Optical design for BIPM imaging system

Abstract

1. Introduction

Light Imaging system for Beam Ionization Profile Monitor (BIPM) was designed to allow simultaneous operation of fast MAPMt and two new types of intensified standard resolution CCD cameras. The main reason for designing the optics was mainly the poor resolution of the preliminary setup limiting seriously the detectors performance and the need of a second optical path for the Multi Anode Photo Multiplier. Increase of the optical luminosity was also necessary for low intensity beams.

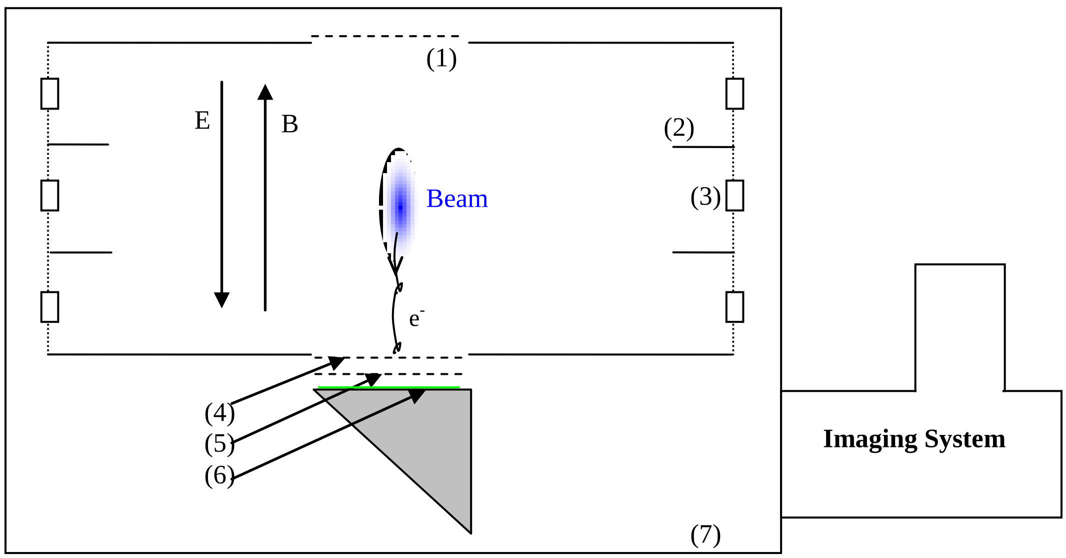

Fig. 1. *BIPM detector representation*

(1)…Cathode grid
(2)…Field homogenization electrodes
(3)…Resistors
(4)…Multi-Channel Plate (MCP_{in}) entrance electrode
(5)…MCP_{out} exit electrode
(6)…Phosphor plate deposited on constantan and fused silica optical prism
(7)…Vacuum tank

2. Design targets

Maximal lens diameter was fixed to 50.2mm due to the hole in the IPM dipole magnet where the light path was leading. The overall system length was limited to approx. 70cm including camera body. Position of the light splitter was fixed. It was decided not to place any optics inside the vacuum tank.
The main design parameter was the paraxial magnification. It was calculated simply as *m = image size / object size.* Object size was the length of the phosphor screen and the image as the shortest side of the larger CCD element used.
Two new CCD type sensors were considered. The EM CCD (Electron Multiplied) and EB CCD (Electron Bombarded). Both devices do not need any further light amplification. The EB CCD has to be tilted by 90° due to its different dimensions (see fig. 2.1).
Focusing of the system should be possible in a reasonable range.
Designed optics has to fit inside the C-mount system and have a reasonable cost.
Numerical aperture in the image plane has to be reasonably limited, because the CCD elements do not accept rays at higher angles.
The imaging aberrations should be kept below 1% with respect to the transverse beam size measurement.

Main design dimensions	
Object size (Phosphor)	44 x **44**mm
EM CCD size	11.52 x **8.64**mm
EB CCD size (2/3'')	8.8 x 6.6mm
Multi Anode PM (2nd path) size	32 x **32**
Paraxial magnification	0.196 (or smaller)
Paraxial magnification (MAPMt)	0.7
Distance to the first lens	250mm
Minimum distance to detector	450mm

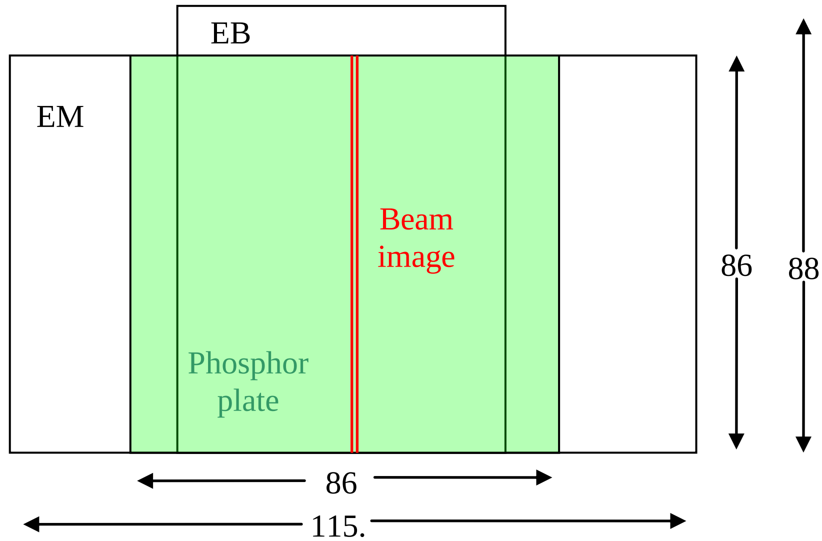

Fig. 2. *EM and EB CCD chip orientation and size*

3. Design concept and Starting point for optimization

Two commercially available doublets are placed between the vacuum window and the splitting prism with an aperture stop amid. Magnification of this part is matched to the MAPMt and no more lenses are used downstream the splitter.

Between the splitter and the CCD in the straight path, an objective is placed to match the magnification to the smaller square diagonal of the EM CCD. Objective lenses can be produced on customer order.

The Petzval 150 year old design with 2 positive power doublets was used as the starting point for the optimization.

4. Optimization and Final design

Optimization of an optical design required a merit function incorporating target values and constraints of the system. Major part of this function was generated by the ZEMAX program to optimize mainly on the RMS spot size for the defined image points and a range of wavelengths 520 – 580nm with a maximum weight at 550nm. A higher number of dimensional constraints had to be carefully set and progressively modified with the optimization evolution. Only reasonable glasses and shapes were used.

During optimization, the first lens of the objective was found as not crucial for the performance and optimization continued with only three lenses. There were several attempts to substitute the designed lenses with some commercially available ones, but this degraded the system's performance too much.

The diameter and length of the last element was found as the major constraint, because it had to fit inside the C-mount and be mechanically hooded outside of it.

Because of mounting difficulties, the front surface of the last element (fig. **3.**) was fixed to be flat without any important losses of image quality. The whole group has a possibility of focalization by its axial movement.

The final design consists of two Optosigma© doublets (200.1 and 169.8mm focal length), a diaphragm almost in the middle of them and objective (3 elements in one group). Due to suppliers stock problems the first and second elements are made from the same glass.
The finally used materials were SK16, SK16 and SF14.

The main merit target was in fact just the x component of the RMS image spot; because mainly that one contributes to the resolution of the beam image (summing the lines along the y coordinate). One can see (**fig. 5**) that the achieved resolution (RMS spot size in the image space) was from 25µm in the image center to 37µm at the edge.

Geometrical distortion was also one of the merit function constraints, because it could contribute to the systematic error. One can see the maximum distortion of 2.4%, but the beam image should never be in that region. Moreover, this is the maximum deviation from linear imaging and is almost constant for the whole image column and (With a small beam) by summing the lines one gets just a position error.

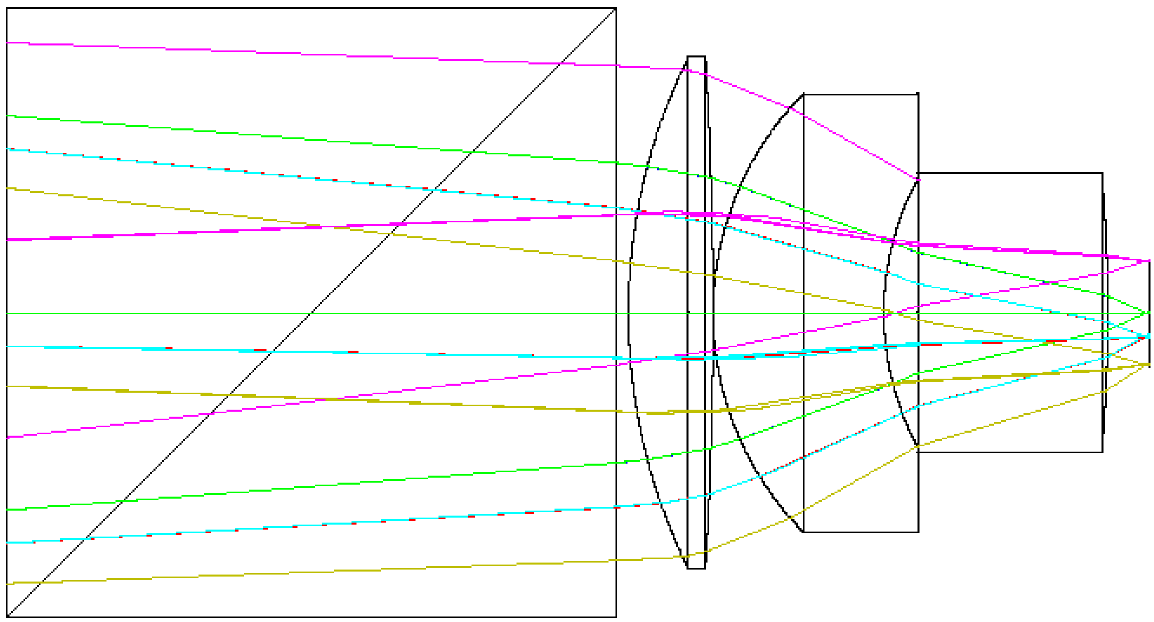

Fig. 3. *Detail of the 3-element objective following the splitter*

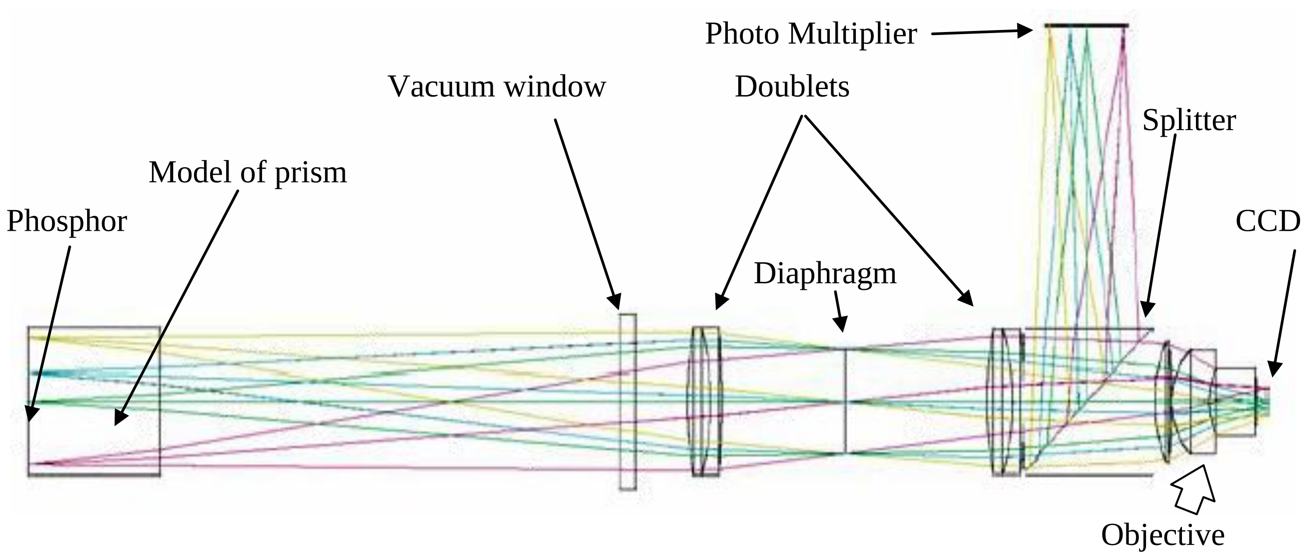

Fig. 4. *Description of the designed optical paths with 2 detectors*

Final design parameters (Zemax output)	
Effective Focal Length :	90.24992
Back Focal Length :	-13.63504
Total Track :	428.9591
Image Space F/# :	1.825016
Paraxial Working F/# :	1.220339
Working F/# :	1.247366
Image Space NA :	0.3791332
Object Space NA :	0.0784591
Stop Radius :	17.94123
Paraxial Image Height :	4.643525
Paraxial Magnification :	**-0.1921504**
Entrance Pupil Diameter :	49.45158
Entrance Pupil Position :	314.1709
Exit Pupil Diameter :	28.7407
Exit Pupil Position :	35.41758

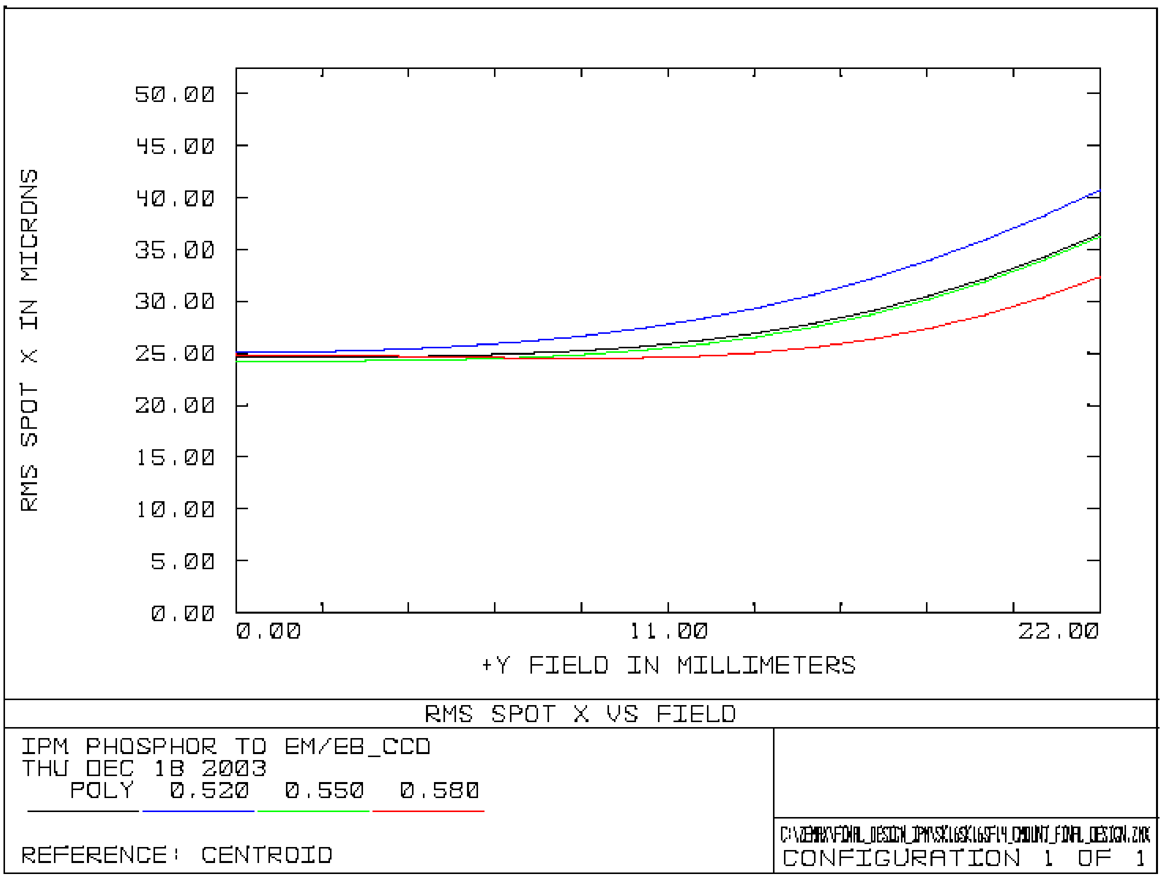

Fig. 5. *Transverse component of the RMS spot in image space (field in object space)*

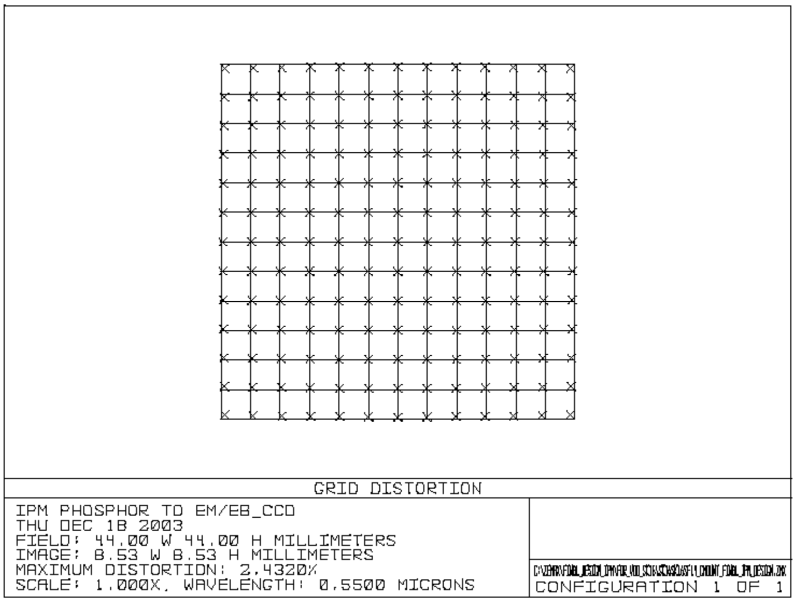

Fig. 6. *Geometrical distortion of a regular grid in the image space*

Calculated systematic errors of measured beam size		
Average beam size in SPS	**2.3mm (26GeV)**	**0.6mm (450GeV)**
Beam size on CCD (IS)	439 μm	141 μm
Max spot size (MS)	37 μm	37 μm
Measured beam size $\sigma = (IS^2+MS^2)^{0.5}$	441 μm	146 μm
Relative error	**0.36%**	**3.3%**
Min spot size (mS)	25 μm	25 μm
Measured beam size $\sigma = (IS^2+mS^2)^{0.5}$	439.7 μm	143.2 μm
Relative error	**0.16%**	**1.5%**

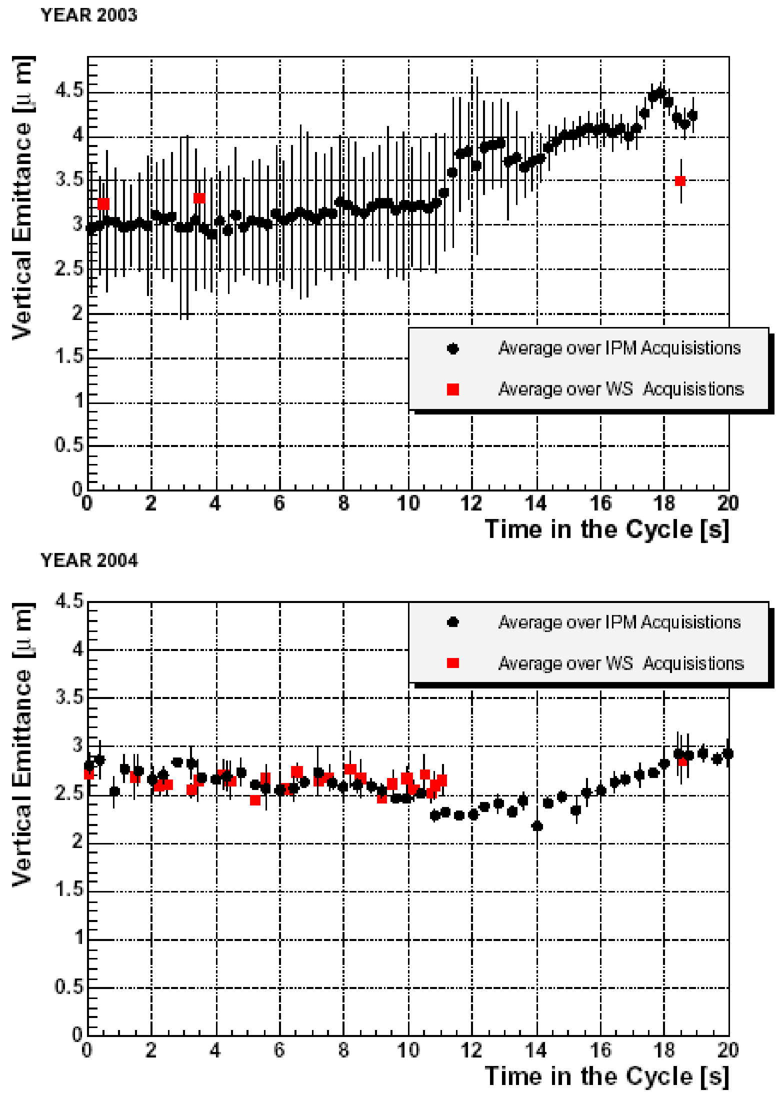

Figure 7.15: IPM acquisitions with LHC nominal beam and comparison with the wire scanners

Fig. 7. IPM acquisitions with nominal LHC beam and comparison with wire scanners