TRANSVERSE AND LONGITUDINAL EMITTANCE MEASUREMENTS IN THE ELSA LINAC

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Abstract

The ELSA rf linac has been designed to deliver high-brightness electron beams. The present paper deals with the transverse and longitudinal emittance measurements, at different positions along the ELSA beam line, and the analysis of their variations as a function of the photo-injector parameters : rf field on cathode, drive laser spot size, magnetic field generated by the anode focusing lens, bunch charge and duration. Simulation codes have been used in order to reduce the parameter ranges and to minimize the number of measurements. Experimental results are presented and compared to simulation code expectations. For 2.0 nC, 100 A electron bunches, a normalized emittance of about 12 $\pi.mm.mrad$ at the linac exit has been measured.

1 INTRODUCTION

To reach a high-efficiency regime in converting the electron-beam energy into photon energy in the wiggler of a free-electron laser (FEL), constraining requirements are imposed on the main parameters of the electron beam. It must be a high-brigtness beam with high-density bunches. This implies a large peak current with a low transverse emittance.

To fullfil these operating conditions, a research and development program has been undertaken at Bruyères-le-Châtel since 1987; this FEL program, called ELSA, has been described previously[1]. It involves the use of a low-frequency laser driven photo-injector running at 144 MHz[2], and a 433 MHz radio-frequency accelerator[1,2].

In order to insure proper operation of the machine, numerous electron diagnostics have been installed: these are Faraday cups and current transformers for beam current monitoring, beam position monitors, profile monitors for beam size, magnetic spectrometers for measuring energy spread, and a streak camera associated with transition radiation screens for bunch length measurement.

Investigation of the beam transverse emittance behaviour with beam charge, drive laser spot size and anode coil current is presented, as well as recent longitudinal emittance results.

2 EMITTANCE MEASUREMENT TECHNIQUES

At a given location of the transport line, the beam transverse and longitudinal phase space can be described in terms of an ellipse with symmetric-matrix representation :

$$\Sigma = \begin{pmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{pmatrix} \qquad (1)$$

and the normalized emittance is related to the beam matrix by the formula : $\epsilon_n = 4\beta\gamma\pi\sqrt{det.\Sigma}$

In the electron transport from point 0 to point 1, the beam ellipse transforms according to the relation :

$$\Sigma(1) = R.\Sigma(0).R^t \qquad (2)$$

where R is the transport matrix in the linear approximation from point 0 to point 1. If we assume that $det.R = 1$ then $det.\Sigma(1) = det.\Sigma(0)$, that is, beam emittance is conserved throughout the transport. These equations are used in three different ways, on ELSA, to determine the beam emittance.

2.1 *The three-gradient technique*

The three-gradient, or quad-scan, technique is used to mesure beam transverse emittance on the ELSA accelerator[3]. It consists in associating a profile monitor to a quadrupole lens located upstream. A set of three profile measurements, corresponding to three different values of the current in the lens, is sufficient to determine the three coefficients of the beam matrix, and therefore the beam emittance. A larger number of profile measurements would provide a more precise determination of these quantities.

2.2 *The three-distance technique*

Transverse emittance is also measured by means of the three-screen, or distance, technique, which requires profile measurement on at least three screens located in a drift region. An alternative technique consists in using only two screens, provided that the beam has a waist in one of them. This technique provides a rapid estimate of the beam emittance and is very useful during beam-tuning procedure.

2.3 *The three-RF phase technique*

Longitudinal emittance measurements are performed by measuring the beam pulse length with a streak camera and the energy spread in the middle of the 180 degrees bend, as a function of the rf phase[3]. Compression of the pulse length is performed by the bend which is non-isochronous [4].

3 EXPERIMENTAL PROCEDURE

Diagnostics based on imaging techniques are very powerful since they give access to electron beam properties such as spatial profile and emittance. These quantities use the light emitted by conversion screens, moved in the electron-beam path by actuators. The optical image of the beam is transmitted in real time to a TV camera through an optical transport line.

3.1 Conversion screens

Optical transition radiation (OTR) converters are widely used on the ELSA facility[5]. The OTR screens are of different nature, shape and size depending on their location along the machine.
Converters made of 8 μm thick Kapton films, on which aluminium is evaporated (0.3 μm in thickness) are mainly used. They constitute excellent OTR screens with a perfectly reflecting surface, good mechanical properties and weak x-ray production. However,an attempt was made to reduce the film thickness to less than 1 μm in order to ensure a good behaviour for high power beams.
Metallic screens are also used ; Al,Mo,Ni of $\sim$ 10 μm and massive stainless-steel cylindrical rods.

3.2 Data acquisition and processing

The screens are viewed by CCD (or SIT) cameras whose video signal is digitized through an image processing device composed of a Sofretec PITER 500 frame grabber, a 486 DX PC computer and a TV monitor. Each image is digitized with 256 possible gray levels and stored in a 512 x 512 bytes memory. Images can be stored, also, on a Bernouilli box, with 90 Mb removable disk.
A dedicated computer code ENLIGNE, in C language, has been developed to serve two purposes :
- fast on-line processing of data for operation and control of beam transport.
- off-line precise and detailed image processing for emittance determination.
Attempt is made to have an on-line emittance-calculation procedure.

4 STATISTICAL AND SYSTEMATICAL ERRORS

4.1 Beam fluctuations

There are three sources of stastistical errors; photon number fluctations in a single pixel of the camera, signal digitization, and beam fluctuations. At the moment, the main contribution comes from the last one. They are propagated using the standard variance-covariance algebraic matrices.

4.2 Optical resolution

The main source of systematic errors comes from the limiting resolution of the optical system either in the transverse plane for CCD camera or in time for the streak camera. Using, for instance, a 50 μm wire across the screen, we are able to estimate this limiting resolution in the transverse plane and subtract it from each measurement. The goal is to be far enough from this limitation during the measurements.
Two other sources of errors could occur; the limiting optical acceptance angle associated with OTR emitted radiation and imperfect modeling of the transport. The first one was investigated using the RTO code which simulates the photon emission in 3D-space; the second one was investigated by adding higher order effects using the code COSY.

5 MEASUREMENTS AND RESULTS

5.1 Transverse emittances

Beam transverse emittance was measured at the end of the linac by means of the three-gradient technique. The beam is focused in both vertical and horizontal directions by using a triplet and scanned with the last one (figure 1). Data are taken for 7 to 10 different values of the quadrupole current. The deduced second-order moments of the spatial distributions and their standard deviations are combined to corresponding quadrupole currents in a least-squares fitting routine, to yield transverse emittance in the two directions.

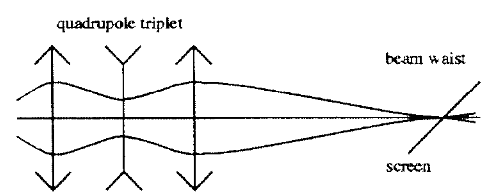

Figure 1: Quad-scan technique.

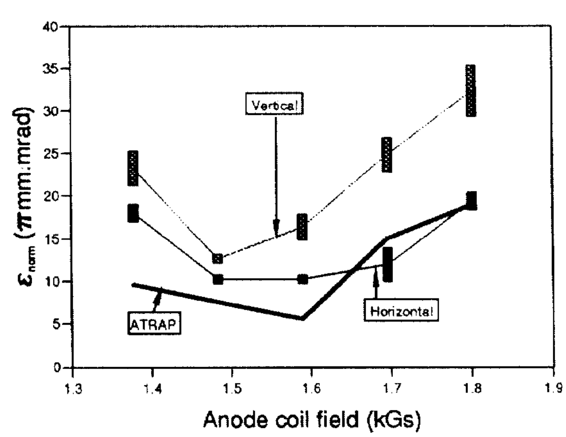

Figure 2: Transverse emittance for 0.2 nC; I = 10 A.

Because of radial and longitudinal space-charge effects, transverse emittance is strongly dependent on the field of the anode coil located in the photo-injector. It has been investigated for three different bunch charges: 0.2, 1.0 and 2.0 nC. The normalized transverse (vertical and horizontal) emittances are presented in figures 2,3 and 4. All the

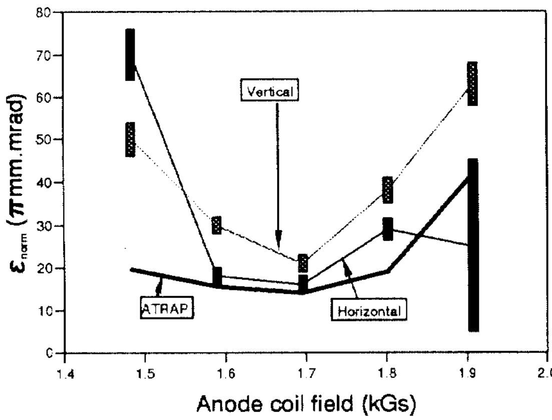

Figure 3: Transverse emittance for 1.0 nC; I = 50 A.

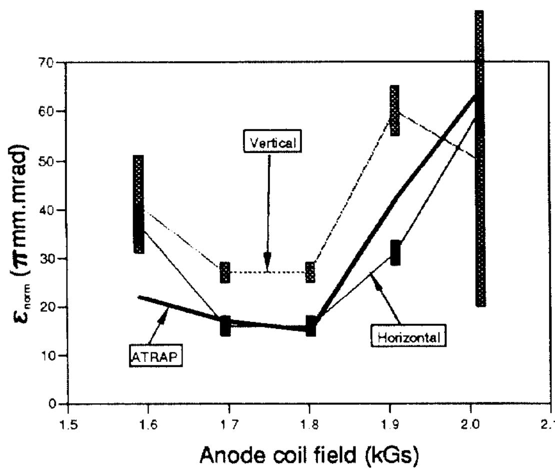

Figure 4: Transverse emittance for 2.0 nC; I = 100 A.

measurements were made at a kinetic energy of 16.5 MeV. At the exit of the photo-injector,the energy was $\sim$ 1.8 MeV with a -30 degrees phase shift. The drive laser pulse duration was $\sim$ 20 ps and the spot diameter on the photocathode was 4 mm.

The difference of emittance value between horizontal and vertical planes is probably due to alignment imperfections of the anode coil at the exit of the photo-injector, which is known to be tilted and down compared to the RF cavity axis. Simulations made with the ATRAP[6] code are in agreement with the data except at low anode-coil field. Actually, the drive laser beam is illuminating the cathode at an angle of about 65 degrees relative to the injector axis inducing a delay as large as 10 ps for two opposite points of the 4 mm in diameter spot size. For 20 ps laser pulses, this effect is quite important and results in pulse elongation. Moreover, the electron beam is no longer axisymmetric and split in two parts for low anode-coil field. This pathologic effect could explain large values of the measured transverse emittances compared to simulation results as given by the ATRAP code. In the near future, a more conventional drive laser incidence angle close to 5 degrees will be used instead.

5.2 *Longitudinal emittance*

In pulse length compression experiments, the non isochronous transport of the 180 degrees bend is used along with the appropriate phase of the 433 MHz cavities to bunch the beam. The experiment is performed by measuring the beam pulse length with a streak camera using emission from an optical transition radiation view screen . The energy spread of the beam is also measured at another view screen positioned in the middle of the bend. The time

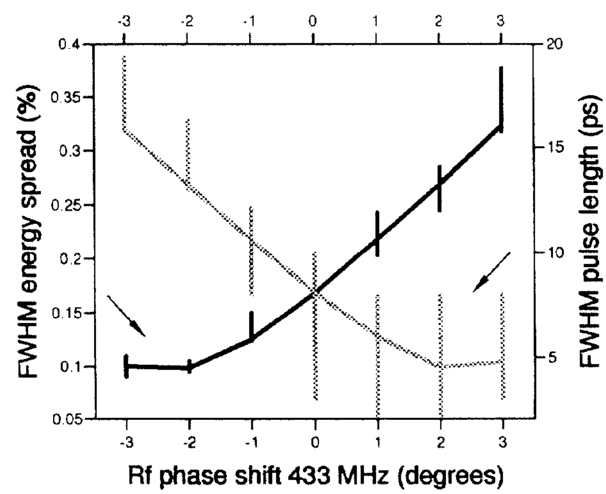

Figure 5: Energy spread and pulse length for Q=0.6 nC.

resolution of the acquisition system is about 9 ps, limiting the accuracy of the pulse length measurements. A first-order model (using the TRANSPORT code) was used to fit to the energy spread data, providing the longitudinal phase space (Δt,$\Delta E/E$) and was compared to the pulse length measurements[4] shown in figure 5.

6 REFERENCES

[1] R. Dei-Cas et al., Proc. 10th Int. Free-Electron Laser Conf., Jerusalem 1988, Nucl. Instr. and Meth. A285 (1989) 320.

[2] P. Balleyguier et al., Proc. 12th Int. Free-Electron Laser Conf., Paris, France 1990, Nucl. Instr. and Meth. A304 (1991) 308.

[3] P. Balleyguier et al., "Non-Linear RF Feedback in ELSA Accelerator", Proc. 4th Int. EPAC Conf., London, England 1994.

[4] S. Joly and D. Dowell et al., Nucl. Instr. and Meth. A341 (1994) 386.

[5] G. Haouat et al., DIPAC 93 - Montreux, Switzerland, 1993.

[6] J.L. Coacolo and J.M. Dolique. code ATRAP, unpublished.