Experimental work on laser acceleration technologies 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 (8 J, 300 TW) provided by FLAME [2], and high brightness beams (+10^10 A/m^2-rad^2) provided 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 bunch 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 analyze the experimental results and to further optimize the photo-injector working point in order to finally meet the bunch length and synchronization requirements. This can be obtained by investigating and exploiting the difference between the longitudinal dynamics of the bunches, that is, 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 launches 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][8].

Abstract

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

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 dipole 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:

$$\delta z = z_0 + R_{560} \delta E + T_{560} \delta \beta_0 = \delta \beta_0 E_0 = \delta E = E_0$$

while its normalized energy error can be expressed according to:

$$\delta \beta_0(z) = \beta_0(z) - \beta_0 = \frac{R_{560}}{E_0} \delta E + T_{560} \delta \beta_0$$

Compressed bunch length

$$\sigma_z^2 = \frac{R_{560}^2}{E_0} \sigma_0^2 + (1 + h R_{560}) \sigma_0^2 + 3(h R_{560} + R_{560} \beta_0 h^2) \sigma_0^2$$

Conditions to minimize the bunch length:

$$\frac{\sigma_z}{\sigma_0} = \frac{R_{560}}{E_0} = \frac{T_{560}}{E_0} = \frac{h R_{560}}{E_0} + R_{560} \beta_0 h^2$$

In the SPARC dogleg we have \(R_{560} \approx 0.8\), while the first accelerating structure (S1) pre-compresses the bunch (RF compression) and imparts a relative 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 of the dogleg transport matrix coefficients are \(R_{560} = 0.8\) mm, \(T_{560} = -389\) mm, while performing a second order fit of the particle distribution in the longitudinal phase space downstream S1 we obtain:

\[\sigma_z = 90 \text{ fs}\]

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).

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

ATJ measured with RFD in line exit:

\[\Delta t_{\text{line}} = \sum_{i=1}^d \Delta t_i \]

\[\sigma_{\Delta t_{\text{line}}} = \sqrt{\sum_{i=1}^d \sigma_{\Delta t_i}^2} \]

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

Expected ATJ with respect to PC laser at line exit:

\[\Delta t_{\text{line}} = (c_1 - 1)^2 \sigma_t_{\text{rms}} + c_2 \sigma_{\Delta t_{\text{RFD}}} + c_3 \sigma_{\Delta t_{\text{EOS}}} \]

\[\sigma_{\Delta t_{\text{line}}} = \frac{\sigma_t_{\text{rms}}}{\sigma_{\Delta t_{\text{RFD}}}} (c_1 + c_2 + c_3) \]

with:

\[\sigma_t_{\text{rms}} = 34 \text{ fs} \]

\[\sigma_{\Delta t_{\text{RFD}}} = 22 \text{ fs} \]

\[\sigma_{\Delta t_{\text{EOS}}} = 48 \text{ fs} \]

Expected ATJ with respect to PC laser at line exit:

\[\Delta t_{\text{line}} = \frac{\sigma_t_{\text{rms}}}{\sigma_{\Delta t_{\text{RFD}}}} (c_1 + c_2 + c_3) \]

\[\sigma_{\Delta t_{\text{line}}} = \frac{\sigma_t_{\text{rms}}}{\sigma_{\Delta t_{\text{RFD}}}} (c_1 + c_2 + c_3) \]

\[\sigma_{\Delta t_{\text{line}}} = 60 \text{ fs} \]

ATJ after hybrid compression measured with EOS:

\[\Delta t_{\text{line}} = \left( c_1 + c_2 + c_3 \right) \sigma_{\Delta t_{\text{RFD}}}^2 + \left( c_1 + c_2 + c_3 \right) \sigma_{\Delta t_{\text{EOS}}}^2 \]

\[\sigma_{\Delta t_{\text{line}}} = \left( c_1 + c_2 + c_3 \right) \sigma_{\Delta t_{\text{RFD}}}^2 + \left( c_1 + c_2 + c_3 \right) \sigma_{\Delta t_{\text{EOS}}}^2 \]

\[\sigma_{\Delta t_{\text{line}}} = 26 \text{ fs} \]

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.

The setup implemented at SPARC LAB has experimentally proven that the hybrid compression scheme leads to much bunch durations below 50 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 photo-injector 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

[5] RFD, INFN Frascati e Laboratori Nazionali di Frascati