AUTOMATED IMAGE QUALITY OPTIMIZATION FOR SYNCHROTRON LIGHT INTERFEROMETERS*

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ABSTRACT

Jefferson Lab has been using Synchrotron Light Interferometers (SLI) for real time high resolution, non-invasive measurement of electron beam energy spread in two experimental halls for over two years. An SLI is a classic device, which generates synchrotron light interference patterns by means of a double slit. The beam energy spread is calculated on the basis of the visibility (contrast) of the interference pattern produced by the SLI. The results of the calculations are sensitive to the position of the double slit with respect to the synchrotron light beam illuminating it. Even small changes of the electron beam trajectory in the accelerator can significantly distort the shape of the interference pattern and decrease the reliability of these results. To improve this situation, we developed a state machine control application, which automatically adjusts the positions of the SLI double slits and the mirrors directing light on these slits. The paper describes the main ideas implemented in this application and its performance.

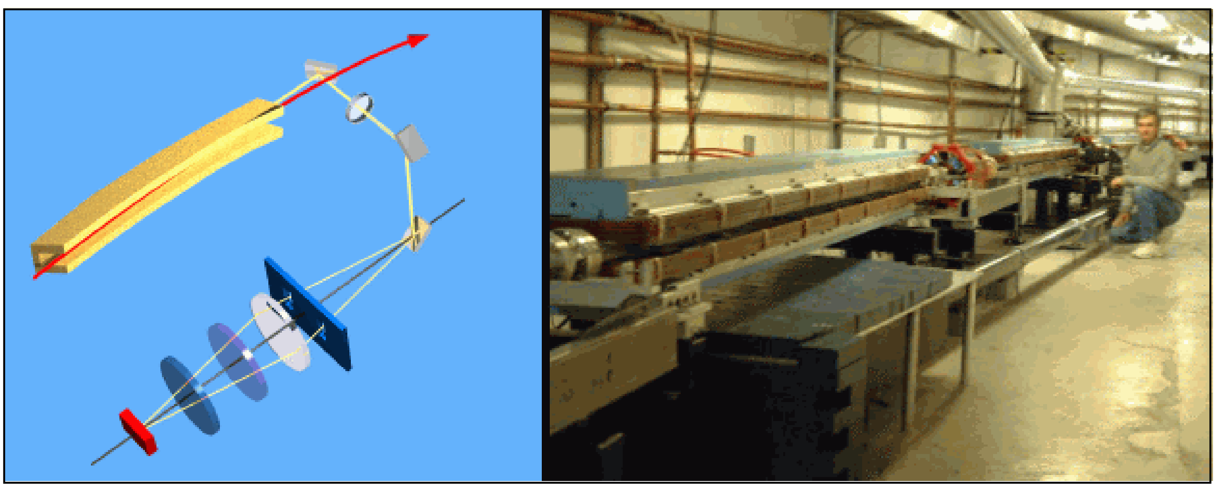

Figure 1: Basic SLI configuration and one of the interferometers installed at Jefferson Lab (the Hall A experimental beam line).

INTRODUCTION

The SLI beam diagnostic technique [1] is completely non-invasive and has successfully been implemented at several accelerator centers all over the world. The SLI design at Jefferson Lab is a "classic" 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). A limited space and relatively high radiation in the accelerator tunnel strongly influenced the SLI design and implementation [2].

SLI CONFIGURATION AND CONTROL

The synchrotron light generated by the electron beam in a dipole magnet is extracted through a quartz window by a mirror installed in a vacuum chamber. Two additional adjustable mirrors guide the synchrotron light through the SLI optical system (Fig. 1). One of them is controlled by a remote computer with the use of an RS-232 communication interface and is called the active SLI mirror. Its main task is to send synchrotron light to the CCD camera head through a long (~5 m) plastic pipe,

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diffraction slits, and all SLI optical components (a narrow band pass filter, a polarization filter, and a video camera objective lens), in the direction opposite to the direction of the electron beam. The CCD camera registers synchrotron light interference patterns, the properties of which depend on the transverse size of the electron beam in the accelerator. The CCD camera and optical components are placed in an optical box, which shields them from the external light. A double slit assembly with a predefined set of distances between slits and small slit openings is located right in the front of the camera objective lens. The assembly is moved in horizontal and vertical directions by remotely controlled stepper-motors. The SLI video camera (the STV video system from the Santa Barbara Instrument Group [3]) is equipped with its own control box that has an RS-232 interface to an external computer. The camera has very high quantum efficiency (~70% for λ=630 nm that is used for image analysis applications at Jefferson Lab). 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.

SLI elements are controlled by means of a distributed multi-component software in an EPICS environment [4]. The software consists of the SLI control and data processing packages. The integration part of these packages is the SLI data reliability concept that requires the definitions of the SLI data model and its reliability.

SLI DATA MODEL

If an SLI double slit is illuminated by synchrotron light, the SLI interference pattern can be described by the following multi-parameter function that we call the SLI data model [5]:

$$y(x) = A(x, x_0, I_b, I_0, a, b, V, \varphi) = I_b + I_0 \left(\frac{\sin a(x - x_0)}{a(x - x_0)} \right)^2 \left(1 + V\cos(b(x - x_0) + \varphi)\right). \quad (1)$$

Here a, b, and φ depend on the size of the slits, the slit separation D, and the phase difference of the light reaching the slits respectively; I_b is a background signal, I_0 is determined by the intensity of the synchrotron light source, x_0 is the shift of the interferogram with respect to the origin of the image axis x and V is the visibility (contrast) of the interference pattern, which can be written as [6]:

$$V = \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} = \frac{2\sqrt{I_1 I_2}}{(I_1 + I_2)} |\gamma_{12}|. \quad (2)$$

In equations (2), I_{max} and I_{min} are the maximum and minimum intensities of the interference fringes, I_1 and I_2 are the light intensities on slits 1 and 2. The parameter $|\gamma_{12}|$ is the degree of coherence of the synchrotron light on slits 1 and 2, which in case of Gaussian electron beams has a simple relation to the RMS beam size σ_{beam}:

$$|\gamma_{12}| = \gamma_{12} = e^{-\frac{2\pi^2 D^2}{\lambda^2 R^2 \sigma_{beam}^2}}. \quad (3)$$

Here R is the distance between the synchrotron light source (the electron beam) and the used double slit.

If the light intensities on the slits are equal to each other ($I_1 = I_2$) then from equations (2) and (3) it follows that:

1) $\gamma_{12} = V$ and the beam size can be calculated directly from the visibility V of the interference pattern and
2) the visibility V of the SLI interferogram has its maximum value.

The requirement of equal light intensities on the slits is one of the most important components of the SLI data model. With a fixed position of a double slit and small fluctuations of the beam trajectory in the accelerator around its design orbit, it can always be fulfilled by the adjustment of the position of the active SLI mirror. We call this mirror adjustment procedure as the SLI image quality optimization.

SLI DATA MODEL RELIABILITY

Since any model is only an approximation of a real process, we need some criteria for the consistency of the SLI data model (1) with the experimental data. The most important parameter of this model is the visibility *V* that gives us the beam size and energy spread estimates. To find *V,* we fit the SLI interference pattern minimizing the following function:

$$\psi = \psi(\vec{x}) = \sum_{i=1}^{N} \frac{\left(y(x_i) - A(x_i, x_0, I_b, I_0, a, b, V, \varphi)\right)^2}{\sigma_i^2} \tag{4}$$

where *N* is the number of points x_i used on the SLI image and σ_i are the measurement errors of these points. The fit is based on the standard Levenberg-Marquardt method [7].

One can show that if the parameters $Params=\{x_0,I_b,I_0,a,b,V,\varphi\}$ are known and the experimental data with the measurement errors σ_i satisfy equation (1), the probability distribution for ψ is exactly

$$p(\chi^2, n) = \frac{1}{2^{n/2}\Gamma(n/2)} \left[\chi^2\right]^{n/2-1} e^{-\chi^2/2}, \tag{5}$$

$$0 \le \chi^2 < \infty, \Gamma(z) = \int_0^{\infty} e^{-t} t^z dt$$

where $n=N$. It is called the “chi square” distribution with *n* degrees of freedom.

We now introduce now the next criterion for the SLI data model and data fit quality that we call the SLI data model reliability:

$$\alpha(\psi, n) = \int_{\psi}^{\infty} p(\chi^2, n) d\chi^2. \tag{6}$$

If the parameters *Params* of function (1) are known, then we can calculate $\alpha(\psi, N)$ for each observed interference pattern. When $\alpha(\psi, N)$ is close to 100%, we say that the agreement between the SLI data model and experimental data is good. If $\alpha(\psi, N)$ is close to 0% (very small) then the agreement is obviously bad and the shape of the interference pattern is not described by function (1).

If *k* parameters of data model (1) are not known, we can fit the SLI interference pattern with the use of this function to find these parameters and calculate $\alpha(\psi, N-k)$. When after the fit $\alpha(\psi, N-k)$ is close to 100%, we say that the data fit is good and function (1) describes the interference pattern very well. If $\alpha(\psi, N-k)$ is small then the data fit is bad.

In terms of classical problems of setting up and testing hypotheses, $\alpha(\psi, n)$ can be defined as the probability to wrongly reject the SLI data model (1) on the basis of the measurement results. The higher reliability of the model obviously means its better consistency with experimental data.

SLI DATA RELIABILITY CONCEPT AND ITS IMPLEMENTATION

Now we are ready to formulate the SLI data reliability concept. The concept is a set of the standard procedures that are used in the SLI operations.

One of the most important procedures of the SLI operations is the SLI calibration. It is performed for each accelerator mode by experts in beam diagnostics and the SLI. During the calibration procedure, the positions of a double slit and the active SLI mirror are adjusted to provide equal light intensities on the slits. As mentioned above, these positions correspond to the maximum available visibility *V* of the SLI interference pattern, the shape of which satisfies the SLI data model (1). The visibility control is based on the results of the data fit (4) with the SLI data model reliability for this fit and the visual analysis of the obtained interferograms. The beam size calculated from the visibility is then compared with the data from Optical Transition Radiation Monitors (OTR) and wire-scanners, which are located near the SLI in the accelerator. Usually the data agreement is very good at this point.

The significant data disagreement may indicate some problems with the SLI components that have to be fixed. The calibration procedure gives us the parameters $Params_{cal}$ of the function (1) the most important of which is the visibility V_{cal}.

After the calibration is done, the SLI is switched to its main operational mode. The SLI control and data processing software analyses the interference patterns in real time. For each pattern it calculates the quality of the SLI data fit or the SLI data model reliability $\alpha(\psi, N\text{-}k)$ and the parameters of the fit *Params*. If $\alpha(\psi, N\text{-}k)$ is close to 100% and the beam size calculated from the estimated visibility V is in the specified frames for the used accelerator mode, then the SLI data indicate that the beam in the accelerator of good quality.

The main problem arises, when $\alpha(\psi, N\text{-}k)$ is close to 100% but the estimated visibility V is significantly smaller than V_{cal}. In this case we have the following two possibilities.

1) The beam size really increased and went out of the specified frames. In this case the status of the accelerator must be checked to reduce the beam size.
2) The beam trajectory in the accelerator changed so that after this change the SLI diffraction slits are not equally illuminated by the synchrotron light. In this case one of the requirements of the SLI data model is not satisfied and to get reliable SLI beam size estimates with the use of this model, we have to readjust the position of the active SLI mirror.

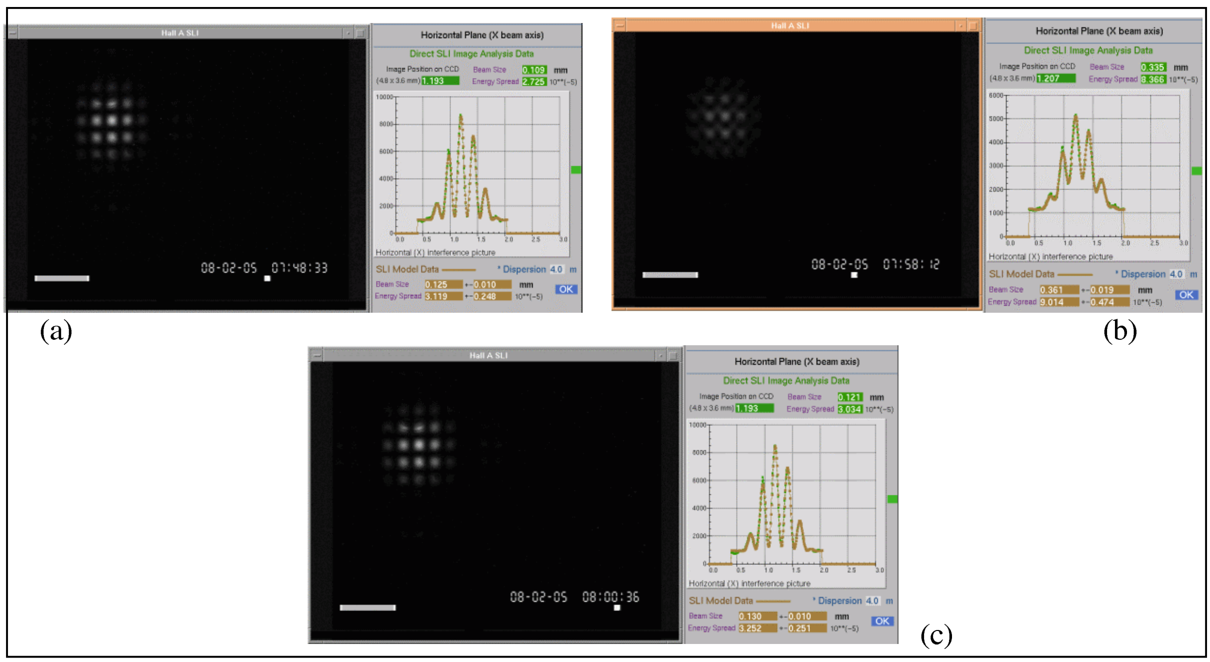

Figure 2: SLI state machine control application test results. Picture (a) shows the initial SLI interference pattern and the calculated horizontal beam size is about 0.12 mm. When the active SLI mirror was turned by a small angle (less than 0.1 arc degrees), the SLI interferogram significantly changed and the calculated beam size became about 3 times bigger according to picture (b). Picture (c) shows the result of the work of SLI state machine control application. The mirror is pulled back into its initial position. The calculated beam size is about 0.13 mm. We note that in all cases the quality of the SLI data fit $\alpha(\psi, N\text{-}k)$ was ~90%.

The solution to the problem lies in making the right choice between these two possibilities. This choice is usually made by the SLI experts on the basis of the SLI data model and its reliability. They move the active SLI mirror around its current position and watch the changes of the SLI data fit quality $\alpha(\psi, N\text{-}k)$ and the visibility V.

1) If for all new mirror positions with $\alpha(\psi, N\text{-}k)$ close to 100%, the visibility V does not get better, then the SLI data model reliability indicates that the beam size in the accelerator increased and the mirror is pulled back to its initial position.
2) If for some new mirror positions with $\alpha(\psi, N\text{-}k)$ close to 100%, the visibility gets better, then the active SLI mirror is moved to the position that corresponds to the maximum value of V and the SLI operations continue.

To automate the above solution and make it available not only to the SLI experts but also to the accelerator operators at Jefferson Lab, the SLI state machine control application has been created. The application is a new part of the SLI data acquisition and control package. It runs on one of the workstations connected to the accelerator control network and communicates with the other SLI control applications via the EPICS Channel Access protocol. The corrections of the active SLI mirror positions are performed by the application on the requests of the users who want to make sure that the SLI data are reliable. Some software test results are presented in Fig. 2.

The tests of the SLI state machine control application were successful. For these tests we simulated the SLI problems by moving the active SLI mirror out of its optimal position and then ran the application. In most cases, the software was able to correctly readjust the position of the active SLI mirror in about one minute.

CONCLUSION

The main goal of the automated SLI image quality optimization implemented in the SLI state machine control application is to provide the accelerator operations team with a new powerful beam diagnostic tool. This tool is able not only to monitor the reliability of the SLI data in real time but also help non-invasively identify the problems with such important beam parameters as the transverse size, the trajectory (or energy), and the relative energy spread. We plan to test the SLI state machine control application in the conditions when the beam size changes significantly and make this application available for accelerator operations by the beginning of the next year.

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