Numerical Studies for Bunch Length and Bunch Arrival Time Jitter Minimization in Preparation of a Laser-Plasma Wakefield Acceleration Experiment with External Injection at the SPARC_LAB Facility

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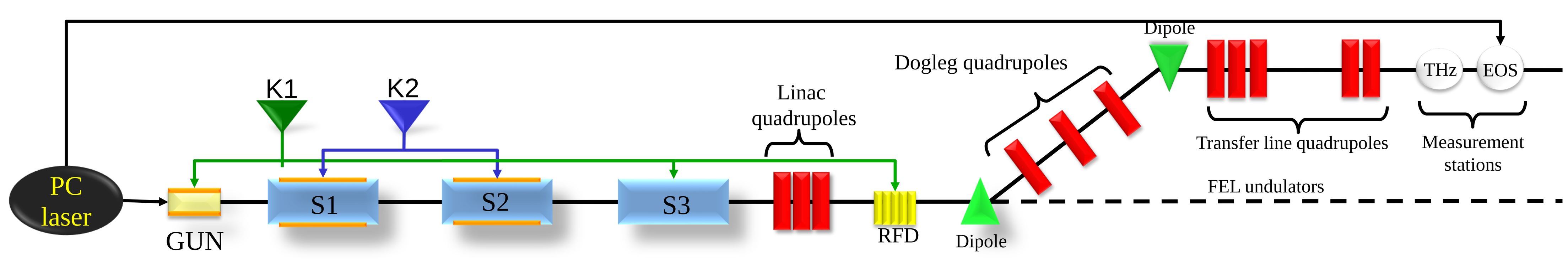
Abstract

Experimental research on plasma acceleration techniques is one of the most important activities presently ongoing at SPARC_LAB **[1]**, the multidisciplinary facility of INFN Frascati Laboratories, where electron bunches of energy up to 170 MeV feed four experimental beamlines. The facility has a unique capability of exploiting the combined use of high power laser pulses (6 J, 300 TW) provided by FLAME **[2]**, and high brightness beams (≈10^{15} A m^{-2} rad^{-2}) produced by the SPARC photo-injector **[3]**. A run dedicated to the study of acceleration of short bunches externally injected in a laser driven plasma wave is in preparation. Very high accelerating fields and good beam quality are expected, provided that both bunch length and relative time jitter between the injected beam and the plasma wave can be kept in the 10 fs range. According to experimental measurements, at present the SPARC beam characteristics are not very far from the external injection experiment specifications. The paper presents the status of the numerical studies performed to analyse the experimental results and to further optimize the photo-injector working point in order to fully meet the bunch length and synchronization requirements. This can be obtained by investigating and exploiting the difference between the longitudinal dynamics of the bunch particles, that experience space charge forces, and that of the multi-shot bunch centroids. In particular, the overall RF induced energy chirp is different, giving the opportunity to fully complete the bunch compression process downstream a non isochronous transfer line (the dogleg), while preserving a good degree of correlation between the beam arrival and launch times. Then, the bunch results accelerated and compressed, while its centroid is still fairly synchronous with respect to the photocathode laser and any other laser system sharing the same optical oscillator **[4][5]**.

1. Bunch Length and Bunch Arrival-time jitter measurements at SPARC_LAB



Laser Parameters	Experimental value	simulation
X(Y) spot (rms)	(230± 5) um	230 fs
Pulse duration (rms)	(450 ± 50) fs	450 fs
Beam parameters	**Experimental value**	**simulation**
Charge	(50 ± 2) pC	50 pC
Energy	(81.2±0.1) MeV	81 MeV
Energy spread	(400±10) keV	410 keV
Duration	(68±18) fs	65 fs
Normalized emittance	(1.7±0.2) um	1.8um

A 50 pC electron beam is accelerated, compressed and positively chirped by the first accelerating structure (S1) by means of the velocity bunching (VB) technique. After further acceleration, the beam is sent in a non-isochronous dogleg line, acting as magnetic compressor, consisting of three dispersion-matching quadrupoles placed between the two dipoles and five additional focusing quadrupoles in the final straight path. Downstream the dogleg both the bunch length and the arrival time jitter (ATJ) relative to the photo-cathode (PC) laser can be measured with an electro-optic sampling (EOS) system.

2. Longitudinal dynamics in a dogleg beamline

The longitudinal coordinate z of a generic particle with respect to the reference one downstream the compressor non-isochronous transfer line (the dogleg) is given by:

$$z_f \approx z_0 + R_{56}\delta_0 + T_{566}\delta_0^2 \quad \delta_0 = \sigma_E/E_0 \quad \sigma_E = E - E_0$$

while its normalized energy error can be expressed according to:

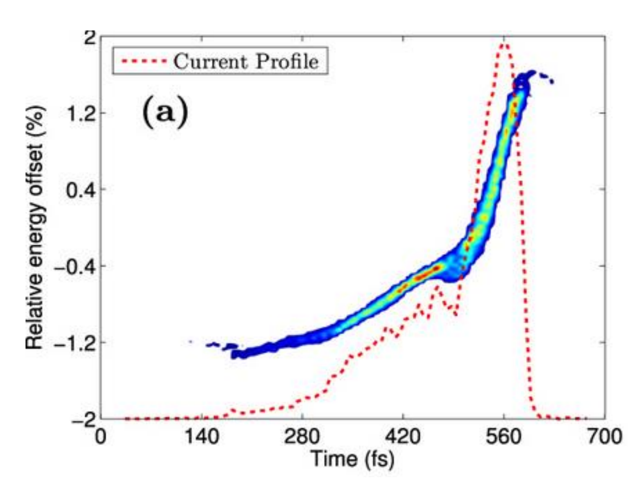
$$\delta_0(z_0) = \delta_u + h_1 z_0 + h_2 z_0^2 \dots$$

Compressed bunch length

$$\sigma_{z,f}^2 = R_{56}^2\sigma_{\delta u}^2 + (1 + h_1 R_{56})^2\sigma_{z,i}^2 + 3(h_2 R_{56} + T_{566}h_1^2)^2\sigma_{z,i}^4$$

Conditions to minimize the bunch length: $h_1 = -\frac{1}{R_{56}}, h_2 = -\frac{T_{566}}{R_{56}}h_1^2 = -\frac{T_{566}}{R_{56}^3}$

In the SPARC dogleg we have R_{56}<0, while the first accelerating structure (S1) pre-compresses the bunch (RF compression) and imprints a positive energy chirp on it. The RF compression is obtained by injecting the beam in S1 ahead the crest (-88 deg) so that particles in the bunch tail are accelerated more than those in the head. At the working energy the values ot the dogleg transport matrix coefficients are **R_{56} =-8,2 mm**, **T_{566}= -839 mm**, while performing a second order fit of the particle distribution in the longitudinal phase space downstream S1 we obtain:



h_1= 204.1 m^{-1}	h_2=1.5 x 10^7 m^{-2}	δu=60 keV

→ σ_{z_f}= 90 fs

3. Arrival time jitter analytic model and benchmarks

We define the ATJ as the shot-to-shot arrival time fluctuation of bunch centroids relative to a fixed position along the machine. It can be due to fluctuations of either RF fields inside accelerating structures or magnetic fields within dispersive elements or laser timing on PC. The synchronization system distributes a stable RF reference generated in a µ-wave Master Oscillator (RMO) through a coaxial cable star network. All clients are locked to the RMO with electronic PLLs (in particular, the residual time jitter between RMO and PC laser is < 50 fs).

In our model the ATJ sources are: the PC Laser (Δt_l); K1 (Δt_2), that feeds the RF-Gun, S3 and the RFD; K2 (Δt_3) that feeds S1 and S2.

$$\frac{\Delta E_0}{E_0} \approx c\sum_{i=1}^{3} h_{1_i}\Delta t_i \qquad \Delta t_{linac} \approx \sum_{i=1}^{3} c_i \Delta t_i$$

$$\sum_{i=1}^{3} h_{1,i} = 0 \qquad \sum_{i=1}^{3} c_i = 1 \qquad \Delta t_{dogleg} \approx \sum_{i=1}^{3}(c_i + h_{1,i}R_{56})\Delta t_i$$

Expected absolute ATJ (wrt RMO)

$$\sigma_{t_{linac}}^2 = \sum_{i=1}^{3} c_i^2 \sigma_{t_i}^2$$

$$\sigma_{t_{dogleg}}^2 = \sum_{i=1}^{3}(c_i + h_{1_i})^2 \sigma_{t_i}^2$$

To measure ATJ we can use either the RFD or the EOS system. The first measures the ATJ (at the end of the linac) with respect to RF sources, the second (at the end of the dogleg) with respect to PC laser.

coefficients	On crest	Velocity bunching
c_1	0.7 ± 0.2 (0.66)	-0.1 ± 0.4 (-0.14)
c_2	0.3 ± 0.1 (0.34)	-0.2 ± 0.5 (-0.07)
C_3	0.1 ± 0.9 (0.01)	1.2 ± 0.5 (1.18)
$h_{1,1}$ [m^{-1}]	-1.8 ± 1.2 (-0.8)	-93 ± 22 (-90)
$h_{1,2}$ [m^{-1}]	-0.6 ±1.2 (-0.4)	41 ± 23 (38)
$h_{1,3}$ [m^{-1}]	2.8 ± 2.5 (1.2)	42 ±35 (52)

ATJ measured with RFD at linac exit:

$$\sigma_{t_{linac}}^2 \approx c_1^2\sigma_{t_L}^2 + (c_2 - 1)^2\sigma_{t_{K1}}^2 + c_3^2\sigma_{t_{K2}}^2$$

$\sigma_{t_{linac}}$= 34 fs → $\sigma_{t_{K1}} \approx \sigma_{t_{K2}}$ = 22 fs and σ_{t_L} = 48 fs

Expected ATJ with respect to PC laser at linac exit:

$$\sigma_{t_{linac}}^2 \approx (c_1 - 1)^2\sigma_{t_L}^2 + c_2\sigma_{t_{K1}}^2 + c_3^2\sigma_{t_{K2}}^2$$

→ $\sigma_{t_{linac}}$= 60 fs

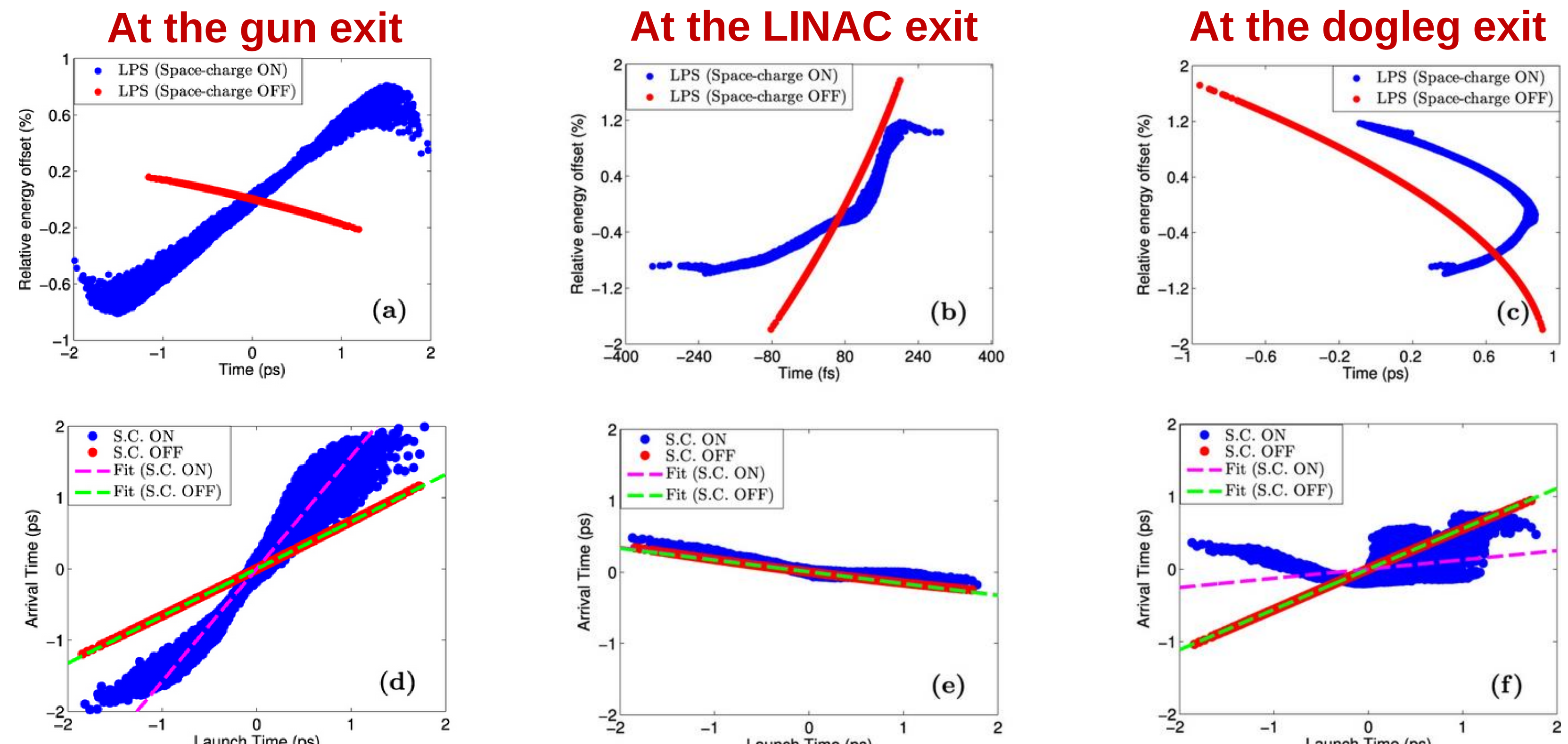
ATJ after hybrid compression measured with EOS:

$$\sigma_{t_{linac}}^2 \approx (c_1 + h_{1,1}R_{56} - 1)^2\sigma_{t_L}^2 + (c_2 + h_{1,2}R_{56})^2\sigma_{t_{K1}}^2 + (c_3 + h_{1,3}R_{56})^2\sigma_{t_{K2}}^2$$

→ $\sigma_{t_{dogleg}}$= 26 fs

4. Relative ATJ reduction with the hybrid scheme

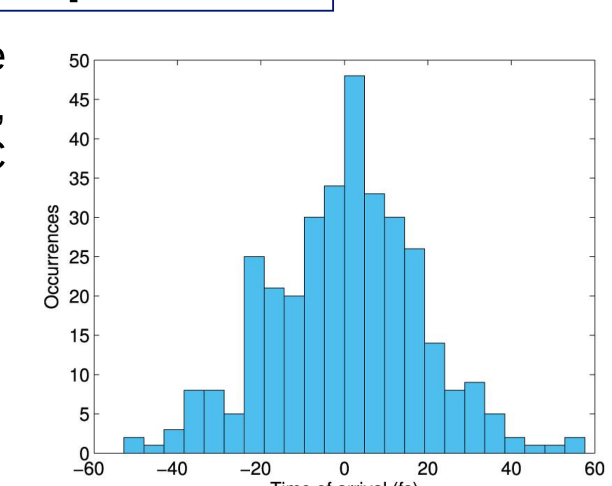
At the gun exit **At the LINAC exit** **At the dogleg exit**



The General Particle Tracer (GPT) code has been used to study the longitudinal beam dynamics. Intra-bunch dynamics is strongly affected by space charge forces, while multi-shot dynamics of bunch centroid it is not. Due to the RF compression process, the particles are injected in the dogleg with a time error that mostly depends on the time of the RF and only weakly depends on their initial launch time. Consequently, up-stream the dogleg the bunch time of arrival is poorly linked to the PC laser. However, because of the space charge contribution, the intra-bunch energy chirp is different from that of the multi-shots centroid footprint. Then, the passage in the dogleg will compress in different ways the two distributions (intra-bunch particles and bunch centroids).

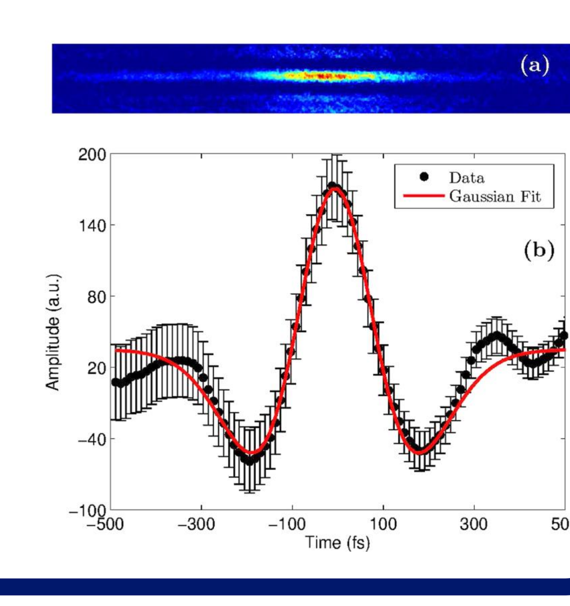
5. Conclusions and future perspectives

The EOS allows us to measure the bunch length and the relative timing-jitter between the PC laser and the beam, since the EOS probe laser is directly split from the PC laser oscillator and then amplified.



Bunch duration	Value (fs)	Relative ATJ	Value (fs)
Theoretical model	90	Theoretical model	26
GPT simulation	92	GPT simulation	25
Experimental data	90 ± 7	EOS	19 ± 5

The setup implemented at SPARC_LAB has experimentally proven that the hybrid compression scheme can provide **bunch durations below 90 fs** and **arrival timing-jitter relative to the photo cathode laser below 20 fs rms.**



These numbers (especially the ATJ) are not far from those required by experiments of external injection of electron bunches in a laser generated plasma wave. Numerical studies to optimize the photoinjector working point in order to further improve these performances are in progress.

This studies are also extremely important for the future projects of the INFN Frascati Labs.

References:.
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