ISOTEST – A CHALLENGING PROJECT USING HIGH POWER LASERS

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OUTLINE

1. Introduction. ISOTEST Project
2. Pre ISO History
3. ISOTEST objectives
4. Principles and schematics
5. VariSpot® and new preliminary results
6. Conclusion

1. Introduction. ISOTEST Project

ISOTEST = Facility for beam diagnosis and characterization of optical components using high power laser beams and ISO standards

Key words:

- ISO = International Organization for Standardization (Geneva, Switzerland)
- High power laser beams:
  - 10 Hz repetitively pulsed Nd:YAG laser, 6 ns pulses, 0.5 MW – 100 MW peak power@1064 nm, 7 W average power
  - 2 kHz repetitively pulsed Ti:sapphire laser, 200 fs pulses, 10 MW – 2 GW peak power@775 nm, 1.2 W average power
- Beam diagnosis = Measuring the energetic and temporal (ISO 11554/2000), as well as the spatial (ISO 11146-1,2,3/2004,2005) beam characteristics
- Characterization of optical components = Laser-induced damage threshold (LIDT), 1-on-1 and S-on-1 procedures (ISO 11254-1,2/2000,2001); assurance (certification) of laser power/energy handling capabilities (ISO 11254-3/2006)

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Sponsors and Team

Sponsors

UNIUNEA EUROPEANĂ

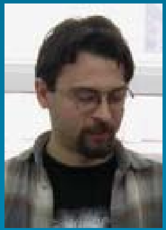
GUVERNUL ROMÂNIEI

Instrumente Structurale 2007 - 2013

NASR - National Authority for Scientific Research (ANCS-POSCCE)

Current team

(+ 2 new members to join)



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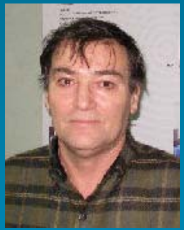

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(aka Maxwell's Demon)

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Technical Manager

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2. Pre ISO History

Annual symposia on laser damage: NBS/NIST, Boulder, CO, since 1969

Round-robin tests: 1976, 1982 (published 1984)

Need for standards

Knowledge of laser-induced damage in optical materials cannot advance until definitions, testing procedures, and analytical methods are standardized. Eight laboratories in Europe and the U.S.A. participated in laser-induced damage testing; the papers in the 1 Nov. 1984 issue of *Applied Optics* discuss their findings.

Table III. Compilation of Laser-Induced Damage Threshold Fluences (J cm^{-2}) Obtained in the Round-Robin Test

Coatings facility	RS		TS		LT		DN	
	$F_{min(D)}$	$F_{max(ND)}$	$F_{min(D)}$	$F_{max(ND)}$	$F_{min(D)}$	$F_{max(ND)}$	$F_{min(D)}$	$F_{max(ND)}$
Berne	0.40	0.30	0.40	0.40	1.20	0.61	0.20	0.30
	0.40	0.30	0.40	0.30	0.41	0.19	0.30	0.30
	0.40	0.30	0.30	0.40	0.53	0.23	0.30	0.20
Avg	0.40	0.30	0.37	0.37	0.71	0.34	0.27	0.27
LLNL	9.5	7.0	11.2	11.2	5.7	3.4	5.1	3.4
	11.2	9.5	11.2	9.5	5.7	4.7	5.1	3.4
	13.1	10.7	10.4	8.2	1.8	1.4	3.5	2.3
Avg	11.3	9.1	10.9	9.6	4.4	3.2	4.6	3.0
AFWL	28.5	53.6	12.0	37.0	1.5	4.3	3.4	5.8
Avg	28.5	53.6	12.0	37.0	1.5	4.3	3.4	5.8
K'lautern	71.5	82.0	81.4	90.8	15.4	19.8	19.8	23.7
	82.5	93.0	63.3	79.2	21.5	33.5	19.8	22.0
	88.0	96.3	69.9	89.6	24.2	34.7	14.3	18.2
Avg	80.7	90.4	71.5	86.5	20.4	29.3	18.0	21.3
Hanover	53.5	65.3	36.4	42.4	8.2	10.0	4.4	7.3
	53.2	67.8	38.4	42.7	6.2	9.5	3.8	6.4
	58.0	62.0	29.4	33.6	9.5	10.6	5.8	9.4
Avg	54.9	65.0	34.7	39.6	8.6	10.0	4.7	7.7
NWC	91.7	255.1	117.2	146.0	56.7	131.9	44.5	125.0
	153.3	253.1	112.2	161.3	23.5	52.4	50.6	153.6
	178.8	257.8	116.4	89.9	15.2	163.7	82.3	151.6
Avg	141.3	255.3	115.3	132.4	31.8	116.0	59.1	143.4
GEC[a]	14.4	86.2	10.7	86.3	17.7	90.0	9.8	53.8
	15.1	86.2	11.7	86.3	13.8	90.0	14.3	86.2
	11.1	86.2	11.1	86.3	13.8	90.0	11.4	53.8
Avg	13.5	86.2	11.1	86.3	15.1	90.0	11.8	64.6
Siemens	2.6	8.0	16.4	28.5	0.8	3.0	10.6	18.0
	2.6	7.8	26.6	37.5	1.0	2.6	21.6	37.5
	2.8	5.2	21.1	37.5	10.0	11.0	13.0	37.5
Avg	2.7	7.0	21.4	34.5	3.9	5.5	15.1	31.0

[a] $F_{min(D)}$ data for 15-nsec pulses and $F_{max(ND)}$ data for 25-nsec pulses.

1 November 1984 / Vol. 23, No. 21 / APPLIED OPTICS 3747

After 1982 round-robin test:

Discrepancy between different labs: almost 3 orders of magnitudes, for identical samples and wavelengths

Example of variability of experimental conditions for LIDT

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Table I. Summary of Experimental Conditions Used at Various Laser Laboratories

Laboratory	K'lautern	Hannover	LLNL	AFWL	Berne	Siemens	GEC	NWC
Sample set No.	..0,..1	..2,..3	..4	..5	..6	..7	..8	..9
Cleaning	blow dry air	blow dry N_2	Ethanol wipe	Ethanol wipe	blow dry N_2	blow dry N_2	blow dry N_2	blow dry N_2
Sample location	in F	in F	near F	in F	50 before F	in F	in F	in F
Focal length [mm]	150	50	4000 – 6000	1200	1000	50	100 and 300	165
Mode of operation $TEM_{m,n}$	0.0	∞,∞	0.0	0.0	0.0	multi	0.0	0.0
Polarization	circ.	lin.	lin.	lin.	lin.	lin.	lin.	lin.
Spot size d[μm], FW at $1/e^2$ intensity	470	210	4000	360	1100	340	150	40
Pulse length τ [ns], FWHM	10	12	1	5.9	$35 \cdot 10^{-3}$	20	15 and 25	13
Number of pulses per sample	20	20 – 40	⩾ 4	100	10	⩾ 10.000	500	30
Number of pulses per site	1	1	1	1	1	⩾ 10.000	1	1
Site selection	presel.	presel.	random	random circ.	presel.	random	random + presel.	random
Local separation [mm]	1 – 3	~2	5	~1	3	3 – 4	0.2	1
Assessement of damage	He-Ne-scattering	He-Ne-scattering, Nomarski micr.	visual micr. induced light	Nomarski micr.	He-Ne-scattering visual obser.	visual micr.	visual micr.	He-Ne-scattering
References	10	11,12	13,14	2,9	15	16	17	18

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3. ISOTEST objectives

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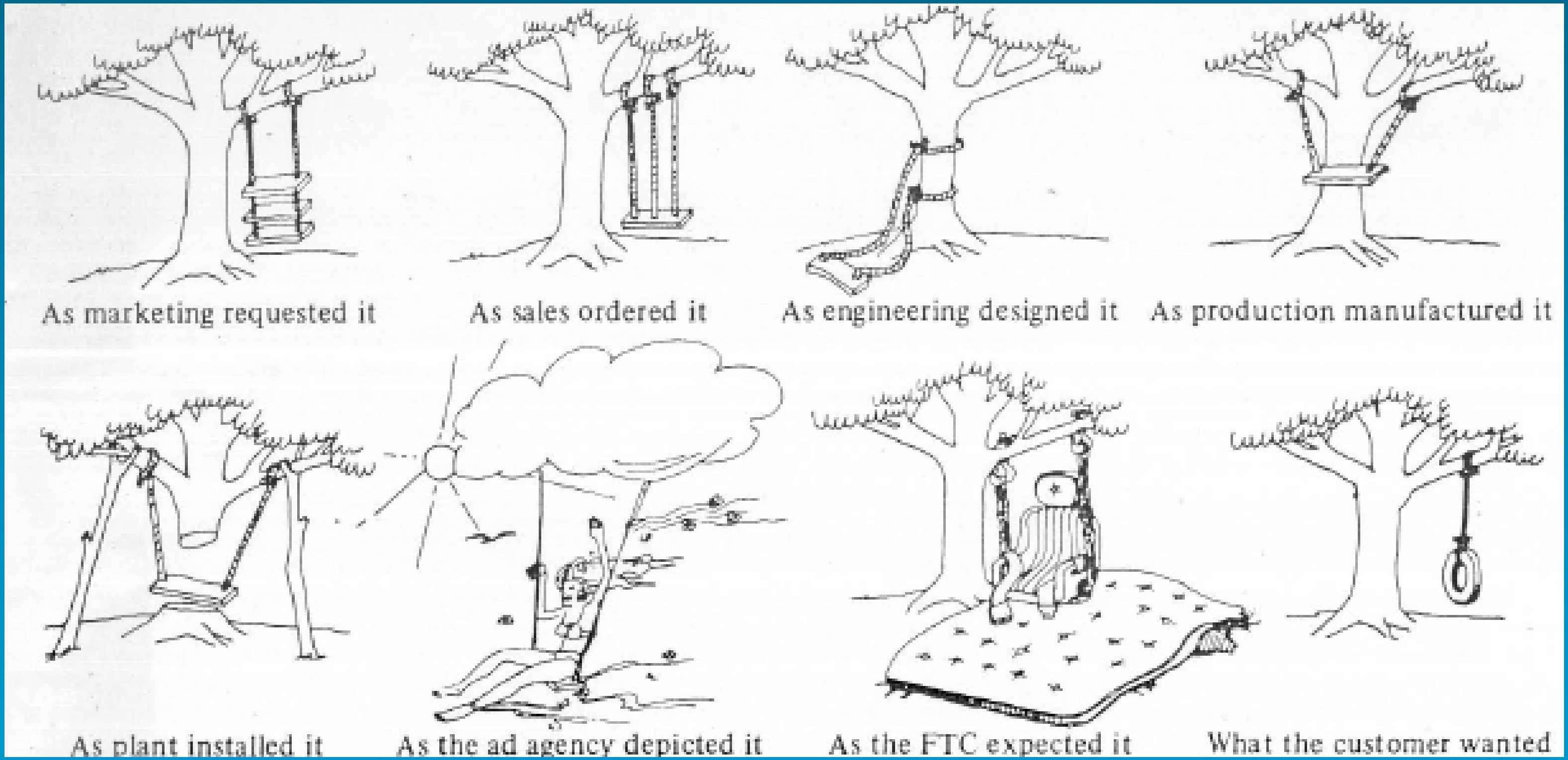
The importance of well-defined objectives and of team work

(avoiding what happened with the Swing Project, below)



Objectives

O1. Developing a method and a device for diagnosis of the main characteristics of high power laser beams according to the ISO 11146-1,2,3 and ISO 11554 standards

O2. Developing an automated test station (ISOTEST) for beam diagnosis and for the characterization of optical components / materials subjected to high power laser beams according to ISO standards

O3. Developing procedures for laser beams diagnosis and for test, measurements, and characterization of optical components and materials in high power laser beam, according to ISO standards

O4. Accreditation of the SSLL from the Laser Department of NILPRP by the Accreditation Association of Romania (RENAR) to perform tests / measurements and ISO certifications by using the ISOTEST facility. Dissemination of the results and of the opportunities offered by the ISOTEST facility

Parameters of interest (excerpts)

Energetic characteristics:

- Average power (P_{ave}) – W
- Energy per pulse (E_p) – J

Temporal characteristics:

- Pulse repetition frequency (f_{rep}) – Hz
- Pulse shape
- Pulse duration (τ_{FWHM}) – fs, ns

Spatial characteristics (ST and ASA beams):

- Beam profile (transverse – different, specific locations, and longitudinal)
- Spot sizes, waist sizes (D, D_x, D_y, D_0, D_{0x}, D_{0y}) – mm
- Waists locations (z_0, z_{0x}, z_{0y}) – mm
- Rayleigh ranges (z_R, z_{Rx}, z_{Ry}) – mm
- Divergences (θ, θ_x, θ_y) – rad
- Beam propagation ratios (Siegman, ISO 11146-1) (M^2, $M^2{}_x$, $M^2{}_y$)
- Effective beam propagation ratio (Nemes + Siegman, ISO 11146-2,3) ($M_{eff}{}^4$)
- Intrinsic astigmatism (Nemes + Siegman, ISO 11146-2,3) (a)

Parameters of interest (excerpts)

Damage characteristics:

- Effective spot area on target (A_{eff}) – cm^2
- Effective pulse duration (t_{eff}) – fs, ns
- Pulse peak power (P_p) – W
- Pulse energy density (fluence) on target (H) – J/cm^2
- Pulse power density (irradiance, not intensity) on target (E) – W/cm^2
- Number of pulses irradiating a site (target) – N_p
- Minimum number of pulses damaging a site (target) – N_{min}

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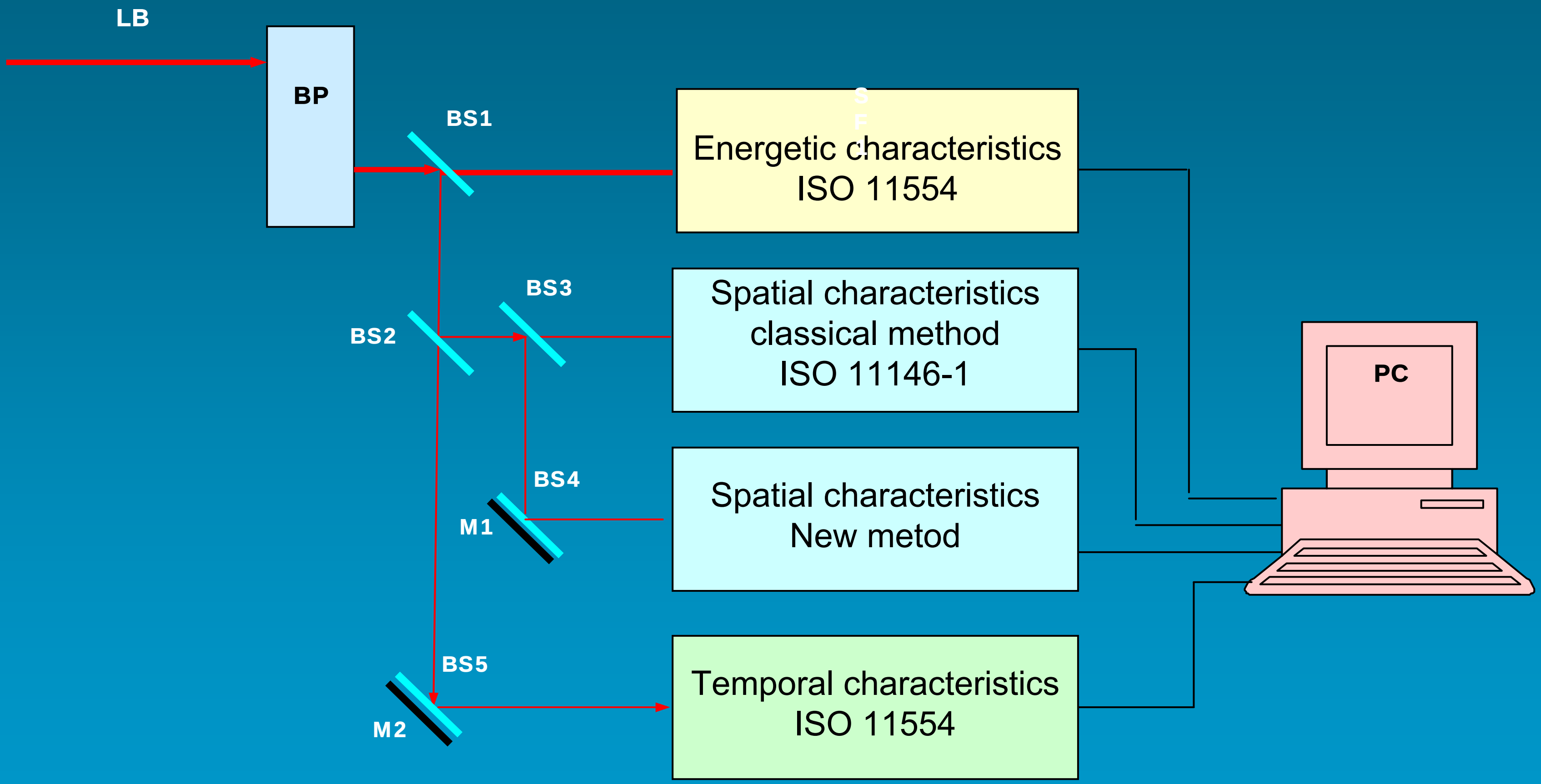
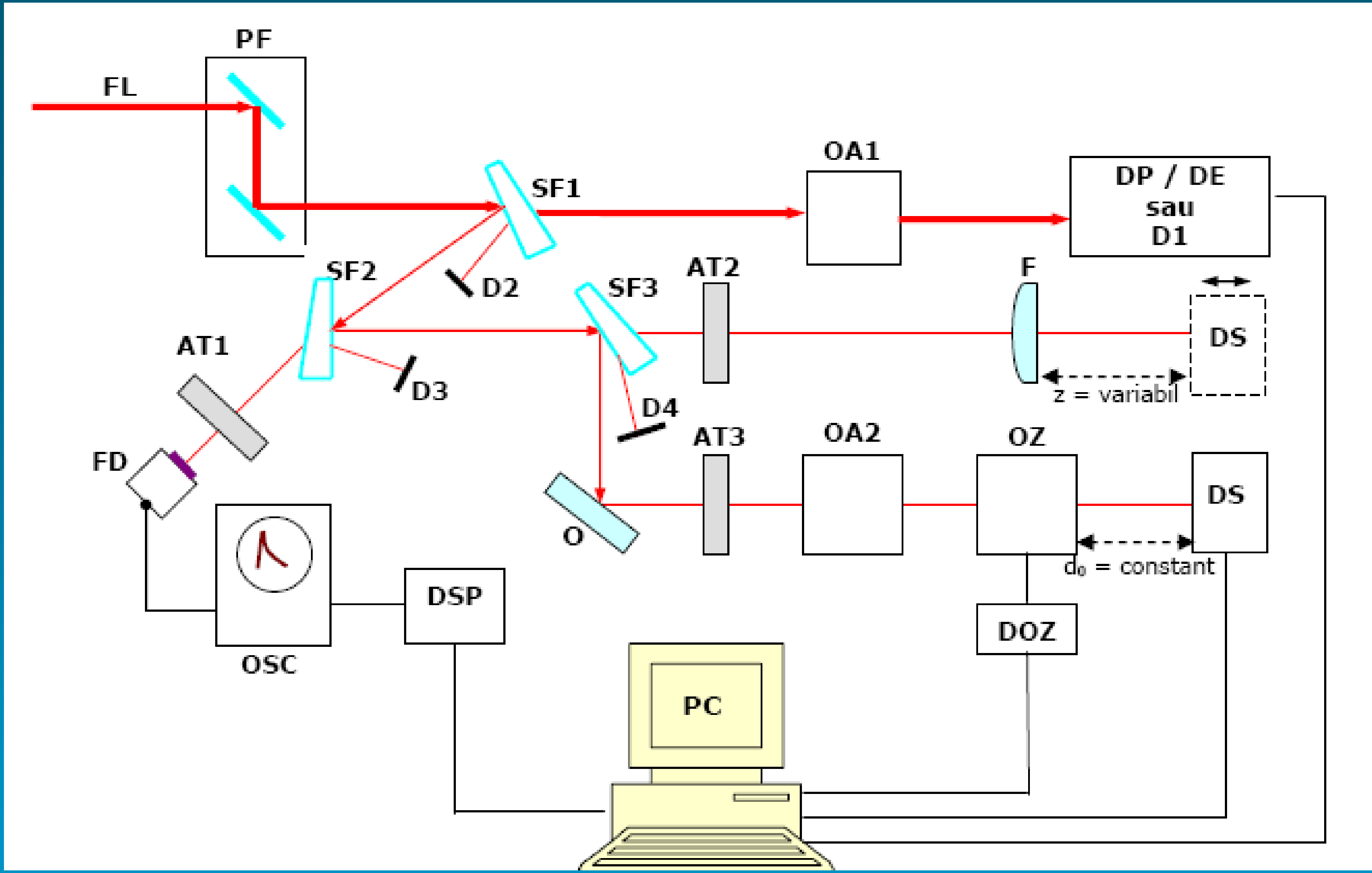
4. Principles and schematics

Beam diagnosis



Principle schematic for beam diagnosis



Block diagram for beam diagnosis

(temporal diagnosis schematic applies only to ns pulses)

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Damage characteristics

Types of tests:

- Damage 1-on-1
- Damage S-on-1
- Assurance of non-damage

ISO recommendations:

- Large spot on target (0.2 mm – 0.8 mm)
- Irradiating 20 sites with the same fluence/irradiance for statistics
- Using 10 – 12 steps of different fluences/irradiances between 100% damage probability and 0% damage probability

→ For S-on-1 procedure, S = 1000, f_{rep} = 10 Hz, 4 ns – 6 ns pulses

→ ≈ 5 h to measure one sample

→ For S-on-1 procedure, S = 200000, f_{rep} = 2 kHz, 200 fs pulses

→ ≈ 5 h to measure one sample

→ Need for automated test

Example of S-on-1 test result (ISO 11254-2)

EXAMPLE

Consider the data collected for a typical coating given in Figure C.1. For this experiment, a least square fit gives $H_{\mathrm{th},1} = 30{,}0$, $H_{\mathrm{th},\infty} = 7{,}19$ and $\Delta = 0{,}778$. This realistic characteristic damage curve is displaced by $d = 1{,}45$ in order to mark the safe operations limit. The displacement $d = 1{,}45$ corresponds to an intercept of the displaced characteristic damage curve with the lowest damage threshold measured for 100 pulses.

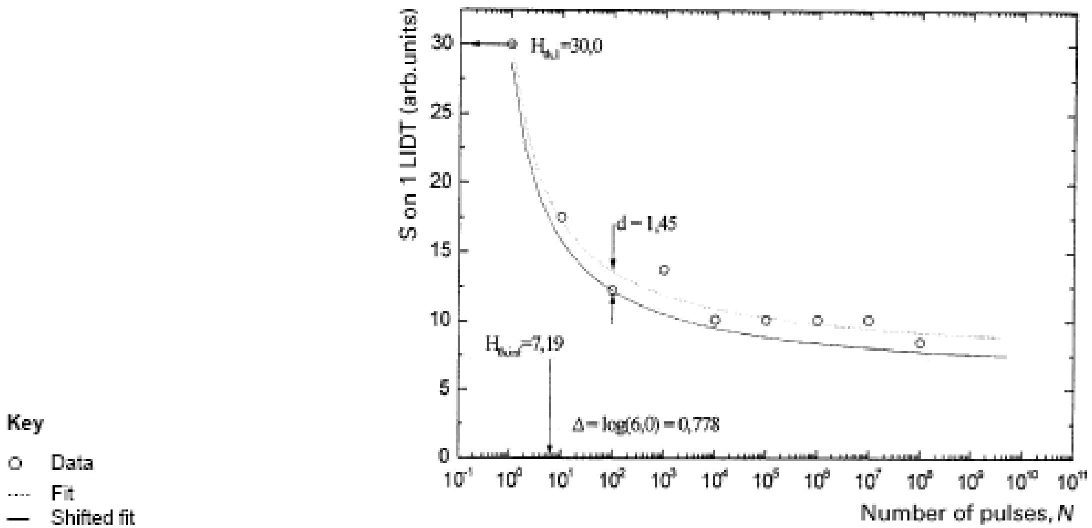
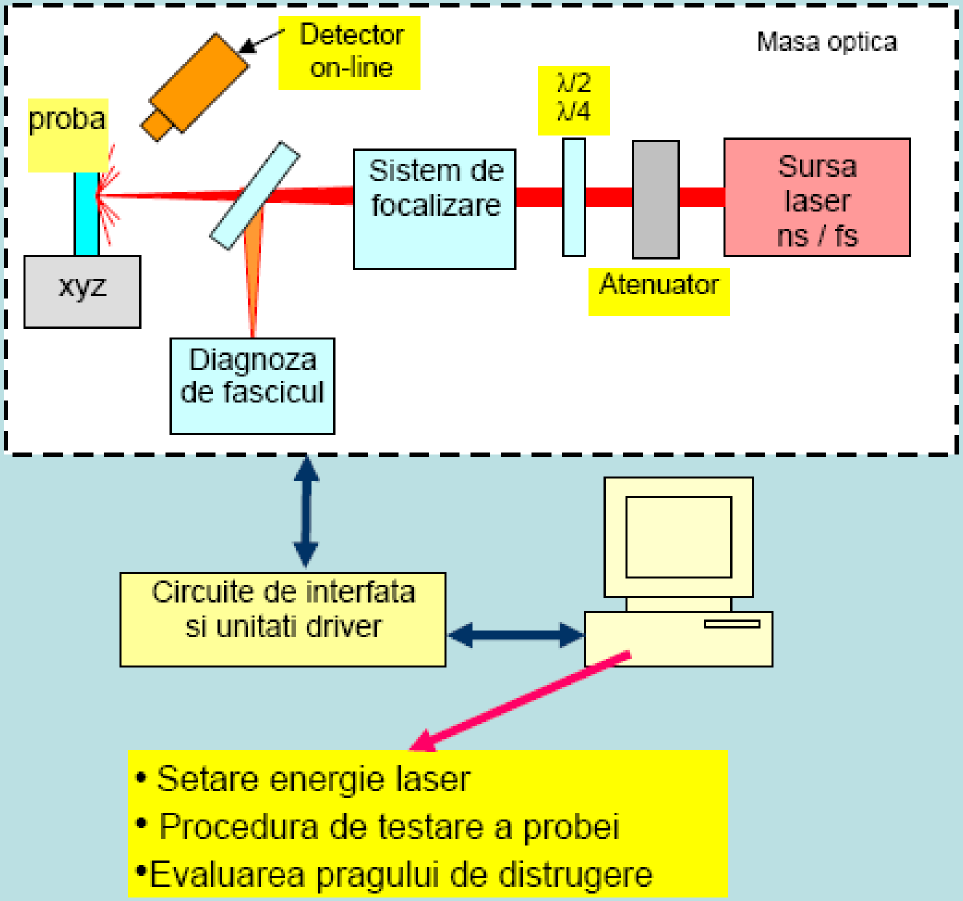


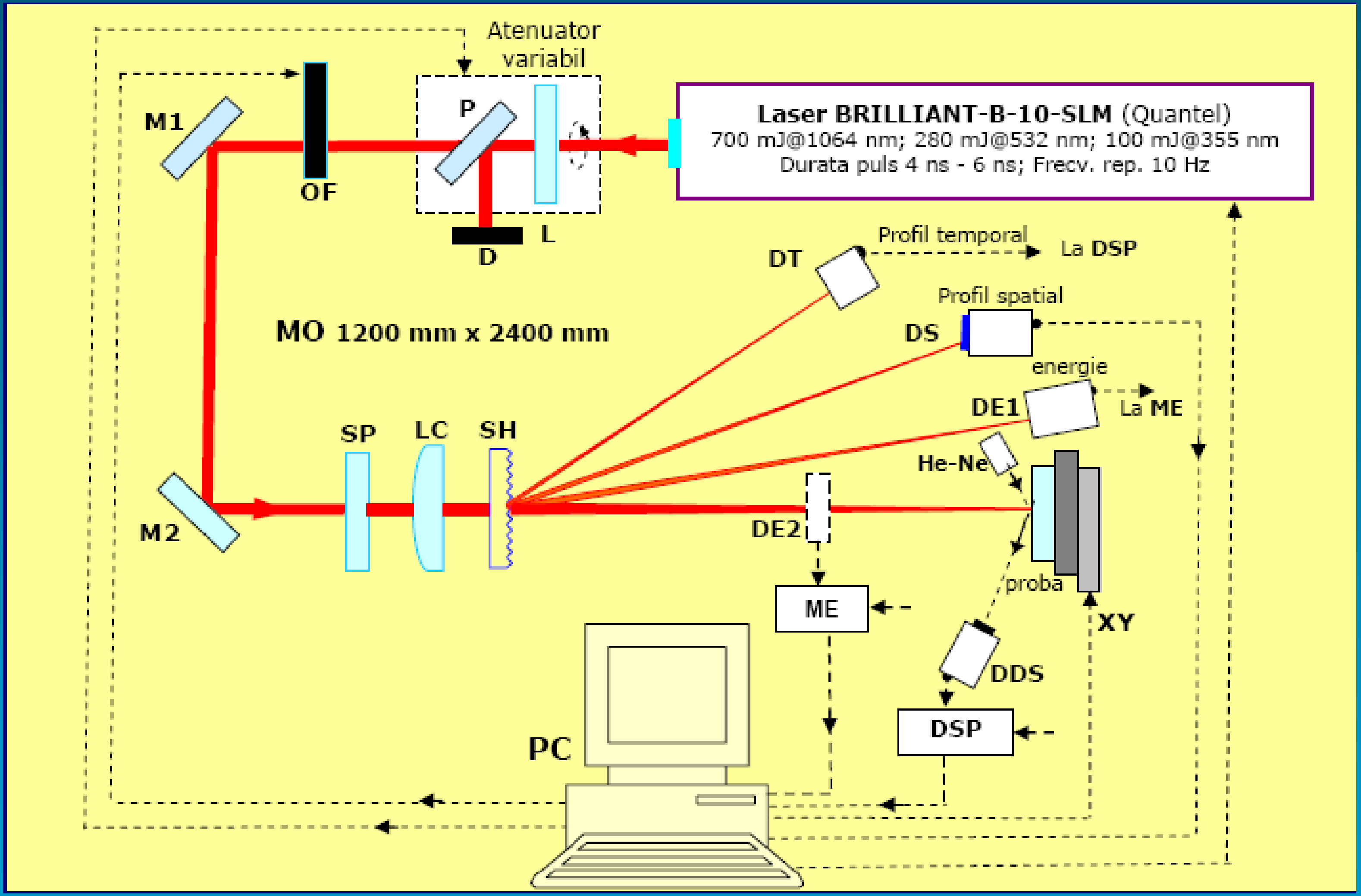
Figure C.1 — Measured S-on-1 damage threshold as a function of pulse number, *N*, with fit according to equation C.1 (laser mirror, 248 nm)

Typical S-on-1 experimental points, the fit curve, and the extrapolation to the non-damage (assurance) level of the component

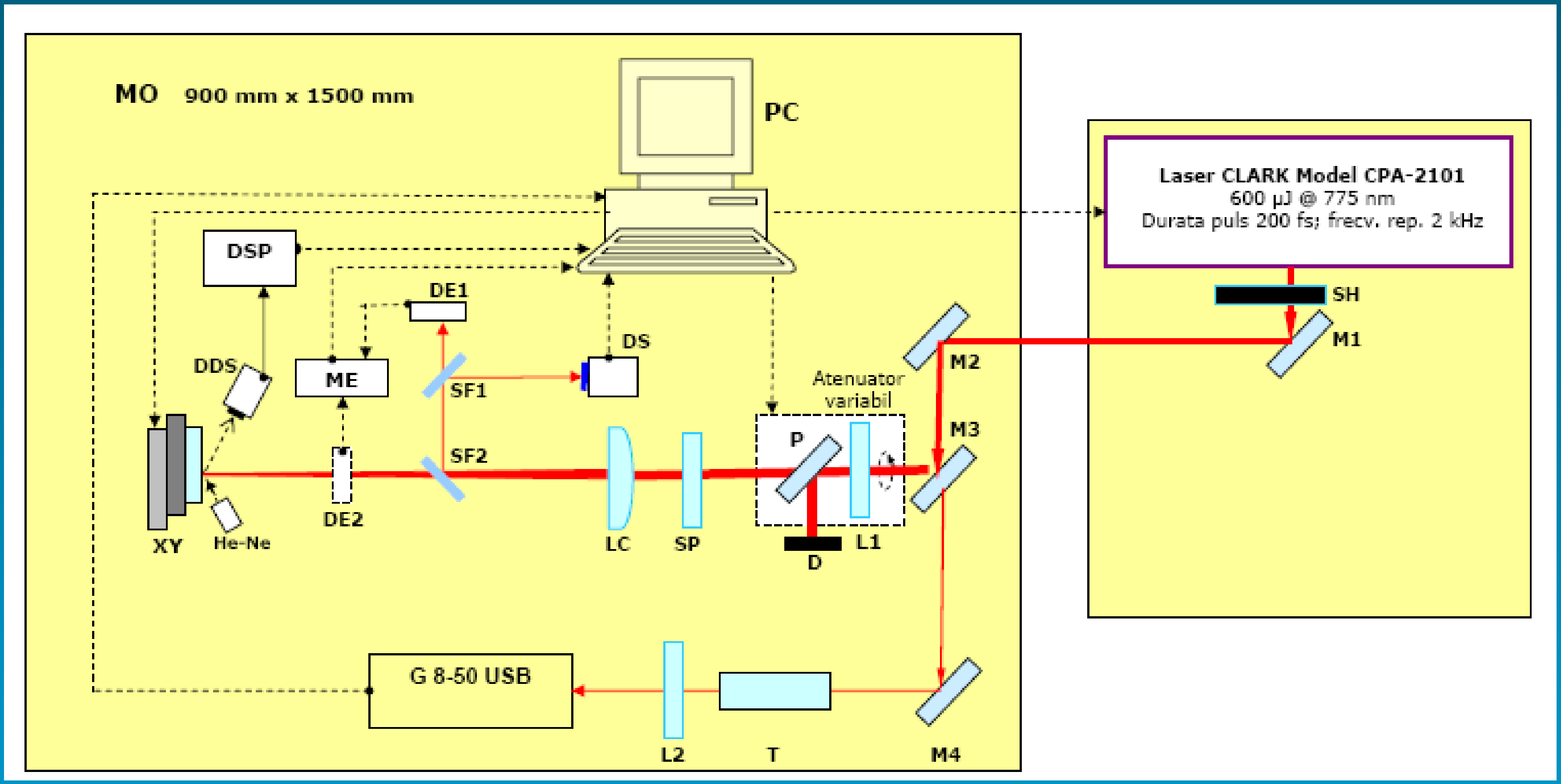
Principle schematic for damage tests setup



Block diagram for experimental setup – S-on-1 LIDT with ns pulses

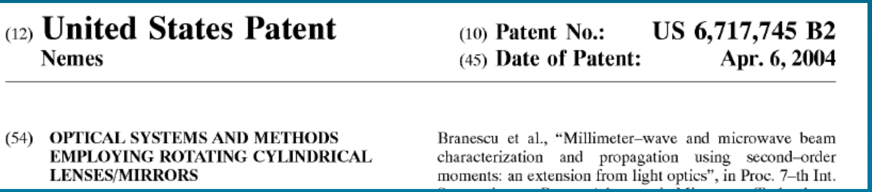


Block diagram for experimental setup – S-on-1 LIDT with 200 fs pulses



5. VariSpot® and new preliminary results

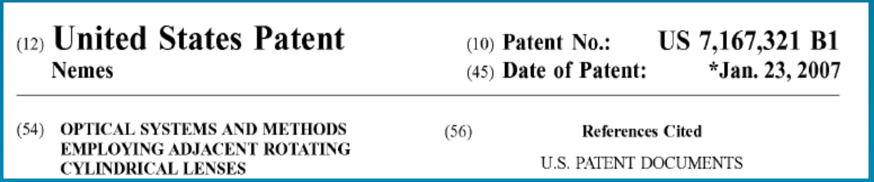
VariSpot® = New family of zoom optical systems – rotating cylindrical lenses (Nemes - US Pat. # 6,717,745/2004; # 7,167,321/2007



(12) **United States Patent** (10) **Patent No.:** **US 6,717,745 B2**
Nemes (45) **Date of Patent:** **Apr. 6, 2004**

(54) OPTICAL SYSTEMS AND METHODS EMPLOYING ROTATING CYLINDRICAL LENSES/MIRRORS

Branescu et al., "Millimeter–wave and microwave beam characterization and propagation using second–order moments: an extension from light optics", in Proc. 7–th Int.

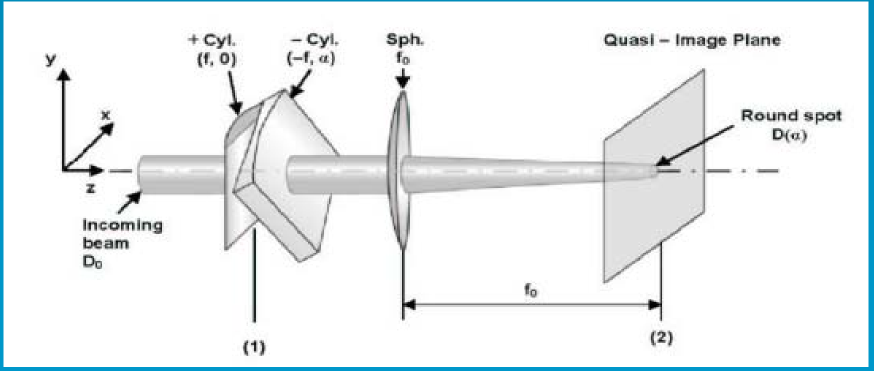


(12) **United States Patent** (10) **Patent No.:** **US 7,167,321 B1**
Nemes (45) **Date of Patent:** ***Jan. 23, 2007**

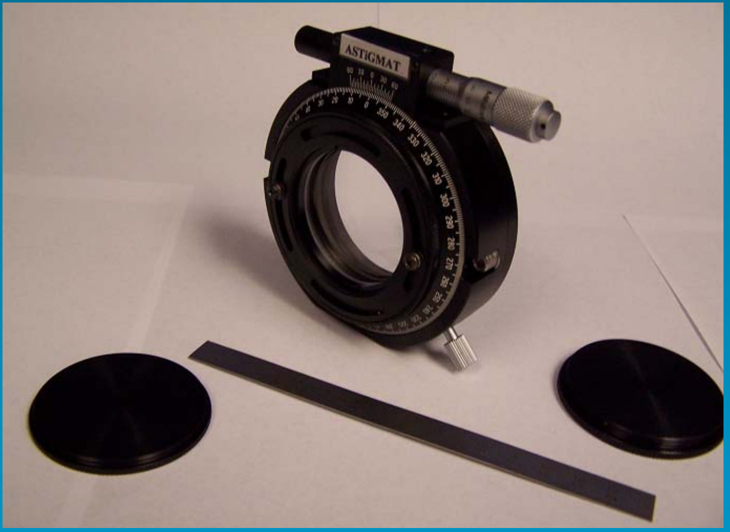
(54) OPTICAL SYSTEMS AND METHODS EMPLOYING ADJACENT ROTATING CYLINDRICAL LENSES

(56) References Cited

U.S. PATENT DOCUMENTS



VariSpot® principle – example1



VariSpot® type FS-500-1-266

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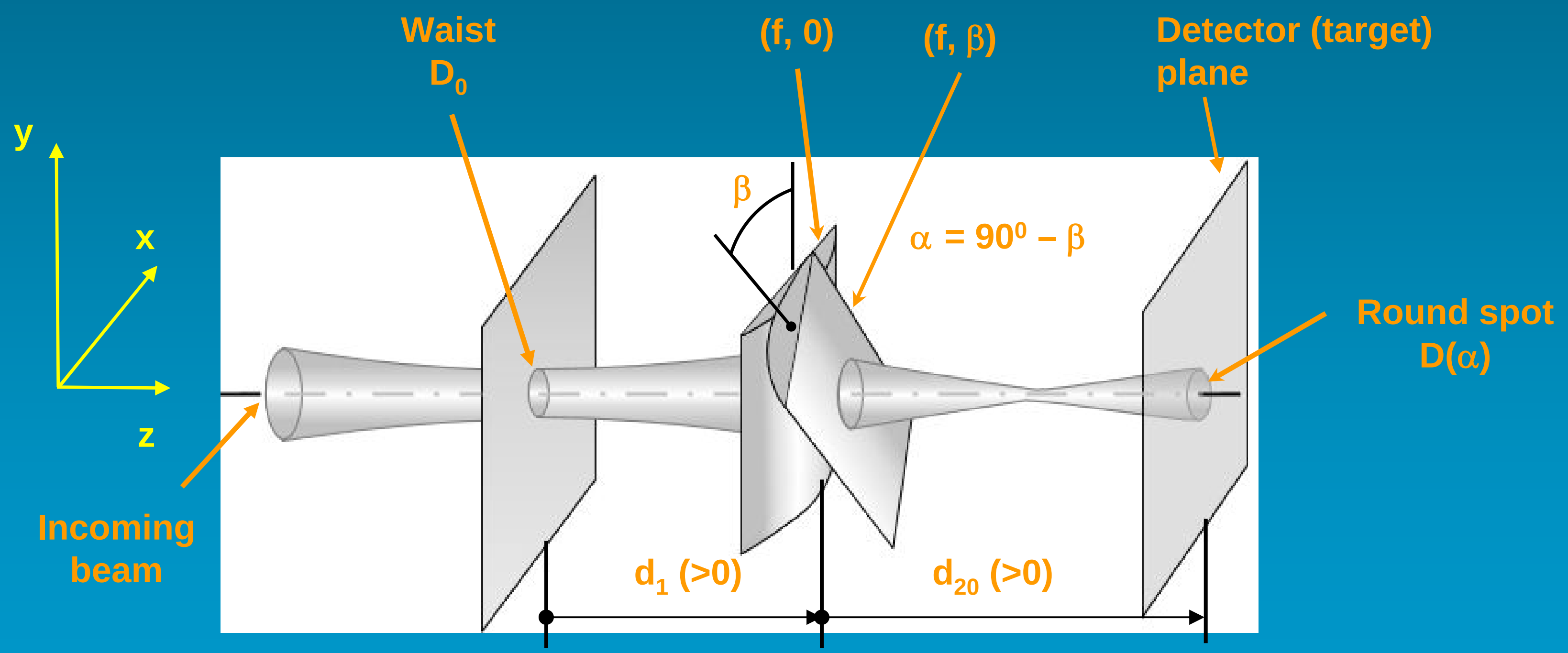
VariSpot® principle – example 2

2 - lens system:

+ Cylindrical lens, cylindrical axis fixed, vertical (f, 0)
+ Cylindrical lens, cylindrical axis rotatable about z (f, β)



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Measuring spatial beam characteristics

- Basic concepts

  Types of beams (geometrical classification, ISO 11146 -1,2,3)

  - ST, ASA, RSA, GA

- Parameters of interest for:

	ASA beam	ST beam
- Waist size(s):	w_{0x}, w_{0y}; D_{0x}, D_{0y}	w_0; D_0
- Waist location(s):	z_{0x}, z_{0y}	z_0
- Beam divergence(s):	θ_x, θ_y	θ
- Rayleigh length(s):	z_{Rx}, z_{Ry}	z_R
- Beam propagation ratio(s):	M^2_x, M^2_y	M^2

- Methods to measure laser beam spatial parameters

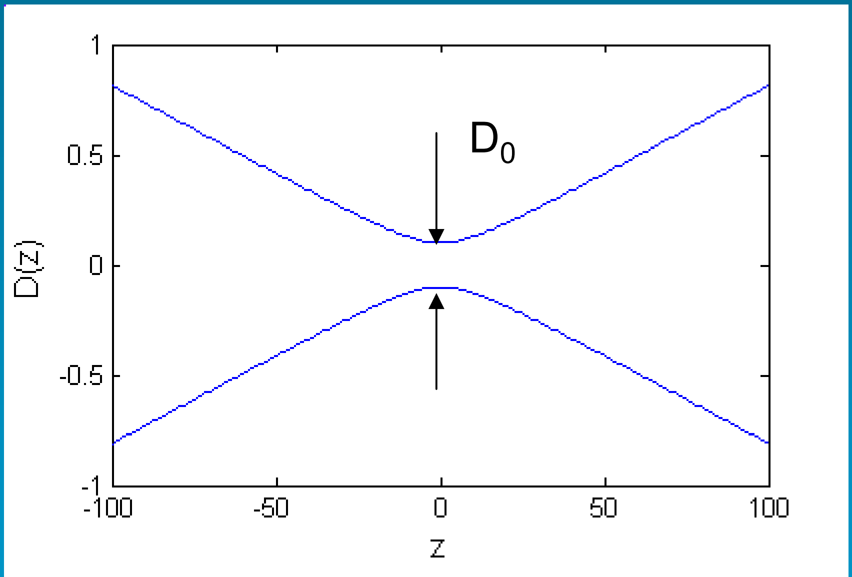
  - Classical (ISO 11146-1): Spherical lens and longitudinal (z axis) movement

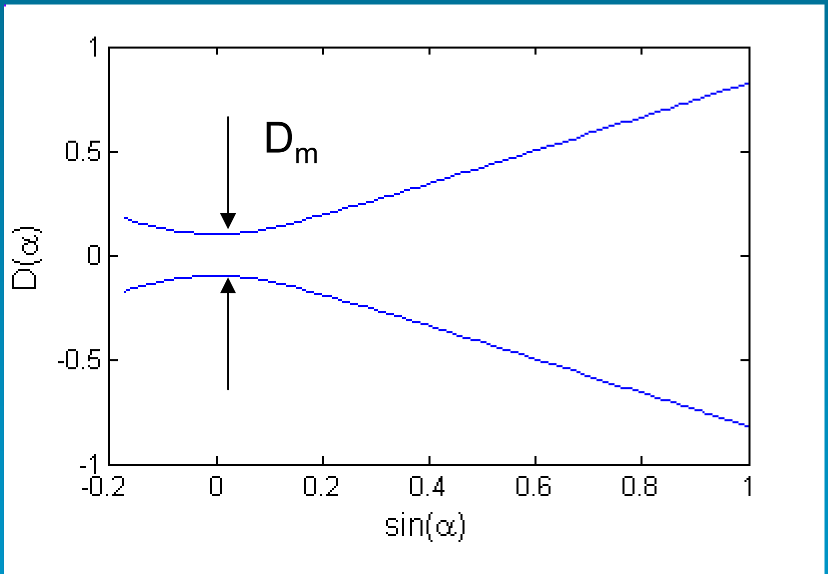
  - New method: Cylindrical optics and rotational (angular) movement → VariSpot®

VariSpot® input-output relations

Schematic of spot size variation ("propagation")

Free-space	VariSpot®
D(z)	D(α)





$$D(z) = D_0 (1 + z^2/z_R^2)^{1/2}$$

$$D(\alpha) = D_m [1 + \sin^2(\alpha)/r^2]^{1/2}$$

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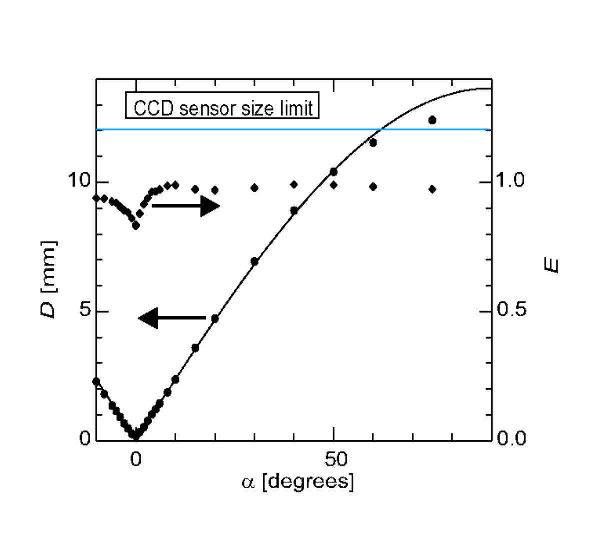
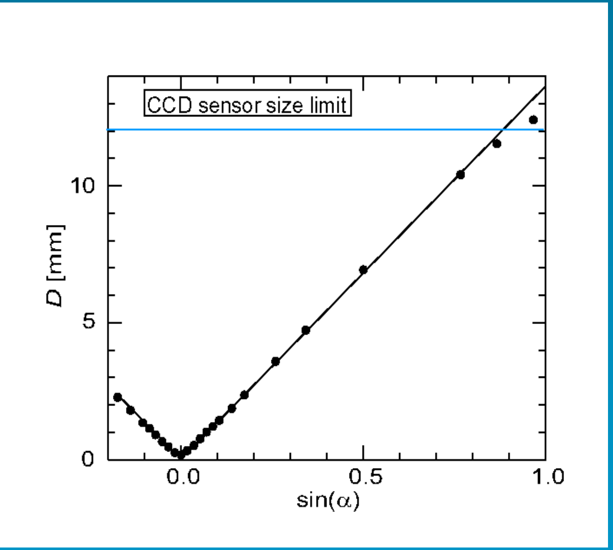
VariSpot - image-mode: Flat-top (Fermi-Dirac) beam
Experiments support the theory

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

Image-mode → $D(\alpha) \approx D_M \sin(\alpha)$





$D(\alpha)$ versus α

$E = d_{min}/d_{max}$ versus α

$D(\alpha)$ versus $\sin(\alpha)$

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Theory and method of measuring spatial beam parameters

- Find and measure d_{20} by locating the round spot after VariSpot
- Measure $D(\alpha)$ at the appropriate target plane (at d_{20}) for different α
  Include D_m, the "angular near-field", and the "angular far-field" for α
  Similarity to ISO 11146 standard for near-field and far-field in free-space
- Fit $D(\alpha)$ and determine D_m, α_0, r

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

- Recover by calculations the original beam parameters (general case):

$$M^2 = (\pi/4)D_m^2 f/(r d_0^2 \lambda)$$

$$D_0 = D_m f/\{d_{20}[(1 - f/d_{20})^2 + r^2]^{1/2}\}$$

$$z_R = rf/[(1 - f/d_{20})^2 + r^2]$$

$$d_1 = f(1 - f/d_{20})/[(1 - f/d_{20})^2 + r^2]$$

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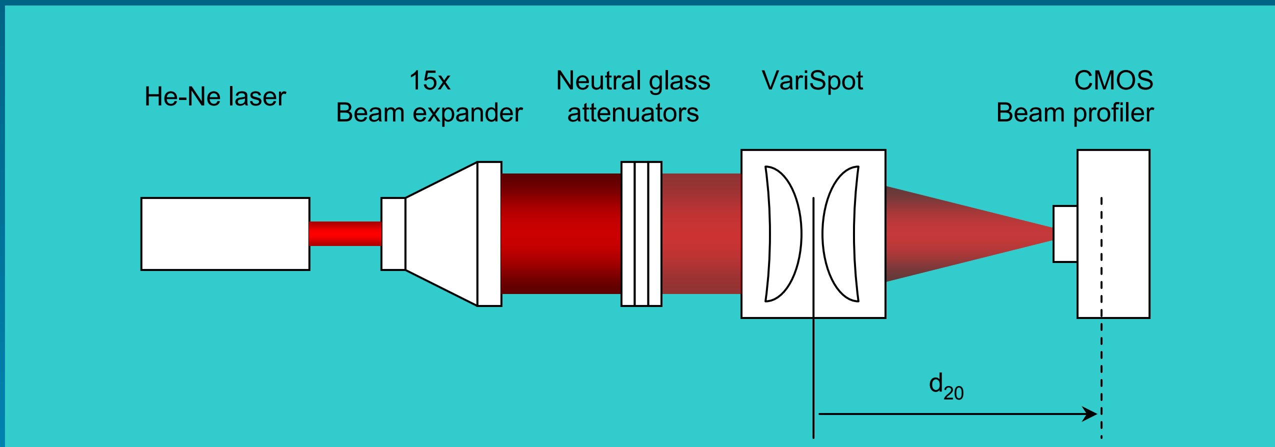
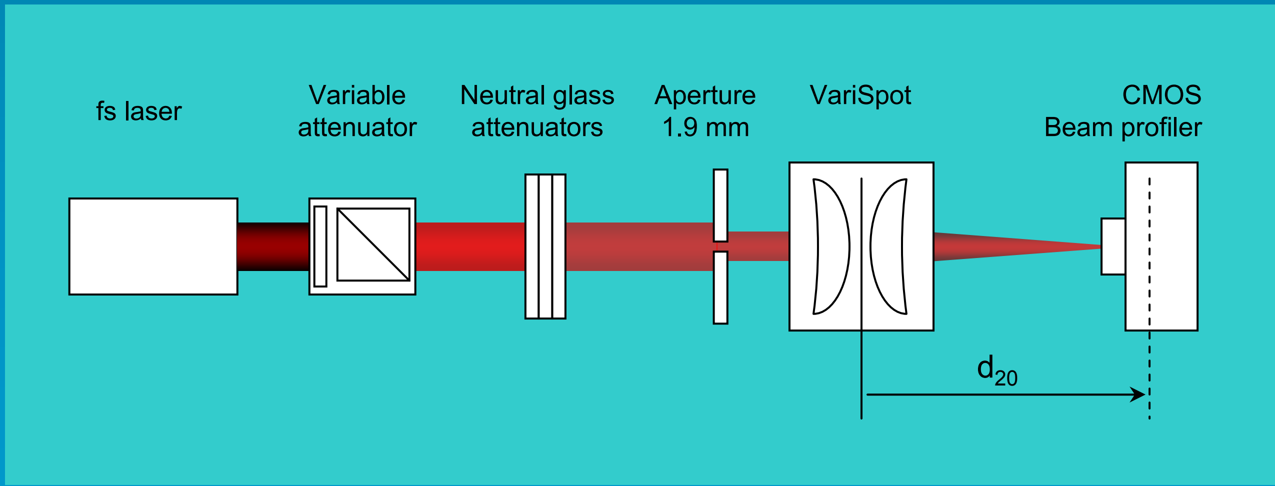
Preliminary experiments to measure M^2

(from G. Nemes, M. Ulmeanu, M. Zamfirescu, Paper 7194-6, PW, San Jose, USA, Jan. 2009)

Experimental setups





Equipment and systems used for preliminary experiments

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Femtosecond laser data (Clark-MXA, Inc., USA)

Type: CPA - 2101
Femtosecond laser with regenerative amplifier
Pulse duration: 180 - 200 fs
Pulse repetition frequency: 2 kHz
Wavelength: 775 nm
Max. pulse energy: 0.6 mJ
Attenuated beam: pulse energy - few nJ

VariSpot® data (ASTiGMAT™, USA)

Type: FS-300-1-UV-VIS-NIR (for He-Ne laser); f_{633} = 302 mm
Type: FS-380-1-VIS (for fs laser); f_{775} = 370 mm - 382 mm
$\alpha = 0^0 - \pm 90^0$
Manually rotatable mount, $\pm 0.25^0$ resolution

Beam profiler data (Photon, Inc., USA)

Type: USBeamPro, PS-2323 USB2.0
Detector type: CMOS
Pixel size: 6.7 μm square
Detector size: 1280 x 1024 pixels; 8.6 mm x 6.9 mm
ADC dynamic range: 10 bit
Additional attenuator: gray glass, ND = 4

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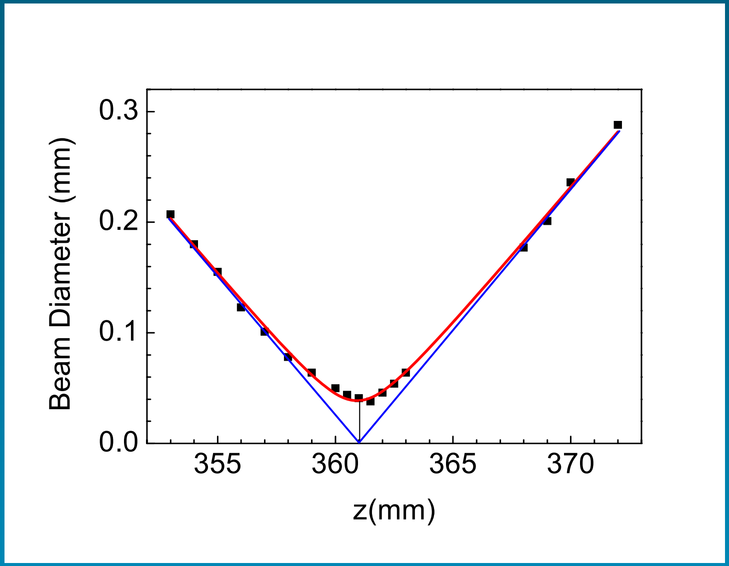
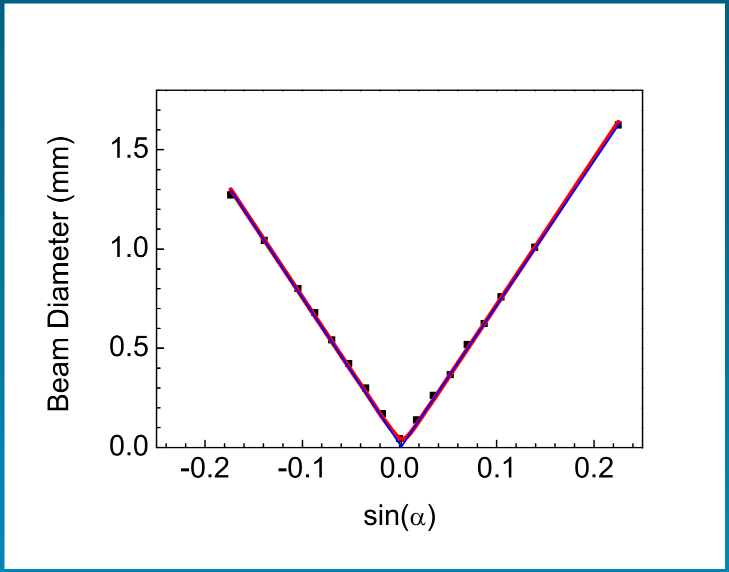
Results of preliminary experiments

He-Ne laser experiments ("well collimated" incoming beam)





VariSpot FS300 as spherical lens

Camera translated along z axis

$\lambda = 0.633 \times 10^{-3}$ mm

$D_m = 0.039$ mm

$z_0 = 361$ mm

$z_R = 1.55$ mm

$M^2 = 1.20$

VariSpot FS300 by changing α

Camera fixed at $d_{20} = f = 302$ mm

$\lambda = 0.633 \times 10^{-3}$ mm

$D_m = 0.038$ mm

$\sin(\alpha_0) = 0.0026$

$r = 0.00516$

$M^2 = 1.15$

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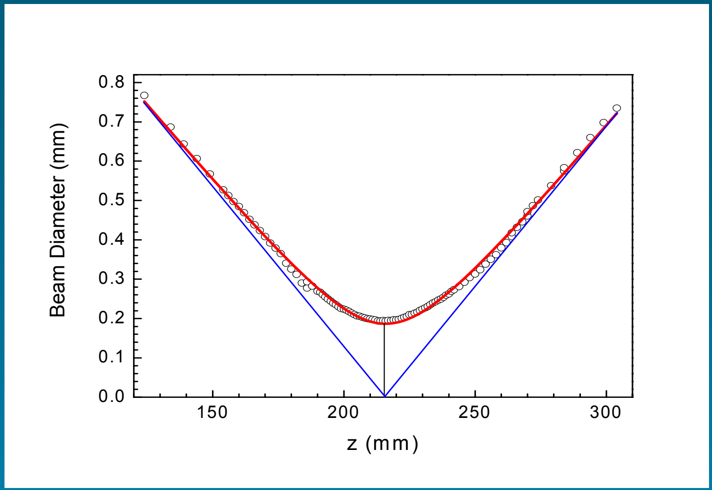
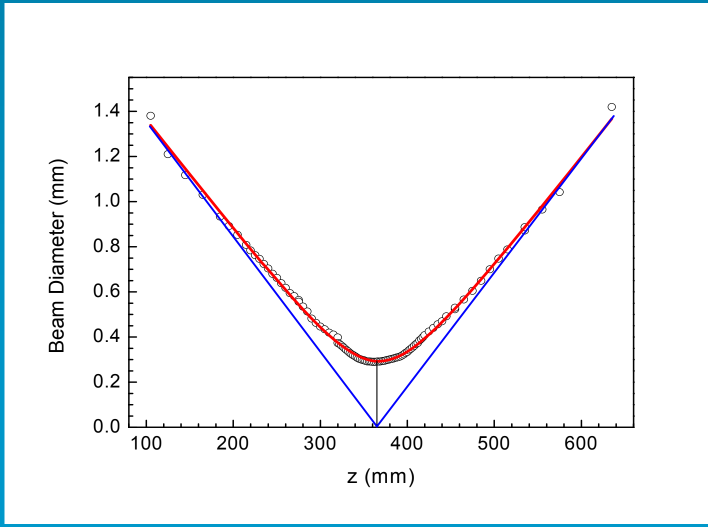
Femtosecond laser experiments (moving camera along z)



Conventional method: spherical lens f = 257 mm

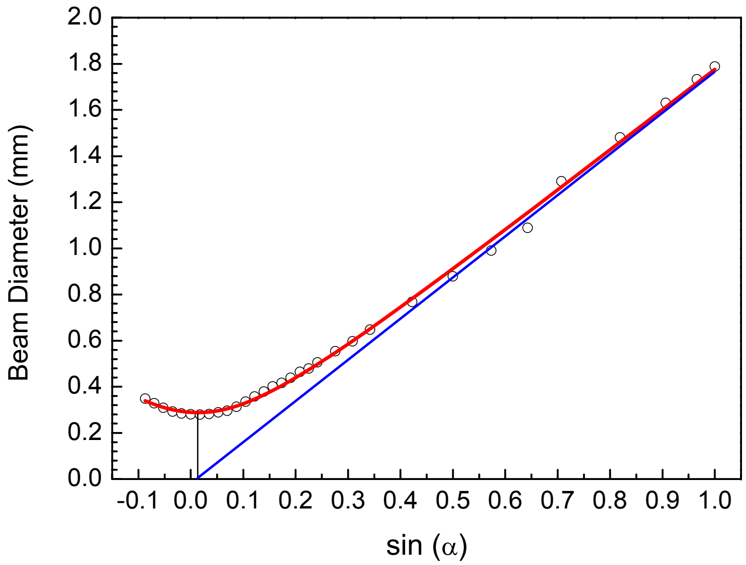
$\lambda = 0.775 \times 10^{-3}$ mm
$D_m = 0.187$ mm
$z_0 = 216$ mm
$z_R = 23.6$ mm
$M^2 = 1.54$



Conventional method: VS380 as spherical lens

$\lambda = 0.775 \times 10^{-3}$ mm
$D_m = 0.293$ mm
$z_0 = 367$ mm
$z_R = 58.8$ mm
$M^2 = 1.52$

Femtosecond laser experiments (fixed camera at d_{20})



VS380 by changing α, and $d_{20} = f$, or

$d_{20} = f_{eq}$

$D_m = 0.288$ mm

$\sin(\alpha_0) = 0.0132$

$r = 0.162$

$M^2 = 1.51$ (with f = 373 mm; d_{20} = 365 mm)

$M^2 = 1.40$ (with $f_{eq} = d_{20}$ = 370 mm)

(uncertainty in d_{20} due to elliptical spot)

Range of M^2 in all three experiments: 1.40 - 1.54

Note: Compare to catalog data for fs laser: $M^2 < 1.5$

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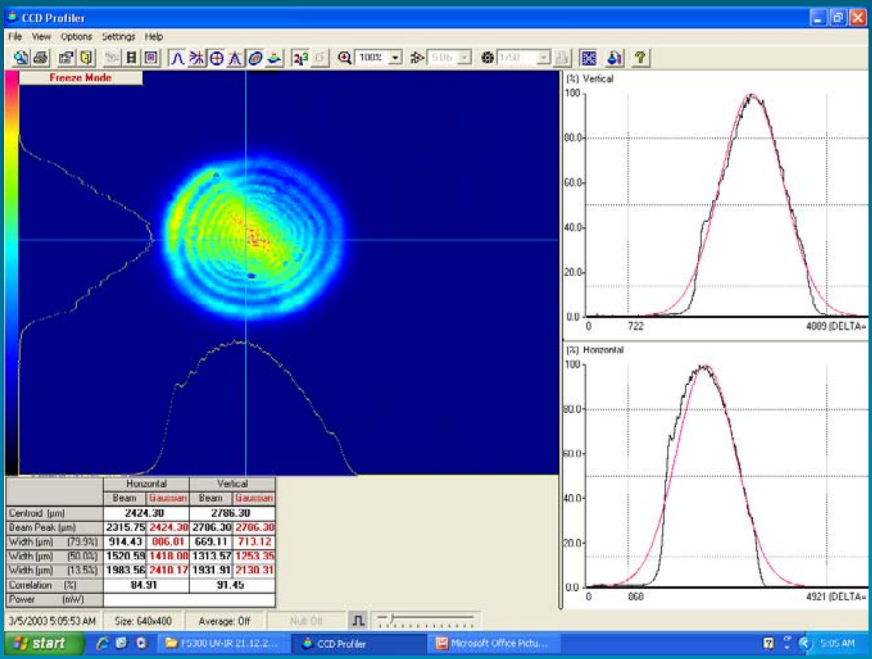
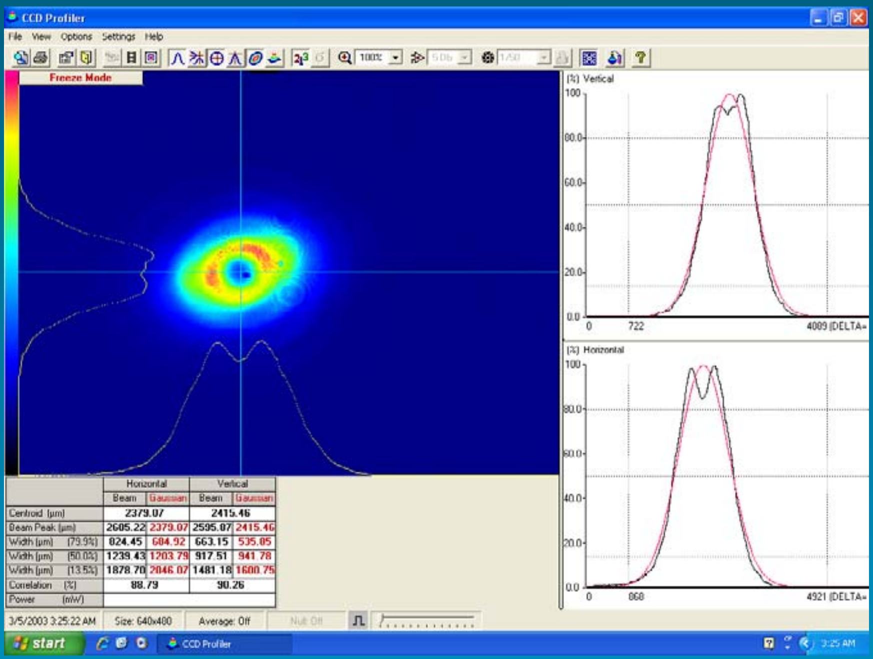
Example of fs laser beam spot in free-space





50 mm after 1.9 mm dia. aperture

720 mm after 1.9 mm dia. aperture

(CCD-type beam profiler)

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Discussion

- Sources of errors for He-Ne laser measurements

  - Gray glass attenuators

  - Limited angular resolution of VariSpot® rotating mount

  - Minimum spot size too small for CMOS camera spatial resolution

  However, M^2 = 1.15 - 1.20 (< 5% relative error)

- Sources of errors for fs laser measurements

  - The laser beam is ASA or RSA and not ST (even after a round aperture)

  (No theoretical equivalence between an ASA beam and a ST beam)

  - Gray glass attenuators

  - Thin lens approximation for VariSpot® → corrections (partially done)

  However, M^2 = 1.40 - 1.54 (≤ 10% relative error)

6. Conclusion

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- ISOTEST is a complex, challenging, and realistic project
- We have the necessary expertise to develop the facility and to search and advance the new measuring methods for laser beams
- A new method to measure spatial beam parameters was introduced, using rotating cylindrical optics and fixed camera position (no translation)
- Comparison to classical methods shows reasonable (≤ 10% relative error) agreement
- Considerable future work is necessary to fulfill the four major objectives of the ISOTEST project

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