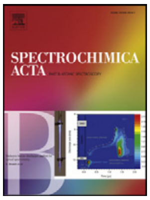
Spectrochimica Acta Part B 123 (2016) 179–183

Contents lists available at ScienceDirect

Spectrochimica Acta Part B

journal homepage: www.elsevier.com/locate/sab



Development of a large depth of field collection optics for on-line Laser-Induced Breakdown Spectroscopy applications☆

Daniele A. Redoglio [a], Elena Golinelli [b], Sergio Musazzi [b], Umberto Perini [b,*], Franco Barberis [b]

[a] *Physics Department, Università degli Studi di Milano, Via Celoria 16, 20134 Milano, Italy*
[b] *T&D Technologies Department, Ricerca sul Sistema Energetico – RSE, Via Rubattino 54, 20134 Milano, Italy*

A R T I C L E I N F O

Article history:
Received 15 January 2016
22 June 2016
Accepted 17 July 2016
Available online 25 July 2016

Keywords:
Laser-induced breakdown spectroscopy
Collection optics
Online measure
Mirror
Ray tracing

A B S T R A C T

This paper deals with the study of the collection optics required by a LIBS system that has to perform on-line analysis of moving samples whose distance may vary during measurements. Main requirement of this system is to maintain good collection efficiency over a wide range of sample distances by using a fixed focus optical arrangement. The selected configuration is based on the use of two spherical mirrors with the same curvature radius. Tests carried out on an experimental prototype are in good agreement with the previously performed simulations.

1. Introduction

Elemental analysis of moving samples, like e.g. raw minerals transported by conveyor belts, is one of the most challenging applications of a LIBS measuring system in industrial plants [1–3]. Most of the LIBS systems, conceived for the analysis of moving samples transported by conveyor belts, undergo to some common requirements: a small size to simplify the installation, a quite large operating distance to prevent interactions with the transported material, and, in order to allow the analysis of a large number of elements, a wide spectral range. One of the main difficulties in performing such measurements is represented by the variable distance at which the samples are located when passing through the measuring point. In fact, because of their optical configuration, conventional LIBS systems start reducing their performances (mainly in terms of collection efficiency) as soon as the position of the samples falls outside a very limited range of distances from the collection optics. This problem has been solved in the past by means of feedback controlled devices, utilizing either optical systems with variable focal length or mechanical systems that keep the collection optics at a fixed distance from the sample [4,5].

To avoid the use of servo-mechanisms and, at the same time, to provide reliable LIBS systems robust enough to work in industrial plants, we have developed an innovative measuring system [6] using an on-axis configuration –based on a fixed focus collection optics with a large depth of field– capable of maintaining a good collection efficiency over a wide range of measuring distances.

In this work we present the study which led to the development of the collection optics including a comparative analysis with some of the most conventional systems. Among all the investigated systems, three different configurations provided the most interesting results. The first one was an ideal air spaced achromatic lens system, a refractive component that can operate over a wide spectral range with a negligible chromatic aberration; the other two were a parabolic and a spherical mirror based configurations, which are intrinsically immune from chromatic aberration.

As a result of this analysis, we found that the use of two spherical mirrors with the same curvature radius, although affected by a residual astigmatism, provides a good tradeoff between depth of field and collection efficiency. Tests with an experimental mock-up reproducing this optical system have also been carried out and their results compared with the previously performed simulations.

2. Analysis of different collection optics configurations

The specific application for which this study has originally been conceived, was the on line analysis of raw coal, transported by the conveyor belts feeding the burners of power plants. This measuring system required the collection of the plasma emitted light over a broadband spectrum, ranging from 200 nm to 900 nm; the distance between the measuring system and the conveyor belt was required to be of the order of 1 m to allow for large variations in the coal height on the conveyor belt. The collected light was delivered to the spectrometers through a 600 μm core, 0,22 N.A. optical fiber.

☆ Selected paper from the 8th Euro-Mediterranean Symposium on Laser Induced Breakdown Spectroscopy (EMSLIBS 2015), Linz, Austria, 14-18 September 2015.

* Corresponding author.
E-mail address: perini@rse-web.it (U. Perini).

http://dx.doi.org/10.1016/j.sab.2016.07.009
0584-8547/

Different solutions have been considered under the hypothesis of utilizing an on-axis LIBS configuration (see Fig. 1), which is the most convenient arrangement when the sample distance is not constant; a LIBS system, in fact, can only perform measurement in the region where the laser and the collection optic axes intersect. Either a holed mirror or a dichroic mirror could be employed to separate the focused laser beam from the emitted radiation traveling in the opposite direction; a holed mirror is however preferable for our application, because the high power laser could easily damage the dichroic mirror [7].

The different optical systems have been analyzed and compared, employing both commercial software (WinLens3D) and properly developed ray-tracing algorithms. The parameters selected to compare the systems were the collection efficiency, the depth of field and the shape of the collection volume. The collection efficiency has been defined as the fraction of light, emitted by a point like source, that the system is actually able to fed into the final collecting element. As such, it is a dimensionless quantity and it is function of the relative position of the light source and the collection optic. The depth of field has been defined as the FWHM of the optical efficiency, measured along the optical axis; also, the collection volume has been defined as the volume inside which the collection efficiency is at least 50% of the maximum value.

2.1. Single lens

A single lens represents the simplest refraction based collection system. It should be noticed, however, that the use of lenses is not immune from inconveniences, like e.g. spherical aberration, glass transmission and chromatic aberration. Problems arising from spherical aberration can easily be solved by using aspheric lenses, commercially available in a large variety of diameters and focal lengths. Care, however, has to be paid in the selection of the optical glasses, as most of them exhibit good transmission only over a limited spectral range. Among the most used ones, only two show a good transmission over the whole ideal measuring spectral range (from 200 nm to 1100 nm), namely the fused silica and the calcium fluoride. While the latter material has better optical quality, its mechanical properties are worse, since it is brittle and prone to be damaged by humidity and thermal shocks. Fused silica, instead, is a stable and reliable material. However, lenses made with these materials exhibit great chromatic aberration. When operating in the wavelength range 200–1100 nm with a fused silica plano-convex lens, a chromatic aberration as large as 19% of its effective focal length at 500 nm is observed. As a consequence, once the distance between the lens and the collecting optical fiber has been chosen, the efficiency of the collection system is strongly affected by the wavelength of the light, since only a small fraction of the spectrum can actually be coupled into the collecting fiber. As an example, Fig. 2 shows the calculated collection efficiency of a plano-convex fused silica lens (diameter 1 in., focal length 2 in.) as a function of the collected wavelength. As it can be noticed the collection efficiency rapidly decreases outside the 250–350 nm spectral range.

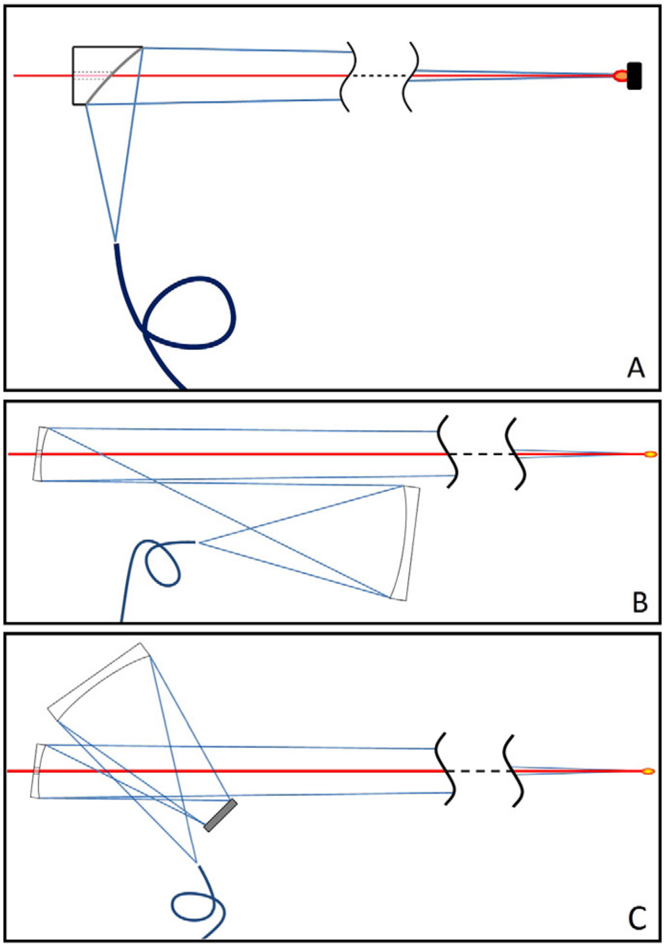


Fig. 1. Schematic representation of an optical system employing: A) a single, holed, parabolic mirror. B) Two spherical mirrors. C) Two spherical mirrors and a plane one to fold the optical path.

To overcome this problem, achromatic lenses must be used. Most of these lenses, however, are manufactured by gluing their components together using UV-cured optical adhesives. As a consequence, they do not transmit wavelengths lower than 320 nm. The use of air-spaced corrected triplets, an apochromatic lens systems made by three optical elements held together by an external housing, is therefore mandatory. As the simulation shows (Fig. 3), this kind of solution exhibits both a good depth of field and a large field of view. It should also be noticed that there is a large volume, surrounding the working point, where the collection efficiency is almost independent of the lateral displacement of the emitting source. However, commercially available air-spaced achromatic triplets are quite expensive and usually with a small aperture (typically smaller than 1 in.) which drastically limits the collecting angle and therefore their collection efficiency, especially when working distances are quite large. In addition, the use of CaF_2 optical elements makes these components unsuitable for application in harsh environments.

2.2. Parabolic mirrors

The simplest way to avoid the problems stemming from chromatic aberration is the use of mirror based collection optics, which is a common practice among LIBS experiments performed in laboratory controlled environments.

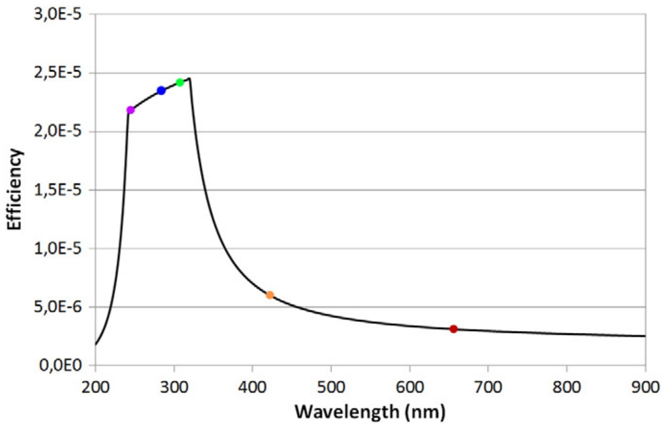


Fig. 2. Collection efficiency of a plano-convex fused silica lens as a function of the wavelength.