Invited_Talk_Diaspora_Stiintifica_WE10_Bucharest_Romania, 17 Sept. 2008

The quest to understand and control very short laser light disc – pulses

George Nemeş

- ASTiGMAT, Santa Clara, CA, USA; gnemes@astigmat-us.com

- EE Department, School of Engineering, Santa Clara University, Santa Clara, CA, USA; gnemes98@hotmail.com

ASTiGMAT

OUTLINE

1. INTRODUCTION. BEAMS vs. SHORT LASER DISC – PULSES
2. NEW SPATIAL – TYPE OPTICAL SYSTEMS
3. SPATIAL – TEMPORAL ANALOGY
4. FROM 4x4 SPATIAL MATRICES TO 6x6 or 8x8 SPATIAL – TEMPORAL MATRICES FOR DISC – PULSES
5. PHASE – SPACE SPATIAL – TEMPORAL OPTICS
6. CONCLUSION

1. INTRODUCTION
BEAMS vs. SHORT LASER DISC – PULSES

Goal

- Understanding short laser pulses
- Exploratory approach: Extending concepts from laser beam optics into laser disc – pulses optics

1.1. Regular (stationary) laser beam

1.2. Non – stationary (pulsed) laser beams: beam – pulses

1.3. Extremely short laser pulses: laser disc – pulses

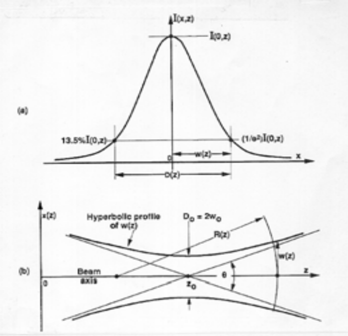
1.1. Regular (stationary) laser beam

Beam concept. Beam = Light distribution that is:

- (Quasi)stationary = time (quasi)invariant = CW or “long” pulse;
  - τ – pulse duration; $\tau \to \infty$ (practically $\tau \geq 1$ ns); propagation ignored
- (Quasi)monochromatic: $\Delta\lambda \ll \lambda_0$
- Extends longitudinally on a length L; $L \in (-l_0, l_0)$, $l_0 \to \infty$;
  - $L = c\tau$; $c = 3 \times 10^8$ m/s;
- Has a waist of diameter D_0; $\lambda_0 \ll D_0 \ll L$
- Can be represented as a paraxial ($\theta \leq (1/\pi)$ rad) distribution of rays

Example: λ_0 = 1064 nm; D_0 = 3 mm; $\tau = (1 - 10)$ ns → L = (300 – 3000) mm;

Beams → Only spatial properties are of interest



ASTiGMAT

1.2. Non – stationary (pulsed) laser beams: beam – pulses

Pulsed – beam (beam - pulse) concept. Beam - pulse = light distribution that is:

- Non-stationary = time dependent = “short” pulse; τ = (10 – 1000) ps

  Propagation properties – important (spatial – temporal coupling)

- Polychromatic: $\Delta\lambda < \lambda_0$

- Longitudinal extent $L \sim (1 - 10)D_0$; $\lambda_0 << D_0 \leq L$

- Ray and divergence concepts still apply (with some care)

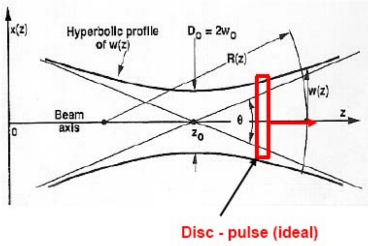
Example: λ_0 = 1064 nm; D_0 = 3 mm; τ = 10 ps → L = 3 mm;

Beam – pulse → Spatial and temporal properties are of interest

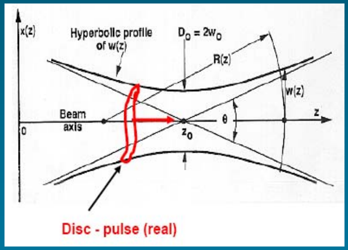
1.3. Extremely short laser pulses: laser disc – pulses

Laser disc - pulse concept:

- Non-stationary = “extremely short” pulse; $\tau = (0.1 – 10000)$ fs
- Propagation properties → strong spatial – temporal coupling (spatial – temporal astigmatism)
- Extremely polychromatic: $\Delta\lambda \sim \lambda_0$
- Longitudinal extent L; $\lambda_0 \leq L << D_0$



Disc - pulse (ideal)



Disc - pulse (real)

Example: $\lambda_0 = 775$ nm; $D_0 = 3$ mm; $\tau = 100$ fs → L = 30 μm → Light disc

Disc – pulse → Spatial and temporal properties are of interest

New theory/analysis is necessary

- Ray and divergence concepts → need reevaluation. Do they apply?
- Lenses and free-spaces (air) → no more close to ideal → new analysis
- Spatial – temporal astigmatism can be very strong → decoupling

Exploratory approach: Look at existing theory and extend it (if you can!)

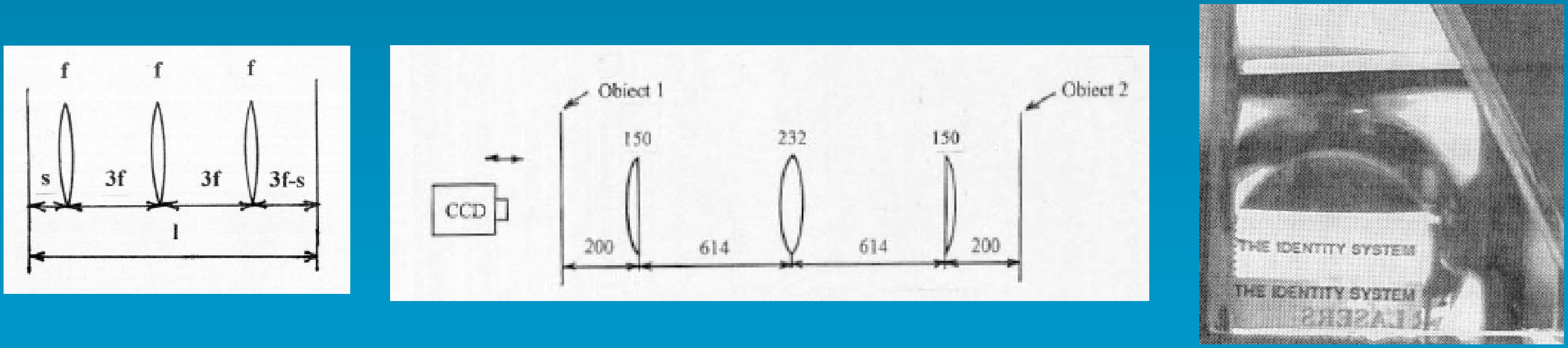
2. NEW SPATIAL – TYPE OPTICAL SYSTEMS

(a) New spatial optical systems with fixed parameters

- Identity $S = I = \{\{1,0\},\{0,1\}\}$
- Pseudo-identity $S = -I = \{\{-1,0\},\{0,-1\}\}$
- Negative space $S = \{\{1,-|d|\},\{0,1\}\}$
- Pseudo-space, pseudo-lens; any physically obtainable ABCD system

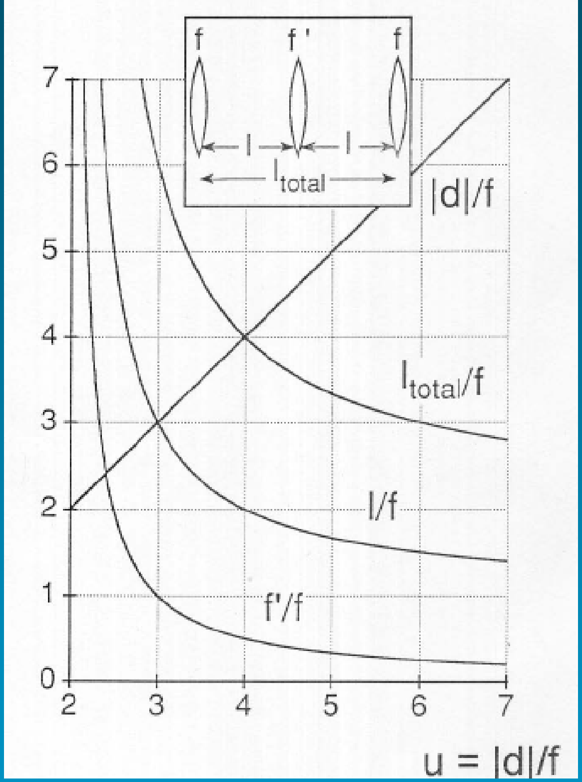
$$S = \{\{A,B\},\{C,D\}\};\ AD - BC = 1$$

Examples



Identity

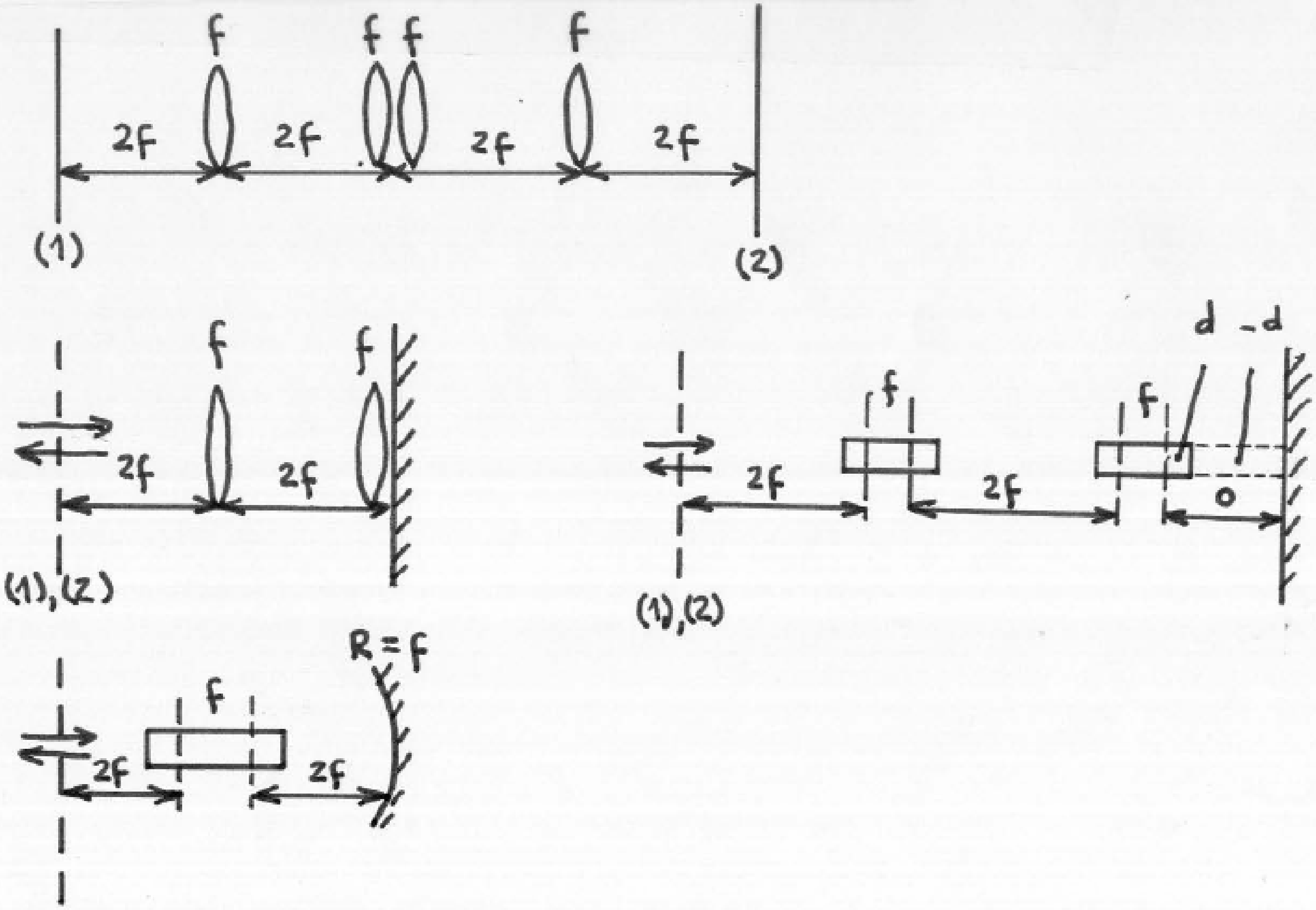
Examples (continued)



Negative space: |d| = f(2f ’ + f)/f ’

Suggested application of identity/pseudo-identity

Thermal lens effect compensation in active media



(b) New spatial optical systems with adjustable parameters (zoom)

- VariSpot® → Round spots, adjustable diameters (20 μm – 30 mm), fixed working distances (25 mm – 5000 mm), τ = 150 fs – CW
- VariFoc™ → Round, square, elongated spots, x,y sizes and working distances independently adjustable
- VariPol™ → Linear polarizer device with adjustable extinction ratio (for VariSpot® to get a constant irradiance and variable spot size)
- Other zoom-type configurations: VariQuad, VariSymm, VariSpace (1D)

All are based on cylindrical optics

ASTiGMAT

VariSpot®

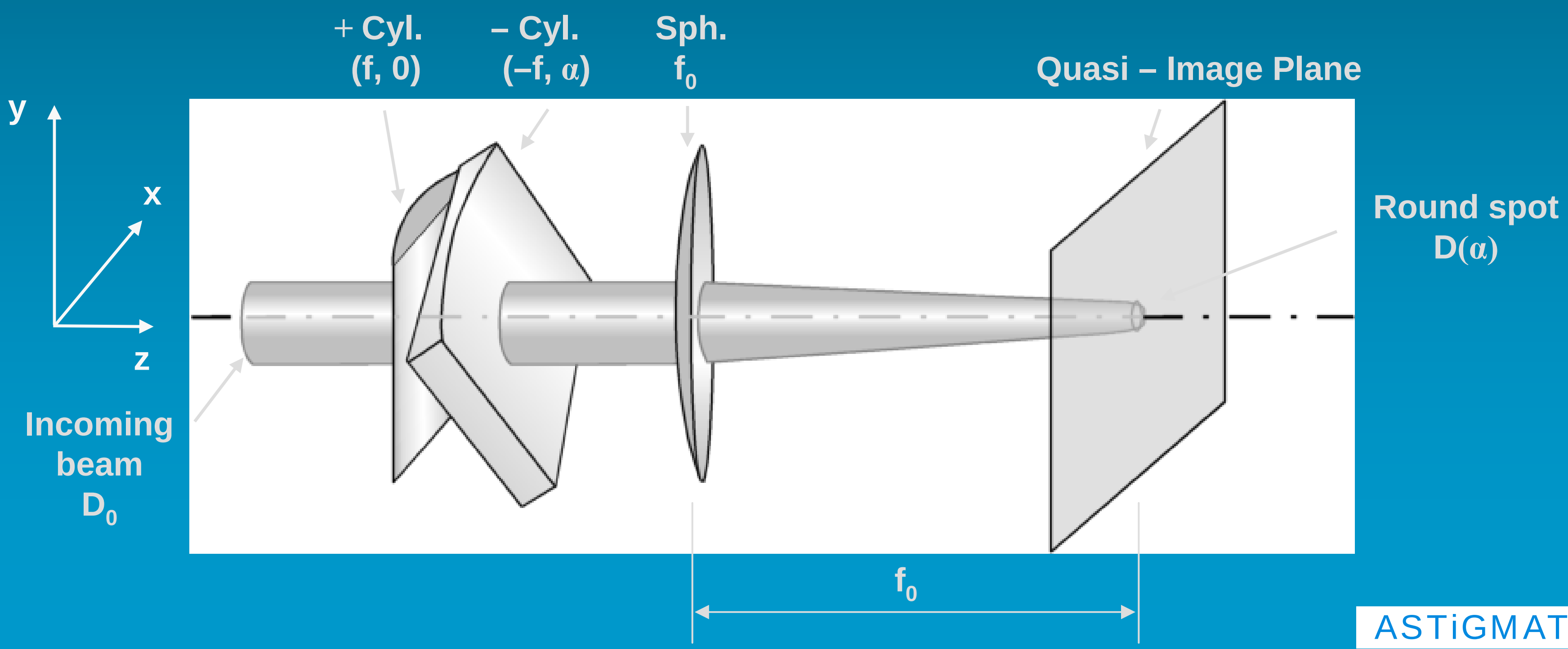
VariSpot® - one possible block diagram: short length

3 - lens system:

+ cyl. lens, cyl. axis vertical (f, 0)

- cyl. lens, cyl. axis rotatable about z (-f, α)

+ sph. lens (f_0) + free-space of length d = f_0 (back-focal plane)



VariSpot® - long length version

VariSpot® FL - 140 - VIS

VariSpot® - short length version (industrial)

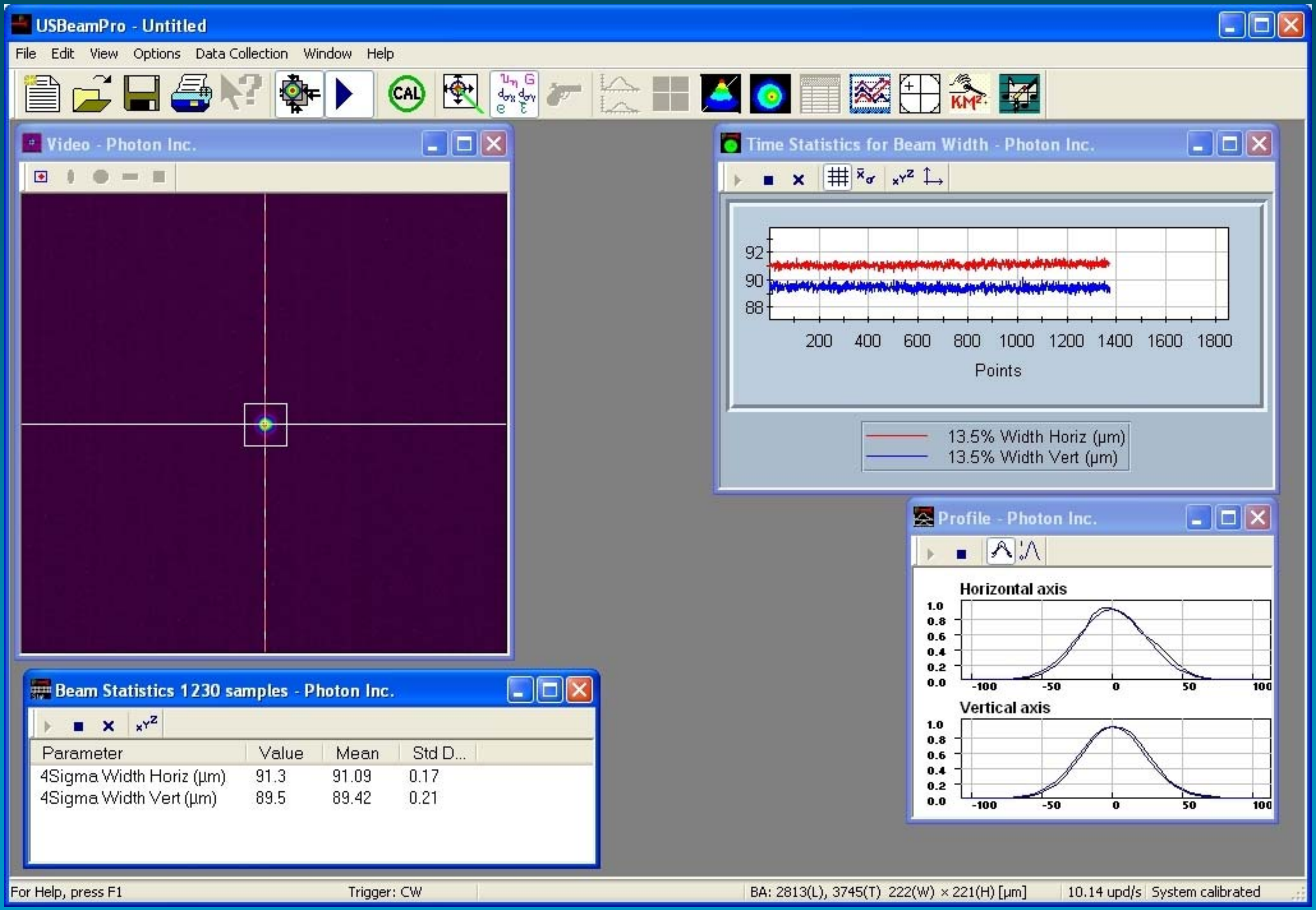
VariSpot® FS - 400 - 1064

VariSpot® FS-500-1-266

ASTIGMAT

VariSpot® FS-500-1-266 in 266 nm, 30 ps laser beam-pulse

Small spot (0.1 mm) of FS-500-1-266 in He-Ne laser



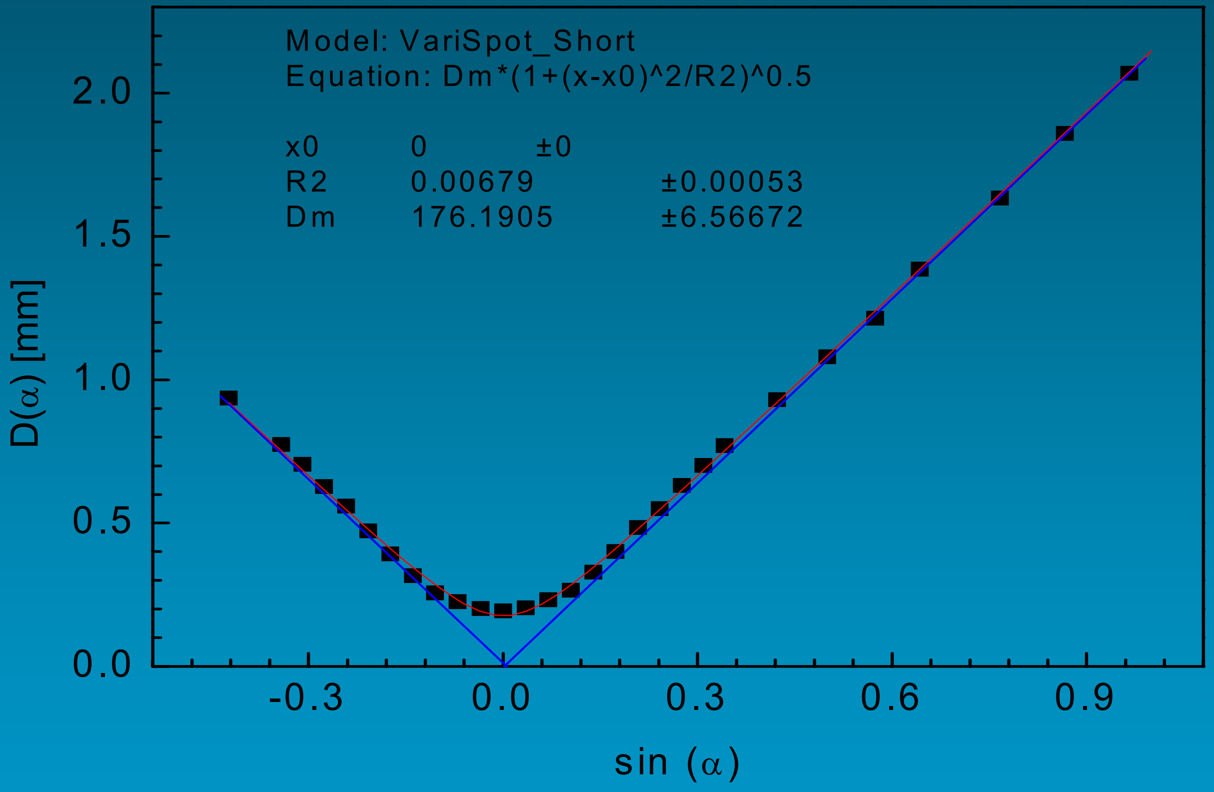
Parameter	Value	Mean	Std D...
4Sigma Width Horiz (µm)	91.3	91.09	0.17
4Sigma Width Vert (µm)	89.5	89.42	0.21

For Help, press F1 | Trigger: CW | BA: 2813(L), 3745(T) 222(W) × 221(H) [µm] | 10.14 upd/s | System calibrated

ASTIGMAT

VariSpot® FS 300 -1-UV-NIR in 180 fs laser

$$D(\alpha) = D_m\ [1 + (\sin(\alpha)-\sin(\alpha_0))^2/(f / z_R)^2]^{1/2}$$

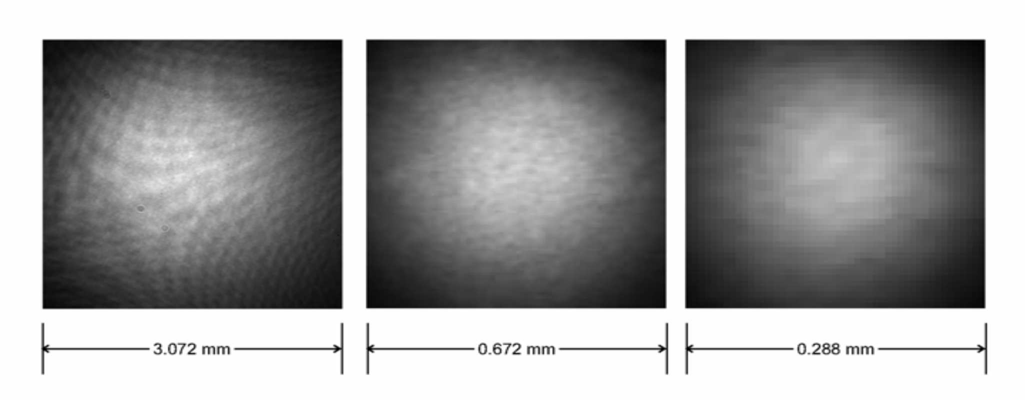


ASTIGMAT

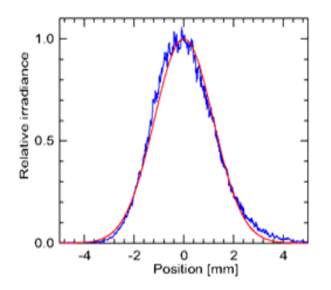
VariSpot® + N_2 laser (337 nm, UV)

ASTIGMAT

VariSpot® image-mode (G. Nemes, J. A. Hoffnagle, “Optical system for variable resizing of round flat-top distributions”, Proc. SPIE **6290** (2006))

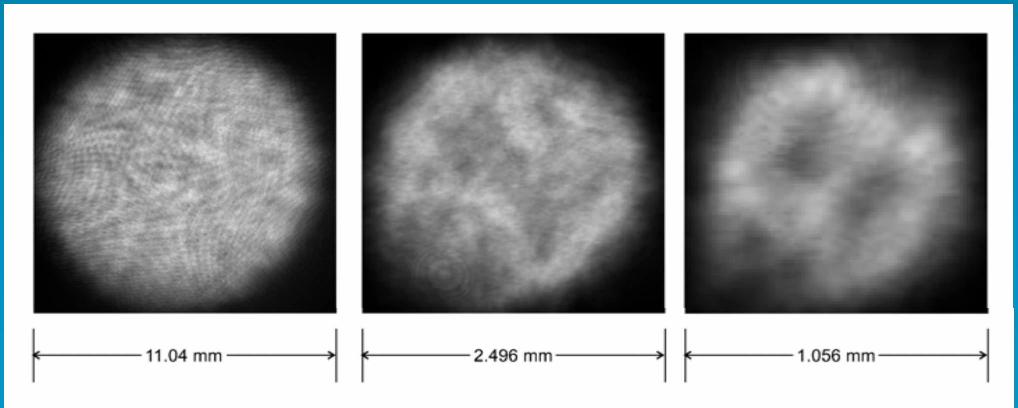


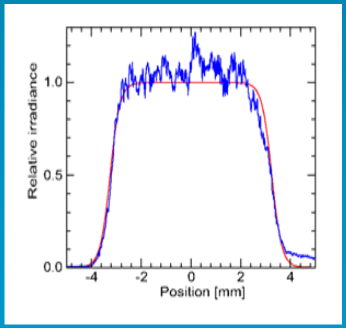
Gaussian beam

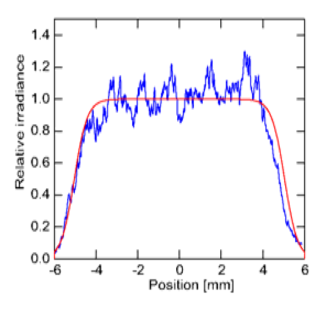


$\alpha = 50^0$ $\alpha = 10^0$ $\alpha = 4^0$

Fermi-Dirac (flat-top) beam







Input beam

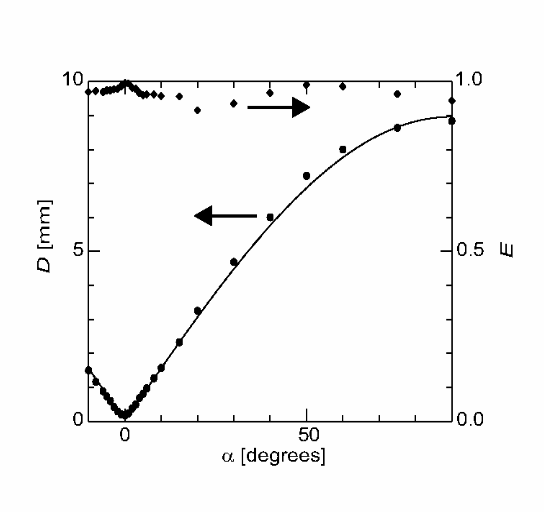
Output beam $\alpha = 50^0$

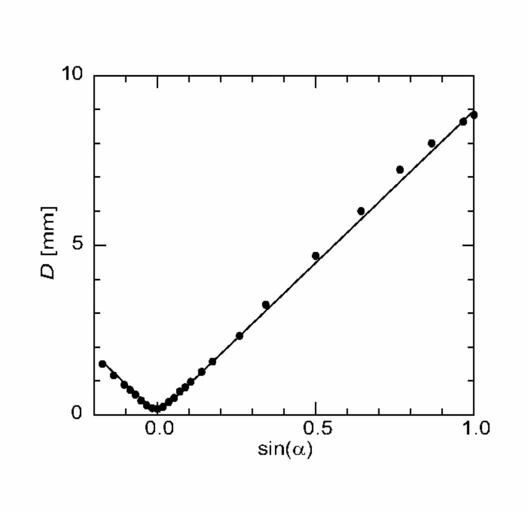
ASTIGMAT

VariSpot® - image-mode: Gaussian beam

Image-mode → $D(\alpha) \approx D_0(f_0/f)\sin(\alpha) = D_M\sin(\alpha)$

Gaussian beam





$D(\alpha)$ vs. α

$E = d_{min}/d_{max}$ vs. α

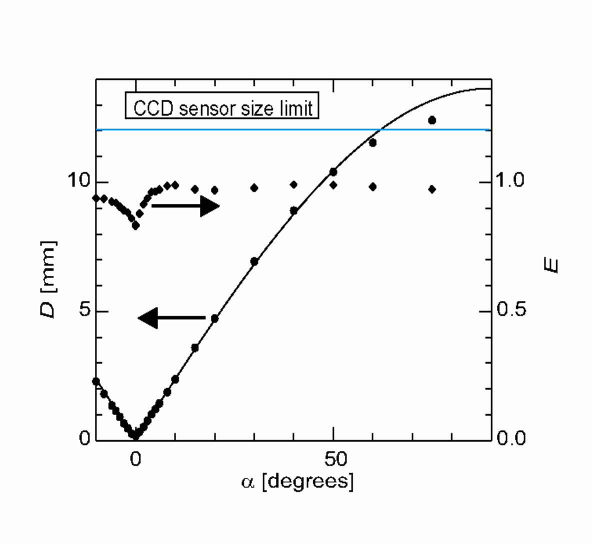
$D(\alpha)$ vs. $\sin(\alpha)$

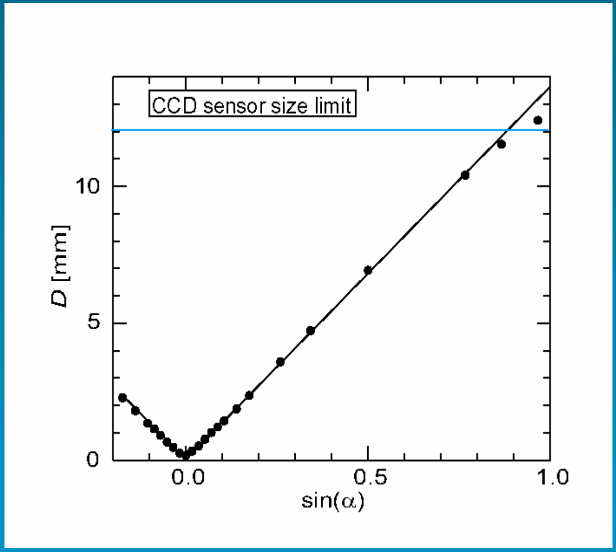
ASTIGMAT

VariSpot® - image-mode: Flat-top (Fermi-Dirac) beam

Image-mode → $D(\alpha) \approx D_0(f_0/f)\sin(\alpha) = D_M\sin(\alpha)$

Flat-top (Fermi-Dirac) beam





$D(\alpha)$ vs. α

$D(\alpha)$ vs. $\sin(\alpha)$

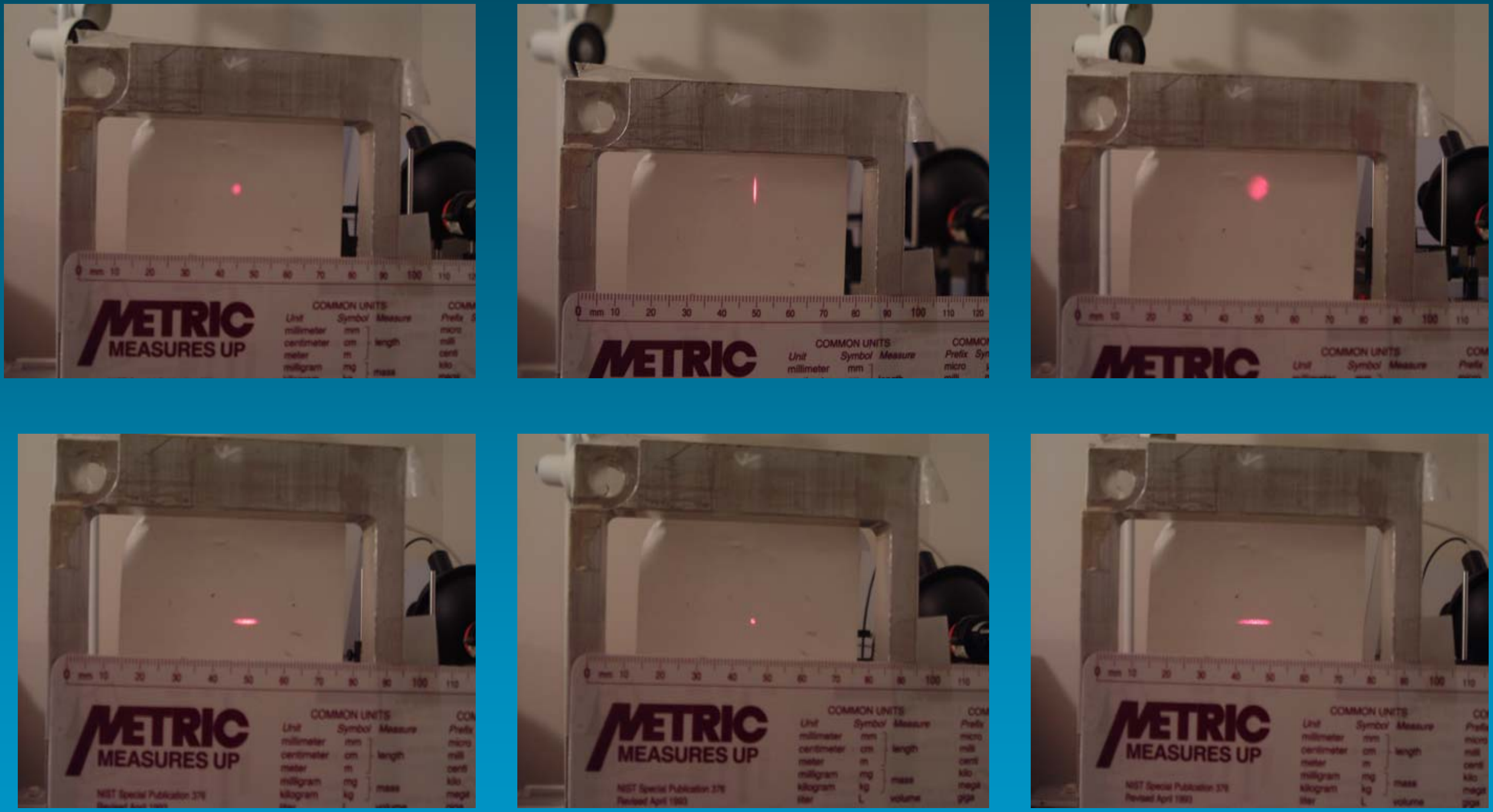
$E = d_{min}/d_{max}$ vs. α

ASTIGMAT

VariFoc^{TM} – demo unit

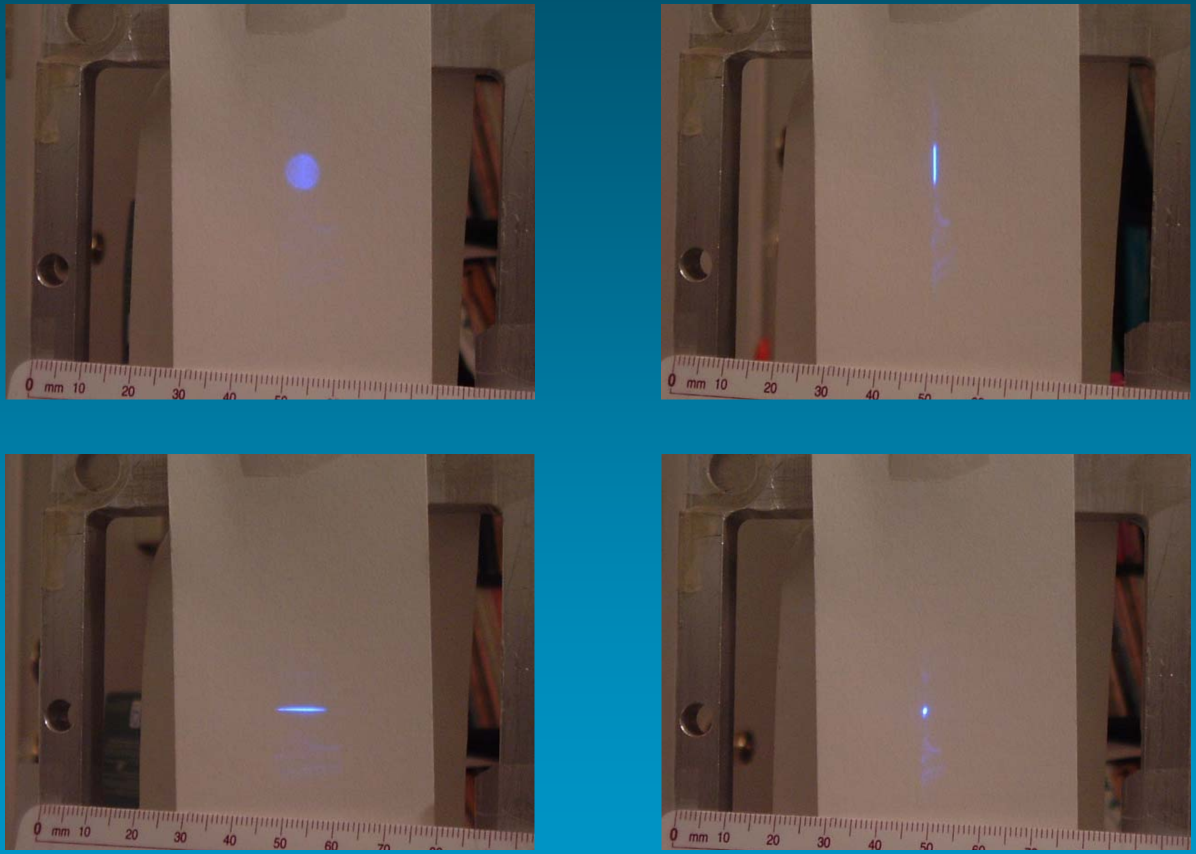
ASTIGMAT

VariFoc$^{\text{TM}}$ + collimated diode laser (670 nm)



ASTIGMAT

VariFoc^{TM} + N_2 laser



ASTIGMAT

3. SPATIAL – TEMPORAL ANALOGY

Known spatial – temporal analogy (Akhmanov; Froehly, Martinez; Dijaili; Kostenbauder; Kolner; Nazarathy; Yariv; Godil; Trebino; and others)

Spatial lens → temporal lens (quadratic temporal phase modulator)
Spatial free-space (spatial diffraction) → temporal dispersion (in fibers)

k_x (spatial frequency) → ω (temporal frequency)
x (transverse coordinate) → $t - z/v_g$ (time, moving reference frame)
$1/k$ (wave vector reciprocal) → $-\beta''$ (GVD coefficient)

2x2 spatial matrix optics → 2x2 temporal matrix optics
4x4 (2 spatial + 2 temporal) matrix optics
6x6 (4 spatial + 2 temporal, decoupled from spatial) matrix optics

Suggestion: Finding the temporal matrices analog to the new spatial 2x2 matrices

4. FROM 4x4 SPATIAL MATRICES TO 6x6 or 8x8 SPATIAL – TEMPORAL MATRICES FOR DISC – PULSES

Existing results in 4x4 spatial matrix optics (Nemes, Siegman, Serna)

- Classification and identification of any ABCD matrix representing an optical system (stigmatic - ST; aligned simple astigmatic - ASA; rotated simple astigmatic - RSA; general astigmatic - GA)
- General and constructive synthesis procedure for any 4x4 ABCD-type spatial optical system physically obtainable
- Geometrical classification and identification of any 4x4 **P** matrix representing a physical beam (ST; ASA; RSA; GA, including degeneracies)
- Obtaining the general beam invariants at transformation through spatial optical systems in 4x4 matrix treatment: intrinsic astigmatism, a; maximum intrinsic astigmatism, a_M; $0 \leq a \leq a_M$
- General, constructive procedure to decouple any beam (GA → ASA or ST)

Suggestion:

- Existing (complete) 4x4 matrix theory for spatial optical systems and beams → 6x6 (?) or 8x8 (perhaps) matrix theory for spatial – temporal optical systems and disc – pulses (including spatial – temporal invariants, general astigmatism and decoupling)

- Looks appealing but not easy!

5. PHASE – SPACE SPATIAL – TEMPORAL OPTICS

Existing results (Liouville; Boltzmann; Hamilton; Wigner; Ville; Lapostolle; Lawson; E. Wolf; Bastiaans; Lohmann; Brenner; K.B. Wolf; G. & M. Nemes; Ozaktas; Dragoman; and others)

Types of phase-spaces (PS) used in optics and signal theory:

2-D, spatial-type → (x, θ); (x, k_x)

2-D, temporal type → (t, ω)

4-D, spatial-type → $(x, y, \theta_x, \theta_y)$; (x, y, k_x, k_y)

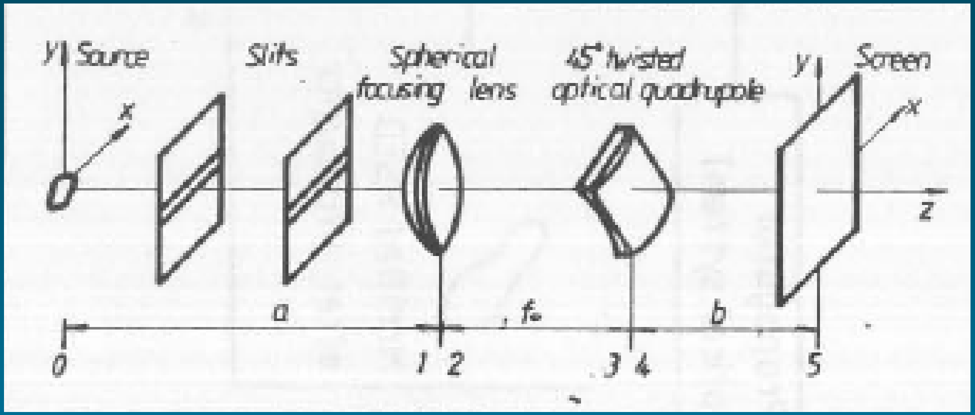
4-D, spatial 2-D + temporal 2-D → (x, t, θ, ω)

6-D, spatial 4-D + temporal 2-D → $(x, y, t, \theta_x, \theta_y, \omega)$

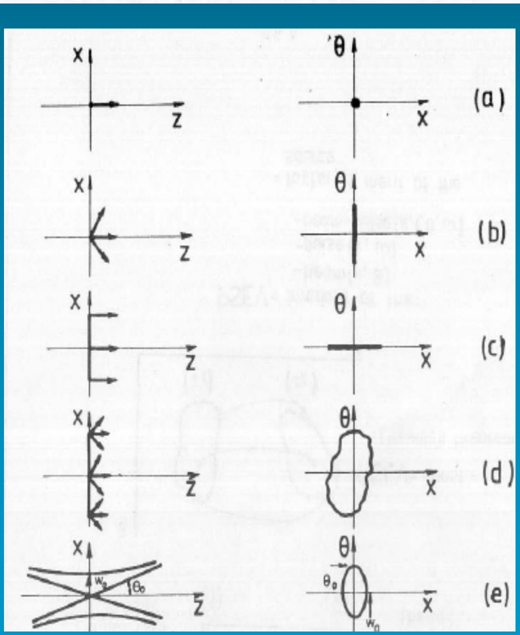
Note: The optical systems act as phase-space transformers on appropriate rays or ray-pulses (corresponding to the PS dimension)

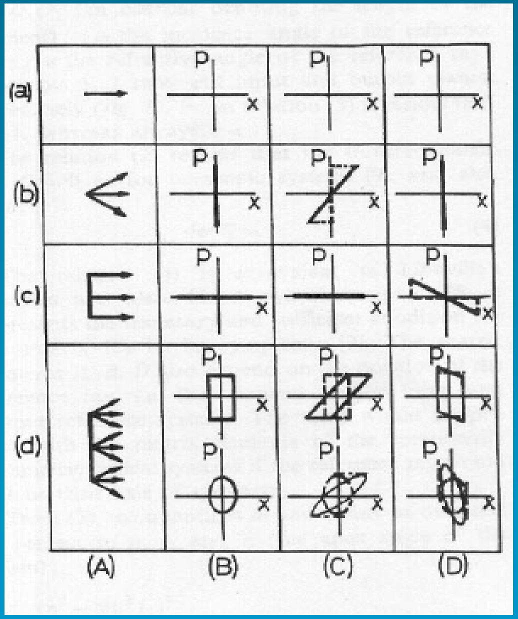
Liouville – Boltzmann theorem: lossless and gainless systems preserve the PS measure (“volume”)

Original experiments in Spatial 2-D Phase-Space (PS)



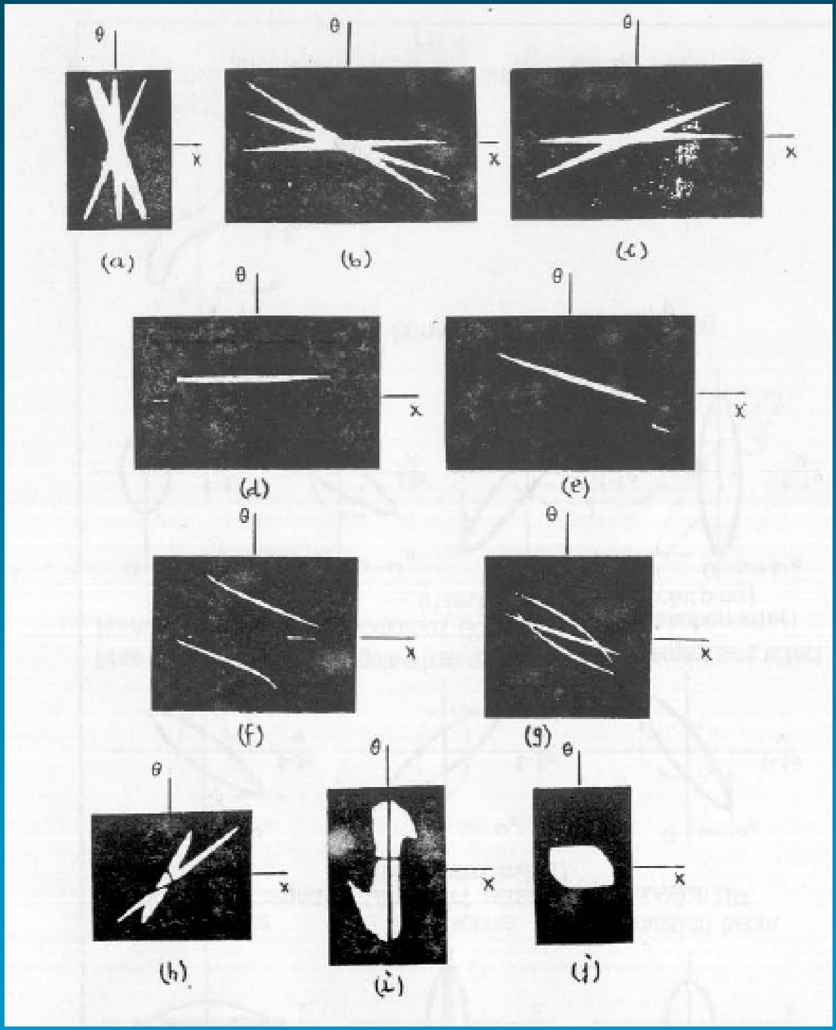
Experimental set-up





Ideal and real light sources and their transformation through free-space and lens, in PS

Original experiments in Spatial 2-D Phase-Space



- (a) Point source, free-space
- (b) Plane wave, convergent lens
- (c) Plane wave, divergent lens
- (d) Prism effect on plane wave
- (e) Prism effect on convergent beam
- (f) Spherical aberrations, (+) lens
- (g) Comma-type aberrations, (+) lens
- (h) Liouville-Boltzmann theorem, free-space and large “PS volume” source
- (i) Spherical aberrations of (+) lens, large “PS volume” source
- (j) PS filtering: PS device acceptance boundary (in very large “PS volume” source)

- Suggestions:

Extending the phase-space approach to treat laser disc – pulses, by using spatial – temporal analogy

- Needs:

  New theory
  New experiments

6. CONCLUSION

- Short laser pulses need a reconsideration of classical geometrical and physical optics concepts: ray, optical system, beam → disc – pulse concept

- The new, original results of treating spatial optical systems and laser beams using 2x2 and 4x4 spatial matrices might be extended to treat laser disc – pulses using 8x8 matrices

- Simple concepts and experiments in 2-D spatial phase-space might be extended in higher – dimensional phase-spaces associated to disc – pulses

- The expected results might justify the theoretical and experimental efforts

- Newcomers in the field are welcome!