The dynamics and interplay of beam hosing and self-modulation in experimental conditions

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Ask me! The author would be happy to give you more details whenever you find this symbol. ?

Motivation

- When a long ($L \gg \lambda_p$) particle beam propagates in plasma, it is subject to both the **hose instability (HI)** and the **self-modulation instability (SMI)**
- Concepts for single-stage, TeV-scale **plasma wakefield acceleration (PWFA)** rely on long particle beams as the driver
- **Beam hosing** causes the centroid of the beam to oscillate with increasing amplitude and is potentially detrimental to PWFA, though it can be suppressed after saturation of the SMI under certain conditions [1]
- **Self-modulation** can be seeded **(SSM)** to avoid instability and to generate high-amplitude wakefields, as in the case of the AWAKE experiment [2]
- Both instabilities typically modulate the beam centroid (hosing) or radius (self-modulation) **at the plasma wavelength λ_p**

Parameters for particle-in-cell simulations

- 3D simulations of a long proton bunch propagating along 10 m of plasma using OSIRIS [6], with a 10-centimeter-long moving window
- **Plasma:** $n_0 = 0.5 \times 10^{14}\,\mathrm{cm}^{-3}$
- **Proton bunch:** $\sigma_{zb} = 12$ cm, $\sigma_{rb} = 200$ µm, $N_b = 1.8 \times 10^{11}$, $\gamma \approx 480$
- **Seeding methods:**
  - **SM:** Cut in bunch profile ?
    Initial radius fluctuation: $\sigma_{y0}(\xi) = \mathbf{A}\sin(k_p\xi)$
  - **H:** Initial radius fluctuation: $y_{c0}(\xi) = \mathbf{A}\sin(\mathbf{k}\,\xi)$

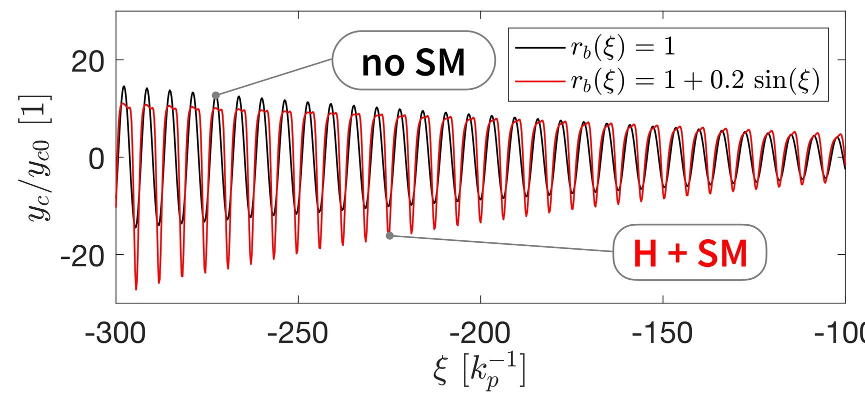
Expectations from theory

- Beam hosing has been observed under particular experimental conditions in AWAKE [3]
- Some of these events point to specific regimes of beam hosing: **"coupled hosing"** and **"long-wavelength hosing"**

Coupled regime

- When the seed levels for hosing and self-modulation are comparable, **linear wakefield theory** predicts a coupled regime where the centroid oscillation becomes asymmetric [4]

Beam centroid according to theory*

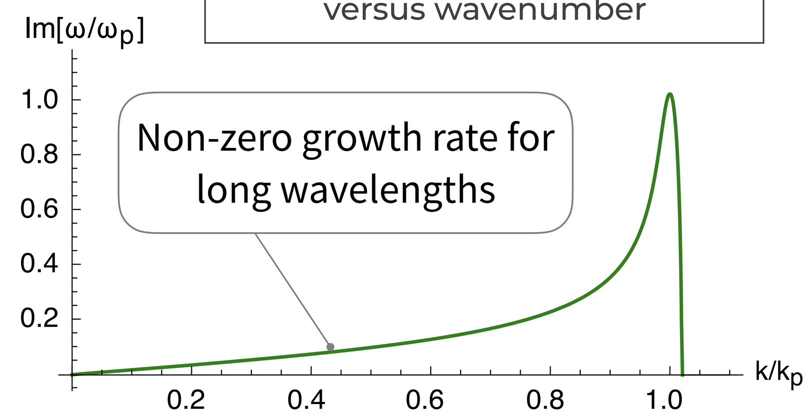


* Numerical solution of the differential equation for y_c assuming a non-evolving beam radius, up to $k_\beta z = 0.5$ (where $k_\beta = k_b/(2\gamma)^{1/2}$ and k_b is the beam wavenumber).

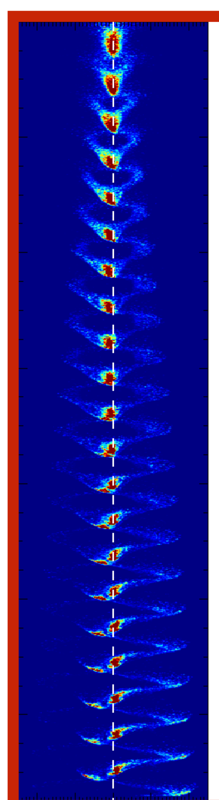
Long-wavelength regime

- Similarly to **laser hosing** [5], beam hosing can grow at different wavelengths than λ_p (or wavenumbers than k_p)
- This becomes evident in the **growth rate as a function of k**, obtained by assuming plane-wave solutions to the differential equation for y_c ?

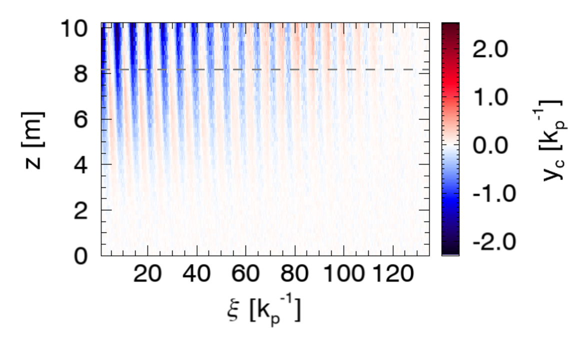
Growth rate for beam hosing versus wavenumber



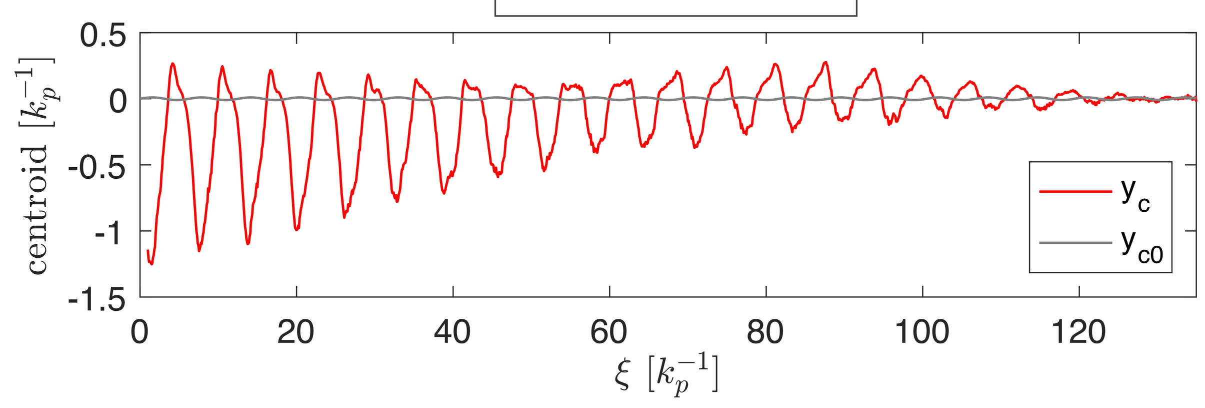
Simulations of the coupled and long-wavelength regimes



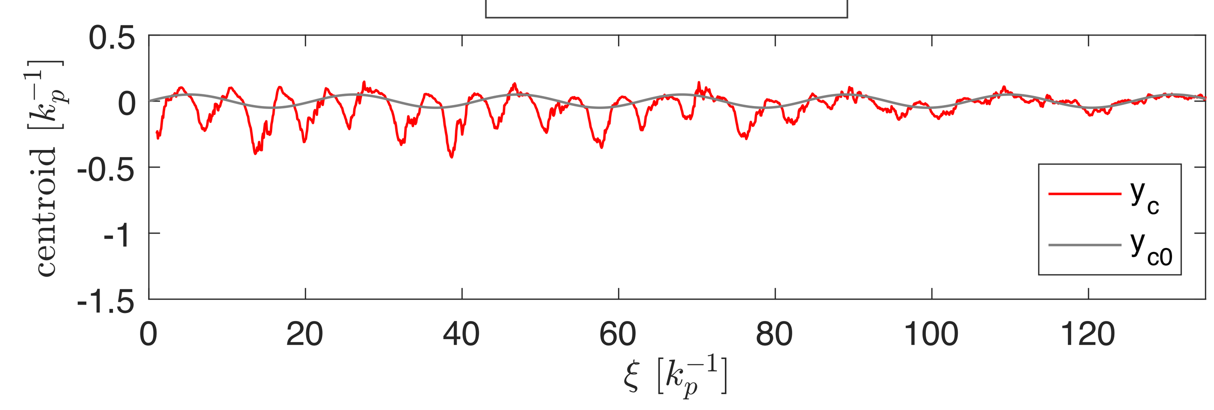
- A **simulation** of AWAKE conditions where both **hosing and self-modulation are seeded** (at k_p) shows similar centroid features as theory predicts for the coupled regime

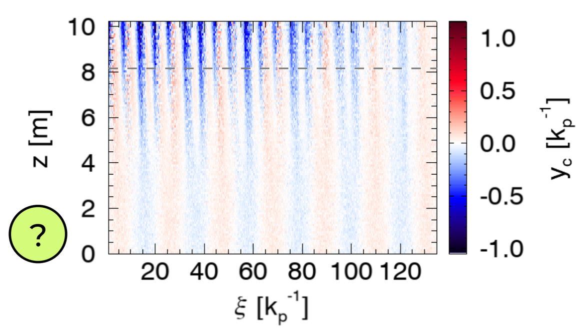


Beam centroid



Beam centroid





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- The coupled regime is still observed even when the initial centroid perturbation y_{c0} is at a **longer wavelength** ($k = 0.3\,k_p$)
- A simulation where **only hosing at 0.3 k_p was seeded** showed **no significant growth** after 10 m (not shown)

Takeaways: A regime where self-modulation and hosing couple to each other produces distinct features, and some hosing events in AWAKE are consistent with this regime
Simulations suggest that long-wavelength hosing will only develop in AWAKE conditions if coupled with self-modulation

Comparing seed levels

- How can we **quantify the level of seeding** for an arbitrary initial bunch profile?
- Method to quantify the "seed levels" for hosing and self-modulation S_h and S_{sm}:

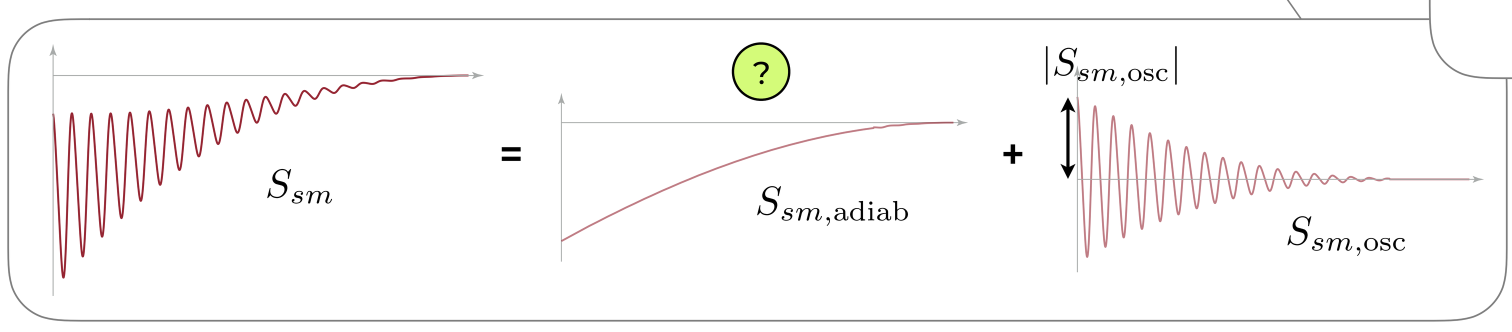
  1) Use the right side of the differential equations for hosing and self-modulation

$$\frac{d^2 y_c}{dz^2} = \frac{m_e}{\gamma M_b}\underbrace{\frac{\langle F_y\rangle}{eE_0}}_{S_h}$$

?

$$\frac{d^2 \sigma_y}{dz^2} = \frac{m_e}{\gamma M_b}\underbrace{\frac{\langle (y-y_c)F_y\rangle}{\sigma_y\, eE_0}}_{S_{sm}} + \frac{\varepsilon_y^2}{\sigma_y^3}$$

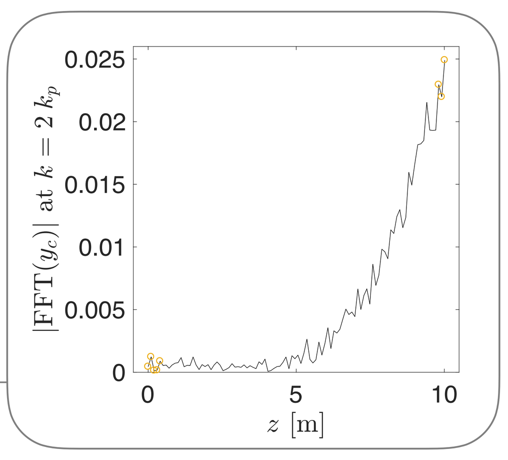
  2) Take only amplitude of oscillatory component of seed level $|S_{\cdot,osc}|$, e.g.



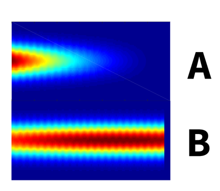
- One characteristic of the coupled regime is the **growth of harmonics of k_p** in the FFT of the centroid [4]
- Method to quantify "coupling" (growth Γ_c):

  1) Use the ratio of the signal at $k = 2\,k_p$ at the end of the simulation ($z = 10$ m) to the initial one

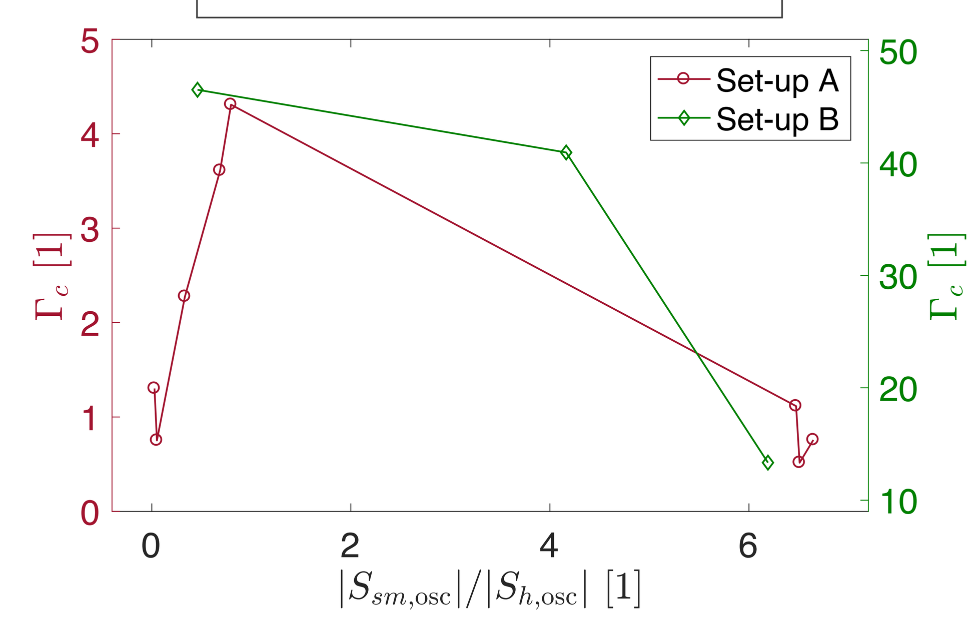
$$\Gamma_c = \frac{|\mathrm{FFT}(y_c)|_{2k_p,10m}}{|\mathrm{FFT}(y_c)|_{2k_p,0}}$$



- Does this method confirm the **expectation for the coupled regime**? (coupling happens when S_h and S_{sm} are similar)
- Seed level analysis applied to **several simulations** with different seeding methods and amplitudes (two different set-up's A and B)
- Results are **consistent** with what we expect, though more data points are required



Growth of second k_p harmonic vs. ratio of SM to H seed level



Takeaway: A method to quantify hosing and self-modulation seed levels was proposed, and a first test yielded results that are consistent with theoretical expectations for the coupled regime

References

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