RECENT DEVELOPMENTS IN THE APPLICATION OF THE MULTICHANNEL FABRY-PEROT TO PLASMA SPECTROSCOPY

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JOURNAL DE PHYSIQUE *Colloque C 2, supplément au n° 3-4, Tome 28, mars-avril 1967, page* C 2 - 226

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Résumé. — L'interféromètre de Fabry-Pérot multi-canal par réflexion, s'est montré un instrument important pour l'analyse de la forme des raies spectrales quand une grande luminosité et une bonne résolution dans le temps sont nécessaires. Il a été appliqué à l'étude de plusieurs problèmes de physique des plasmas, par exemple la détermination de la température cinétique, dans une décharge « pinch » toroïdale dans un mélange d'hydrogène et d'hélium. Une nouvelle méthode utilisant des lentilles de Fresnel a été étudiée. Les mesures préliminaires indiquent que le nombre de canaux disponibles par cette méthode n'est limité que par la finesse de l'interféromètre.

Abstract. — The reflection multichannel Fabry-Perot has proven an important tool for the analysis of spectral line shapes where high luminosity and good time-resolution are required. It has been applied to several plasma physics problems, for example to determine kinetic temperatures in a toroidal pinch discharge in a mixture of hydrogen and helium. A new method utilizing Fresnel lenses has been devised. Preliminary measurements indicate that the number of channels available by this method is limited only by the finesse of the interferometer.

1. **Introduction.** — Until little more than a decade ago, the Fabry-Perot interferometer was generally thought of as wasteful of light and being of use only when maximum resolving power was needed. Two events, both connected with the Laboratoire Aimé Cotton in France, contributed heavily to reversing the situation. Multilayer dielectric reflecting mirrors with their extremely low absorption losses were developed, mainly at the Laboratoire mentioned, and Jacquinot pointed out the [1] geometrical luminosity advantages of the axially symmetric instruments. With the new mirrors, the Fabry-Perot is almost universally recognized as the most luminous of the direct-recording spectrometers.

In plasma physics, the shape and shift of spectral lines leads in many cases to important diagnostic data. In particular, the line breadth may give the Doppler temperature, the density, or even the magnetic field depending on the experimental conditions. Shifts may yield collective motions such as ion drifts or plasma rotation.

Two conditions often present in laboratory plasmas, however, serve to make accurate measurements difficult : 1) The intensity of the line-spectrum is generally low. This is especially the case in optically thin highly ionized hydrogenic plasmas, where only impurities radiate line spectra. The purer the plasma, and hence the more interesting, the weaker the spectrum. 2) The other difficulty is that since confinement is by far the most difficult problem in high temperature plasma physics, a large number of the interesting experimental situations are extremely rapidly changing, with characteristic times of tens and hundreds of nanoseconds.

The multichannel Fabry-Perot was chosen to satisfy the conditions of highest luminosity and speed, limited only by the photomultiplier characteristics.

2. **The Multichannel Fabry-Perot.** — When light from an extended monochromatic source falls upon a Fabry-Perot interferometer, fringes are formed at the focus of a lens behind the instrument. If the light is isotropic and the mirrors comprising the instrument are perfectly flat and parallel, the shape and position of the fringes are described by the well-known Airy formula for the transmission which yields the familiar expression for the Fabry-Perot fringe maxima :

$$n = 2\,\sigma\mu t \cos\theta\,, \qquad (1)$$

where n is the interference order number, σ the wave number of the radiation, and θ the angle of inclination from the normal.

In a multichannel device a convenient arrangement is N channels of equal wavenumber width, $\Delta\sigma$. Since the region of interest is near the axis, the cosine in (1) may be expanded, obtaining :

$$\sigma - \sigma_0 = \tfrac{1}{2}\,\sigma\theta^2\,, \qquad (2)$$

where σ_0 is the wavenumber of the radiation at $\theta = 0$.

Differentiating (2), and if we use a lens with focal length f to form the fringes, and the paraxial condition, we obtain, setting $\sigma - \sigma_0 = \Delta\sigma$:

$$\Delta\sigma = \Delta S \sigma (2 \pi f^2)^{-1} , \quad (3)$$

where ΔS is an annular element of area in the fringe pattern formed by the camera lens. Since $\Delta\sigma \ll \sigma$ we see that equal elements of spectral width $\Delta\sigma$ fall into equal-area annular zones of area ΔS.

It is clear therefore that if we wish to construct a multichannel photoelectric Fabry-Perot we must collect light in the plane of the fringes in equal-area concentric circular zones. The light from each such zone constitutes one of the channels and must be thrown into a separate photomultiplier, means being provided to record the resulting signals as a function of time.

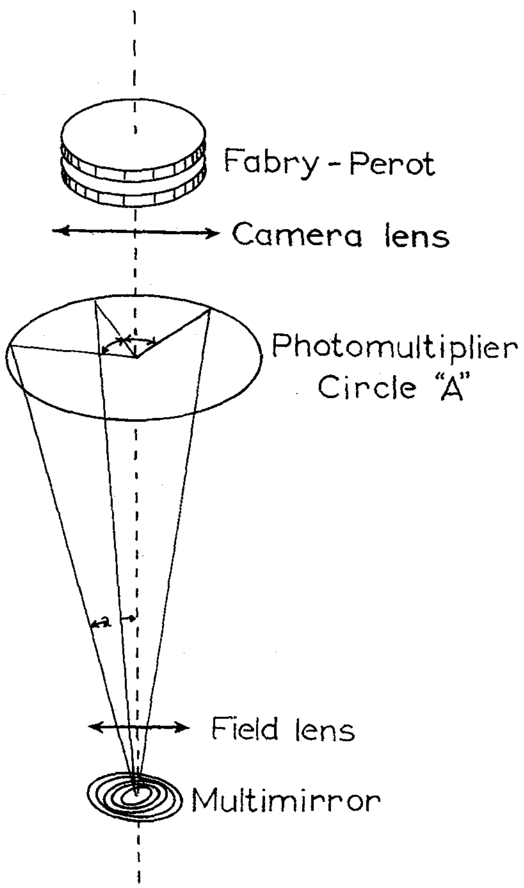

FIG. 1. — The reflection Fafnir principle. The light enters from above. Haidinger fringes formed at the multimirror are broken up into zones of equal $\delta\sigma$ and reflected into separate photomultipliers at « A ».

3. **The Multimirror Fafnir Device.** — The first instrument constructed along these lines of which the author has knowledge [1*a*] was built at Princeton in 1959. The zones were ring mirrors cut from glass, of the requisite size, and mounted on a brass support machined at various angles to throw the light into each of 8 photomultipliers, see figure 1. In this figure, three of the mirrors are shown. They are set at angle φ with the axis and their principal planes differ by θ from each other. The field lens serves to focus the camera lens on the photomultipliers, which are placed on circle « A ».

This instrument was applied [2] to problems at the Princeton Plasma Physics Laboratory, but suffered from inaccuracies due to the difficulty in manufacturing the glass annular rings to the requisite accuracy.

To overcome this difficulty, the next Fafnirs were constructed [3] of a nesting set of stainless steel tubes. A typical such tube is shown in figure 2. The dimensions d_R are chosen to satisfy the equal-area rule. The upper surface of each tube was milled to the angle φ from the horizontal and optically polished. When assembled, each tubed was turned an angle θ from the adjacent ones ; the finished array is shown in figure 3. Twelve channels were used in these instruments.

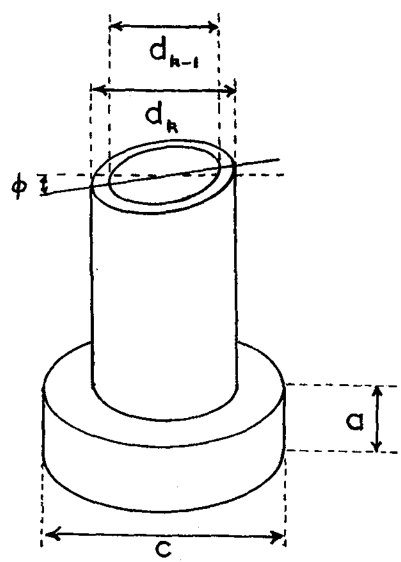

FIG. 2. — One of the stainless steel tubes of the 12-fold Fafnir multimirror. The upper surface is optically polished and aluminized.

Using a narrow line of cadmium, traces were made to test the equality of the channels. These are shown in figure 4. The Fabry-Perot used here was controlled by 3 barium titanate ceramic elements. The interplate spacing, t, was varied between the two traces, shifting the maximum from channel 5 to channel 10. The shape of the line remains the same, indicating the substantial equality of the channels.

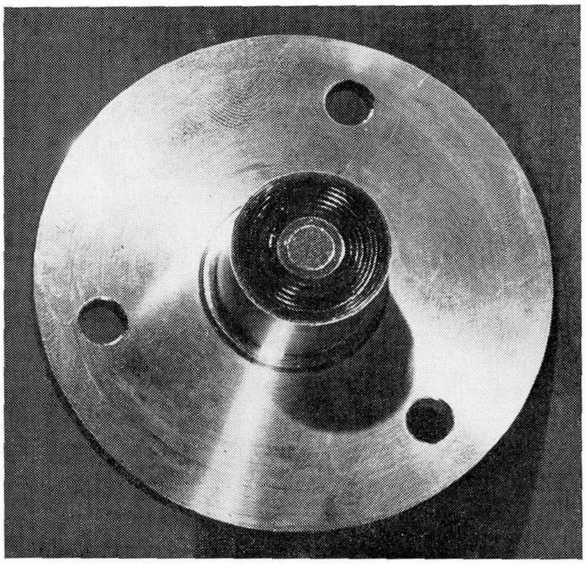

FIG. 3. — The assembled 12-fold multimirror.

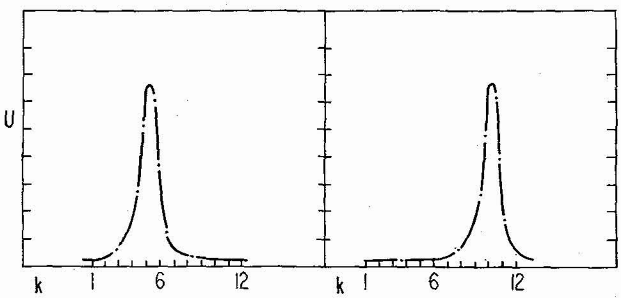

FIG. 4. — A narrow cadmium line measured by the Fafnir for two values of the Fabry-Perot spacing, *t*.

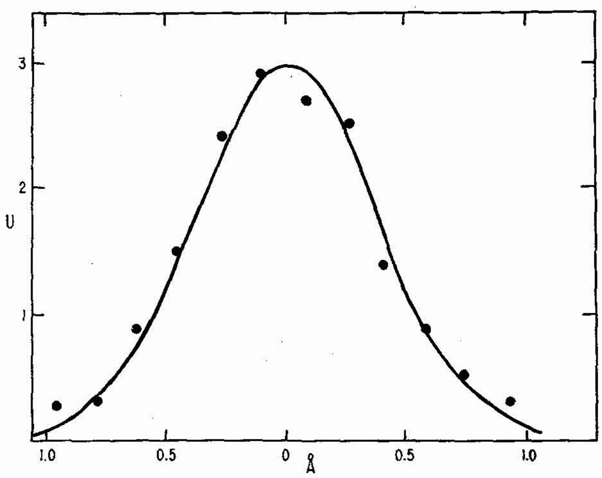

FIG. 5. — A line of hydrogen as measured by the Fafnir in the toroidal pinch machine TA-2 000.

4. **Application to a Plasma.** — The 12-channel instrument was then applied to a toroidal pinch discharge with mixtures of hydrogen and helium. [4] Results were obtained at a particular time for H_β for example, which is shown in figure 5. From similar data, provided the line-broadening is mainly Doppler, the ion or neutral kinetic temperature in the plasma may be deduced. Typical results are shown in figure 6.

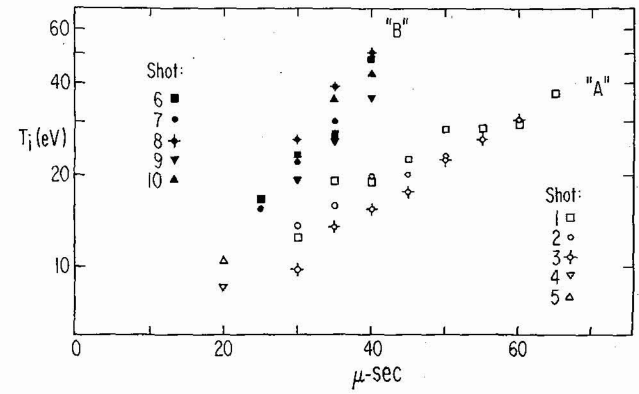

FIG. 6. — The time behavior of helium in a toroidal pinch discharge deduced from the Doppler broadening of the ionized helium line at 4 686 Å.

5. **The Fresnel Fafnir.** — Because of shadowing effects in the outer zones, twelve channels is nearly the upper limit for a reflection multichannel device. Of other possibilities, Fresnel lenses seem to offer the simplest solution for high channel numbers.

An experimental 16 channel device was built using plastic Fresnel lenses.

The operation of this instrument is similar to that described above except that it acts in transmission instead of reflection. Each equal-area zone in the focus of the Fabry-Perot is refracted in a different direction by its part of the Fresnel lens.

This is done by means of zones cut with a lathe from a commercial Fresnel lens of focal length 20″. The center of each zone is displaced by a distance r_R from the optical center of the original Fresnel lens. The result is that, as in the reflection Fafnir described above, images of the Fabry-Perot are displaced by each zonal lens from the optical axis so that they can be directed each into a separate photomultiplier. In this case, the distance of each image from the optical axis in the focal plane of the Fresnel lenses is just r_R, as defined above. In the first model the zones were arranged in a rough spiral, the light from the central zone being directed farthest to the outside.

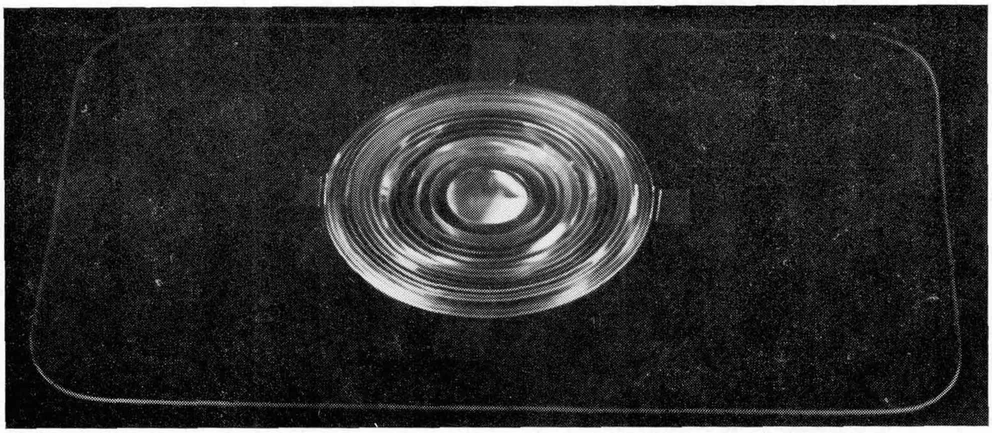

FIG. 7. — The Fresnel Fafnir.

The Fresnel Fafnir as assembled is shown in figure 7 and the image pattern formed with parallel incident light is shown in figure 8.

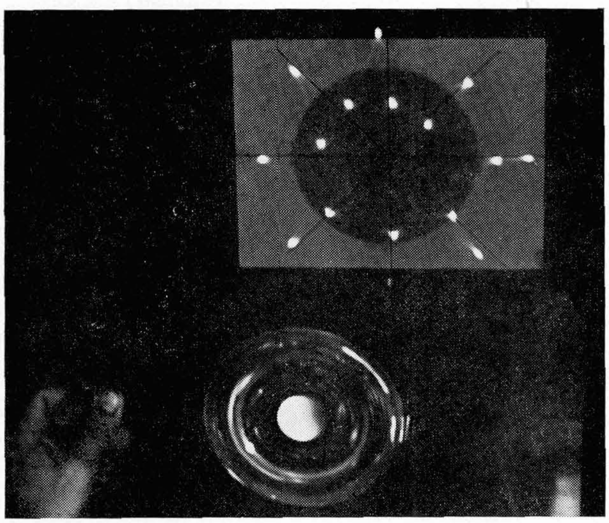

FIG. 8. — The pattern of images formed by the Fresnel Fafnir for incident parallel light. The diameter of the pattern is approximately 22 cm.

In any optical device made with plastic components the problem of dimensional stability is important. Accordingly, six months after manufacture, the dimensions of the zones were checked. They are listed in table 1. The rings satisfy the equal area condition with a mean deviation of less than 3 % except for the last two. The departure of these from the correct dimensions is probably due to an error in construction.

TABLE 1

Ring N°	Outside diameter of ring (inches)	Ring thickness ($r_B - r_A$)	Area of ring (sq. inches)
—	—	—	—
Center	$D =$ 1.35	— — —	1.43
# 2	$D =$ 1.91	.280	1.43
# 3	$D =$ 2.345	.215	1.43
# 4	$D =$ 2.71	.179	1.42
# 5	$D =$ 3.025	.155	1.47
# 6	$D =$ 3.31	.142	1.39
# 7	$D =$ 3.575	.130	1.47
# 8	$D =$ 3.825	.123	1.47
# 9	$D =$ 4.055	.116	1.41
# 10	$D =$ 4.28	.112	1.48
# 11	$D =$ 4.49	.103	1.45
# 12	$D =$ 4.69	.101	1.44
# 13	$D =$ 4.89	.098	1.40
# 14	$D =$ 5.065	.088	1.41
# 15	$D =$ 5.20	.088	1.13
Outside # 16	$D =$ 5.41	.083	1.69
	$\pi r^2 =$ 22.89		22.92 in^2. Total

There seems to be no reason why the number of channels cannot be further increased, until limited by the finesse of the Fabry-Perot interferometer itself.

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