FIBEROPTICS-BASED INSTRUMENTATION FOR STORAGE RING LONGITUDINAL DIAGNOSTICS*

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Abstract

Many beam diagnostic devices in today's synchrotron rings make use of the radiation emitted by the circulating particles. Such instruments are placed in close proximity of the accelerator, where in many instances they cannot be easily accessed for safety consideration, or at the end of a beamline, which, because of its cost, can only move the light port a few meters away from the ring.

We present a study of the coupling of synchrotron light into an optical fiber for all those applications where the longitudinal properties of the beam are measured (i.e. bunch length, phase, intensity, etc.). By choosing an appropriate fiber it is possible to keep attenuation and dispersion at negligible values over a large bandwidth, so that this method would allow to have the diagnostic instruments directly in the control room, or wherever convenient, up to several hundreds of meters away from the tunnel. This would make maintaining and replacing instruments, or switching between them, possible without any access to restricted areas. Additionally, the few components required to be near the ring (lenses and couplers) in order to couple the light into the fiber are intrinsically radiation hard.

INTRODUCTION

In today's accelerators all the diagnostic devices that make use of the emitted synchrotron radiation have to be placed in relatively close proximity of the machine. Even dedicated beamlines, which are nonetheless very expensive, can at best place the light port a few tens of meters away.

In this paper we begin the study of a diagnostic system that employs optical fibers to transport the synchrotron light at much greater distances. This is especially useful in high-energy machines, where the vicinity of the accelerators is characterized by very high radiation levels and is only sporadically accessible.

The main issues we identified are the choice of a particular fiber, with respect to the light spectrum available from a given machine. We show how there are different strategies one can adopt in dealing with attenuation and dispersion introduced by the propagation into the fiber. Another subject of paramount importance is the coupling of the synchrotron radiation, generally propagating in free space, into the optical fiber. We have conducted experiments on two beamlines at the Advanced Light Source to understand what fraction of the available intensity can be injected into the fiber and which characteristics of the source are important in order to maximize that figure.

PROPAGATION OF SYNCHROTRON RADIATION INTO OPTICAL FIBERS

Optical fibers are commercially available mainly at three infrared wavelengths: 850, 1310 and 1550 nm. There also exist fibers in the visible range, but their characteristics make them not suitable for our application. A fundamental requirement for a fiber optics-based system is therefore that the particular light port should have a photon flux high enough to yield, after all the attenuation and losses, a number of photons compatible with the maximum integration time and the minimum signal-to-noise ratio allowed.

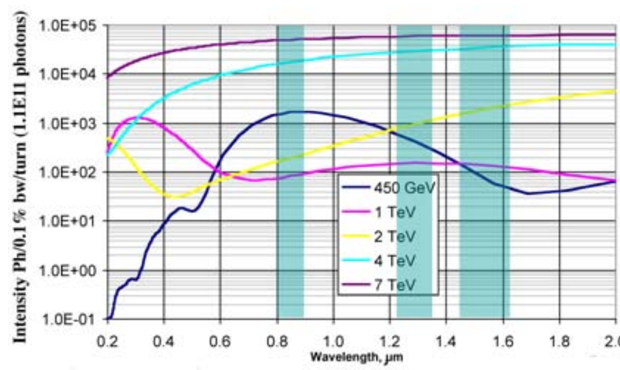

Figure 1: Photon flux from the LHC longitudinal diagnostics light port.

As an example we show in Fig.1 the photon fluxes available at various beam energies from the dedicated synchrotron light diagnostic port in the Large Hadron Collider. Shaded areas correspond to 10% bandwidths centered on the wavelengths listed above.

Propagation of the synchrotron radiation in optical fibers is affected by two phenomena: attenuation and dispersion. Since commercial fibers were developed for long-distance communications, attenuation is not generally a problem given the relatively short fiber lengths we plan to use. Fibers at 850 nm have the highest losses (about 2.5-3 dB/km), while the attenuation in the longer wavelength fibers is only a few tenths of dB/km. We therefore are of the opinion that synchrotron light attenuation could be an issue only in extreme cases characterized by very weak signals and long transmission lengths.

Far more important are the effects of dispersion in the propagation. Its careful evaluation weighs tremendously

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in the decision of which fiber to use and on the final performance of the system. We will now list the characteristics of the more widely available fibers. Radiation-hard fibers generally perform a little worse, but can withstand total doses in excess of 10^9 rad.

Multi-mode fibers

Multi-mode fibers are characterized by larger core diameters (typically 50-100 μm) than the corresponding single-mode ones. This allows a much easier coupling of synchrotron radiation into the fiber. On the negative side, because of intermodal dispersion, these fibers cause an elevated signal distortion. The standard figure of merit in this respect is the bandwidth-distance product, which can be in the range of a few hundreds of MHz•km. From the approximated equation $BW \approx \frac{1}{2\Delta t}$ we can estimate that such a fiber allows a resolution in the order of 100 ps after 100 m. In case a finer resolution is needed, it is still possible to use multi-mode fibers, but the signal needs to be sampled with the necessary resolution near the light port, after which dispersion is no more a problem since the signal carries only an intensity information, while the sampling window provides the temporal information. To this end we show in the last paragraph how such a system can be rather cheaply assembled from off-the-shelf components.

Multi-mode fibers are widely used in telecommunications in the 850 and 1310 nm regions.

Single-mode fibers

Commercial single-mode fibers have core sizes of below 10 μm, which complicates the coupling. In addition, there are losses caused by the geometric matching of the transverse section of the synchrotron light coming out of the ring with the shape of the fiber only mode. These can be corrected only to some extent by the use of lenses. Single-mode fibers are nominally dispersion free around 1310 nm. The total delay Δt in a given bandwidth Δλ can be calculated as:

$$\Delta t = \Delta\lambda D(\lambda) L \tag{1}$$

where L is the fiber length and the zero-dispersion slope is given by

$$D(\lambda) = \frac{S_0}{4}\left(\lambda - \frac{\lambda_0^4}{\lambda^3}\right) \tag{2}$$

where S_0 and λ_0 depend on the particular fiber composition and its technological process and are of the order of 0.1 ps/(nm^2•km), or less, and ~1310 nm respectively.

From Eqs.(1) and (2) we can estimate the total delay introduced between wavelengths at the boundary of 10% bandwidth, after propagation in 100 m of fiber, which turns out to be of the order of a few ps or less around 1310 nm and 200-300 ps at 1550 nm.

From the above figure we can conclude that, unless the machine flux is much greater at the longer wavelength, the shorter length fiber appears as a more viable candidate for our application. It is nonetheless possible to add to the system a short length of dispersion compensating fiber, in case one is interested in reducing the dispersion at 1550 nm and utilize that wavelength instead.

COUPLING EXPERIMENTS AT THE ALS

As previously stated the other main issue when trying to use optical fiber is the actual coupling of the synchrotron light from some light port into the fiber. We have seen in the previous section how multi-mode fibers, with their much larger core sizes, are characterized by a higher coupling efficiency.

We conducted experiments on one of the ALS diagnostic beamlines, using a single-mode fiber in order to have an estimate of coupling in a sub-optimal scenario.

In order to couple light from a source into a fiber efficiently, the light from the source must, in first instance, be injected within the numerical aperture. To couple the light to the step-index single-mode fibers, the injected light must additionally be matched as closely as possible to the transverse intensity profile of the mode that will propagate in the fiber [2].

To this end, the synchrotron radiation parameters have to be well understood. The opening angle of the synchrotron radiation in the vertical plane is well defined by the beam energy and bending angles, and can be calculated with the formula that can be found in many books, but the divergence in the horizontal plane has to be experimentally determined.

Beam Line 3.1 utilizes two K-B mirrors to focus the synchrotron radiation horizontally and vertically; the focusing points are 0.8 meter apart, outside the vacuum chamber. Flat mirrors are used to bring visible and infrared light out for beam diagnostic purposes.

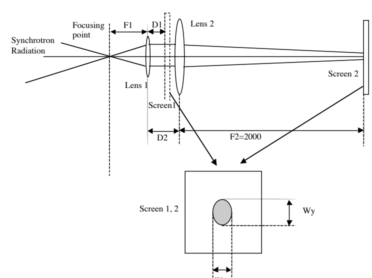

Figure 2: Transverse beam size measuring setup. (F1=40 mm, D2 arbitrary).

The setup shown in Fig.2 was used to determine the synchrotron radiation source properties on the two ALS diagnostic beamlines (BL3.1 and BL7.2).

Steps:

1. Setup Screen 2 and Lens 2; make sure the distance between them is 2 m.
2. Insert Lens1, and move Lens 1 along the main optical axis to adjust the distance between the focusing point and Lens1 while looking at the

beam spot on Screen 2, until the spot size reaches its minimum dimensions.

3. Measure the size of the spot: W_x2 and W_y2.
4. Move Lens 2 out off the beam path, put Screen 1 at the distance of D1=100mm.
5. Measure the beam size W_x1 and W_y1.

The measurements showed that beam divergence at x direction is only 1.5 mrad for both beam lines, which also is consistent with the theoretical calculation, but in the y direction, divergence is quite large: 60 mrad for beam line 7.2 and 17.5 mrad for beam line 3.1.

The single mode fiber core size has diameter of 9 μm, in order to receive as much as possible of the light, a focusing lens of 6 mm should be used based on the θ_x of 1.5 mrad, therefore, most of the light with large divergence will be lost.

Table 1: Summary of beamline measurements and estimated coupling factor.

Beamline	3.1	7.2
Spotsize at screen 1 $W_x1 \times W_y1$ (mm)	2.0 x 3.0	1.5 x 13.0
Spotsize at screen 2 $W_x2 \times W_y2$ (mm)	3 x 35	3 x 120
Divergence $\theta_x \times \theta_y$ (mrad)	1.5 x 17.5	1.5 x 60
Coupling efficiency	2.6%	0.23%

In our measurements, an ocular with focusing length of 10 mm, NA=0.25 was used to couple the synchrotron radiation into the fiber. The efficiency was 5% as the measurement showed, which is also consistent in the order of magnitude with the estimation listed in Tab. 1, where divergence is calculated as $\theta_*=W_*2/f2$ and the theoretical efficiency is given by

$$9 \cdot f_c \theta_y \frac{f_c\, 2\tan^2\left[\arcsin(0.11)\right]}{W_x 1 \cdot W_y 1} \tag{3}$$

CONCLUSIONS

Our initial results in the development of a fiberoptics-based instrumentation for synchrotron rings show that commercially available optical fibers are well suited for this application. Depending on the photon flux available, one can choose to operate with single-mode fibers, which feature negligible dispersion and can be used for high time resolution measurements, or multi-mode fiber, characterized by higher coupling efficiency, but which require a sampling device near the light port, for most time-resolved applications.

In any case, we believe the method presented in this paper to be a promising one, which could find application of most machines and it is worth of further investigation.

REFERENCES

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