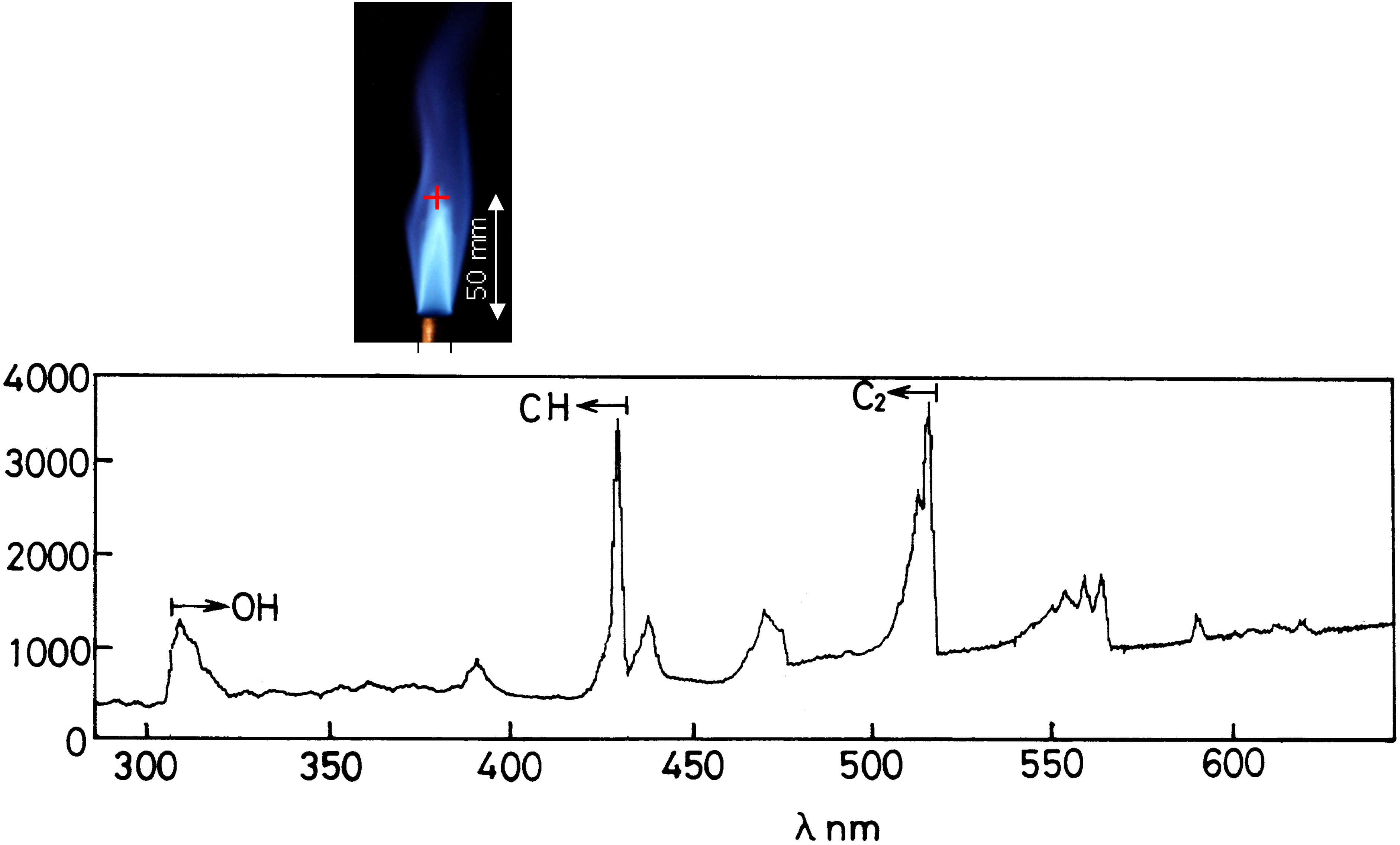
ラジカル自発光と
その計測

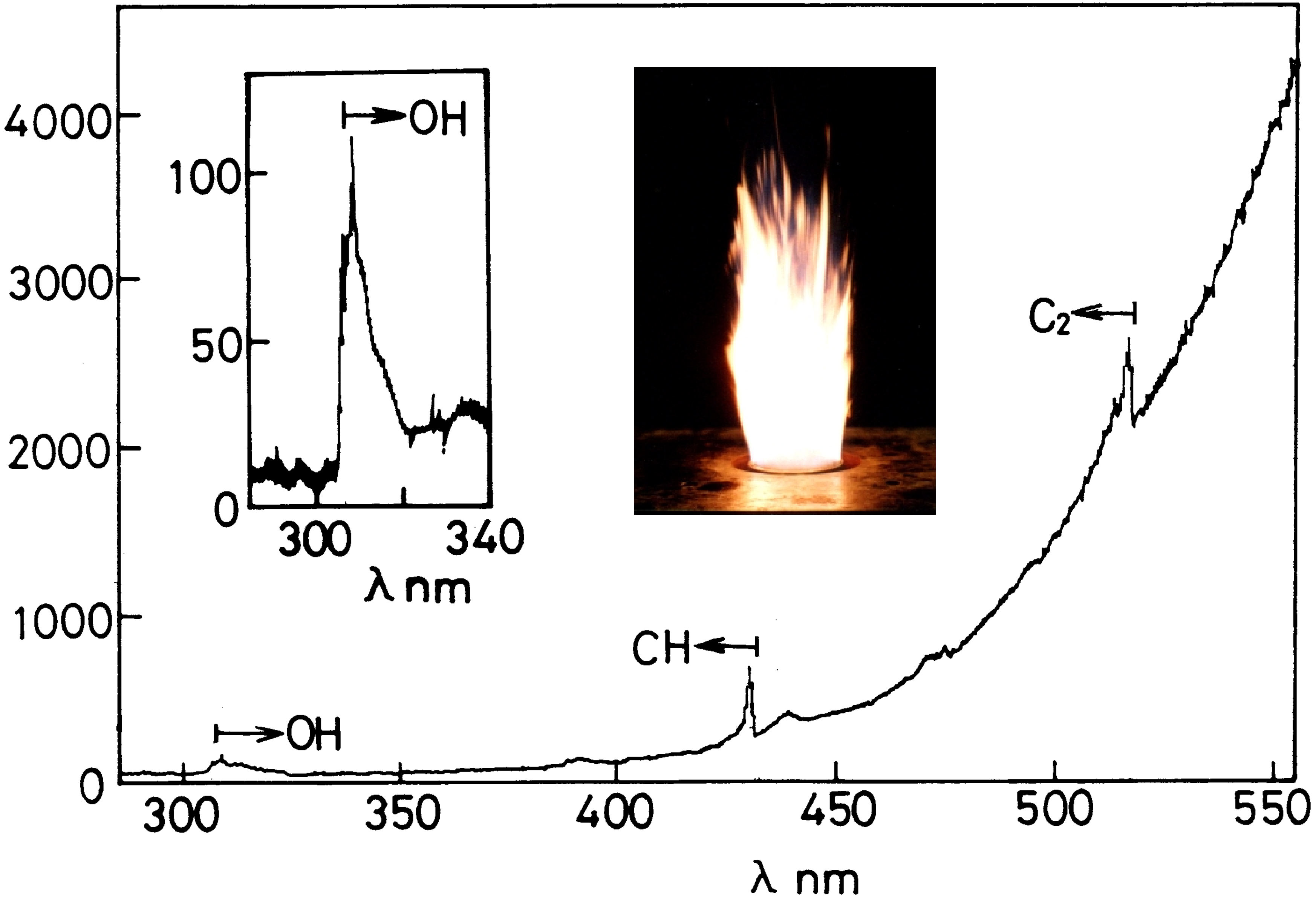
燃焼工学講座
赤松 史光

Spectrum of flame luminosity



Non-luminous Flame

Spectrum of flame luminosity



Luminous Flame

OH and CH radical chemiluminescences

OH and CH chemiluminescences are emitted in the deactivation course (2) of OH* and (4) of CH* produced from the reaction (1) and (3), respectively.

$$CH + O_2 \longrightarrow CO + OH^* \qquad (1)$$

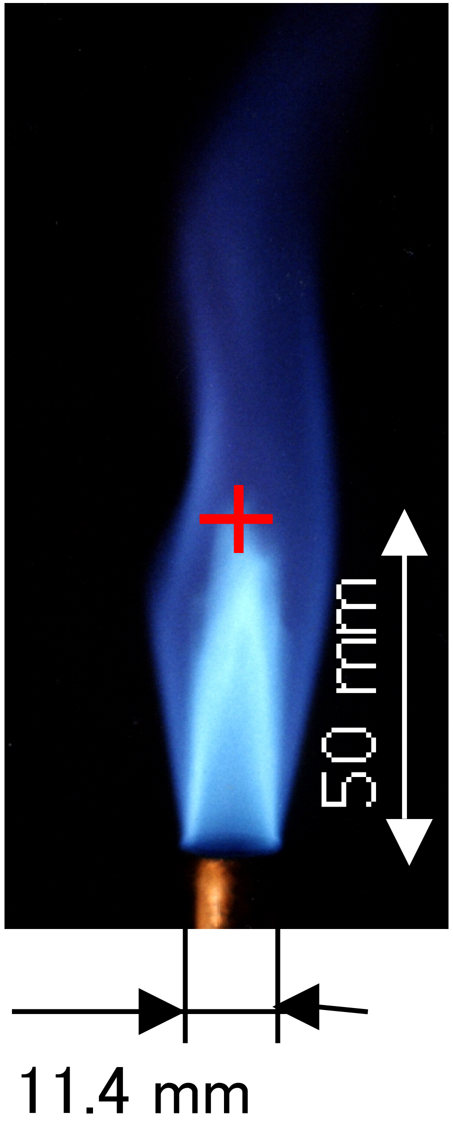
$$OH^* \longrightarrow OH + h\nu \qquad (2)$$

$$C_2 + OH \longrightarrow CO + CH^* \qquad (3)$$

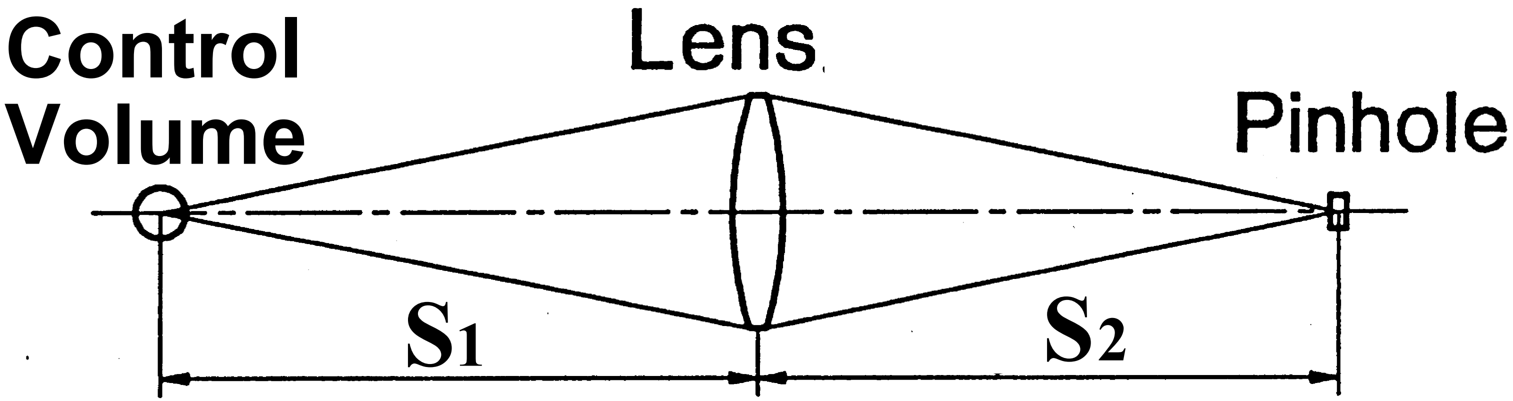
$$CH^* \longrightarrow CH + h\nu \qquad (4)$$

where the superscript * denotes an excited state, *h* is the Plank's constant, and ν is the frequency of the chemiluminescence.

Direct photograph of Bunsen flame with measurement point



Single-lens optics for point measurement



Paraxial Approximation, Gaussian Lens Equation

$$\frac{1}{f_0} = \frac{1}{S_1} + \frac{1}{S_2} \rightarrow$$

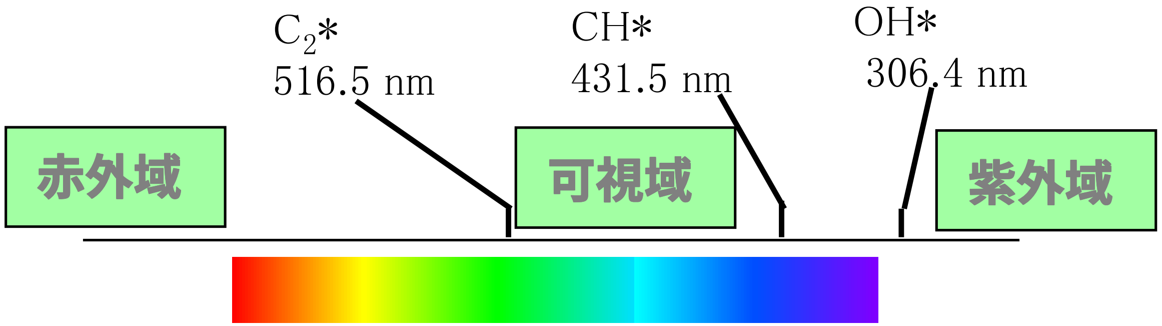
In Typical Case,

$$S_1 = S_2 = 2f_0$$

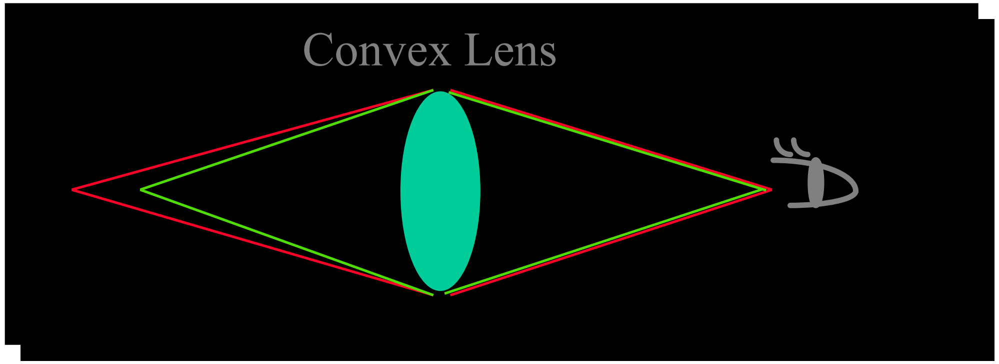
***f0*: Focal Length**

For Example, $\left(\begin{array}{l} f_0 = 150(\mathrm{mm}) \\ S_1 = 300(\mathrm{mm}) \end{array} \right.$, **Then** $S_2 = 300(\mathrm{mm})$

Chromatic aberration of optics

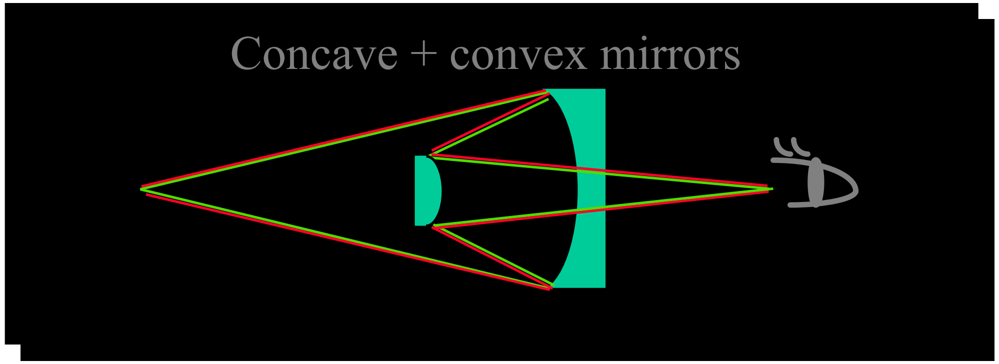


Conventional method



Convex Lens

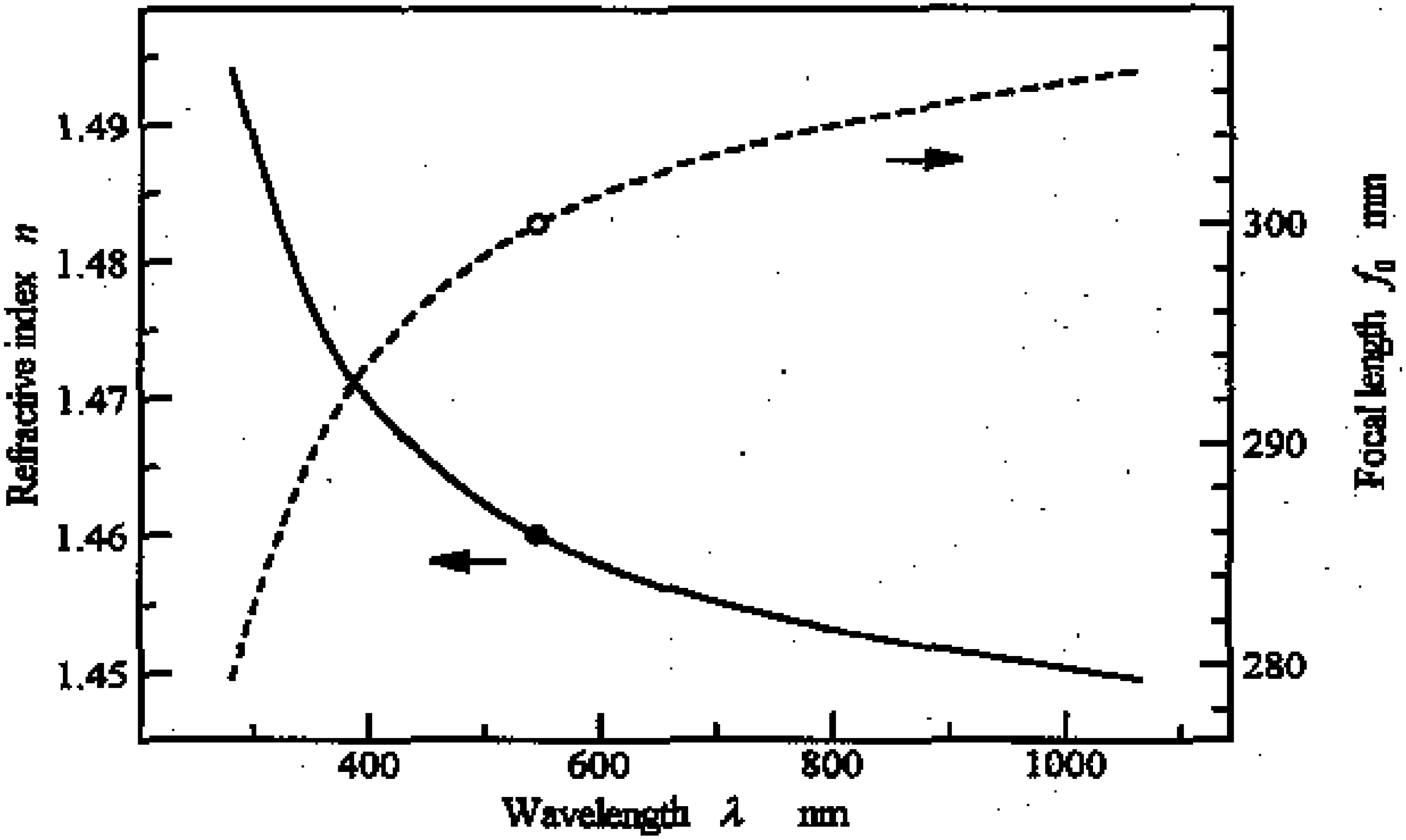
Newly proposed method



Concave + convex mirrors

Refractive index and focal length as functions of wavelength

$$\frac{1}{f_0} = (n-1)\left(\frac{1}{r_1} - \frac{1}{r_2}\right)$$



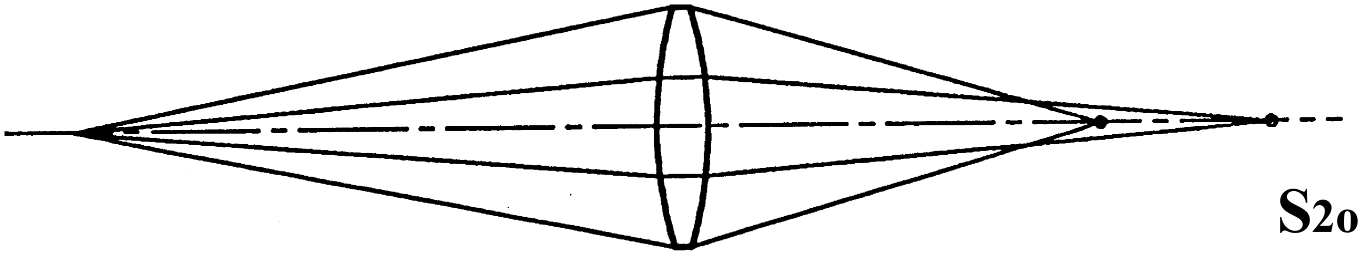
Typical aberration of point measurement optics

D_L=50mm, f_0=150mm → Paraxial App. GLE $S_2 = 300$ mm

Ray-Tracing Method

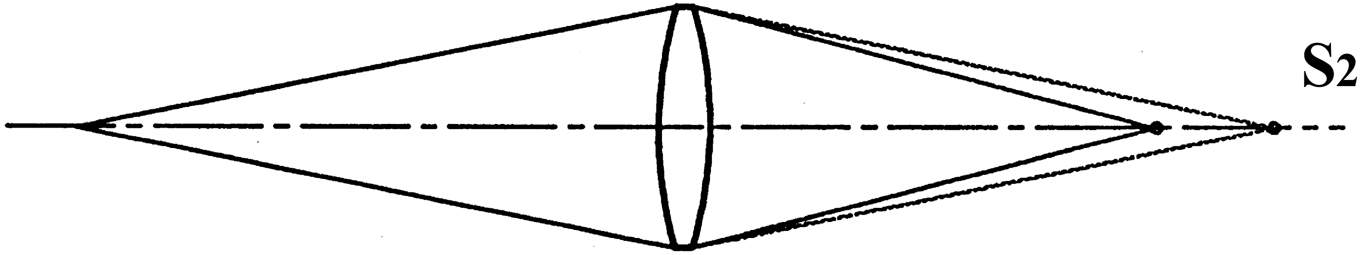
$S_{2opt} = 285.1$ mm

at Wave Length for Lens Design, $\lambda = 546.1$ nm



Spherical Aberration

Rays passing through outer portion of lens are focused closer to the lens.



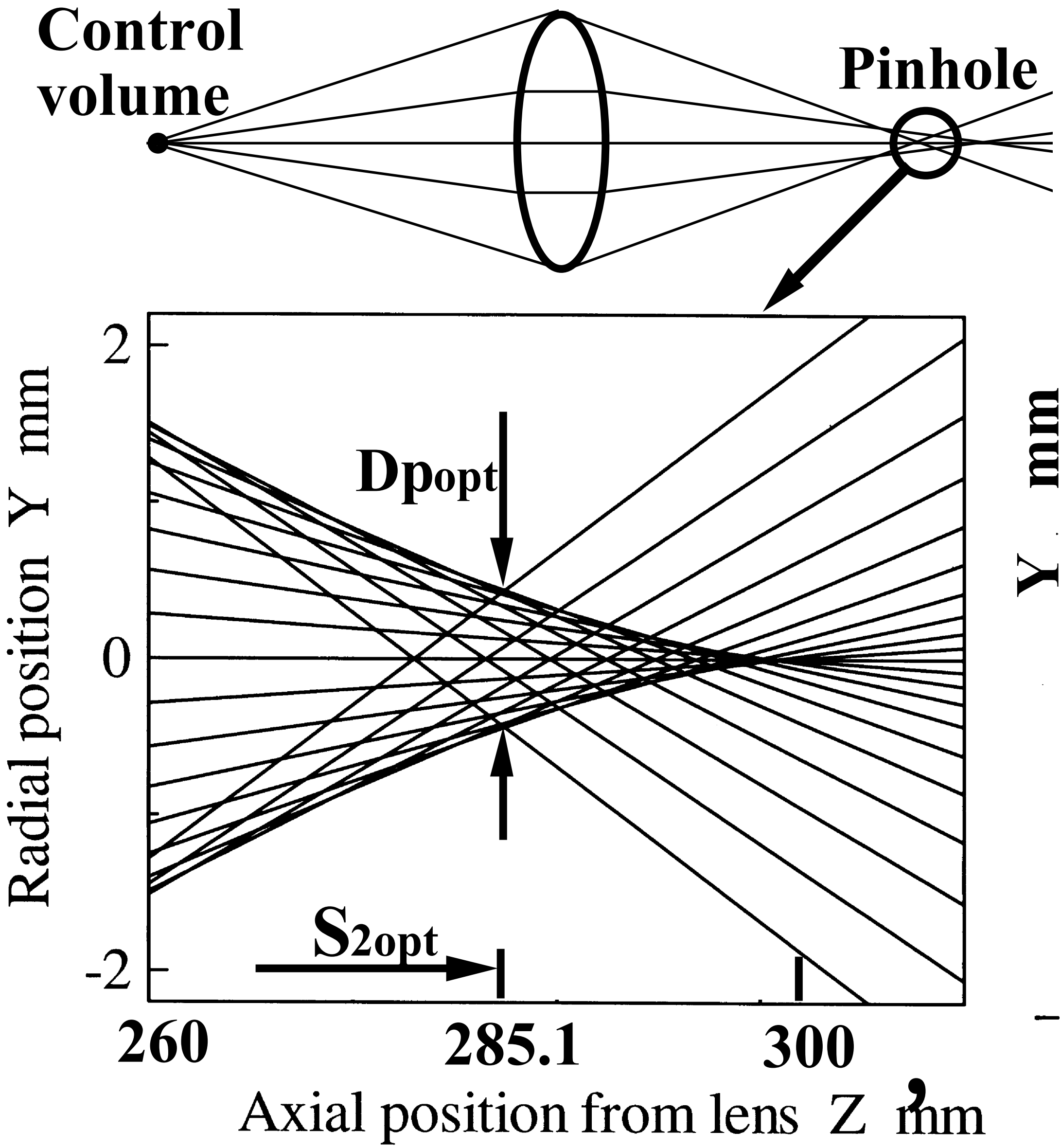
$S_{2opt} = 257.4$ mm

at OH-radical Wave Length, $\lambda = 310$ nm

Chromatic Aberration

The shorter the rays' wave length,
The shorter the focal length

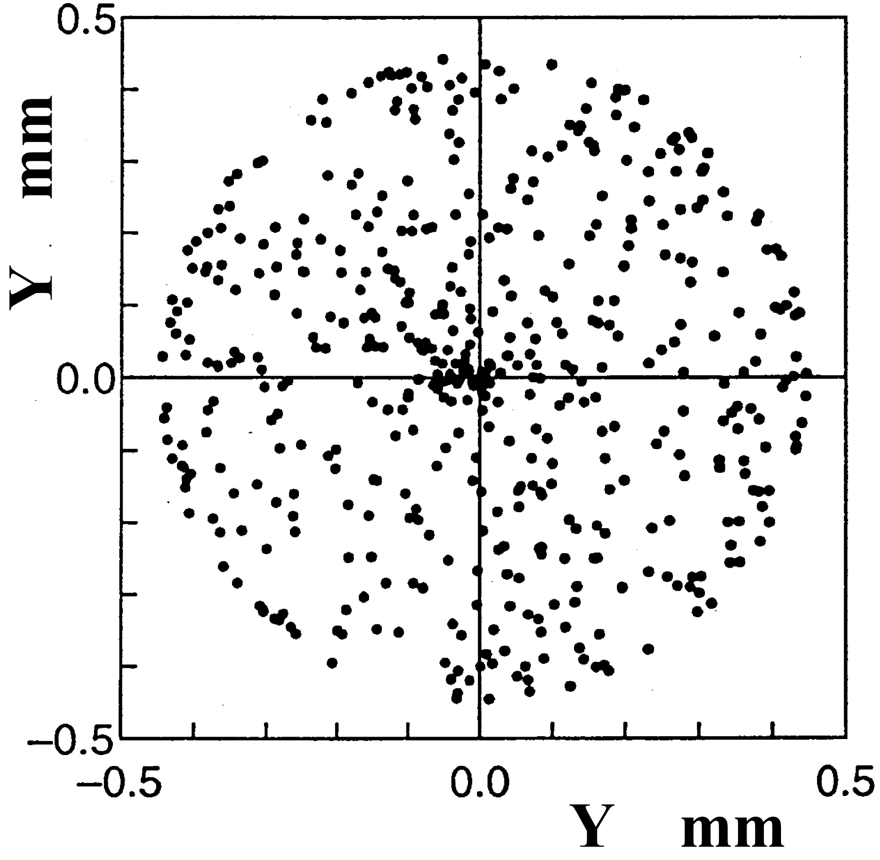
Optimum pinhole location and diameter using ray-tracing method (D_L=50mm)



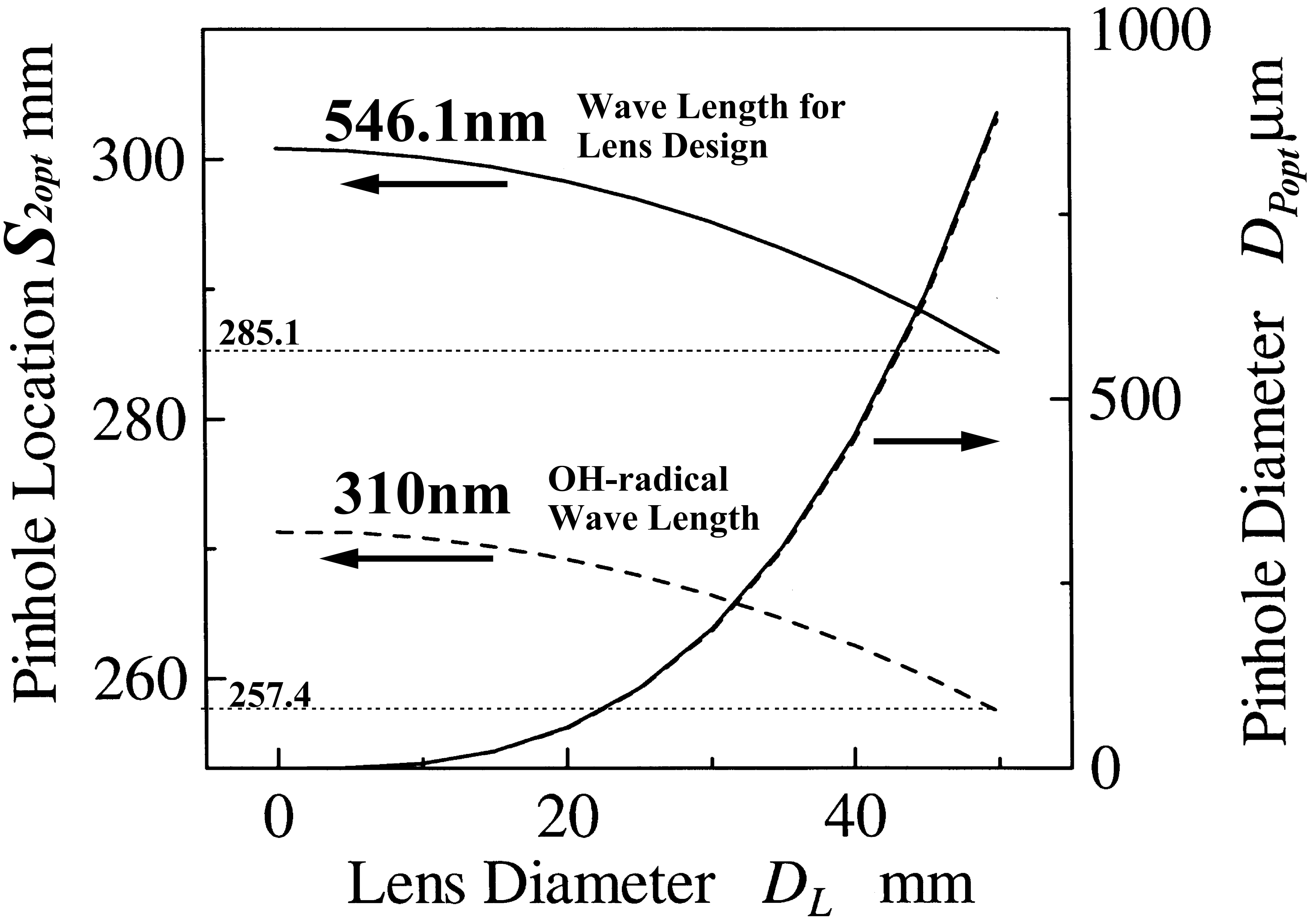
Ray-Tracing Method

(light wave length for the lens design: 546.1nm)

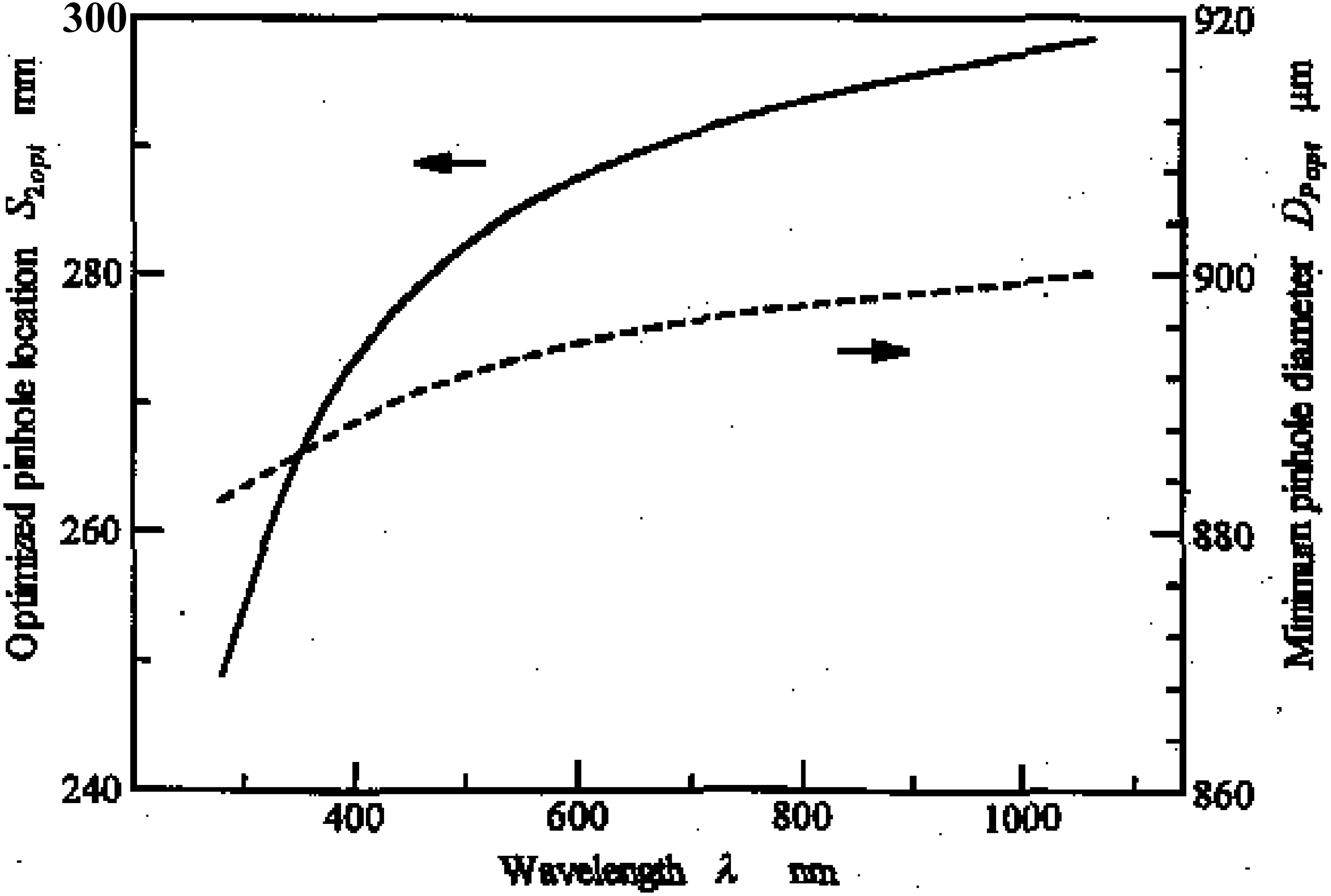
Circle of Least Confusion



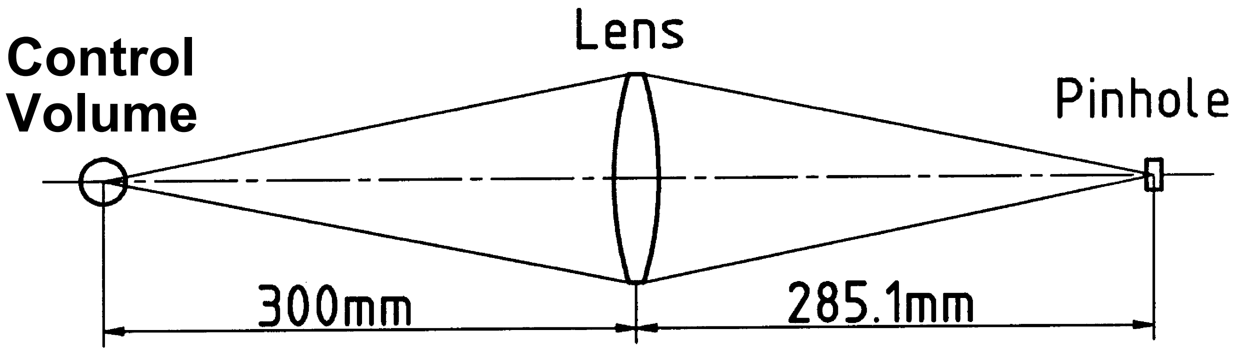
Optimum pinhole location and diameter as functions of lens diameter



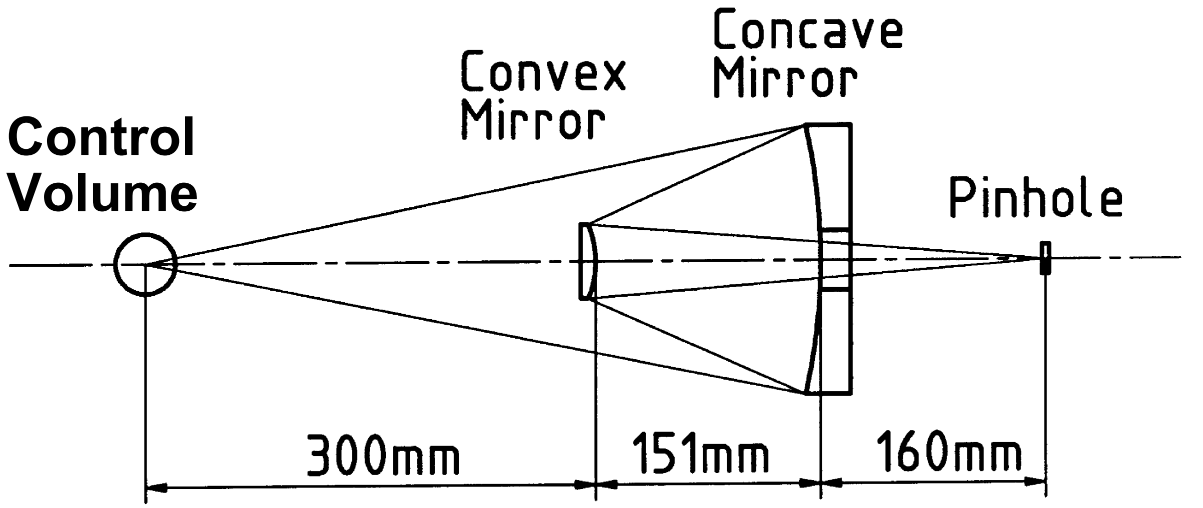
Optimum pinhole location and diameter as functions of wavelength



Single-lens optics and Cassegrain optics

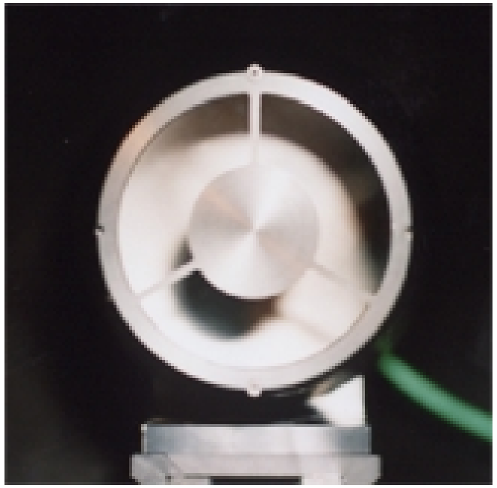


Single-Lens Optics

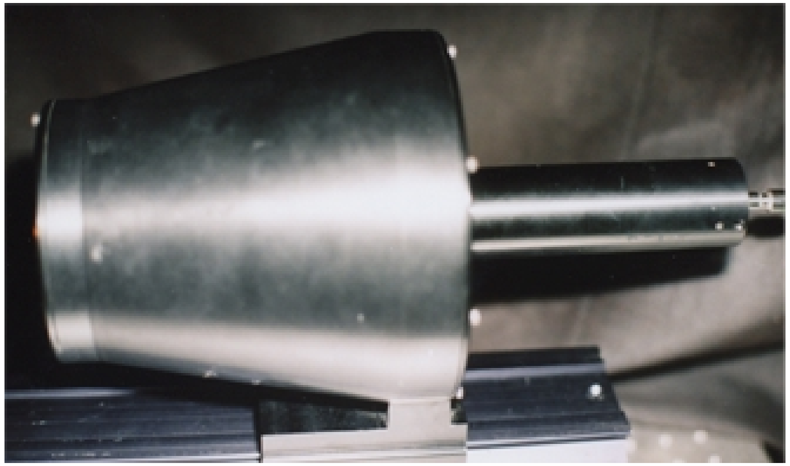


Cassegrain Optics

Multi-color Integrated Cassegrain Receiving Optics (MICRO)

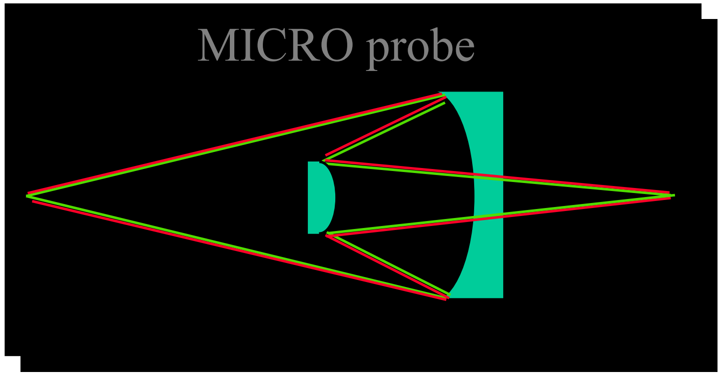


Front view

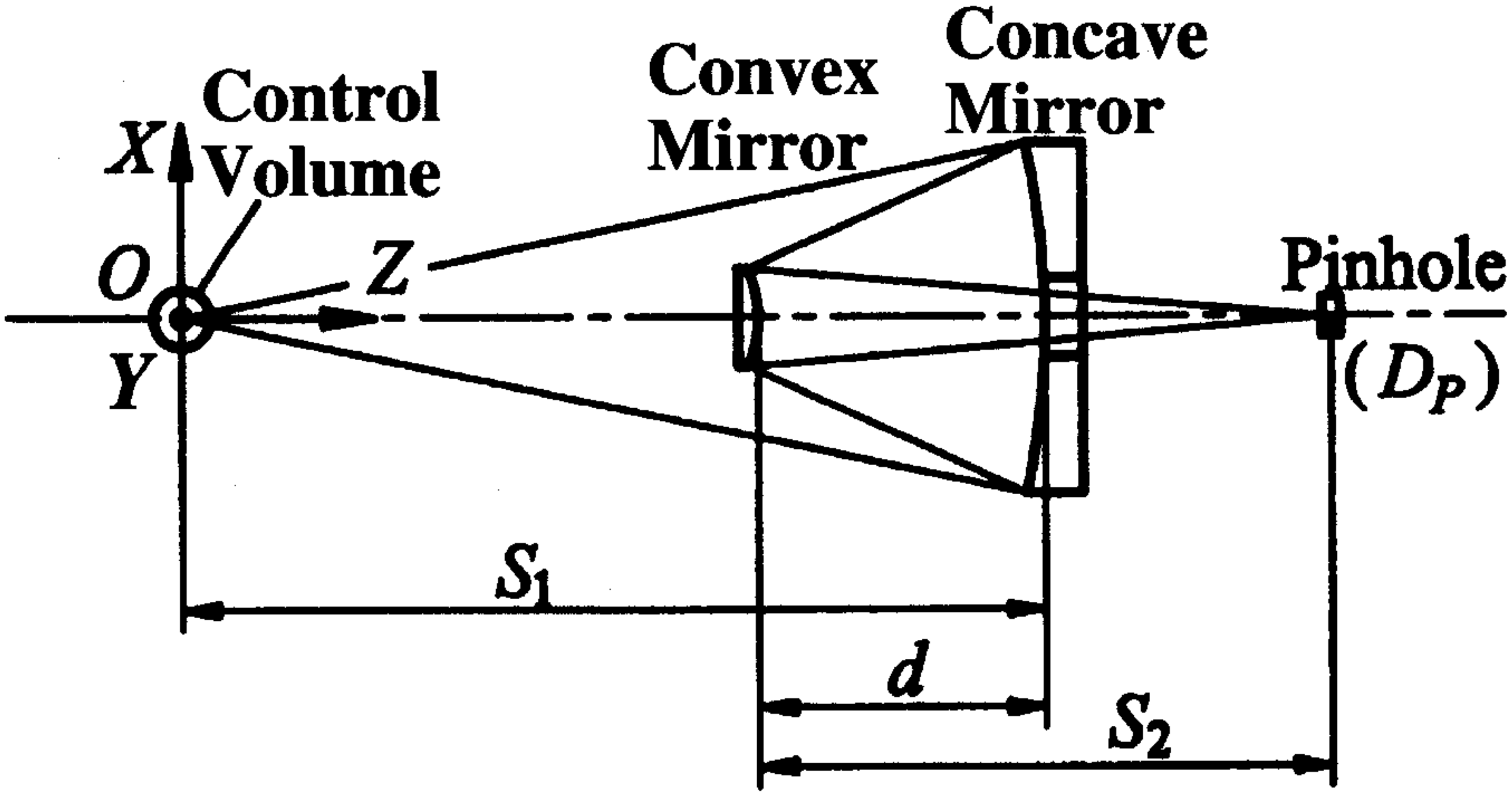


Side view

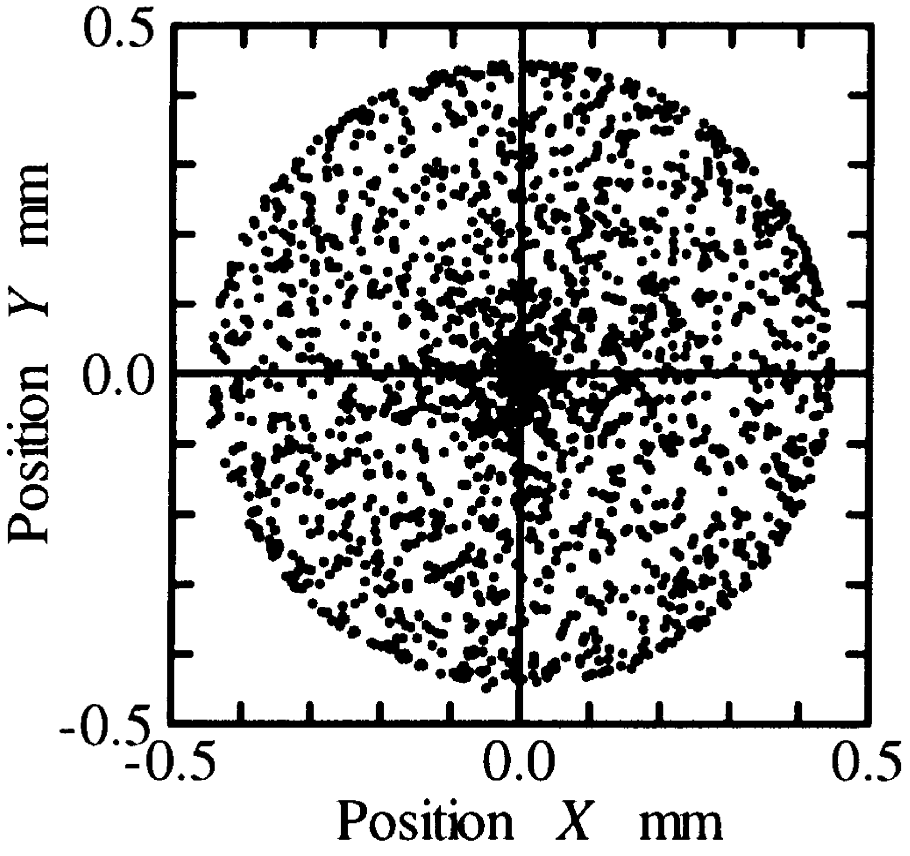
Bird eye’s view



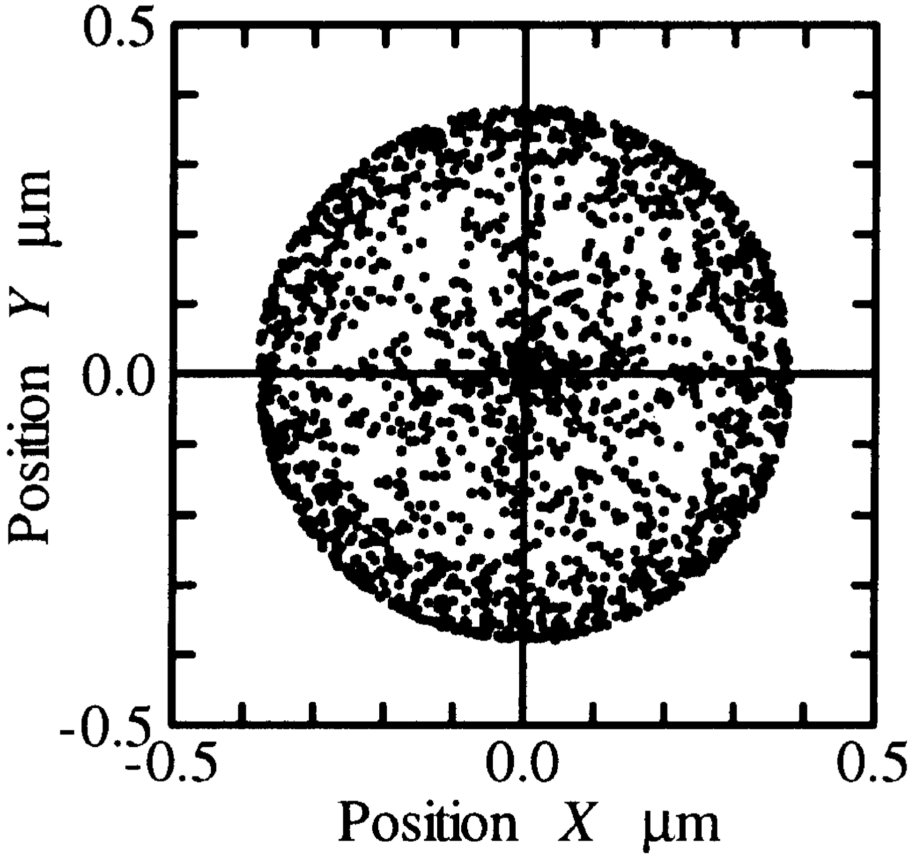
Cassegrain optics



Sperical aberration of single-lens and Cassegrain optics



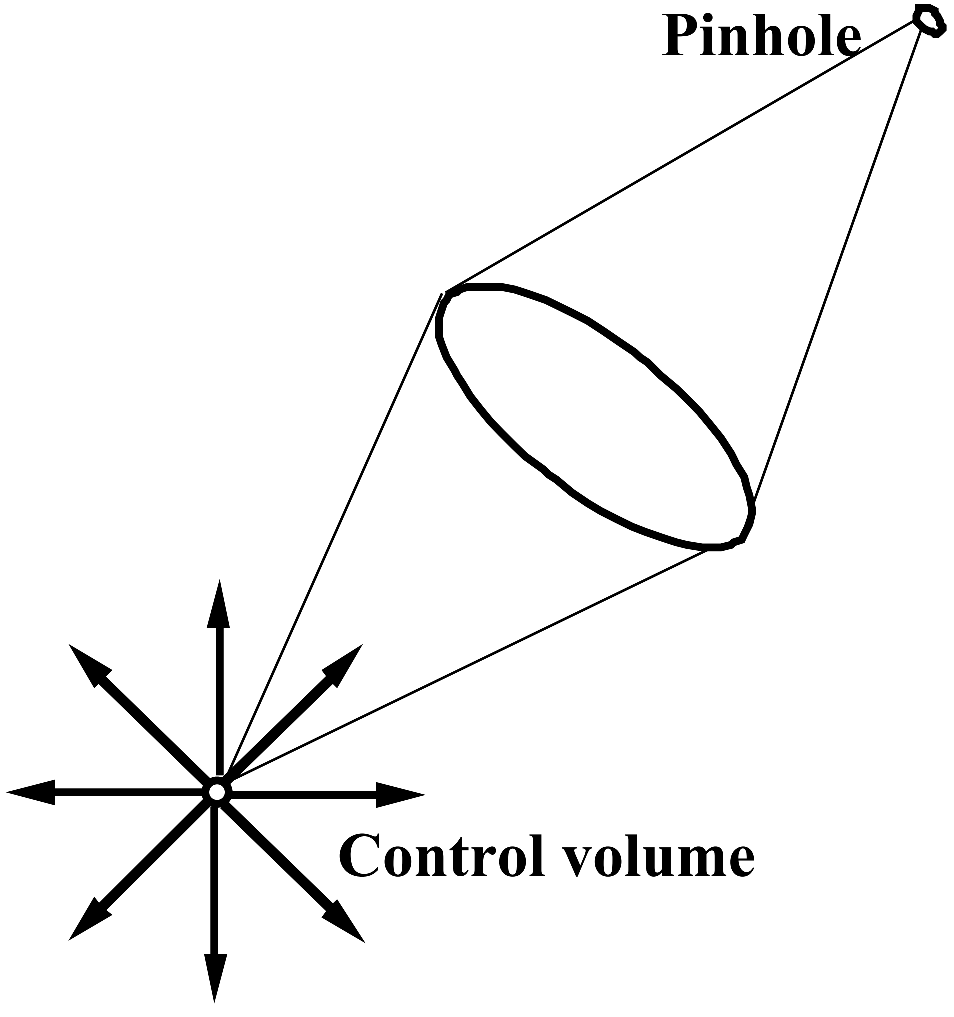
Single-Lens Optics

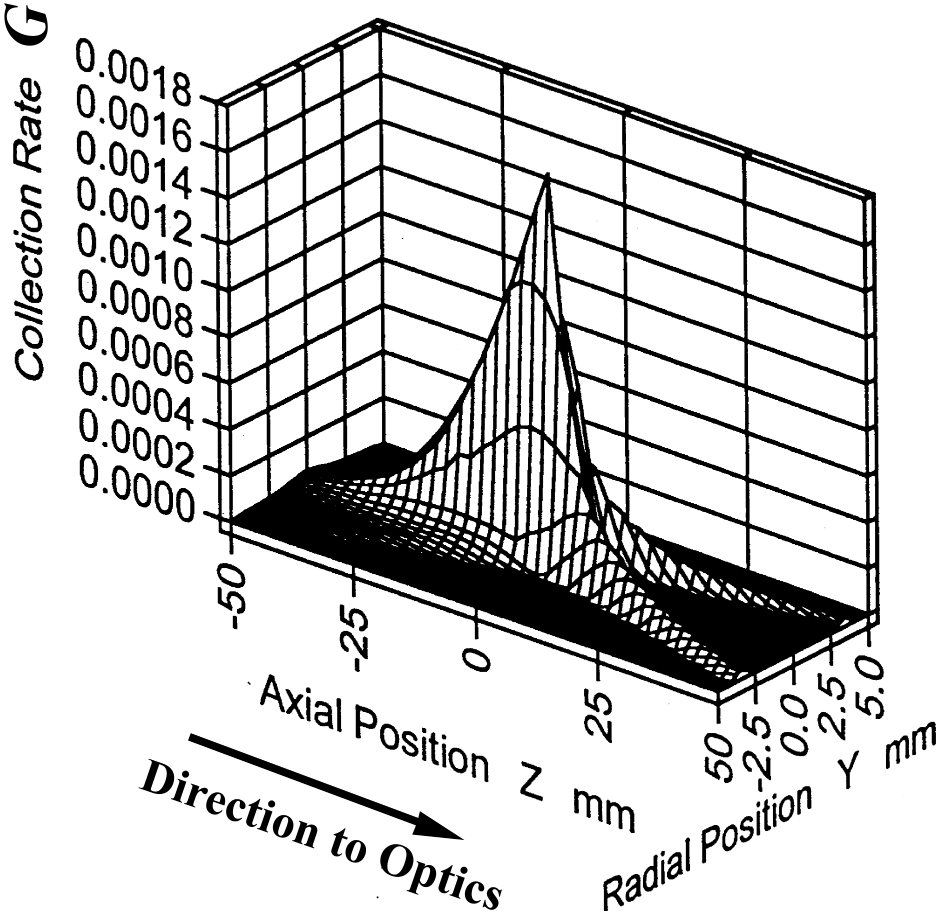


Cassegrain Optics

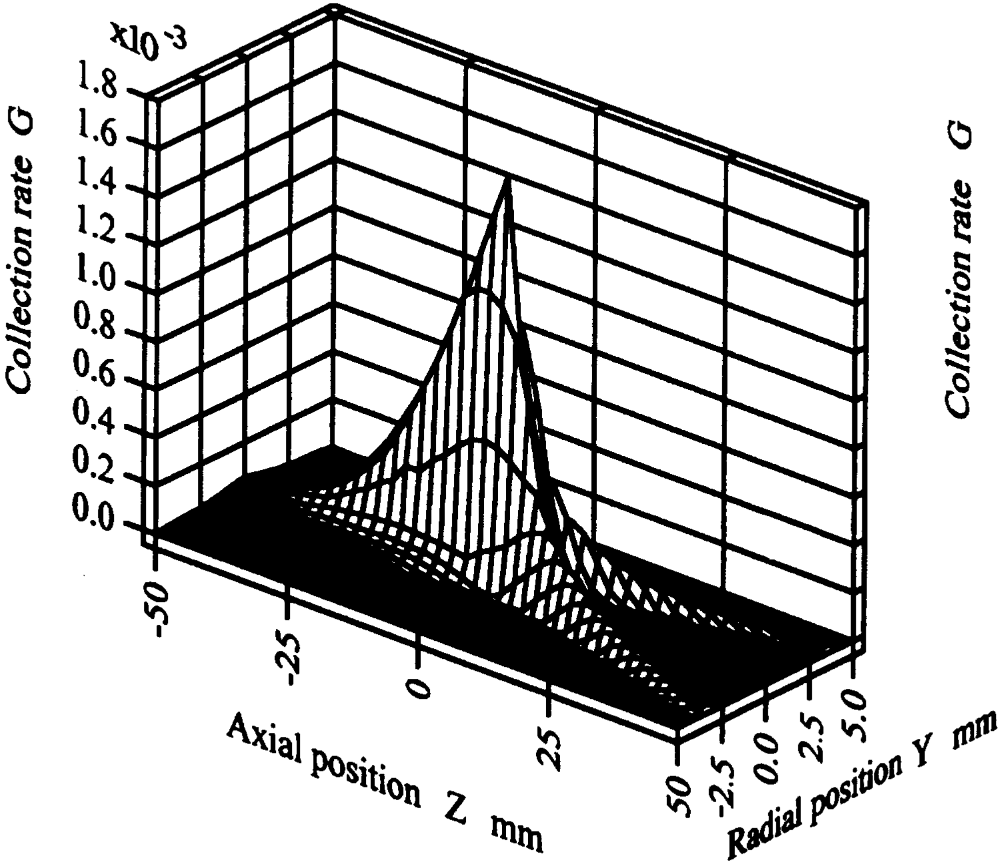
Estimation method of point measurement optics and distribution of collection rate

$$\text{Collection Rate } G = \frac{\text{Solid Angle of Optics}}{\text{Total Solid Angle }(4\pi)} = \frac{\text{Rays collected onto Pinhole}}{\text{Total Rays}}$$

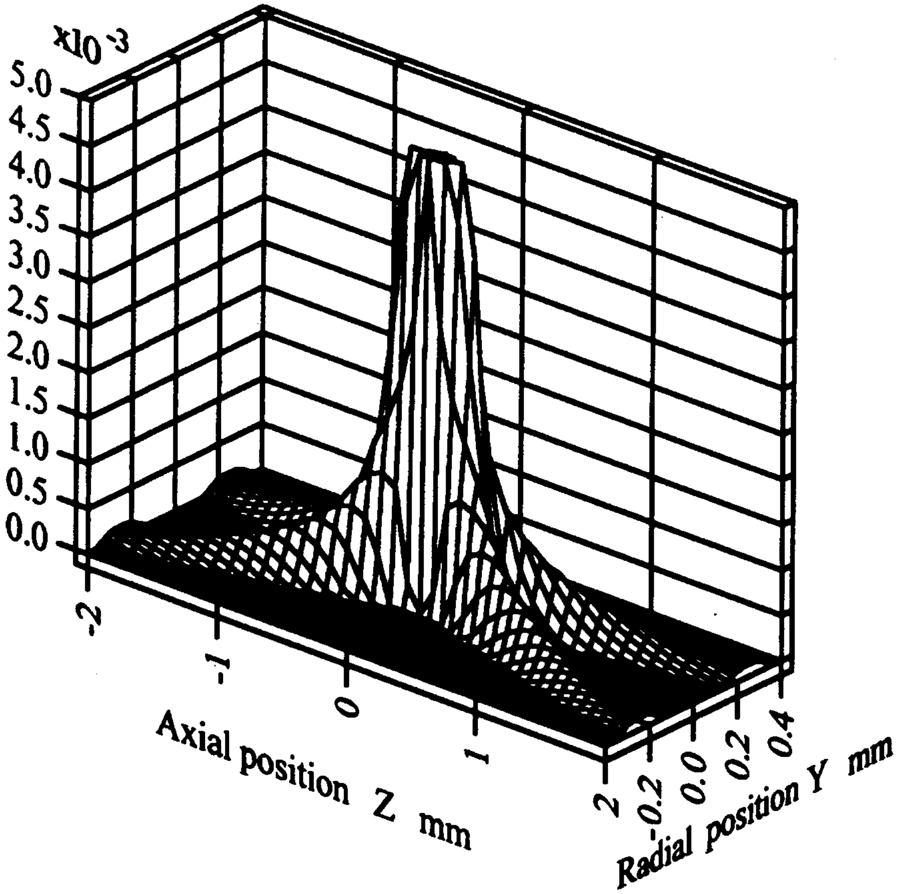




Collection rate distributions of single-lens and Cassegrain optics

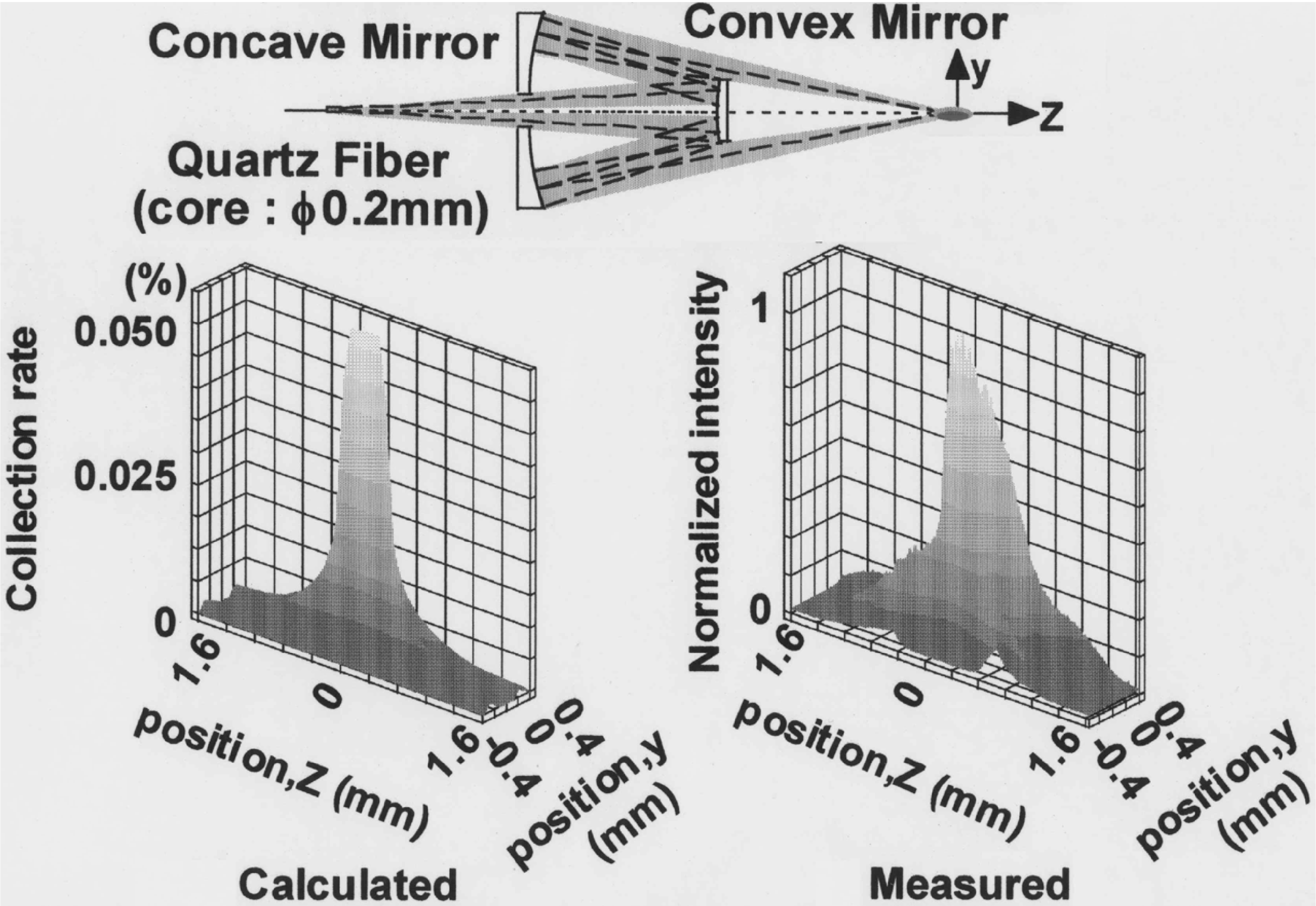


Single-Lens Optics



Cassegrain Optics

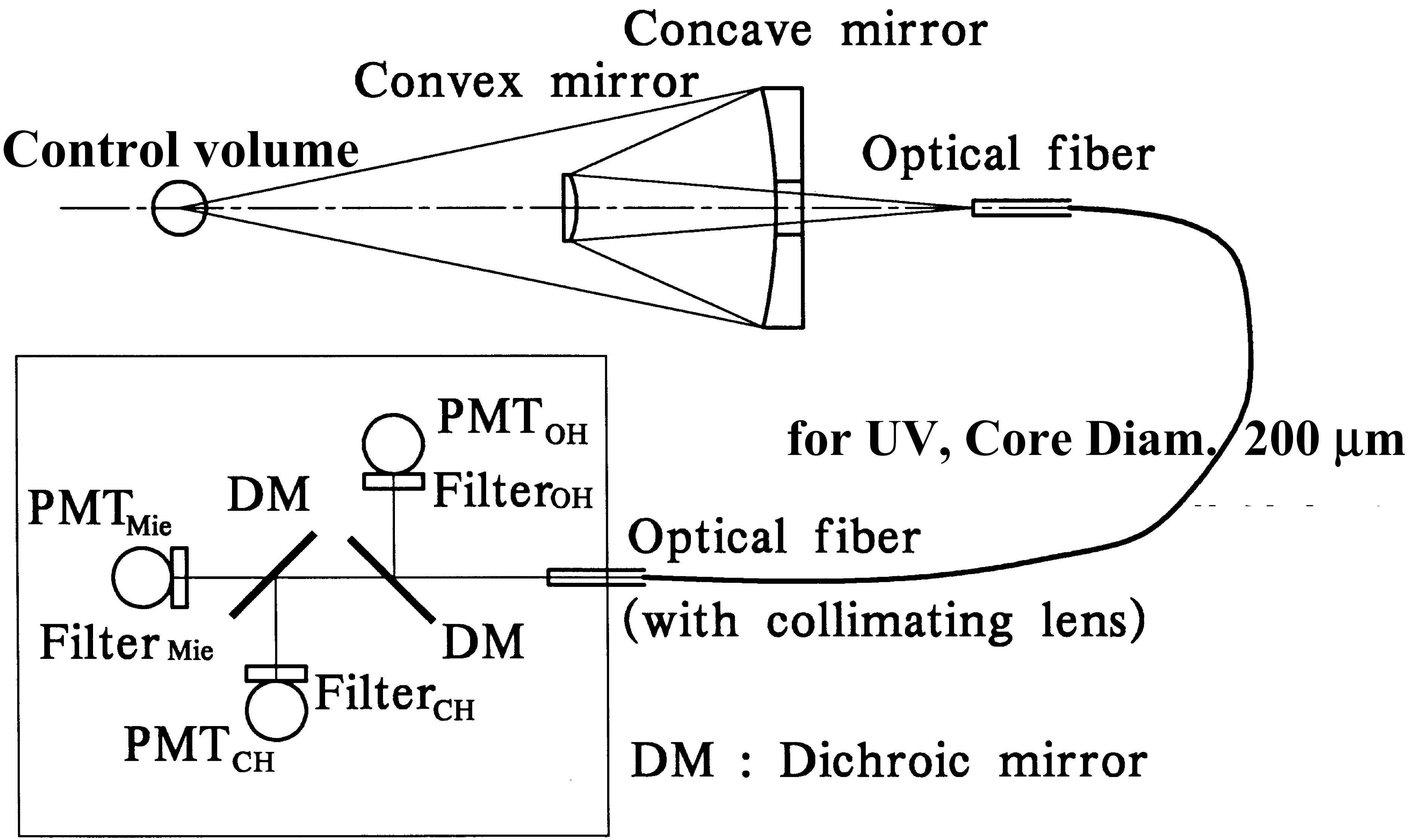
Measured collection rate distributions



Calculated

Measured

Light detection system of Cassegrain optics



Concave mirror

Convex mirror

Control volume

Optical fiber

for UV, Core Diam. 200 µm

PMT$_{\mathrm{OH}}$

Filter$_{\mathrm{OH}}$

PMT$_{\mathrm{Mie}}$

DM

Optical fiber

(with collimating lens)

Filter$_{\mathrm{Mie}}$

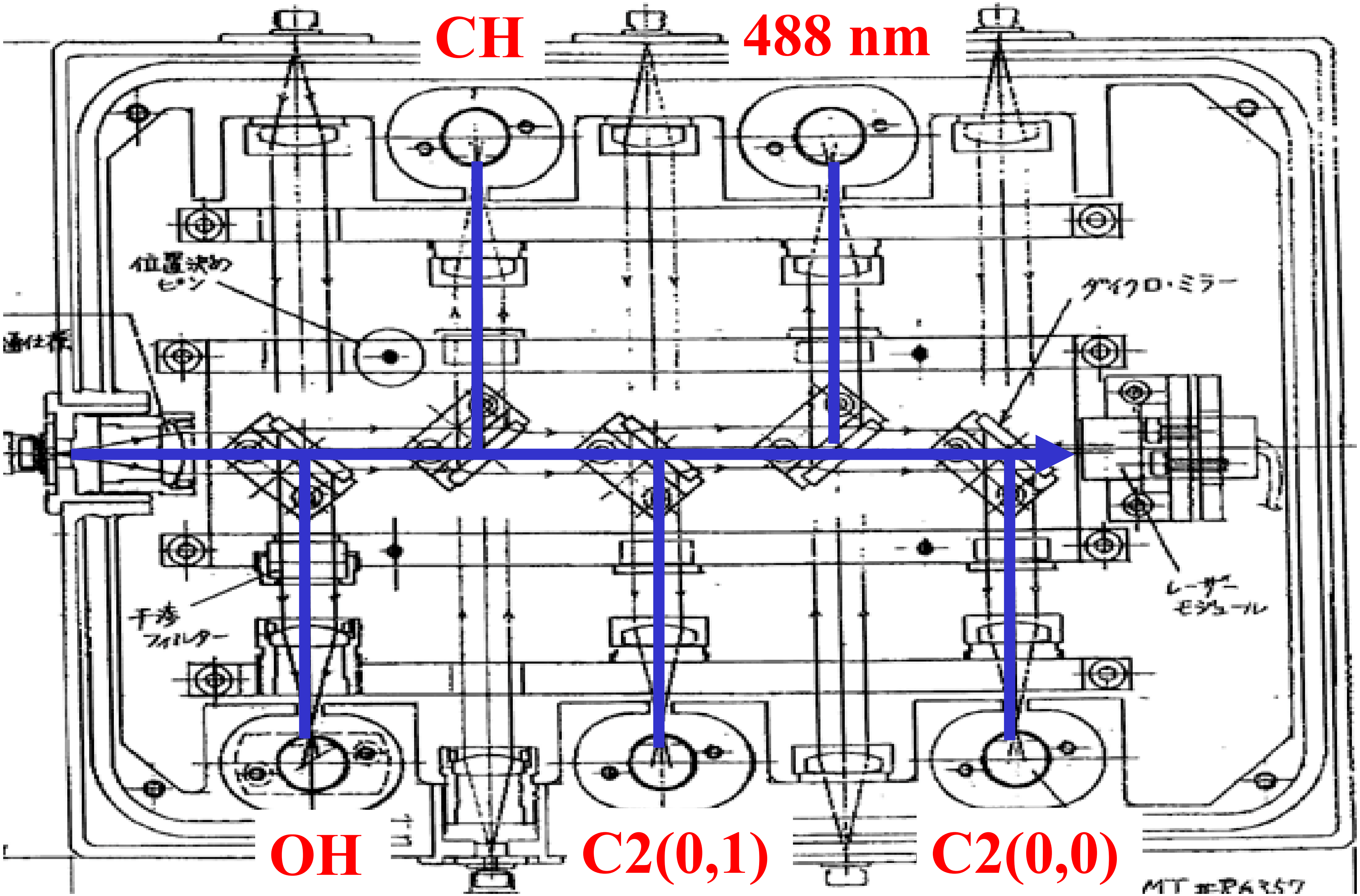
DM

Filter$_{\mathrm{CH}}$

PMT$_{\mathrm{CH}}$

DM : Dichroic mirror

New Light detection system of Cassegrain



Advantage of the MICRO system

- **No Chromatic Aberration**
  Consisting of only mirrors

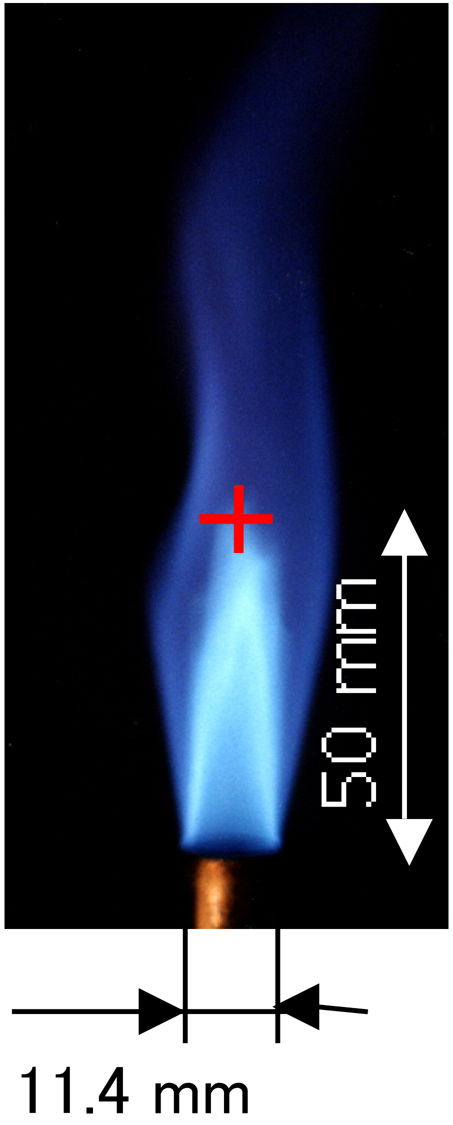
- **Minimum Spherical Aberration**
  Optimization of two mirrors' curvature combination

- **Very High Light Collection Rate**
  Large diameter optics can be available due to elimination of spherical aberration.

- **Short Control Volume Length Along Optical Path**
  Minimum spherical aberration and masking effect of the center of convex mirror

- **Easy Alignment of Optics**
  Control volume can be visualized

Direct photograph of Bunsen flame with measurement point



Ion current and OH chemiluminescence

Ion current is produced from the following reactions.

$$CH + O \text{ ---> } CHO^{+} + e^{-} \qquad (1)$$

$$CH + C_2H_2 \text{ ---> } C_3H_3^{+} + e^{-} \qquad (2)$$

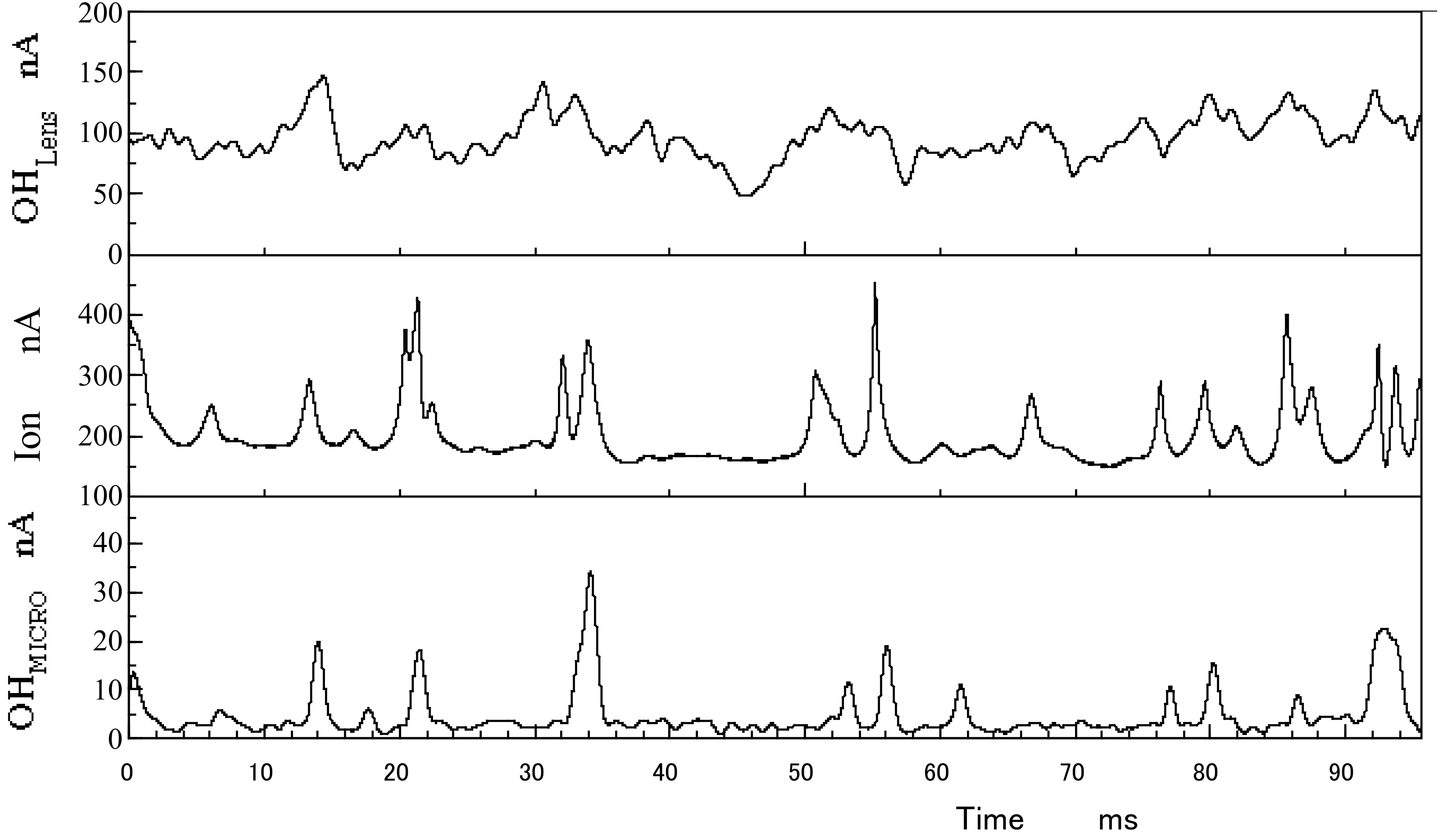
OH chemiluminescence is emitted in the deactivation course (3) of OH* produced from the reaction (4).

$$CH + O_2 \text{ ---> } CO + OH^{*} \qquad (3)$$

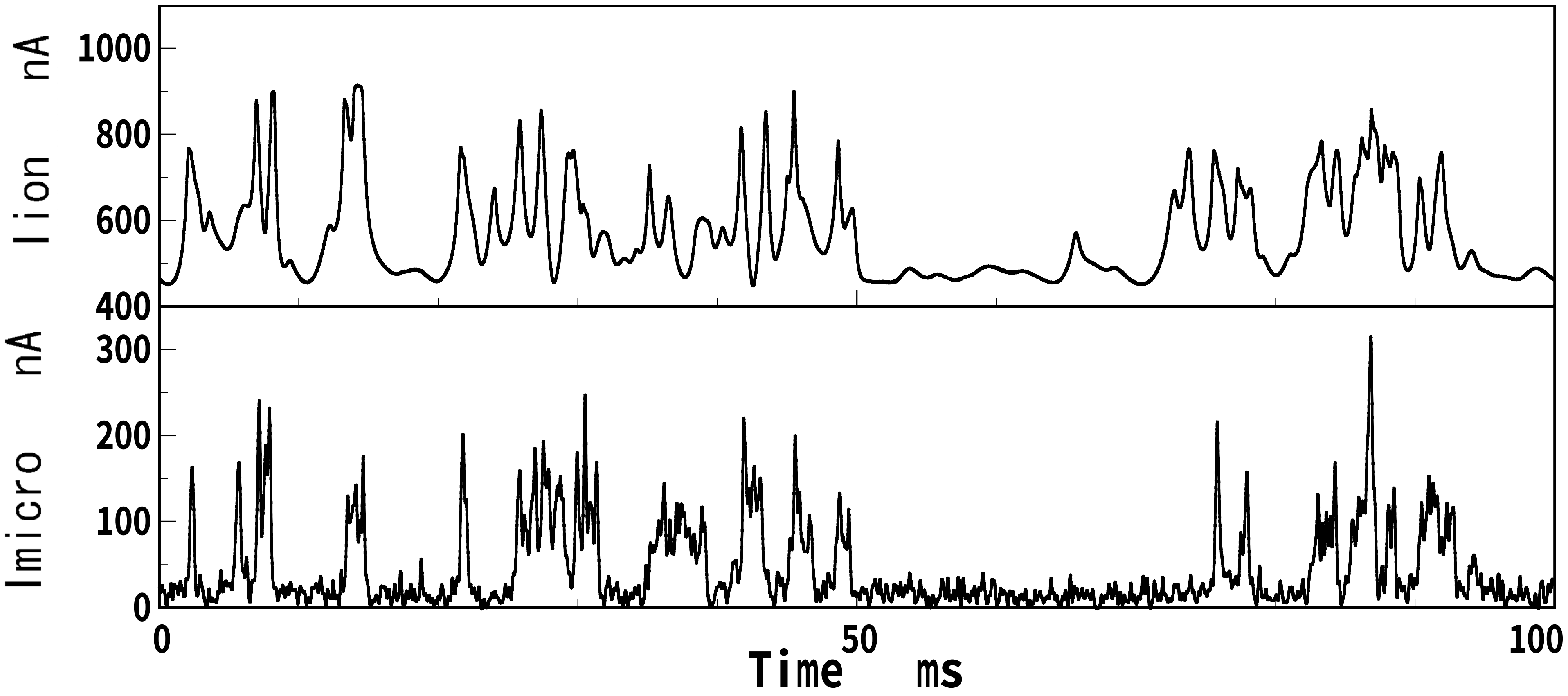
$$OH^{*} \text{ ---> } OH + h\nu \qquad (4)$$

where the superscript * denotes an excited state, *h* is the Plank's constant, and ν is the frequency of the chemiluminescence.

Time-series signals of ion current obtained by electrostatic probe, and OH chemiluminescence obtained by MICRO and single-lens optics

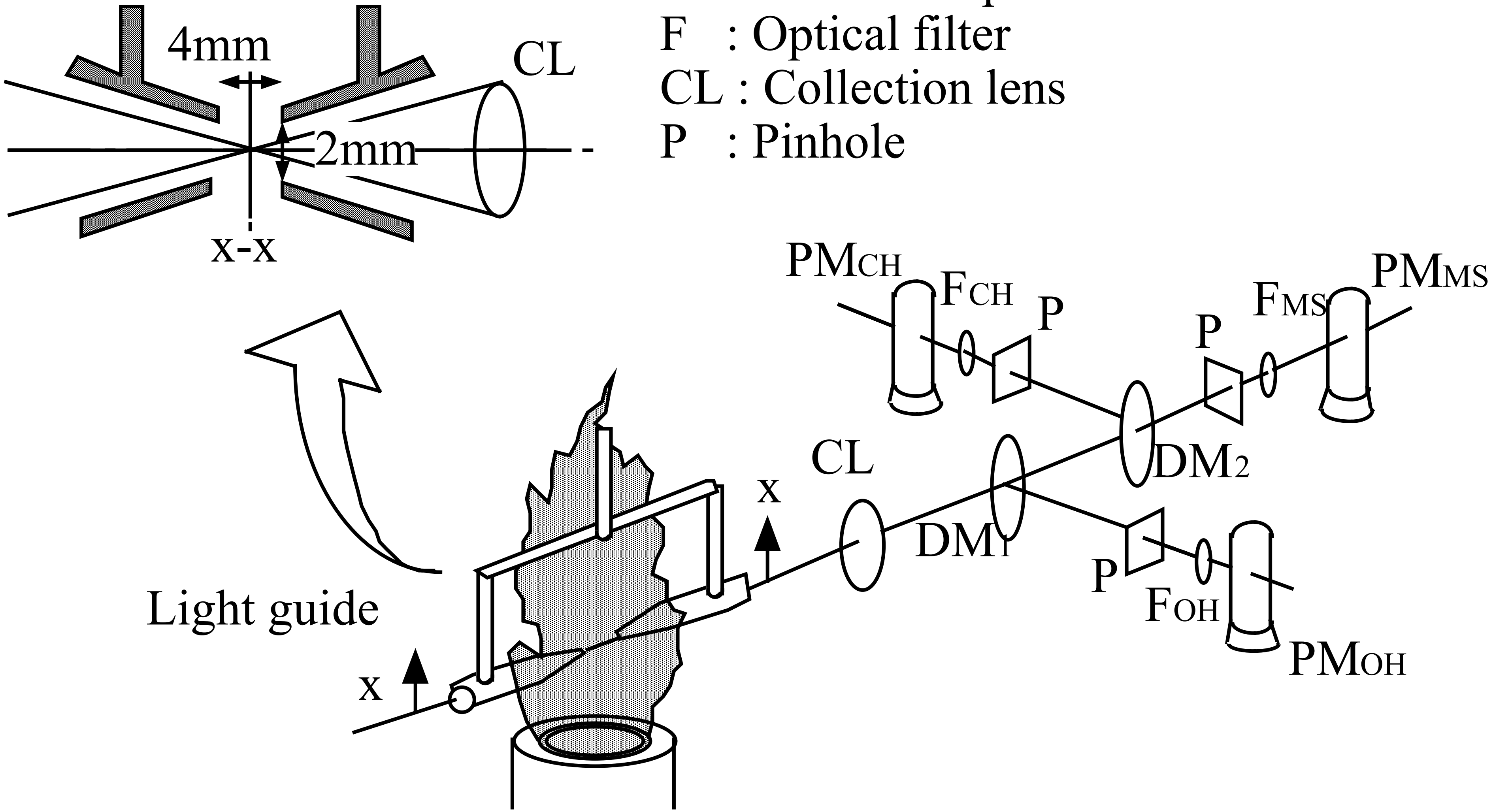


Time-series signals of OH radical chemiluminescence by the MICRO and ion current by the electro-static probe

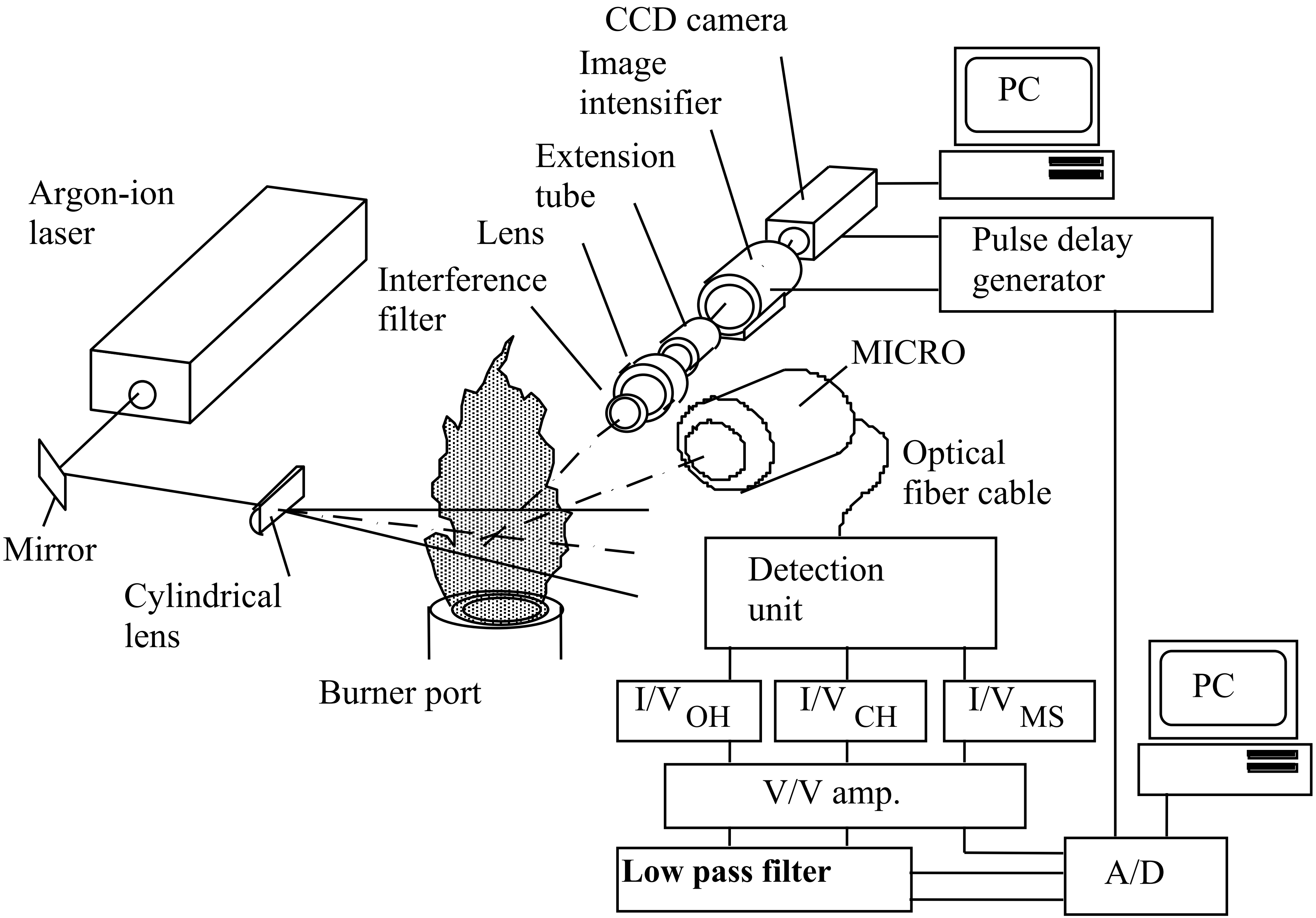


Previous point measurement system

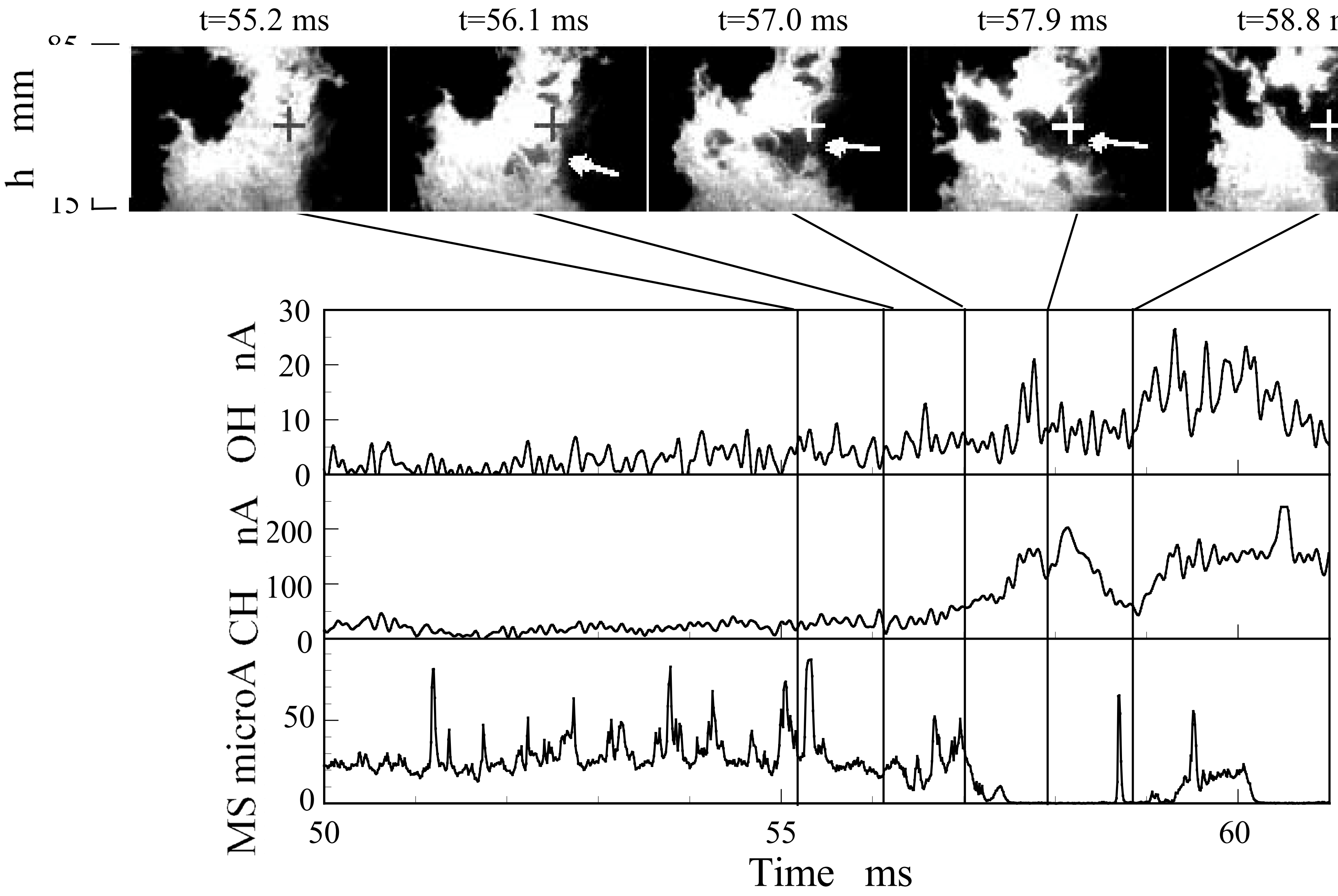
DM: Dicroic mirror
PM: Photomultiplier
F : Optical filter
CL : Collection lens
P : Pinhole



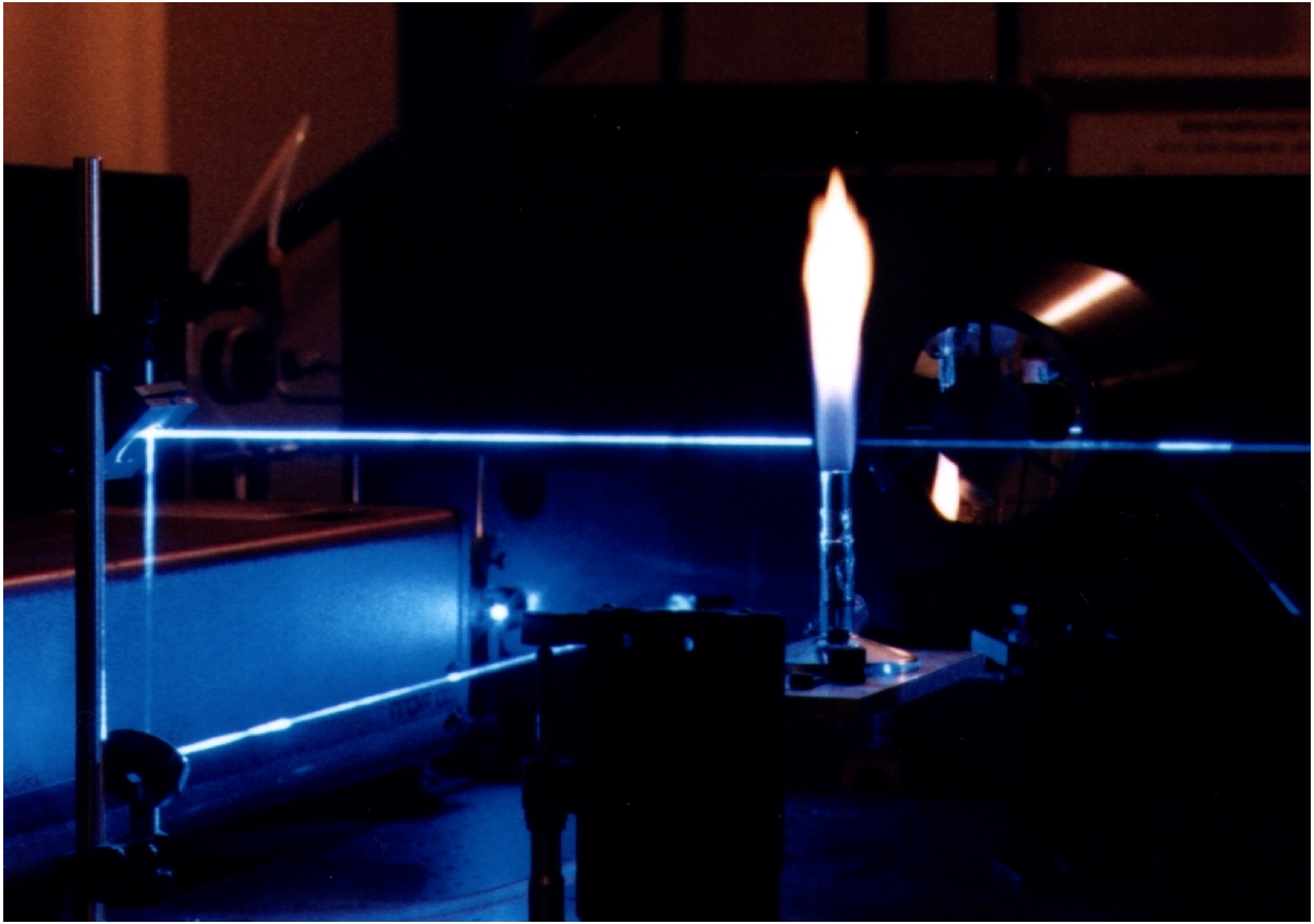
Example of MICRO Application



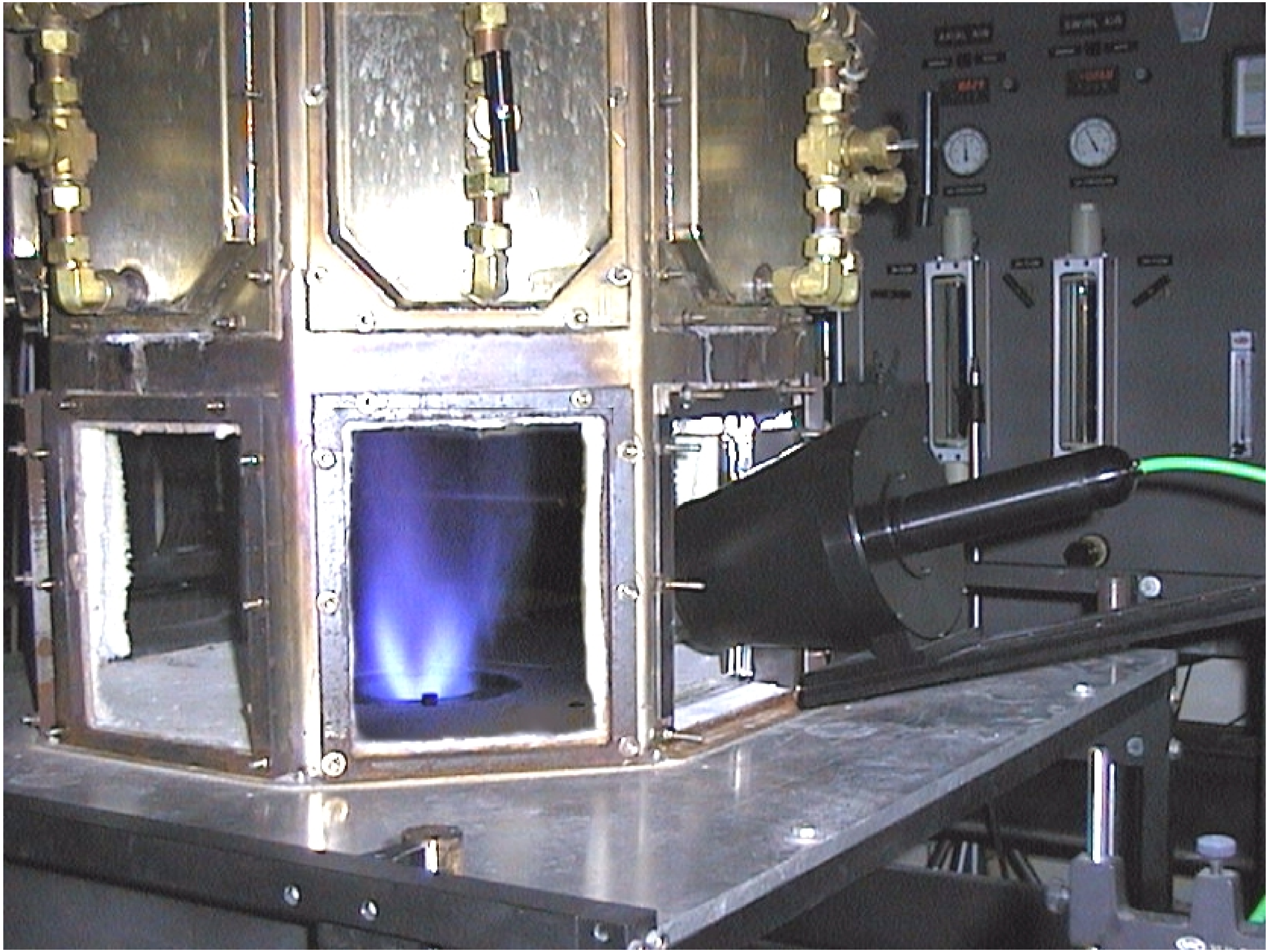
Simultaneous measurement with images



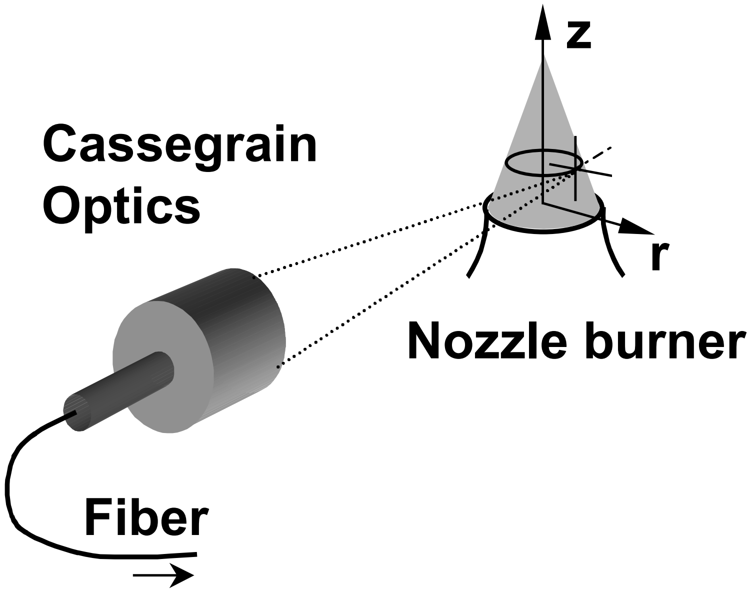
Rayleigh scattering measurement

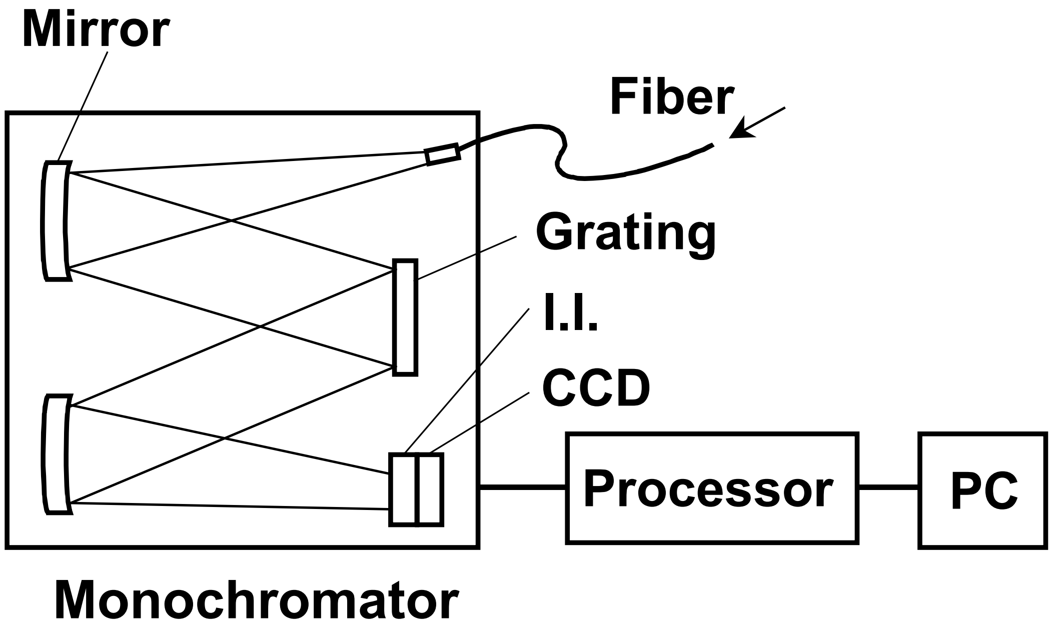


Photograph of experiment

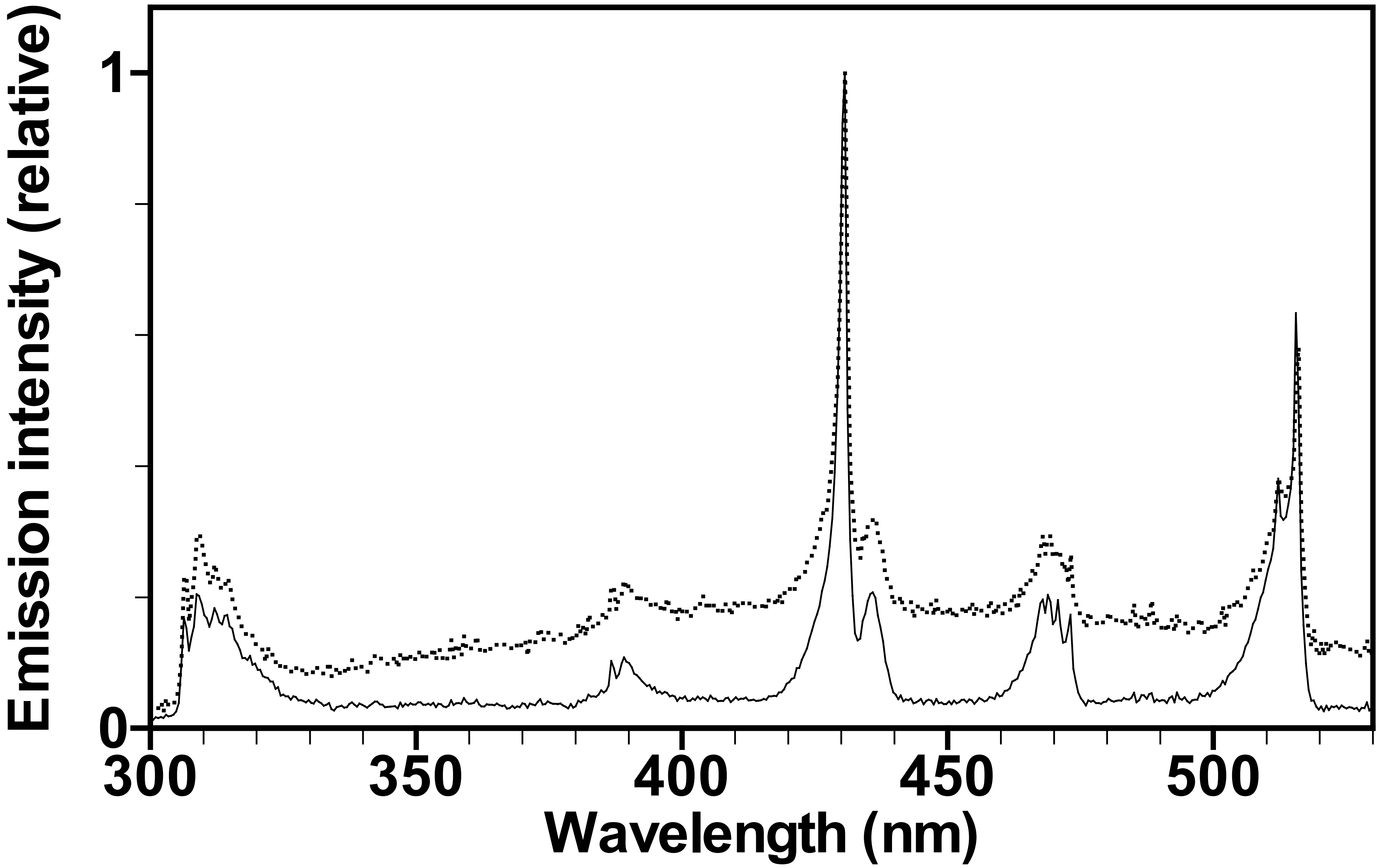


Measurement of spectrum

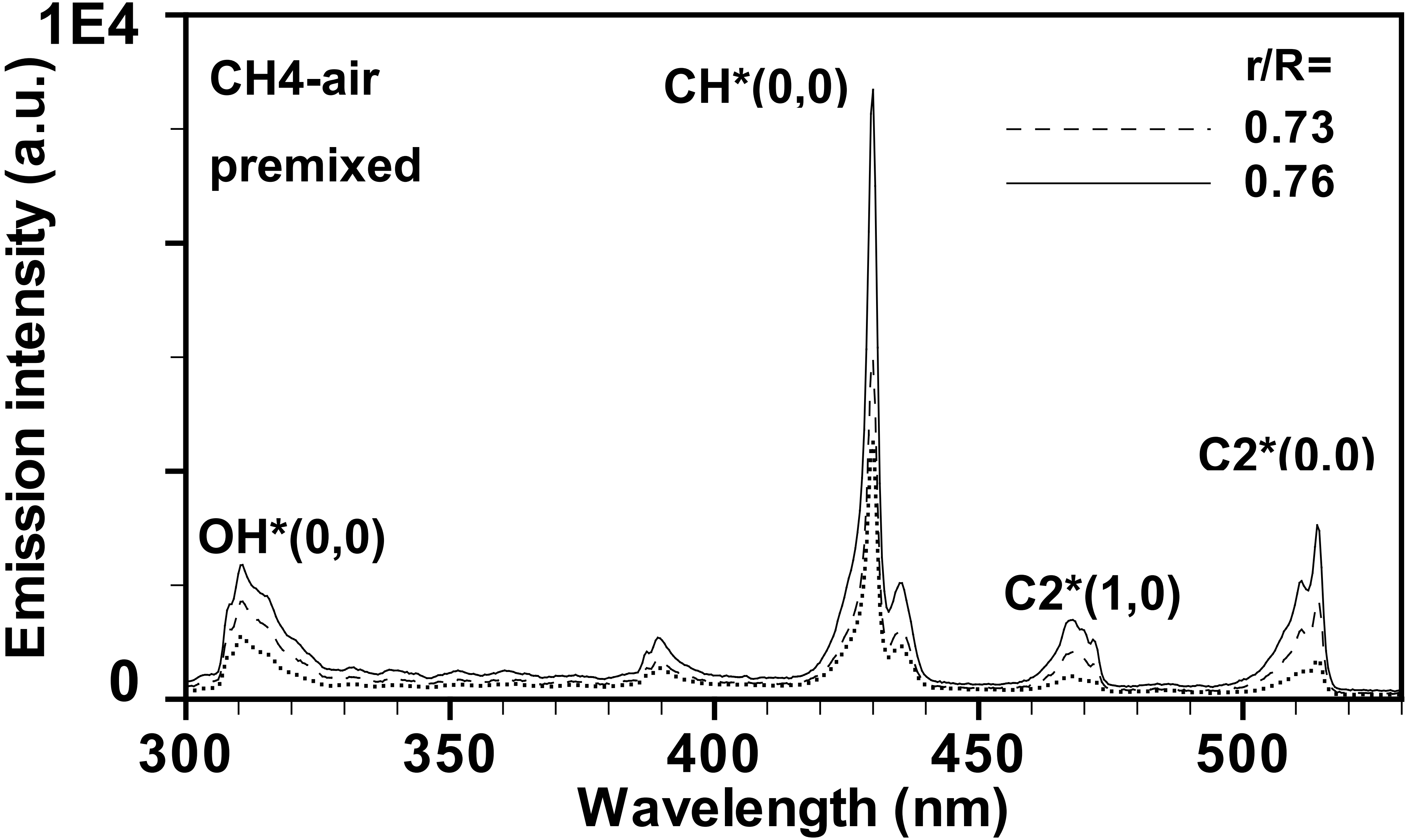




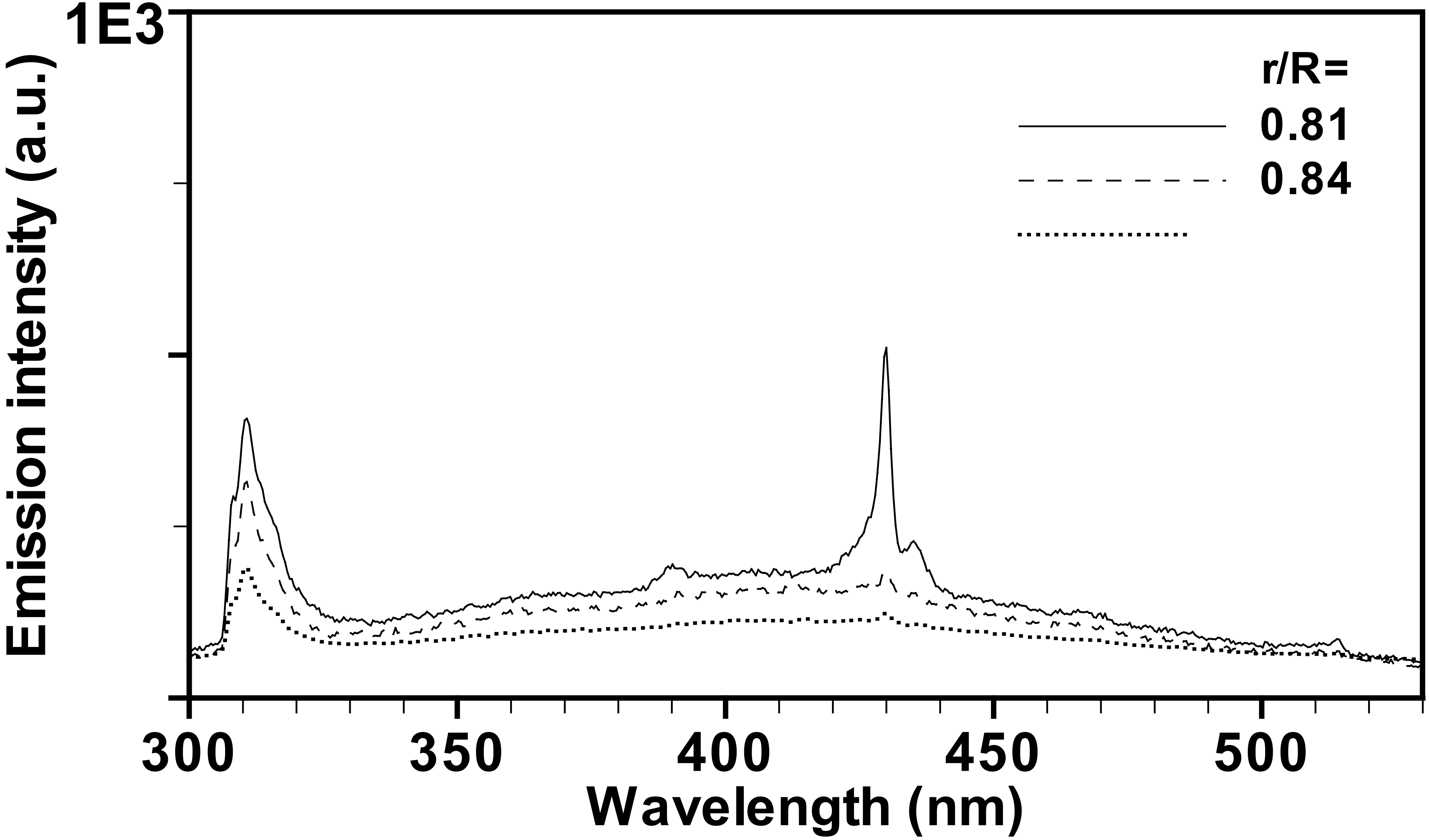
Spectrum of flame luminosity



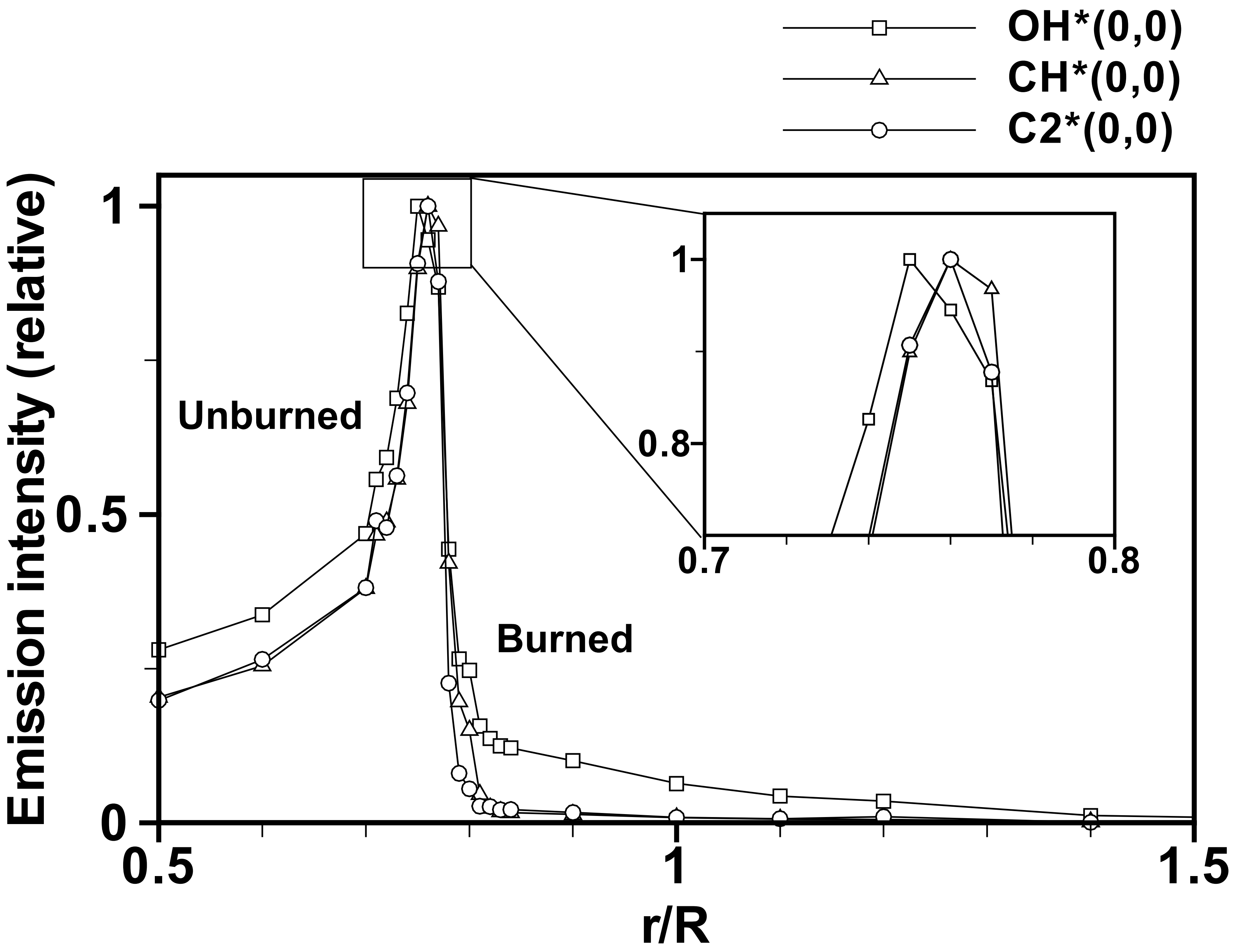
Change of spectrum with location



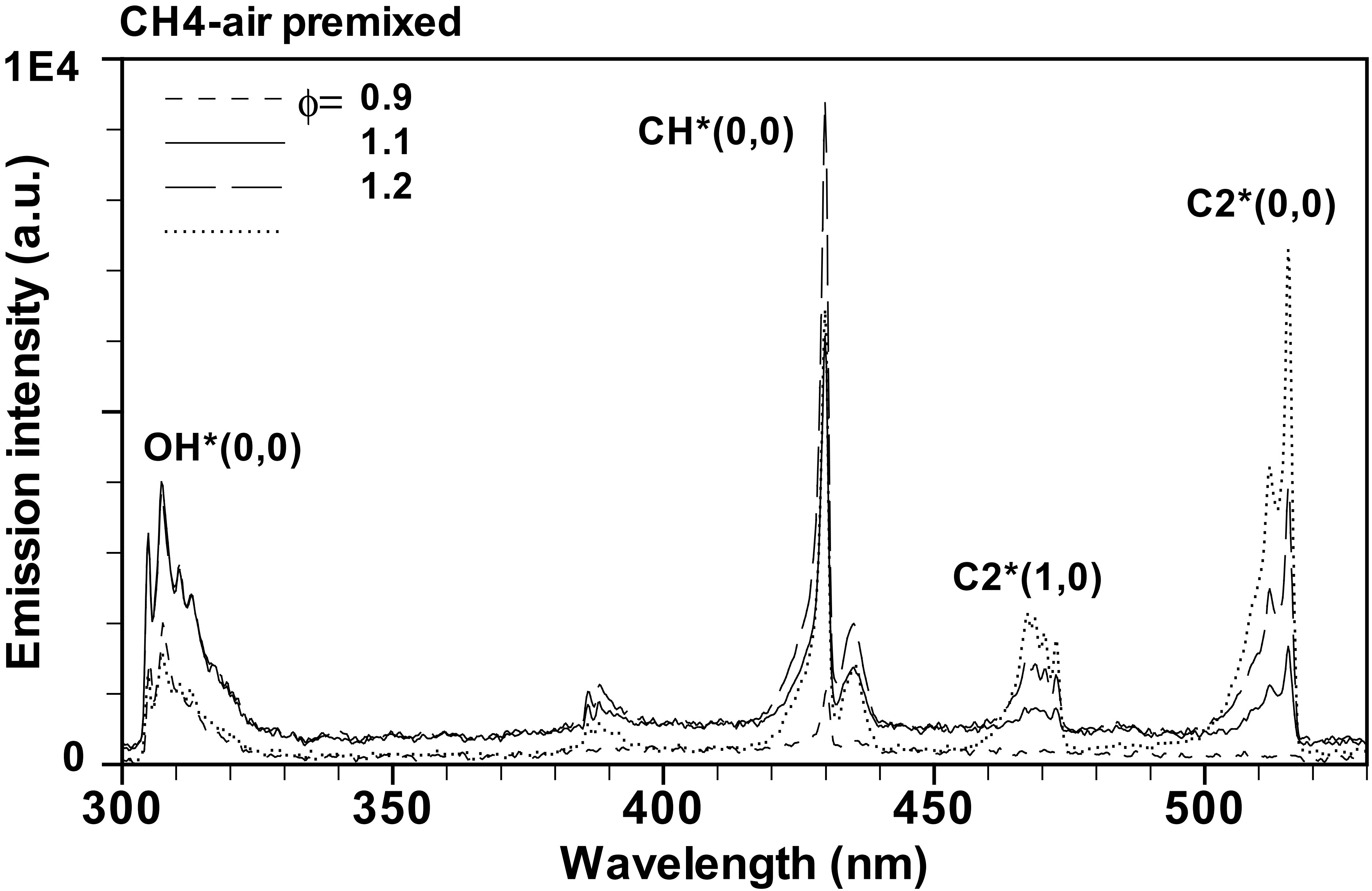
Change of spectrum with location



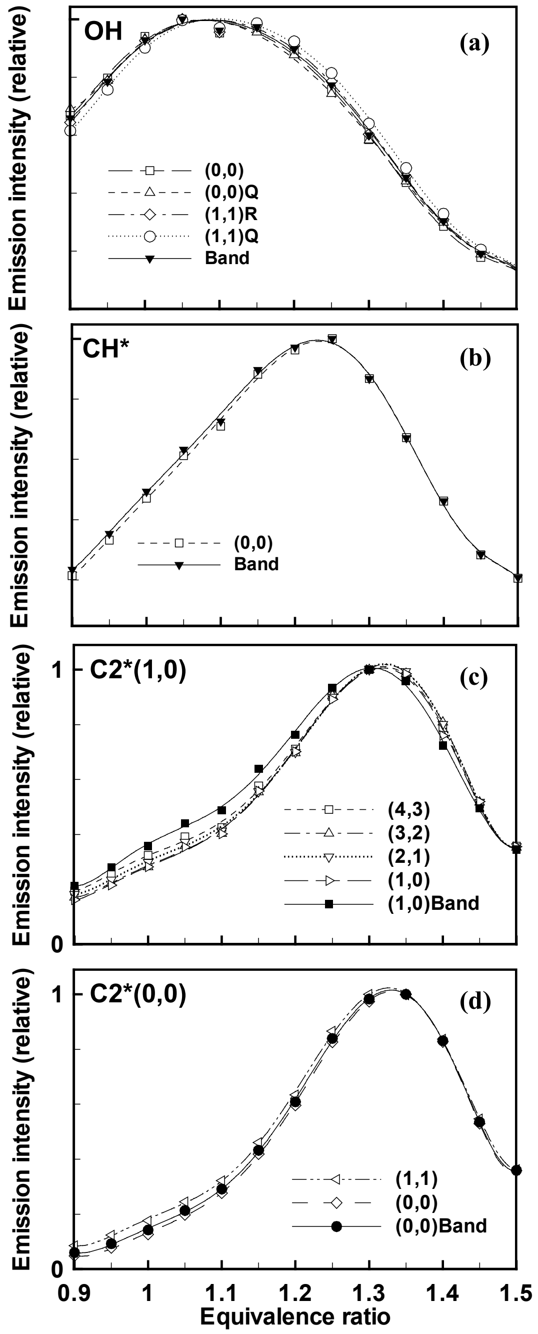
Locations of chemiluminescence intensity peak



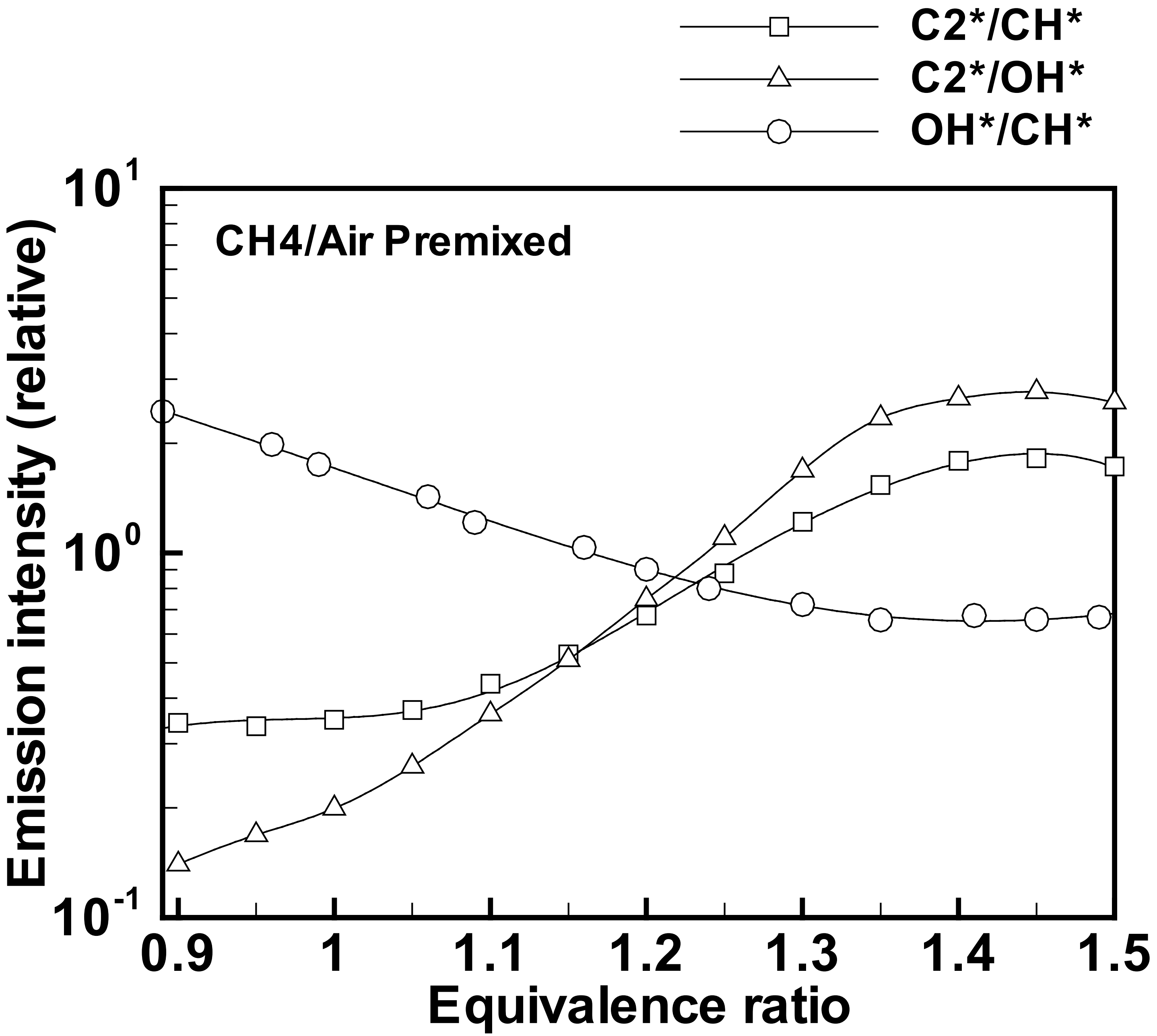
Change of spectrum with equivalence ratio



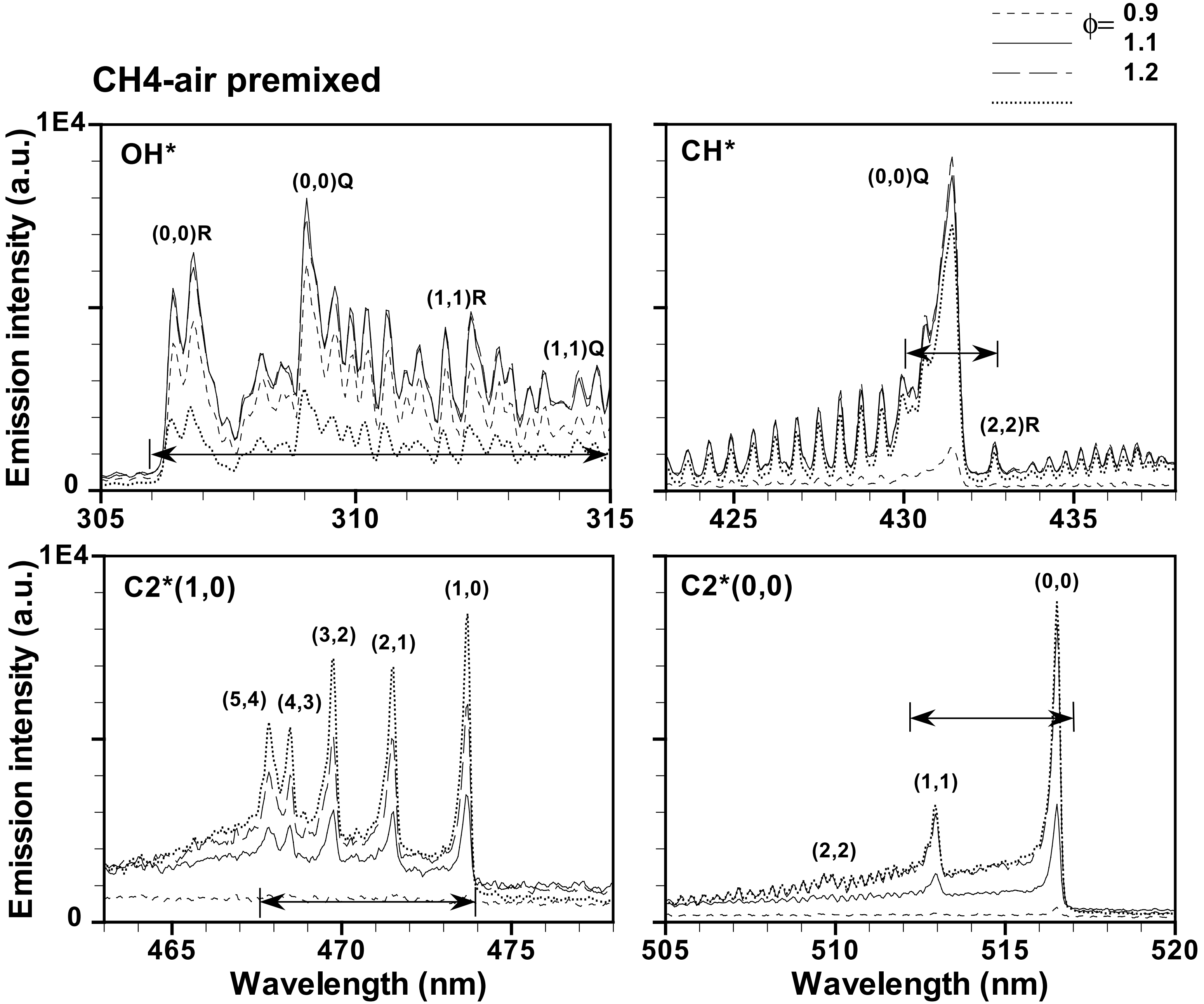
Change of peak intensity with equivalence ratio



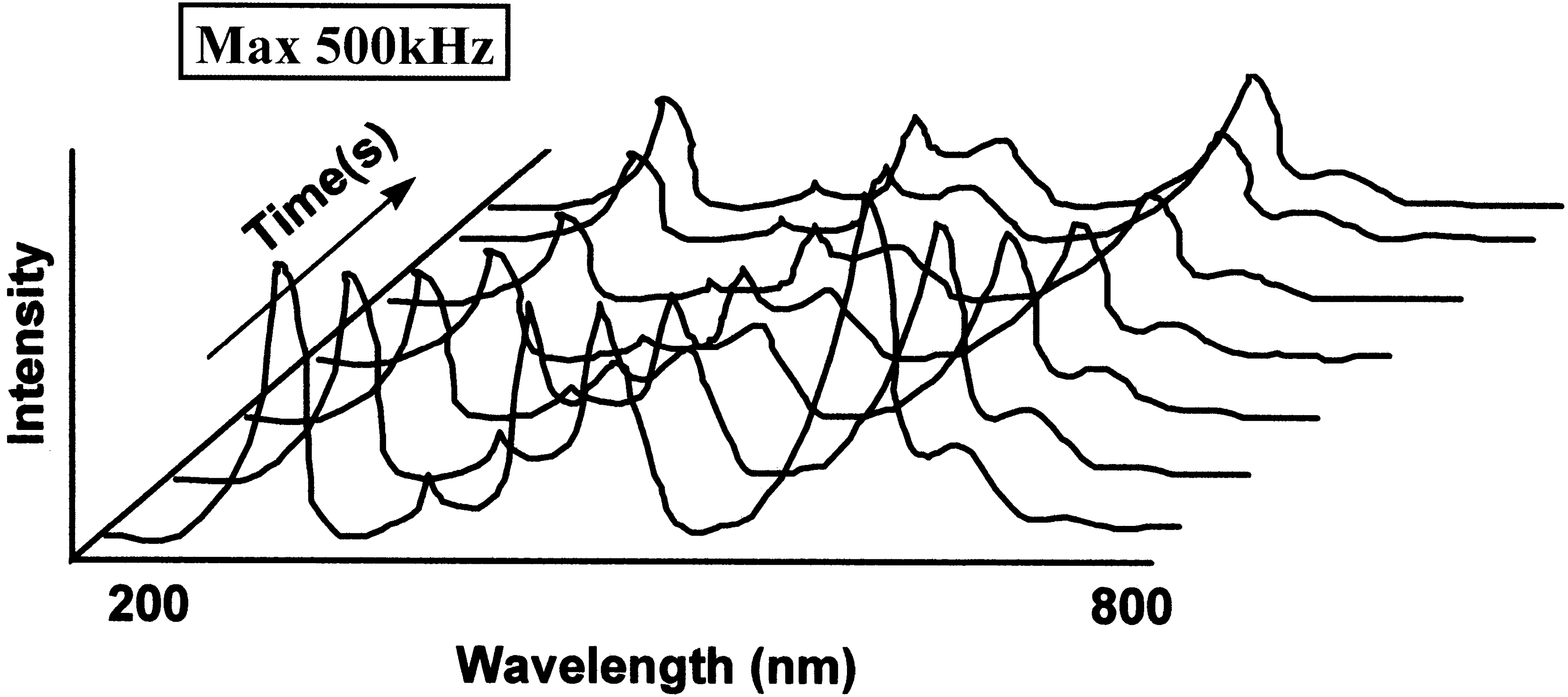
Single-lens optics for point measurement



Change of spectrum with equivalence ratio



Measurement of time-series spectrum



Multi-point measurement