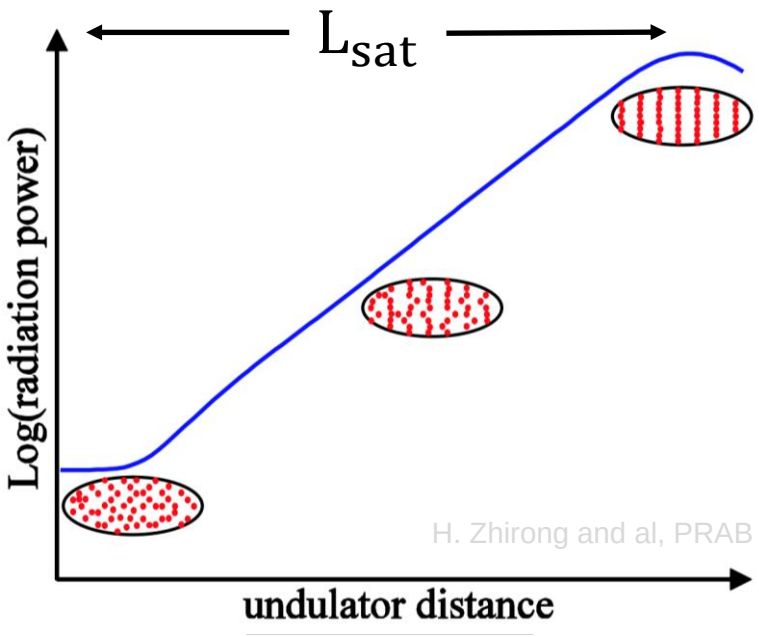
Experimental measurement of the saturation length of SM

Arthur CLAIREMBAUD

Saturation length of an instability

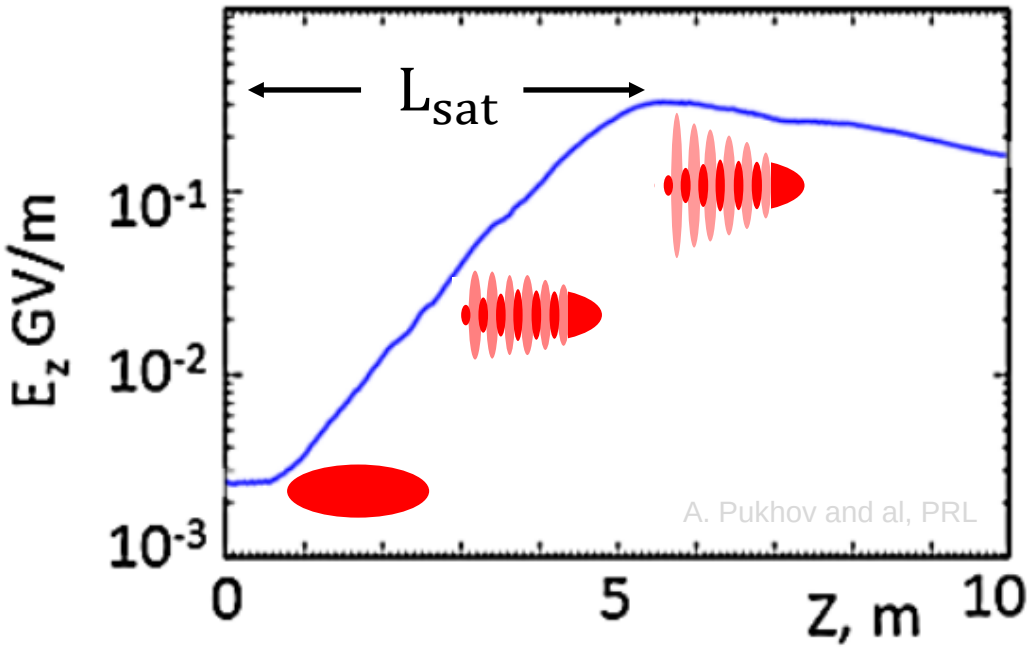


Microbunching instability in FELs

- Bunch modulates along undulator
- Longitudinal process
- Exponential growth of radiation power
- Saturates when fully microbunched

- Growing quantity can be measured directly

➔ Defines undulator length to reach max. power



Self-modulation instability in plasmas

- Bunch modulates along the plasma
- Transverse process
- Quasi-exponential growth of wakefield amplitude
- Saturates when fully microbunched

- Growing quantity can't be measured directly

➔ Why important for SMPWFA ?

Context for AWAKE

PRL 107, 145003 (2011) PHYSICAL REVIEW LETTERS week ending 30 SEPTEMBER 2011

Phase Velocity and Particle Injection in a Self-Modulated Proton-Driven Plasma Wakefield Accelerator

A. Pukhov,[1] N. Kumar,[1] T. Tückmantel,[1] A. Upadhyay,[1] K. Lotov,[2] P. Muggli,[3] V. Khudik,[4] C. Siemon,[4] and G. Shvets[4]
[1]*Institut für Theoretische Physik I, Universität Düsseldorf, 40225 Germany*
[2]*Budker Institute of Nuclear Physics and Novosibirsk State University, 630090 Novosibirsk, Russia*
[3]*Max-Plank-Institut für Physik, 80805 München, Germany*
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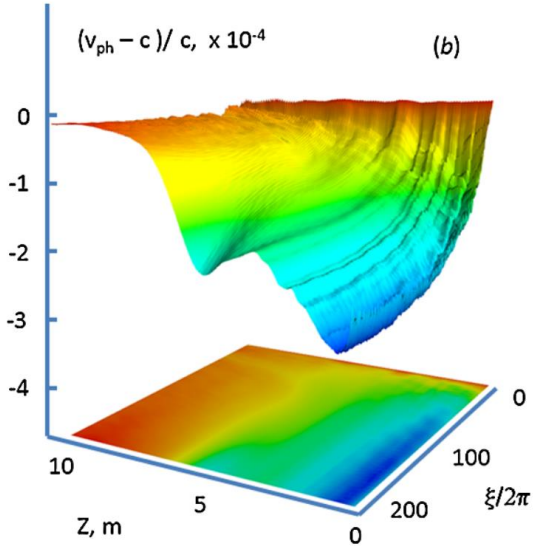

- During growth of SM, $v_{ph} < v_g$ (see Helena's talk)
- Electrons may experience defocusing or deccelerating regions of the wakefields
- Solution is to inject the witness beam where the $v_{ph} \approx v_{g,e}$

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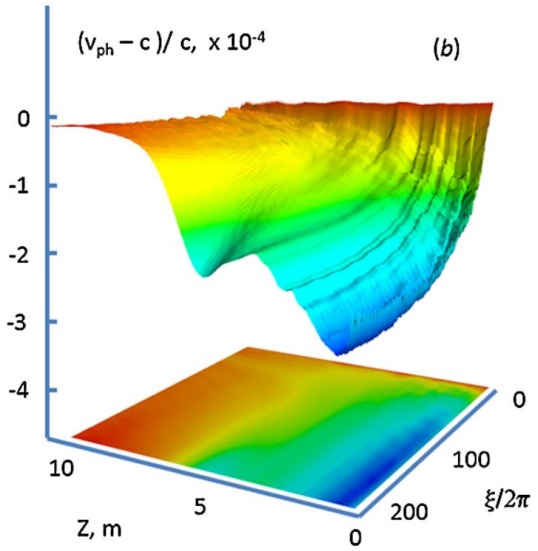

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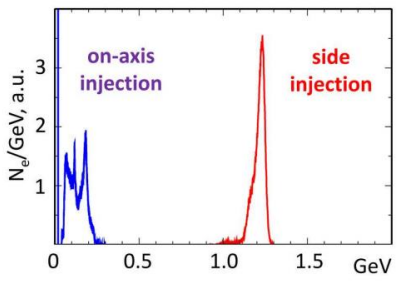

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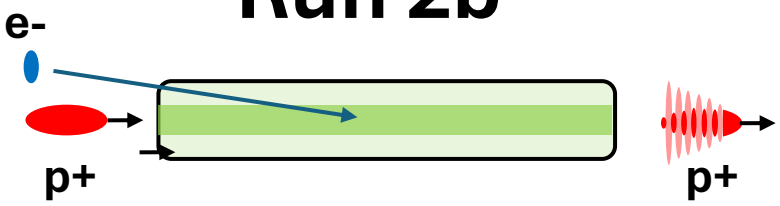
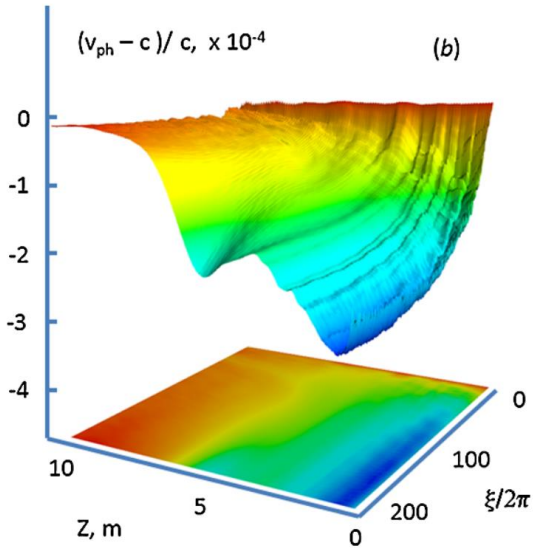
Run 2b



Side injection...



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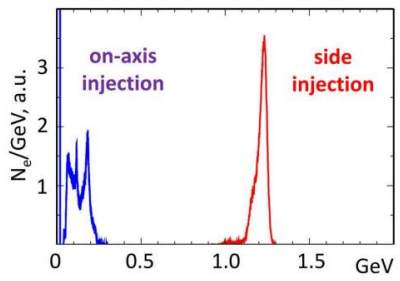
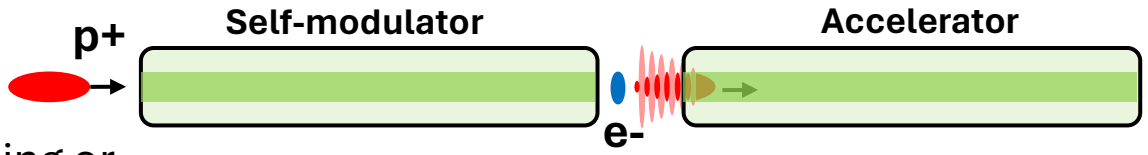


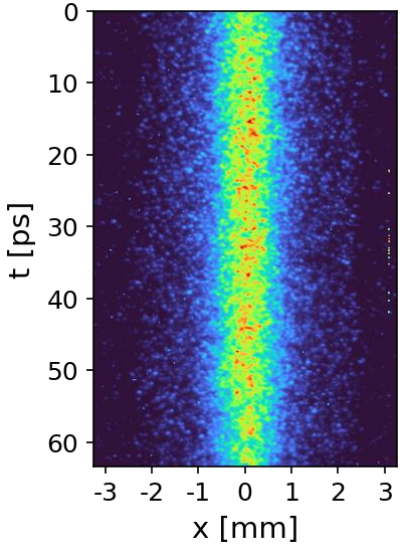
Run 2c



SM needs to saturate within the self-modulator length

Self-modulation instability

PLASMA OFF



Initial wakefields

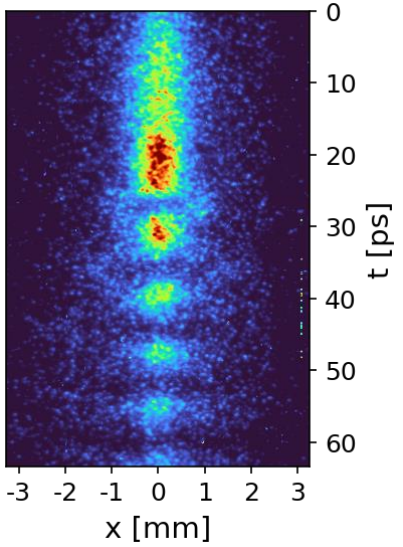
Transverse wakefields act on bunch

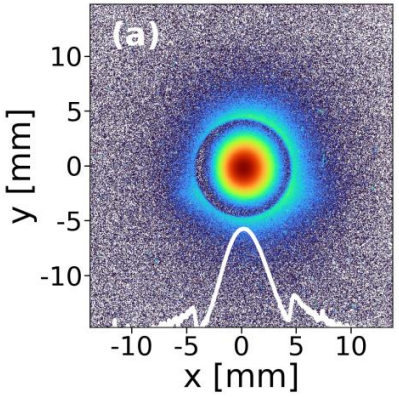
Bunch density modulates (microbunches + halo)

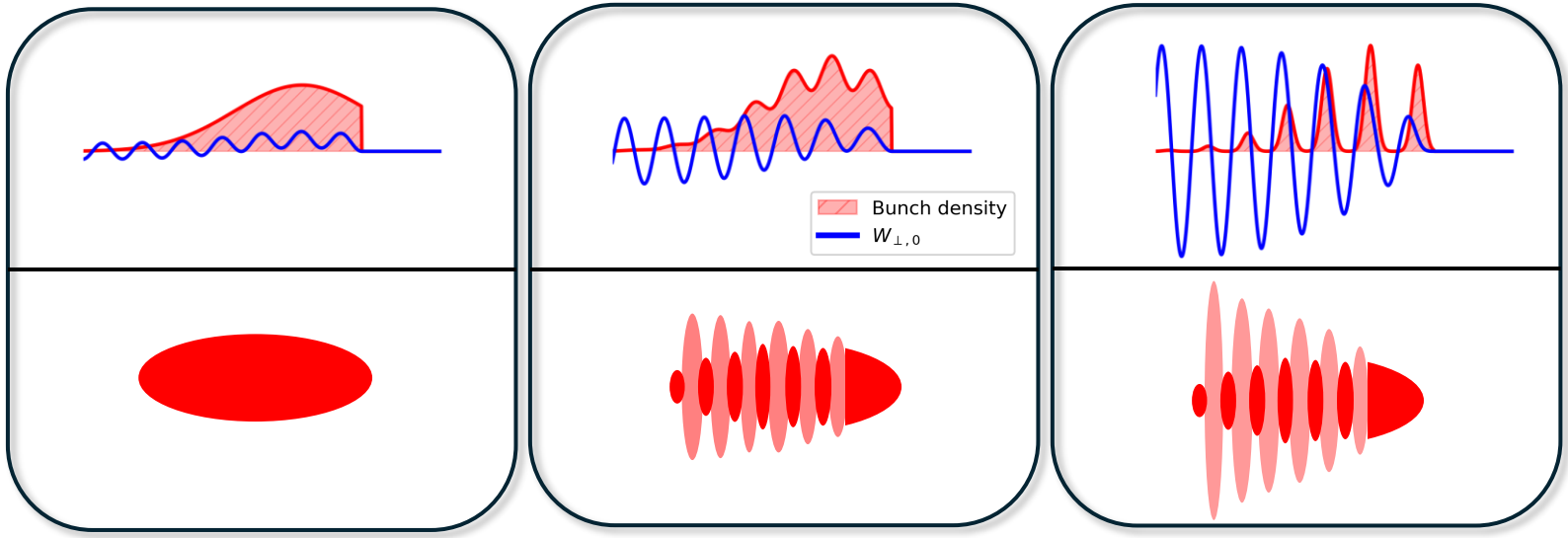
Wakefield amplitude increases

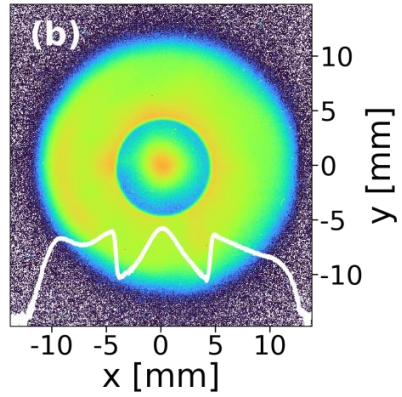
Bunch is fully modulated SM saturates

PLASMA ON









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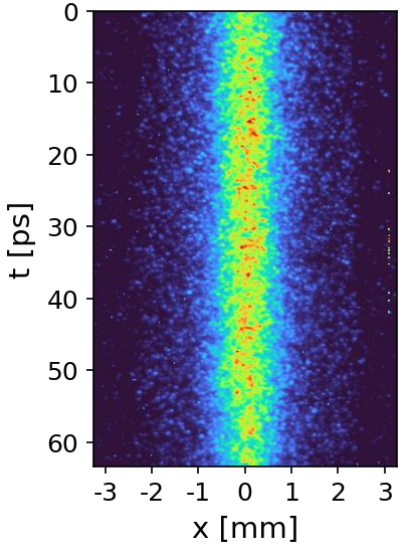

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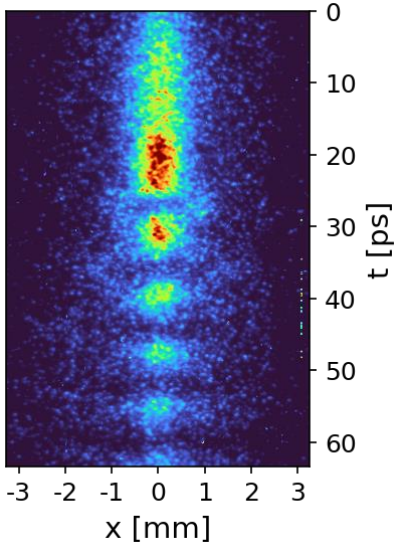

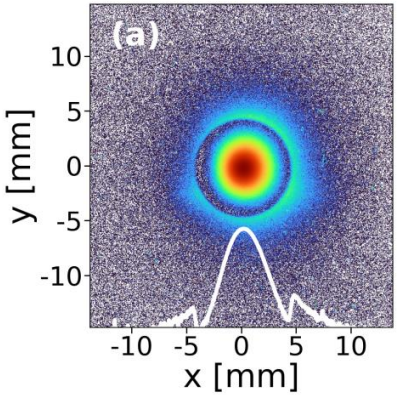

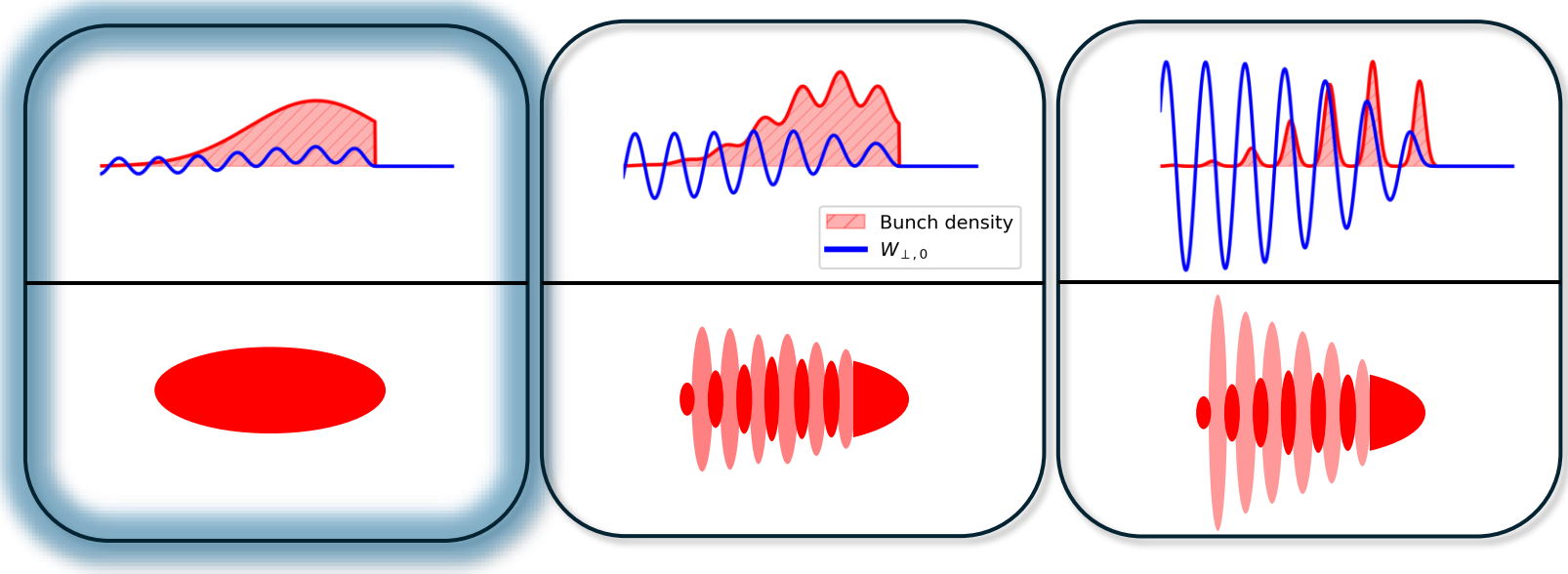

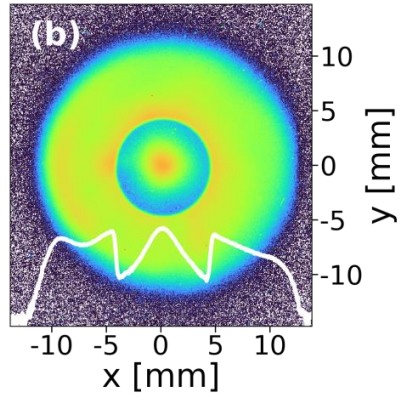

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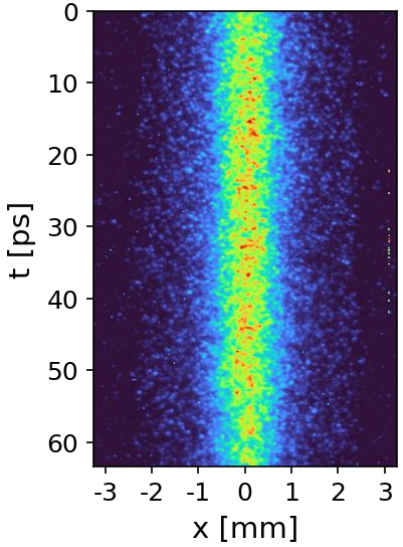

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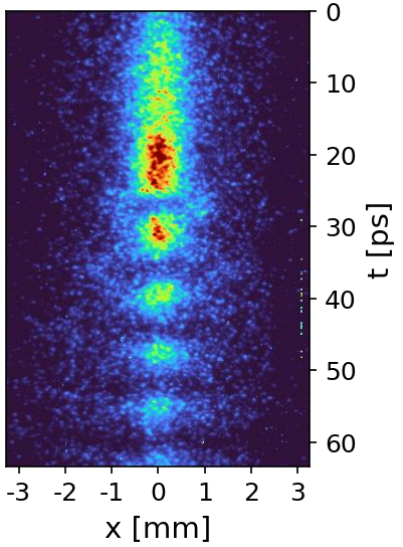

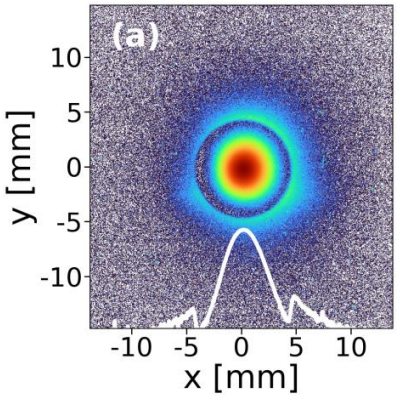

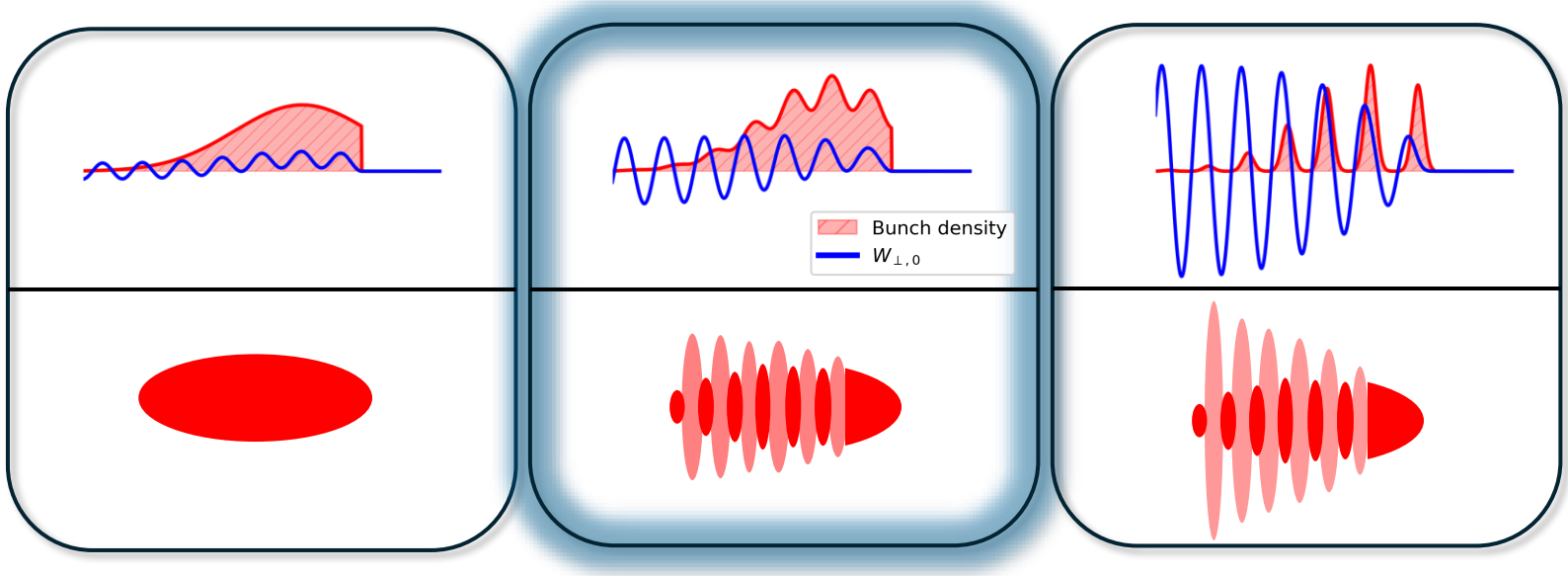

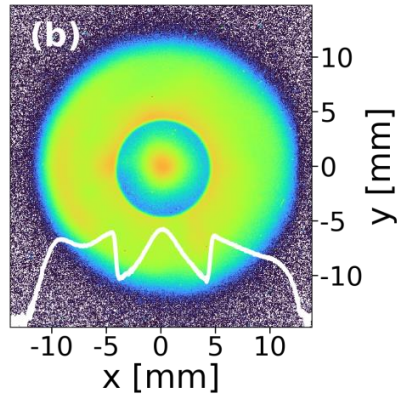

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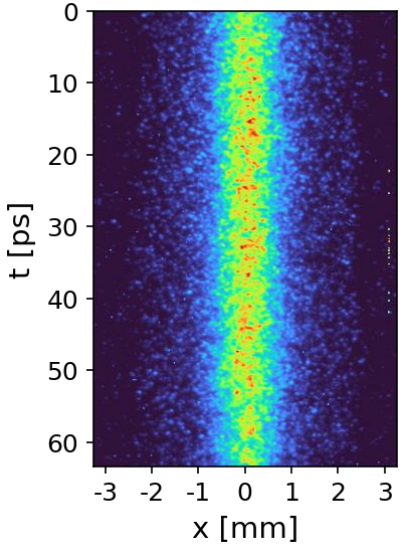

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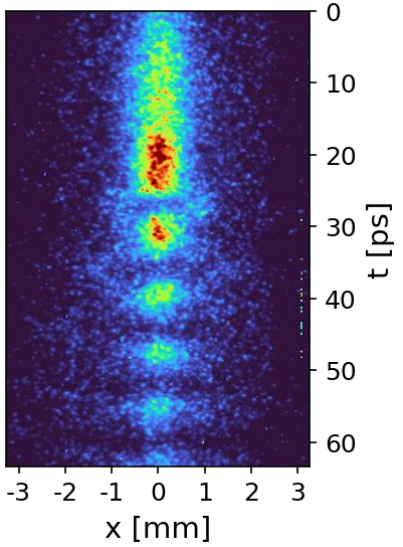
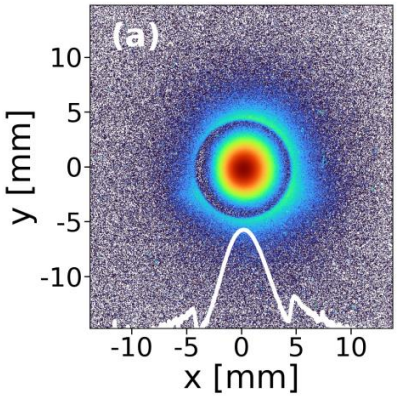
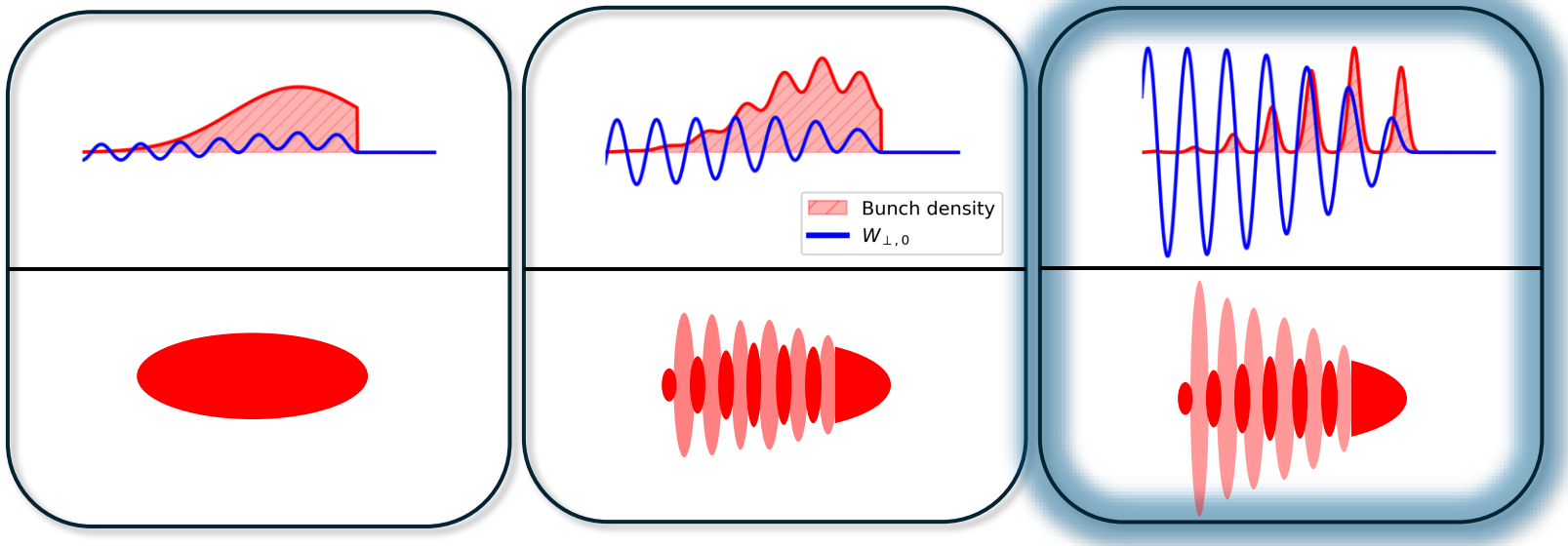
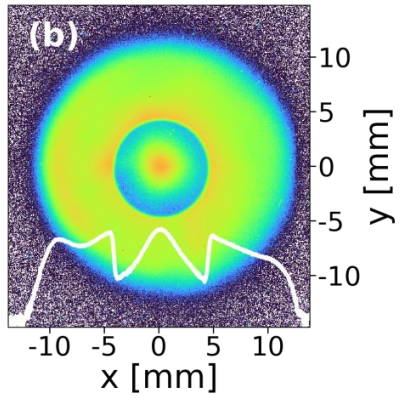
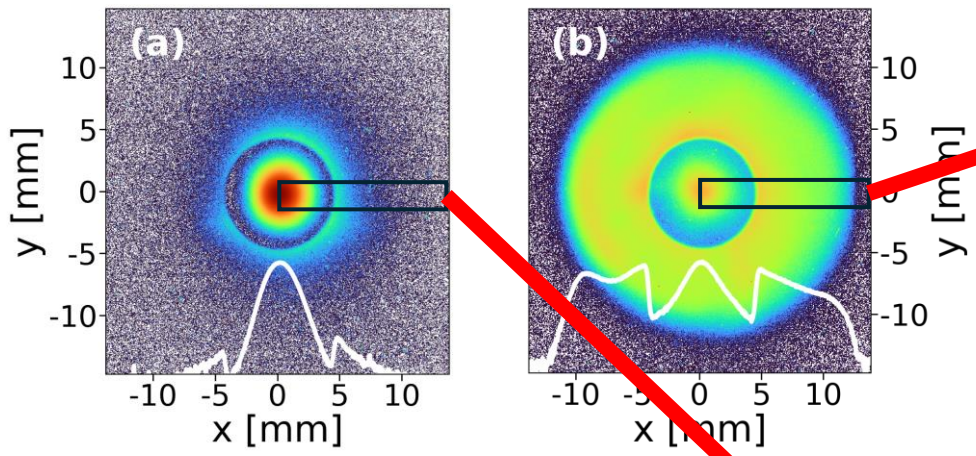


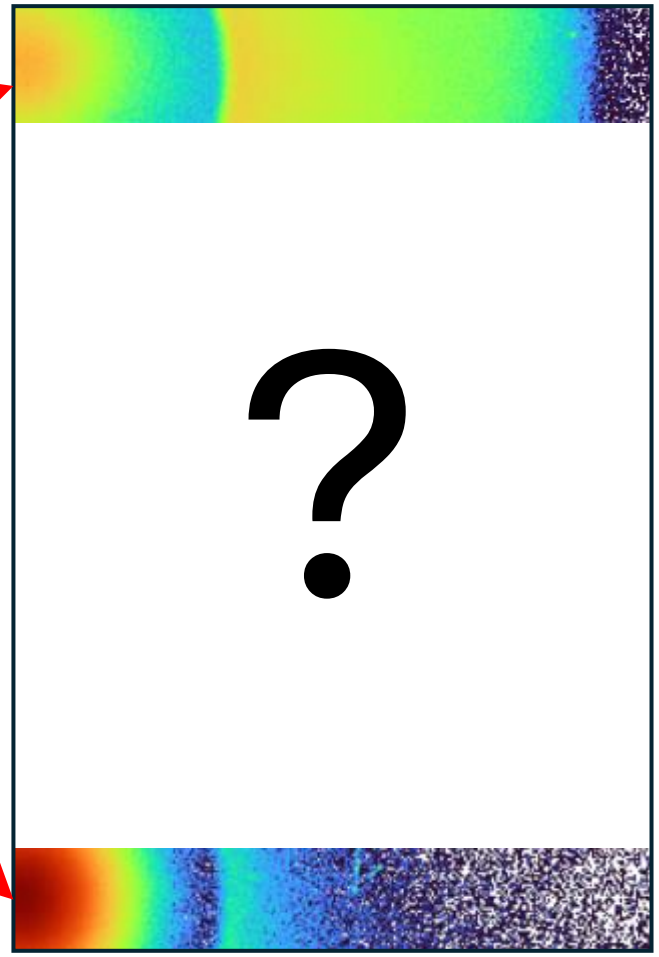






Halo of defocused particles





10m of plasma

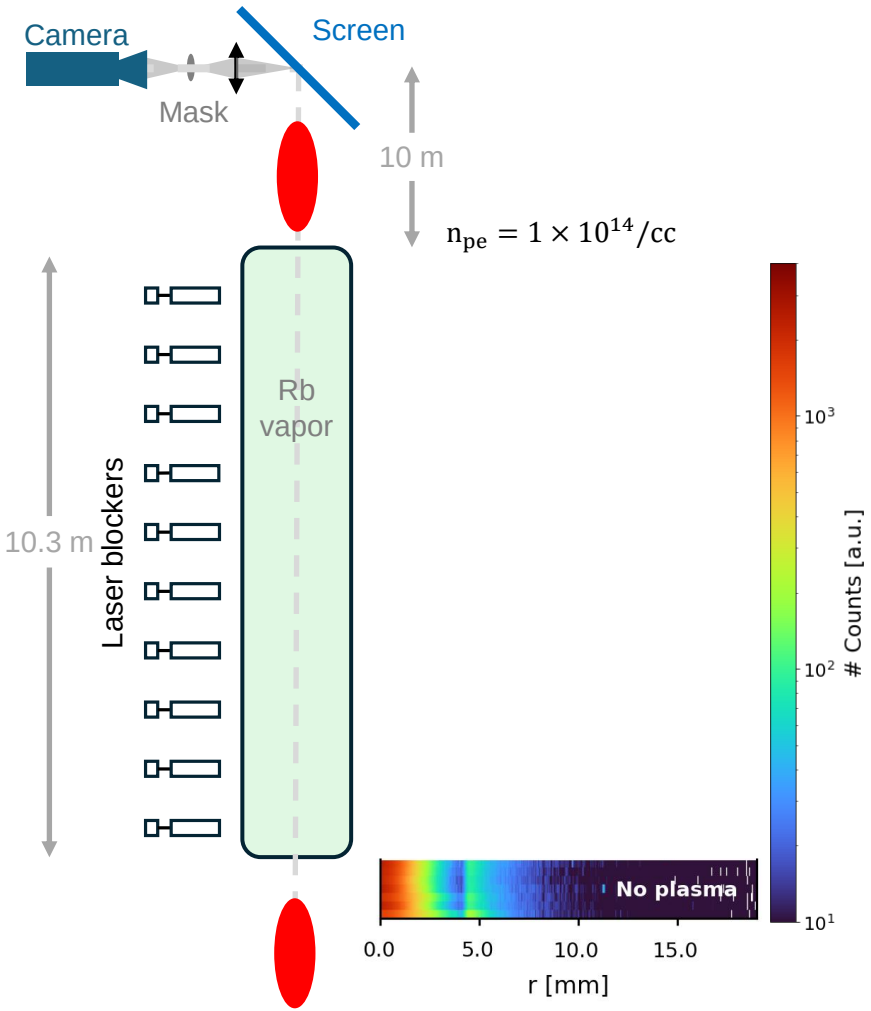
No plasma

Zeroth order expectation:
➔ SM saturates when bunch fully modulated*

- *when the halo is fully formed and defocused particles drift ballistically

Goal: Determine the location along the plasma where this halo stops forming

Halo formation along the plasma



- Slice of the halo (~10 events per slice)
- Vapor is ionized by a relativistic ionization front (RIF)
- We vary the plasma length (L_p) by stopping the laser at different locations
- $L_p = [0.5, 1.5, 2.5, \ldots, 9.5]$ m

- SM develops over different distance
- SM is seeded – process is reproducible

- Observing the state of the bunch at different plasma lengths is equivalent to observing the evolution of the bunch along the plasma

Proton bunch :

- $N_b = 3 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 200$ μm
- $\sigma_t = 170$ ps
- $t_{RIF} = 100$ ps

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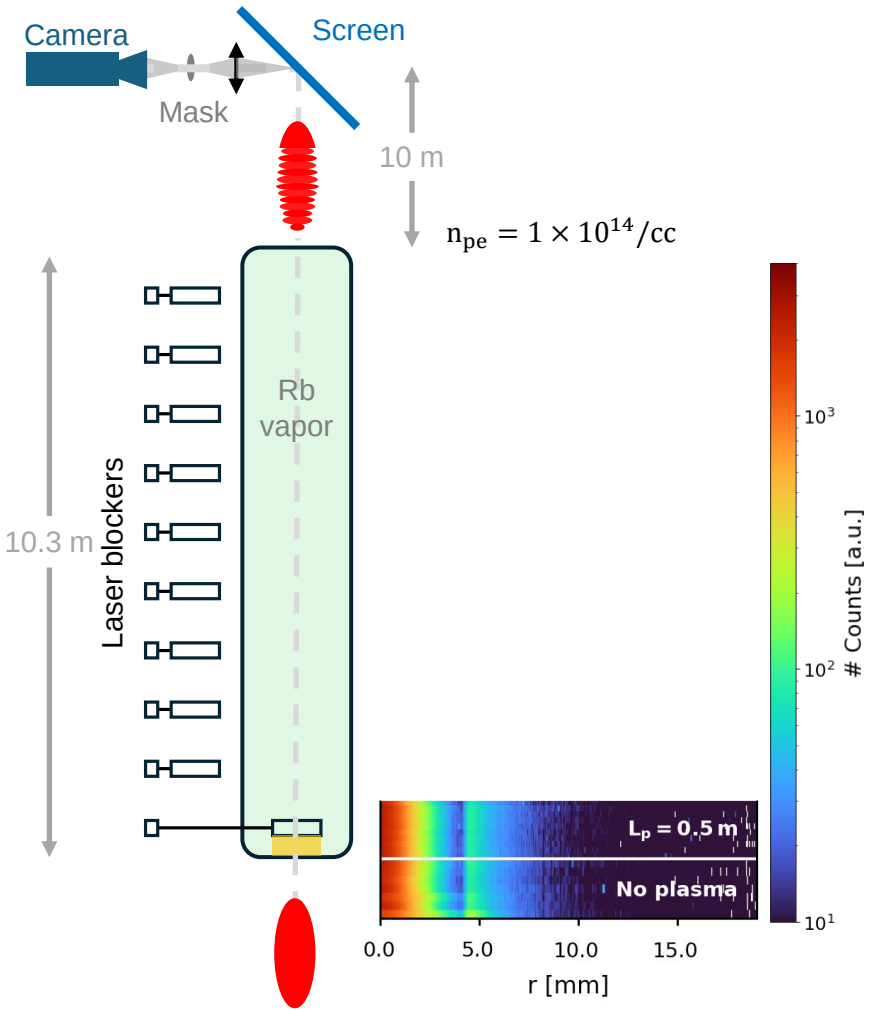

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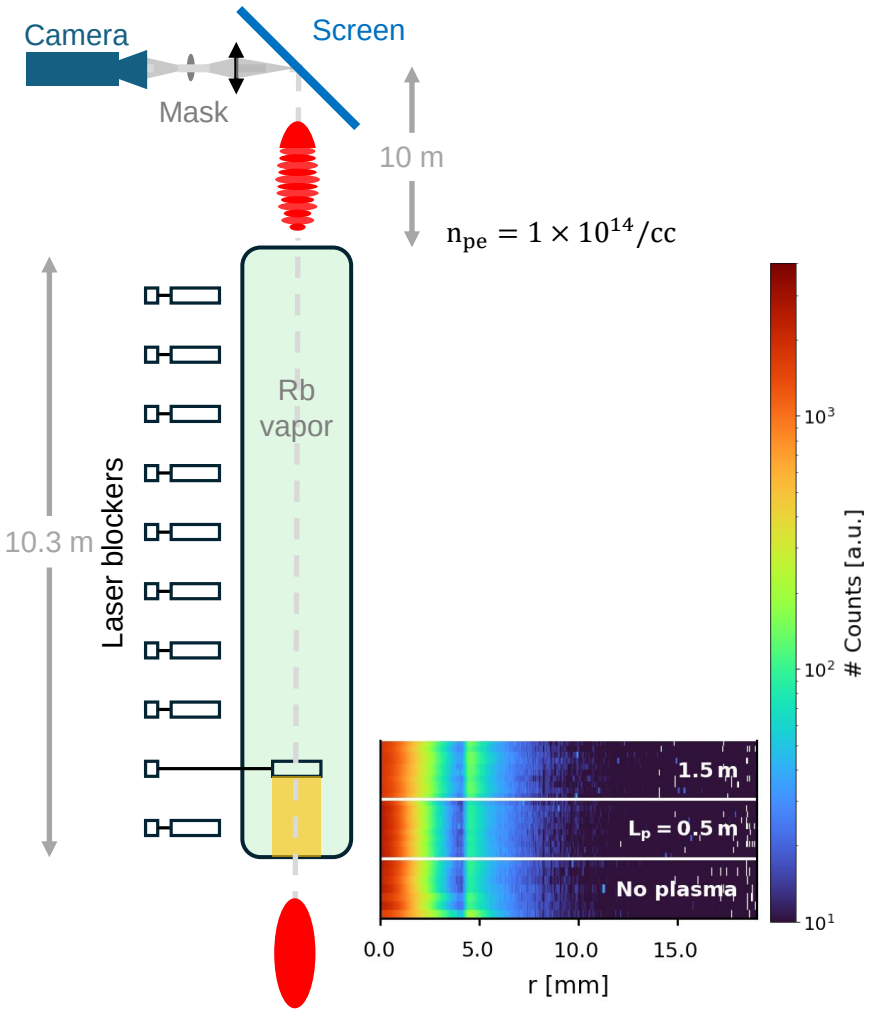

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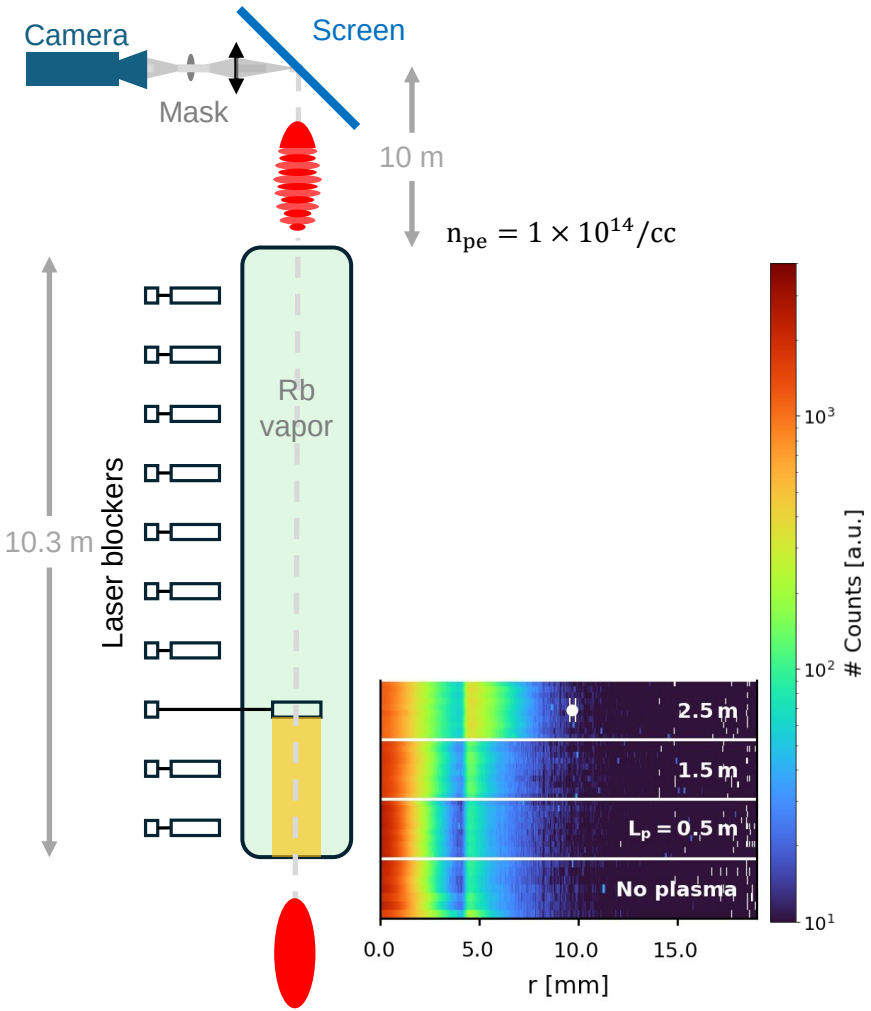

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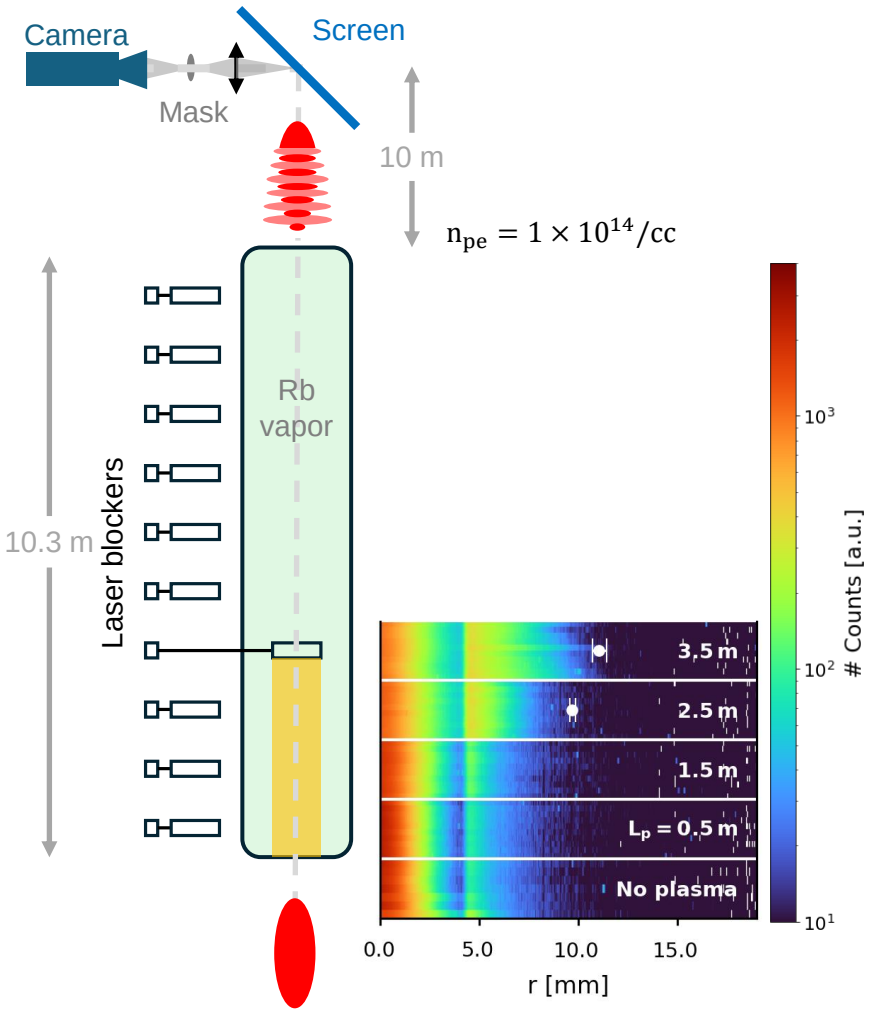

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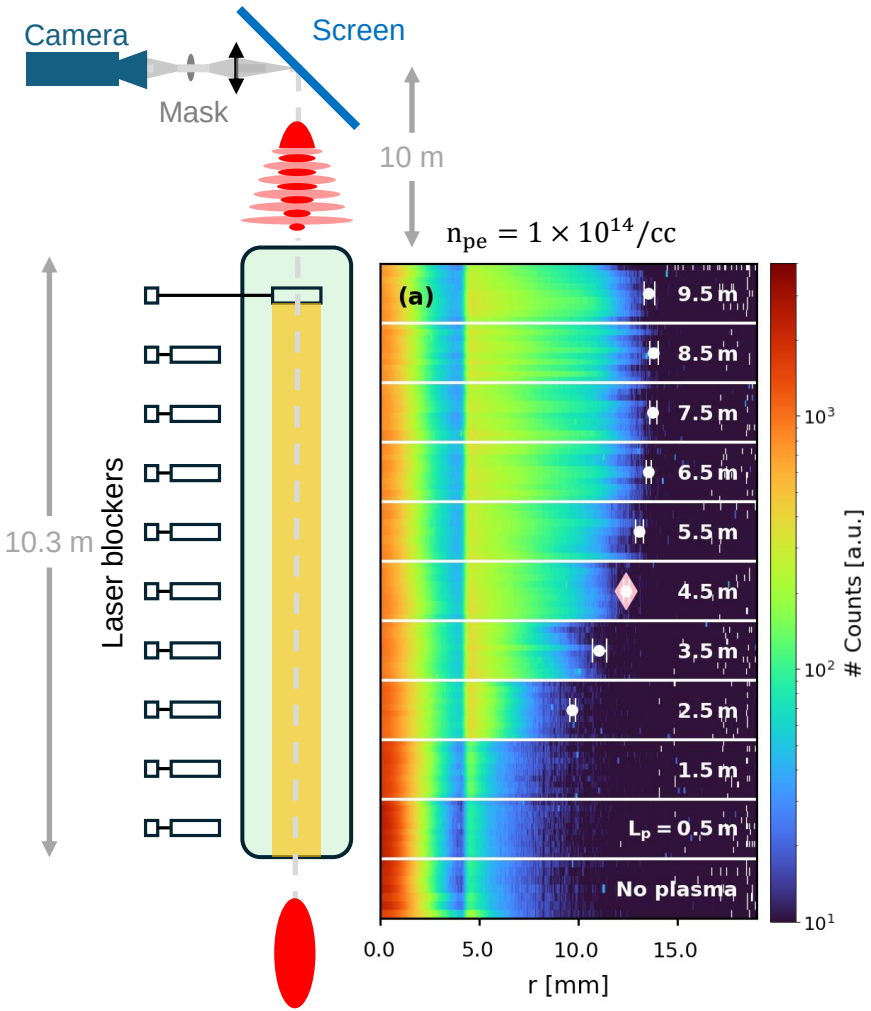
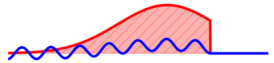


Evolution in three phases:

1) $\mathbf{L_p = 0 \text{ to } \cong 1.5 \text{ m}}$:
   - Little evolution of bunch
   - Wakefields:
     - Small amplitude
     - Predominantly focusing



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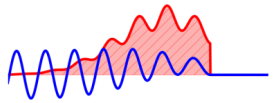

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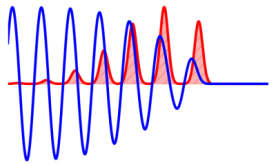
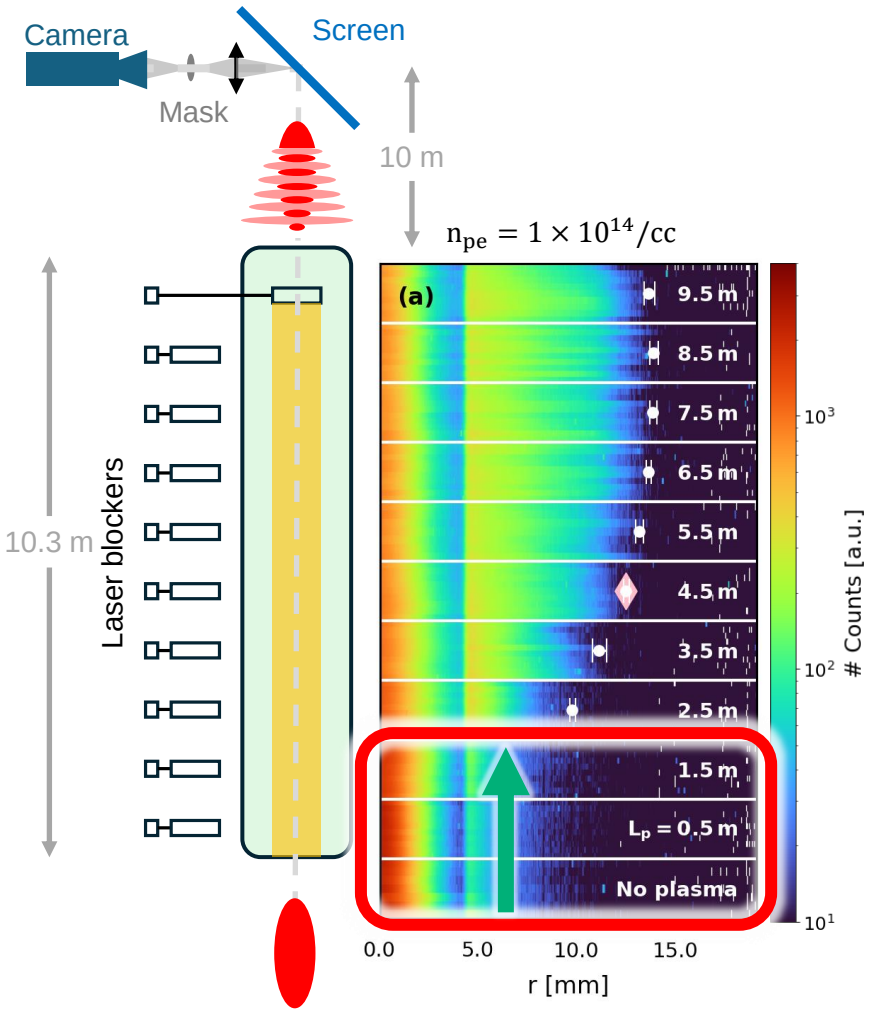
   - Halo radius stops increasing
   - Distribution essentially unchanged

Signature expected from SM saturation



Halo formation along the plasma



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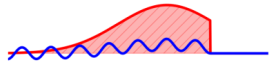

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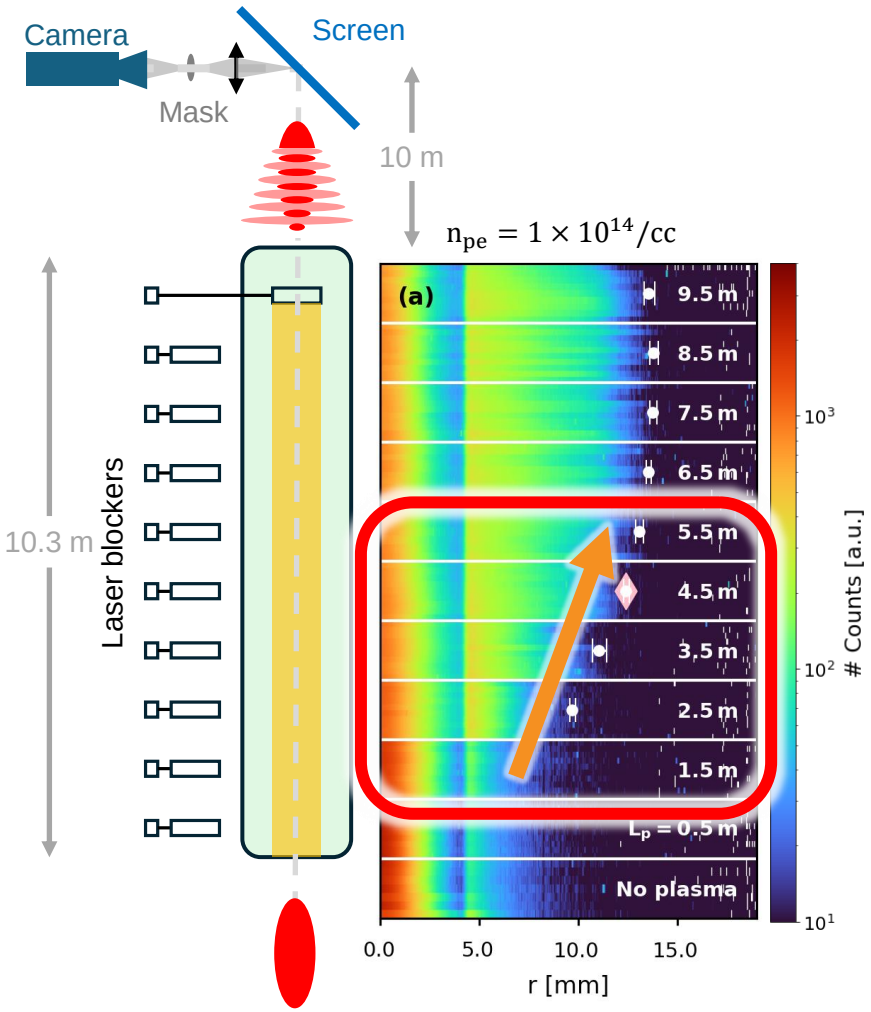

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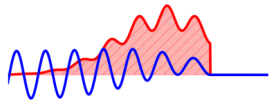

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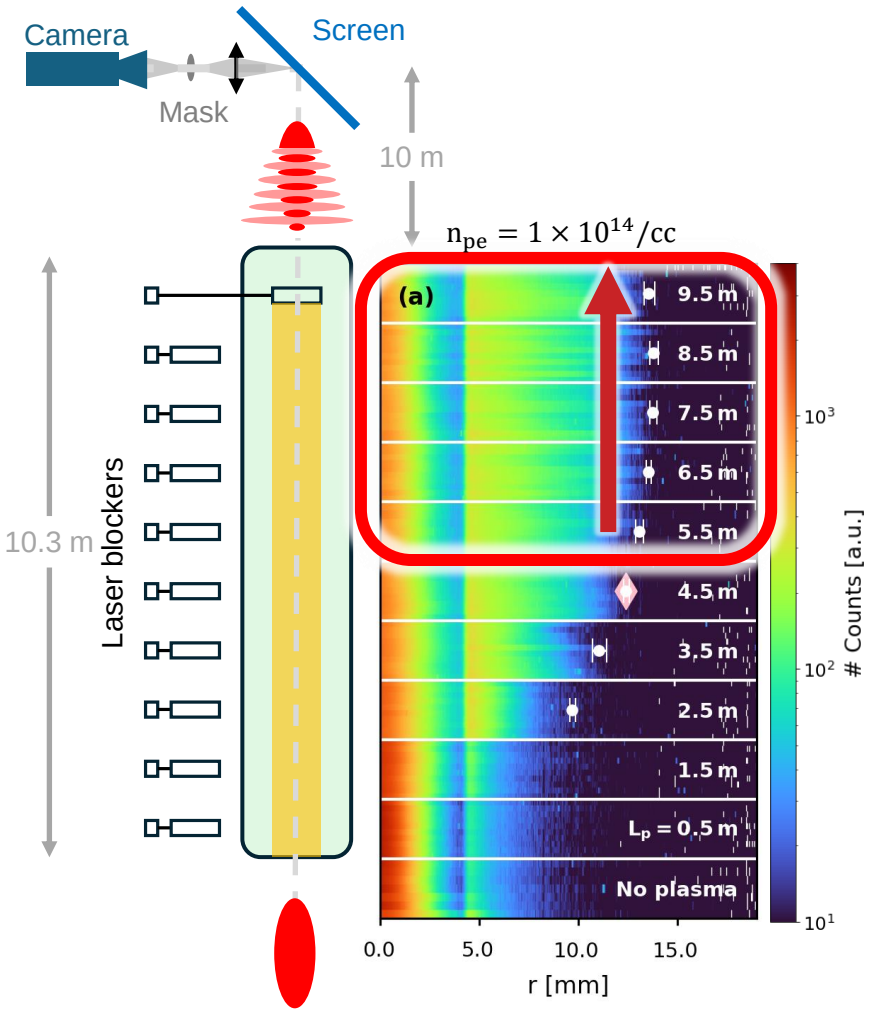

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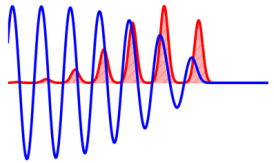
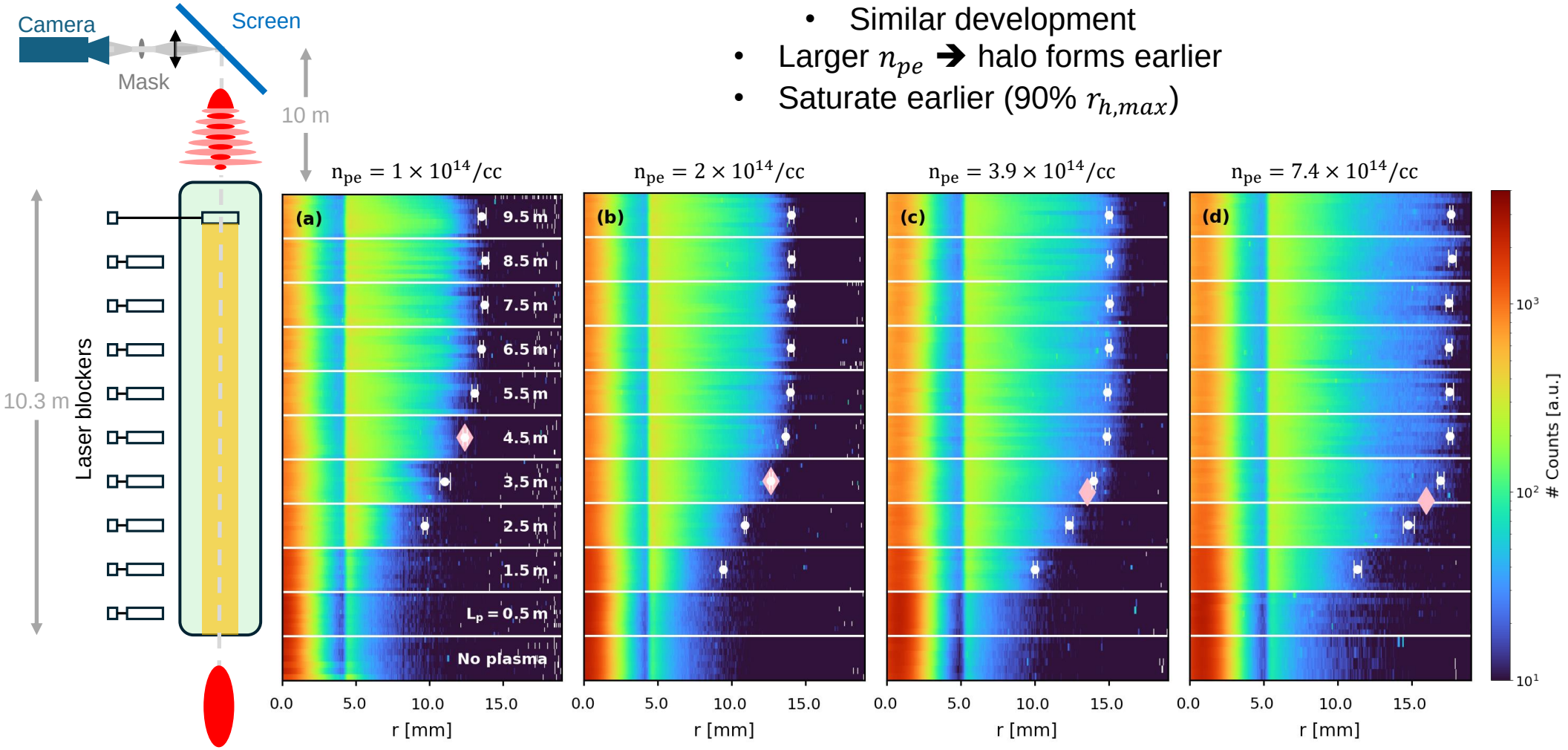


Halo formation along the plasma

Proton bunch :
- $N_b = 3 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 200$ µm
- $\sigma_t = 170$ ps
- $t_{RIF} = 100$ ps

- For all plasma densities
  - Similar development
- Larger n_{pe} ➔ halo forms earlier
- Saturate earlier (90% $r_{h,max}$)



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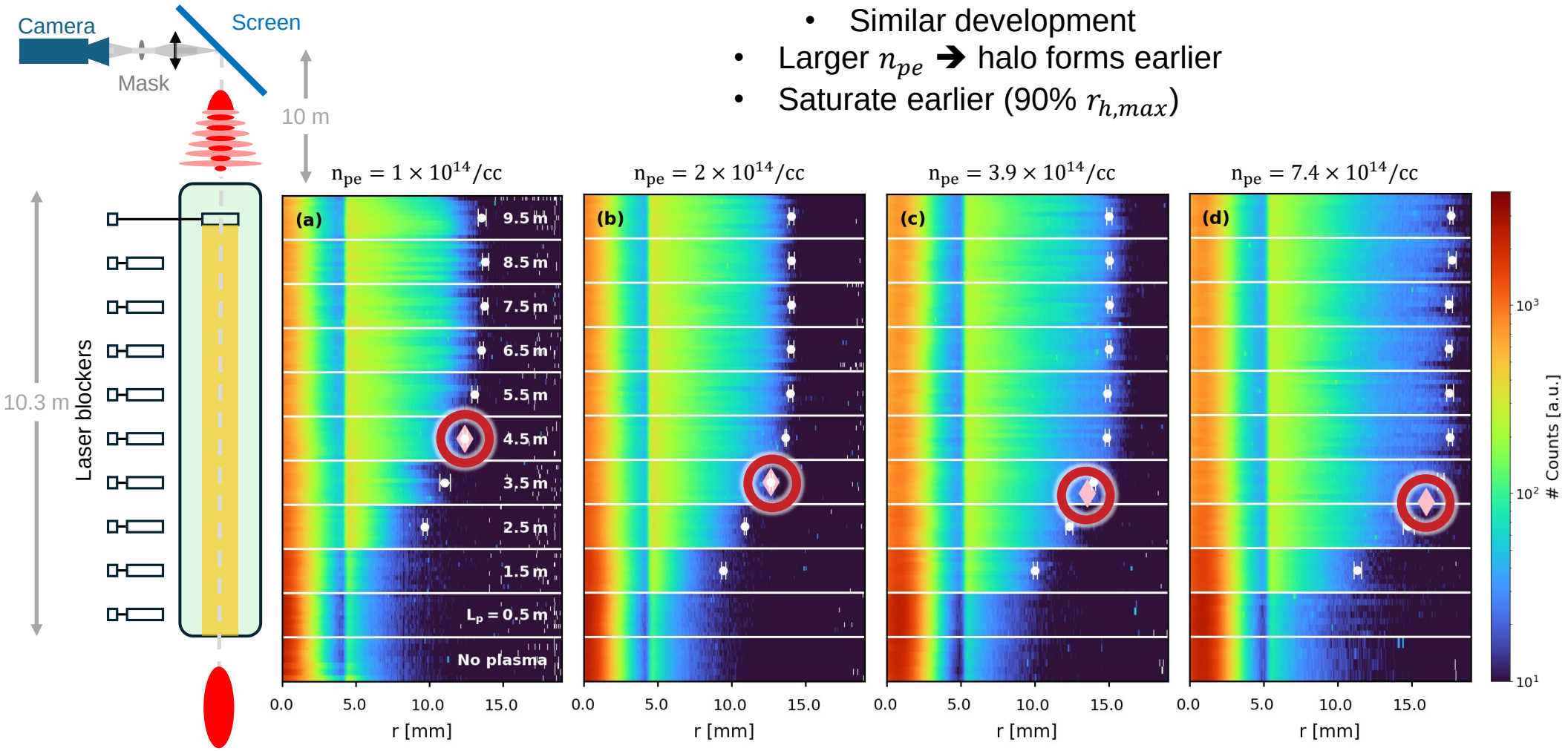
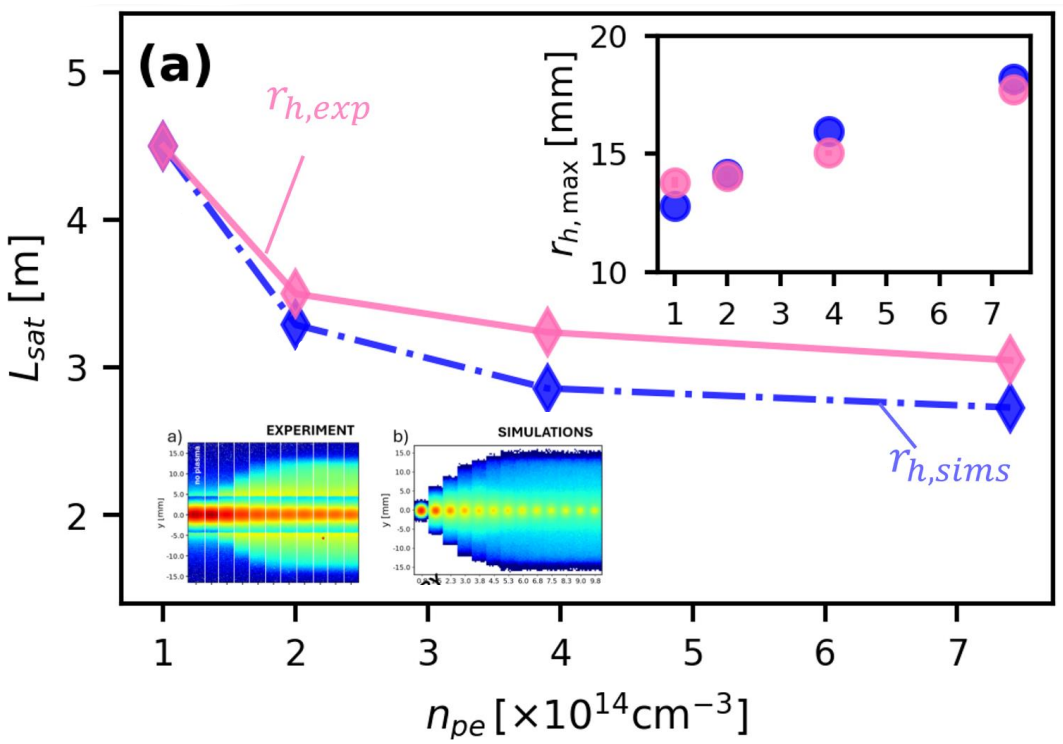


Comparison with simulation results



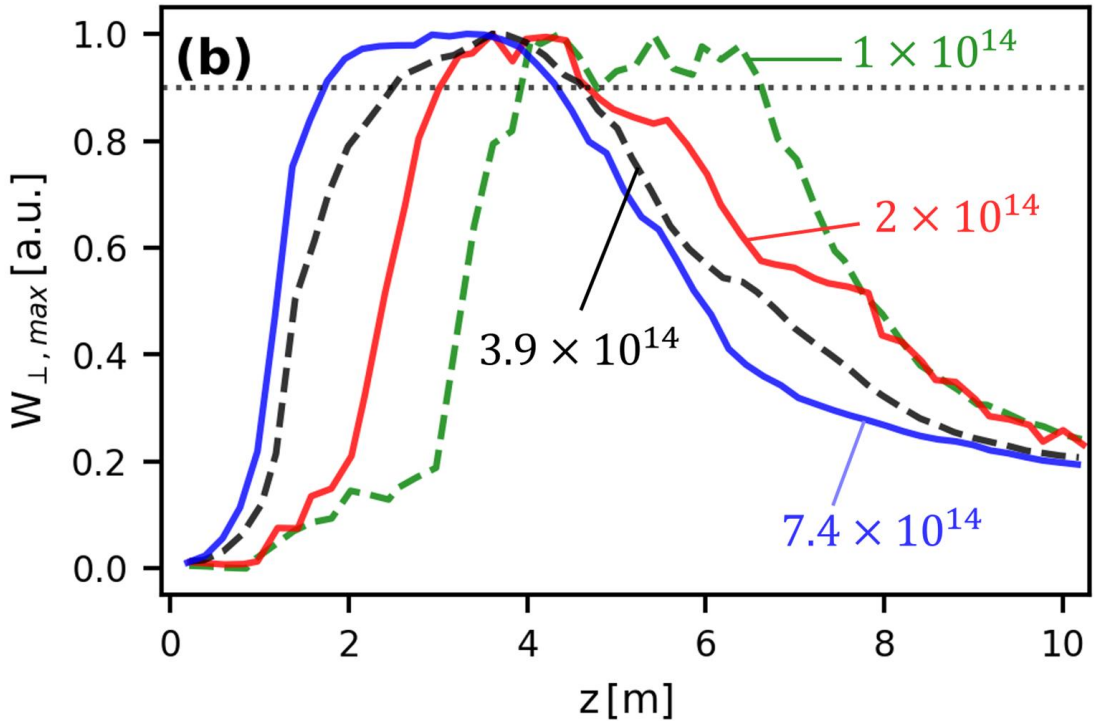
- Saturation of the halo
- Zeroth order expectation ➔ Saturation of the wakefields
- Need to show it…

- Comparison with LCODE simulation results

- Excellent agreement between exp. and sim. results on saturation length of the halo and halo max. radius
- Halo saturate earlier for larger n_{pe}

- Simulations allow us to look at the wakefield amplitude…

Comparison with simulation results

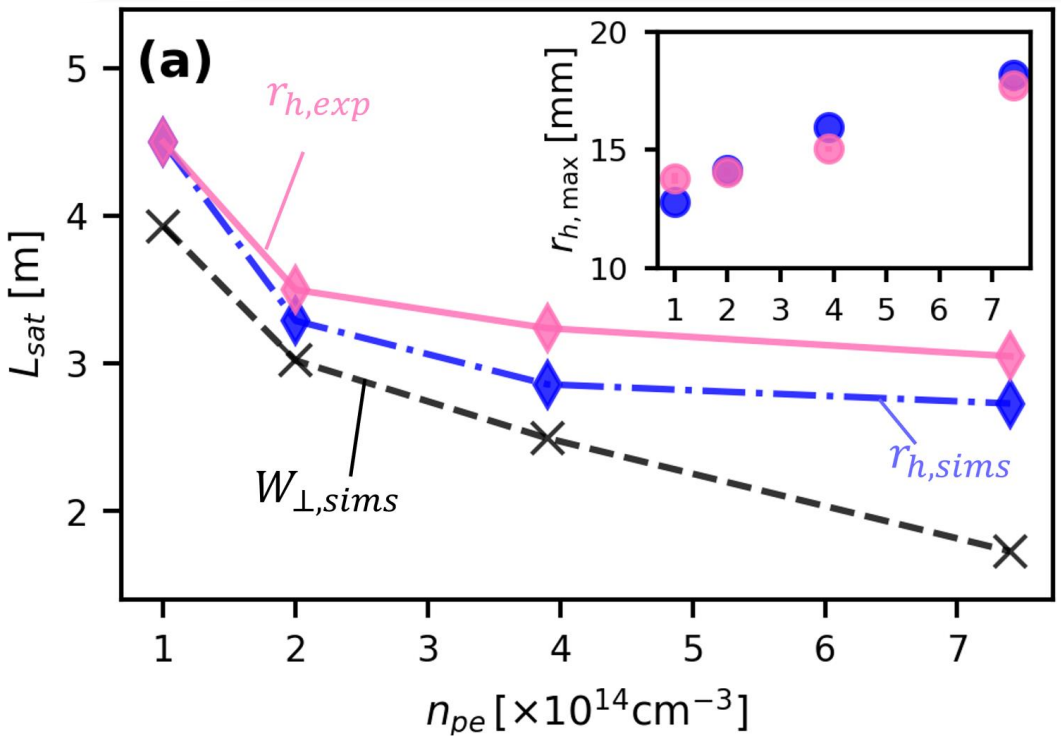


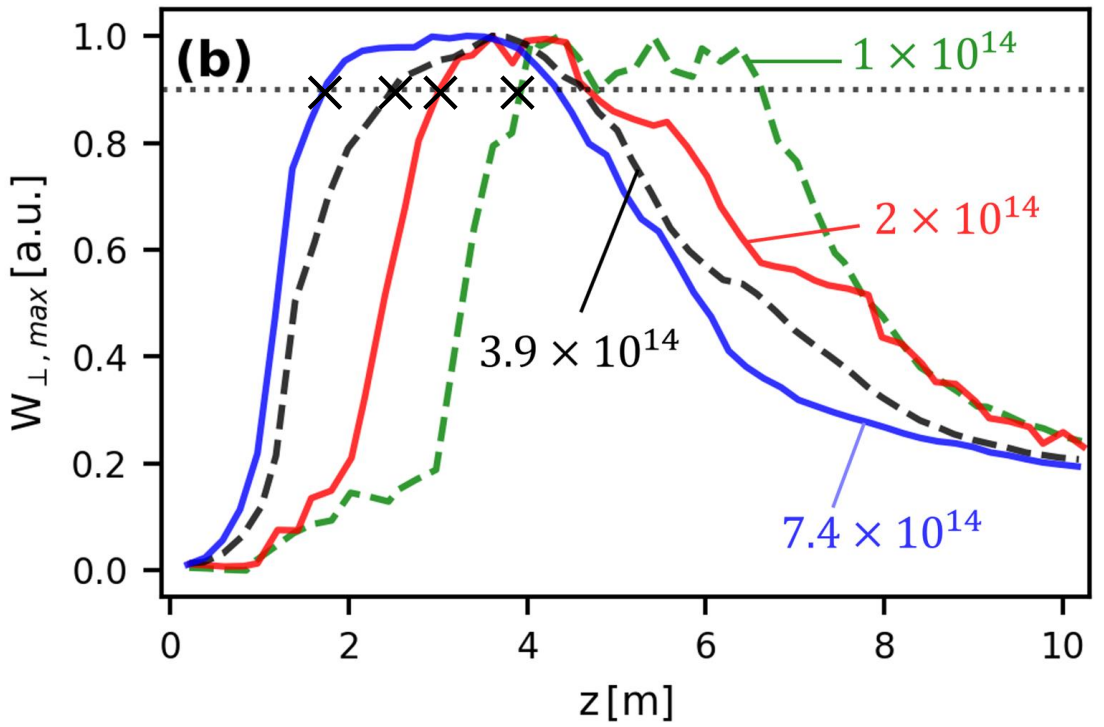
- Transverse (defocusing) field amplitude along the plasma
- Max amplitude at any xi along the bunch (from front to $\mu - \sigma_t$)
- Normalized field amplitude

- Grows, saturate and decay
- Grows earlier for larger n_{pe}
- We can define the saturation of the fields and of SM at 90% max value

- Saturate earlier for larger n_{pe}

Saturation length versus n_{pe}





- Fields/SM saturate earlier than halo

- Still, the sat. length of halo provides a **good estimate** for sat. length of the fields ($\Delta L < 1$m)

- **Saturation length decreases with n_{pe}**

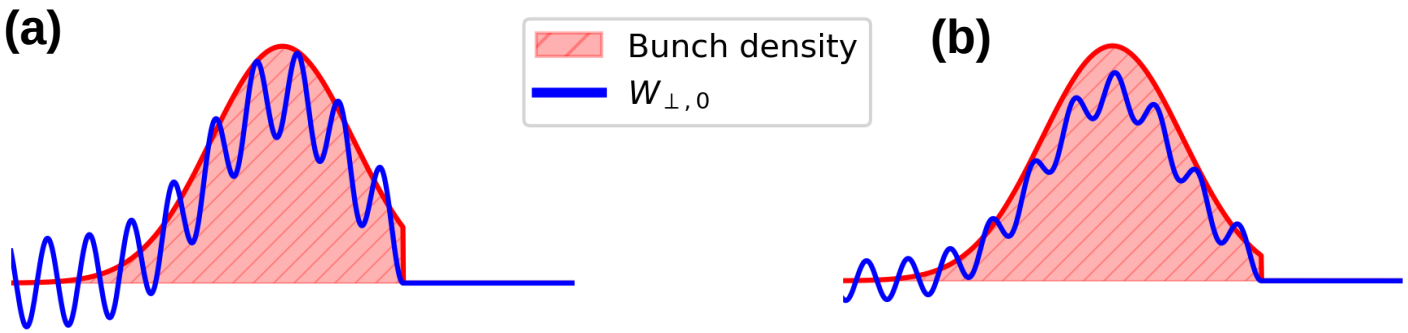
- Transverse (defocusing) field amplitude along the plasma
- Max amplitude at any xi along the bunch (from front to $\mu - \sigma_t$)
- Normalized field amplitude

- Grows, saturate and decay
- Grows earlier for larger n_{pe}
- We can define the saturation of the fields and of SM at 90% max value

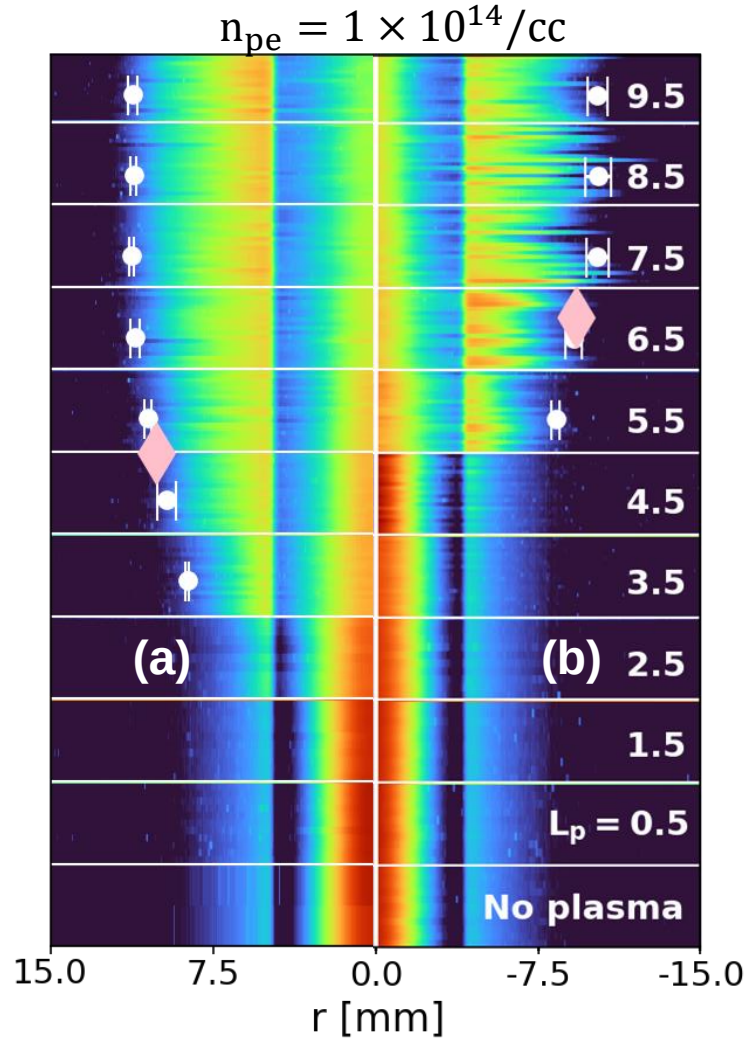
- Saturate earlier for larger n_{pe}

Effect of initial field amplitude

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



- Vary $W_{\perp,0}$ by varying RIF timing
  - (a) $t_{rif} = 350ps$, (b) $t_{rif} = 550ps$ $\Rightarrow \boldsymbol{\Delta N_b < 2.5\%}$
- Right: $W_{\perp,0,b}$ from RIF too low: SM develops from noise ➔ **SMI**
- 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)



$W_{\perp,0,a} > W_{\perp,0,b}$

Conclusions

What ?

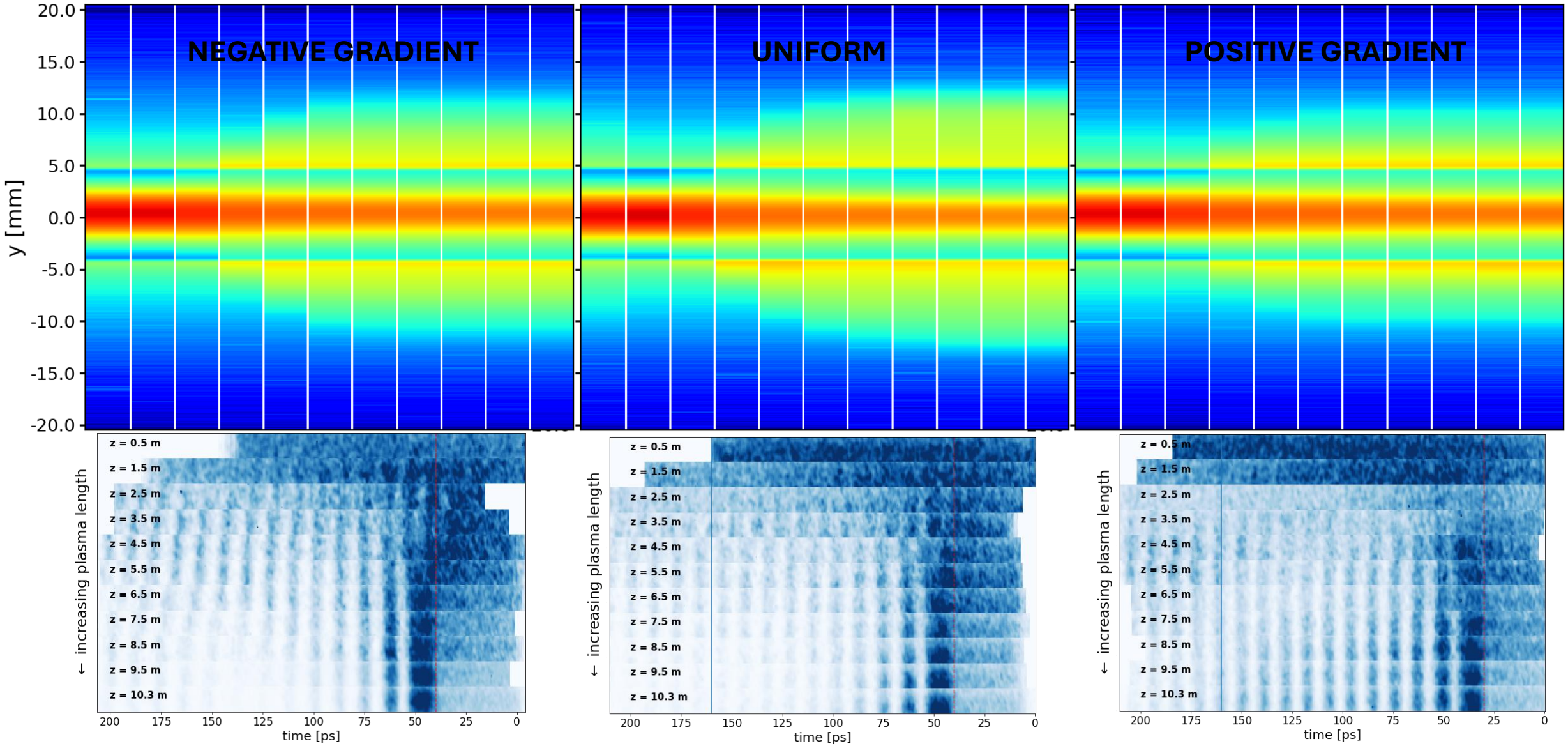
- We determined the **saturation length of SM** for the first time
- For all parameters relevant to AWAKE, $\mathbf{L_{sat} \sim 2 - 5\ m < 10\ m}$
- $\mathbf{L_{sat}}$ decreases when $\mathbf{n_{pe}}$ increases
- $\mathbf{L_{sat}}$ decreases when $\mathbf{W_{\perp,0}}$ increases

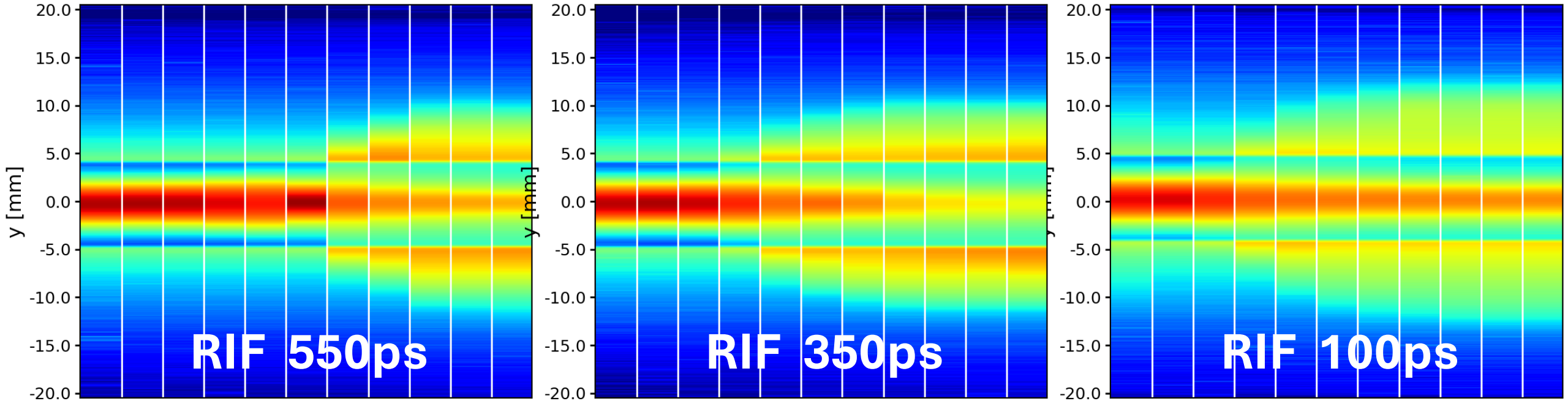
How ?

- 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]**


NEGATIVE GRADIENT
UNIFORM
POSITIVE GRADIENT
y [mm]
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
z = 0.5 m
z = 1.5 m
z = 2.5 m
z = 3.5 m
z = 4.5 m
z = 5.5 m
z = 6.5 m
z = 7.5 m
z = 8.5 m
z = 9.5 m
z = 10.3 m
← increasing plasma length
200 175 150 125 100 75 50 25 0
time [ps]


20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
-20.0
y [mm]
RIF 550ps
RIF 350ps
RIF 100ps

Logic

1 - Saturation length definition ➔ Growing quantity for AWAKE ➔ wakefields ➔ hard to diagnose directly

2 - Relevance for AWAKE ➔ Pukhov 2011

3 - Self-modulation – reminder ➔ feedback loop leads to growth
3 b) Plasma off – plasma on – pictures and mask explanation

3c) Halo explanation + exp setup - measure the modulation

3d) Extract a slice – animation with question mark in between ➔ Need to change the plasma length

4) In awake, plasma is created by a laser pulse
4) This means that the plasma can be stopped along the 10m source by stopping the laser
4) This allows us to vary the length of the plasma, and therefore the distance over which SM develops

4) We can then look at the evolution of the beam halo along the plasma

4) Three phases
Focusing – low wf
Defocusing – def.foc. Alternating – growth of wf
Stops growing – Here halo particles have exited the wf – they drift ballistically

halo radius saturates here at 4.5m
repeat this procedure for 4 npe, all other parameters unchanged

Larger npe ➔ faster the formation of the halo, the smaller Lsat

5) But so far this sat. is sat. of the halo, not of the wakefields, and although our first order explanation suggest that the two are the same, lets verify
5b) We do 2D particle in cell numerical simulations using LCODE
same procedure and extract first the saturation of the halo
agreement is excellent <0.5m, and even the radius of the halo in the simulations is comparable as that of the experiment ➔ confirms that the sims represent the exp. For this measurement
5c) We can now look at W_perp we have very good agreement here too ➔ show all the curves and then make

5c) This confirms that the sat. of the halo provides a good estimate for the sat of the fields.

6) We can also look at the SSM vs SMI case
6a) How do we seed SM
2,5%
10x Wperp initial
7) Saturates earlier ➔ More reproducible

8) What How and Why

9) Manuscript in preparation ➔ Will be shared with the collaboration hopefully very soon