

Wakefield Dephasing Measurement of a Self-Modulating Proton Bunch

IPAC'26 – 17th International Particle Accelerator Conference

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Helena Jaworska and the AWAKE Collaboration

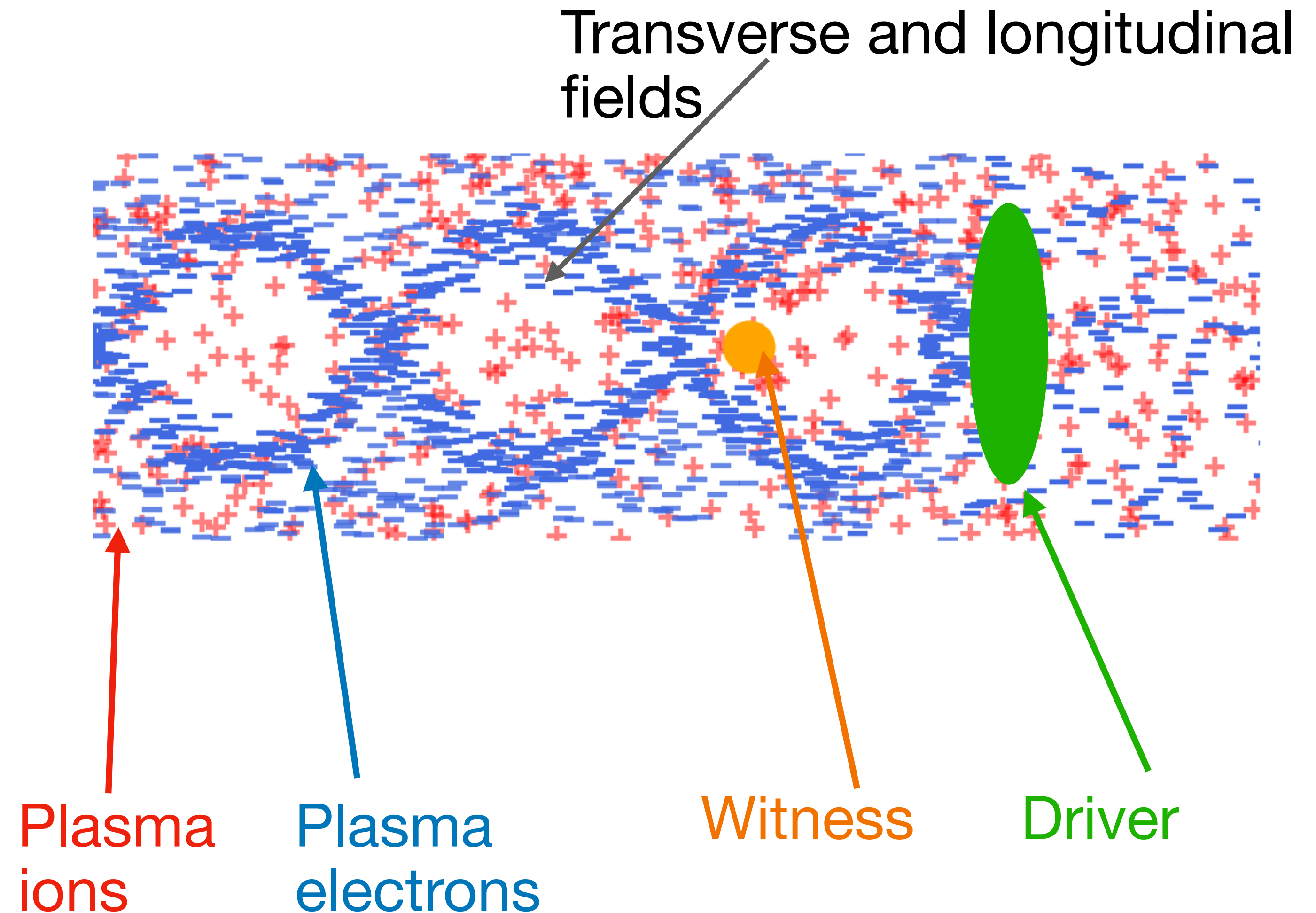
Outline

- Introduction to Plasma Wakefield Acceleration
- AWAKE at CERN: Proton Bunch Self-Modulation
- Measurement of the Wakefield Phase Velocity During Self-Modulation
- Control of the Phase Velocity Using Plasma Density Gradients
- Summary & Conclusion

Plasma Wakefield Acceleration

Motivation

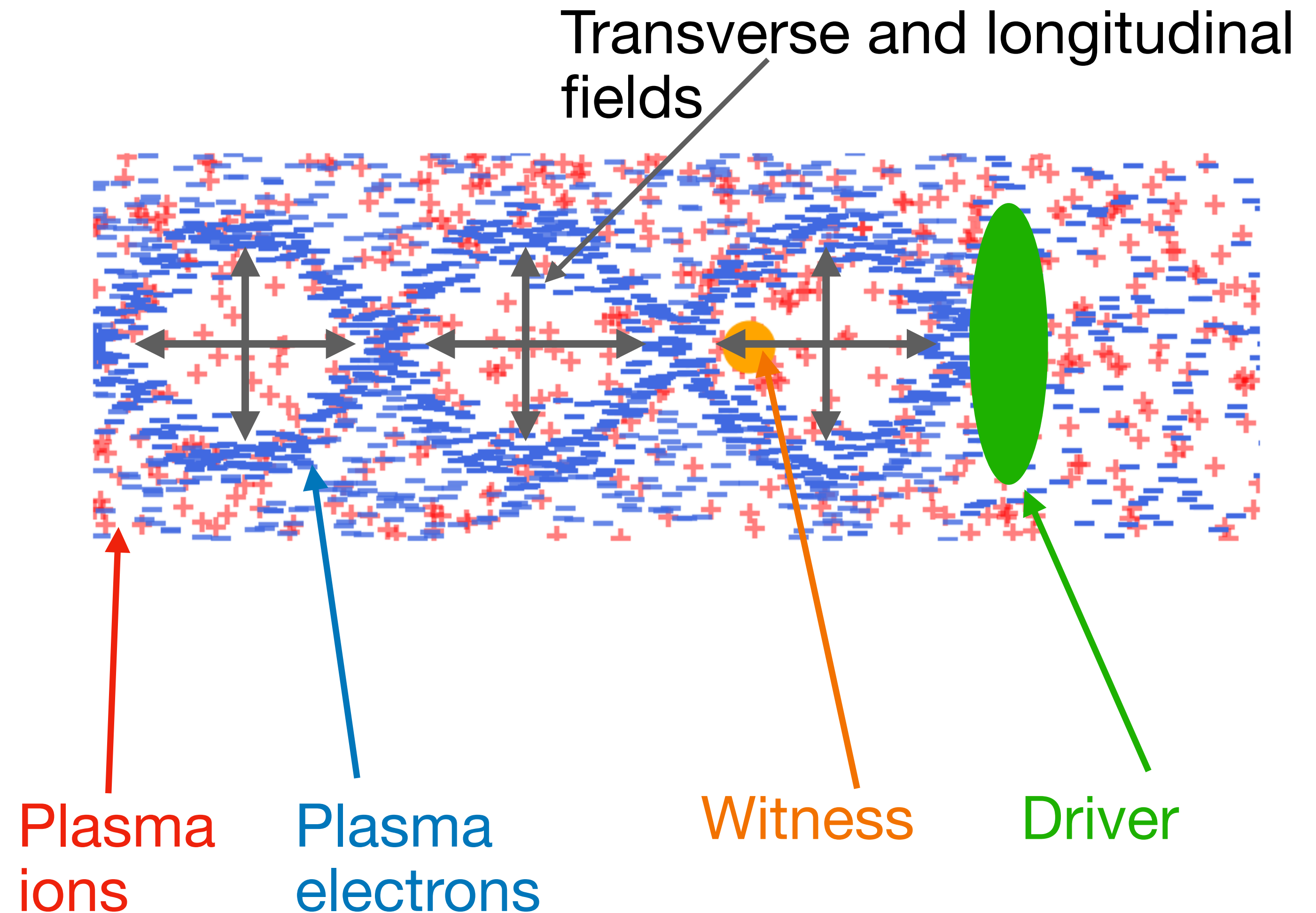
- Create high-amplitude fields in plasma using a driver (particle bunch or laser pulse)
- Use these fields to accelerate charged particles (witness bunch) with gradients >1 GeV/m
- For effective acceleration: phase velocity of the wakefields \sim velocity of the witness



Plasma Wakefield Acceleration

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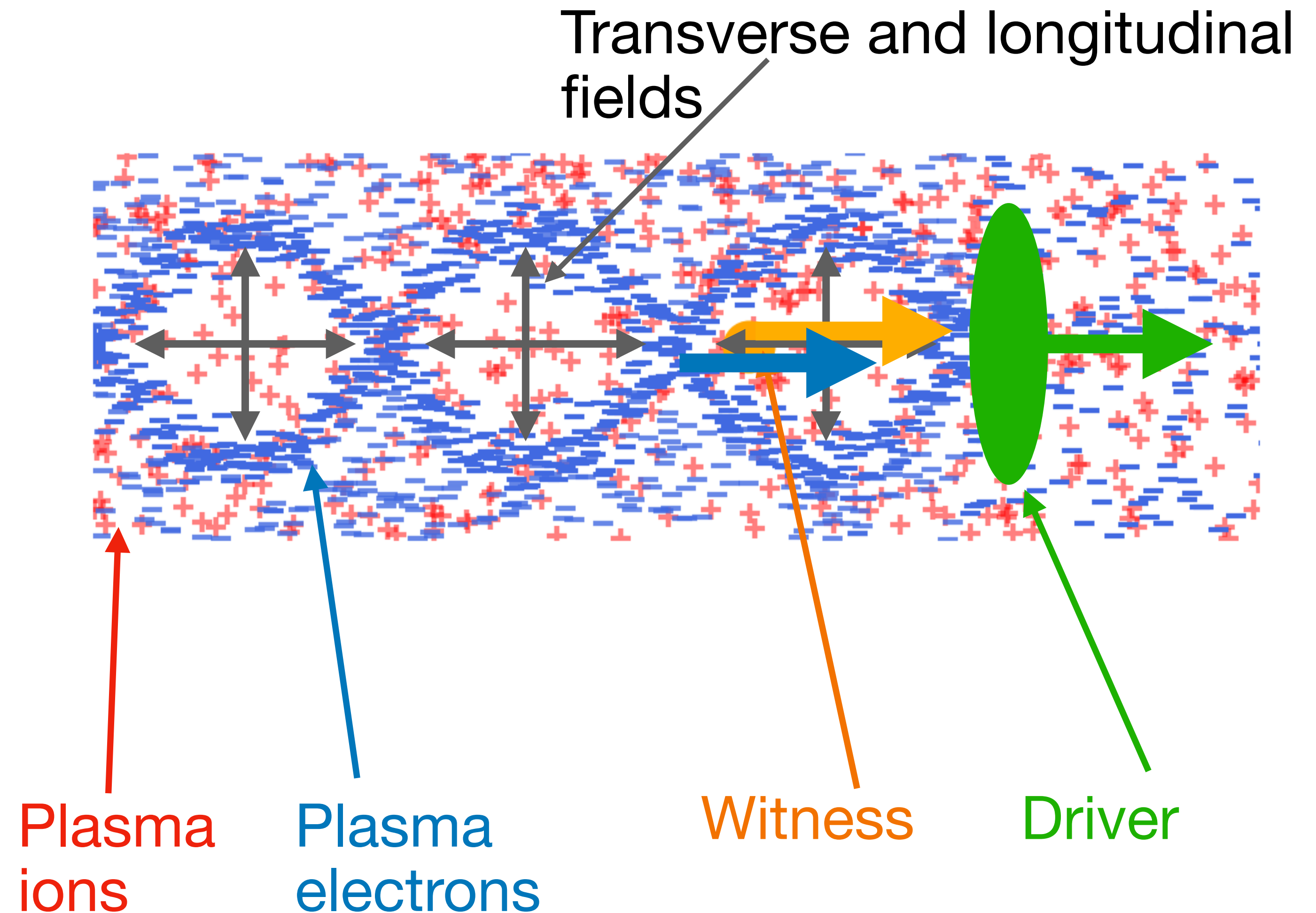
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Plasma Wakefield Acceleration

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Radiofrequency (RF) Cavities

Current Technology



CERN-PHOTO-201902-032, SPS RF accelerating cavities removed from the tunnel of the accelerator

- Metallic structures
- Acceleration gradient < 100 MeV/m, limited by electrical breakdown
- Adjustable phase velocity

Plasma Wakefield Acceleration

Not limited by electrical breakdown

- Acceleration gradient on the order of the cold plasma wave breaking field

$$eE = m_e \omega_{pe} c \sim 100 \frac{eV}{m} \sqrt{n_{pe} [cm^{-3}]}$$

i.e.:

$$\sim 1 GeV/m \text{ for plasma density of } n_{pe} = 10^{14} cm^{-3}$$

$$\sim 100 GeV/m \text{ for plasma density of } n_{pe} = 10^{18} cm^{-3}$$

→ Could enable compact linear accelerators for e.g. high-energy physics, medical applications, material science, industrial applications.

Acceleration Result Examples

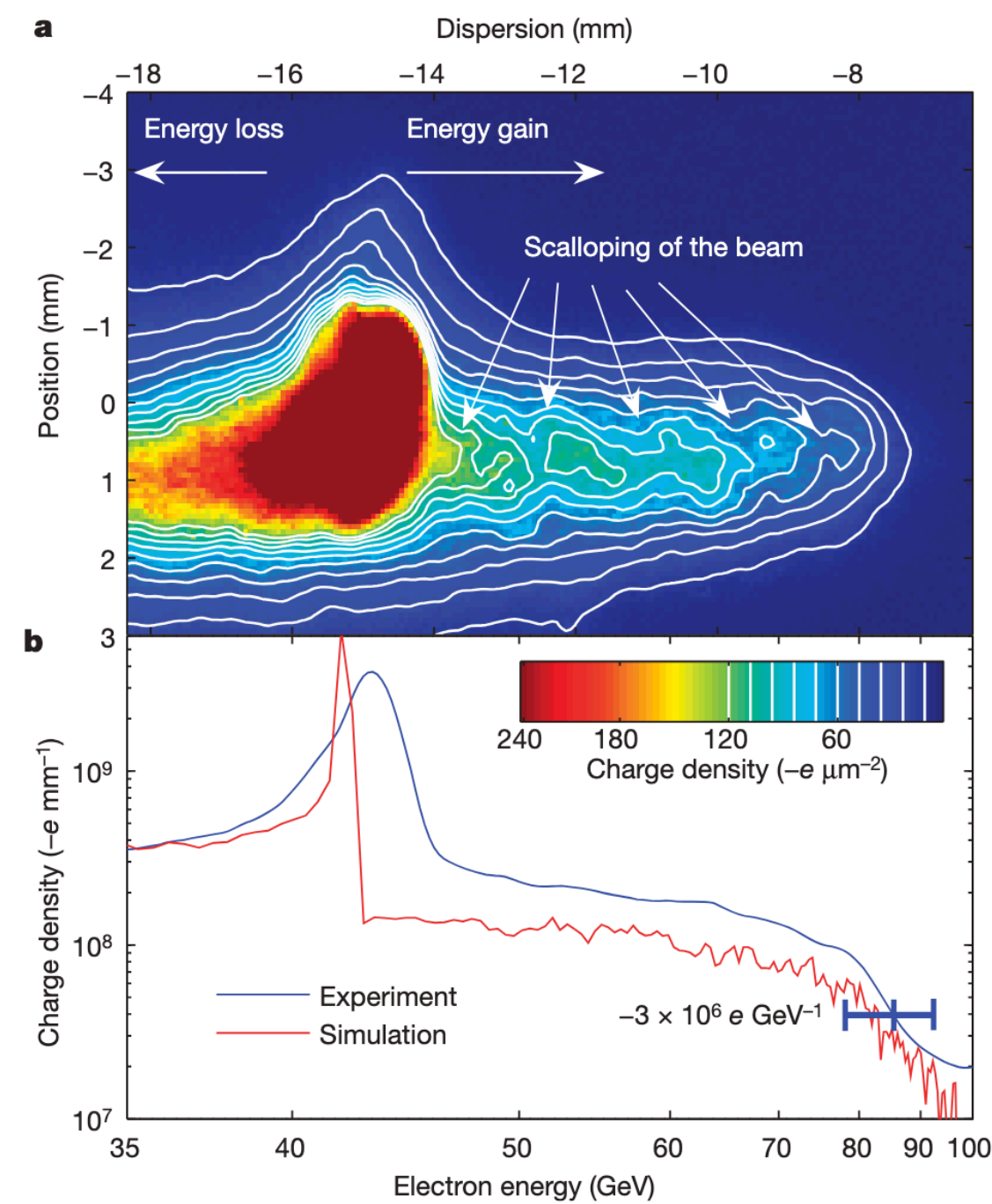
Record energy gain

Acceleration Result Examples

Record energy gain

SLAC (Stanford, CA, USA): Electron Beam Driver

I. Blumenfeld et. al, Nature, 445, 741-744 (2007)



- Energy gain: $\sim 42 \text{ GeV}$ in 85 cm of plasma

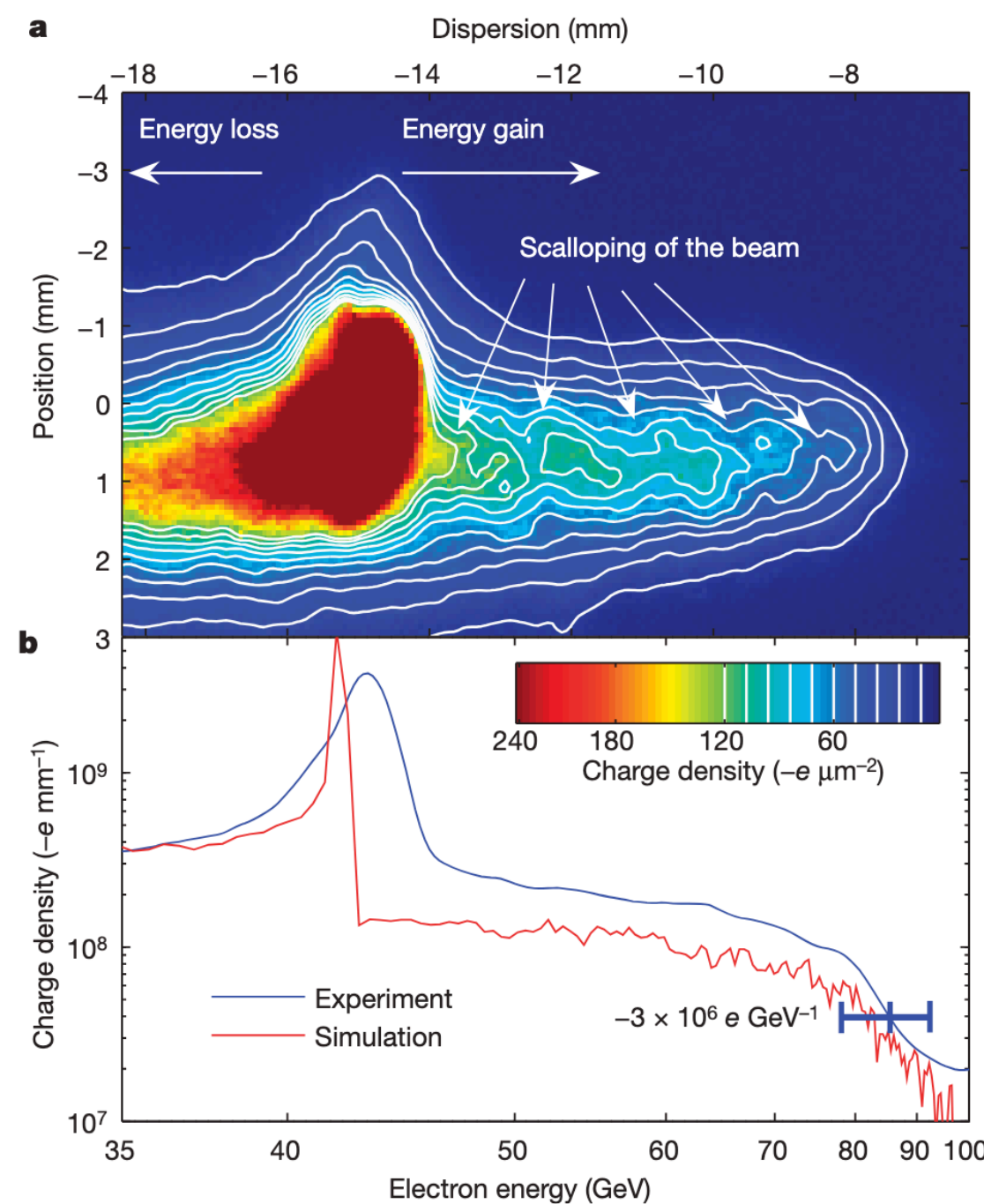
→ **Acceleration Gradient: $\sim 52 \text{ GeV/m}$**

Acceleration Result Examples

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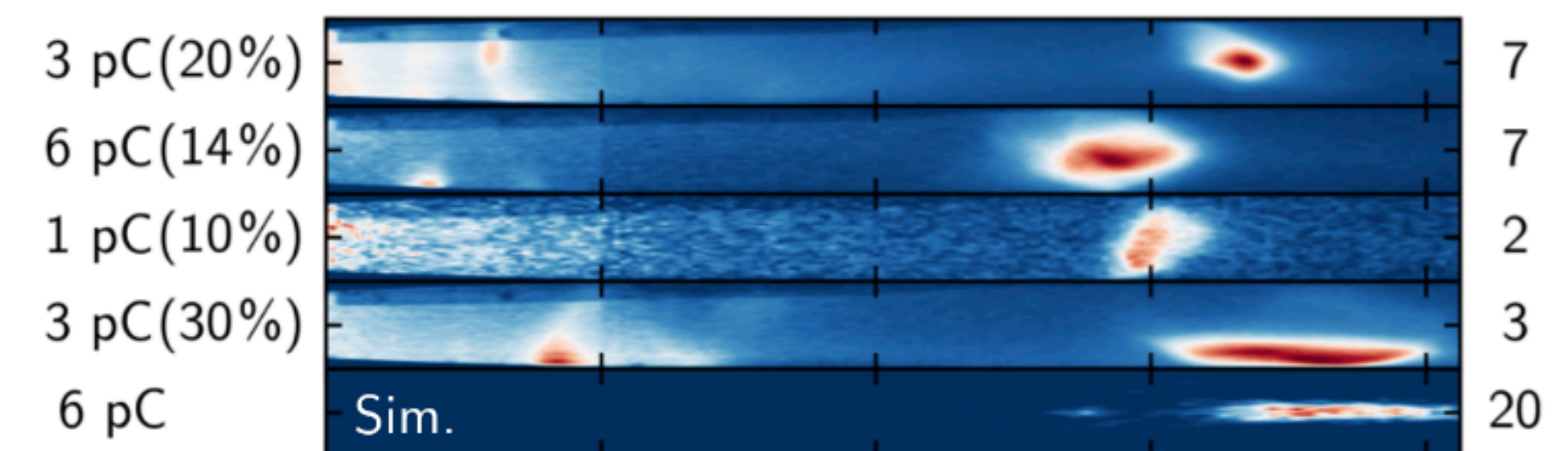
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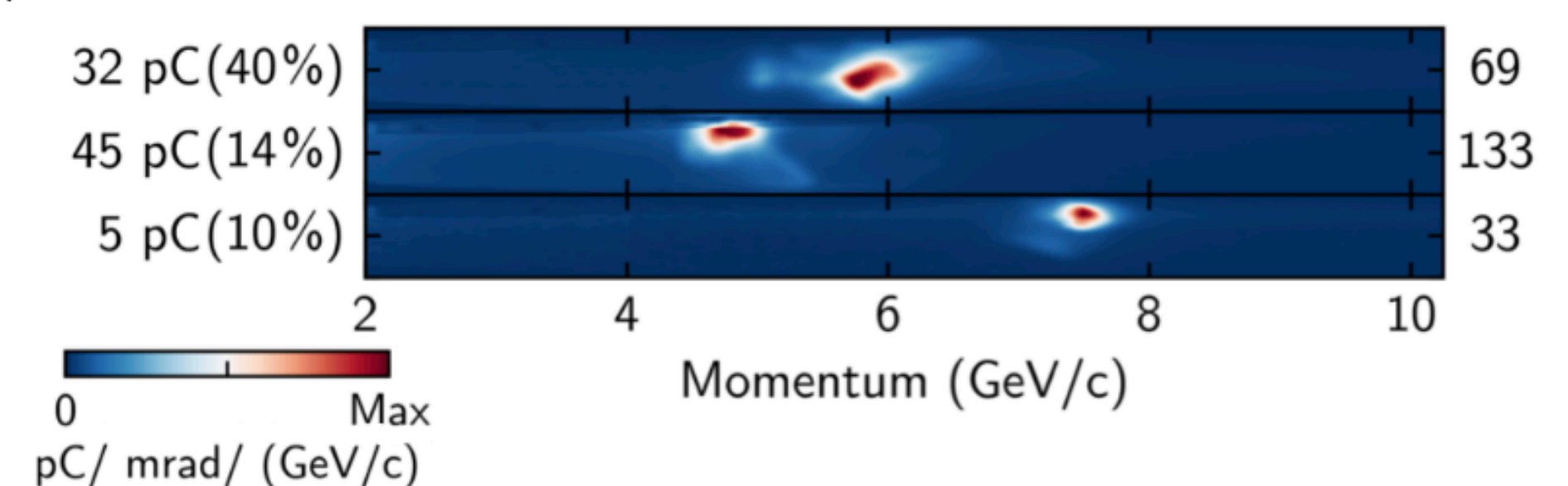
BELLA (Berkeley, CA, USA): Laser Pulse Driver

A. Picksley et. al, PRL, 133, 255001 (2024)

(c) H_2 over 30 cm, 1% N_2 over 12 cm



(d) H_2 over 30 cm, 5% N_2 over 12 cm



- Energy gain: $\sim 9.2 \text{ GeV}$ in 30 cm of plasma

→ **Acceleration Gradient: $\sim 30 \text{ GeV/m}$**

Reaching Very High Energies

Achievable Energy Gain Limited by the Driver

Reaching Very High Energies

Achievable Energy Gain Limited by the Driver

How to increase the energy gain further?

- Staging of multiple plasmas, with a new driver each time → challenging

Reaching Very High Energies

Achievable Energy Gain Limited by the Driver

nature
physics

ARTICLES

PUBLISHED ONLINE: 12 APRIL 2009; CORRECTED ONLINE: 24 APRIL 2009 | DOI: 10.1038/NPHYS1248

How to increase the energy gain further?

- Staging of multiple plasmas, with a new driver each time →challenging
- Increasing energy of the driver particles → experiment at CERN: AWAKE

Proton-driven plasma-wakefield acceleration

Allen Caldwell^{1*}, Konstantin Lotov^{2,3}, Alexander Pukhov⁴ and Frank Simon^{1,5}

Reaching Very High Energies

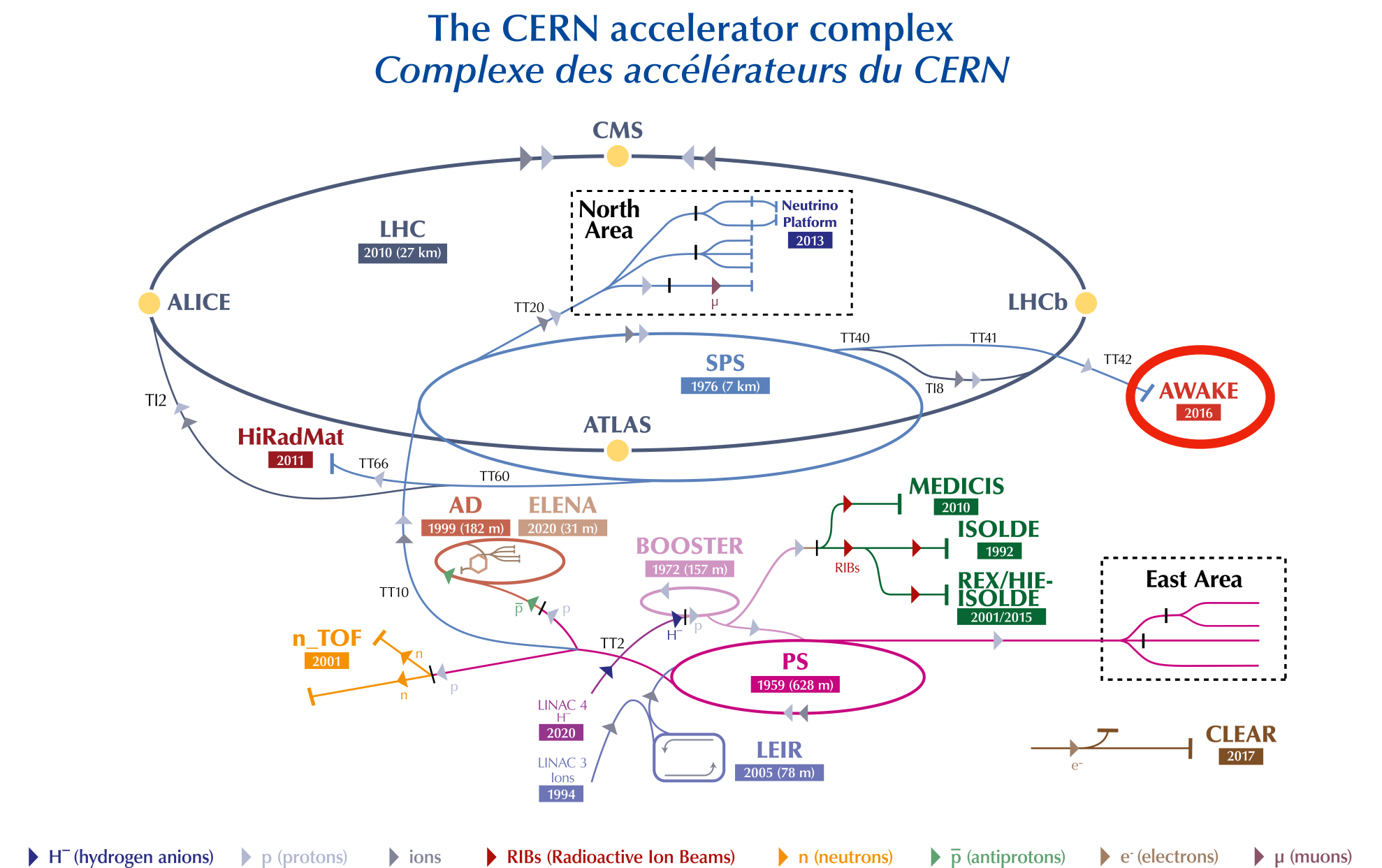
Achievable Energy Gain Limited by the Driver

How to increase the energy gain further?

- Staging of multiple plasmas, with a new driver each time → challenging
- Increasing energy of the driver particles → experiment at CERN: AWAKE
 - 400 GeV proton bunches from the SPS as drivers

Proton-driven plasma-wakefield acceleration

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SPS Bunches Too Long To Effectively Excite Plasma Wakefields

- Ideal: bunch length (σ_z) on the order of the plasma electron wavelength (λ_{pe})
 - For AWAKE: $\lambda_{pe} \approx 1 \text{ mm}$
 - SPS proton bunch: $\sigma_z \approx 5 \text{ cm}$
- Would not drive high-amplitude wakefields

SPS Bunches Too Long To Effectively Excite Plasma Wakefields

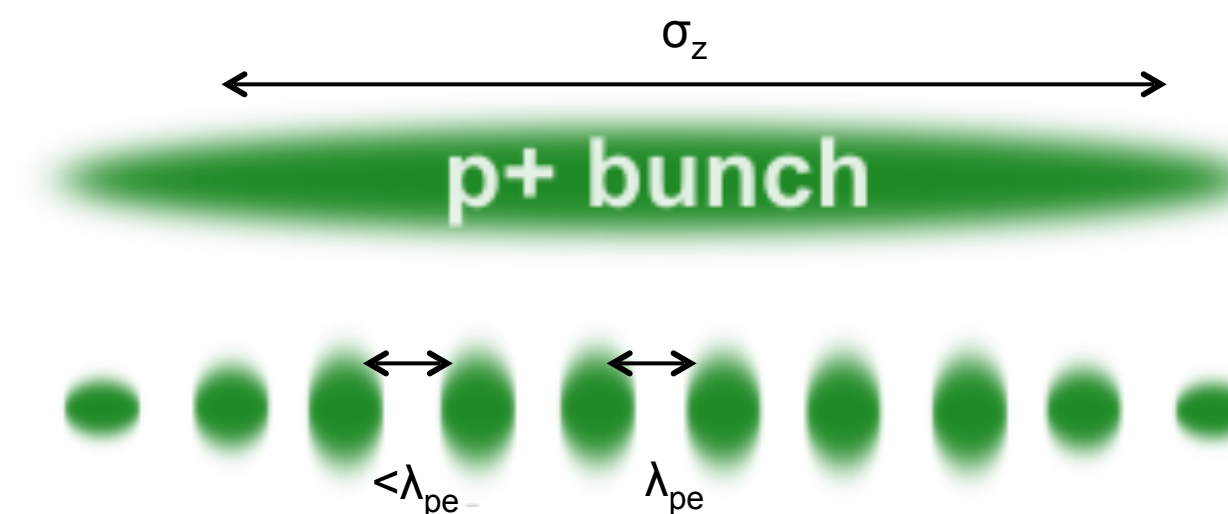
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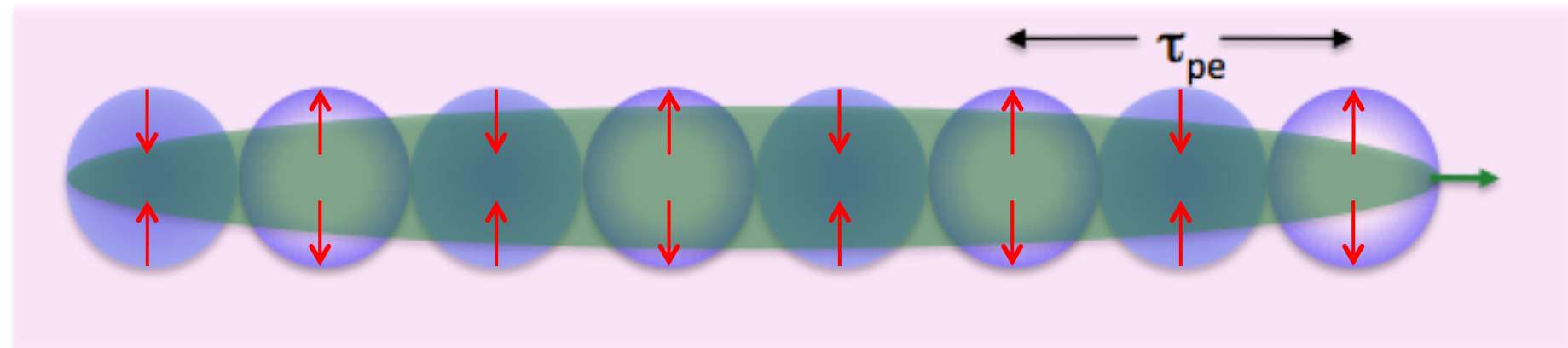
→ Would not drive high-amplitude wakefields

- Solution: use a plasma process → Self-Modulation Instability
- Forms a micro bunch train that resonantly drives high-amplitude wakefields



- Spacing of the micro bunches at λ_{pe}

Self-Modulation Process

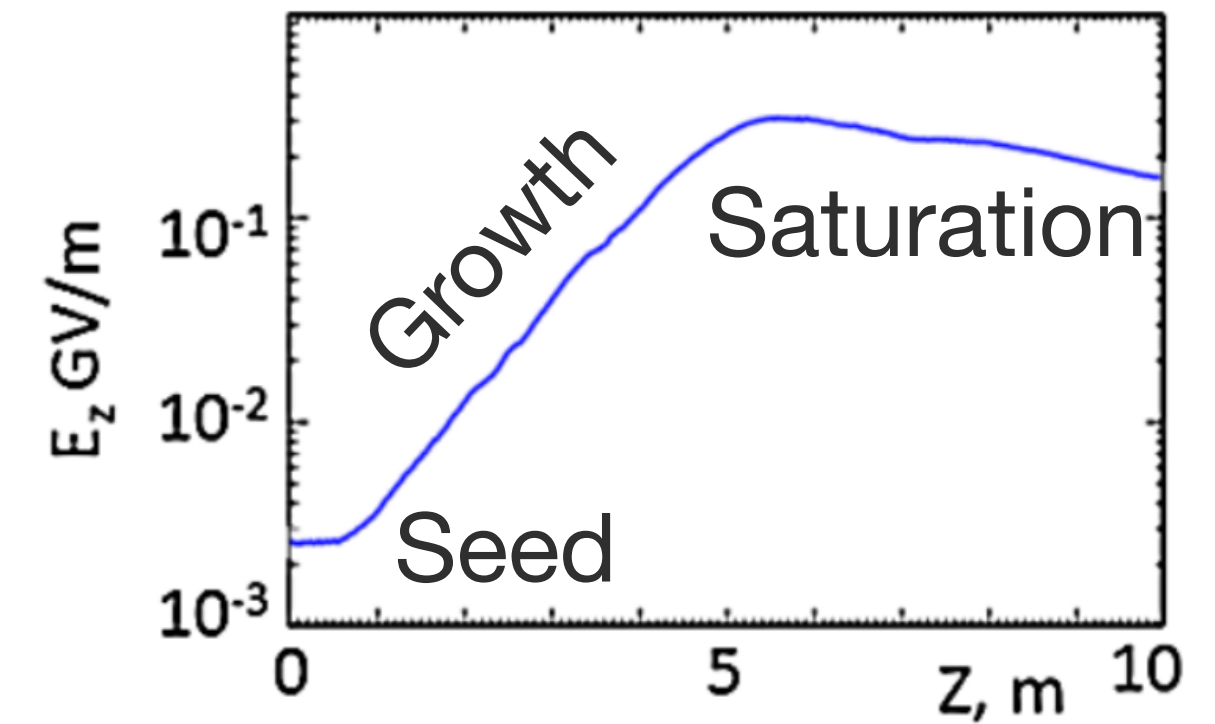


Self-modulation

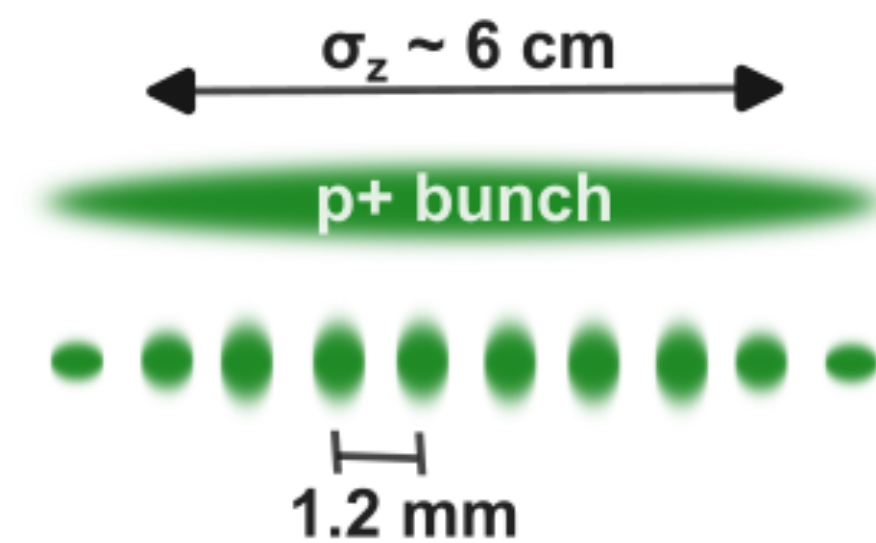
Growth mechanism:



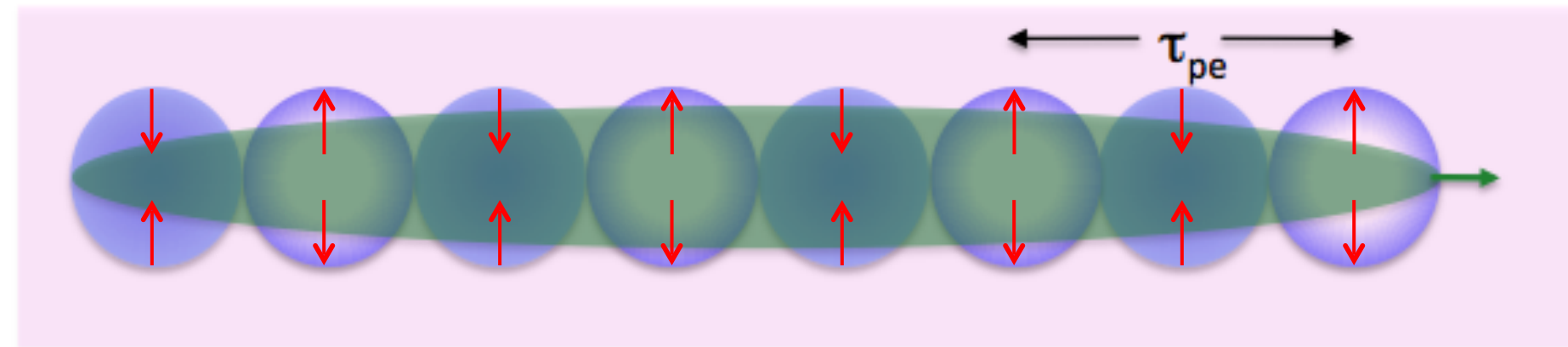
Initial (transverse) wakefields



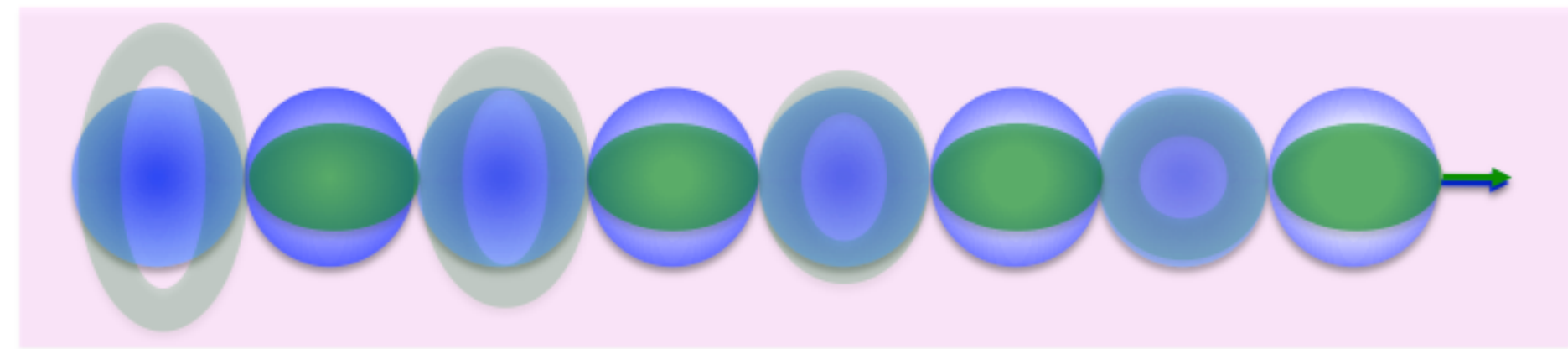
Pukhov, PRL107 145003 (2011)



Self-Modulation Process



Self-modulation



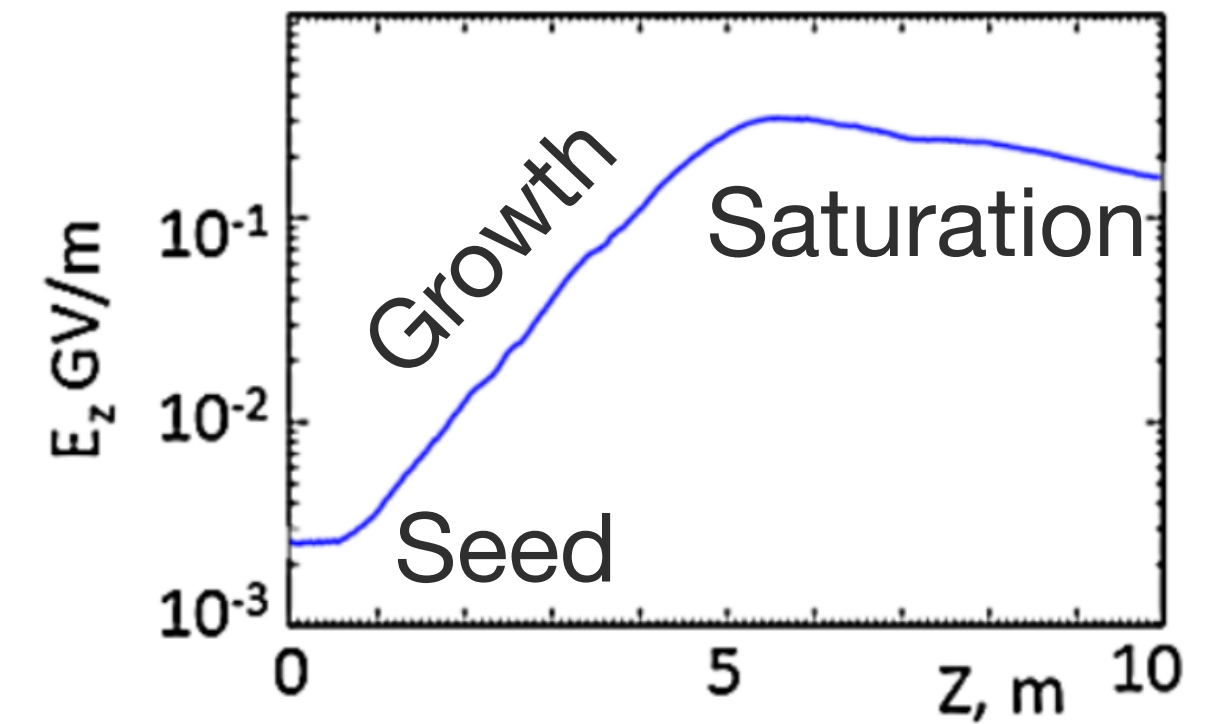
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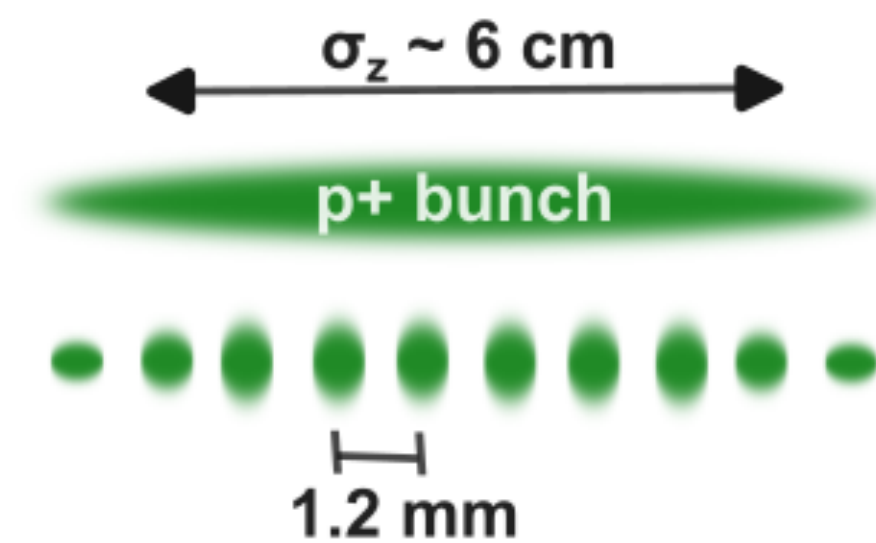
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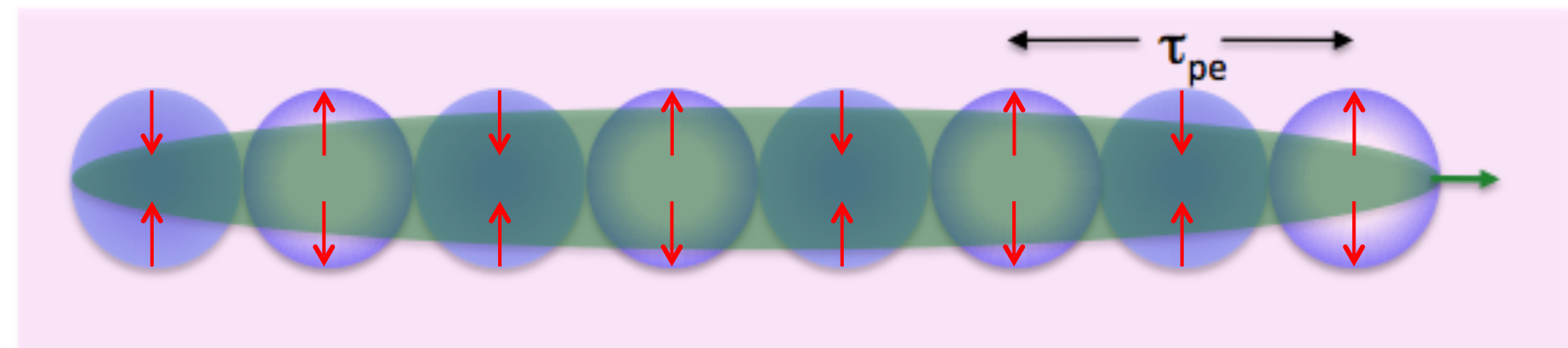
Periodic focusing/defocusing



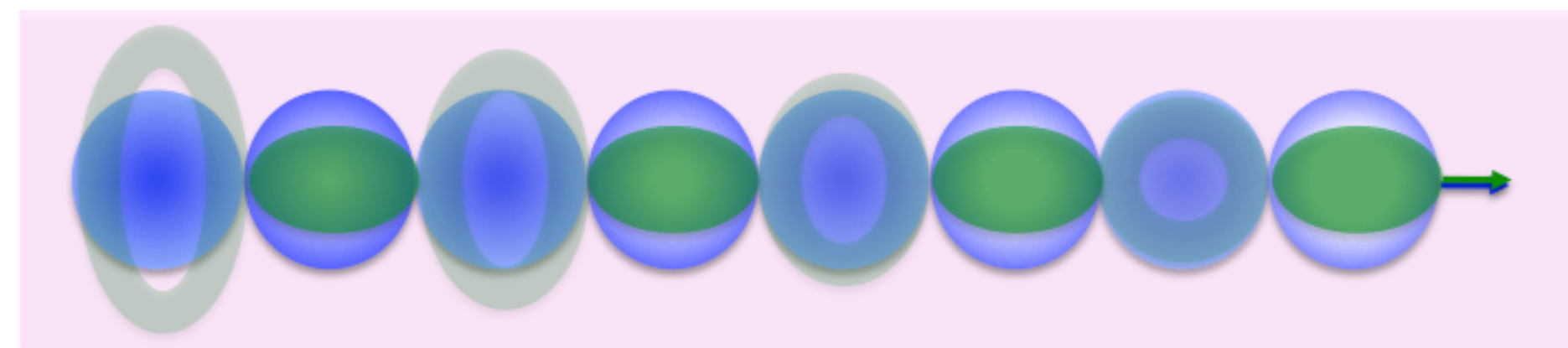
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Self-Modulation Process



Self-modulation



Self-modulated bunch



Growth mechanism:



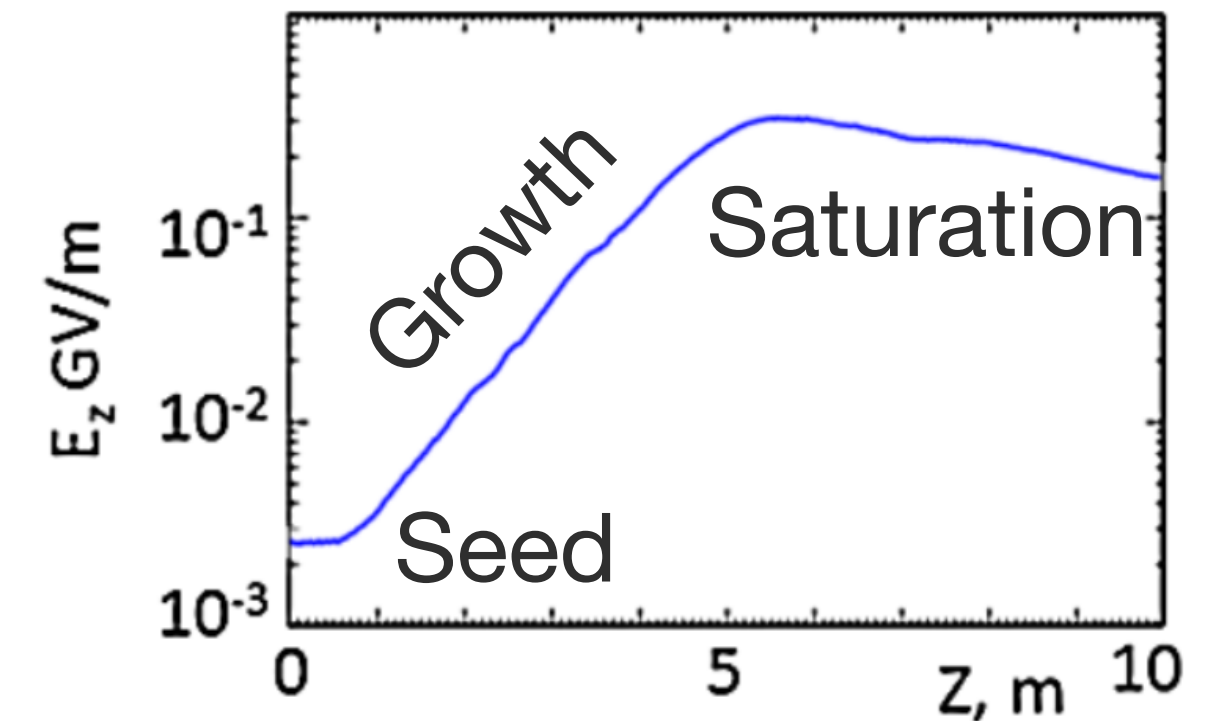
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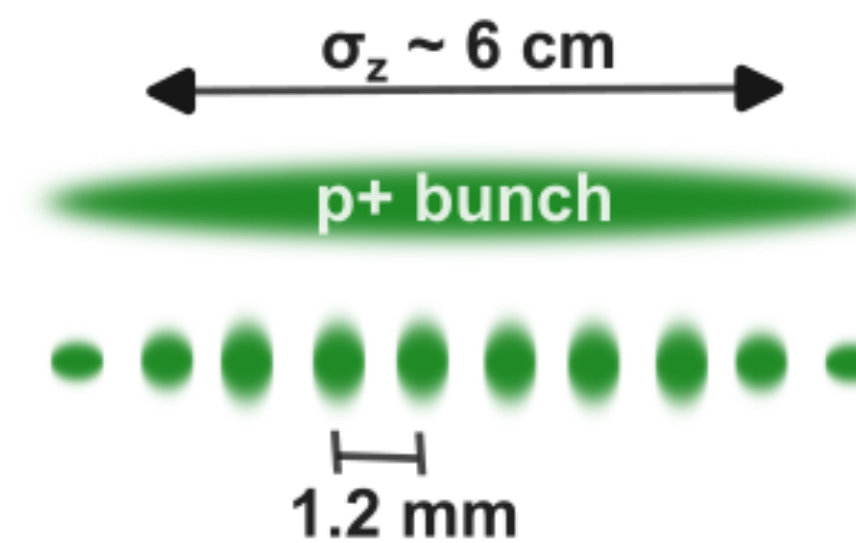
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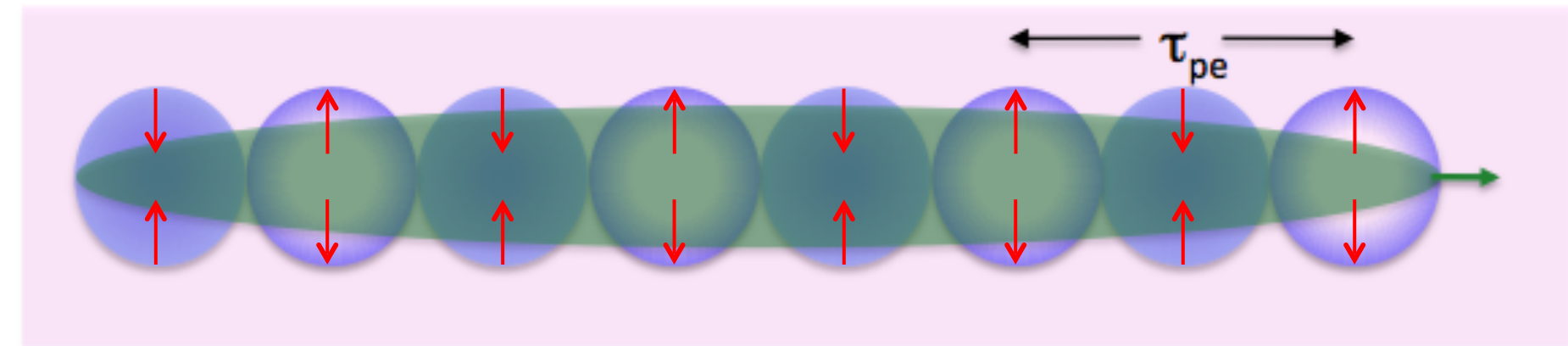
Density modulation



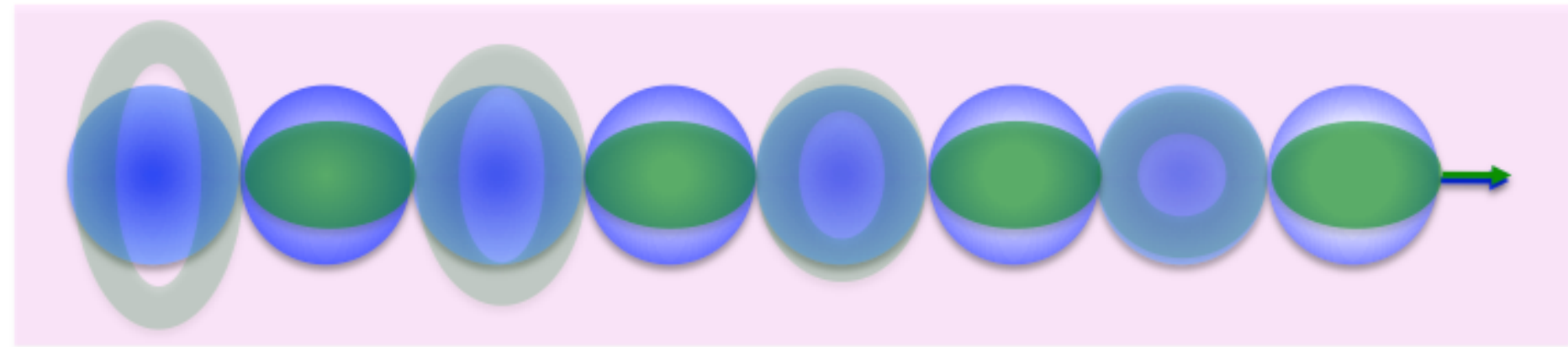
Pukhov, PRL107 145003 (2011)



Self-Modulation Process



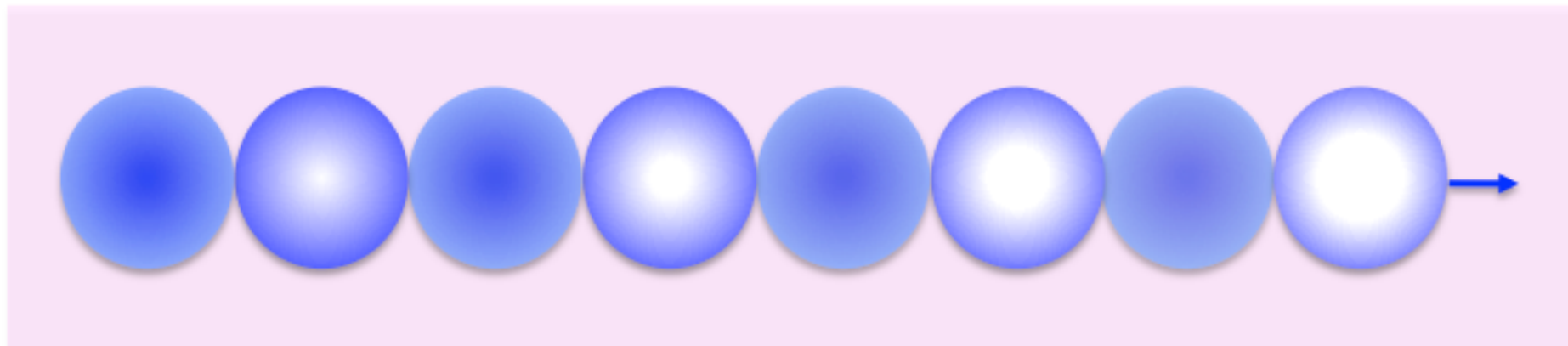
Self-modulation



Self-modulated bunch



Plasma wakefields



Full modulation – bunch train

Growth mechanism:



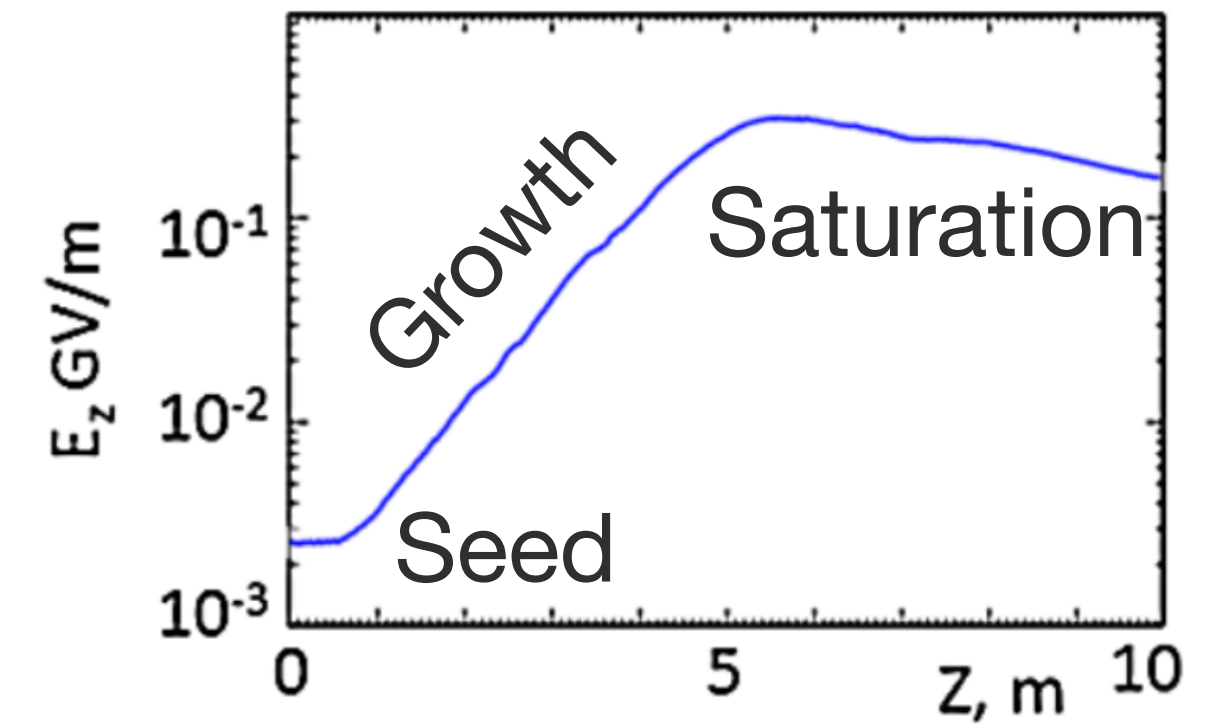
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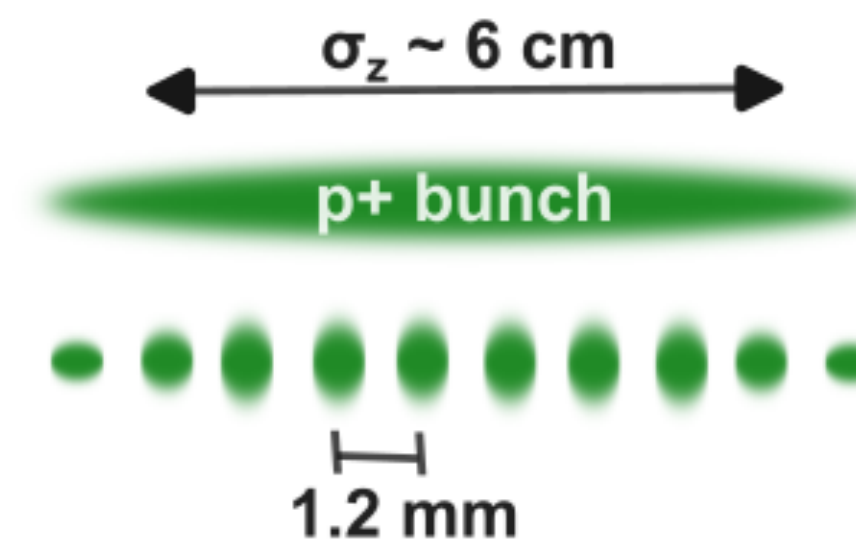
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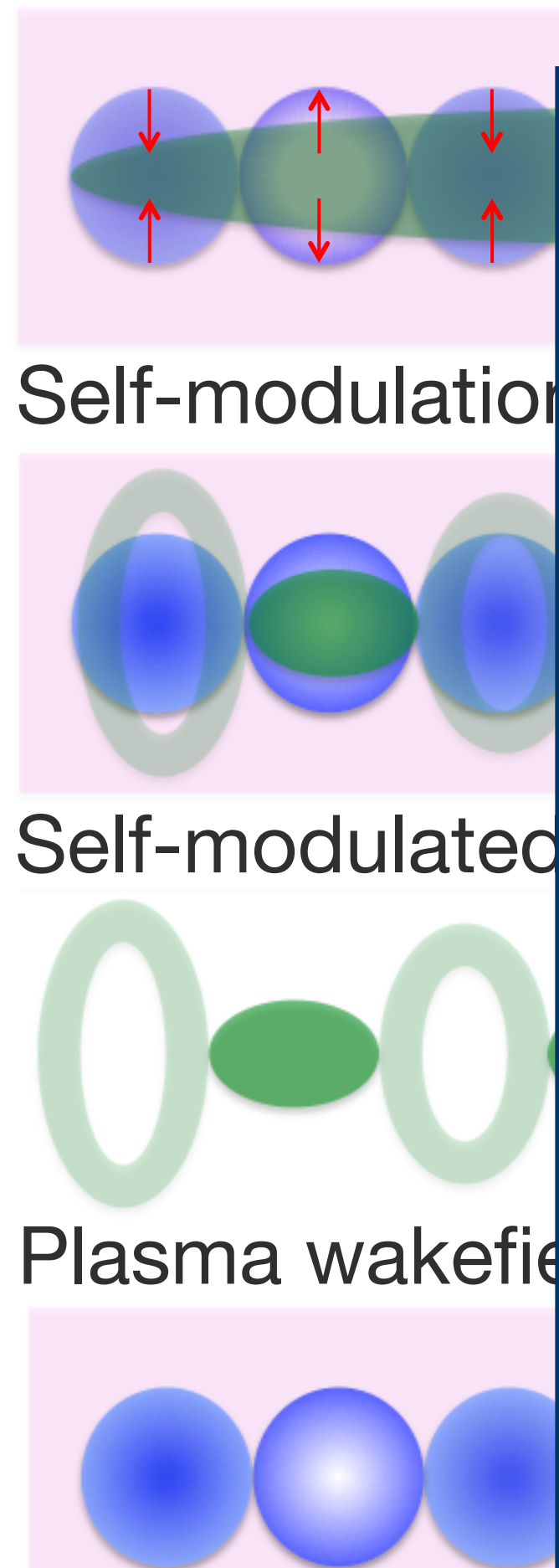


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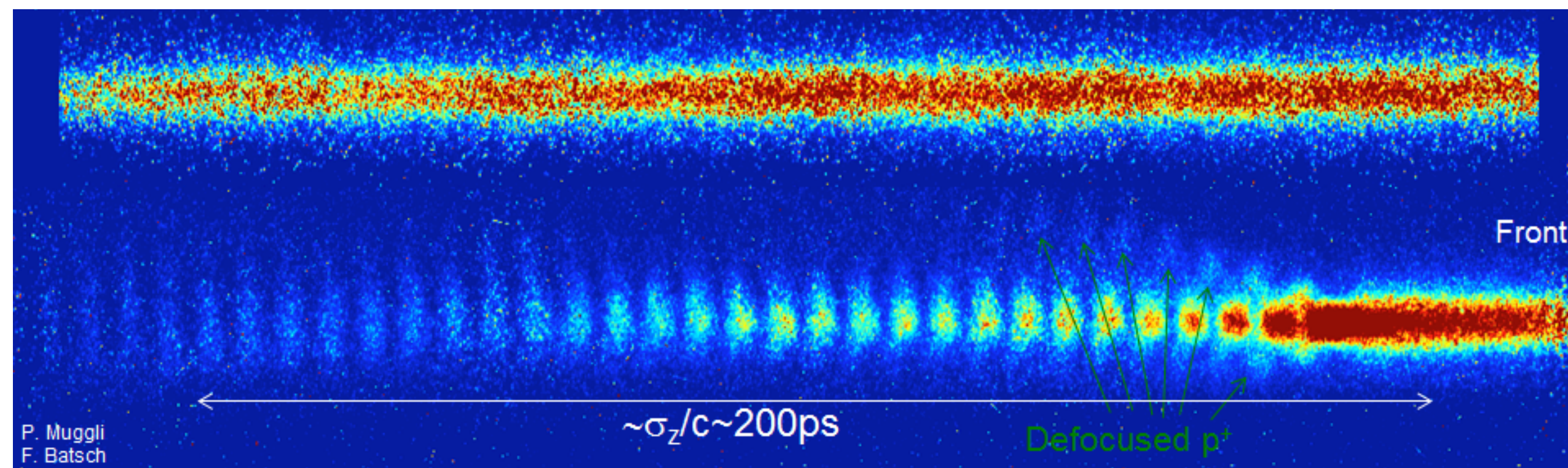


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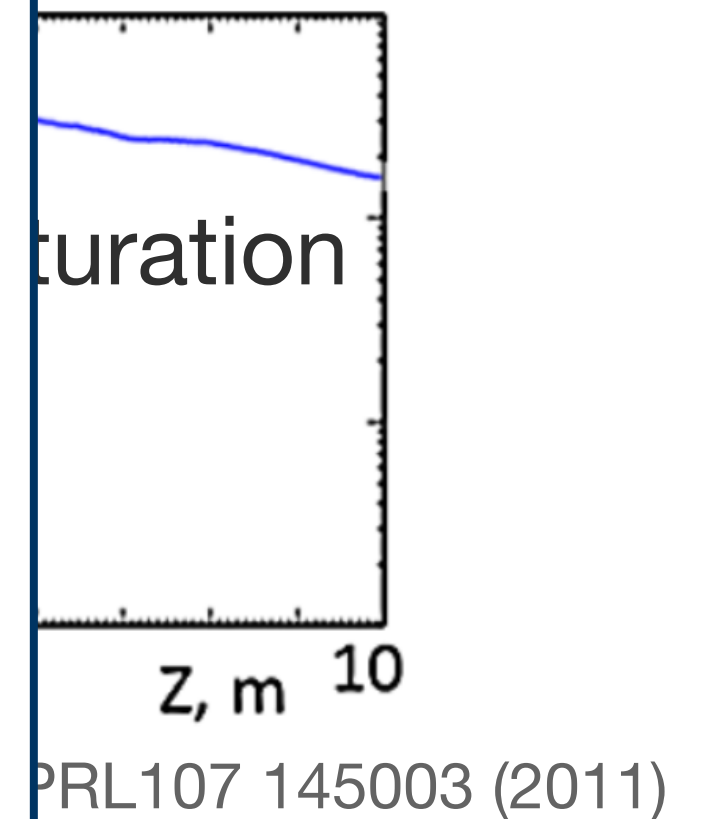


Self-modulation demonstrated in AWAKE



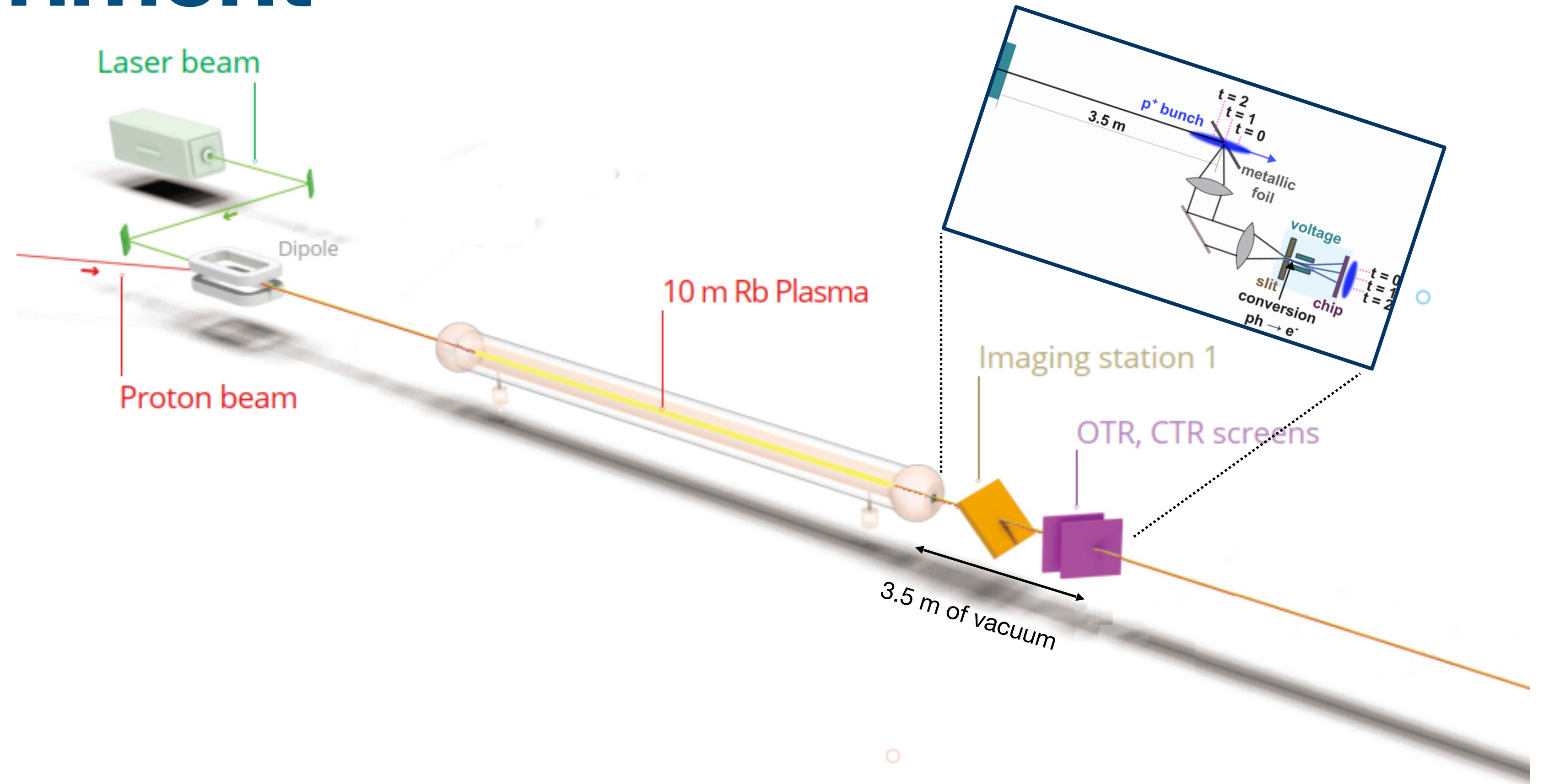
AWAKE Collaboration, Phys. Rev. Lett. **122**, 054802 –2019
 M. Turner and the AWAKE Collaboration, Phys. Rev. Lett. **122**, 054801 (2019)
 F. Batsch and the AWAKE Collaboration, Phys. Rev. Lett. **126**, 164802 (2021)

- Streak camera images: pictures of the beam in time
- Measured 3.5m after the plasma exit, with a plasma length of 10.3 m

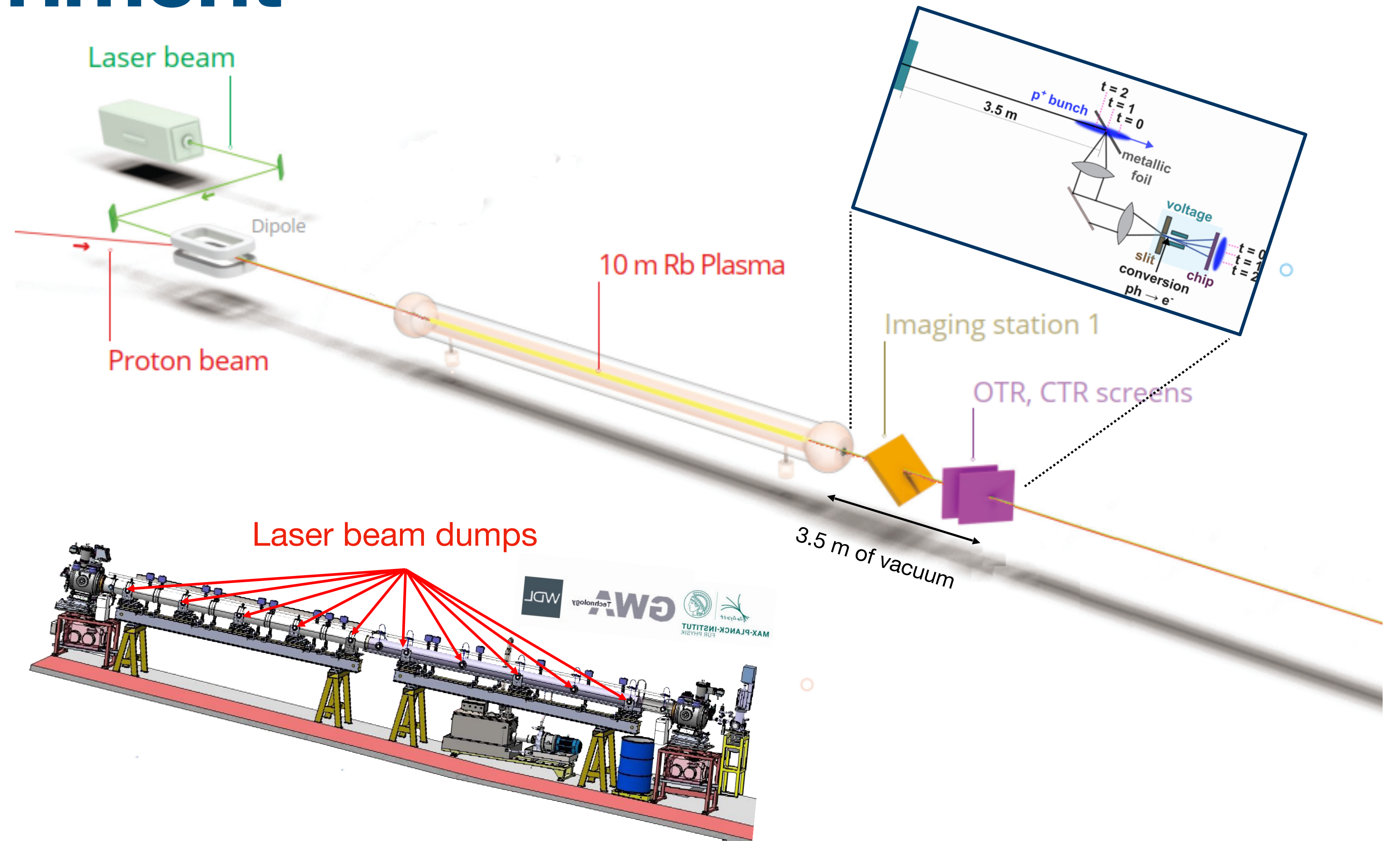


1.2 mm

AWAKE Experiment

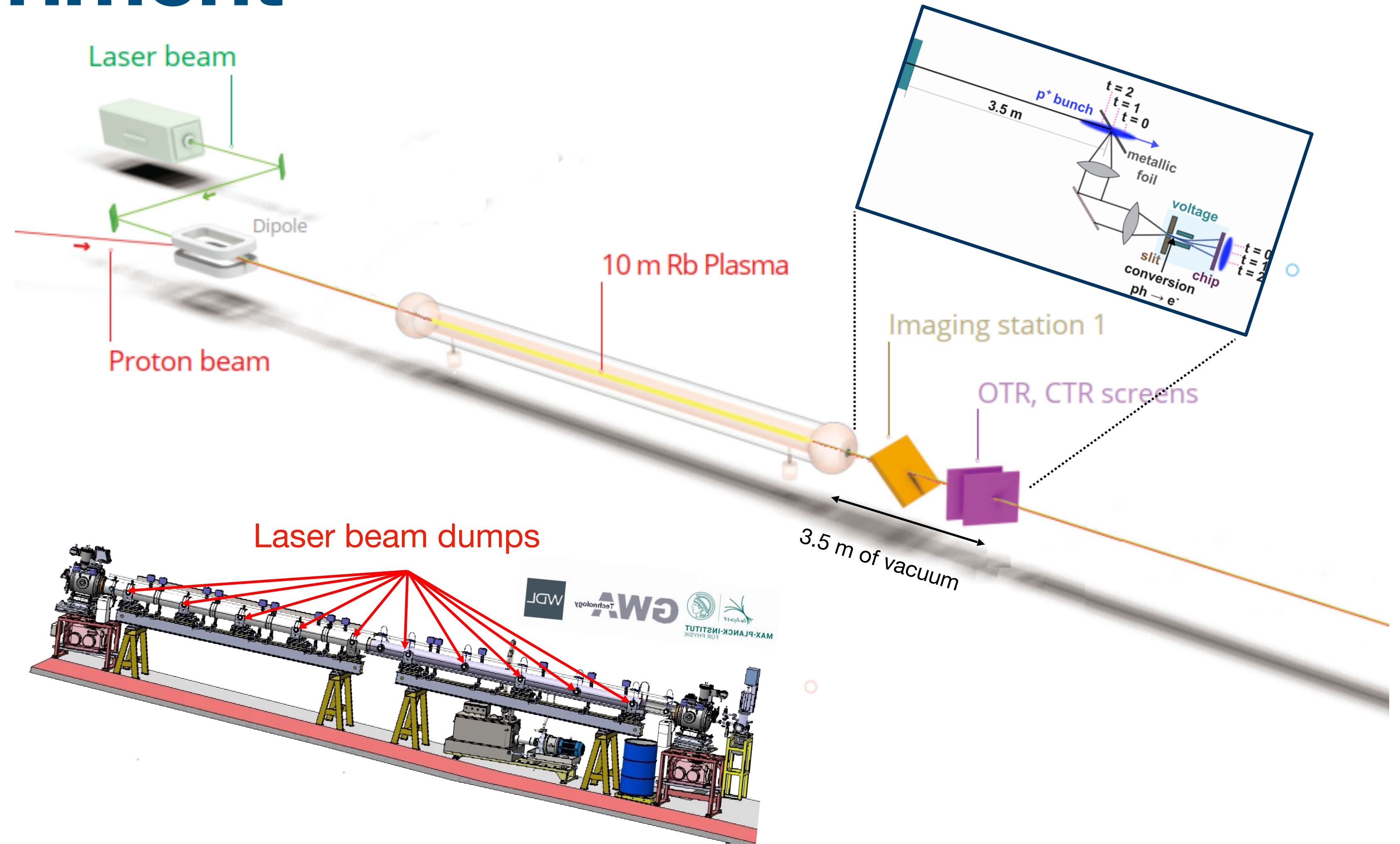


AWAKE Experiment



- Thin laser beam dumps for changing plasma length
- From 0.5 to 10.3 m in 11 steps

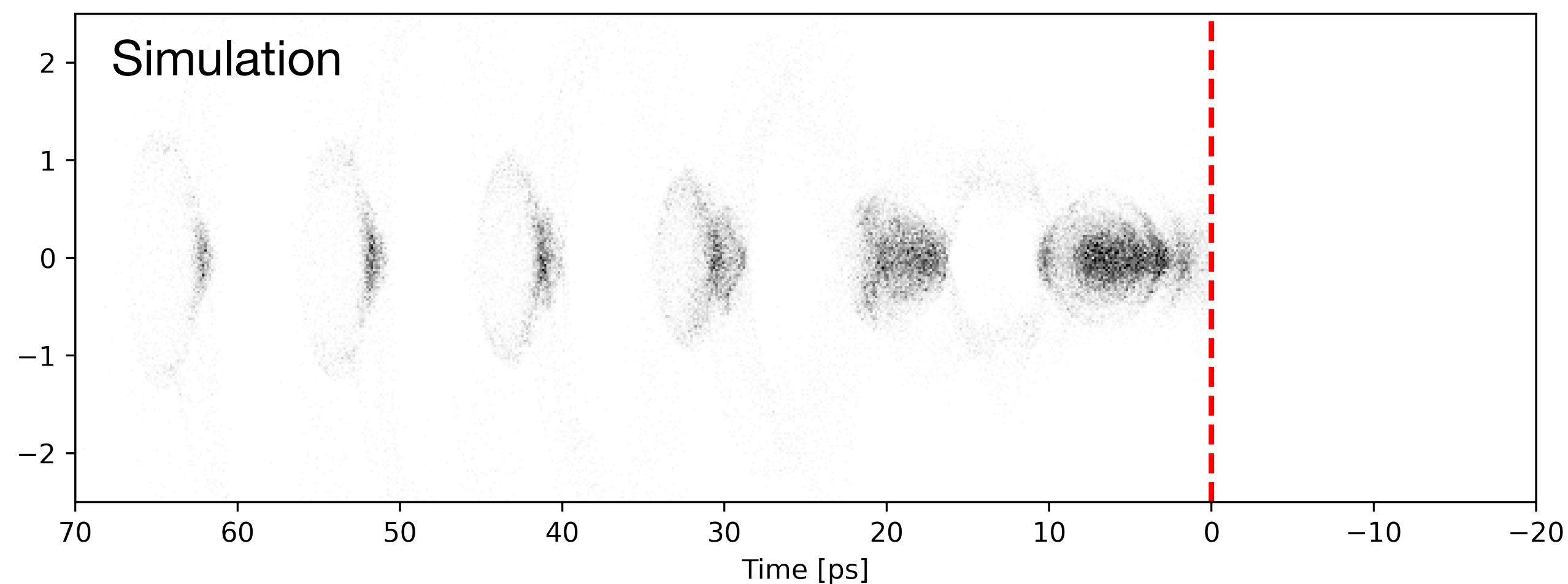
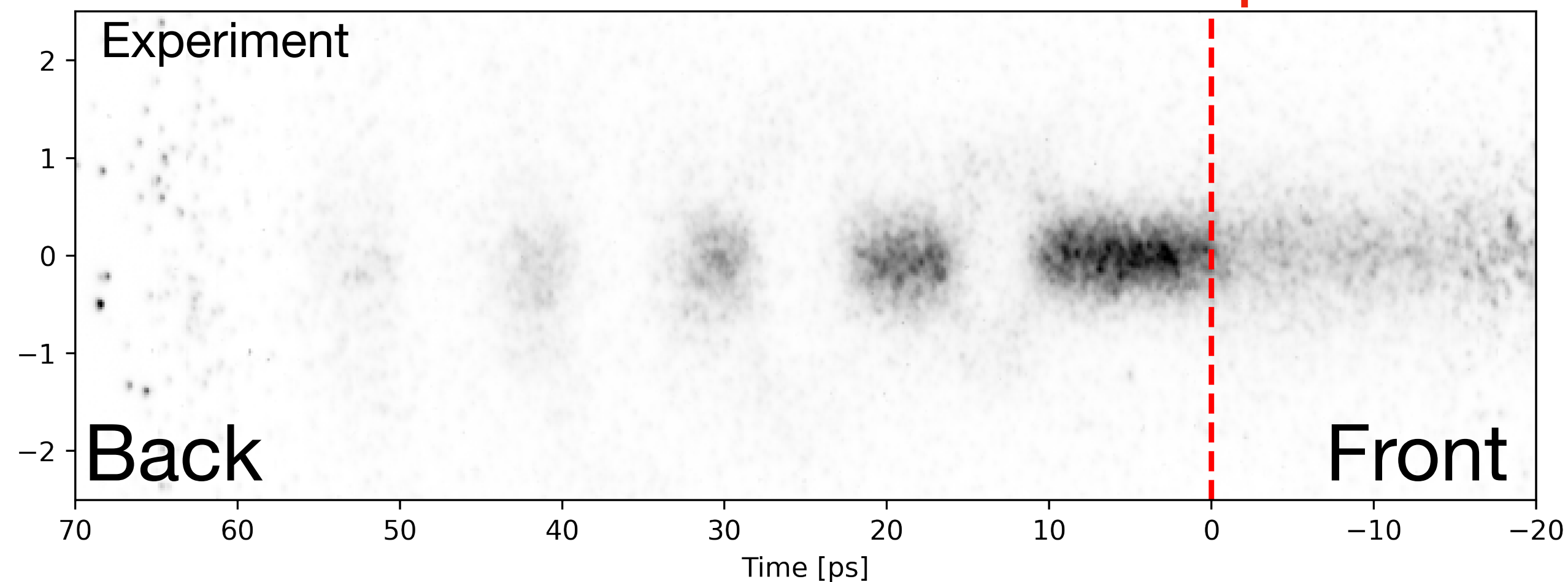
AWAKE Experiment



- Thin laser beam dumps for changing plasma length
- From 0.5 to 10.3 m in 11 steps
→ Enables insight into the evolution of the SM development in the experiment

Measurements Results

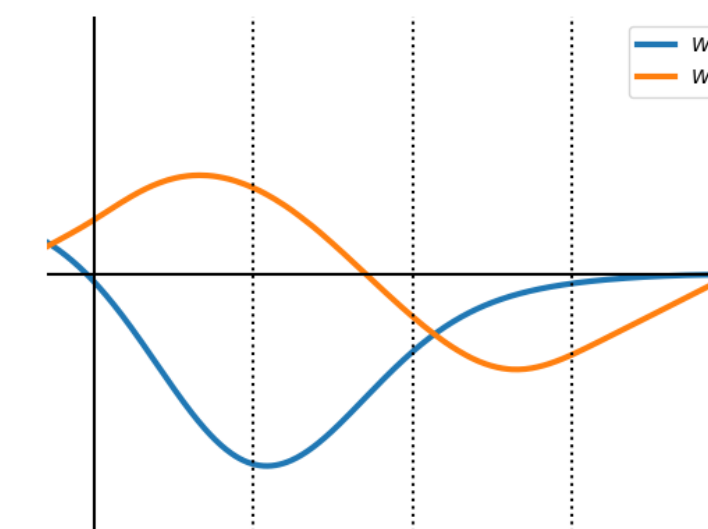
Laser pulse



After 10.3 m of plasma and 3.5 m of vacuum propagation

Observations:

- Clear formation of micro bunches for the part of the proton bunch that propagated in plasma
- 1st and 2nd micro bunches are longer than λ_{pe}

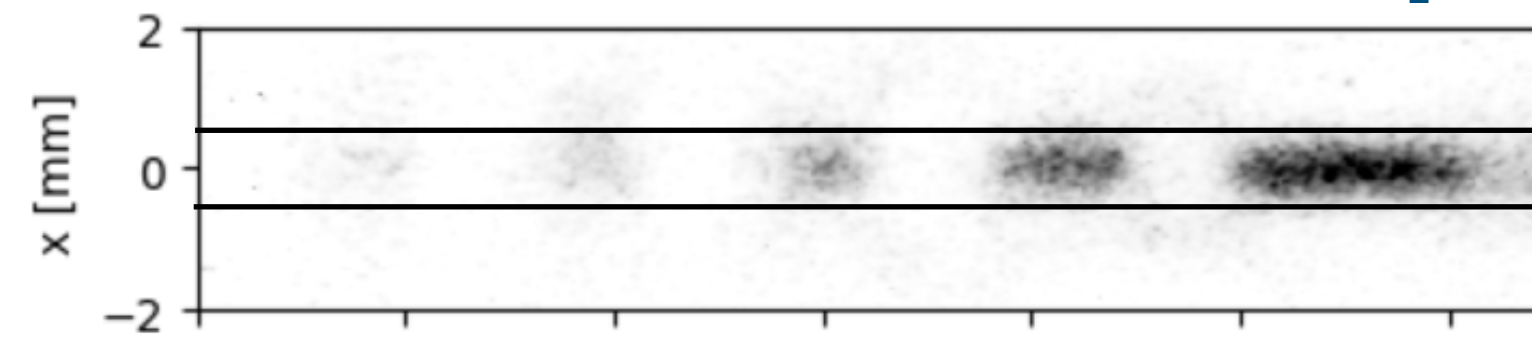


→ Because transverse and longitudinal wakefields are out of phase, yet causality requires both to start at zero

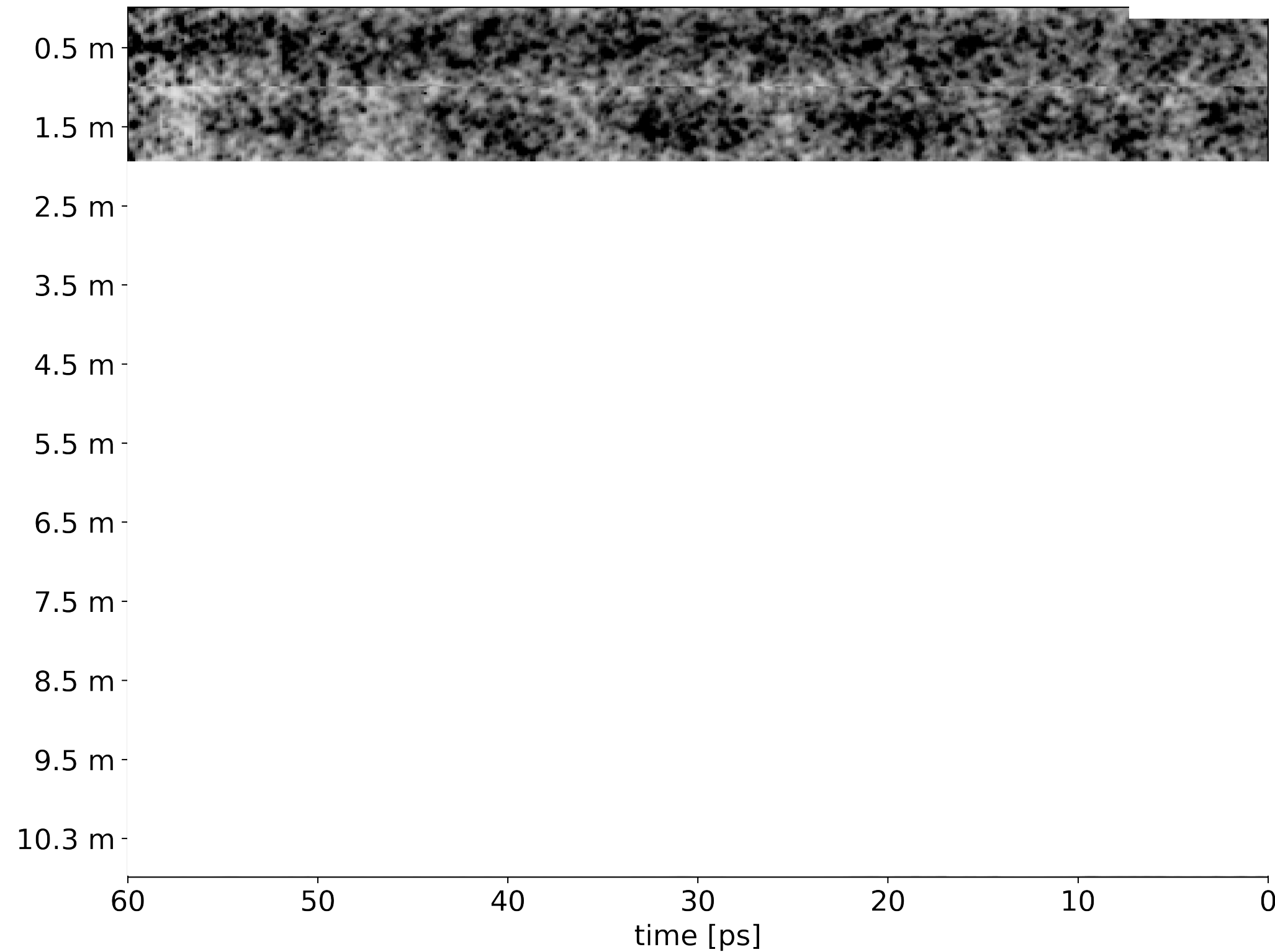
- Excellent agreement with the results of 2D cylindrical numerical simulations

Evolution: Varying Plasma Length (L_{pl})

Proton Bunch Evolution



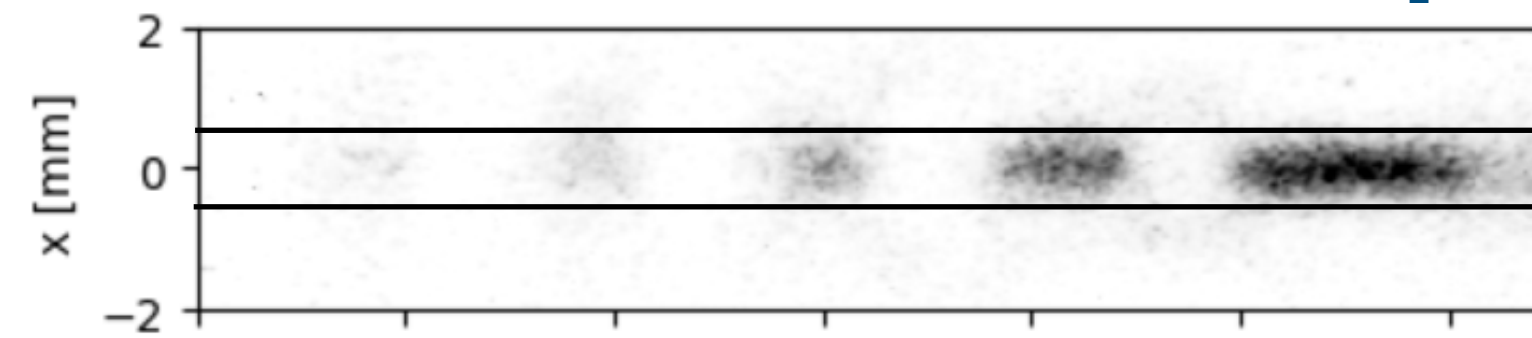
Select subsection



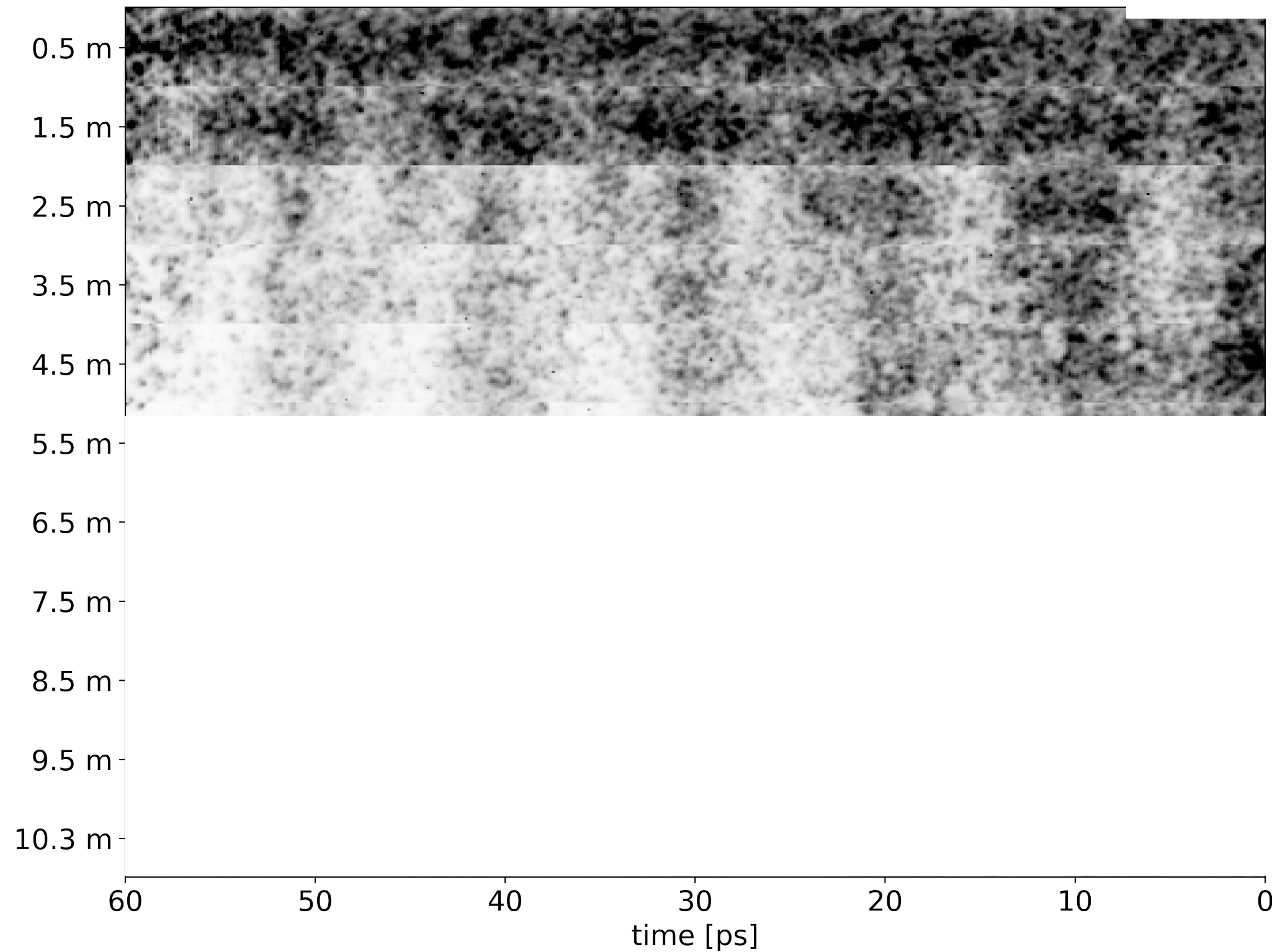
Bunch density not yet modulated

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Proton Bunch Evolution



Select subsection

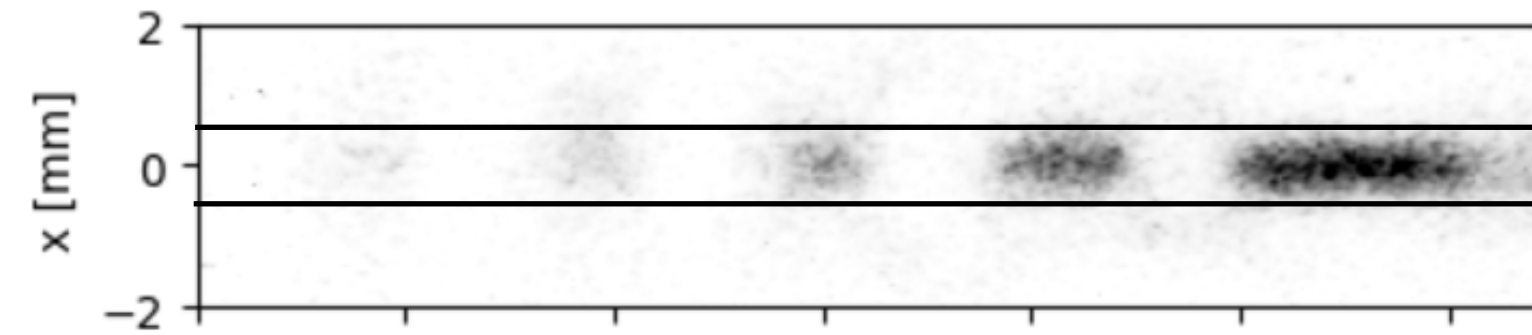


→ Bunch density not yet modulated

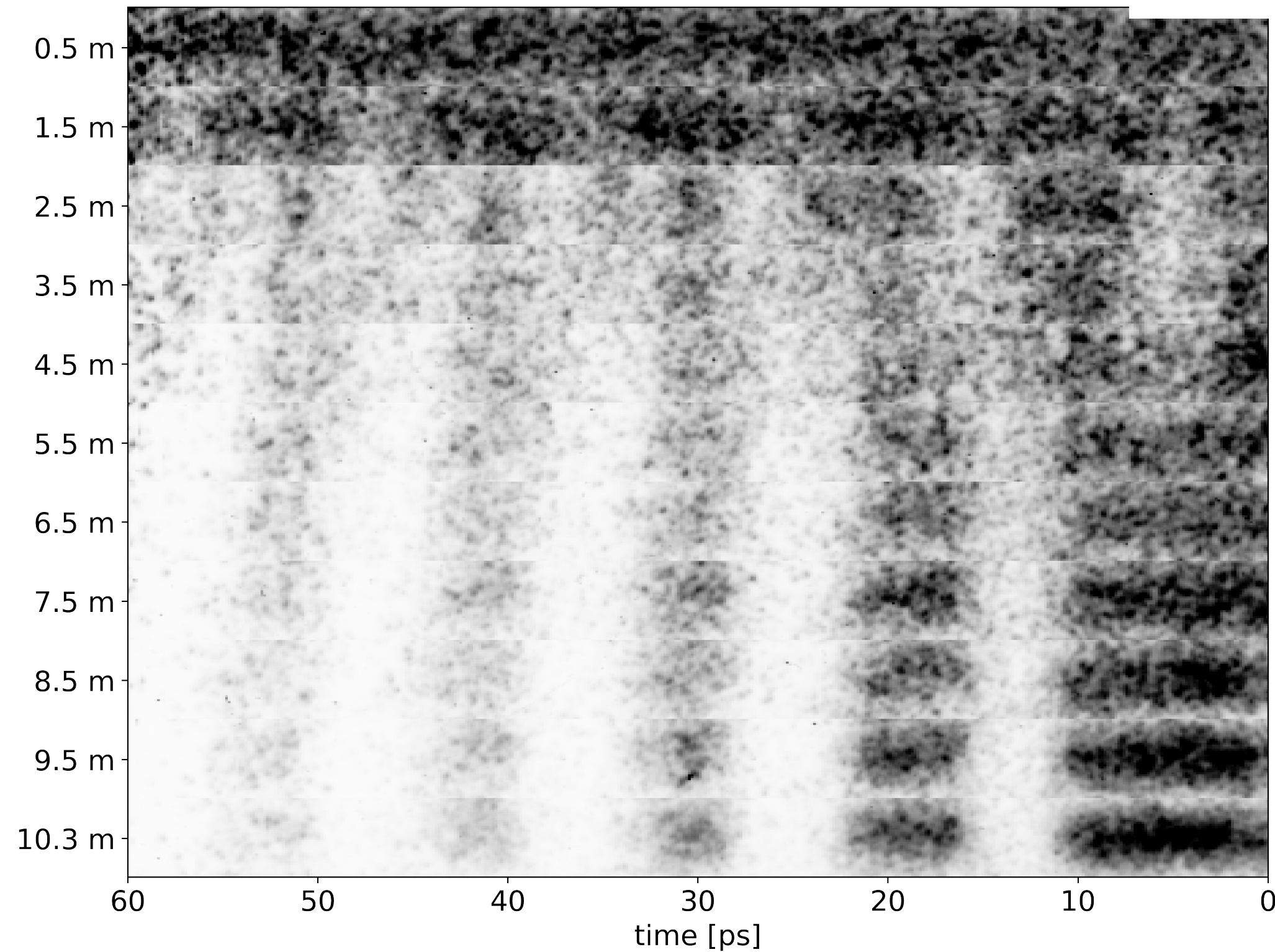
→ Modulation developing

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Select subsection



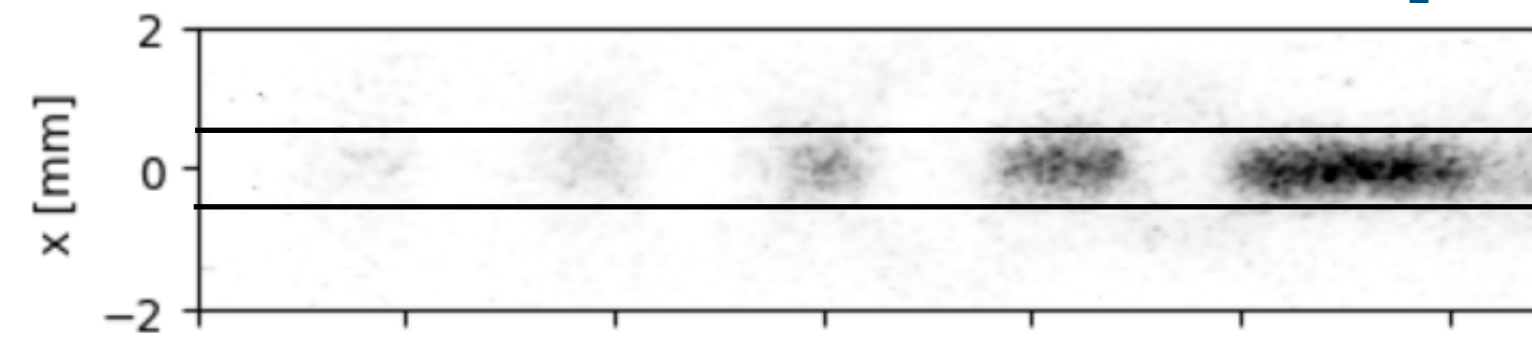
→ Bunch density not yet modulated

→ Modulation developing

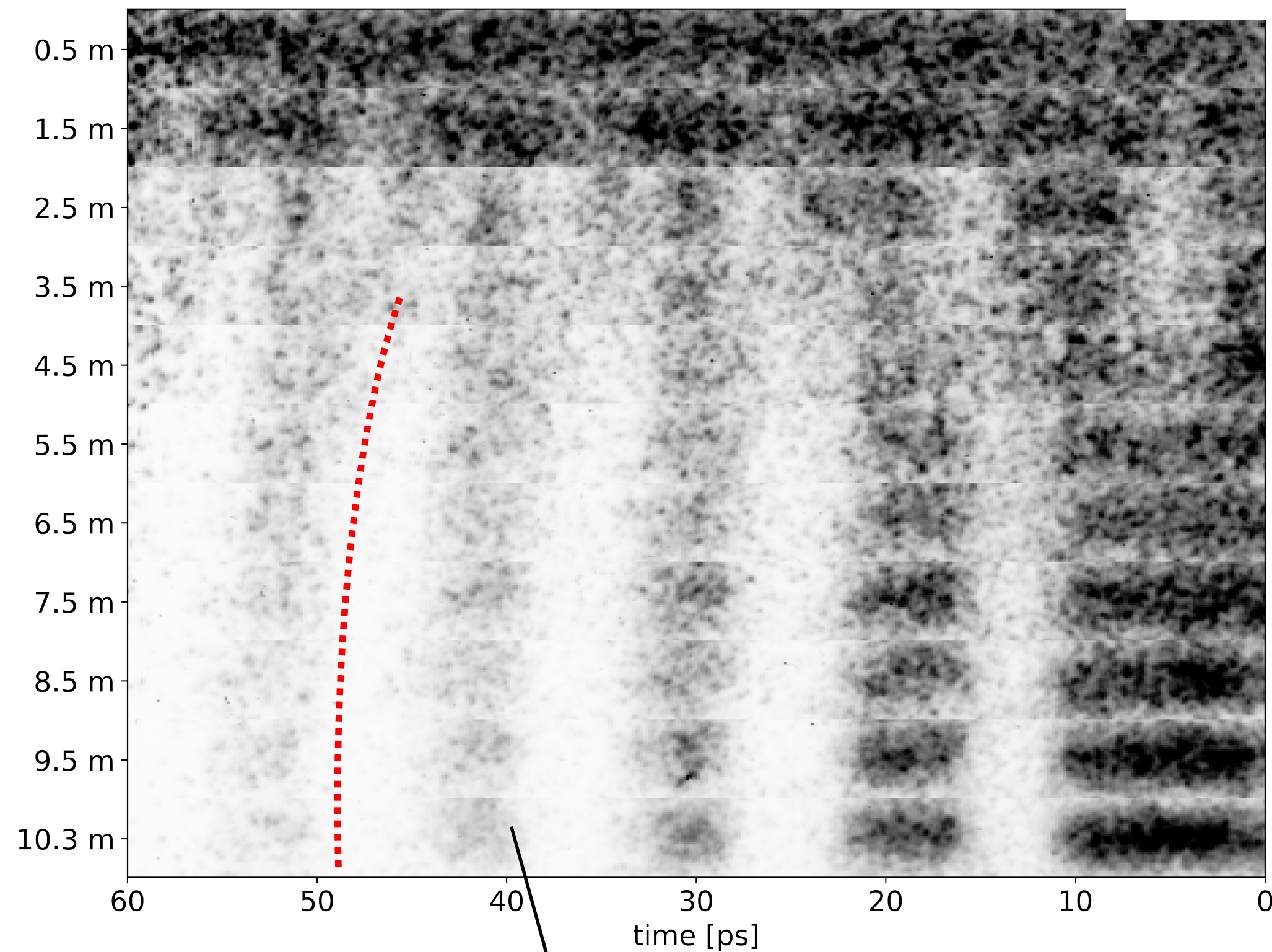
→ Fully modulated

Evolution: Varying Plasma Length (L_{pl})

Proton Bunch Evolution



Select subsection



→ Bunch density not yet modulated

→ Modulation developing

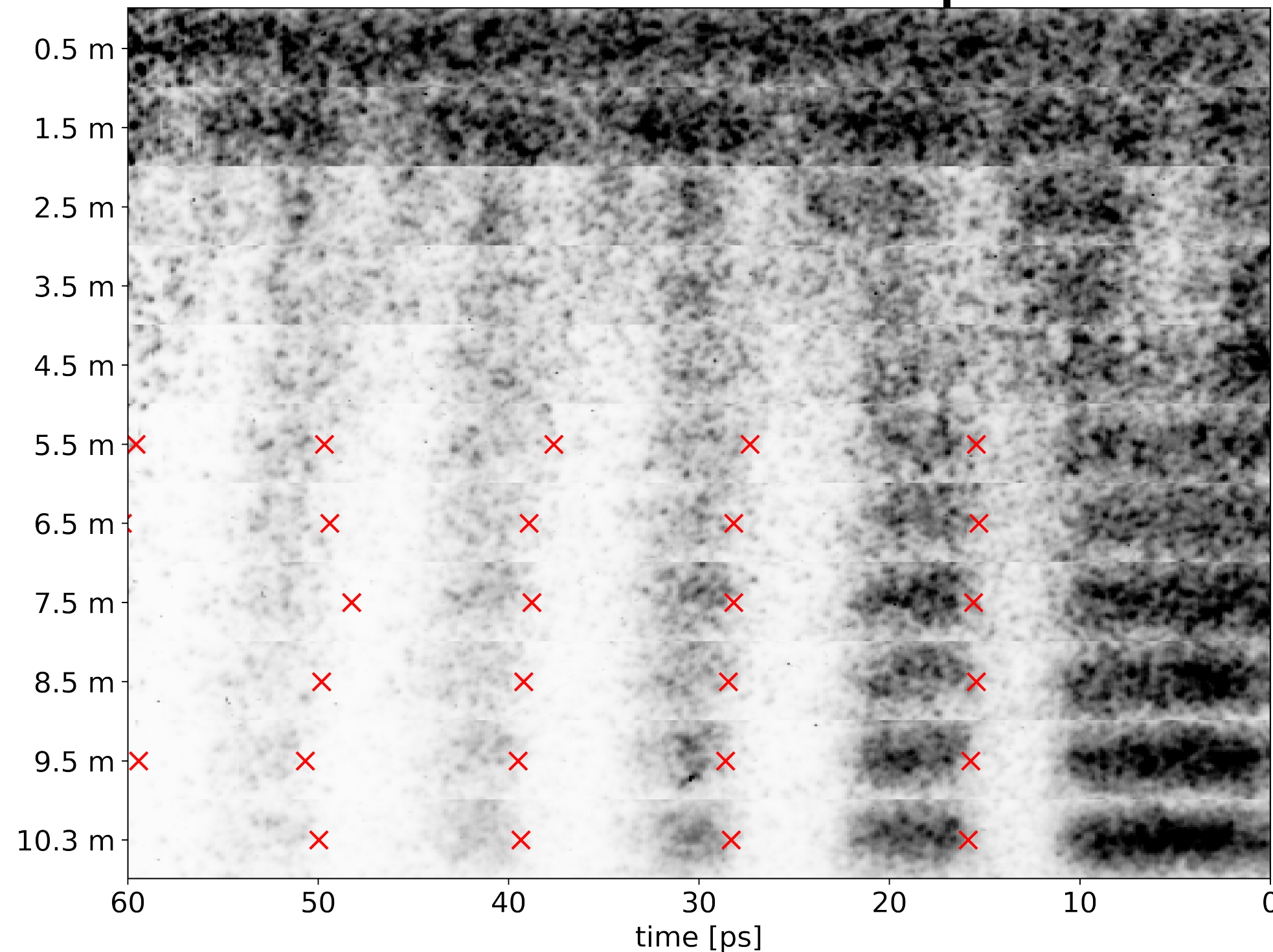
→ Fully modulated

Start of the micro bunch moving backwards ?

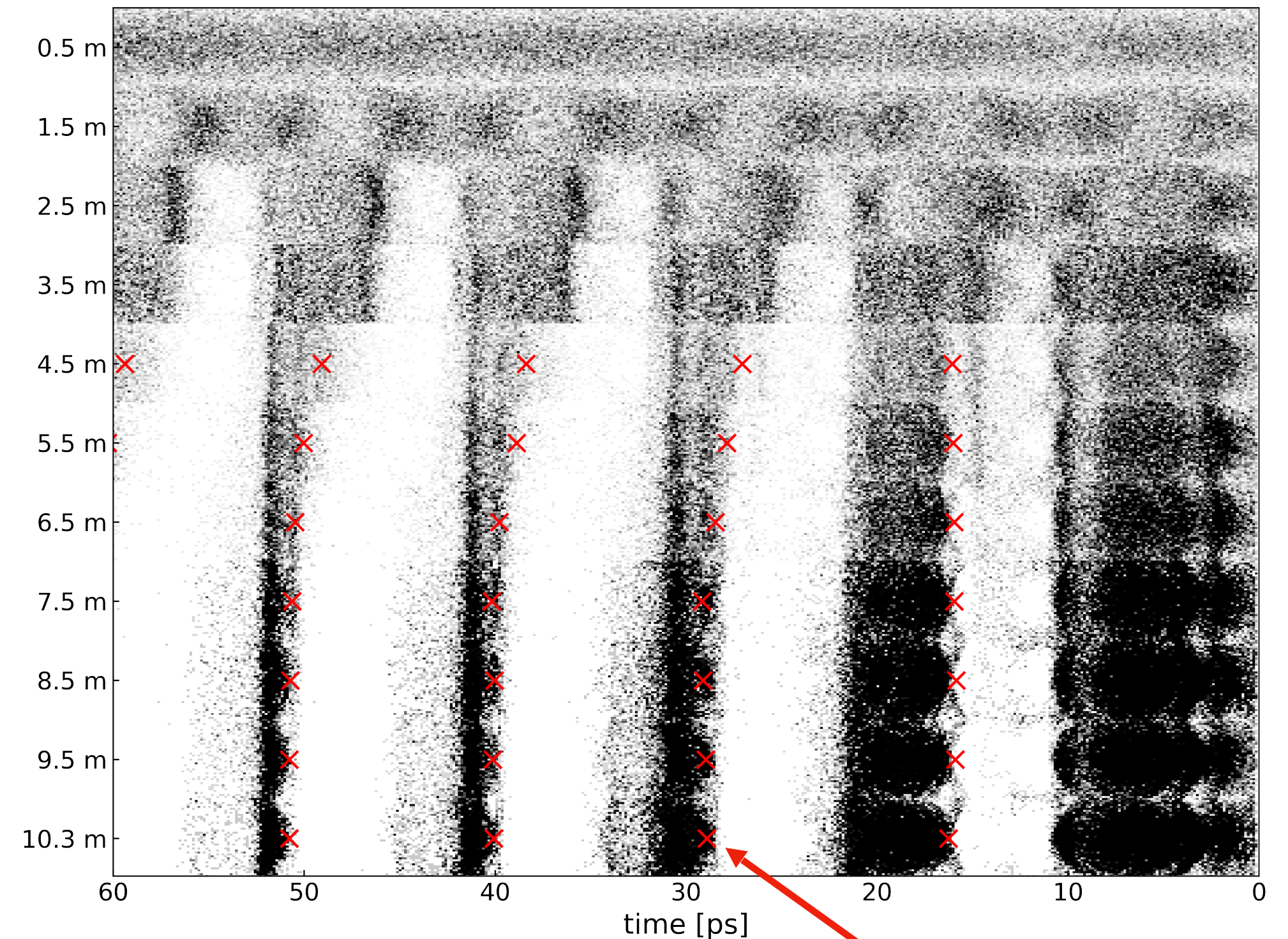
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Proton Bunch Evolution

Experiment



Simulation

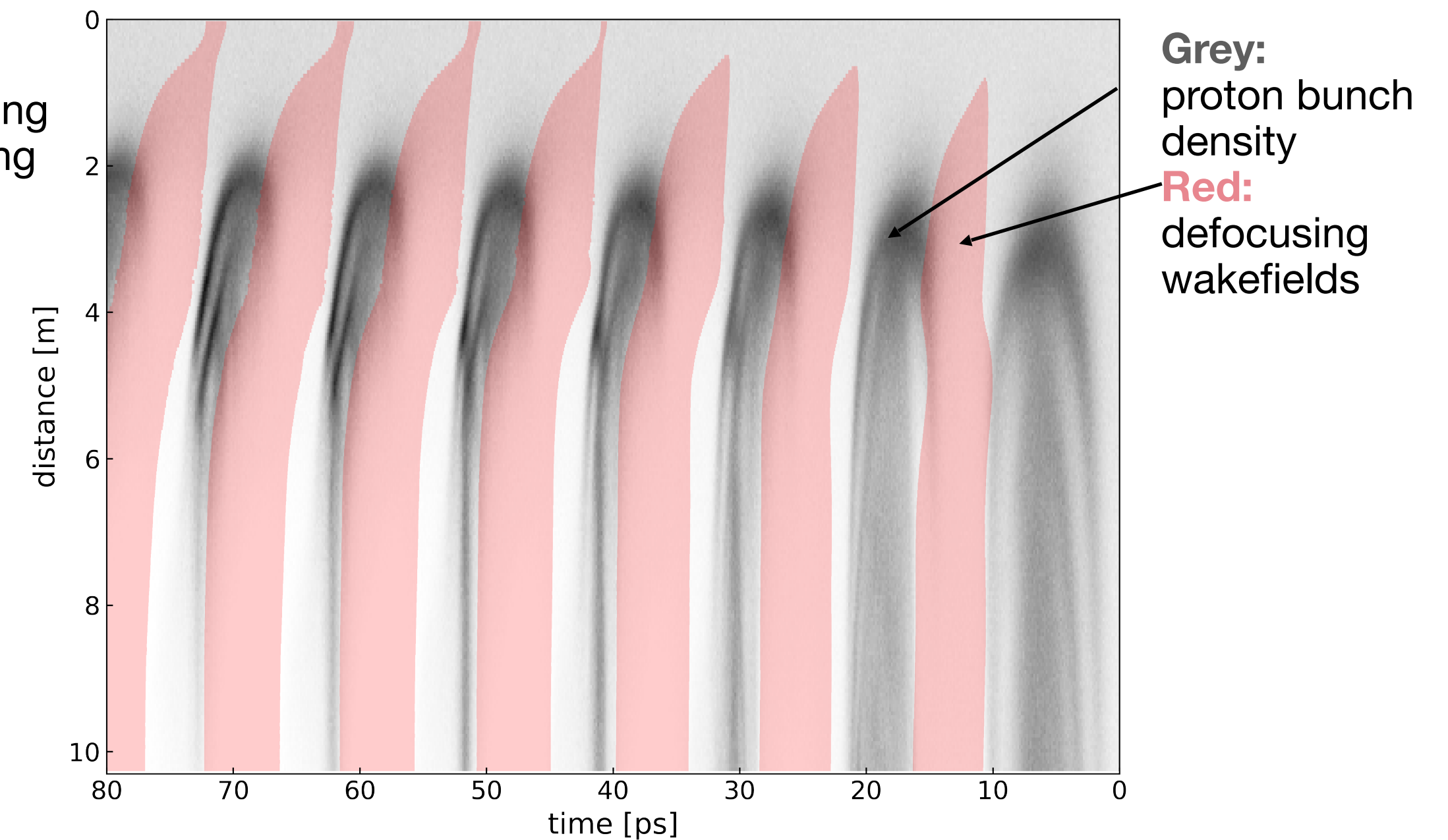
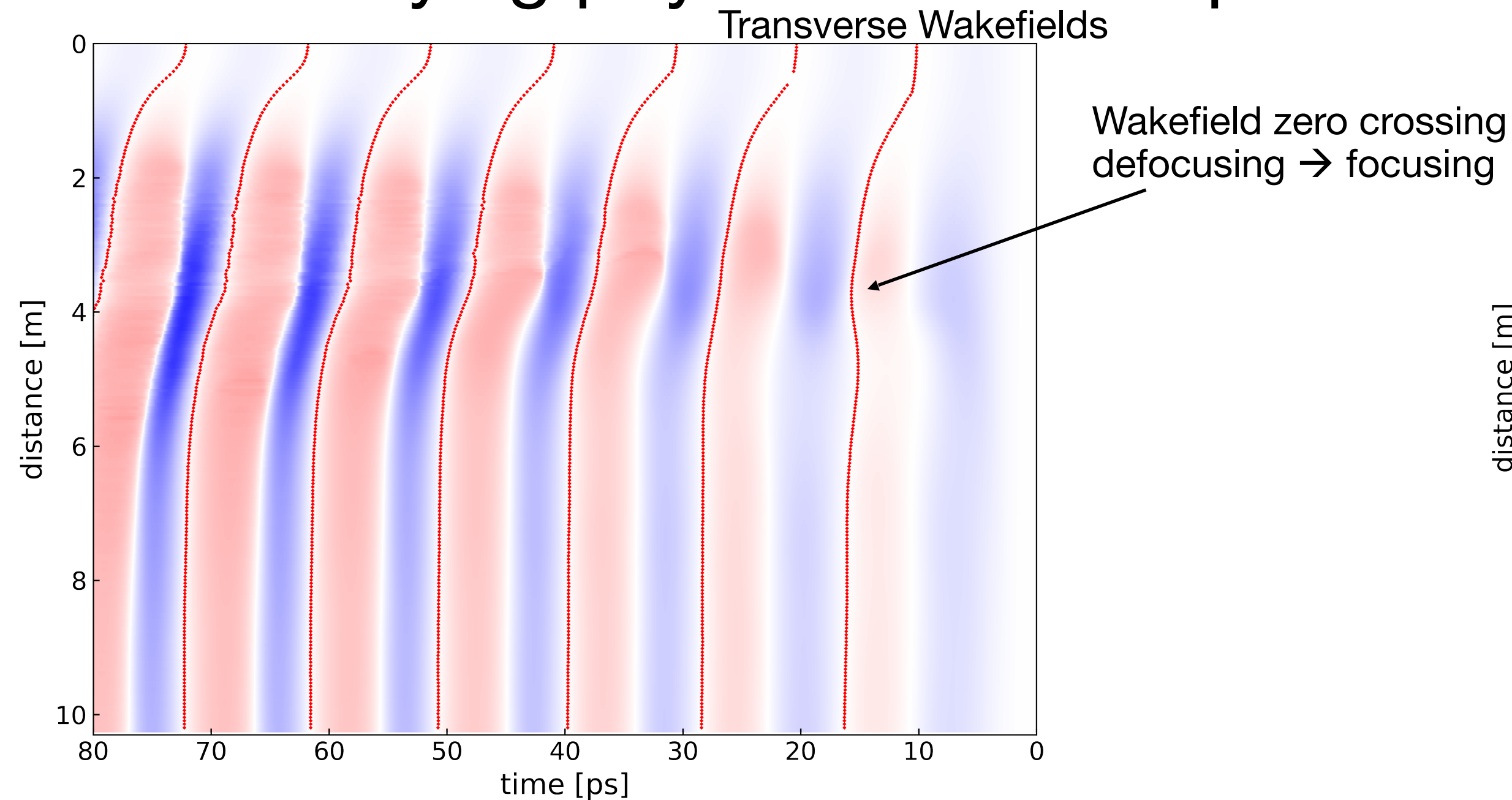


- Excellent agreement between experiment and simulations
- Start of the microbunch moving backward !

Micro bunch start

Wakefield Phase Velocity

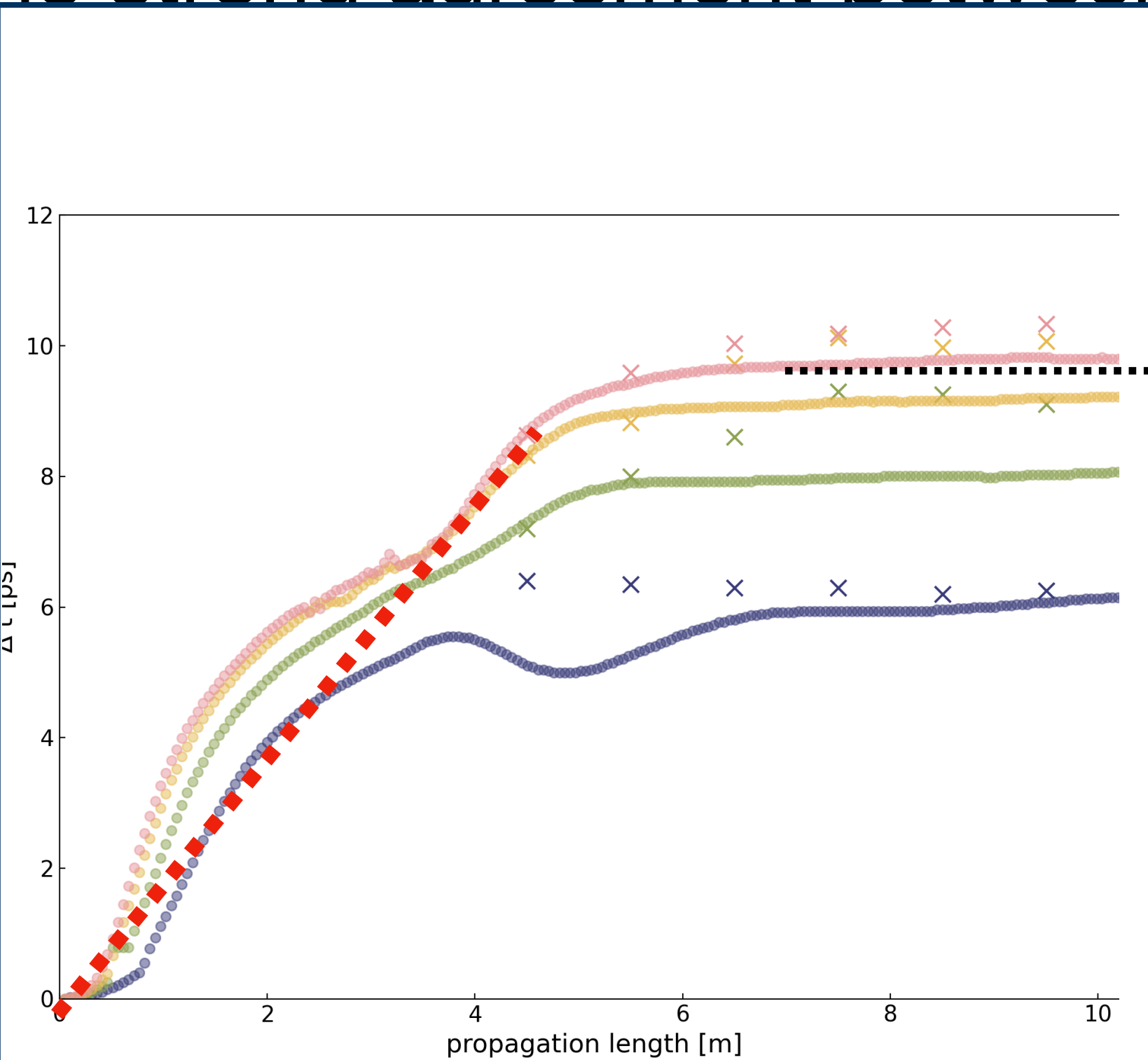
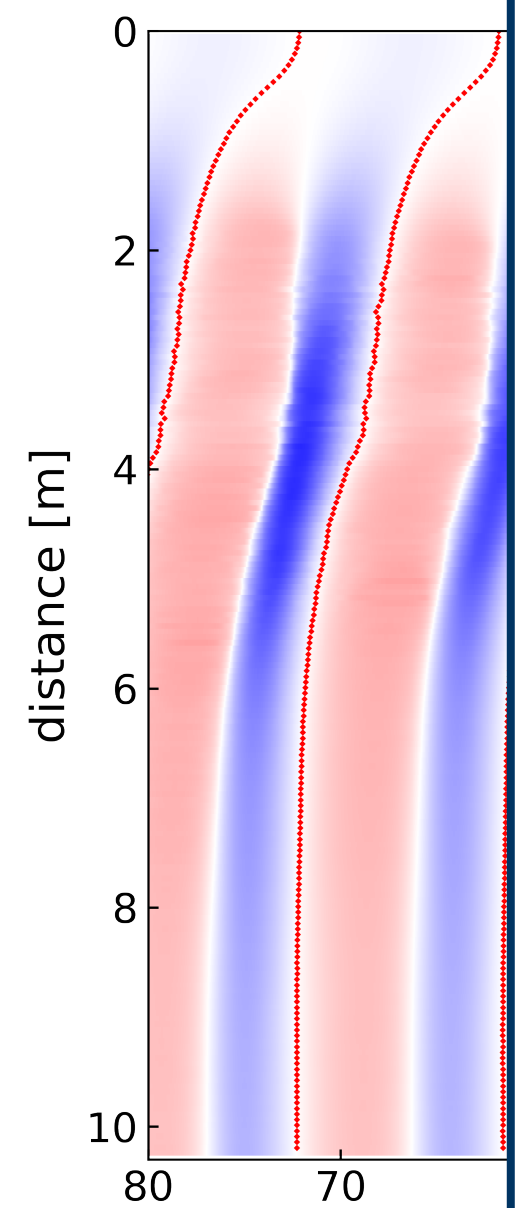
- Given the strong agreement between simulations and experimental results, the underlying physics can be explored using simulations



- Wakefield phase is shifting backwards during the evolution of SM
- Predicted by Pukhov, PRL 107, (2011)
- Microbunches are starting later as the defocusing region is shifting backwards
- Start of the micro bunches therefore a good proxy for the wakefield phase for different L_{pl}

Wakefield Phase Velocity

- Given the strong agreement between simulations and experimental results, the und



Blue: proton bunch density
Red: defocusing wakefields

- Can now be used to evaluate the phase velocity during the evolution of SM
 $\rightarrow \gamma \sim 30$
 - And evaluate at which point along the plasma the phase velocity stabilizes
 $\rightarrow L_{pl} > 7m,$
- important for acceleration, as particles need to be injected after that point

Wakefie
the evol

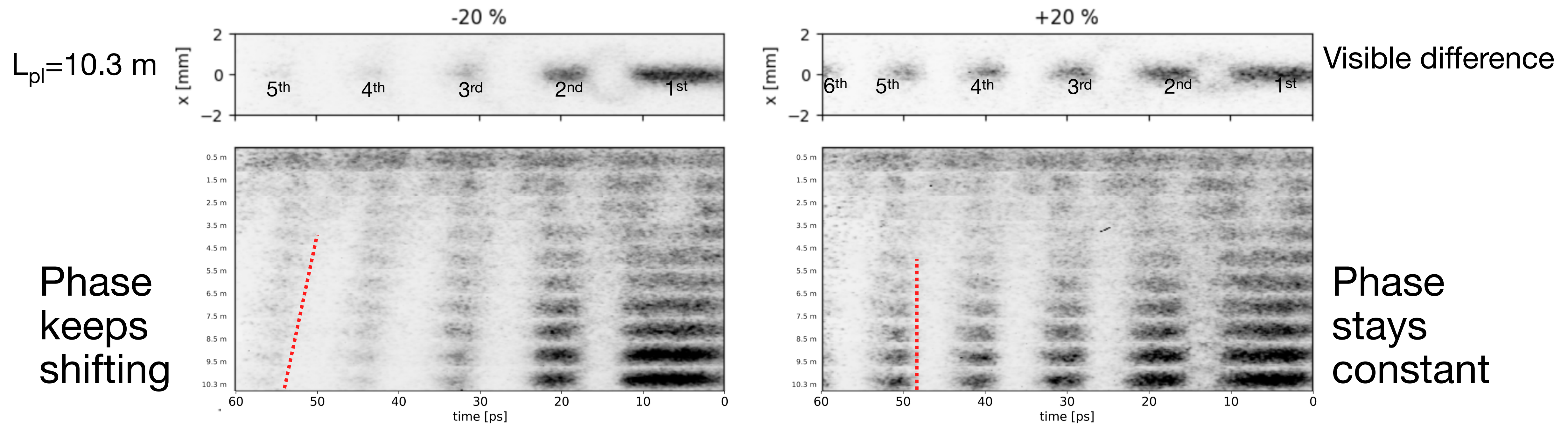
the
wards

- Predicted by Pukhov, PRL 107, (2011)
- Start of the micro bunches therefore a good proxy for the wakefield phase for different L_{pl}

Phase Velocity Control

Plasma Tapering

- Measurements until now performed using a uniform plasma density
- Can also add a linear density gradient to adjust the phase



Summary & Conclusions

- Plasma wakefield accelerators offer a promising route toward compact linear accelerators
 - Efficient acceleration requires the wakefield phase velocity to closely match the particle velocity
- Estimating the micro-bunch onset across varying plasma lengths enables tracking of wakefield phase velocity
 - Strong agreement observed between experimental results and simulations
- Plasma density gradients allow to control the wakefield phase velocity
 - Particularly relevant for mitigating dephasing effects