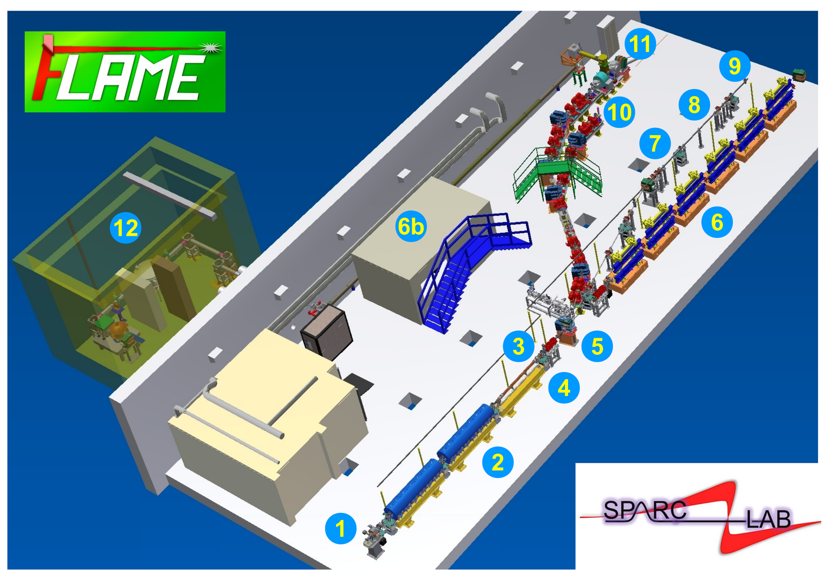
Generation of hollow driver bunches followed by ultra-high brightness witness for plasma wakefield acceleration

R. Pompili[1]*, E. Chiadroni[1], A. Cianchi[2], M. Ferrario[1], F. Villa[1]

[1]Laboratori Nazionali di Frascati, Via Enrico Fermi 40, 00044 Frascati, Italy, [2]University of Rome Tor Vergata and INFN, Via della Ricerca Scientifica 1, 00133 Rome, Italy

SPARC-LAB test-facility

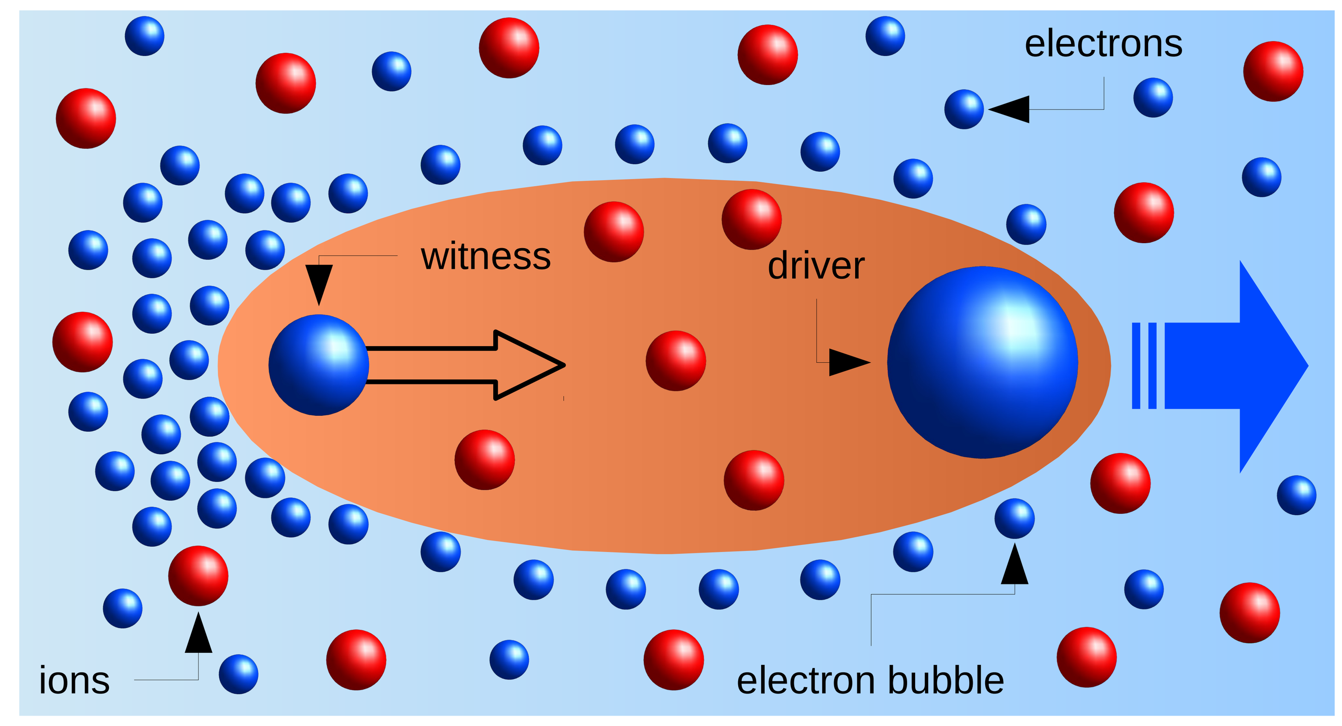


SPARC-LAB (*Sources for Plasma Accelerators and Radiation Compton with Lasers and Beams*) is a test-facility based on the 180 MeV SPARC electron linac and the 300 TW FLAME laser system [1]. Bunch up to 1 nC charge are produced by a laser hitting on the photo-cathode of a RF-gun (1). The RF-gun is followed by three accelerating sections (2) and a THz radiation source (3). A Plasma Wakefield Acceleration (PWFA) experiment is located upstream the THz station. Four beam-lines follow the RF Deflector (4) and the main dipole (5). They are devoted to Free Electron Laser (FEL, 6) both in SASE and seeded (6b) schemes; beam diagnostics (7) based on THz radiation (8) and Electro-Optical Sampling (9); Laser Wakefield Acceleration (LWFA) by external injection (10); X-rays source by Thomson scattering (11) between the e-beam and the FLAME laser (12).

Plasma Wakefield Acceleration of a witness bunch

Plasma wakefield acceleration (PWFA) has demonstrated the ability to produce very high gradients to accelerate electrons [2, 3] and positrons [4]. In PWFA, a drive bunch of charged particles passes through a plasma with average density n_p, thereby generating a wakefield that accelerates a witness bunch traveling behind the drive bunch. Driver bunches with high density n_b and lengths shorter than the plasma wavelength λ_p ($\approx$ 330 μm for $n_p \approx 10^{16}$ cm^{-3}) are required to produce larger and larger accelerating gradients, whose intensity scales approximately as n_b/n_p [5].

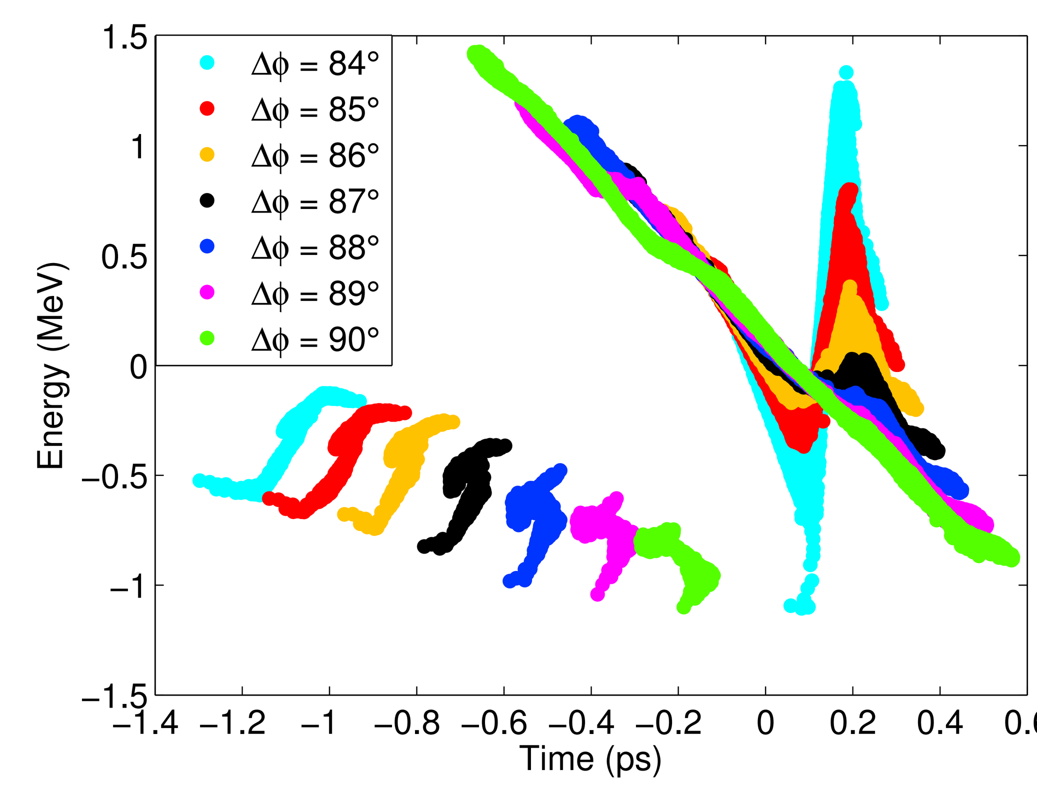
The witness has even more stringent requirements: its length must be $\sigma_z \ll \lambda_p$ in order to avoid energy spread and emittance growth during acceleration [6, 7]. A proper bunch compression scheme is thus mandatory to manipulate the longitudinal phase space (LPS) of the bunch train.



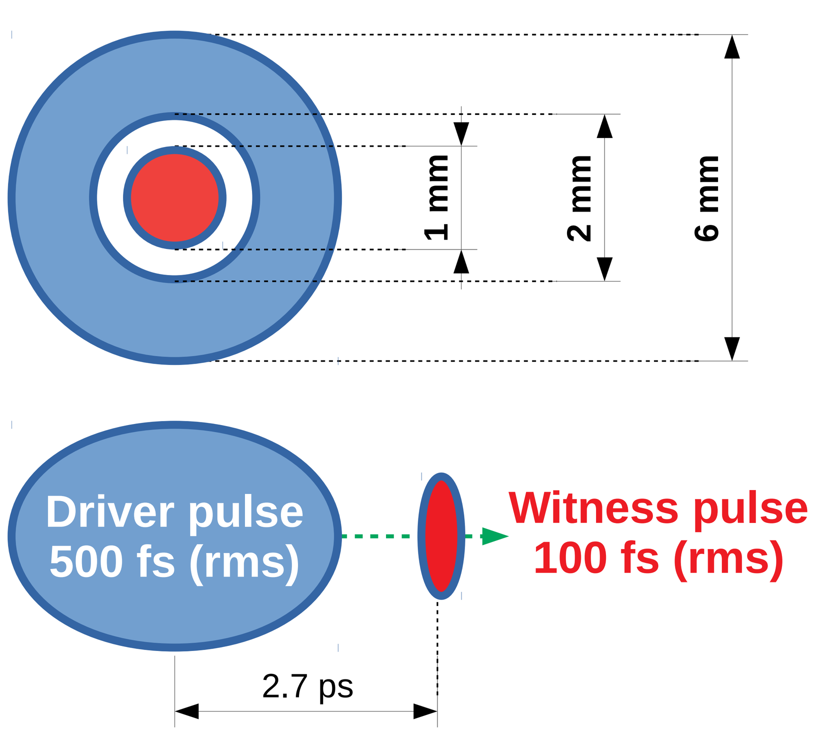
RF velocity-bunching of a two-bunch train

Velocity-bunching (VB) is a longitudinal compression technique in which a low energy beam is injected into a RF traveling wave in correspondence of its zero-crossing, where the field is accelerating (decelerating) for the tail (head) of the beam [8]. The wave induces a correlated time-velocity chirp on the beam leading to a rotation of its LPS if the injected beam is slower than the phase velocity of the wave. The field phase thus slips back to phases where the field is accelerating, but is simultaneously chirped and compressed.

The plot shows the LPS of a bunch train consisting of a driver ($Q_d = 200$ pC) and witness ($Q_w = 20$ pC) simulated for the SPARC_LAB photo-injector for different compression phases of the first TW section (S1). The two bunches are produced by sending two laser pulses on the photo-cathode [9]. The resulting LPS strongly depend on the choice of the S1 phase that sets the temporal distance between the bunches and their relative longitudinal compression.



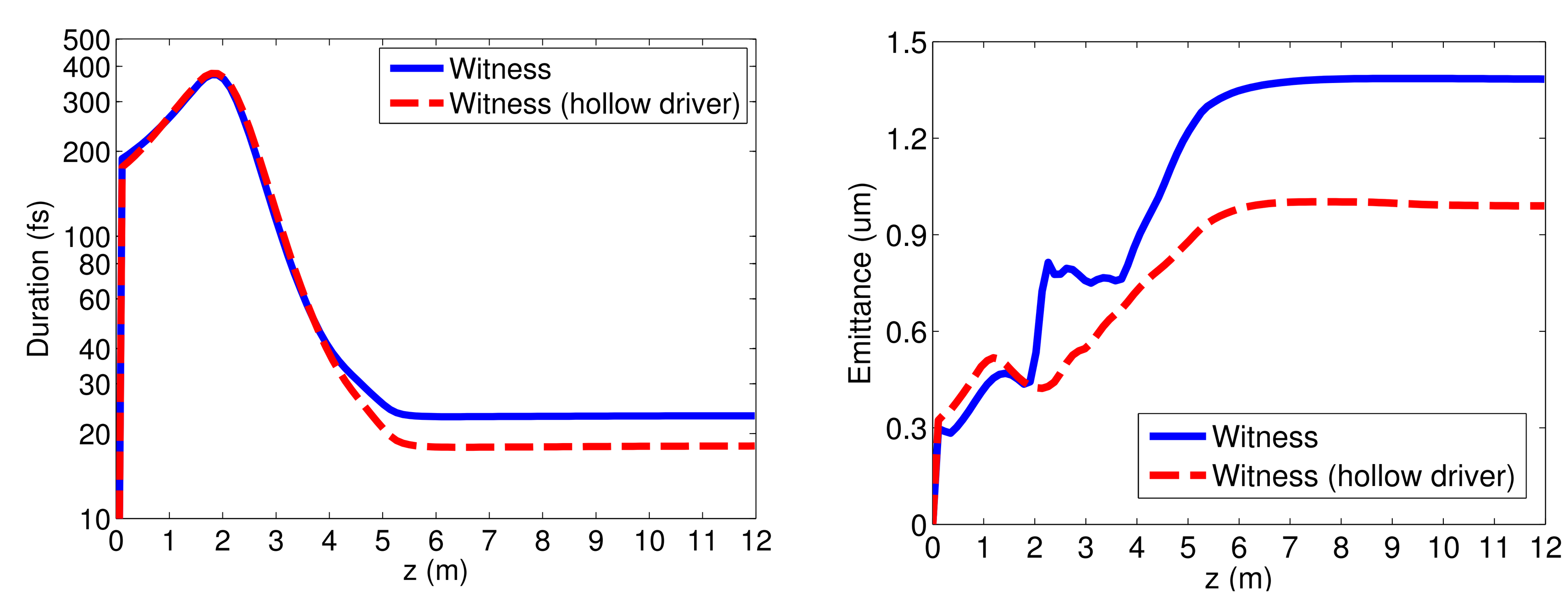
Hollow laser setup



Laser setup on the photo-cathode. The driver pulse has a donut-shape transverse profile, with its hole larger than the dimensions of the witness pulse. The temporal order of the pulses is reversed with respect to the final bunch configuration since it will be rotated and longitudinally compressed during VB. Since space-charge forces would push the particles toward the axis of the hollow driver, its transverse size is set in order to avoid it.

Driver bunch with hollow profile

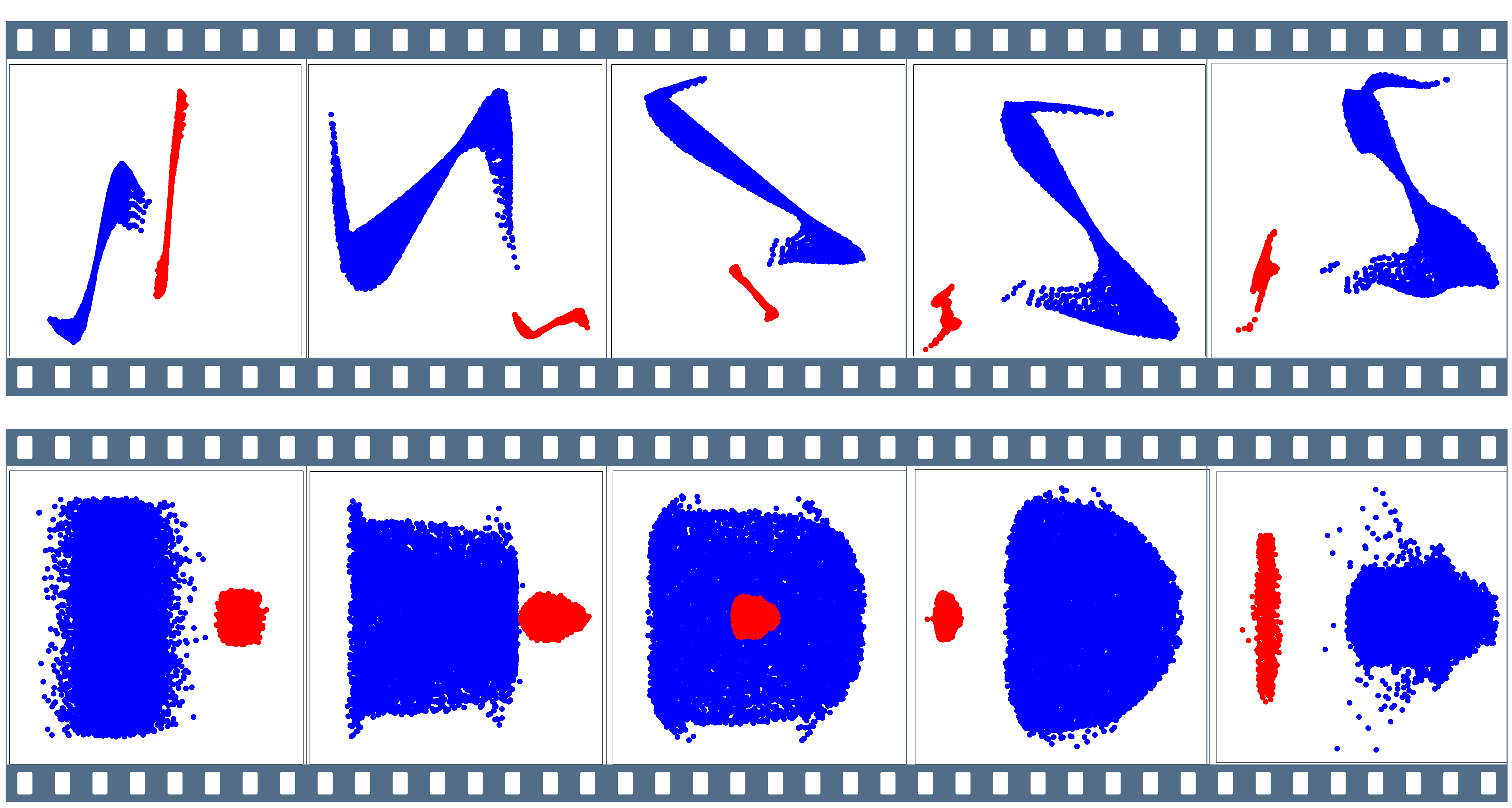
The optimal working point for PWFA requires a driver-witness distance $\approx \lambda_p/2$ and an ultra-short witness ($\sigma_z \ll \lambda_p$). In the 200 + 20 pC scenario the best witness parameters we achieved result in 23 fs (rms) duration and 1.4 μm emittance. We found that the crossing with the high-charge driver during VB actually acts as a nonlinear lens for the witness causing its emittance growth. The crossing also interferes with the RF compression and prevents to reach the maximum compression point.



For these reasons we employed a donut-like transverse profile for the driver. We use a hollow driver laser pulse on the photo-cathode and tune the magnetic optics of the photo-injector in order to preserve such a profile during the bunch crossing. The witness thus undergoes its own compression, down to 18 fs (-21%) without being affected by the driver space-charge effects (0.9 μm emittance, i.e. -35%).

Hollow beam start-to-end simulation

Evolution of the hollow driver (blue) and witness (red) bunches along the SPARC_LAB photo-injector. The plots show the E vs. z (top) and x vs. z (bottom) snapshots at different times. The bunch crossing (central plots) occurs in S1, at $z = 3.1$ m from the photo-cathode.



Gun exit | Before crossing | Crossing | S1 exit | Linac exit

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*e-mail address: **riccardo.pompili@lnf.infn.it**