# PRESENT PERFORMANCE OF THE LOW-EMITTANCE, HIGH-BUNCH CHARGE ELSA PHOTO-INJECTED LINAC

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*Abstract*

ELSA is a 19 MeV rf linac in operation since 1992 at Bruyères-Le-Châtel. Its rf photoinjector operates at the very low frequency of 144 MHz, and the linac on the 3rd harmonic, at 433 MHz. Owing to these low frequencies, bunches of 15 nC are accelerated with a low energy dispersion (0.1% rms). Recent measurements of the beam phase space showed that, at low current (1 nC, 60 ps), the transverse normalized rms emittance is about 1 µm, close to the theoretical floor for rf guns.

## 1 INTRODUCTION

The ELSA facility was designed in the late 80's, as a test bench for physics and technology of high-efficiency FELs [1]. Despite stability issues mainly due to the laser system, we were able to demonstrate the main characteristics of the high-efficiency, low-spectral brightness *post-sideband* regime predicted by our group [2,3].

Reliable FEL operation put constraining requirements on the parameters of the electron beam and led us to extensive measurements of the beam (transverse and longitudinal) phase space [4,5]. Most of these measurements were done with a 20-30 ps laser pulse width and a maximum bunch charge of 5 nC. Due to a poor vacuum in the old photoinjector (a few $10^{-9}$ mbar), the photocathode half-life was very short (1-2 h) and FEL operation was mostly done at 1-2 nC.

ELSA is now mainly used as a high-brightness 1-20 MeV electron source or as a picosecond hard X-ray source (by bremsstrahlung on a thick Ta or W target). The new injector solved the photocathode lifetime problems and modifications are underway to reduce the drive laser pulse-to-pulse fluctuations.

The ongoing ELSA-2 upgrade, and especially the Thomson source project [6] made necessary the extension of the previously reported beam measurements, to high bunch charges (up to 15 nC) and long pulses (60 ps). The ability to accelerate such bunches, while maintaining a low emittance, is a direct benefit of the very low frequency of the rf linac.

## 2 OVERVIEW OF THE ELSA FACILITY

The ELSA facility (cf. fig. 1) has already been described in several papers [1,3].

The accelerator consists of a 144 MHz photoinjector followed by three 433 MHz accelerator sections. The rf sources and main power supply limit the duty cycle to a 150 µs macropulse at a repetition rate of 10 Hz. For low currents (10 mA), the maximum beam energy is 2.7 MeV at the injector exit and 19 MeV at the linac exit.

The main beamline component is a three-dipole, doubly achromatic, non-isochronous ($R_{56}$=5 ns), 180° bend. In the FEL experiments, this *demi-tour* is used to compress the bunches while injecting them on the FEL resonator axis.

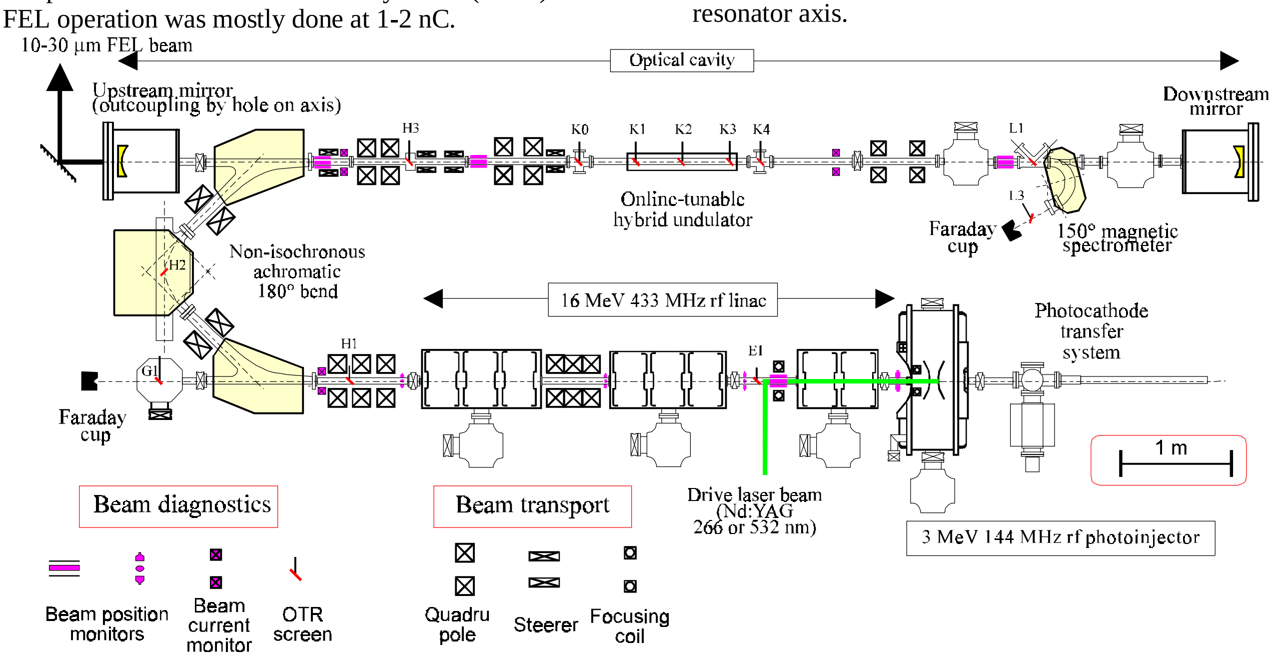


Fig. 1 : overview of the ELSA beamlines

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The Nd:YAG drive laser is able to deliver a pulse train tailored for each application, from a single pulse to a 150 µs, 144 MHz train. In the standard FEL mode, the train frequency is 14.4 MHz. After second harmonic generation at 532 nm in a KTP crystal, the typical energy is 1-10 µJ/pulse. The pulse duration can be tuned from 10 to 120 ps.
Two types of photocathodes are prepared in a separate lab and transferred by fours on the injector : $Cs_3Sb$ (or $K_2CsSb$) and $Cs_2Te$. For the second type, a BBO crystal is used to produce a 266 nm laser beam.
The very good vacuum in the photoinjector ($1\text{-}2.10^{-10}$ without rf) allows the XSb cathodes to remain usable for several days. Their initial mean quantum efficiency (Q.E.) is 1-2%. The more robust $Cs_2Te$ cathodes are mainly used in case of poor vacuum or for high-reliability experiments, but the available charge is lower, because of the low conversion efficiency in the UV.
The FEL oscillator is described in [3] and references therein. Proved operation is in the 10-40 µm range.

## 3 LONGITUDINAL PHASE SPACE

### *3.1 Experimental procedure*

The details of the experimental setup have already been described [4,5]. The temporal pulse shape of the electron bunches and drive laser pulses are simultaneously acquired with a synchroscan streak camera (ultimate resolution = 2 ps) before and after the 180° bend (H1 and K0 screens, cf. fig. 1). The light radiator is a thin aluminized kapton foil, used as an Optical Transition Radiation (OTR) converter. In order to improve the effective resolution of the streak camera, the red part of the OTR light spectrum is selected with an optical filter. The bunch charge is monitored along the beamline by several current monitors and on the beam dump (Faraday cup).

### *3.2 Measurements and discussion*

The measurements presented in this paper highlight the bunch charge limit of the photoinjector. The laser pulse duration was tuned to 60 ps, in order to use thel potential of the accelerator low frequency, while keeping a low energy spread : 60 ps are equivalent to 9.4° of phase at 433 MHz, i.e. 0.1% rms energy spread if the bunch is injected in phase with the rf.
Experimental results of pulse lengthening as a function of the bunch charge are plotted on fig. 2, along with ATRAP simulations [7]. ATRAP is a code specifically designed to handle the dynamics of electron beams in high-gradient photoinjectors. It includes a sophisticated treatment of the space charge forces (both internal and with the wall), using the retarded Lienard-Wiechert potentials. The agreement between data and simulation is fairly good. The observed lengthening of the pulse above 150 A (1200 A/cm$^2$) is related to the saturation of the emitted current, when the self-fields cancel the accelerating field.
This saturation behavior is more obvious on fig. 3, where the extracted bunch charge is plotted versus the laser energy. The linear part at low laser flux gives the Q.E. of the photocathode. At high flux, the extracted charge is close to the calculated ATRAP limit.

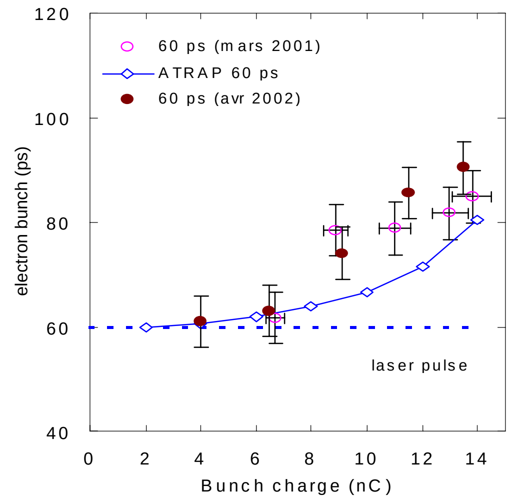


Fig. 2 : Length of the electron bunch at the linac exit, as a function of the bunch charge (laser spot diameter on photocathode = 4 mm).

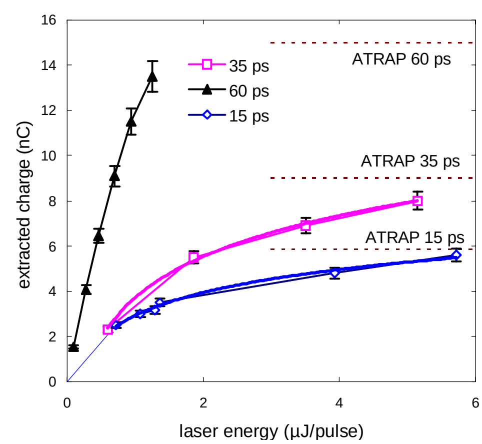


Fig. 3 : Bunch charge measured at the linac exit as a function of the drive laser pulse energy. The slope at the origin corresponds to the cathode quantum efficiency : 1.0 % for the 15 and 35 ps data and 3% for the 60 ps data.

An intriguing fact is that the virtual cathode instability, observed a few years ago on ELSA [5] and also (but less clearly) on the Orsay CANDELA photoinjector [8], was not reproduced this time. At the maximum value of 1800 A/cm$^2$ (14 nC in 80 ps, cf. fig. 2), the electron pulse remains roughly gaussian. This is to be compared with the behavior observed in 1995 with 23 ps laser pulses : above a value of about 1000 A/cm$^2$, the bunch splitted first in two, then in three sub-bunches separated by 50-100 ps.

## 4 TRANSVERSE PHASE SPACE

### *4.1 Experimental setup*

The transverse emittance at the linac exit is measured by means of the quadrupole scanning technique. Though widely used, this method still remains difficult to master. As an example, the Los Alamos group pointed out that insufficient dynamics in the video acquisition can lead to an underestimation of the emittance, whereas a recent paper [12], comparing quad scan and slit methods reports that the former seems to overestimate the emittance.

In order to get consistent values, we take several precautions :

- the beam transverse profile is measured by OTR screens (already described in section 3)
- the acquisition is done with an intensified CCD camera, whose gain is adjusted to use the full dynamics of the frame grabber
- background is subtracted on the images
- each point of the scan is averaged over 10 shots
- 6 to 8 points are taken for each scan (3 only are required for the parabolic fit).

We also take into account in the data analysis, the effect of linear space charge in the drift between the quadrupole and the screen. This type of correction was recently applied to emittance measurements of the Thomson source project photoinjector at LLNL [9]. Data treatment is no longer analytic. It is implemented by coupling a TRACE3D core with a CERN library minimization routine (MINUIT). We found that the computed correction is almost linear with respect to the beam current. The deduced slope is :

$$\Delta\varepsilon_{n,rms} = 8\,\mu\text{m/kA}$$

### 4.2 Measurements and results

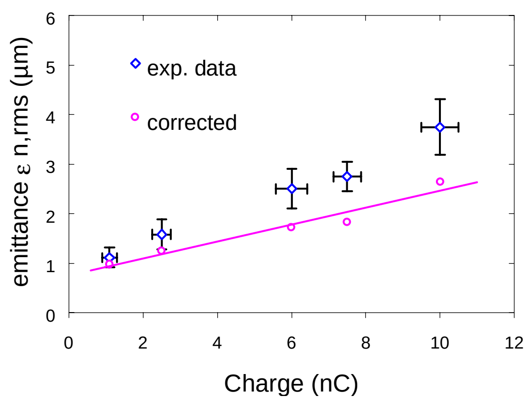


Fig. 4 : Transverse normalized emittance at the linac exit, vs. bunch charge, with and without the space charge correction. The drive laser pulse width is about 60 ps.

Measurements were taken between 1 and 10 nC (cf. fig. 4). For each value, the current in the anode coil is tuned to minimize emittance (cancellation of the linear term of emittance growth).

Compared to the previously reported results [4], the bunch charge range is extended from 3 to 10 nC, while keeping similar or better emittance.

The 1 µm limit at low charge is very close to the thermal emittance, which is estimated to 0.5-1 µm for a 2 mm radius cathode [10,11]. The contribution to the emittance, due to the fringe magnetic field of the anode coil (1 mT), is almost negligible (about 0.1 µm).

In conclusion, compared to other photoinjectors in operation throughout the world [10], the ELSA photoinjector, with its unique very low rf frequency, achieves one of the lowest observed emittances.

## ACKNOWLEDGMENTS

The authors wish to thank the ELSA team for their helpful assistance, and especially A. Bloquet, V. Le Flanchec and M. Millerioux.

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