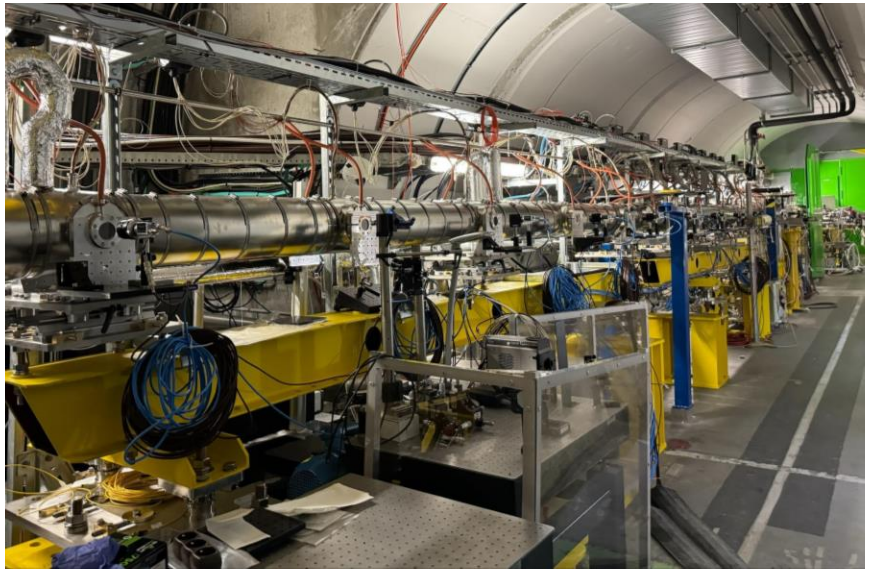

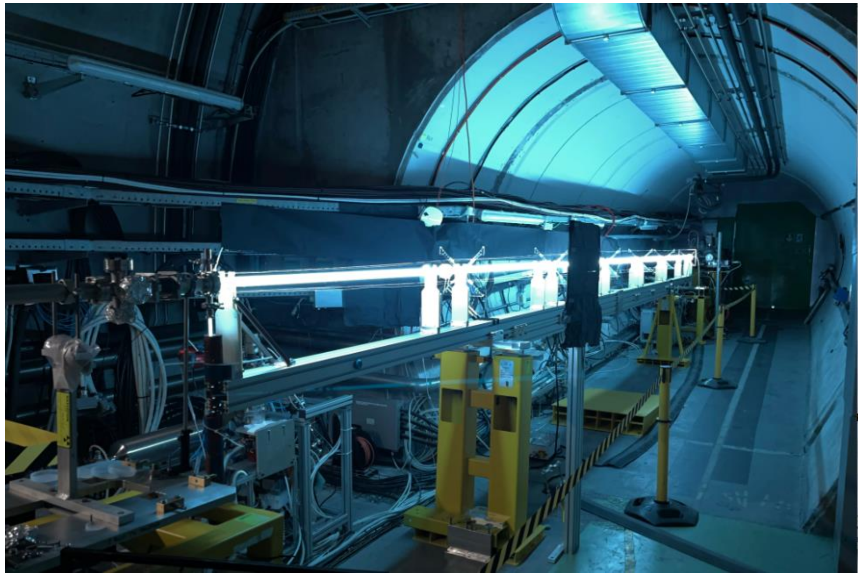

AWAKE: proton-driven plasma wakefield acceleration for particle physics applications

A. CLAIREMBAUD, Max Planck Institute for Physics

Outline

- Introduction to the AWAKE Experiment at CERN
- Demonstration of Amplitude-Reproducible Self-Modulation by Seeding
- Measurement of the Saturation Length of the Self-Modulation Instability
- Moving forward…

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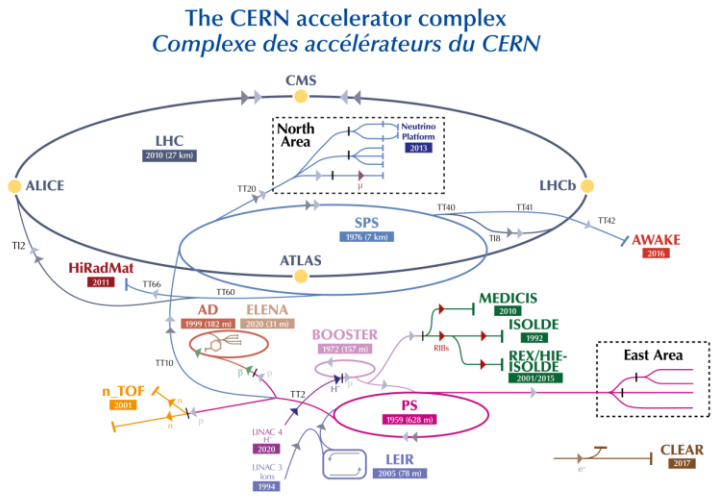

to excite wakefields in a (currently)
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driver parameters:

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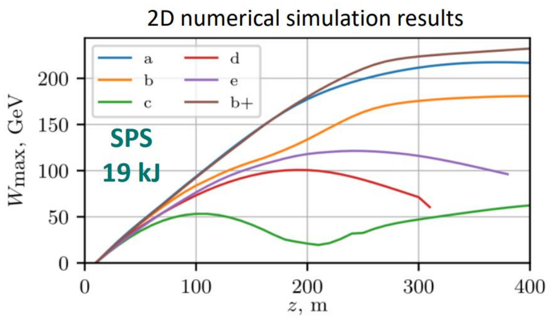
K. V. Lotov & P. V. Tuev, Plasma Phys. and Control. Fusion, 63, 125027 (2021)



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To excite ~**GV/m-amplitude** wakefields

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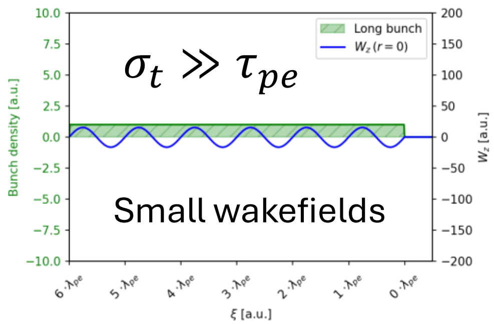
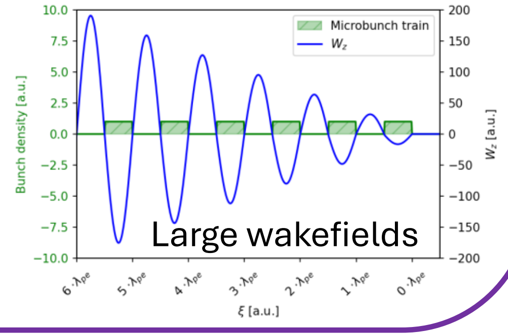


Microbunch train



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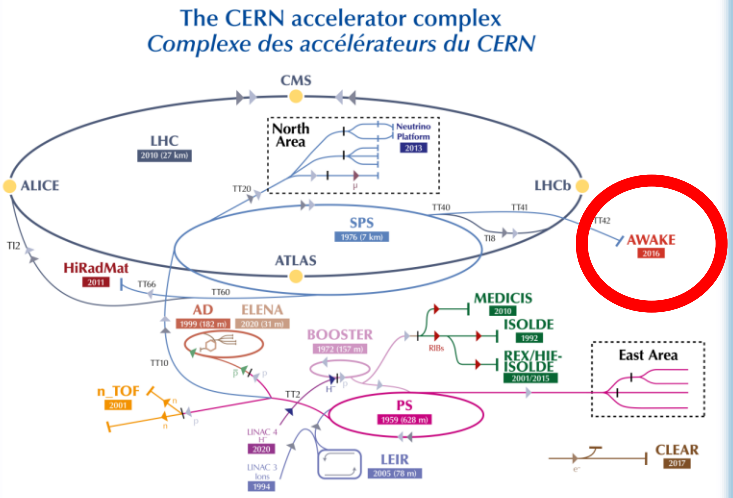

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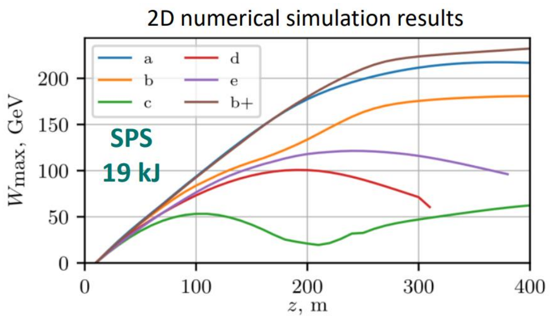

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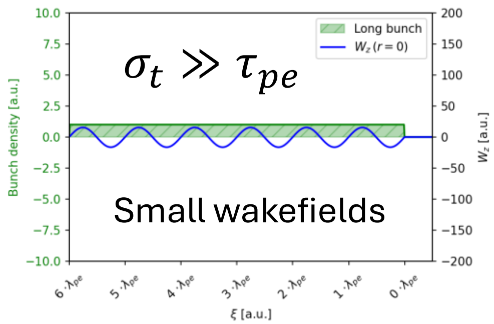

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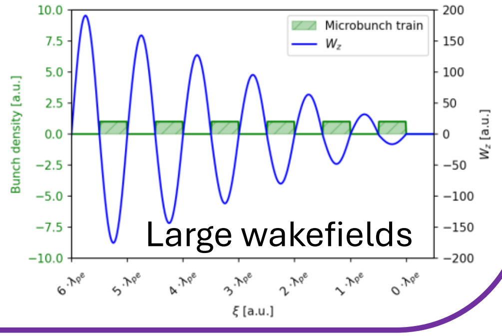

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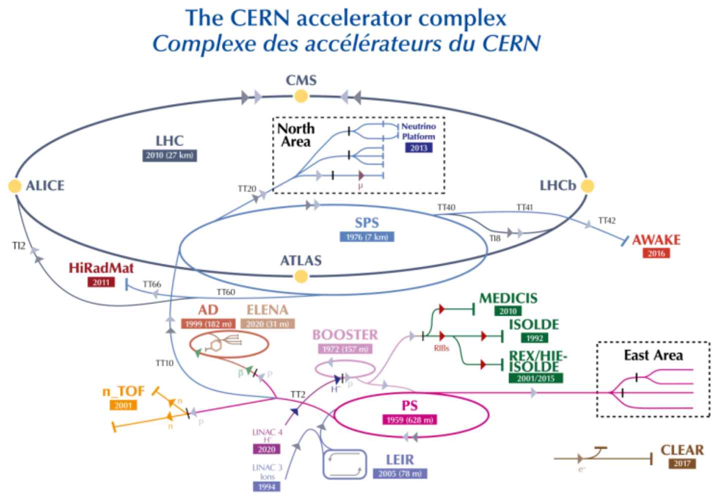

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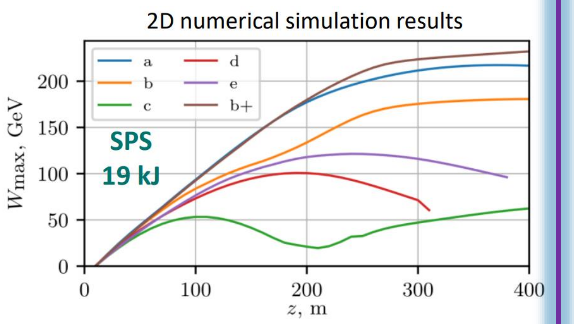

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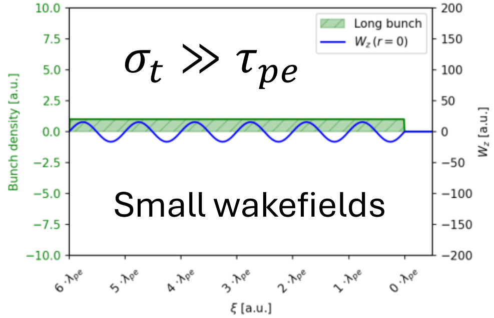

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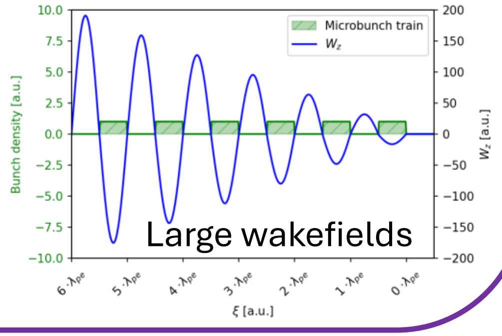

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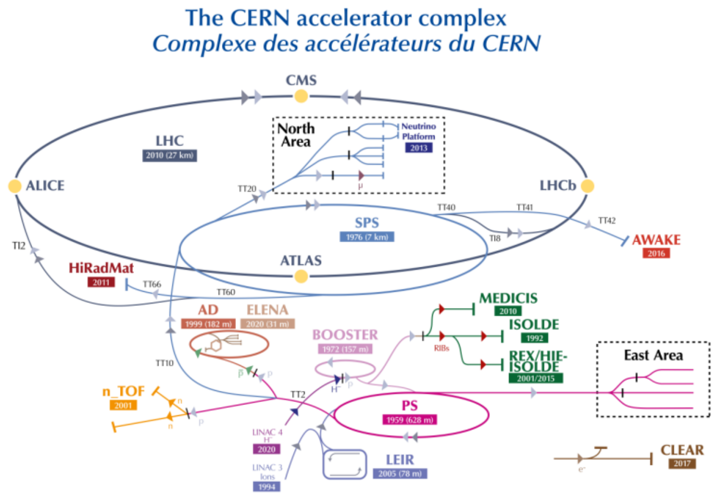

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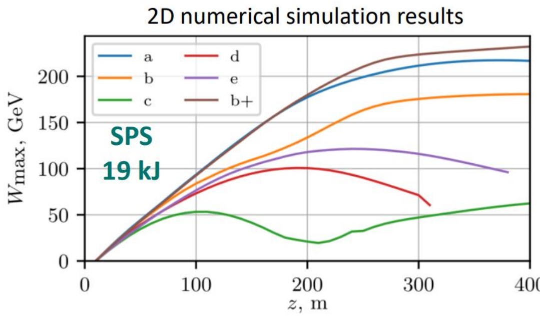

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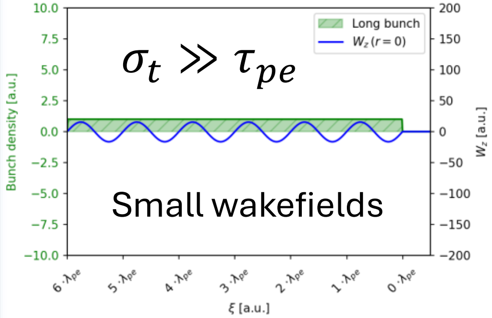

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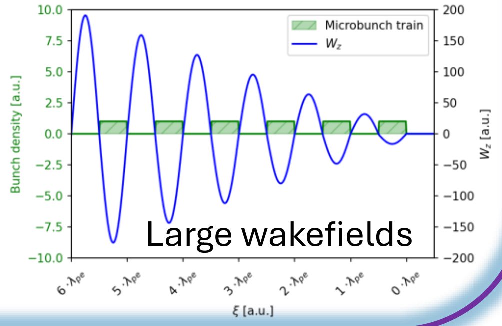

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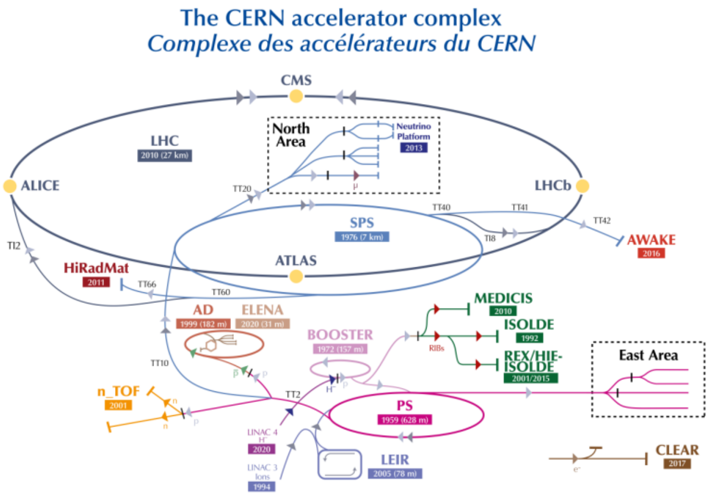

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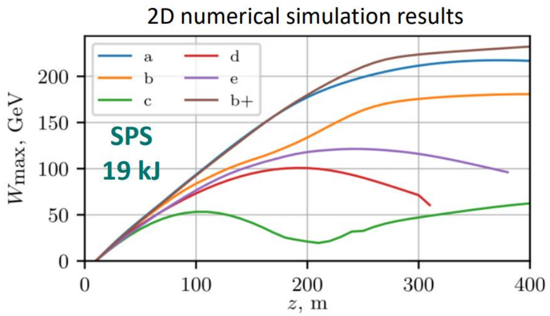

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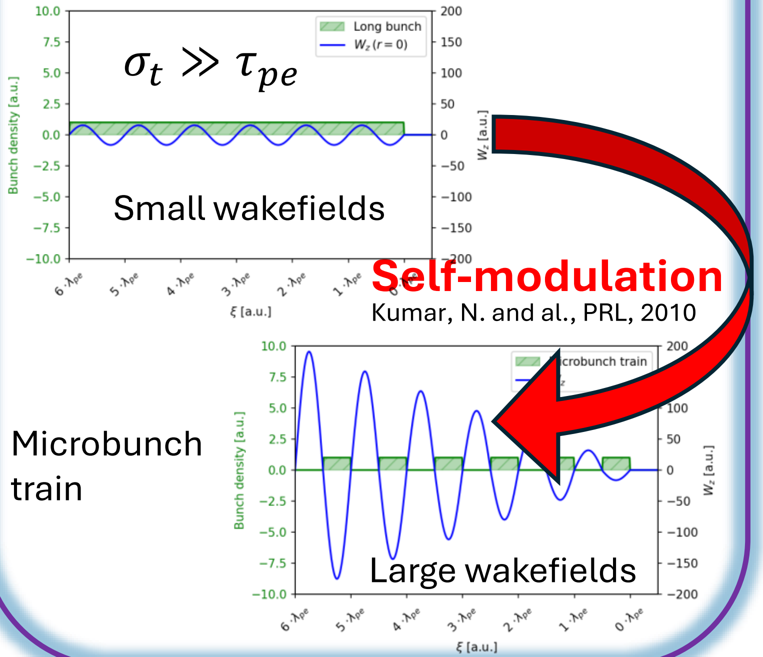
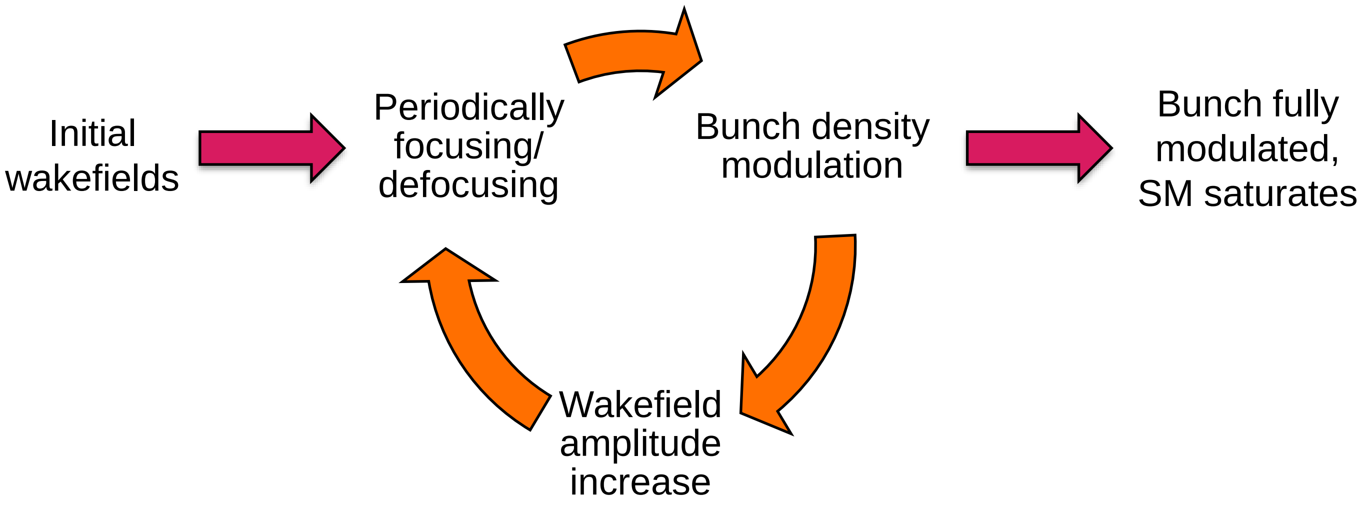
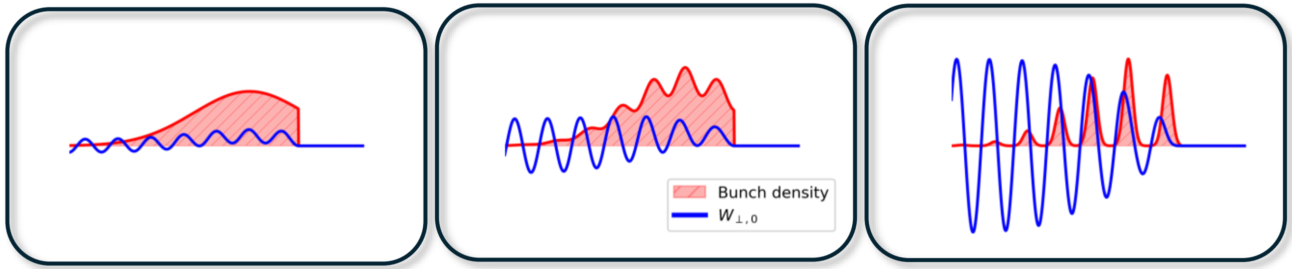


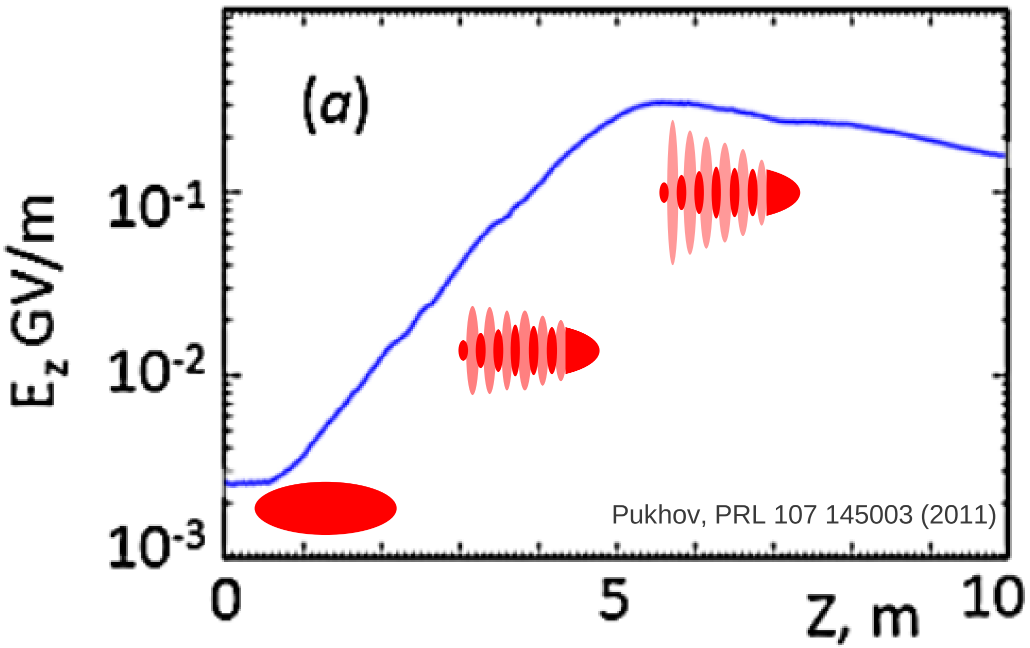
Self-modulation instability

bunch duration : $\sigma_t \gg \tau_{pe}$: plasma period

$$170ps \gg 4 - 11ps$$







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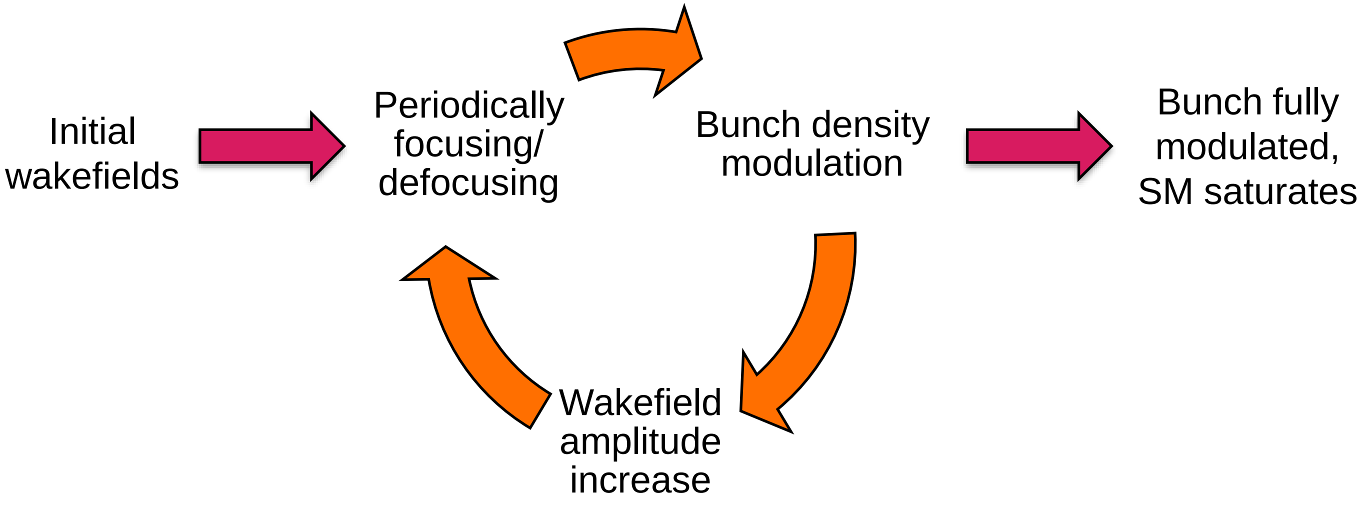

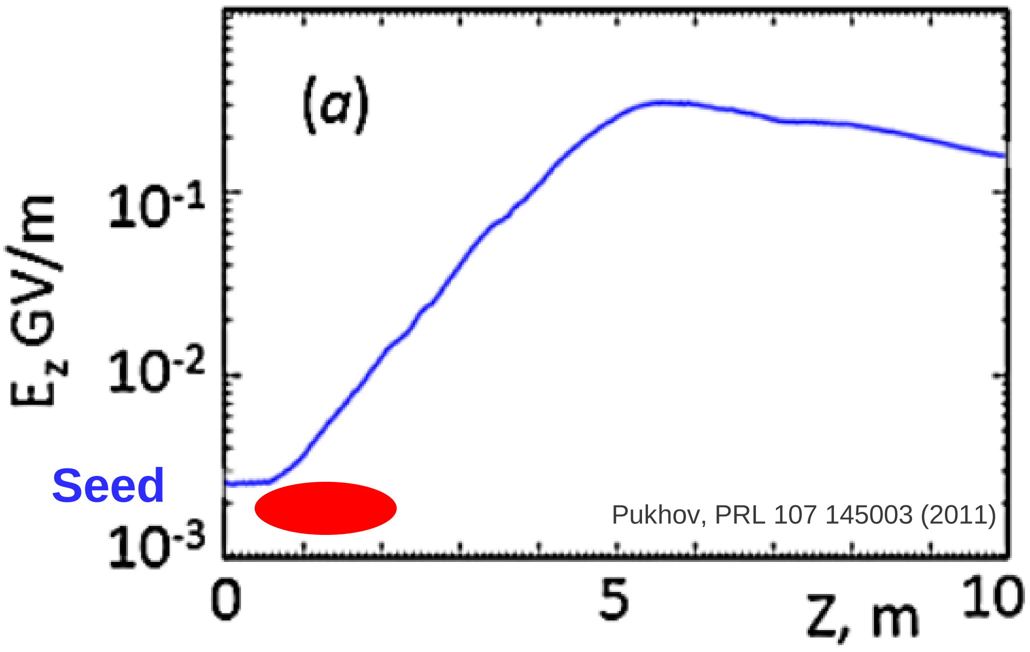

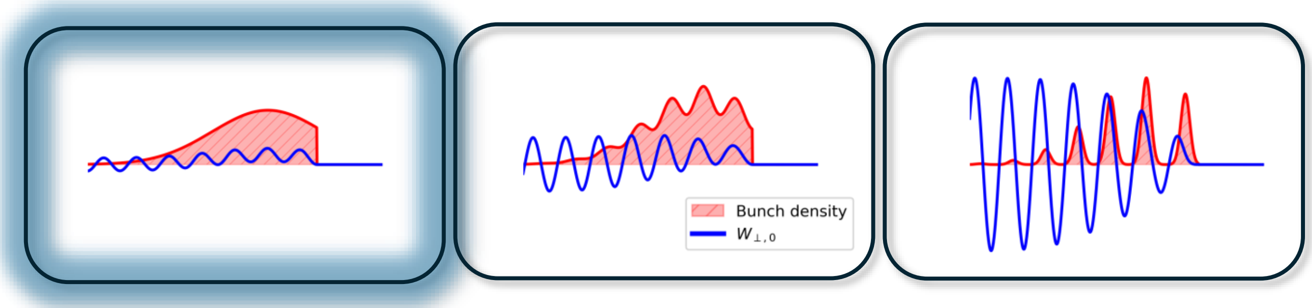

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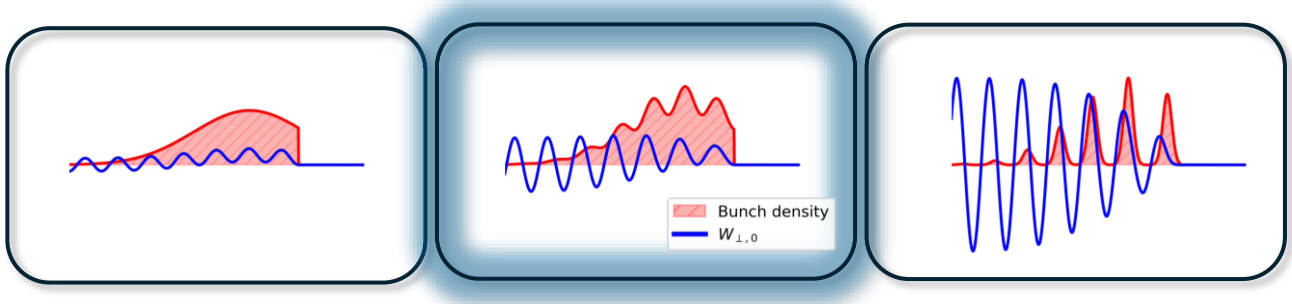
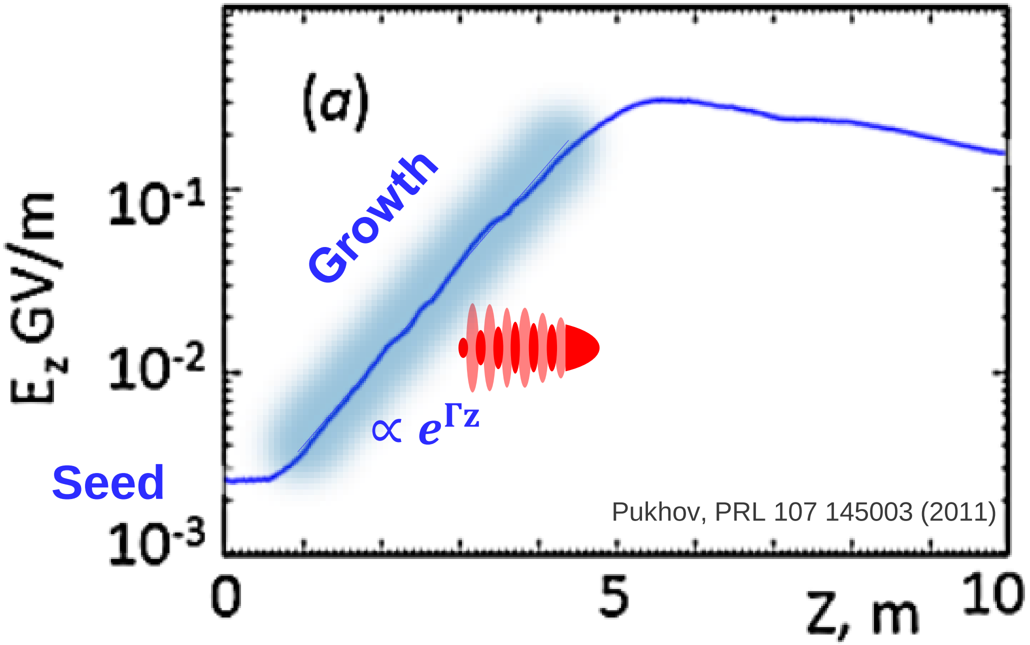
Initial wakefields → Periodically focusing/ defocusing → Bunch density modulation → Wakefield amplitude increase → Periodically focusing/ defocusing

Bunch density modulation → Bunch fully modulated, SM saturates





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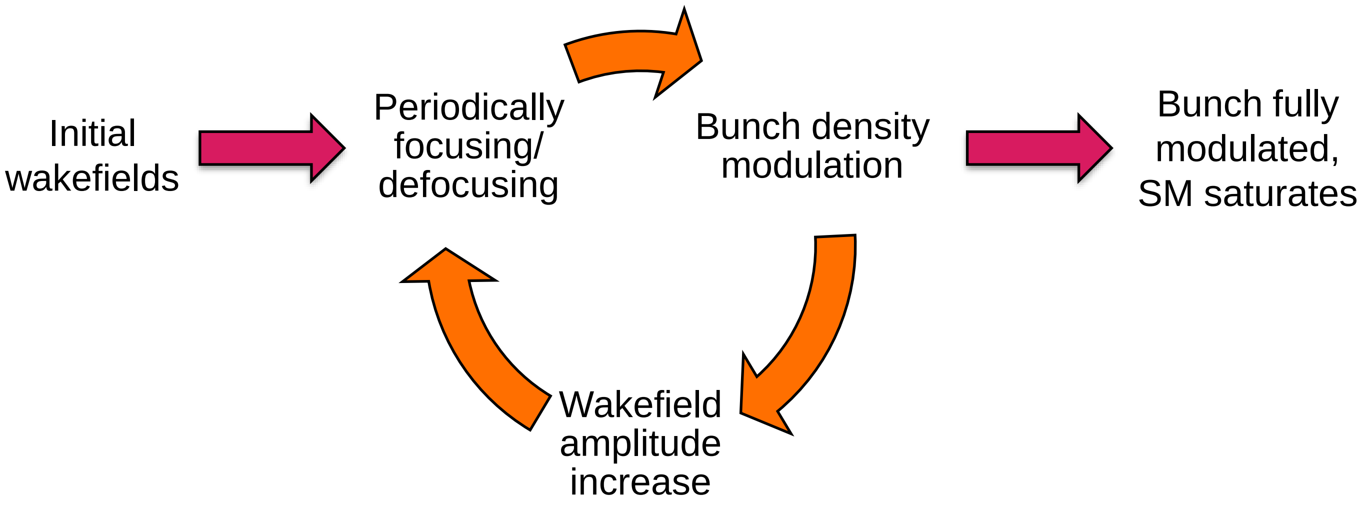

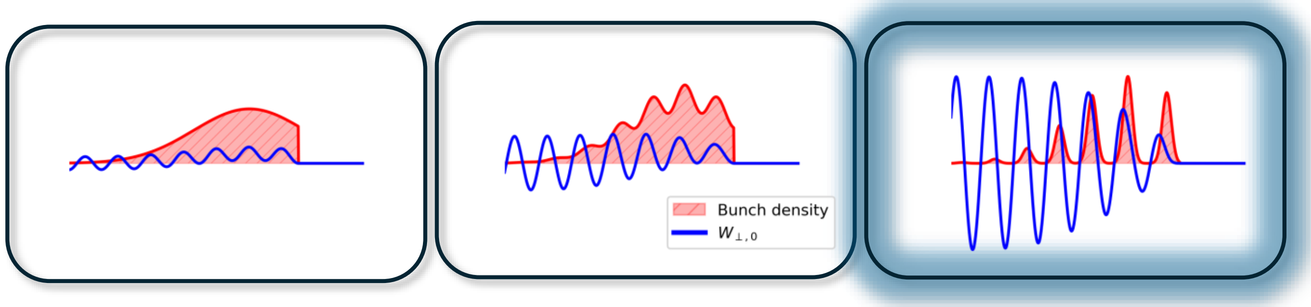

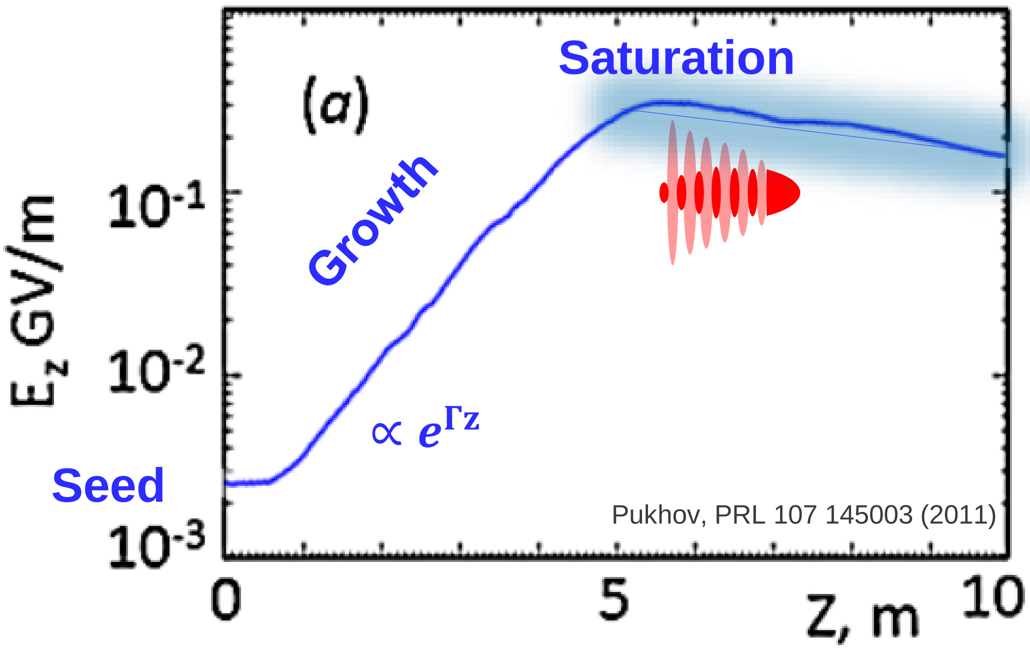

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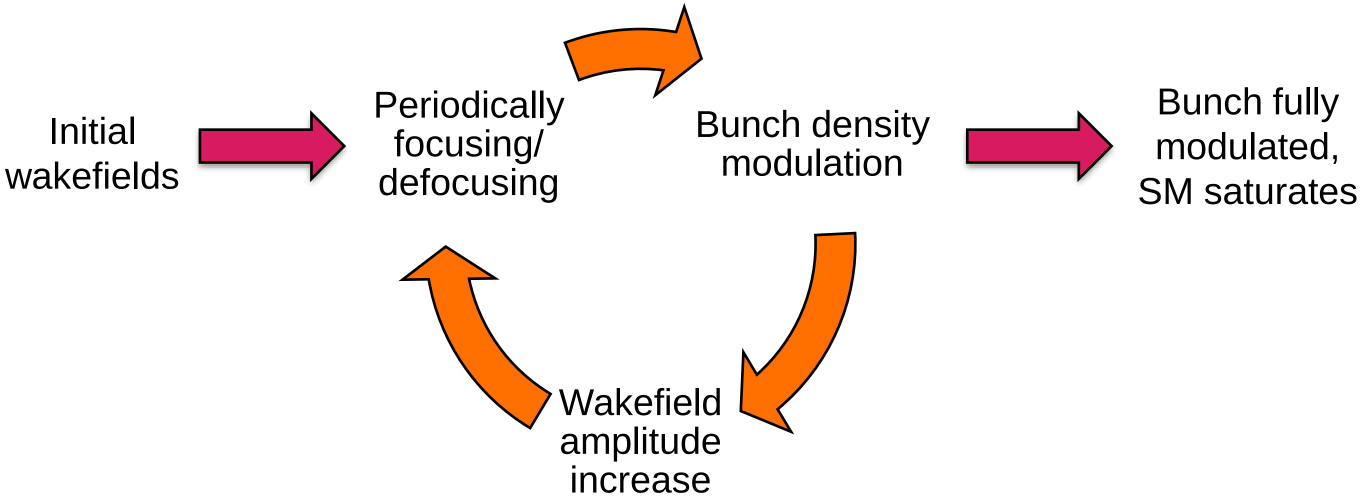
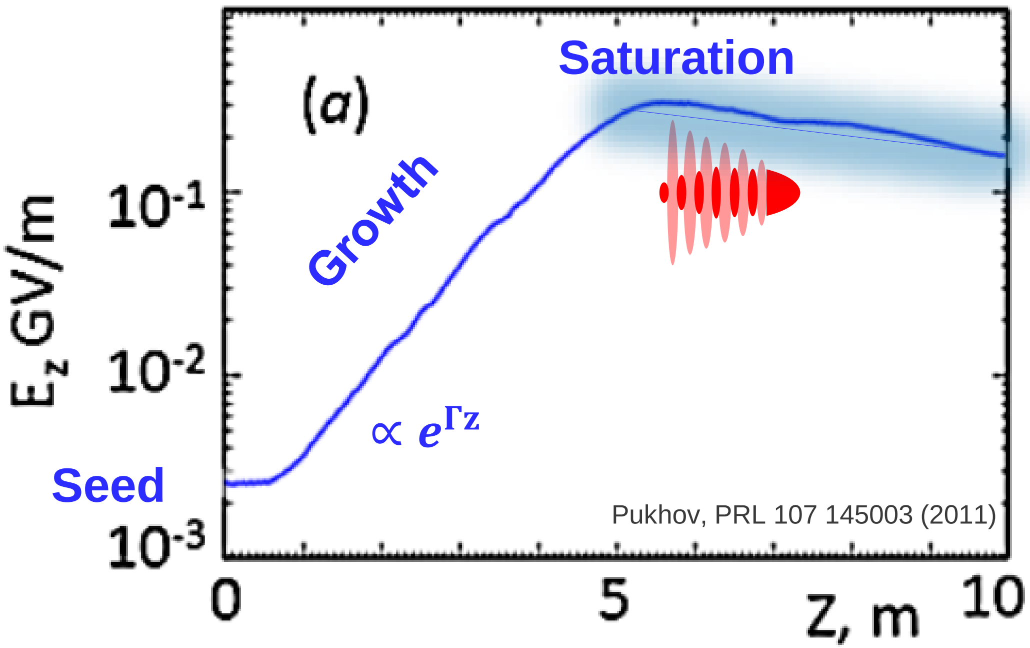
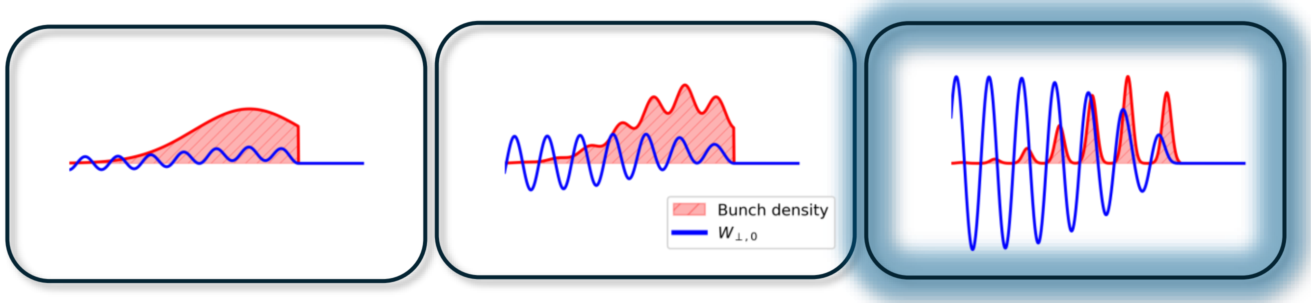


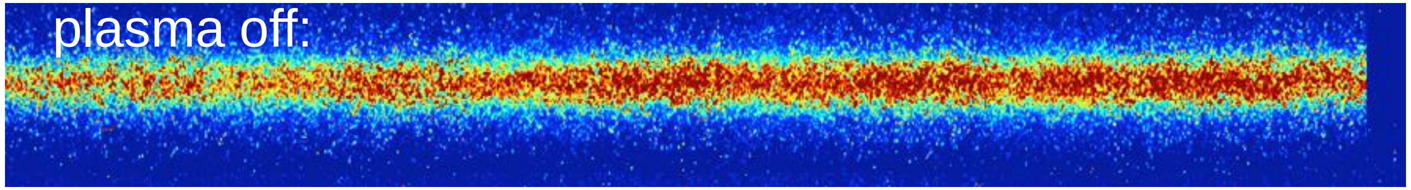




- Acceleration must occur after saturation of SM

→ Large wakefields after saturation
→ Event-to-event variations are typically smaller after saturation than during exponential growth

Self-modulation in AWAKE



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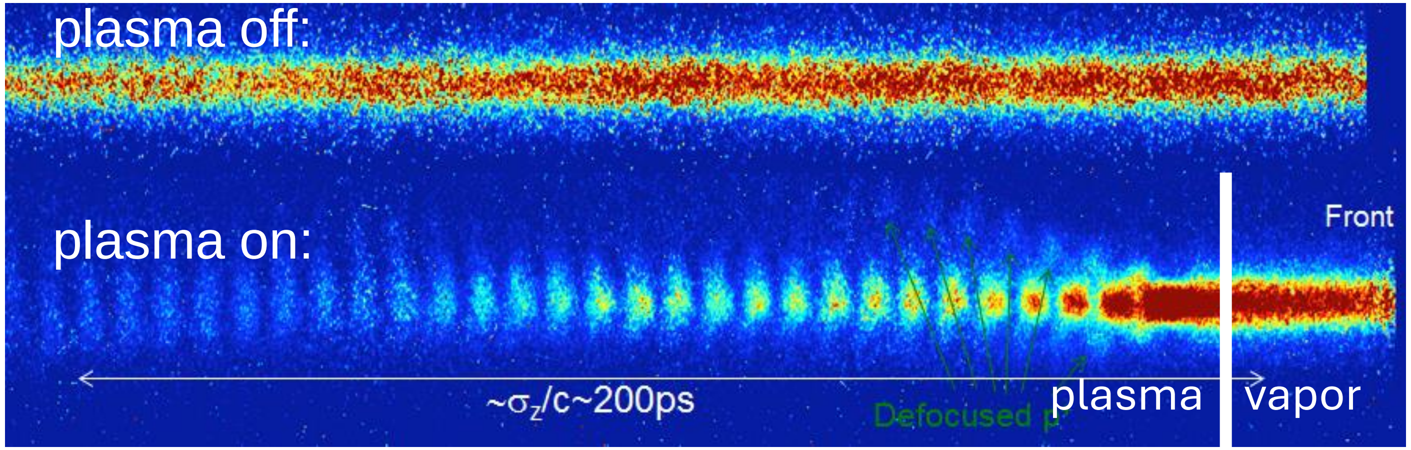

- Bunch is self-modulated after 10m of plasma
- Train of microbunches separated by defocused protons

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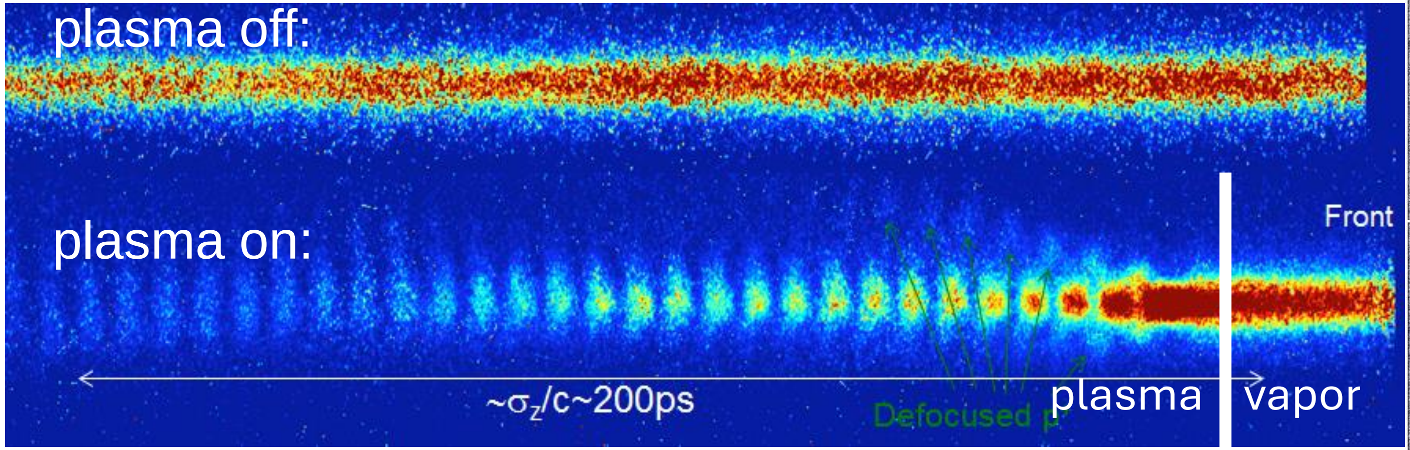

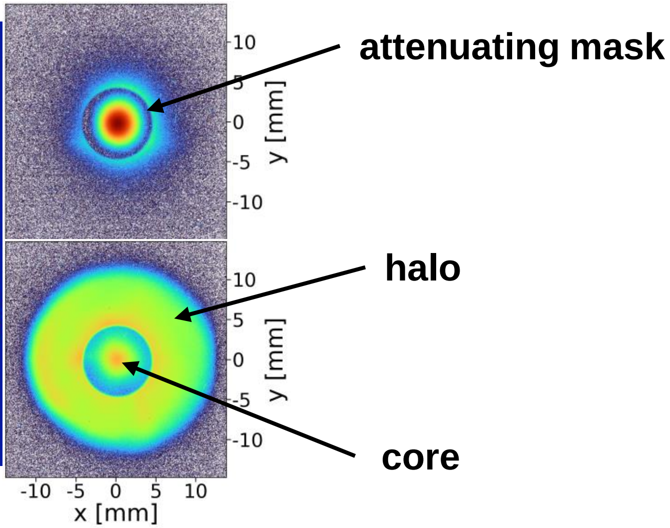

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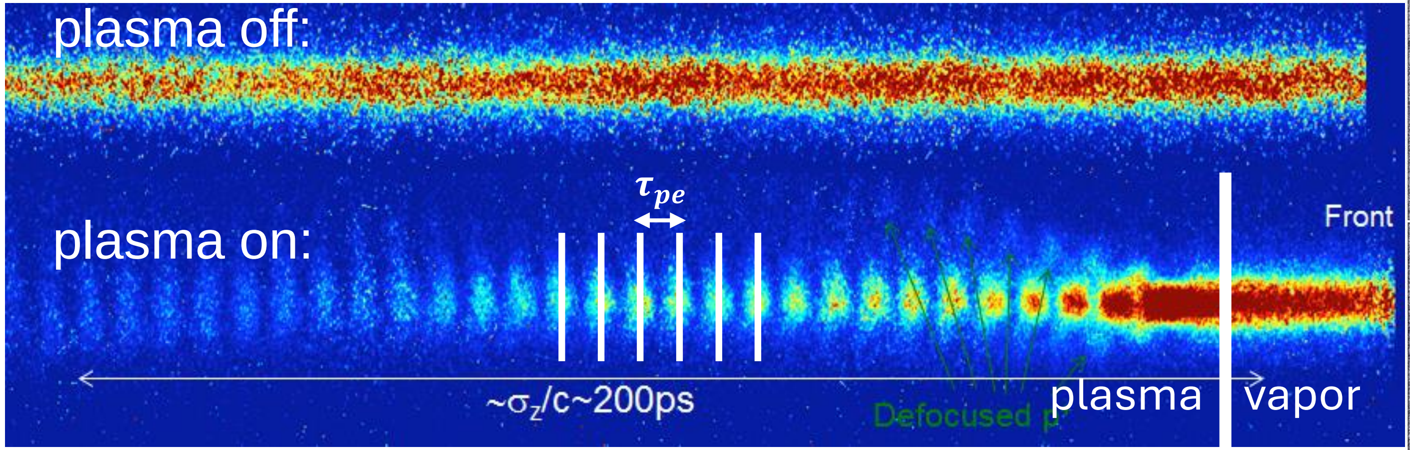

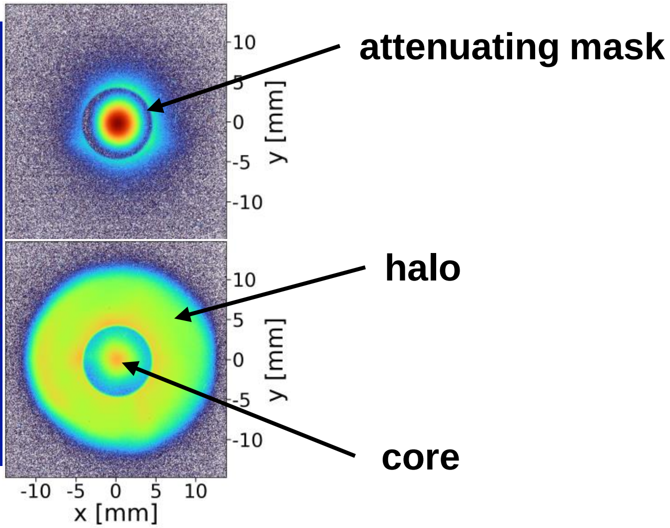

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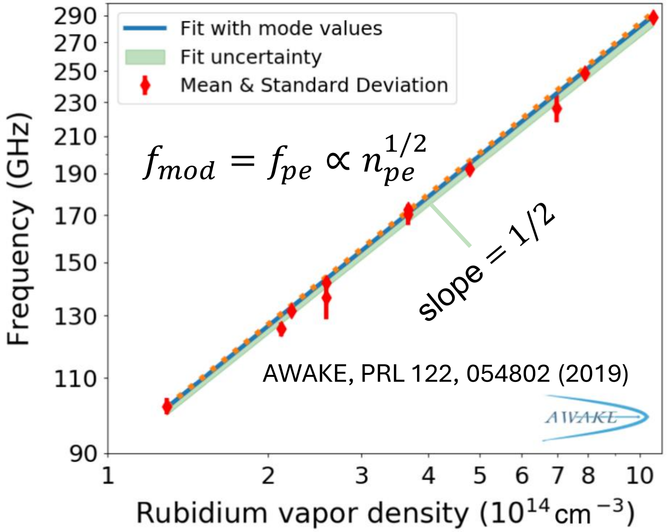

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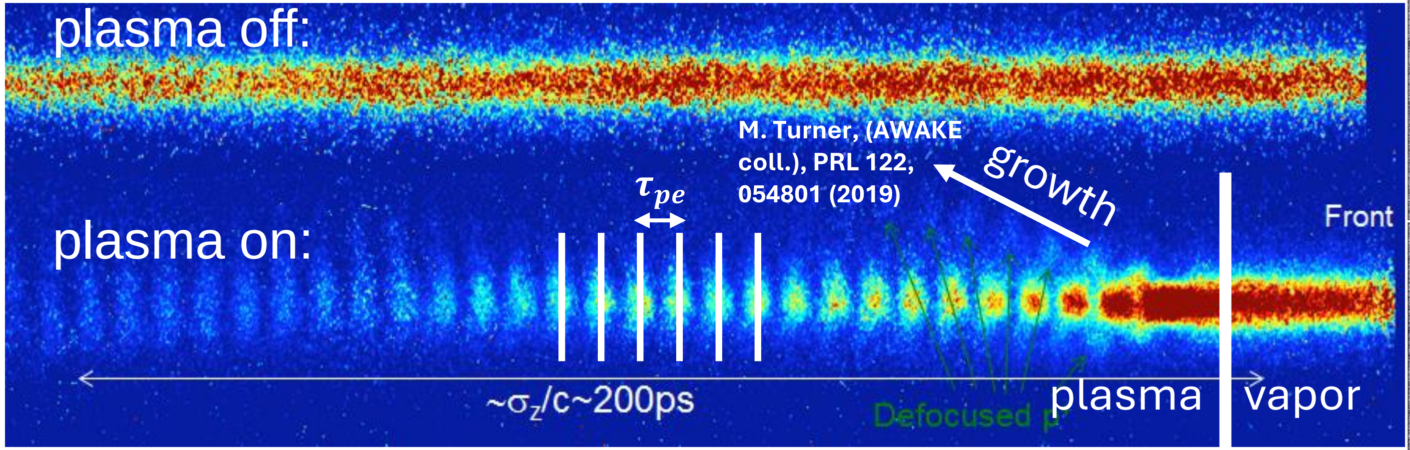

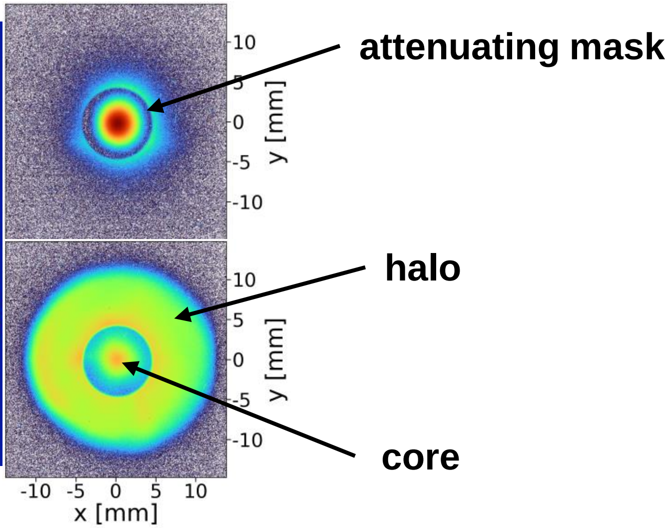

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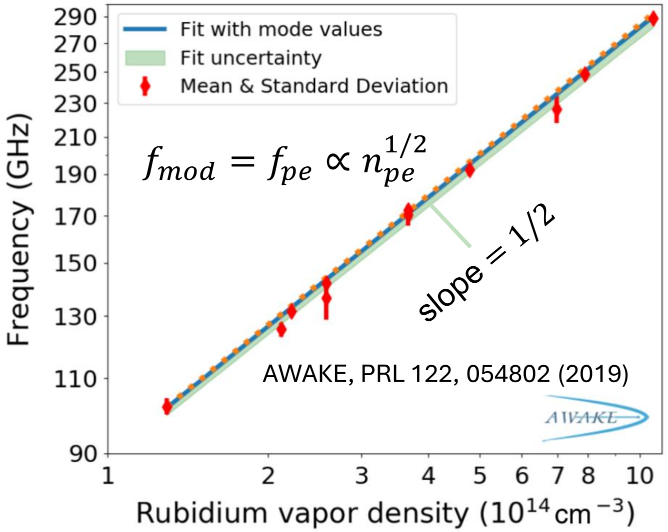
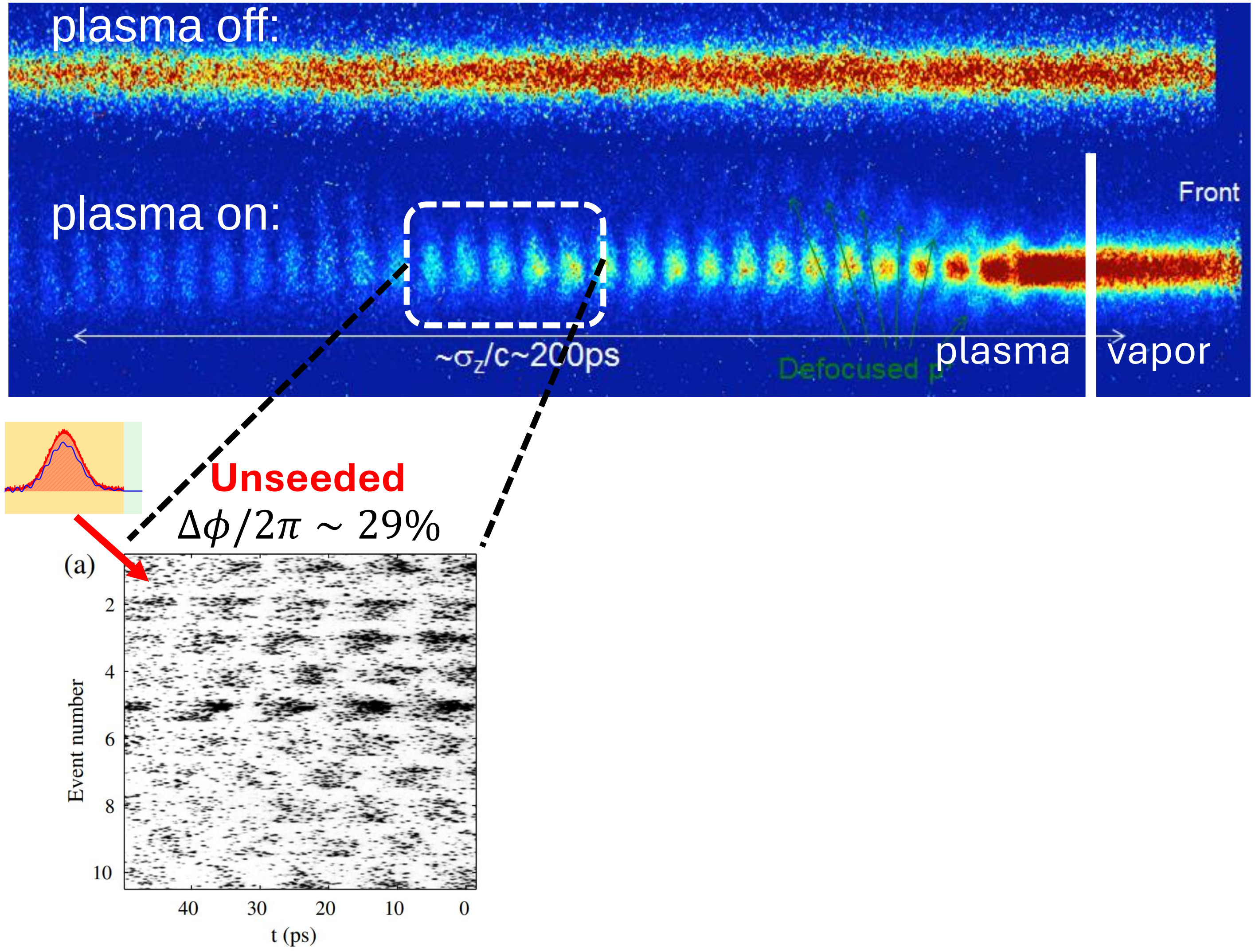
- Growth of transverse wakefields along bunch and plasma



Seeding of SM



F. Batsch (AWAKE coll.), PRL 126 (2021)

- SM is an instability – process must be reproducible for accelerator

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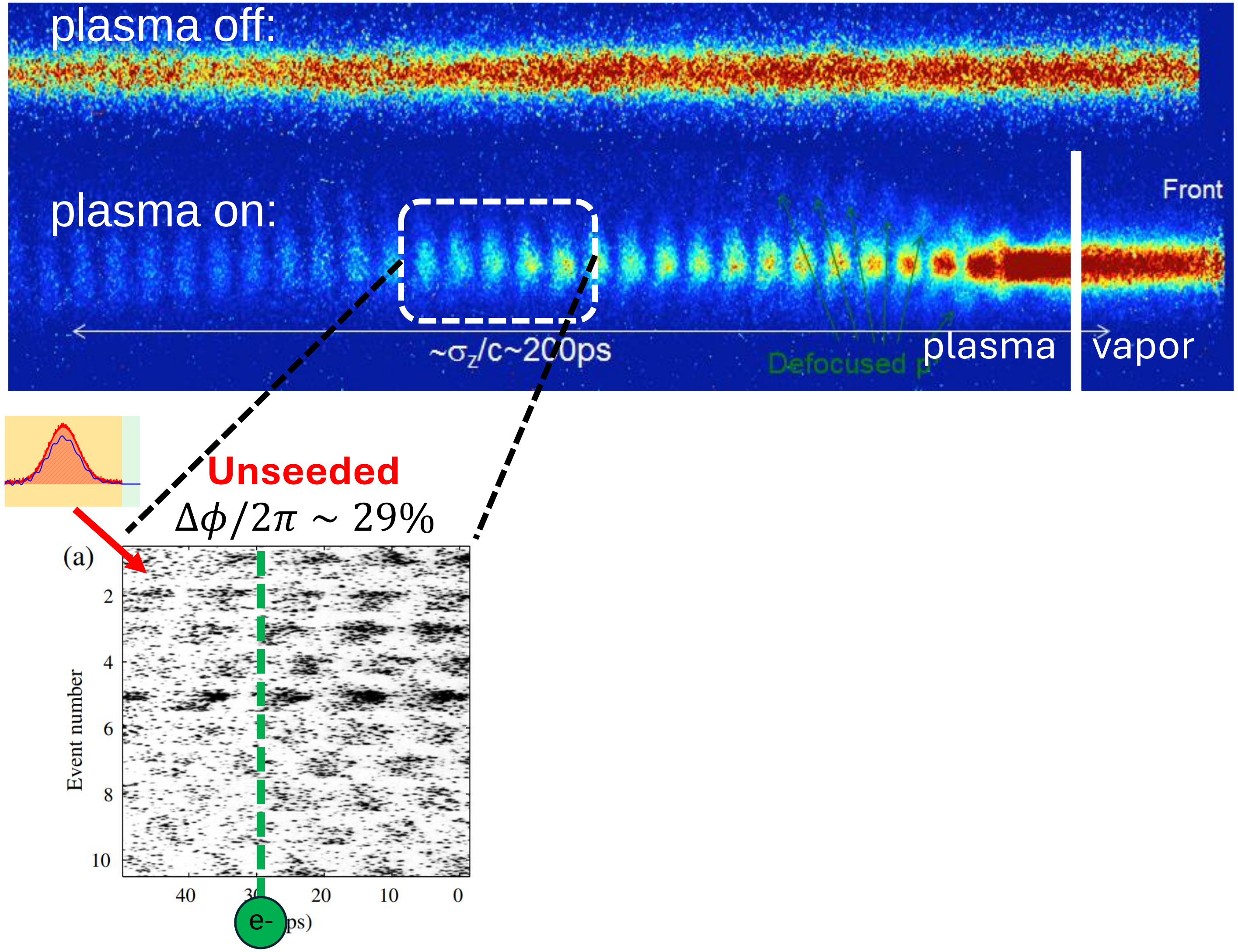

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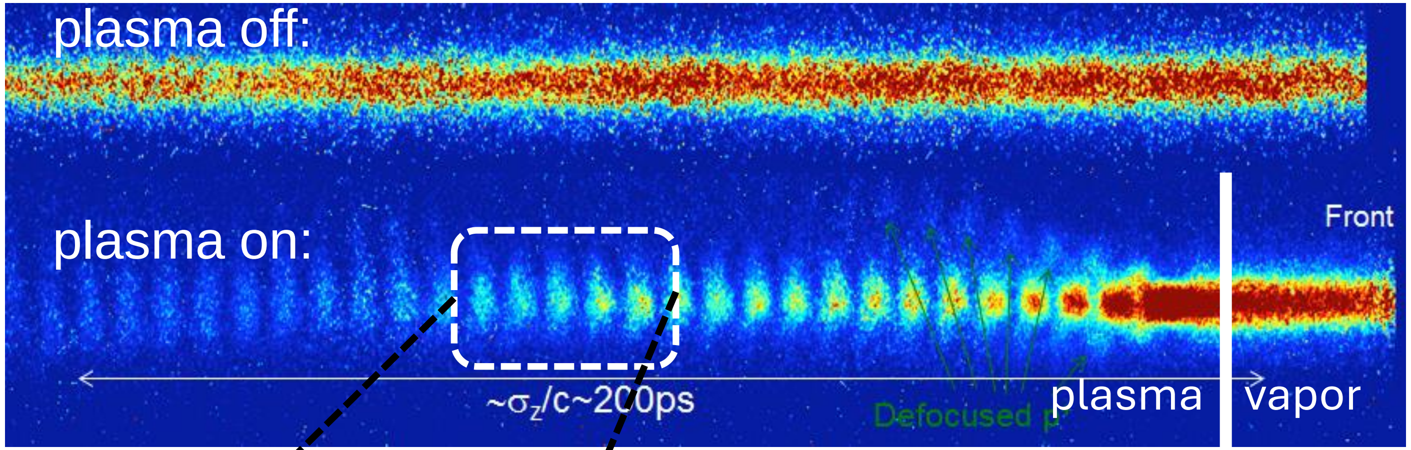
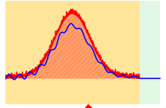
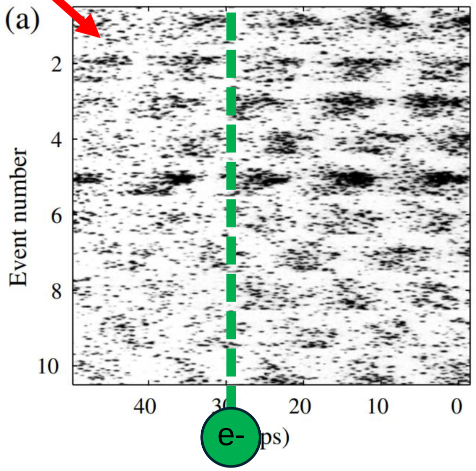


Relativistic
Ionization
Front (RIF)



Unseeded

$\Delta\phi/2\pi \sim 29\%$



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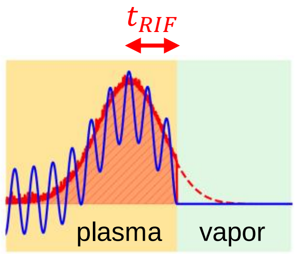
- Generating plasma along bunch creates beam-plasma density onset

→ Results in initial wakefields

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$



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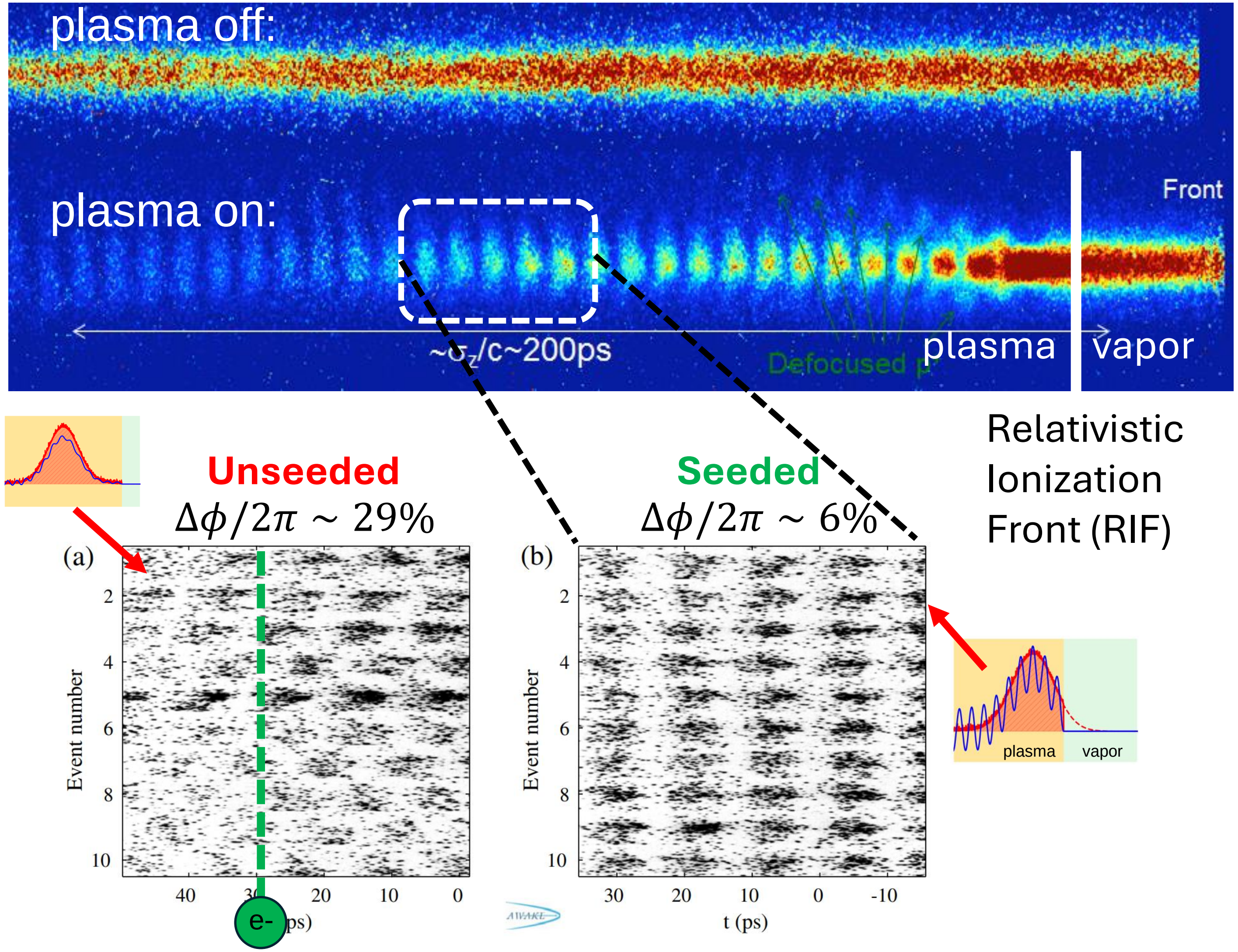

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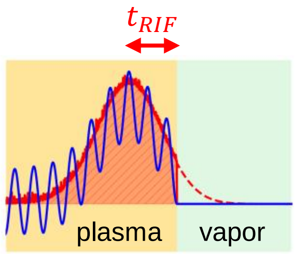
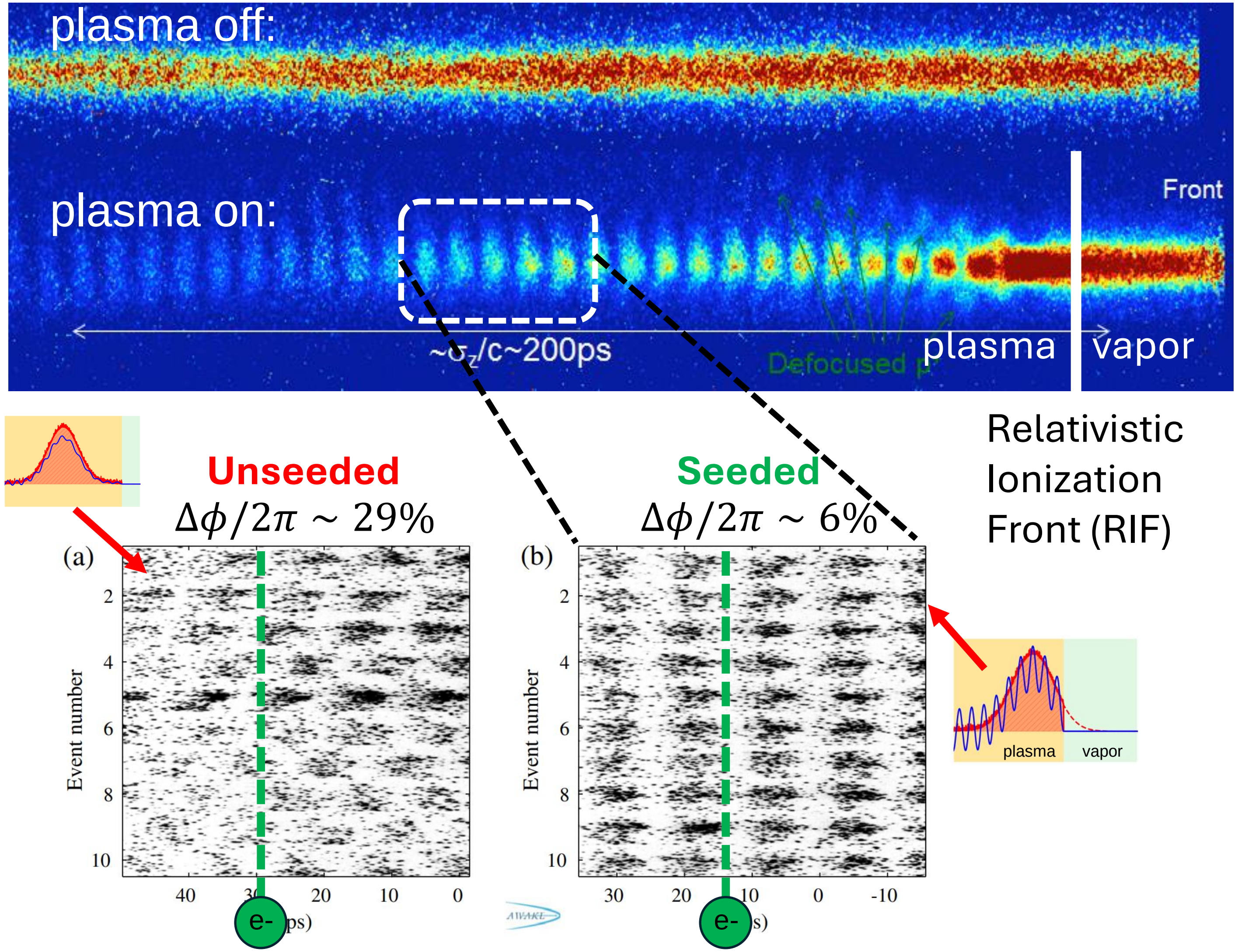


→ **Wakefield phase reproducible** from event to event

Seeding of SM



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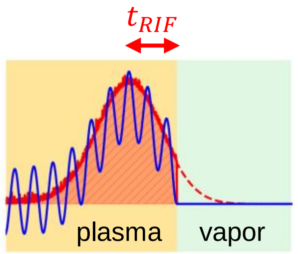
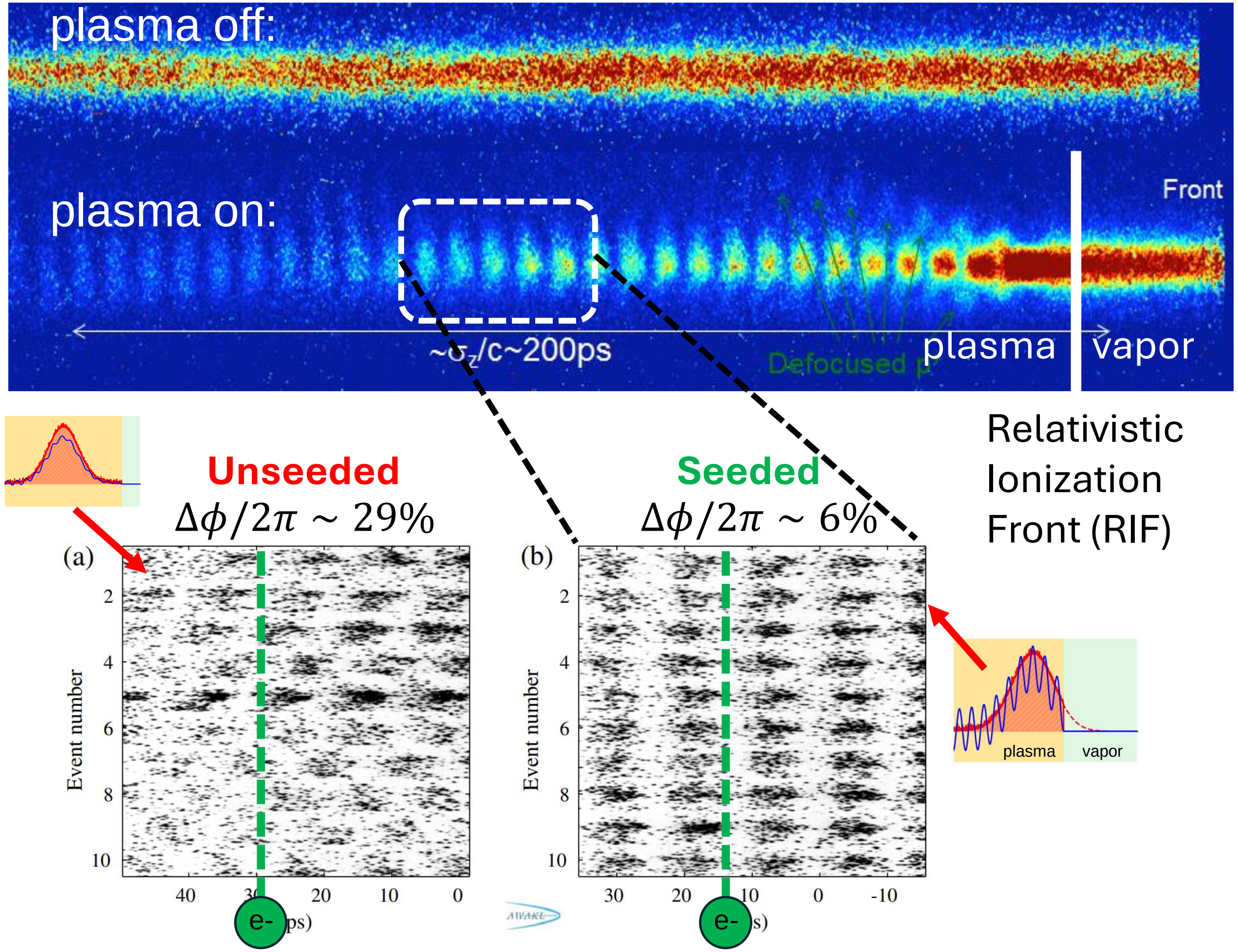


→ **Wakefield phase reproducible** from event to event

→ Deterministic, external injection of witness bunch can occur

Seeding of SM

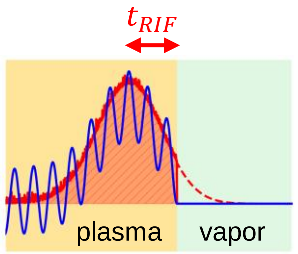


F. Batsch (AWAKE coll.), PRL 126 (2021)

- SM is an instability – process must be reproducible for accelerator
- SM can be seeded
- Generating plasma along bunch creates beam-plasma density onset

→ Results in initial wakefields

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$



→ **Wakefield phase reproducible** from event to event

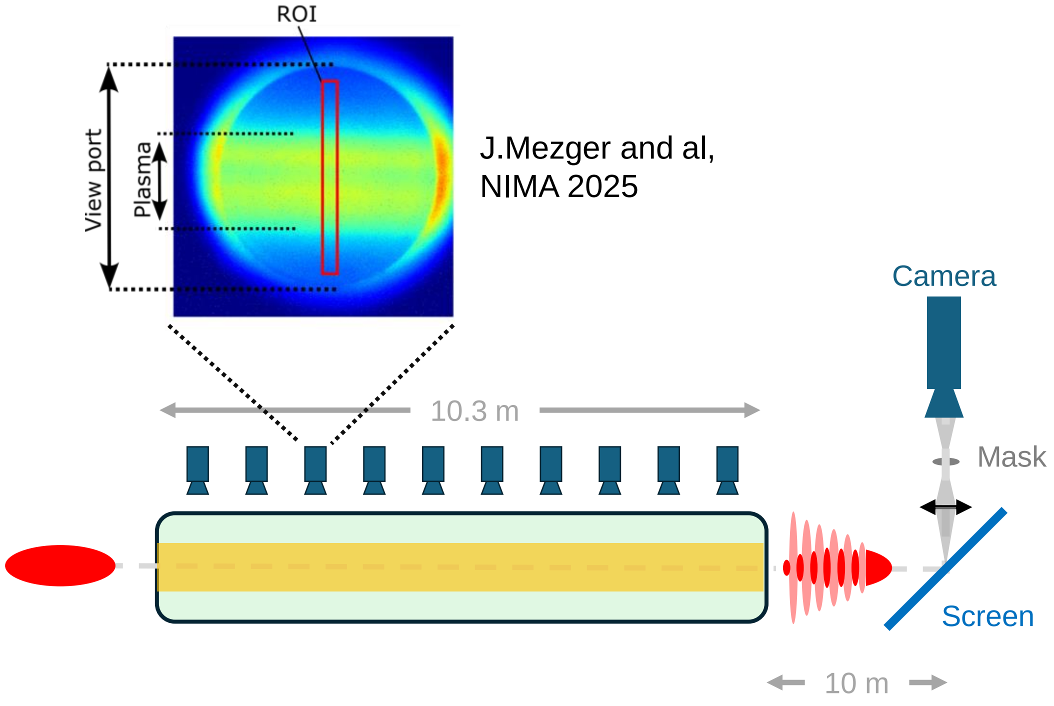
→ Deterministic, external injection of witness bunch can occur

→ Reproducible amplitude of the wakefields ?

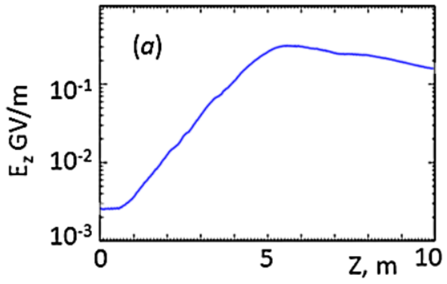
Outline

- Introduction to the AWAKE Experiment at CERN
- Demonstration of Amplitude-Reproducible Self-Modulation by Seeding
- Measurement of the Saturation Length of the Self-Modulation Instability
- Moving forward…

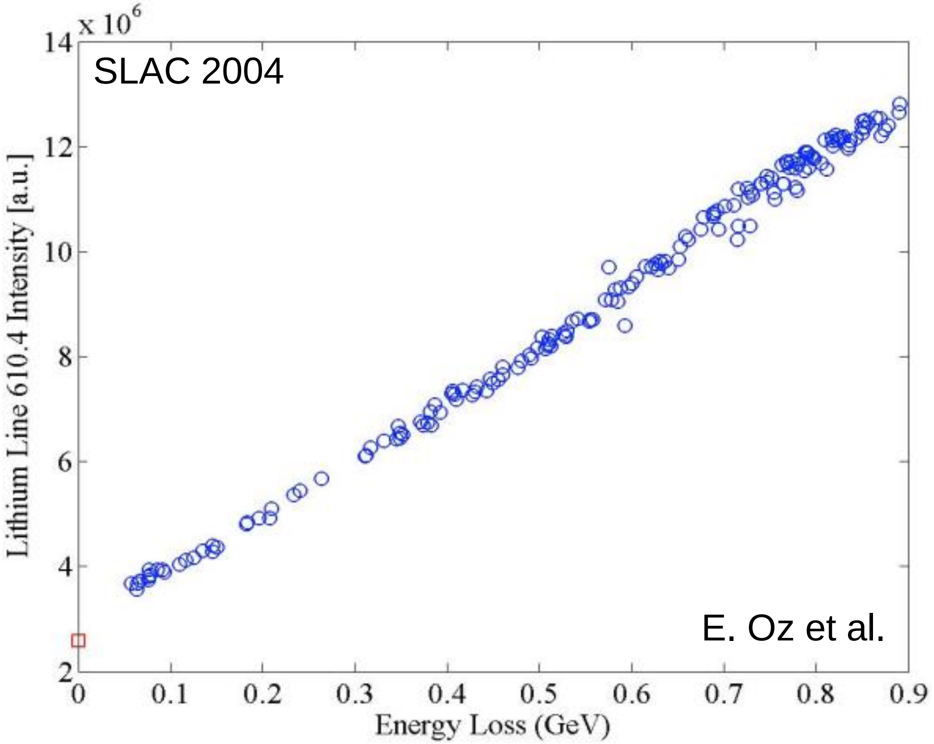
Amplitude reproducibility



- Wakefield amplitudes are difficult to measure directly

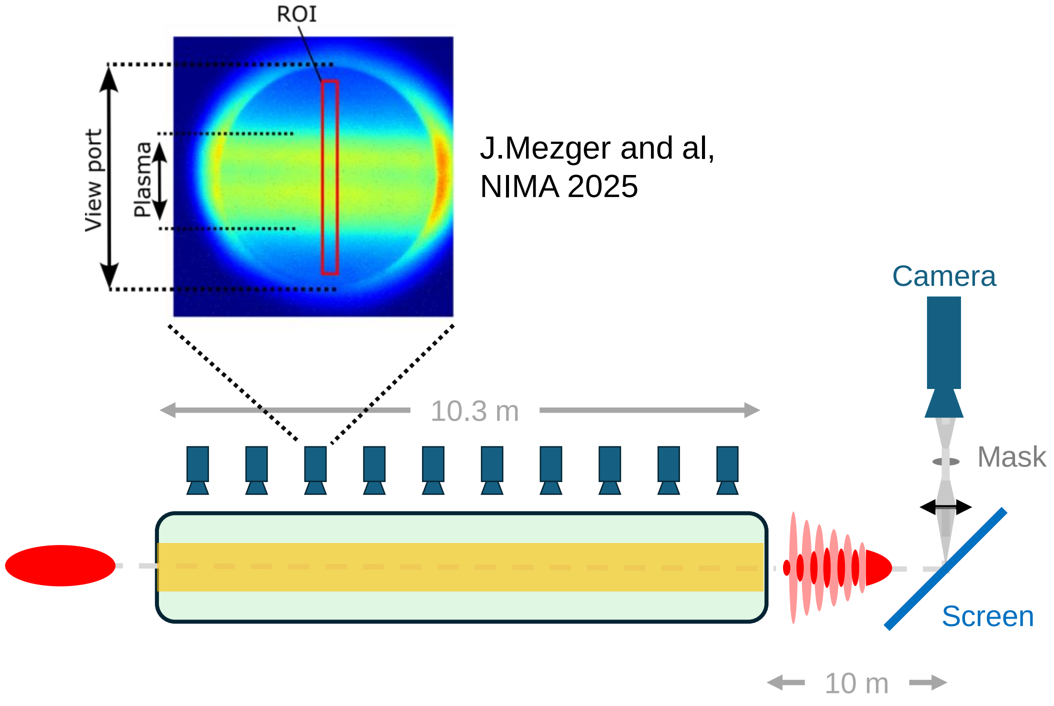


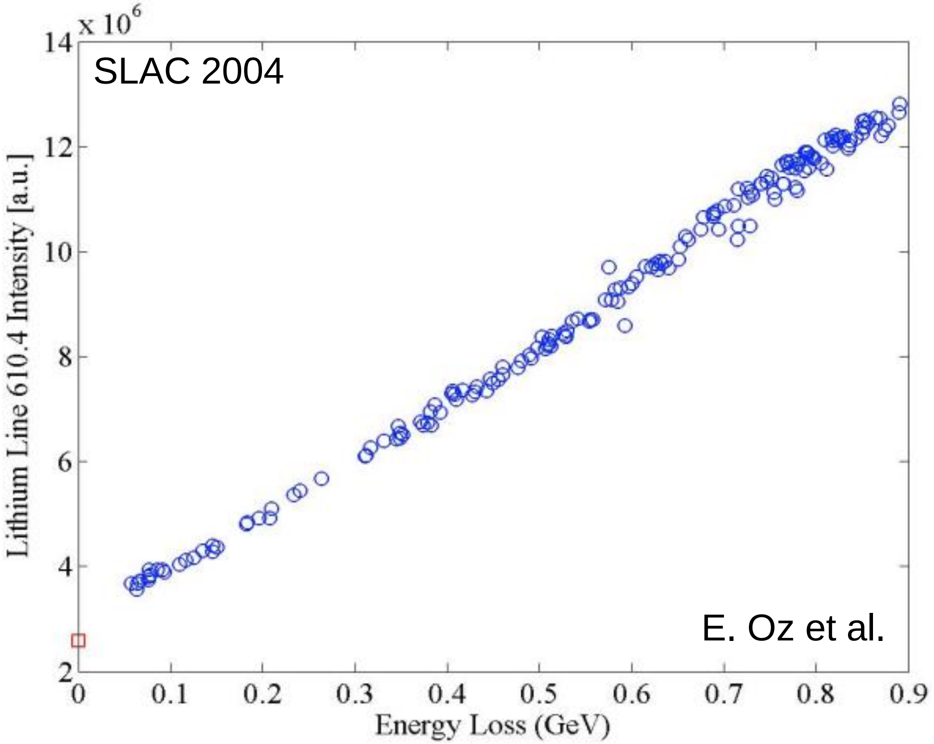
Pukhov, PRL 107 145003 (2011)



- **Light emitted ∝ energy loss**
- Energy loss through driving of wakefields
- Can be used to assess the reproducibility of wakefields

Amplitude reproducibility





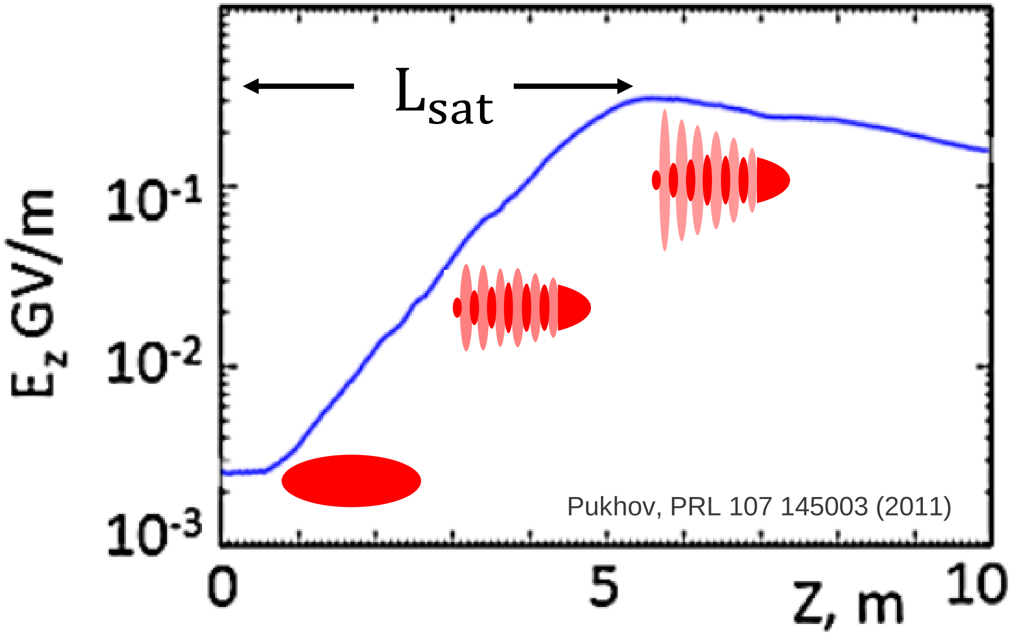
- Wakefield amplitudes are difficult to measure directly

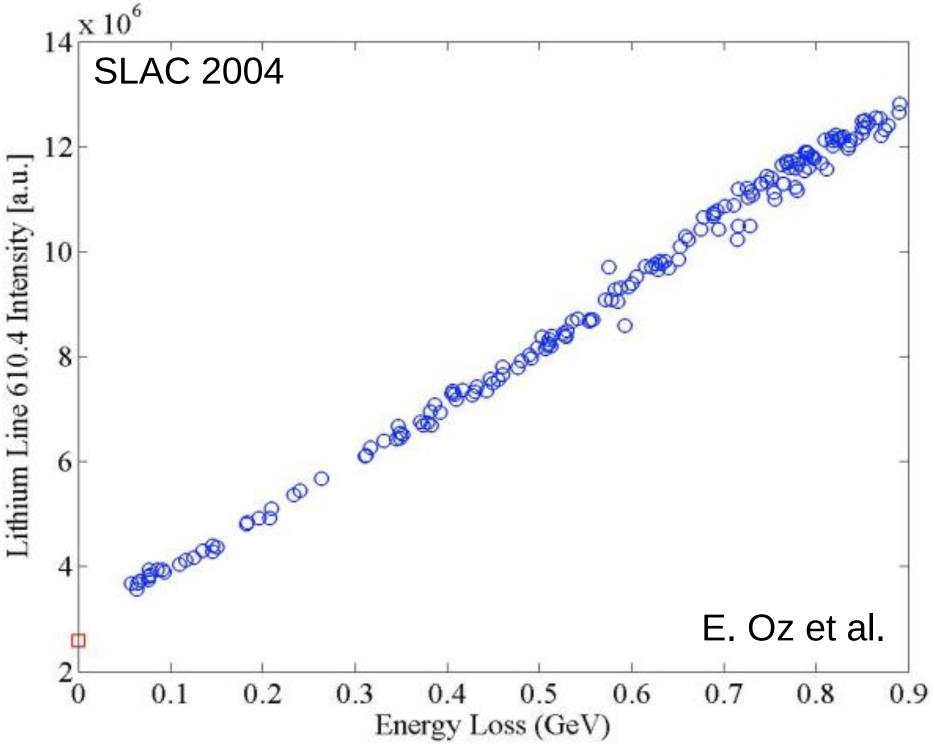
- **Light diagnostic:**

  - **10 cameras** recording the **light** emitted by the plasma
  → energy deposited by the bunch

- **Light emitted ∝ energy loss**
- Energy loss through driving of wakefields
- Can be used to assess the reproducibility of wakefields

Amplitude reproducibility



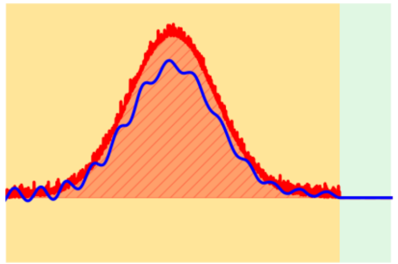


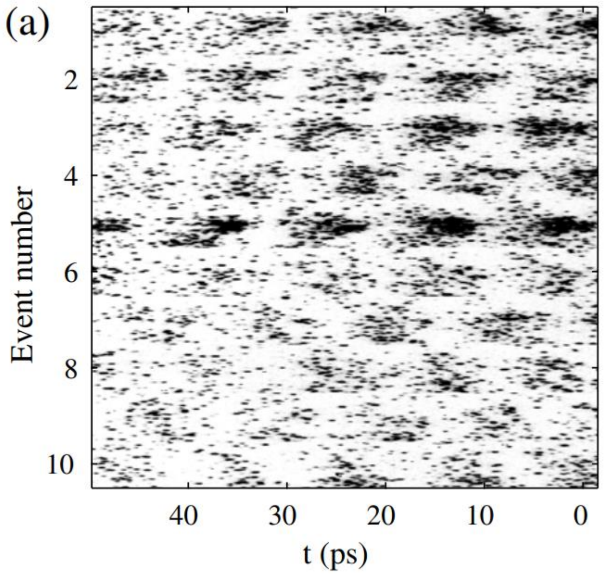
- Expect to observe growth, saturation and decay of the signal along z

- **Light emitted ∝ energy loss**
- Energy loss through driving of wakefields
- Can be used to assess the reproducibility of wakefields

Light emission

Proton bunch :
- $N_b = 0.5 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 180$ µm
- $\sigma_t = 170$ ps

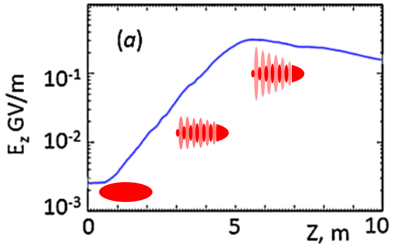




- SM is not seeded

→ when it grows from noise

→ when timing of microbunches vary randomly from event to event



Pukhov, PRL 107 145003 (2011)

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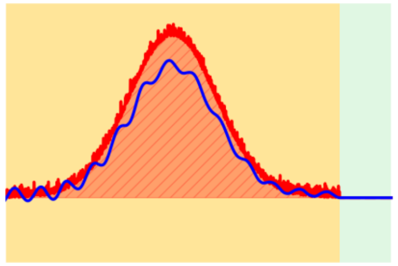
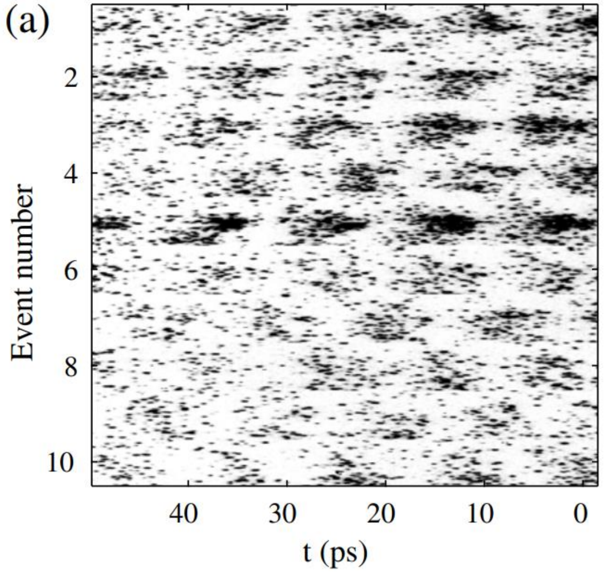
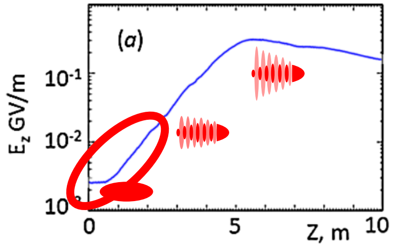






Pukhov, PRL 107 145003 (2011)

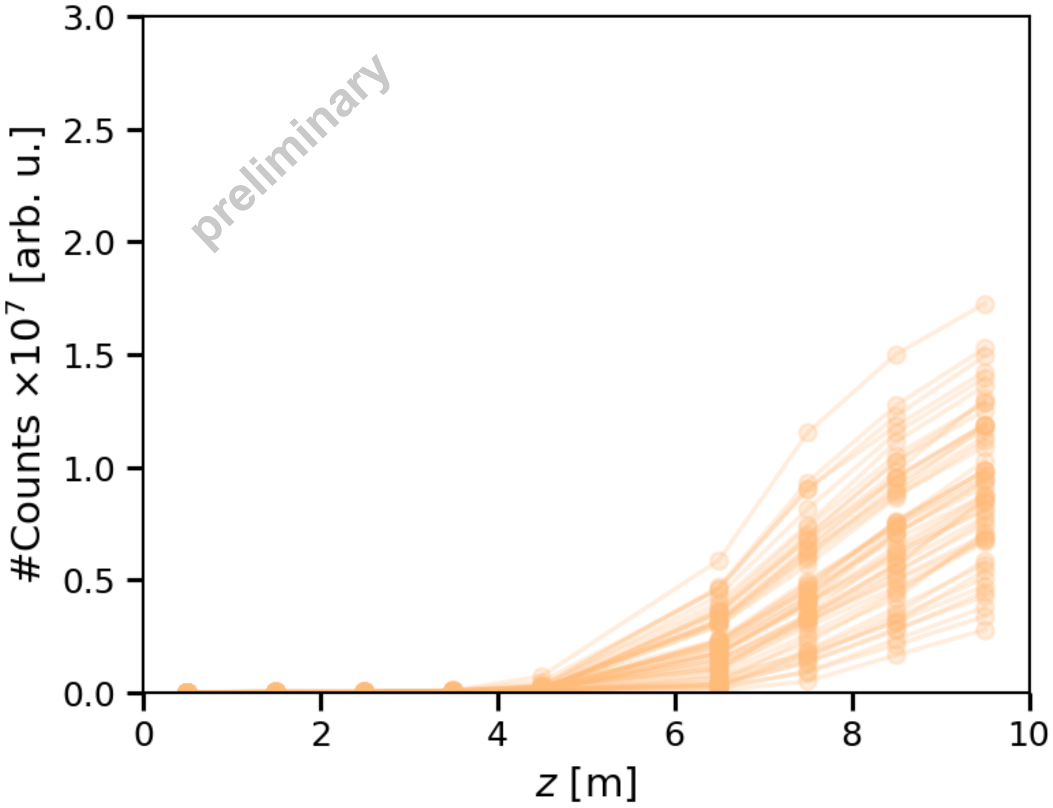
- SM is not seeded
→ when it grows from noise
→ when timing of microbunches vary randomly from event to event

- 10 cameras along plasma
- ~ 50 consecutive events

- Light signal
→ Starts from low level
→ Increases along plasma

- Consistent with growth of SM along plasma

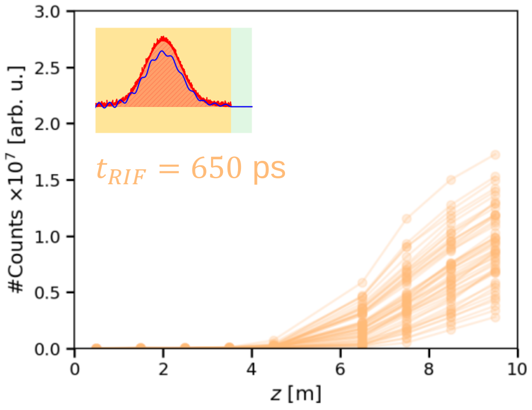
- Large event-to-event variations



Light emission

preliminary

Unseeded



- Random phase (SM is unseeded)

→ SM grows from noise or features in the bunch

→ Initial conditions vary from event to event

Proton bunch :

- $N_b = 0.5 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 180$ µm
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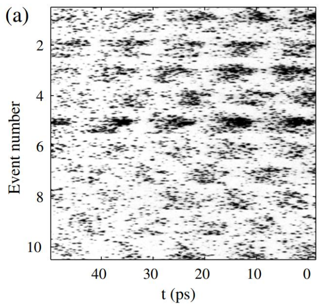
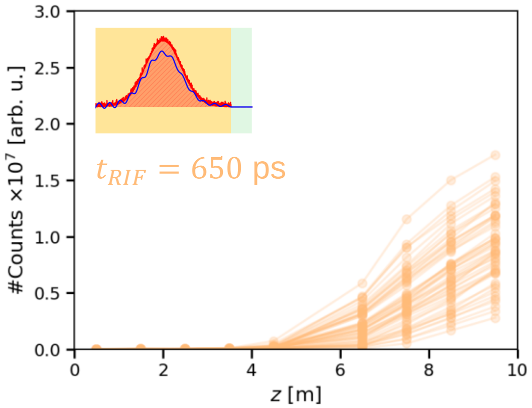


Light emission

preliminary

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded



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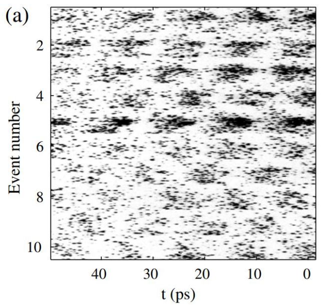

Light emission

preliminary

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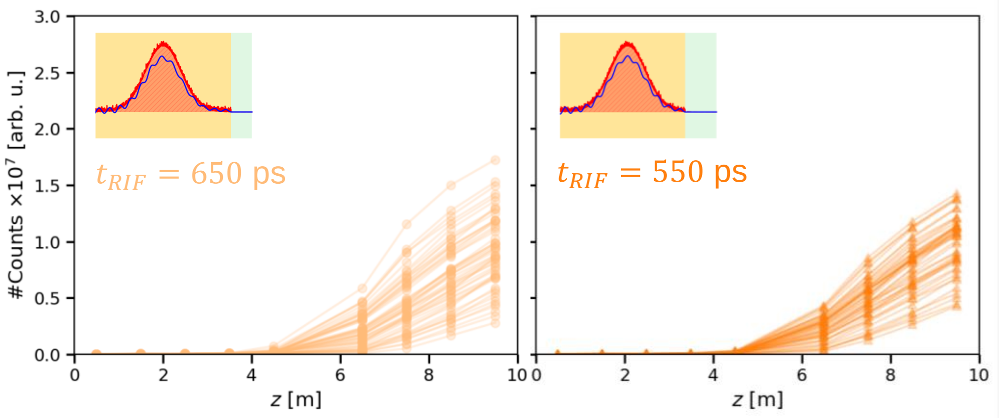

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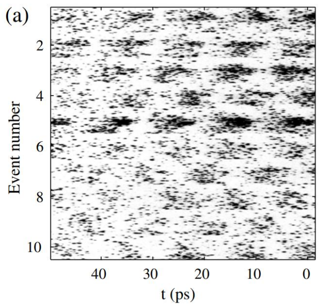
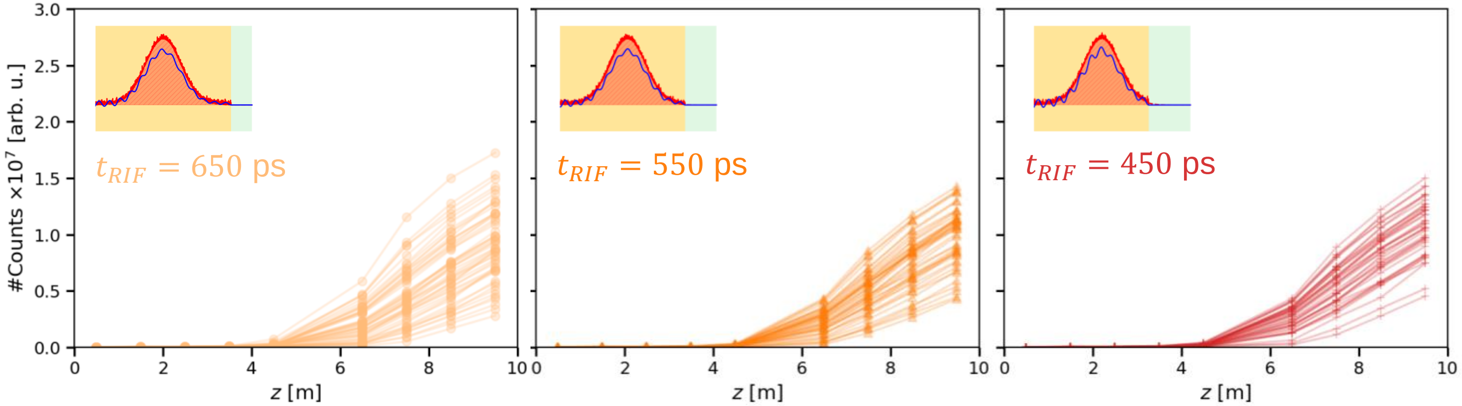


Light emission

preliminary

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded



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→ Initial conditions vary from event to event

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- $E = 400$ GeV
- $\sigma_r = 180$ µm
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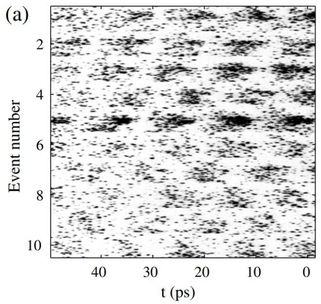
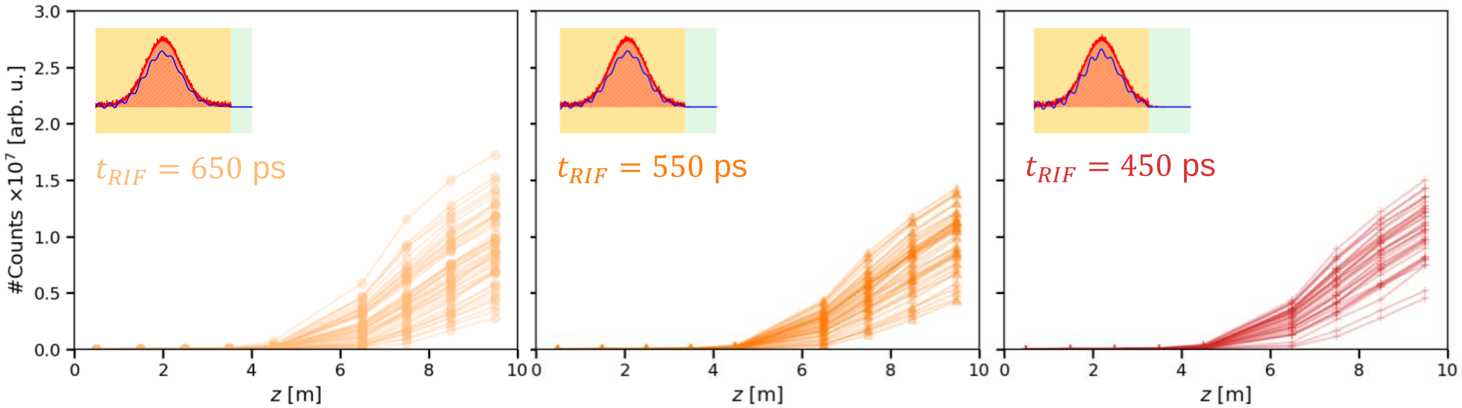


Light emission

preliminary

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded



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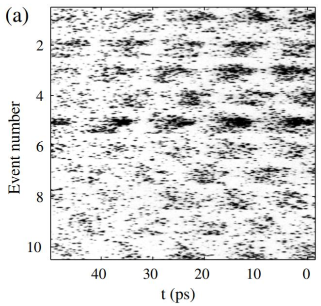
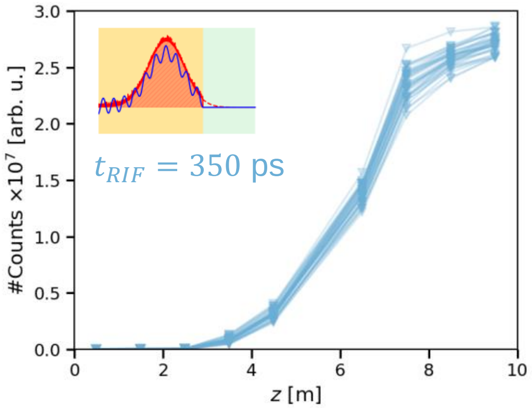
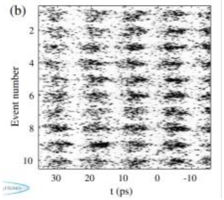


Seeded



- Phase reproducible (SM is seeded)

→ SM grows from controlled initial conditions

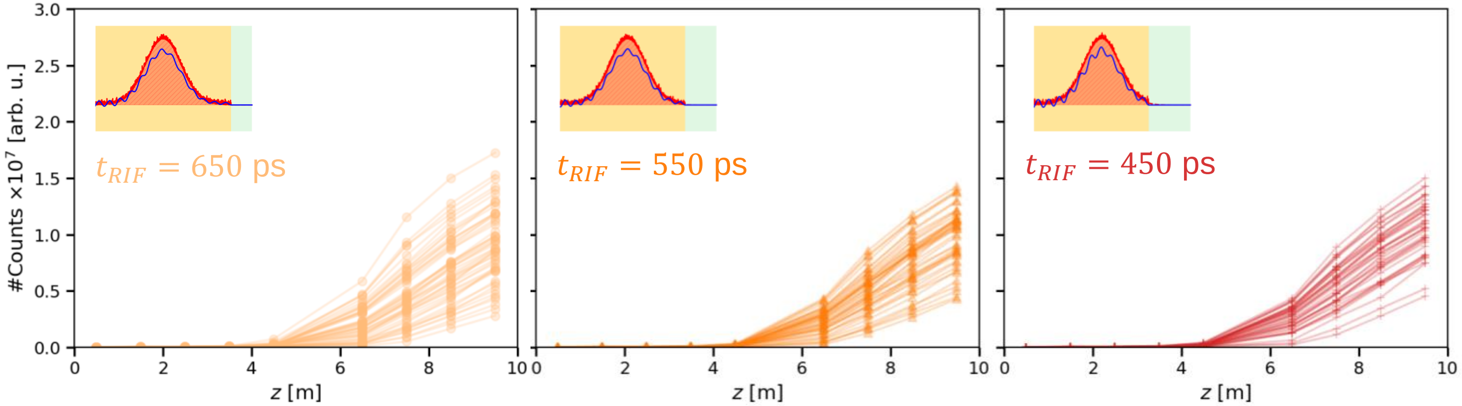


Light emission

preliminary

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded



- Random phase (SM is unseeded)

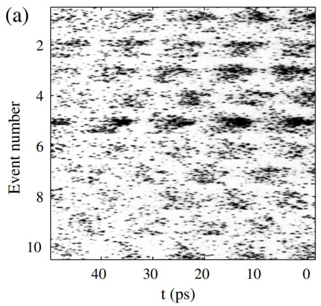
→ SM grows from noise or features in the bunch

→ Initial conditions vary from event to event

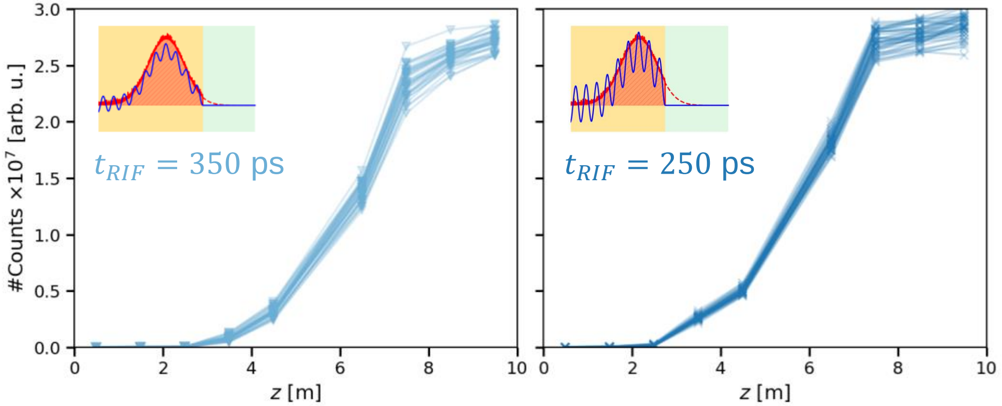
- Late growth
- SM does not saturate within 10m

Proton bunch :

- $N_b = 0.5 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 180$ µm
- $\sigma_t = 170$ ps



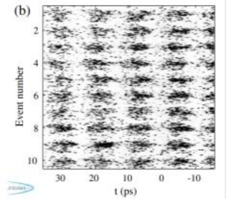
Seeded



- Phase reproducible (SM is seeded)

→ SM grows from controlled initial conditions

- Earlier growth
- SM saturates at z~8m

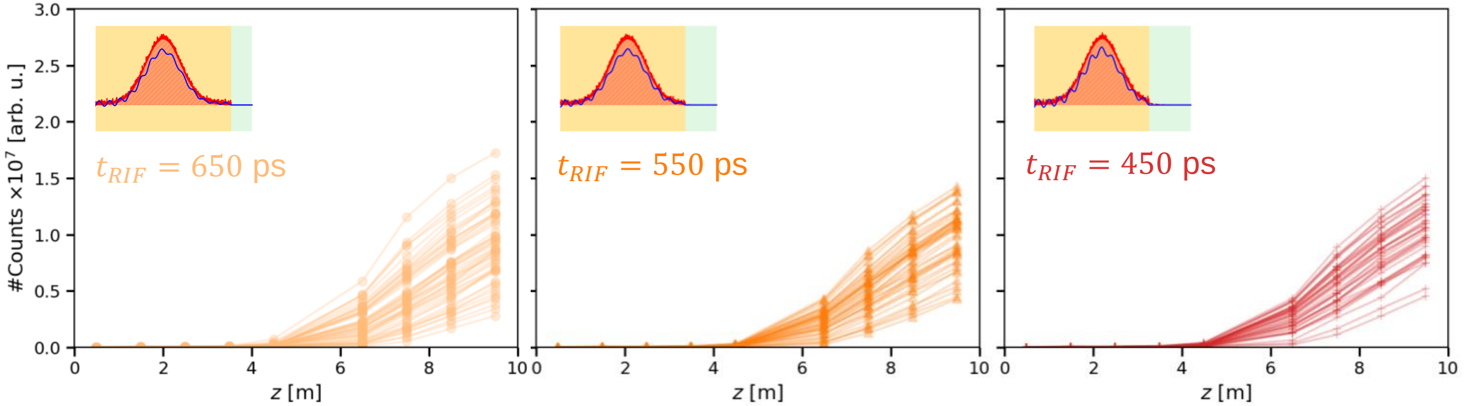


Light emission

preliminary

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded



- Random phase (SM is unseeded)

→ SM grows from noise or features in the bunch

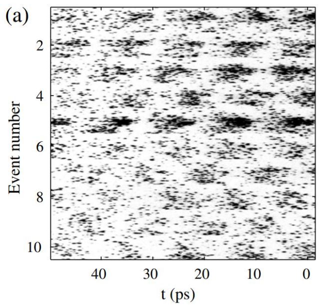
→ Initial conditions vary from event to event

- Late growth
- SM does not saturate within 10m

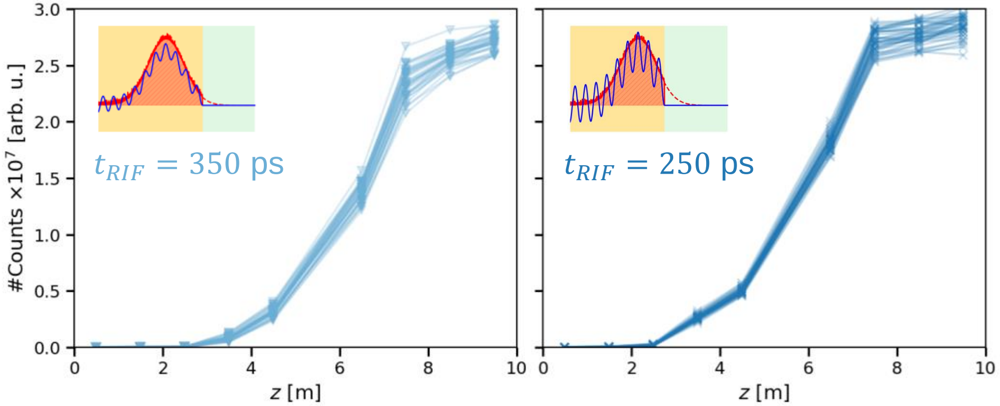
- Large variations from event to event

Proton bunch :

- $N_b = 0.5 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 180$ µm
- $\sigma_t = 170$ ps



Seeded



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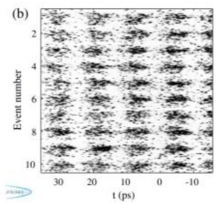


- Earlier growth
- SM saturates at z~8m

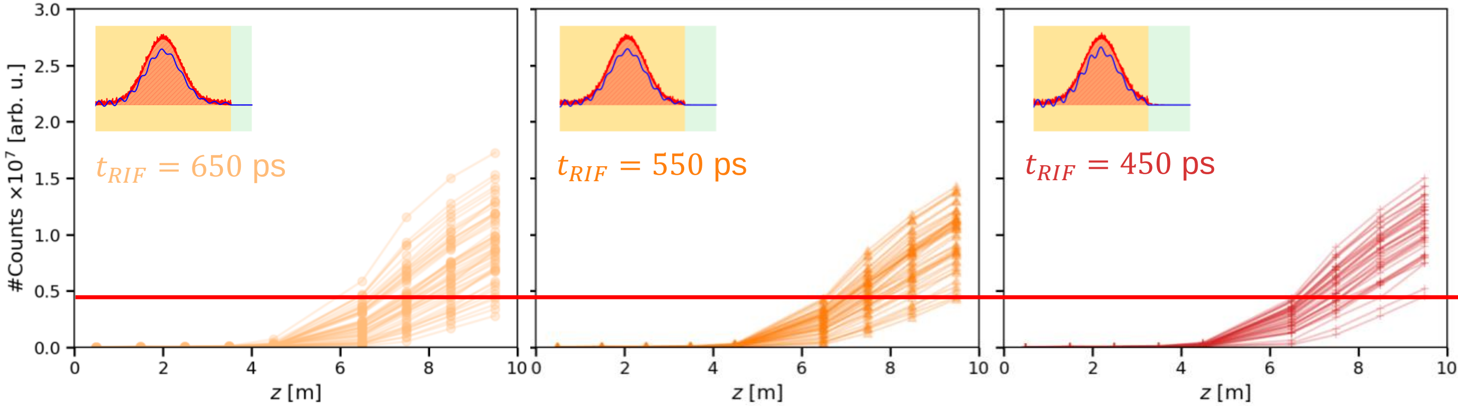
- Smaller variations from event to event

Light emission

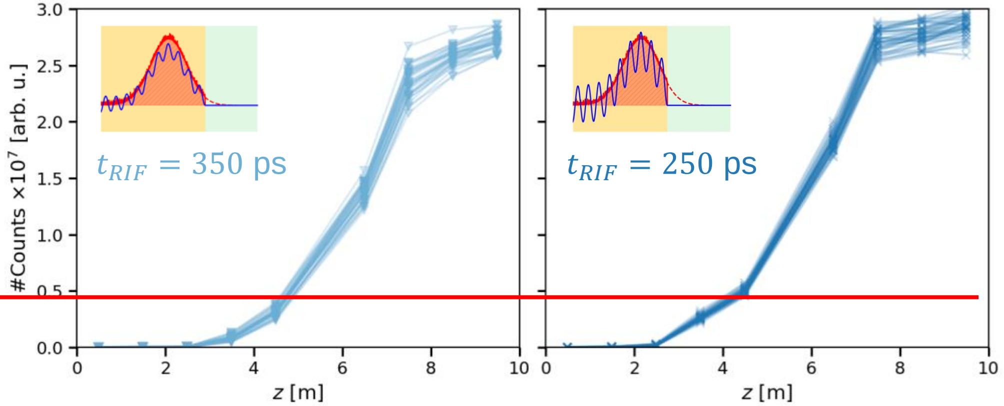
preliminary

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded



Seeded

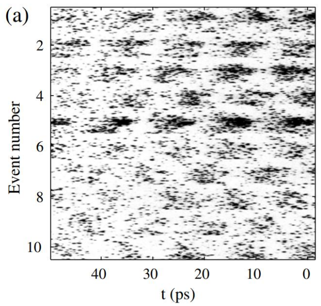


- Random phase (SM is unseeded)
→ SM grows from noise or features in the bunch
→ Initial conditions vary from event to event

- Late growth
- SM does not saturate within 10m

- Large variations from event to event
  - at same signal level

Proton bunch :
- $N_b = 0.5 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 180$ µm
- $\sigma_t = 170$ ps



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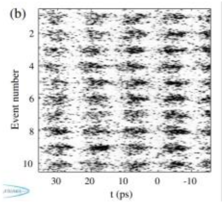


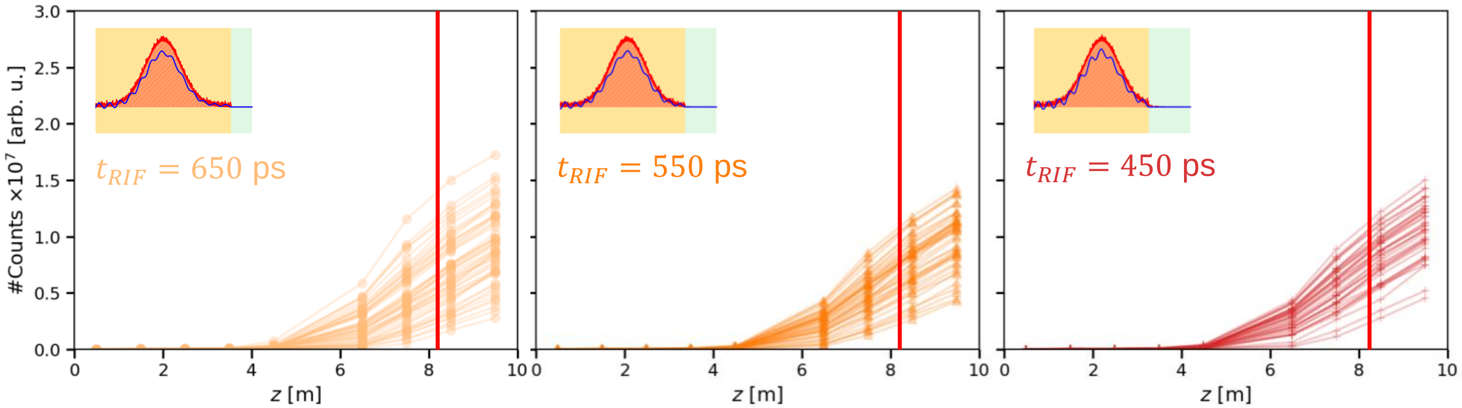
- Smaller variations from event to event
  - at same signal level

Light emission

preliminary

$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded



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→ SM grows from noise or features in the bunch

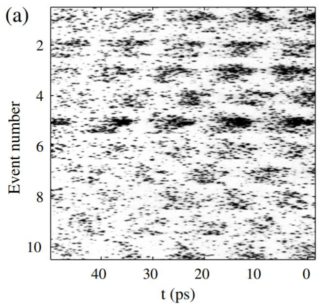
→ Initial conditions vary from event to event

- Late growth
- SM does not saturate within 10m

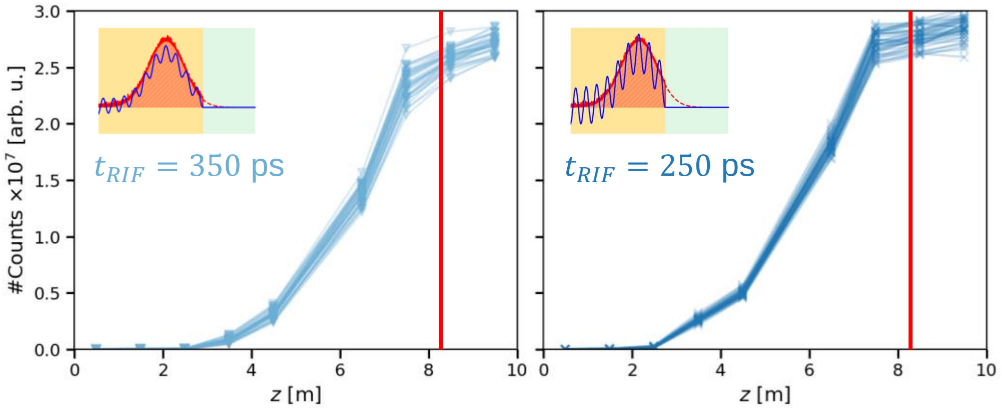
- Large variations from event to event
  - at same signal level
  - at same location along plasma

Proton bunch :

- $N_b = 0.5 \times 10^{11}$
- E = 400 GeV
- σ_r = 180 μm
- σ_t = 170 ps



Seeded



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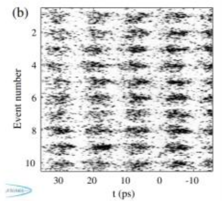
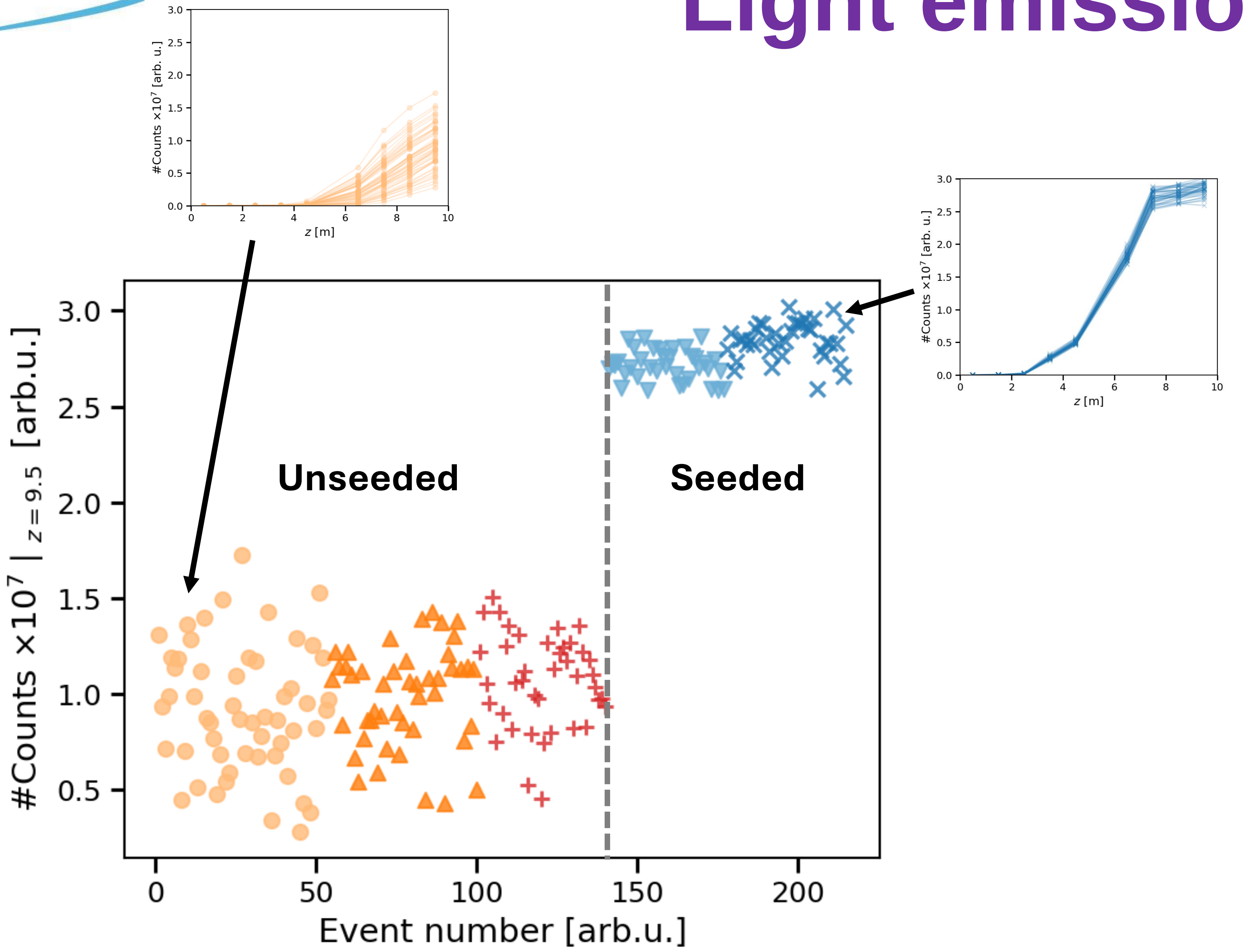
→ SM grows from controlled initial conditions



- Earlier growth
- SM saturates at z~8m

- Smaller variations from event to event
  - at same signal level
  - at same location along plasma

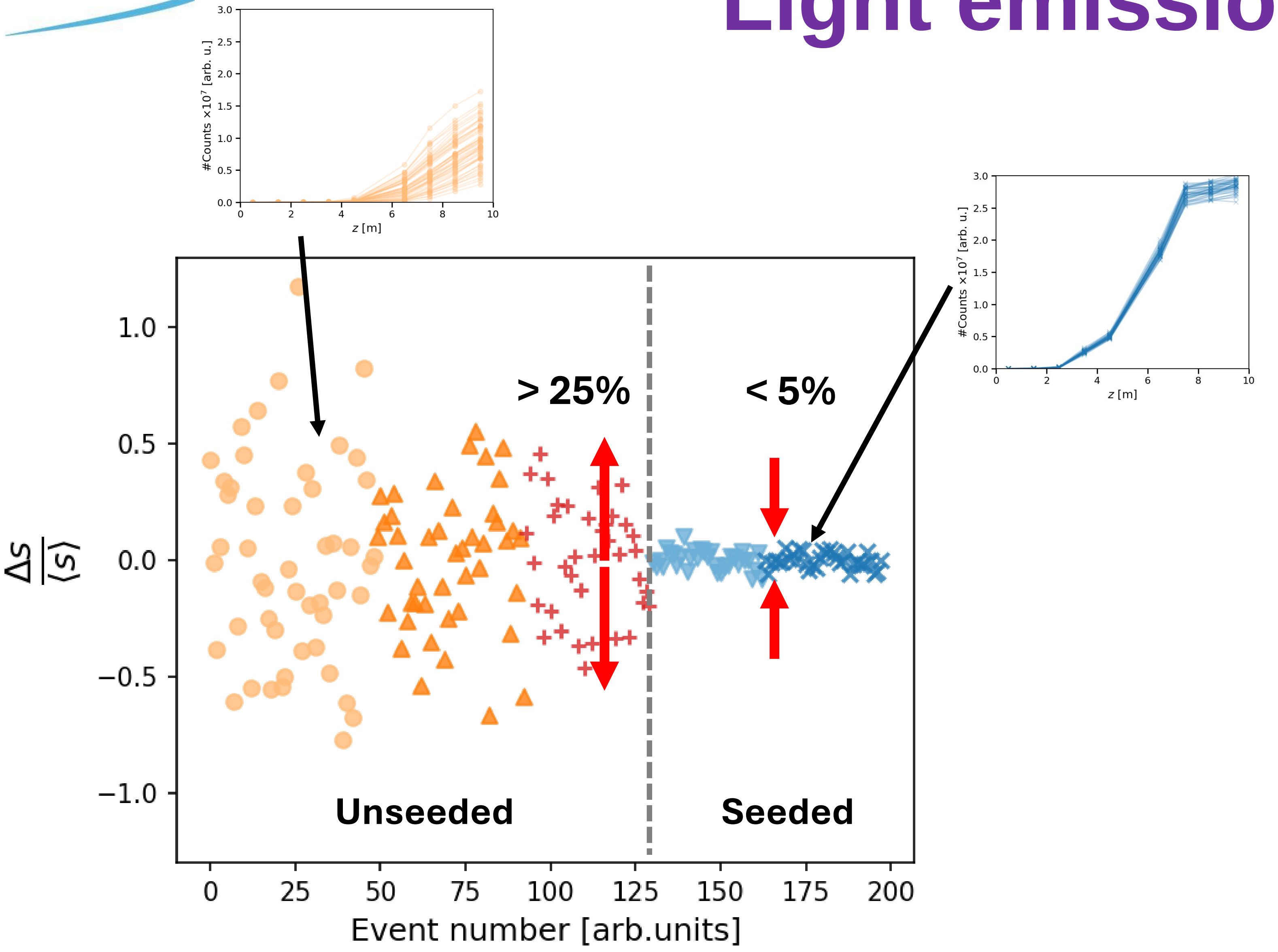
Light emission



- Sum of signal from 10 cameras
  → total energy deposited by the bunch
- More light when seeded
  → Higher initial wakefields
  → Earlier growth
- Controlled initial conditions
  → absolute variations are smaller when seeded than when not

preliminary

Light emission



- Clear difference in relative variations

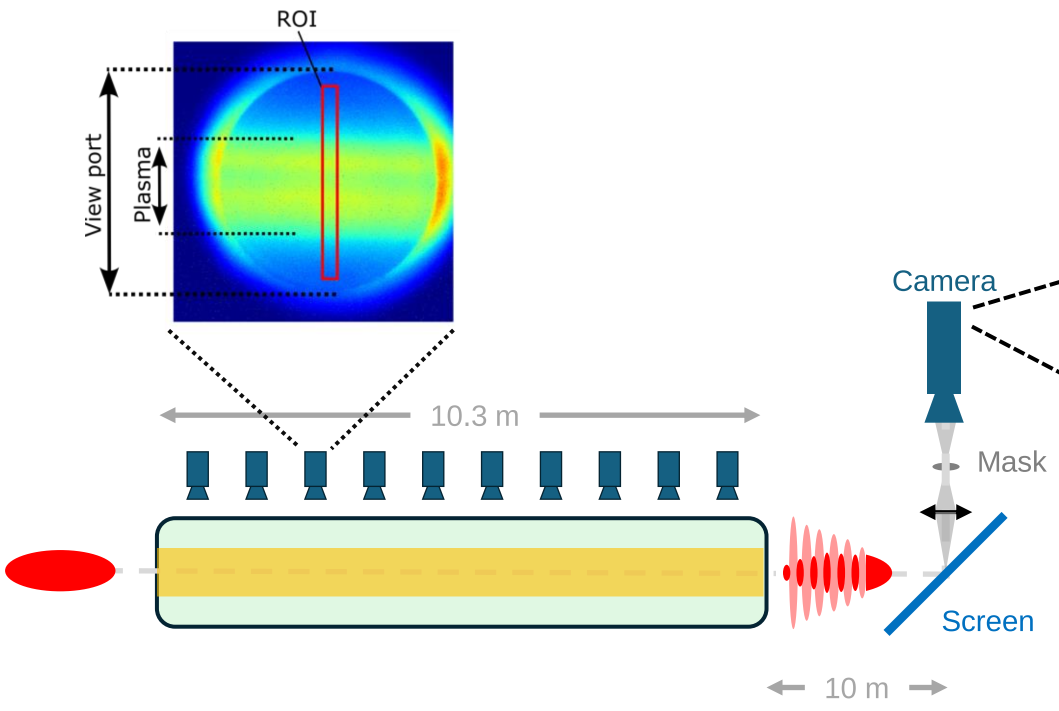
- **Unseeded** → $\frac{\Delta s}{s} > 25\%$
- **Seeded** → $\frac{\Delta s}{s} < 5\%$

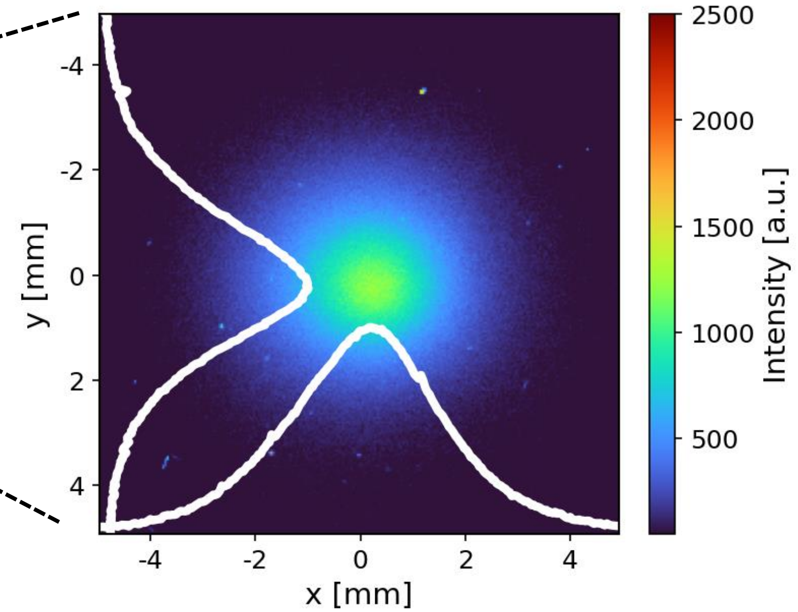
- Contribution of fluctuation of input parameters on remaining seeded variations, e.g.,

→ $N_b, \sigma_r, \sigma_t, z_{waist}, \ldots$

preliminary

Amplitude reproducibility





- Light measurement is **non-destructive**

- **Transverse bunch profile** can be observed **for the same events**

- SM is a transverse process

→ Shows cumulative effect of transverse wakefields over 10m of plasma

$$r \propto p_\perp \propto \int_0^z W_\perp(z)dz$$

- Larger transverse wakefields

→ More defocusing

→ Larger transverse size at screen

Proton bunch :

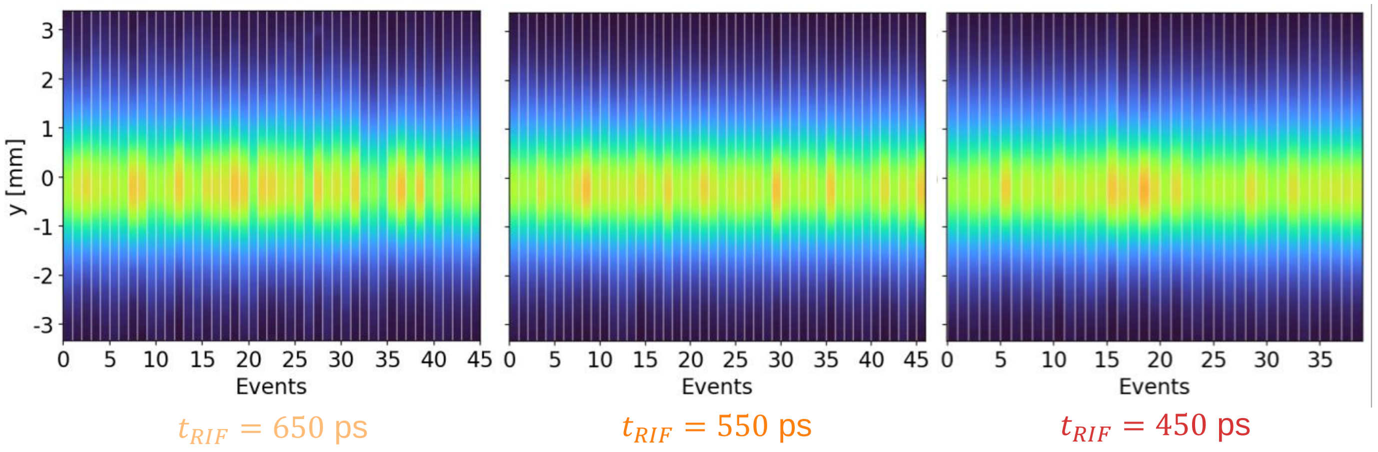
- $N_b = 0.5 \times 10^{11}$
- $E = 400$ GeV
- $\sigma_r = 180$ µm
- $\sigma_t = 170$ ps

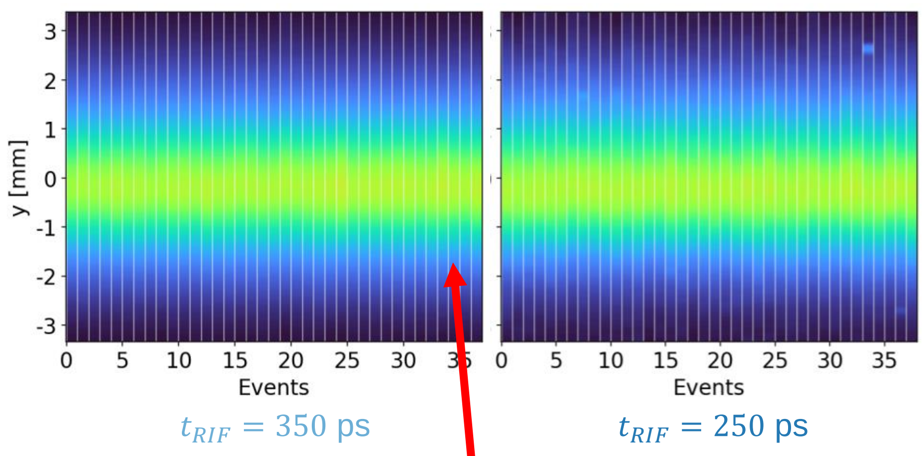
Effect of transverse wakefields

preliminary

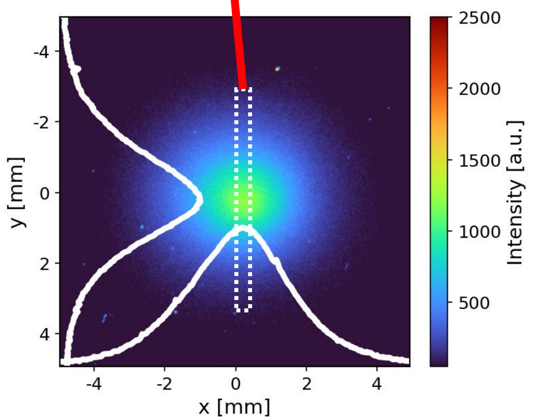
$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded | **Seeded**





- Waterfall plot of corresponding transverse bunch profiles
- Shows cumulative effect of transverse wakefields on the bunch over 10m of plasma
- More reproducible when seeded

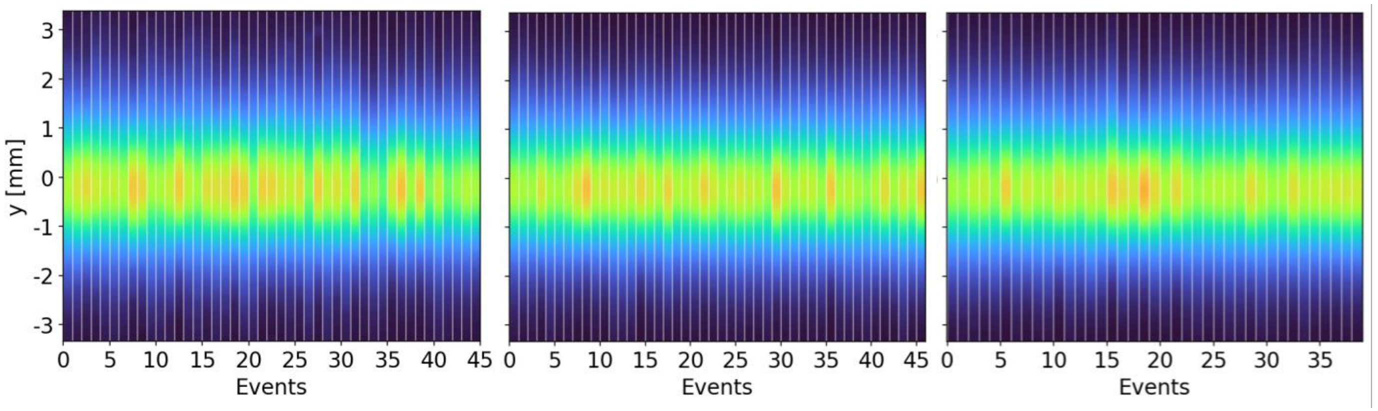


preliminary

Effect of transverse wakefields

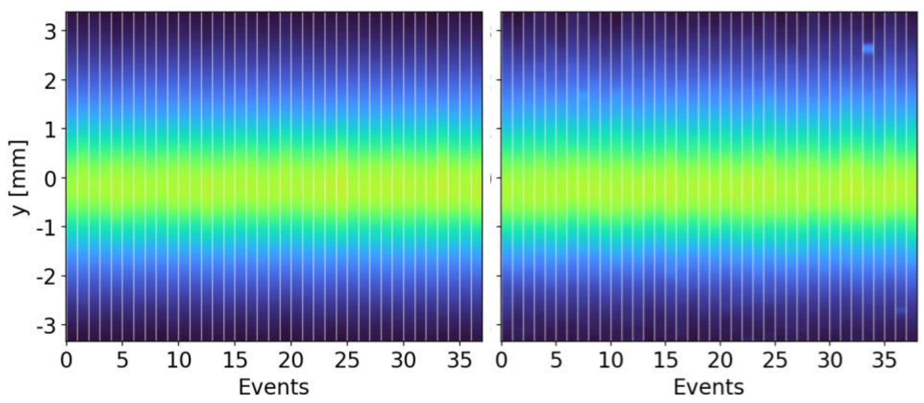
$$W_{\perp,0} \propto n_b(t = t_{RIF})$$

Unseeded

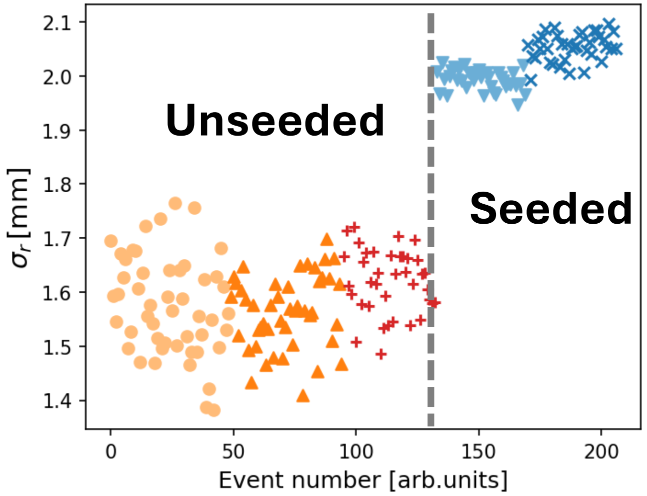


t_{RIF} = 650 ps t_{RIF} = 550 ps t_{RIF} = 450 ps

Seeded

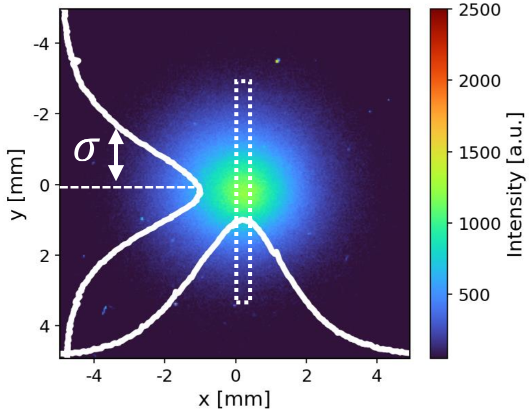


t_{RIF} = 350 ps t_{RIF} = 250 ps



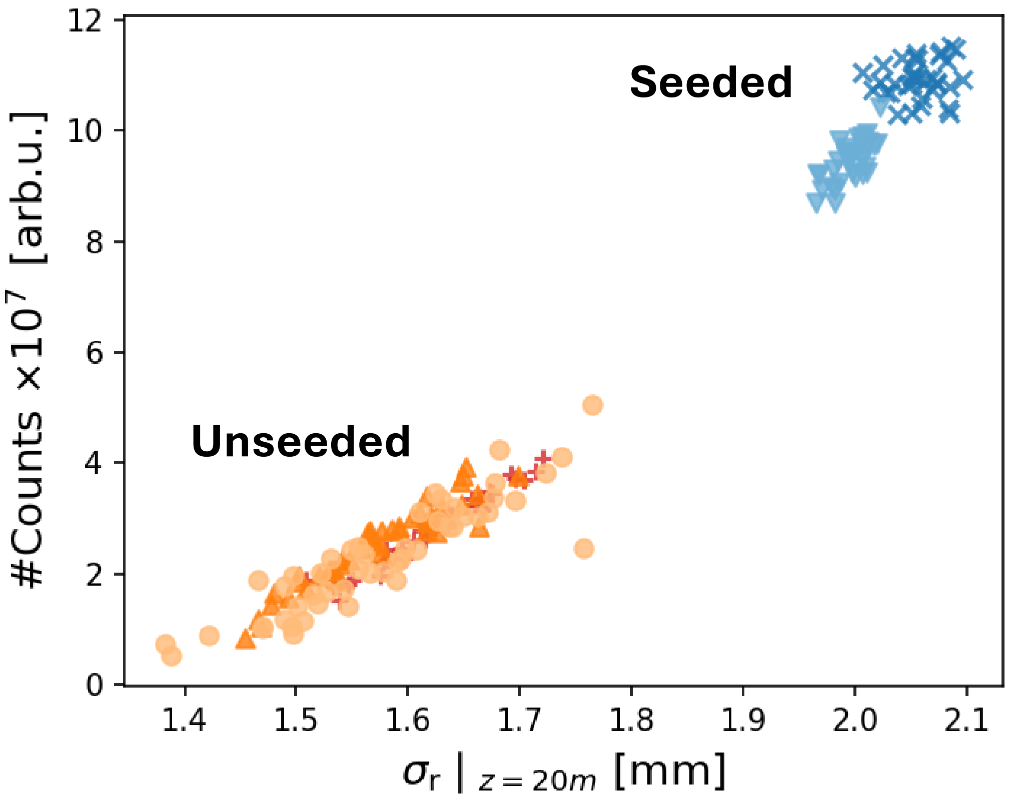
- Seeding leads to larger wakefields
→ Larger transverse size at the screen

- More reproducible when seeded



preliminary

Two independent diagnostics

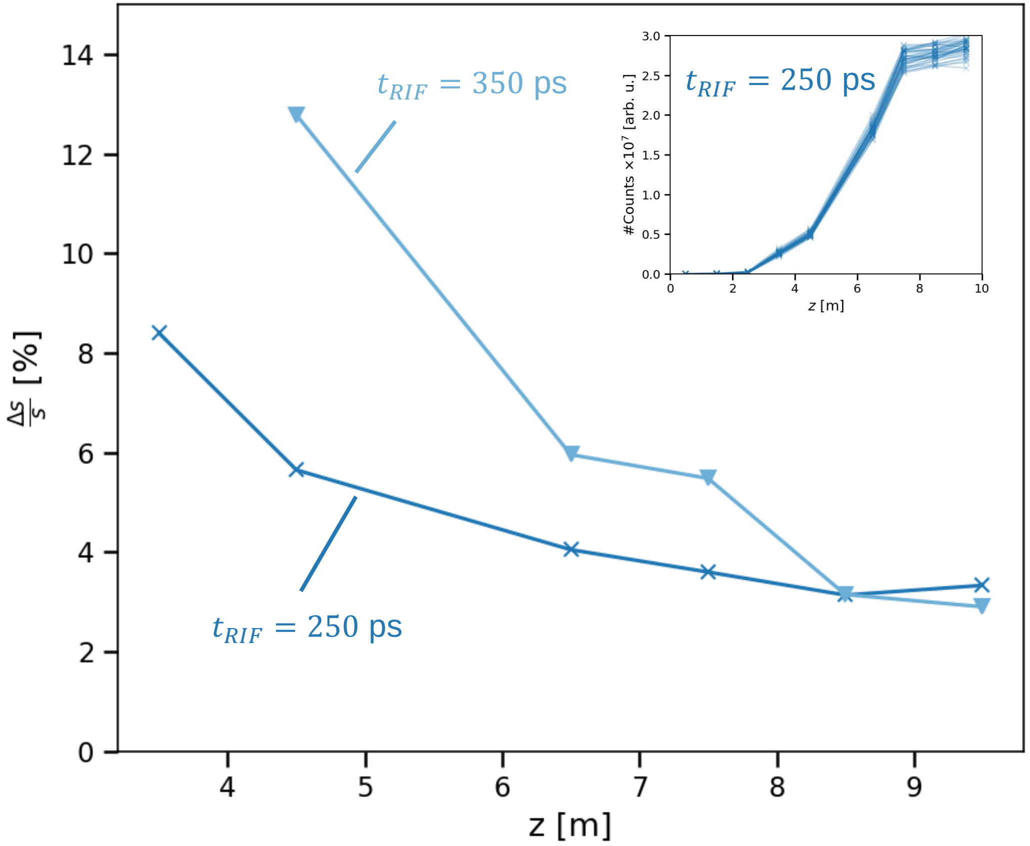


- Clear correlation between light and transverse size

- Larger wakefields
→ More energy deposited
→ More defocusing

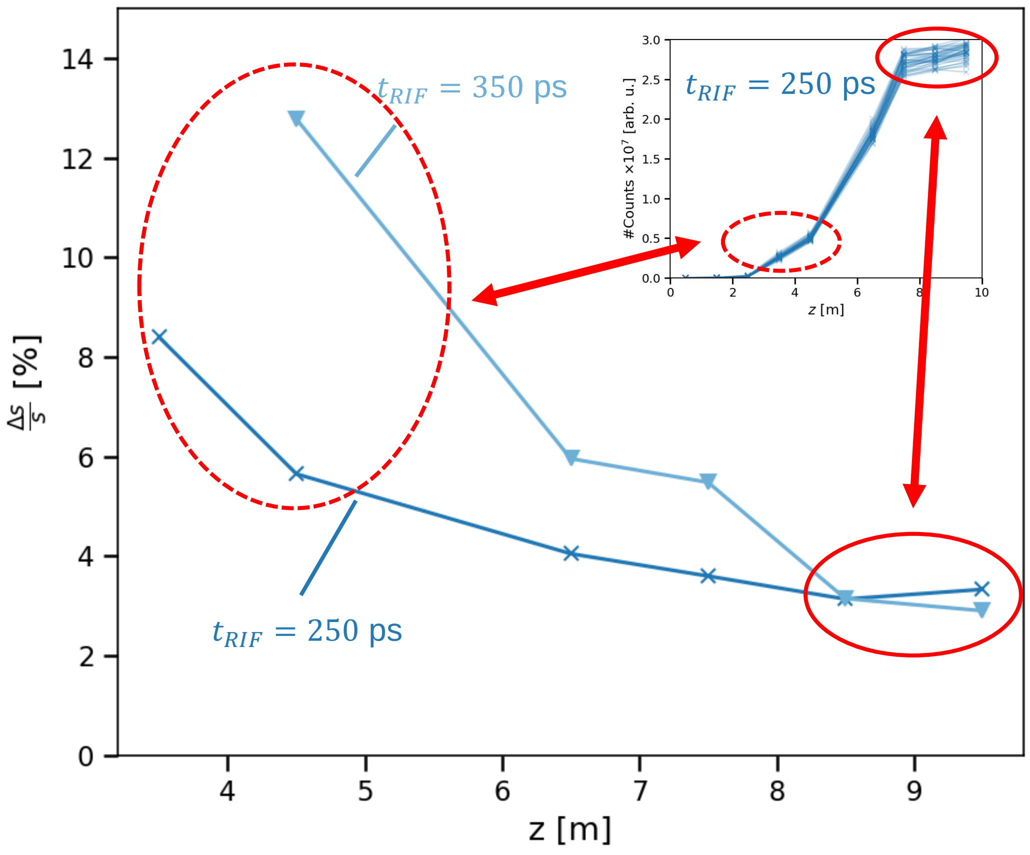
- Two independent diagnostic show consistent event to event information

Relative variations along z



- Relative variations decrease along plasma
- Larger during growth than at saturation

Relative variations along z



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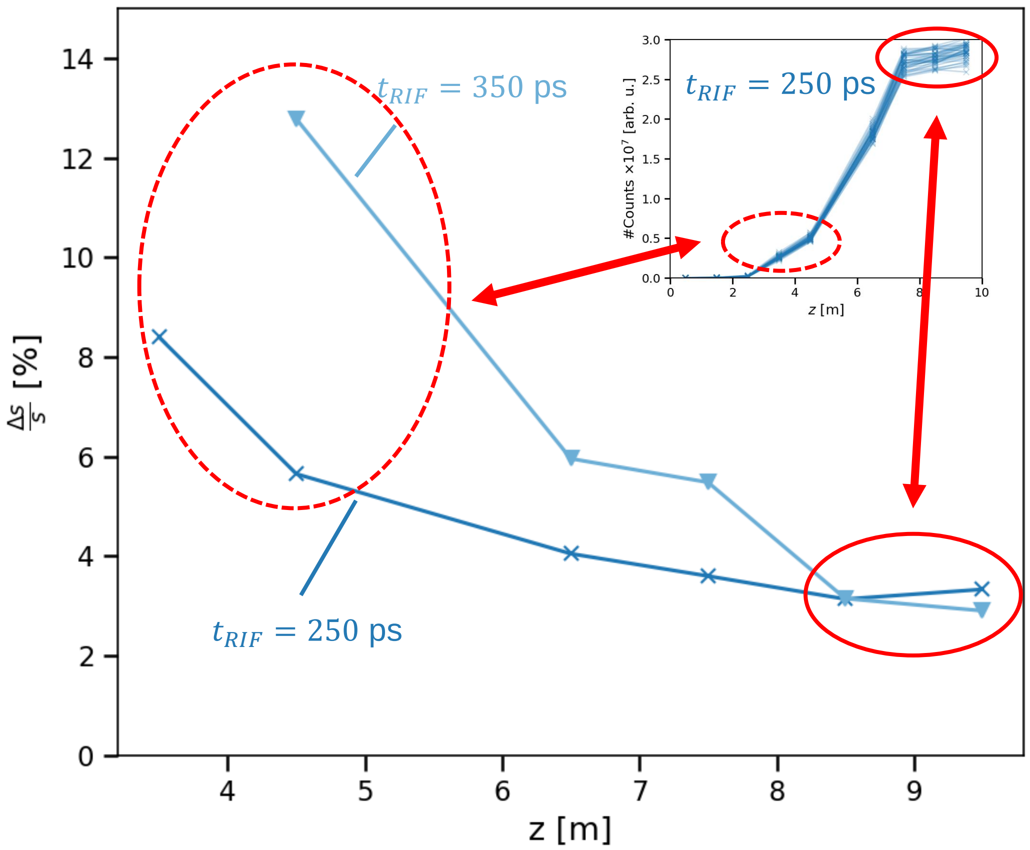
preliminary



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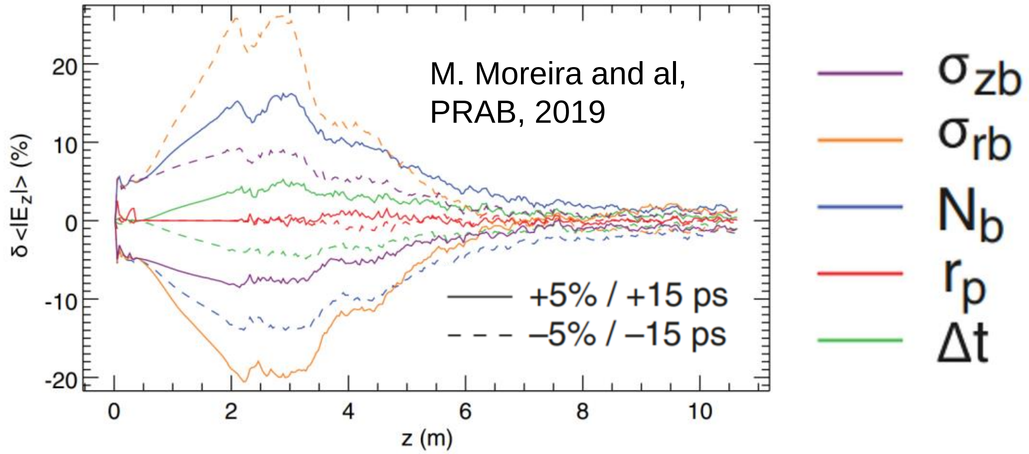
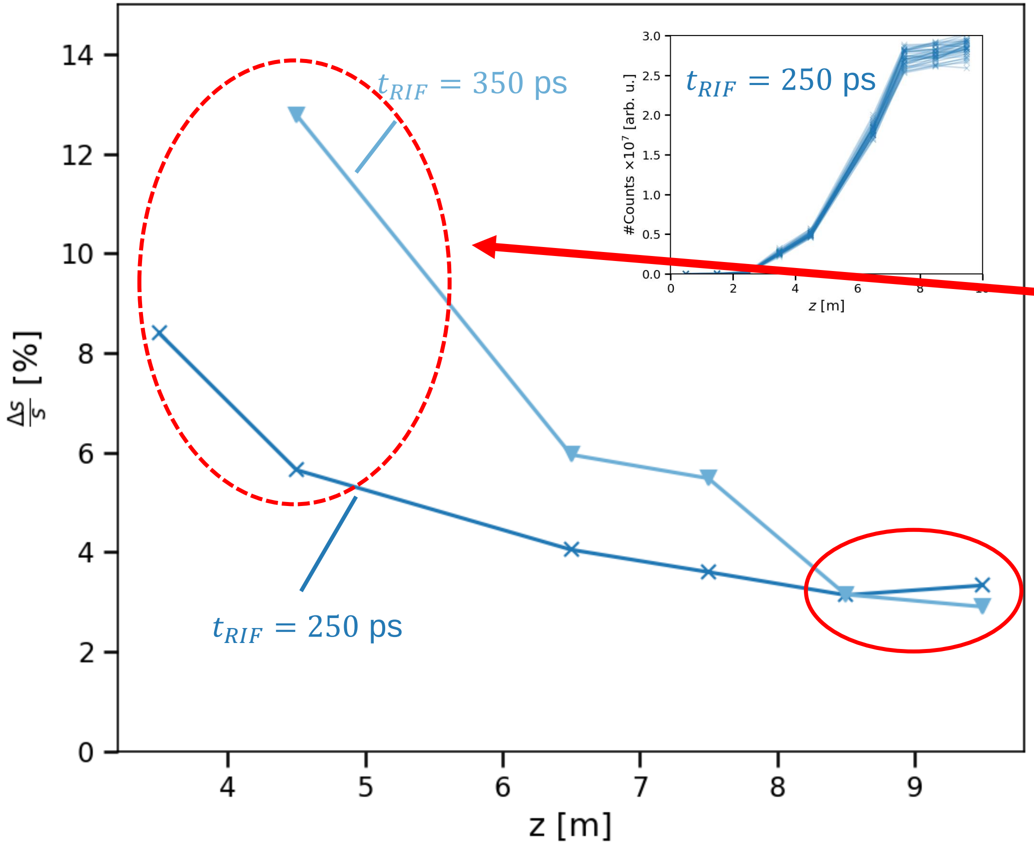


- Influence of fluctuations of input parameters decreases after saturation
- Acceleration of witness bunch must occur after saturation of SM

preliminary

Relative variations along z



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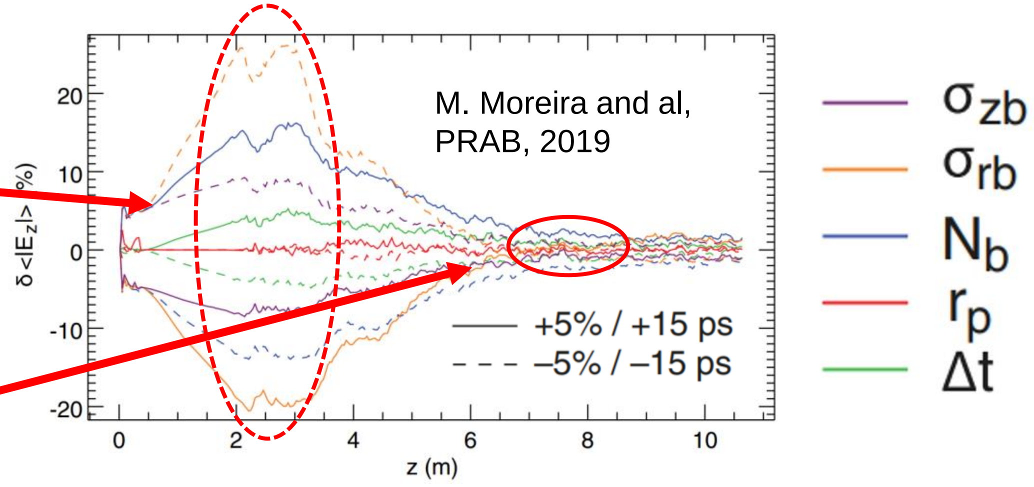

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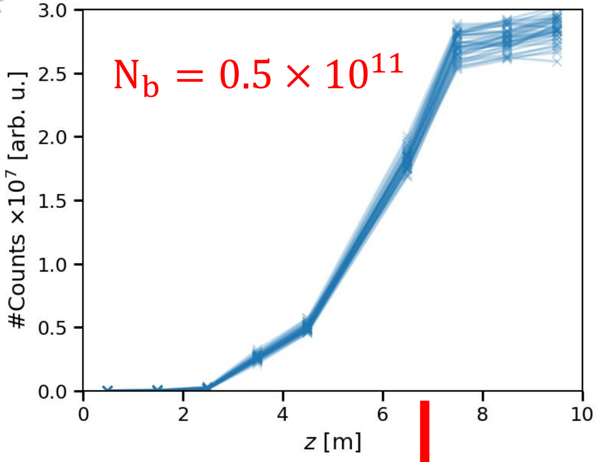
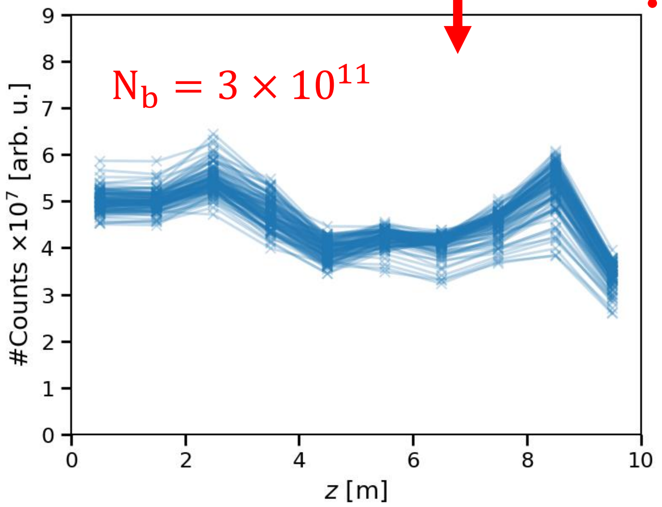
High bunch population

preliminary





Proton bunch :

- $E = 400$ GeV
- $\sigma_r = 180\ \mu m$
- $\sigma_t = 170$ ps

$N_b = 0.5 \times 10^{11} \rightarrow N_b = 3 \times 10^{11}$

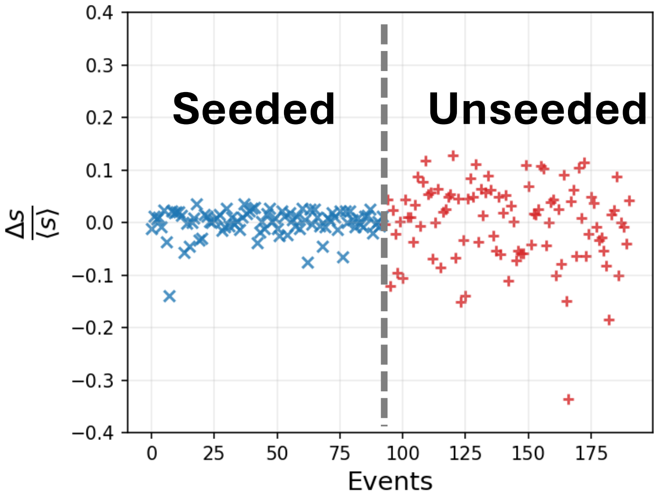
At high bunch population

- Signal along z doesn't look like expected growth and saturation

→ Energy flows along plasma

→ Need another diagnostic for saturation length of SM for high bunch population

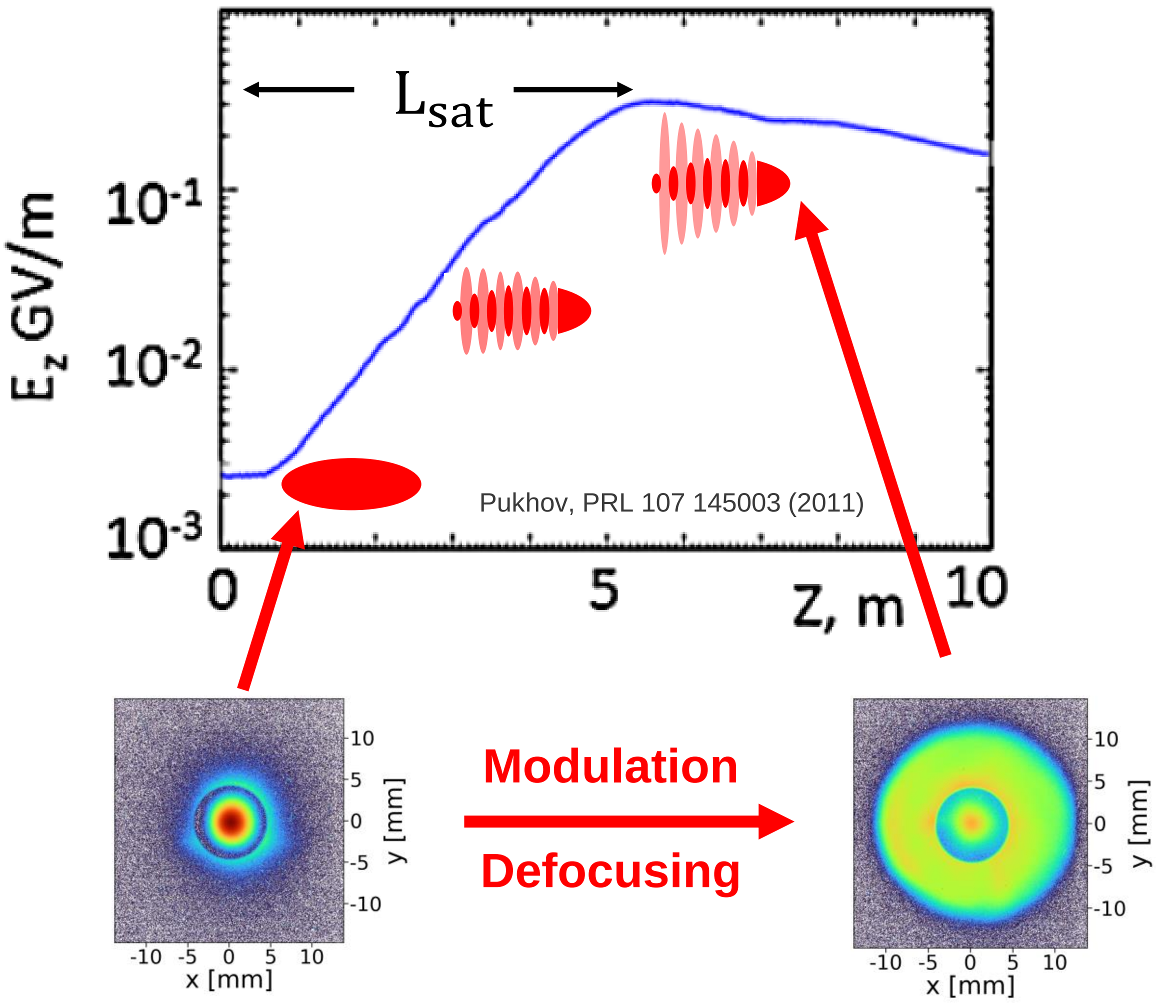
→ Sum of signal still shows transition in reproduciblity



Outline

- Introduction to the AWAKE Experiment at CERN
- Demonstration of Amplitude-Reproducible Self-Modulation by Seeding
- Measurement of the Saturation Length of the Self-Modulation Instability
- Moving forward…

Saturation length of SM



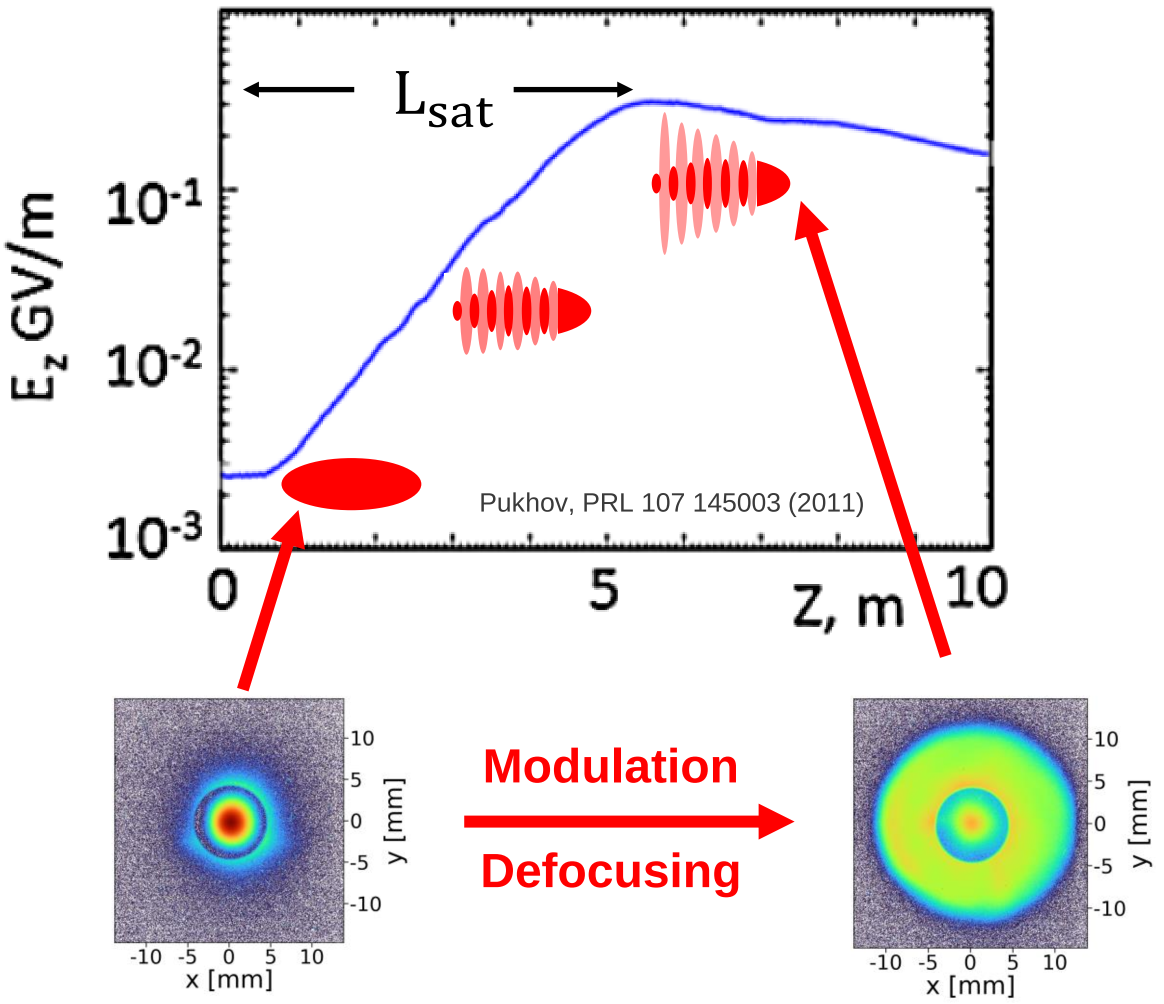
- **Modulation** of bunch **leads to growth** of wakefields

→ Zeroth order **expectation**: wakefields **saturates** when modulation stops

- Modulation = **transverse process**

→ Stops when halo is fully formed and defocused protons drift ballistically

Saturation length of SM



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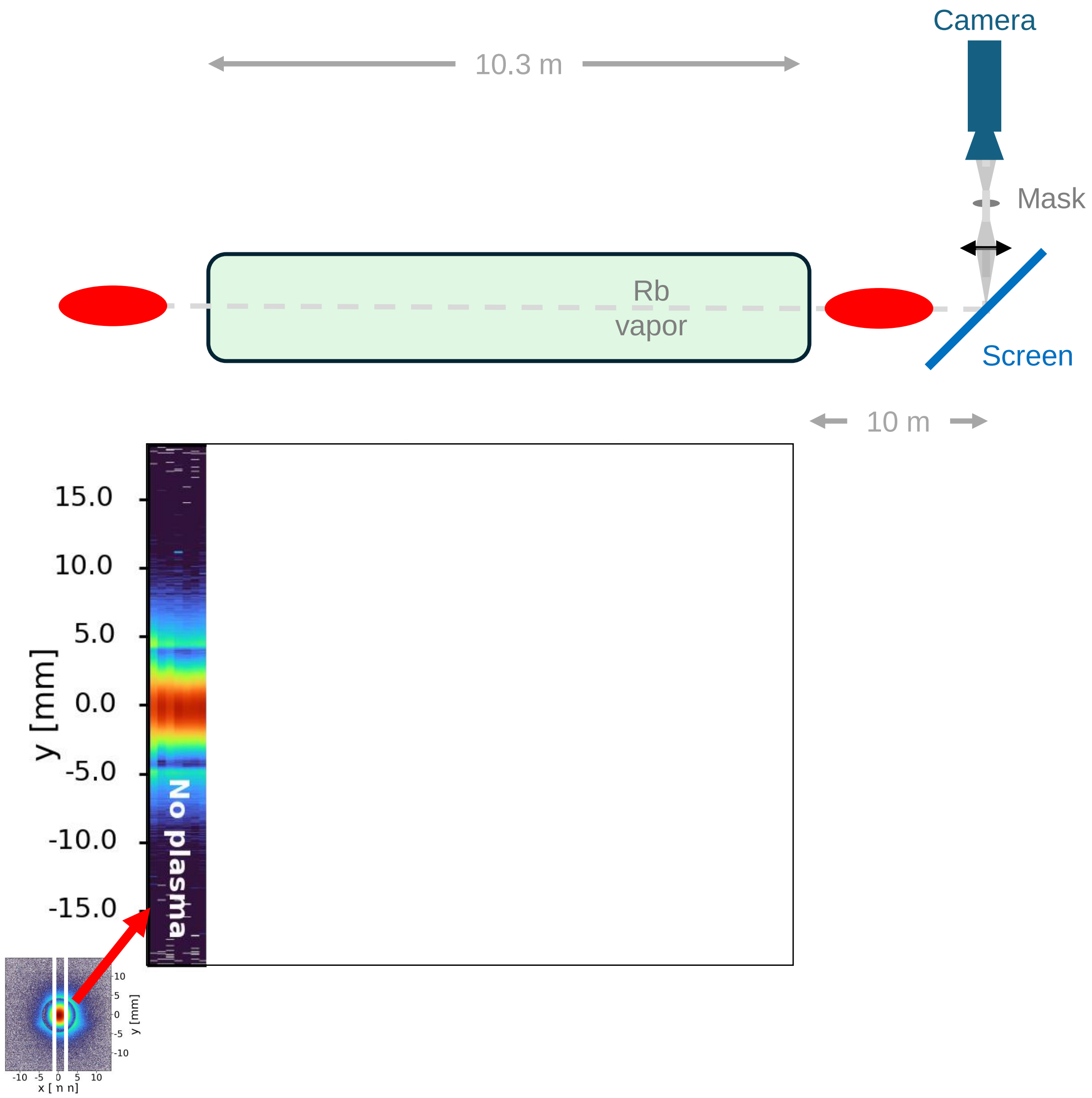
Halo stops forming along z at L_{sat} ?

Halo formation along the plasma



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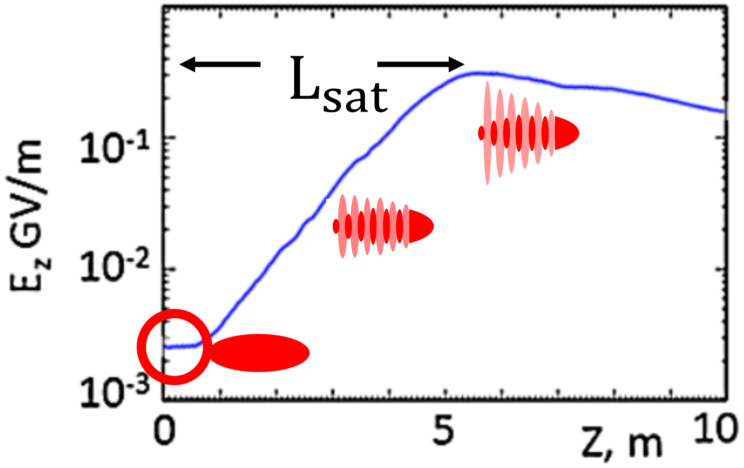
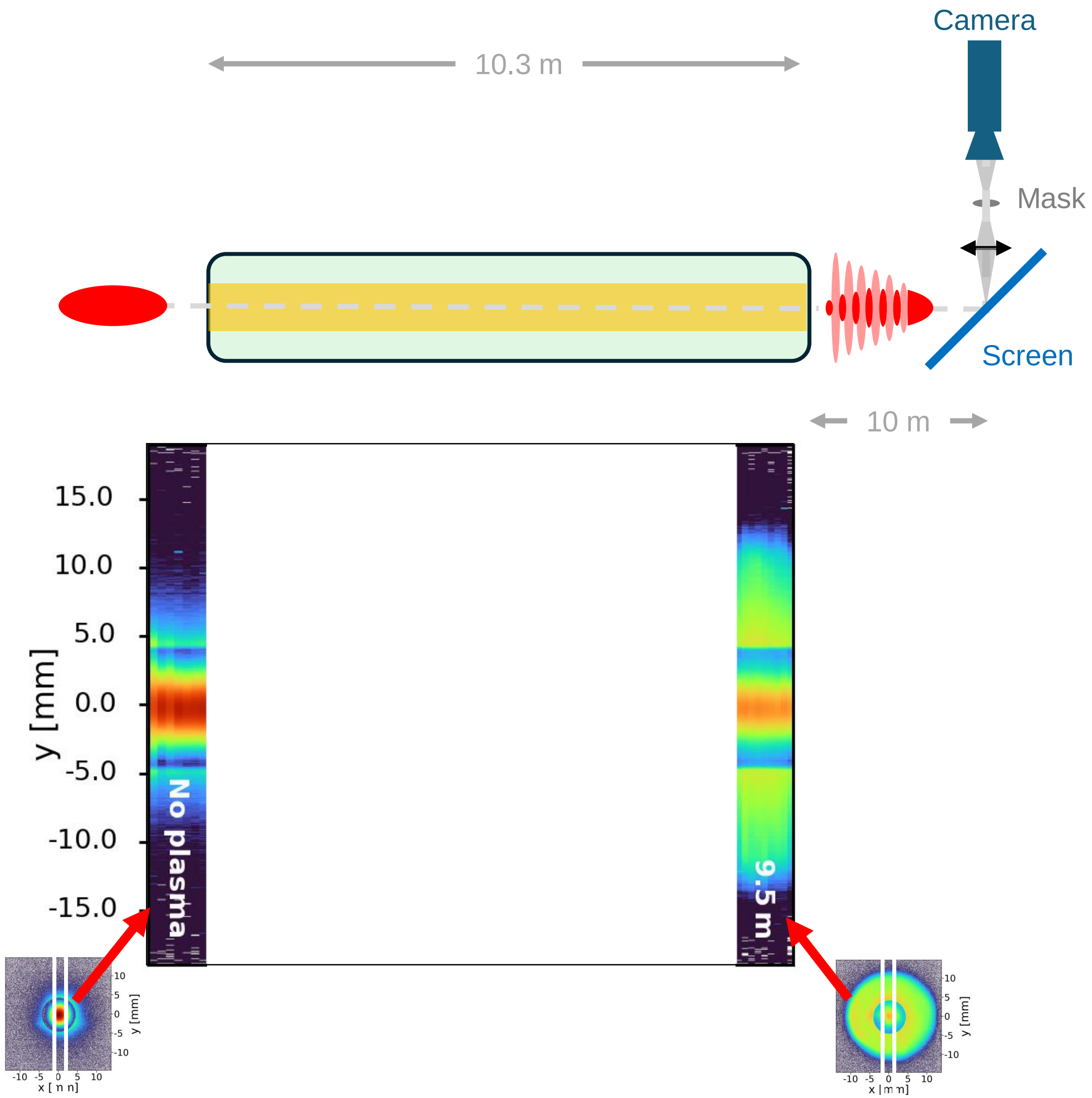


Goal: Determine location along the plasma where halo stops forming

- Plasma is a "black box", we see:

→ what goes in

Halo formation along the plasma



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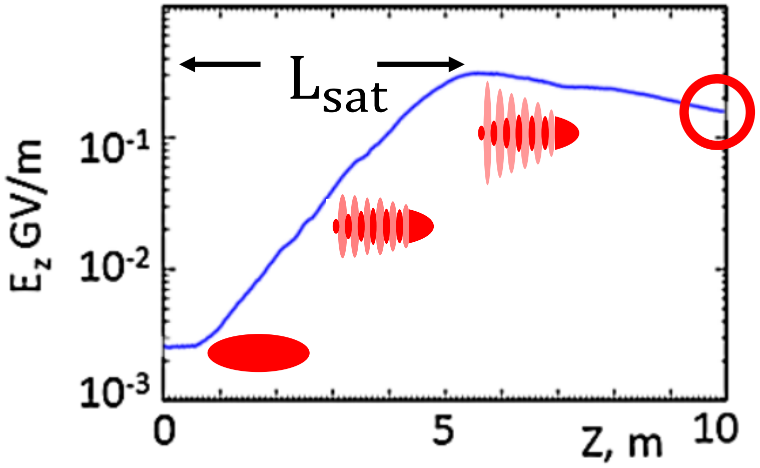

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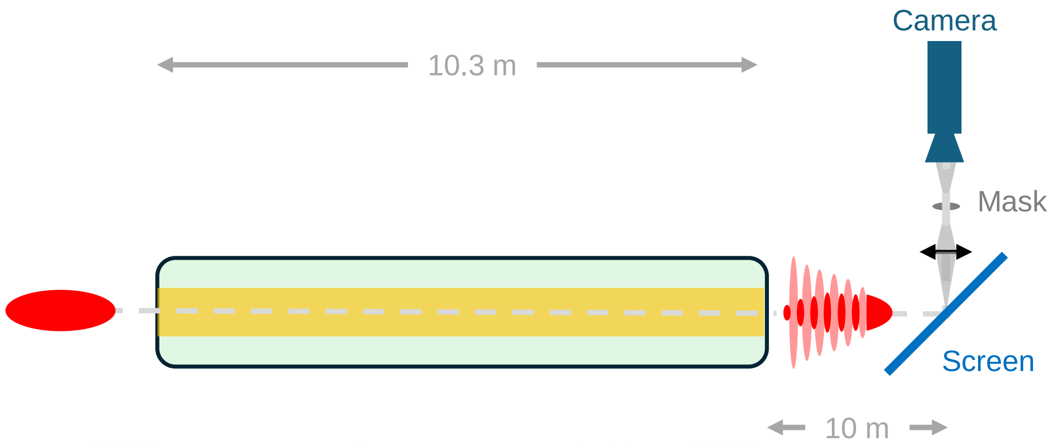

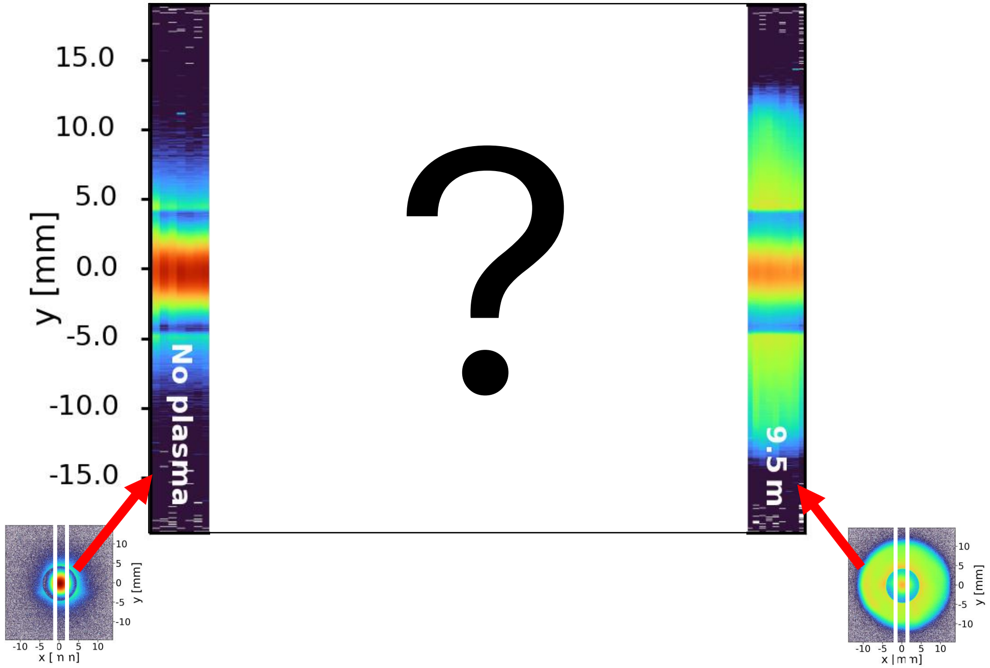

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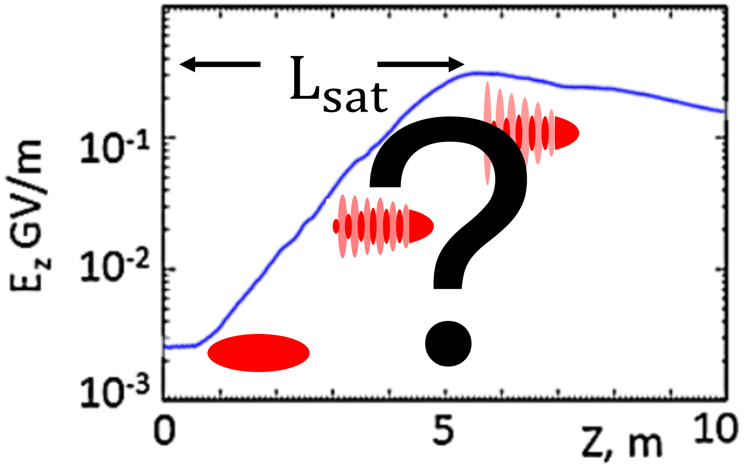

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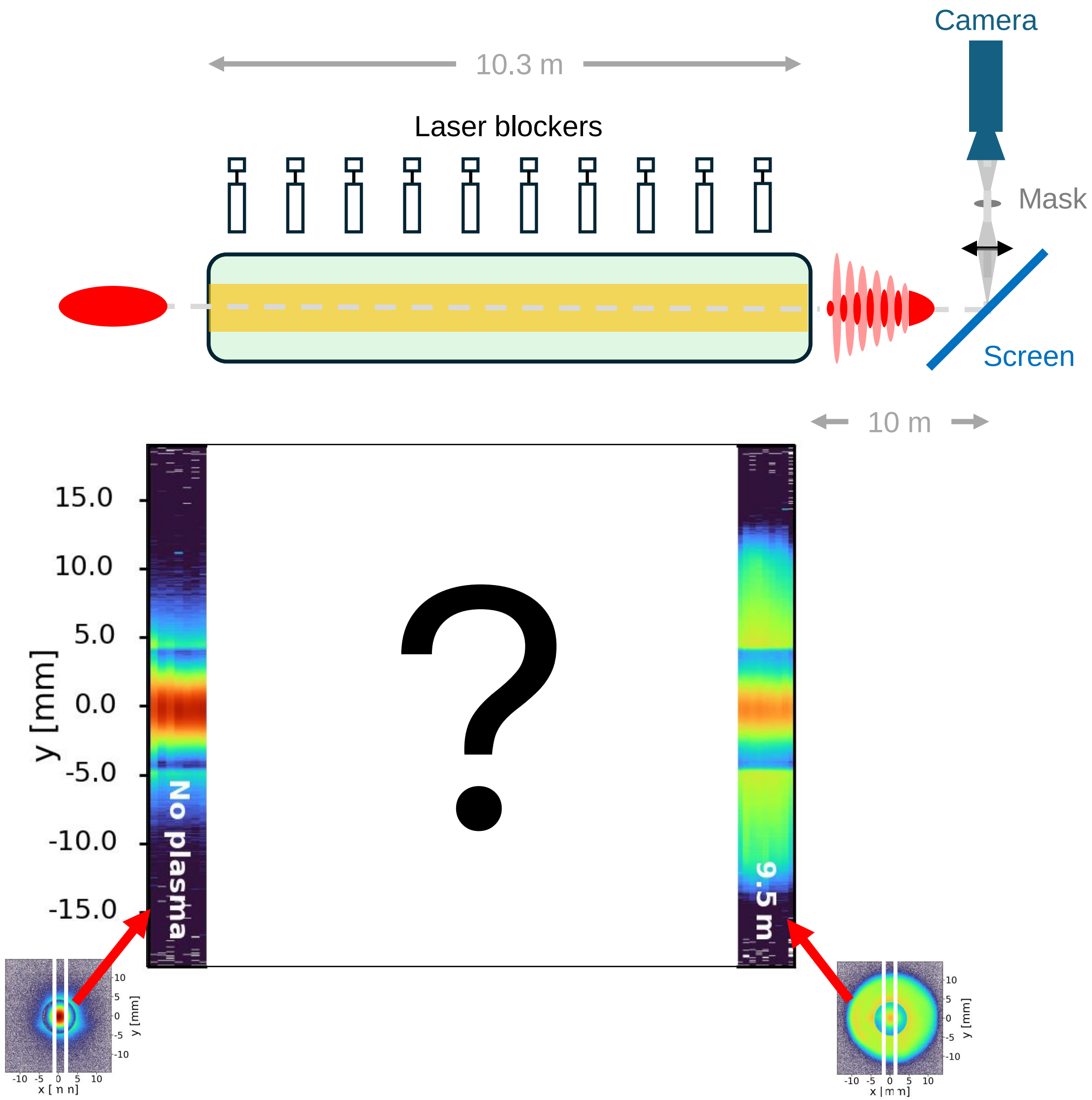

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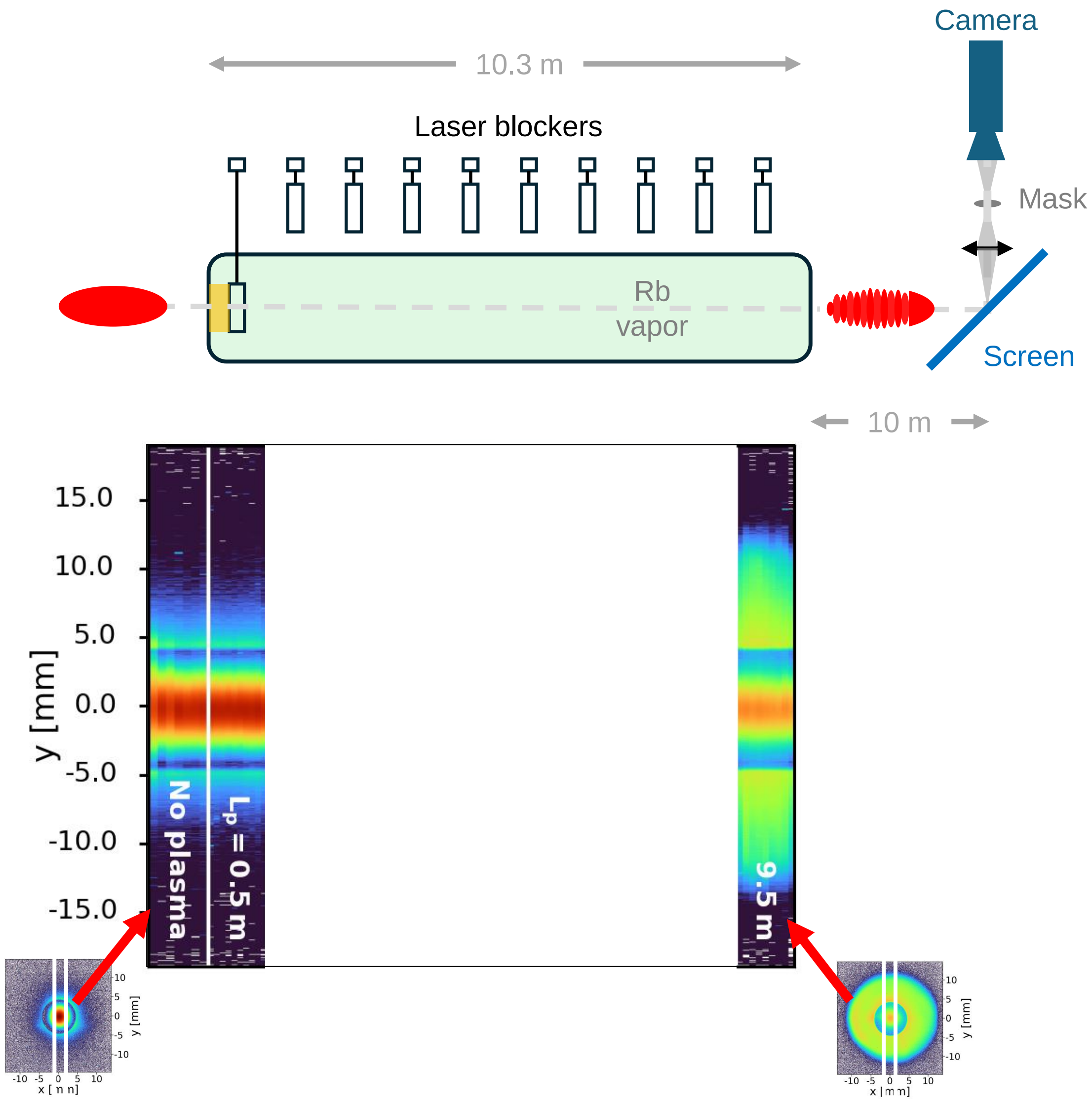
- $L_p = [0.5, 1.5, 2.5, \ldots, 9.5]$ m
- SM develops over different distances
- Process is seeded (reproducible)

→ varying L_p ⇔ observing state of bunch at different z on single event

Halo formation along the plasma



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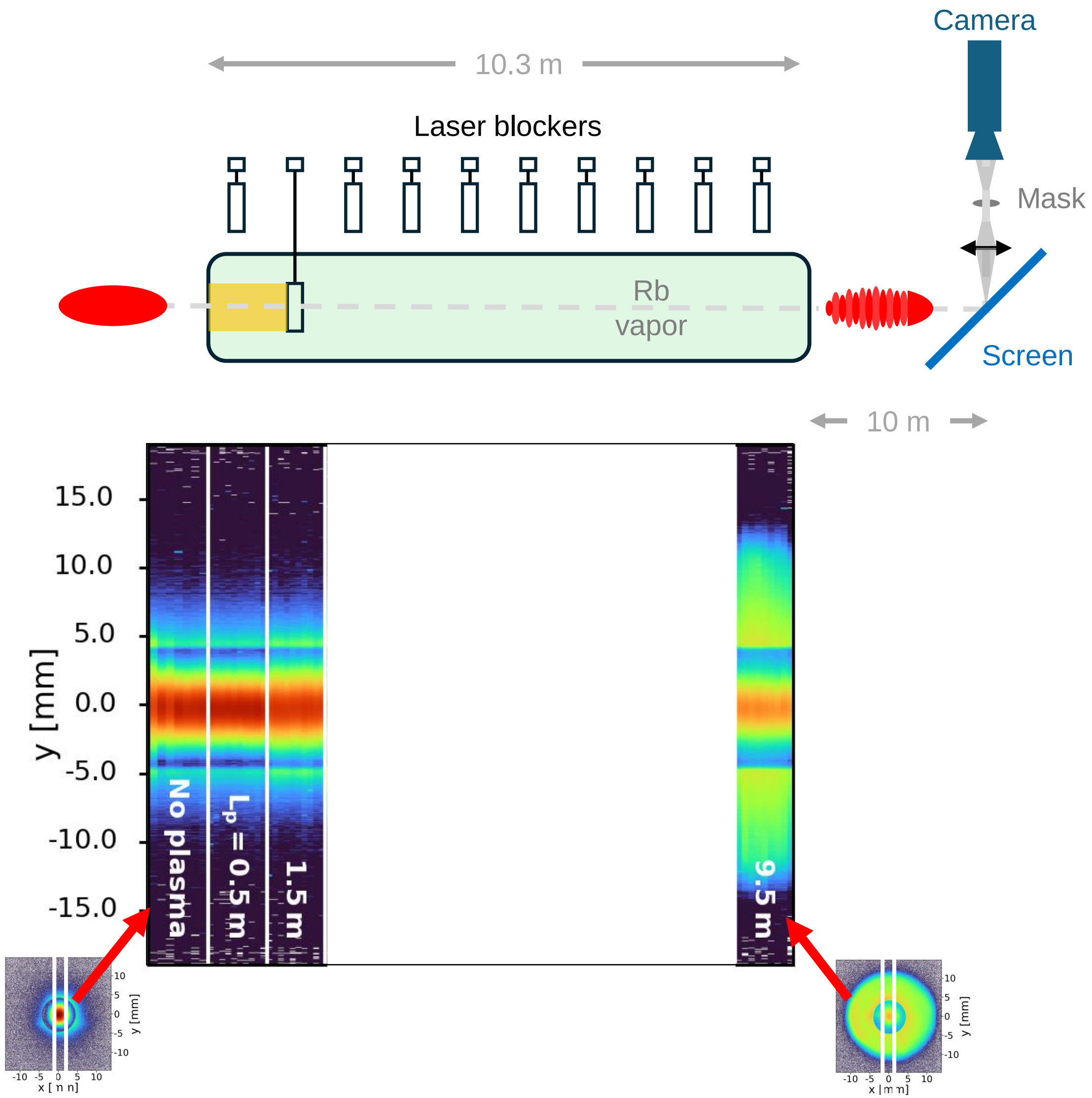

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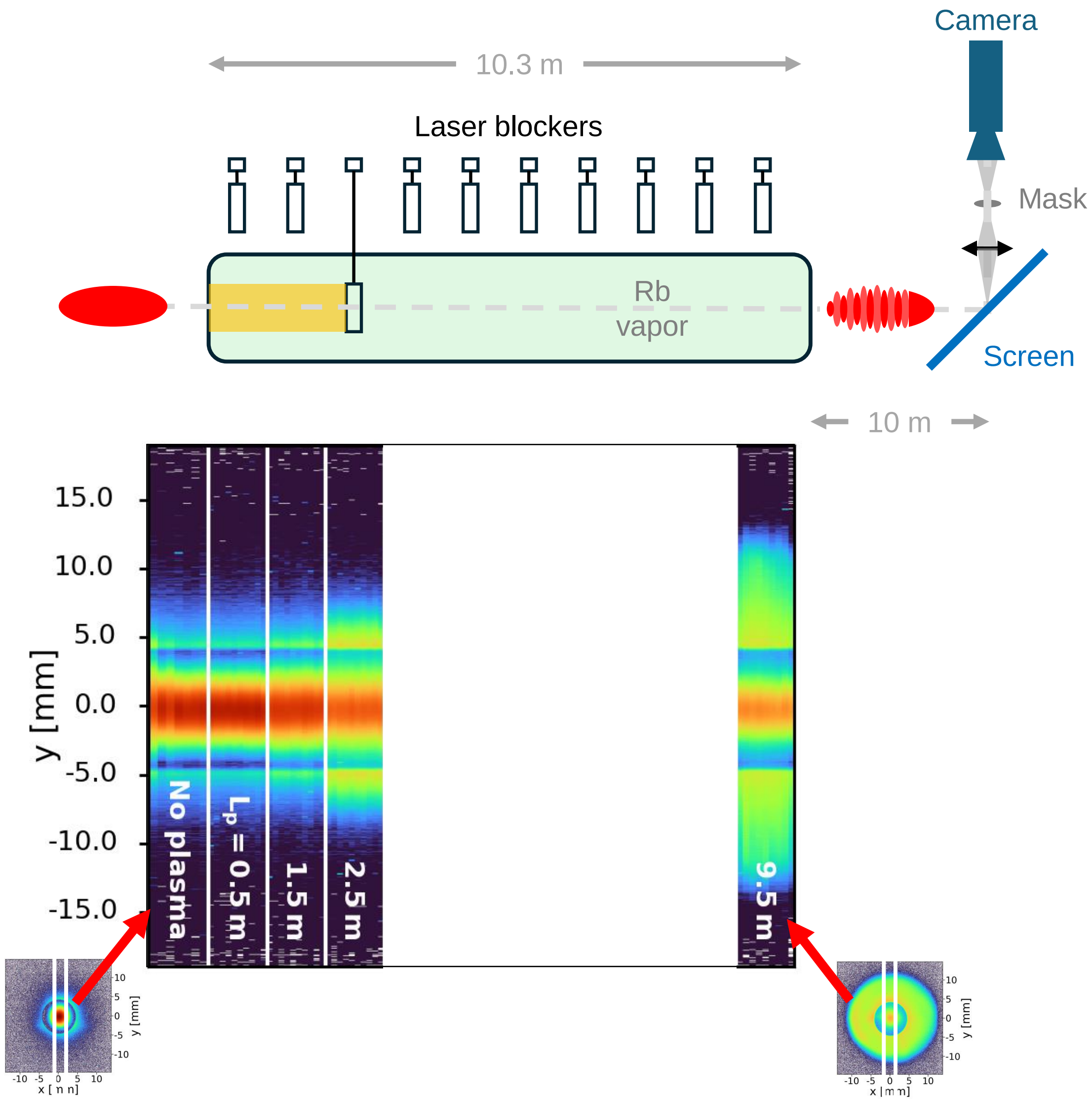

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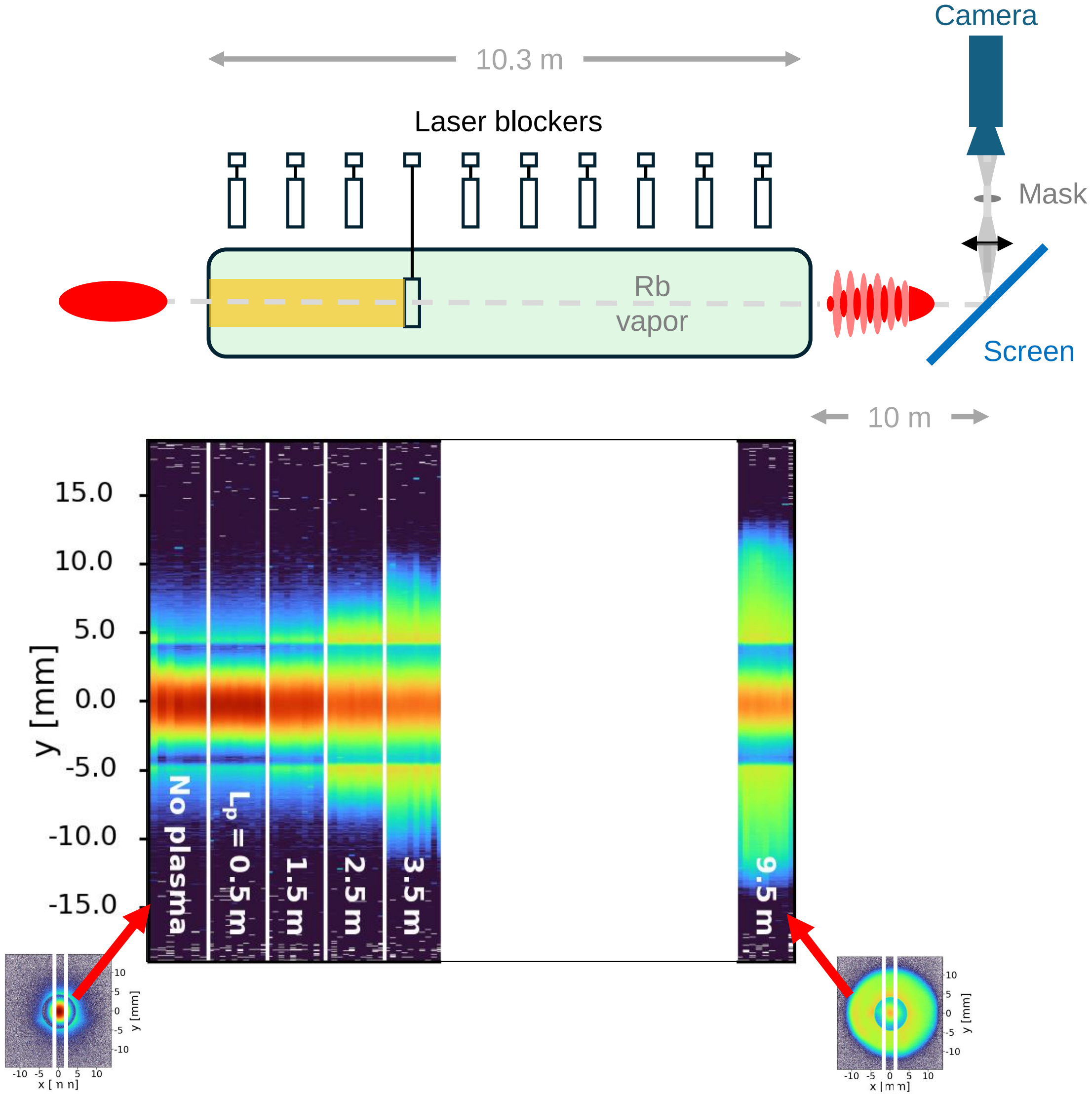

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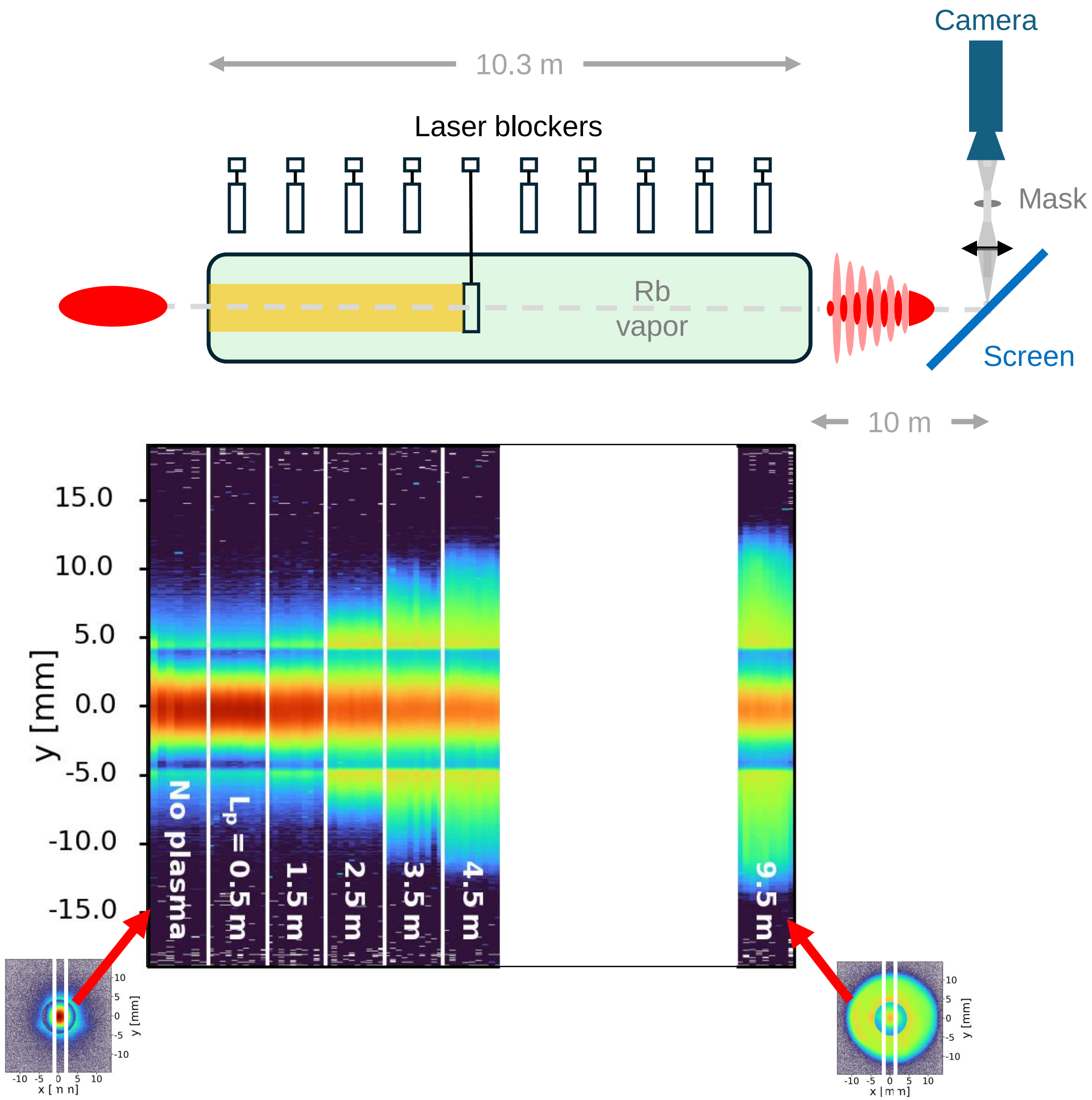

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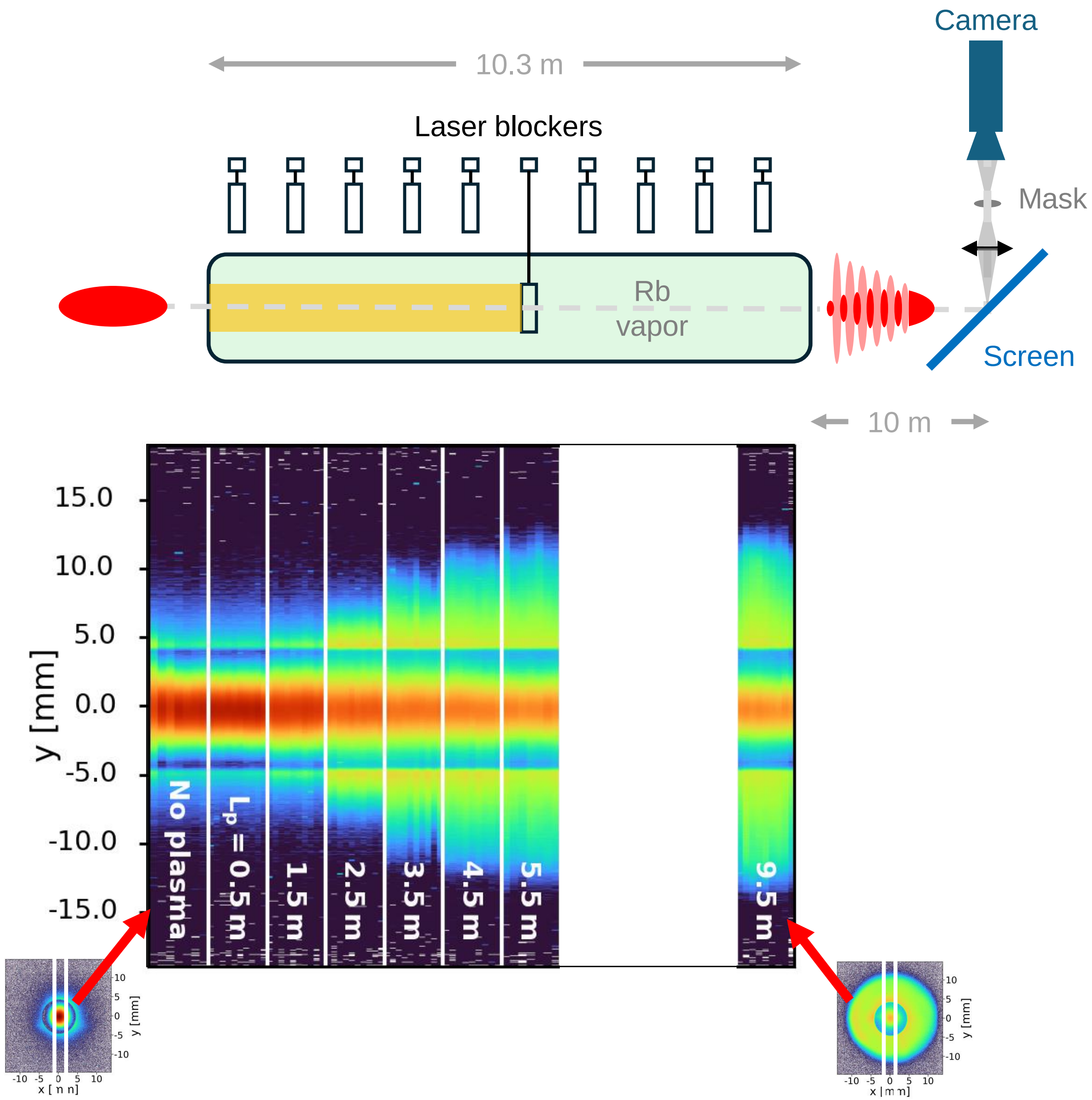

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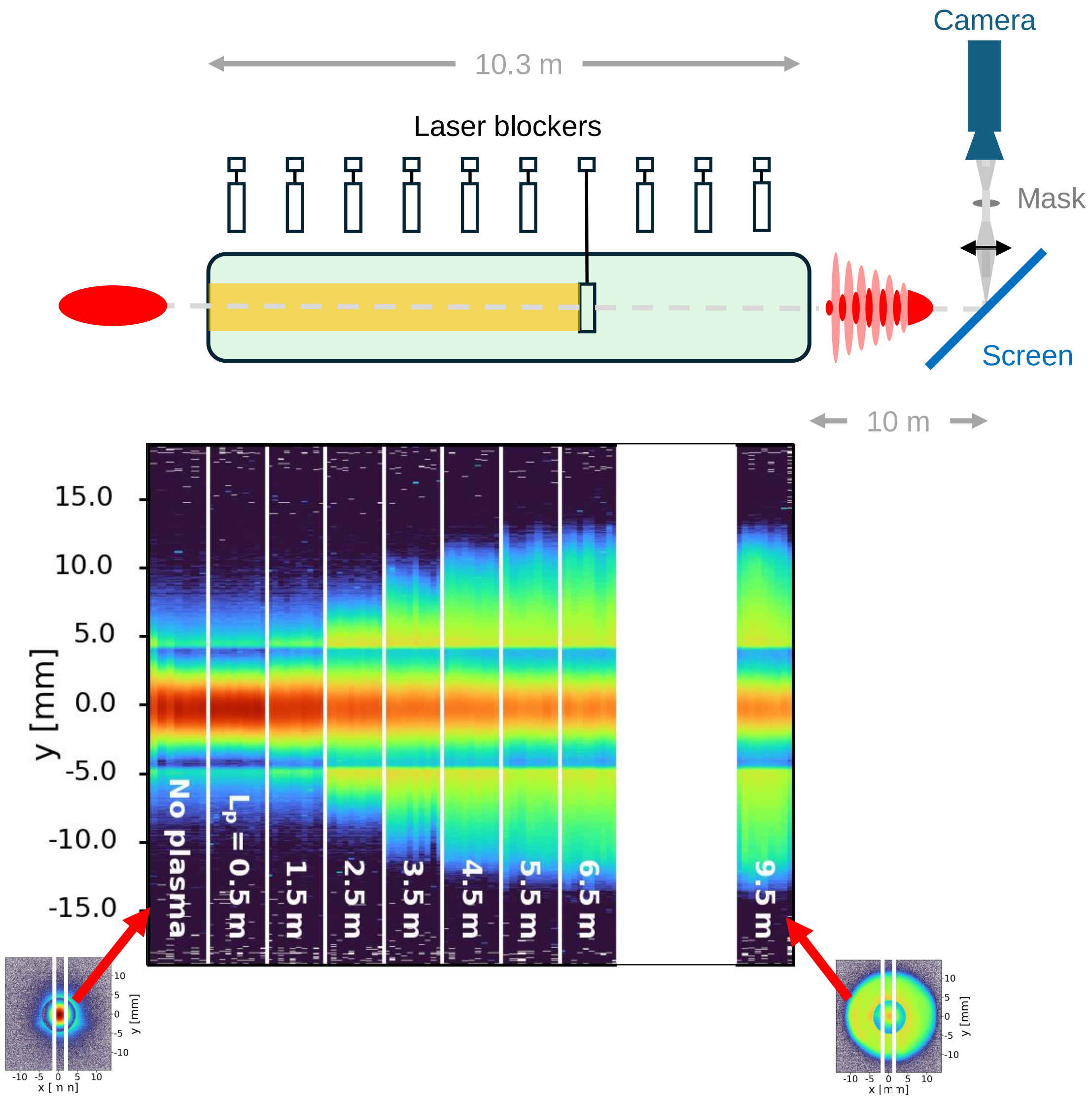

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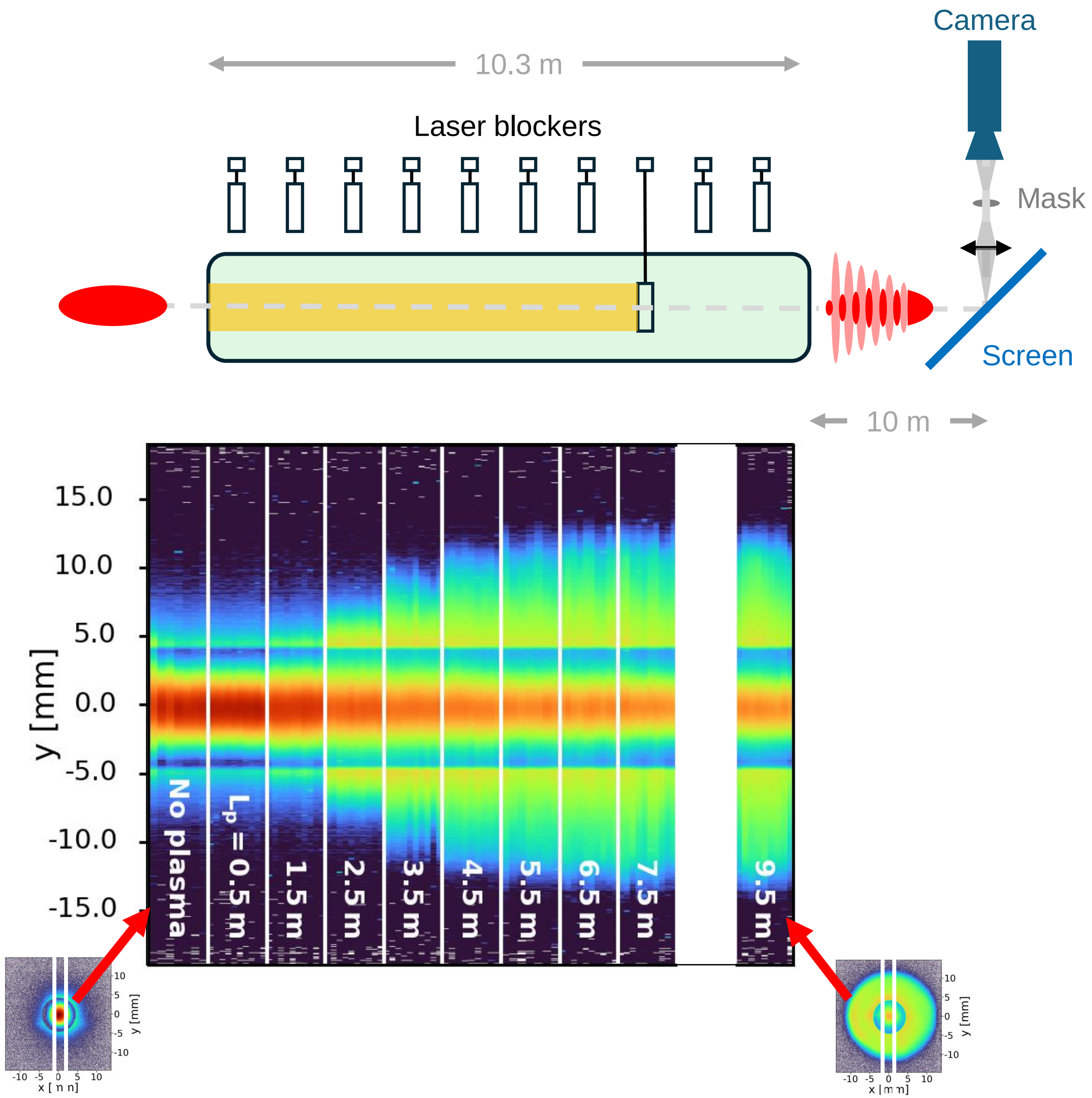

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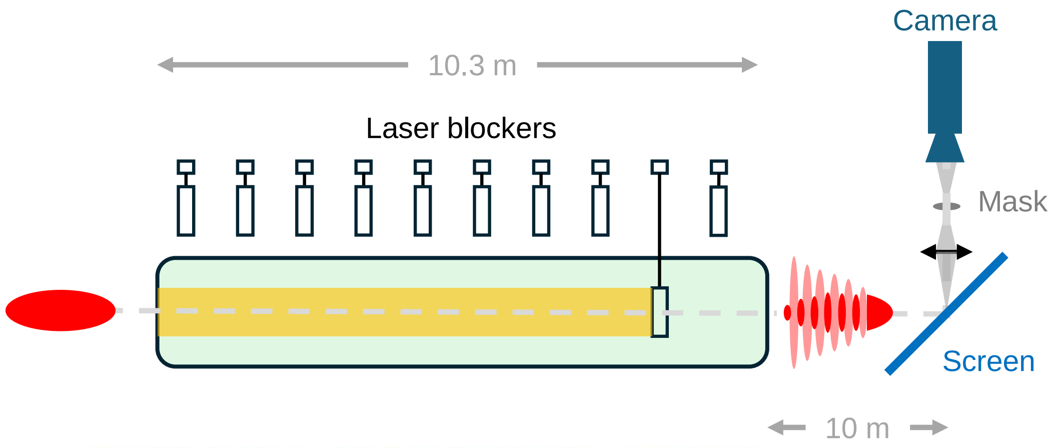

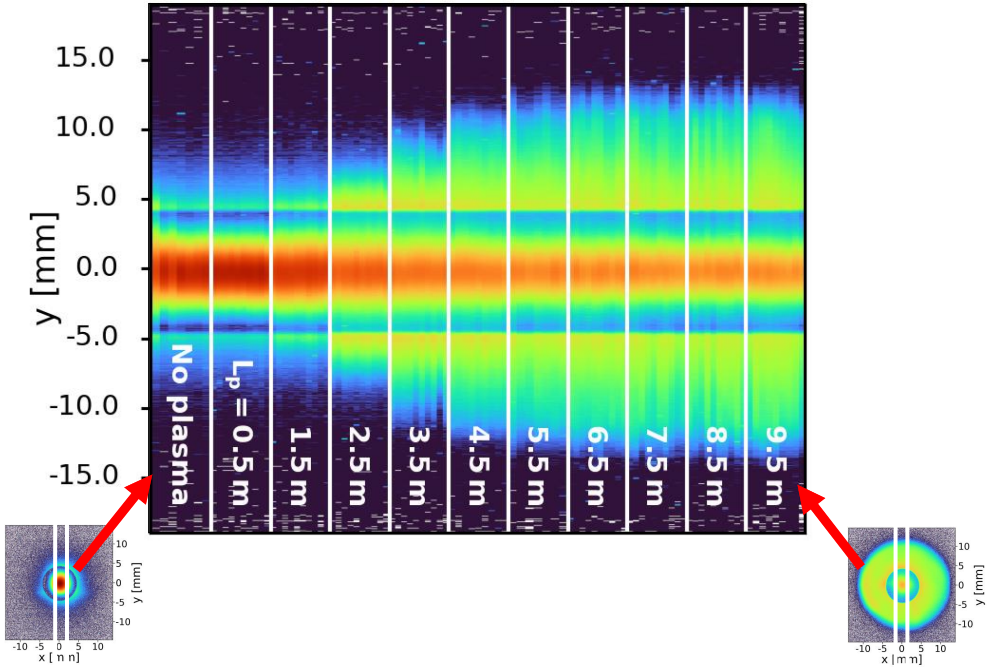

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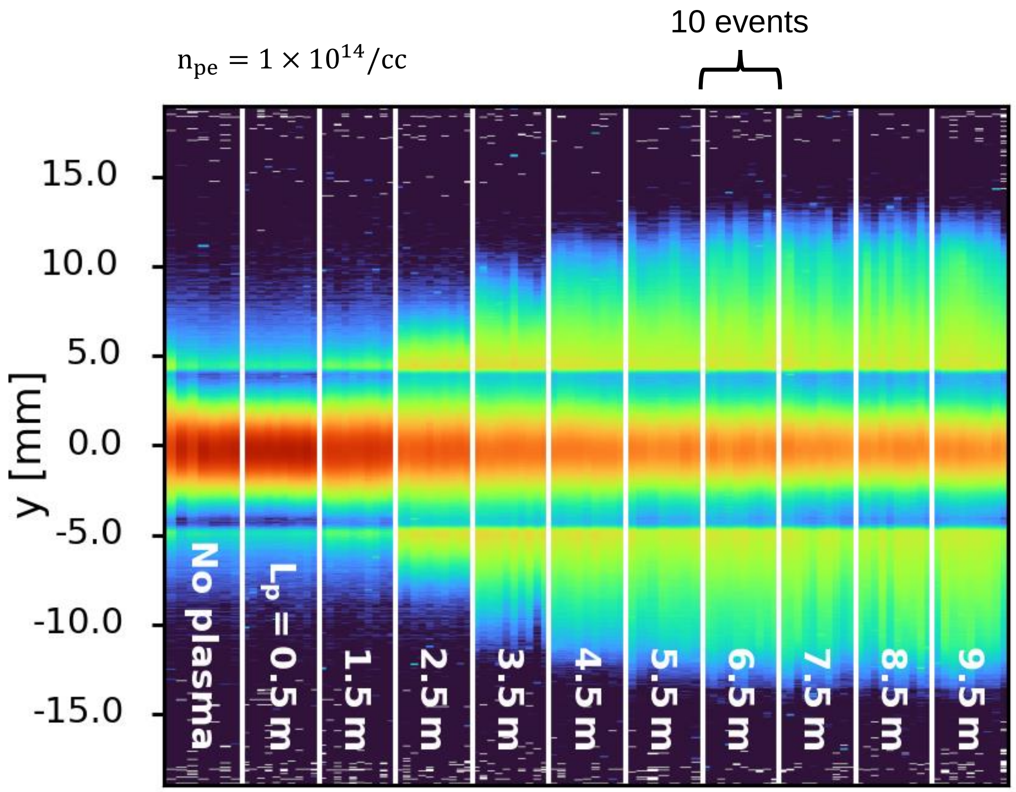
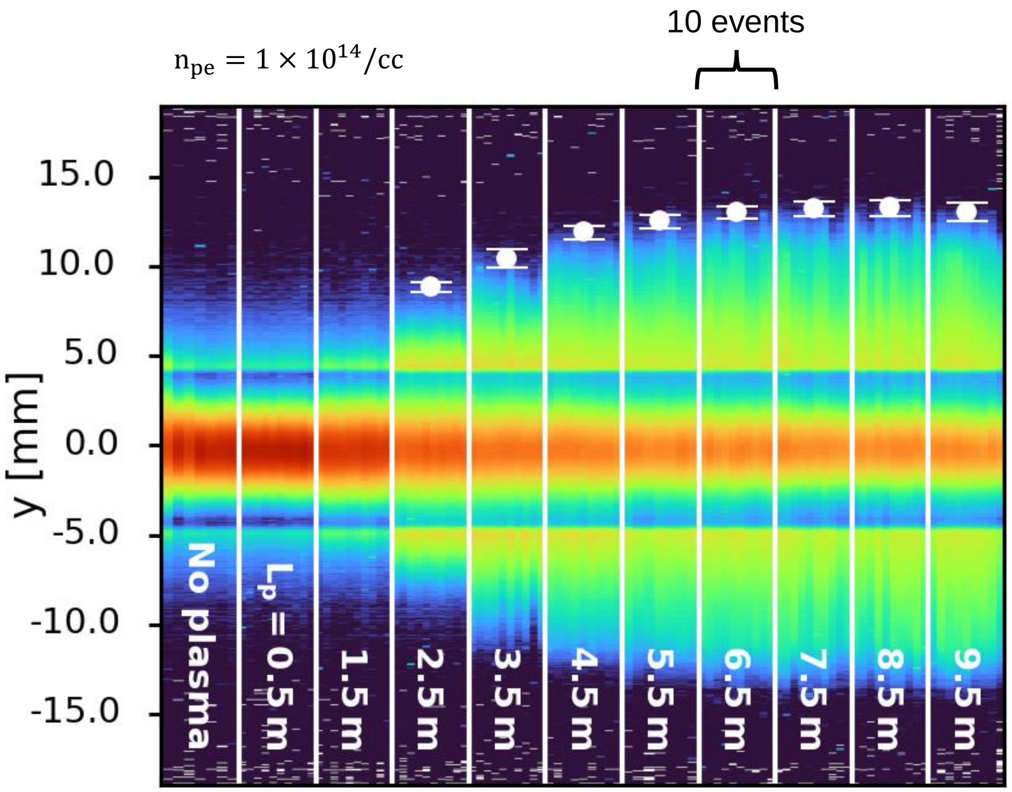
Halo formation along the plasma

$n_{pe} = 1 \times 10^{14}/cc$



Halo formation along the plasma



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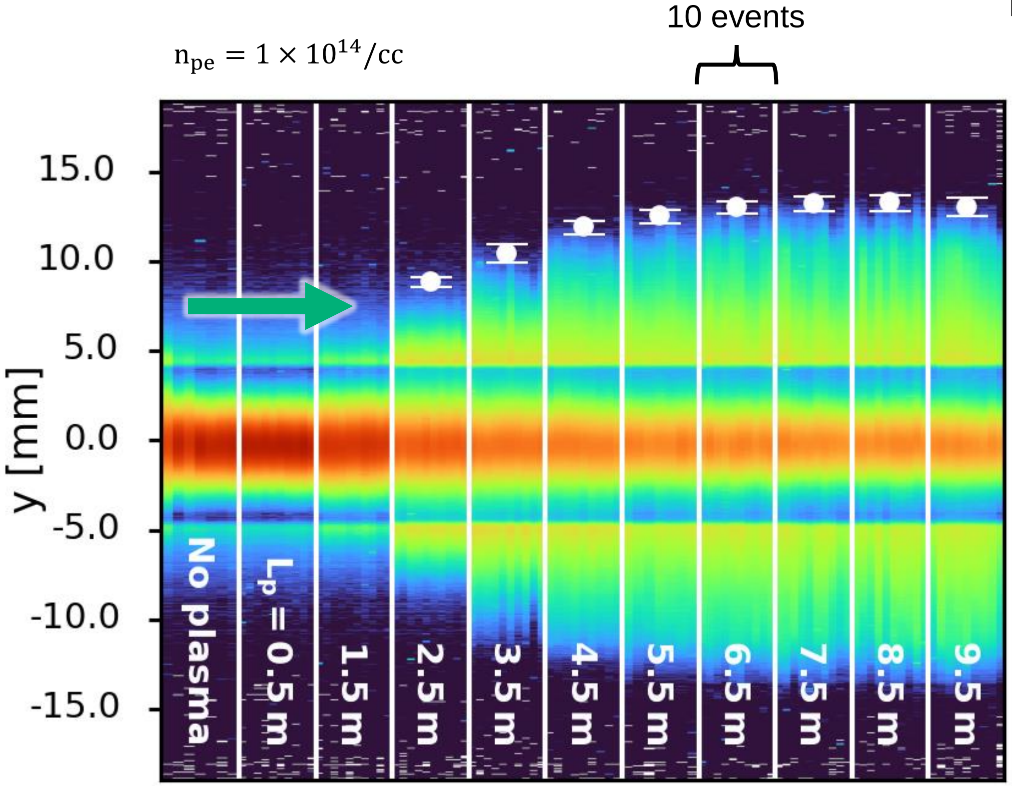
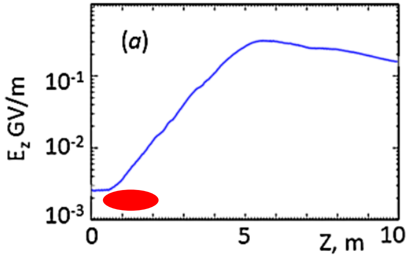
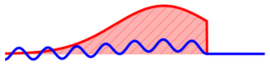




Pukhov,
PRL 107
145003
(2011)

Evolution in three phases:

1) $L_p = 0$ to $\cong 1.5$ m:



- Little evolution of bunch
- Wakefields:
  - Small amplitude
  - Predominantly focusing

2) $L_p \cong 1.5$ to $\cong 5.5$ m:

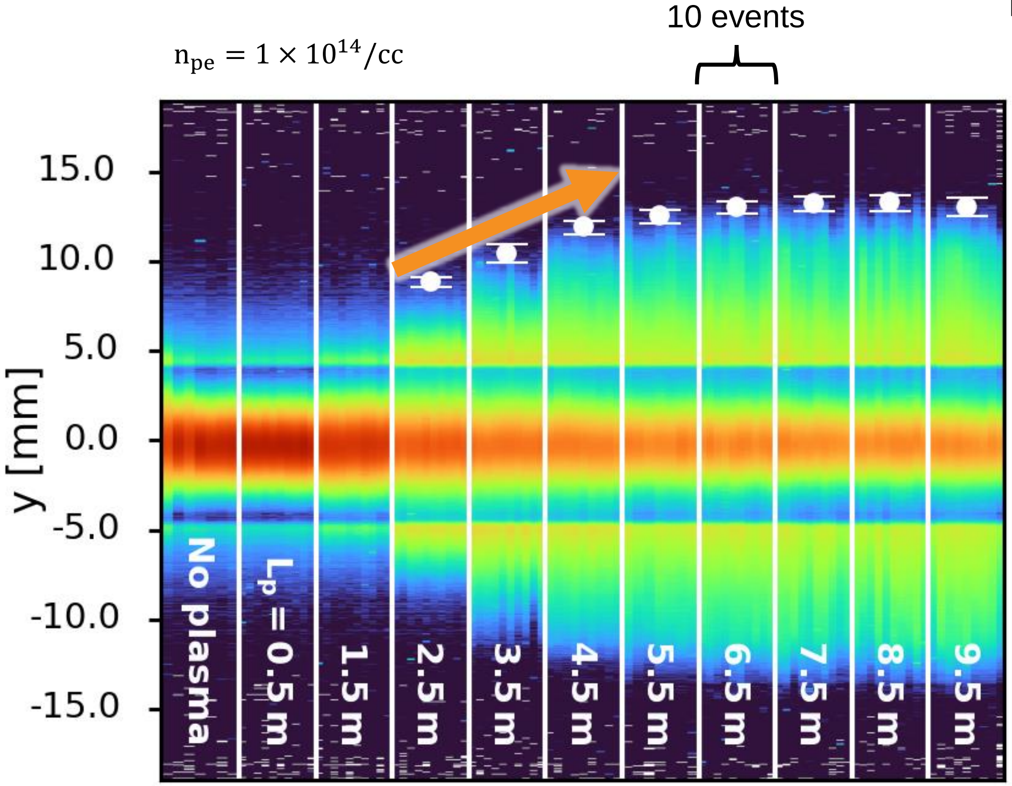
- Halo forms:
  - Charge redistributes transversely
  - Halo radius increases
- SM grows:
  - Wakefields acquire defocusing regions
  - Wakefields increase in amplitude

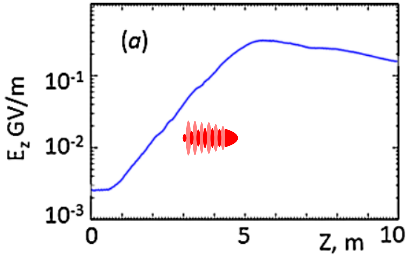
3) $L_p \cong 5.5$ to $\cong 9.5$ m:

- Halo radius stops increasing
- Distribution essentially unchanged

Signature expected from SM saturation

Halo formation along the plasma





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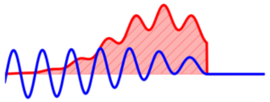

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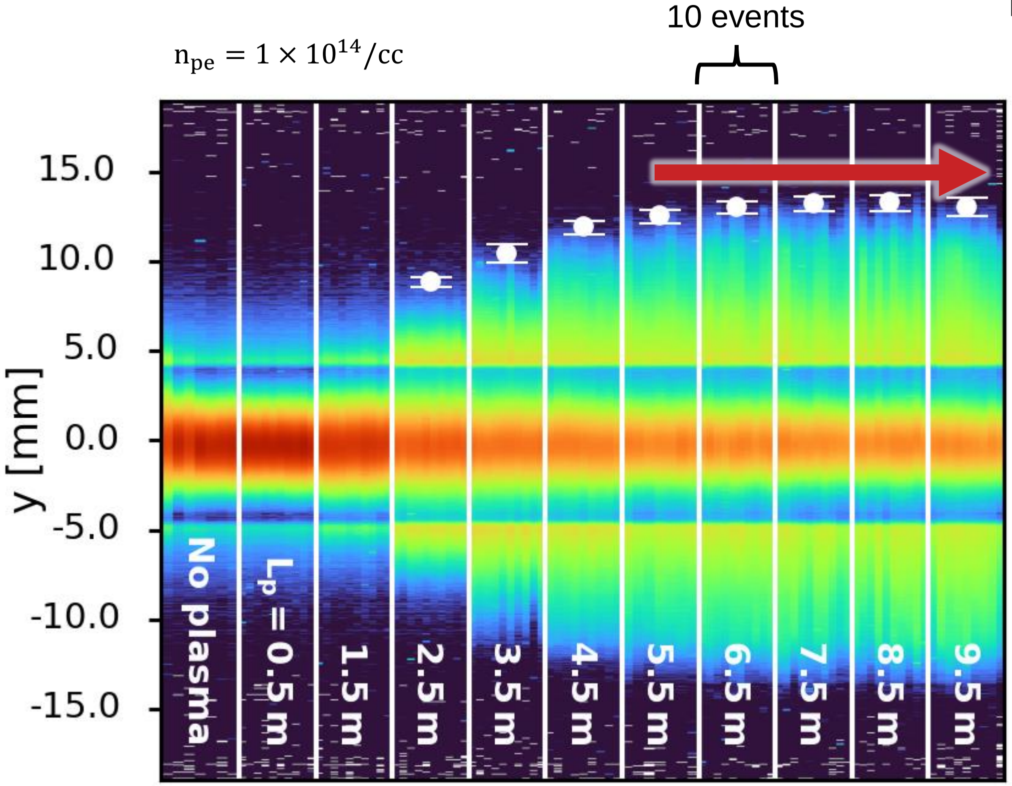

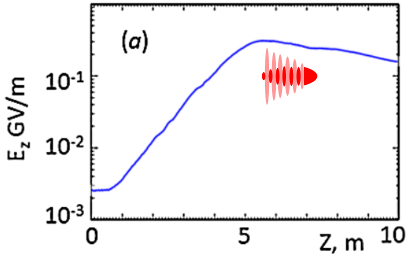

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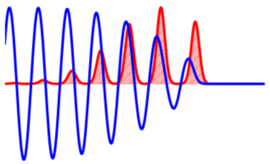

Halo formation along the plasma

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

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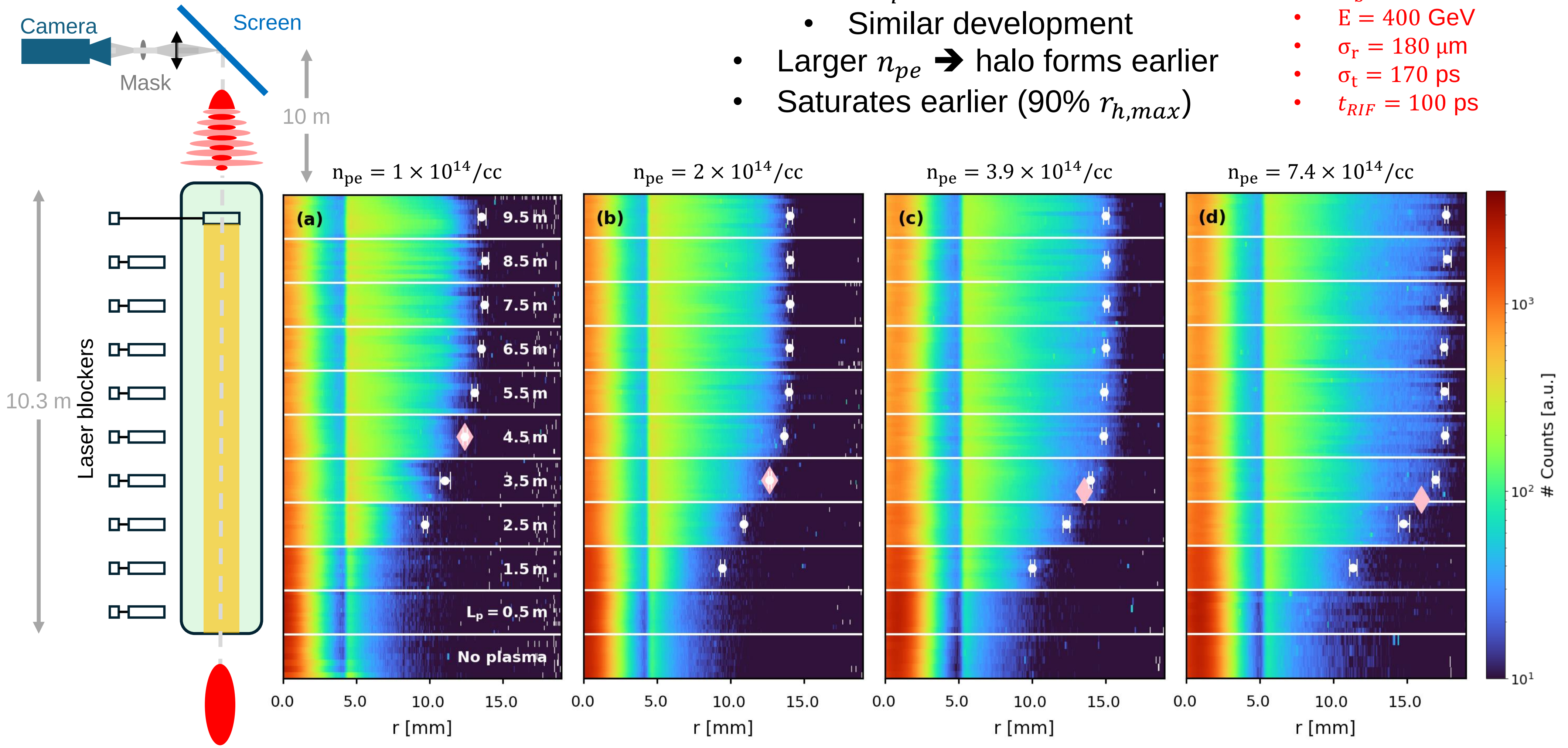

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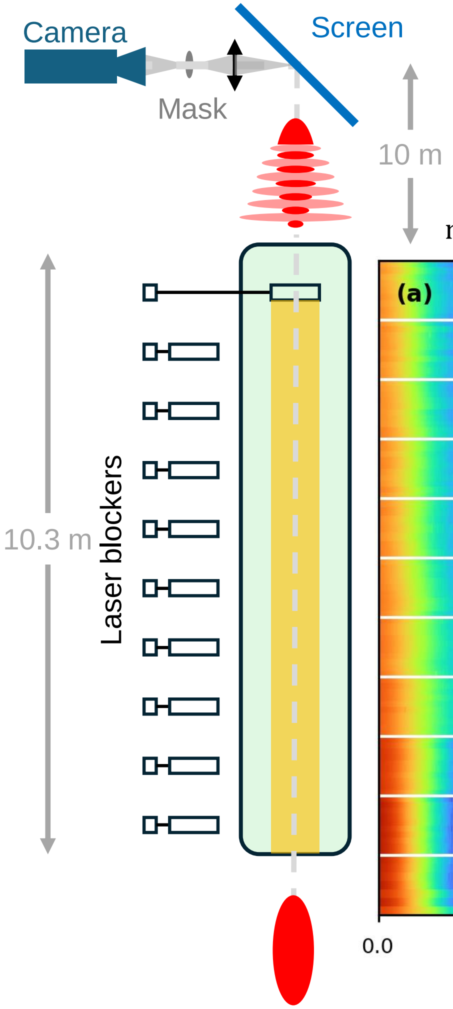
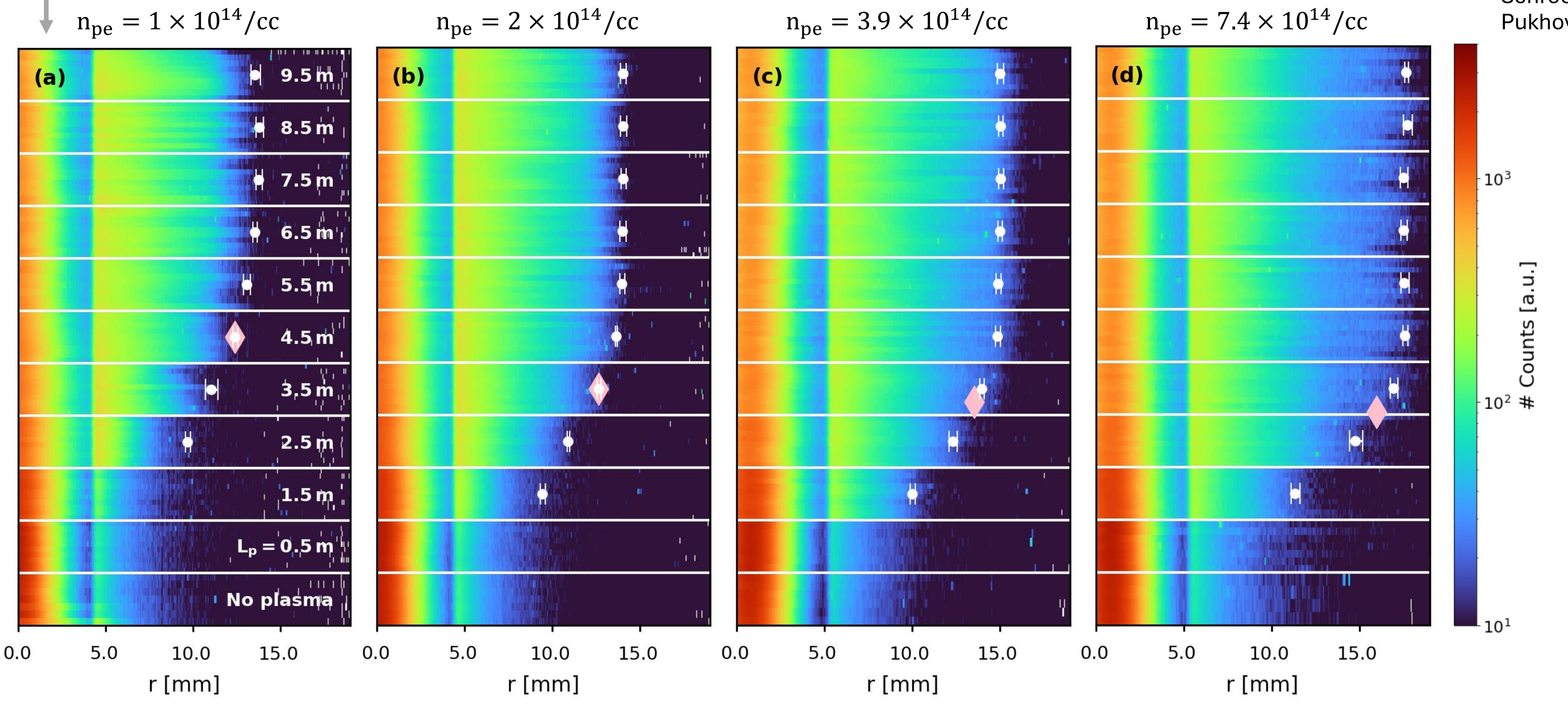
- $t_{RIF} = 100$ ps

$$\Gamma \propto n_{pe}^{1/6}$$

Kumar, N. and al., PRL, 2010
Schroeder, C. B. and al., PRL, 2011
Pukhov, A. and al., PRL, 2011





Halo formation along the plasma

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

Proton bunch :
- $N_b = 3 \times 10^{11}$
- $E = 400$ GeV
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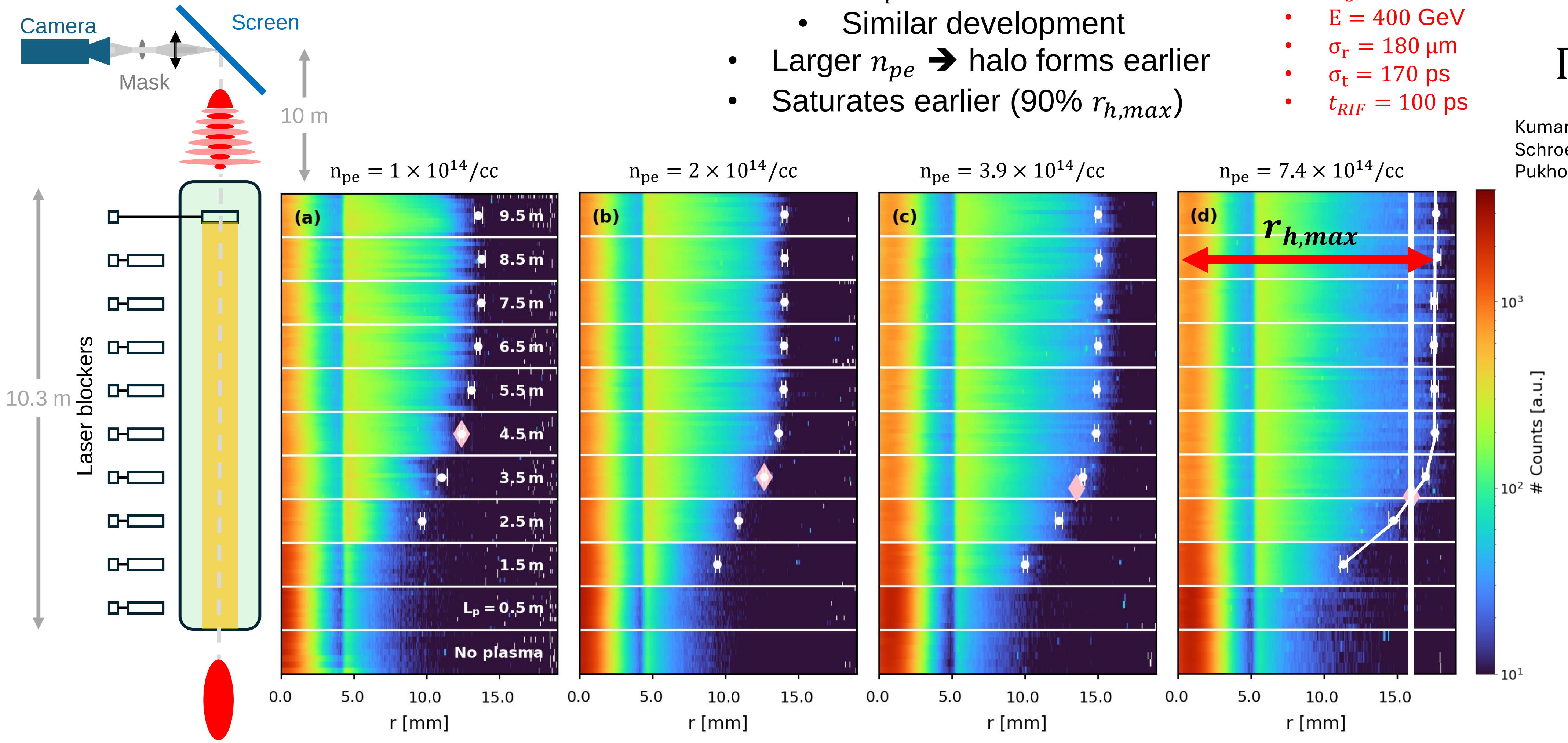

$$L_{sat,r_h} = L_p(r_h = 0{,}9\, r_{h,max})$$

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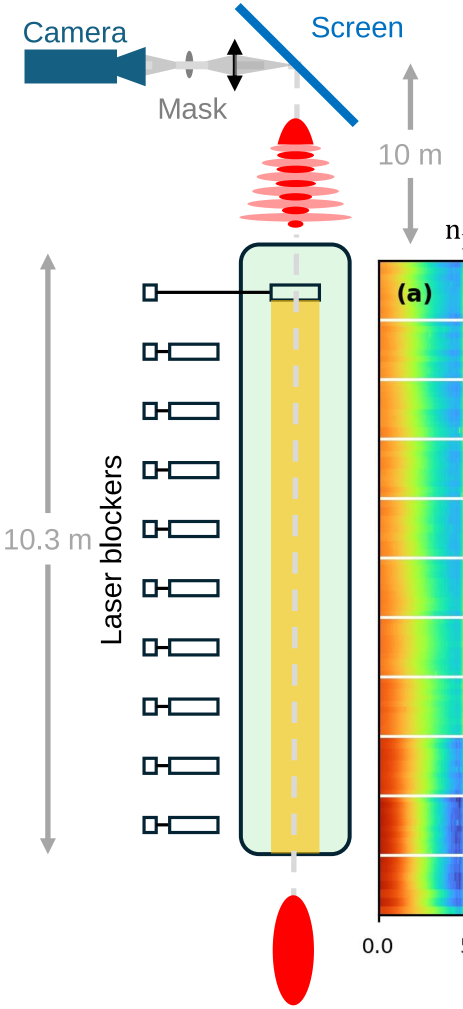

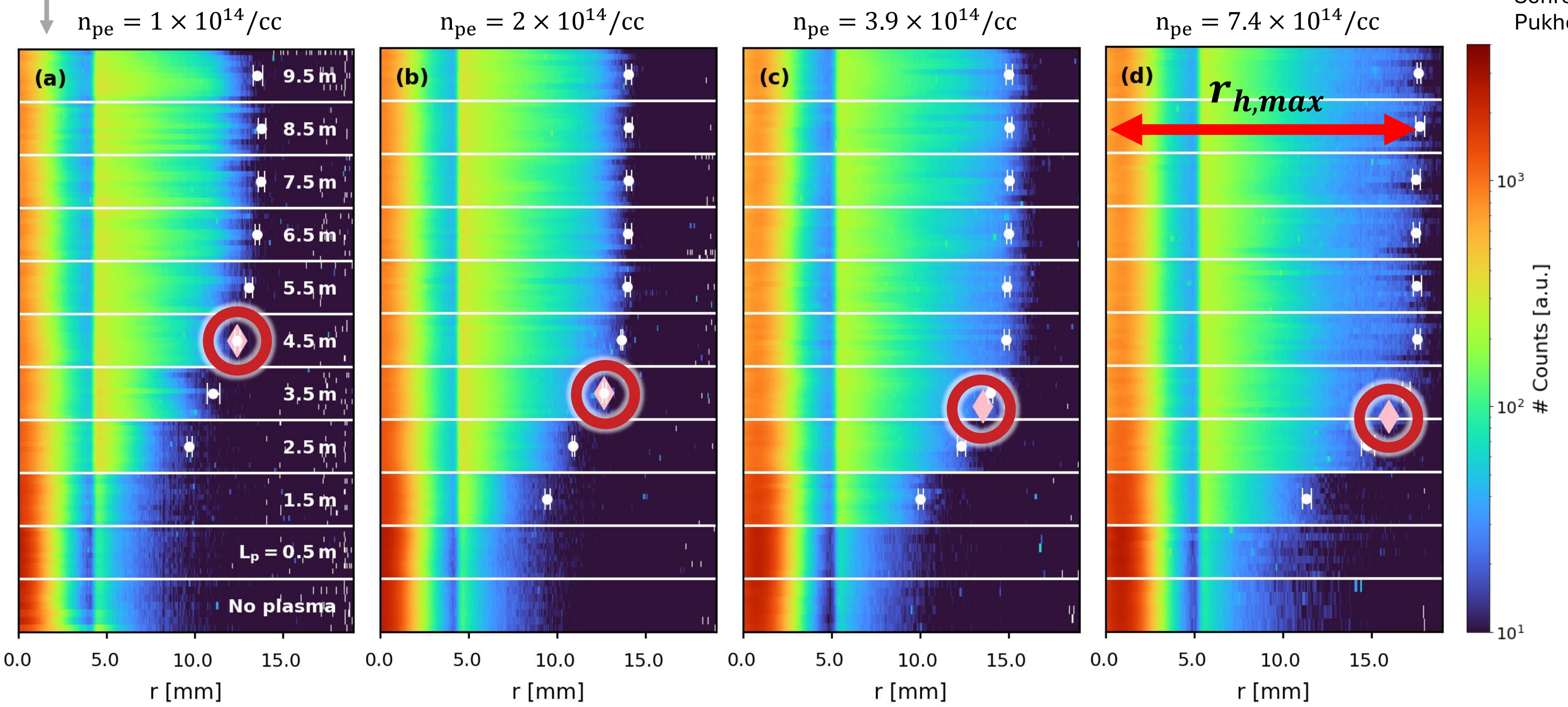

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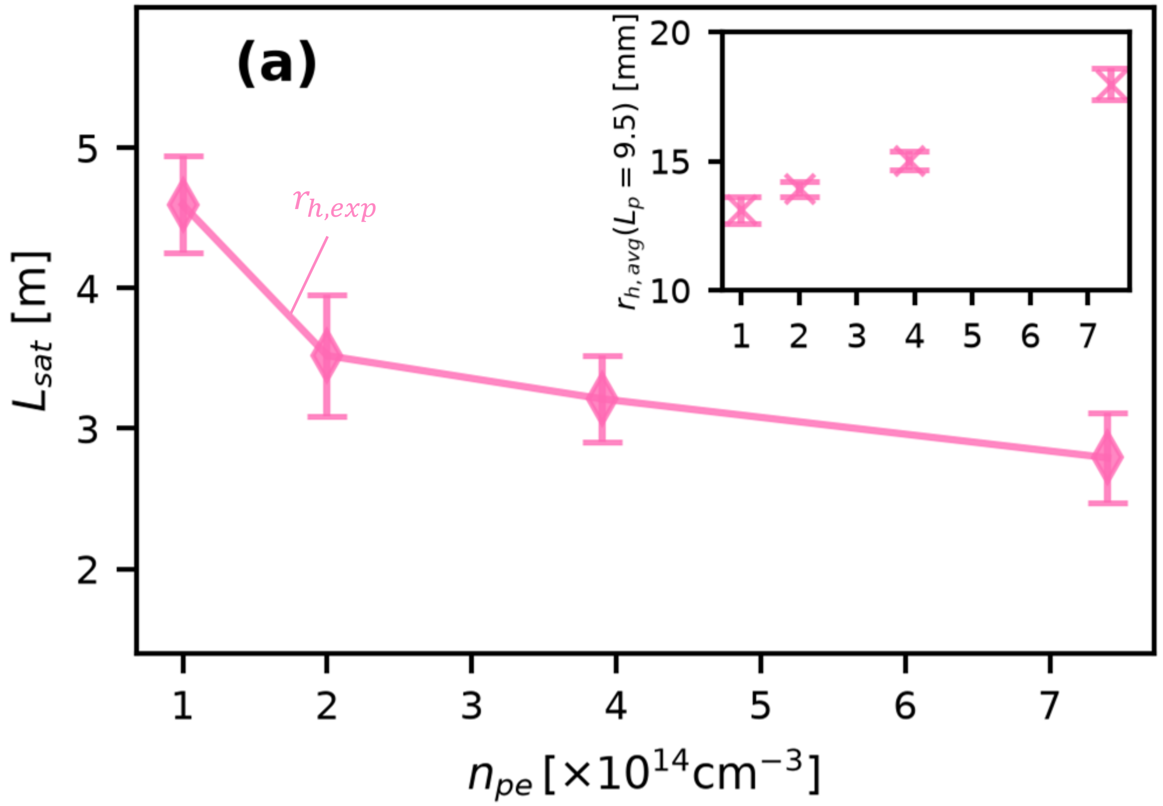
Comparison with simulation results



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

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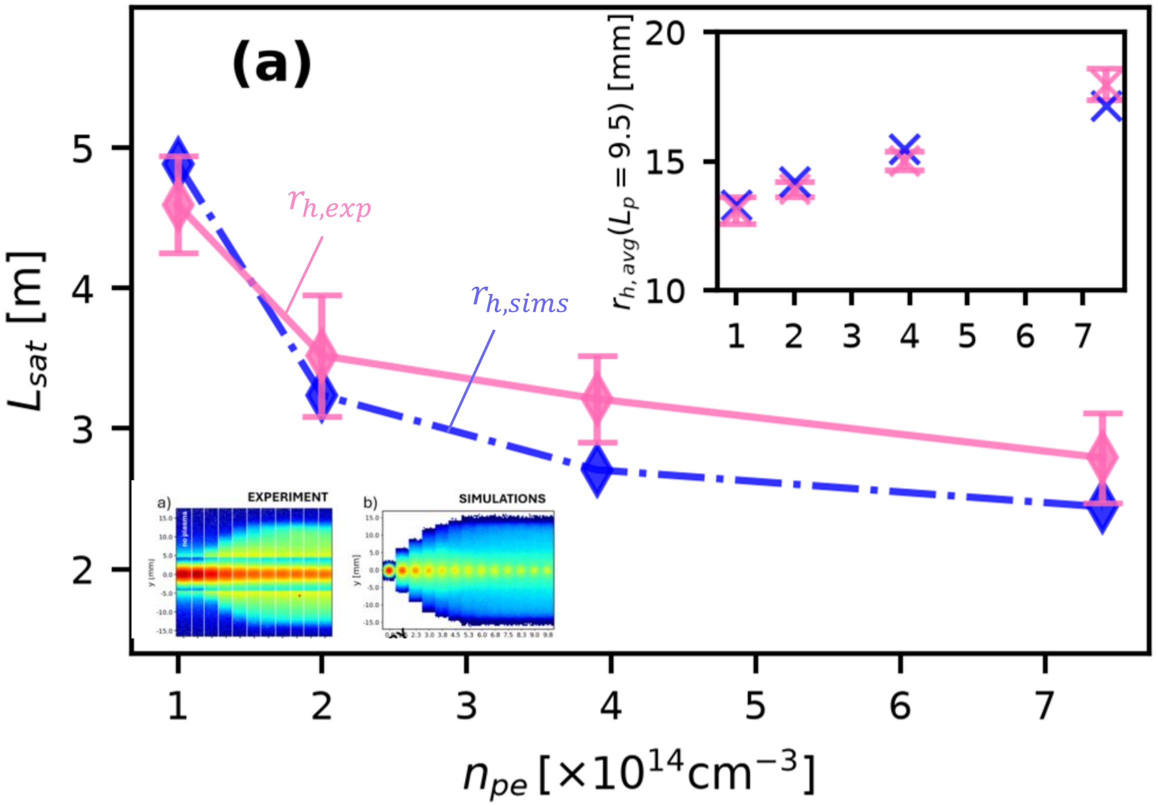

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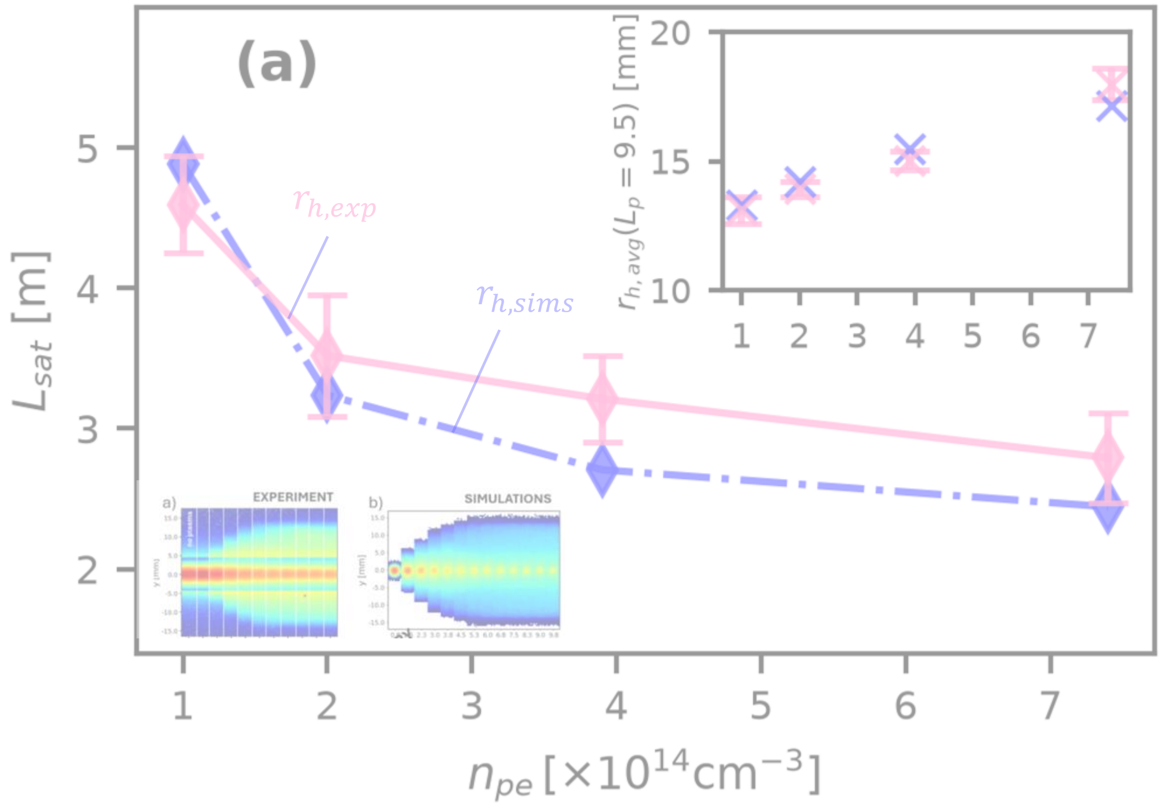
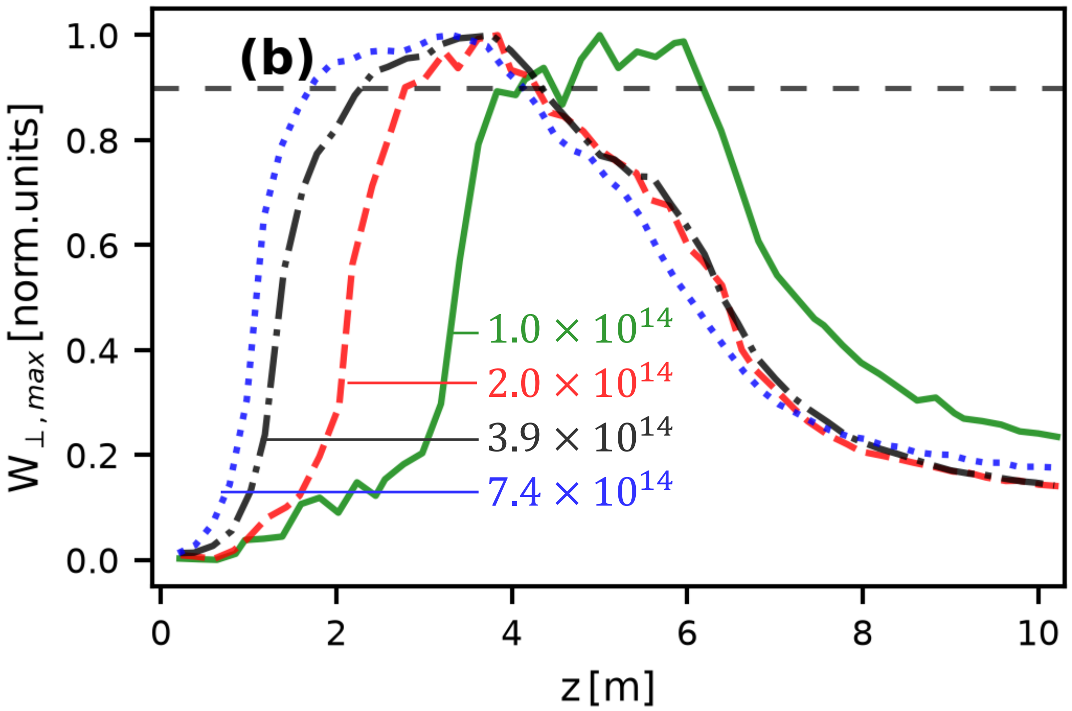
- Need to show it…

- Good agreement between exp. and sim. results
- LCODE (2D axisymmetric)

Comparison with simulation results

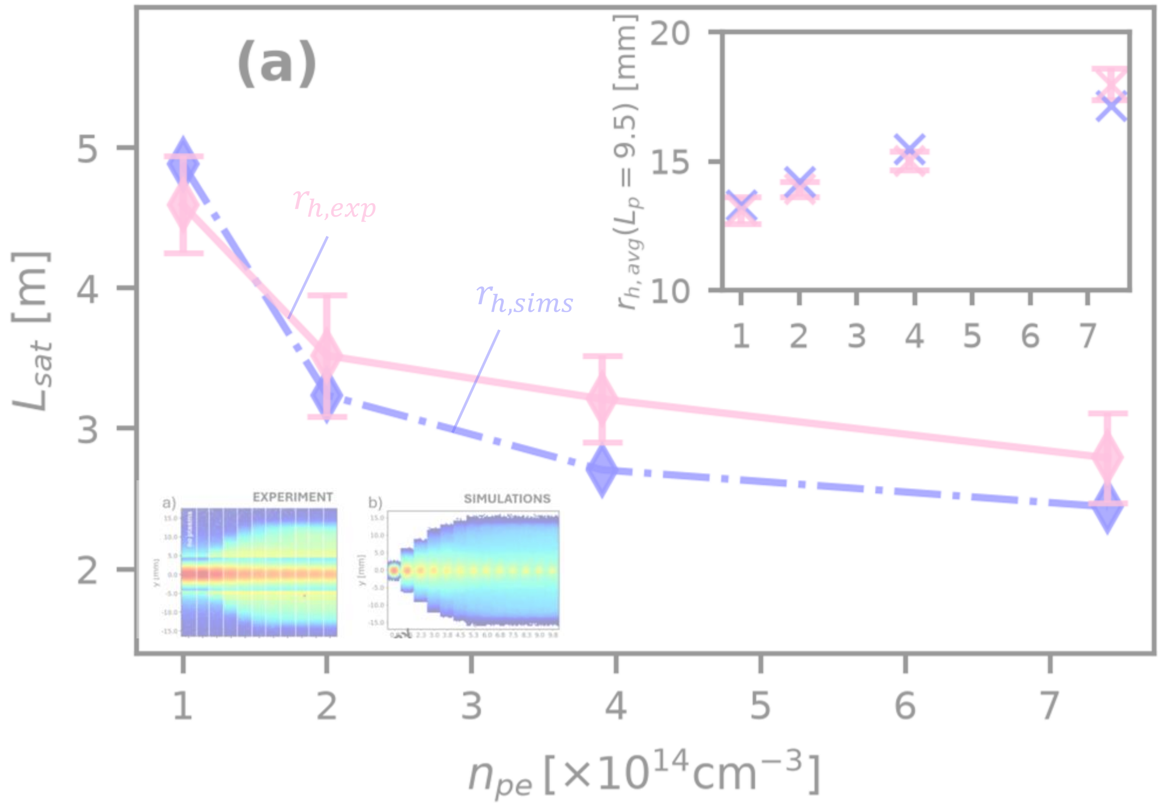


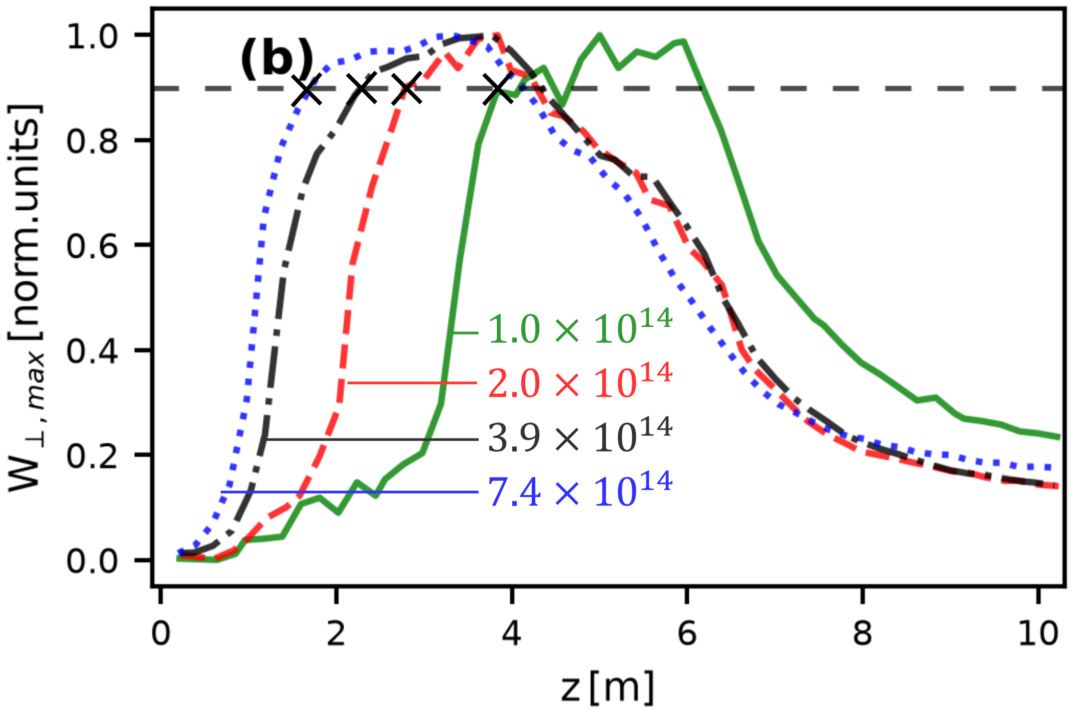


- Normalized transverse field amplitude along z
- Maximum field along the bunch ($t_{rif} > \xi > -\sigma_t$)
- Grows, saturate and decay

- L_{sat} → 90% maximum
- Saturates earlier for larger n_{pe}

Comparison with simulation results





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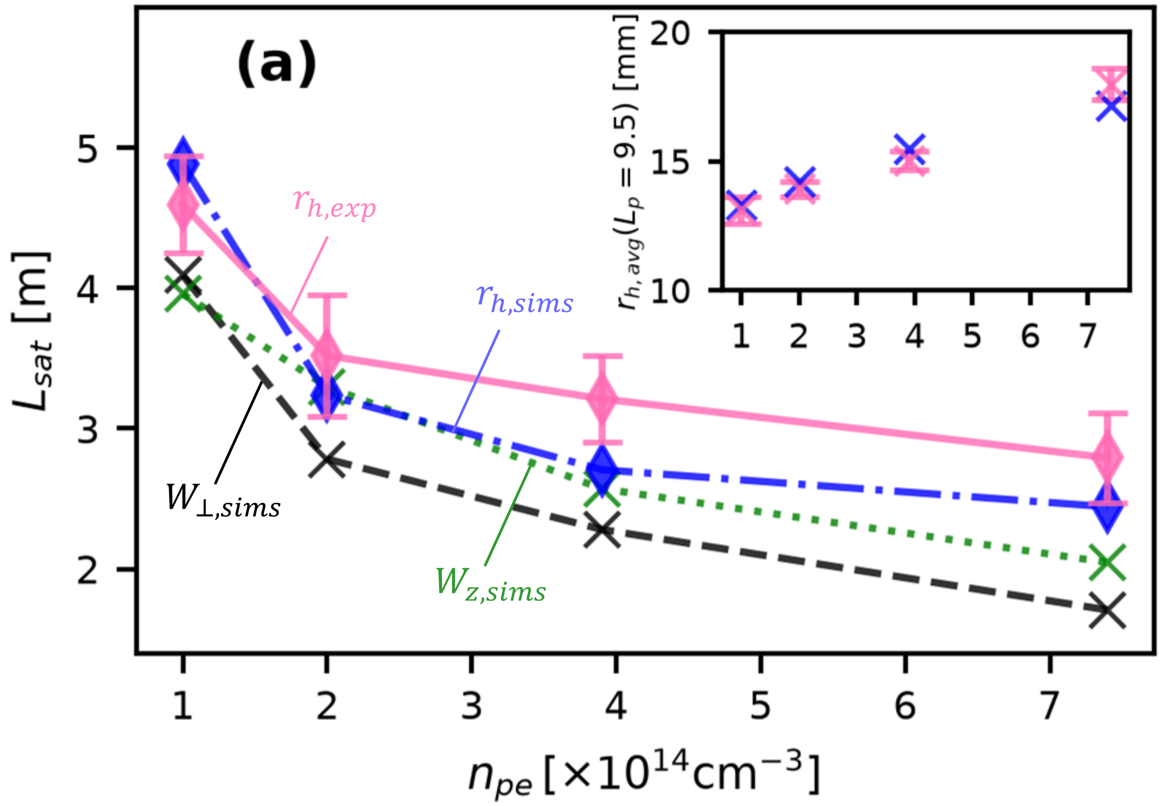

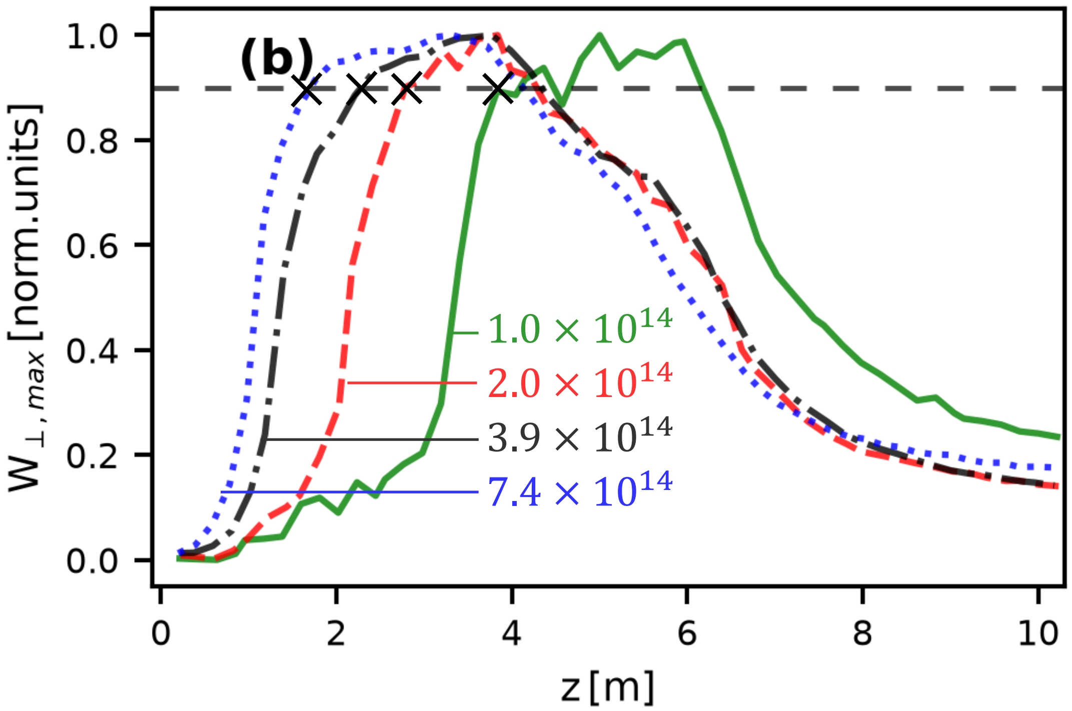

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- L_{sat} → 90% maximum
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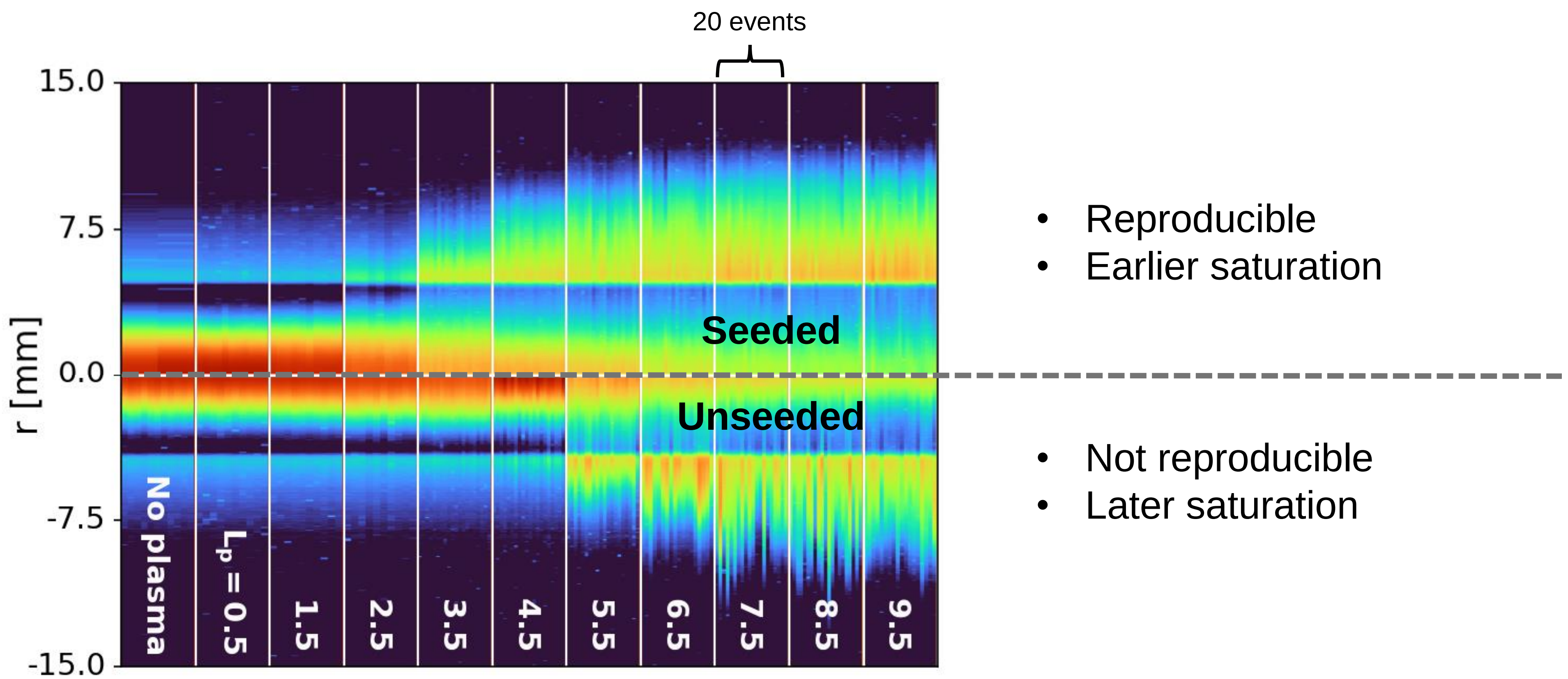
- Fields saturate earlier than halo
- Good estimate for the saturation of the fields ($\Delta L_{sat} < 1$m)

Seeded vs Unseeded



- Reproducible
- Earlier saturation

- Not reproducible
- Later saturation

Seeded $W_{\perp,0}$ > Unseeded $W_{\perp,0}$
→ L_{sat} decreases with initial wakefield amplitude

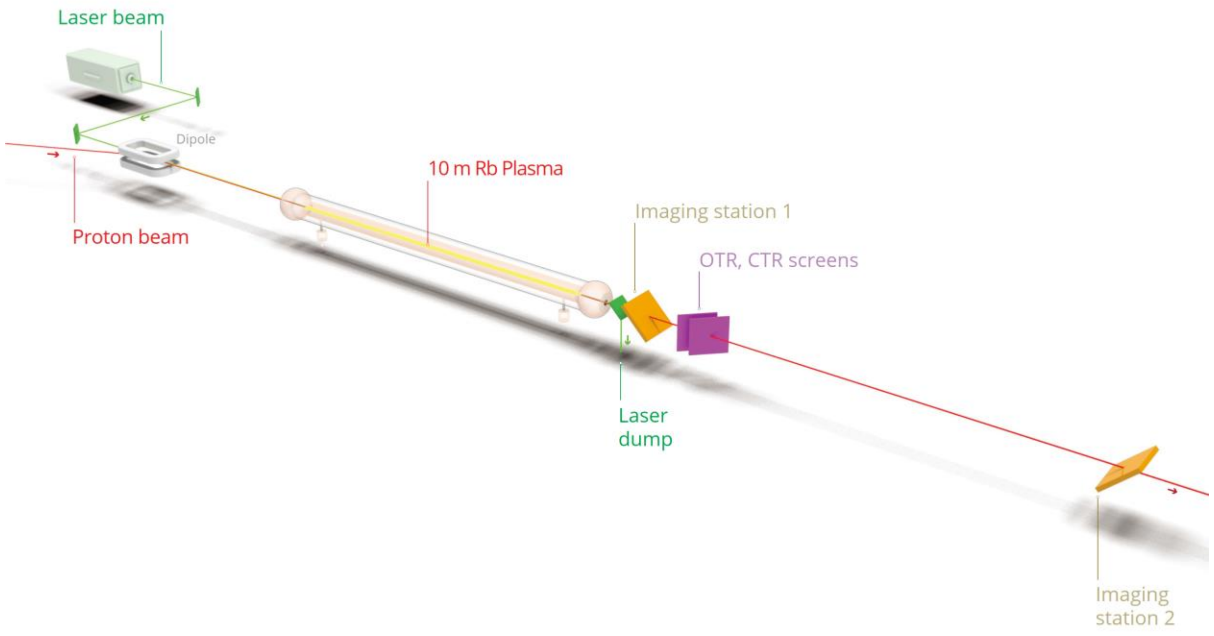
- Consistent with light measurements !

Outline

- Introduction to the AWAKE Experiment at CERN
- Demonstration of Amplitude-Reproducible Self-Modulation by Seeding
- Measurement of the Saturation Length of the Self-Modulation Instability
- Moving forward...

Moving forward

- Demonstration of SM of proton bunch at AWAKE
  - Modulation
  - Growth of wakefields



Moving forward

- Demonstration of SM of proton bunch at AWAKE
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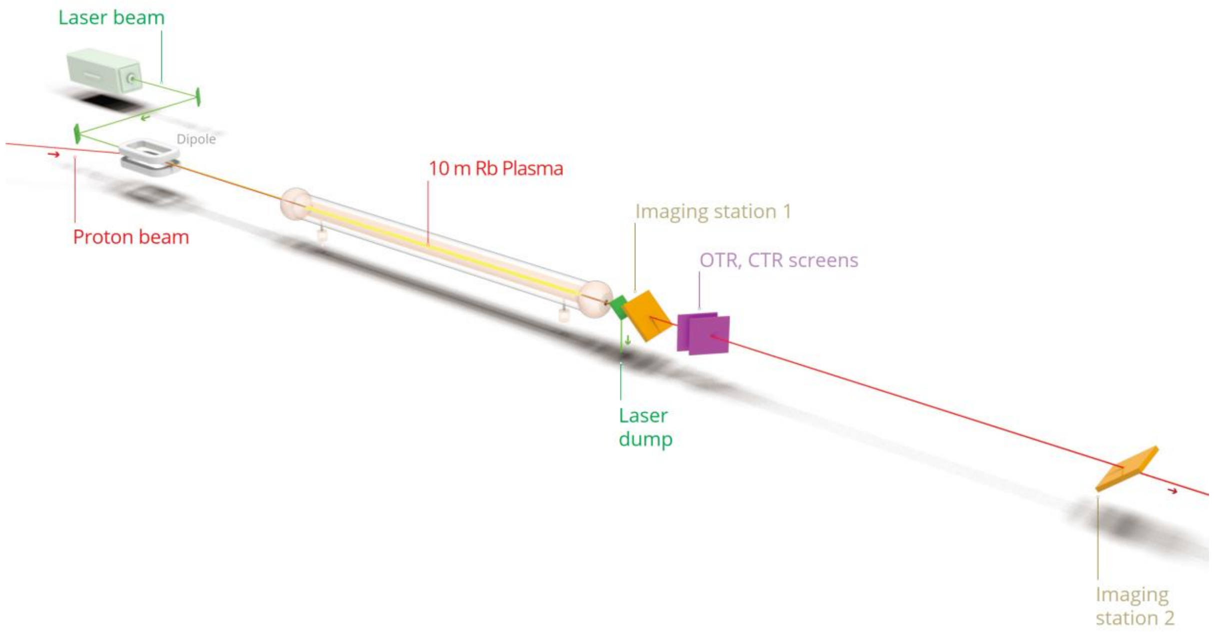
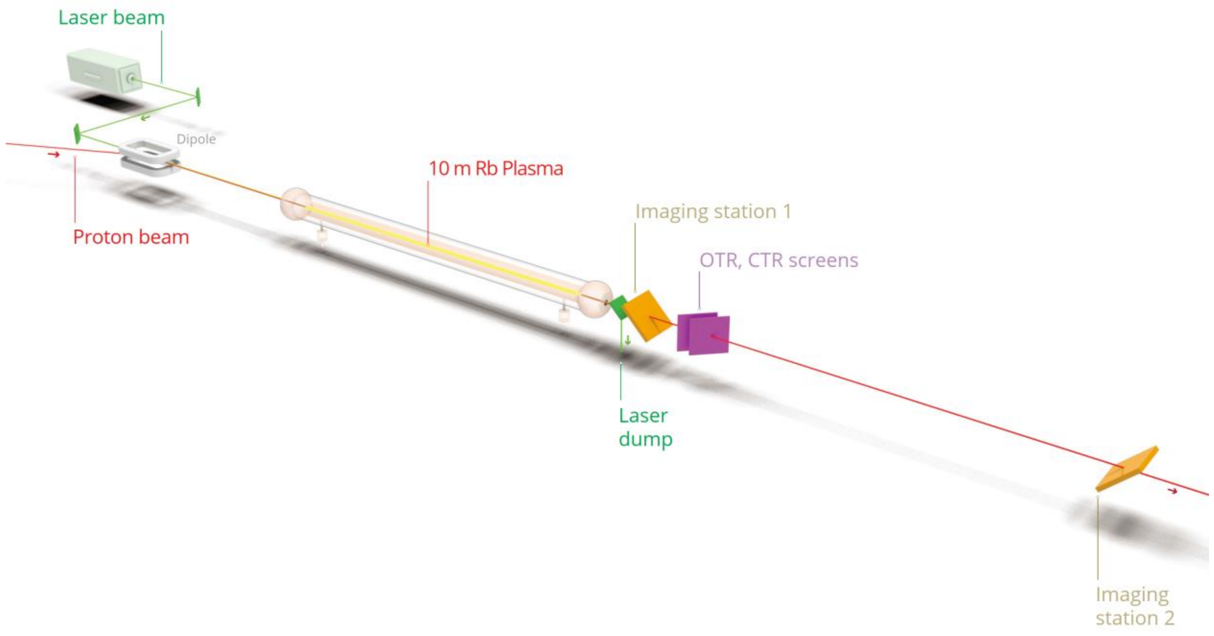
  - Growth of wakefields
- Control of the process: reproducible in timing



Moving forward

- Demonstration of SM of proton bunch at AWAKE
  - Modulation ✓
  - Growth of wakefields ✓
- Control of the process: reproducible in timing ✓

→ Reproducible in amplitude ✓



Moving forward

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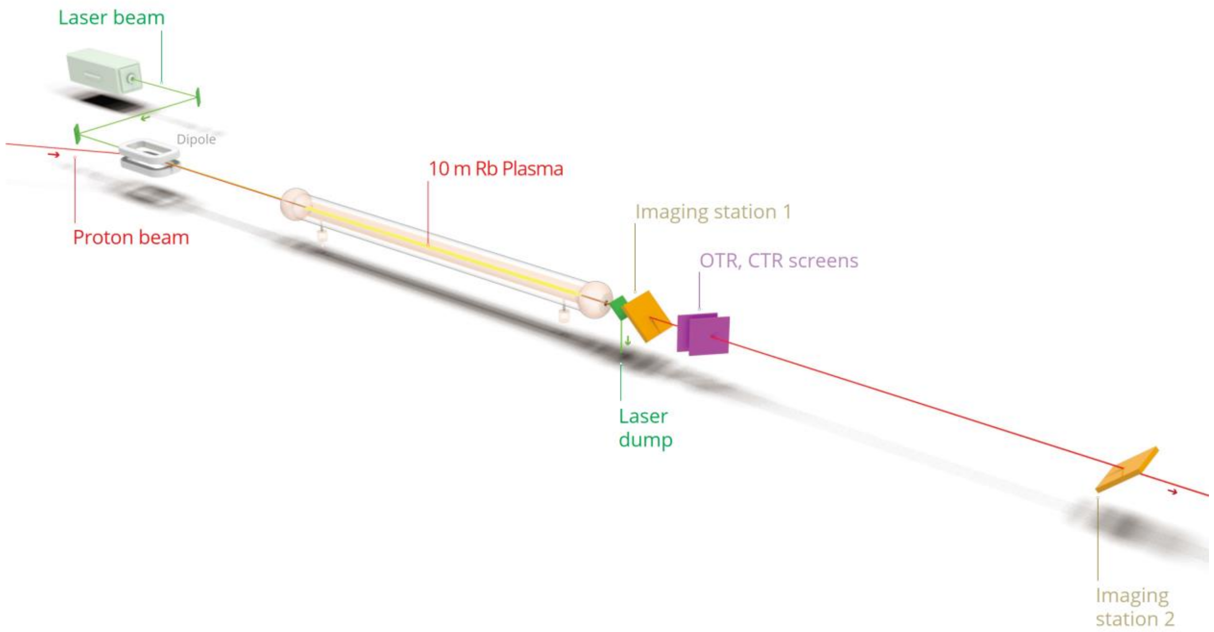

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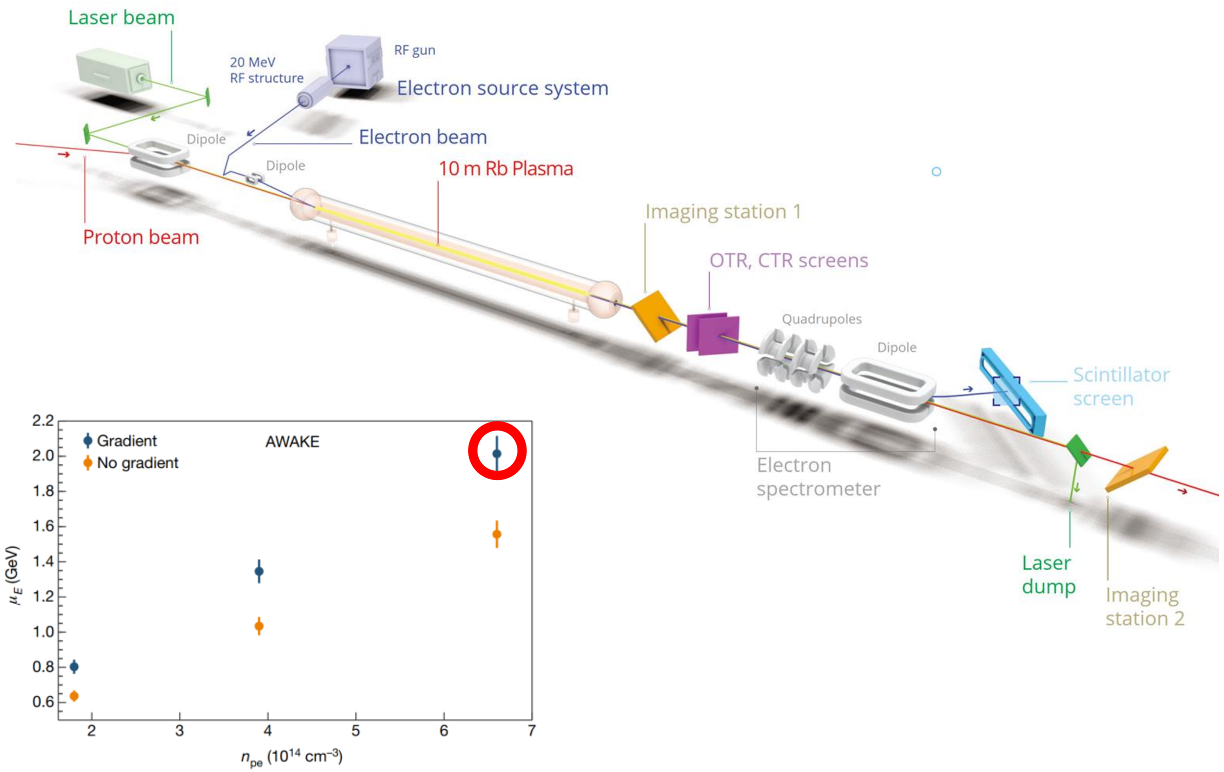

AWAKE Collab. *Nature* 561, 363–367 (2018)

Energy gain of 2 GeV
Up to 2.8 GeV now with a density step !

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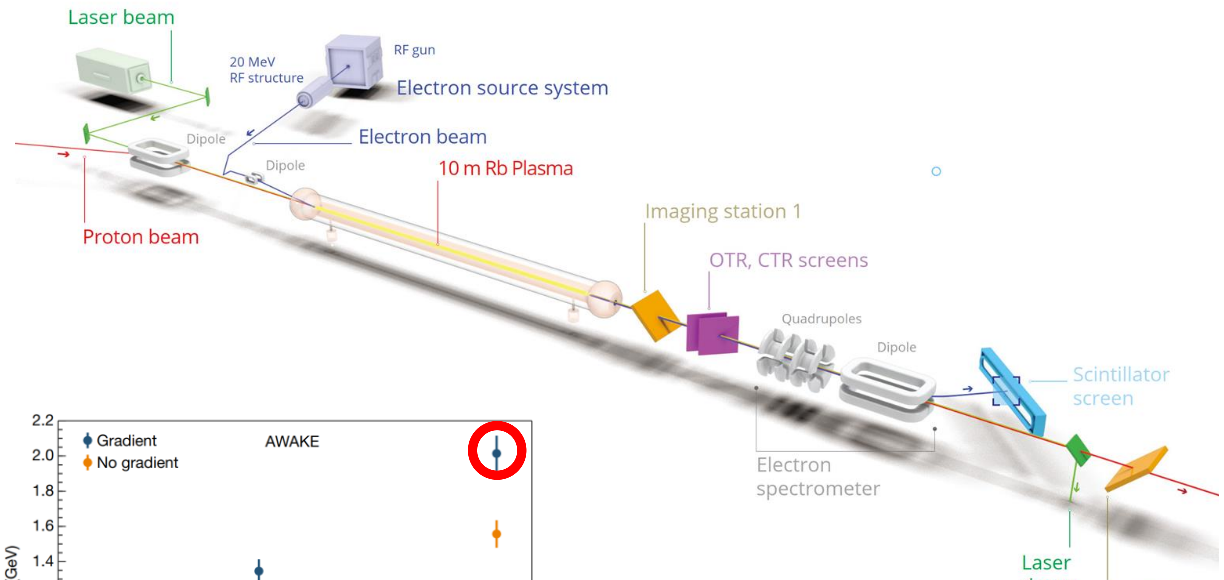

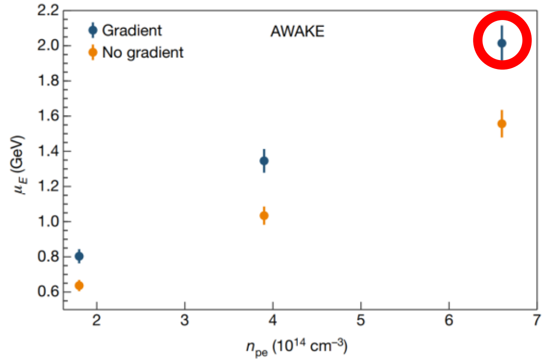

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Next step ?

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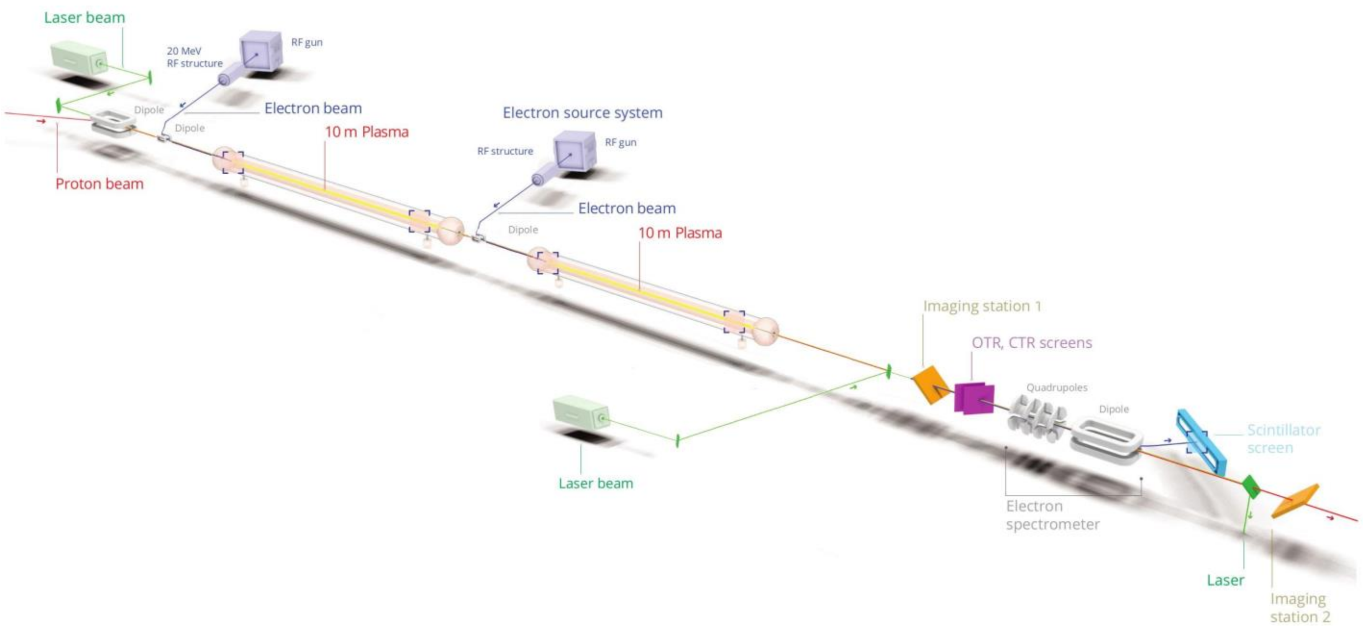

Next step ? **Beam quality and scalability !**

Moving forward

- Demonstration of SM of proton bunch at AWAKE
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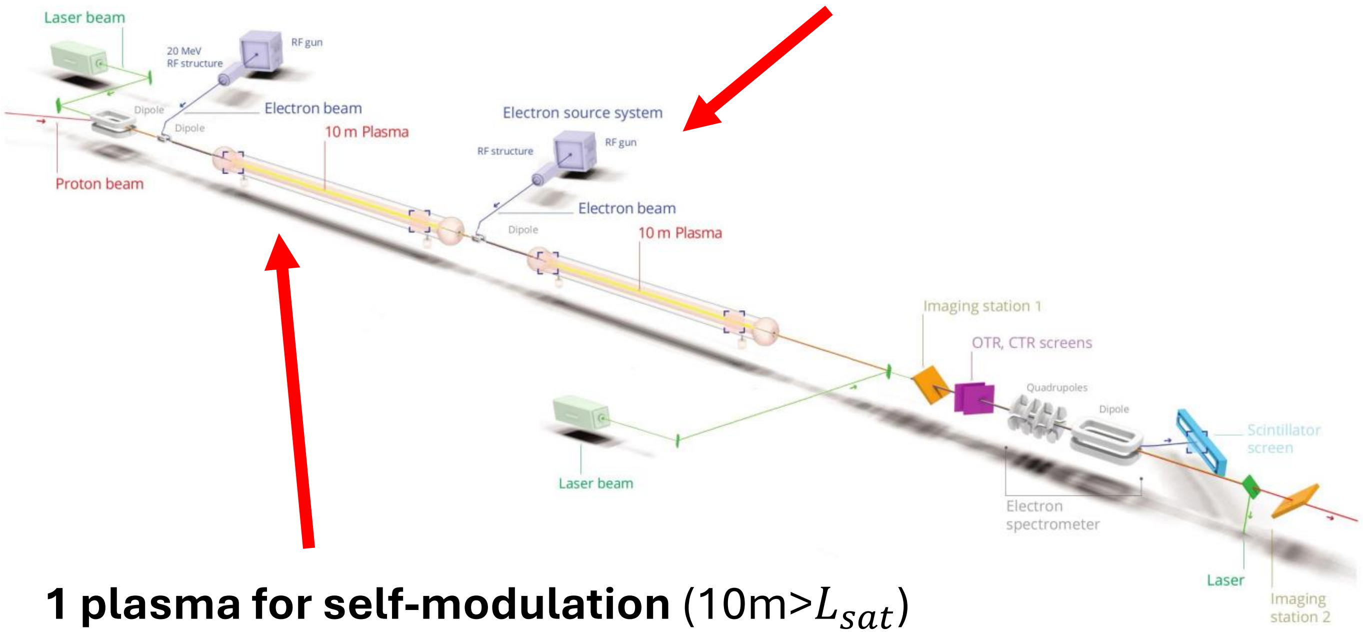
Injection of electrons after saturation of SM



1 plasma for self-modulation (10m>L_{sat})
+1 for acceleration
+ on-axis injection
+ beam loading

Next step ?

Beam quality and scalability !

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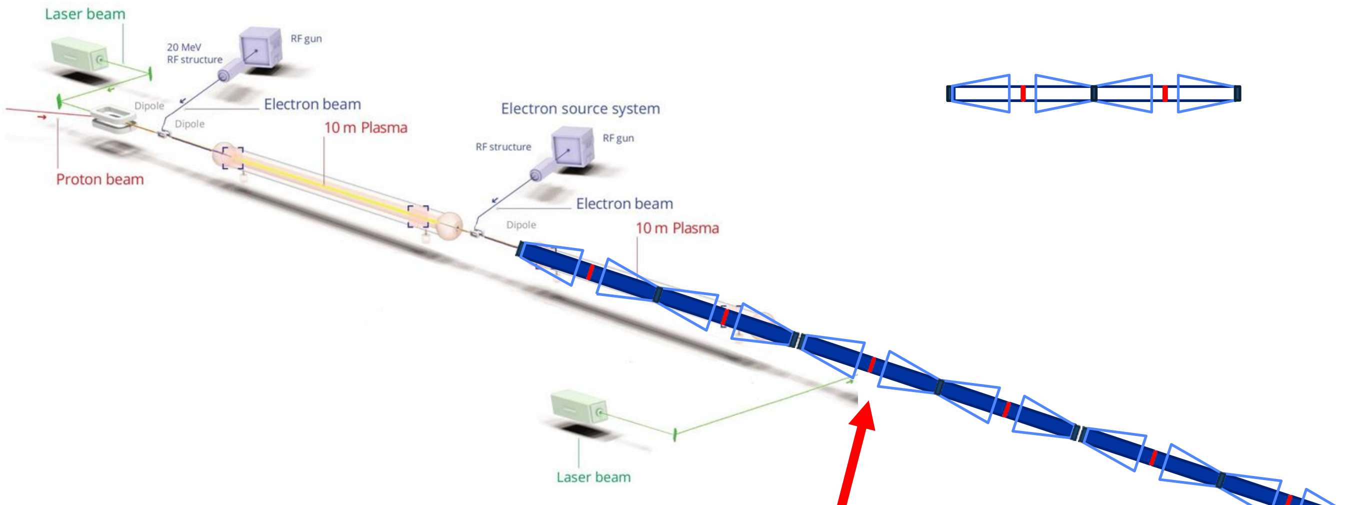
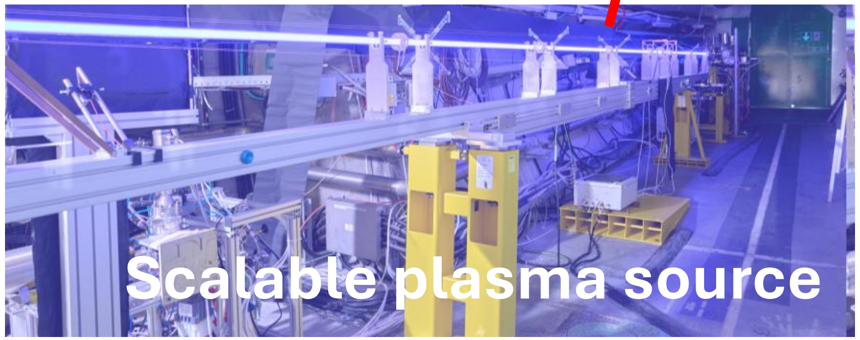


C. Amoedo, A.Sublet and al.



Next step ?

Beam quality and scalability !

Conclusion

AWAKE :
- AWAKE aims to be a **proton-driven** PWFA for **particle physics applications**
- SPS bunches allow for **GV/m-amplitude** wakefields for **10s** to **100s** of meters in a **single plasma**
- SPS bunches are long, first need to be **self-modulated**

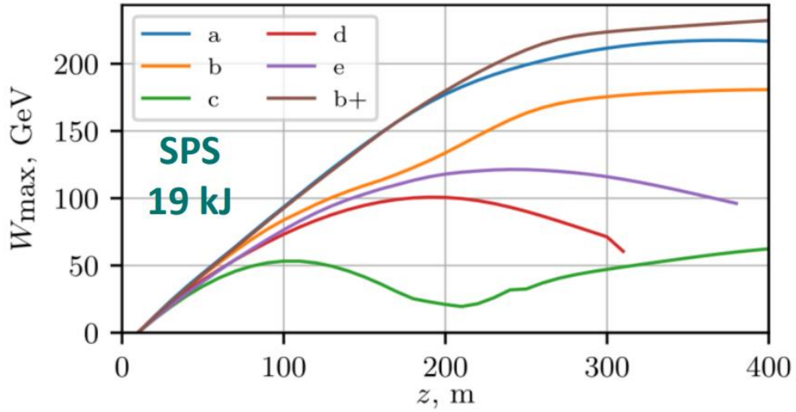
Previous results :
- Seeding SM makes phase of wakefields more reproducible

New results:
- Seeding SM makes the **amplitude** of the wakefields more **reproducible**
- Variations decrease at saturation
- SM **saturates** in less than 10m

Next:
- On-axis, external injection of witness bunch in second plasma
  - **After saturation**, with **reproducible** wakefields both in **phase** and **amplitude**

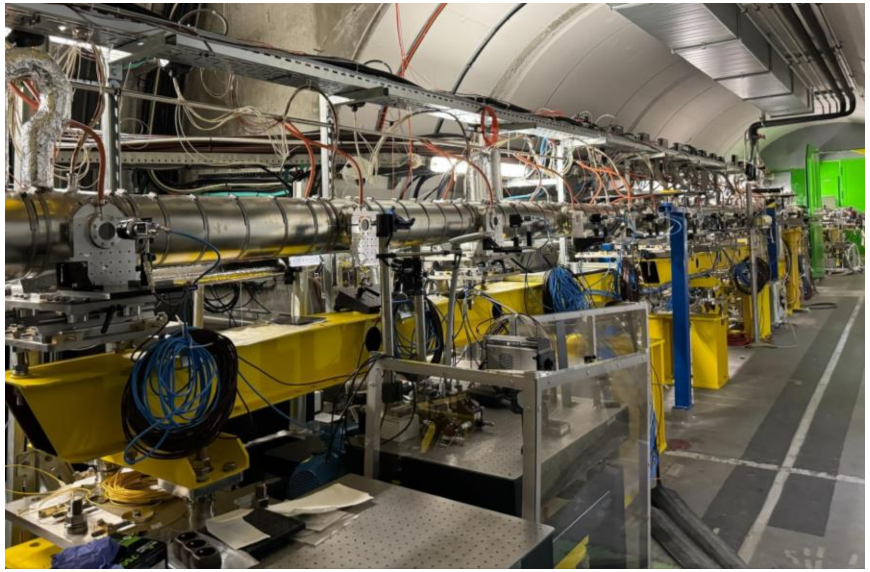
- Scalable plasma for the accelerator, **10s** to **100s** of meters

2D numerical simulation results



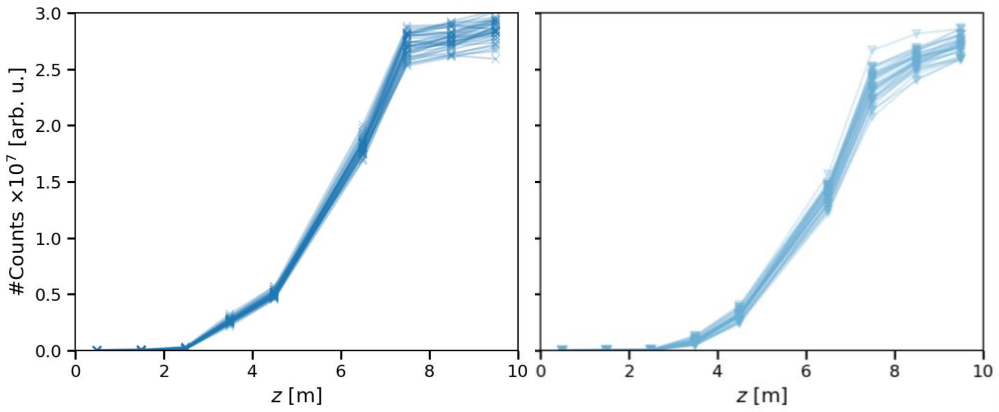
K. V. Lotov & P. V. Tuev, Plasma Phys. and Control. Fusion, 63, 125027 (2021)

Thank you for your attention !

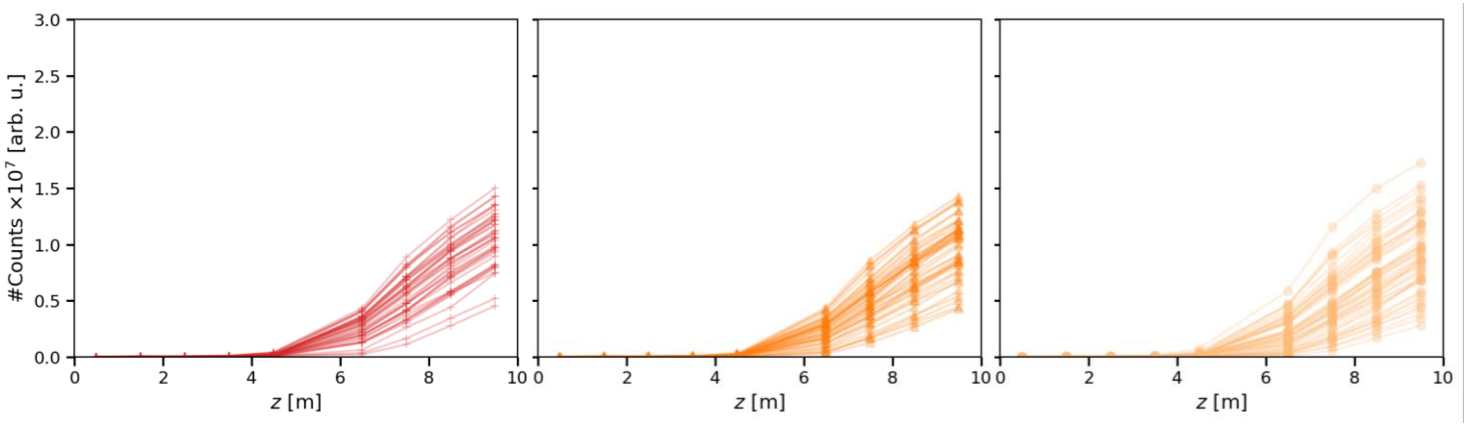


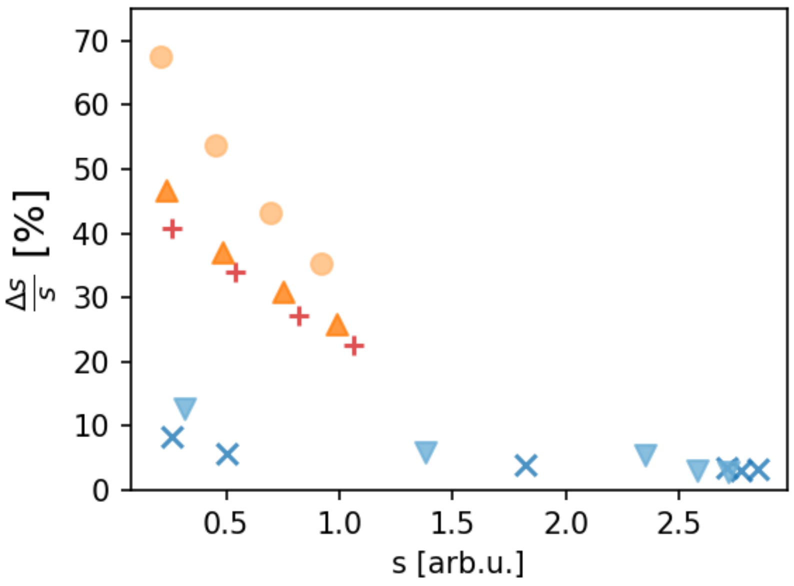
Backup: reproducibility

Seeded

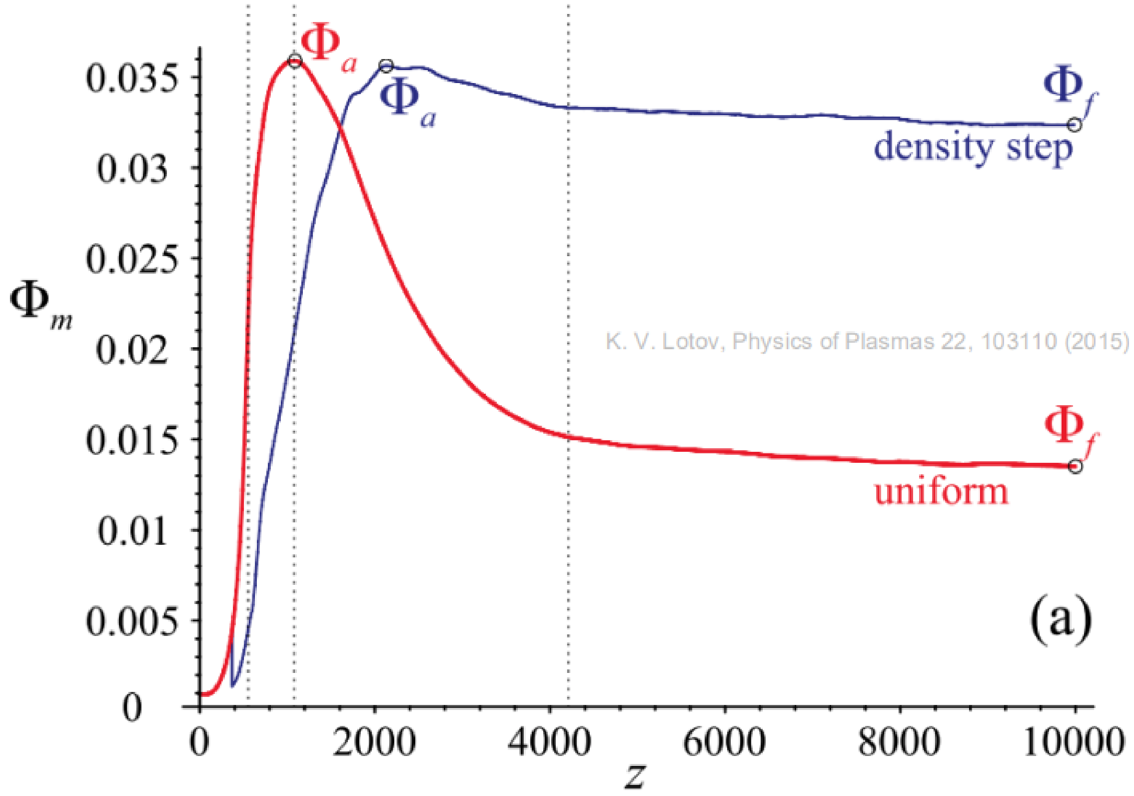


Unseeded

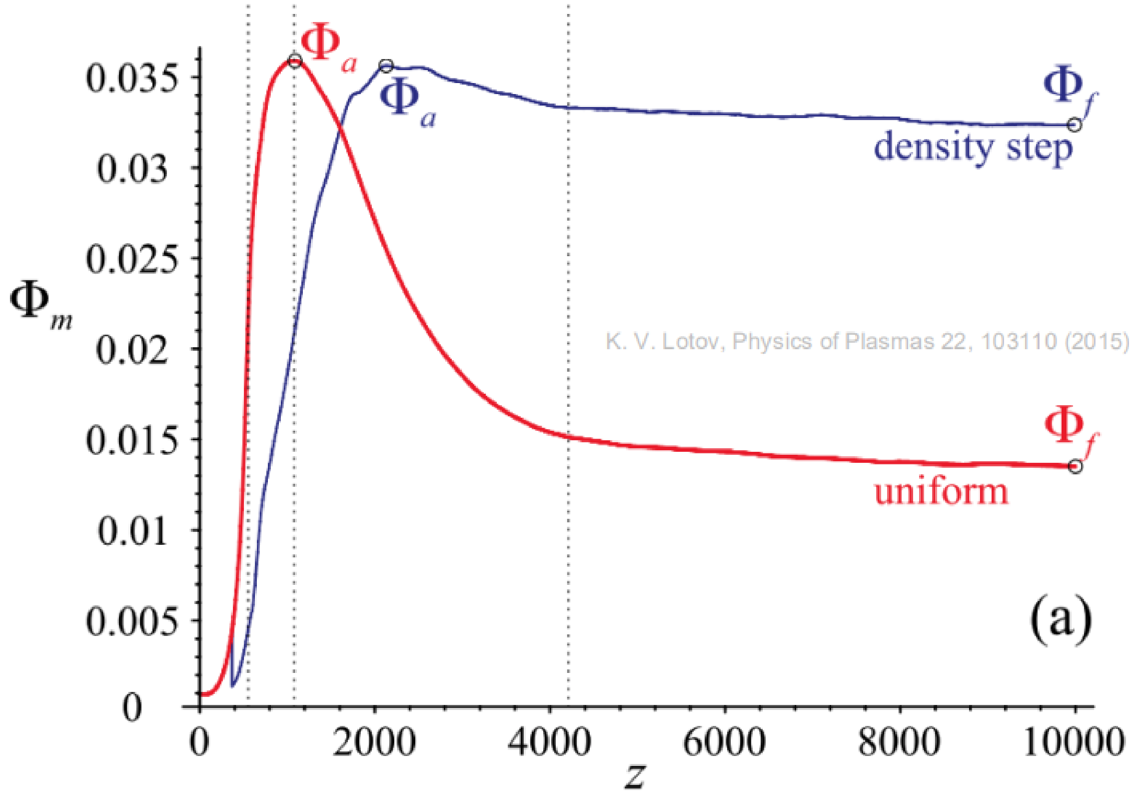


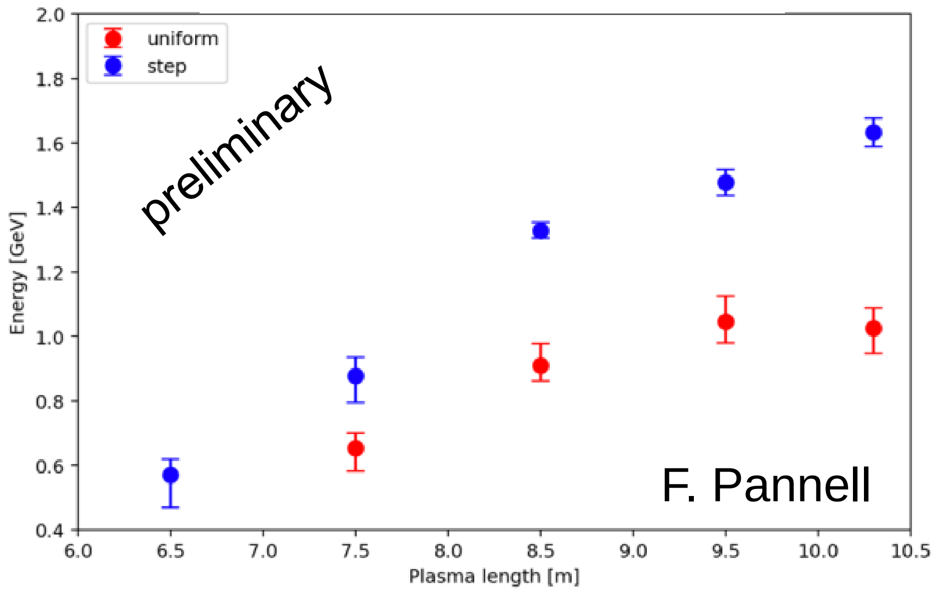


Backup: density step



Backup: effect of the step





Parameter	Uniform	Step
Plasma density	$3.8 \times 10^{14} cm^{-3}$	$3.8 \times 10^{14} cm^{-3}$
Proton RIF	+200ps	+200ps
Electron delay	-400ps	-400ps
Injection z	1.5m	1.5m
Step height	-	2.3%
Step z	-	1.25m

Backup: witness bunch params.

Parameter	Nominal Value	Tolerance	Adjustment Range
Energy	150 MeV	n.a.	n.a.
Energy spread	0.2 %	< 1 %	n.a.
Charge per bunch	100 pC	± 5 pC	100-400 pC
Normalised emittance	2 mm mrad	$\pm$0.2 mm mrad	n.a.
Bunch length	200 fs	$\pm$10 fs	+100 fs
Beam arrival time[1]	t=0	$\pm$50 fs	$\pm$1 ns
Beam H/V position	0/0	$\pm$10 μm	$\pm$1 cm
Beam waist location	z=0	$\pm$0.5 mm	$\pm$1 cm
Beam radius @waist[2]	5.76 μm	$\pm$1 μm	5-10 μm
Beam angle	0 μrad	$\pm$10 μrad	$\pm$10 mrad

Table 4: Summary of experimental specifications and tolerances for the 150 MeV electron bunch at injection. Parameter control and measurement accuracy should be similar to the tolerance.

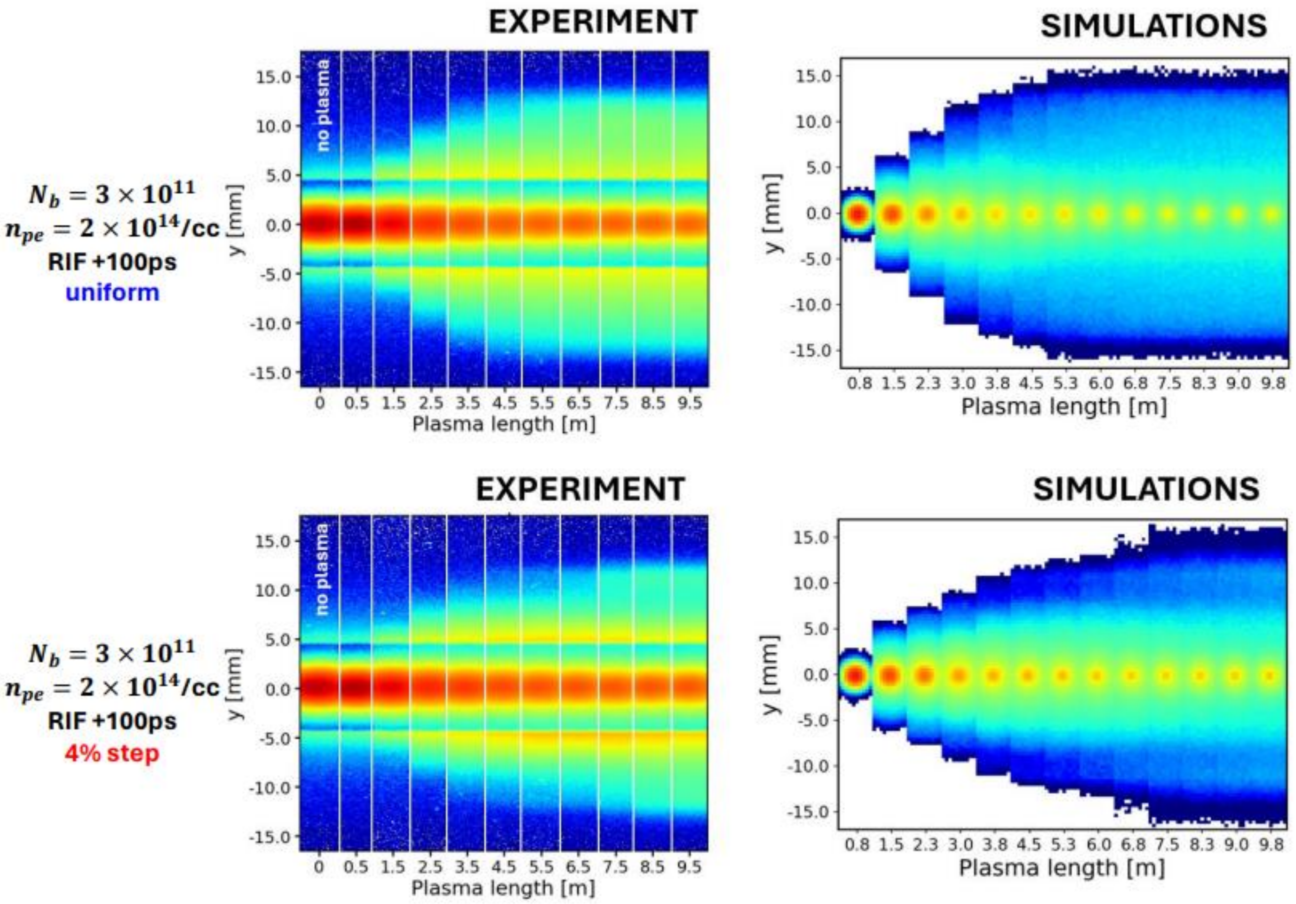
Backup: run 2c goals

AWAKE Run 2c is designed to demonstrate the acceleration of externally injected electron bunches while maintaining control over their beam quality. The key objectives are summarized below:

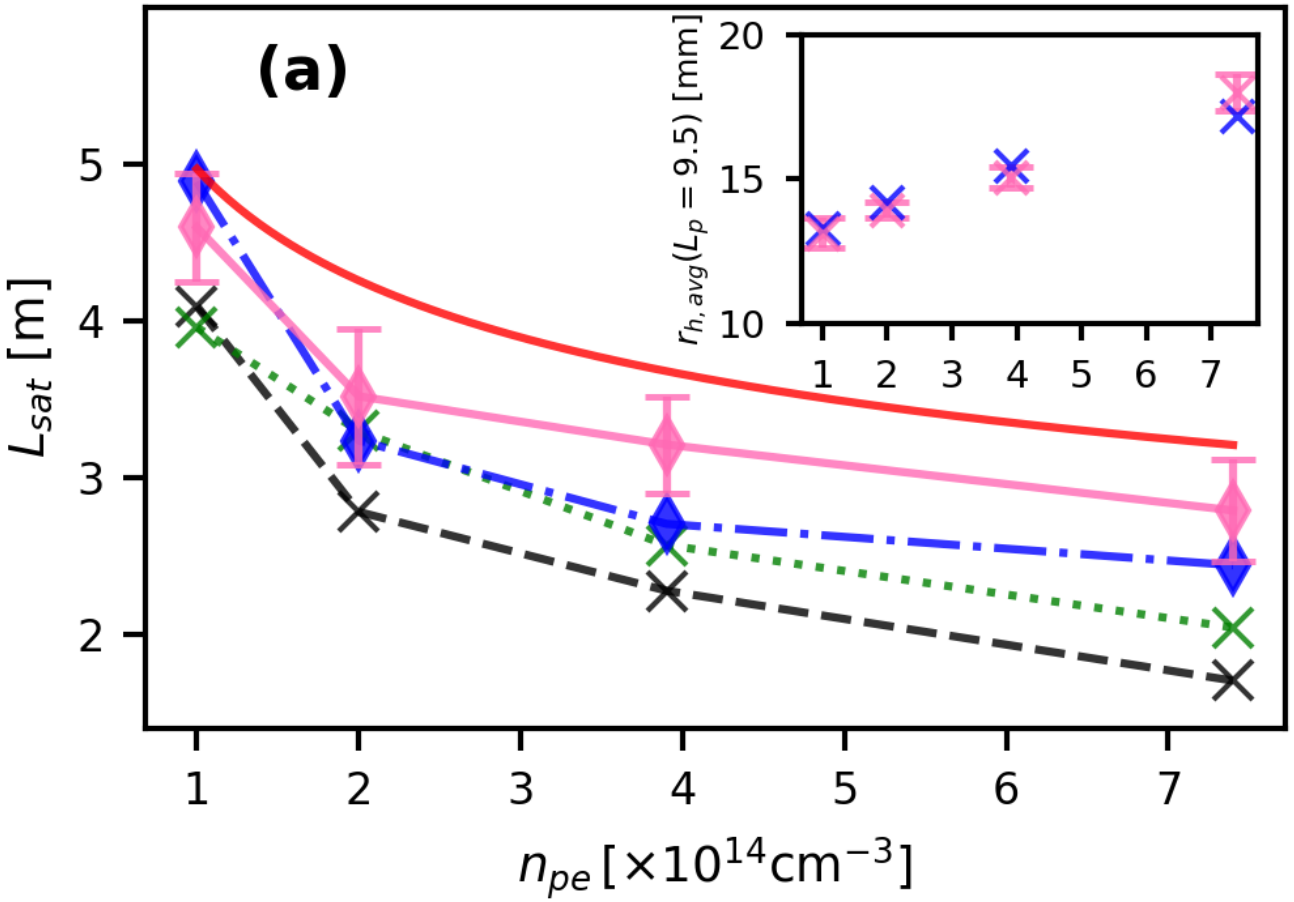
Important

- Achieve energy gain greater than 4 GeV.
- Maintain beam emittance within 2–30 mm mrad.
- Ensure final relative energy spread is below 10 %.
- Deliver accelerated charge approaching 100 % of the injected charge.

Backup: density step on halo



Backup: theory scaling



Same nb of exponentiations ?

Expected scaling $\propto n_{pe}^{-1/4}$