X-RAY PINHOLE CAMERA FOR EMITTANCE MEASUREMENT IN SOLARIS STORAGE RING

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Abstract

The measurements of the emittance can be done indirectly by measuring the transverse beam size using the synchrotron radiation produced by it. X-ray pinhole camera is widely used system for the transverse beam profile measurement and emittance feedback. However this method is predominantly applied to the middle and high energy storage rings. At Solaris storage ring with the nominal energy of 1.5 GeV, the design of the beamline was modified to provide sufficient X-ray photon flux for proper imaging. The successful installation and commissioning of the X-ray pinhole beamline allows now to measure the emittance and helps in proper 3rd harmonic cavities tuning against the coupled bunch mode instabilities. The paper describes the design details, simulations and measurement results obtained during the beamline operation.

INTRODUCTION

The first X-ray diagnostic beamline was installed and commissioned in the Solaris storage ring in the mid of 2018. This X-ray diagnostic beamline has been designed to measure the transverse beam profile and to monitor the emittance and their stability during the beam decay.

The Solaris light source consists of 600 MeV linear accelerator, dog-leg transfer line, 1.5 GeV storage ring with 96 m circumference and can store a beam up to 500 mA current. The designed parameters of 1.5 GeV storage ring are presented in Table 1. A detailed description of the machine and the layout can be found in [1–4].

Table 1: The Solaris Storage Ring Main Parameters

Parameter	Value
Energy	1.5 GeV
Max. current	500 mA
Circumference	96 m
Harmonic number	32
Horizontal emittance	6 nm rad
Coupling	1 %
Tunes Q_x, Q_y	11.22, 3.15
Electron beam size (straight section centre) σ_x, σ_y	184 µm, 13 µm
Electron beam size (dipole centre) σ_x, σ_y	44 µm, 30 µm

The Solaris has been operating with the beam in storage ring since May 2015 and currently serves two beamlines

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(PEEM/XAS with two end-stations, and UARPES with one end-station). Three more beamlines: PHELIX, XMCD and LUMOS – second diagnostic beamline have received funding and will be installed and commissioned in next few years.

PINHOLE CAMERA SETUP

There are two diagnostic beamlines at the Solaris, an X-ray PINHOLE and an optical LUMOS beamlines. The first X-ray diagnostic beamline was installed and commissioned in the Solaris storage ring in the mid of 2018. A schematic layout of this beamline is shown in Fig. 1. The second diagnostic beamline will be activated in Solaris at the second half of 2019.

The PINHOLE diagnostic beamline uses the X-ray light form a bending magnet. The bending magnets in the storage ring produce photons in the broad energy range from infrared to hard X-ray. The synchrotron radiation (SR) from the middle of the 7.5° dipole magnet is extracted through a vacuum window. In case of PINHOLE beamline, the SR passes from vacuum to air through a 0.4 mm thick CVD (chemical vapour deposited) diamond window, which acts also as a filter. The bandwidth of the source filtered by the window goes from approximately 3 keV to above 35 keV with a peak photon flux at 7 keV. After exiting the window, the X-rays pass through 57 mm of air to the pinhole cross. The pinhole is placed behind the window, as close as possible to the source. The distance between the X-ray source point and the pinhole is 2.75 m. A rectangular pinhole was made from horizontal and vertical tungsten slit. Whole tungsten block of rectangular pinhole is mounted on four-axis optical table.

After passing through the pinhole cross, X-rays reach the scintillator crystal and are converted to the visible light at the image plane by a thin (0.2 mm) LuAG(Ce) (Lutetium Aluminium Garnet - Lu3Al5O12:Ce) scintillator crystal with a peak emission of 535 nm. LuAG(Ce) phosphor screen is located an additional 3.98 m (of air layer) downstream from the pinhole, so that the image is magnified by a factor of 1.45. The optical light from scintillator is reflected 90 degree with a mirror and imaged by a CCD camera. For alignment purposes, the screen, mirror and CCD camera are mounted together in a x-z translation stage.

PINHOLE SYSTEM DESIGN

The resolution limit of the X-ray pinhole system depends on used photon energy, the distance between X-ray source, pinhole and screen (detector) and beta-value at the source.

The beamline was optimized for operating with smaller than nominal (500 mA) stored beam current, what is cru-

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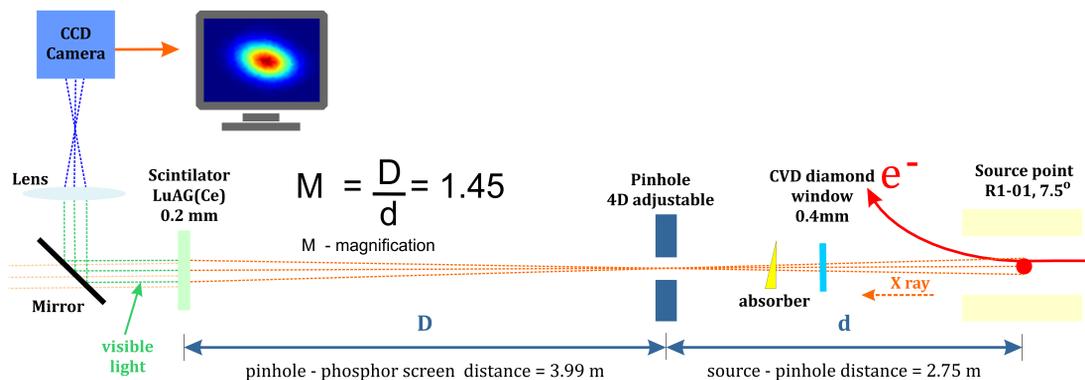
Figure 1: X-ray pinhole beamline schematic.

cial for the decaying beam operation mode in Solaris. The synchrotron radiation spectrum from a bending magnet is filtered in energy and intensity by 0.4 mm CVD window. Before the final selection of the CVD window, many different variants were considered. The spectra of the synchrotron radiation were first simulated for various thicknesses aluminum attenuator which gave a rough idea of choosing the optimized pinhole size. For Solaris storage ring with horizontal emittance of 6 nmrad with the 1% coupling even thin Al allows to obtain desired beam size imaging. Instead of an aluminum exit window a CVD (chemical vapour deposited) diamond with thickness of 400 um was chosen. It improves the simulated photon flux by a factor of 200.
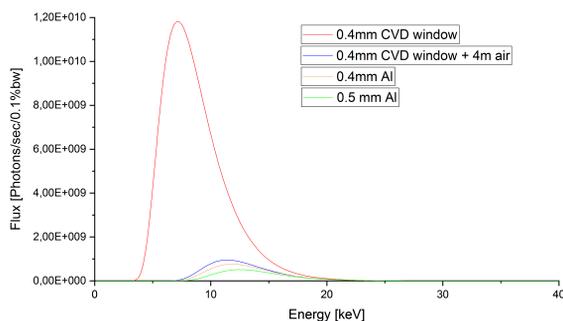
Figure 2: XOP results for bending magnet radiation behind.

For this choice the X-ray flux is high enough to measure the emittance with lower beam currents (even <10 mA with longer camera exposure time). However, during an injection and early ramping stage, in the energy range between 535 – 1200 MeV, the beam is not visible. Figure 2 shows the photon beam spectra after 0.4 mm Al window, 0.4 mm CVD window and 0.4 mm CVD window with 4 m of air calculated by using XOP software package [5].

The source has a spectrum from approximately 3 keV to above 35 keV with peak photon flux at 7 keV. By finding the optimum between the pinhole shadow and the diffraction limit, an optimum aperture size can be found to which correspond a minimum resolvable beam size and emittance.

The optimum aperture can be estimated with an analytical expression at the power spectrum maximum of the source:

$$A_{opt}^2 = \frac{\sqrt{12}}{4\pi} \frac{\lambda dD}{d + D} \tag{1}$$

Where A_{opt} is an optimal pinhole aperture, d — distance from the source to the pinhole slits, D — distance between pinhole and imaging system and λ — X-ray wavelength. It represents the pinhole slits distance close to the diffraction limit. In Solaris case the optimal aperture is A_{opt} = 22 µm.

To convert X-ray to visible light 0.2 mm LuAG(Ce) scintillation screen was chosen. This scintillator provide excellent properties for imaging with lower energies. Calculated spectra for YAG and LuAG scintillator screens are shown in Fig. 3.
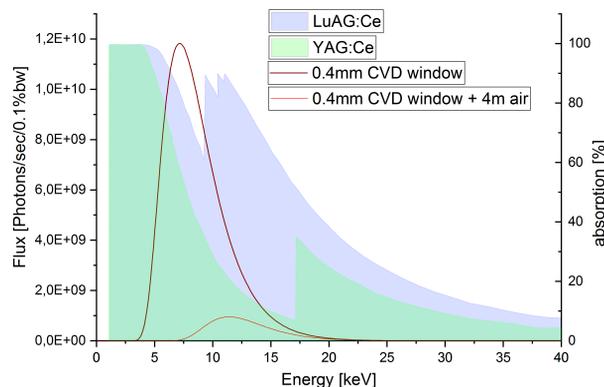
Figure 3: Comparison of X-rays absorption in YAG and LuAG scintillator screens. Spectrum calculated by XOP for bending magnet radiation behind 4 mm CVD window (spectrum before pinhole) and 0.4 mm CVD window with 4m of air (spectrum before scintillator screen).

The optical light from the scintillator is imaged by a CCD camera. The acquired image is processed in a homemade developed software. This software consists of three layers: Taurus based GUI, TANGO Controls devices and PLC

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program. Among the available options, the program fits Gaussian curves to determine the beam sizes and calculates emittance, beam position and other parameters.

To obtain accurate beam size results, the exposure time is adjusted to keep the maximum intensity of the image in the range of 70–90% of the maximum intensity (i.e. pixel values between 170 and 230 for the 8-bit CCD).

The final image is a combination of the photon image, the diffraction on a pinhole, a special effect of X-ray screen and the quantization of the CCD.

EMITTANCE MEASUREMENT

The emittance is an important property of the beam. Measurements of the emittance can be done indirectly by measuring the transverse beam size using the synchrotron radiation produced by it. The horizontal and the vertical emittance are calculated by using the following formula:

$$\sigma_i^2 = \beta_i \epsilon_i + (\eta_i \sigma_i)^2 \tag{2}$$

Where σ_i is the measured beam size in the horizontal or vertical plane, respectively (i = x,y), β_i and η_i are the betatron and dispersion functions at the source point and in the corresponding plane, ϵ_i and σ_i are the emittance and the relative energy spread of the electron beam.

Point Spread Function Calibration

An electron beam imaging by the analysis of emitted X-ray photon beam requires the Point Spread Function (PSF) calibration. Measured total beam size should be reduced by the total PFS contribution (σ_{PFS}^2) which is composed of two distortions: pinhole PFS ($\sigma_{pinhole}^2$) and imaging blur (σ_{image}^2) which can be added in squares as in following equation:

$$\sigma_{PSF}^2 = \sigma_{image}^2 + \sigma_{pinhole}^2 \tag{3}$$

Contribution to the overall PFS from imaging system can be easily derived by measuring the slope of X-ray cutt-off edge on pinhole blade as presented in Figure 4.

Pinhole PFS can be derived analytically by calculating two contributions — photon blur though the pinhole aperture (σ_{blur}^2) and diffraction on the edges (σ_{diff}^2). This components are described by following set of equations:

$$\sigma_{diff}^2 = \frac{\sqrt{12}}{4\pi} \frac{\lambda D}{A} \tag{4}$$

$$\sigma_{blur}^2 = \frac{A}{\sqrt{12}} \frac{D+d}{d} \tag{5}$$

In result of image processing and PSF calibration the beam imaging was obtained during standard machine operation. The transverse profile of the electron beam is presented in Figure 5.
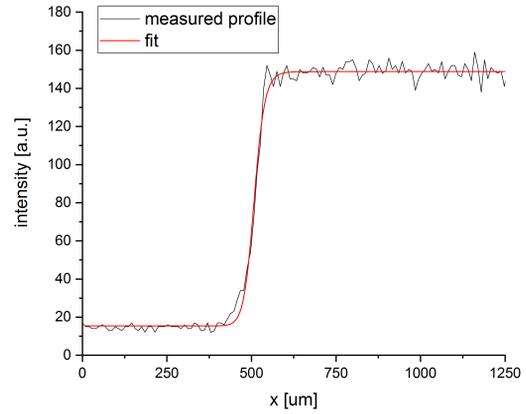
Figure 4: Resolution of the CCD camera with mirror and LuAG:Ce screen.
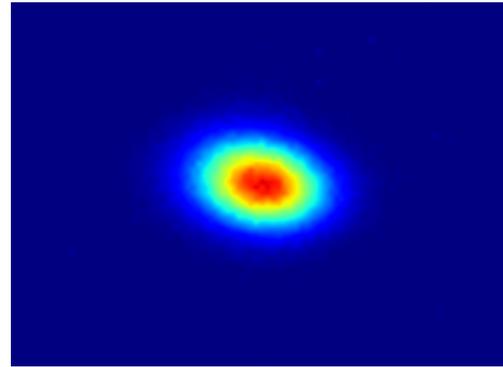
Figure 5: The image of the electron beam at 250 mA, horizontal/vertical emittances are 7.893/0.0626 nm respectively.

SUMMARY

The first diagnostic beamline was installed and activated in the SOLARIS synchrotron storage ring. The successful installation and commissioning of the X-ray PINHOLE beamline allows now to measure the emittance, helps in proper 3rd harmonic cavities tuning against the coupled bunch instabilities and avoiding transverse emittance blow-up on uncoupled higher order modes of RF cavities.

ACKNOWLEDGEMENTS

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