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LENGTH MEASUREMENT OF HIGH BRIGHTNESS ELECTRON BEAM THANKS TO THE 3-PHASE METHOD

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Abstract

The goal of 3-phase method is to determine the length of an electron beam without dedicated diagnostics by varying the measurement conditions of its energy spread, through a change in the RF phase of an accelerating structure. The originality of the measurements performed at PHIL and PITZ comes from the fact that it is applied on high-brightness electron beams of few MeV generated by RF photo-injectors.

First measurement has been done on PHIL accelerator at LAL [1], showing a good agreement with the expected length. More precise results obtained with a RF gun at PITZ will be shown, well as those obtained with a standing wave booster [2]. Finally, measurements at higher energy performed on the HELIOS Linac at SOLEIL with travelling wave accelerating structures will be exposed [3].

THEORETICAL PRINCIPLES

The 3-phase method is based on a beam transport with linear transport matrix, without taking into account the effect of space-charge forces, in purely sinusoidal accelerating fields with no transverse components. With only a longitudinal drift between the accelerating structure (which RF phase is varied) and the dipole magnet measuring the beam energy spread, the longitudinal transport matrix takes the following form :

$$\begin{pmatrix} \mathrm{E} & F \\ D & 1 \end{pmatrix}$$

leading to the Equation 1 for the 3 beam longitudinal parameters : rms energy spread σ_E, rms time/energy correlation σ_{Et} and rms length σ_t.

$$\sigma^2_{\mathrm{E_f}} = D^2\sigma^2_{t_i} + 2D\sigma_{Et_i} + \sigma^2_{E_i} \qquad (1)$$

"i" indices denotes quantities at the entrance of the accelerating structure, and "f" indices at the entrance of the dipole magnet.

Equation 1 shows that with at least 3 measurements of σ_{Ef} for 3 different values of D, namely for 3 different RF phases of the accelerating structure, it is possible to extract the beam longitudinal parameters σ_{ti}, σ_{Eti} and σ_{Ei} thanks to a least-square inversion. It is noteworthy that the reconstructed beam length σ_{ti} is the one at the entrance of the accelerating structure. It is therefore particularly interesting to use this method with a RF photo-injector, since the electron beam length to reconstruct is then known as being that of the laser pulse generating the beam. It thus allows testing the accuracy of 3-phase method. It requires establishing the longitudinal transfer matrix of a RF photo-injector, which is difficult since the electron velocity vary from 0 to relativistic along its path.

It has been done by taking inspiration in the model of K.J. Kim [4], which analytically describes the beam dynamics in RF photo-injector, leading to the following expression for the "D" coefficient of the RF gun longitudinal transport matrix :

$$D = 2\pi fmc^2\left(1-\frac{\cos(\varphi)}{2\alpha\sin^2(\varphi)}\right)\left(\alpha kL\cos(\Phi_f) - \frac{\alpha}{2}\sin(\Phi_f) + \frac{\alpha}{2}\sin(\Phi_f + 2kL)\right)$$

with f the accelerating frequency, m the electron mass, c the speed of light in vacuum, k the wave vector, L the length of the gun, $\alpha=(eE_m)/(2kmc^2)$, E_m the amplitude of the accelerating field and φ its RF phase. Φ_f is the beam final phase given by :

$$\Phi_f = \varphi + \frac{1}{2\alpha\sin(\varphi)}\left(\sqrt{(1+2\alpha\sin(\varphi)kL)^2 - 1} - 2\alpha\sin(\varphi)kL\right)$$

In the case of RF accelerating structures located after the gun, an ultra-relativistic approximation is done by considering the electron velocities constant to c. It leads to the following expression for the "D" coefficient :

$$D = \pi feE_m g(\varphi)$$

with $g(\varphi)=\cos(\varphi)L-(1/k)*\cos(kL+\varphi)\sin(kL)$ for a standing wave accelerating structure and $g(\varphi)=2L\sin(\varphi)$ for a travelling wave accelerating structure.

MEASUREMENTS

Measurements Done at PHIL

PHIL is a 3GHz RF photo-injector test bench located at LAL (Orsay) [1]. It schematically consists in a RF gun and a dipole magnet, located 4m downstream, to measure the beam energy and energy spread. The laser pulse used at PHIL has a Gaussian longitudinal profile with 3.6ps rms length.

Measurements of electron beam length at the gun photocathode thanks to the 3-phase method has been performed at PHIL for several gun peak accelerating field, namely several beam energy at gun exit. The beam charge was around 100pC. The results of these measurements, compared with the laser pulse length, are shown in Figure 1.

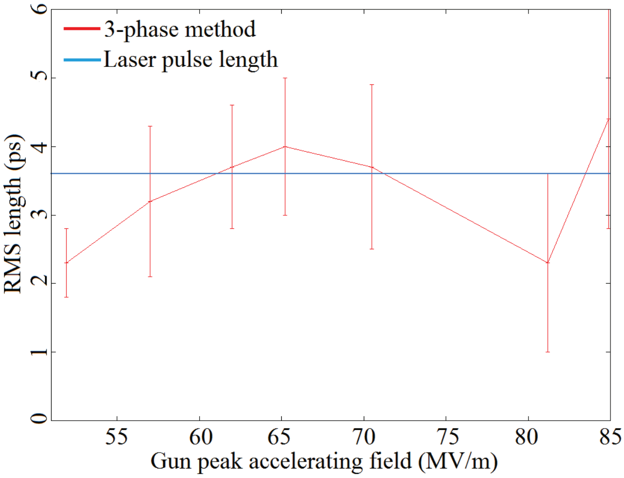

Figure 1 : rms beam length deduced from 3-phase method at PHIL versus gun peak accelerating field.

The measurements shown in Figure 1 are in good agreement with the expected length, except for the point at lower gun peak accelerating field. It can be explained by the non-inclusion of space-charge forces in the used model. Indeed, the effect of these forces becomes more and more important when the gun peak accelerating field decreases. However, the gap with the expected value remains quite low (22% taking the error bars into account) showing that 3-phase method is trustable to obtain a good estimation of the beam length also at not ultra-relativistic energy.

One can clearly see in Figure 1 that the error bars remain important, since the precision on the reconstructed beam length varies between 20% and 55%. This is due to the fact that the measure of energy spread is not automated at PHIL. It thus prevents to acquire a large number of energy spread and also to properly symmetrise them with respect to the energy spread minimum, which are however two important conditions to improve the precision of the least-square method used to invert Equation 1.

Measurements Done at PITZ

PITZ is a 1.3GHz RF photo-injector test bench located at DESY (Zeuthen) [2]. It especially includes a standing wave booster cavity, allowing performing beam length measurements in addition to the RF gun. The laser pulse used at PITZ is longitudinally adjustable. Long flat-top profile with 24ps FWHM length and 2ps rise/fall time (σ_t=6.8ps rms) and short flat-top profile with 5.8ps FWHM length and 2ps rise/fall time (σ_t=1.9ps rms) have been used to perform measurements.

The measurements with the RF gun have been done with a beam charge of 20pC and a peak accelerating field of 60MV/m, corresponding to a beam energy of 6.25MeV at the exit. Table 1 shows the results of the measurements performed with the gun.

Table 1:3-Phase Measurements With the RF Gun at PITZ

Laser profile	**Expected length (laser length)**	**Beam length by 3-phase method**
Long flat-top	6.8ps rms	6.2 +/- 0.3ps rms
Short flat-top	1.9ps rms	1.8 +/- 0.1ps rms

As expected, the measurements by 3-phase method are here more precise than those obtained at PHIL, since the precision is about 5%. This is due to the RF phase feedback implemented at PITZ, which enables phase stability better than 1° so improvement in measurement precision. There is also a good agreement with the expected values, though with a slight discrepancy of 9% (4.5% taking the error bars into account) in the long flat-top case. As the space-charge forces are not an issue here, the main assumption for this discrepancy is the mis-modelling of the gun accelerating field by a pure sinusoidal wave with no transverse component.

The length measurements with the booster have been done with a beam charge of 20pC and a peak accelerating field of 17.5MV/m, corresponding to a beam energy of 21.7MeV at the exit. The measurement has been done for the two previous laser profile and for different gun RF phase (0° denotes the RF phase maximizing the beam energy). Table 2 shows the results of the measurements performed with the booster, compared with the prediction of the ASTRA beam dynamics code [5].

Table 2:3-Phase Measurements With the Booster at PITZ

Laser profile	**RF phase of the gun**	**ASTRA predictions**	**3-phase results**
Long flat-top	-20°	7.67ps rms	7.5 +/- 0.2 ps rms
Long flat-top	0°	5.85ps rms	6.0 +/- 0.2 ps rms
Long flat-top	+20°	3.95ps rms	4.1 +/- 0.1 ps rms
Short flat-top	-15°	2.37ps rms	2.2 +/- 0.1 ps rms
Short flat-top	0°	2.06ps rms	1.8 +/- 0.1 ps rms
Short flat-top	+20°	1.81ps rms	1.5 +/- 0.1 ps rms

Table 2 shows that 3-phase method allows a good reconstruction of the beam length variations at the booster entrance in function of the gun RF phase. 3-phase measurements for the short flat-top profile are however slightly below the ASTRA predictions (from 0.2ps to 0.3ps). The preferential explanation is still the mis-modelling of the booster accelerating field by a pure sinusoidal wave with no transverse component. Table 3 shows in fact the results of ASTRA simulations on the future PHIL layout (with a booster) with the real profiles of the accelerating fields and with purely sinusoidal profiles.

Table 3 : ASTRA Simulation of 3-Phase Measurement With a Booster at PHIL

ASTRA field type	ASTRA length predictions	3-phase length results
real	353fs rms	428fs rms
sinusoidal	357fs rms	381fs rms

The measurements done at PITZ with the booster therefore shows that 3-phase method is perfectly suitable to have a good estimation of the length of an electron beam of few MeV generated by a RF photo-injector, since the deviation from the ASTRA predictions is at maximum of 17% (12% taking the error bars into account).

Measurements Done at SOLEIL HELIOS Linac

The HELIOS Linac of SOLEIL [3] is in particular composed of 2 travelling wave accelerating structures at 3GHz, which can be used to perform bunch length measurement by the 3-phase method.

It is noteworthy that a long beam is bunched in 5 bunches by a RF buncher located upstream of these structures. The length measured by 3-phase method is then not that of every single bunch, but the mean of these 5. Our measurements have been done with the second structure, so with a beam around 67MeV at the entrance, for two different beam charge of 650pC and 210pC. We choose to work with this low number of bunches and beam charge in order to have a negligible effect of beam-loading, which could significantly affect the measures otherwise.

The mean rms bunch length obtained with 3-phase method for the beam charge of 650pC is 4.0 +/- 0.2ps, while the one obtained for the beam charge of 210pC is 3.3 +/- 0.5ps. It corresponds to bunches spreading over few degrees of RF phase, which is coherent after RF bunching. These values are also confirmed by the fact that the reconstructed beam energy spread by 3-phase method at the entrance of the second travelling wave structure corresponds to the one measured with this structure turned off. Finally, the diminution of the rms bunch length with the beam charge is also coherent, since the space-charge forces are lower implying a more efficient bunching.

These results have now to be compared with the simulations, especially to see if the diminution of the mean rms bunch length with the beam charge is predicted and in the correct proportion.

CONCLUSION

Our measurements have shown that 3-phase method, despite its numerous approximations, is totally trustable to compute a good estimation of the length of a low-charged few MeV electron beam generated by a RF photo-injector. 3-phase method is moreover a very cheap and technologically simple method, since it requires only a RF accelerating structure and a system to measure the energy spread which are common elements on an electron Linac. It is therefore a good alternative to common beam length measurement methods, like Cerenkov detector or Transverse Deflecting Cavity, which are more expensive and technologically complicated to implement.

We have only tested the 3-phase method on electron beams with rms length between 1ps and 10ps. It would therefore be very interesting to study the applicability of 3-phase method for shorter beams, namely around 100fs rms, and also for longer beams around 100ps rms. The study with 100fs rms beams will soon be possible on PHIL accelerator at LAL.

Comparison with the beam length coming from a Cerenkov detector is intended on ELYSE facility at LCP (Orsay, France) [6].

Another axis for further study will be to develop a 3-phase method taking into account the effect of space-charge forces, in order to see if it is possible to apply it for heavy-charged electron beam (>1nC).

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REFERENCES

[1] M. Alves & al., “PHIL photoinjector test line”, Journal of Instrumentation, Vol. 8, January 2013

[2] S. Rimjaem & al., “Diagnostics Systems for Characterizing Electron Sources at the Photo-Injector Test Facility at DESY, Zeuthen site”, Siam Physics Congress 2011, http://pitz.desy.de/publications/2011

[3] SOLEIL website : http://www.synchrotron-soleil.fr/portal/page/portal/SourceAccelerateur/Accelerateurs

[4] K.J. Kim, “RF and Space Charge Effects in Laser-Driven RF Electron Guns”, Nucl. Instr. Meth., A275, 201 (1989)

[5] K. Floettmann, “ASTRA, A Space-charge TRacking Algorithm”, Version 3.0, October 2011, http://www.desy.de/~mpyflo/

[6] J. Belloni & al., “ELYSE, a picosecond electron accelerator for pulse radiolysis research”, Nucl. Instr. Meth., A539, March 2005, p. 527-539