ELECTRON BEAM DIAGNOSTICS ON THE ELSA FREE ELECTRON LASER

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Abstract

Several diagnostics have been installed on the electron linear accelerator of the ELSA free-electron-laser. They include beam current transformers, Faraday cups, beam position monitors, profilers, magnetic spectrometers for mean-energy and energy-spread determination, and a streak camera associated with Cerenkov or transition-radiation screens for time profile measurement of the electron bunches. These diagnostics are of primary importance for controlling the beam transport throughout the machine down to the undulator, and for optimizing the coupling between the electron and laser beams.

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-brightness beam with high-density bunches. This implies large peak current and low transverse emittance as well as small energy spread and pulse duration.

To fulfill these operating conditions a research and development program has been undertaken at Bruyères-le-Châtel since 1987; this FEL program, called ELSA, is described in refs.[1,2]. It involves the use of a low-frequency laser-driven photo-injector running at 144 MHz [3-6], a 433 MHz radio-frequency linear accelerator [1,5,7] and a tunable, hybrid, tapered wiggler placed in an optical cavity [1,8].

In order to ensure proper operation of the machine, numerous electron diagnostic equipments have been installed. There are Faraday cups and current transformers for beam current monitoring, beam position monitors, profilers for position, profile and transverse emittance determination, magnetic spectrometers for measuring mean energy and enrgy spread of electron bunches, and a streak camera associated with Cerenkov or transition-radiation screens for bunch length measurement.

These diagnostic equipments are presented here and recent measurement results are reported.

Beam current measurements

Current monitors and associated electronics were designed to optimise their responses towards the temporal structure of the electron beam. The ELSA machine delivers macro-pulses, of 50 to 200µs duration, with a repetition rate of 0.5 to 10Hz. The macro-pulses consist of micro-pulses of 30 to 150ps full width at half maximum and 0.1 to 10nC charge, the time separation between the electron bunches being 69.2ns (14.44MHz).

Faraday cups are set up at the extremity of the acceleration line and close to the focal plane of the beam-dump bending magnet placed behind the wiggler. They were designed with special care to suppress electron losses from secondary emission. The output of the Faraday cups is charged with a precise 50Ω resistor and the voltage signal is integrated with a time constant of 10µs so that one observes an envelope corresponding to the macro-pulse current (Fig.1).

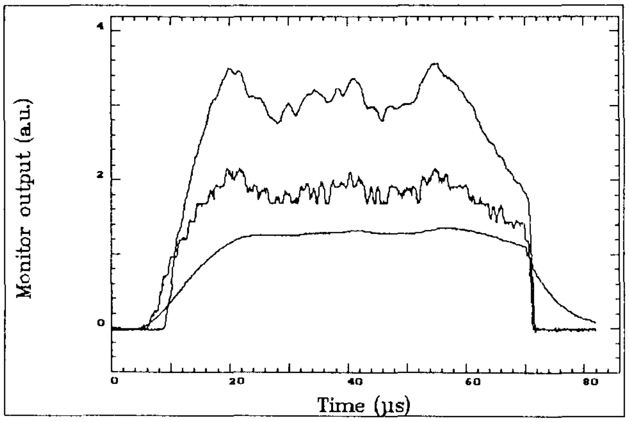

Figure 1 : Current signal, during the macro-pulse, for: Stripline BPM (top), Beam current transformer (middle) and Faraday cup (bottom). The time structure observed on the signals is generated by the drive laser.

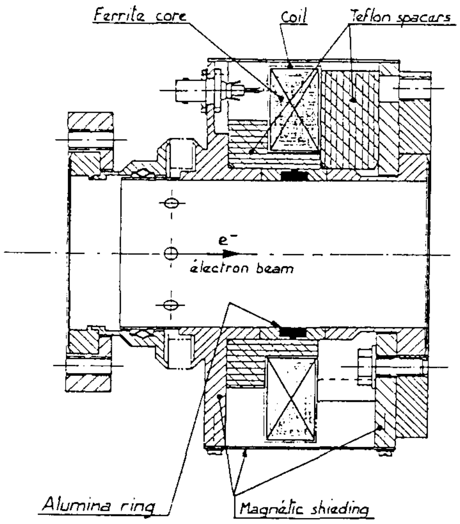

Figure 2 : Longitudinal section of a beam current transformer.

Current transformers have been developed to complement Faraday cups. These non-destructive monitors yield continuous information on the beam current. They consist of a coil, of 36 turns wound on a ferrite toroïdal core, installed on the beam pipe as shown in Fig.2. The coil is terminated with a 10Ω resistor and connected to an electronic unit which amplifies and integrates the signal to give the macro-pulse current (Fig.1) and the charge of the electron bunches. The machine is equiped with four current transformers placed in front and back of, respectively, the 180° deflecting magnet system (U-turn) and the wiggler [3].

Beam position monitors

Beam position monitors (BPM) consisting of four 10 cm-long stripline electrodes, for part of them, and of four 14 mm-diameter button electrodes, for the others, have been developed. Since they are non-interceptive, BPMs are very useful for the permanent control of the beam in the machine and the adjustment of the magnet, quadrupole and steerer currents for centering the beam along the acceleration and transport system. Four stripline monitors, depicted schematically in Fig.3, are located at places where enough space is available on the machine, whereas five circular button detectors are situated on the acceleration line, where drift spaces are reduced because of space-charge effects on the electron bunches, and two rectangular button detectors are installed between the three bending magnets of the achromatic U-turn loop [3].

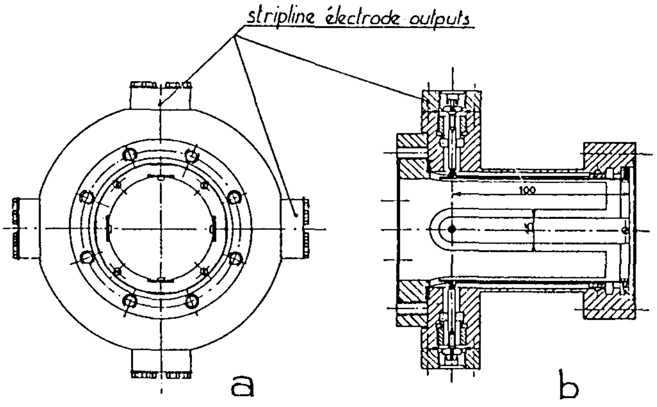

Figure 3 : Transverse (a) and longitudinal (b) sections of a stripline beam position monitor (BPM).

A computer code, based on the resolution of Poisson's equation, has been developed; it simulates the response of the four electrodes for given geometries corresponding to the stripline and button monitors, and for given positions of the electron beam relatively to the monitor symmetry axis. The calculated data are then used to deduce a polynomial expression relating the beam position to the four electrode indications. The results of this simulation code compare fairly well with measurements obtained from a calibration experiment in which the electron beam was replaced by a rigid linear wire whose position was well determined and through which a pulsed current circulated.

Monitors have been machined with high precision and associated high speed electronics, described elsewhere [9], has been carefully tuned so that the position of the beam, close to the center of the BPMs, is determined with an accuracy better than ±0.1mm. In addition to beam-position information along the machine, BPMs yield indication on the electron beam current (Fig.1).

The signal processing electronics connected to the current sensing monitors (Faraday cups, current transformers and BPMs) has been designed to offer two main features: i) Fast and easy observation of the beam behaviour by direct visualisation on an oscilloscope (Fig.1); ii) Analysis on a TV screen of beam position and intensity fluctuations along the machine by data acquisition and processing on a micro-computer [10].

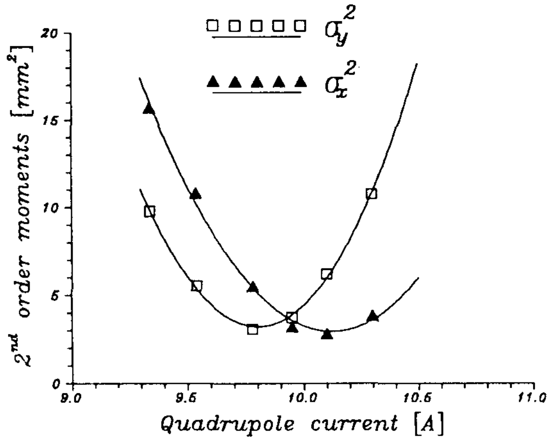

Figure 4 : Transverse emittance measured through the three-gradient technique. Beam energy is 4.2 MeV; current is 0.2nC per micro-pulse. Estimated emittance: 100 π mm.mrad.

Beam profile

Transverse profile of the electron beam is measured in two ways: i) with scintillating screens consisting of 1mm-thick disks of alumina doped with 0.5% chromium (Al_2O_3:Cr) which stand ultra-high vacuum; since they are very sensitive these scintillators are used to observe low-intensity beams; ii) with optical transition radiation (OTR) screens which are either 1mm-thick disks of highly polished stainless steel, or foils of aluminium or nickel stretched between two rings; OTR screens in the form of bevel-edged stainless-steel cylinders are installed in the wiggler vacuum chamber. These detectors are used for high-intensity beam observation, above 0.5nC per electron bunch.

The screens, mounted on actuators, are viewed by CCD video cameras the signal of which is sent to a data acquisition and processing computer. A TV screen displays, also, the beam profile during experiments; this allows positionning and focusing adjustments in the beam acceleration and transport lines. The accumulated data are processed off-line to yield characteristic parameters such as beam transverse dimensions, inhomogeneities and moments of the spatial distribution.

Transverse emittance

Transverse emittance is a most important quantity for the performance of a FEL. It is currently determined on ELSA by means of the three-gradient method which consists in measuring the beam profile on the same screen for, at least, three different values of the current (or magnetic field) in a magnetic lens or quadrupole placed upstream. A greater number of measurements would yield an emittance value with better accuracy. In this method it is assumed that beam emittance is conserved in the transport from the magnetic lens to the screen. The measured data are processed to get the second-order moments of the spatial distribution, from which the Twiss parameters of the emittance ellipse are deduced. Results obtained at low energy, around 4MeV, are presented in Fig. 4.

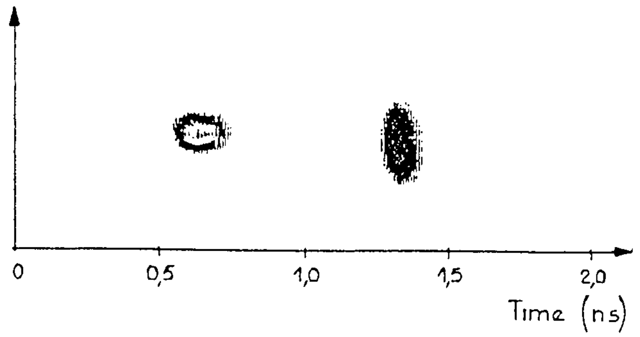

Figure 5 : Streak-camera image showing the time spread of the drive-laser (left) and the electron-beam (right) micro-pulses. Estimated FWHM of electron bunches is 130 ps.

Transverse emittance was measured on the photoelectric injector injector through the "pepper-pot" technique. The experimental set-up is described in ref.[5], and results for a 1.8 MeV, 8 nC electron beam are presented in ref.[11]. This technique yields direct measurement of beam emittance; however, it cannot be used at high energies because of the large stopping range of electrons in the pepper-pot disk.

Longitudinal emittance

Longitudinal emittance is determined from the measurement of the electron-bunch energy dispersion and time spread.

Energy dispersion and mean energy are measured at two locations on the machine: in the middle of the analysing magnet of the U-turn and in the focal plane of the beam-dump bending magnet. The energy profile is obtained from the light emission of Al_2O_3:Cr scintillators and OTR screens moved in the beam path and viewed by CCD video cameras. Recorded data are processed to yield moments of the distributions. These data are combined with the spectrometer parameters (magnetic rigidity and energy resolution power) to give mean energy and energy dispersion of the electron bunches.

Time spread of the electron bunches is obtained through the light emitted by a Cerenkov or OTR screen inserted in the beam and analysed by a streak camera. Earlier measurements, at low energies (around 1.5MeV) and low currents, were made with a pure fused-silica plate which generated Cerenkov radiation. OTR foils or thick disks are now in use because they are much simpler to handle and they deliver enough light at energies around 17MeV. A beam splitter is inserted in the drive-laser path allowing the temporal profile of both laser and associated electron pulses to be simultaneously analysed by the streak camera (Fig. 5).

Conclusion

Electron beam diagnostics have been designed to meet two requirements: i)control and operation of the beam acceleration from photo-injector to accelerating cavities, and its transport in the U-turn down to the wiggler; ii)determination of the beam characteristic parameters, that is, its brightness, obtained from intensity and transverse emittance measurements, and its longitudinal emittance, resulting from energy-dispersion and time-spread measurements. These diagnostics are routinely and satisfactorily running.

Further developments are planned to measure energy dispersion and transverse emittance in a single macro-pulse by using OTR properties.

Aknowledgement

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