ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS007

SHORT BUNCH EXPERIMENT AT EXALT FACILITY

C. Bruni*, J-N Cayla, S. Chance, V. Chaumat, N. Delerue, N. ElKamchi, P. Lepercq, H. Purwar,
LAL,CNRS/IN2P3, Universite Paris-Saclay, Orsay, France
E. Baynard, M. Pittman, CLUPS, Orsay, France
B. Lucas, O. Neveu, CNRS LPGP Univ Paris Sud, Orsay, France
T. Vinatier, DESY, Hamburg, Germany

Abstract

Nowadays, different applications required short bunches, with low energy spread and low emittances. On EXALT facility, we perform an experiment with a short (≈100 femtosecond) laser pulse on a photocathode in a 3 GHz RF gun. We perform the measurement of the single photon emission process with a copper cathode. We show that the longitudinal photoinjector model via transfer matrix is suitable for the reconstruction of the bunch duration even in short pulse model with an increased accuracy charge below 20 pC. We clearly measure the parabolic profile in the energy spectrum resulting from blow out phenomena at the cathode due to strong space charge forces. Measurements are also compared with the Astra simulations.

DRUM EXPERIMENT AT EXALT FACILITY

EXALT is a merging of two installation : PHIL test line photoinjector [1] and LASERIX [2] high power Ti:Sa laser. The aim of the facility is first to explore the beam dynamics for low energy short bunches (DRUM experiment), and second, to have a unique facility where experiment combining high power lasers and short bunches are available, one of the goal being the laser plasma wake field acceleration [3]. We first use a leakage of a high power Ti:Sa laser LASERIX for the photocathode of the PHIN 3 GHz RF gun. One of the goal of the facility is to explore the beam dynamics and the multiphoton process. Then, we managed the duration of the laser pulse with an optic compressor (100fs - 2 ps) and the wavelength with frequency doubling stage (Ultraviolet, infrared or visible) as shown in Fig. 1. We can set at the cathode different wavelength and laser duration. We recently solve the synchronisation issue of the two independent synchronisation systems of the equipment [4]. The DRUM experiment started after this achievement (see Fig. 2 for a schematic of the test line). The objective is to explore the beam dynamics in the blow out linear expansion of the short bunches at the cathode, to explore multiphoton emission process at the cathode, and to measure the bunch duration of a 3 to 10 MeV electron beam. To quantify the photoemission, the charge extracted from the gun is measured with an ICT. We dispose also of different YAG screen station to measure the transverse spot profile of the electron bunch. Different solenoid are in the line to focus the beam at the photoinjector exit and at the entrance of the spectrometer.

* bruni@lal.in2p3.fr

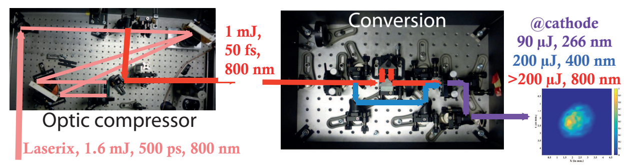

Figure 1: Schematic of the pulse compressor and the frequency conversion of the Ti:Sa laser LASERIX for the 3GHz RF gun cathode

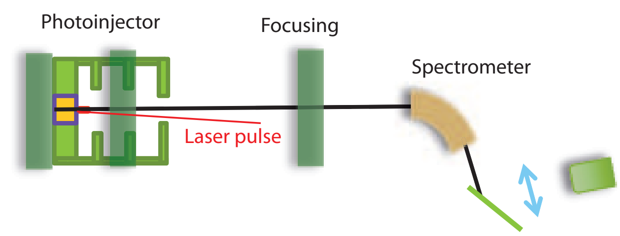

Figure 2: schematic of the PHIL test line used for the DRUM experiment. The laser pulse is send to the cathode in the RF gun. Different solenoids are allowed for focusing a spectrometer combined to a YAG screen and imaging are available for energy spread measurements

In fact, one of the goal of the DRUM experiment at EXALT facility is to retrieve the electron bunch duration with the 3 phase measurement. The method is detailed in the next section and is based on the energy spread measurement.

BUNCH LENGTH MEASUREMENT METHOD

Short bunch duration measurement can be done in different ways : electro optic sampling, transverse deflecting cavity, smith purcell radiation. At an energy of 5 MeV, the electro optic sampling and smith purcell radiation have a resolution which is in the ps range and are not suitable in our case. Concerning the transverse deflecting cavity it required additional klystron, which required large funding. We choose a robust, low cost and simple method to measure the bunch duration : the 3 phase method. This method is equivalent to the transverse emittance measurement with the 3 gradient method, but for the longitudinal emittance. 3 phases is a rather simple method to reconstructed the initial bunch duration with a least 3 measurement of the final energy spread. We consider there an element R, which acts on the longitudinal parameters of the electron bunch. Then, the energy spread at the element exit σ_{Ef} depend on the transfer matrix term of the element R and of the longitudinal

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS007

bunch parameters: the initial bunch duration σ_{ti}, the initial correlated energy/duration term σ_{Eti} and the initial energy spread σ_{Ei}^2. In fact, from the envelop equation, we have :

$$\sigma_{Ef}^2 = R_{65}^2\sigma_{ti}^2 + 2R_{65}R_{66}\sigma_{Eti} + R_{66}^2\sigma_{Ei}^2 . \quad (1)$$

The goal now is to measure the final bunch energy spread σ_{E_f} for **n** (at least 3) different values of the matrix R. Varying phase of the accelerating section during experiments is the simplest way of changing the R_{65} element of the matrix R for the photoinjector accelerating structure. Thus,

$$\underbrace{\begin{pmatrix} \sigma_{E_f\mathbf{1}}^2 \\ \vdots \\ \sigma_{E_f\mathbf{n}}^2 \end{pmatrix}}_{\mathbf{Y}} = \underbrace{\begin{pmatrix} R_{65\mathbf{1}}^2 & 2R_{65\mathbf{1}}R_{66\mathbf{1}} & 1 \\ \vdots & \vdots & \vdots \\ R_{65\mathbf{n}}^2 & 2R_{65\mathbf{n}}R_{66\mathbf{n}} & 1 \end{pmatrix}}_{\mathbf{A}} \underbrace{\begin{pmatrix} \sigma_{t_i}^2 \\ \sigma_{Et_i} \\ \sigma_{E_i}^2 \end{pmatrix}}_{\mathbf{X}} . \quad (2)$$

Solving for $\mathbf{X}$ using the least square method, we obtain $\mathbf{X} = \left(\mathbf{A}^T\mathbf{A}\right)^{-1}\mathbf{A}^T\mathbf{Y}$.

We choose here to measure the bunch length at the cathode emission. Then, we measure the energy spread at a photoinjector exit with the spectrometer.

LONGITUDINAL MODEL OF THE PHOTOINJECTOR

On EXALT, as only the gun is available as accelerating structure, we developed a longitudinal matrix from the model developed by KIM [5], with improvement on the calculation of the phase slippage of the electrons over the gun due to fact that the energy is almost at rest of mass at the cathode to reach quasi relativistic one in 12 cm [6]. We have to note, that in this case, the bunch length reconstructed is the one of the electron bunch at the cathode, i.e. in most common cases, the laser duration. In this model, we consider a purely sinusoidal accelerating field in the RF gun $E_z(z,t) = E_m\cos(kz)\sin(2\pi ft + \Phi_0)$ with E_m the accelerating gradient, f the RF frequency of the field, k the wave number of the field and Φ_0 the initial RF phase seen by of the electron at the cathode, z is the longitudinal coordinate. The phase of the RF field is Φ(z)=2πft−kz+Φ_0 and by definition, $dz/dt = c\sqrt{\gamma^2-1}/\gamma$ with the time and γ the Lorentz factor. According to the kinetic power theorem and by considering a first zone in the photoinjector where $\gamma \approx 1$ and $\Phi(z) \approx \Phi_0$ and by two iterations, the model is ($\alpha = \frac{eE_m}{2m_ec^2k}$):

$$\Phi(z) = \frac{1}{2\alpha sin(\Phi_0)}\left(\sqrt{(\gamma_0 + 2\alpha k sin(\Phi_0)z)^2 - 1}\right. \\ \left. -2\alpha k sin(\Phi_0)z - \gamma_0 + 1\right) + \Phi_0$$

$$\begin{aligned} \gamma(z) &= \gamma_0 + \alpha(k sin(\Phi(z))z \\ &+\frac{1}{2}(cos(\Phi(z)) - cos(\Phi(z) + 2kz))) \end{aligned}$$

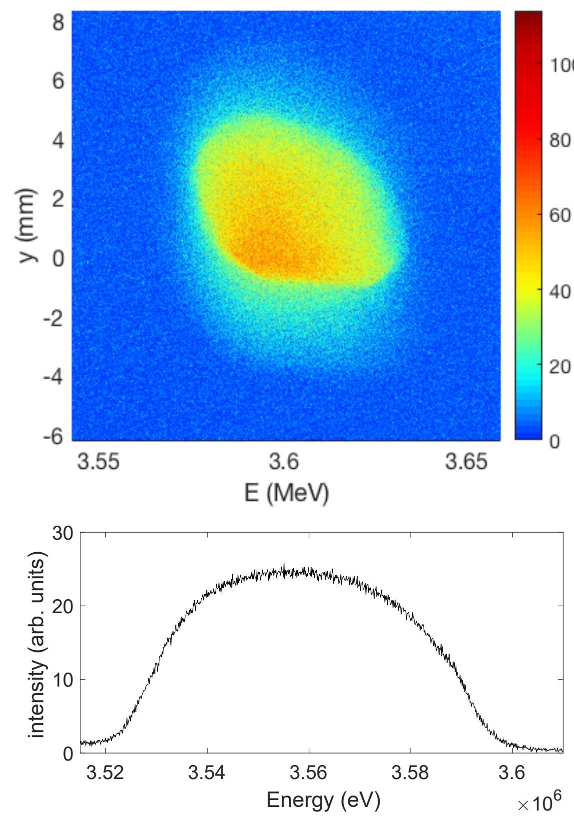

Figure 3: top : image of the YAG screen after the spectrometer. bottom, energy distribution profile of the electron bunch. Both cases are in the case of short laser duration at the cathode illumined by UV light.

To end, by differentiation of Φ_f and γ_f, we obtain the matrix element for the photoinjector as follow for $\Delta\Phi$ ($= 2\pi f\Delta t$) and ΔE_f:

$$\begin{aligned} R_{55} &= 1 - \frac{cos(\Phi_0)}{2\alpha sin^2(\Phi_0)}; R_{56} = 0; R_{66} = 1 \\ R_{65} &= 2\pi f m_e c^2(\alpha k L\cos(\Phi_f) - \frac{\alpha}{2}\sin(\Phi_f) \\ &+\frac{\alpha}{2}\sin(\Phi_f + 2kL))(1 - \frac{\cos(\Phi_0)}{2\alpha sin^2(\Phi_0)}) \end{aligned}$$

For the 3-phase measurements, we use these matrix elements to model the beam dynamics in the photoinjector.

180 FS BUNCH LENGTH MEASUREMENTS WITH 3 PHASE METHOD

We performed measurements of the energy spread versus the RF phase of the photoinjector for different laser duration at the cathode. First we observed that the energy spread has a parabolic shape as expected by the linear expansion at the cathode due to the high charge density as shown in Fig. 3.

Then, we measure the behavior of the energy spread versus RF phase in the case of short bunches at the cathode.

ISBN: 978-3-95450-208-0 doi:10.18429/JACoW-IPAC2019-WEPTS007

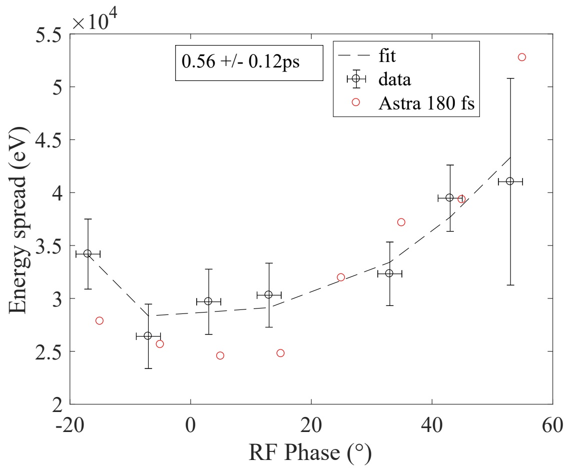

Figure 4: FWHM Energy spread versus the RF phase. Measurement have been done in EXALT facility with a charge of 10 pC and a electron bunch energy of 3.6 MeV. The FWHM bunch duration at the cathode of 560 fs +/− 120 fs is measured with the 3 phase method and the photoinjector model. The measurement are compared with tracking simulation using a 180 fs rms laser duration at the cathode and fit well with experiment.

As expected by the envelop equation and the photoinjector model, the behavior is almost flat versus the RF phase. The minimum energy spread measured for 10 pC of charge with a smooth focusing toward the spectrometer is 26 keV FWHM. Other 80 degrees of RF phase, the energy spread increase by less than a factor two. As an example for two picosecond laser duration at the cathode, the energy spread increases by a factor more than 5 other the same range of RF phase.

With weighted least mean square method, 560 fs FWHM bunch duration at the cathode has been measured with the 3 phase method and the photoinjector model. As the energy distribution is parabolic, this correspond to 180fs RMS value (the ratio between FWHM and rms is $\sqrt{10}$ in case of parabolic profile). In Fig. 4, the measurement are represented with dotted points with the associated rms fluctuation values. The dotted line correspond to the model applied with the initial longitudinal parameter of the electron bunch reconstructed with the 3 phase method. To end, we compare the FWHM results with Astra [7] simulation with an initial laser duration of 180 fs rms. The agreement with the measurement is encouraging, the small difference coming from the weak number of macroparticle taken for the tracking simulations and due to the fact that we take FWHM values for the simulated profile.

CONCLUSION

By impinging a femtosecond laser at the cathode, we are able to obtain short bunches, which have to be used close to the photoinjector to avoid bunch lengthening. Different wavelength and laser duration are available. First experiment show that the 3 phase method is suitable to measure less than 500 fs FWHM bunch duration. A standing wave booster section will be installed at the exit of the photoinjector to slow down the bunch lengthening and to measure the bunch duration at the photoinjector exit. Future experiment are foreseen to combine short bunches with infrared high power laser.

ACKNOWLEDGEMENTS

This work was funding by P2IO

REFERENCES

[1] M Alves *et al.*, “PHIL photoinjector test line”, *Journal of Instrumentation*, vol. 8, no. 01, pp. T01001–T01001, Jan. 2013. doi:10.1088/1748-0221/8/01/t01001

[2] D. Ros *et al.*, “LASERIX: An open facility for developments of EUV and soft X-ray lasers and applications—Developments of XUV sources using high power laser facilities: ILE, ELI”, *Nucl. Instr. Meth.*, vo.l 653, pp. 76–79, Oct. 2014.

[3] E. Baynard *et al.*, “Status report of the ESCULAP project at Orsay: External injection of low energy electrons in a Plasma”, *Nucl. Instr. Meth.*, vol 909, pp. 46–48, Nov. 2018.

[4] N. Delerue *et al.*, “Synchronization of a Photo-Injector and a High Power Laser With Independent Clocks”, in *Proc. 8th Int. Particle Accelerator Conf. (IPAC’17)*, Copenhagen, Denmark, May 2017, pp. 3935–3937. doi:10.18429/JACoW-IPAC2017-THPAB093

[5] K. J. Kim, “Rf and space-charge effects in laser-driven rf electron guns”, *Nucl. Instr. Meth.*, vol. 275, pp. 201–218, Feb. 1985.

[6] T. Vinatier, C. Bruni, S. Chancé, and P. M. Puzo, “Length Measurement of High-brightness Electron Beam thanks to the 3-Phase Method”, in *Proc. 5th Int. Particle Accelerator Conf. (IPAC’14)*, Dresden, Germany, Jun. 2014, pp. 3459–3461. doi:10.18429/JACoW-IPAC2014-THPME095

[7] K. Flöttmann, *ASTRA: A space charge tracking algorithm*