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# The birth of Tor Vergata Fabry-Pérot interferometer

**L. Giovannelli, F. Berrilli, M. Cocciolo, D. Del Moro, A. Egidì,  
R. Piazzesi and M. Stangalini**

Dipartimento di Fisica, Università di Roma *Tor Vergata*, Via della Ricerca Scientifica, I-00133 Rome, Italy

E-mail: giovannelli@roma2.infn.it

**Abstract.** Fabry-Pérot tunable filters are of great interest in high spectral resolution imaging for both ground-based and space astronomical observations. Major advantages include imaging capabilities and the study of extended astronomical sources, such as the solar photosphere. The high transparency of the instrument allows the high time-resolution necessary for the observation of fast dynamic processes. The prototype here presented has been developed as part of the study for the narrow band channel of the ADAHELI mission. The ADvanced Astronomy for HELIophysics (ADAHELI) is a solar satellite designed to investigate the dynamics of solar atmosphere as part of the Italian Space Agency (ASI) program.

## 1. Introduction

A Fabry-Pérot (FP) is an instrument based on multiple beam interferometry. It consists of two flat plates which create an optical cavity. The two optical surfaces have a high reflectivity obtained via a dielectric coating; they trap the incoming beam, causing multiple reflections. Interference between the beams depends on the optical path difference (OPD), i. e. the gap between the plates. In this way, the interferometer allows transmission of light at well-defined wavelengths. A spectrometer based on tunable filter is a solution to the modern spectroscopy problem of collecting both spatial and spectral information. Every image taken is nearly monochromatic and it is possible to rapidly change the wavelength of the observation varying the OPD: as a consequence, it is possible to scan absorption lines in an extended range of wavelengths. Jaquinot in 1954 has compared FP and grating spectrometer transparency, having the same instrumental features fixed and operating with the same resolving power [2]. FP spectrometer proved to be the most efficient by a factor of at least 30. This is the reason why the FPs are so attractive for Astrophysics, since the astrophysical sources are usually weak.

If we analyze the spectral response of the instrument, we can see that transparency has several peaks, resembling a comb. The transmission profile depends on the value of the reflectivity  $R$ , the reflecting finesse  $\mathcal{F}_R$  and the interference order  $m$  [1]:

$$\mathcal{F}_R = \frac{\pi\sqrt{R}}{1-R} \quad (1)$$

$$m = \frac{2n}{\lambda} d \cos \theta \quad (2)$$

The order  $m$ , once defined the working wavelength, depends on the refracting index  $n$ , the angle of incidence  $\theta$  and the spacing  $d$ . The incidence angle of the beam on the instrument is

usually set as low as possible, in order to maximize the order, which leaves us with two possible ways to change  $m$ : varying either the refracting index  $n$  or the spacing  $d$ .

The reflecting finesse depends only on the reflectivity  $R$  and is set choosing a suitable multilayer dielectric coating. The free spectral range (FSR) and FWHM of the transmission peak are then:

$$FSR = \frac{\lambda}{m} \quad (3)$$

$$FWHM = \frac{FSR}{\mathcal{F}_R} \quad (4)$$

It is evident that the reflecting finesse  $\mathcal{F}_R$  and the interference order  $m$  are the parameters that define the characteristics of the FP. The FSR is the maximum wavelength range we can scan with a single peak. The FWHM related to the spectral resolution.

We are realizing a prototype interferometer at the Solar Physics Laboratory of University of Rome Tor Vergata. We have chosen the instrument characteristics to match the required performance of a tunable interference filter for solar physics applications, both for ground and space use. The main goal is to produce an instrument suitable for the ADAHELI satellite mission (see section 2). A couple of FP interferometers with an adjustable optical cavity dimension has been proposed as the core of the narrow band channel of the satellite. The prototype is intended to be an important step towards the instrument realization.

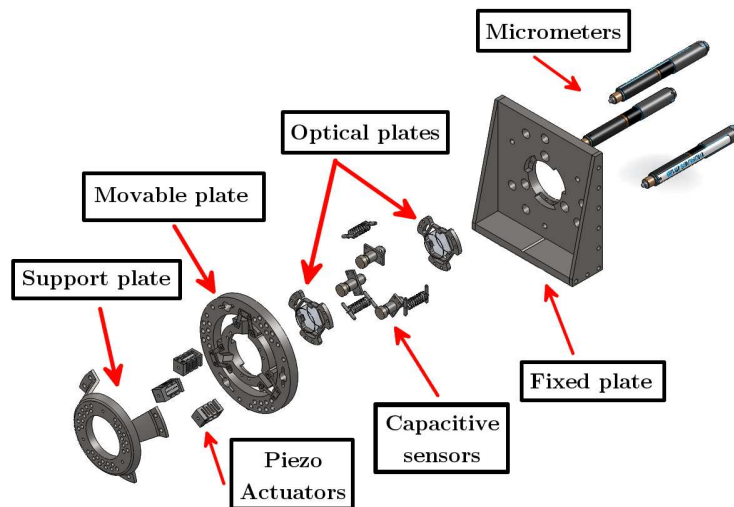
## 2. The ADAHELI mission

ADAHELI is a small-class low-budget satellite mission with the main aim to monitor solar flares and to study the dynamics of different layers of the solar atmosphere [3]. ADAHELI design has completed its Phase-A feasibility study in December 2008, in the framework of ASI (Agenzia Spaziale Italiana) 2007 Small Missions Program. University of Rome Tor Vergata was the scientific institution leader of the project and CGS SpA was the leader industrial partner. ISODY [4], Interferometer for Solar Dynamics, is the Gregorian telescope of the satellite. It is designed to obtain high resolution spatial, spectral, and temporal polarimetric images of the solar photosphere and chromosphere. The Focal Plane Assembly of the ISODY instrument comprises two visible near-infrared science optical paths or channels: the Narrow Band (NB) and the Broad Band (BB) channels. The principal optical path of the NB channel includes two FP interferometers used in axial-mode and in classic mount and a filter wheel carrying four interference filters used as pre-filters to select one of orders coming from the FPs [5].

## 3. Prototype Design

The chosen type of FP is a scanning optical cavity with a gap servo control system. The basic idea of the prototype is an instrument capable of maintaining two partially reflecting mirrors at the required distance, parallel within the tolerances. Since the wavelength position of the filter transmission peak is determined by the gap dimension  $d$  (see equation 2), this distance must be varied in order to scan a certain spectral range of interest. However,  $d$  has to be constant during the instrument acquisition time. In addition, positioning repeatability must be guaranteed in order to obtain the same spectral points in successive measures. To achieve these goals we have used piezoelectric actuators and capacitive sensors. The combination of these two technologies in a servo controlled system grants the necessary stability and repeatability ( $\lambda/3000$  over one day or more [6]).

We have designed the opto-mechanics of the laboratory prototype to house a pair of 1" (25.4 mm) partially reflecting mirrors, three micrometers, three piezoelectric actuators and three high sensitivity capacitive sensors. A schematic image of the setup is shown in figure 1.



**Figure 1.** Prototype exploded view.

The maximum allowed travel is 12 mm for micrometers and 15  $\mu\text{m}$  for piezoelectric actuators. The capacitive sensors working distance is 50  $\mu\text{m}$ .

We have designed this prototype to decouple two different movements of the optical surfaces, in order to enable a coarse and fine adjustments of the cavity gap.

This decoupling is achieved by separating the movable plate into two concentric rings. Adjustments are performed either by the three micrometers or the three piezoelectric actuators placed in a 120°-symmetry around the etalon.

The inner ring, which houses the movable optical surface, is controlled by the piezoelectric actuators which can vary the gap size within opto-mechanical specifications. The outer ring is connected to the inner ring by three V-shaped flexures, therefore a micrometer displacement moves both the inner and the outer ring, while a piezoelectric actuator displacement moves the inner ring of the movable plate only.

### 3.1. Numerical simulation

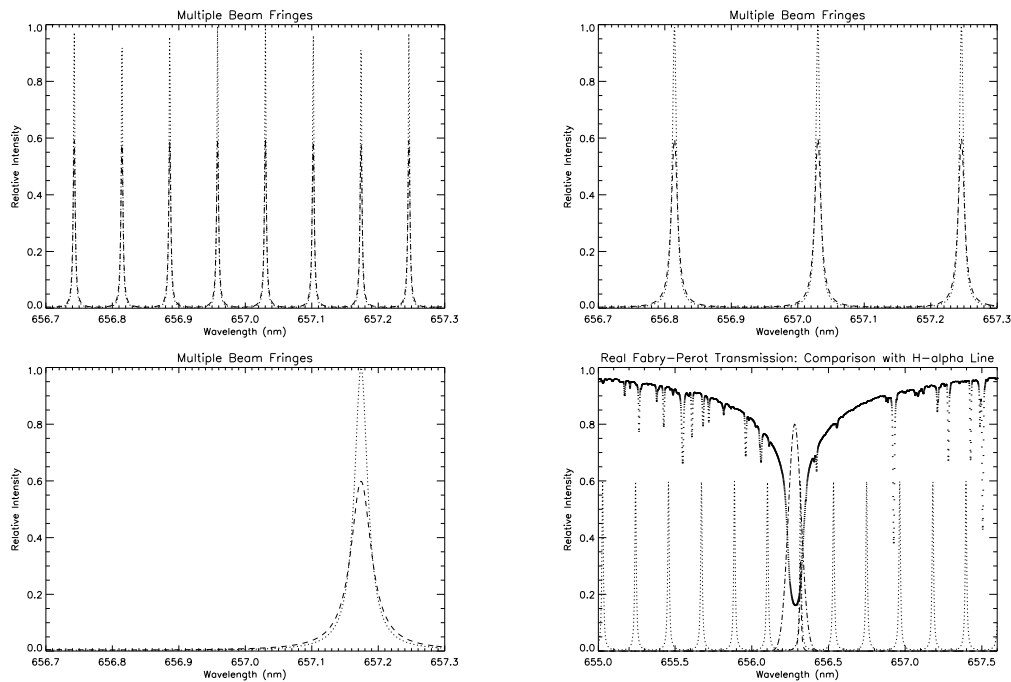
We developed a software to simulate the performance of the prototype. In order to take into account for non-ideal response of the system, we used an effective finesse.

We simulated three FPs, with three different OPD. The pattern obtained is shown in figure 2 for 3.0 mm (top-left panel), 1.0 mm (top-right panel) and 0.3 mm (bottom-left panel). The broadening of the transmission profile and the lowering in transparency for the real case (dashed line) is significant and shown in the previously mentioned panels. The simulation aim is to decide what value of the OPD makes the instrument more suitable to scan the H-alpha line, taking into account the available prefilter.

In a trade-off between the FSR and FWHM set by the optical gap, and using equation 4, the 1.0 mm value is accepted for the tests.

### 3.2. Piezo tests

Fine adjustments of the movable optical plate is achieved using piezoelectric actuators. Piezo actuators can perform sub-nanometer moves, have no rotating or sliding parts that cause friction and dissipate virtually no power in static operation. They have a nominal displacement of 15  $\mu\text{m}$  under an applied voltage of 100 V and have the possibility to reach nanometric precision. They



**Figure 2.** FP numerical simulations. Dotted: ideal FP profile; dashed: effective FP profile. From upper left to bottom right the OPDs are: 3 mm, 1 mm, 0.3 mm, 1 mm together with  $H_\alpha$  absorption line and prefilter profile (dot-dashed).

are operated using an analog driving signal; the system is computer operated via a Digital to Analog Converter (DAC) that has a 16-bit resolution, resulting in 0.15 mV minimum output voltage step. After the signal processing by the controller, this results in a 0.44 nm minimum step of the piezo actuator.

Unfortunately, the piezoelectric actuator response to the signal is non-linear and follows a hysteresis cycle. This issue can be overcome using a closed loop control system, which involves a high precision distance sensor. In this case, we have used a capacitive sensor with a static resolution  $< 1$  pm. The capacitive sensor has a working range centered at a distance of 50  $\mu$ m from the target. The piezo actuator has been proven to be able to operate in low pressure and low temperature compatible with space environments (2 K and 0.5 bar).

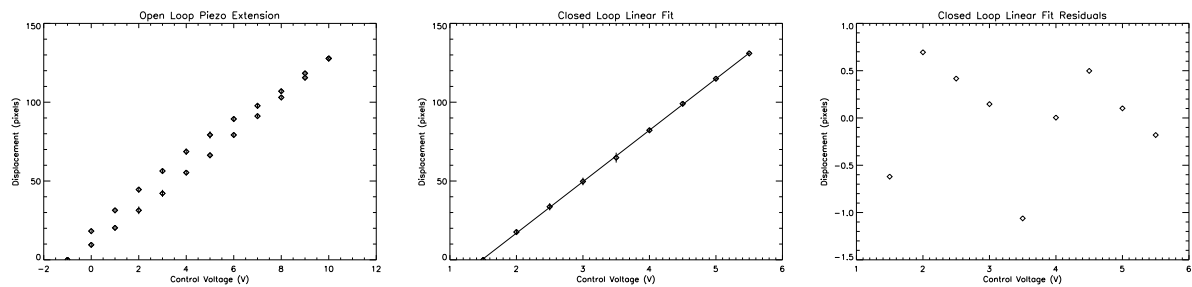
In order to test the reliability of the opto-mechanical actuator, both in closed and open loop operation mode, we realized a device to test the actuator in a controlled situation on the optical bench and developed the dedicated software.

We obtained open loop measures using 1 V steps from  $-1$  V to 10 V as low-voltage driving signal. The hysteresis cycle of the piezo is evident (see the left panel of figure 3): bottom points refers to piezo elongation, while top points refers to piezo retreat. Maximum elongation is  $14.1 \pm 0.2$   $\mu$ m, which is near the nominal value of 15  $\mu$ m.

We also obtained closed loop measures using a reduced control voltage range, still able to cover the full range of piezo extension. 0.5 V steps from 1.5 V to 5.5 V were used as low-voltage driving signal.

The response is linearized with respect to the open loop data as it is evident from the linear fit and related residuals (middle and right panel of figure 3).

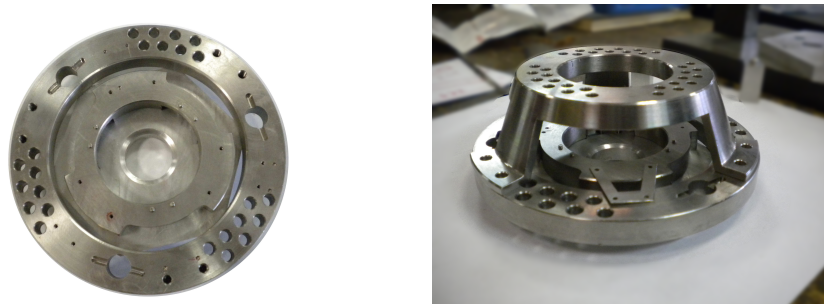
Also the maximum extension of the piezo is  $14.8 \pm 0.2$   $\mu$ m in closed loop mode.



**Figure 3.** Piezo-actuators elongation data, from left to right: open loop hysteresis, closed loop with linear fit and related residuals.

### 3.3. Initial assembly phase

Prototype assembly has started with the production of the first pieces. We chose stainless steel for the construction of all the mechanical parts. Stainless steel has been selected mainly for its stiffness properties, low cost and availability. The two concentric rings of the movable plate have been realized with a maximum surface error  $< 40 \mu m$  over the whole surface. Images of the plate are provided in figure 4.



**Figure 4.** Movable plate: inner and outer rings (left), rings and support plate (right).

## 4. Conclusions and Future Developments

In this work, we have presented the design of a laboratory prototype Capacitance Stabilized Fabry-Pérot interferometer. First, we introduced the basic FP theory and presented the results of a FP numerical model. From these results, we designed a FP prototype optimized for the scan of the  $H_\alpha$  line, but also suitable for the whole visible range. Along with its implementation, we have presented the mechanical, electronic and optical characteristics of the prototype in details and some of the tests we performed on its basic components.

In the near future, we plan to execute the optical and spectral qualification of this prototype.

Furthermore, we are working on a space implementation of the FP in order to start space qualification tests. The design has been update to match the more demanding operating environment requirements, such as the launch stresses and the large thermal variations.

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