PHOTOINJECTOR EMITTANCE MEASUREMENT AT STAR

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Abstract

STAR is an advanced Thomson source of monochromatic and tunable, ps-long, polarised X-ray beams in the 40-140 keV range. The commissioning has started at the U. of Calabria (Italy). The light source is driven by a high-brightness, low-emittance electron beam produced in a LINAC allowing for the source tunability and spectral density. This note reports on an emittance measurement schema based on the insertion of a slit mask in the vacuum chamber dedicated to the photocathode laser entrance. Results of the simulation of the measurement technique are reported, and the use of the data for the optimisation of the accelerator performance are detailed. The experimental setup and the application developed in EPICS for image recording and analysis are also described.

INTRODUCTION

The STAR Facility

STAR (Southern european Thomson source for Applied Research) [1,2], in commissioning at the Univ. of Calabria (Italy), is a Thomson source of monochromatic tunable, ps-long, polarized X-ray beams, 20-140 Kev ranging. The project is an Univ. of Calabria, CNISM, INFN and Sincrotrone Trieste collaboration. A S-band 1.6 Cell RF gun (100 Hz rep. rate) followed by one S-band 3 meters Traveling Wave (TW) accelerating cavity will produce electron bunches boosted up to 60 MeV. After the gun a solenoid, coupled with the TW cavity, performs the emittance correction [3-5]. Downstream a dogleg brings the beam on a parallel line, removing the background X-ray radiation. The peculiarity of this Linac is the ability to produce high quality electron beams, with low emittance and high stability, allowing to reach spot sizes around 15-20 µm, with a pointing jitter of the order of a few microns. The collision laser is based on a 100 Hz Yb:Yag, 400-500 mJ (5ps FWHM), synchronized to a second Yb:Yag photocathode laser and to the RF system to better than 1 ps time jitter.

Emittance Measurement in Space-Charge Dominated Regions

The technique used to measure the beam emittance, in both the horizontal/vertical planes, is based on a system of horizontal/vertical slit arrays, followed by a screen forming an optical image of the beam projected cross section. The purpose of such a measurement system is to slice up the beam into separated linelike sources, or beamlets. The incoming beam, space charge dominated, is splitted into emittance dominated beamlets. The low current, small rms width beamlets have the same uncorrelated transverse momentum spread as the original beam. The slicing combined with a drift, which reveals the spread in velocities as spatial information at an intensity-sensitive detector, allows a full reconstruction of one of the beam's transverse phase planes. The beamlets width gives a measure of the transverse momentum distribution at each slit, and the centroid of the beamlets gives the correlated offset of the momentum distribution. To be simultaneously space charge-free but easily detectable, the beamlets have charges about a few tens of pC. This method is the most suited to measure beam emittance in the STAR gun nominal conditions, i.e., 500 pC electron bunch at 5.5 MeV, and it is the one described for the first time in [7]. Alternative to the multislit mask, a single slit can be moved across the beam spot as shown in Fig. 1.

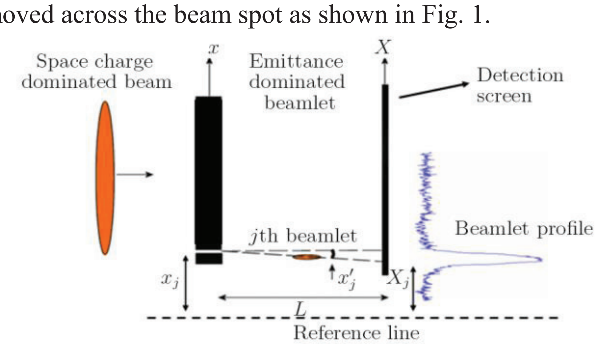

Figure 1: Slit-based emittance measurement scheme. Taken from [6].

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Emittance Formula

The beam is sliced in N_b beamlets by the slits in the measurement plane or it is sampled in N_b beamlets. The center of the j_{th} beamlet at the slit plane is labeled x_j, while X_j, is the j_{th} beamlet centroid as resolved at the detection screen. The correlated beam divergence x'_j is, thus given by Eq. (1) where L is the distance between the emittance measurement plane and the detection screen.

$$x'_j = \frac{X_j - x_j}{L} \quad (1)$$

The normalized rms-emittance is given by Eq. (2), where n_j is the number of particles in the beamlet passing through the j_{th} slit and hitting the detection screen and N is the total number of collected particles. The mean beam divergence x'_j on the j_{th} slit is computed with Eq. (1); σ_j is the rms spread in divergence of the j_{th} beamlet; $\langle x \rangle$ and $\langle x' \rangle$ are the mean position and mean divergence of all the beamlets; γ is the Lorentz boost. The emittance is expressed solely in terms of measurable parameters.

$$\begin{aligned}\varepsilon^2 &= \Upsilon^2(\langle x^2\rangle\langle x'^2\rangle) - \langle xx'\rangle) \\ &= \frac{\Upsilon^2}{N^2}\left\{\left[\sum_{j=1}^{N_b} n_j(x_j - \langle x\rangle)^2\right]\left[\sum_{j=1}^{N_b}[n_j\sigma_j'^2 + n_j(x_j' - \langle x'\rangle)^2\right] - \left[\sum_{j=1}^{N_b} n_j x_j x_j' - \overset{2}{N}\langle x\rangle\langle x'\rangle\right]\right\}\end{aligned} \quad (2)$$

SIMULATION

Detailed simulations have been carried out to assess the performance of the emittance measurement procedure. As tracking code has been used Astra [8]. The chosen charge at cathode is 500pC, Ref. [1] reports all main data. At the cathode a thermal emittance of 1.2 mm mrad (1mm rms laser spot) has been chosen. The particles were tracked from the cathode up to a distance of 2 m. In all simulations half million macro electrons have been used. This number generates sufficiently accurate results for the purpose of this study. Figure 2 shows emittance and envelope as a function of the longitudinal position of the electron bunch using the design field value 0.31T for the gun solenoid. The emittance value is 3 mm mrad at position (z = 0.55 m) of the vacuum chamber dedicated to the photocathode laser entrance where we plan to insert the multi-slit for the emittance measurement. At the position of the detection screen (z = 0.135 m), the bunch is still focusing (by the solenoid). To easily measure the emittance with the slit method, the magnetic field value has been decreased to 0.285T in order to have a constant envelope up to the screen.

The measurement simulation has been carried out in four steps. First, the same distribution as above has been generated, and Astra tracked this particle cloud from z = 0 m to z = 0.55 m, on where the slits is placed. The particle file generated by Astra has been then handled with a Python script that iterated through each electron, removing those whose position did not align with the splits of the a hypothetical multi-slit. The stripped particle distribution has been then fed to Astra again, tracking the electrons from the multi-slit to a fictitious screen 0.8m away from the multi-slit.

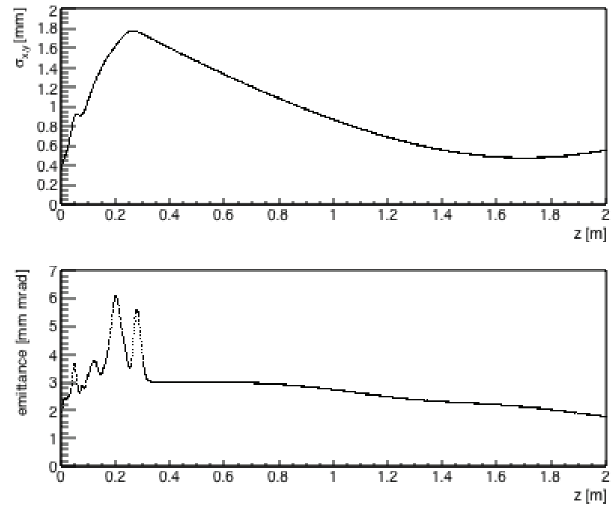

Figure 2: Envelopes and emittance as a function of the longitudinal beam position.

Then they have been imported to ROOT [9] for emittance analysis. A 7x50 µm horizontal multi-slit with 500 µm spacing has been simulated, as well as a second 15x50 µm multi-slit with 600 µm spacing. Figure 3 shows the beamlet image as seen at the detection screen for the latter. The slit width is chosen to be 50µm as a compromise between two main requirements: a negligible emittance degradation by space charge; a sufficient beamlets charge for a good signal/noise ratio on the screen.

Emittance Measurement from Simulated Data

The particle distributions at the screen has been plotted generating one-dimensional plots, consisting of a number of peaks representing the slits on the screen. Figure 4 shows a beamlet profile for a horizontal emittance measurement. The peaks were identified using a ROOT peak finding method. The method identifies a peak by looking for downward zero-crossings in the first derivative that exceeds a certain threshold. A macro then fits a Gaussian curve for each peak and computes residuals. The width, position and area of the Gaussians were then used to evaluate Eq. 2 to finally obtain the emittance value.

The normalized rms-emittance measurement, using 15x50 µm multi-slits 600 µm spaced, gives 2.9 mm mrad, in a good agreement with the expected value. A cross-check simulation with a full 3D space charge routine has been done, which gives 2.8 mm mrad. With 7x50 µm multi-slits 500 µm spaced the emittance measurement gives ~2 mm mrad for both 2D and 3D simulations, as a consequence of the sampling limited to the core of the electron bunch. Vertical emittance measurements give similar values.

Beam Dynamic Optimization by the Emittance Measurement

The measurement here presented is peculiar for its position, which is the closest available respect to the gun exit. Usually emittance measurements are done after its compensation, or in the emittance double minimum region [4]; about 0.8-1.2 m from the cathode. An emittance value acquired at 0.55 m, as in this note, shows two main advantages:

The machine fine-tuning by tracking codes is often underestimate. This kind of Linacs easily show good performances and, also without a fine-tuning driven by simulations, are able to drive different experiments. The machine goodness setting is given by experimental results. In case of challenging applications worldwide under design, as for high performing Thomson/Compton sources, this criterion in no longer valid. The emittance measurement here described became very important to follow the simulation results.

Gun or solenoid's unwanted multipolar fields can break the bunch charge cylindrical distribution in the low energy region with very damaging effects on the beam quality. These effects must be corrected as close as possible to the cathode. The diagnostic described in this note, together with the use of strip quads inside the gun solenoid [10], gives the possibility to compensate the asymmetry, in terms of positions and transversal momentums, with a great benefit for the beam dynamics.

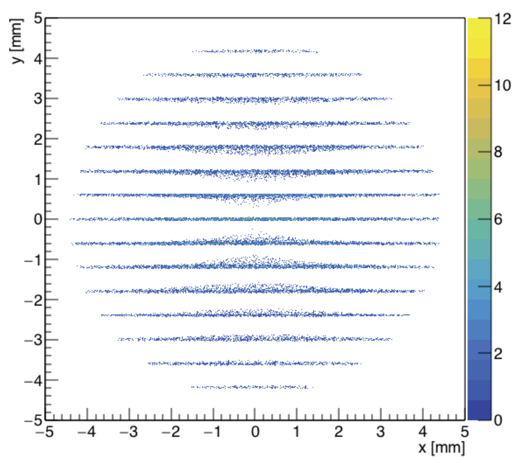

Figure 3: Beamlet image produced by a 15 x 50 µm multi-slit with 600 µm spacing as seen at the detection screen.

EXPERIMENTAL SETUP FOR EMITTANCE MEASUREMENT

Beamlets will be generated by a slit mask installed in the vacuum chamber dedicated to the photocatode laser entrance, intercepting the beam at the gun solenoid exit. The mask, mounted on a vertical actuator, is made out of 2mm thick tungsten plate equipped both with an array of 7 slits (50 µm width spaced of 500 µm) and with two additional separated single slits (50um and 100um) used to transversally scan the beam by collecting images from different positions in multi-shot measurements mode. Design criteria of the mask is described in [11]. Beamlets emerging from the slit-mask are intercepted by means of a downstream Ce:YAG radiator installed at a 0.8m distance from the slit.

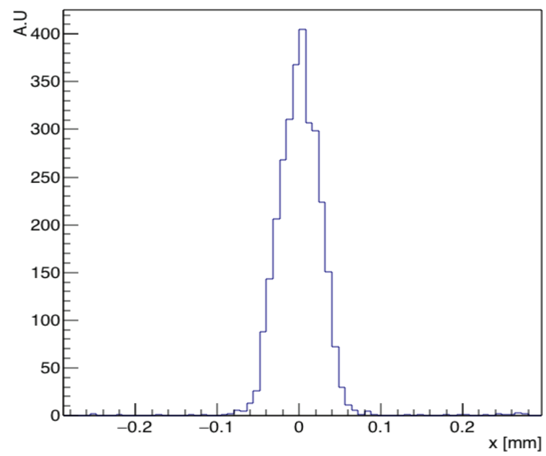

Figure 4: Typical beamlet profile at the detection screen.

Digital CCD cameras (Basler SCA640) equipped with a 105 mm macro lens will be used. The magnification obtained with a field of view of the screen around 9 x 7 mm gives a calibration of ~15 µm/pixel. The estimated resolution in the beam divergency due to finite slit width is ~180 µrad.

AUTOMATED ONLINE PROCEDURE

The STAR control system [1] is based on the EPICS infrastructure. Concerning the emittance measurement, the elaboration is implemented inside the EPICS contex, in order to monitor the emittance parameter as the other machine variables. The procedure consists of four main steps: acquiring images on the screen by a camera, image elaboration, emittance calculation and result presentation. To implement the first step is used a modified EPICS device support which allows to acquire one or more snapshots, the second and third steps are implemented using the IOC-OCTAVE server [12] which enriches the control system with OCTAVE mathematical capabilities. OCTAVE contains well tested algorithms which are used by a large community of scientists for mathematical elaboration purpose. The last step is the emittance variable saving as EPICS PV (Process Variable) and its graphical presentation to the user. As possible future ideas to implement, in order to reduce the elaboration time, will be the use of fast embedded platform, such as FPGA or GPU to spread the computational effort on more customly designed calculation units [13-14], saving the process time.

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