Experimental Measurement of the Saturation Length of Self-Modulation Instability

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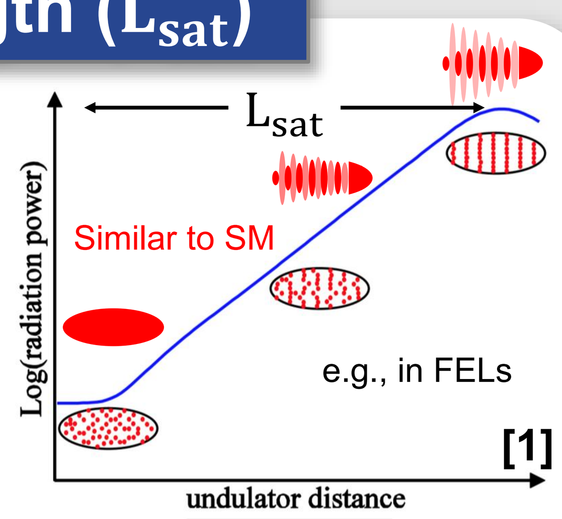
Abstract

A long, narrow bunch propagating in plasma is subject to the self-modulation (SM) instability, a transverse process. We study the evolution of SM along the plasma by changing the length of plasma over which the bunch propagates. In particular, we observe the effect of the transverse wakefields on the bunch by measuring the size of the halo of defocused particles at a screen downstream from the plasma. We observe that the maximum radius of the halo changes with beam and plasma parameters. Numerical simulation results suggest that there is a correlation between the plasma length for which the halo is fully formed, and the plasma length for which the SM process saturates. We study this halo formation for different parameters, and compare it with numerical simulations results.

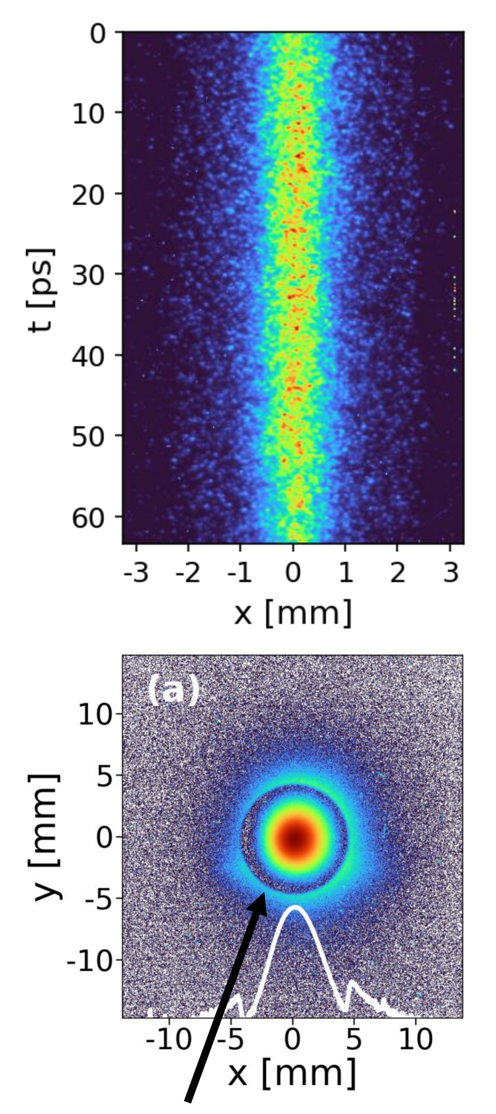
Saturation length (L_{sat})

- L_{sat}: distance over which growing quantity becomes maximum
- For FELs: defines undulator length required to reach maximum power
- For SM: defines plasma length required to reach high amplitude wakefields [2]

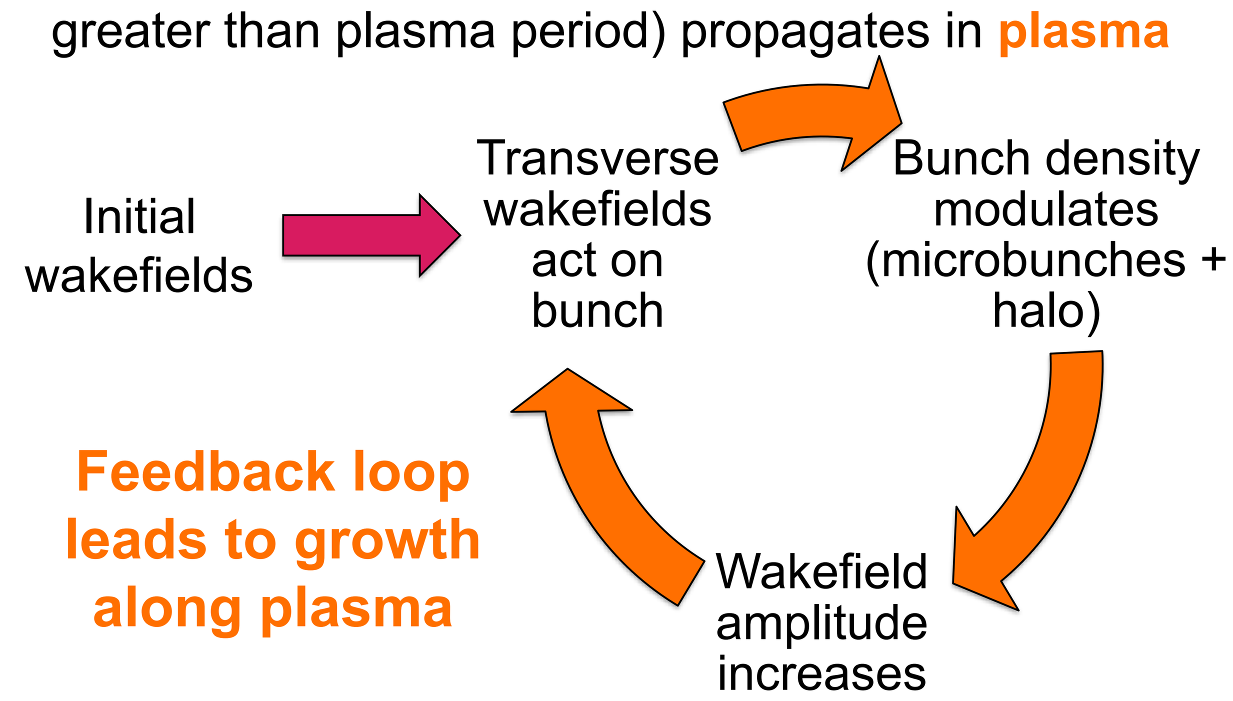


Self-Modulation (SM)

PLASMA OFF



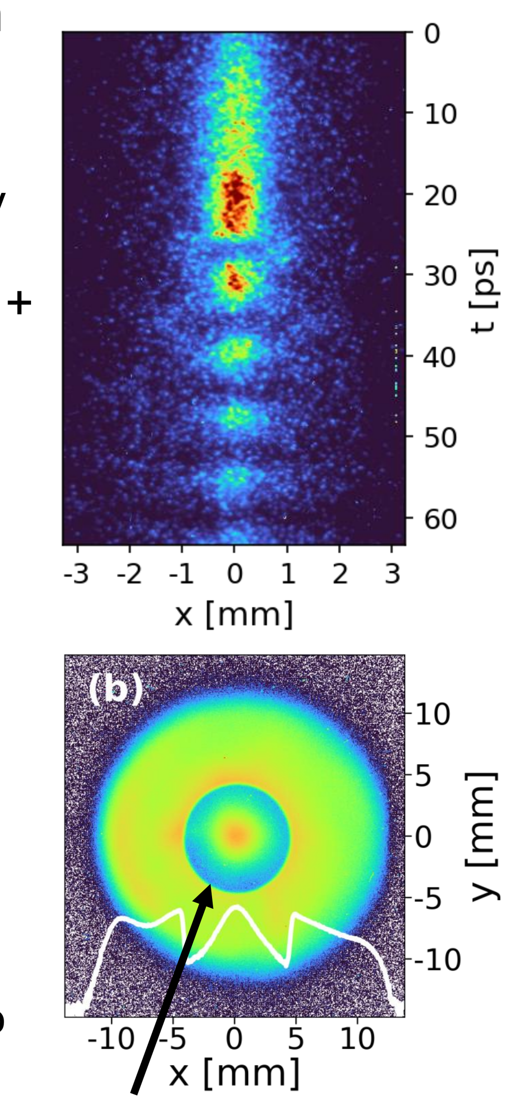
Instability that develops when long bunch (duration greater than plasma period) propagates in plasma



- Growth saturates when the bunch cannot modulate further
  - When the train of microbunches is formed
- SM is a transverse process: formation of the train leads to halo of defocused particles

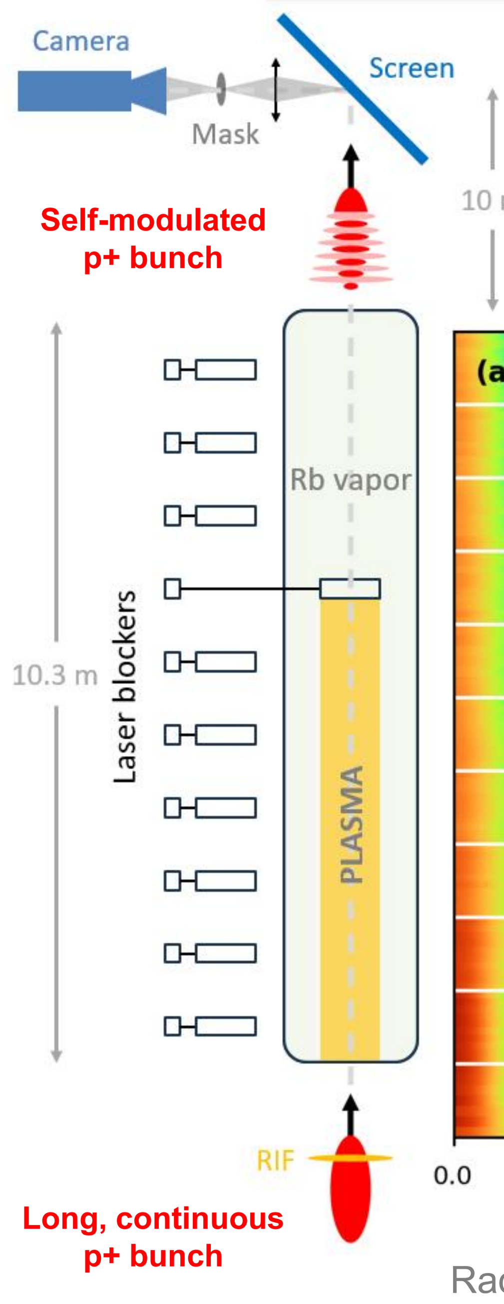
Halo stops forming when SM saturates ?

PLASMA ON



Mask allows simultaneous observation of halo and core without saturating camera

Experimental setup

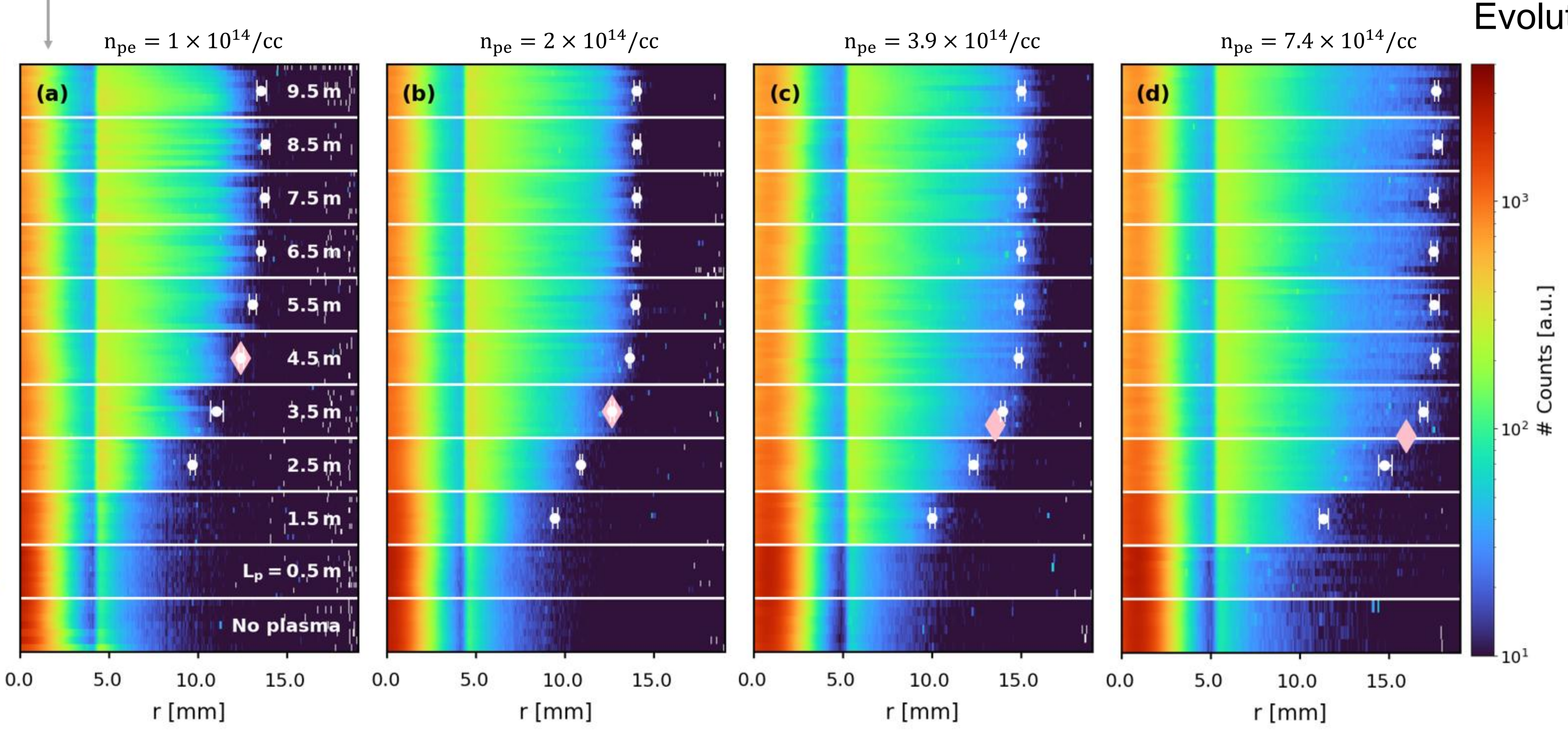


Plasma :
- 120 fs – 200 mJ laser pulse (RIF)
- Ionizes rubidium vapor
- Plasma density (n_{pe}) $1 - 10 \times 10^{14}$/cc
- Variable length $L_p = 0.5 - 9.5$ m

Proton bunch :
- $N_b = 3 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 200$ μm
- $\sigma_t = 170$ ps >> $\tau_{pe} \cong 3 - 12$ ps

SM develops !

L_{sat} versus plasma density



Radial slices of transverse distribution of bunch at screen for different L_p. White symbols: radius of the halo r_h. Pink diamonds: saturation point of radius ($r_h = 0.9\, r_{h,max}$).

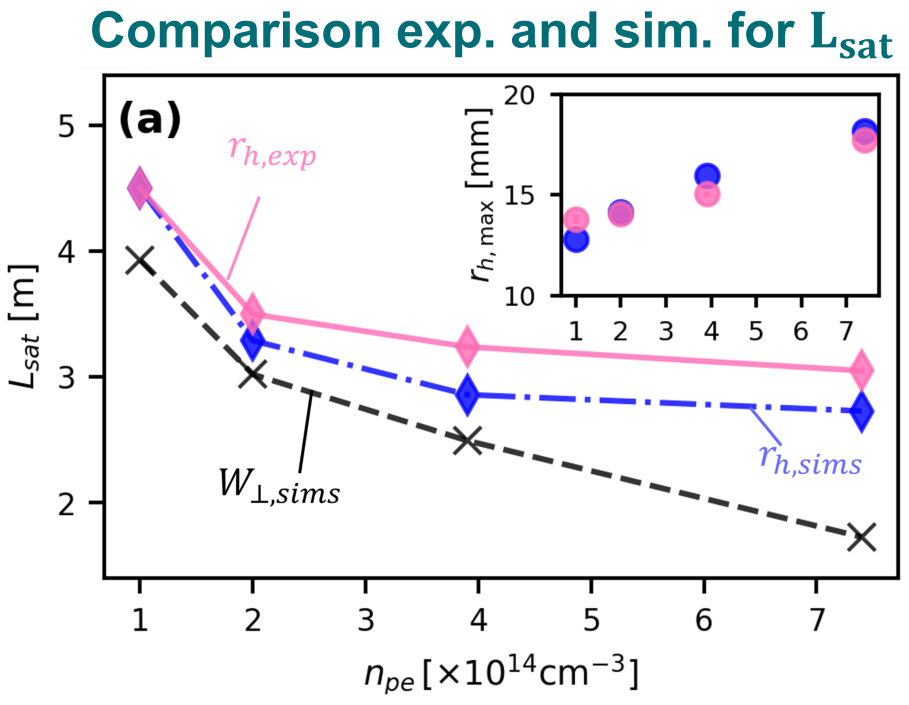
Evolution of the halo in three phases [Fig.(d)]:

1) $L_p = 0$ to $\cong 0.5$ m:
   - Little evolution of bunch
   - Wakefields:
     - Small amplitude
     - Predominantly focusing
2) $L_p \cong 0.5$ to $\cong 4.5$ m:
   - Halo forms:
     - Charge redistributes transversely
     - Halo radius increases
   - SM grows:
     - Wakefields acquire defocusing regions
     - Wakefields increase in amplitude
3) $L_p \cong 4.5$ to $\cong 9.5$ m:
   - Halo radius stops increasing
   - Distribution essentially unchanged

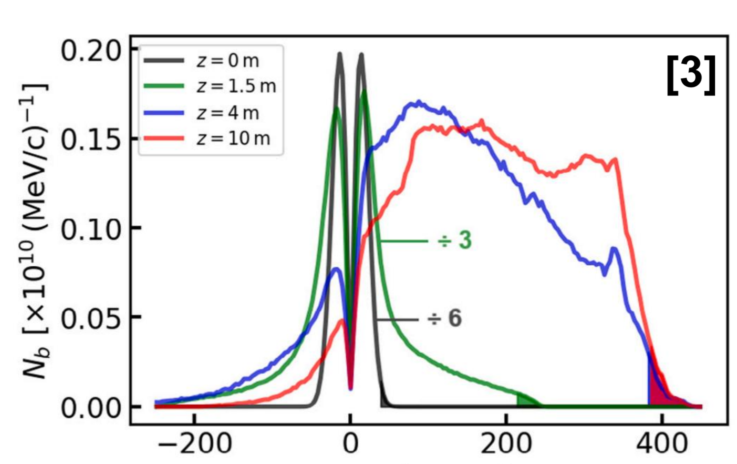
Signature expected from SM saturation

Experiment and simulation

Comparison exp. and sim. for L_{sat}

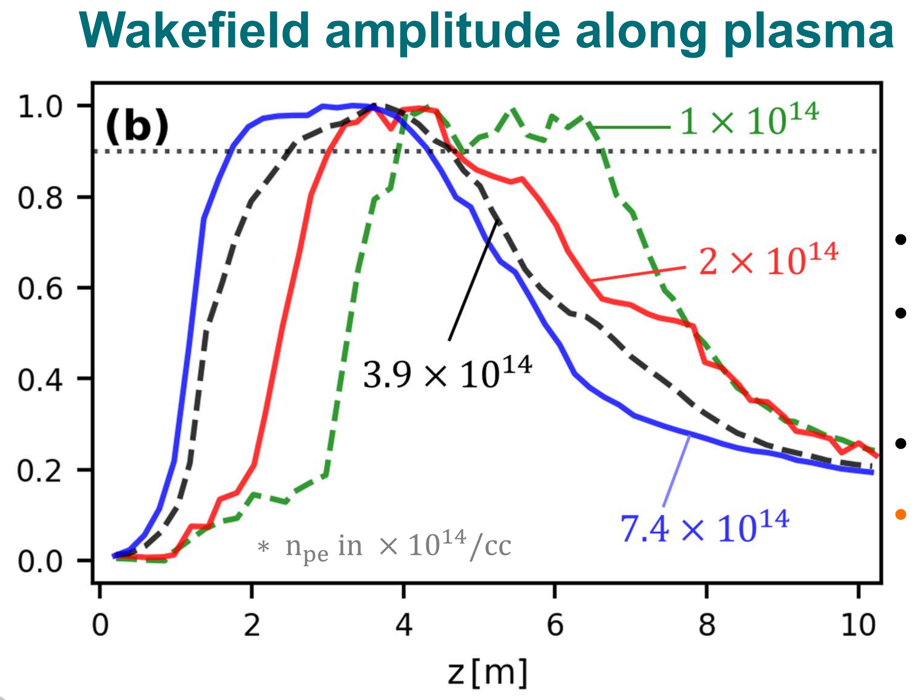


- Saturation defined as 90% of max value
- Excellent agreement between exp. and sim. (L_{sat}, $r_{h,max}$)
- L_{sat} decreases when n_{pe} increases
- Halo saturation length provides good estimate for SM saturation length



Bunch train continues to shed protons past saturation, but they acquire less transverse momentum

Wakefield amplitude along plasma

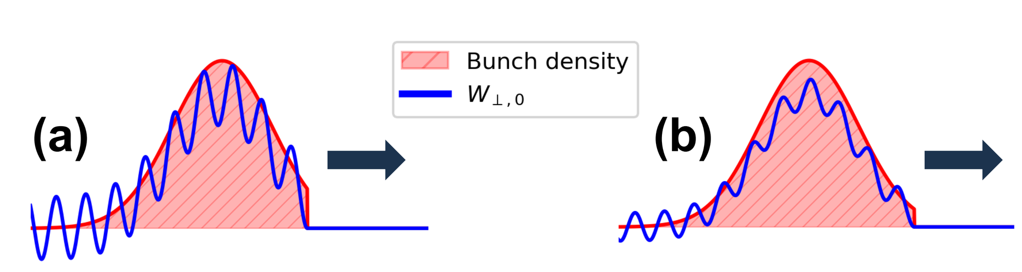


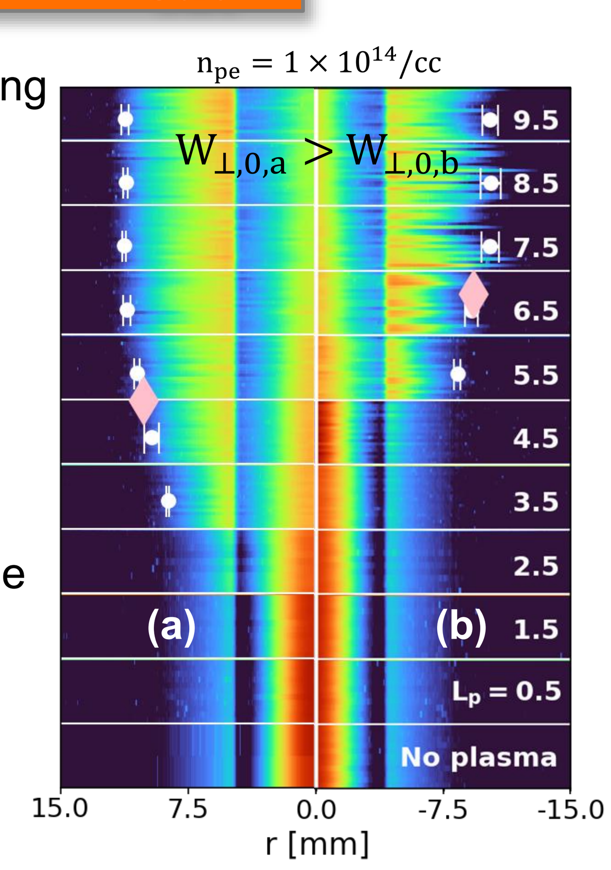
- Fields grow, saturate and decay
- Saturation occurs earlier when n_{pe} increases
- Black crosses on [Fig.(a)]
- L_{sat} decreases when n_{pe} increases

LCODE simulations

Initial wakefield ($W_{\perp,0}$) on L_{sat}

- $W_{\perp,0}$ proportional to bunch density at RIF timing along the bunch





- Vary $W_{\perp,0}$ by varying RIF timing ($\Delta N_b < 2.5\%$)
- Right: $W_{\perp,0,b}$ from RIF too low: SM develops from noise
- Clear difference between the two evolution
  - Halo visible earlier for larger $W_{\perp,0}$ ($W_{\perp,0,a} > W_{\perp,0,b}$)
  - SM saturates earlier for larger $W_{\perp,0}$
  - More variations when not seeded (instability)

What ?

- We determined the saturation length of SM for the first time
- For all parameters relevant to AWAKE, $L_{sat} \sim 2 - 5$ m < 10 m
- L_{sat} decreases when n_{pe} increases
- L_{sat} decreases when $W_{\perp,0}$ increases

How ?

- By measuring the radius of the halo of defocused protons formed during SM development for different lengths of plasma
- By comparing exp. and sim. results
- Saturation of the halo provides good estimate for saturation of SM

Why ?

- L_{sat} is a fundamental parameter of SM
- Measuring L_{sat} is crucial for the design of plasma wakefield accelerators using a long (self-modulating) drive bunch
- Injection of witness bunch must occur after L_{sat} [2]

[1] Review of x-ray free-electron laser theory, H. Zhirong and al, Phys. Rev. Accel. Beams, 2007
[2] Phase Velocity and Particle Injection in a Self-Modulated Proton-Driven Plasma Wakefield Accelerator, A. Pukhov and al., Phys. Rev. Lett., 2011
[3] Development of self-modulation as a function of plasma length, A. Clairembaud and al., NIMA, 2025

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