CONTINUOUS SOLAR SIMULATOR FOR CONCENTRATOR PHOTOVOLTAIC SYSTEMS

T. THIBERT[1*], M.-L. HELLIN[1], J. LOICQ[1], E. MAZY[1], J.-M. GILLIS[1], F. LANGUY[2],
S. HABRAKEN[2], J.-H. LECAT[1], J.-M. DEFISE[1]
[1] LIEGE SPACE CENTRE, University of Liège, Avenue du Pré-Aily, 4000 Liege, BELGIUM
[2] HOLOLAB, University of Liège, Physics Department, Allée du 6 Août, 4000 Liege, BELGIUM
* Corresponding author: t.thibert@ulg.ac.be

ABSTRACT: A continuous solar simulator for measuring performance of concentrator photovoltaic (CPV) systems is presented. The illumination system is based on a Xenon lamp, a homogenizer rod, shaping optics and a 30cm diameter collimator. The design optimises the reproduction of the characteristics of direct solar illumination: 32' divergence, high spatial homogeneity, sun-like spectral distribution, with a maximum intensity of 250W/m². It accommodates pass-band and attenuation filters to tune the beam output. It operates in continuous mode, allowing to investigate CPV thermal aspects as well. The present paper addresses the concept design of the solar simulator and associated performance results.
Keywords: Concentrators, Characterisation, System Performance.

1 INTRODUCTION

CPV technology is increasingly recognized for its potential to cut down the cost of solar energy generation. Many design variations are under development and research in the field is still ongoing. This research requires adequate test facilities, and one of the most useful is arguably an indoor illumination system dedicated to high concentration – especially in countries with low solar potential like Belgium.

In recent years, the Liège Space Centre has been developing a Continuous Solar Simulator in the frame of a CPV research program sponsored by the Walloon Region (Belgium). The developments range from design and analysis to prototyping and validation tests on lens samples and concentrator PV elements.

This paper begins with a brief description of illumination system requirements, commenting their importance in the context of CPV testing. The solar simulator design is then addressed, including optical, thermal, mechanical and electrical design. Finally, the simulator having been built and aligned, performance results are presented.

2 SOLAR SIMULATOR REQUIREMENTS

The specifications for the solar simulator are derived from test requirements for concentration photovoltaic elements. These tests concern the validation of the optical design and manufacturing of CPV optics (prototype Fresnel lenses), as well as the evaluation of the efficiency of a CPV system combining optical elements and solar cells.

The performance of a CPV lens is linked to the characteristics of the spot formed at the lens focus: shape, spatial extension, intensity profile. Spectral characteristics are also important, since chromatic aberrations are known to induce efficiency losses.

In order to measure these features in laboratory, an artificial light source is required. This light source shall be representative of the solar flux, with the following characteristics.

2.1 Beam geometry

One of the main requirements is to have a nearly collimated beam, with a divergence of 32 arc minutes. An error on the beam divergence would result in an error on the spot size at the focal plane of a lens placed in the beam; therefore this feature is important for accurate measurements.

The beam shall be sufficiently large to illuminate one optical element, and the intensity shall be uniform over the lit area. For this project the acceptable variation of intensity was specified to 5% of average value over a minimum area of 5cm x 5cm, with a target area of 20cm x 20cm.

2.2 Beam spectrum

Multi-junction solar cells (e.g. GaInP/GaInAs/Ge) used in CPV systems are very sensitive to spectrum, therefore spectral representativity of the light shall be studied to allow CPV system performance assessment. Direct sun spectrum shall be taken as reference [1].

For chromaticity study of optics, it is interesting to dispose of monochromatic light, at several wavelengths over solar spectral range.

2.3 Beam power

In the concentrated spot, local irradiance is multiplied by the same order of magnitude than the concentrator power (typically x500). Multi-junctions solar cells increase in efficiency with such high concentration. Therefore it is appealing to dispose of high beam power to study related effects. Maximum direct sun irradiance is 850W/m².

On the other side low power is sufficient and even necessary to operate safely a CMOS camera placed in the focal plane of concentrator optics (beam irradiance < 0.1W/m²).

Therefore it was specified an output irradiance higher than 100W/m² (target 800W/m²), and the possibility to attenuate output beam of several orders of magnitude (min. OD3).

2.4 Continuous mode

Typical solar simulators for PV modules employ a flash lamp synchronized with the measurement of an I-V curve. This principle has also been implemented for concentration PV modules [2]. Flash systems are perfectly fit for fast I-V characterization of PV systems.

However, our test objectives allowed another approach. A light continuously ON would add a valuable comfort during experimentation. Continuous mode enables investigation of CPV thermal aspects as well.

A continuous light source implies to manage cooling inside the source bloc, and possibly on test samples, but synchronization aspects are no more needed.

To complete this mode a shutter was required to shut the beam OFF temporarily during tests.

Such requirements were not available in commercial on-the-shelves products. CSL has consequently undertaken the task of designing its own solar simulator.

3 SYSTEM DESCRIPTION

3.1 Optical design

The solar simulator consists of two parts: a source bloc (Figure 1) and a collimator (Figure 2).

- The source bloc allows to collect a maximum of flux from the light source it shelters. It homogenizes the light flux and shapes the beam to adapt it to the collimator.
- The collimator collimates the output beam and manages straylight.

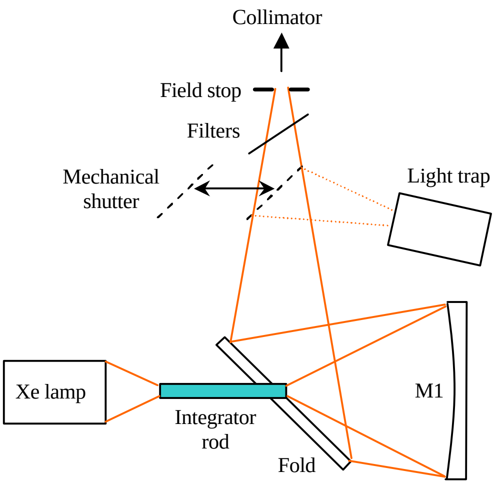

Figure 1: Source bloc optical design

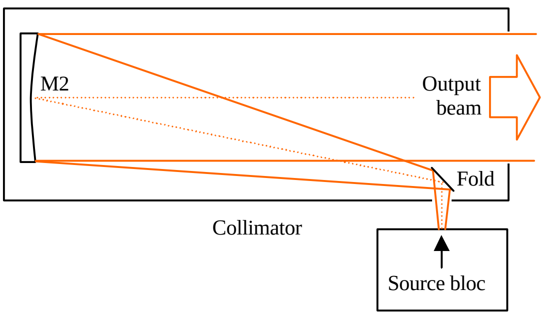

Figure 2: Collimator and Source bloc

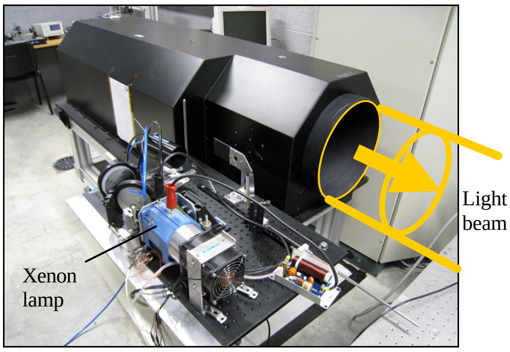

Figure 3: CSL Continuous Solar Simulator (during alignment)

The light source is a powerful Xenon arc lamp equipped with an elliptical reflector. Xenon lamp provides a continuous spectrum close to direct light spectrum [2]. The choice of the lamp model has been optimized to maximize the simulator output power. It is interesting to note that a higher power lamp does not necessary imply a higher simulator output power. Indeed, the size of the source has also an importance considering the law of conservation of étendue.

The integrator selects a part of the light flux at the focus of the lamp and defines a spatially homogenous object for the next optical system. The integrator consists in a fused silica rod with polished ends.

The shaping optics collects the beam at the integrator output and adapts it to the collimator to minimize losses. A spherical mirror images the output of the integrator on the collimator focus, and a flat mirror folds the beam. The folding mirror is accommodated with a central hole for the tip of the integrator rod.

The optical design takes the opportunity to reuse an existing collimator with 300mm diameter spherical output mirror, which drives the output beam diameter. The collimator assembly was developed during a previous project at CSL for straylight measurements, and its design is particularly clean in term of straylight.

3.2 Mechanical design

The mechanical setup includes several additional elements:

- A mechanical shutter to shut off the output beam without turning off the lamp. This is useful to extend the lamp lifetime.
- A filter holder (neutral density and/or band-pass)
- Hoods to extend the operator eyes lifetime.

3.3 Thermal design

Continuous operation mode implies management of the thermal power losses. Air and water cooling is implemented inside the source bloc.

- The lamp is equipped with air-cooled finned housing.
- A water-cooled thermal baffle at the level of the integrator rod entrance absorbs light flux that doesn't enter in the rod.
- A water-cooled light trap dissipates the power reflected by the mechanical shutter or the filters.

3.4 Electrical design

A specific alimentation bloc has been designed to manage Xenon lamp operation. It integrates useful features such as injected current intensity adjustment, automatic trigger management, and lamp temperature monitoring. It includes a security based on a redundant temperature sensor directly placed on the lamp housing fins. The alimentation bloc accommodates 500W-1000W lamps, for more flexibility during future developments.

4 RESULTS

An innovative part of the design concerns the use of an integrator rod (see Figure 4). This element revealed to be source of uncertainty in the performance prevision. Several rod designs were investigated on the field, including mirror-coated or TIR sides, rough and polished faces, and geometrical variations. The results presented correspond to a compromise between output power and spatial uniformity.

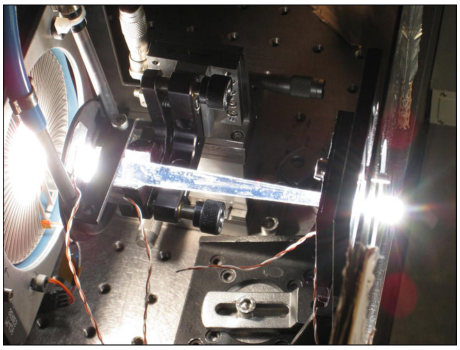

Figure 4: Integrator rod and Xenon lamp

Measurements with fiber spectrometer (VIS+IR) were performed to record the output spectrum. Theodolite measurements confirmed the 32’ divergence, specified by design. Radiometric budget is given in Table I.

Table I: Radiometric budget

Lamp optical power	129 W	
Integrator input power	92 W	on F 12 mm
Source bloc output power	13 W	
Output beam diameter	235 mm	
Output flux	255 W/m²	

Output beam intensity map is pictured on Figure 5. This map is a (non burned) camera picture of the beam illuminating a screen, whose intensity is scaled with measurements taken with a pyranometer. It presents a very uniform profile on a 25cm diameter disc, except for a darker central spot. This spot is due to central obstruction of Xenon lamp features (cathode and spider), that is not completely compensated by integrating rod.

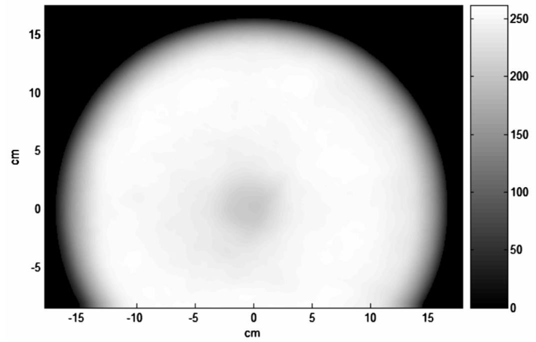

Figure 5: Output beam intensity map (W/m²)

Beam spatial uniformity is illustrated on Figure 6. It represents isovalues of intensity, with maximum intensity scaled to 1. Central dark spot reduces the useful area to the beam perifery. The beam presents an annulus of 11cm wide within 90% of maximum, and of 7cm within 95%. This allows to illuminate an object of 10cm x 10cm with a variation of intensity of ±5% of the average value, or an object of 6cm x 6cm with a variation of intensity of ±2.5% of the average value. These results are better than the initial specifications.

Further research will concentrate on integrator rod design in order to improve output beam uniformity.

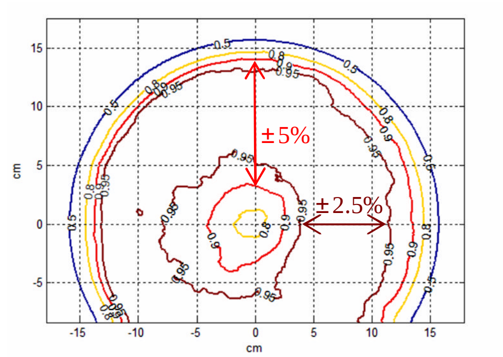

Figure 6: Output beam spatial uniformity. Isovalues show intensity as a percentage of beam maximum.

5 CONCLUSION

The first continuous solar simulator for photovoltaic concentrator system has been developed. Its illumination system is based on a Xenon lamp, a homogenizer rod, shaping optics and a 30cm diameter collimator, which simulates natural sun light. It has been thoroughly characterized, demonstrating collimation, irradiance level, spectrum and spatial uniformity of the light.

The simulator is already being used at CSL, allowing indoor research on CPV systems.

6 REFERENCES

[1] C. A. Gueymard, D. Myers, and K. Emery, 2002, “Proposed reference irradiance spectra for solar energy systems testing”, Solar Energy, 73, 443-467.

[2] C. Dominguez, I. Anton, and G. Sala, 2008, “Solar simulator for concentrator photovoltaic systems”, Optics Express, 16(19).