Witness-driver beam dynamics optimization in the SPARC_LAB photoinjector

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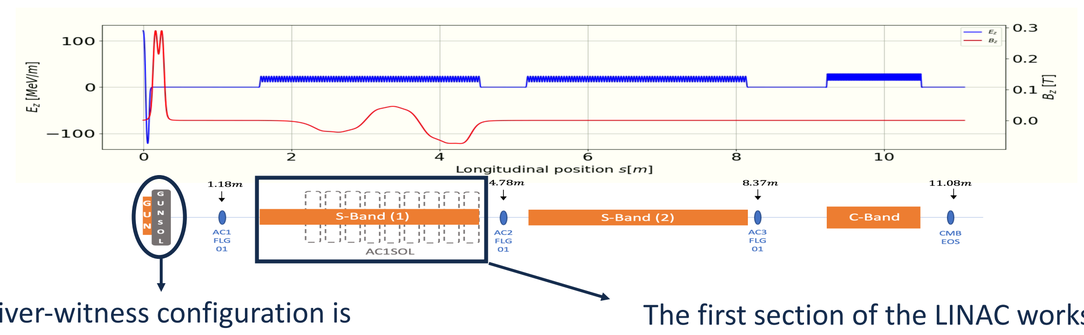
ABSTRACT

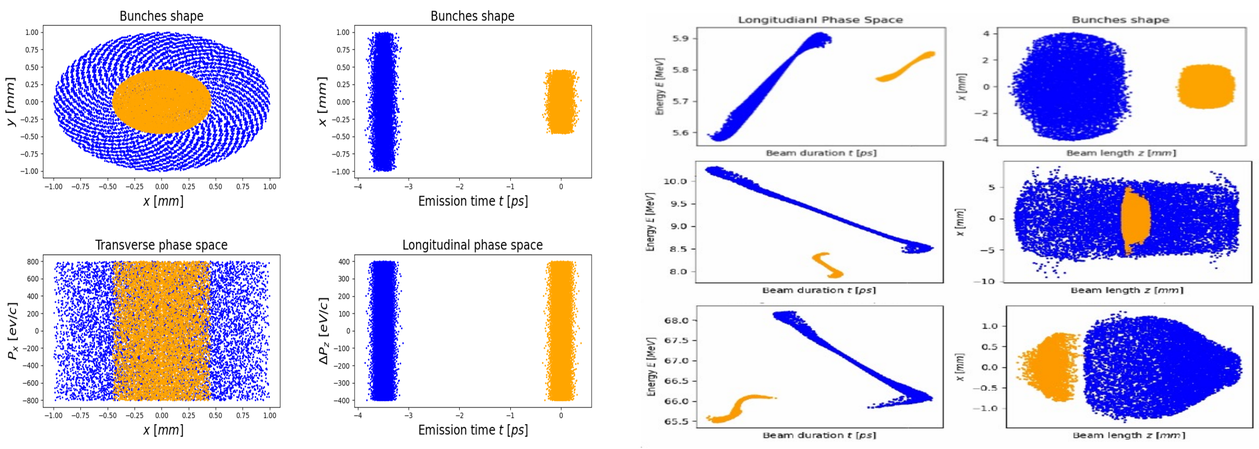
The SPARC-LAB test facility at LNF (Frascati) is equipped with a high-brightness photo injector used to explore and develop advanced beam manipulation techniques. This photo-injector can generate high brightness two electron bunches (witness and driver) needed for plasma acceleration. To obtain these, the cathode of the photo-injector at SPARC-LAB is illuminated by a train of laser pulses, while the first acceleration section exploits the "velocity bunching" technique. This combination allows for the creation of well-controlled electron bunch trains with high brightness. The goal of this research is to optimize the dynamics of the photo-injector to improve the beam quality and enhance the performance of plasma acceleration. To achieve this, beam dynamics analyses have been performed, involving the scanning and variation of different parameters of the electron beams, using the ASTRA simulation code. The results obtained from these optimization studies have then been applied in the operation of the actual machine setup and have been positively confirmed by good experimental results concerning the stability and accelerating gradient in the plasma.

a. WITNESS-DRIVER BUNCHES GENERATION



Driver-witness configuration is generated at the cathode

The first section of the LINAC works in the velocity bunching configuration



b. HIGH BRIGHTNESS BEAM PARAMETERS

Low emittance - High energy
High current - Low energy spread

"pancake" or "blowout" regime $\frac{eE_0\tau_L}{m_e c} \ll \frac{\sigma_0}{\epsilon_0 E_0} \ll 1$

→ E_0 is the effective field on the cathode: **Large Field – large launch phases**

→ τ_L is the laser duration: **Short bunch**

→ σ_0 is the surface charge density: **Large transverse spots**

Two beam evolution: *velocity bunching*

- **The temporal distance between witness and driver**
- **Short bunches**

Short witness → low energy spread in plasma

Improve plasma booster performances

- **High charge** → *High plasma gradient*
- Bunches distances: $\lambda/2 \sim 1\ ps$

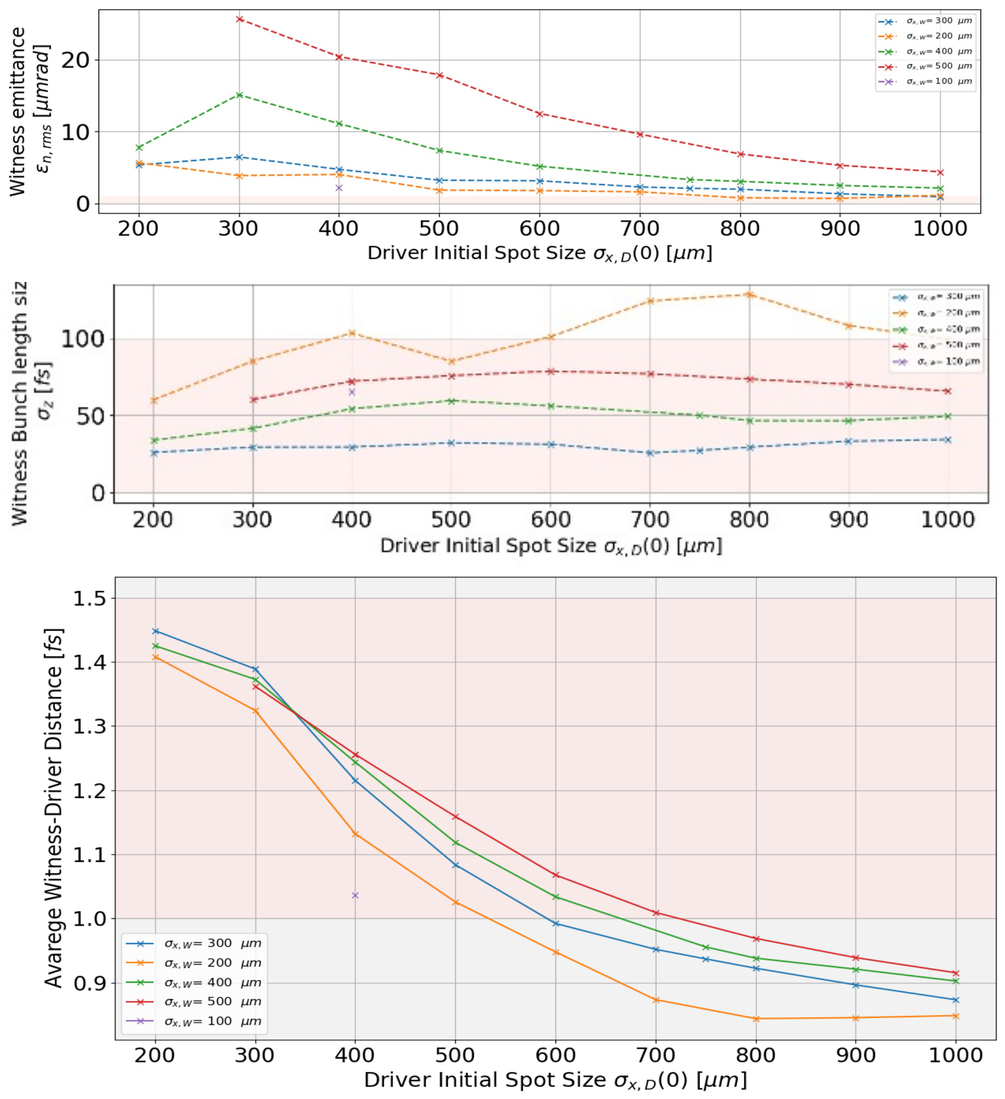
To avoid overlap **short bunches** are required

#	*Witness*	*Driver*
$\varepsilon_{n,rms}\ [\mu m]$	[0,1.5]	None
$\sigma_z\ [fs]$	<100	<450

Witness-Driver distance

Δt [ps]	[1,1.6]

c. COMB BEAM PARAMETER SCAN



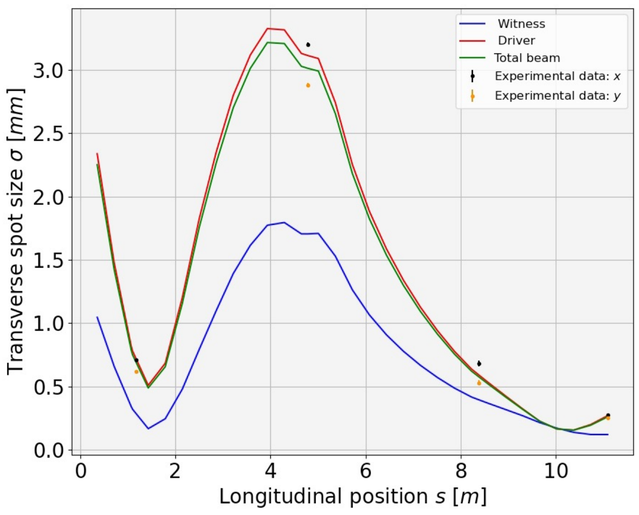
d. PARAMETERS @ THE CATHODE

Driver:
Charge: $\mathbf{500\ pC}$
Spot radius: $\mathbf{1\ mm}$ (uniform)
Laser duration: $\mathbf{100\ fs}$ (rms)

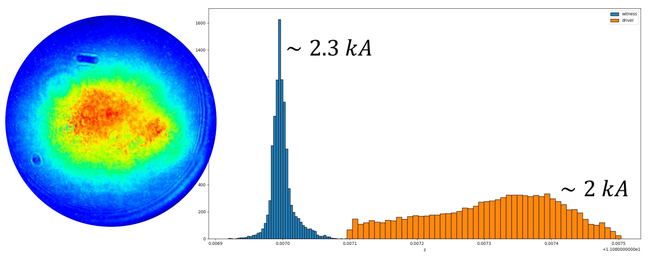
Witness:
Charge: $\mathbf{50\ pC}$
Spot radius: $\mathbf{450\ \mu m}$ (uniform)
Laser duration: $\mathbf{100\ fs}$ (rms)

Distance:
$\mathbf{3.5\ ps}$
(witness before driver @ cathode)

e. SIMULATION vs DATA



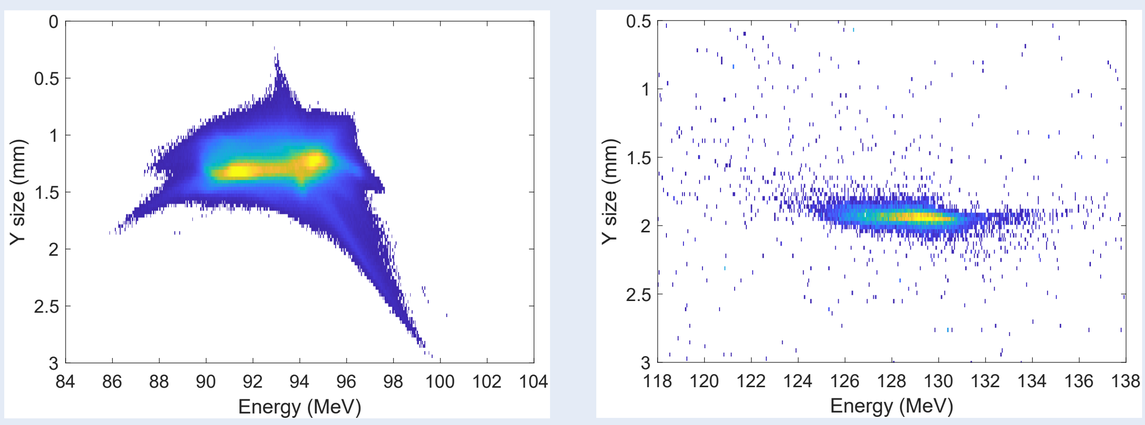
	Simulation	Data	Error [%]
$E[MeV]$	95.4	96.44 ± 0.38	1.1
$\varepsilon_x[\mu mrad]$	6.8	10.0 ± 3.18	32.0
$\varepsilon_y[\mu mrad]$	6.8	6.05 ± 2.55	4.6
$\sigma_z[fs]$	570	545	4.6
$\Delta t[ps]$	1.05	1.10	4.5



f. HIGH GRADIENT PLASMA ACCELERATION

Without plasma acceleration:
witness energy= $\mathbf{95.5\ MeV}$

With plasma acceleration:
witness energy= $\mathbf{129\ MeV}$



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