"INVERSE ILLUMINATION METHOD FOR CHARACTERIZATION OF CPC CONCENTRATORS"

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OUTLINE

Introduction

The “direct” method of optical characterization

The “inverse” method of optical characterization

Applications of the “inverse” method

* Half-Truncated CPC (HT-CPC)
* Truncated and Squared CPC (TS-CPC)

Conclusions

INTRODUCTION

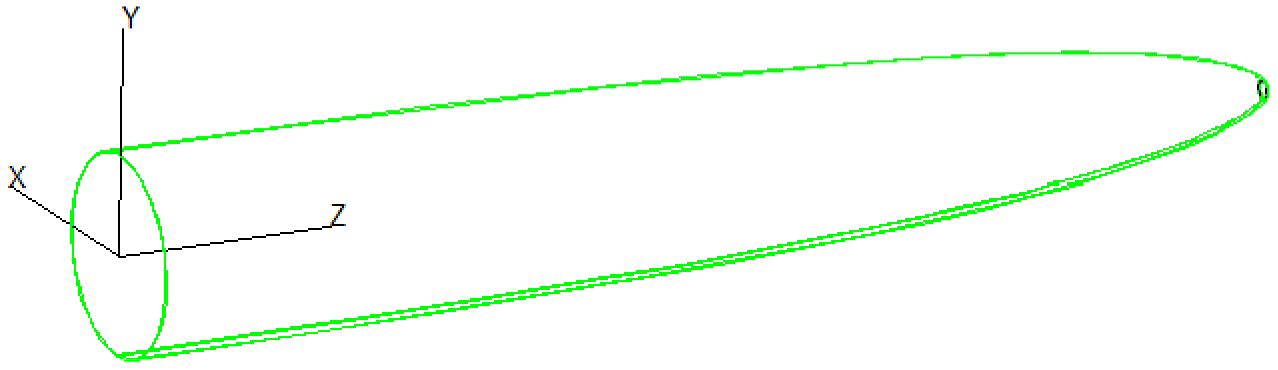
CPC concentrators have been widely used as secondary collectors for Solar Concentration Systems.

Their specific characteristics is the ability to attain the maximal optical acceptance for a given level of optical concentration.

Real CPC systems, however, may suffer from mechanical defects introduced during the realization stage.

A quick method is therefore needed to assess the actual acceptance and energy transfer efficiency in correspondence of beams incoming under different impinging angles.

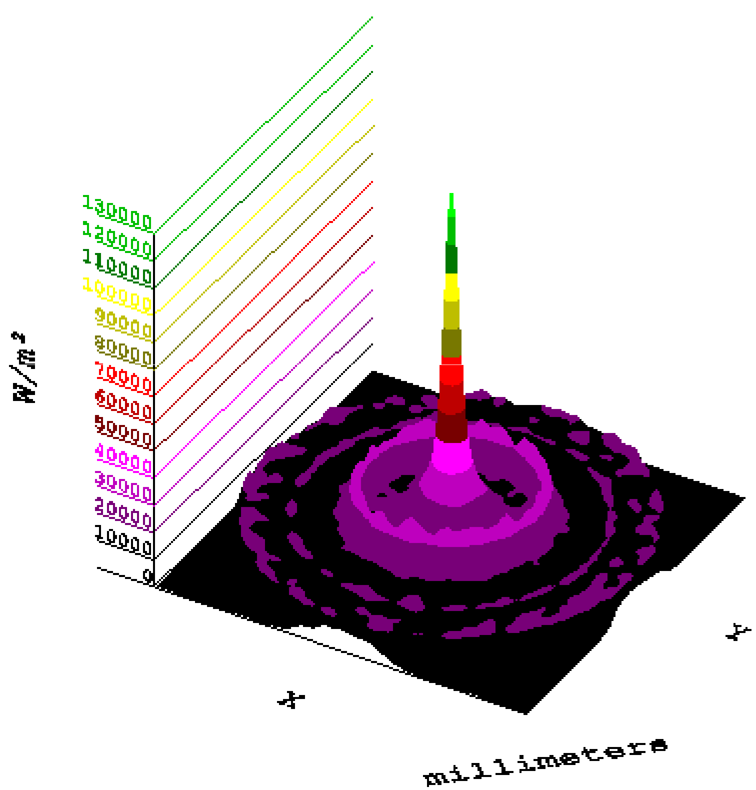
A version of an ideal 3D-CPC



ideal cpc
r(out) = 5 mm
Axis tilt = 5°
r(in) = 57.4 mm
L = 712.9 mm

… and its target illumination profile for normal irradiance

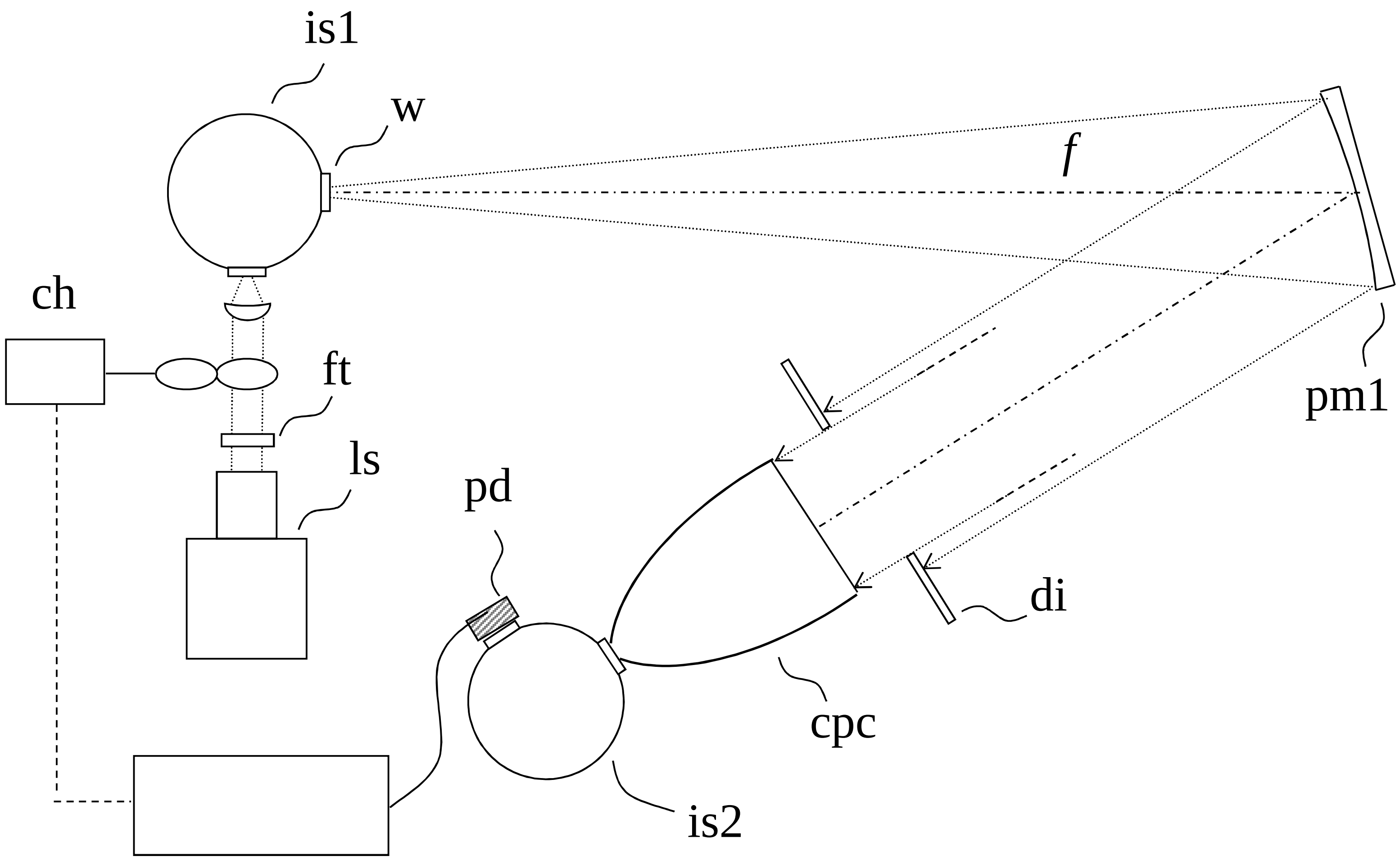
Total - Irradiance Map for Absorbed Flux
Object 2 Surface 1



Irradiance Min:2.5392e-008 W/m², Max:1.285e+005 W/m², Ave:8680.3 W/m²,
RMS:7121.5, Normalized Flux:0.86803 49954 Incident Rays

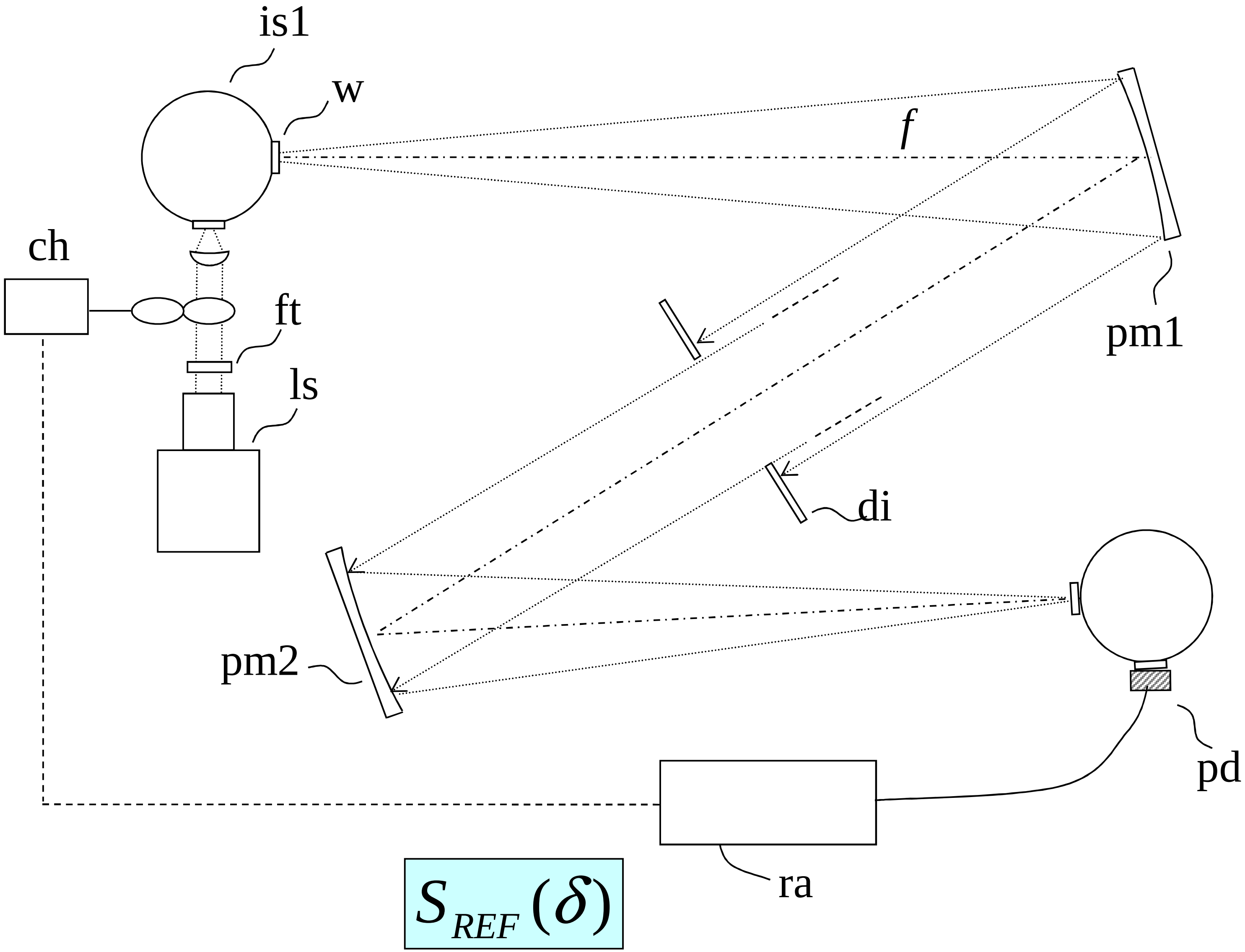
DIRECT METHOD FOR OPTICAL CHARACTERIZATION OF SOLAR CONCENTRATORS

Measurement of input flux



$S_{CPC}(\delta)$

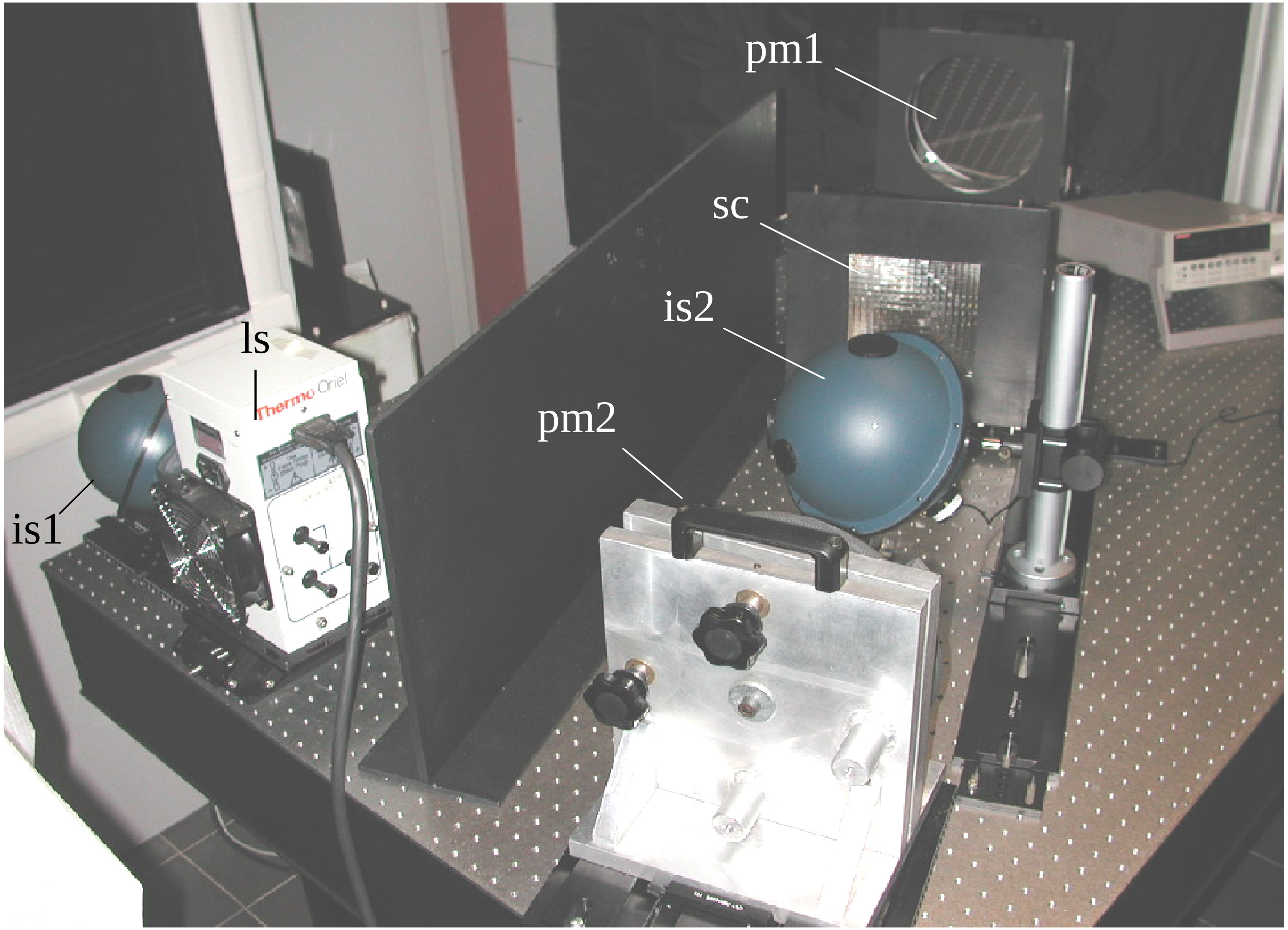
Measurement of <u>output</u> flux



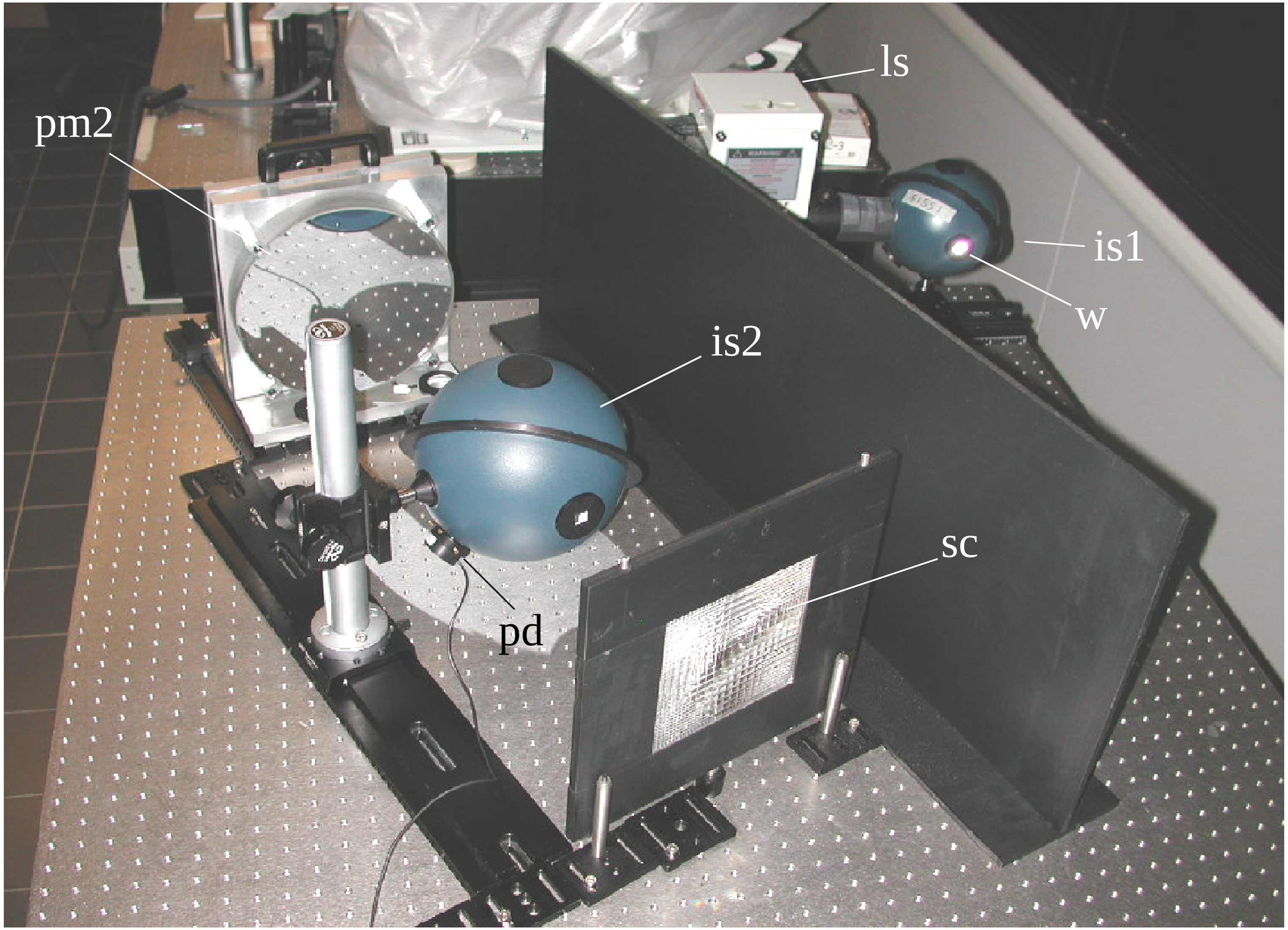
Optical efficiency as function of incidence angle δ

$$\eta(\delta) = S_{CPC}(\delta) \cdot \frac{R_{pm}}{S_{REF}}$$

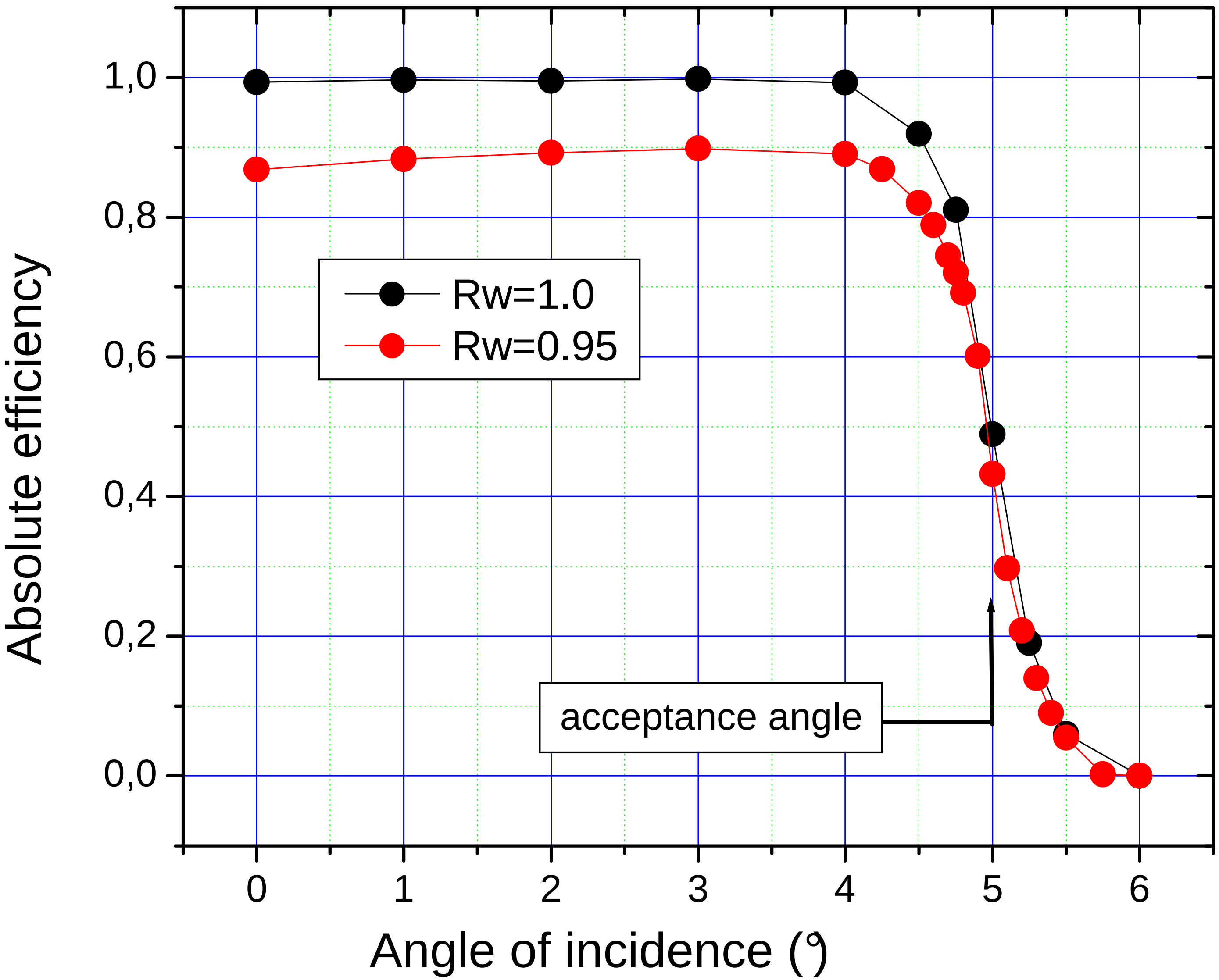
The optical apparatus



The optical apparatus



The optical efficiency



Average number of reflections

$$R_w = 1.0 \qquad \text{(constant with } \delta\text{)}$$

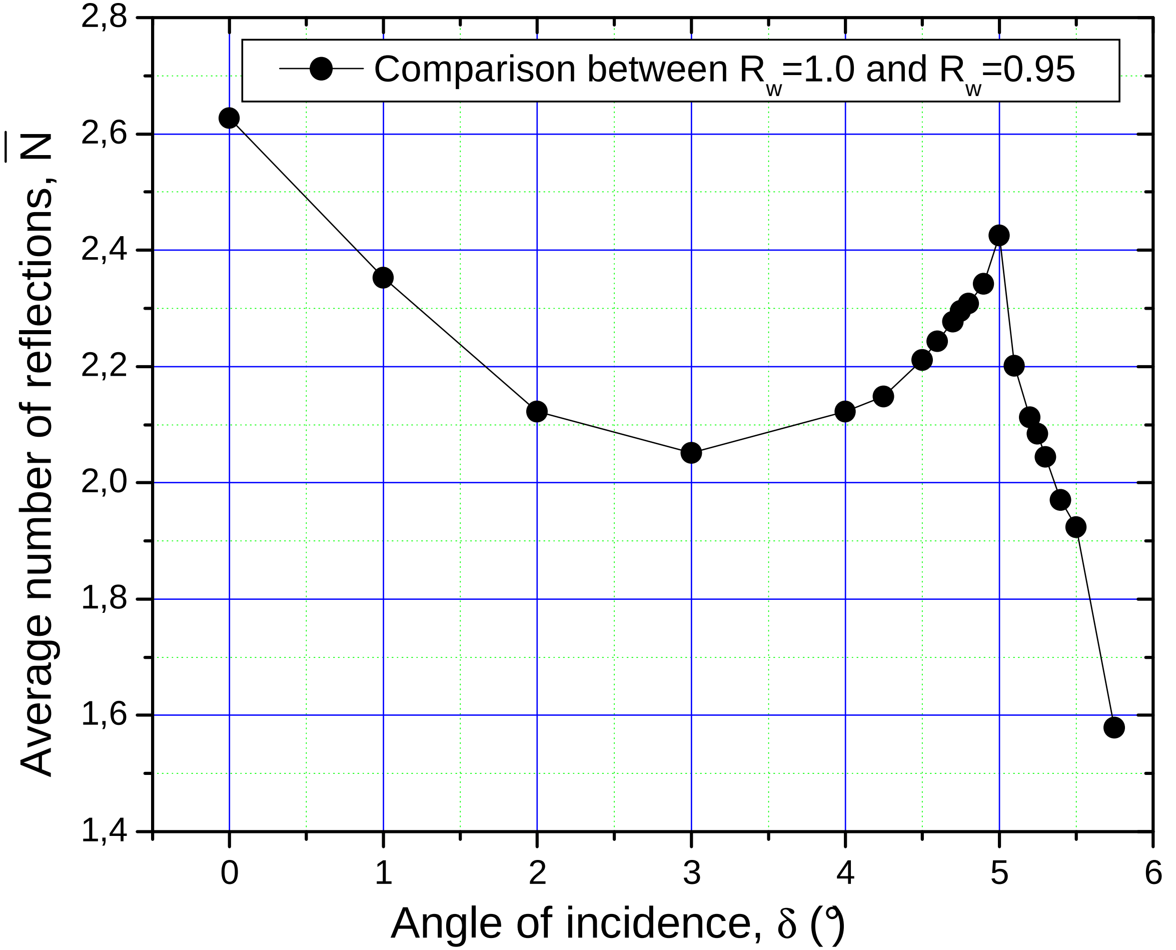
$$\eta(\delta) = \Phi_{out}(\delta) / \Phi_{in}$$

$$R_w^{'} = 0.95 \quad \text{(constant with } \delta\text{)}$$

$$\eta'(\delta) = \Phi_{out}^{'}(\delta) / \Phi_{in} = \Phi_{out}(\delta) \cdot (R_w^{'})^{\overline{N}(\delta)} / \Phi_{in}$$

$$\overline{N}(\delta) = \frac{1}{\ln R_w^{'}} \cdot \ln \frac{\eta'(\delta)}{\eta(\delta)}$$

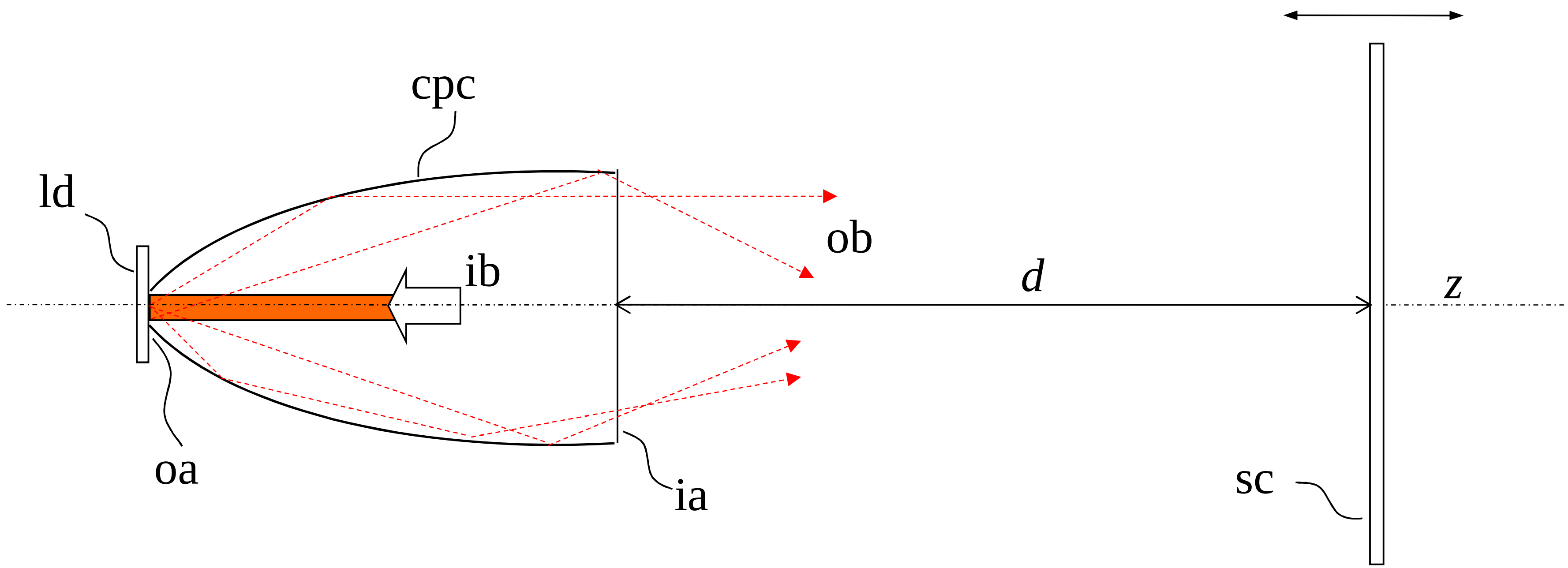
Average number of reflections



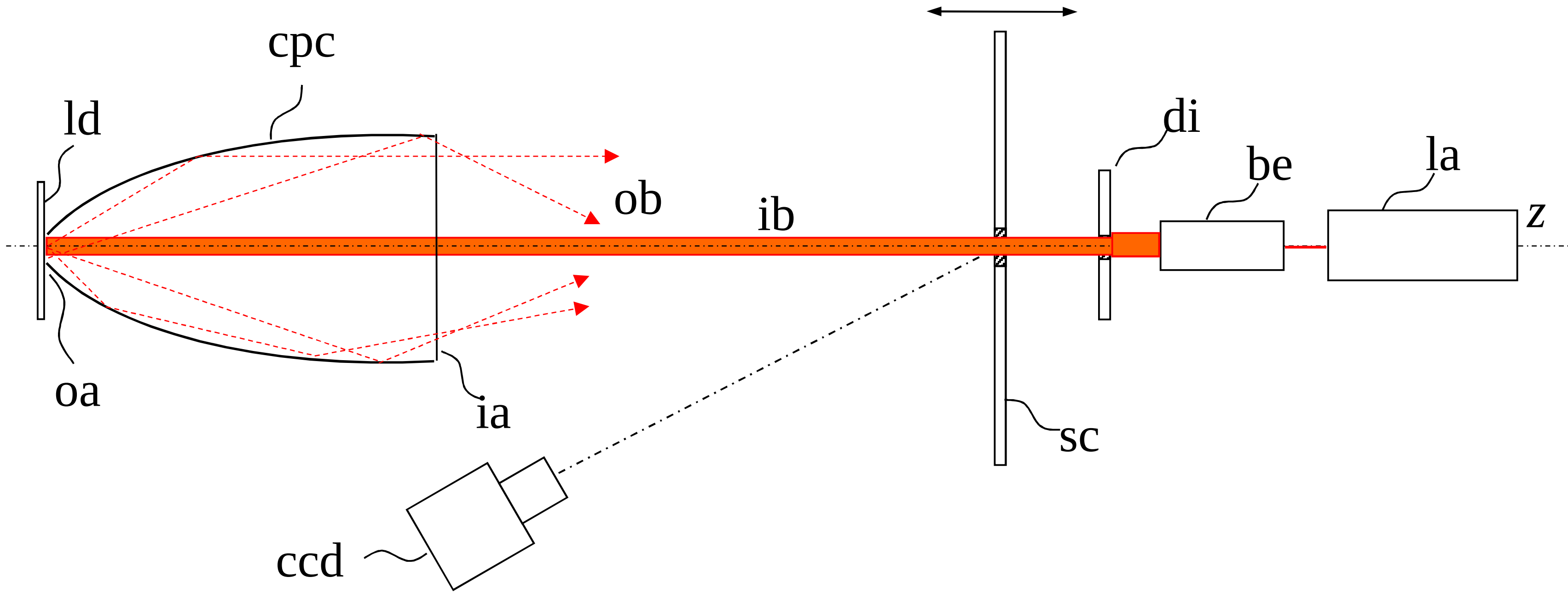
Obtained by comparison between output flux of CPC at R_w=1 and R_w=0.95

INVERSE METHOD FOR OPTICAL CHARACTERIZATION OF SOLAR CONCENTRATORS

The basic principle

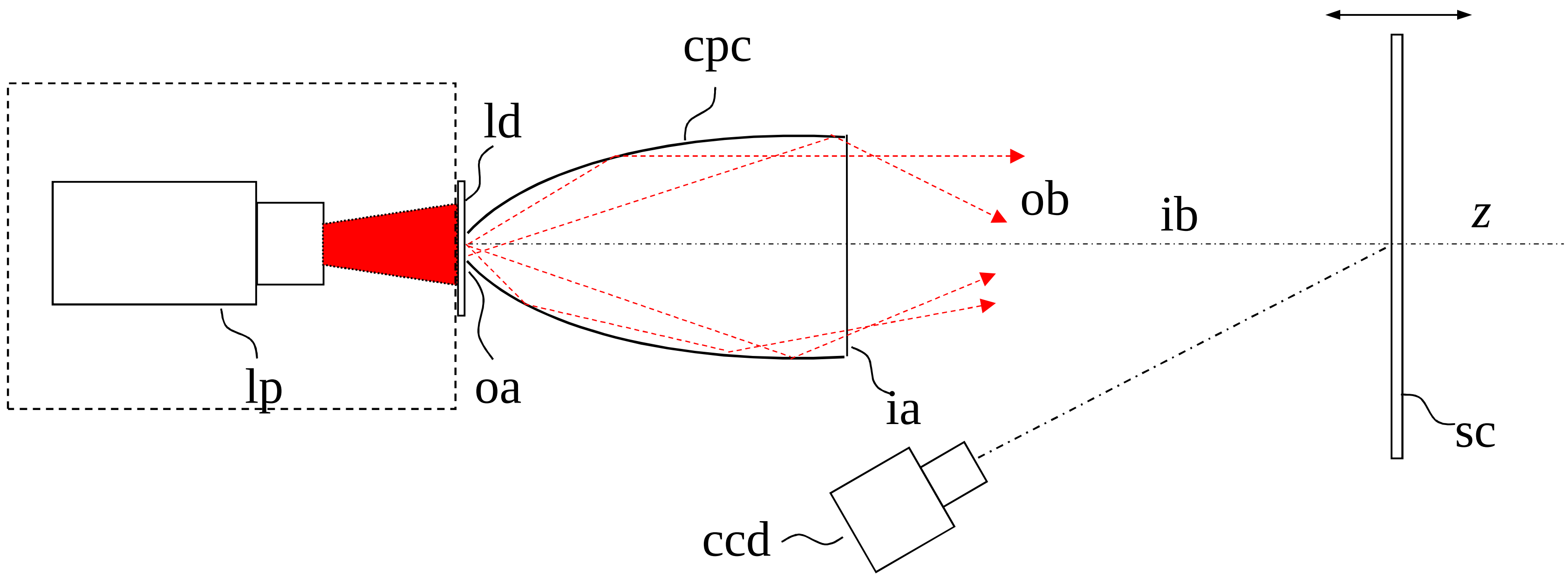


Experimental set-up



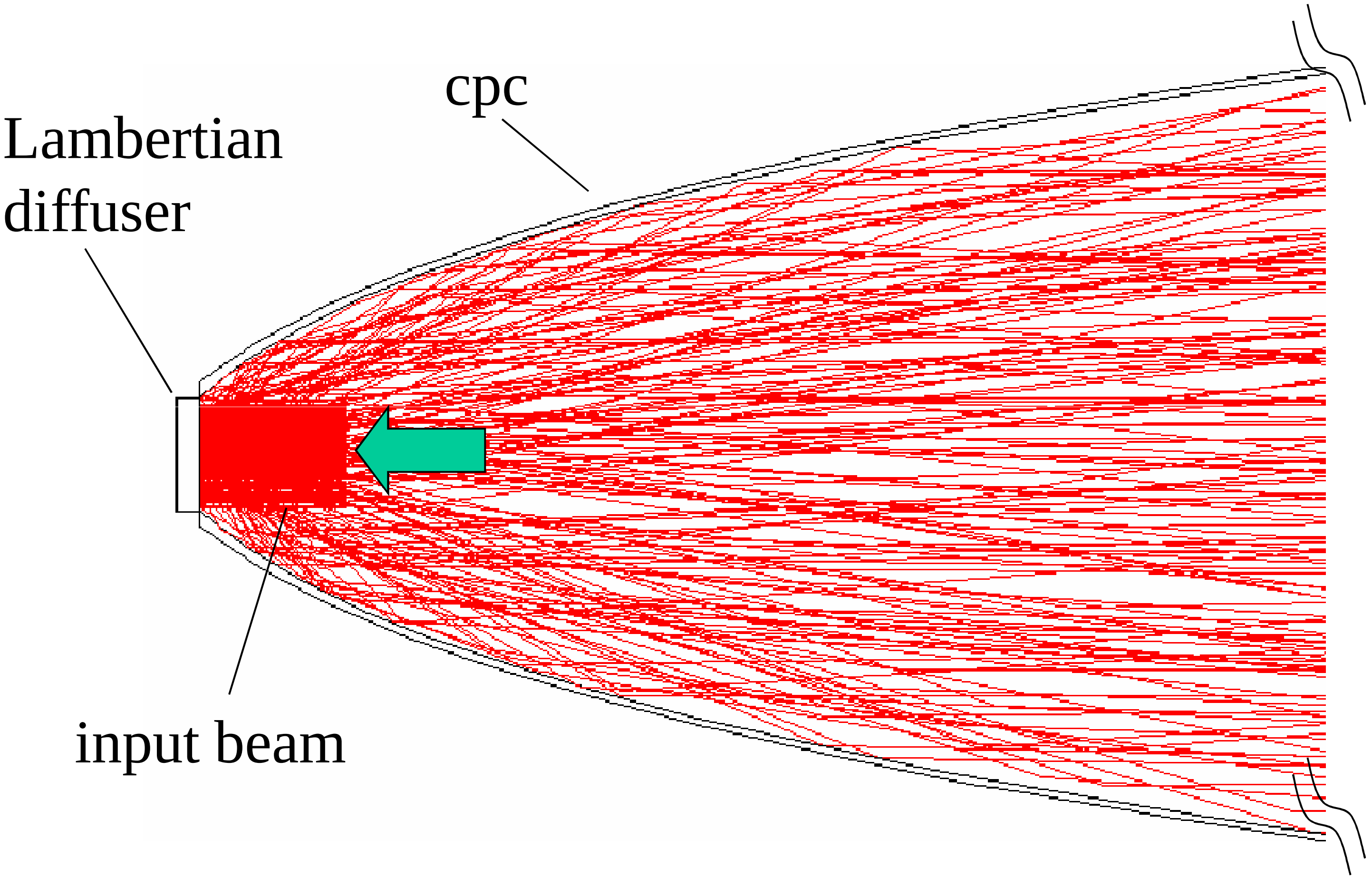
Illumination from the front side

Experimental set-up



Illumination from the back side

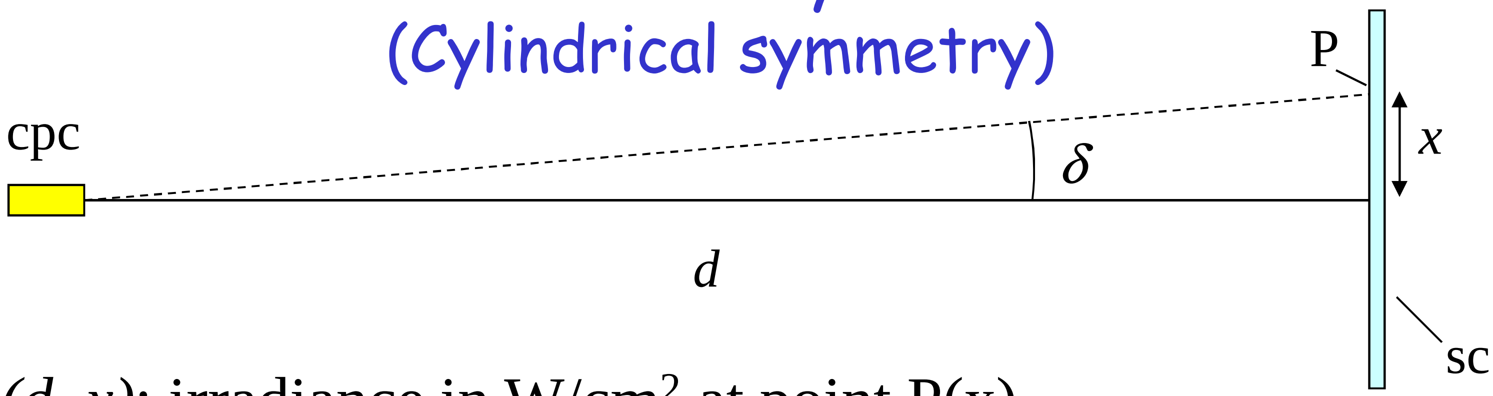
Example of raytracing with TracePro®



THEORY OF

INVERSE METHOD

Theory
(Cylindrical symmetry)



$E(d, x)$: irradiance in W/cm^2 at point P(x)

$L(\delta)$: radiant intensity

$$L(\delta) = L(d, x) = E(d, x) \cdot \frac{r^2}{\cos^2 \delta} = E(d, x) \cdot \frac{d^2}{\cos^4 \delta}$$

$L_{rel}(\delta)$: relative radiance

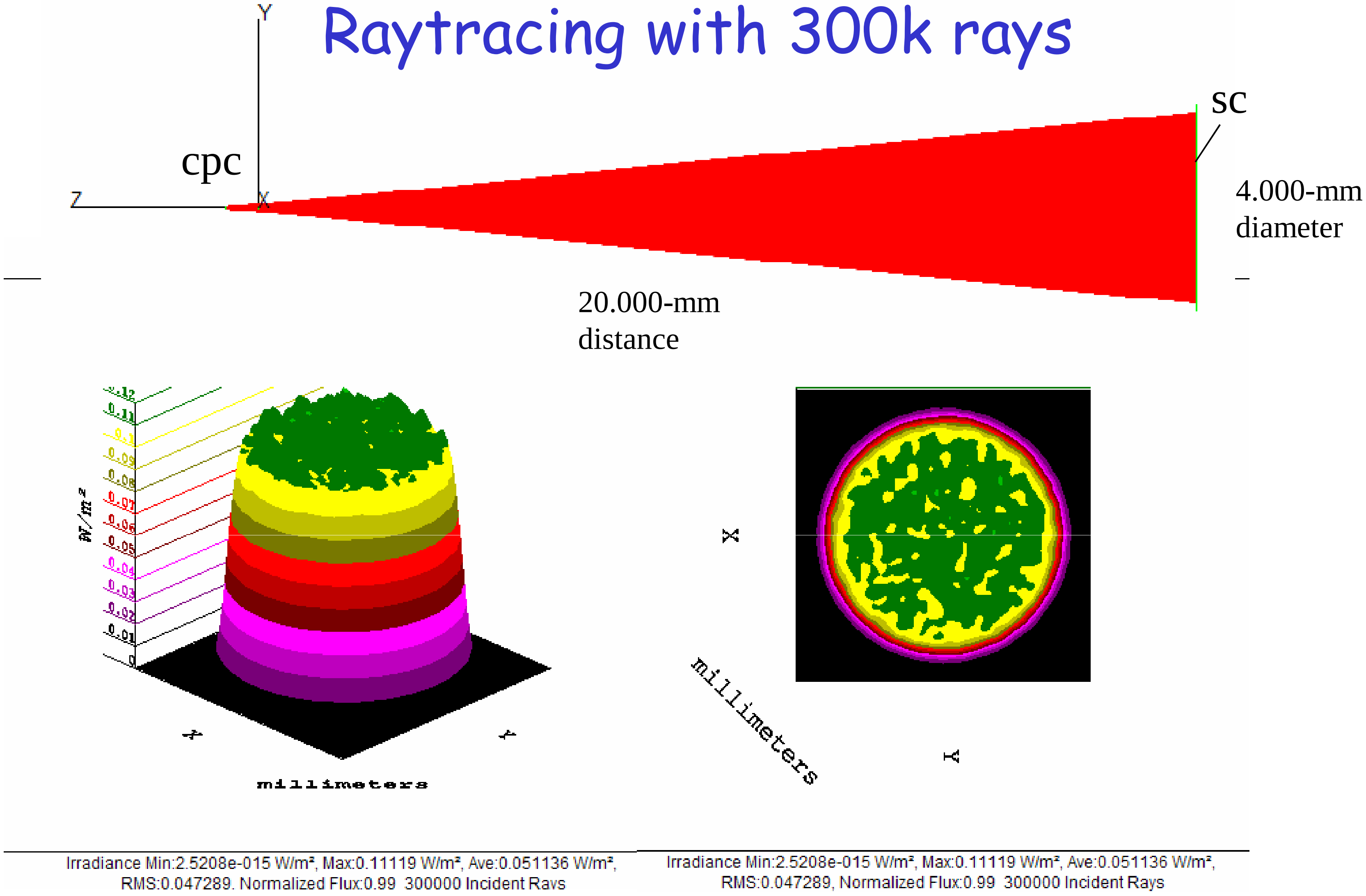
$$L_{rel}(\delta) = \frac{L(\delta)}{L(0)} = \frac{E(d, x)}{E(d, 0)} \cdot \frac{1}{\cos^4 \delta} = E_{rel}(d, x) \cdot \frac{1}{\cos^4 \delta}$$

Theory

$$L_{rel}(\delta) = \eta_{rel}(\delta)$$

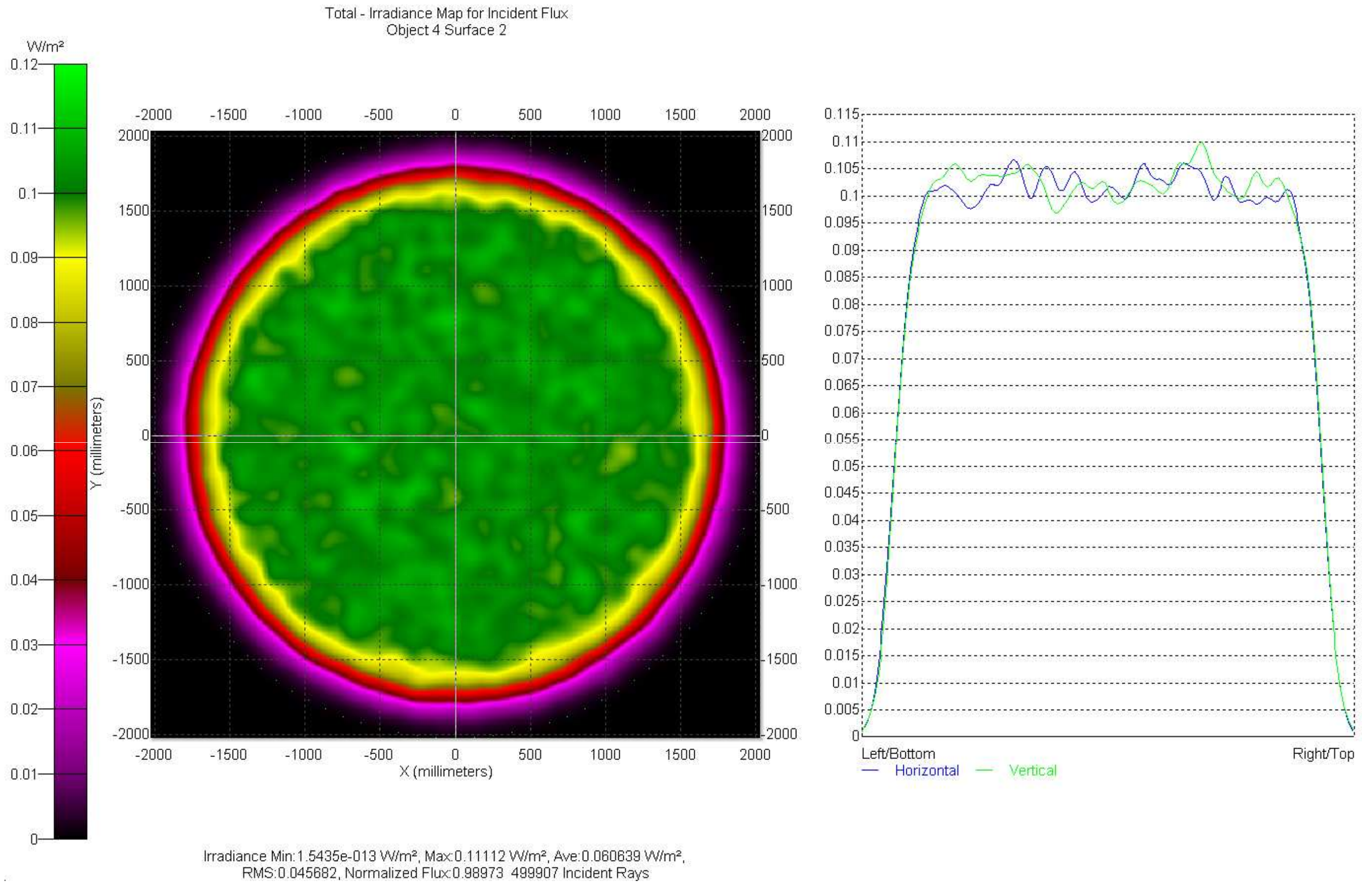
$\eta_{rel}(\delta) =$ relative optical efficiency of CPC concentrator

Raytracing with 300k rays



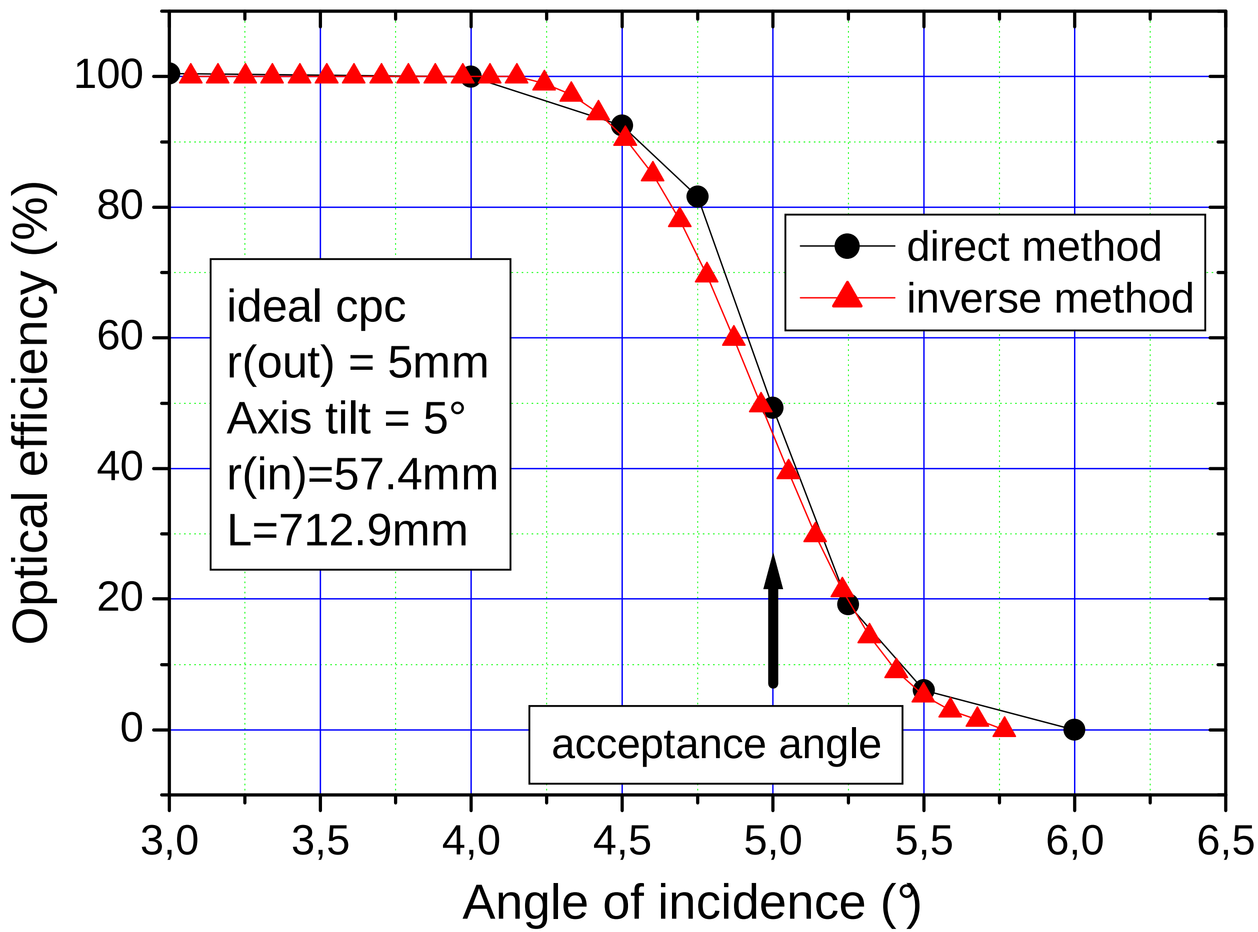
Irradiance distribution on the screen at large distance

Irradiance distribution



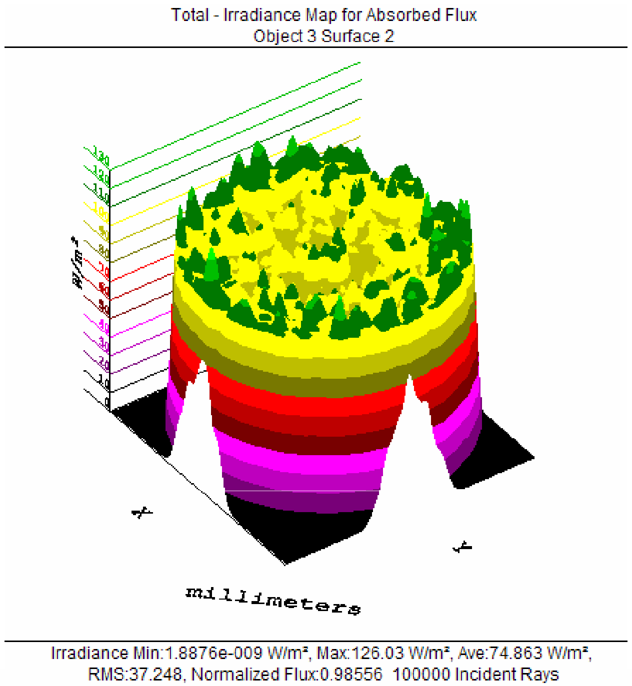
Irradiance map (left) and x/y profile (right) (500k rays)

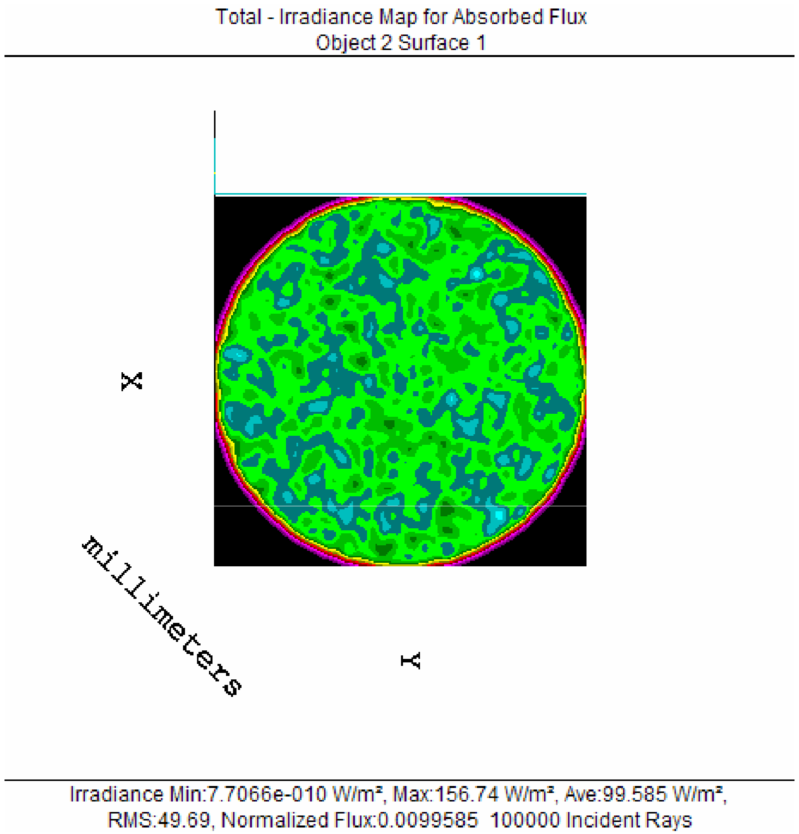
Optical efficiency

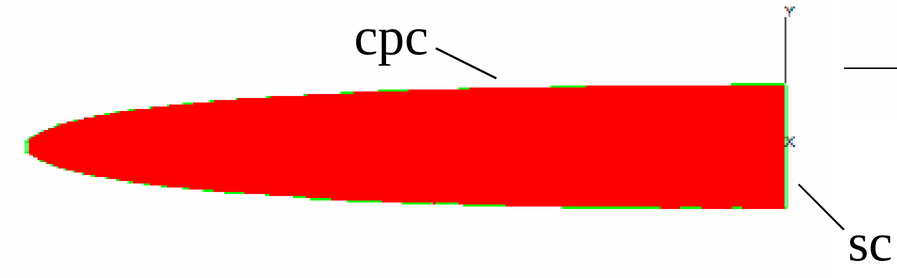


Comparison between direct and inverse method

Irradiance distribution







Screen faced directly on the CPC aperture

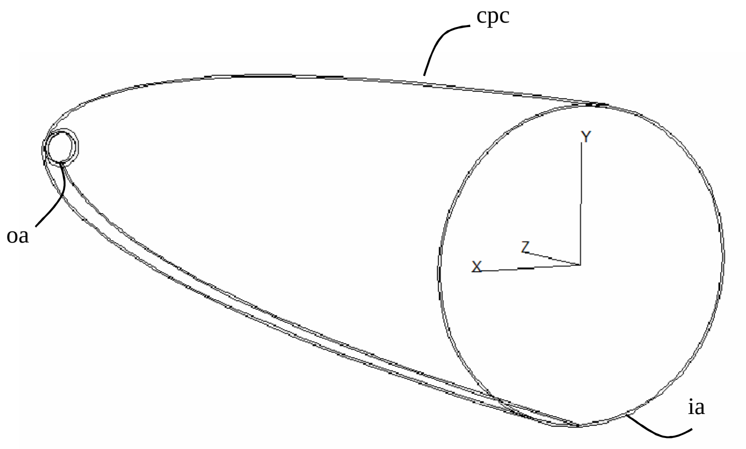
APPLICATIONS

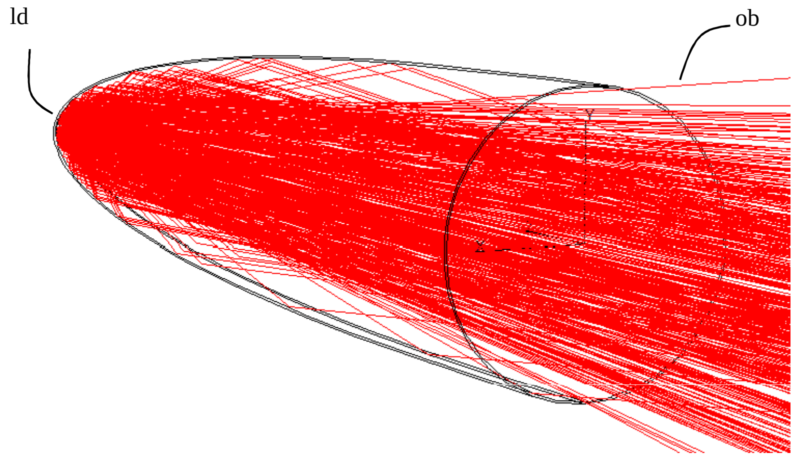
Half-Truncated CPC (HT-CPC)

<u>Inverse analysis</u>

<u>Simulations with TracePro</u>

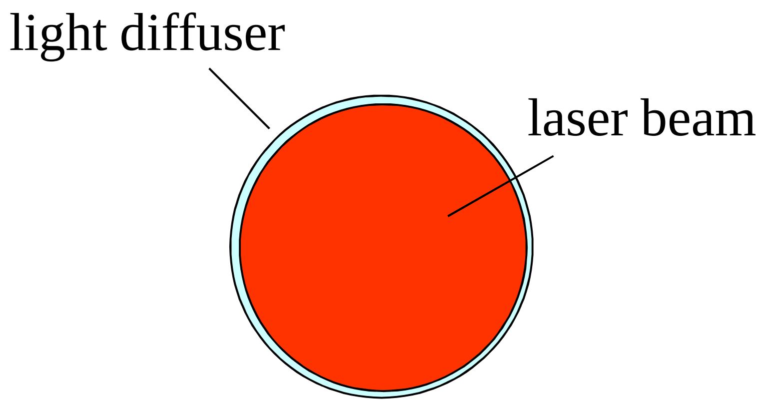
Half-Truncated CPC (HT-CPC)



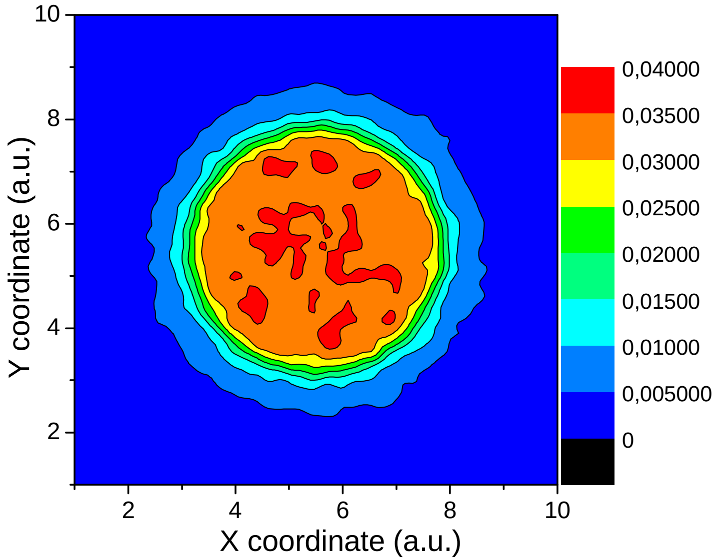


HT-CPC
r(out) = 5 mm
Axis tilt = 5.1°
r(in) = 52 mm
L = 358 mm

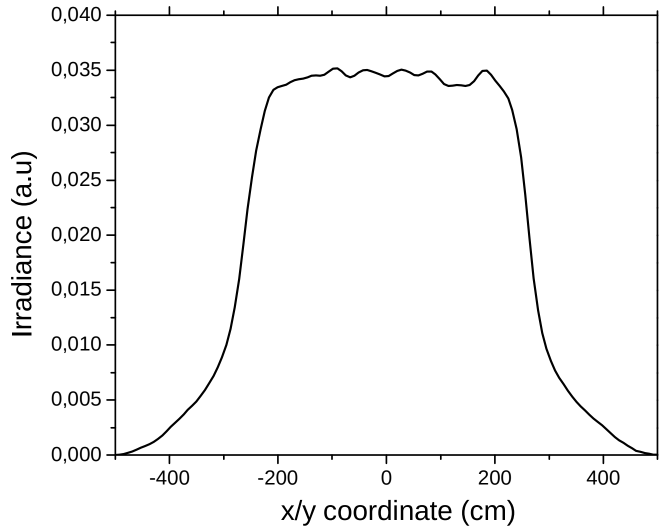
Centered laser beam
diffuser totally illuminated
Screen at <u>large distance</u>



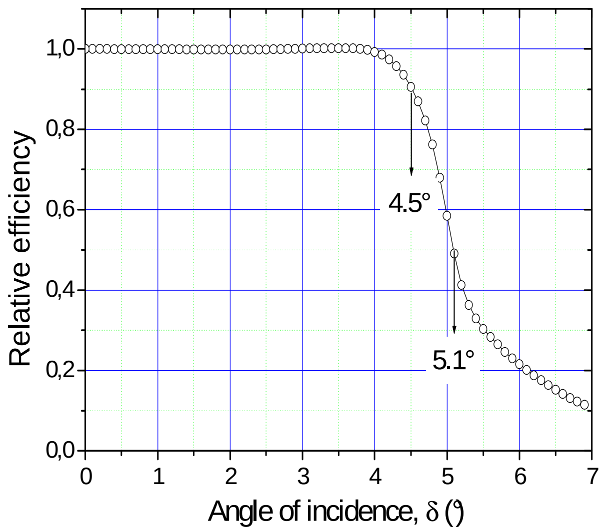
Inverse analysis (HT-CPC)



Irradiance surface



Irradiance x/y profile

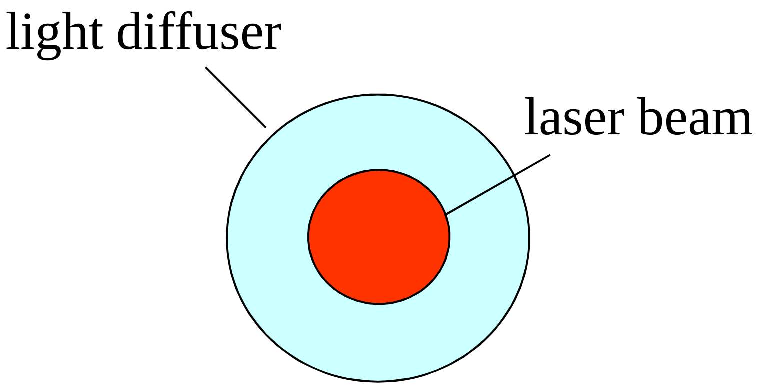


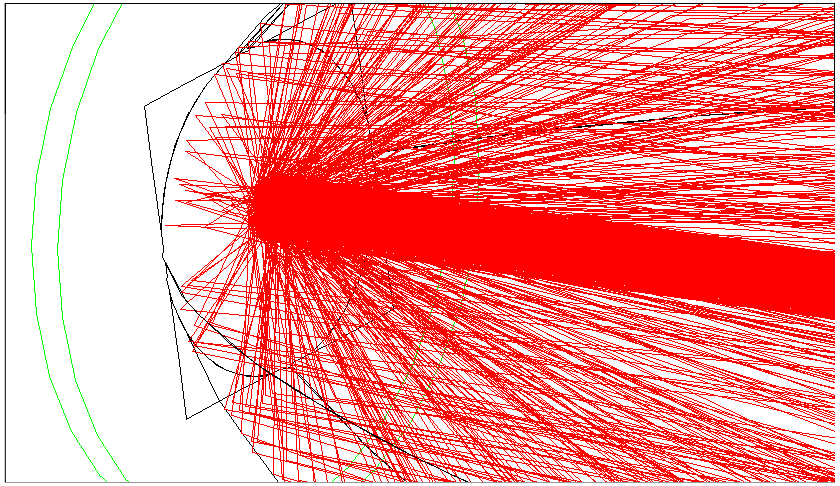
Relative efficiency

Acceptance angle:

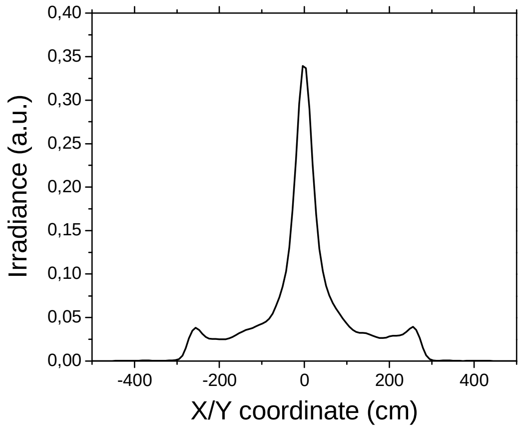
4.5° (90% Efficiency)
5.1° (50% Efficiency)

Centered laser beam with variable cross section

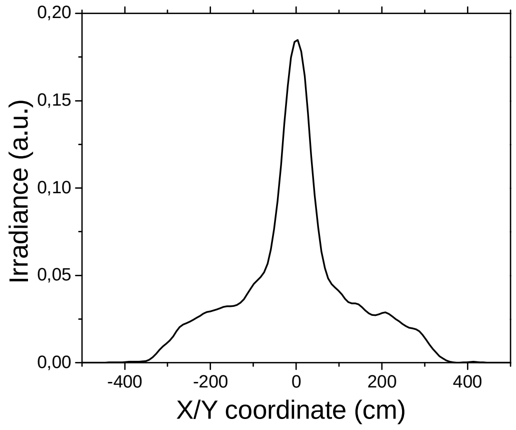




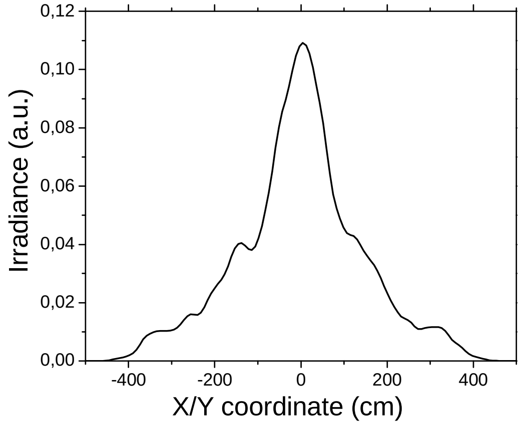
Inverse analysis (HT-CPC)



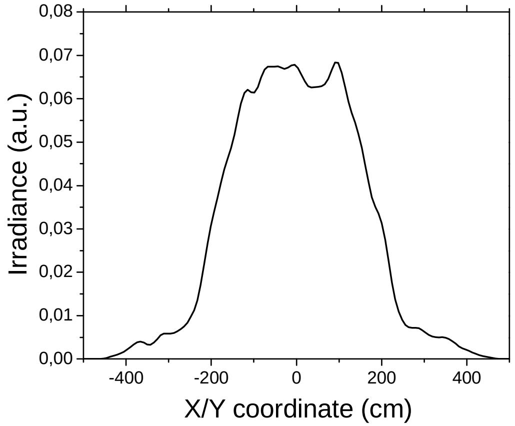
R= 0.05 mm



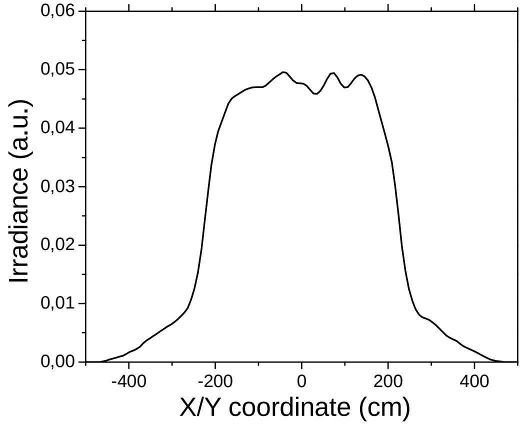
R= 0.5 mm



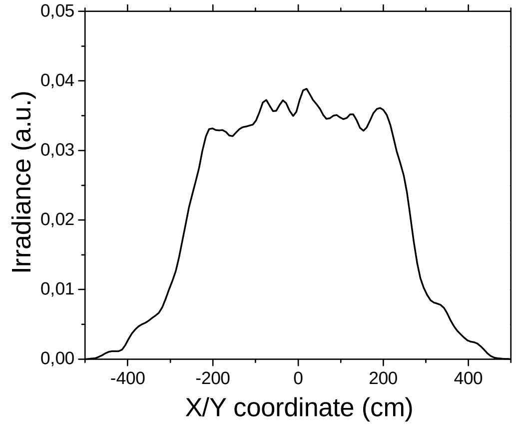
R= 1.0 mm



R= 2.5 mm

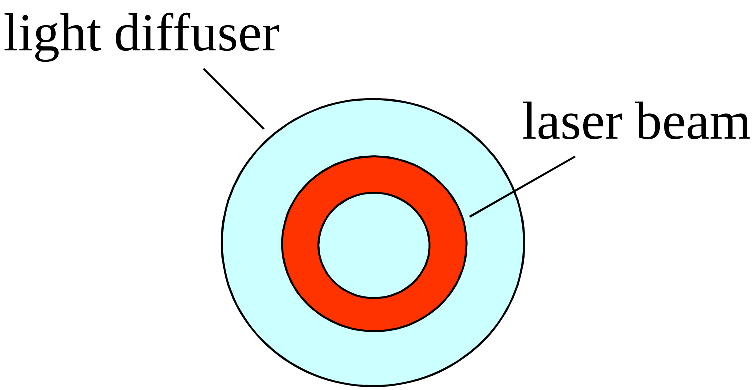


R= 3.5 mm

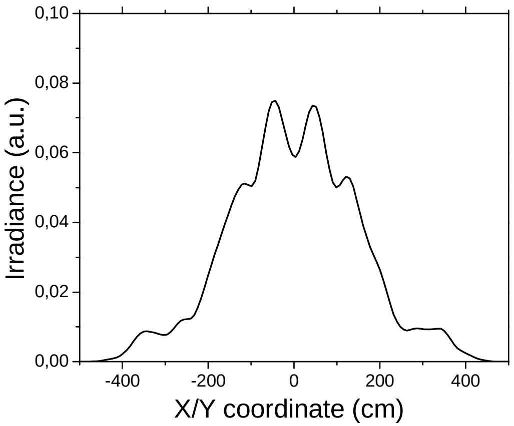


R= 5.0 mm

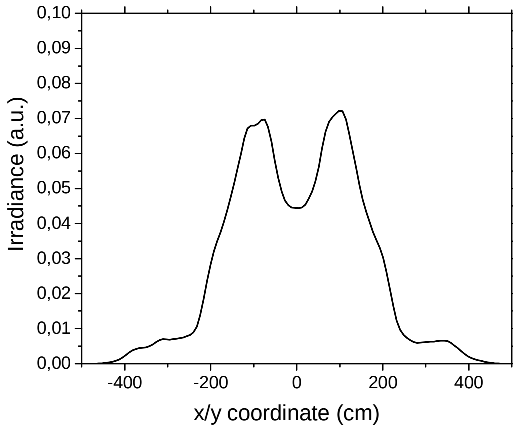
Centered laser beam with shape of annulus and variable internal radius (constant area = 3.14 mm^2)



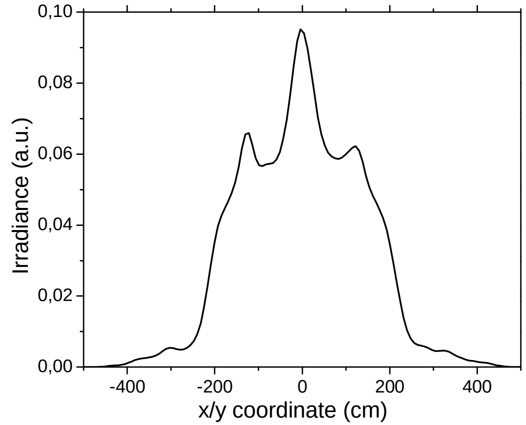
Inverse analysis (HT-CPC)



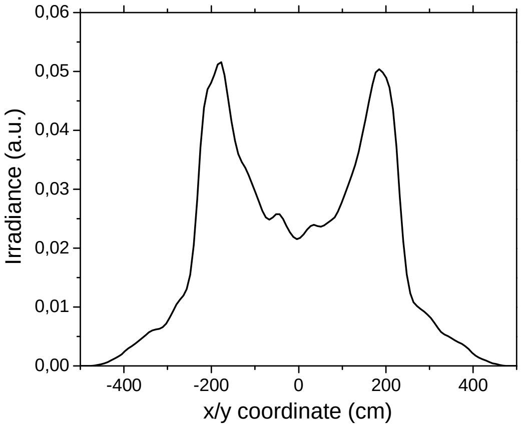
R= 0.5 mm



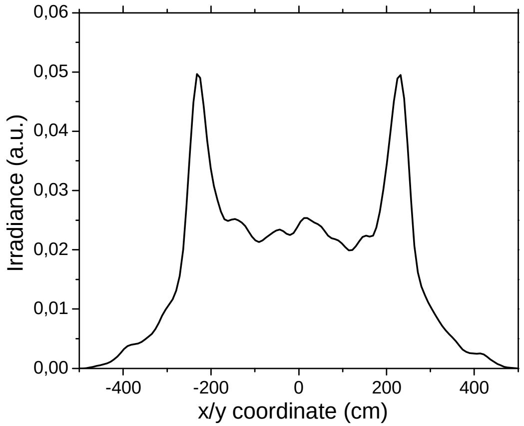
R= 1.0 mm



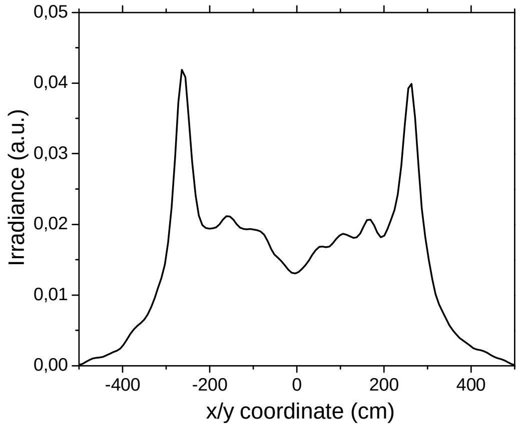
R= 2.0 mm



R= 3.0 mm

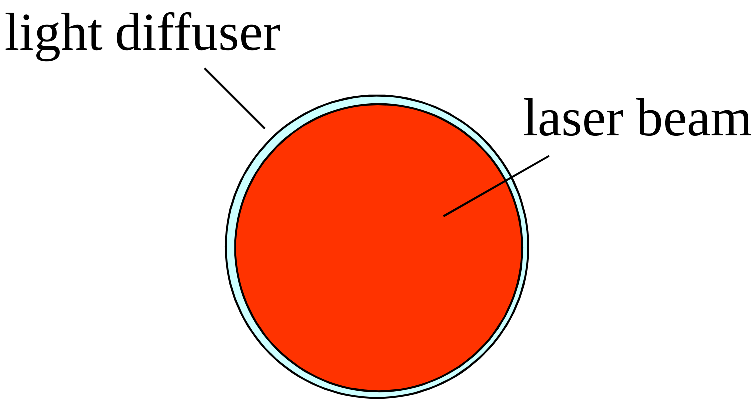


R= 4.0 mm

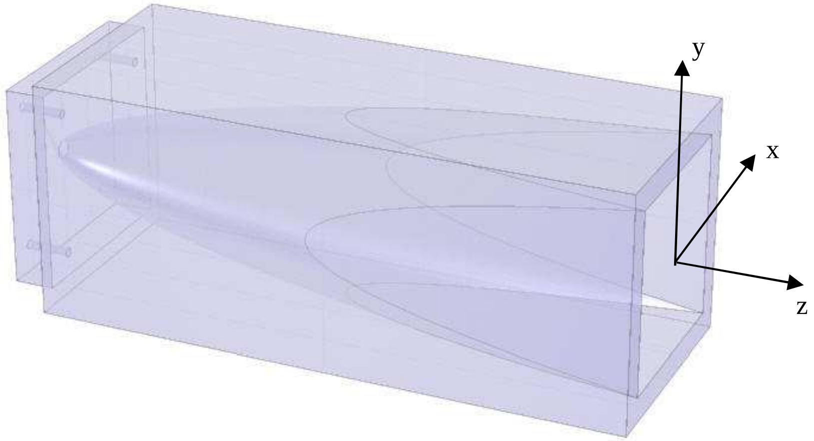


R= 4.9 mm

Centered laser beam
Diffuser totally illuminated
Screen at variable distance



Truncated and Squared CPC (TS-CPC)



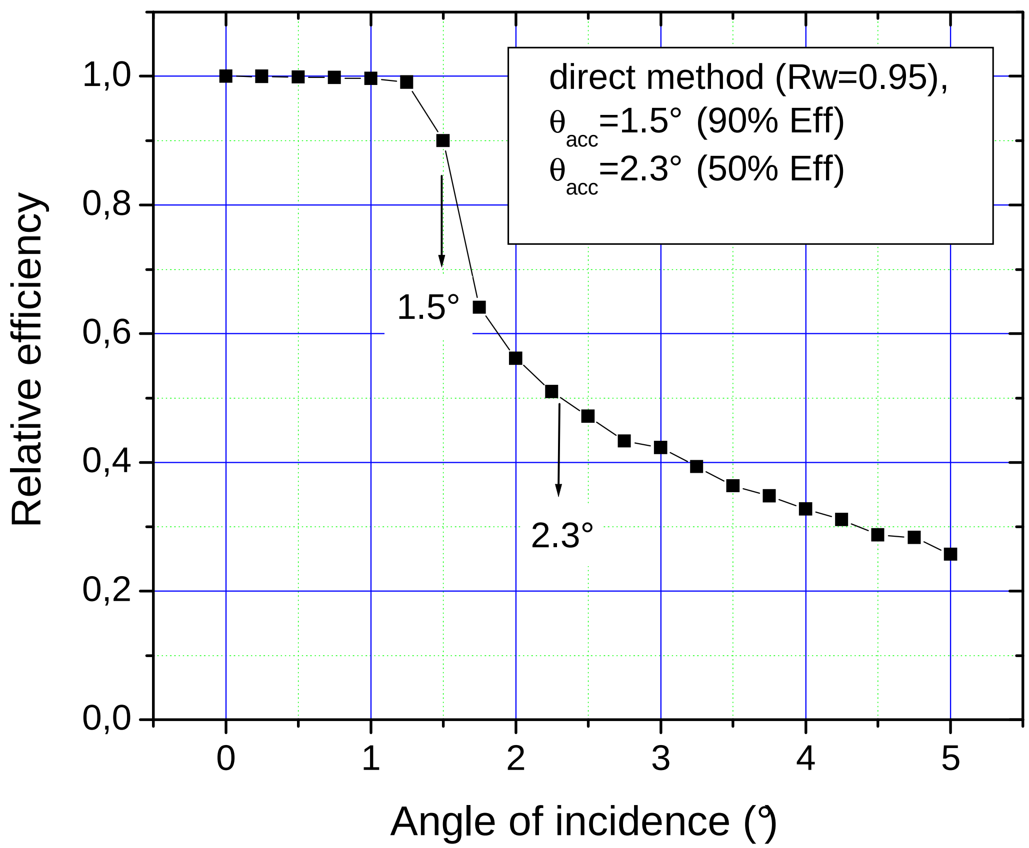
TS-CPC
r(out) = 5 mm
l(in) = 100 mm
L = 350 mm

Truncated and Squared CPC (TS-CPC)

Direct analysis

Simulations with TracePro

Truncated and Squared CPC (TS-CPC)



Acceptance angle:

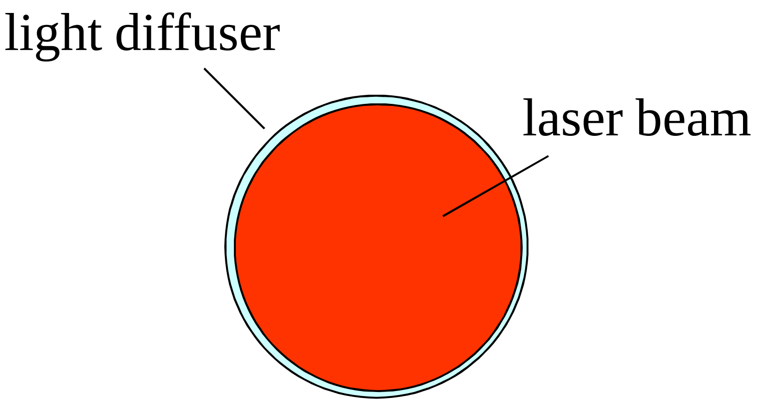
1.5° (90% Efficiency)
2.3° (50% Efficiency)

Truncated and Squared CPC (TS-CPC)

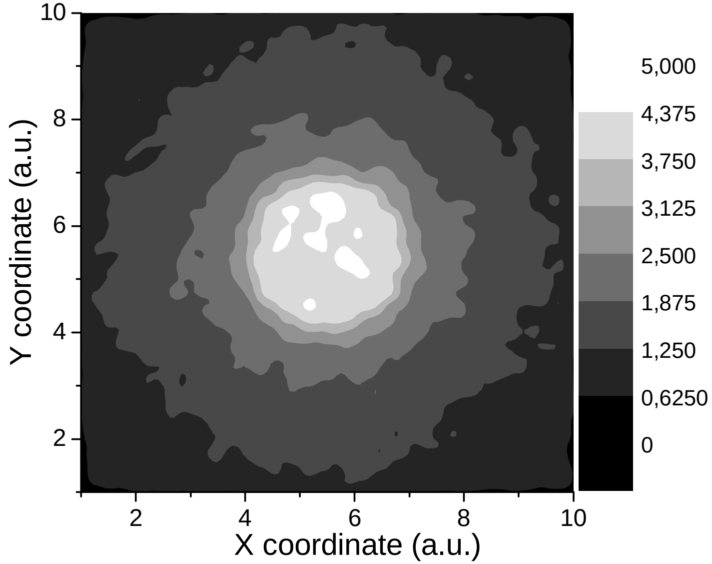
Inverse analysis

Simulations with TracePro

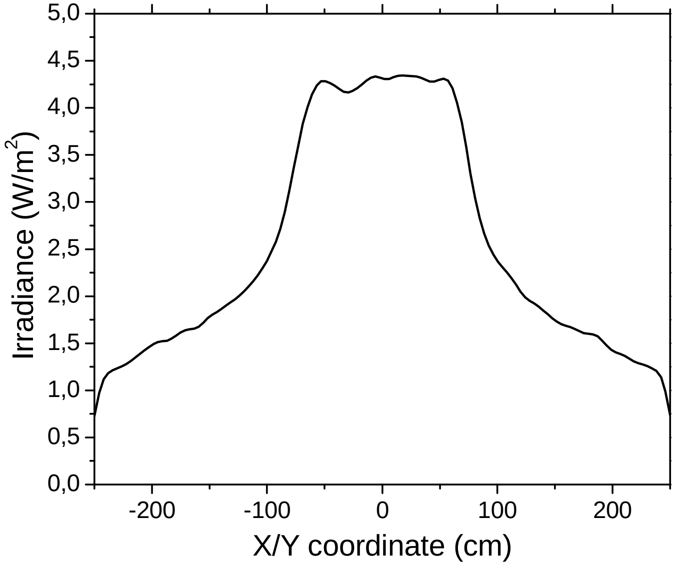
Centered laser beam
diffuser totally illuminated
Screen at <u>large distance</u>



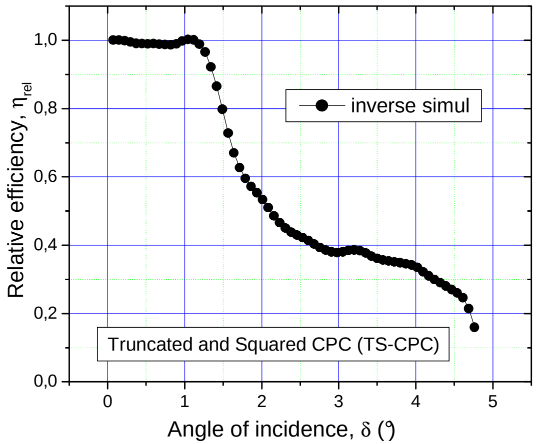
Inverse analysis (TS-CPC)



Irradiance surface



Irradiance x/y profile

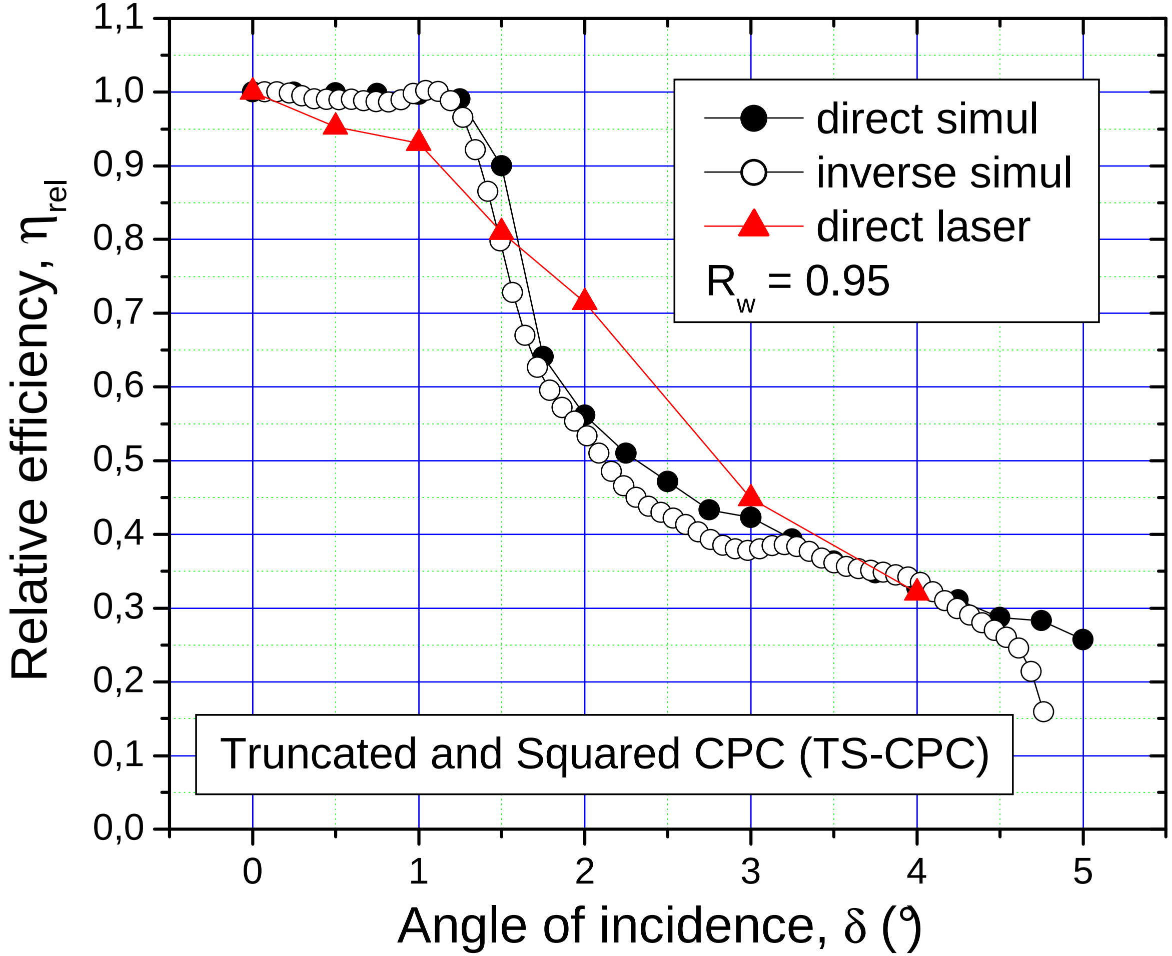


Relative efficiency

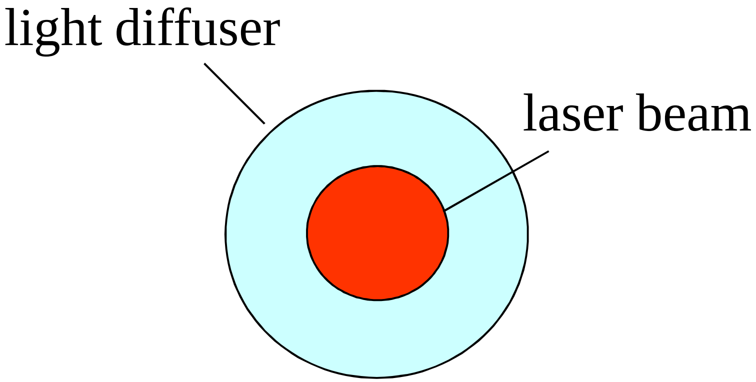
Acceptance angle:

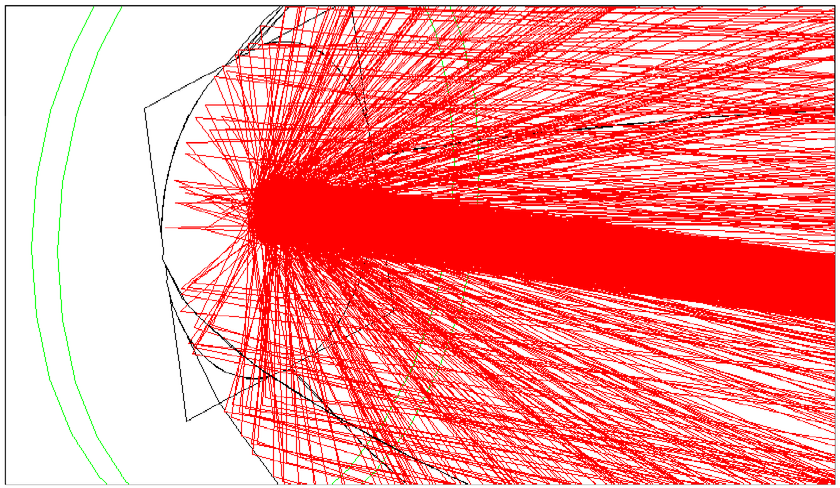
1.4° (90% Efficiency)
2.1° (50% Efficiency)

TS-CPC - Comparison between direct and inverse methods

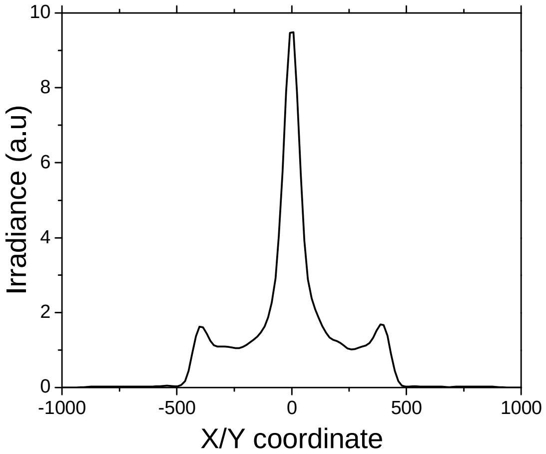


Centered laser beam with variable cross section

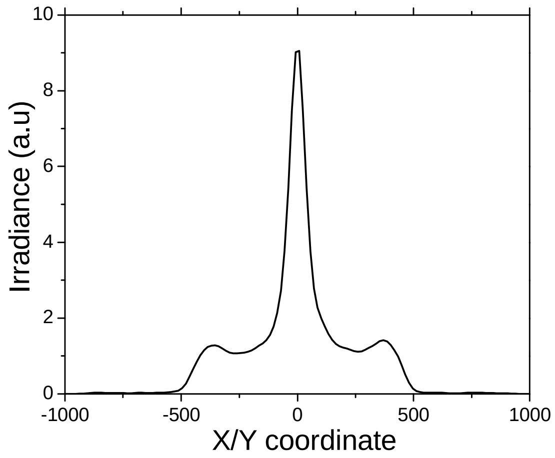




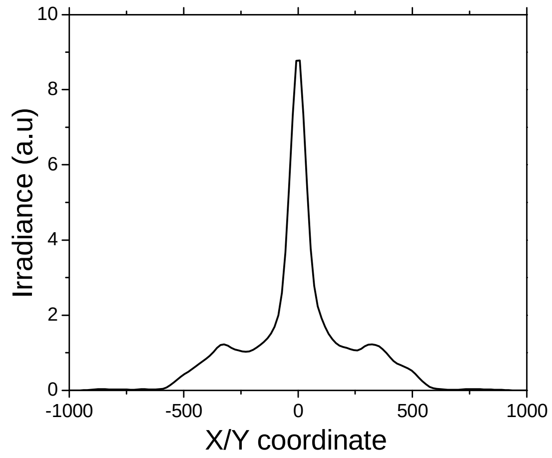
Inverse analysis (TS-CPC)



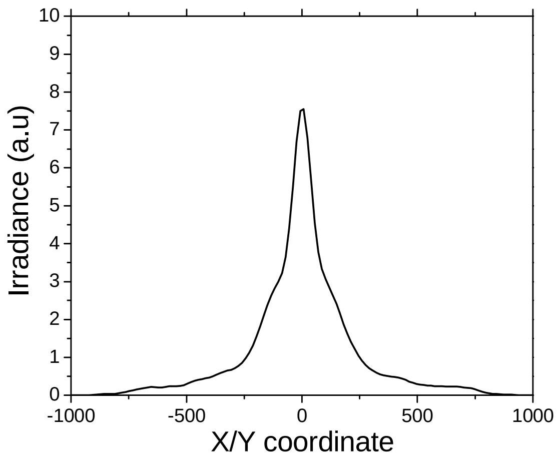
R= 0.05 mm



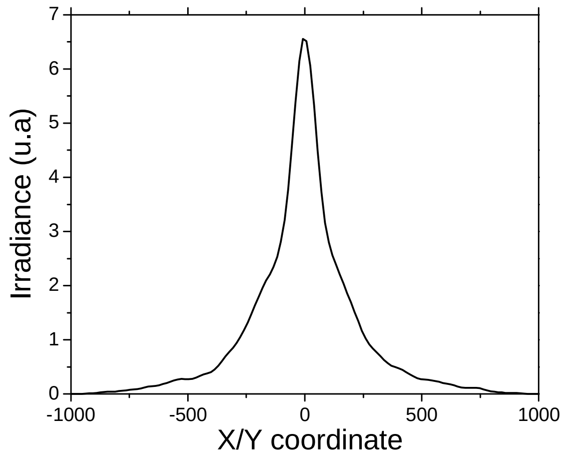
R= 0.5 mm



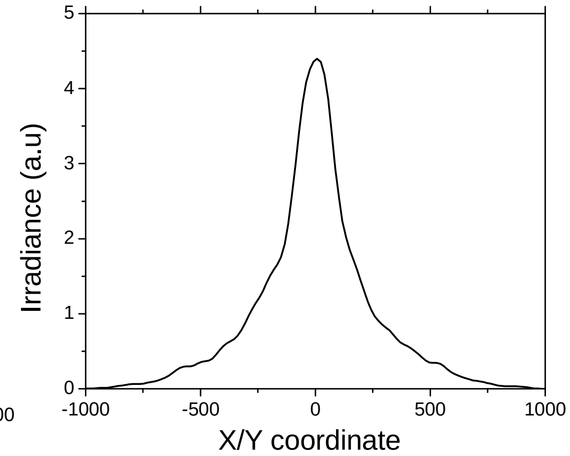
R= 1.0 mm



R= 2.5 mm

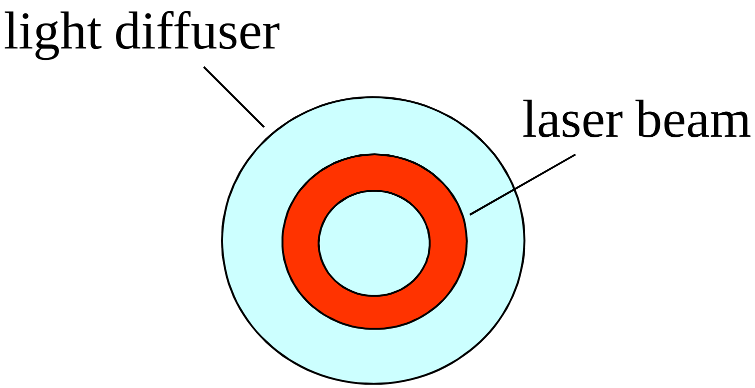


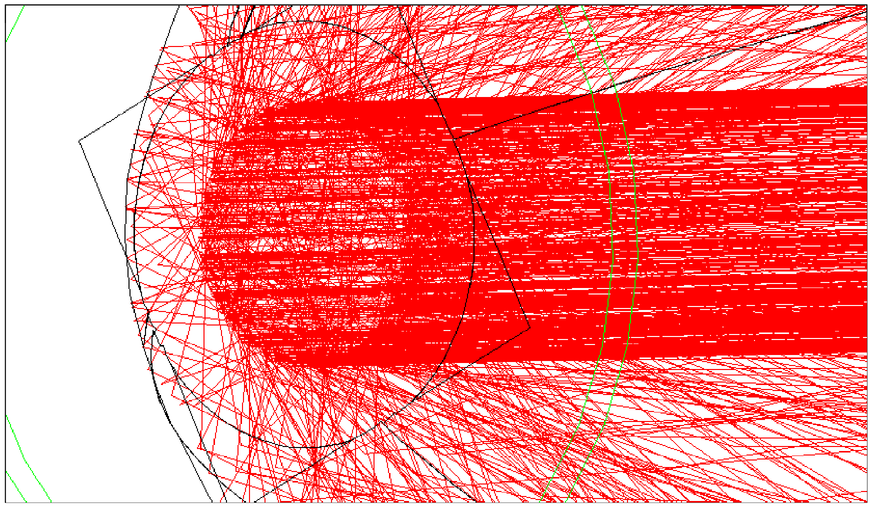
R= 3.5 mm



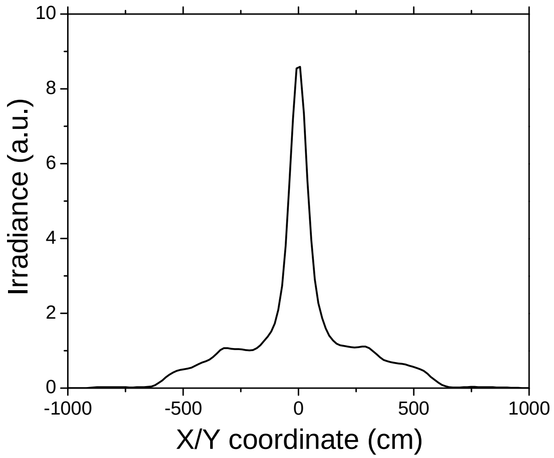
R= 5.0 mm

Centered laser beam with shape of annulus and variable internal radius (constant area = 3.14 mm^2)

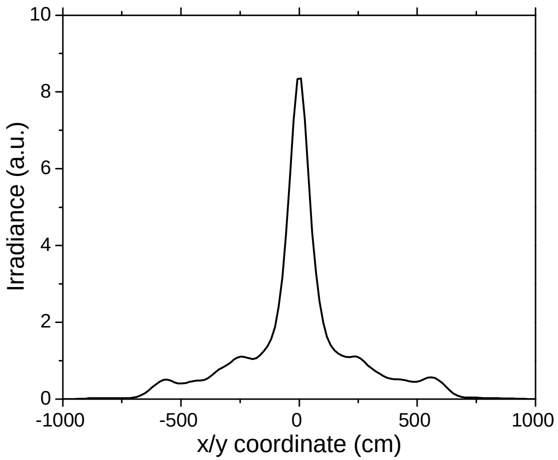




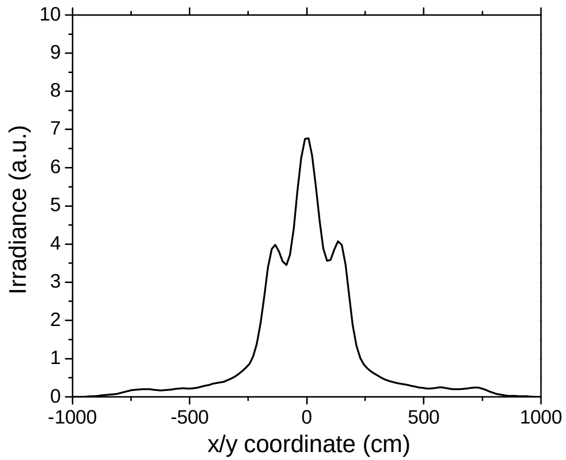
Inverse analysis (TS-CPC)



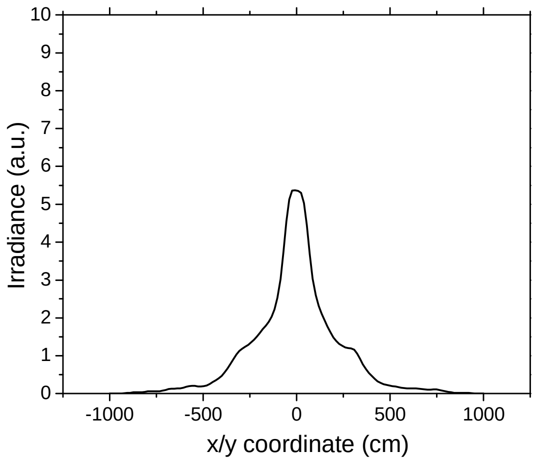
R= 0.5 mm



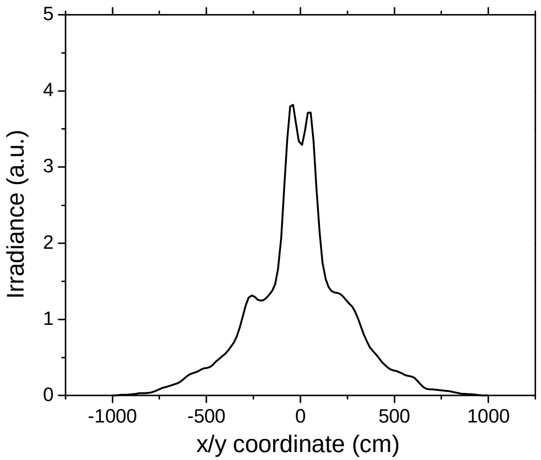
R= 1.0 mm



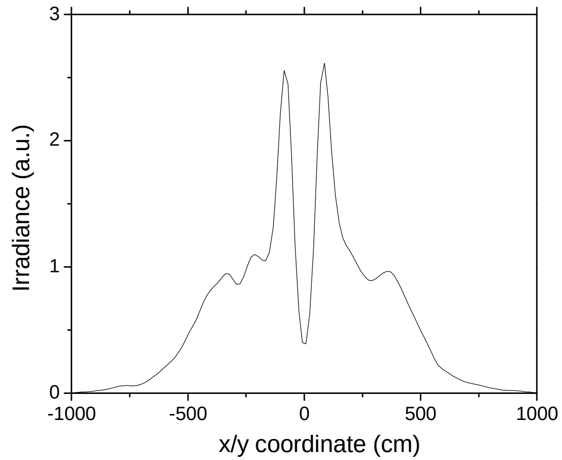
R= 2.0 mm



R= 3.0 mm

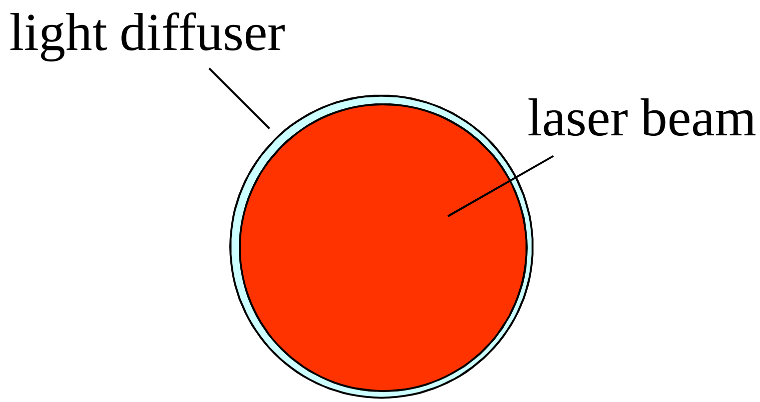


R= 4.0 mm

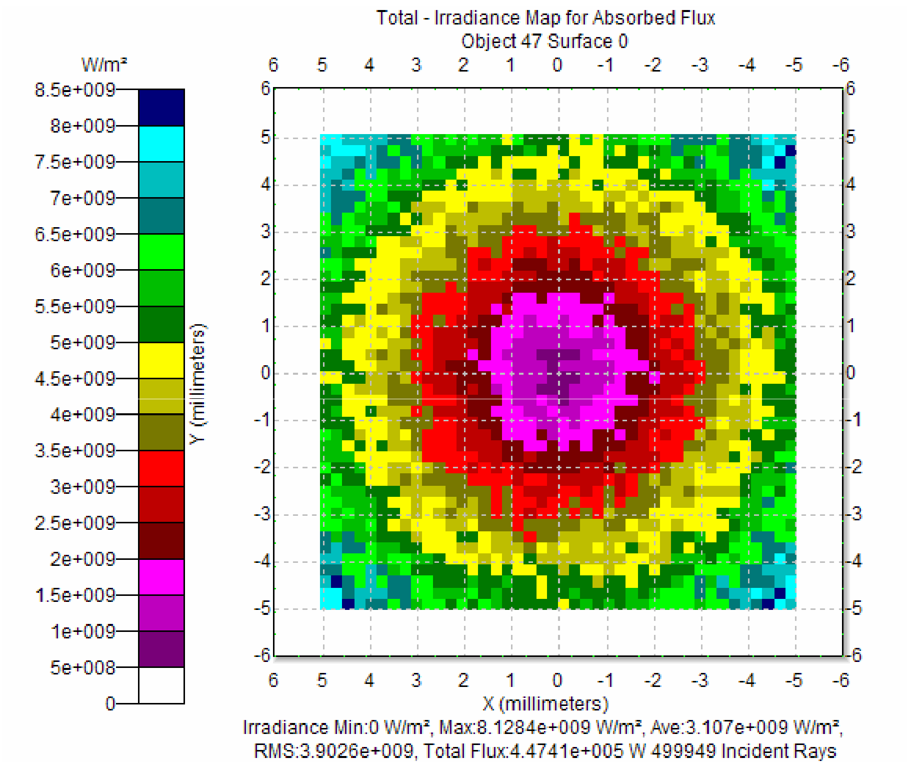


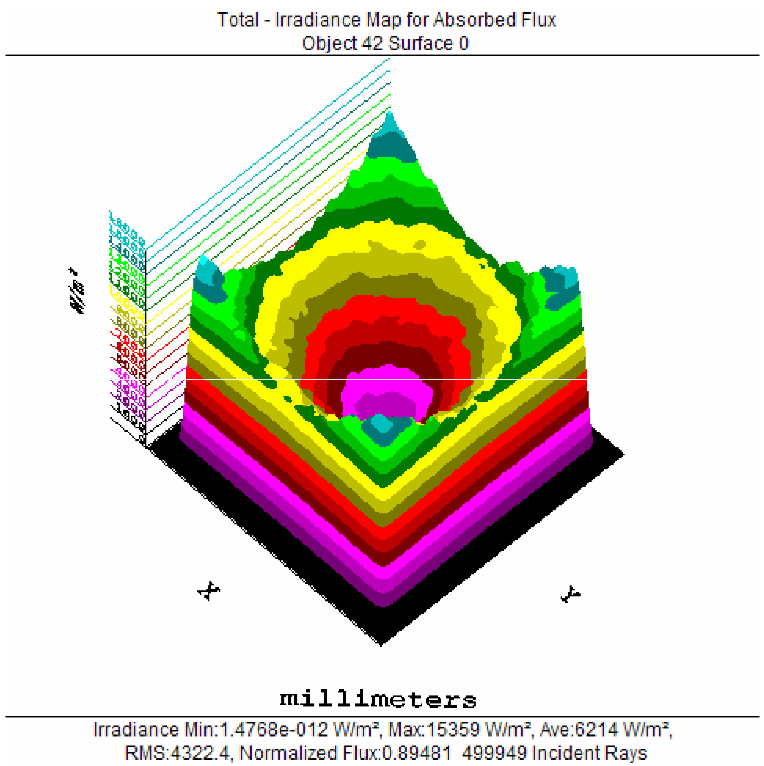
R= 4.9 mm

Centered laser beam
Diffuser totally illuminated
Screen at variable distance



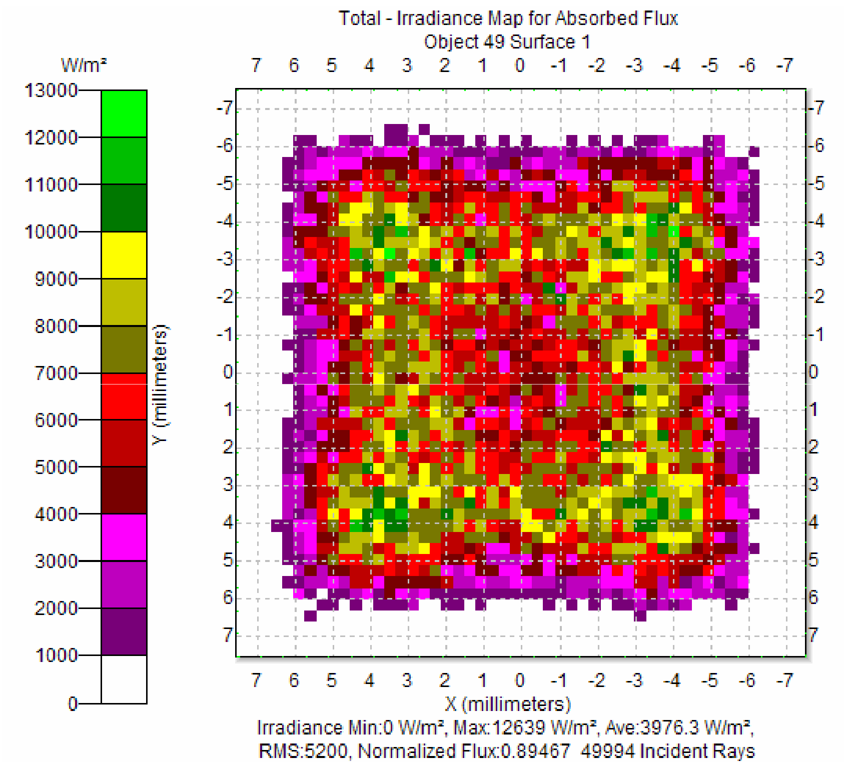
Inverse analysis (TS-CPC)

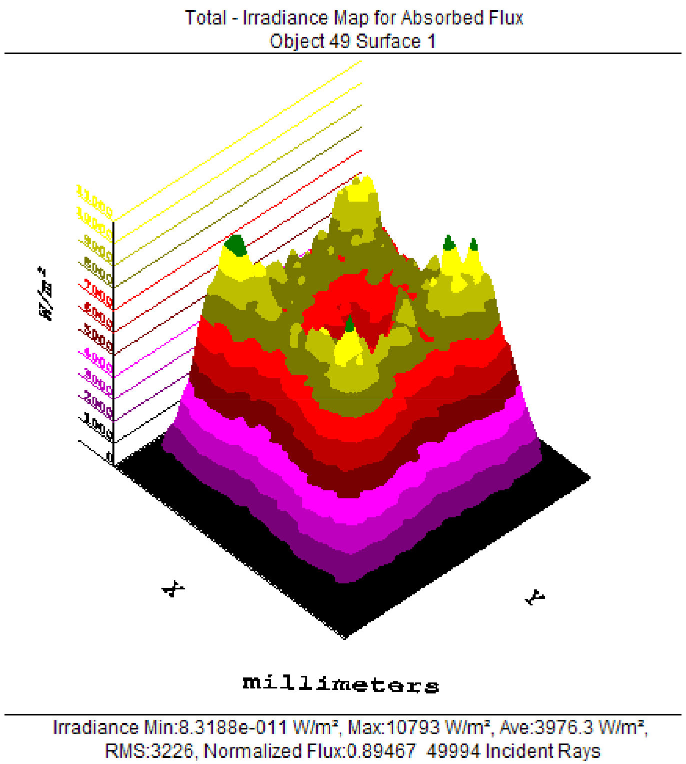




d = 0 cm

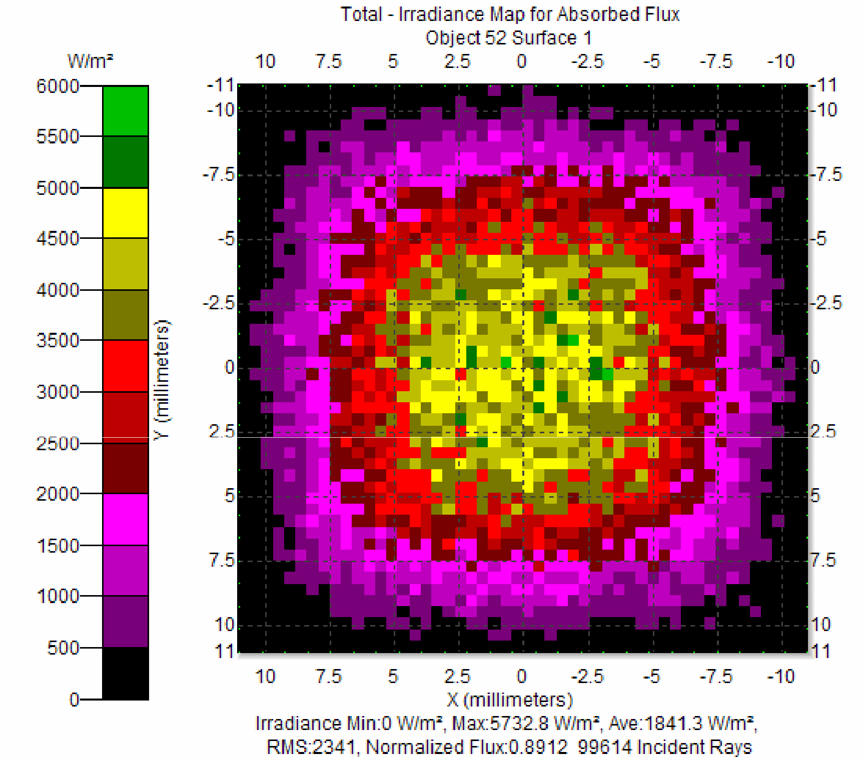
Inverse analysis (TS-CPC)

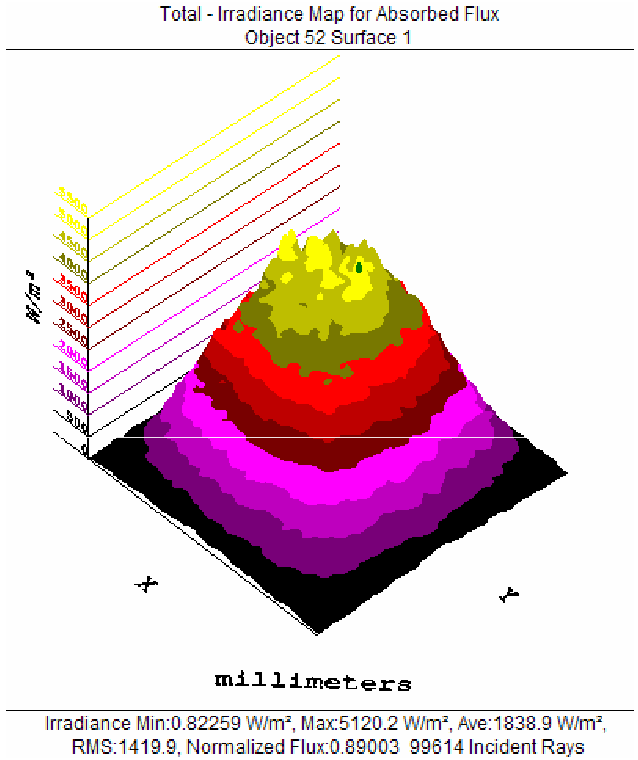




d = 10 cm

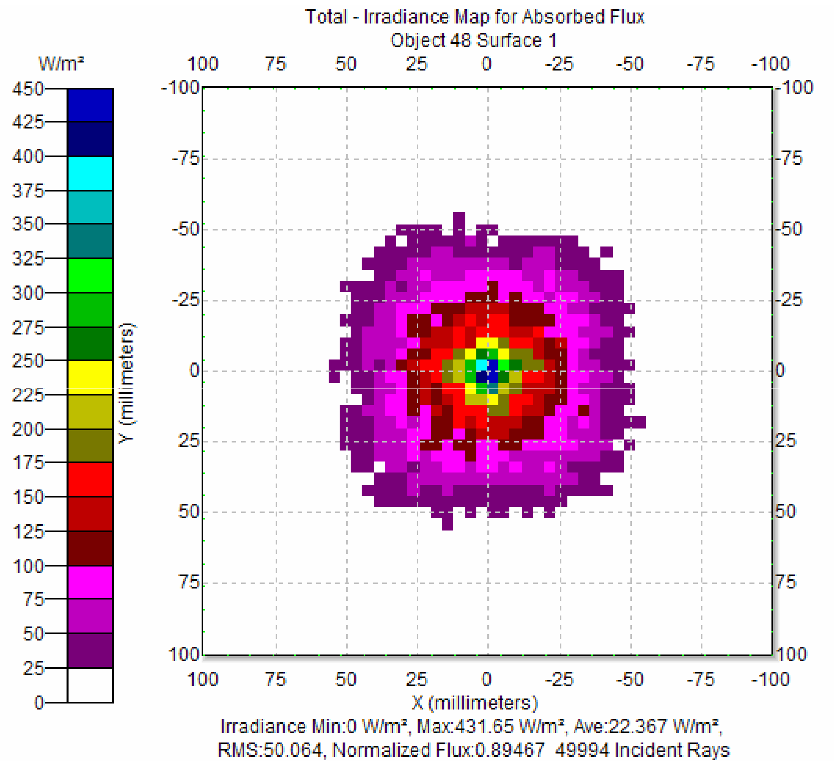
Inverse analysis (TS-CPC)

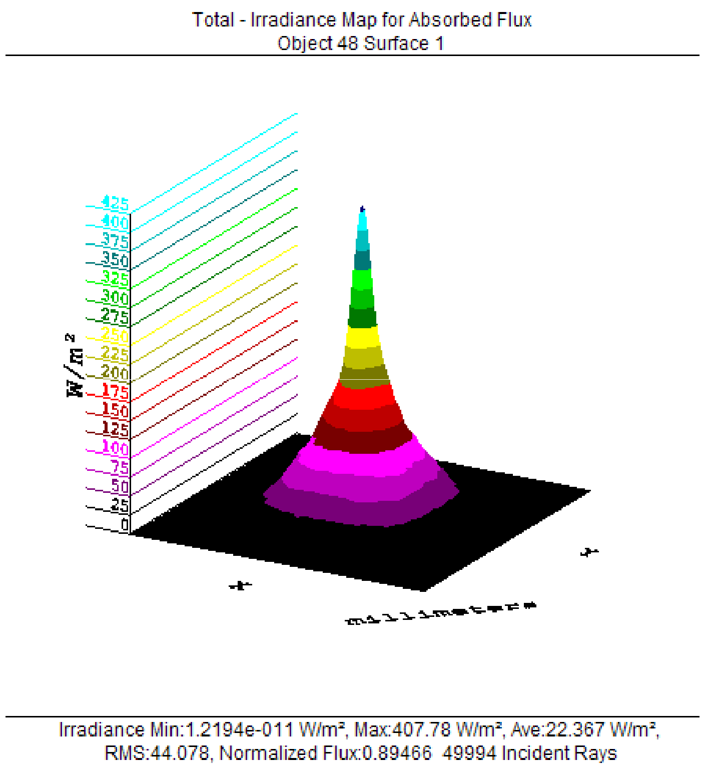




d = 40 cm

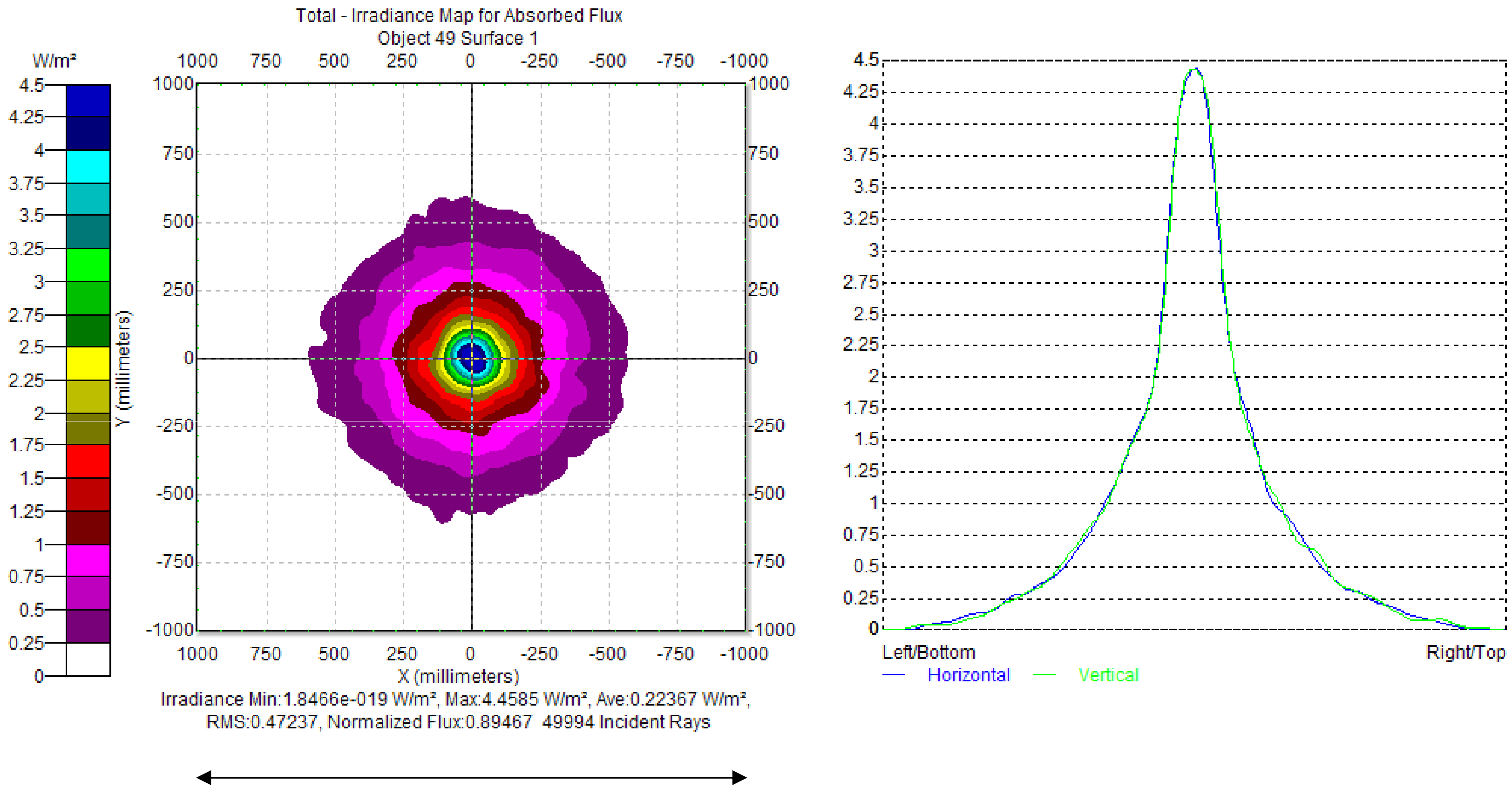
Inverse analysis (TS-CPC)





d = 300 cm

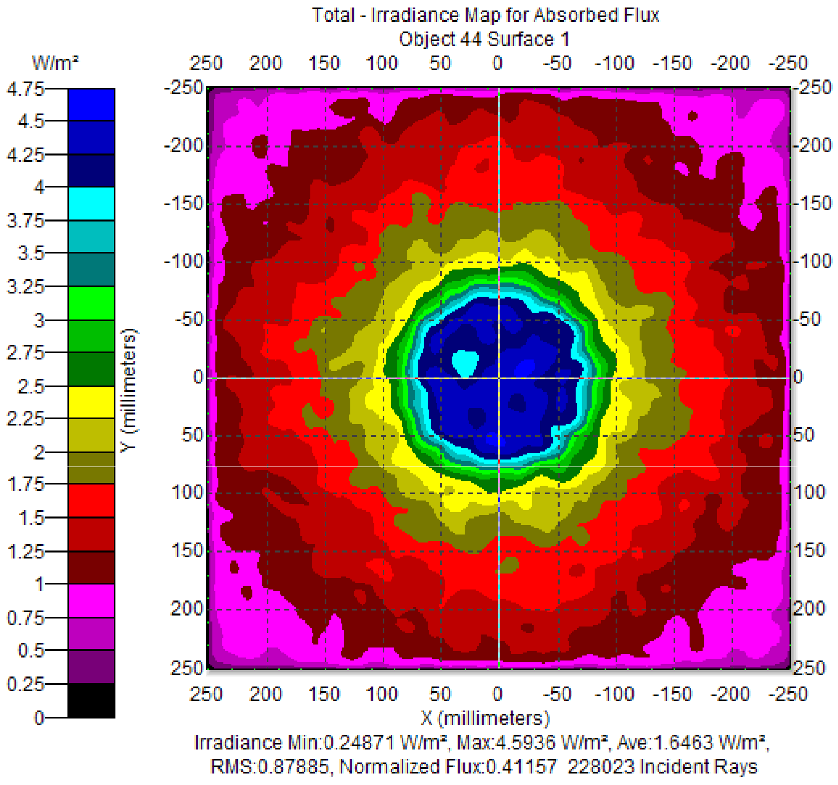
Inverse analysis (TS-CPC)

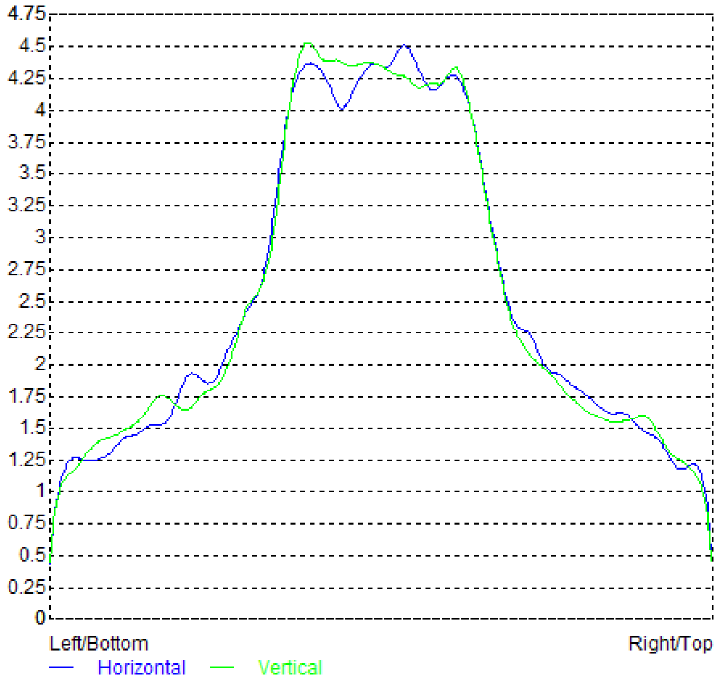


2000 cm

d = 3000 cm

Inverse analysis (TS-CPC)





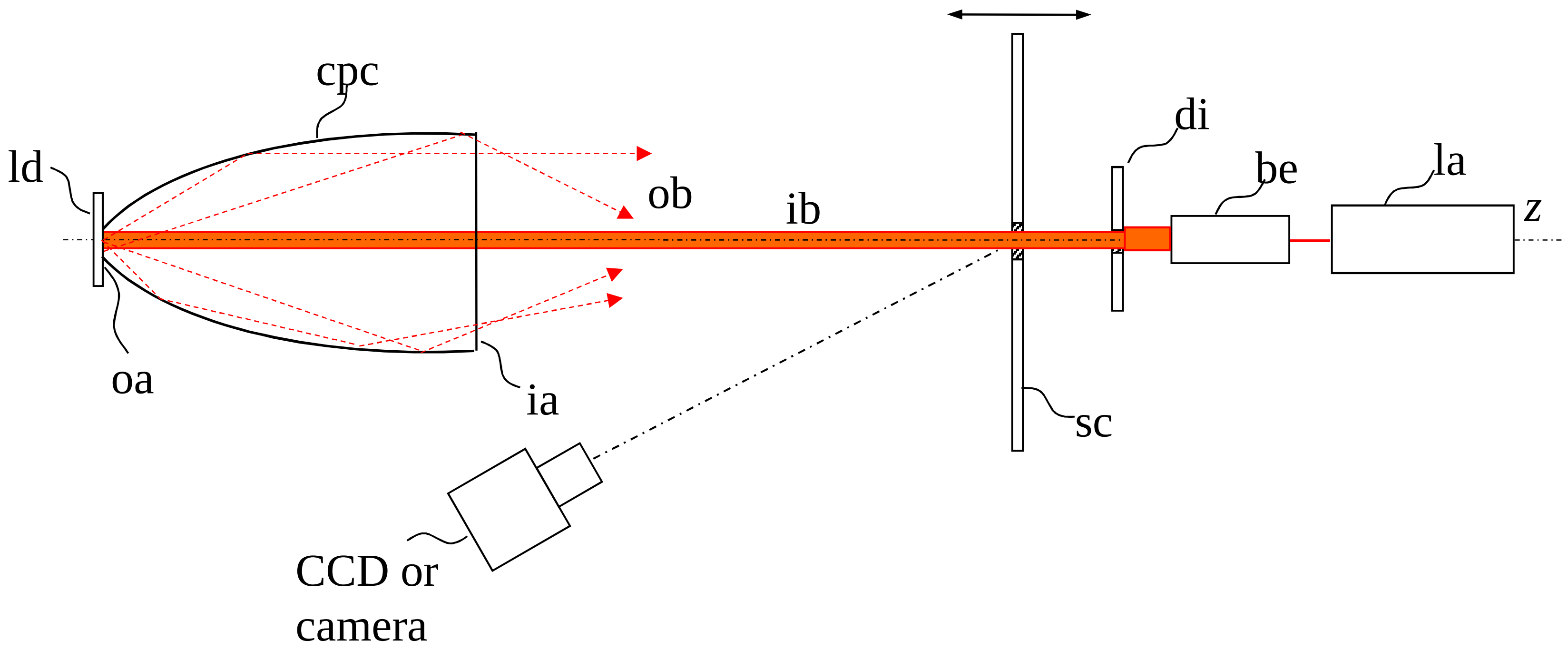
500 cm

d = 3000 cm

Truncated and Squared CPC (TS-CPC)

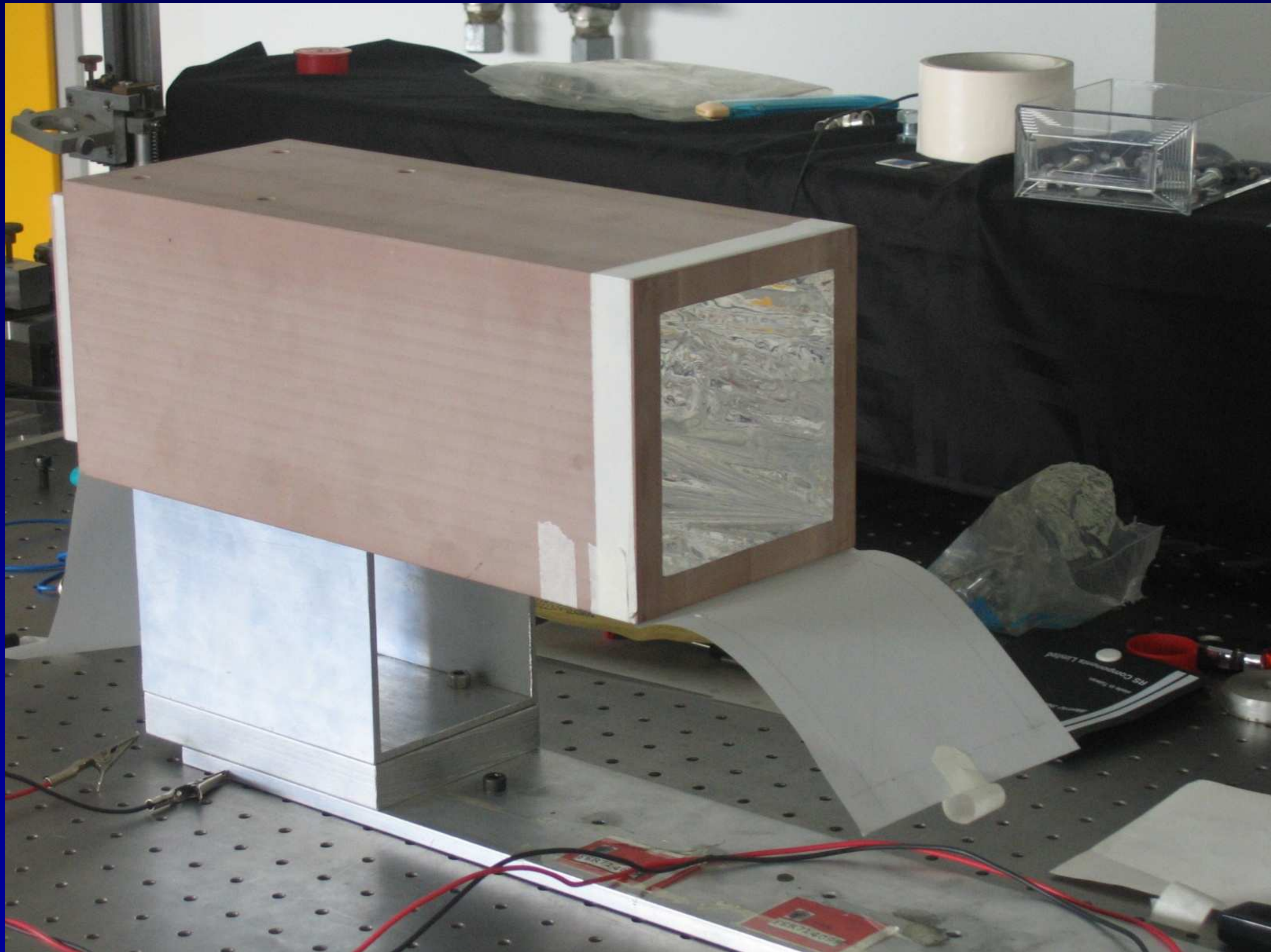
Inverse analysis

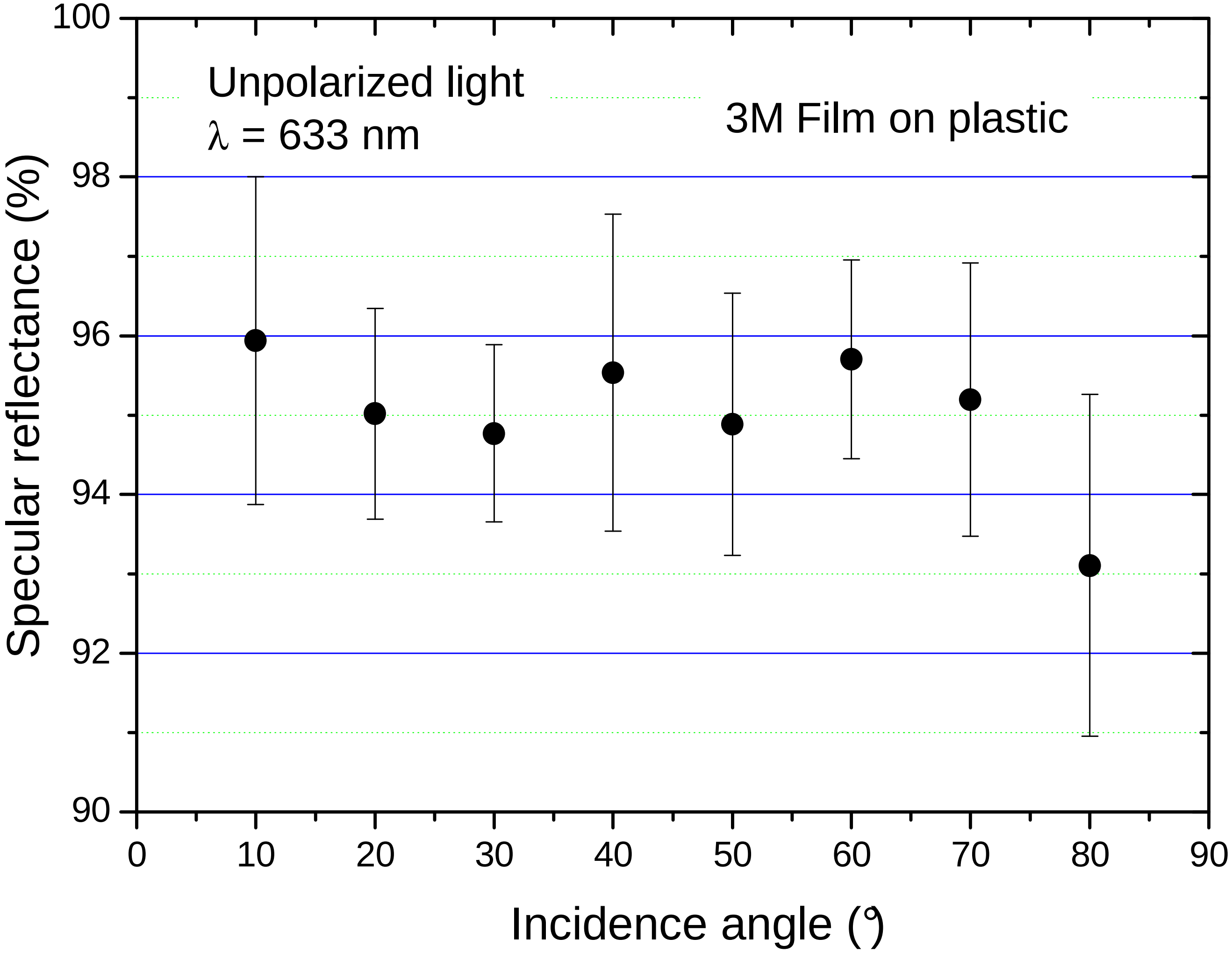
Experiments



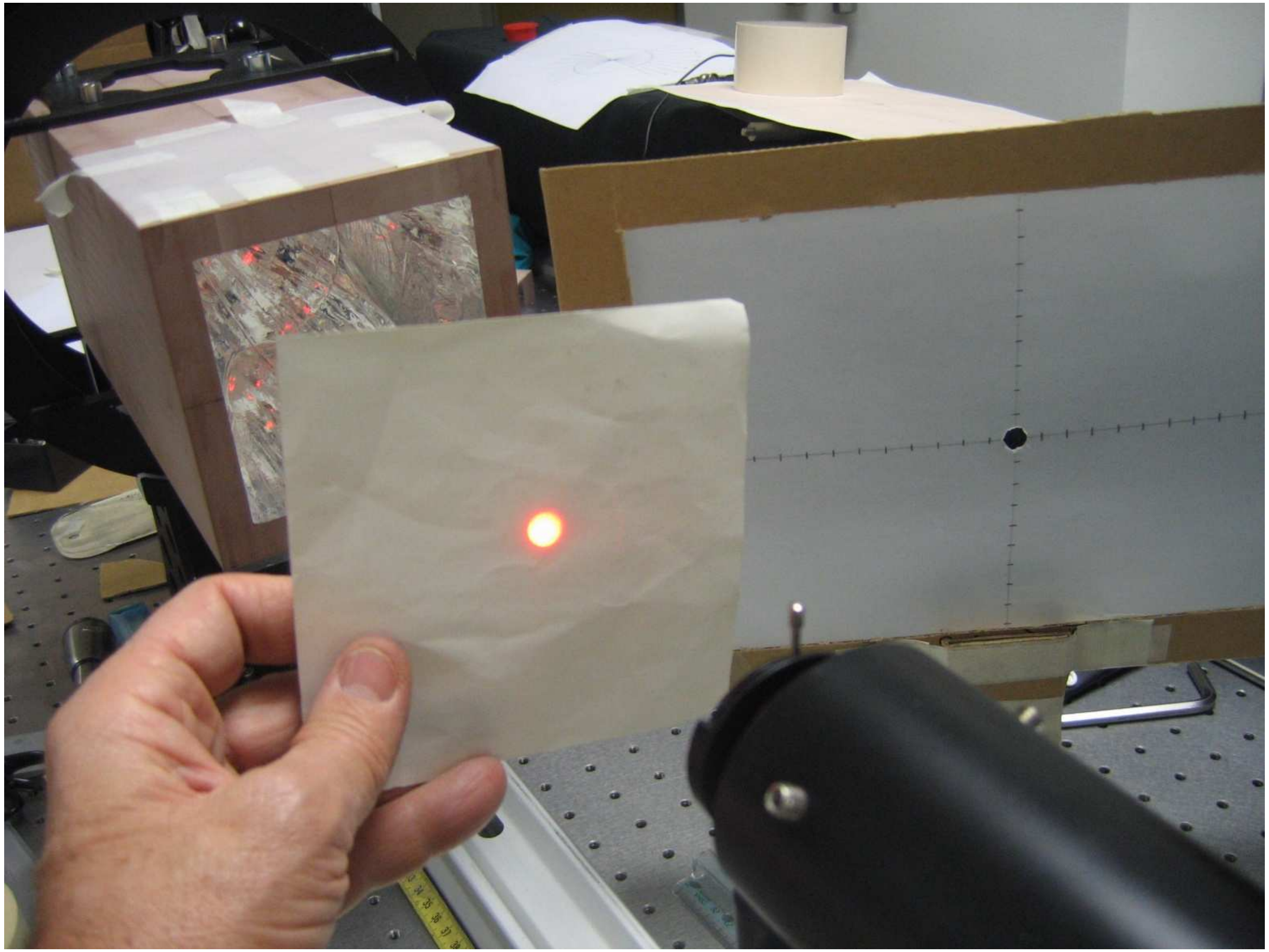
Experimental set-up

Truncated and Squared CPC (TS-CPC)

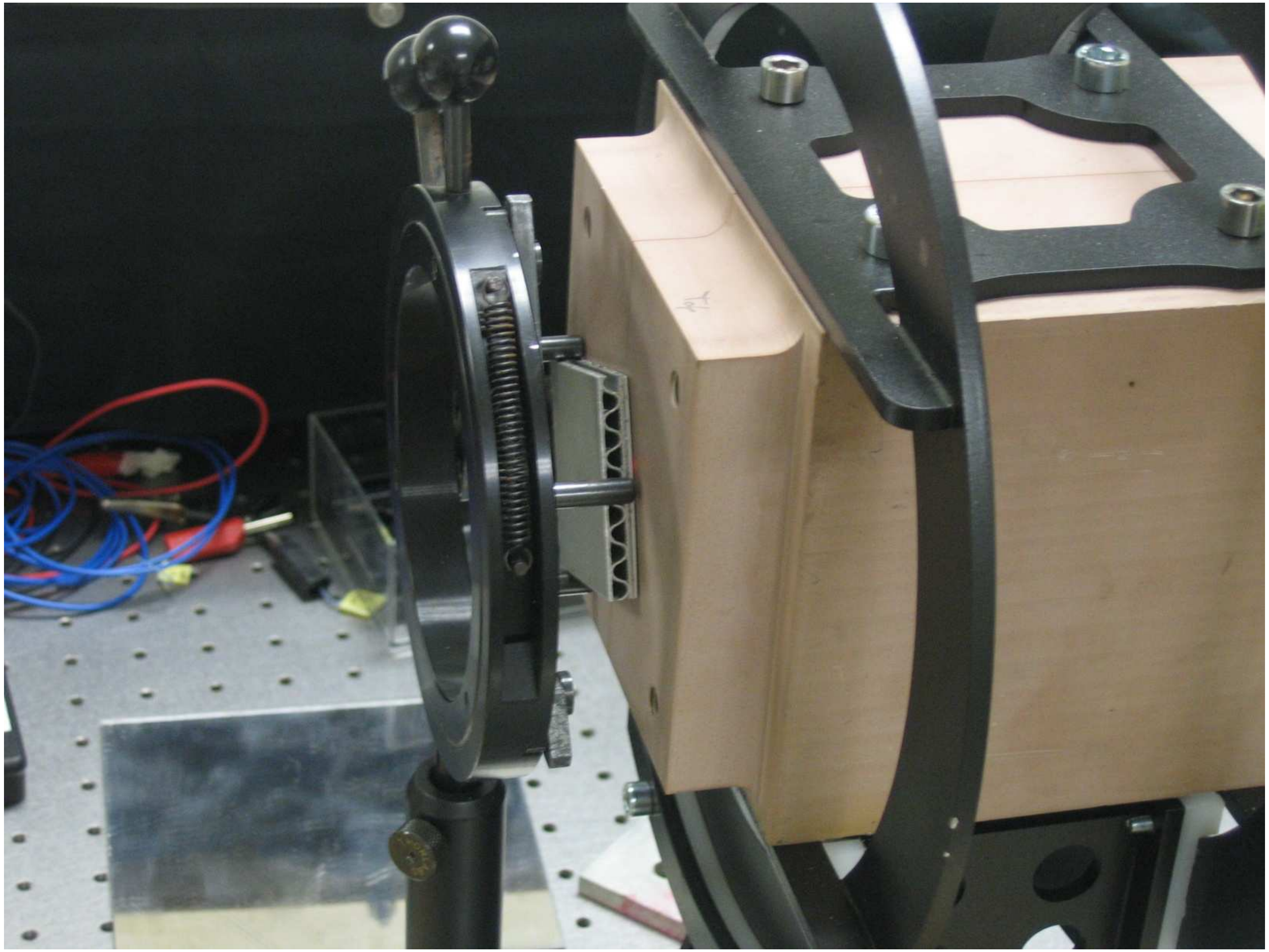




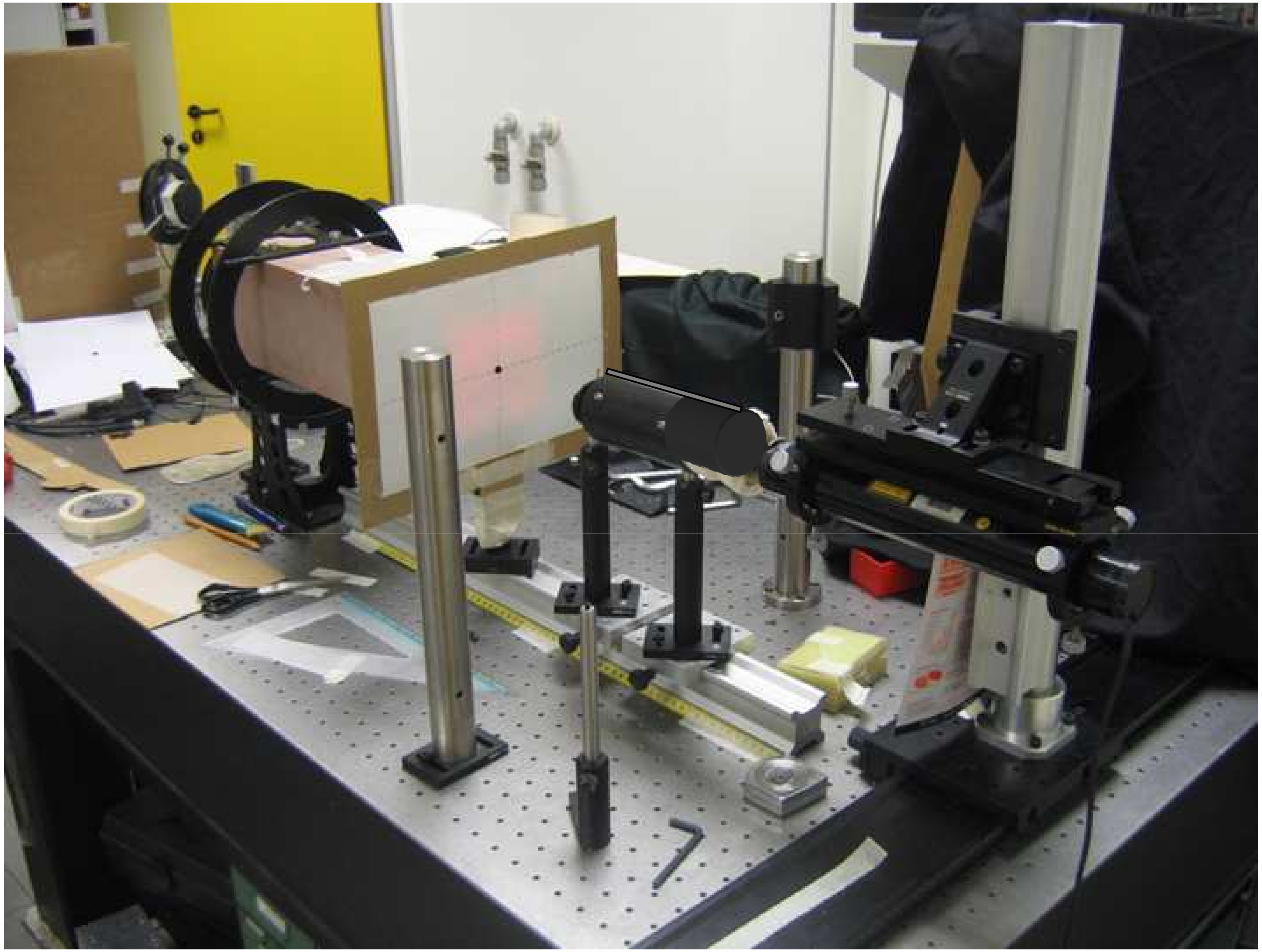
Average Reflectance of 3M film: 95±1%



Preparation of the expanded laser beam

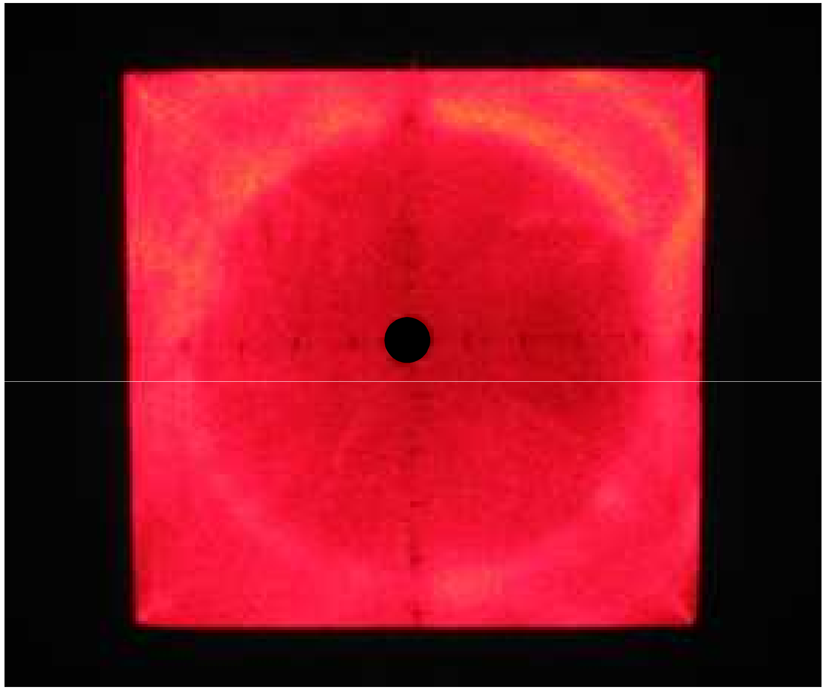


A light diffuser is faced to the exit window on the back of the cpc

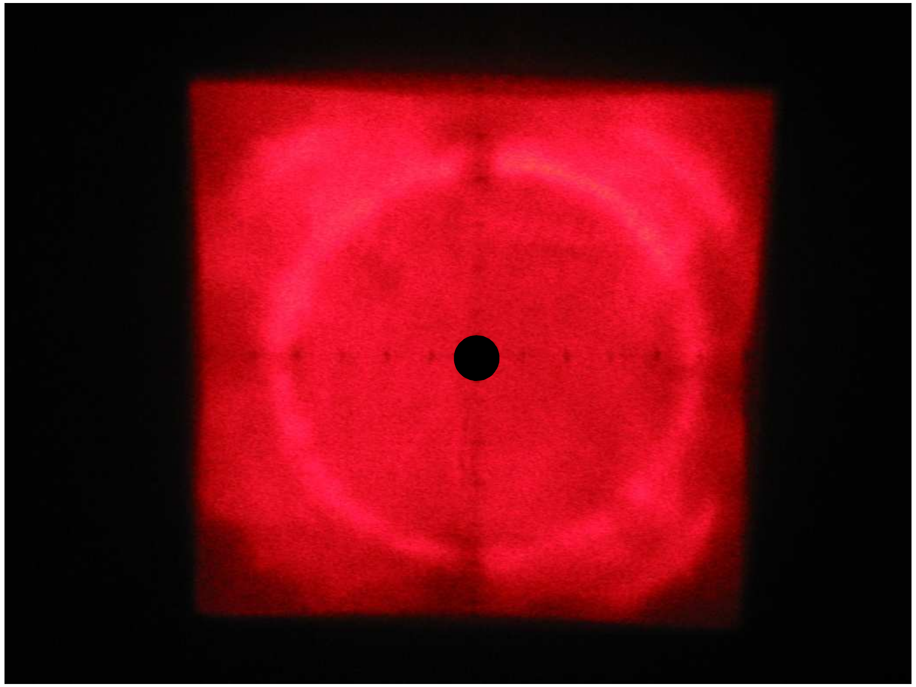


Light diffused by the cpc is projected on the screen

Digital camera measurements on the backreflected beam



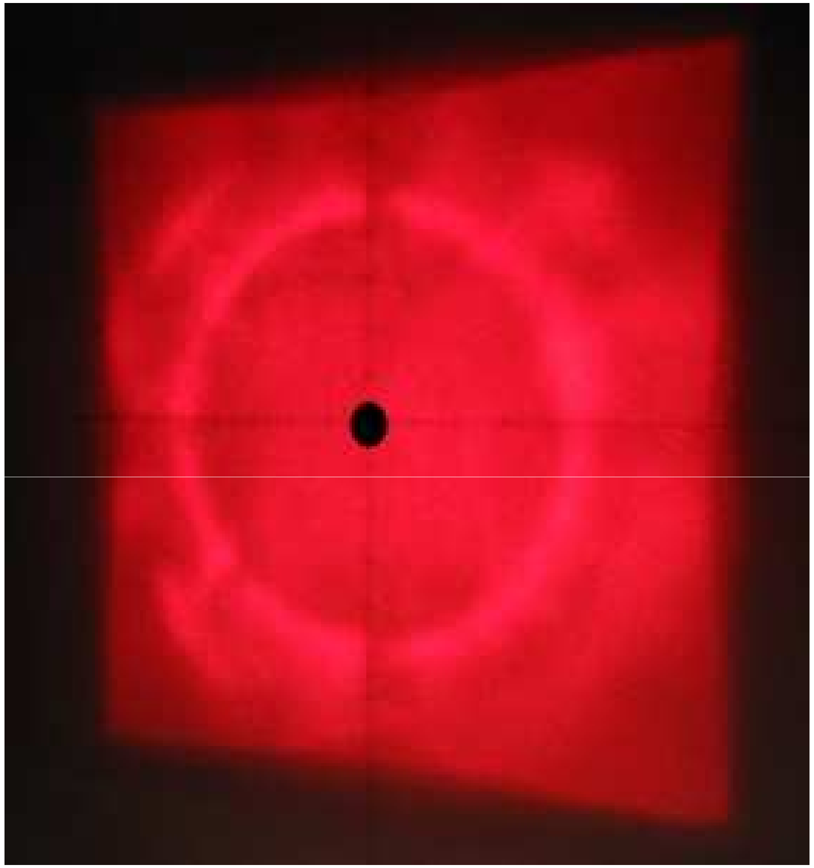
0 cm distance



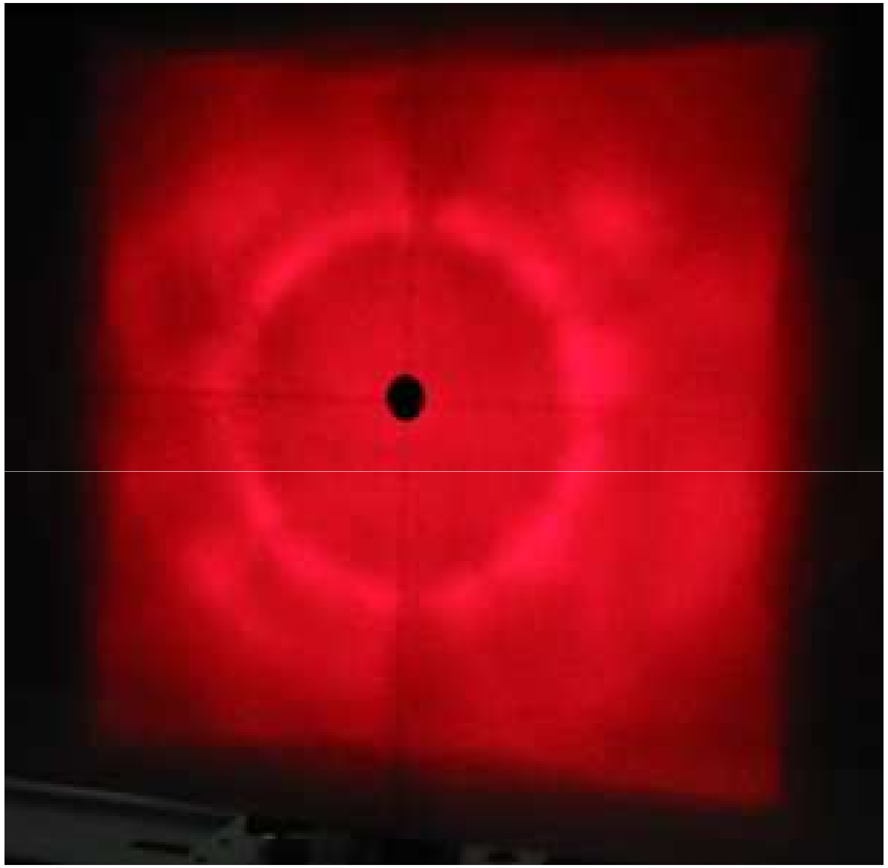
10 cm distance

Non expanded laser beam

Digital camera measurements on the backreflected beam

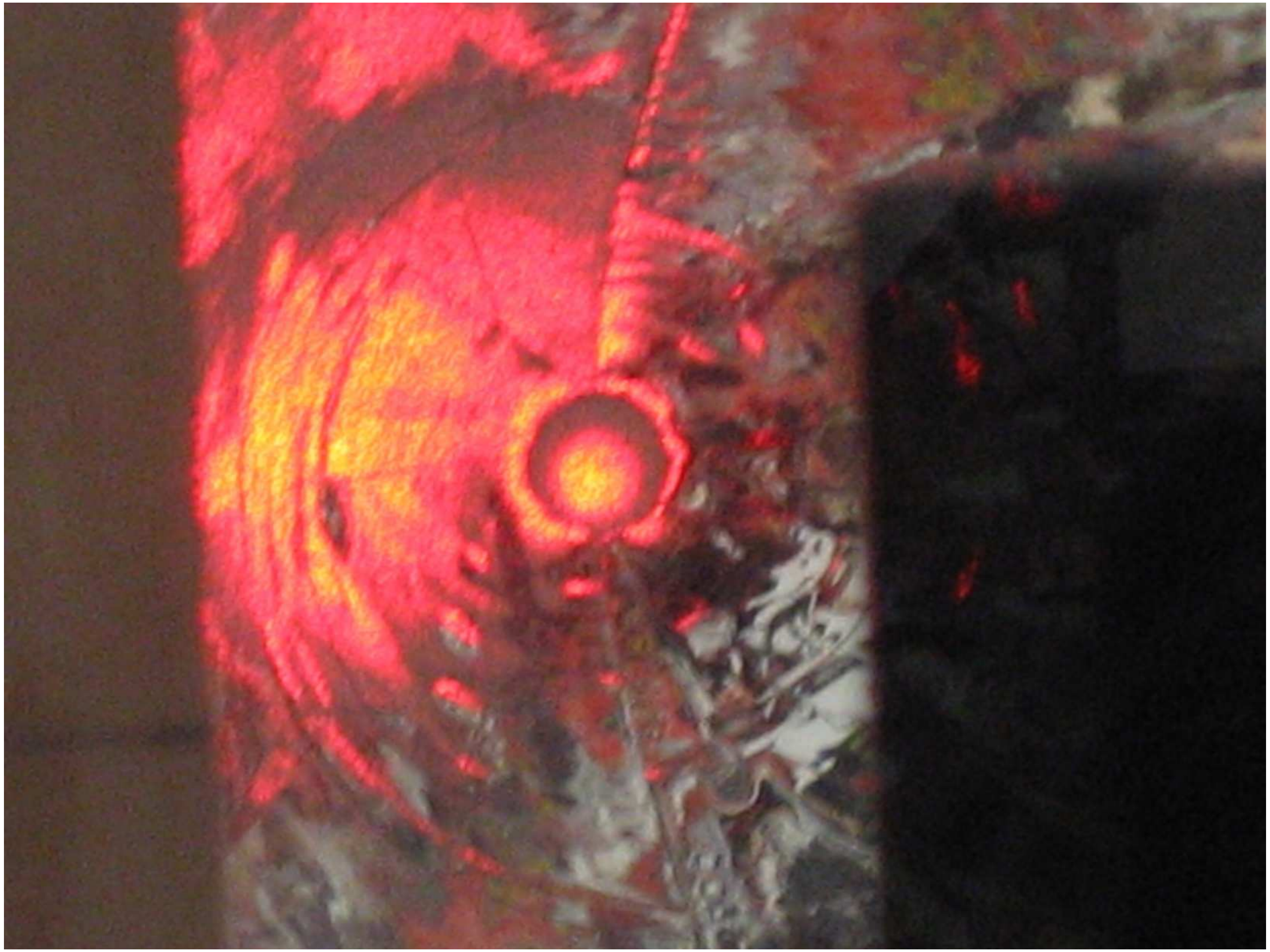


20 cm distance



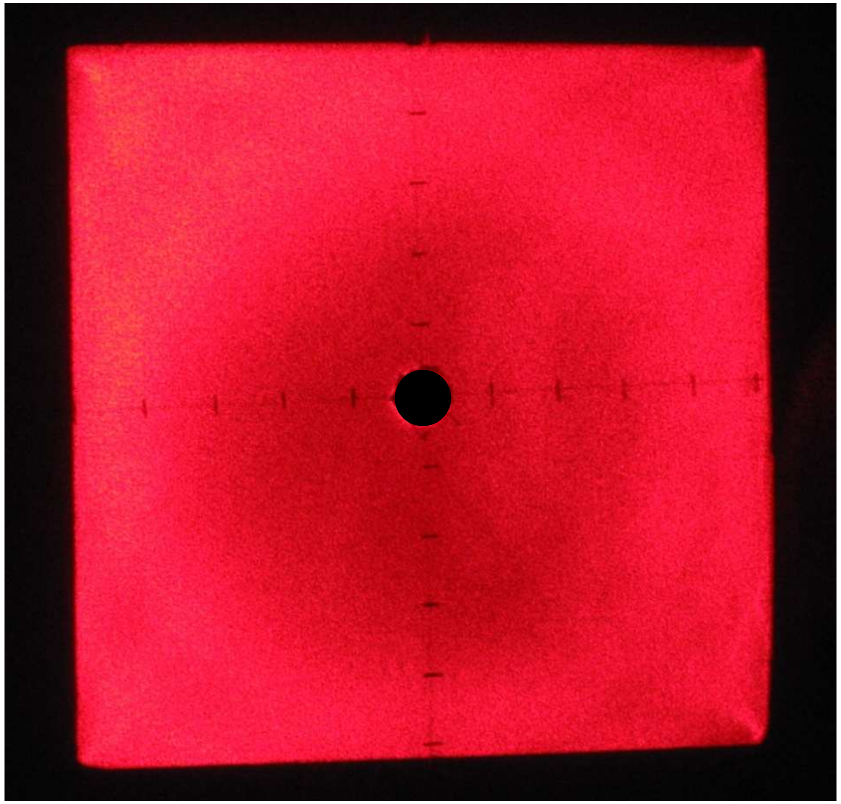
40 cm distance

Non expanded laser beam

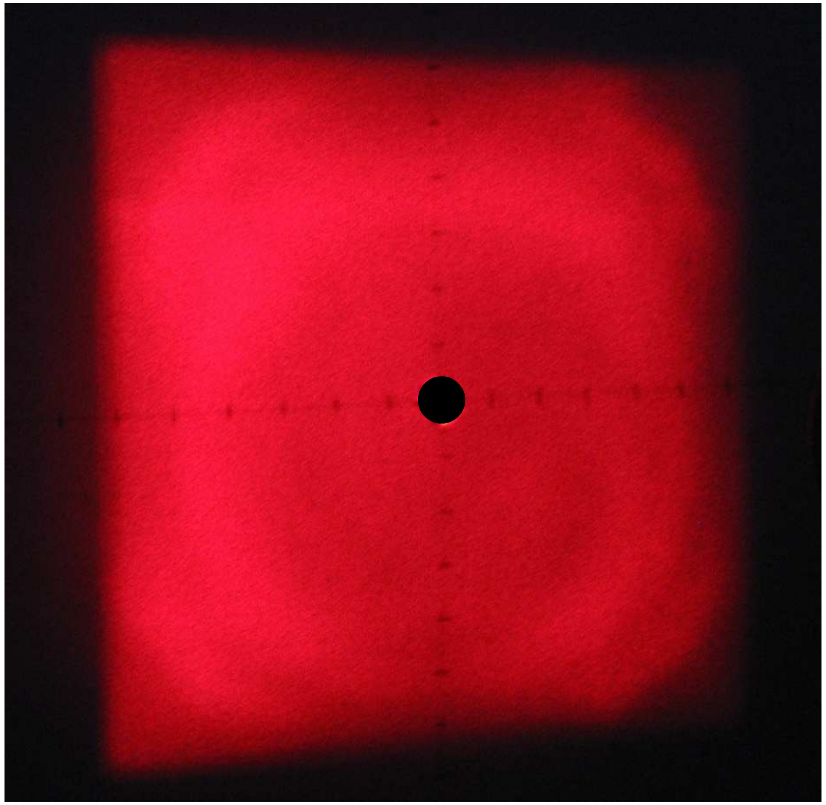


Light diffuser totally illuminated by the expanded laser beam.

Digital camera measurements on the backreflected beam



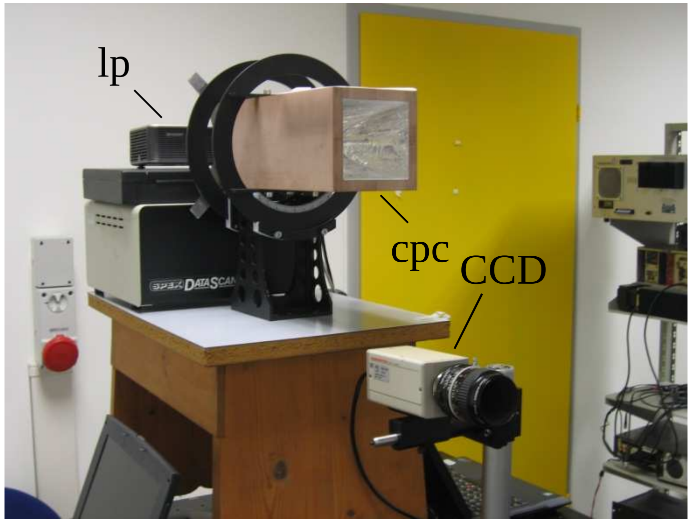
0 cm distance

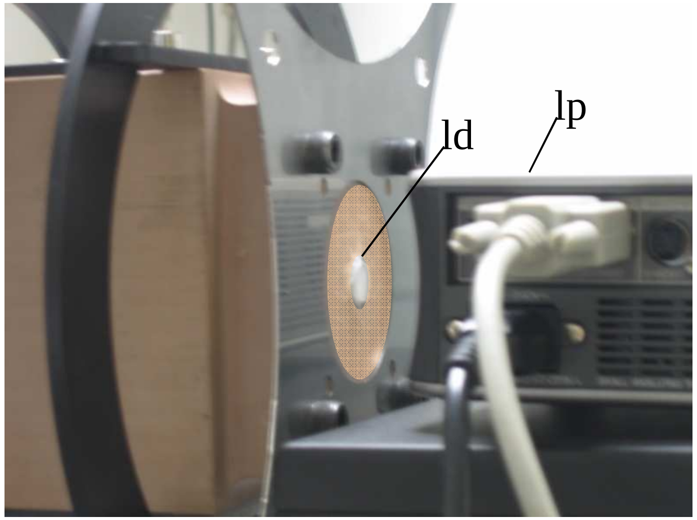


20 cm distance

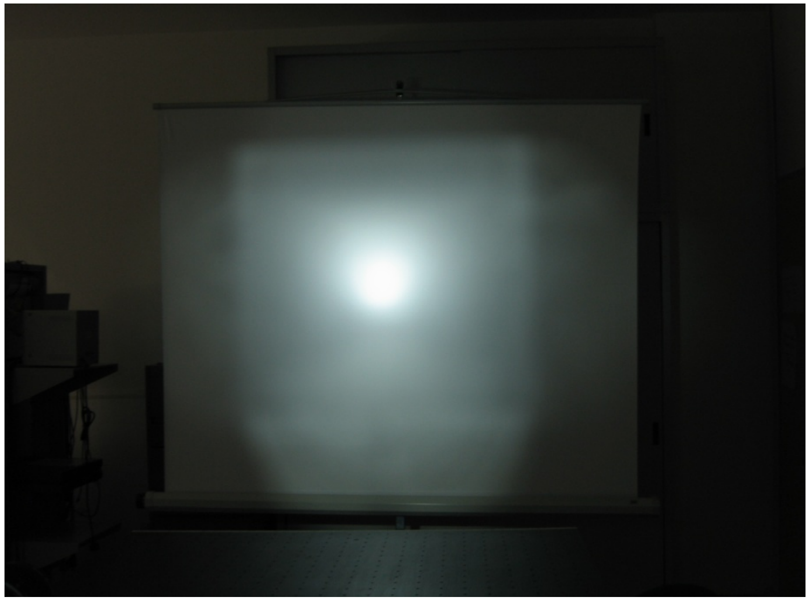
Expanded laser beam

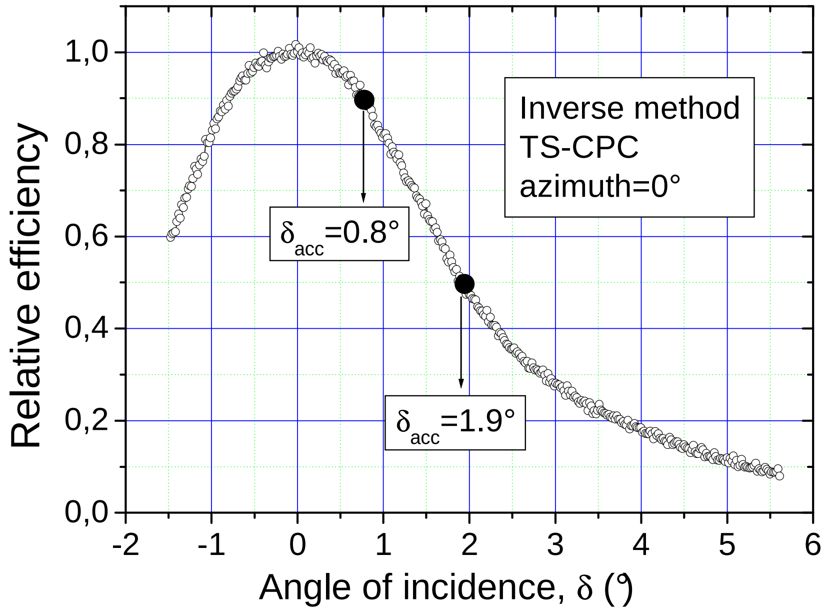
Truncated and Squared CPC (TS-CPC)





A semitransparent diffuser is used
to produce the lambertian light source





Summary of results

Method		Ideal 3D-CPC		TS-CPC		HT-CPC	
		90% Eff	50% Eff	90% Eff	50% Eff	90% Eff	50% Eff
Direct	Simul	4.5°	5.0°	1.5°	2.3°	4.5°	5.1°
	Exp			1.1°	2.8° (laser)		
Inverse	Simul	4.5°	5.0°	1.4°	2.1°	4.5°	5.1°
	Exp			0.8°	1.9°		

The experimental inverse method applied by using a semitransparent diffuser underestimates the acceptance angles because the light source is far to be lambertian.
Also the laser method gives only an approximate estimation of acceptance angles.

CONCLUSIONS

We have introduced a new method of characterization of solar concentrators, called ILLUME.

The experimental setup is very simple to realize, requiring only a laser or a lamp and a digital camera or a CCD

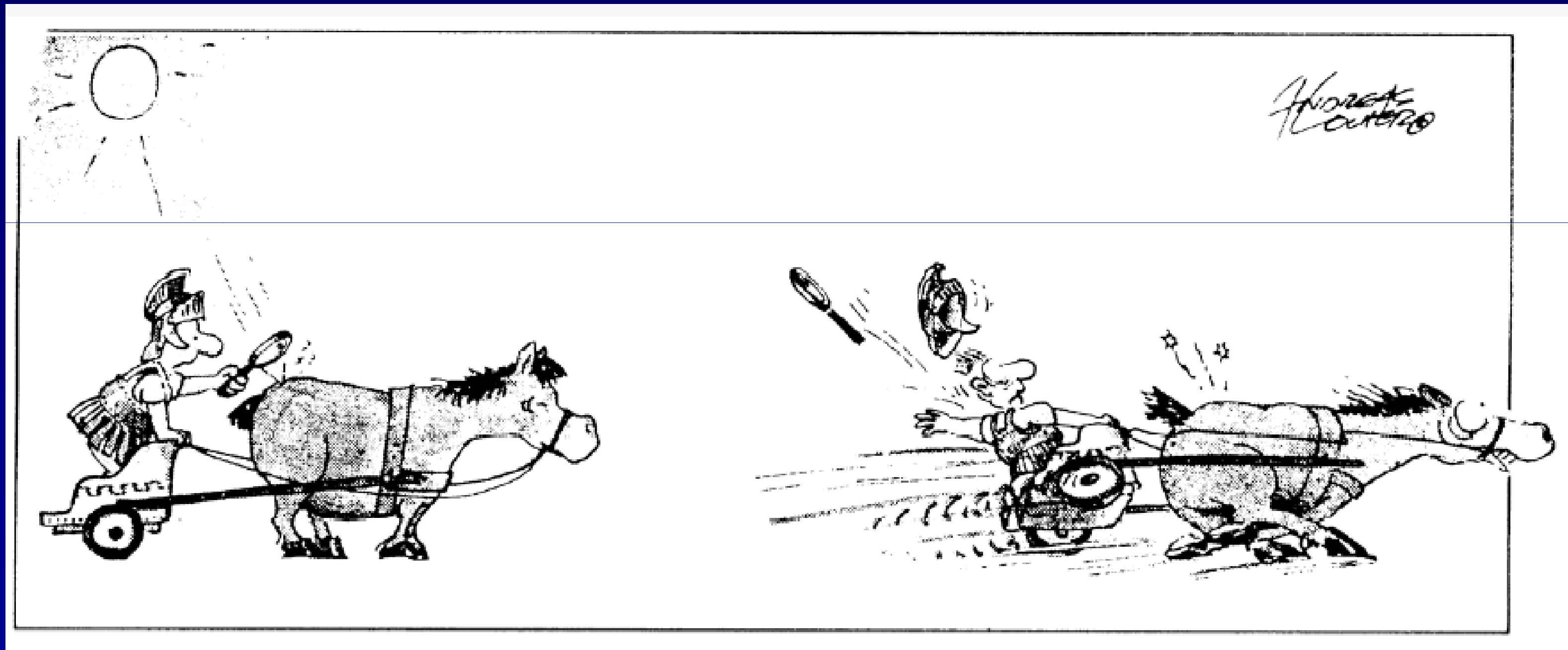
A single simulation or a single experimental measurement is sufficient to determine the relative optical efficiency and the acceptance angle of the concentrator.

We have tested the ILLUME method on different types of nonimaging concentrators.

In all cases, optical efficiency and acceptance angle were consistent with conventional methods of characterization.

The end

Thanks



Solar concentration in ancient Rome