Stability of the Plasma-Modulated Plasma Accelerator (P-MoPA)

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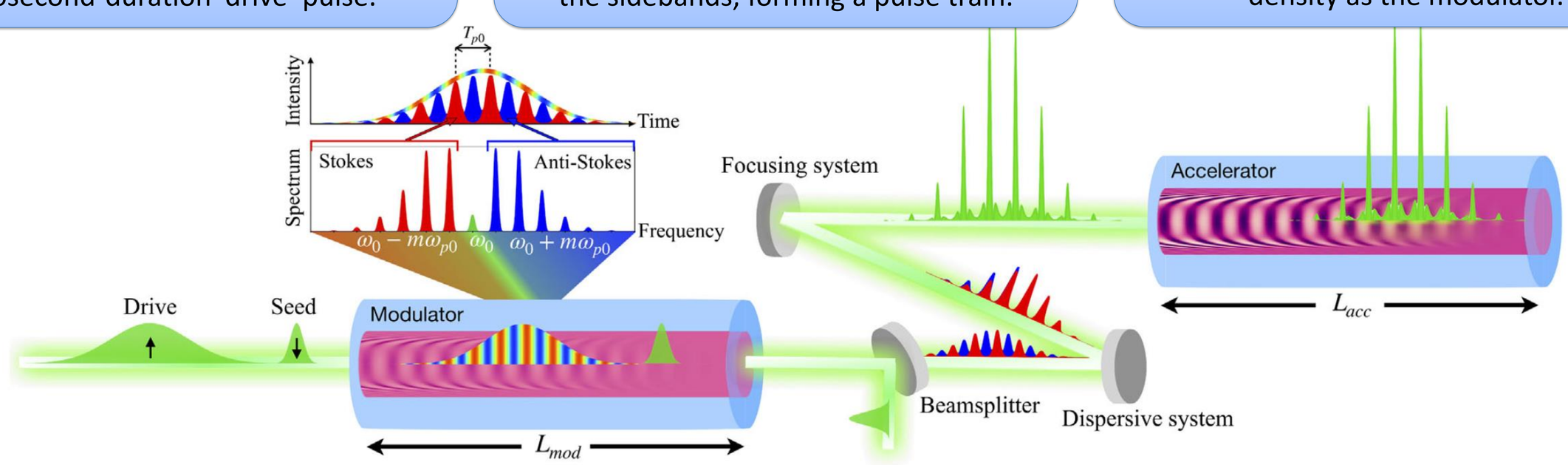
P-MoPA: GeV-scale accelerators driven by kilohertz lasers

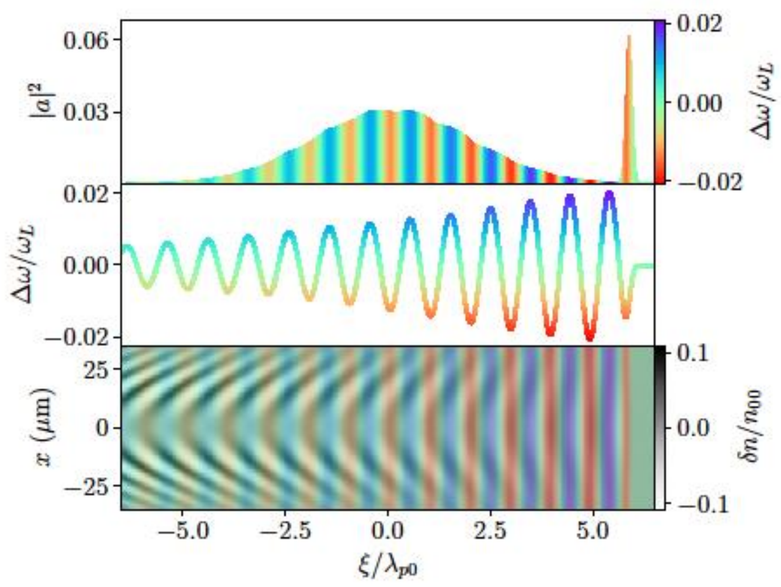
1. Modulation
The short low-energy 'seed' pulse excites a wake to spectrally broaden the high-energy picosecond-duration 'drive' pulse.

2. Compression
A dispersive optical system with appropriate GDD removes the relative spectral phase of the sidebands, forming a pulse train.

3. Acceleration
A large amplitude wake is resonantly excited in a plasma channel with the same density as the modulator.



The Plasma Modulator



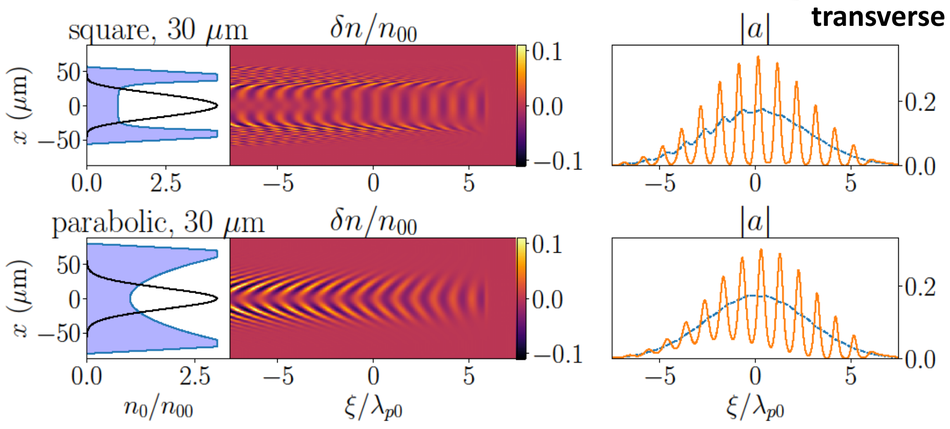
Spectral modulation is accumulated by the drive as it co-propagates with the seed wake.

Despite transverse wake structure, the spectral modulation is independent of transverse coordinate.

$$\frac{\Delta\omega(\xi; L_{\mathrm{mod}})}{\omega_L} = -L_{\mathrm{mod}} \frac{2c^2}{\omega_L^2 w_0^2} \left\langle \frac{\partial}{\partial\xi} \frac{\delta n(r, \xi; |a_s|^2)}{\Delta n} \right\rangle_{\perp}$$

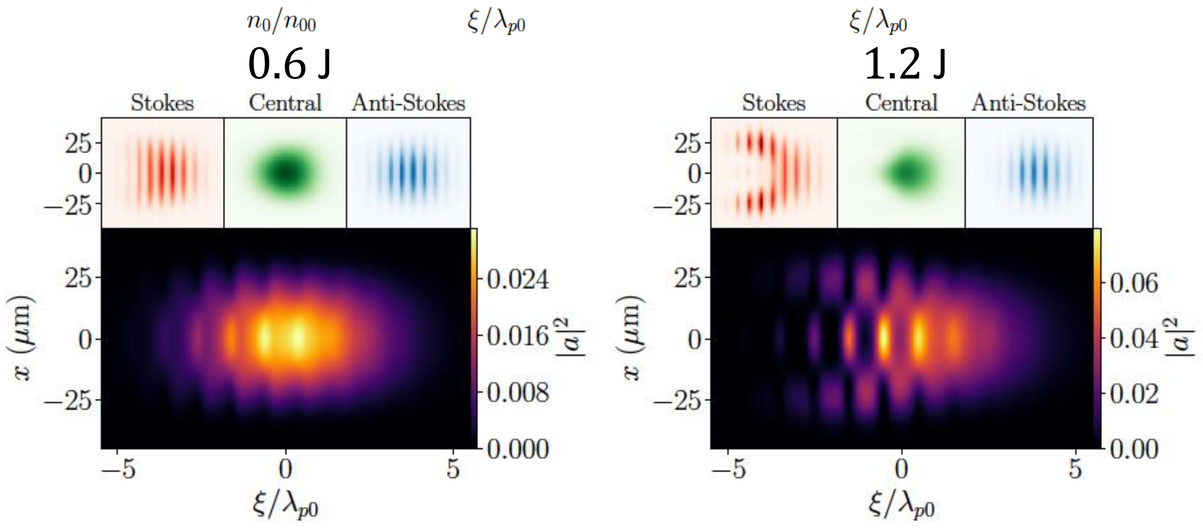
seed wake

intensity-weighted transverse average



0.6 J

1.2 J



Drive energy can reach the multi-Joule range before the onset of the transverse mode instability.

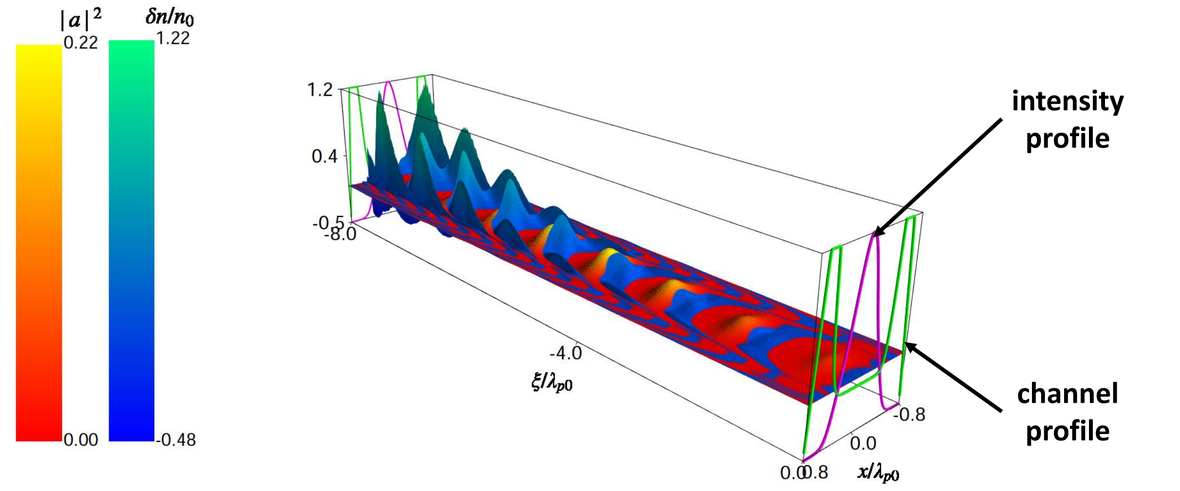
$$\left| \frac{\delta w/w_0}{\delta n_s/n_{00}} + \frac{k_{p0}^2 w_0^2}{8} \right| \frac{\omega_{p0} W_{\mathrm{drive}} \lambda_L^2}{\pi w_0^2} \ll P_{\mathrm{mod}}$$

seed wake

spot size mismatch

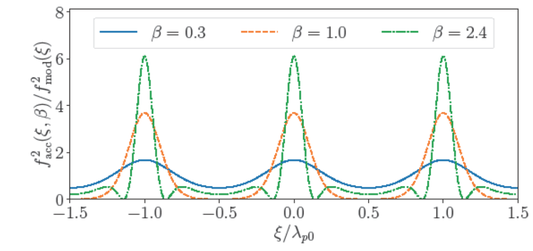
$$P_{\mathrm{mod}} = \frac{32\pi^2 m_e^2 \epsilon_0 c^5}{e^2} \approx 220\,\mathrm{GW}$$

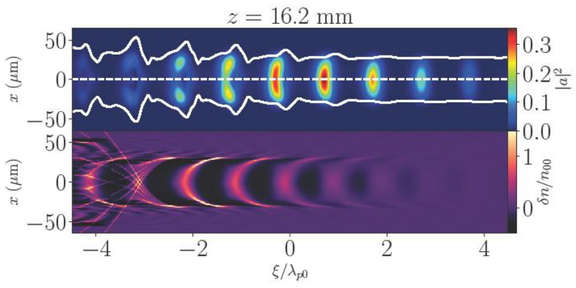
The Accelerator Stage



The longitudinal profile achieves its peak efficiency at modulator parameter β=1.43, driving a 72% larger wake than an ideal beatwave of the same energy.

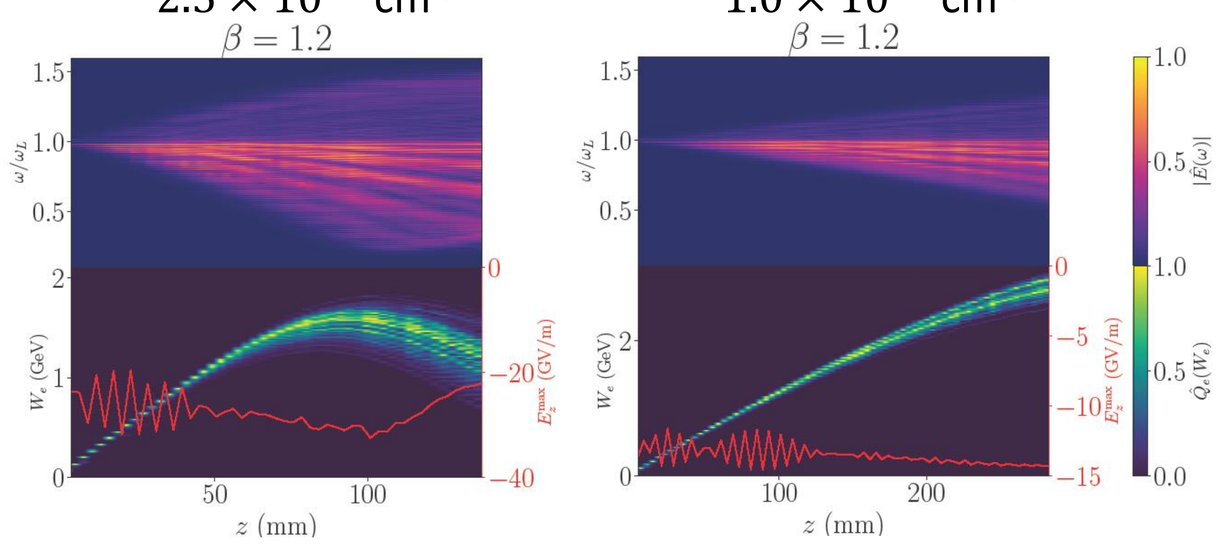
P-MoPA pulse trains resonantly drive wakefields in the partial bubble regime, reaching multi-GeV energy gains.





2.5×10^{17} cm^{-3}

1.0×10^{17} cm^{-3}



Taking into account constraints set by both plasma stages, 1.5 GeV and 3 GeV energy gains are feasible in 100 mm and 300 mm accelerators respectively.

[1] O. Jakobsson *et al.*, *Phys. Rev. Lett.*, **127**, 184801 (2021)
[2] J. J. van de Wetering *et al.*, *Physical Review E*, **108**, 015204 (2023)

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