Intrinsic normalized emittance growth in laser driven electron accelerators

M. Migliorati *et al.*

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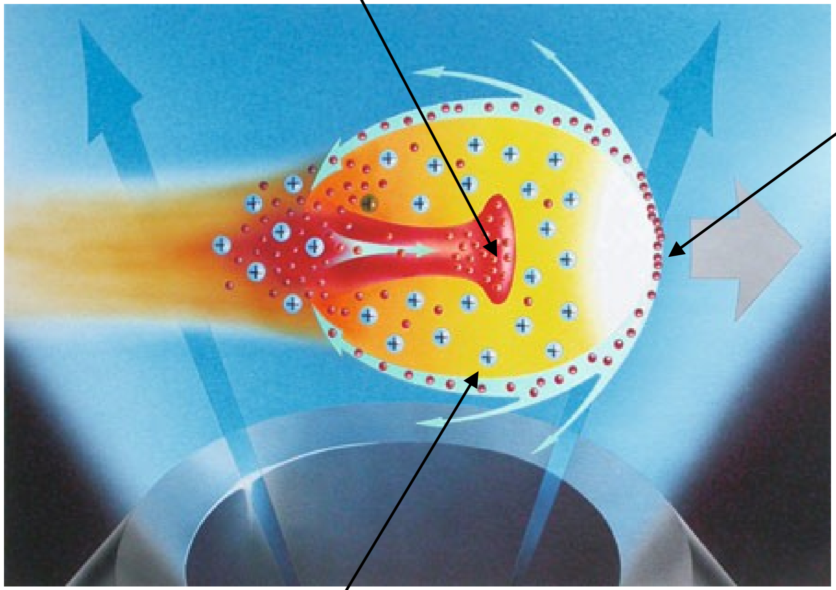
Overview

- Electron bunch emittance achieved by the conventional accelerators and plasma based accelerators is discussed.
- The study is carried out for electron parameters achieved using self-injected 3D bubble regime.
- Simulation of laser plasma interaction has been carried out using 3D particle in cell (PIC) code ALADYN optimizing the laser plasma interaction in order to achieve highest electron energies from laser-driven electron accelerators.
- Migliorati et. al. showed that normalized emittance of electrons get rapidly worse when it leaves the interaction region in laser driven electron accelerators which makes them quickly unusable for any beam transport.

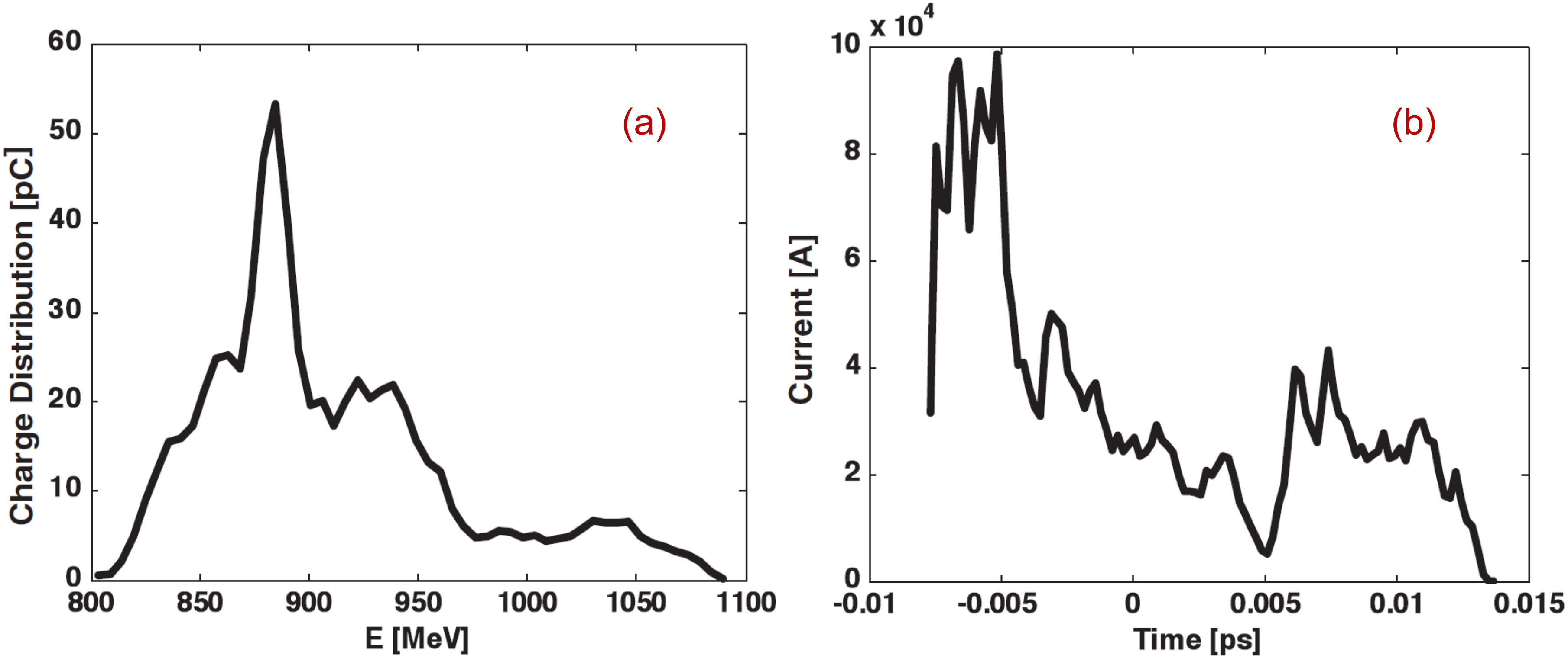
Before Proceeding further

Bubble acceleration



The laser pulse propagates from left to right and, almost like a light-bullet, pushes the electrons (red) transversally out of its path. The heavy ions (blue) are left behind, their strong electric field pulls some of the electrons into the bubble transversally and then accelerates them to relativistic energies. The resulting normalized mean particle energy is in the order of few MeVs.

Initial Electron Distribution

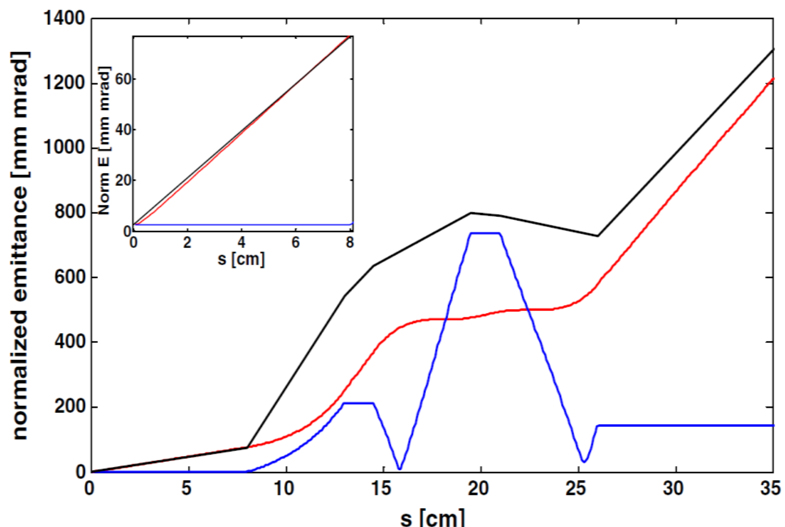


Charge distribution vs energy (a) and current vs time (b) of initial electron distribution as obtained with the PIC code ALADYN

Normalized transverse emittance

Normalized transverse emittance is given by ⟨ ⟩ ( )

- For conventional accelerator the first term is negligible, e.g. for SPARC photo injector @ 5MeV the ratio between the first and the second term is 10^{-3} while at 150 MeV it is ~ 10^{-5}
- For plasma vacuum interface the first term has the same order of magnitude as of conventional accelerator at low energies; however due to rapid increase in the bunch size, it becomes predominant compared to the second term.



→ Calculation is validated

Normalized transverse emittance along a transport line using magnetic quadrupoles. Comparison between TSTEP simulations (red line), ⟨ ⟩ ( ) (black line), approximation (blue line). Inset: Zoom of the initial drift.

Cause of emittance worsening

- Beam has large energy spread.
- Betatron frequency depends on energy.
- During the drift, particles rotate with different velocities in transverse phase space, widening the bunch trace space area, resulting the normalized emittance as a function of drift length and energy spread.

  Considering the transverse beam size increase due to free diffraction at sufficiently long drift, the bunch size becomes , then normalized emittance reads

  $$ * \quad \langle \; \rangle \; (\qquad\qquad) $$

- Behavior for slice normalized emittance → If we consider a thin slice, the energy correlation can usually be neglected compared to the uncorrelated energy (which accounts for randomly distributed energy of the electrons inside the bunch). Therefore, if this contribution is small, the beam slice would have the same behavior of a conventional beam.

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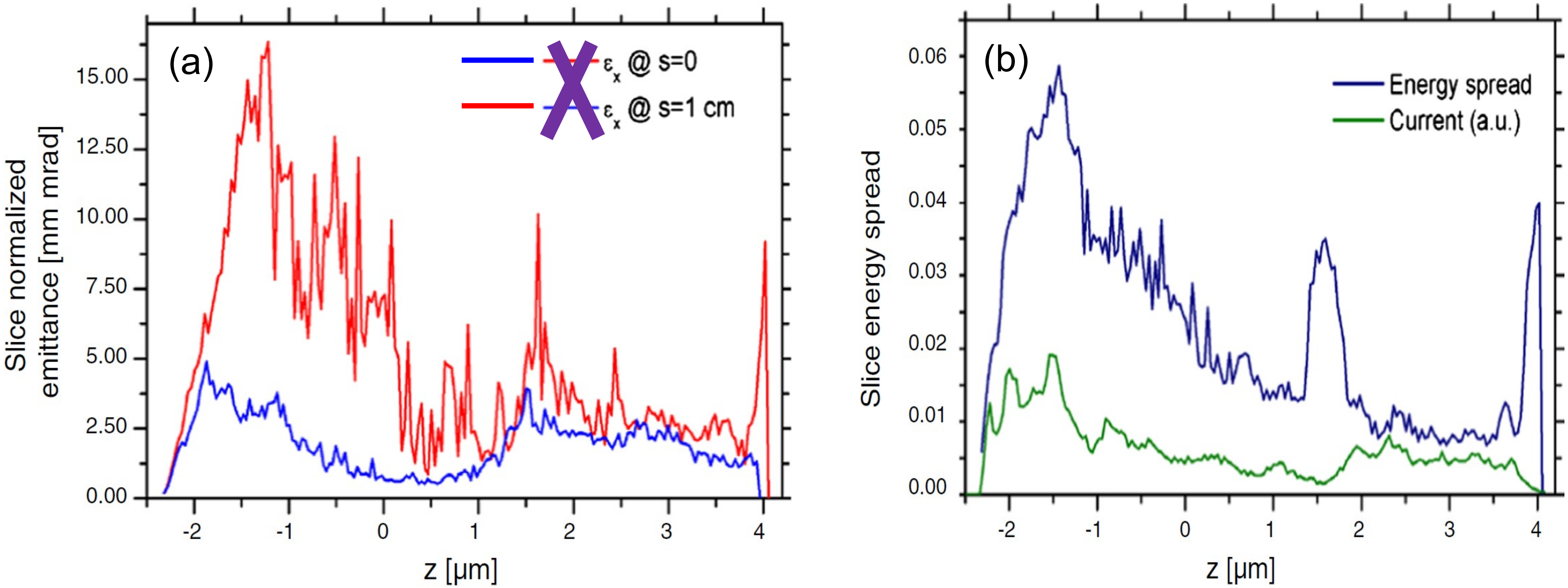
Slice normalized emittance

* ⟨ ⟩ ( )



Comparison of slice normalized emittance at the interaction point and after a 1 cm drift space (a) and slice energy spread (b). The number of slices in the longitudinal plane is 200.

→ Strong emittance degradation in regions with large slice energy spread.

Conclusion

- The laser driven electrons undergo a very strong, undesired normalized emittance worsening when leaving the interaction region, reaching quickly intolerable values.
- Capturing laser driven electron beams, conserving a decent percentage of its initial current and preserving a reasonable normalized emittance, requires optical elements positioned close to the interaction point and with a focal length in the order of the bunch Twiss beta function. **This is out of reach with the present-day magnet technology.**
- Beam worsening behavior is primarily due to the combined effect of a high energy spread and a high beam divergence.
- These parameters have therefore to be better controlled inside the plasma i.e. with proper shaping of plasma channel.

Thank you for your kind attention and to Dr. Matthias for his valuable suggestions and discussion.

Simulation Parameters

For plasma

Plasma length – 4.1mm

Plasma ramp – 100 μm

Electron density – $3\times10^{18} cm^{-3}$

Electron avg. energy – 910MeV

Electron bunch charge – 700pC

Energy spread σ_E -6.4%

Bunch length σ_Z -2 μm

Transverse beam size σ_X – 0.5 μm

Transverse divergence $\sigma_{x'}$ – 3mrad

Emittance ε – 1.4×10^{-3}mm.mrad

Normalized emittance ε_n – 2.5mm.mrad

For laser

Peak power – 200TW

Wavelength – 0.8μm

Prepulse contrast ratio – 10^{10}

Pulse duration (FWHM) – 30fs

Beam waist at focus – 15.5 μm

Intensity – $5\times10^{19} Wcm^{-2}$

What is SPARC

The ***SPARC* (Sorgente Pulsata e Amplificata di Radiazione Coerente)** project is to promote an R&D activity, oriented to the development of a high brightness photo-injector to drive SASE-FEL experiments at 500 nm and higher harmonics generation. The machine is installed at **INFN-LNF (Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati)**.