Observing Self-Modulation Growth through Light Emission of Dissipating Wakefielfds

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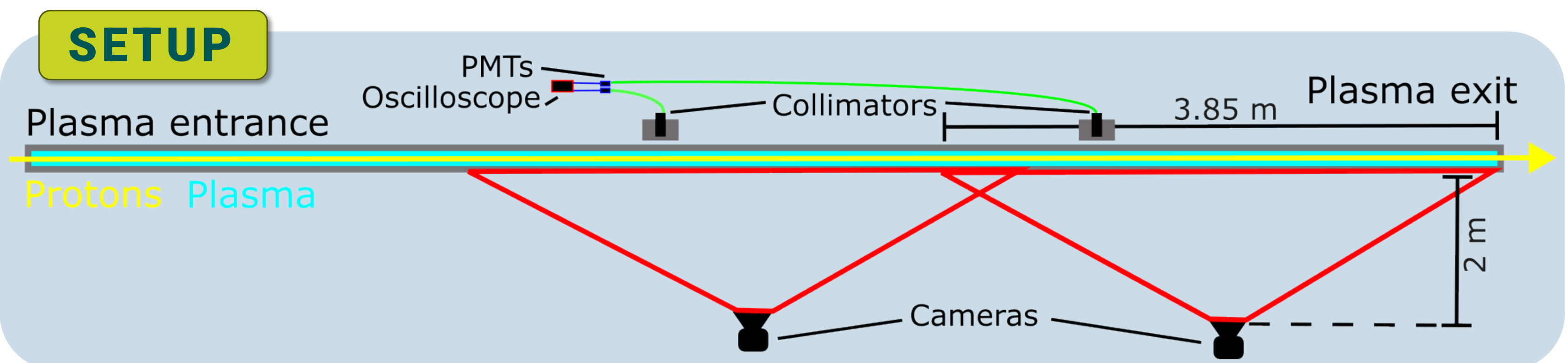
ABSTRACT

At AWAKE, self-modulation of a long relativistic proton bunch is used to drive high-amplitude wakefields. As the proton bunch self-modulates while propagating through the 10 m long plasma, the amplitude of the wakefields grows. Measuring the wakefield amplitude directly has not been possible so far. However, as the energy stored in the wakefields is dissipated, some fraction of it is emitted as light. By measuring the intensity of the light, we observe for the first time the growth of the self-modulation process along the plasma. By varying bunch and plasma parameters, we investigate the dependencies of the self-modulation growth. When imposing a density gradient along the plasma, we also observe growth suppression, as predicted by theory.

DISCHARGE PLASMA SOURCE (DPS)

The discharge plasma source provides **flexible plasma parameters** for conducting experiments **investigating bunch-plasma instabilities**, especially the self-modulation instability. The plasma density can be set for each event.

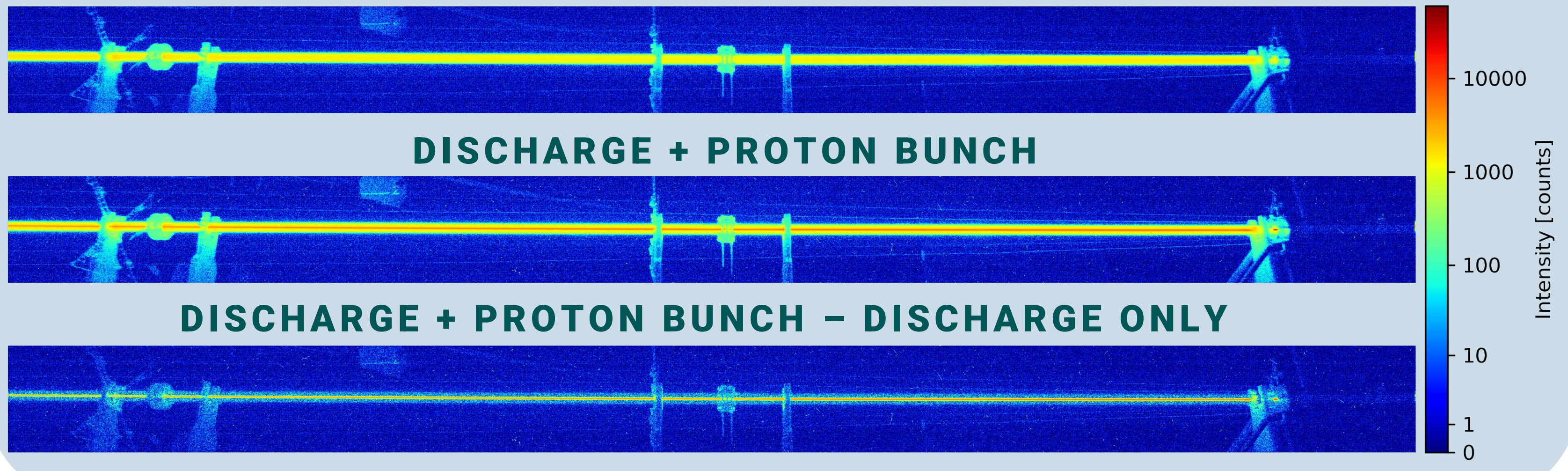
SETUP



DISCHARGE

The plasma is created by a discharge through a noble gas → Xe at 16 Pa
- Peak current 500 A
- Current pulse duration ~ 35 us
- Peak plasma density n_{pe} = 12 x 10^{14} cm^{-3} ~ 30% ionization
- Diameter of plasma column: 26 mm (inner diameter of discharge tube)

CAMERAS



CAMERA SPECIFICATIONS

- 1 us exposure time
- Image size 5280 x 400 pixels
- Spatial resolution < 1 mm
- Single camera FOV ~ 3.7 m
- Combined camera FOV: ~ 7m

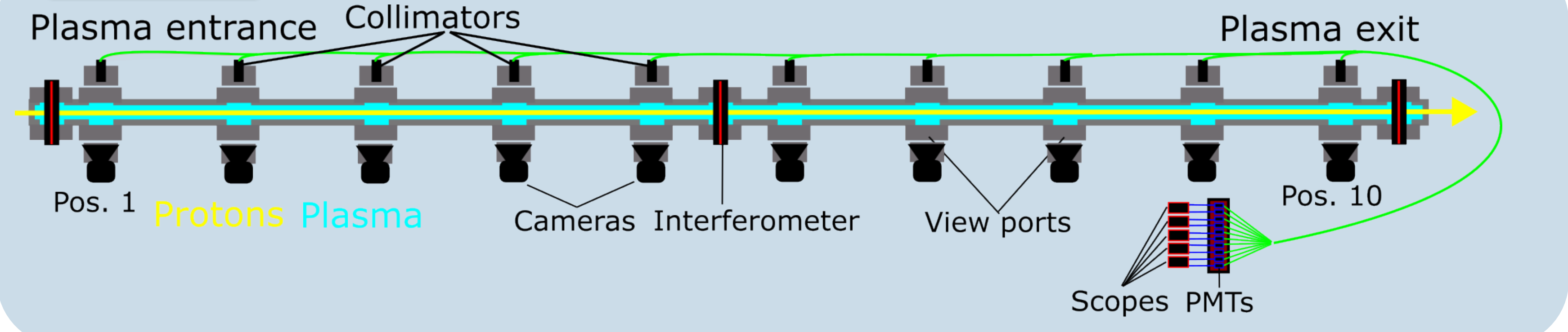
DATA PROCESSING

- Image operations correcting for:
  - Distortion
  - Vignetting
  - Perspective
- Discharge only events subtracted
- Pixel counts summed vertically
- Median filter to remove radiation noise on CCD

VAPOR PLASMA SOURCE (VAPS)

The vapor plasma source provides a **highly uniform plasma** suitable for electron acceleration and **studying the effects of different plasma density profiles** along the axis of propagation. It features a rubidium vapor in thermal equilibrium, which is ionized by an ultrashort laser pulse.

SETUP



LASER

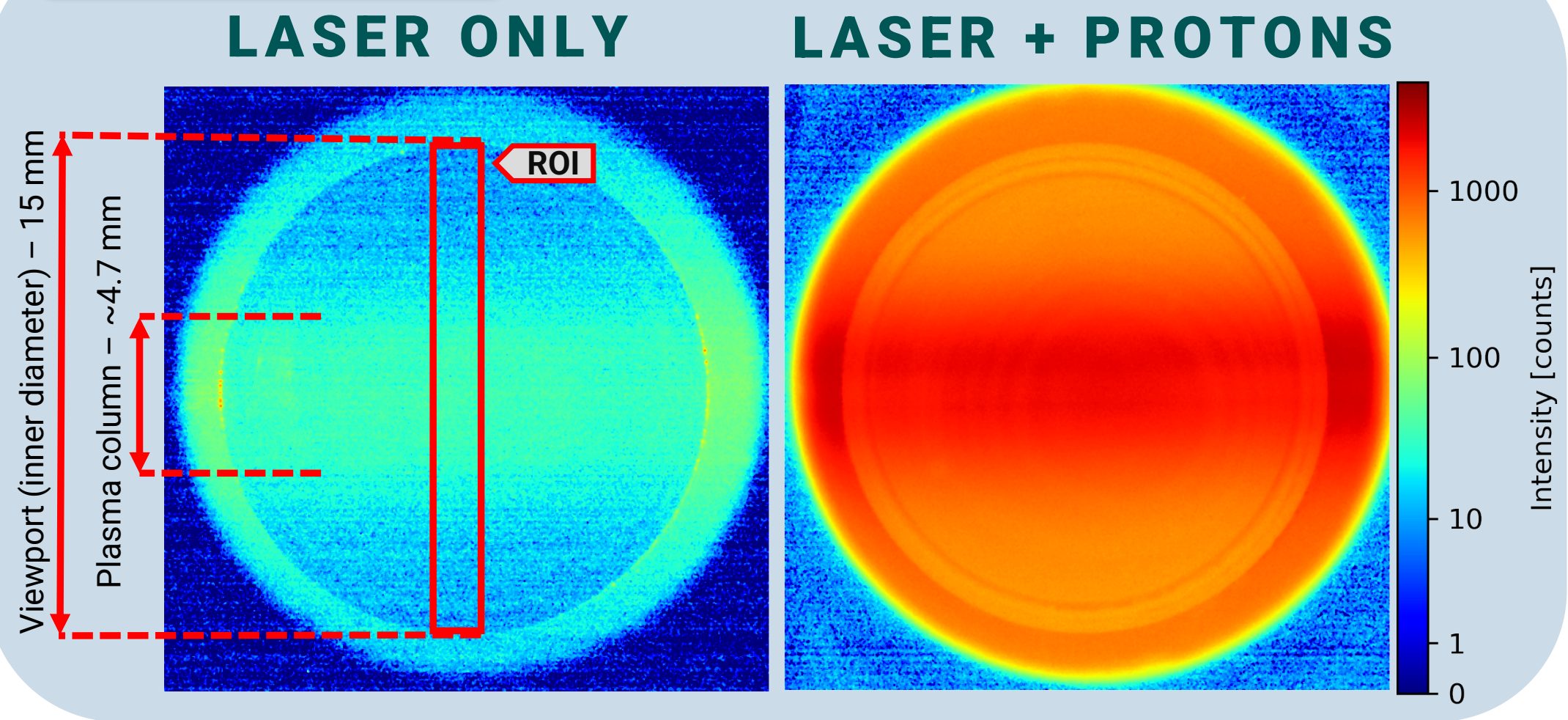
- 780 nm Ti:Sa-laser
  - Pulse duration: 100 fs
  - Pulse energy: 100 mJ → full ionisation
- **Propagated with p^+-bunch** (RIF)
  - → Large controlled perturbation
  - → **Seeded self-modulation**

DATA PROCESSING

- Image cropped to ROI
- Pixel counts summed
- Laser only events subtracted
- Calibration applied
  - Filters
  - Aperture

CAMERAS

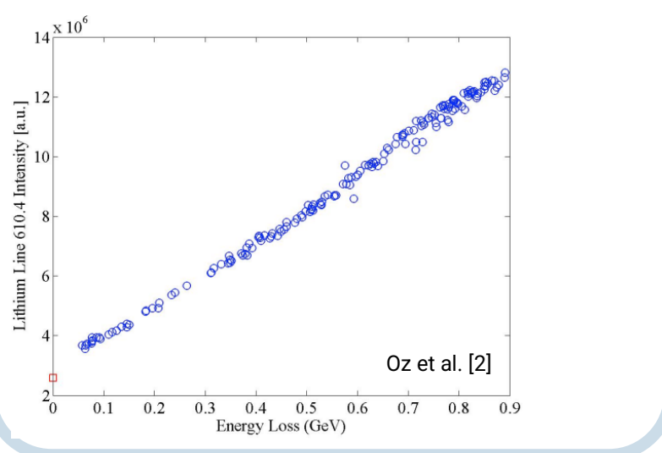
- 40 us exposure time
- Image size 750 x 750 pixels



WAKEFIELD DISSIPATION

Wakefields **dissipate their energy** through many convoluted effects. In all cases, the energy ends up as kinetic energy of the electrons and ions, therefore increasing the rate of inelastic collisions **causing spectral light emission** [1].

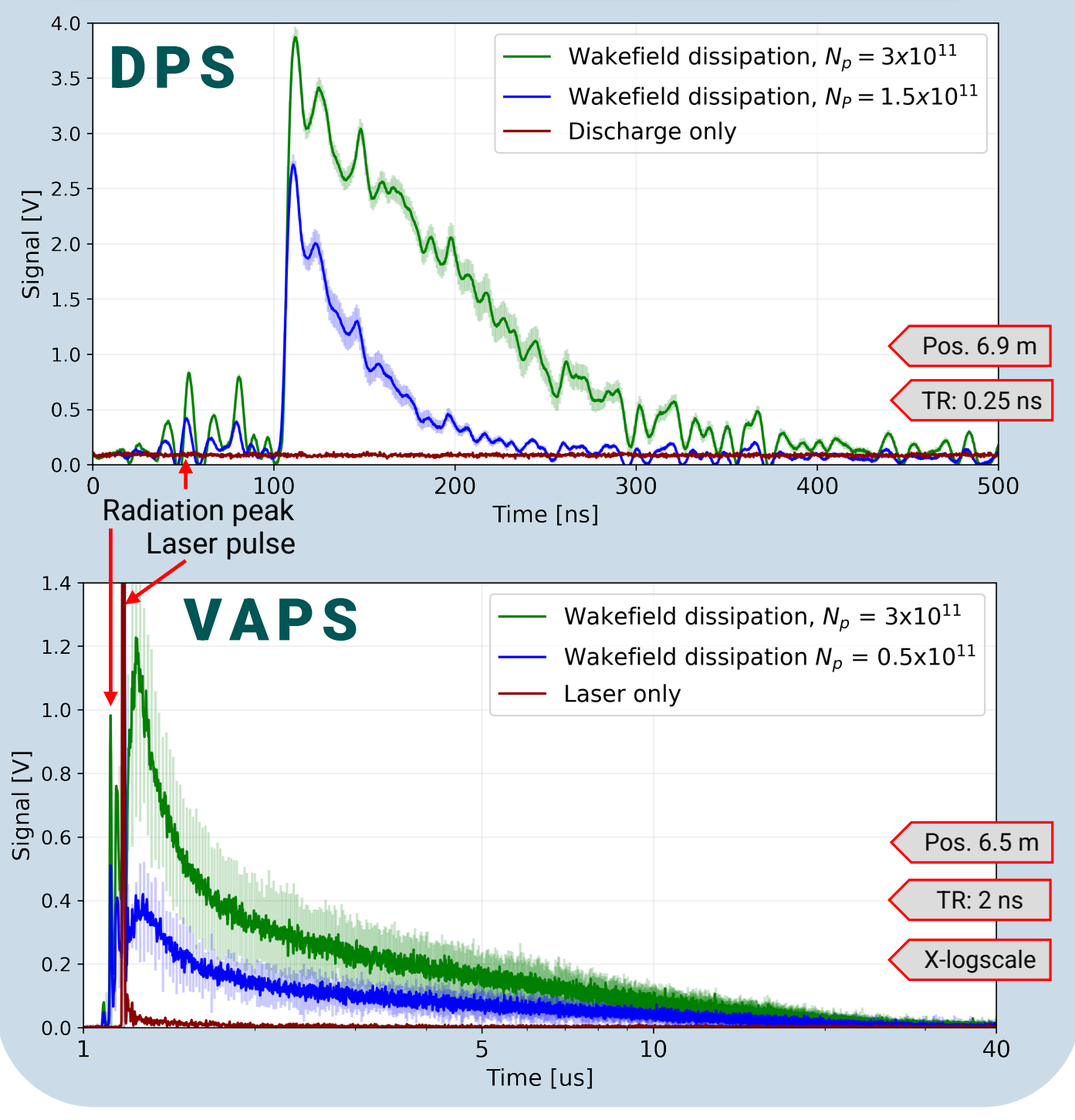
Measurements of plasma light in an electron based PWFA show a linear relation between spectral light intensity and energy loss of the bunch [2].



TIME RESOLVED SIGNAL

- Dissipation peak duration:
  - (above detection threshold)
  - → DPS: ~ 200-400 ns
  - → VAPS: ~ 30-40 us
- Dissipation peak maximum:
  - → DPS ~ 12 ns after excitation
  - → VAPS ~ 60 ns after excitation
- **Higher bunch density** - larger wakefield amplitude expected
  - **→ more light emitted**

PHOTOMULTIPLIERS



SELF-MODULATION GROWTH

The transverse components of wakefields have focusing and defocusing phases. As the proton bunch undergoes self-modulation, **protons in the defocusing phase are ejected**, leaving behind a train of micro-bunches in the focusing phase. The micro-bunches amplify the initial wakefields and the **wakefield amplitude grows** at a similar rate as the self-modulation instability.

PARAMETERS

- N_p = 1.5 x 10^{11} protons
- Approx. Gaussian profile
  - σ_z = 5 cm
  - σ_r = 165 µm
- n_{pe} = 2.5 - 12.5 x 10^{14} cm^{-3}

GROWTH RATE

- Analytic expression for cylindrical bunch profile

$$\rightarrow E_r(z) = E_{r,0} e^{z\,\Gamma(z)}$$

- $\Gamma \propto n_{pe}^{\frac{1}{6}}$, $\Gamma \propto z^{-\frac{1}{3}}$ [3]
- Valid only in the linear regime

PLASMA LIGHT

- **Intensity increasing along the plasma**
- From 3-7 m: growth function fitted:

$$f(x) = a \times e^{z^{\frac{2}{3}} b}$$

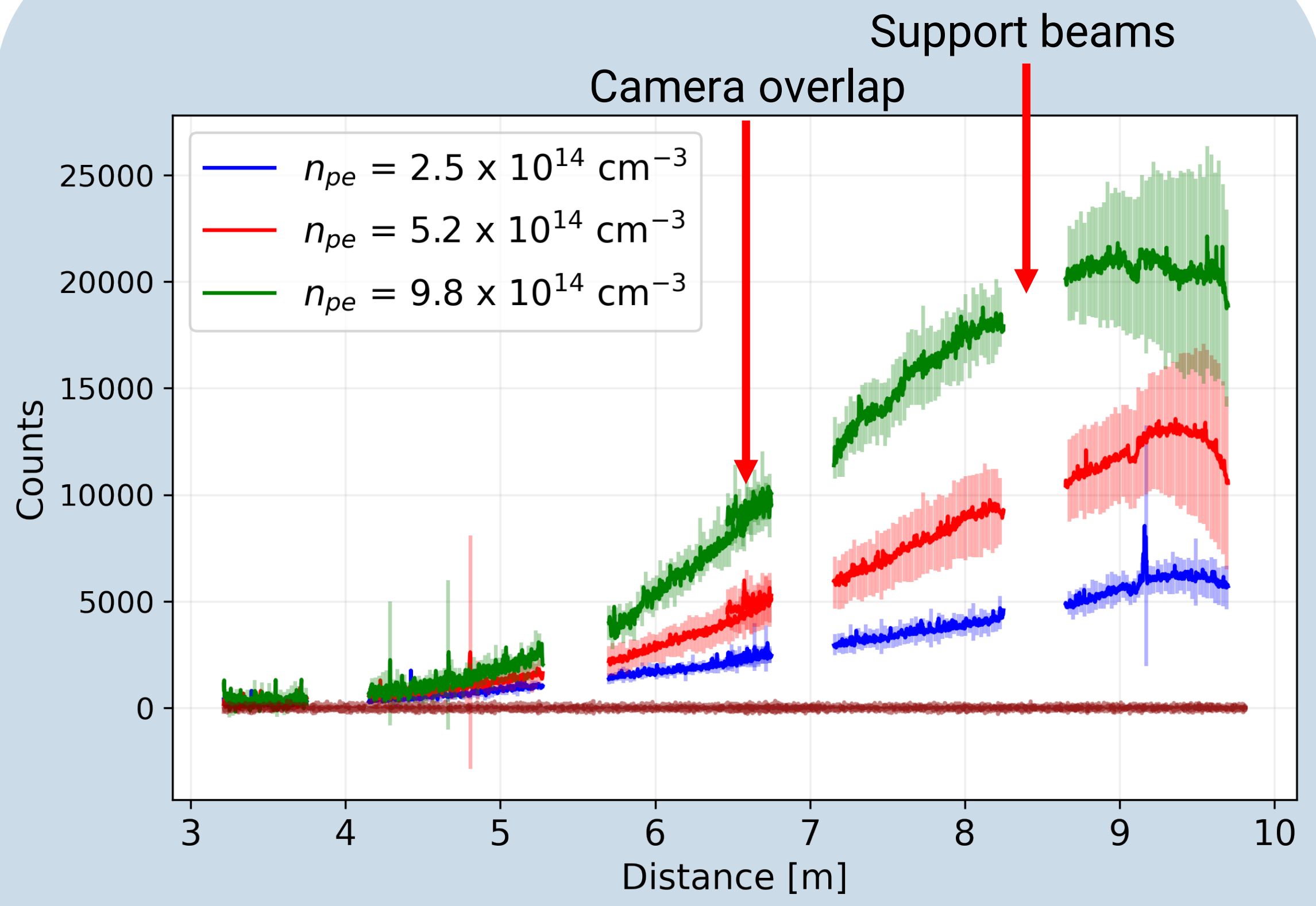
→ Growth rate

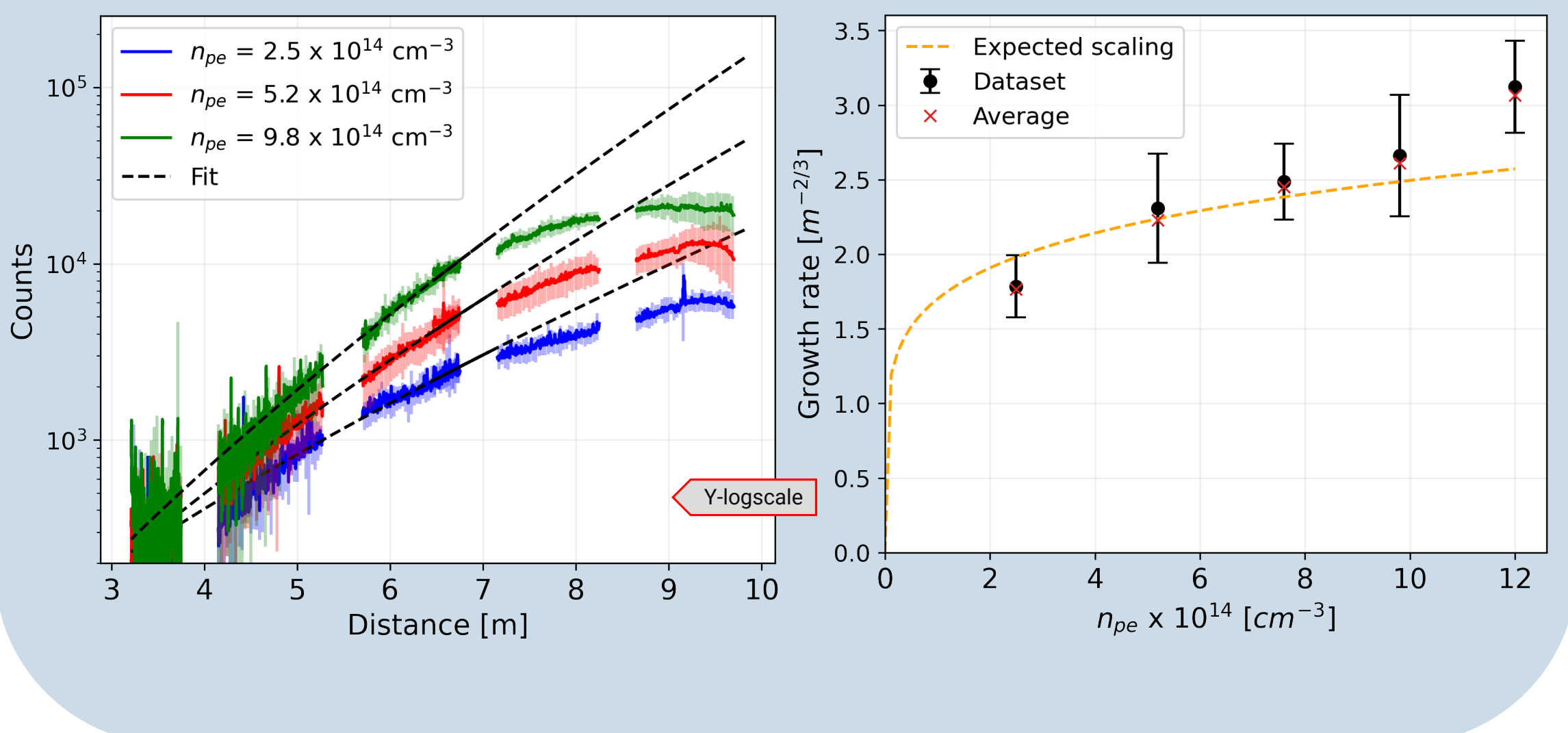
- **Higher plasma density**

Higher growth rate

- Saturation at 9-10m

INTENSITY PROFILES (DPS)





GROWTH SUPPRESSION

A **density gradient along the plasma**, causes the phase of the wakefields to shift along the bunch. For a large gradient, focusing and defocusing forces alternate at a fixed position along the bunch. This **inhibits the formation of a micro-bunch train**, and the self-modulation instability is effectively suppressed. We demonstrate the experimental observation of this effect, which has been theorized in 2012 by C. B. Schröder et al. [4].

PARAMETERS

- N_p = 0.5 x 10^{11} protons
- Approx. Gaussian profile
  - σ_z = 5.4 cm
  - σ_r = 167 µm
  - RIF (leading edge) position: +6 cm
- n_{pe} = 2 x 10^{14} cm^{-3}

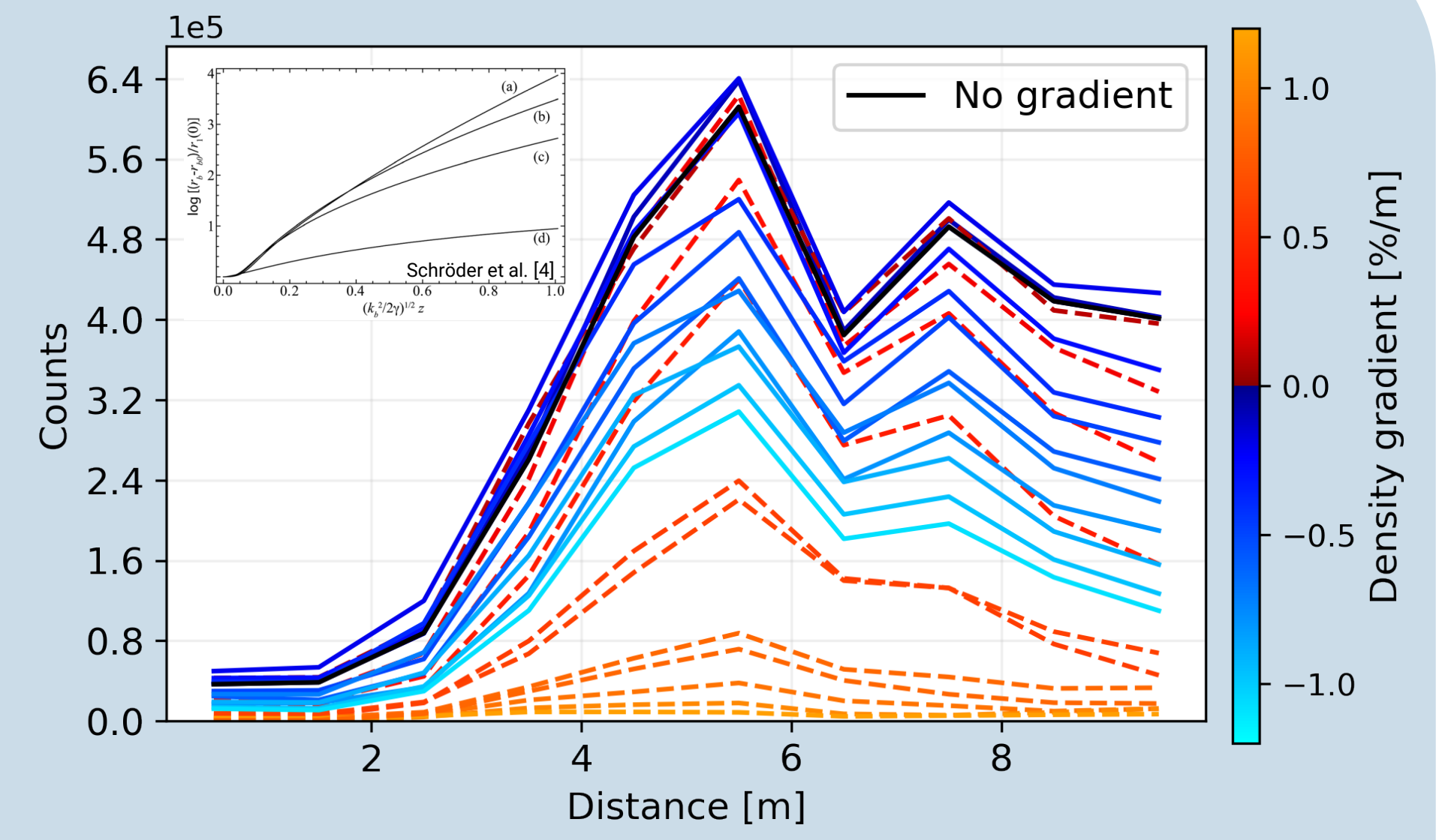
DENSITY GRADIENT

- Density controlled with temperature of upstream / downstream Rb reservoirs
- Temperature difference → gradient
- Upstream density kept constant
- Rb density tracked by interferometers

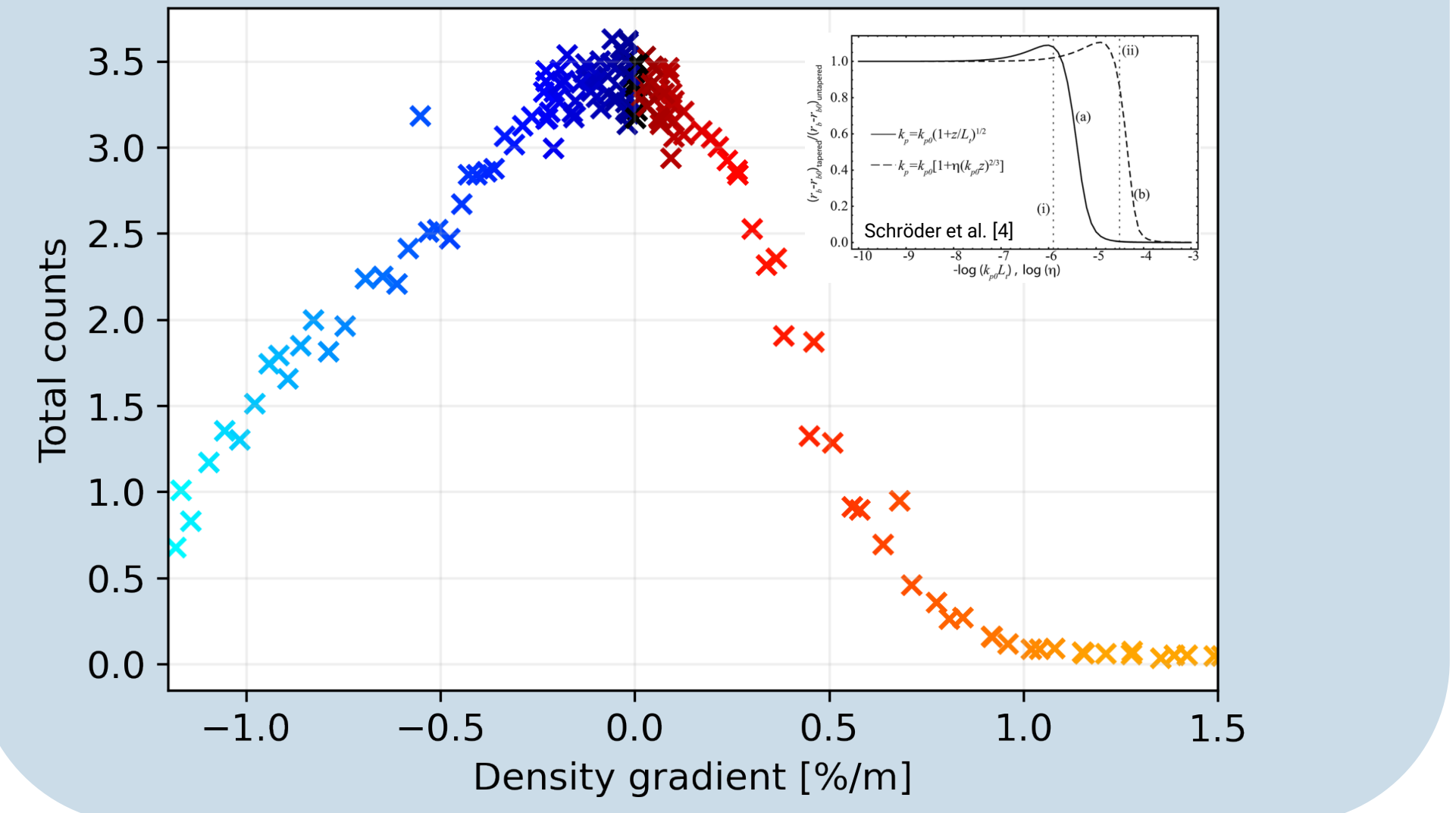
PLASMA LIGHT

- No gradient:
  - Growth between 0.5 to 5.5 m → Saturation
- Positive gradient:
  - Less light > 0.1 %/m
  - **No light > 1%/m**
    - **→ self-modulation fully suppressed**
- Negative gradient:
  - Less light < -0.25 %/m
  - Still some light at -1.2%/m
    - → self-modulation **not** fully suppressed

INTENSITY PROFILES (VAPS)



ALL CAMERAS SUMMED



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[1] P. Muggli et al. "Plasma Light As Diagnostic For Wakefields Driven By Developing Self-Modulation Of A Long Particle Bunch", Proceedings AAC 2022 (2023)
[2] E. Oz et al. "Optical Diagnostics for Plasma Wakefield Accelerators", AIP Conference Proceedings **737**, 708 (2004)
[3] A. Pukhov et al. "Phase Velocity and Particle Injection in a Self-Modulated Proton-Driven Plasma Wakefield Accelerator", PRL **107**, 145003 (2011)
[4] C. B. Schröder et al. "Particle beam self-modulation instability in tapered and inhomogeneous plasma", Phys. Plasmas **19**, 010703 (2012)