MAX-PLANCK-INSTITUT
FÜR PHYSIK

LIGHT AS A DIAGNOSTIC FOR WAKEFIELDS

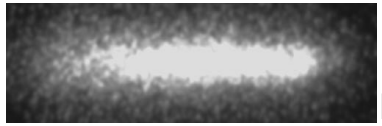
Presented by Jan Mezger

CONTENTS

- Plasma only measurements
- Seed wakefield measurements
- Light profiles

MOTIVATION

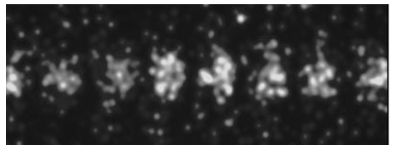
p+ bunch



Self-modulation

10 m plasma

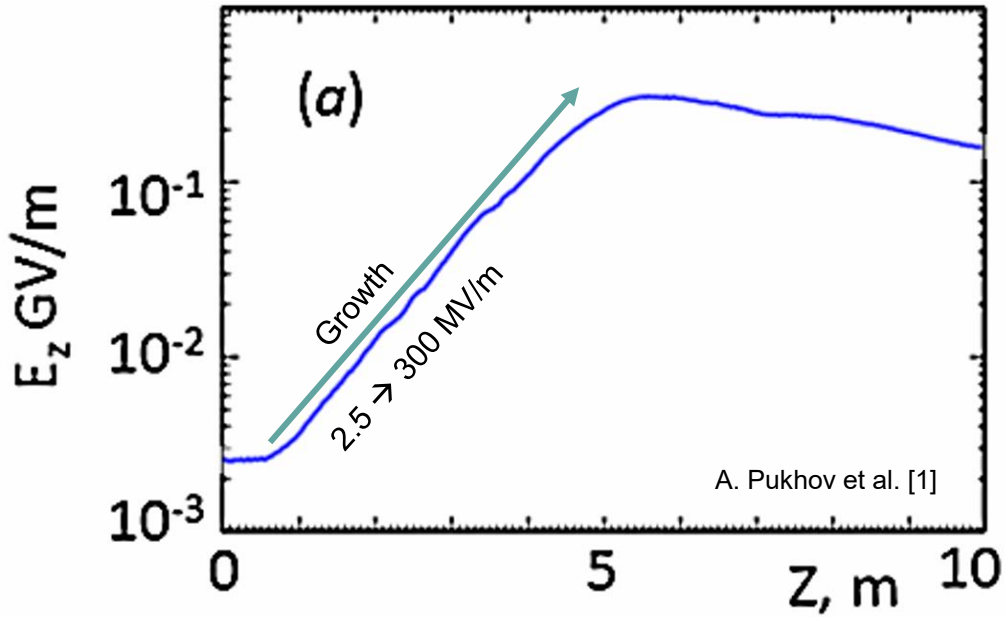
micro-bunch train

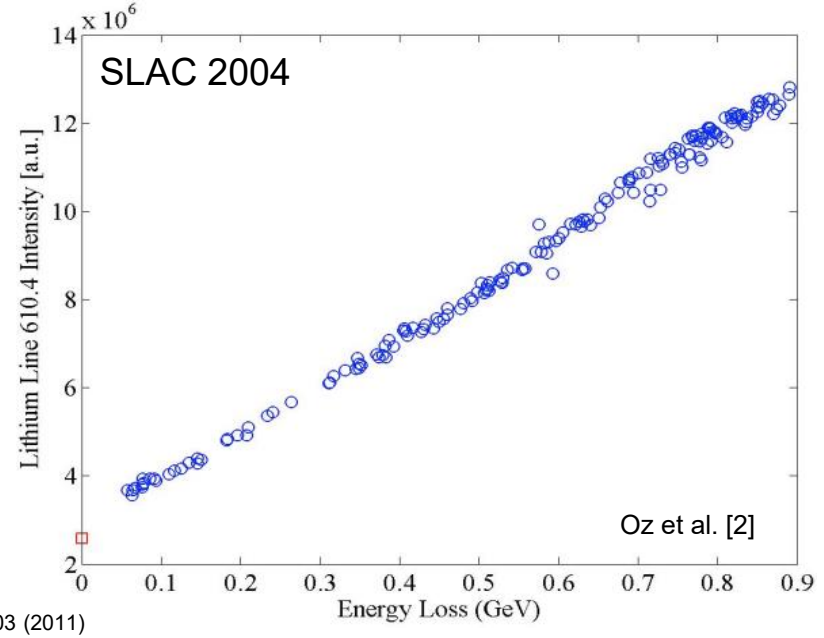


- Wakefields evolve as the p+ bunch self-modulates
- Other diagnostics measuring before / after plasma
- Looking for non-intrusive diagnostic to look inside the plasma

→ Light emission of plasma as measurement of wakefield amplitude along plasma?

Simulated wakefield amplitude

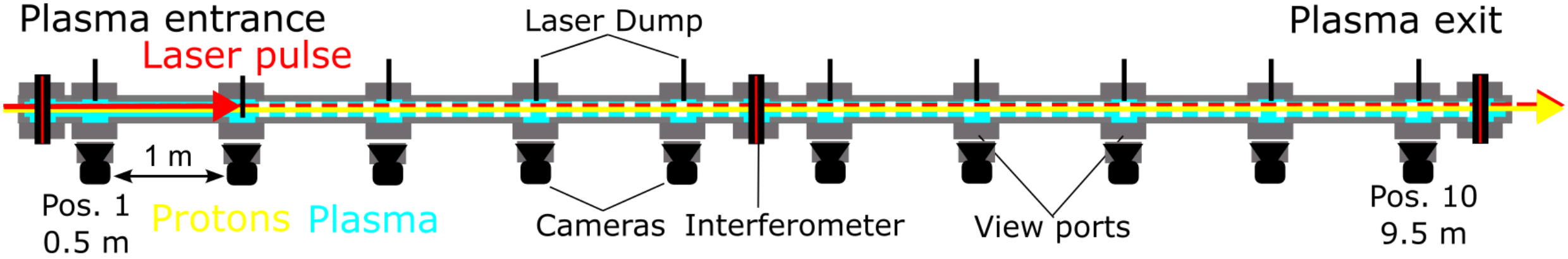


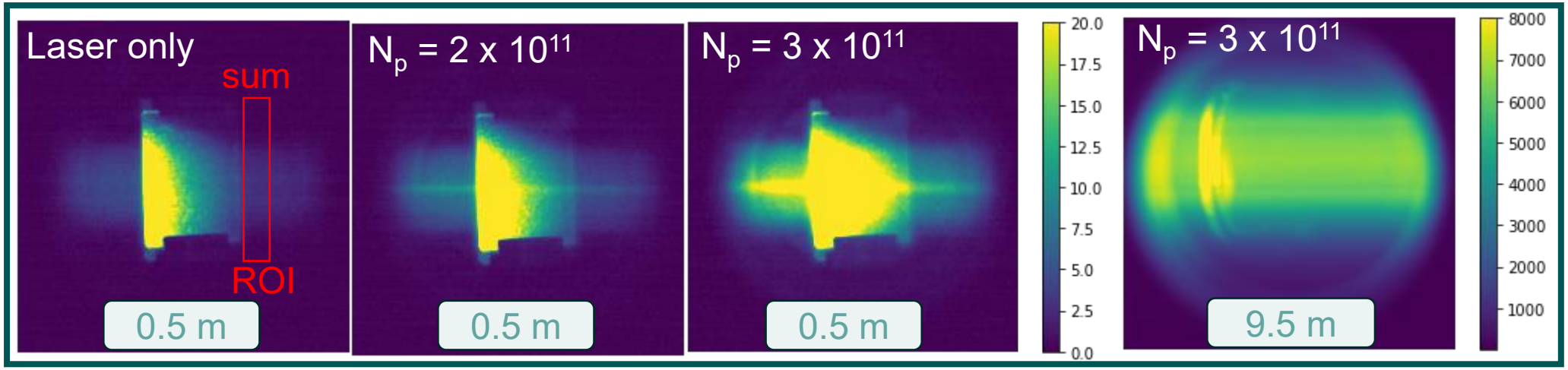


Light vs. Energy deposited by drive bunch

[1] A. Pukhov et al. “Phase Velocity and Particle Injection in a Self-Modulated Proton-Driven Plasma Wakefield Accelerator”, PRL 107, 145003 (2011)
[2] E. Oz et al. “Optical Diagnostics for Plasma Wakefield Accelerators”, AIP Conference Proceedings 737, 708 (2004)

IMPLEMENTATION – SETUP

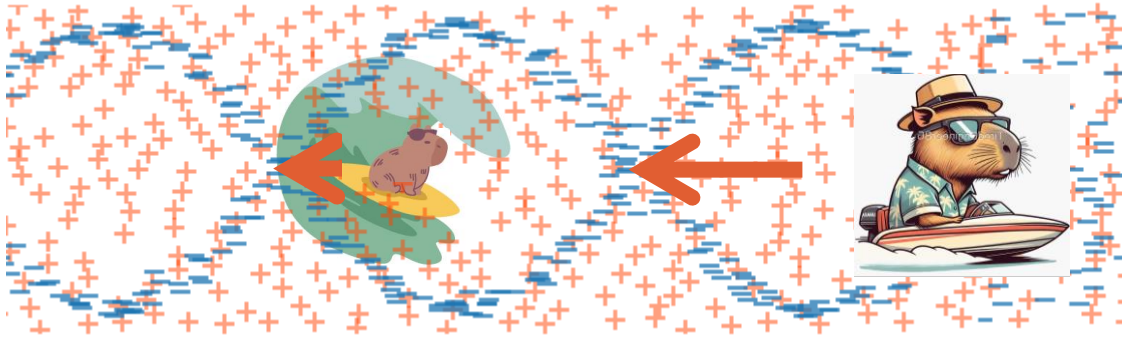




WHAT EXACTLY ARE WE MEASURING?

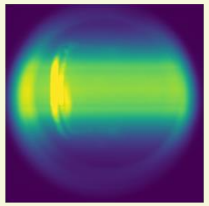
Wakefields

→Energy in coherent motion of electrons and electric field



Cameras / PMTs

→Light measuement



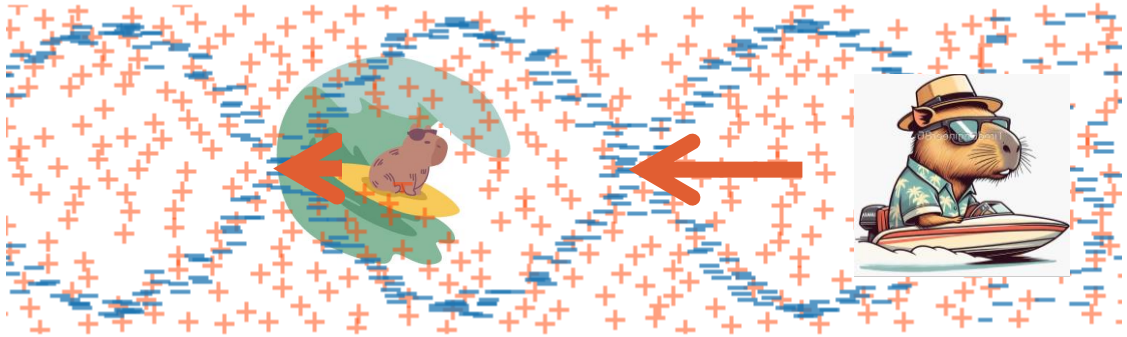
Claim:

Light diagnostics measure a quantity related to wakefields

WHAT EXACTLY ARE WE MEASURING?

Wakefields

→Energy in coherent motion of electrons and electric field



Ion motion, wave breaking, collisions

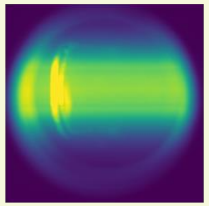
→Energy in random motion of electrons

Inelastic collisions (ionization, excitation)

→Light emission

Cameras / PMTs

→Light measuement



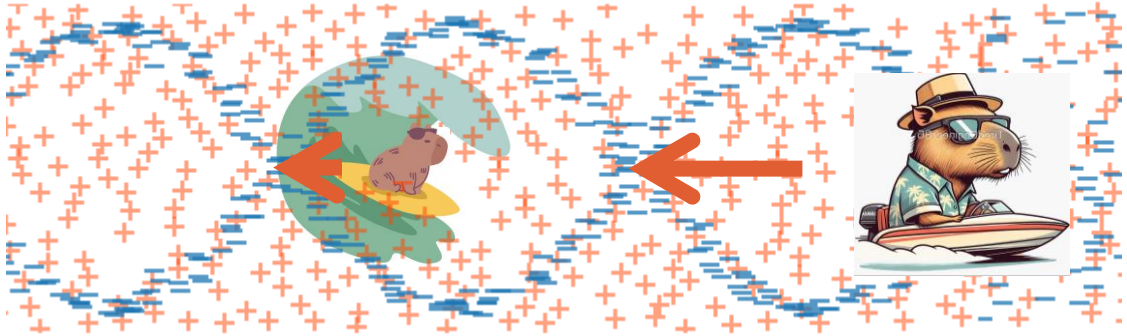
Claim:

Light diagnostics measure a quantity related to wakefields

WHAT EXACTLY ARE WE MEASURING?

Wakefields

→Energy in coherent motion of electrons and electric field



Ion motion, wave breaking, collisions

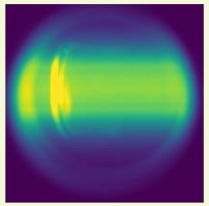
→Energy in random motion of electrons

Inelastic collisions (ionization, excitation)

→Light emission

Cameras / PMTs

→Light measuement



Assumption 1:

Energy in wakefields is proportional to energy locally deposited in plasma

Assumption 2:

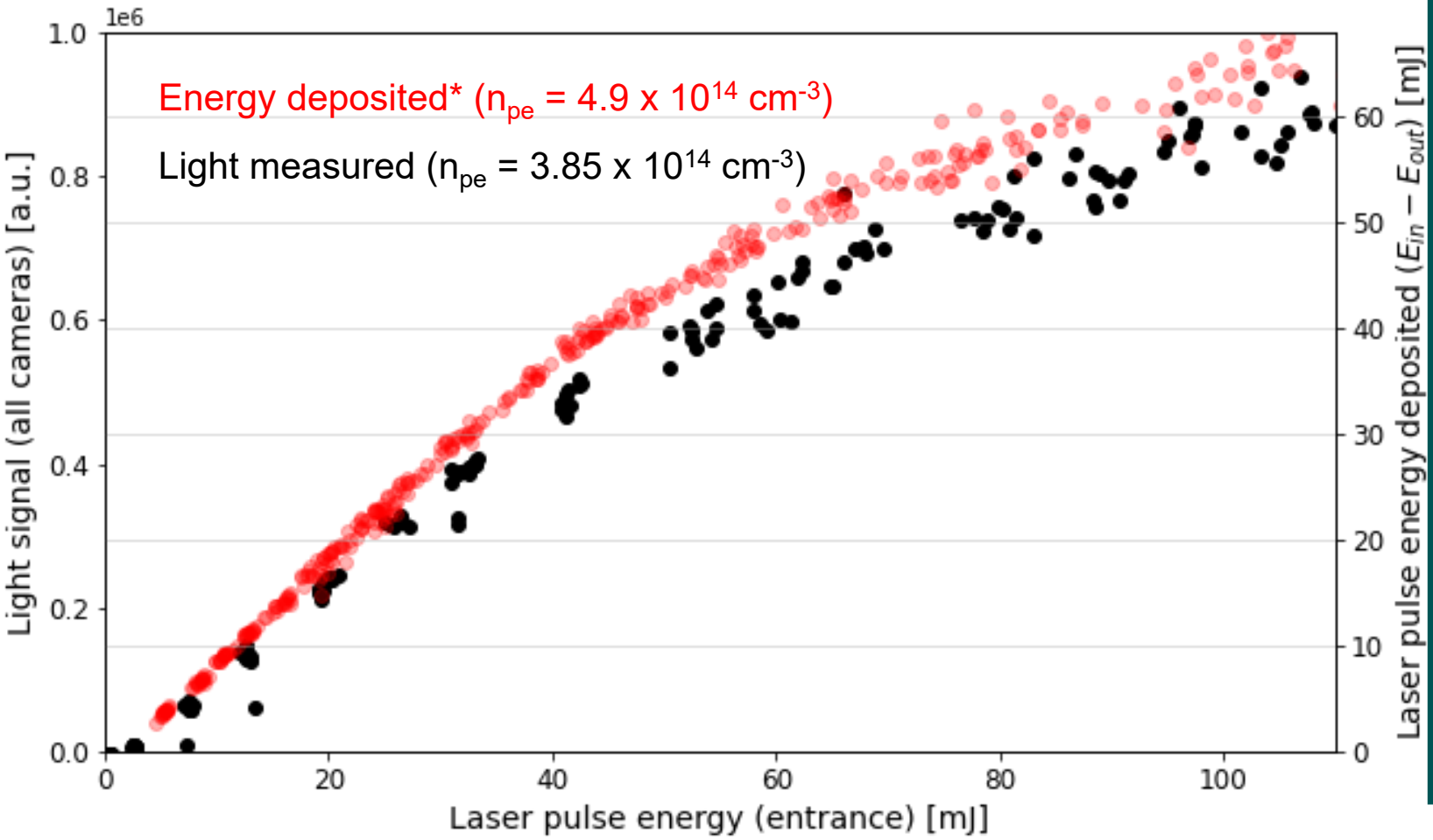
Light emitted is proportional to energy deposited

Claim:

Light diagnostics measure a quantity related to wakefields

VALIDATING ASSUMPTIONS

Light emitted is proportional to enegy deposited?



- Laser induced plasma

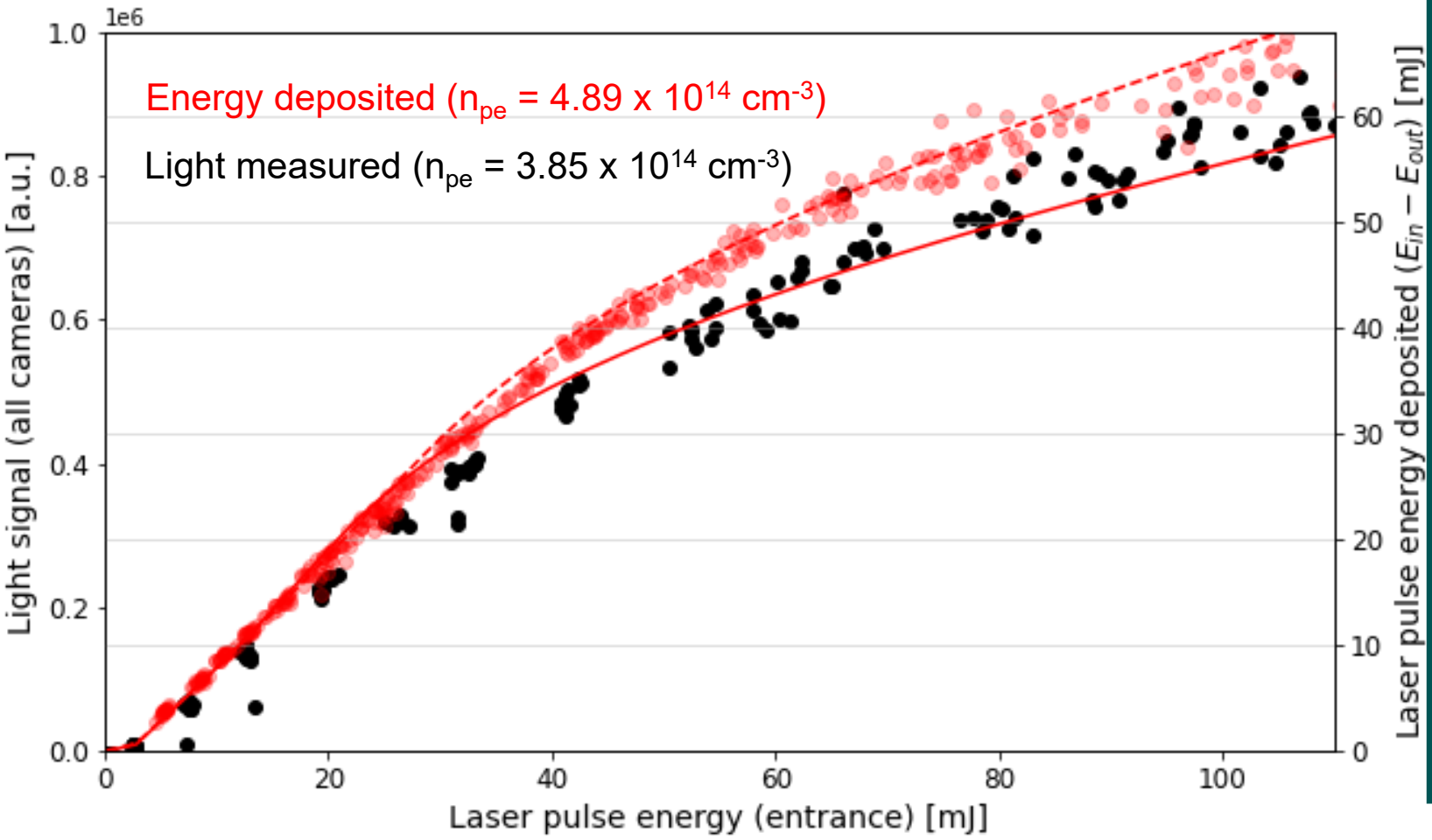
→ Laser pulse deposits energy while propagating

- Light signals and deposited energy follow similar trend

*Data for the laser pulse energy loss curtesy of Dr. Gabor Demeter: G. Demeter et al. “Generation of10-m-lengthscale plasma columns by resonant and off-resonant laser pulses”, Optics & Laser Technology 168 (2024)

VALIDATING ASSUMPTIONS

Light emitted is proportional to enegy deposited?

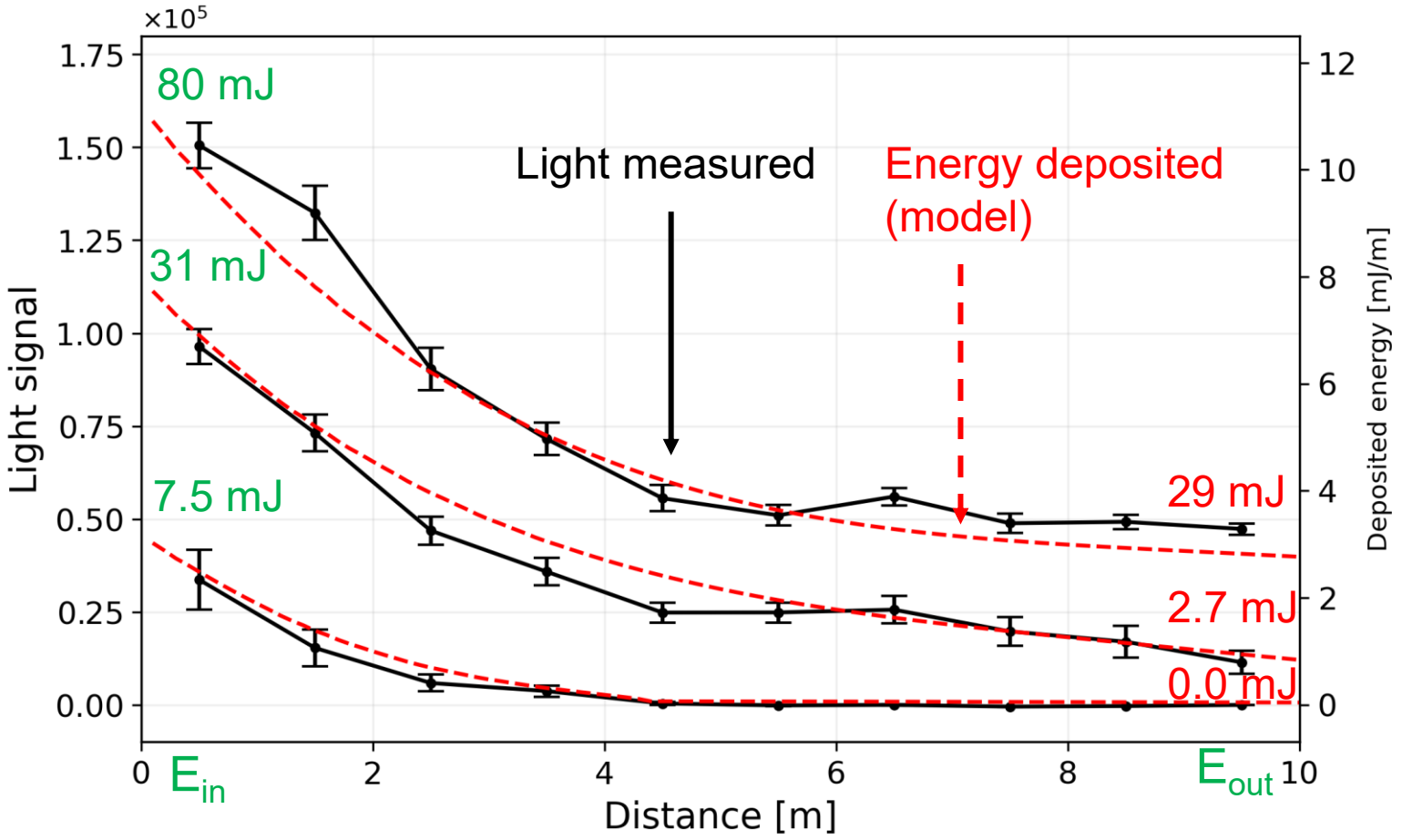


- Laser induced plasma

→ Laser pulse deposits energy while propagating

- Light signals and deposited energy follow similar trend
- Physical model of laser pulse propagation through rb vapor describes data well

VALIDATING ASSUMPTIONS



Light emitted is proportional to enegy deposited?

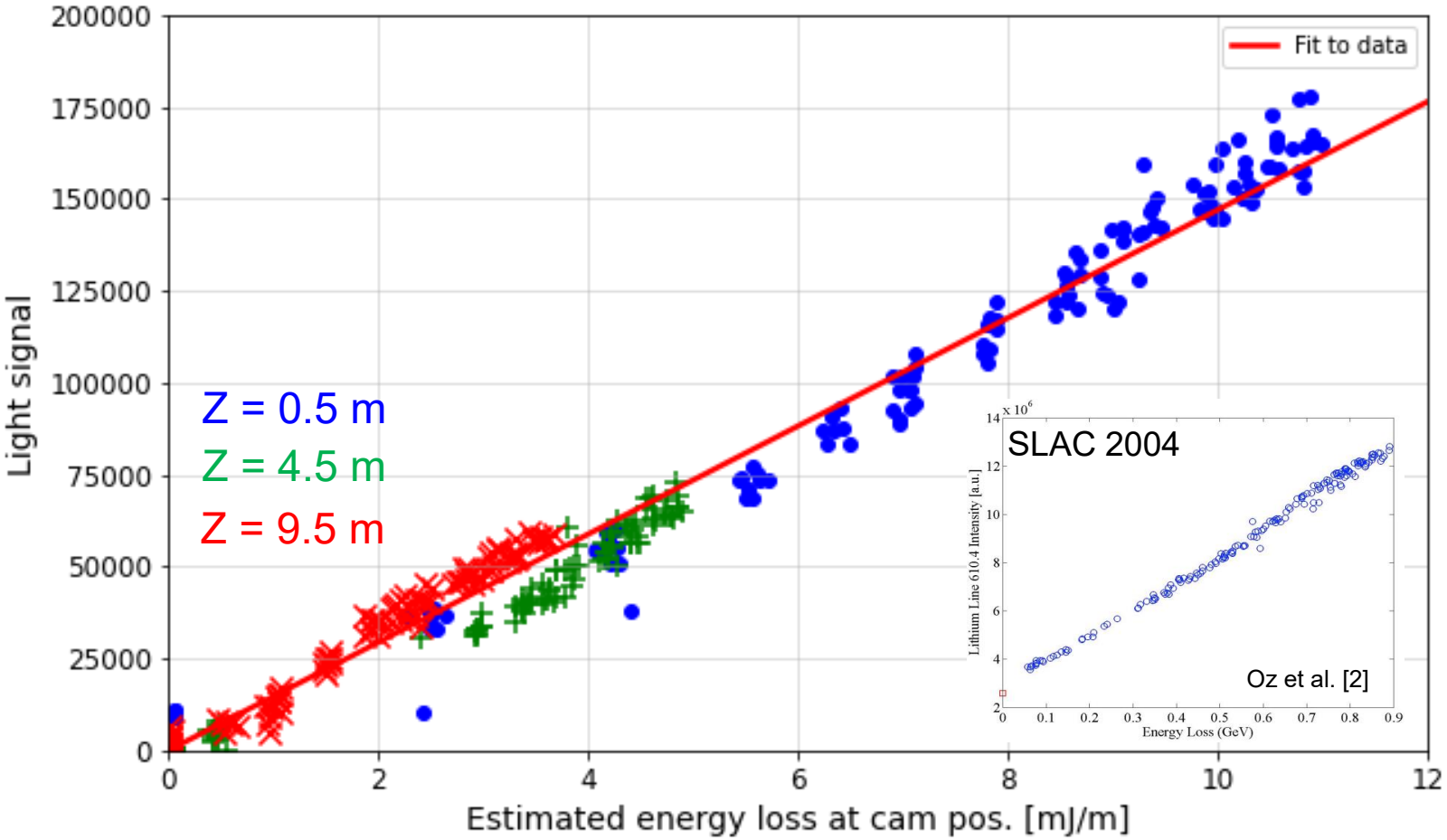
- Laser induced plasma

→ Laser pulse deposits energy while propagating

- Light signals and deposited energy follow similar trend
- Physical model of laser pulse propagation through rb vapor describes data well

→ Also along z!

VALIDATING ASSUMPTIONS



Light emitted is proportional to enegy deposited?

- Laser induced plasma

→ Laser pulse deposits energy while propagating

- Light signals and deposited energy follow similar trend
- Physical model of laser pulse propagation through rb vapor describes data well

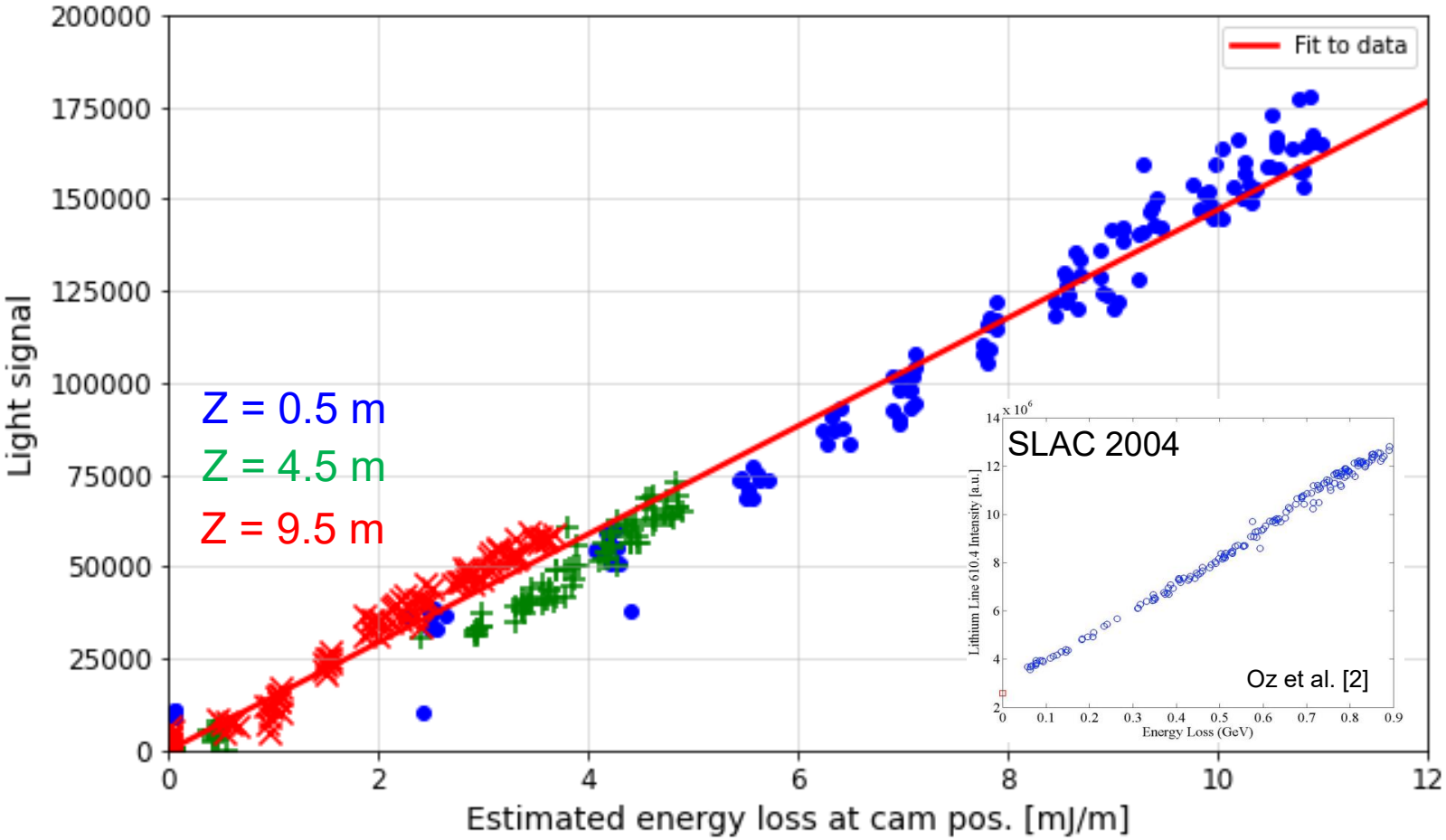
→ Also along z!

- Light signals of individual cameras proportional to energy locally deposited.

VALIDATING ASSUMPTIONS

For a laser pulse and up to 12 mJ/m

Light emitted is proportional to enegy deposited!



- Laser induced plasma

→ Laser pulse deposits energy while propagating

- Light signals and deposited energy follow similar trend
- Physical model of laser pulse propagation through rb vapor describes data well

→ Also along z!

- Light signals of individual cameras proportional to energy locally deposited.

VALIDATING ASSUMPTIONS

Linear Theory: $\frac{\Delta n_b}{n_b} \ll 1$

$$W_z(\zeta, r) = \frac{e}{\epsilon_0} R(r) \int_{-\infty}^{\zeta} n_b(\zeta, r) \cos(k_{pe} \cdot (\zeta - \zeta')) d\zeta'$$

$$W_r(\zeta, r) = \frac{e}{\epsilon_0 k_{pe}} \frac{dR(r)}{dr} \int_{-\infty}^{\zeta} n_b(\zeta, r) \sin(k_{pe} \cdot (\zeta - \zeta')) d\zeta'$$

Wakefield amplitude ~ n_b

$$U_E = \int_0^{\infty} r \, dr \int_{L_0}^{L_0+L} dz \left(\frac{\varepsilon_0}{2} \left(W_z(\zeta, r)^2 + (W_r(\zeta, r)^2) \right) \right)$$

Energy in electric field ~ n_b^2

$$\Delta U_b = \int_{V_b} \frac{Q_b}{V_b} W_{z,b}(\zeta, r) dV_b \cdot L$$

Energy lost to deceleration ~ n_b^2

$$\frac{1}{2} \Delta U_b = U_E = U_{kin}$$

Energy loss of drive bunch = Energy in wakefields

Energy in wakefields proportional to energy locally deposited?

- Linear theory: deceleration of drive bunch = energy in wakefields behind bunch

VALIDATING ASSUMPTIONS

Linear Theory: $\frac{\Delta n_b}{n_b} \ll 1$

$$W_z(\zeta, r) = \frac{e}{\epsilon_0} R(r) \int_{-\infty}^{\zeta} n_b(\zeta, r) \cos(k_{pe} \cdot (\zeta - \zeta')) d\zeta'$$

$$W_r(\zeta, r) = \frac{e}{\epsilon_0 k_{pe}} \frac{dR(r)}{dr} \int_{-\infty}^{\zeta} n_b(\zeta, r) \sin(k_{pe} \cdot (\zeta - \zeta')) d\zeta'$$

Wakefield amplitude ~ n_b

$$U_E = \int_0^{\infty} r \, dr \int_{L_0}^{L_0+L} dz \left(\frac{\varepsilon_0}{2} \left(W_z(\zeta, r)^2 + (W_r(\zeta, r)^2) \right) \right)$$

Energy in electric field ~ n_b^2

$$\Delta U_b = \int_{V_b} \frac{Q_b}{V_b} W_{z,b}(\zeta, r) dV_b \cdot L$$

Energy lost to deceleration ~ n_b^2

$$\frac{1}{2} \Delta U_b = U_E = U_{kin}$$

Energy loss of drive bunch = Energy in wakefields

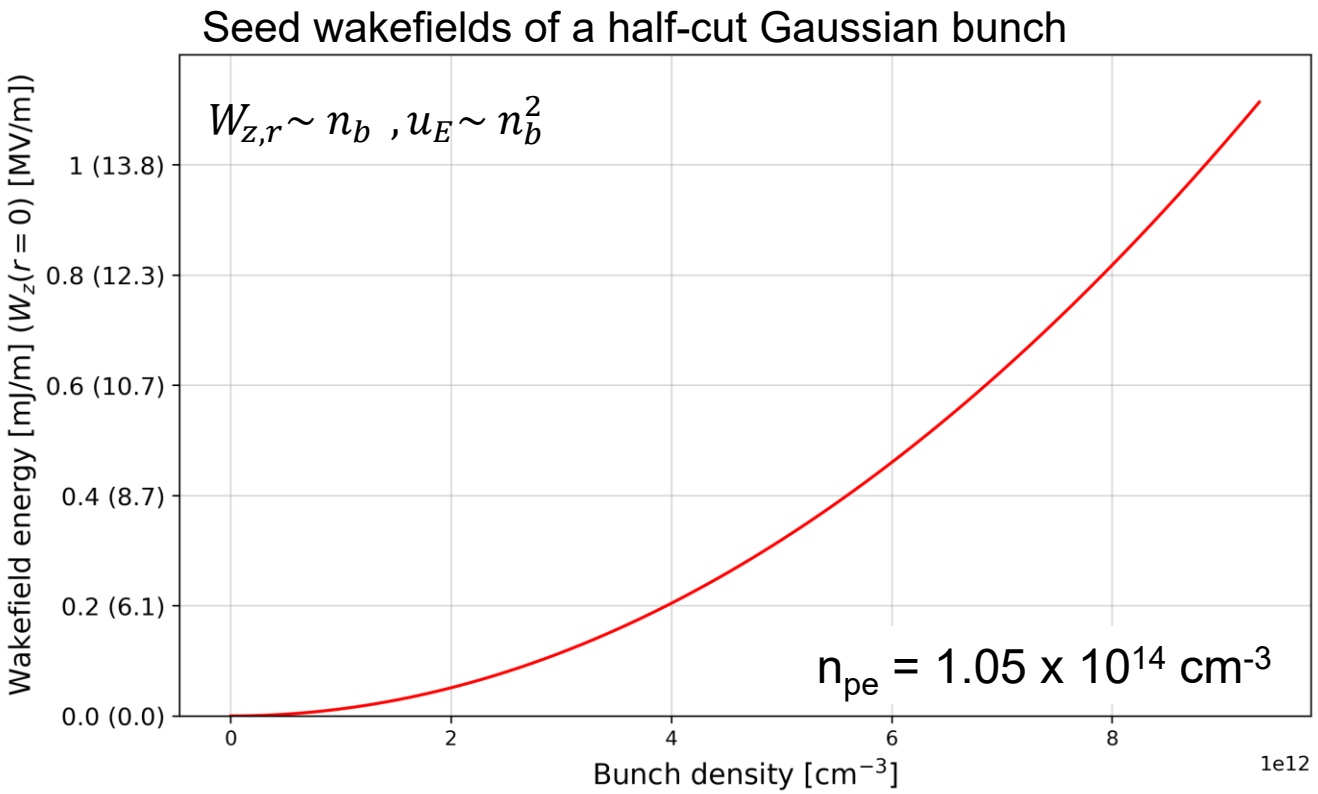
Energy in wakefields proportional to energy locally deposited?

- Linear theory: deceleration of drive bunch = energy in wakefields behind bunch
- Simulations: for low field amplitudes agreement with linear theory, but diverges for large amplitudes
  (Carolinas talk tomorrow morning)

VALIDATING ASSUMPTIONS

Linear Theory: $\frac{\Delta n_b}{n_b} \ll 1$

Seed wakefields: Wakefields of the unmodulated bunch
→ near plasma entrance



Energy in wakefields proportional to energy locally deposited?

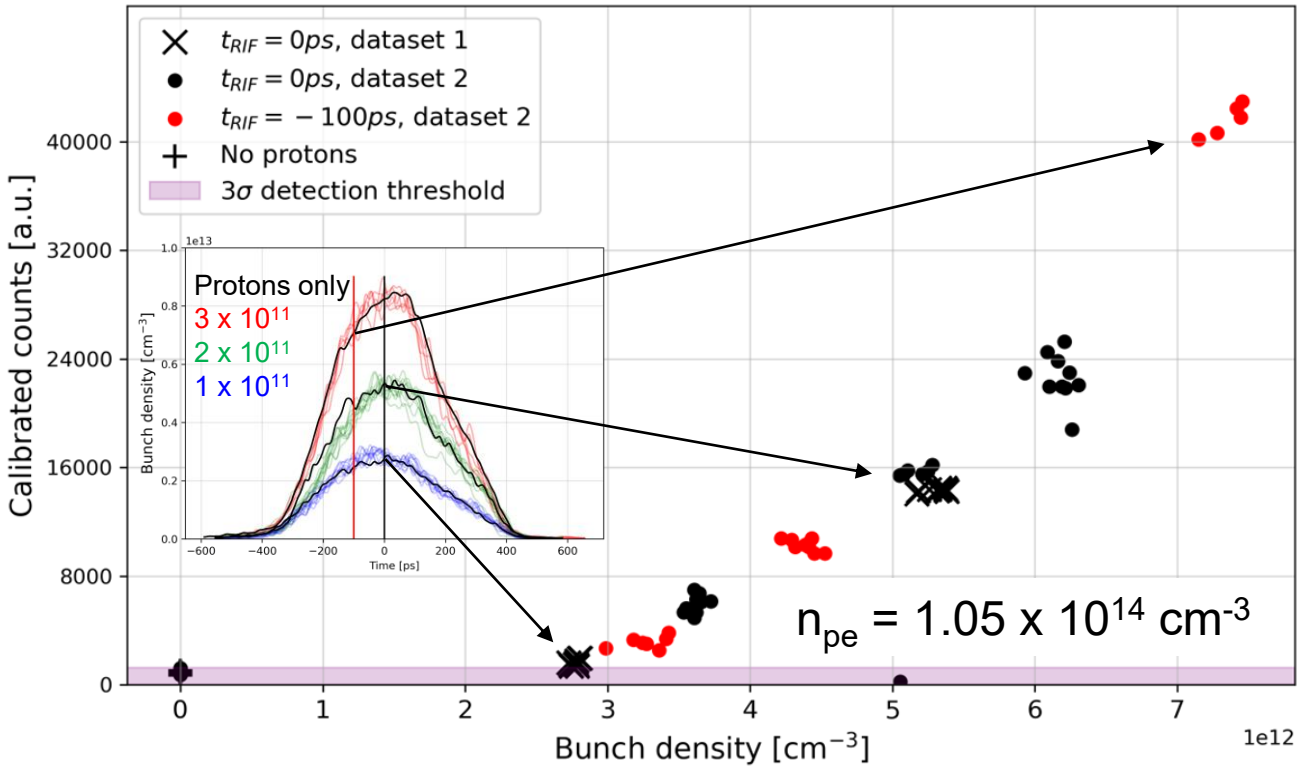
- Linear theory: deceleration of drive bunch = energy in wakefields behind bunch
- Simulations: for low field amplitudes agreement with linear theory, but diverges for large amplitudes
  (Carolinas talk tomorrow morning)

VALIDATING ASSUMPTIONS

Linear Theory: $\frac{\Delta n_b}{n_b} \ll 1$

Seed wakefields: Wakefields of the unmodulated bunch
→ near plasma entrance

Light measurements: Camera position at 0.5m
→ no signs of modulation obverved on bunch profiles



Energy in wakefields proportional to energy locally deposited?

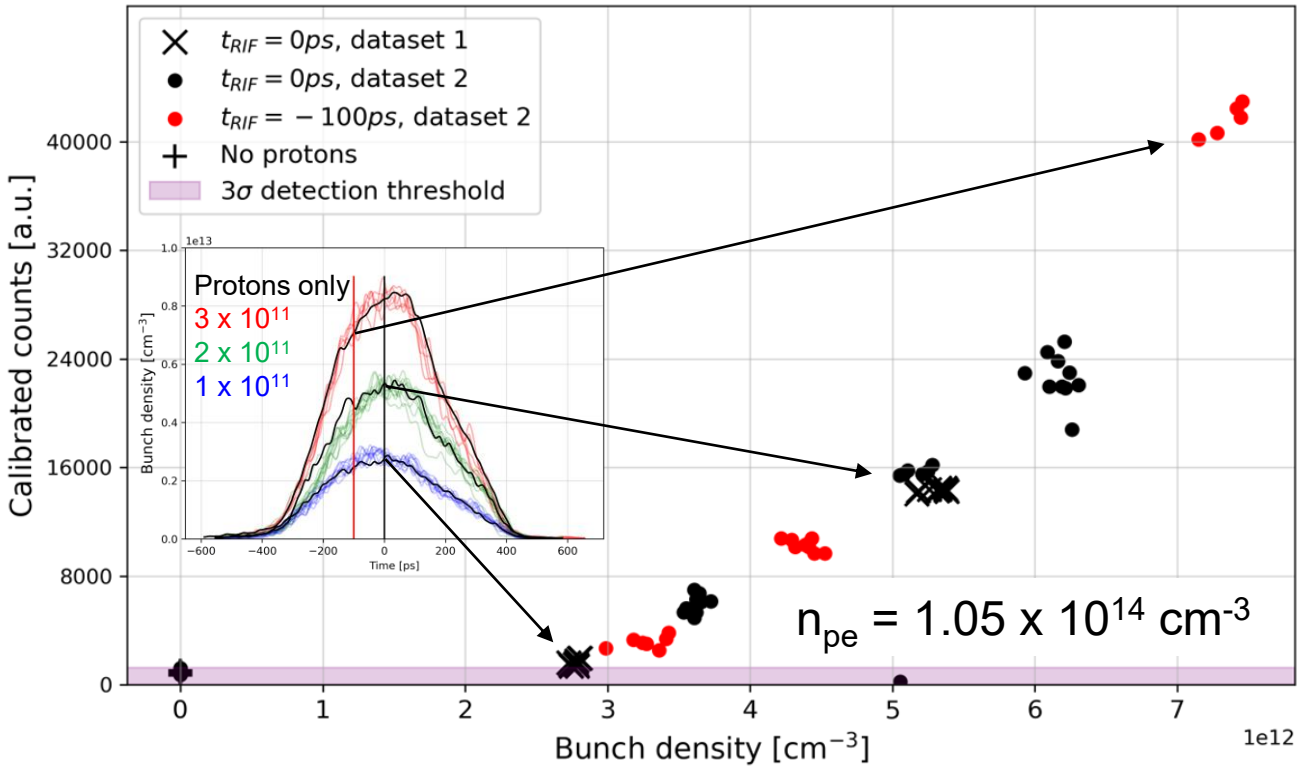
- Linear theory: deceleration of drive bunch = energy in wakefields behind bunch
- Simulations: for low field amplitudes agreement with linear theory, but diverges for large amplitudes
  (First talk tomorrow morning)
- Seed wakefields: Measured light signals suggest a trend consistent with square dependency predicted by linear theory (although other dependencies are not ruled out)

VALIDATING ASSUMPTIONS

Linear Theory: $\frac{\Delta n_b}{n_b} \ll 1$

Seed wakefields: Wakefields of the unmodulated bunch
→ near plasma entrance

Light measurements: Camera position at 0.5m
→ no signs of modulation observed on bunch profiles



Maybe not linearly…

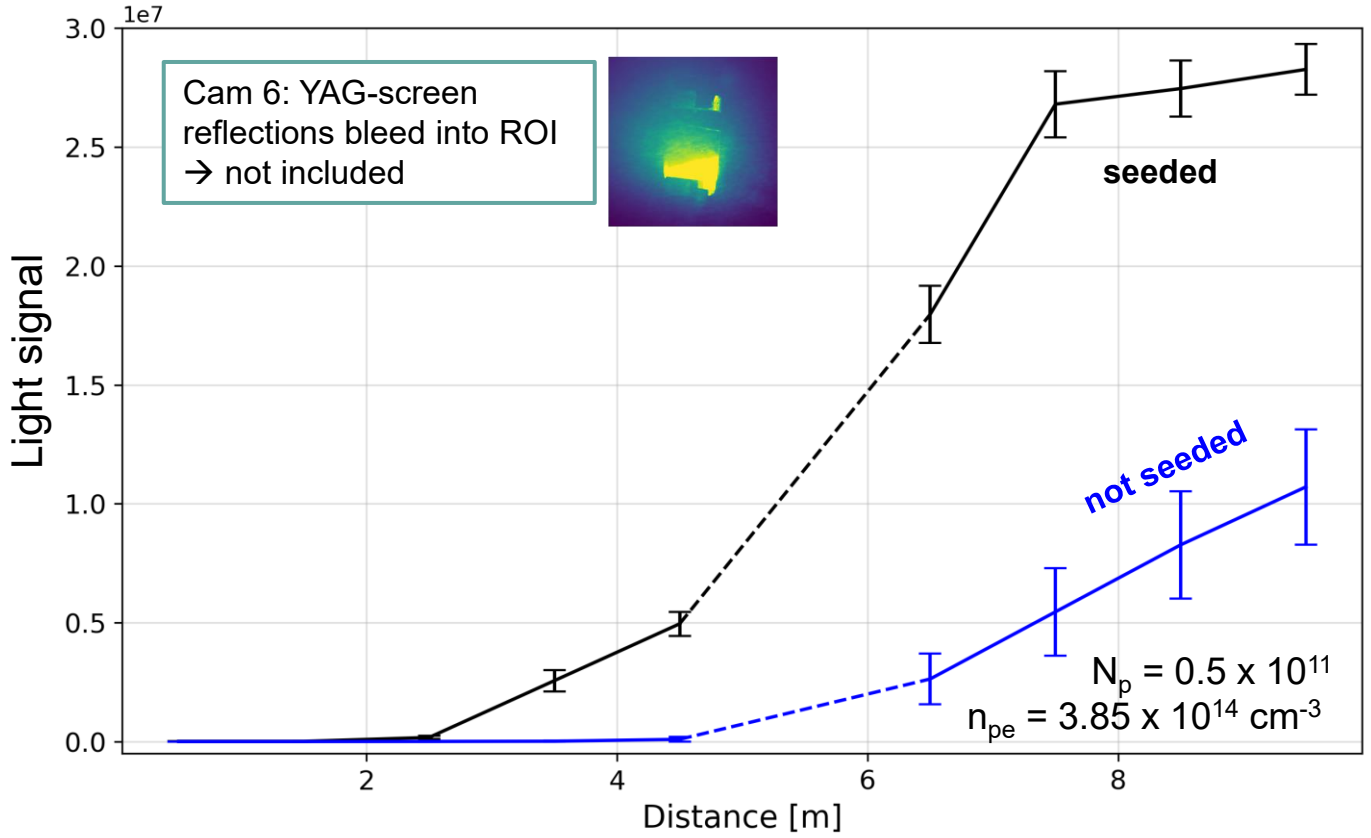
For small wakefield amplitudes

Energy in wakefields proportional to energy locally deposited?!

- Linear theory: deceleration of drive bunch = energy in wakefields behind bunch
- Simulations: for low field amplitudes agreement with linear theory, but diverges for large amplitudes
  (First talk tomorrow morning)
- Seed wakefields: Measured light signals suggest a trend consistent with square dependency predicted by linear theory (although other dependencies are not ruled out)

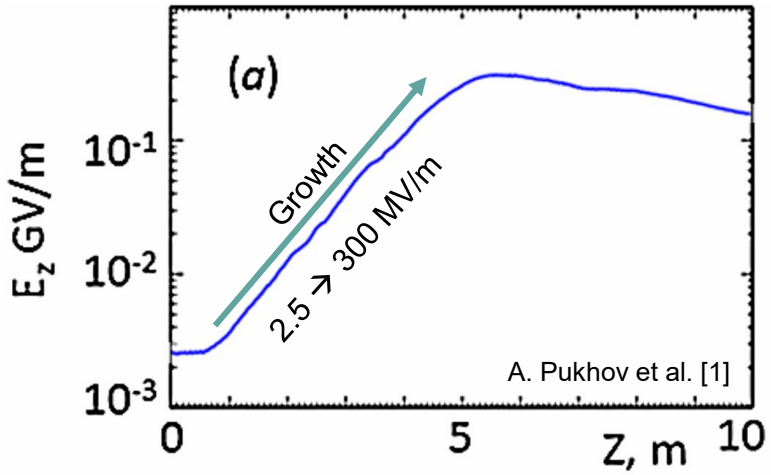
LIGHT PROFILES

Light diagnostics measure a quantitiy related to the wakefields?



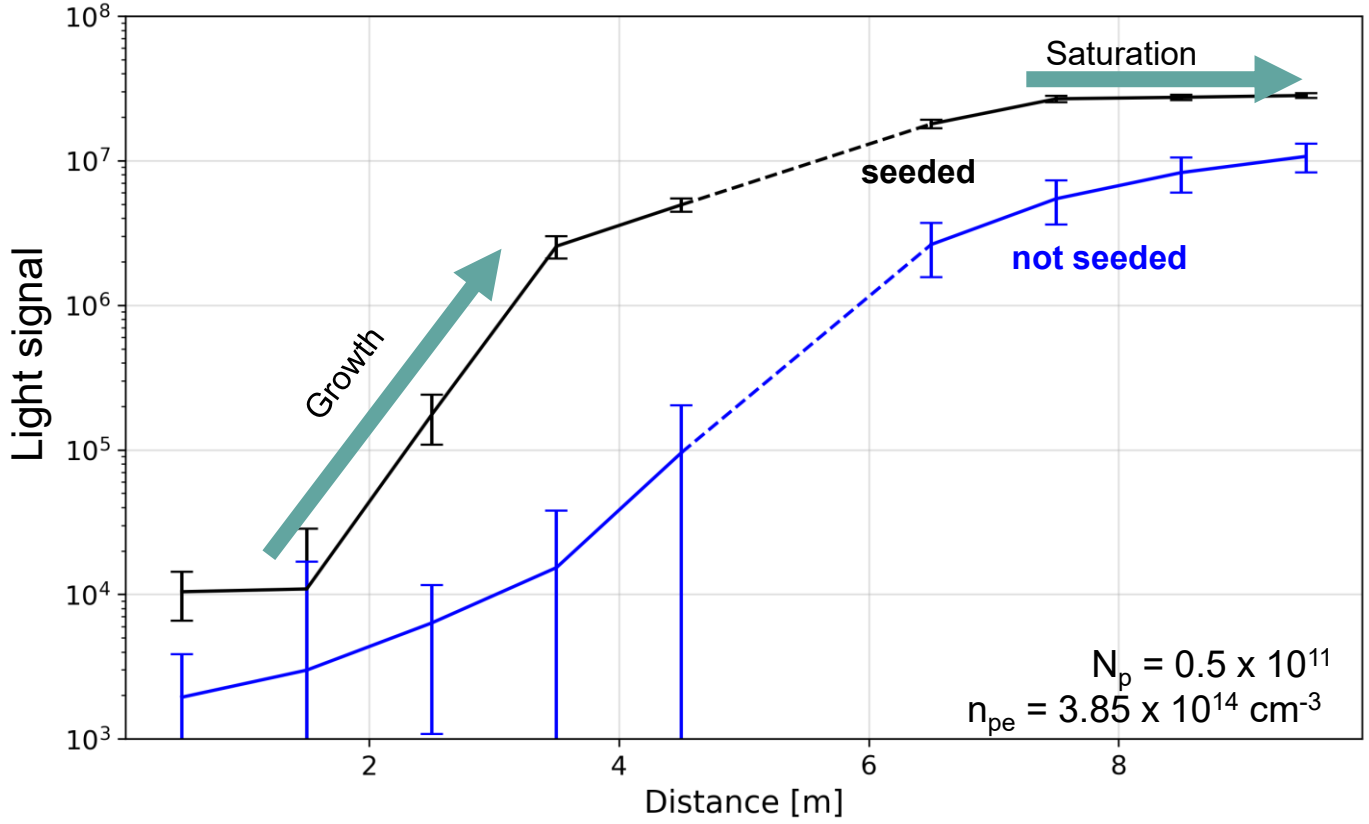
Expectations

- ✓ Growth over several orders of magnitude along z
- ✓ Wakefield amplitude saturates
- ✓ With seeding grows earlier
- ✓ With seeding better reproducibility



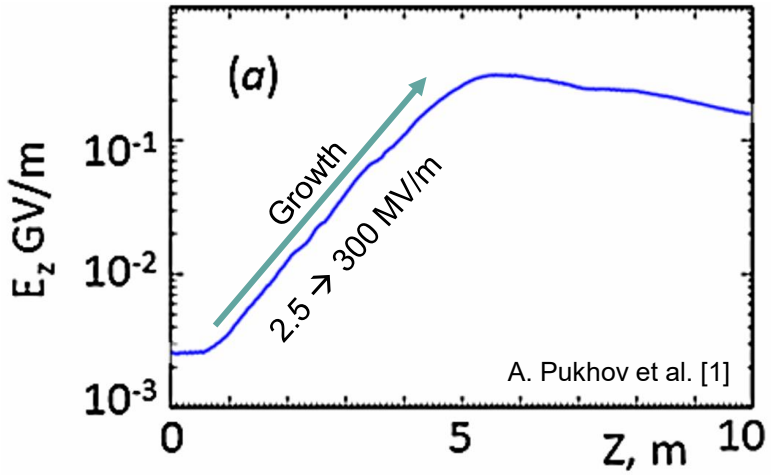
LIGHT PROFILES

Light diagnostics measure a quantitiy related to the wakefields?



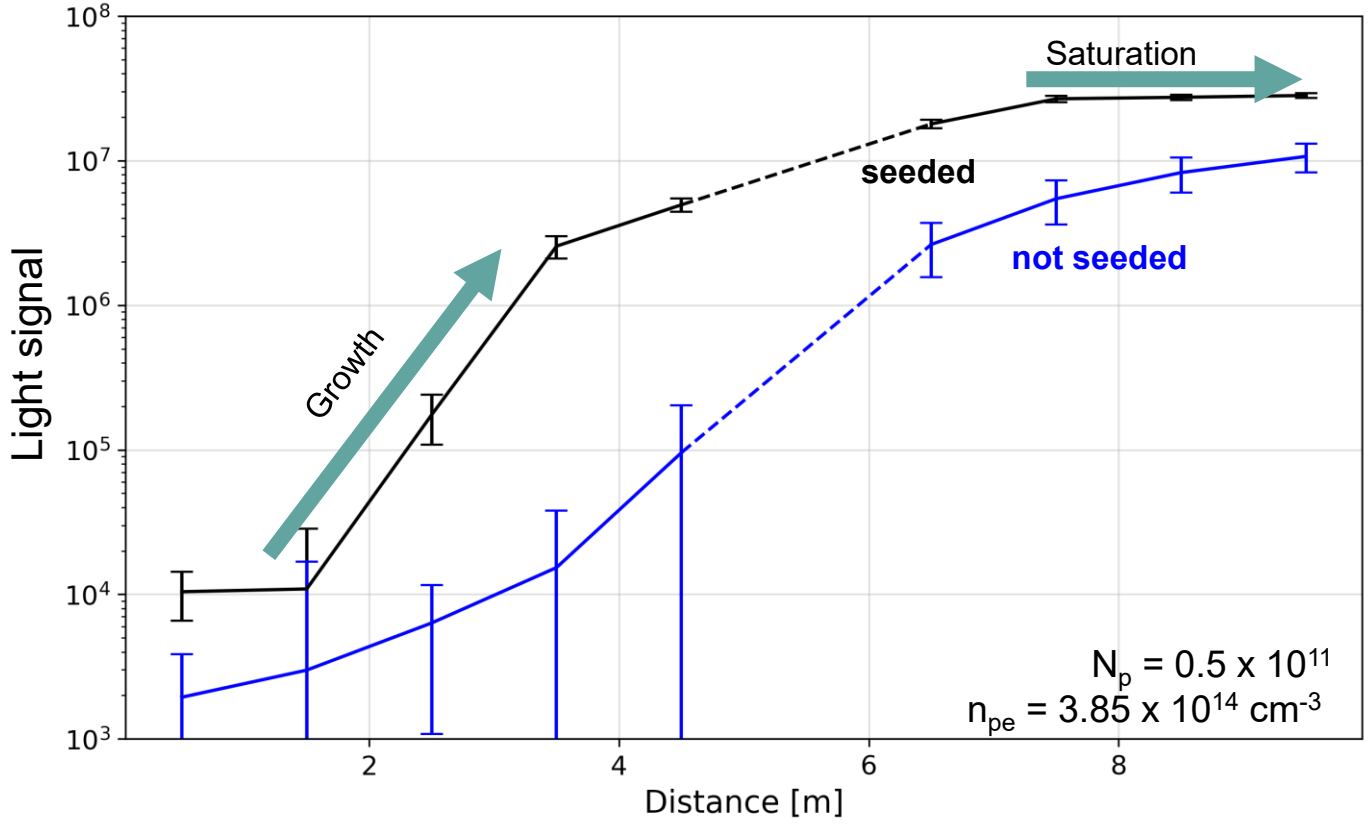
Expectations

- ✓ Growth over several orders of magnitude along z
- ✓ Wakefield amplitude saturates
- ✓ With seeding grows earlier
- ✓ With seeding better reproducibility



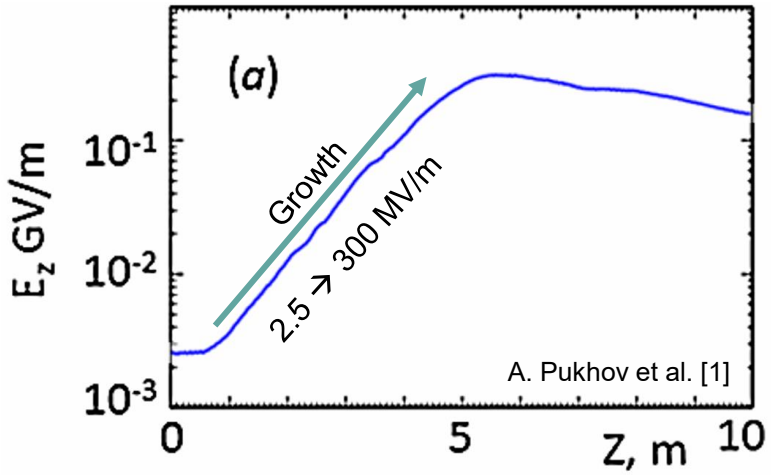
LIGHT PROFILES

Light diagnostics measure a quantitiy related to the wakefields!



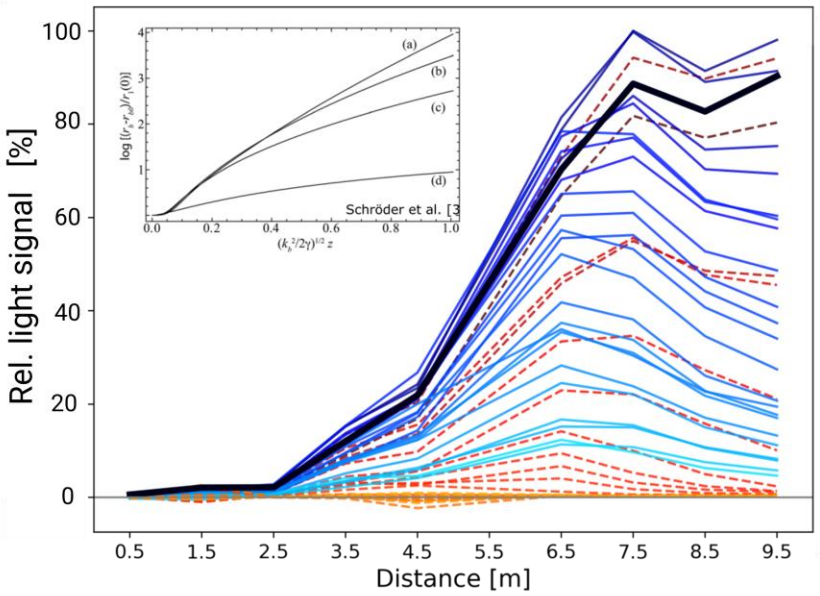
Expectations

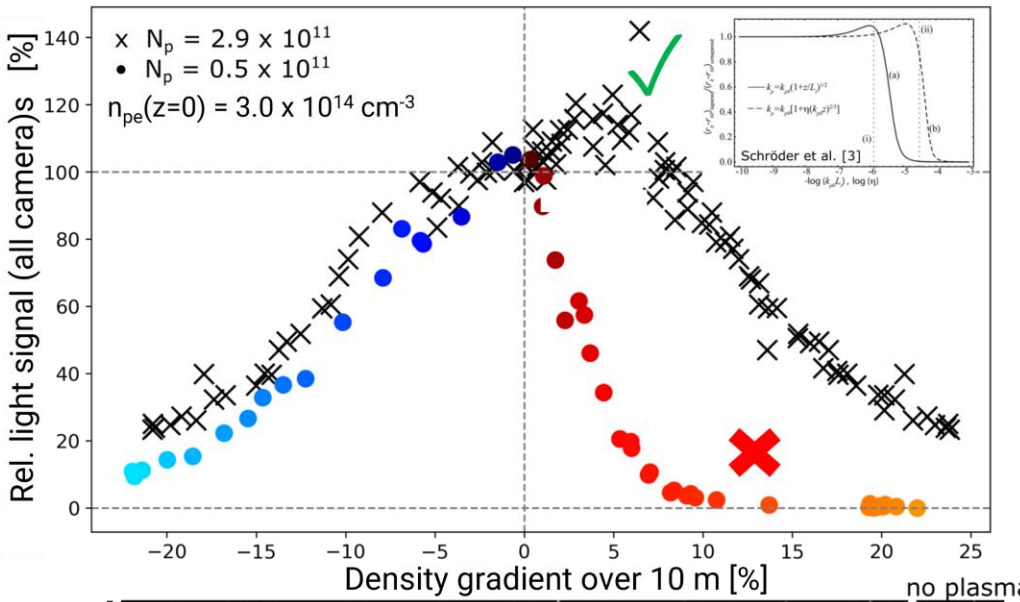
- ✓ Growth over several orders of magnitude along z
- ✓ Wakefield amplitude saturates
- ✓ With seeding grows earlier
- ✓ With seeding better reproducibility



LIGHT PROFILES

Growth suppression with a density gradient



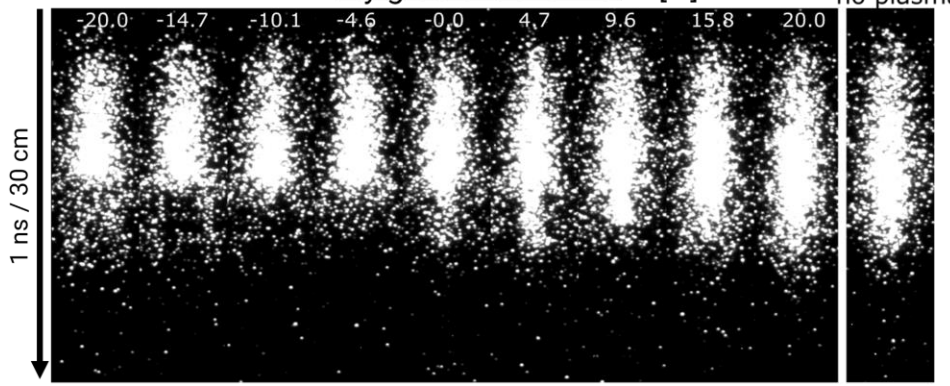


STREAK CAMERA IMAGES

Time resolved images of bunch distribution

- No gradient: modulated p^+ bunch
- >20 % gradient: No modulation (comparable to no plasma)

→ Full suppression of self-modulation growth



Light diagnostics measure a quantitiy related to the wakefields!

- Large density gradient suppresses self-modulation growth ✗
- Small density gradient can compensate phase shift ✓

→ Predicted by theory

- Observing these effects with light

→ Unique possibilities to explore wakefield physics using light diagnostics

[3] C. B. Schröder et al. “Particle beam self-modulation instability in tapered and inhomogeneous plasma”, Phys. Plasmas 19, 010703 (2012)

CONCLUSION

- Established linearity between deposited energy and light measurements for a laser pulse depositing energy up to 12 mJ/m
- Established a proportionality between wakefield amplitude and energy deposited / light measured in the case of seed wakefields

→ Assumptions valid under certain conditions

- Light profiles exhibit characteristics of established wakefield theory

→ Lots of evidence supporting the claim that wakefields measure a quantity related to wakefields

→ Light measurements (especially in combination with other diagnostics) can be used as a tool to investigate wakefield physics