Electron Bunch Seeding of the Self-Modulation Instability in Plasma

L. Verra[1], G. Zevi Della Porta[1], J. Pucek[2], T. Nechaeva[2], M. Bergamaschi[2],
E. Gschwendtner[1], and P. Muggli[2]
(for the AWAKE Collaboration)
[1]CERN Geneva, [2]Max-Planck Institute for Physics Munich

EuroNNAc Special Topics Workshop
19.09.2022

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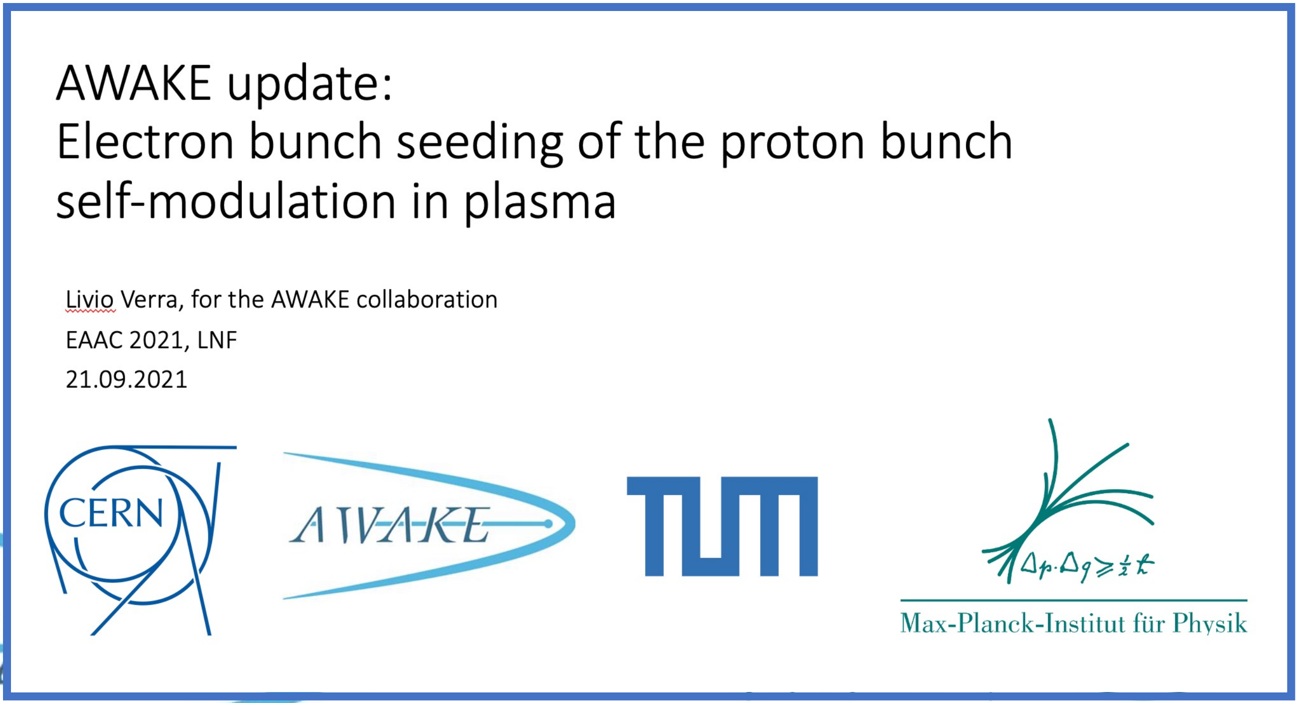


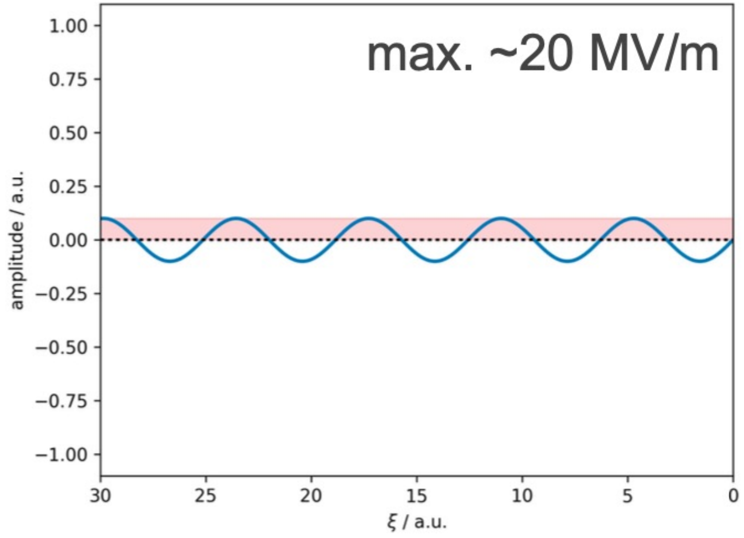
MAX-PLANCK-INSTITUT FÜR PHYSIK

Self-Modulation Instability

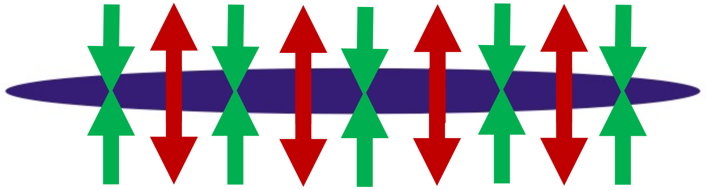
CERN SPS Proton bunch (400 GeV/c)

$\sigma_r \approx 200\ \mu m \ \rightarrow n_{pe} \approx 7 \cdot 10^{14} cm^{-3}$

$\sigma_z \approx 7\ cm \gg \ \lambda_{pe}$= 1.3 mm



Growth mechanism



Initial transverse wakefields

Periodic focusing/defocusing fields

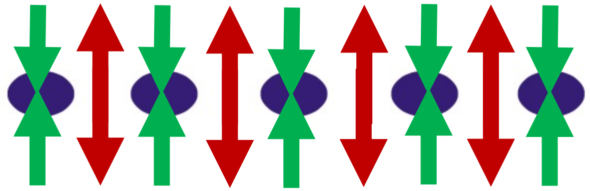
Radial bunch and plasma density modulation

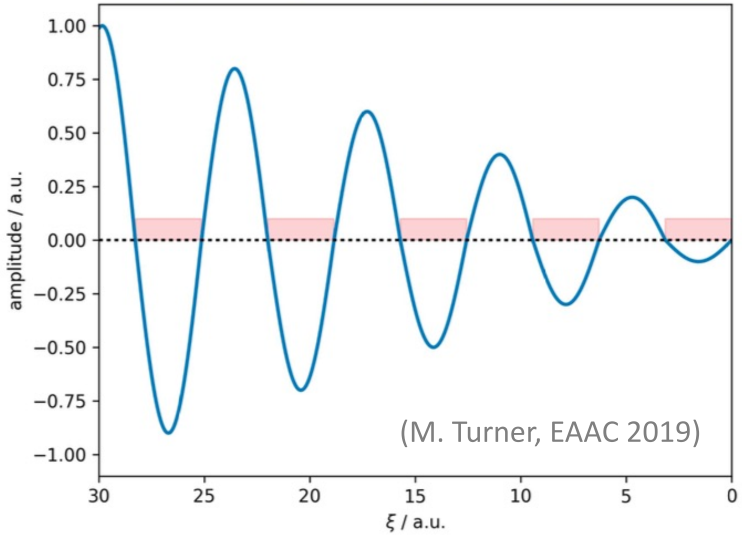
Stronger wakefields

Full modulation

Self-Modulation instability (SMI)

- Resonant wakefield excitation
  → Large wakefields amplitude



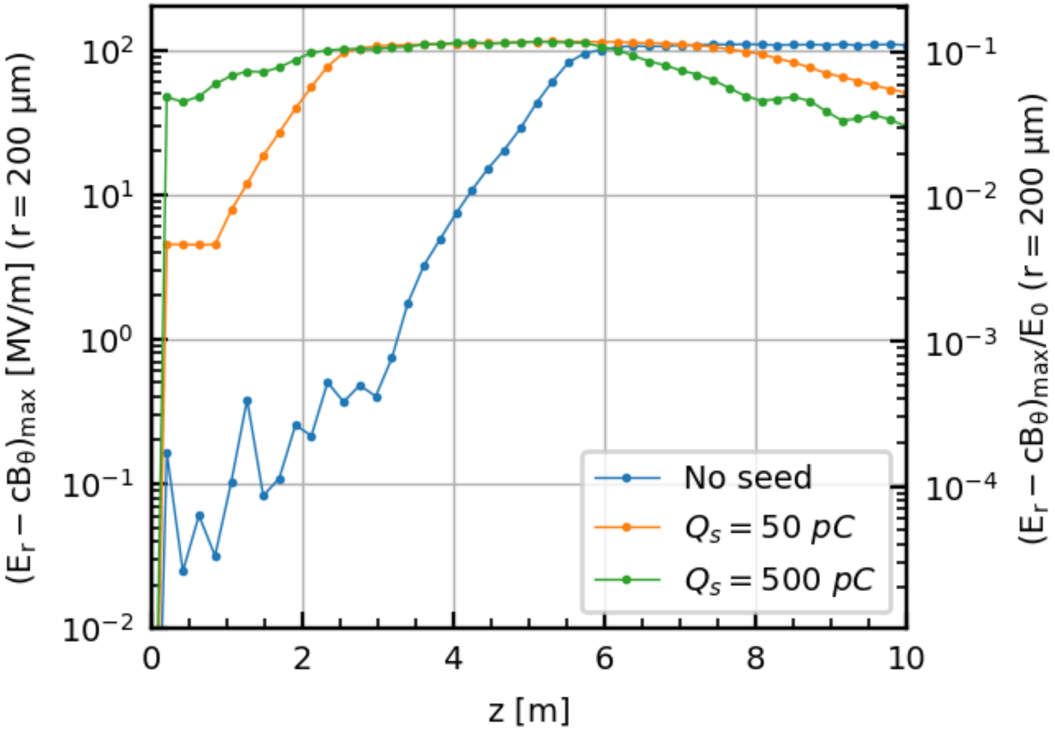


N. Kumar et al., Phys. Rev. Lett. **104** (25), 255003 (2010)
A. Pukhov et al., Phys. Rev. Lett. **107** (14), 145003 (2011)

Seeding of the Self-Modulation

- For precise witness injection, timing and amplitude of the wakefields must be reproducible from event to event
- Obtained by seeding the instability
  → setting timing and initial amplitude of the wakefields
  → controlling the instability

Seeding requires applying wakefields on the proton bunch with amplitude larger than that of the wakefields initially driven by the bunch



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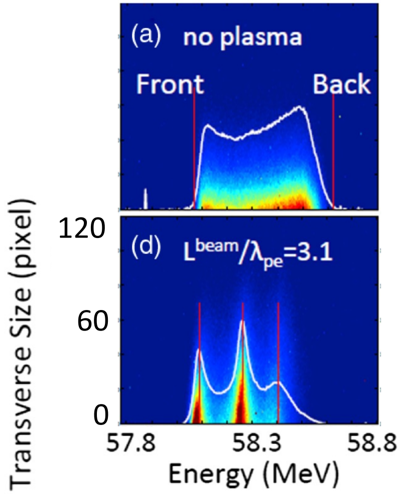
With long electron bunch: tailoring of the longitudinal distribution using a mask



Difficult for high-energy proton bunches

(BNL)

Y. Fang et al., Phys. Rev. Lett. **112**, 045001 (2014)

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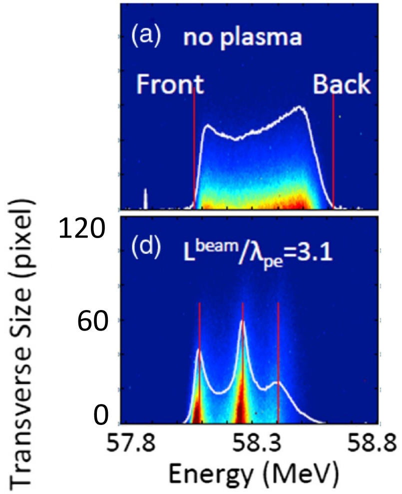

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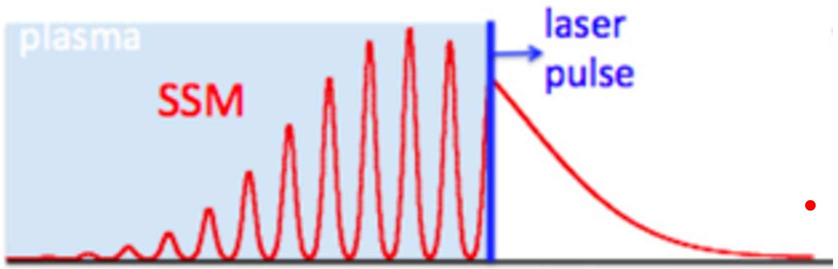
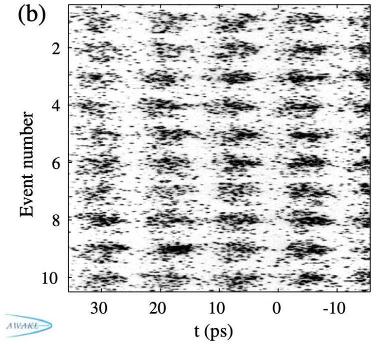
Y. Fang et al., Phys. Rev. Lett. **112**, 045001 (2014)

AWAKE Run 1: ionization-front seeding



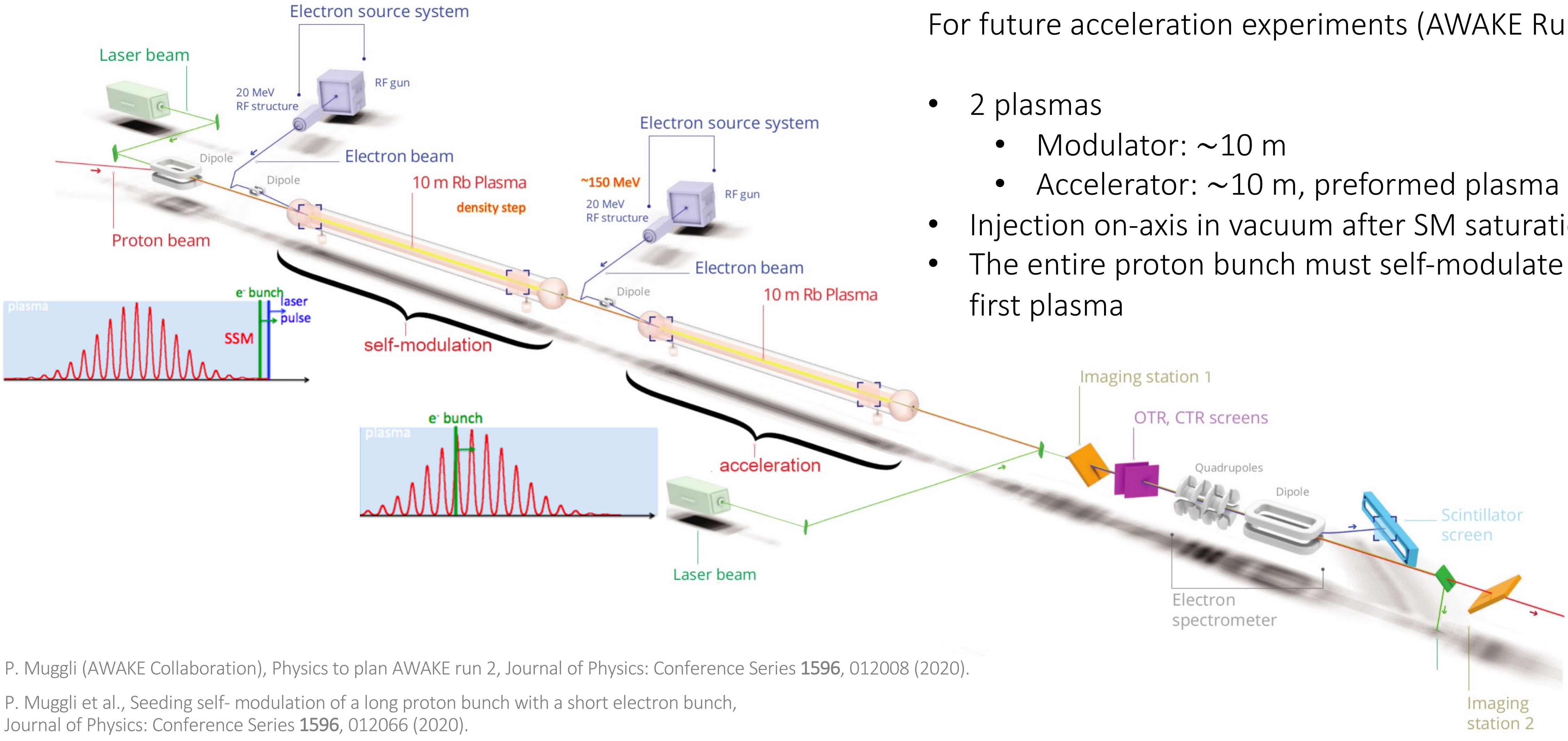


Seed wakefield is provided by the fast onset of the beam-plasma interaction

- The head of the bunch remains un-modulated
- Growth rate and seed wakefields
  depend on the bunch density at the ionization front location
  → no independent control

F. Batsch et al. (AWAKE Coll.), Phys. Rev. Lett. **126**, 164802 (2021)

AWAKE Run 2



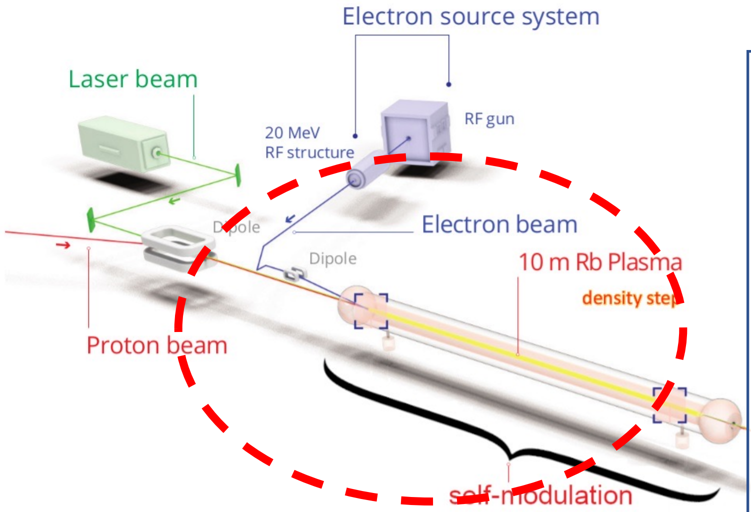
For future acceleration experiments (AWAKE Run 2c):

- 2 plasmas
  - Modulator: ~10 m
  - Accelerator: ~10 m, preformed plasma
- Injection on-axis in vacuum after SM saturation
- The entire proton bunch must self-modulate in the first plasma

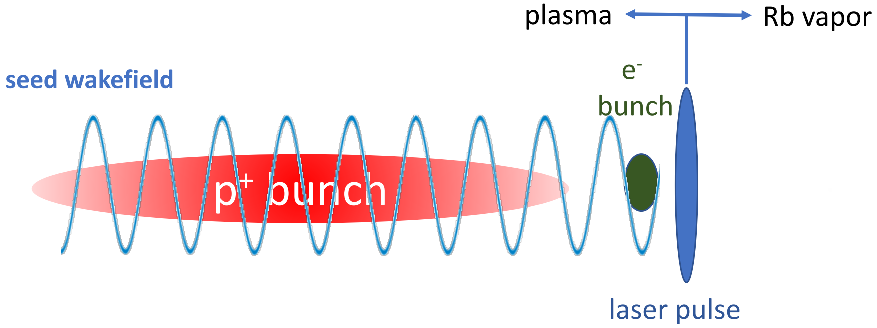
P. Muggli (AWAKE Collaboration), Physics to plan AWAKE run 2, Journal of Physics: Conference Series **1596**, 012008 (2020).

P. Muggli et al., Seeding self- modulation of a long proton bunch with a short electron bunch, Journal of Physics: Conference Series **1596**, 012066 (2020).

AWAKE Run 2a (2021-22): electron bunch seeding



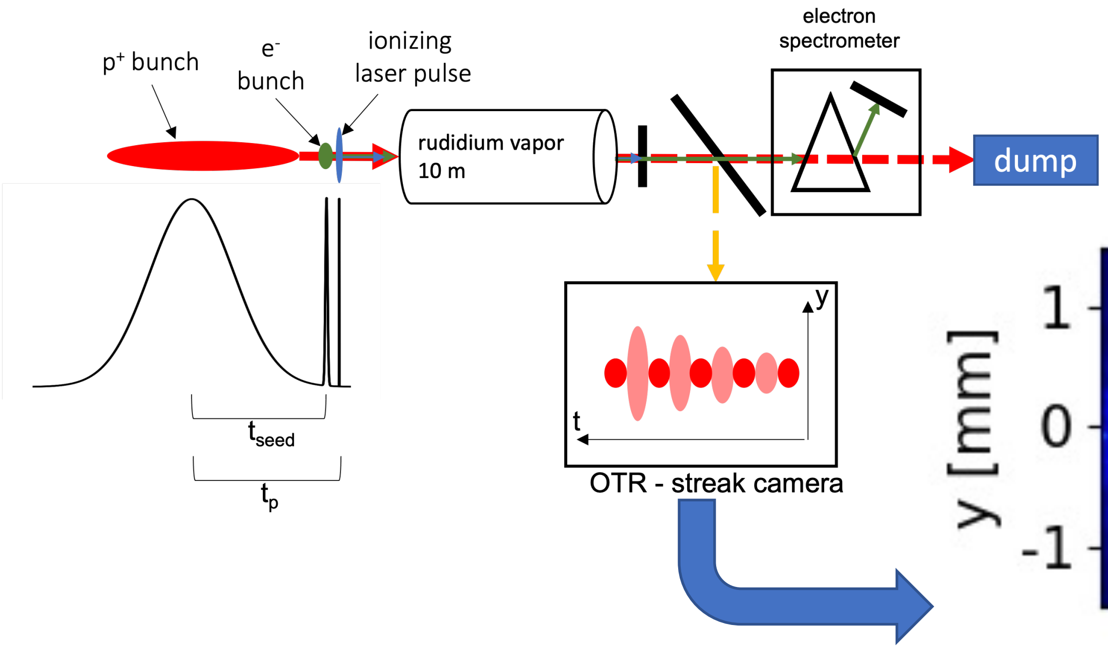
Using the existing facility from Run 1

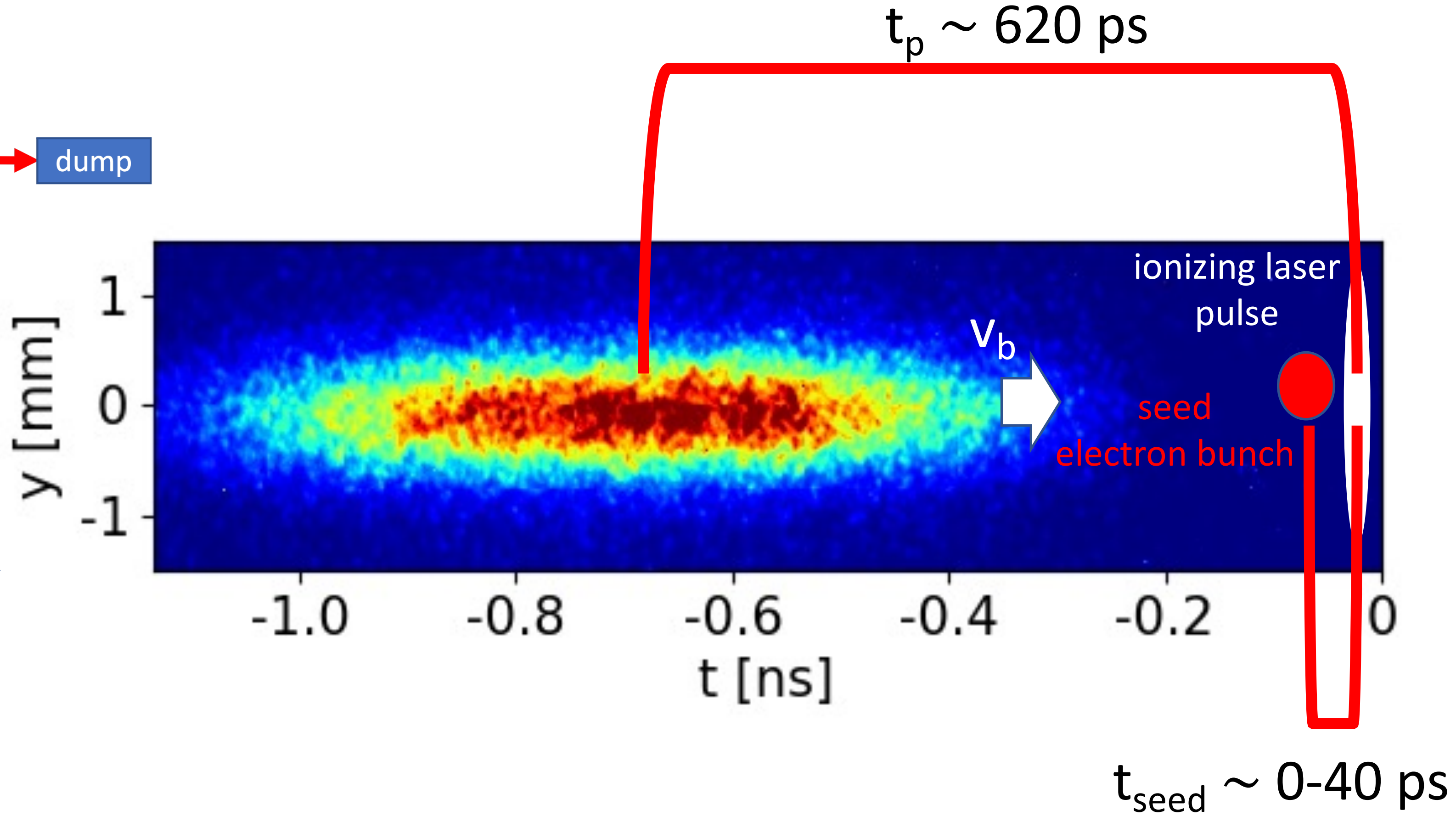


- The electron bunch drives the seed wakefield
- The seed wakefield modulates the p+ bunch charge distribution
- Self-modulation grows from the initial modulation

The entire proton bunch is modulated!

Experimental and timing setup





In the following:
electron bunch:

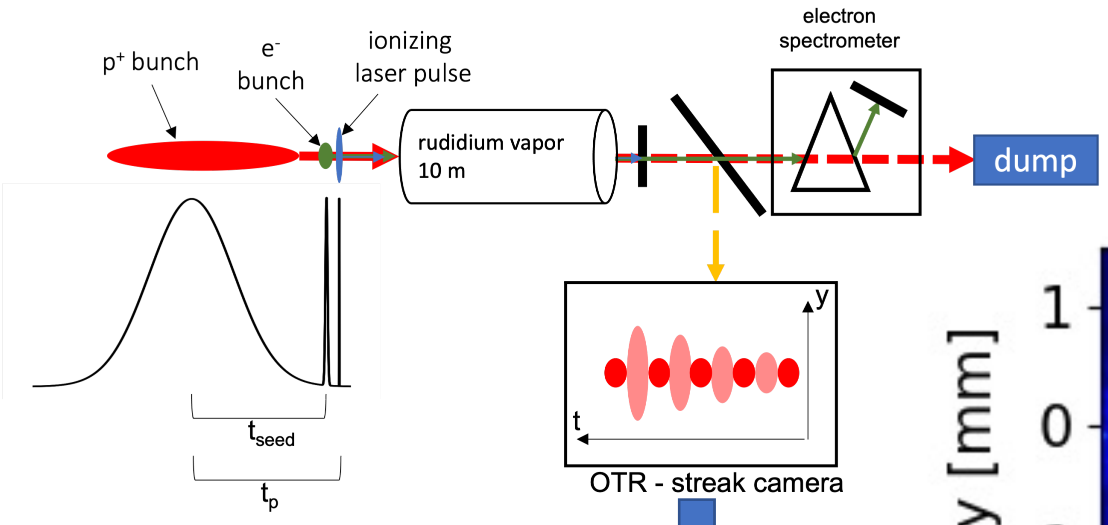
- Q_e = 220 pC
- $\varepsilon_N \sim 1$ µm
- σ_r = 0.2 mm
- $\sigma_t \sim 5$ ps
- E = 19 MeV

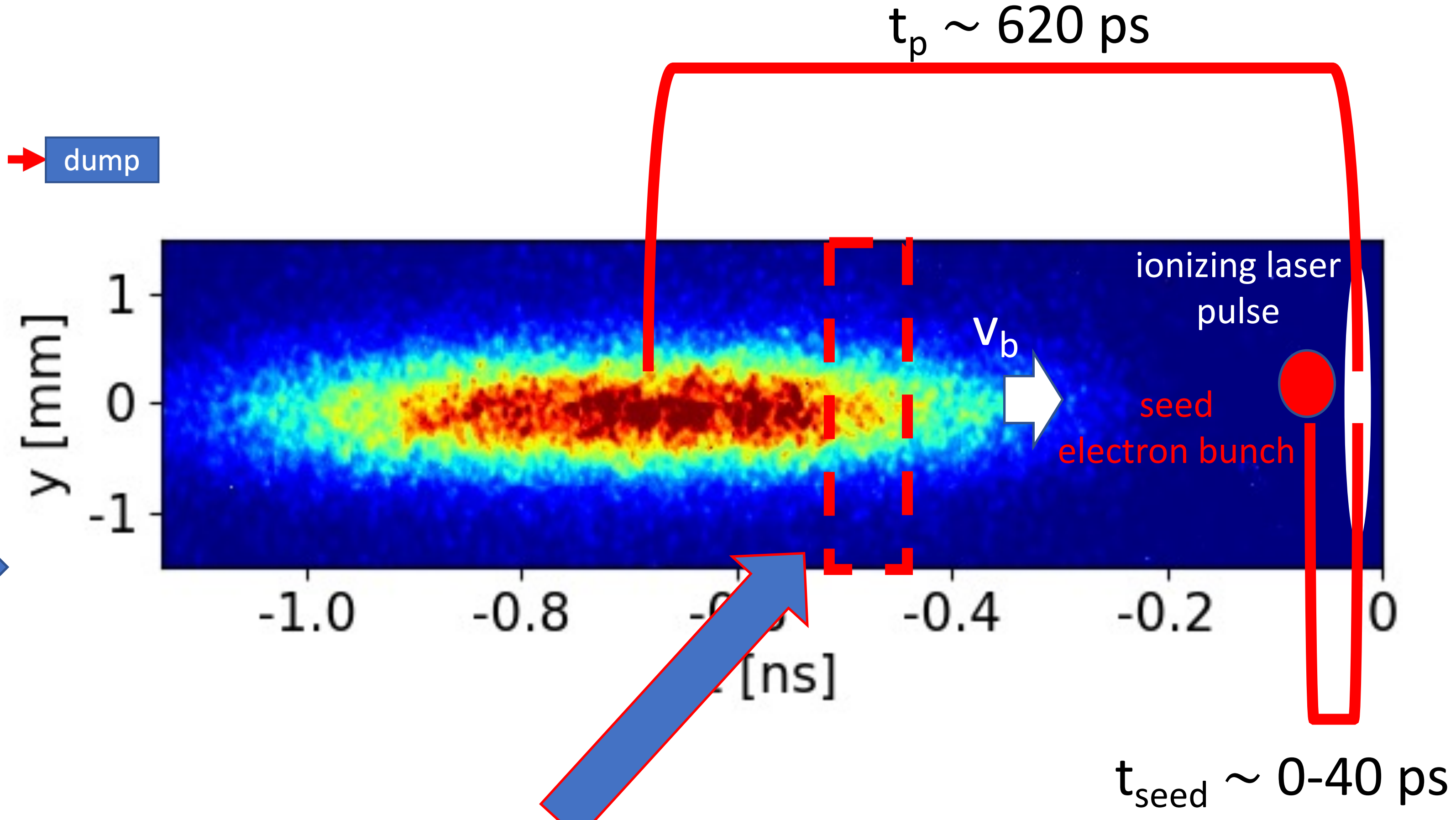
proton bunch:

- Q_p = 15– 47 nC
- σ_r = 0.1 – 0.2 mm
- $\varepsilon_N \sim$ 1.5-3.5 µm
- $\sigma_t \sim 240$ ps
- p = 400 GeV/c

plasma:
$n_{pe} = 1 \cdot 10^{14}\ \mathrm{cm}^{-3}$

Experimental and timing setup





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- p = 400 GeV/c

To prove that the electron bunch seeds SM:

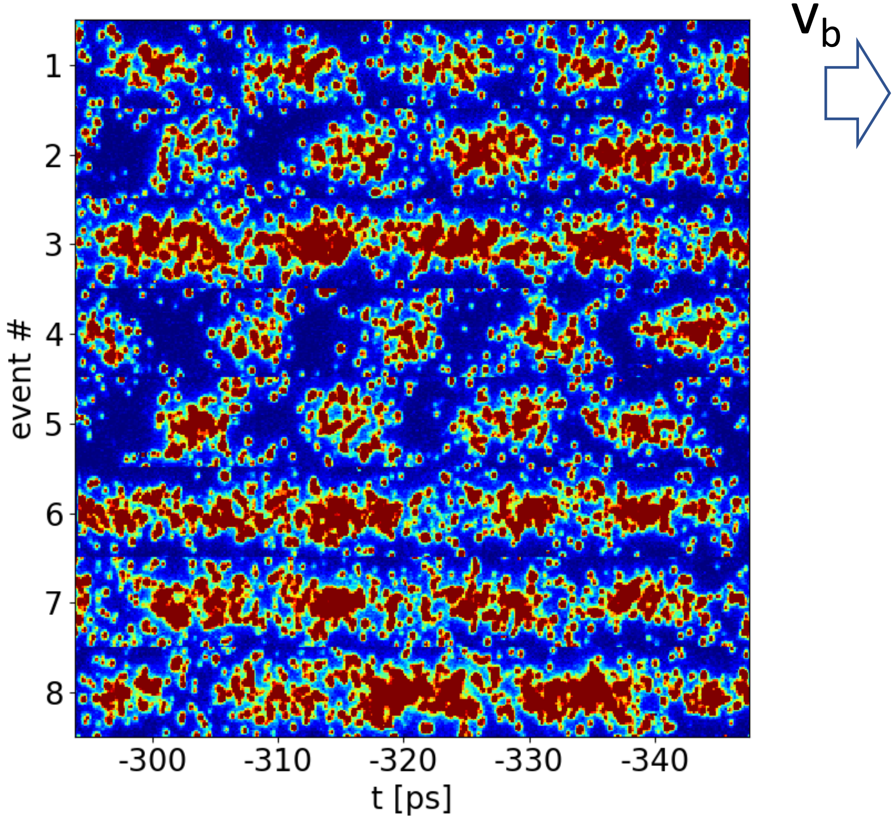
→ study the time structure of the microbunch train at the ps time scale

Electron bunch seeding: timing **reproducibility**

proton bunch charge Q_p=40.8nc
73 ps streak camera window
electron bunch charge Q_e = 250 pC
n_{pe} = $1\cdot10^{14}$ cm^{-3}
→ f_{pe} = 89.7 GHz
T_{pe} = 11.1 ps

Waterfall plots of single-event time-resolved images

No e^- bunch → SMI



rms(t_μ) / T_{pe} ~ 0.23

Electron bunch seeding: timing **reproducibility**

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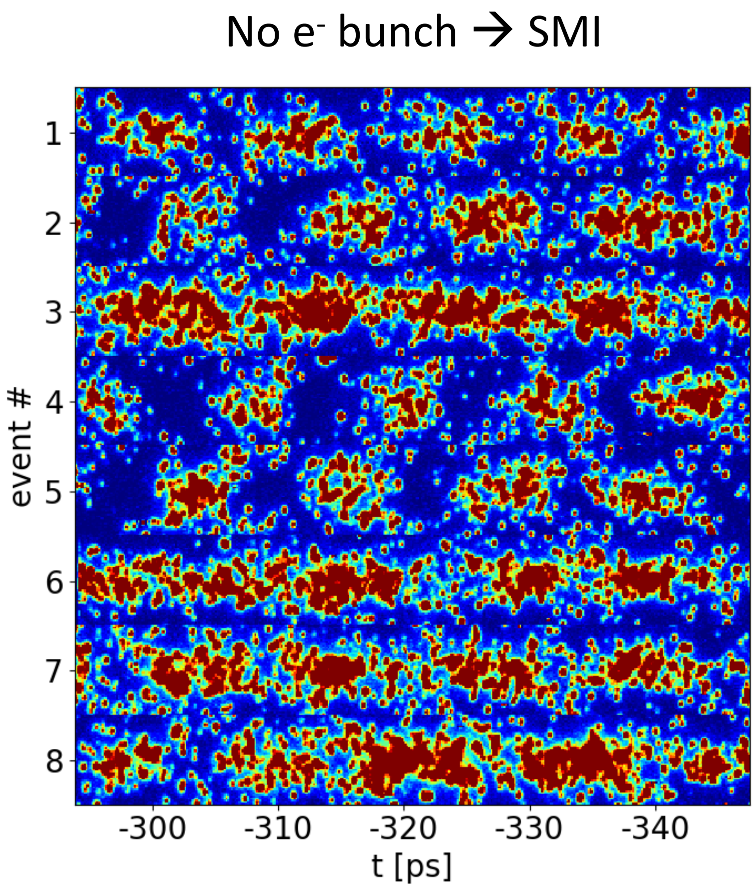
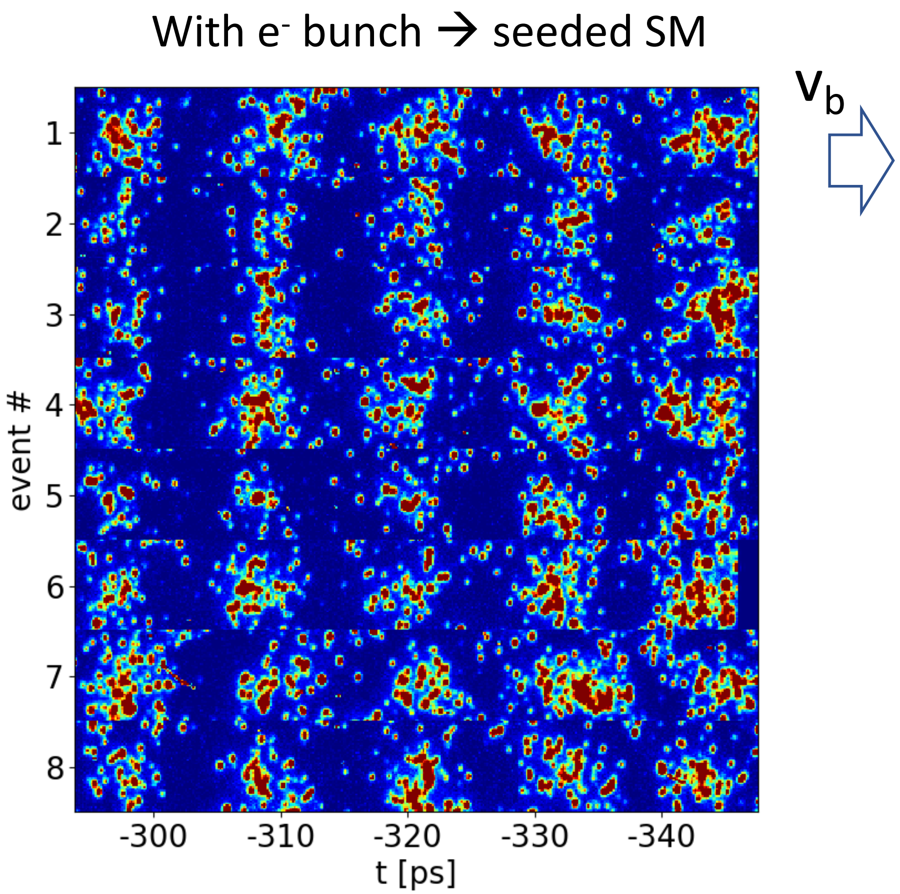
The microbunches appear at the same time t_μ along the bunch event after event

Self-Modulation of the proton bunch is seeded by the electron bunch!

Waterfall plots of single-event time-resolved images



$\mathrm{rms}(t_\mu)$ / T_{pe} ~ 0.23



$\mathrm{rms}(t_\mu)$ / T_{pe} ~ 0.06

Electron bunch seeding: timing **reproducibility**

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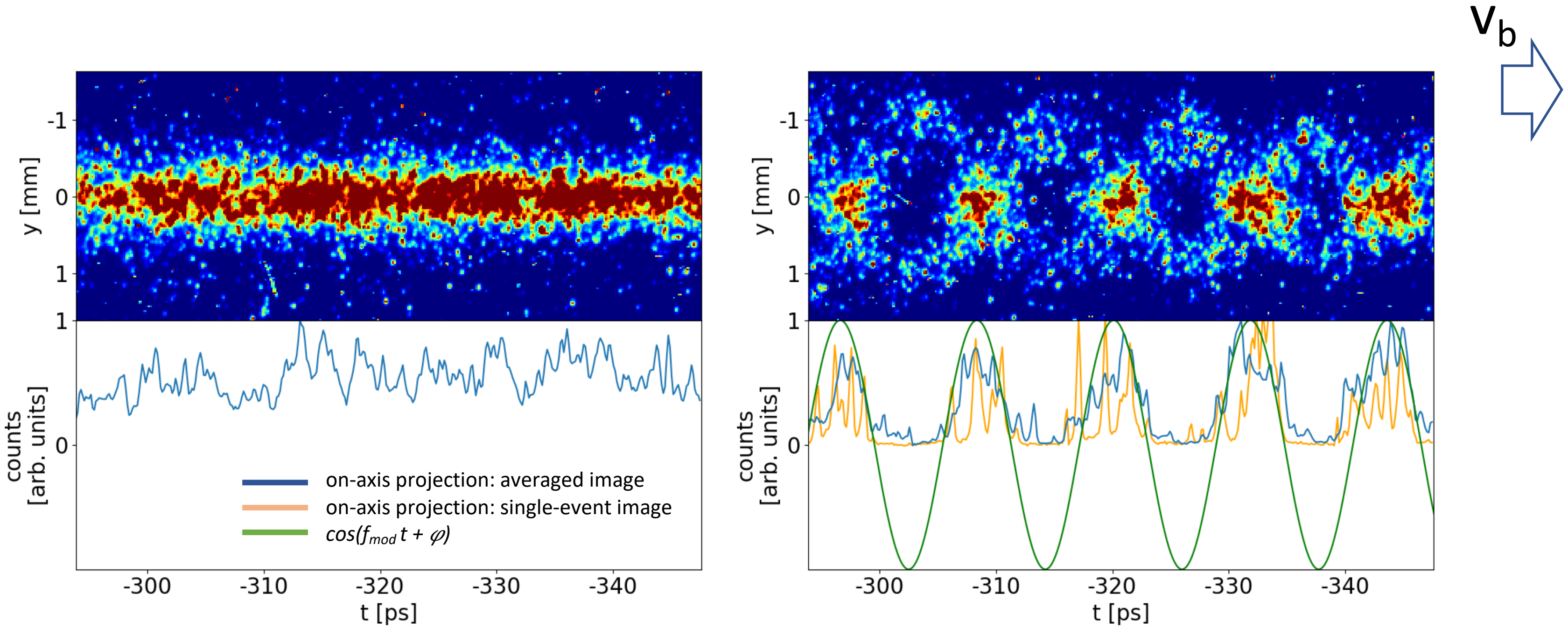
The microbunches appear at the same time t_μ along the bunch event after event

Self-Modulation of the proton bunch is seeded by the electron bunch!

Average of time-resolved images

No e$^-$ bunch → SMI

With e$^-$ bunch → seeded SM

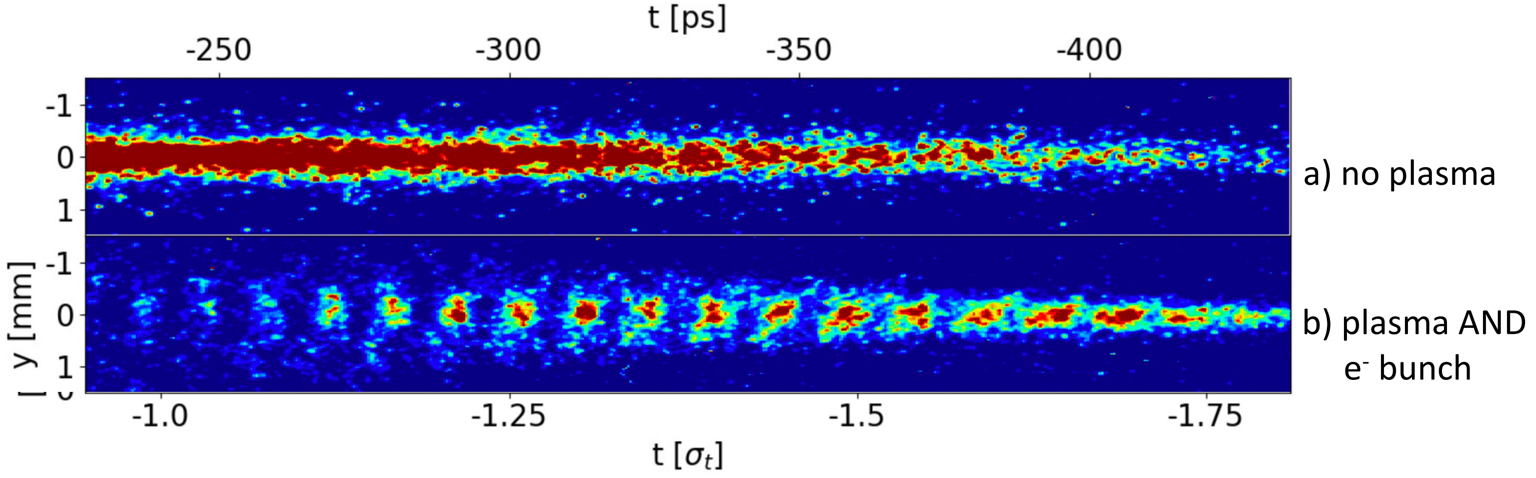


Timing is not reproducible
→ on-axis projection shows no structure
→ <u>no bunch train on average</u>

Timing is reproducible
→on-axis projection shows clear structure!
→ <u>bunch train on average</u>
Modulation at the plasma frequency

Electron bunch seeding: timing **control**

210 ps-scale averaged time-resolved images



- The timing of the modulation is defined by the timing of the seed bunch

→ A shift Δt_{seed} gives a variation in the appearance time of the microbunches Δt_μ

Electron bunch seeding: timing **control**

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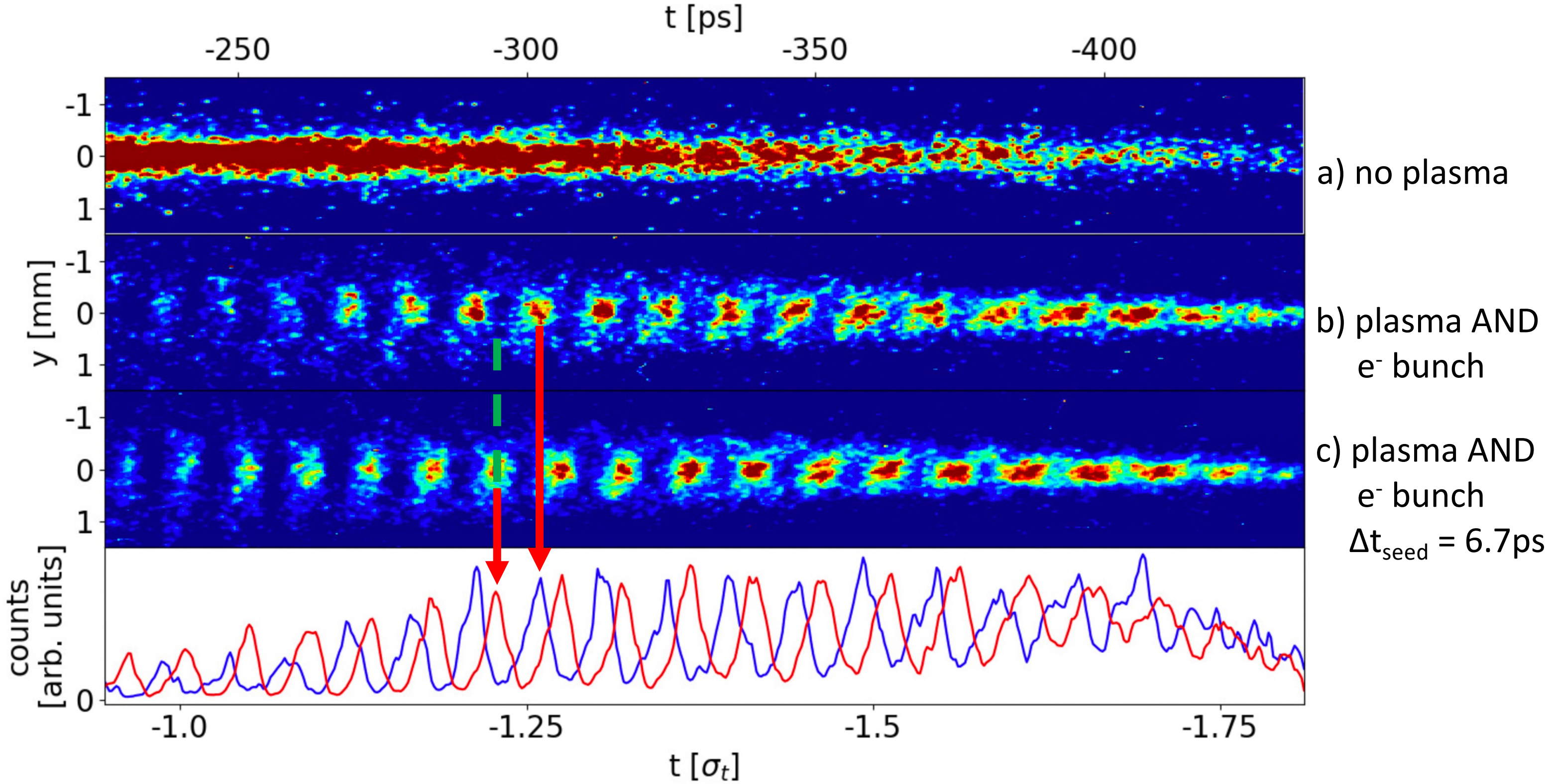


$\Delta t_{\mu} \sim$ 7.2 ps

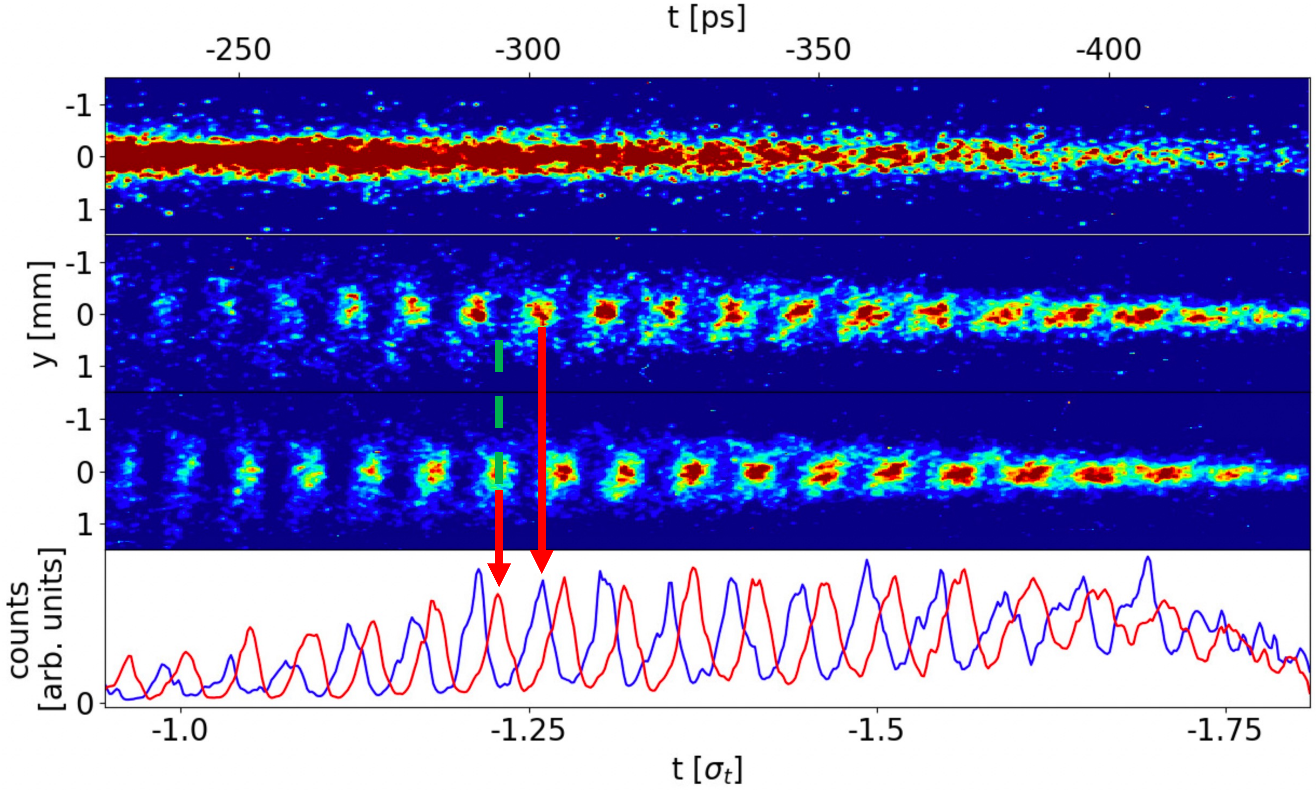
Electron bunch seeding: timing **control**

- The timing of the modulation is defined by the timing of the seed bunch

→ A shift Δt_{seed} gives a variation in the appearance time of the microbunches Δt_{μ}

- SM starts from the bunch front
  → The entire bunch is self-modulated!
  AWAKE Run 2a: electron bunch seeding ✅

210 ps-scale averaged time-resolved images



Δt_{μ} ~ 7.2 ps

Self-modulation growth and growth rate

$$W_{\perp}(z,t) = W_{\perp 0}(Q_e) \cdot e^{\Gamma(z,t;Q_p)z}$$

$$W_{\perp 0} \propto \frac{n_e(Q_e)}{n_{pe}}$$

Seed wakefields amplitude:
depends SOLELY on the
e^- bunch parameters

$$\Gamma \propto \left(\frac{n_p(Q_p)\, t}{n_{pe}\, z}\right)^{\frac{1}{3}}$$

SM growth rate:
depends SOLELY on the
p^+ bunch parameters

Independent control
of the seed wakefields and of the growth rate

Self-modulation growth and growth rate

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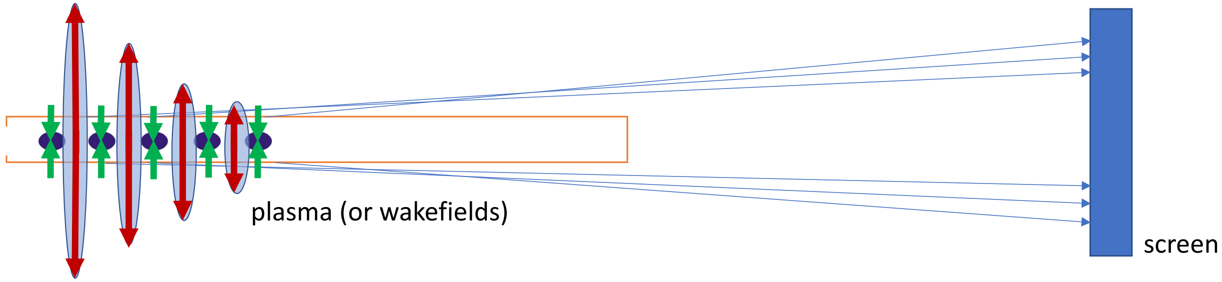
SM growth rate:
depends SOLELY on the
p^+ bunch parameters

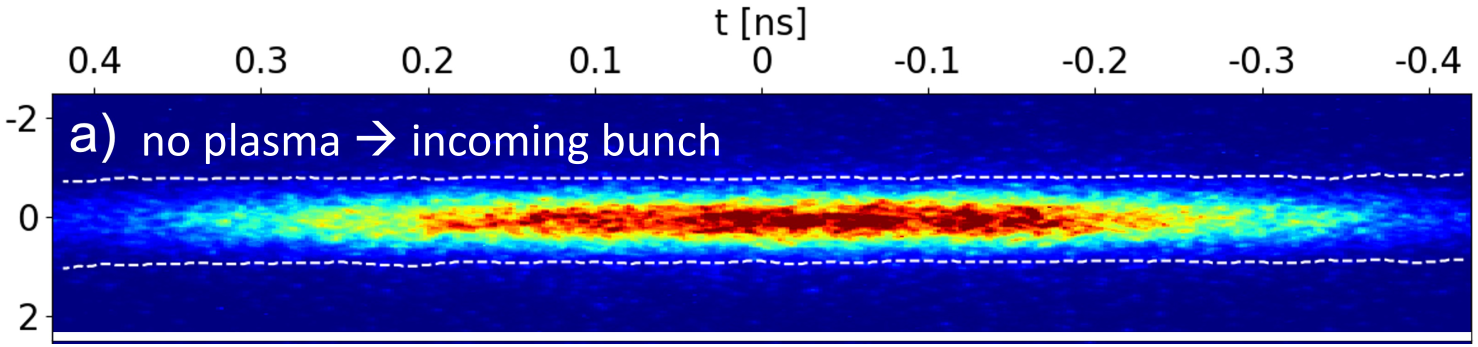
Independent control
of the seed wakefields and of the growth rate

Defocused protons leave the plasma before SM reaches saturation
→ they propagate with straight trajectory ($W_\perp \dashrightarrow p_\perp$)
→ their position at a screens gives information on
the amplitude of the wakefields in the first meters of propagation



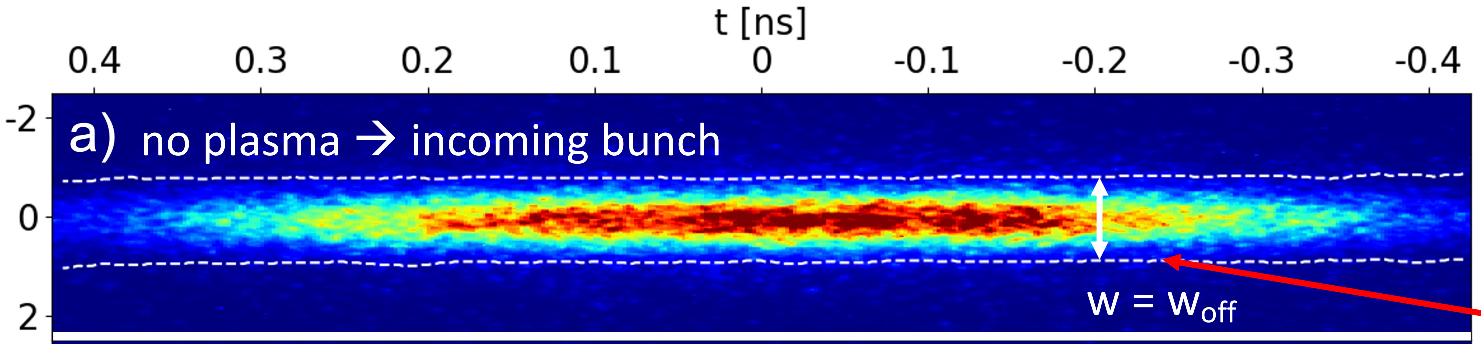
Transverse extent evolution: ns-scale

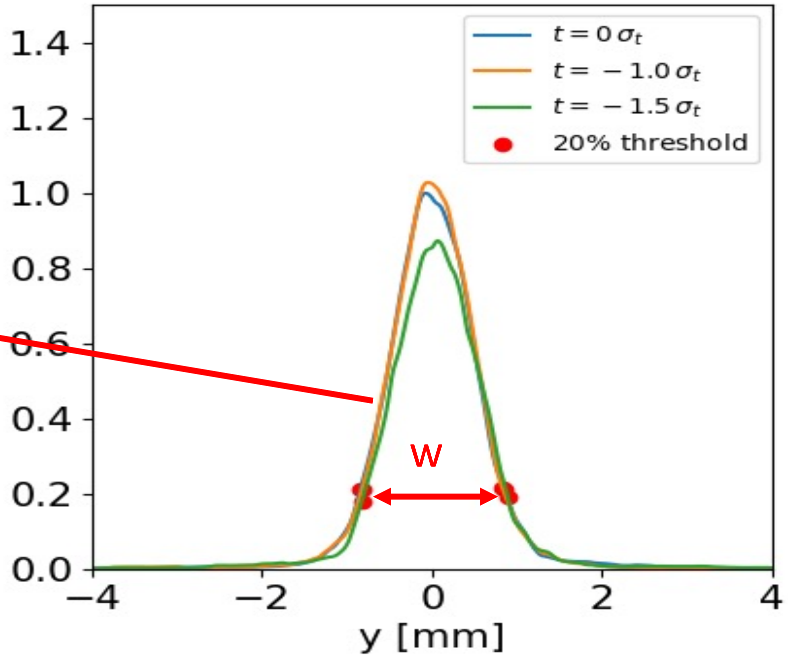
- ns-scale time-resolved images to study the transverse distribution along the bunch
  → not enough time resolution to see the microbunches



Transverse extent evolution: ns-scale

- ns-scale time-resolved images to study the transverse distribution along the bunch
  → not enough time resolution to see the microbunches
- We define the transverse extent w as the full width at 20% of the maximum for each time-column of the image



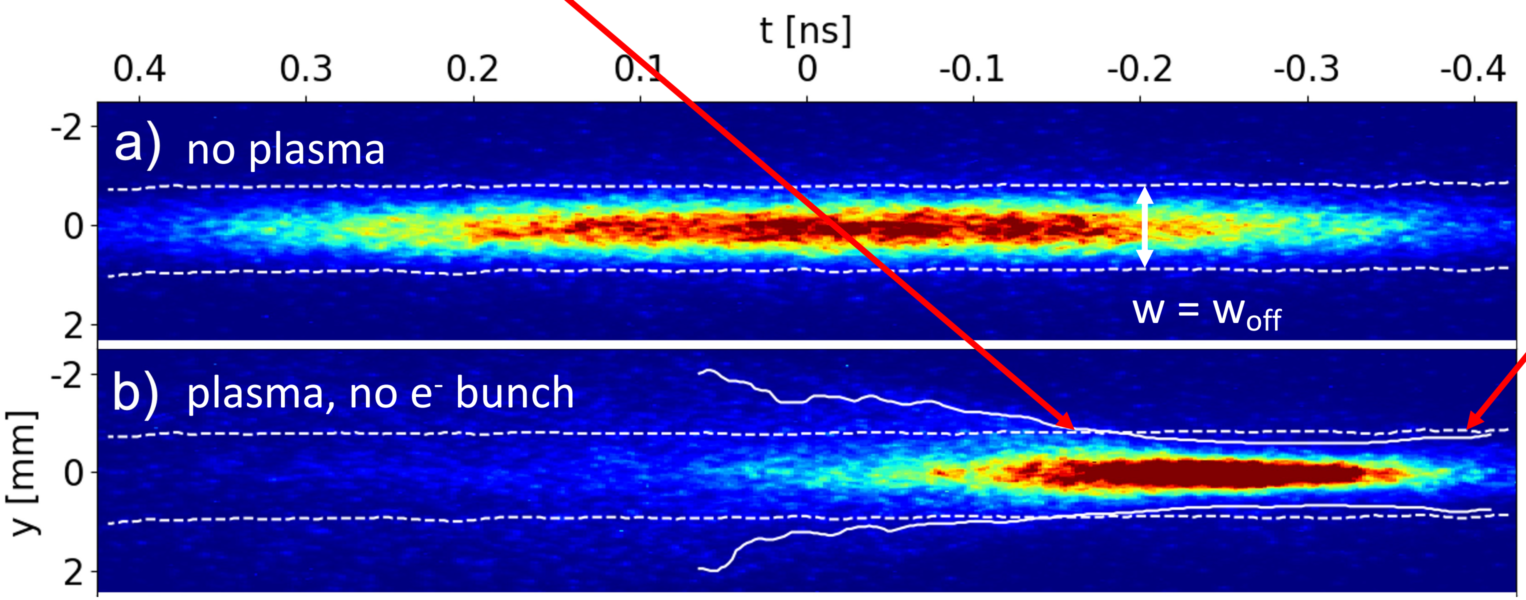


Plasma off
→ Gaussian distribution
→ Constant width along the bunch

Transverse extent evolution: ns-scale

Plasma ON → SMI→ Defocusing of protons

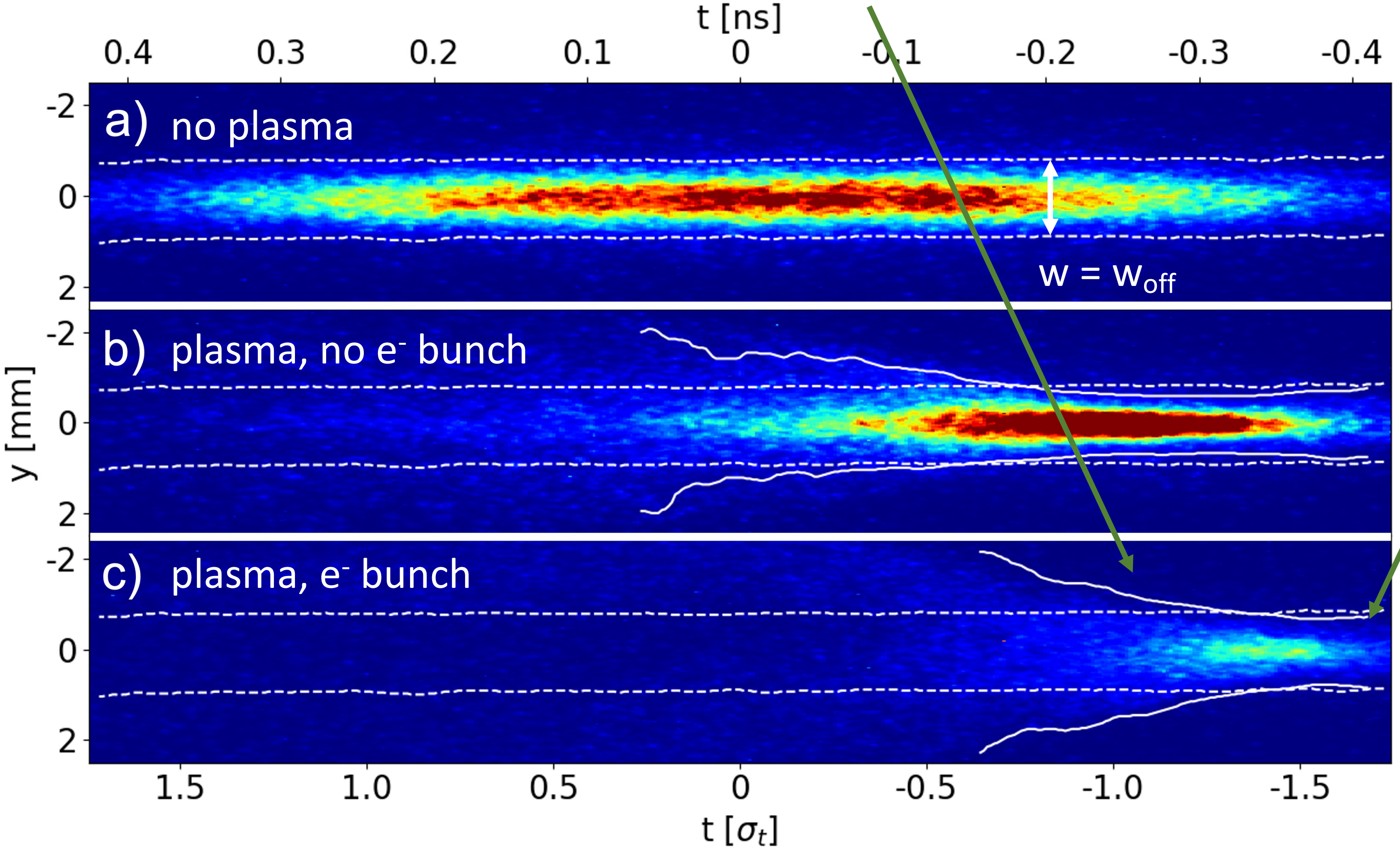
Focusing effect:
plasma adiabatic response



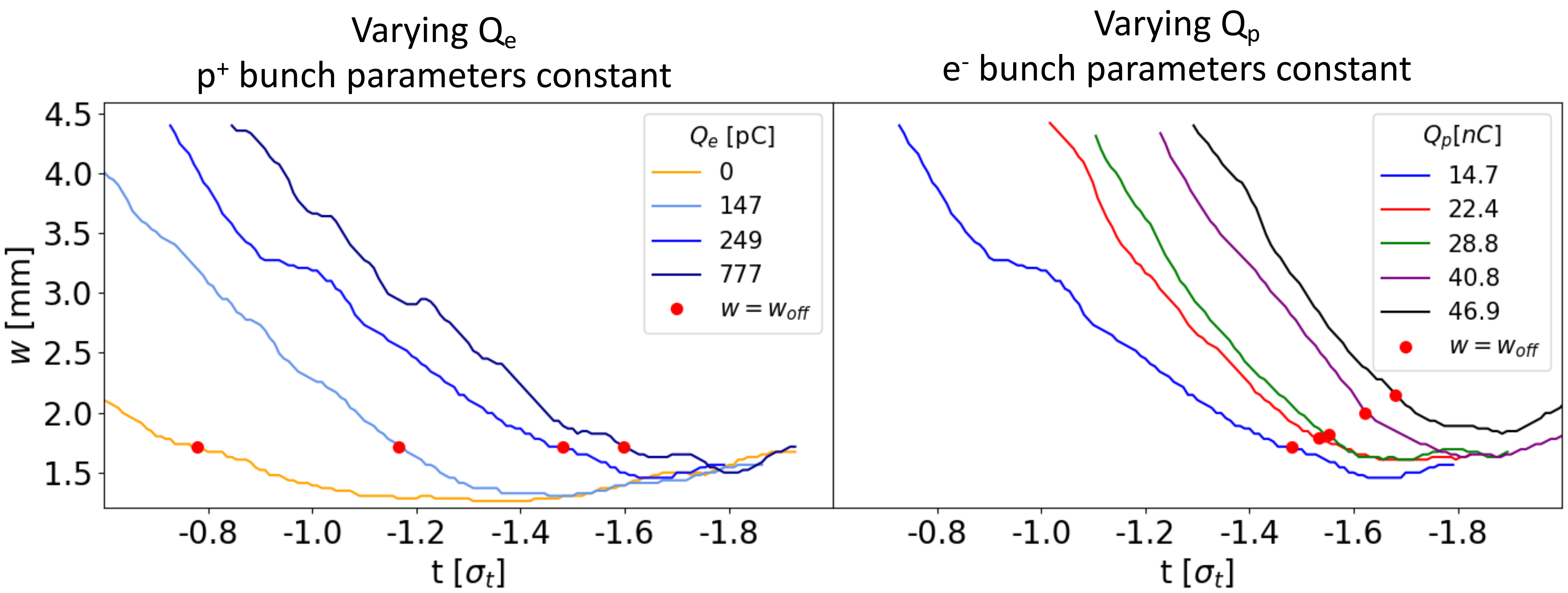
Transverse extent evolution: ns-scale

With seed bunch:
<u>earlier</u> defocusing effect
→ larger growth of the SM
due to the seed wakefields

Same focusing trend also when seeding!



Control of the instability growth



$$W_{\perp 0} \propto \frac{n_e(Q_e)}{n_{pe}}$$

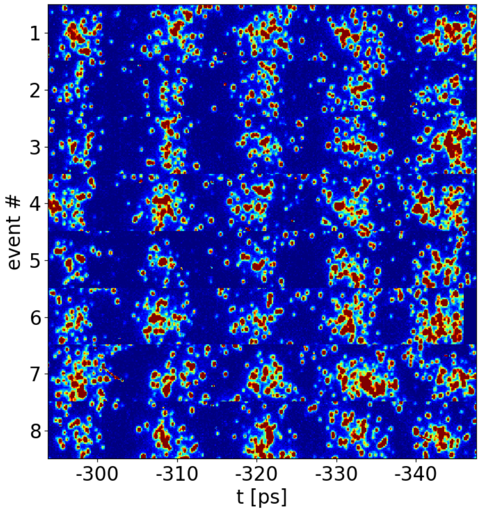
Seed Wakefields Amplitude

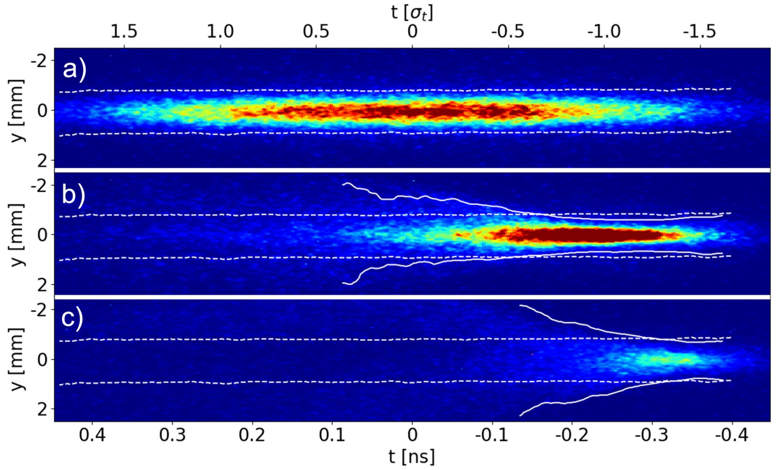
Larger w at any time
when SM defocusing dominates

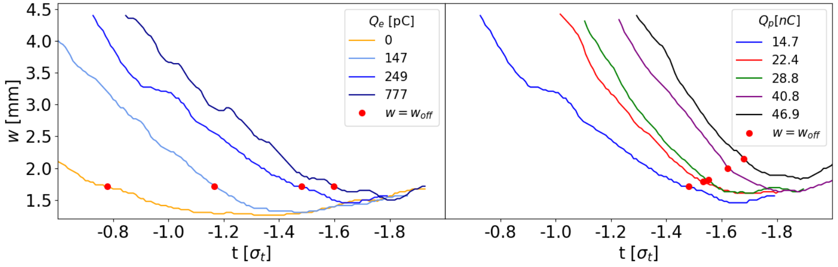
$$\Gamma \propto \left(\frac{n_p(Q_p)\, t}{n_{pe}\, z}\right)^{\frac{1}{3}}$$

Growth Rate
of the Instability

Conclusions







Demonstration:

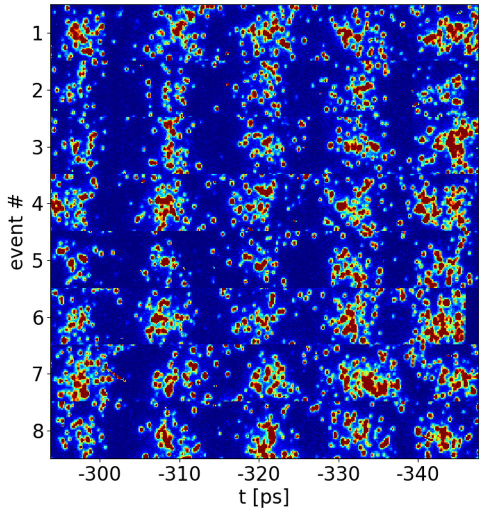
- The electron bunch seeds effectively the self-modulation
- The timing of the wakefields is tied to that of the seed
- The entire bunch self-modulates

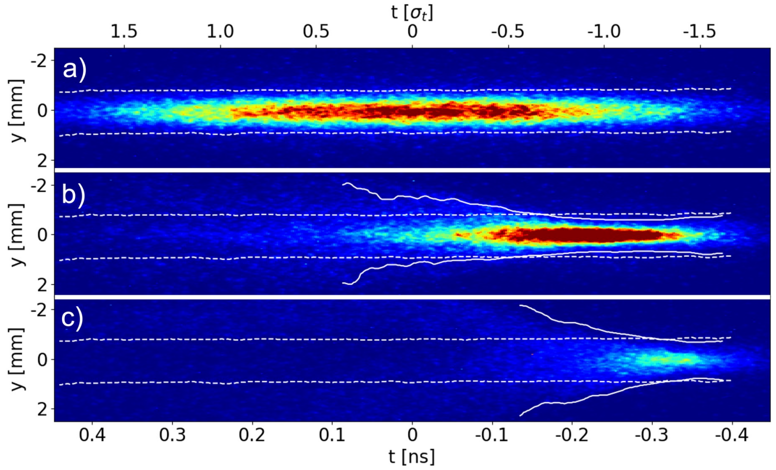
Understanding:

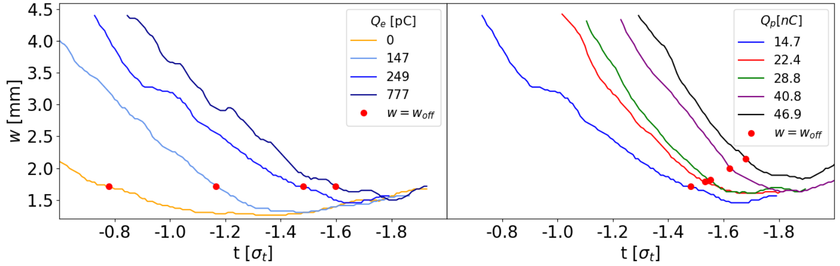
- Earlier defocusing effect when seeding
- Adiabatic focusing effect with and without seeding

- Independent control of $W_{\perp 0}$ and of Γ with Q_e and Q_p

Conclusions







Demonstration:

- The electron bunch seeds effectively the self-modulation
- The timing of the wakefields is tied to that of the seed
- The entire bunch self-modulates

- Important milestone for AWAKE
- Physics result: control of an instability

Understanding:

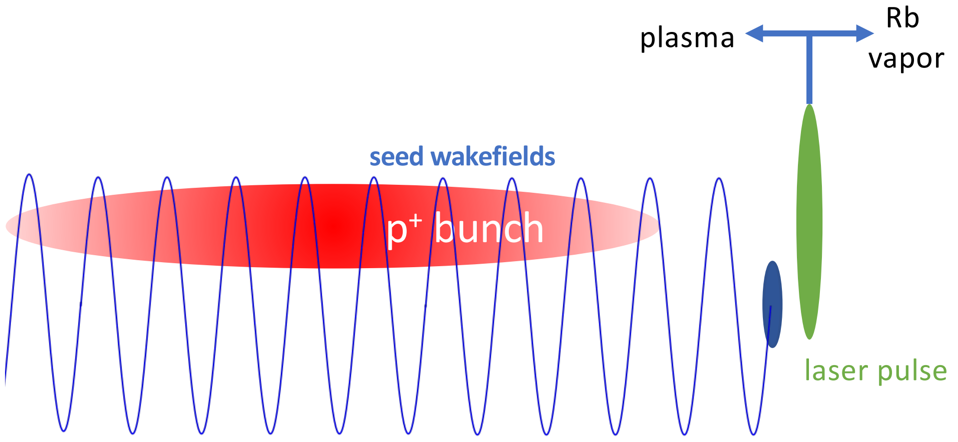
- Earlier defocusing effect when seeding
- Adiabatic focusing effect with and without seeding

- Independent control of $W_{\perp 0}$ and of Γ with Q_e and Q_p

Key results published in:
L. Verra et al. (AWAKE Collaboration), *Controlled Growth of the Self-Modulation of a Relativistic Proton Bunch in Plasma,* Phys. Rev. Lett. **129**, 024802 (2022)

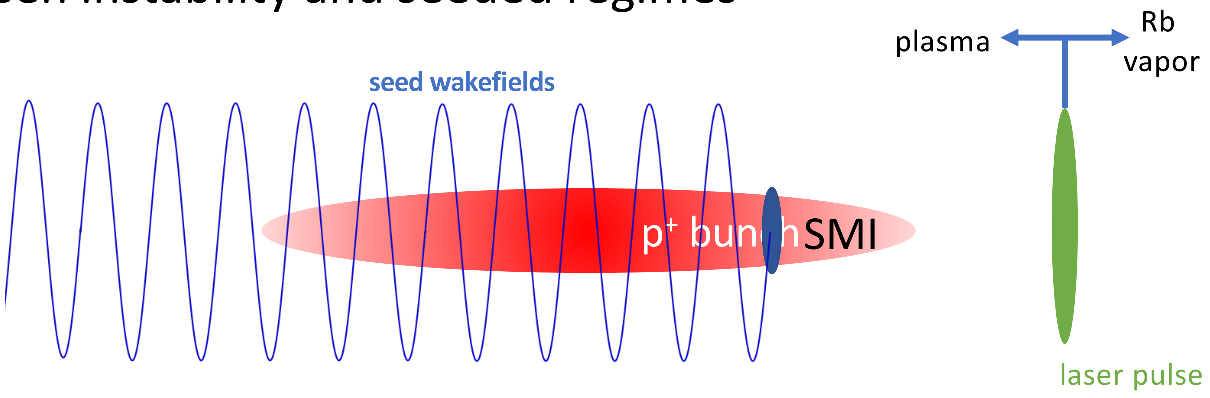
Further physics studies

- Studies on seeded hosing:



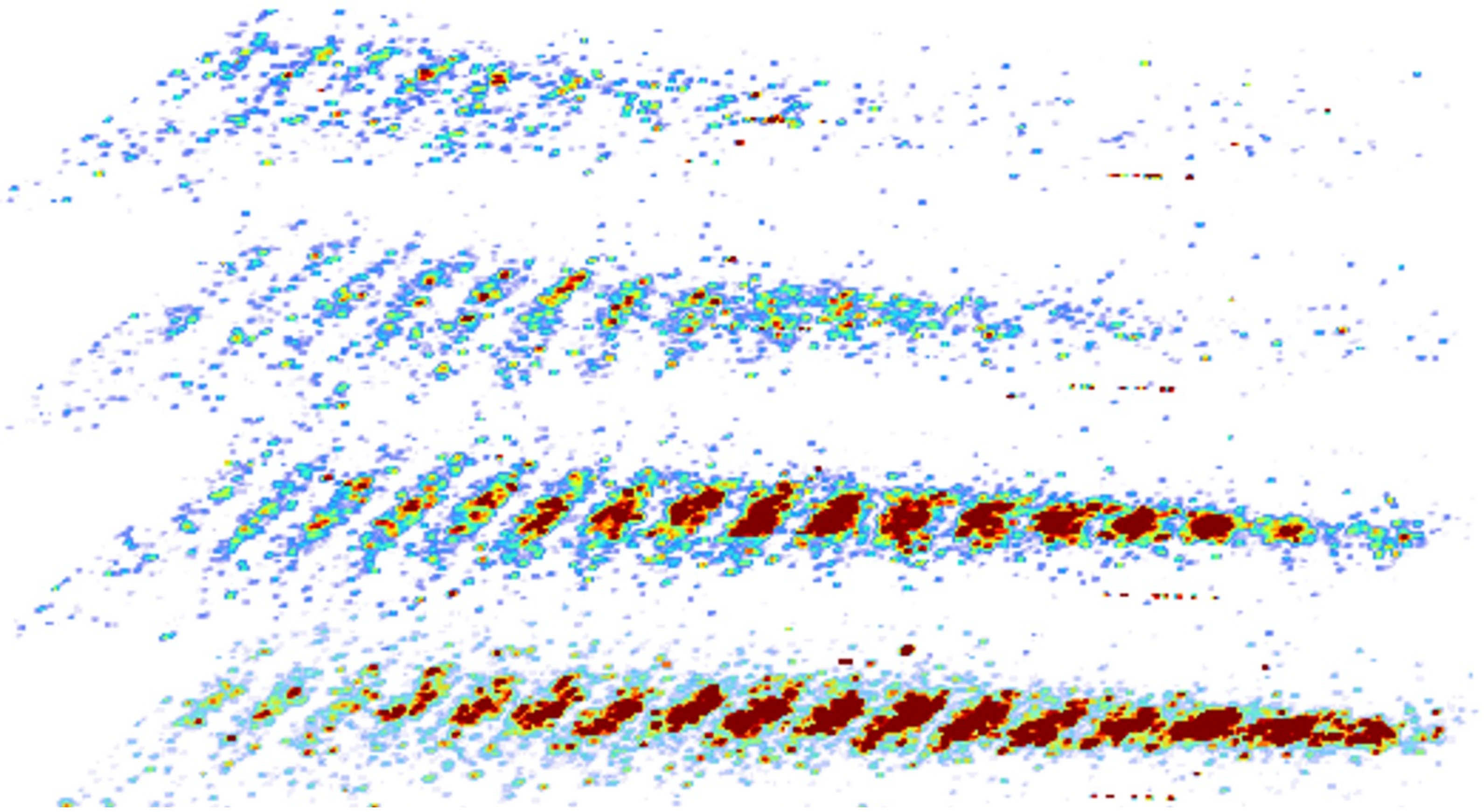
see Tatiana's talk!

- Competition between instability and seeded regimes



see Jan's and Pablo's talks!

Thank you for your attention!

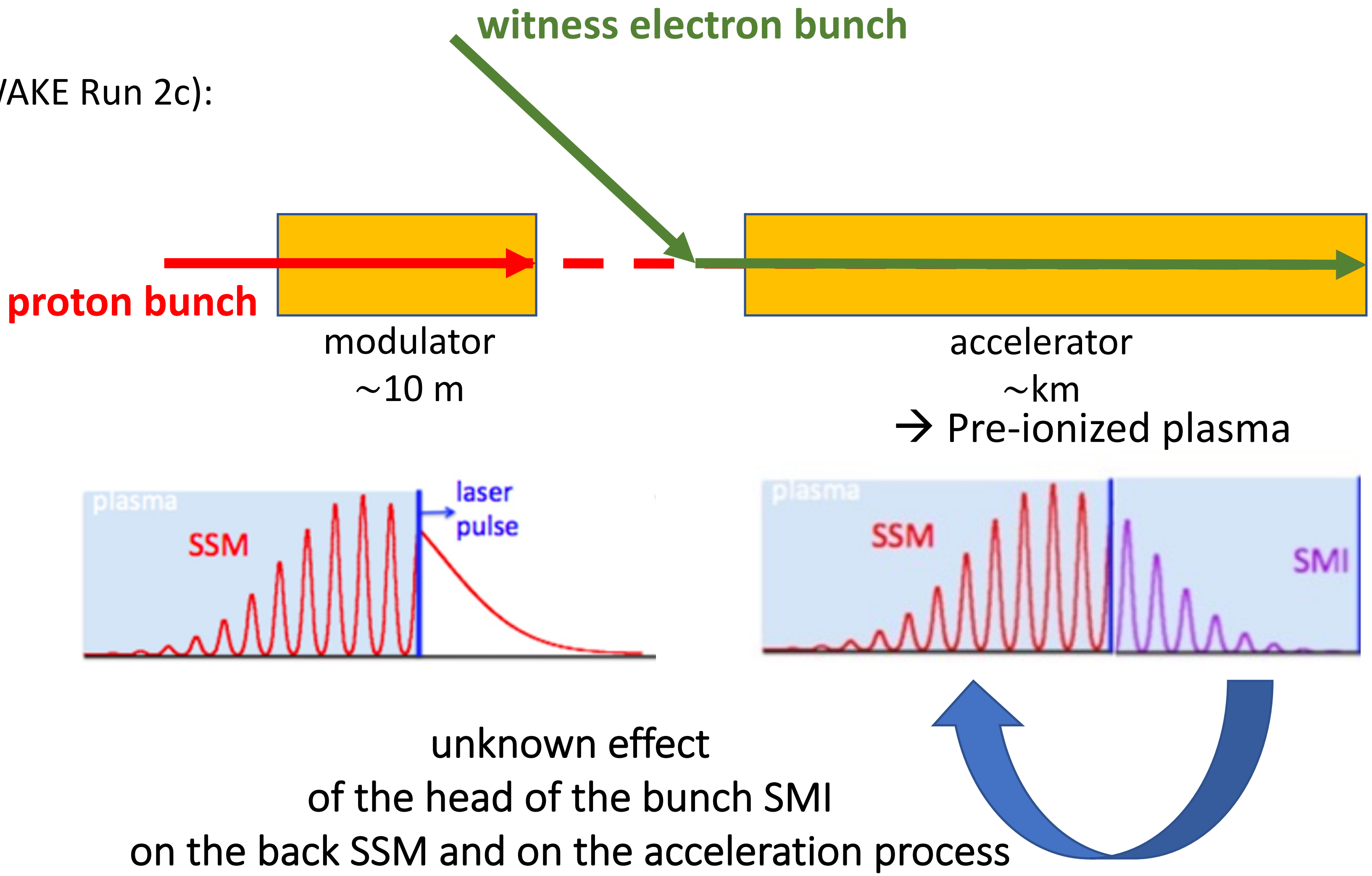


Backup slides

Seeded Self-Modulation for AWAKE Run 2

For future acceleration experiments (AWAKE Run 2c):

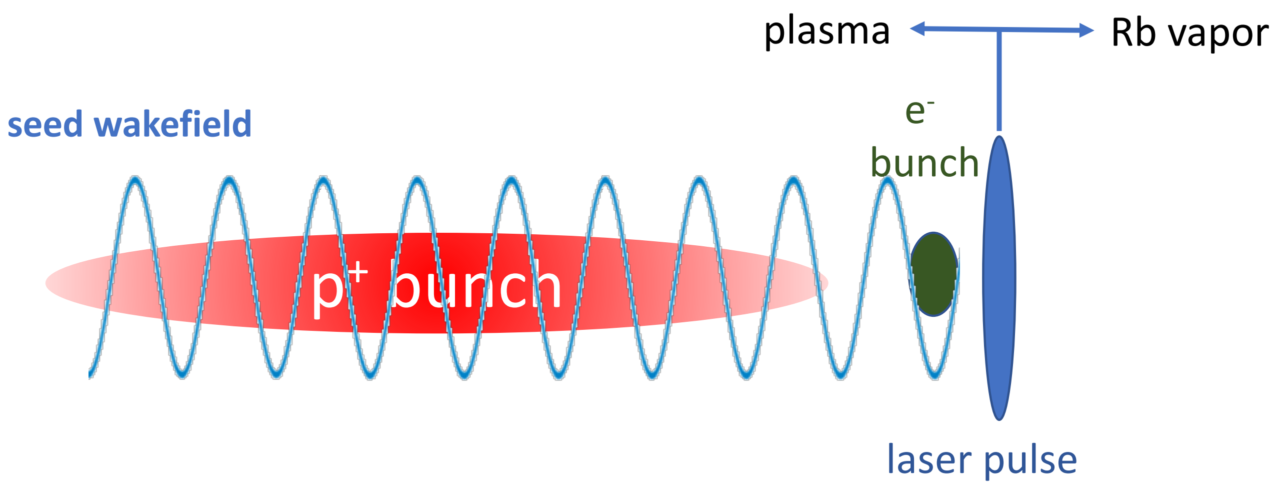
- 2 plasmas
- injection on-axis in gap region after SM saturation



unknown effect
of the head of the bunch SMI
on the back SSM and on the acceleration process

P. Muggli, Physics to plan AWAKE run 2, Journal of Physics: Conference Series **1596**, 012008 (2020).

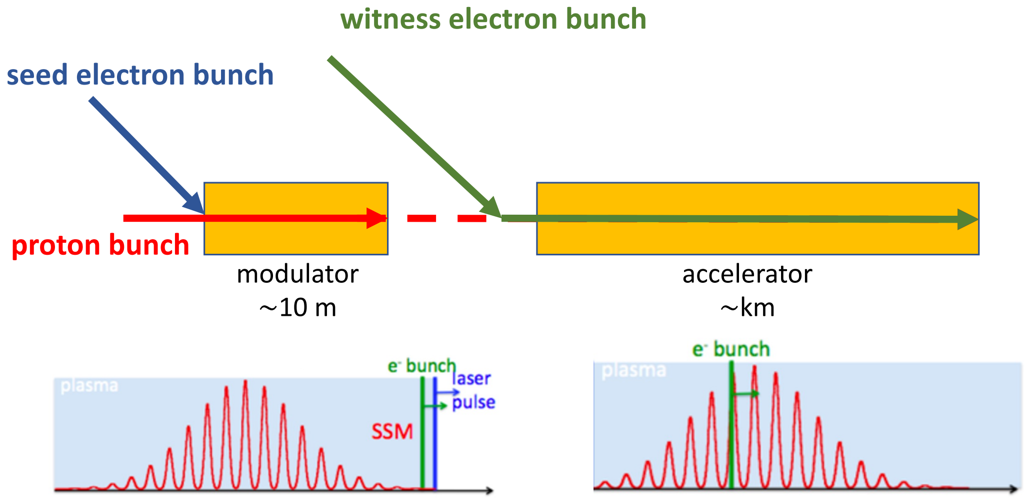
Electron bunch seeding



The entire proton bunch is modulated!

The electron bunch provides the seed wakefield
→ seeding relies on the electron bunch properties:

- initial bunch charge density
- alignment



P. Muggli et al., Seeding self- modulation of a long proton bunch with a short electron bunch, Journal of Physics: Conference Series **1596**, 012066 (2020).

Seed bunch charge scan ($Q_e \rightarrow W_{\perp 0}$)

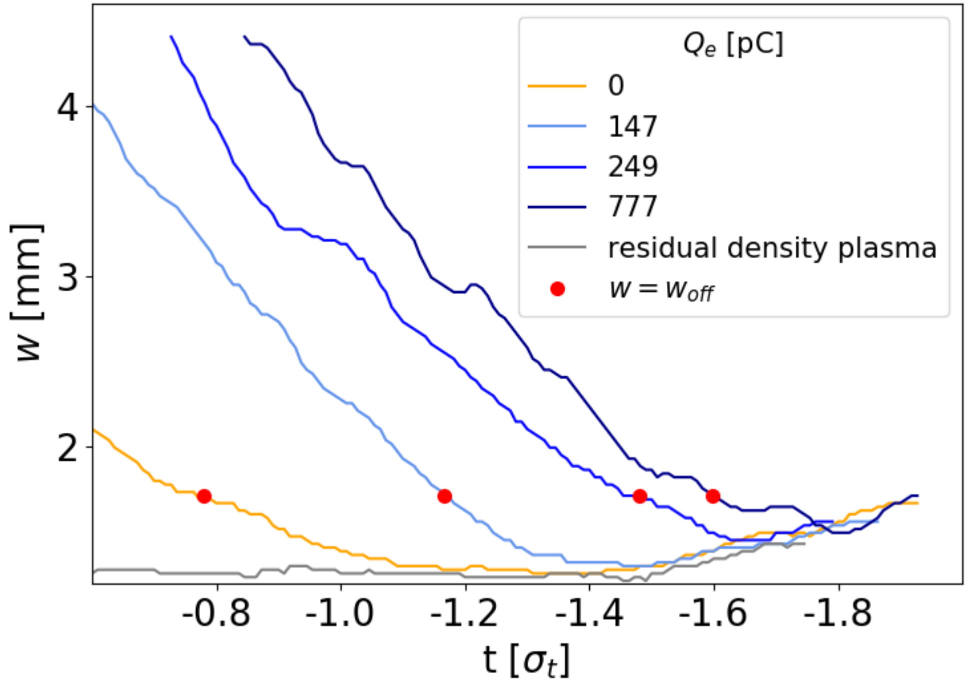
- All profiles with plasma ON follow the same trend in the focusing part

- The larger Qe, the earlier global defocusing starts (i.e, where $w > w_{off}$)
  → SM wakefields (defocusing) dominate over adiabatic focusing earlier
  due to LARGER SEED WAKEFIELDS AMPLITUDE!

- **At any *t* along the bunch, *w* is larger for larger Q_e**
  → LARGER GROWTH
  due to LARGER SEED WAKEFIELDS AMPLITUDE

$$W_{\perp 0} \propto \frac{n_e}{n_{pe}}$$

Varying Q_e
while keeping the p^+ bunch parameters constant



V_b

Proton bunch charge scan ($Q_p \rightarrow \Gamma$)

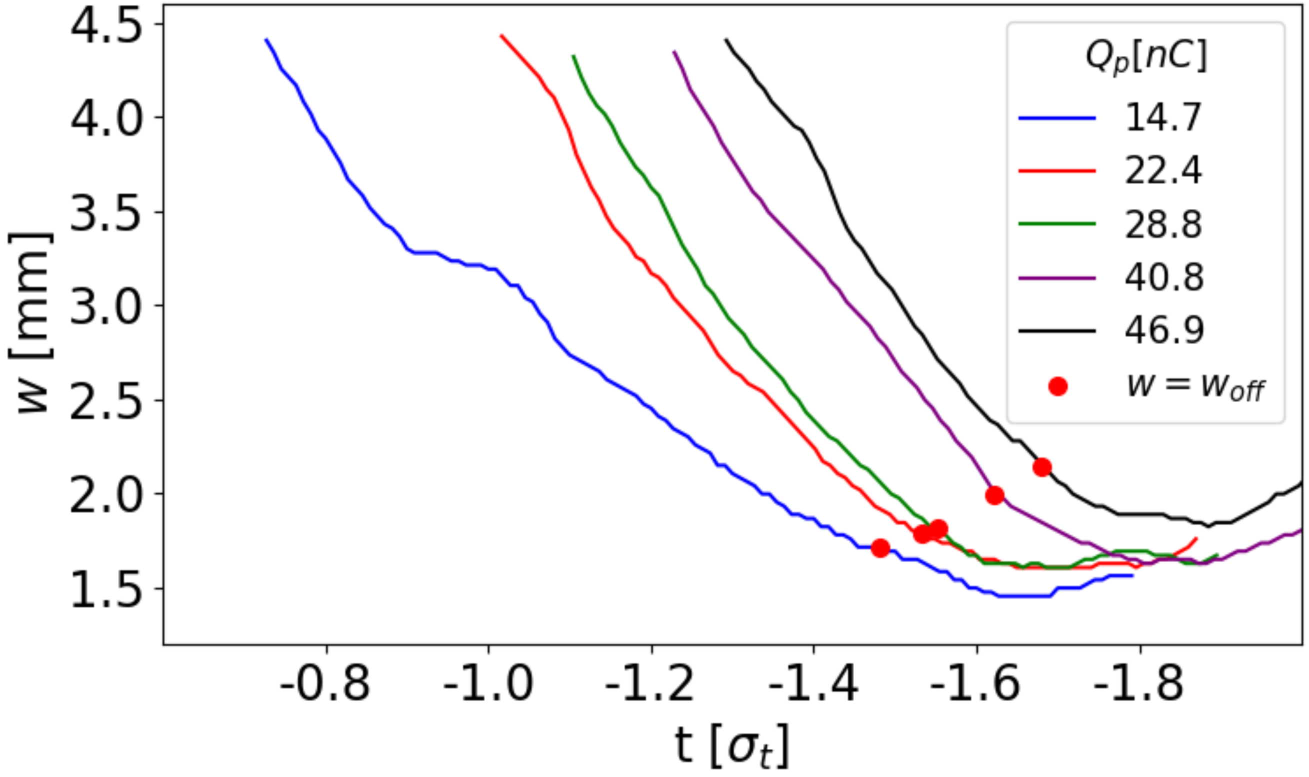
Larger Q_p:

- earlier defocusing effect
  (even if ad focusing in stronger $\propto Q_p$)
- larger w at any time
  when defocusing dominates

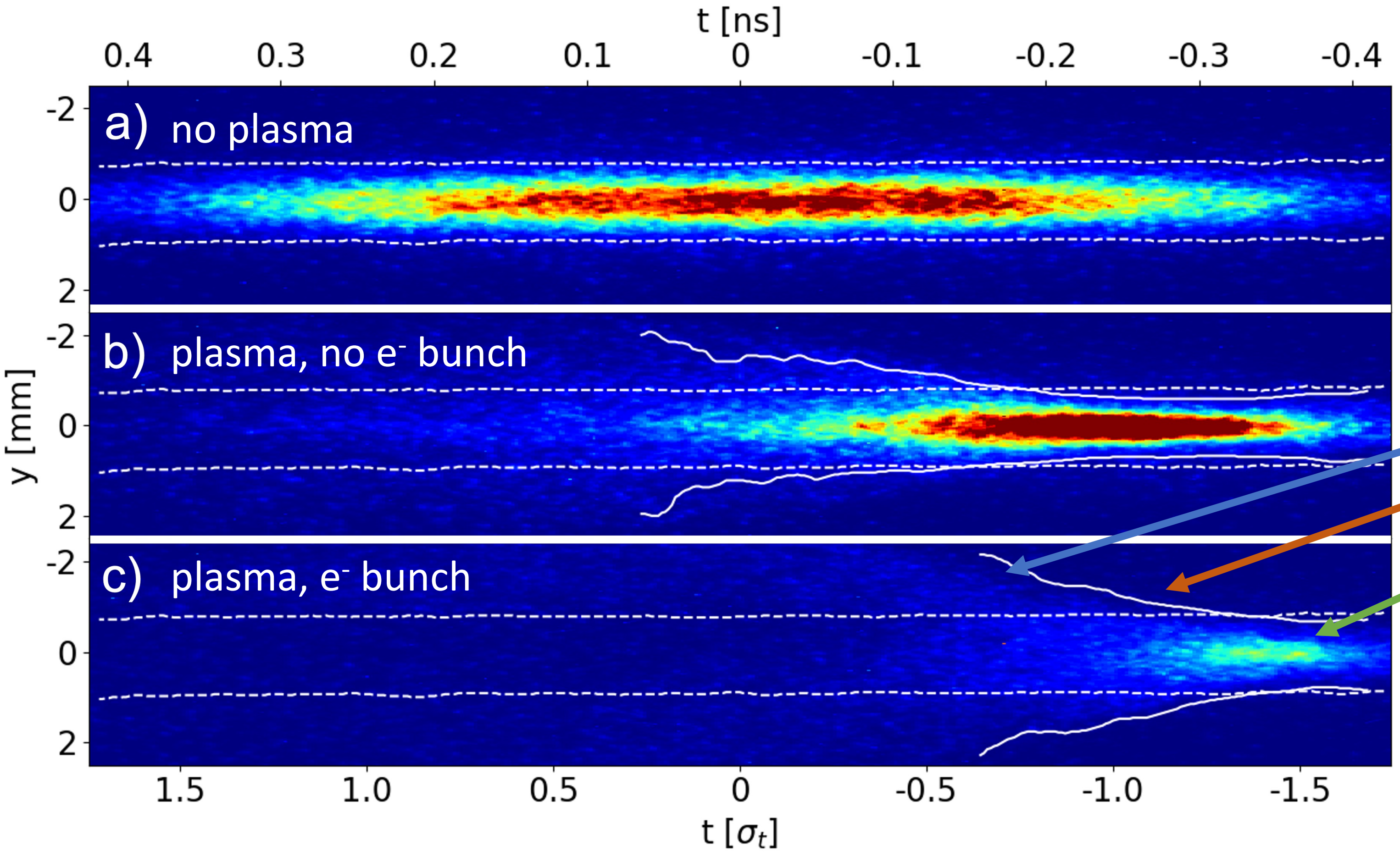
<u>Both effects are due to larger growth rate</u>

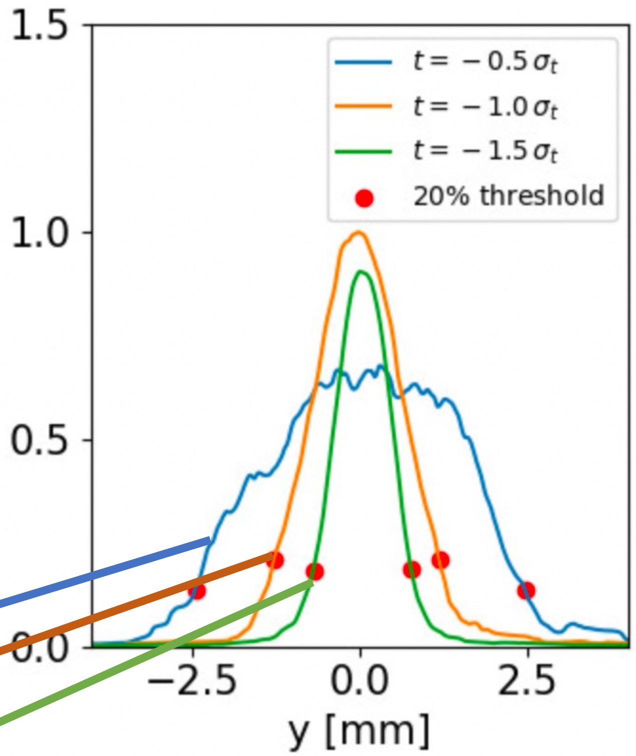
$$\Gamma \propto \left(\frac{n_p\, t}{n_{pe}\, z}\right)^{\frac{1}{3}}$$

Varying Q_p
while keeping the e^- bunch parameters constant

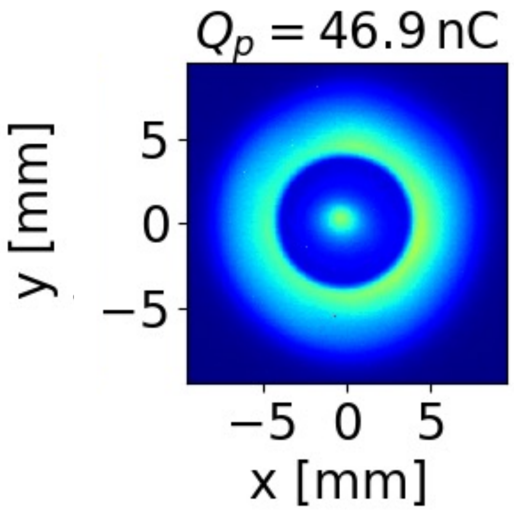


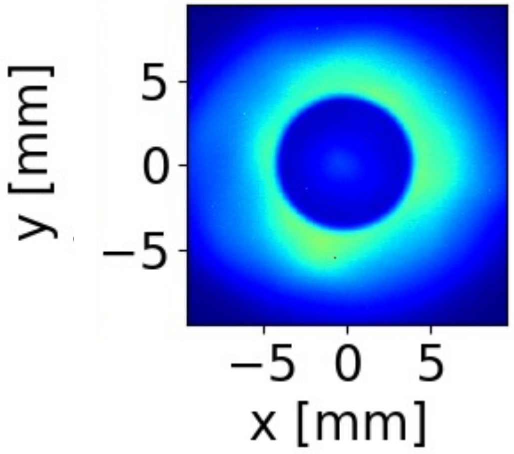
Transverse extent evolution: ns-scale





Transverse time-integrated images

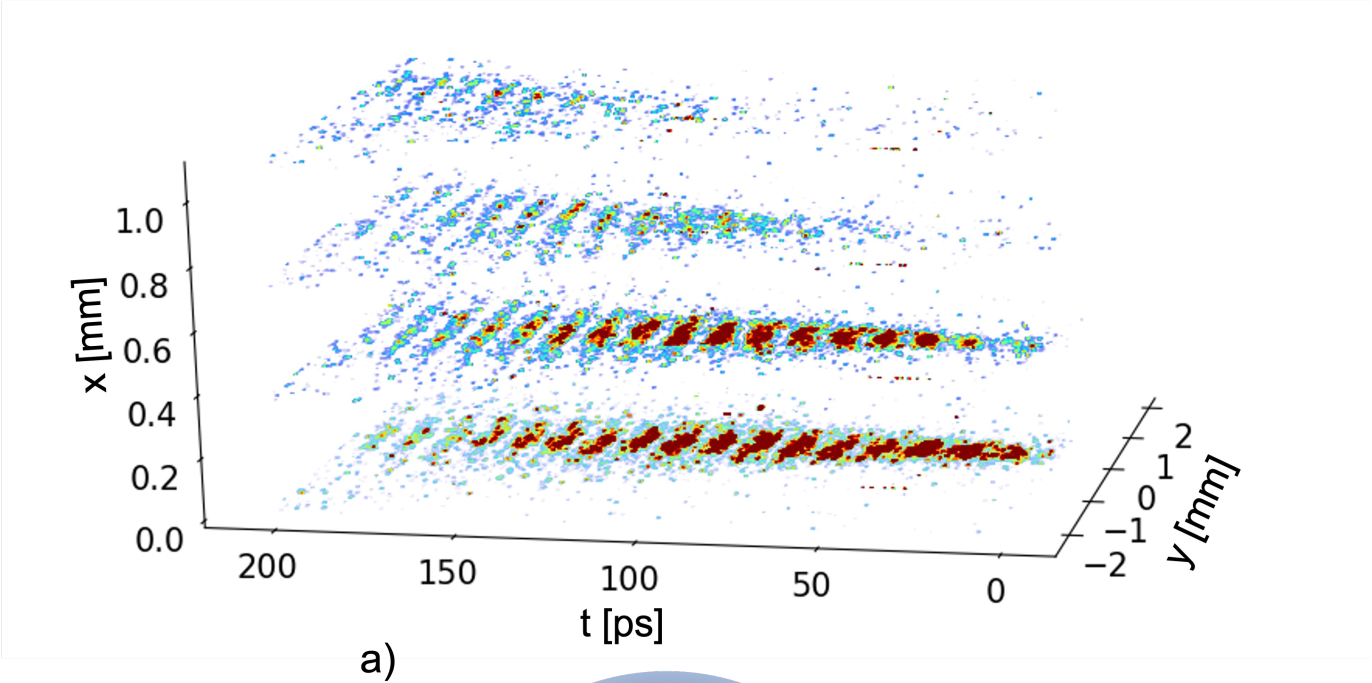


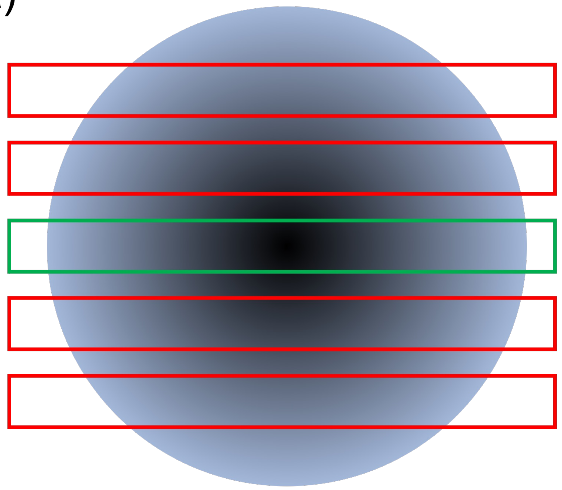


3D imaging

By changing the position of the OTR on the slit, we obtained time-resolved images at different heights.

→ study SM in the plane perpendicular to the slit





Seeded SM reproducibility