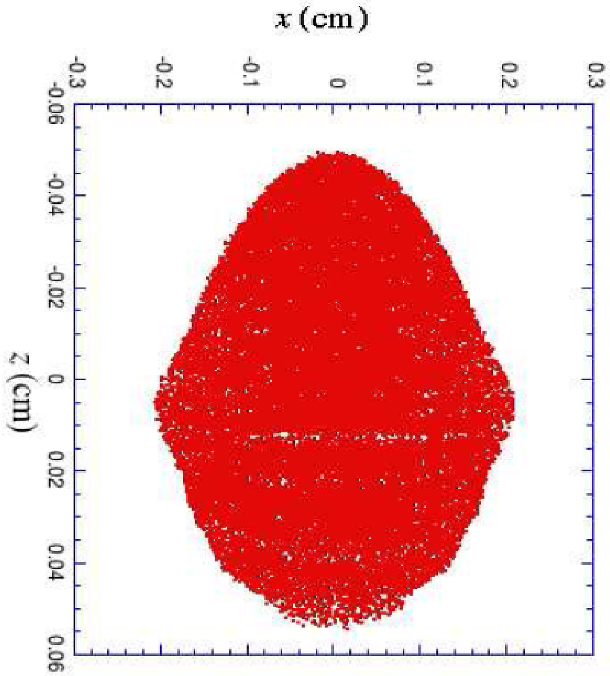


Image charge distortion:

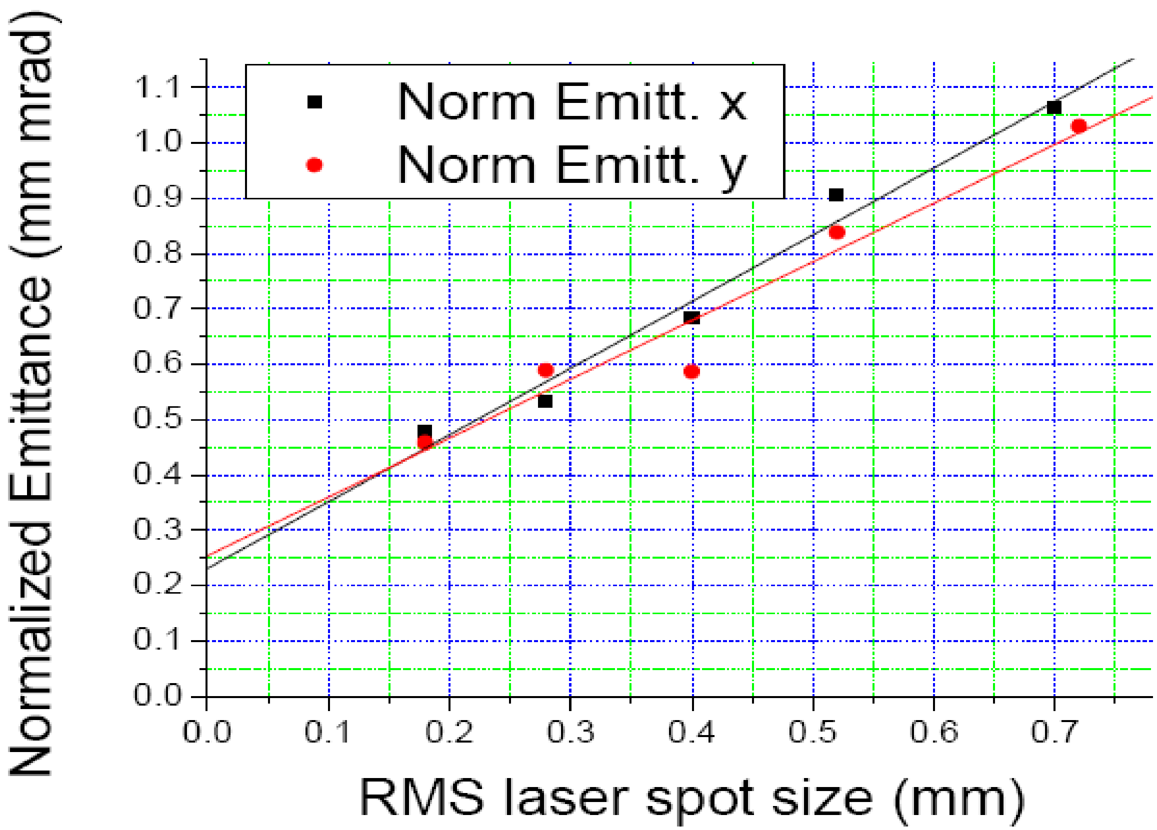




http://www.lnf.infn.it/conference/elba07/talks/Musumeci.pdf
Musumeci et al., Phys. Rev. Lett. 100, 244801 (2008):

Pancake beam: an experiment

- Emittance still quite high: Mg cathode blamed
  - Mg thermal emittance is about 0.55 mm for a 1 mm rms beam size



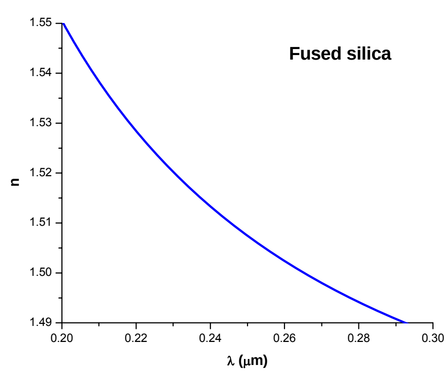
http://www.lnf.infn.it/conference/elba07/talks/Musumeci.pdf

Pancake beam: Summary

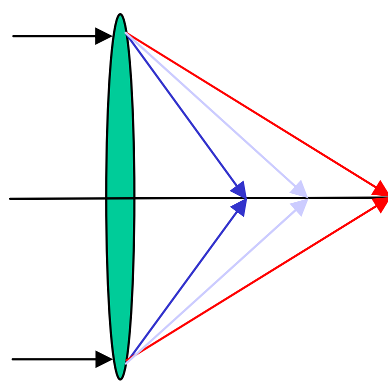
- Pro
  - Easy: Need a short pulse (<100 fs) with initial parabolic/clipped Gaussian transverse distribution, no longitudinal shaping needed
  - High peak current without compression
- Con
  - Not necessarily best for emittance: pancake geometry
  - Image charge effect: cannot put too many charges: 100 pC
  - Short, intense pulse may damage cathodes
  - Fast response precludes many cathode material, stuck with metal
  - Needs high accelerating gradient, stuck to low current rf guns

Ellipsoidal beams: 3D laser shaping

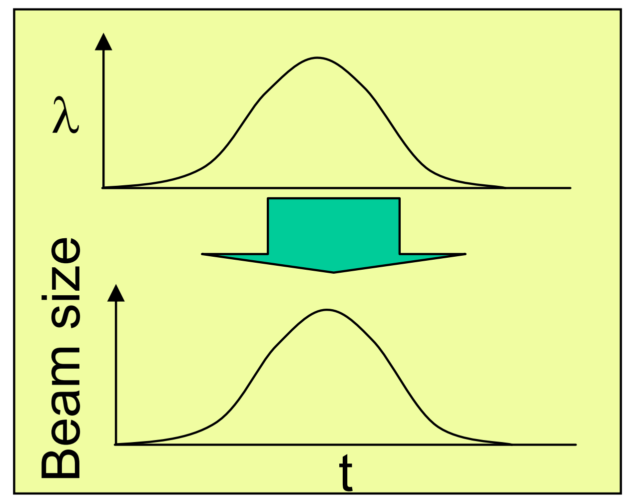
- Refractive index is a function of frequency
- Hence the focal length is function of frequency
- Imposing a cubic phase can result into a parabolic frequency
- Thus at the focus, a time dependent focal size if generate



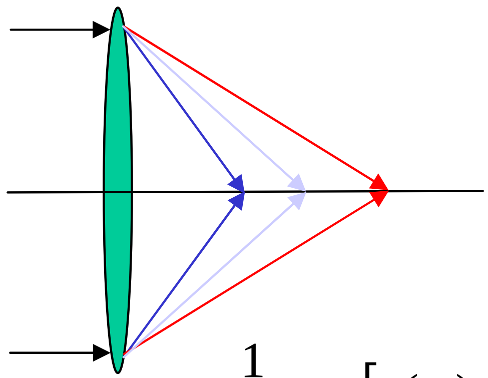
$$n(\omega)$$



$$\frac{1}{f(\omega)} = [n(\omega)-1]\left(\frac{1}{R_1} - \frac{1}{R_1}\right)$$



Ellipsoidal pulse: Gaussian analysis and simulation



$$\frac{1}{f(\omega)} = [n(\omega)-1]\left(\frac{1}{R_1}-\frac{1}{R_1}\right)$$

With ellipsoidal boundaries,

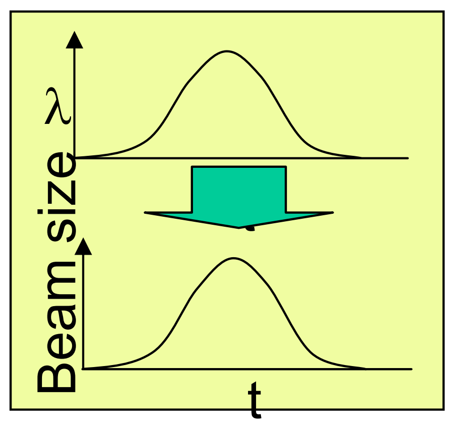
$$\phi(t) = \int[\omega(t)-\omega_0]dt = -\omega_0 t \pm \frac{\Delta\omega}{2}\left[t\left(1-\left(\frac{t}{T}\right)^2\right)^{1/2} + T\sin^{-1}\frac{t}{T}\right]$$

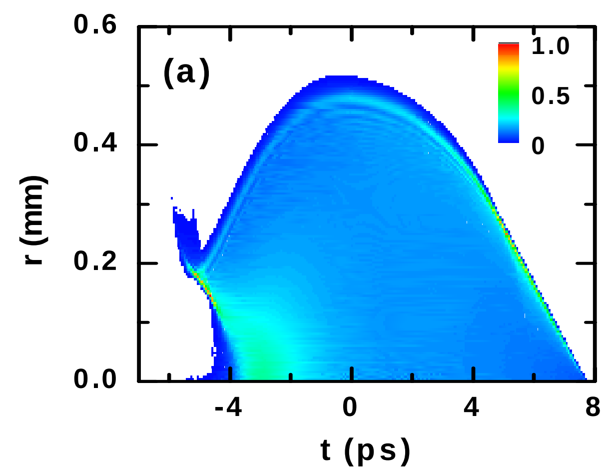
$$A(t) = A_0\left[1-\left(\frac{t}{T}\right)^2\right]^{1/2}$$

$$\delta f = -\frac{f_0}{n_0-1}\chi\delta\omega$$

$$w = w_0\left[1+(\delta f/z_R)^2\right]^{1/2} \propto \delta f \propto \delta\omega$$

$$\delta\omega(t) \propto w(t) = \sqrt{1-(t/T)^2}$$

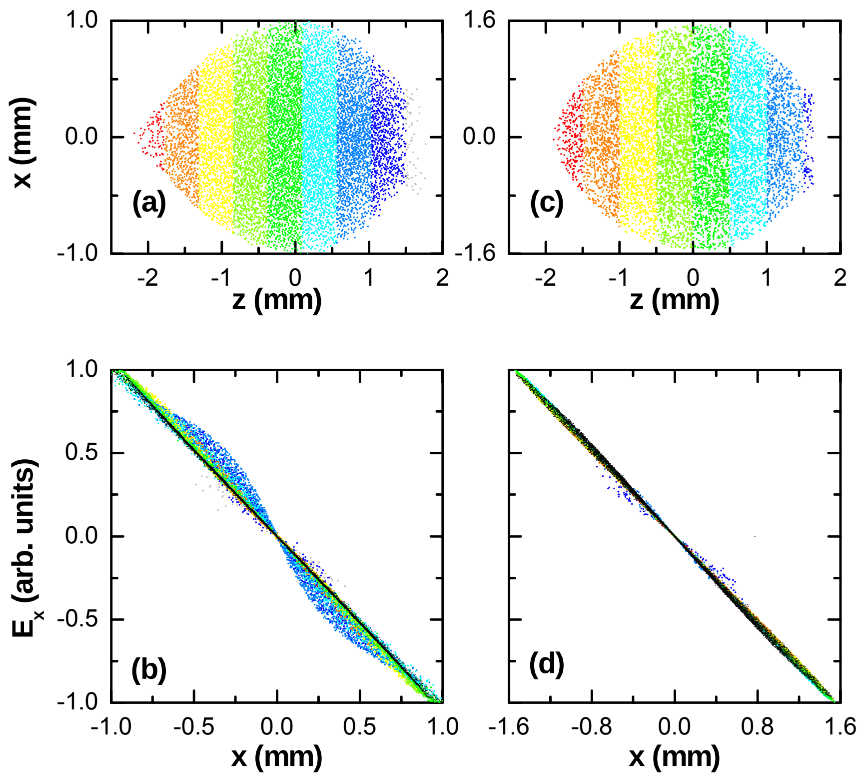




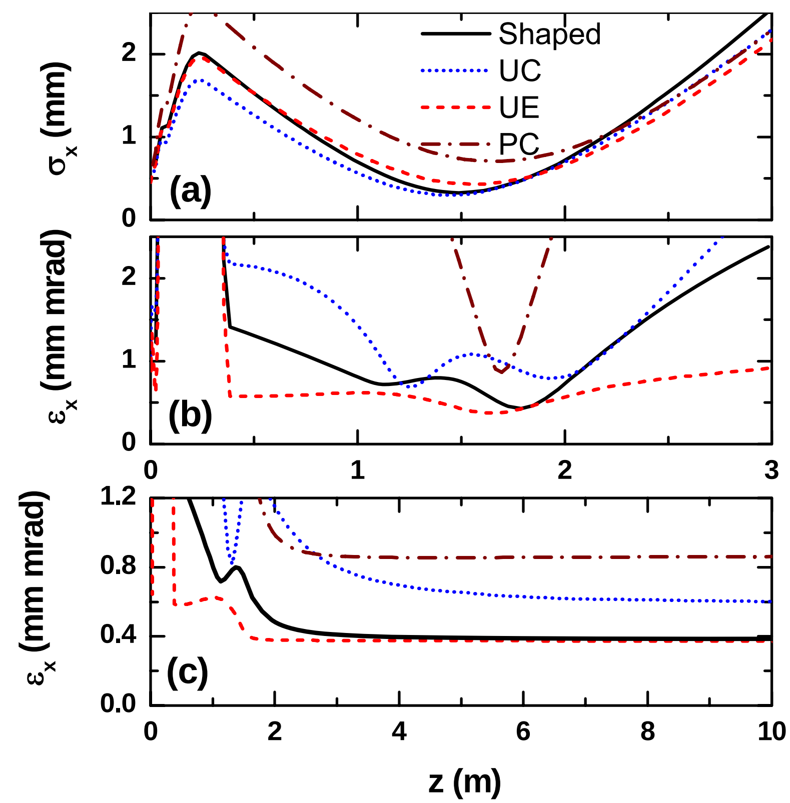
Y. Li and J. Lewellen, PRL 100, 078401(2008)

3D laser pulse shaping: Performance simulation for 1 nC

Beam profile and space charge



Beam size and emittance evolution



Geometry	Shaped	UE	UC	PC
Max radius (mm)	1	1	1	1
Full length (ps)	12	12	10	0.1 rms
ε_x (mm mrad)	0.38 (0.57, 0.65*)	0.36 (0.57)	0.61 (0.79, 0.95*)	0.86 (0.95)

Y. Li and J. Lewellen, Physical Review Letters, in press.

A proof of principle experiment

- 800 nm laser, ZnSe lens as the focal lens
- DAZZLER as the phase modulator
- Achromatic lens for transport

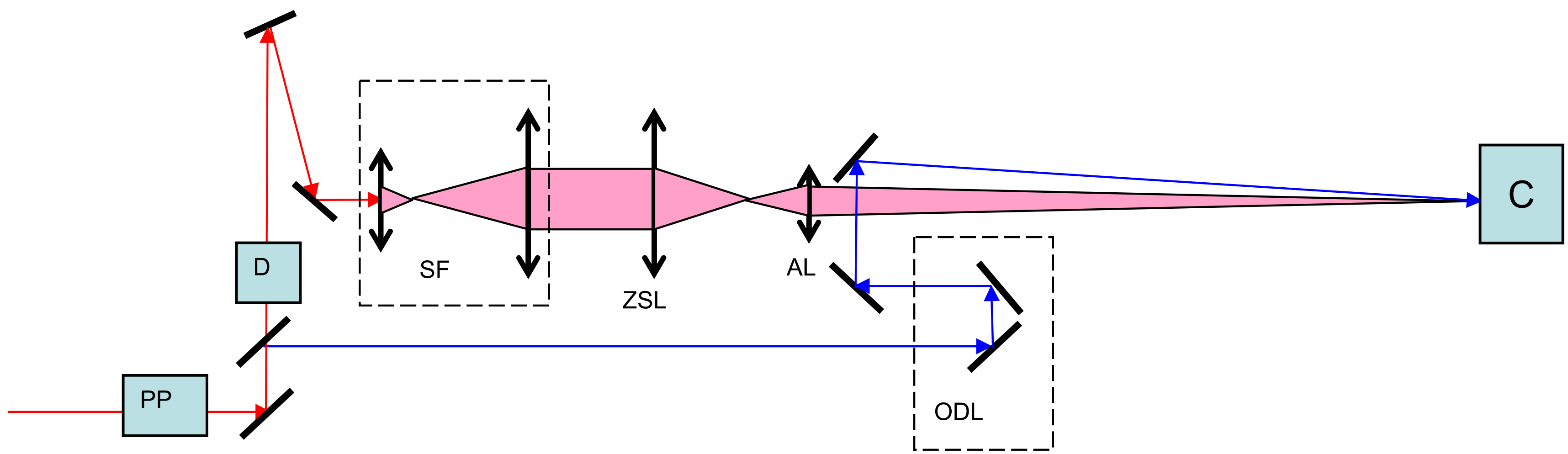
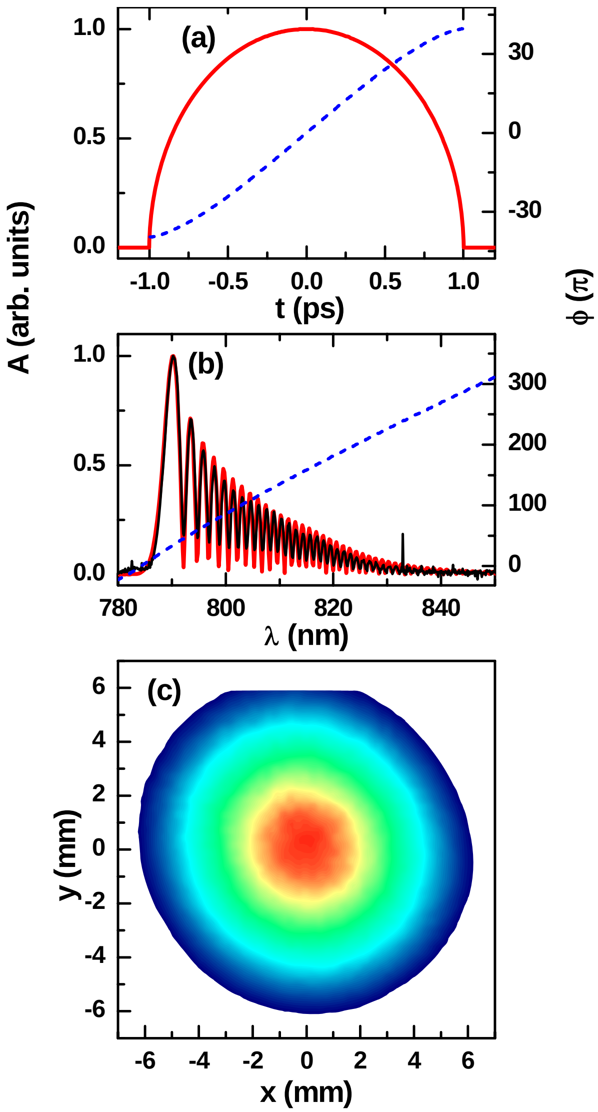
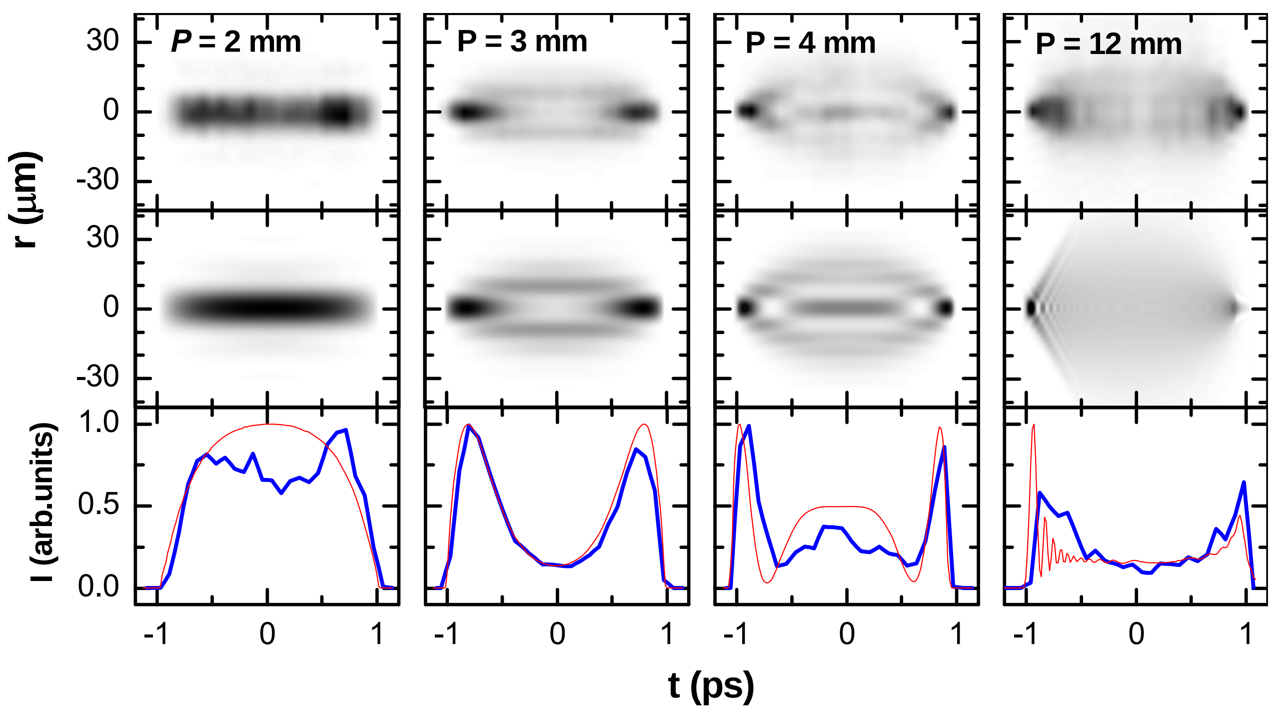


Figure 1. Schematic of the experiment. Keys: PP: pulse picker; D: AOPDF; SF: achromatic spatial filter; ZSL: ZnSe lens; AL: achromatic image relay lens; ODL: optical delay line; C: camera.

Proof of principle results



- Demonstrated validity of the theory and method
- Need to generate the large, flat topped beam fro the ellipsoidal beam
- Frequency conversion



Pulse shaping challenging

- Transverse shaping remains challenging
- Pulse stacking is an active area for research and might provide the solution for the generating flat topped pulse for ERL source in conjunction with a fiber laser
- Preserving shaping during beam transportation
- Adaptive control methods may have problem to cope with the rep rate of new machines such as ERL and ERL based FEL
- True solution for Ellipsoidal beam needs further exploration
- Thermal emittance issue (best measure: 0.55 mm mrad for Mg @ 265 nm, GaAs at 500nm, 1.2 mm mrad for Cu, 265 nm, …)