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LASER INTERFEROMETER FOR THE PRECISE ALIGNMENT OF A LINEAR ACCELERATOR

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Abstract

Since the beam spot size reaches nanometers at a final focusing region in future linear colliders, vibration displacement must be suppressed to the order of nanometers, which we call dynamic alignment hereafter. A technique involving laser interferometers allows such precise measurements of the displacements of accelerator components. In the alignment of linear accelerators, the most important quantity to be measured is transverse to the laser direction, which defines a reference line. In order to realize it, the possibility of using phase-conjugate mirrors with a laser interferometer was investigated.

Introduction

Recent research and development concerning future linear colliders[1] suggest that the beam spot size at the collision point should be reduced to the order of nanometers in order to increase luminosity. To realize this, the dynamic alignment accuracies of such accelerator components as the quadrupole magnets at the final focusing region must be of the order of nanometers, or less. This requires technological innovations in both measuring and controlling the dynamic alignment precision. Although so-called nanometer-technology has been progressing in industries, there had been no need to obtain the same accuracy over such a very long distance as that found in linear accelerators. In the following, we introduce the technology of an ultra-precise laser interferometer[2] developed in gravitational-wave experiments, and examine its sensitivity. The possibility of transverse alignment peculiar to the alignment of a linear accelerator was also investigated using phase-conjugate mirrors.

Laser Interferometer

Principle

The laser interferometer is a Michelson-type, comprising a stable coherent light source (laser), a beam-splitter, and high-reflectivity mirrors at the end of each arm. One of the light beams separated by the beam-splitter enters the longer arm; there it is reflected by the end-mirror and returns to the beam-splitter. The other beam goes to the reference arm and is reflected by a mirror back to the same beamsplitter. By observing the interference pattern of both beams, a vibrational displacement separated by a long distance can be precisely measured relative to the length of the reference arm. The precision is usually determined by the order of the light wavelength, which is not sufficient in our case. We introduced a dark-fringe locking method which had been developed in gravitational-wave experiments, which assured the desired precision.

Sensitivity

The fundamental sensitivity limit is determined by an uncertainty relation based upon a quantum fluctuation of the mirror motion. This is realized when the photon-counting error and the radiation pressure to the mirror are balanced. Since the laser power for such a condition is extremely large, the sensitivity limit is given in terms of the photon-counting error (for instance, about 10^{-15} m/Hz$^{1/2}$ with a laser power of 10 mW(He-Ne).). This value is sufficiently small for our purpose, and is neglected here. The noise source for practical sensitivity is classified into the following items:

[1] Laser noise
[2] Seismic Noise
[3] Thermal Noise
[4] Residual Gas, etc.

[1] Laser noise There are two types of noise sources in a laser: frequency fluctuation and intensity noise. In the case of frequency fluctuation, the interferometer sensitivity is determined by the product of the frequency stability($\delta f / f$) and the absolute difference of the light path. A commercially available He-Ne laser, for instance, has a frequency stability of the order of 10^{-10}. Since the absolute difference of the light path may be long in the interferometer for the alignment of a linear accelerator, possibly reaching 100-1000 m, the sensitivity becomes more than 10 nm. To resolve this, one could stabilize the frequency by locking it to an external Fabry-Perot cavity, or decrease the path difference by using a multipath method for the reference arm. The product of the intensity fluctuation and the residual deviation from a dark fringe when locking limits the sensitivity. For dark-fringe locking, one needs a relatively high modulation frequency, since the intensity fluctuates, especially in a low-frequency region. In the example of the He-Ne laser, the stability of the intensity is about 10^{-4}, which is negligibly small.

[2] Seismic Noise Since the dynamic alignment precision must be high in the low-frequency region, the effects of seismic noise must be considered. The typical spectrum of seismic noise is known to be roughly $10^{-7}/f^2$ m/Hz$^{1/2}$, indicating the necessity of an effective vibration-isolation system for the accelerator components. There are two types of vibration-isolation methods: a passive method using a coil spring or a pneumatic spring, and an active method using feedback control.

[3] Thermal Noise All components of the system, such as accelerator components, mirrors and optical elements, have their own mechanical resonant modes, with which thermal noise is associated. It is also important to note that the vibration-isolation system for seismic noise accompanies thermal noise. In order to decrease thermal noise, one needs a low temperature for the mode, a large effective mass of vibration, an appropriate selection of the resonant frequency and a high mechanical quality factor. Thermal motion is generally very small when the temperature of the mode is 300 K, or the component is in thermal equilibrium with the environmental temperature. It is, however, taken account of in relation to the feedback system of vibration isolation.

[4] Residual Gas Fluctuation of the refractive index of residual gas causes a variation of the effective path length, and limits the sensitivity. A vacuum system is also necessary for suppressing acoustic coupling with environmental noise.

Preliminary Experiments

Preliminary experiments were carried out on a long-arm interferometer in air. Fig. 1 shows the experimental configuration. The arm length is about 80 m and the light source a frequency-stabilized 0.7 mW He-Ne laser. The beam size can be set to about 15 mmϕ by using a beam expander. A retroreflector reflects the beam parallel to the incoming beam, in such a way that the reflected beam into the laser does not disturb its stabilization system. We observed the interference pattern on a screen. The results showed both large coupling with the environmental acoustic noise and the effect of residual gas, suggesting that the vacuum system is essential in the current stage of experiment. We are now preparing a suitable vacuum system and the introduction of a dark-fringe locking method. Each type noise mentioned above will be identified using this system.

Transverse Alignment

The most necessary quantity to measure regarding linear-accelerator alignment, is the transverse one with respect to the laser direction, which defines a reference line. In order to realize this, one of the possibilities to use phase-conjugate mirrors with a laser interferometer was investigated. A phase-conjugate mirror has a novel property in that reflected light always comes back in the direction of injection. Using this property, one could expect to achieve transverse measurements with an interferometer technique. Fig. 2 shows one possible example under experimental study. The light beam of a 15 mW Ar$^+$ laser enters the phase-conjugate mirror at an injection angle of 45 degrees with the crystal surface. The phase-conjugated light is reflected in the same direction as that of the incoming light. The incoming light is also reflected directly to the flat mirror. The ordinary light reflected at the flat mirror returns together with the phase-conjugated light and interferes. From a variation of the interference pattern, one can determine any transverse displacement, which is decoupled with the longitudinal one in this scheme. The experiment with phase-conjugate mirror is, however, very delicate and strongly depends on the power and stability of the laser. Although we have not obtained any definitive experimental results so far, we note our belief that the principle should be reconsidered.

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References

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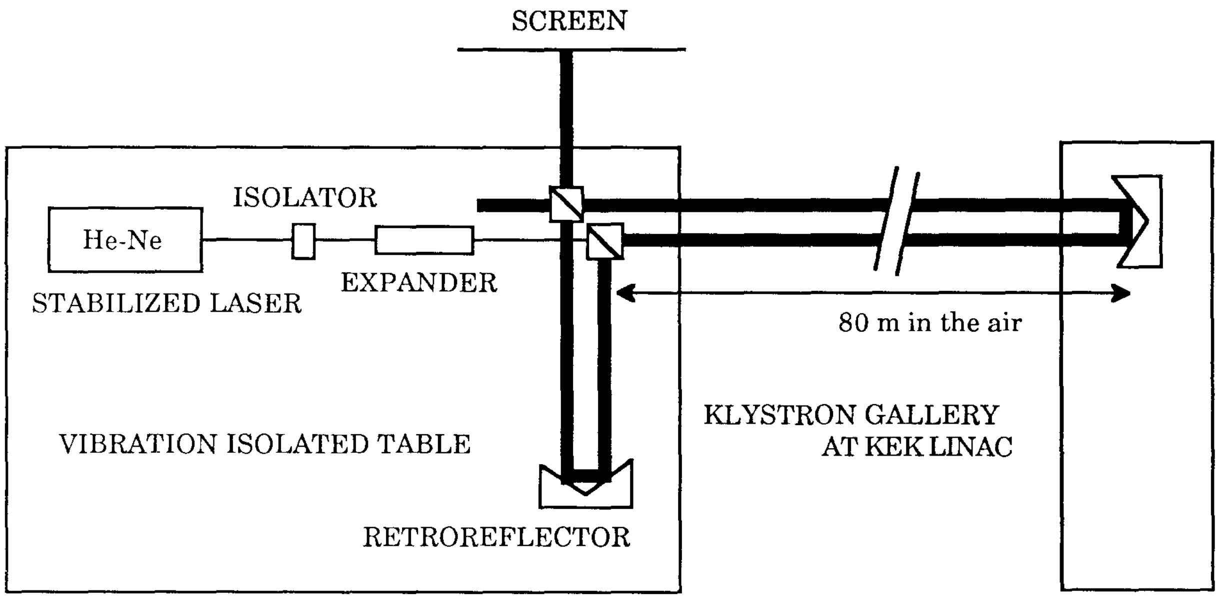

Fig. 1. Preliminary expeiments on a long-arm interferometer in air.

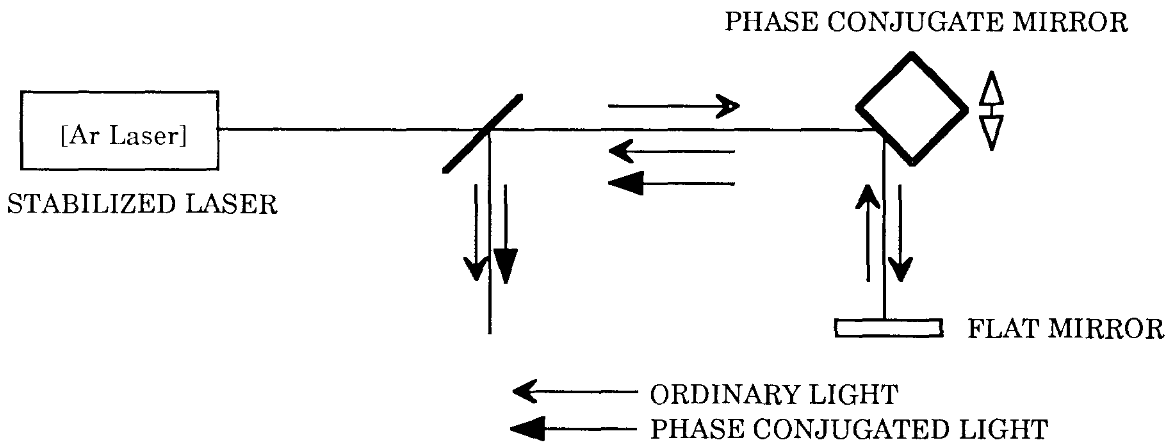

Fig. 2. Transverse alignment with a phase conjugate mirror.