Plasma Wakefield Acceleration at SPARC_LAB: Laser-Plasma Filaments and Resonant Bunch-Train Excitation

Summary of recent experimental results

Galletti et al. (2026, arXiv:2602.22841) Verra et al. (2025, Phys. Rev. E)

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1. Introduction and Motivation

Plasma wakefield acceleration (PWFA) is a technique in which a relativistic electron bunch — the driver — traverses a plasma and displaces plasma electrons, creating a large-amplitude longitudinal electric field (wakefield) in its wake. A trailing witness bunch, correctly timed, is then accelerated by this field. Gradients exceeding GeV/m are achievable, orders of magnitude beyond conventional RF technology. Two recent experimental studies at SPARC_LAB have advanced the state of the art in two complementary directions: the use of laser-generated plasma filaments as a novel plasma source, and the resonant excitation of wakefields using trains of electron bunches.

2. Beam-Driven Acceleration in a Laser-Plasma Filament

2.1 Concept and plasma generation

Conventional PWFA experiments rely on plasmas generated by high-current electrical discharge through a gas-filled capillary. While effective, discharge-based plasmas suffer from stochastic ignition, substantial energy deposition (~ 100 mJ per shot for a 3-cm capillary), and are limited to repetition rates of ~ 100 Hz. The new approach reported by Galletti et al. (2026) exploits laser filamentation: a femtosecond laser pulse propagating through low-pressure nitrogen gas undergoes self-focusing via the Kerr effect, which is balanced by plasma defocusing. The result is an extended, self-guided plasma channel — the filament — without the need for external confinement structures.

At SPARC_LAB, a 10 mJ, 350 fs pulse from a Ti:Sapphire laser is focused into a 3-cm-long, 2-mm-diameter dielectric capillary filled with nitrogen at a density of 10^{16} cm^{-3}. The filament extends ~ 45 mm (approximately 30 Rayleigh lengths), with an rms transverse size of ~ 70 μm and an on-axis plasma electron density of ~ 8×10^{14} cm^{-3}, in excellent agreement with numerical simulations using the envelope equation and the PIC code FBPIC.

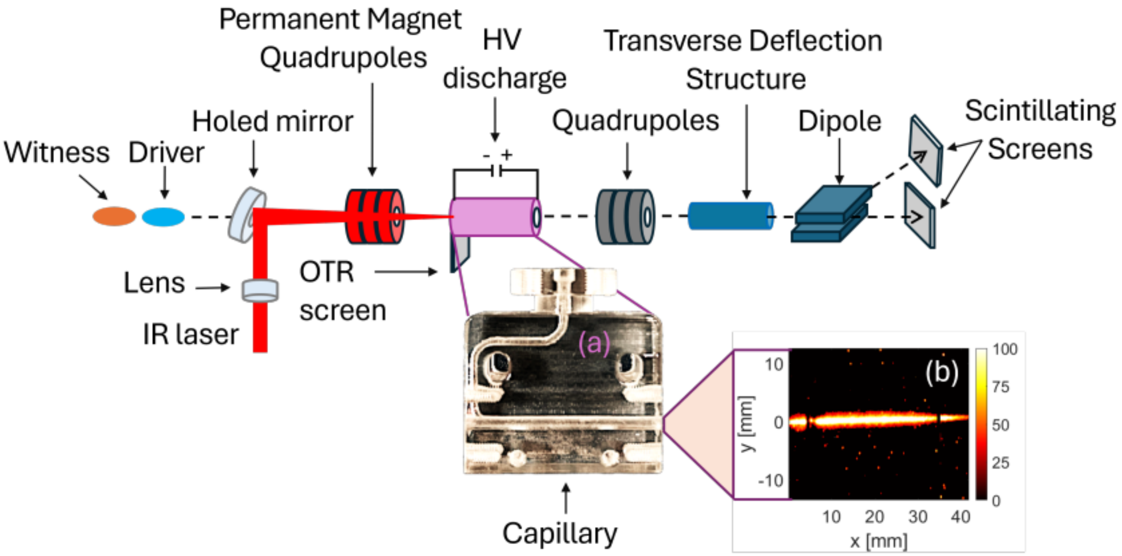

Figure 1. Experimental layout of the SPARC_LAB PWFA campaign. The IR laser pulse is injected co-axially into the capillary via a holed mirror, generating the plasma filament ~ 100 ps before the electron bunches arrive. The inset (b) shows a side-imaging snapshot of the glowing filament.

2.2 Acceleration results

Two electron bunches — a high-charge driver (500 pC, σt = 0.6 ps) and a low-charge witness (50 pC, σt = 0.2 ps) — are accelerated to 97 MeV in the RF linac, then co-focused into the capillary by permanent-magnet quadrupoles. The driver bunch density (nb $\approx 1.5 \times 10^{15}$ cm^{-3}) significantly exceeds the plasma density, placing the interaction in the blowout regime. Energy spectra measured with a magnetic spectrometer show that, with the laser on, the witness bunch gains $\Delta E^{+} \approx 8$ MeV, reaching a final energy of 104.5 ± 0.4 MeV. Over the 3-cm plasma length, this corresponds to an average accelerating gradient of ~ 266 MeV/m. The witness charge and relative energy spread are both preserved.

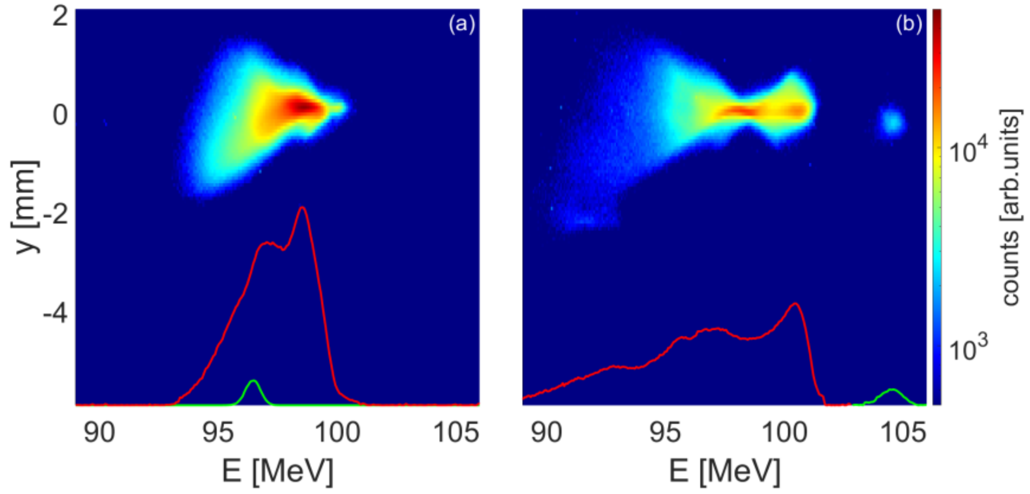

Figure 2. Energy spectra of driver (red) and witness (green) bunches averaged over 100 events: (a) laser off — no plasma interaction; (b) laser on — the witness bunch gains ~ 8 MeV while the driver loses ~ 4 MeV, consistent with wakefield energy exchange.

2.3 Reproducibility and comparison with discharge plasmas

A key advantage of the filament scheme is its reproducibility. Because the same laser system generates both the electron bunches (via a frequency-doubled beamline) and the plasma filament, the timing between the plasma and the beam is intrinsically jitter-free. Over 100 consecutive shots, the witness bunch is successfully accelerated in 95% of events with an rms energy jitter below 0.5%. By contrast, a discharge-based plasma source operated under identical beam conditions achieved acceleration in only 75% of events, with an energy jitter of ~ 1.3% — a factor of three worse.

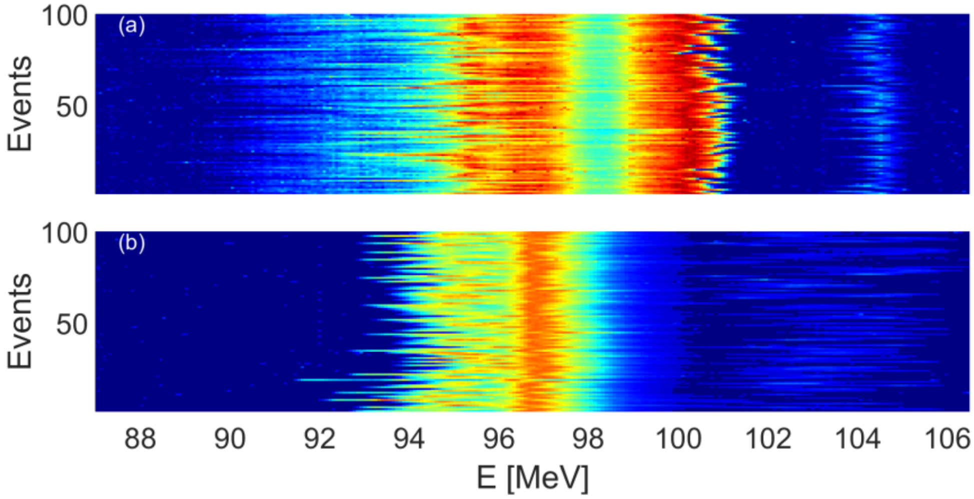

Figure 3. Waterfall plots of 100 consecutive events: (a) filament-based PWFA — the witness peak is narrow and consistent across shots; (b) discharge-based PWFA — wider, less stable witness distribution. The filament configuration achieves a threefold reduction in energy jitter.

The energy deposition of the filament laser is only ~ 2.5 mJ per shot, corresponding to a thermal wall load below 1 mJ/cm² — two orders of magnitude below damage thresholds. This, combined with the use of a commercially available GW-class laser (rather than a TW-class system required for alternative methods), makes the filament approach compatible with operation at tens of kHz repetition rates.

3. Resonant Excitation of Wakefields with Bunch Trains

3.1 Principle of resonant excitation

The second study (Verra et al., 2025) investigates how a train of multiple electron bunches, rather than a single driver, can be used to resonantly build up the wakefield amplitude. When successive bunches are separated by an integer multiple of the plasma electron period Tpe = 2π/ωpe, each new bunch arrives in the decelerating phase of the wakefields driven by the preceding ones. The wakefields add up coherently, and their amplitude grows along the train. This technique is particularly valuable because it allows the use of lower-charge bunches that are easier to handle in a linac, while still achieving large accelerating fields.

The experiment used a train of three bunches (each ~ 32–35 pC, σt ≈ 0.8–1.0 ps) accelerated to 95 MeV, separated by ~ 3.3 ps, chosen to match the plasma electron frequency at the target density of 1.3×10^{15} cm^{-3} (fpe ≈ 323 GHz). Because the bunch density is much lower than the plasma density, wakefields are driven in the linear regime, allowing individual contributions to simply superpose.

3.2 Experimental evidence and enhanced transformer ratio

The measured maximum energy loss increases progressively along the train: $\Delta E^-_{1,2,3}$ = (0.3, 0.7, 0.9) ± 0.1 MeV. The third bunch loses nearly three times the energy it would lose without the preceding drivers, demonstrating that the wakefields driven by each bunch accumulate coherently. By removing individual bunches and measuring the third bunch energy loss in isolation, the team verified that the contributions obey linear superposition to within experimental uncertainty — a result confirmed by FBPIC PIC simulations.

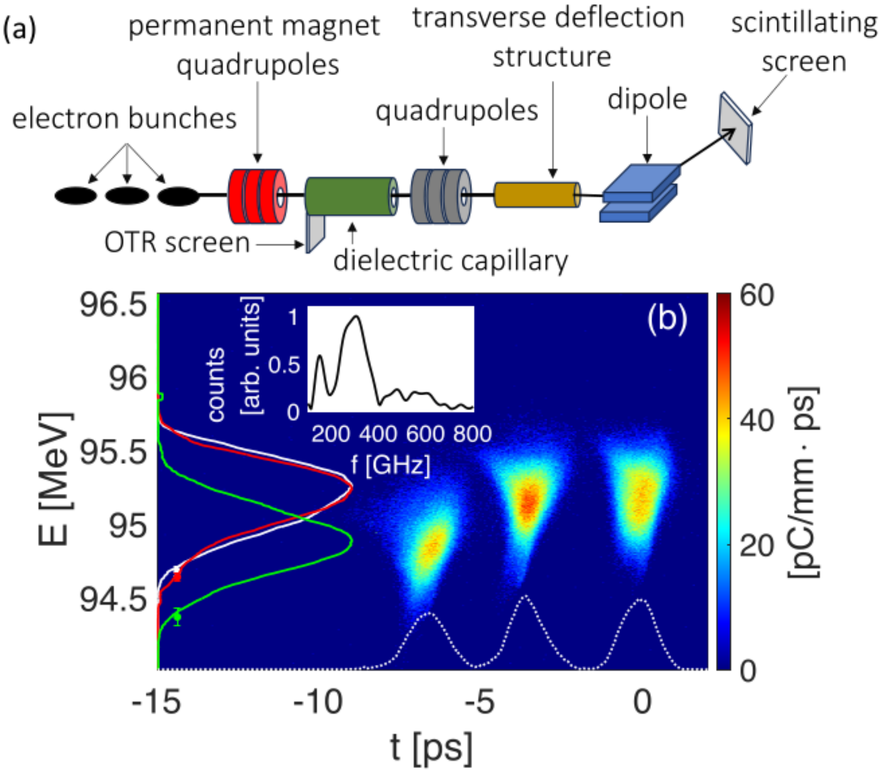

Figure 4. Resonant plasma wakefield excitation (Verra et al., 2025). Top row (a–d): single-event longitudinal phase-space images of the three-bunch train with successive drivers removed. The increasing energy loss of the third bunch is clearly visible. Bottom row (e–h): corresponding FBPIC PIC simulations, showing the plasma density perturbation (colormap) and on-axis wakefield Wz (dotted line) growing in amplitude along the train.

In a second configuration — the ramped-train scheme — two driver bunches are separated by 1.5 Tpe (half-integer spacing), so the second driver rides in the accelerating phase of the first. By increasing the charge of the second bunch, the net deceleration within each driver is equalized, which is the condition for maximizing the transformer ratio $R = \Delta E^+/\Delta E^-$. With a trailing witness bunch, the team demonstrated R = 3.2 ± 0.5, compared to R = 1.5 ± 0.3 with a single driver — confirming the first experimental demonstration of transformer ratio enhancement in a plasma wakefield accelerator using a ramped bunch train.

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4. Conclusions and Outlook

Together, these two studies represent significant advances toward practical, high-performance plasma wakefield accelerators. The laser-filament approach demonstrates that plasma stages can be created with high reproducibility, minimal energy deposition, and intrinsic synchronization with the electron beam — removing a major bottleneck for high-repetition-rate operation. The resonant bunch-train technique opens a route to higher energy-transfer efficiency and transformer ratios well above the single-bunch limit of $R = 2$.

Both results are directly relevant to the EuPRAXIA@SPARC_LAB project, which targets a 60-cm plasma stage operating at ~ 10^{15} cm^{-3} for driving a free-electron laser at few nanometers wavelengths. The filament plasma generation scheme, scaled with a longer capillary, could provide the required plasma length with dramatically lower wall loading than discharge-based sources. Meanwhile, ramped bunch trains could push the witness energy into the multi-GeV range needed for hard X-ray FEL operation, using the same linac infrastructure already in place at Frascati.

Future work will focus on extending the filament length beyond 3 cm, exploring high-repetition-rate operation at kHz, and combining the two techniques — resonant filament-based excitation — as a route toward a compact, sustainable plasma accelerator facility.