XXXVI Int. Wint. Meeting, Bormio, January 1998

A new type of Compton Polarimeter for Jefferson Lab Hall A

J-P Jorda[1 a], *M. Authier*[1], *M. Baylac*[1], *E. Burtin*[1], *Ch. Cavata*[1], *J. P. Chen*[2], *N. Colombel*[1], *P. Deck*[1], *A. Delbart*[1], *N. Falletto*[1], *B. Frois*[1], *P. Girardot*[1], *J. Jardillier*[1], *F. Marie*[1], *J. Martino*[1], *Ph. Mangeot*[1], *D. Neyret*[1], *S. Platchkov*[1], *T. Pussieux*[1], *J. C. Sellier*[1], *Ph. Rebourgeard*[1], *C. Veyssière*[1], *G. Zavattini*[3]

[1]CEA Saclay DSM/DAPNIA, 91191 Gif-sur-Yvette cedex, France.
[2]Jefferson Lab, 12000 Jefferson av., Newport News, VA 23606, USA.
[3]INFN, Via Paradiso, 12, I-44100 Ferrara, Italia.

---

[a] present adress: Université P. & M. Curie (Paris 6), Paris.

Abstract

In this paper, we present the principle and the studies for a new type of Compton polarimeter based on the use of power buildup Fabry-Pérot cavity to get a 3% measurement of the Jefferson Lab electron beam polarization within minutes.

Introduction

To be carried out, the ambitious physics program at *Jefferson Lab* (JLab, Virginia, USA) with polarized electrons needs a high accuracy beam polarization measurement for energy ranging from 1 to 8 GeV and current ranging from 1 to 100 μA.
Both Møller and Compton polarimetry techniques will be used at Jefferson Lab end station A for this measurement. The Møller polarimeter will be suitable only at low current (typically 10 μA) and the measurement cannot be done simultaneously with the experimental data taking. A Compton polarimeter gives a non destructive measurement for higher current beam. Unhappily, for energies down to tens of GeV, the analysis power of the Compton polarimeter is small. With the JLab conditions, a polarimeter designed on the model of the existing ones can achieve a 2% (stat.) measurement only in several days.

In this paper, we first present the principle of the Compton polarimetry; then we demonstrate that a standard laser used as photon source does not allow a quick and precise monitoring of the polarization. We explain the principle of a Power buildup cavity and we present the prototype of the cavity built at Saclay. As a conclusion, we explain the next steps before an installation of such a system on the JLab beam line.

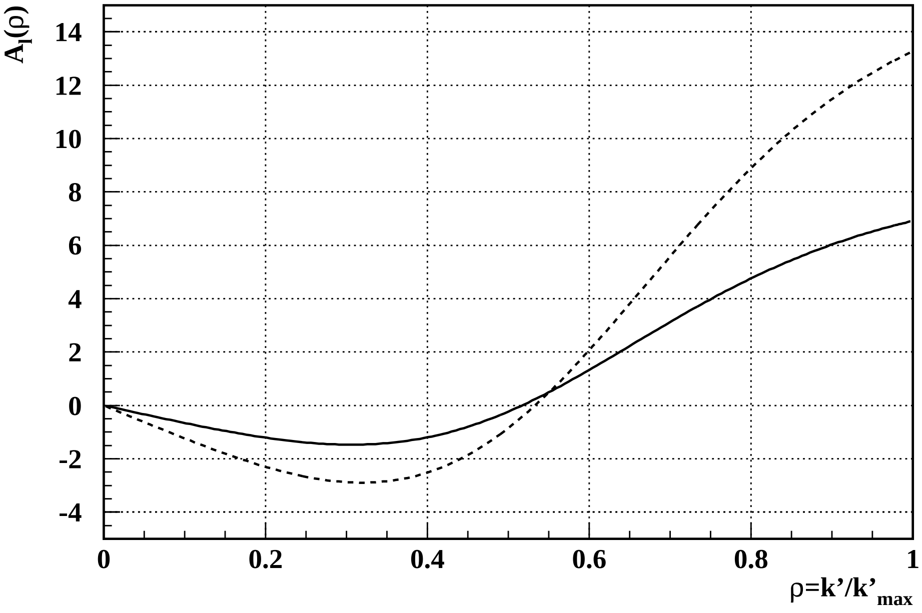

Figure 1: *Longitudinal asymmetry for a 4 GeV electron beam and a green (2.33 eV, solid line) and an IR (1.16 eV, dashed line) laser beam versus the scattered photon energy* k' *over the maximum energy* k'_{max}.

1 Compton polarimetry

In Compton polarimetry, the longitudinal polarization P_e of the electron beam is extracted from the measurement of the asymmetry A_{exp} in elastic scattering of circularly polarized light off the electron beam :

$$A_{exp} \equiv \frac{n^+ - n^-}{n^+ + n^-} = P_e P_\gamma A_l \ , \tag{1}$$

where n_+ and n_- are the numbers of Compton events after and before polarization reversal of the electron beam polarization ($P_e \to -P_e$). In the right term of this equation, the polarization of the light P_γ can be measured with a standard optical method at a 1% level. The asymmetry A_l on the Compton cross section with longitudinally polarized particles is calculated in the framework of QED. So by measuring A_{exp} and P_γ the beam polarization P_e can be calculated. The longitudinal asymmetry A_l is plotted on Fig. 1 as a function of the normalized energy of the scattered photon. This asymmetry is negative at low energy and positive for high energy. To increase the power of analysis A_{exp} has to be measured as a function of the energy.

In the Compton kinematics for GeV electrons and eV photons, the photons are back-scattered at angles of typically 100 μrad. The electrons are scattered at few μrad. A Compton polarimeter is then basically made of 3 parts:

- a circularly polarized photon source (usually a Nd:YAG or an Ar+ laser) with a device measuring the polarization of the light;

- a device to extract the scattered photons from the beam line, e.g a magnetic dipole;
- a photon detector and/or an electron detector.

The drawing of the Compton polarimeter for JLab is given Fig. 2: a 4-dipole magnetic chicane shifts the Compton interaction point (CIP) below the direct beam line; the photon source is made of a Nd:YAG laser and of a Fabry-Pérot cavity to enhance the photon density at the CIP; a photon detector measures the energy of the back-scattered photons going straight from the CIP; the electron detector with the third dipole of the chicane allows to measure the momentum of the scattered electrons.

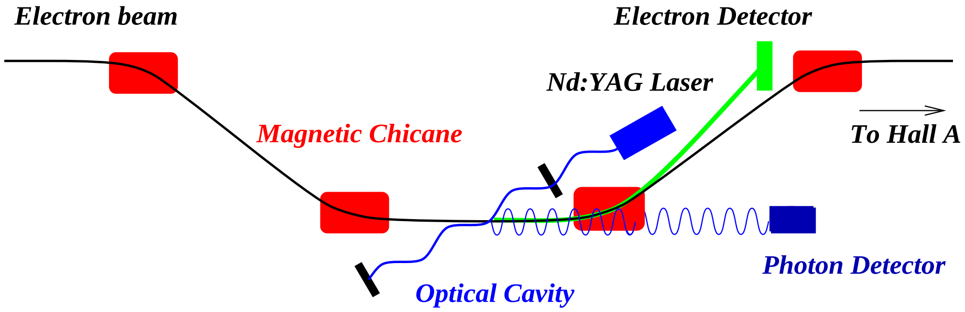

Figure 2: *Drawing of the Compton polarimeter for Jefferson Lab Hall A. The total length is about 15 m. The innovation comes from the Fabry-Pérot cavity, used to enhance the photon density at the CIP.*

2 Why do we need a Fabry-Pérot cavity ?

Because the polarization can fluctuate, the times of measurement is an important feature for our polarimeter. One can evaluate the times t_{mes} needed to measure the beam polarization with a statistical precision $(\Delta P_e/P_e)_{stat}$ with the following relation [1]

$$t_{mes} \simeq \frac{1}{\mathcal{L}\left(\frac{\Delta P_e}{P_e}\right)^2_{stat} P_e^2 P_\gamma^2 \sigma_t < A_l^2 >} \; . \tag{2}$$

where σ_t and $< A_l^2 >$ are weighted values of the cross section and of the squared theoretical asymmetry. In the Jeff Lab standard conditions, and using a 1064 nm Nd:YAG laser, one gets $\sigma_t \approx 0.5$barn. The asymmetry A_l depends on the product kE of the incident particles energies. Using a green laser, the maximum value of A_l, reached for the maximum value of the scattered photon, is 14% at Jeff Lab while it is close to 80% at SLAC for the SLD Compton polarimeter for 50 GeV electrons [2].

The luminosity $\mathcal{L}$ can be evaluated using the relation

$$\mathcal{L} \simeq \frac{2}{\sqrt{2\pi}} \frac{I_e}{e} \frac{P_l}{kc} \frac{1}{\sqrt{\sigma_e^2 + \sigma_\gamma^2}} \frac{1}{\sin\alpha} \ , \tag{3}$$

where I_e is the beam current, P_l the power of the laser beam, σ_e and σ_γ respectivly the sizes at the CIP of the electron beam and of the laser beams, both supposed Gaussian and α the crossing angle between the beams. Using (2) and (3), one can evaluate the time of measurement to get a 1% level statistical error. In the Jeff Lab standard conditions and with $\alpha = 20$ mrad, a powerful (~ 30 W) KrF UV laser is necessary to get a measurement in one hour. Such a laser needs an intricate installation and maintenance, a dedicated building and UV transportation to the CIP.
The proposed alternative for the photon source is an all solid Nd:YAG IR laser coupledg with a power buildup optical cavity, the CIP been located in the center of the cavity (Fig. 3). We want to use a compact and tunable laser made by Lightwave corp. These lasers currently reach a maximum power of 0.7 W.

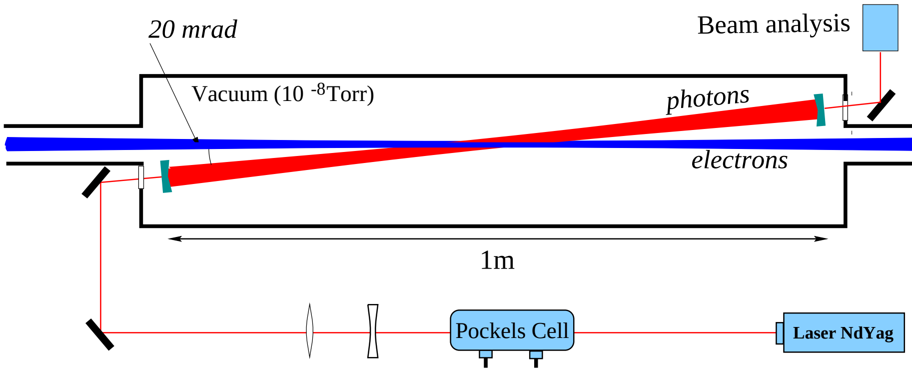

Figure 3: *Principle of the optical cavity based source of photons for the Compton polarimeter.*

3 Basic of Power buildup cavity (PBC)

A PBC is basically a Fabry-Pérot optical cavity made of two hight reflectivity mirrors. This cavity is fed by a laser beam correctly matched with the cavity geometry. The regenerative feedback effect allows to get a high power inside the cavity [5].
The cavity of the polarimeter will be made of two identical concave mirrors (with a radius of curvature of 0.5 m) and will be $L \simeq 0.8$ m long. The matching will be done in order to get Gaussian beam focusing in the center of the cavity (corresponding to the fundamental mode TEM_{00} of the cavity). The size (σ) of the beam will be about 140μm at this point. The expected effect is to get a beam power P_{circ} circulating inside the cavity enhanced by a factor $\mathcal{G}$ with respect to the incident beam power P_{inc}. This gain $\mathcal{G}$ depends on two factors :

- the mirrors characteristics;

- the matching with the incident beam.

For a perfect matching, the gain is given by [5]

$$\mathcal{G}_0 = \frac{T}{(1-R)^2} = \frac{1-R-P}{(1-R)^2} \ , \tag{4}$$

where R, T and P are respectively the power reflectivity, transmission and total losses of the mirrors (supposed identical). Multi-layer Ta_2O_5/SiO_2 mirrors such as those for the Fabry-Pérot cavities of the VIRGO [7] and LIGO [8] projects have high reflectivity ($> 99.98\%$) and low losses (< 10 ppm). With such mirrors we can aim at a maximum gain $\mathcal{G}_0$ close to 10000.

To calculate the real value of the gain, we have to take into account the coupling coefficient C_{00} with the TEM_{00} cavity mode and the frequency tuning. The gain is then given by

$$\mathcal{G} = \mathcal{G}_0 \frac{C_{00}}{1 + \frac{2\mathcal{F}}{\pi} \sin^2\left(\frac{\pi\Delta\nu}{\nu_{FSR}}\right)} \ , \tag{5}$$

where we have introduce the *finesse* $\mathcal{F} \equiv \pi\frac{\sqrt{R}}{1-R}$ and the *free spectral range* $\nu_{FSR} \equiv \frac{c}{2L}$. and $\Delta\nu = \nu_{laser} - \nu_{cavity}$, the difference between the laser frequency and the closest resonant frequency of the cavity. For $\Delta\nu \ll \nu_{FSR}$, the equation (5) can be rewritten

$$\mathcal{G} \simeq \mathcal{G}_0 \frac{C_{00}}{1 + \frac{\Delta\nu}{\Delta\nu_{cav}}}, \tag{6}$$

where $\Delta\nu_{cav} \simeq \frac{\nu_{FSR}}{\mathcal{F}}$ is the optical bandwidth of the cavity. The gain $\mathcal{G}_0$ is then really achieved if C_{00} is close to 1 and if $\Delta\nu \ll \Delta\nu_{cav}$. Making $C_{00} \simeq 1$ depends on our ability to align the incident beam with respect to the cavity optical axis. For the cavity described above, $\Delta\nu_{cav} \simeq 5$ kHz. This value is small with respect to the frequency drift of the laser (typically 75 kHz/s). Besides, a small variation of the cavity length dramatically changes the resonant frequencies of the cavity.

One tricky part of a PBC system is then to lock the laser frequency on to a resonant frequency of the cavity. A suitable method consists of controlling the laser frequency with the so-called Pound-Drever technique [6], based on the analysis of the field reflected by the cavity.

This kind of system has been developed for several physics projects (see e.g. [9]), but none of them has been installed an accelerator environment yet.

4 The Saclay cavity prototypes

Prototypes of Fabry-Pérot cavities have been built at Saclay. They have been used to elaborate the feedback system for the laser frequency control and to test optical alignment procedures and to define the mechanical drawing of the cavity.

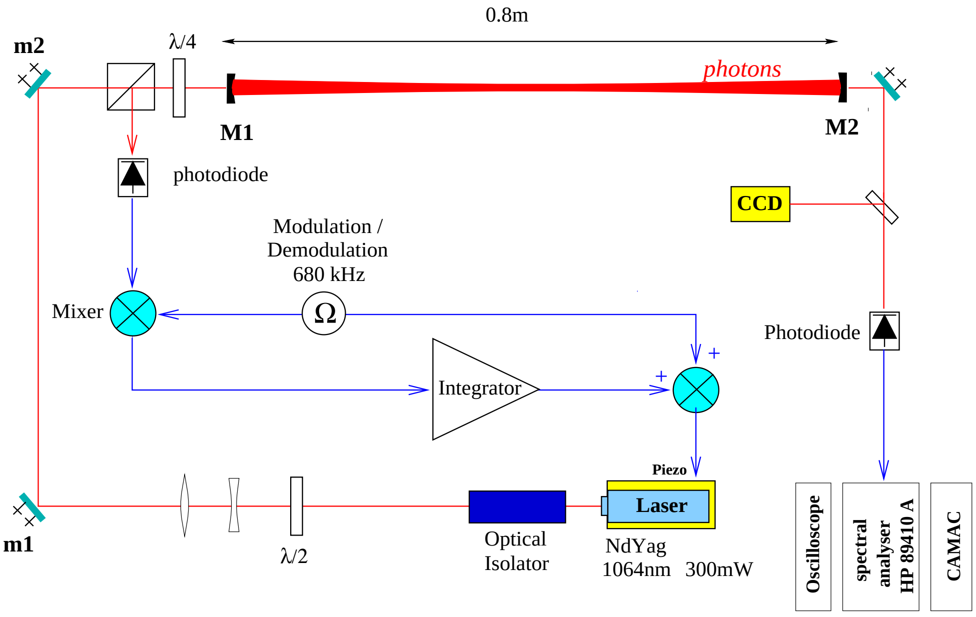

Figure 4: *Setup of the Optical setup for the cavity prototype at Saclay.*

4.1 Description of the prototype

The setup of the prototype is given Fig. 4. It is based on a Lightwave serie 126 Nd:YAG laser. This laser delivers a 300 mW CW laser at 1064nm, with a power stability of $\sim$ 0.1% rms. It is small, reliable and can be remote-controlled, so that it can be installed on the same optical table than the cavity. The feedback system is an adaptation of the PVLAS experiment[10]. It is described in ref. [3] and [4]).

The cavity is made of two mirrors (M1 and M2) mounted on tilting stages. Several types of cavity mirrors and geometry have been used. The well-studied cavity was a non confocal one consisting of two high reflectivity commercial mirrors separated by 0.8 m. The main features of this cavity are given Tab. 1. The alignment of the incident beam with respect to the optical axe of the cavity is achieved using plan mirrors mounted on micrometric tilting stages (m_1 and m_2). The shape of the beam is monitored using a CCD camera. The photodiode located after the cavity allows to measure the transmitted power: knowning the transmission of the optical components from M2 to this photodiode, we can estimate the power of the beam circulating inside the cavity. All the optical and photonic devices are fixed on an optical table (1,2 m$\times$ 1,2 m) isolated from ground vibrations.

4.2 Results

The prototype has been operated successfully, giving a 40 W beam inside the cavity. In standard Jeff Lab conditions, this would allow a measurement of the electron beam at a 1% level statistical error within 3 hours. This power has been held during several

Mirrors	
Ref.	TecOptics B1051.188.000 (distr. by Melles Griot)
Manufacturing	14 layers of ZrO_2/SiO_2
Diameter	25.4 mm (1 in)
Radius of curvature	0.5 m
Measured transmission	$\sim$700 ppm (M1) , $\sim$580 ppm (M2)
Estimated losses	$\sim$ 1300 ppm
length	0.8 m
Transverse size of the beam (σ of the power density)	
Center of the cavity	130 μm
On the mirrors	290 μm

Table 1: *Main features of the prototype of the cavity.*

hours. We have extensively studied the characteristics of the cavity. In particular, we have point out that the observed power fall (see fig. 5) was due to an optical detuning coming from thermal effects in the optical beam line devices. The power stability of the beam has been measured versus frequency. The spectral density of the fluctuations integrated from 0.1 Hz to 10 MHz is about 1%. We have strongly reduced this level by placing the cavity in a vacuum box, suppressing by this way the acoustical vibrations. Alignment procedures have also been tuned; we routinely get a coupling coefficient C_{00} up to 95%.

Better mirrors (made by IPN Lyon, CNRS) have been recently mounted in order to increase the cavity gain. Preliminary results show a total gain of about one thousand. All the tuning will be remote controlled in the final system. An important part of the slow control is now running and the acquisition system is being developed

4.3 Future tests

Several tests will be done soon to improve the prototype. We aim to get a power of 1000 W inside the cavity using the new mirrors. This requires the optimization of the laser frequency feedback control system.

Other tests will concern light polarization. For this we will have to carefully study the cavity mirrors birefringence. Indeed, due to the large number of round trips of the light inside the cavity, even a very small value of mirrors birefringence can lead to a dramatic loss in circular polarization of the light [11].

5 Conclusions and Outlook

A prototype of a Fabry-Pérot cavity has been operated successfully, giving a beam power of 40 W and a beam size (1σ) of 140 μm. In the standard JLab condition, this would allow a polarization measurement at 1% statistical level within 3 hours. Prelim-

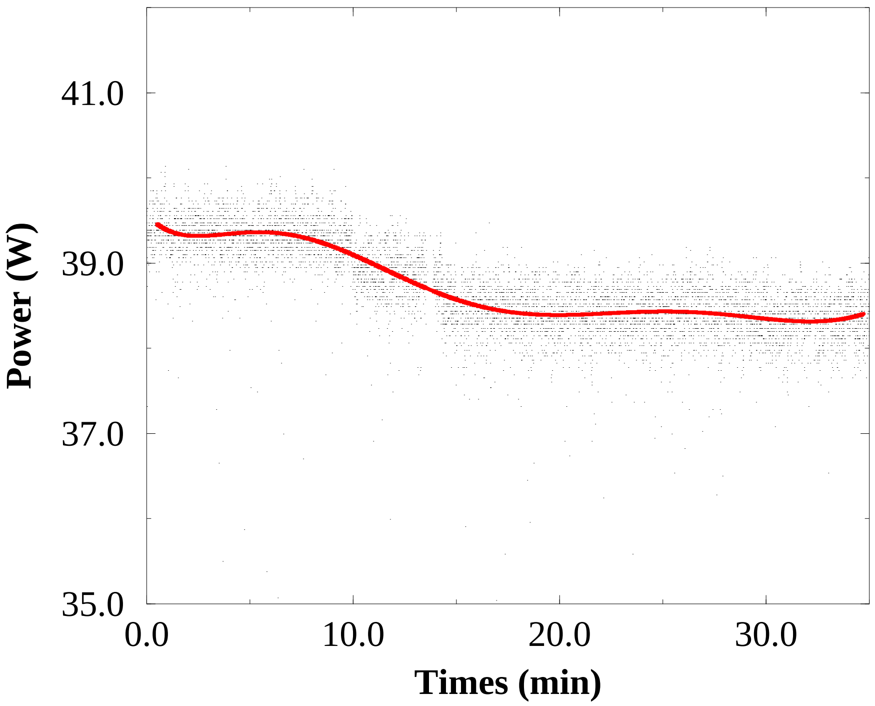

Figure 5: *Variation of the power versus times for the CAV2 cavity. The points are measured values. The line is a polynomial fit. The RMS dispersion aound this slow drift is about 1%.*

inary tests have been done with new mirrors under vacuum. With this configuration, the cavity gain is up to one thousand.

Studies to install a cavity on the JLab beam line are in progress. To maximize the luminosity, a crossing angle as small as 20 mrad is foreseen. The space available to install the cavity is about 1 meter. This leads to locate the mirrors at 5 mm from the electron beam, in the vacuum. For simplicity and reliability considerations, we want to avoid movable mirrors. So they will be fixed on the walls of the cavity vacuum chamber. This requires a very precise mechanical definition to ensure that the cavity will be resonant in the fundamental mode.
We are currently working on the design of a 80 cm monolithic cavity with 1/4 inch, 0.5 m radius of curvature mirrors and total mechanical tolerances of ±0.65 mm. Using IPN Lyon mirrors, this system should give a 1% (stat.) measurement within several minutes [4].

Another concern is radiation damage of the optical elements. A few data exist on radiation damage of the Ta_2O_5/SiO_2 multi-layer mirrors used for Free Electron Lasers [13]. Unfortunately these data are difficult to extrapolate for JLab conditions,

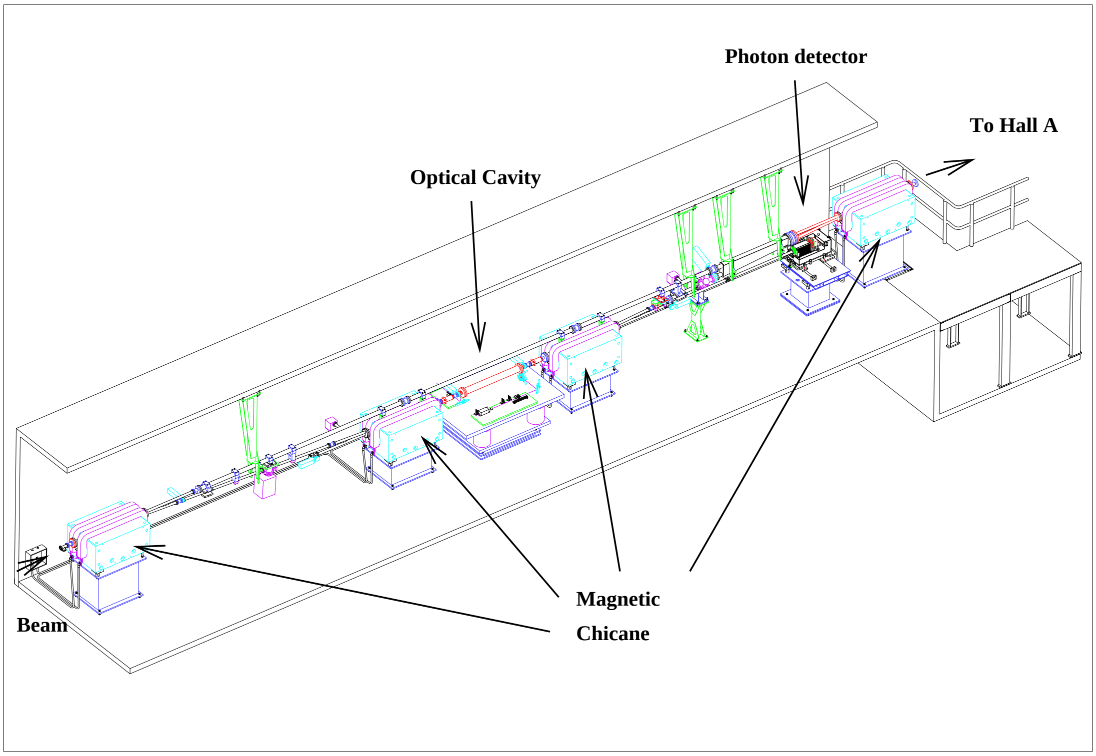

Figure 6: *Setup of the polarimeter at JLab Hall A.*

making a measurement of the mirror degradation mandatory.

The Compton polarimeter will be use for the HAPPEX[12] experiment, which will taking data in April 1998. The setup of this polarimeter is given Fig. 6. The first design of the polarimeter will use a 700 mW laser without cavity. This will be very useful to debug the optical system (designed to look like the one used for the cavity) and the remote-control system. Radiation tests and measurements will be performed too.

The optical cavity should be installed on the beam line in 1999.

References

[1] G. Badin et al., *Conceptual Design Report of a Compton Polarimeter for CEBAF Hall A*, Internal Report DAPNIA-SPhN-96-14 (1996).

[2] M. Woods, "The scanning Compton polarimeter for the SLD experiment" , in *SPIN96 Proceedings*, p. 843-845 , NIKHEF, Amsterdam, 1997

[3] J-P Jorda et al., *A Fabry-Pérot cavity for Compton Polarimetry*, to be published in Nucl. Instr. Meth.

[4] J-P Jorda, *Mise au point d'une cavité Fabry-Pérot pour la polarimétrie Compton*, Thesis DAPNIA/SPhN-97-04T (1997).

[5] A.E. Siegman, *Lasers*, University Science Book, Mill Valley, California (1986).

[6] R.P.W. Drever et al., *Laser Phase and Frequency Stabilization Using an Optical Resonator*, Appl. Phys. B **31** 97-105 (1983).

[7] C. Bradaschia et al., *The VIRGO project*, Nucl. Instr. Meth. A **289**(1990), 519.

[8] A. Abramovici et al., *LIGO, the Laser Interferometer Gravitational-Wave Observatory*, Science **256**(1992),325.

[9] G. Cantatore et al., *Frequency locking of a Nd:YAG laser using the laser itself as the optical phase modulator*, Rev. Sci. Instrum. **66**(1995) 2785-2787.

[10] G. Ruoso, *Realizzatione di una cavità risonante ottica ad alta finezza per la misura della birifrangenza magnetica del vuoto con tecniche ellissometriche*, Università degli Studi di Podava(1994).

[11] C. Wood, *Birefringence, Mirrors and Parity Violation*, Optics and Photonics News, Octobre 1996.

[12] P. Souder et al., CEBAF Experiment no. 91-004.

[13] D. Garzella et al., *Multidielectric mirrors for the SUPER-ACO storage ring free electron laser in the UV*, Proc. Int. Symp. of Optical Interference Coating , Grenoble, juin 1994.