A NOVEL APPROACH TO SYNCHROTRON RADIATION SIMULATION

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Abstract

At the Large Hadron Collider (LHC) at CERN, synchrotron radiation (SR) is used to continuously monitor the transverse properties of the beams. Unfortunately the machine and beam parameters are such that the useful radiation emitted inside a separation dipole, chosen as source, is diffraction limited heavily affecting the accuracy of the measurement. In order to deconvolve the diffraction effects from the acquired beam images and in order to design an alternative monitor based on a double slit interferometer an extensive study of the synchrotron light source and of the optical propagation has been made. This study is based on simulations combining together several existing tools: SRW for the source, ZEMAX for the transport and MATLAB for the "glue" and analysis of the results. The resulting tool is very powerful and can be easily adapted to other synchrotron radiation problems. In this paper the simulation package and the way it is used will be described as well as the results obtained for the LHC and SPS.

INTRODUCTION

During the LHC Long Shutdown (LS1), the two LHC Beam Synchrotron Radiation Telescopes (BSRT) were refurbished in order to cope with the increase of the machine top energy to 6.5 (and later 7) TeV. In fact, the resulting adiabatic reduction of the transverse geometric beam emittance combined with the increased brightness delivered by the injectors will bring the beam size measurement using visible SR imaging technique close or even beyond its resolution limits. Investigating the theoretical resolution of the LHC was the main motivation of the studies presented here. In addition, the versatile tools developed were used for designing the refurbishment of the Super Proton Synchrotron (SPS) beam size monitor and for the feasibility study of a SR interferometer in the LHC.

SIMULATION

The package that has been developed is powerful and can be easily adapted to different SR problems. It is, in fact, based on interfacing existing tools: Synchrotron Radiation Workshop (SRW) [1] for the source description, ZEMAX [2] for the wavefront transport and MATLAB [3] for the "glue" and the analysis of the data.

SRW is a computer code for calculating the detailed characteristics of the SR generated by relativistic electrons, in magnetic fields of arbitrary configuration, in the frequency-domain using near-field methods. Although initially intended for use with electrons, SRW can be applied to protons by introducing the proper scale factors for the energy and the magnetic fields. This code is integrated as a toolbox within the graphing and analysing software "Igor Wavemetrics" [4] to ease the pre and post processing.

Zemax is an optical design program that is used to design and analyse optical systems. In its basic mode, it works by ray-tracing, modelling the propagation of rays through the optical elements. It also includes the Physical Optics Propagation (POP) mode, using diffraction laws to propagate a wavefront sequentially through an optical system element by element. It has to be noted that POP is used for free space propagation; when a wavefront reaches an optical surface, it is decomposed into rays traced geometrically including aberrations and diffraction throughout the surface (i.e. the lens) and then recomposed into a wavefront at its exit.

Matlab and Dynamic Data Exchange: In computing, Dynamic Data Exchange (DDE) is a method of interprocess communication under MS Windows™. It allows one program to subscribe to items made available by another program, enabling Windows applications to exchange data. This communication protocol was chosen for the simulation suite to benefit from the very powerful data analysis tool MATLAB acting as a DDE server to interface SRW and Zemax.

Algorithm Description

As mentioned, SRW and Zemax were identified as the best choice for an accurate characterisation of the emission and propagation of the visible SR fields up to the sensor, including aberrations introduced by imperfections of the optical system.

The code flow shown in Fig. 1 explains how the user, interfacing only with MATLAB, is able to generate and transparently run the necessary SRW and ZEMAX codes and analyse their outputs.

This approach can be used for SR based beam size monitors to calculate the following of an imaging system:

- Line Spread Function (LSF). Defined as the imaging system response to a pencil beam (i.e. null emittance)
- Response to a beam finite size.

LSF is used to describe the resolution of the SR imaging system.

It is simulated by setting the input beam size to zero, with a filament beam defined in SRW within an Igor Procedure File (IPF) generated by MATLAB, describing the magnetic structure set by the user. The IPF is pushed to SRW through the DDE channel and its execution is requested by MATLAB while at the same time providing the input parameters (beam energy, SR wavelength, etc...). The SR electromagnetic

Figure 1: Code Flow.

Figure 2: Uniform Phase Space (position x and angle x')
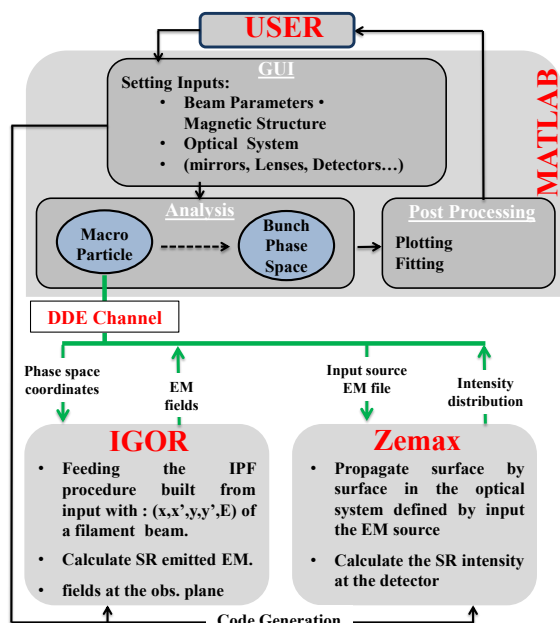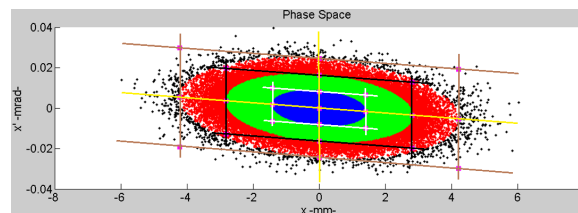Sampling technique applied for finite horizontal beam size.
Simulation of an LHC bunch at injection.

fields, in the observation plane, defined as the surface of the first optical element of the imaging system (usually the in-vacuum extraction mirror), are then calculated. The results are passed back to MATLAB using the same communication channel for normalization and phase correction. Next, a ZEMAX Beam File (ZBF), listing the optical elements (lenses, drifts, mirrors, apertures...) as surfaces, is generated and fed together with the input fields to ZEMAX. After propagation in POP mode to the detector's plane, the light intensity distribution is extracted by Matlab, post-processed and delivered to the user.

Finite Beam Size Response   This involves describing the real SR and its propagation to the detector. Since only the visible (200 nm - 700 nm) SR is considered, and the rms bunch length is several hundreds of picoseconds, the protons can be considered to emit SR incoherently. The final image can therefore be reconstructed by summing the intensities of individual emitters instead of the electric fields. Two different approaches were considered:

- *Weighted Uniform Phase Space Sampling*
  It consists in dividing the transverse phase spaces ((x, x') and (y, y')) into small areas of partial coherence, as shown in Fig. 2, weighted accordingly to the 2D multivariate normal distribution fitting the beam emittance. The LSF of every sampled point is calculated as explained above with the weighted sum of the SR intensity emitted by the sampled macro particles propagated to the detector.

- *Reconstruction by Extrapolation*
  In this case only a few *reference* macro-particles are simulated, with a fit to the results giving a numerical model predicting the SR intensity distribution of every particle in phase space. Even though this worked for the

LHC case, the numerical model is often difficult to find, making this method difficult to adapt to all situations.

APPLICATION TO CERN SR MONITORS

SPS SR Monitor

In the SPS, the SR edge radiation emitted at both input and output of two consecutive main bending magnets is extracted by an in-vacuum mirror 9 m downstream. Figure 3 shows the source intensity distribution at 650 nm calculated by SRW (left) and the LSF (right) after a two stages optical system simulated by Zemax (total magnification 0.6).
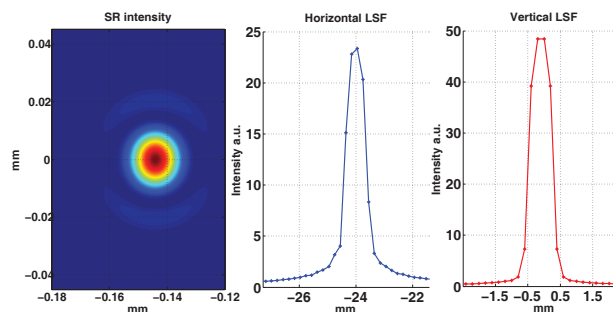

Figure 3: The intensity of extracted SR light on the extraction mirror of the SPS (left), and the horizontal (middle) and vertical (right) LSF at the imaging instrument (units of object mm).

LHC SR Monitor

In the LHC, the visible SR is produced at injection energy (450 GeV) by a superconducting undulator and by an adjacent dipole above 2 TeV. The light is extracted 2 m downstream of the undulator. Figure 4 shows the intensity distribution on the extraction mirror for injection and top energy.

Imaging   The imaging telescope is more than 30 m long; it consists of two achromatic lenses (f=4810 mm and f=300 mm) with a variable focus to cope with the shift in the longitudinal position of the source. The simulations consisted of quantifying the resolution improvement of this diffraction limited optical system at high energy by shifting the working point to lower wavelength in the VUV region (from 400 to 250 nm). The LSF of the system at injection and flat top energy for both wavelengths is shown in Fig. 4.
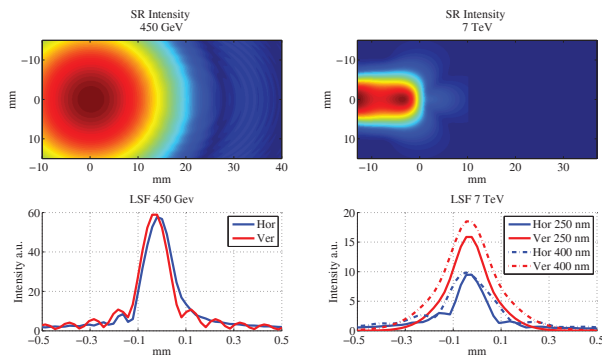
Figure 4: The upper plots show the intensity distribution of the SR on the extraction mirror of the LHC at injection (left) and Flat Top (right). The respective LSF in image mm units (magnification=0.2) is shown in the lower plots.
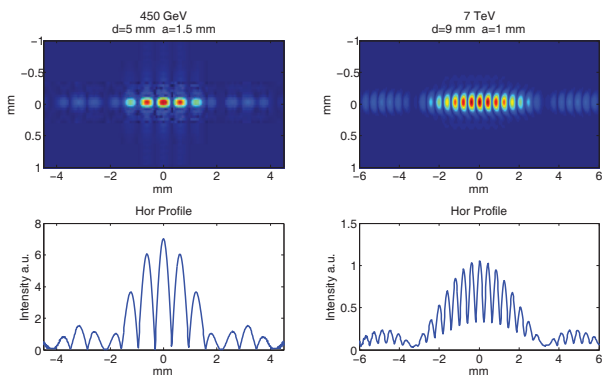

Figure 5: The interference fringes and horizontal LSF as simulated for injection (left) and top (right) LHC energy.

Interferometry   At 7 TeV, the beam size in the LHC ($\sim$180 μm) is comparable to the LSF of the BSRT with SR imaging, even in the UV, diffraction limited. Simulations were carried out to probe whether SR interferometry would allow calculation of the beam size by probing the spatial coherence of the light. This would be a check of the applicability of Van Cittert/Zernike theorem [5] for the LHC beam parameters and the light extraction system layout.

- *LSF*
  The interference pattern of the sampled SR wavefront from a filament beam at the location of the camera was simulated, assuming a two stages optical system preceded by a double slit. As shown in Fig. 5, a substantial difference is observed between the pattern at injection and top energy due to the longitudinal extension of the source (60 cm undulator, 4 m dipole). The reduction of visibility at 7 TeV is due to the *incoherent depth of field* effect [6].

- *Finite distribution Beam*
  For injection energy it was possible to find a numerical model combining the translation operator and reduction factor for different beam sizes corresponding to a normalized emittance from 1 to 5 mm mrad. Reconstruction by extrapolation could therefore be used. At

top energy, only the uniform sampling approach could be used. The SR intensity distribution at the detector in both cases is shown in Fig. 6.
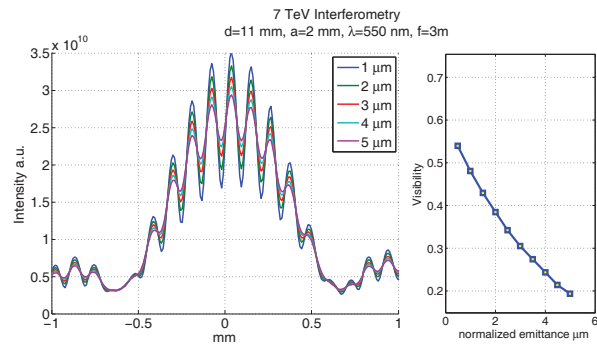

Figure 6: Interference fringe for a range of emittances (left) as well as the predicted visibility as function of the emittance (right).

FUTURE DEVELOPMENT

In order to have a more comprehensive understanding of SR instruments, even when using narrow band filters, it is necessary to simulate polychromatic radiation. The next step will be to include this within MATLAB, automatically combining the results of multiple monochromatic simulations, the transfer function of the bandpass filters and the detector sensitivity.

CONCLUSIONS

A tool was developed to ease the characterization of visible SR based beam size monitors, from the source up to the detector. It can be easily adapted to different optical systems aiding in the design and the optimization phases. The package was used to describe the SR imaging monitors in the SPS and LHC, and was a great help in for designing the SR interferometry to be tested in 2015 in the LHC.

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