SYNCHROTRON LIGHT INTERFEROMETER AT JEFFERSON LAB*

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Abstract

A synchrotron light interferometer has been built at Jefferson Lab in order to measure small beam sizes below the diffraction limit. The device is non-invasive and can monitor the profile of a few microampere electron beam. It follows the design pioneered by T. Mitsuhashi [1] and is a valuable instrument for the CEBAF accelerator. The structure of the interferometer, the experience gained during its installation, and first beam measurement results are presented. Future applications of this device include precise energy spread monitoring ($\sim 10^{-5}$) which is required by some Hall A nuclear physics experiments.

INTRODUCTION

By recirculating electrons through its two superconducting linacs up to five times, CEBAF provides nuclear physics experiments at Jefferson Lab with powerful (up to 0.8 MW) electron beams of high quality. Standard beam energies range from 0.8 to 5.7 GeV. The beam intensity ranges for three existing experimental end stations are: 1 to 180 μA for Hall A, 1 to 30 nA for Hall B, and 0.1 to 180 μA for Hall C. A growing number of experiments at the end stations have begun to require not only very small transverse beam size ($\sigma_{x,y}$<20 μm) and low energy spread ($dE/E<3\cdot 10^{-5}$) but also their continuous monitoring at the critical points of the accelerator. One such critical point in the Hall A beam line is the high dispersion (~ 4 m) location 1C12 which is shown in Fig.1. This is the area downstream of the dipole magnet (the blue element at the center of Fig.1) which has the bending radius of 40 meters.

Figure 1: Location 1C12 in the Hall A beam line with the installed synchrotron light interferometer.

This location has two other beam profile measurement devices: a wire scanner and an optical transition radiation (OTR) monitor. The wire scanner uses 25 μm diameter tungsten wires and has a maximum beam current limit at 5 μA. Wire scans take about one minute to perform and are destructive to the beam. The OTR monitor inserts a very thin (~0.25 μm) carbon foil onto the beam axis [2]. This foil introduces a small amount of halo to the beam which is acceptable to some of the experiments. The forward transition radiation is detected by a CCD camera. The resolution of the OTR monitor, limited by the used CCD camera to about two pixels, is approximately 60 μm of the RMS beam size. This is adequate to the existing but not enough for new beam requirements at Jefferson Lab.

The synchrotron light interferometer (SLI) technique that has been developed at KEK, Japan [1] for measuring very small (down to a few μm) beam sizes and successfully implemented in several electron storage rings all over the world, was very attractive for a new CEBAF beam diagnostic project. A prototype SLI has been designed and installed as a third beam profile diagnostic device at the 1C12 location. The main goals of our synchrotron light interferometer project were to determine the basic structure of the SLI for Jefferson Lab that could easily be replicated and to gain the experience during its installation in the accelerator tunnel and further operations. We also wanted to design and test software that would automate the control functions of all synchrotron light interferometer components and the calculation of the beam size with the use of the SLI data. The three different beam profile monitors at the same location would give us an excellent opportunity to use their measurement results in our work on SLI data processing and analysis models.

SLI AND ITS COMPONENTS

The SLI design at Jefferson Lab is a wave front division interferometer that uses polarized quasi-monochromatic synchrotron light. It has a 3-D structure, with major elements placed on two horizontal levels which are parallel to the ground plane (see Fig.1). Limited space and radiation levels strongly influence the SLI design and implementation.

The synchrotron light generated by the electron beam in the dipole magnet is extracted through a quartz window by the mirror installed in a vacuum chamber. After this window, external light is shielded from the SLI optical system. Two adjustable 45° mirrors guide the light through the optical system. From the first mirror light reflects downward and reaches the second mirror. This mirror is remotely controlled and sends light on the CCD

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through a long (~5 m) plastic pipe and all optical components, in the direction opposite to the direction of the electron beam. The CCD and the optical components are placed in an optical box. A diffraction limited doublet lens (f = 1 m) is used as the camera objective. A narrow band optical filter (λ_0 = 630±10 nm) is used to obtain a quasi-monochromatic light. A polarization filter selects out the σ-polarized component of the synchrotron radiation. A double slit assembly with different distances between slits (from 5 to 20 mm) and small slit openings (1mm×2mm) is located right in the front of the objective lens. It is moved by a remotely controlled stepper-motor. The SLI optical box is shielded by lead blocks to avoid damage to its components from the high radiation in the accelerator tunnel.

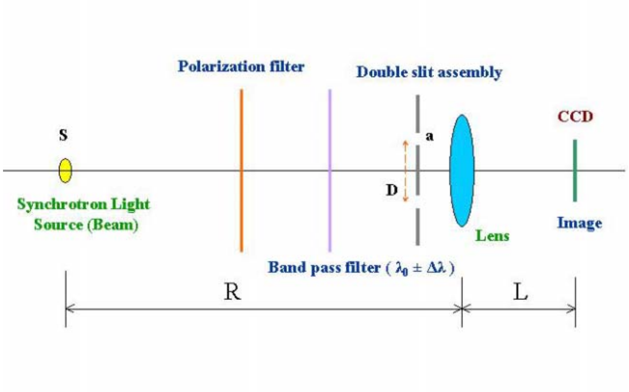

Figure 2: Synchrotron light interferometer outline.

The SLI outline is shown in Fig.2. The double slit assembly is located at the distances R≈9.1 m from the synchrotron light source point and L≈1.1 m from the CCD.

The SLI video camera is the STV digital integrating video system from the Santa Barbara Instrument Group [3]. The camera has its own control box with the RS-232 interface to an external computer. Its quantum efficiency is very high (more than 70%) for λ_0=630 nm and the pixel size is small (7.4μm×7.4μm). An electronic cooling system keeps CCD dark currents extremely low. The exposure time of the camera can gradually be changed from 0.001 seconds to 10 minutes. The CCD camera is connected to an image processor. The SLI image processor is Datacube's MaxVideo MV200 board [4] which is the basic video image processing system for beam diagnostic applications at Jefferson Lab [5]. The STV video camera and MV200 system make it possible for the SLI to measure the sizes of the CEBAF electron beams in a very wide range in energy and intensity.

INTERFEROGRAM ANALYSIS

The SLI interference pattern is captured by the CCD video camera and analyzed by the image processing software running on the MV200 and its host computer (a Motorola PowerPC based IOC) connected to the accelerator control system based on EPICS [6]. As a part of the distributed real-time EPICS database, the digitized images from the video camera and the information about the calculated beam size are available for the accelerator control computer network and can be used for various beam diagnostic applications.

The basic parameter to calculate the beam size is the visibility V of the interference pattern. The visibility is estimated from the intensities of the first (central) maximum (I_{max}) and minima (I_{min}) of the interferogram:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} - I_{\min}} \qquad (1)$$

Assuming a Gaussian beam shape, the RMS beam size can be calculated at the fixed separation of a double slit as [1]:

$$\sigma_{beam} = \frac{\lambda_0 \cdot R}{\pi \cdot D} \sqrt{0.5 \cdot ln\left(\frac{1}{V}\right)}, \qquad (2)$$

where D is the double slit separation (see Fig.2).

SLI image processing and data analysis are performed by new software that has been developed for this project. The MV200 continually processes a large volume of pixels corresponding to the video frames from the CCD camera using parallel pipeline technology. This technology makes it possible for the MV200 not only to routinely perform such important operations for processing as masking the pixels outside the interferogram region and subtraction of a background image but also to calculate the RMS beam size with the use of equations (1) and (2) at a high rate (up to 10 Hz in the multiplexed version of the software). In addition, the SLI data analysis software calculates corrections due to the field depth effects and imbalance between intensities of the two modes of light illuminating the double slit. The software fits the measured interference pattern using a multi-parameter, non-linear model that is based on the ideas from paper [7].

EXPERIMENTAL RESULTS

With the configuration of double slits that has been used for the last few months, the synchrotron light interferometer measured the vertical beam size. Measurements with different distances between slits have been made and the data of the three beam profile monitors at location 1C12 have been analyzed. Typical SLI interferograms are shown in Fig.3.

The measured vertical beam size was in the range from 0.12 to 0.18 mm for various CEBAF operation modes. The data of all three monitors were in very good agreement with each other.

The typical beam requirements from the Hall A users are 5 GeV energy and 100 μA intensity. The SLI beam size measurement time for these currents and energy and with D=5 mm is about 1 second. Since the amount of the emitted synchrotron light is proportional to the beam energy and intensity, the optimal video camera exposure time for each CEBAF operation mode can be calculated. Our experimental results have confirmed these calculations.

The resolution of the SLI depends on the distance between slits D and can be estimated with the use of equation (2). For example, if D=5 mm, then 10 μm difference at the beam size 120 μm makes more than 3 % difference in the visibility. Since the image processing system easily calculates the visibility of the CCD image with 1% accuracy, we can measure the beam size 120 μm with the resolution better than 10 μm.

CONCLUSIONS

The main goals of the SLI project at Jefferson Lab have been achieved. It was demonstrated that the synchrotron light interferometer technique could successfully be used for CEBAF beam diagnostic applications. We have built an automated SLI that is easy to replicate at the other accelerator locations.

The SLI is completely non-invasive and can monitor the profile of a few microampere electron beam. Future applications of this device include precise energy spread monitoring ($dE/E<3\cdot10^{-5}$) that is required by some nuclear physics experiments.

We have gained a great experience in the SLI technique and operation. The most difficult problem during the SLI installation in the accelerator tunnel was the alignment of all its optical components around the optical axis formed by the used mirrors. We are planning to implement some modifications in the synchrotron light interferometer structure that would be very helpful for the future synchrotron light interferometer projects. For example, a possibility to use a He-Ne laser as a SLI reference light source should significantly simplify the work on the SLI installation and tests.

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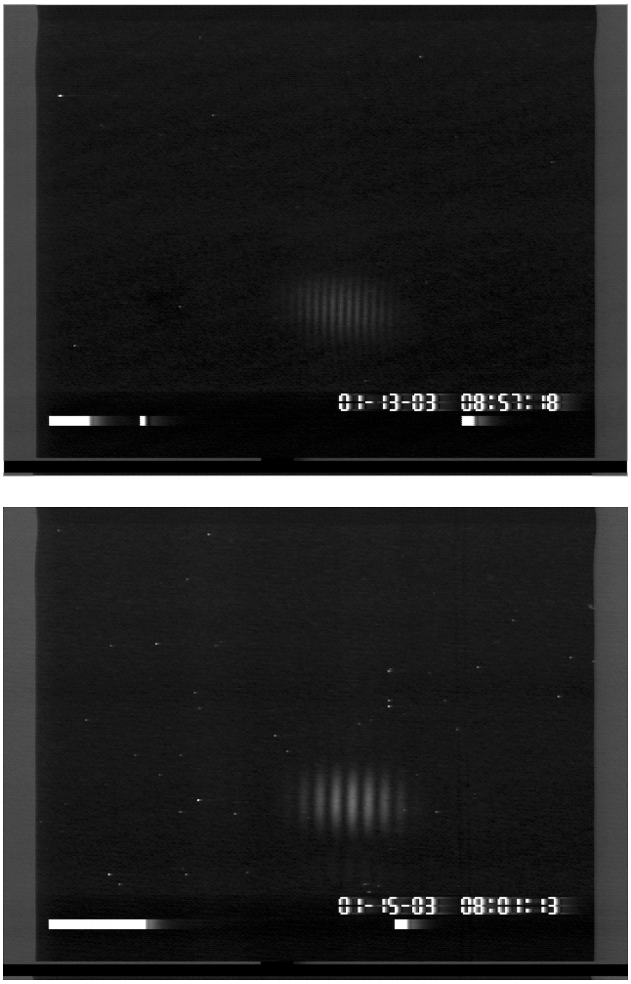

Figure 3. Typical SLI interferograms with D=5 mm (the upper picture) and D=10 mm. The calculated beam size is about 0.12 mm in both cases.