Multiple-Drive-Bunch Plasma Wakefield Acceleration

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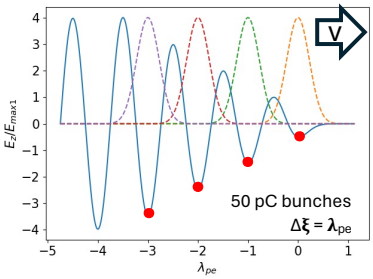
Abstract

A train of charged particle bunches can resonantly drive large amplitude wakefields in plasma, when spaced by integers of one plasma wavelength, and high-transformer-ratio wakefields, when spaced by integers of half plasma wavelength and with properly ramped bunch density. We show with numerical simulations that the SPARC_LAB linear accelerator can provide a train of compressed electron bunches via the velocity bunching technique, and that the coupling between the bunch train and plasma can allow for large-amplitude wakefield excitation (resonant configuration) and for high-transformer-ratio acceleration (anti-resonant configuration).
We discuss the experimental plan at SPARC_LAB.

Resonant Configuration

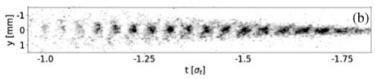


Superposition of wakefields driven by each bunch

→ Resonance when distance = plasma wavelength

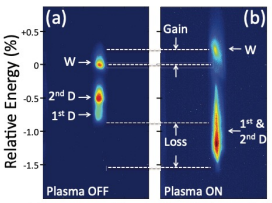
→ Potentially larger amplitude than single bunch with equal total charge

Previous Results:



Resonant wakefields driven by self-modulated p⁺ bunch (AWAKE)

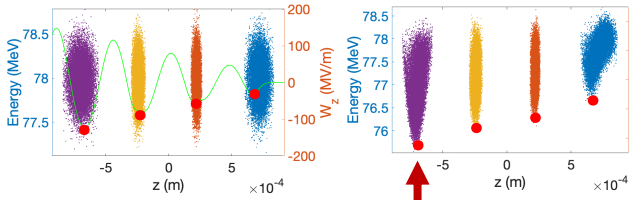
L. Verra et al. (AWAKE Coll.), PRL **129**, 024802 (2022)
AWAKE Coll. , PRL **122**, 054802(2019)
AWAKE Coll. , Nature **561**, 363 (2018)



Witness bunch acceleration

P. Muggli et al., Proceedings of PAC 2011

Linear theory calculations

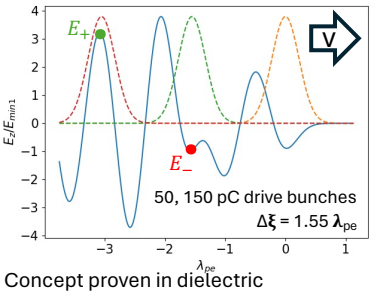


Bunch distribution from GPT
$\Delta\xi = 5$ µm
→ Resonance at $n_{pe} = 5.5 \cdot 10^{15}$ cm^{-3}

$n_b << n_{pe}$ for all bunches ($\sigma_r = 100$µm)
➔ Linear regime

Observable:
Energy loss increases along the train

Anti-Resonant Configuration



Superposition of wakefields driven by each bunch

→ Equal decelerating field within all drive bunches

→ Enhanced transformer ratio $R = \frac{E_+}{E_-}$

→ More efficient energy transfer

→ Longer depletion length

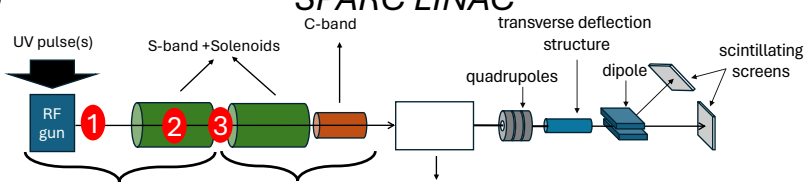
Concept proven in dielectric wakefield accelerator

C. Jing et al., PRL **98**, 144801 (2007)

Experimental Plan:

- Setup Multi-Bunch Configuration (UV + LINAC) ✅
- Demonstrate resonant wakefield excitation (increased energy loss along the train)
- Demonstrate enhanced transformer ratio acceleration using ramped bunch train

SPARC LINAC



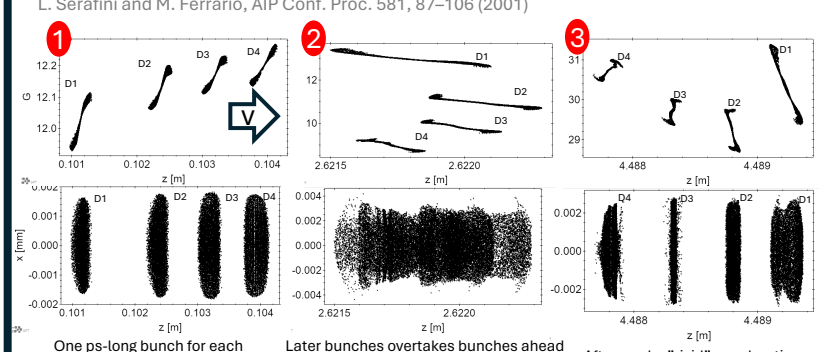
- Bunch compression
- Final bunch spacing
- Emittance control

- Energy spread tuning
- Final energy

INTERACTION CHAMBER:
Final focusing + discharge capillary + Capture System + Diagnostics

Train of compressed bunches generated via velocity bunching

L. Serafini and M. Ferrario, AIP Conf. Proc. 581, 87–106 (2001)

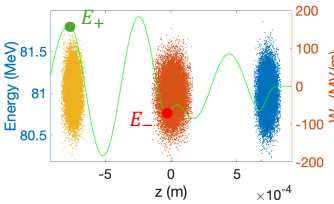


One ps-long bunch for each UV pulse

Later bunches overtakes bunches ahead
→ Bunch compression
→ Crossing of bunches

Afterwards, "rigid" acceleration to 70-150 MeV

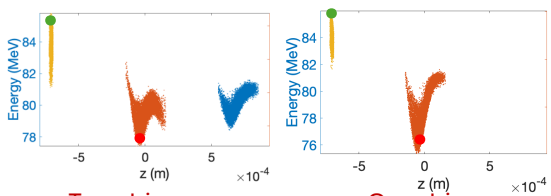
GPT Simulations



→ **R >2 at optimal n_{pe}**

Bunch distribution from GPT
$\Delta\xi = 720$ µm
→ Resonance at $n_{pe} = 3.8 \cdot 10^{15}$ cm^{-3}

Effect of ramps reduces the final value or R, but: enhancement with two ramped drive bunches
→ *observable*



Two drivers:
R = 1.4

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One driver:
R = 0.87

(Further optimization and additional driver to reach R>2)