Plasma Afterglow Light Dynamics and Measurement Techniques of a PWFA Plasma Source

EAAC

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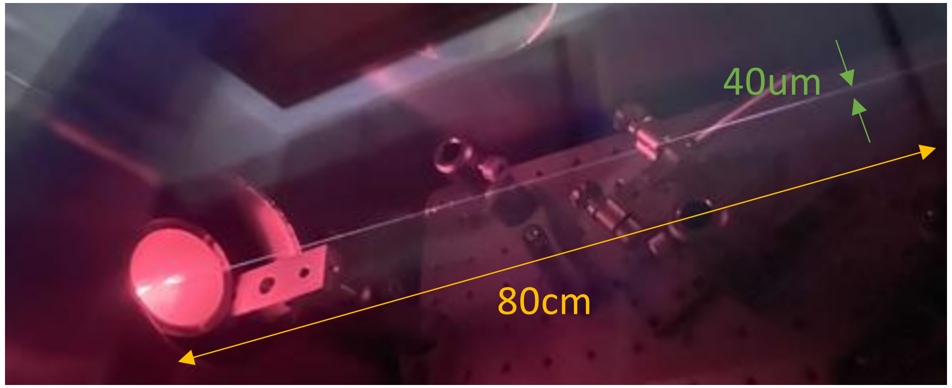
Outline



Plasma Source
Thin, laser-ionized plasma

Temporal Dynamics of the Plasma Light
Plasma formation, electron thermalization, rapid expansion, slow diffusion, neutralization

Experimental Methodology
How to measure the temporal dynamics of the plasma light with a cheap camera?

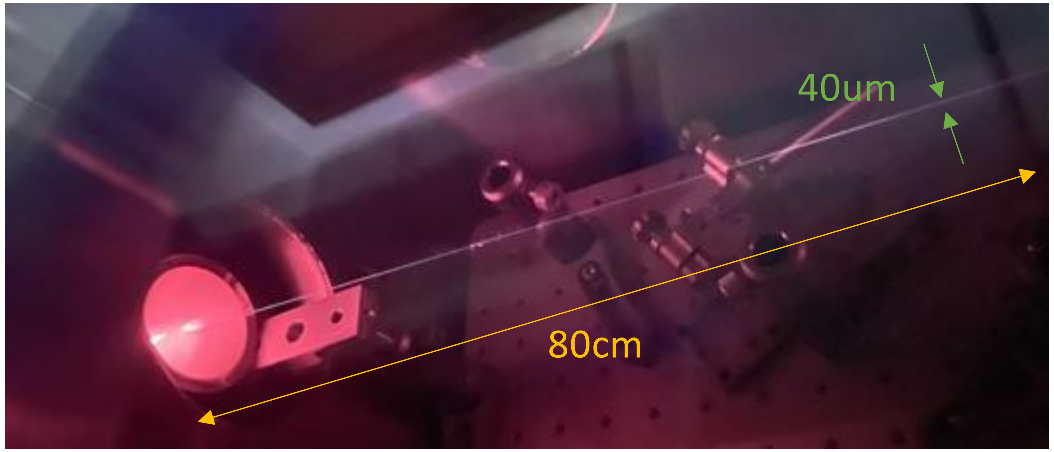
Experimental Results

We present an experimental and simulation-based investigation of the temporal evolution of light emission from a thin, laser-ionized Helium plasma source.

Temporal Evolution of the Plasma Light Emission

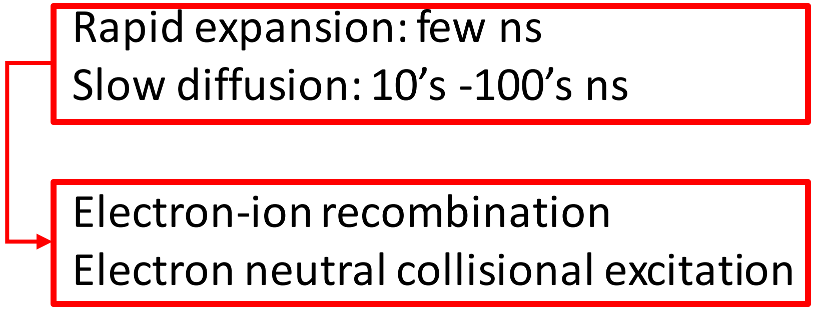
Temporal evolution of a thin laser-ionized plasma

Plasma formation: ~100 fs
Plasma electron thermalization: ~10ps
Rapid expansion: few ns
Slow diffusion: 10’s -100’s ns



Cheap and common GigE camera images integrate over multiple dynamic timescales.

Temporal Evolution of the Plasma Light Emission



Temporal evolution of a thin laser-ionized plasma

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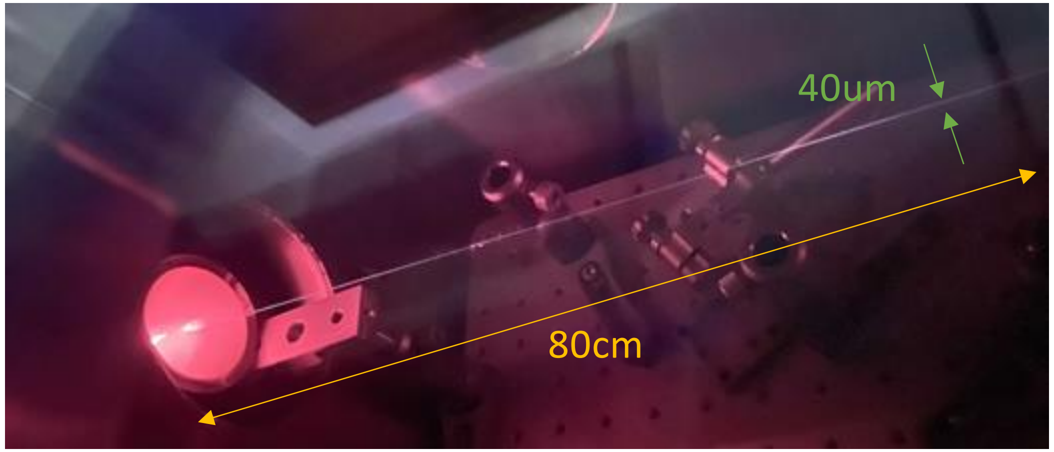
Rapid expansion: few ns

Slow diffusion: 10’s -100’s ns

Electron-ion recombination

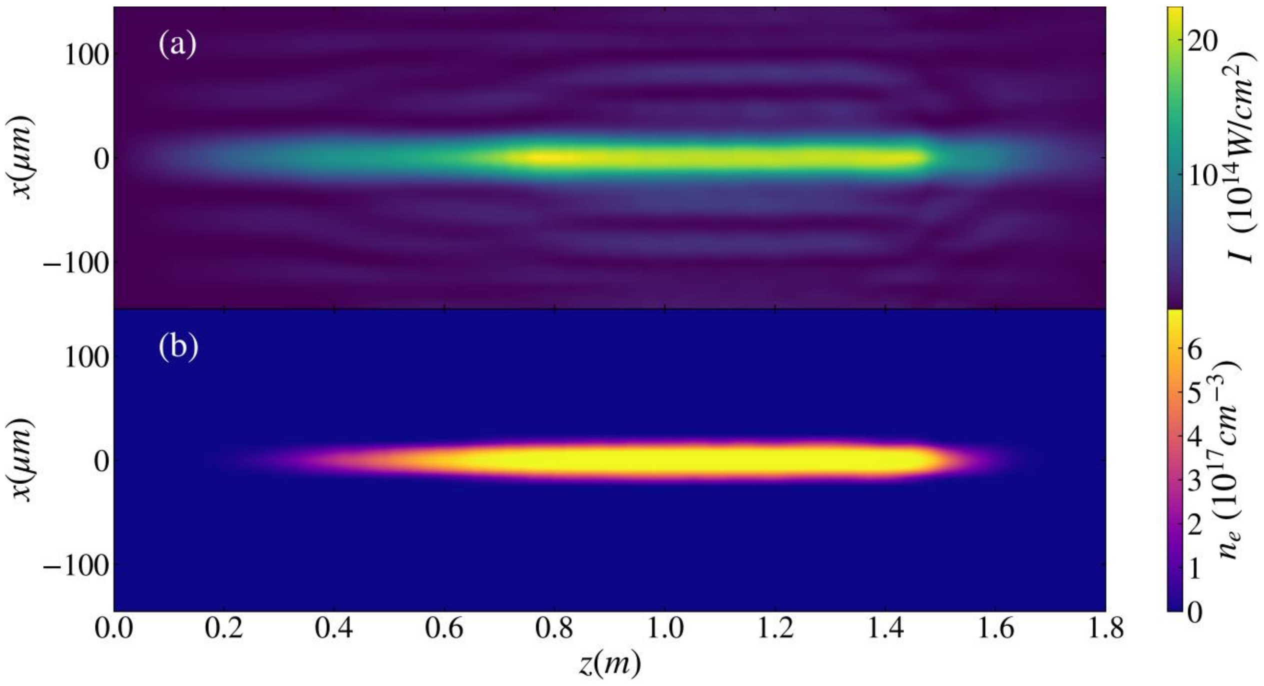
Electron neutral collisional excitation



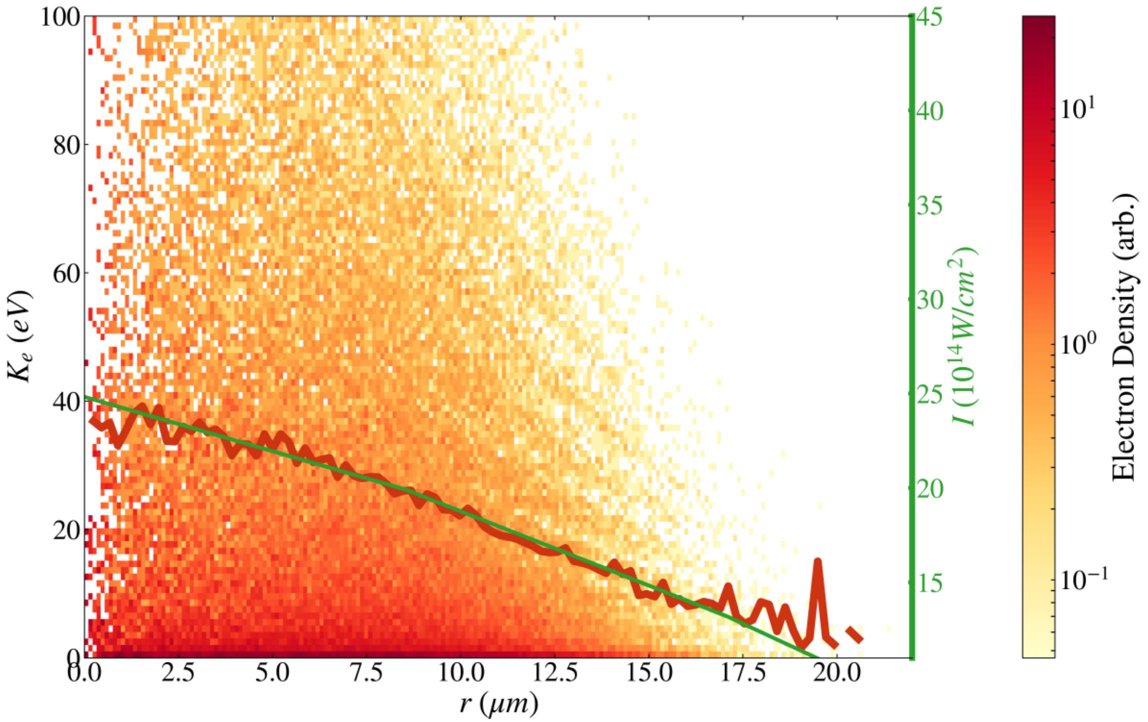
Cheap and common GigE camera images integrate over multiple dynamic timescales.

Modeling – Plasma Formation

Step 1: Split-step Fourier propagation with the ADK model



Step 2: 3D PIC simulation with the ADK model



Modeling ionization by a combination of split-step Fourier algorithm and PIC simulations allows us to acquire the plasma density and plasma electron temperature with reasonable computational resources.

Modeling – Plasma Expansion

Plasma electrons thermalize

On the order of the Spitzer electron self-collision time.

For a plasma with $k_B T_e$= 10 eV and n_e= 1 × 10^{17} cm^{-3}, τ≈ 9 ps.

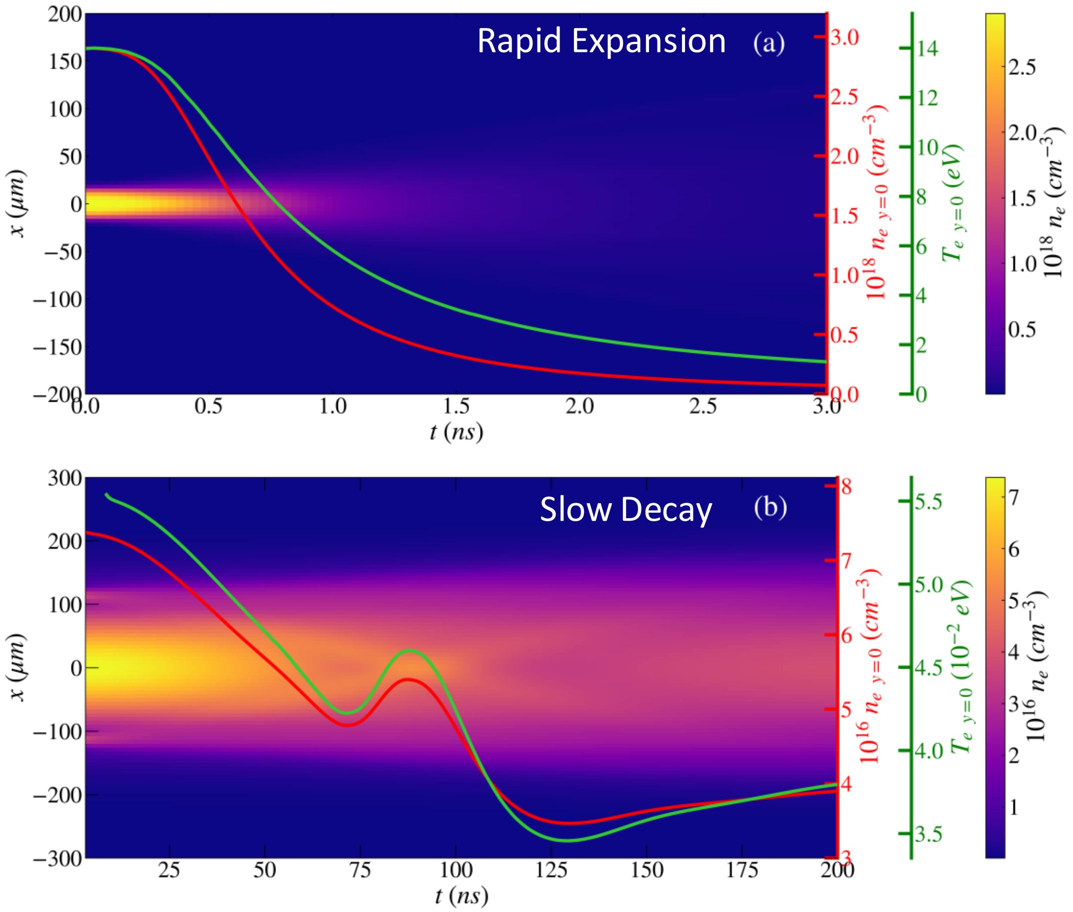
Initial rapid expansion (t= 0-3ns)

We simulate the first 3 ns of the expansion by a two-temperature, single-fluid MHD diffusion code.

T_i= 0.025 eV and T_e~ 10 eV.

Subsequent slow decay (t= 3-200ns)

Two-fluid (plasma and neutral) model calculates the mass diffusion, energy exchange, and temperature exchange.



Simulating the expansion in two steps simplifies the complexity of the model and allows for a higher temporal resolution during the initial rapid expansion.

Plasma Light Emission

Electron-neutral collisional excitation

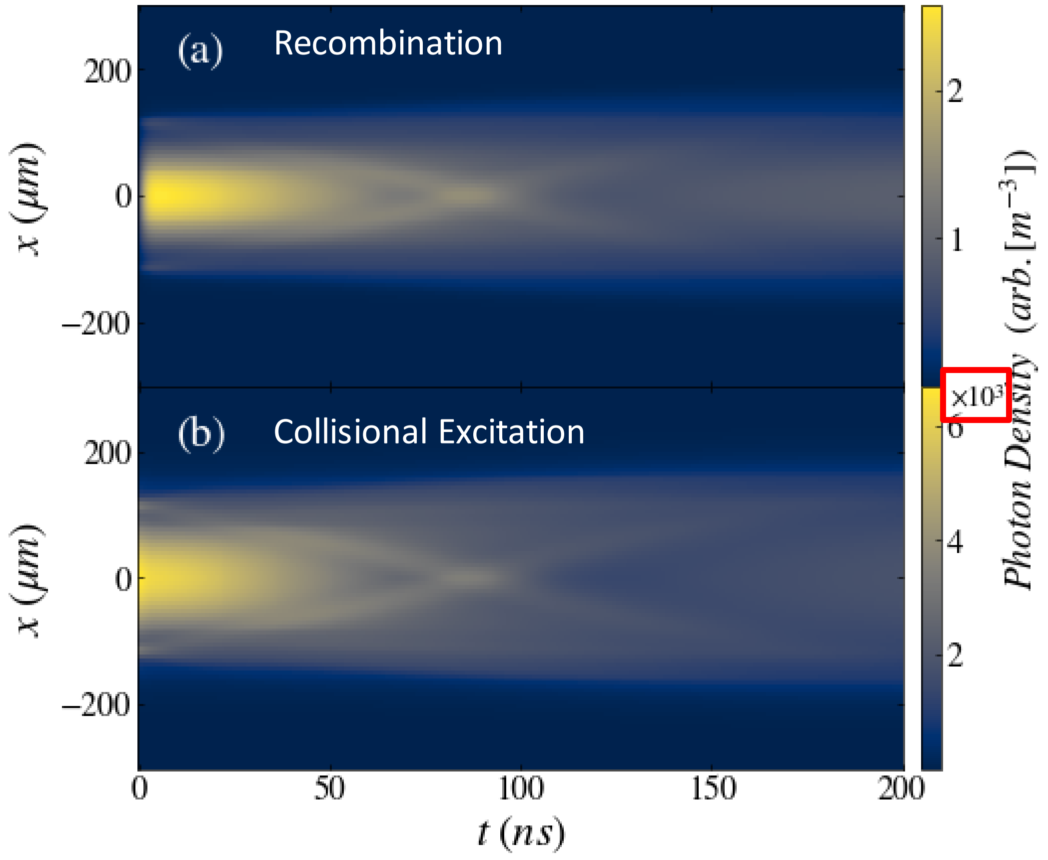
$$\frac{dn_{\gamma exc}(\vec{r},t)}{dt} = n_e(\vec{r},t) < \upsilon_{en}(\vec{r},t) > P_{4p-3d}\; P_{3d-2p}$$

Electron-ion recombination

$$\frac{dn_{\gamma rec}(\vec{r},t)}{dt} = \alpha_r n_e(\vec{r},t)^2\; P_{4f-3d} P_{3d-2p}$$

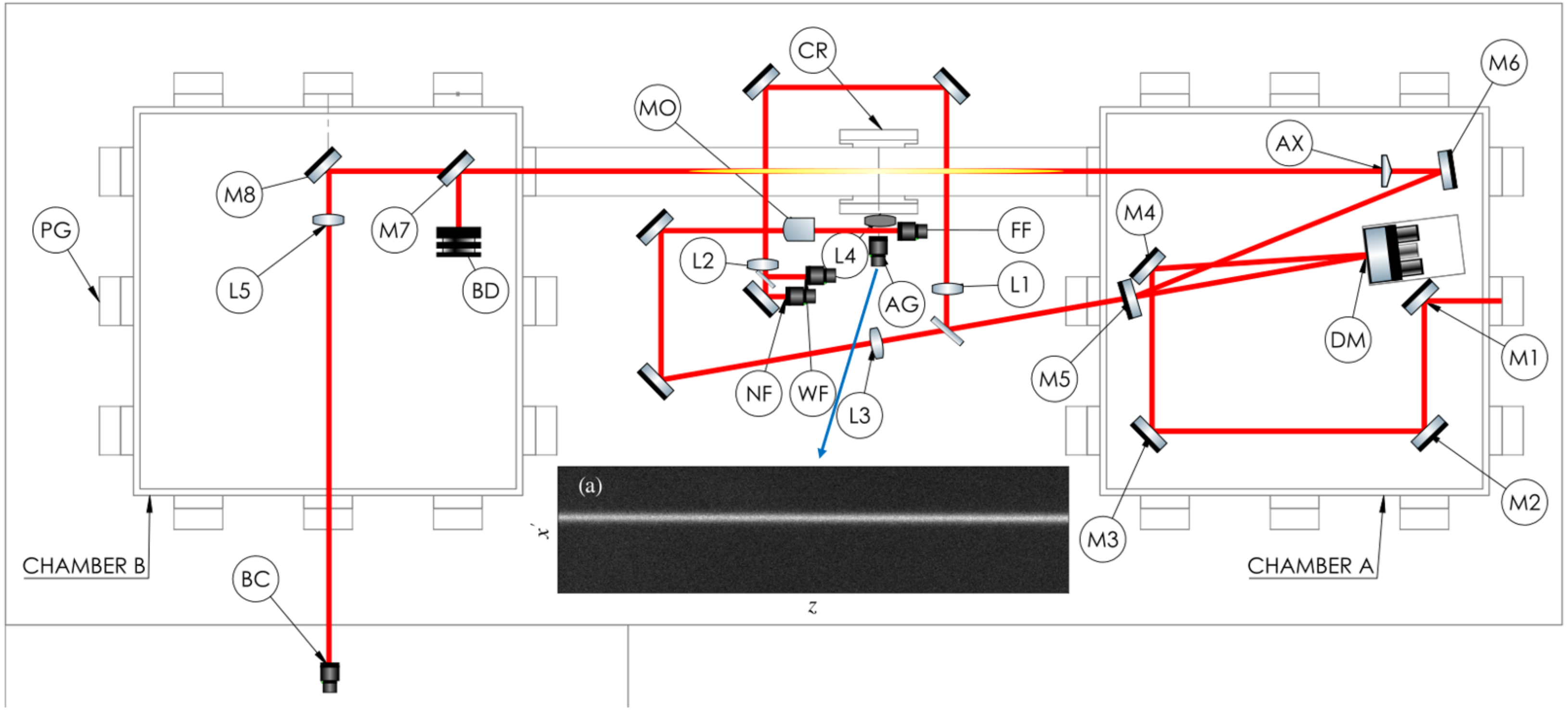
The effects of both the collisional excitation and recombination processes on the plasma density profile evolution are negligible.

This allows us to model the time-resolved plasma expansion first and then numerically evaluate the visible photon emission density.



Collisional excitation dominates the Helium plasma light emission process.

Experiment

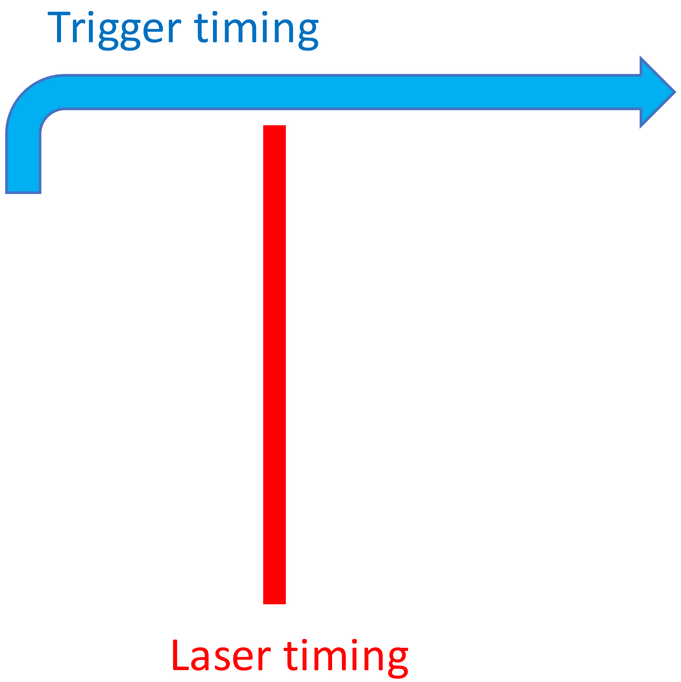


The CMOS GigE camera has a significant internal timing jitter, on the scale of 10 µs. The shortest integration time is on the order of 10 µs, whereas the dynamic timescale of light emission from the plasma is 10’s to 100’s of nanoseconds.

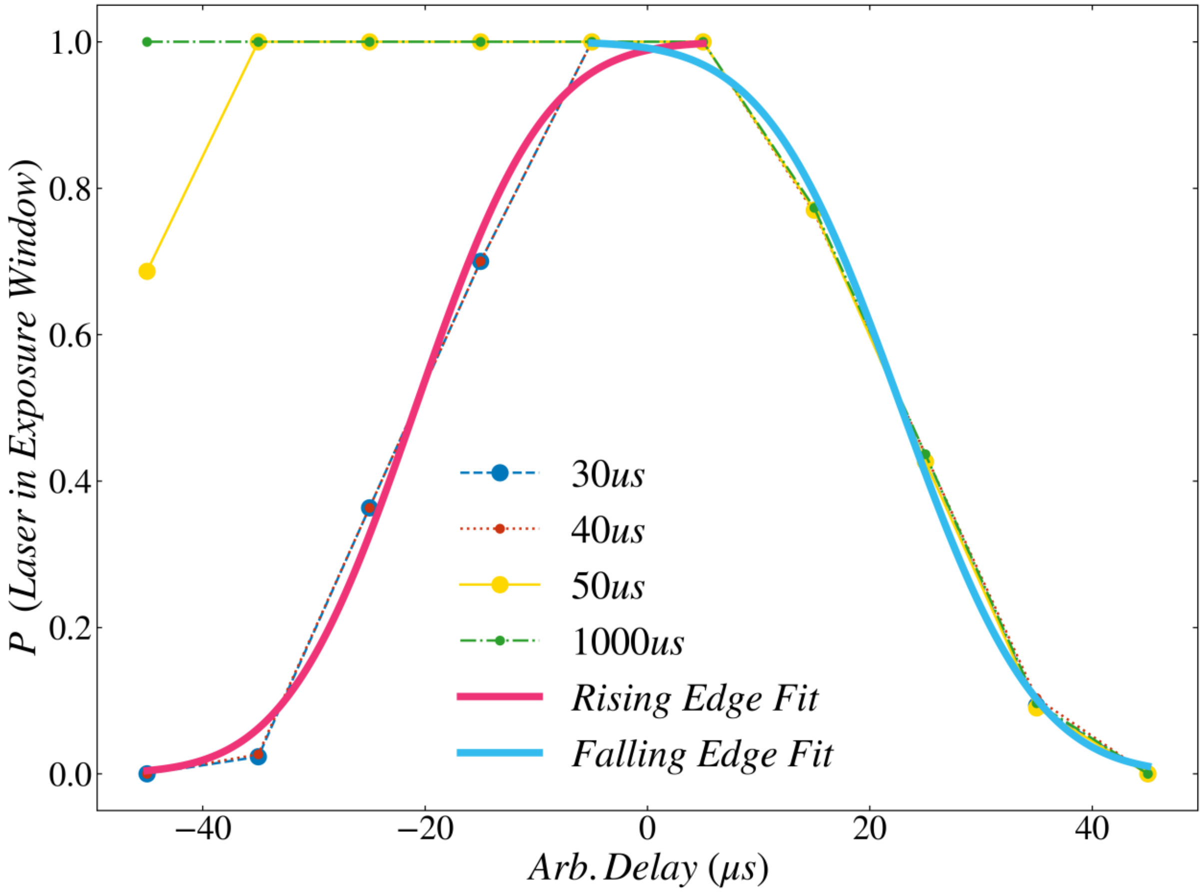
Despite the limitations of CMOS GigE cameras, their cost-effectiveness makes them a preferred choice in high radiation environments.

Camera Trigger Jitter Distribution

University of Colorado **Boulder**

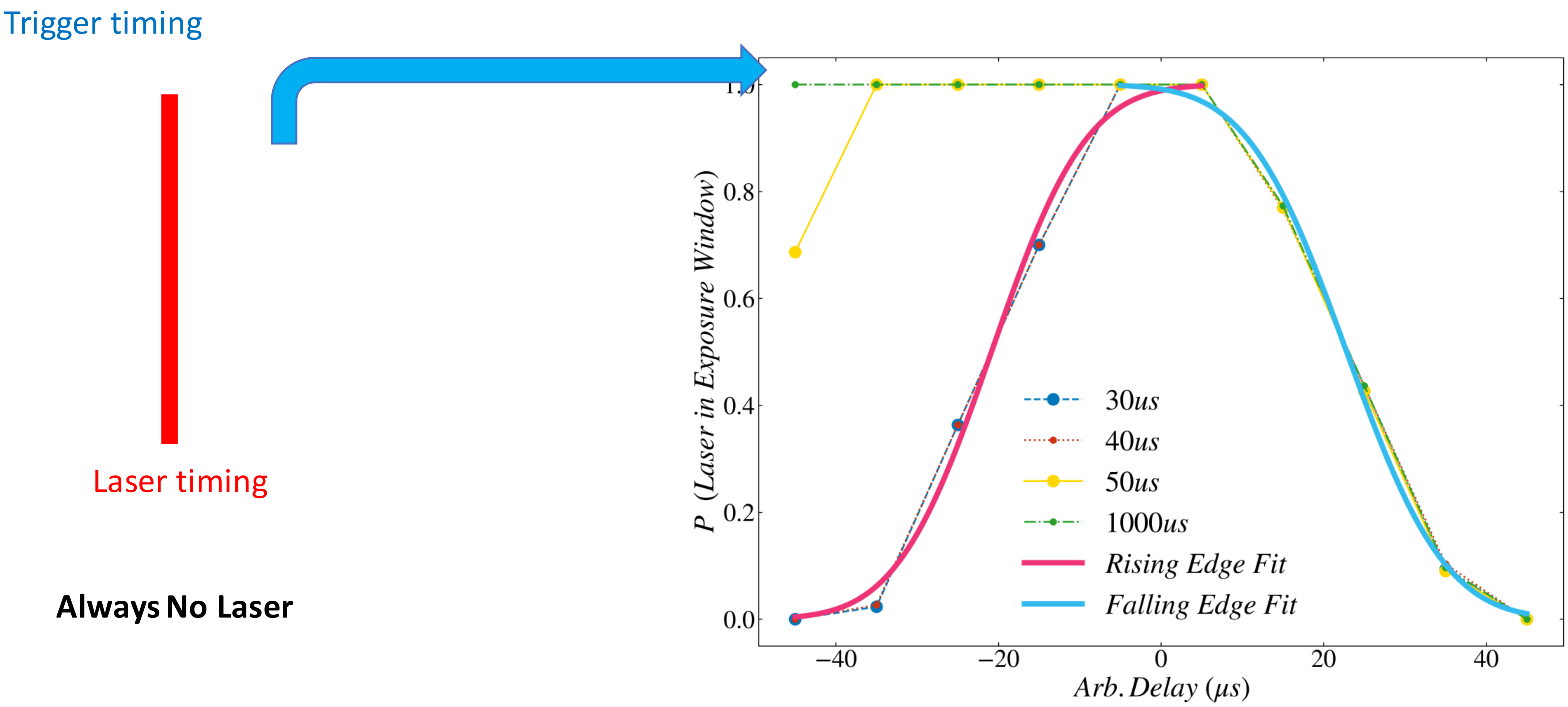


Always See Laser



The laser arrival time serves as a fiducial signal to investigate the camera trigger jitter.

Camera Trigger Jitter Distribution



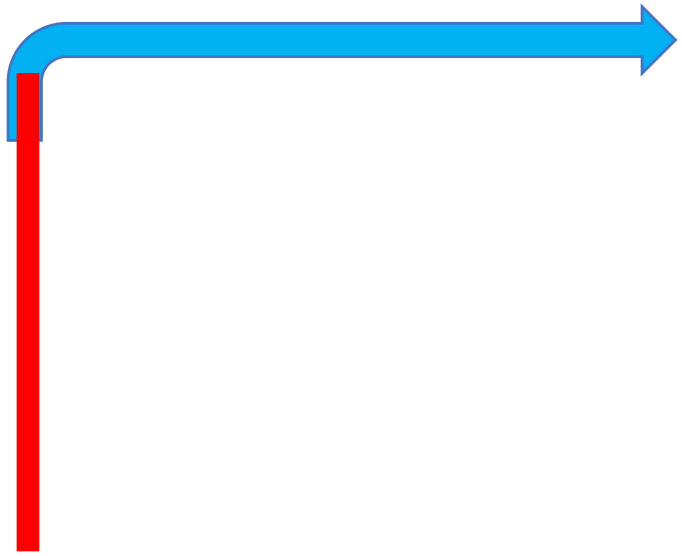
Trigger timing

Laser timing

Always No Laser

The laser arrival time serves as a fiducial signal to investigate the camera trigger jitter.

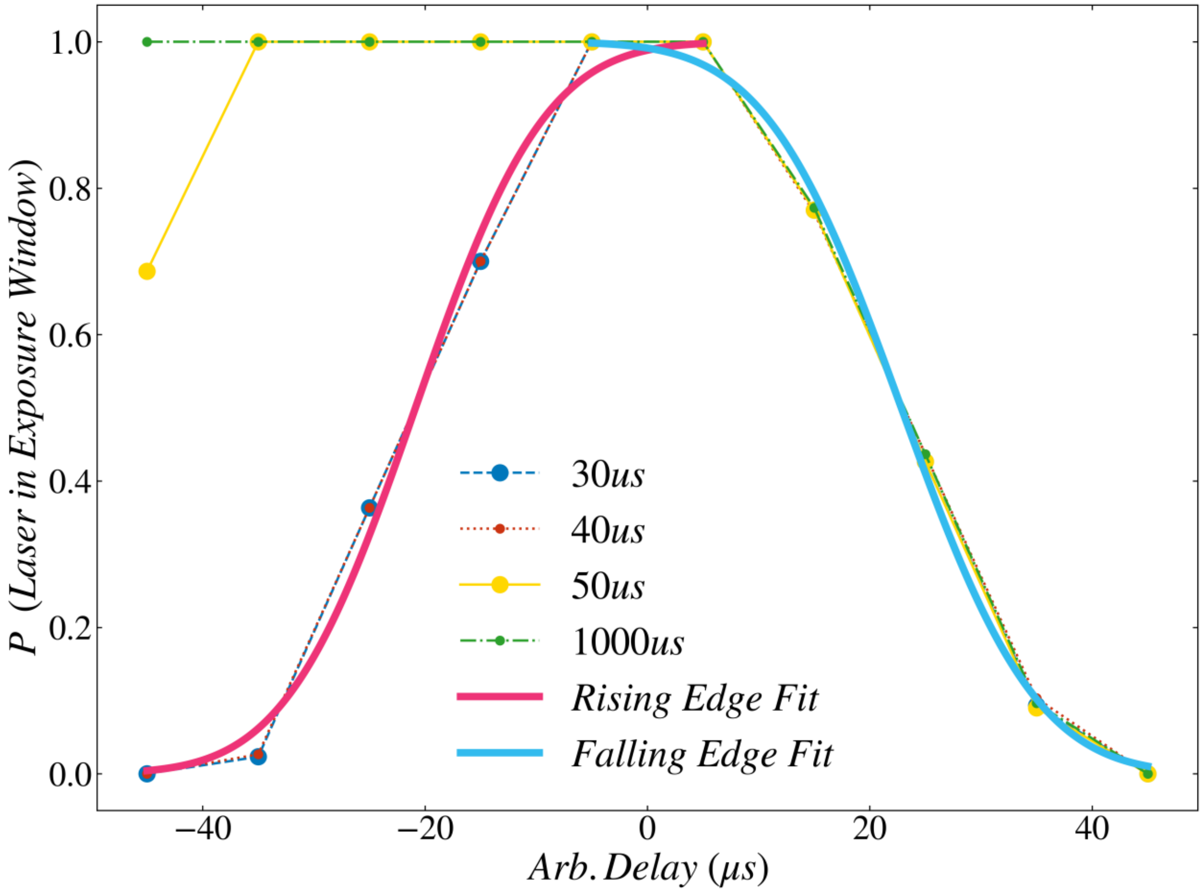
Camera Trigger Jitter Distribution



Trigger timing

Laser timing

Falling Edge



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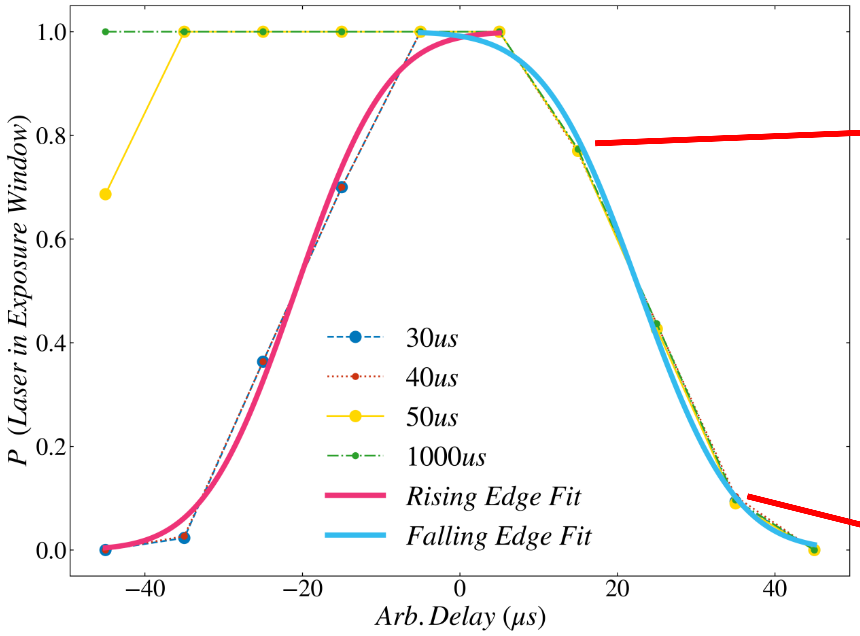
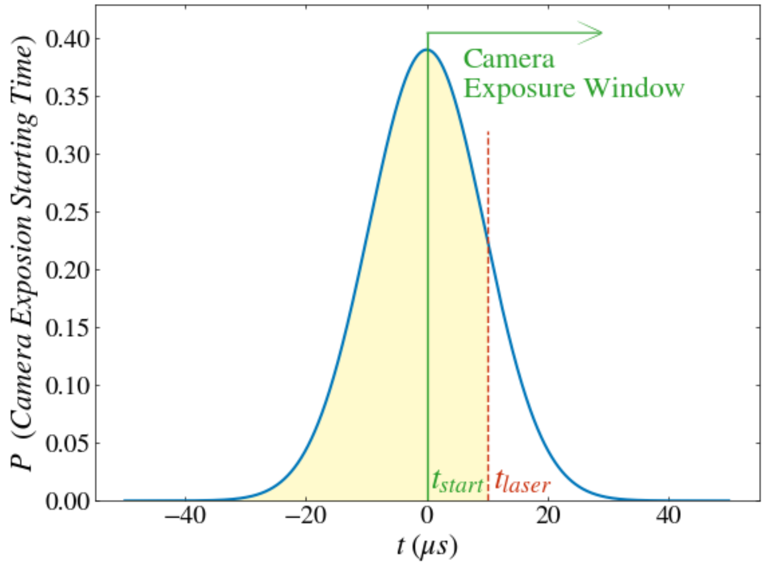
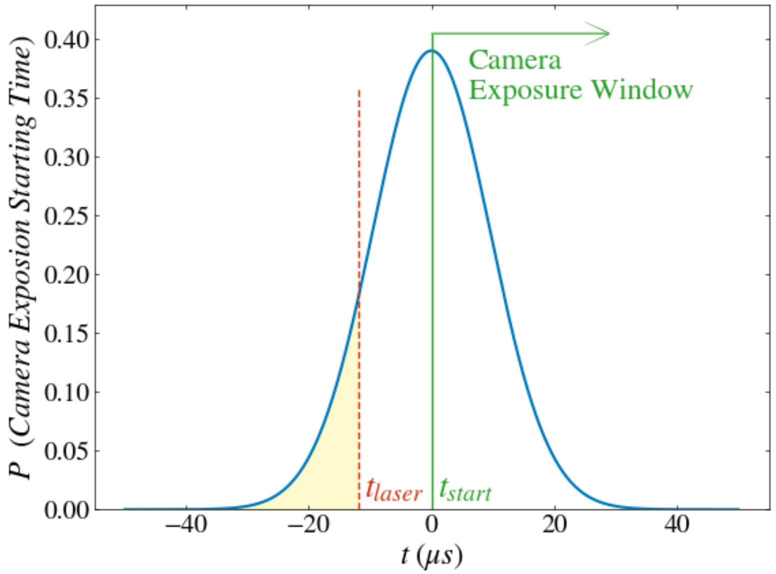


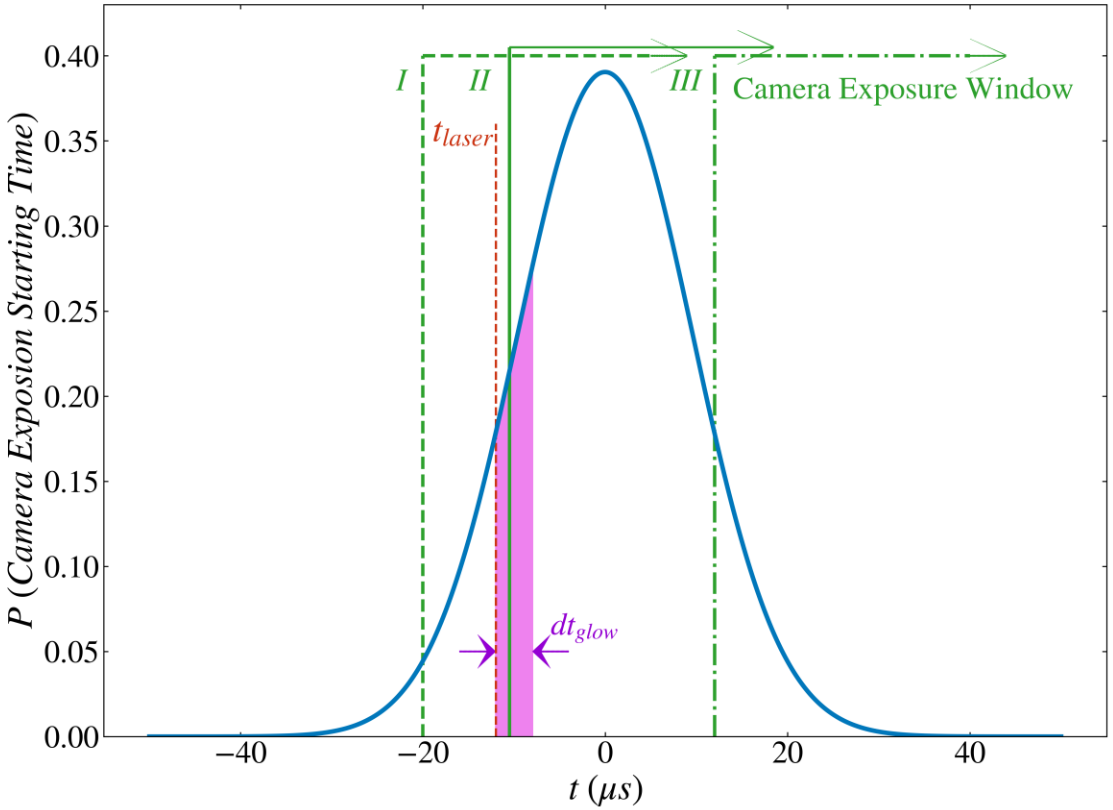




$$J(t) = \int_{-\infty}^{t} j(t)dt$$

The falling edge of probability curve in is the cumulative function of the camera-trigger-jitter distribution.

Plasma Afterglow Time Scale



Plasma afterglow time

The laser pulse creates plasma, which glows for an extended amount of time, dt_{glow}.

Region I

Include both the plasma light and laser light.

Region III

Include neither the plasma light nor laser light.

Region II

Include plasma light **NO laser light**.

Measuring the probability of images that contain plasma light without laser light allows for a statistical measurement of dt_{glow} without a nanosecond gated camera.

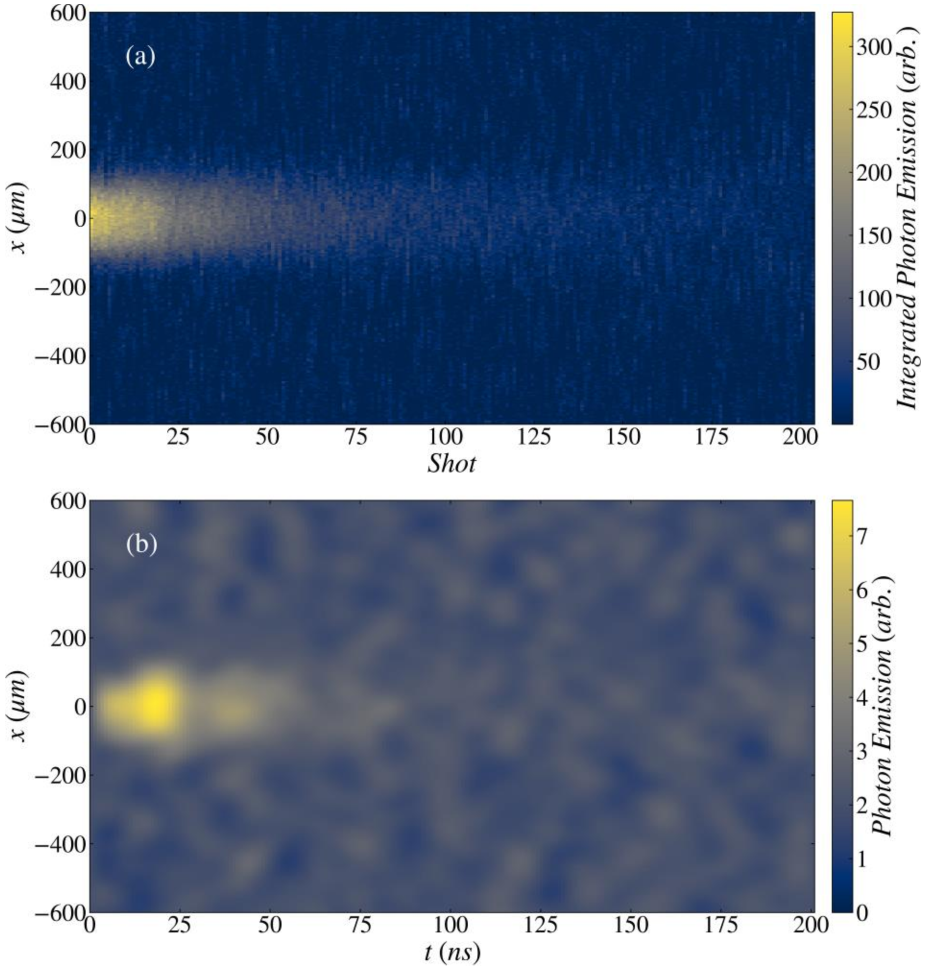
Time Resolved Plasma Light

Plasma light time scale
The decay time scale for our laser-ionized helium plasma light is **194 +/− 14 ns**.

Identify plasma only images
We identified 204 shots with plasma light emission without laser light.

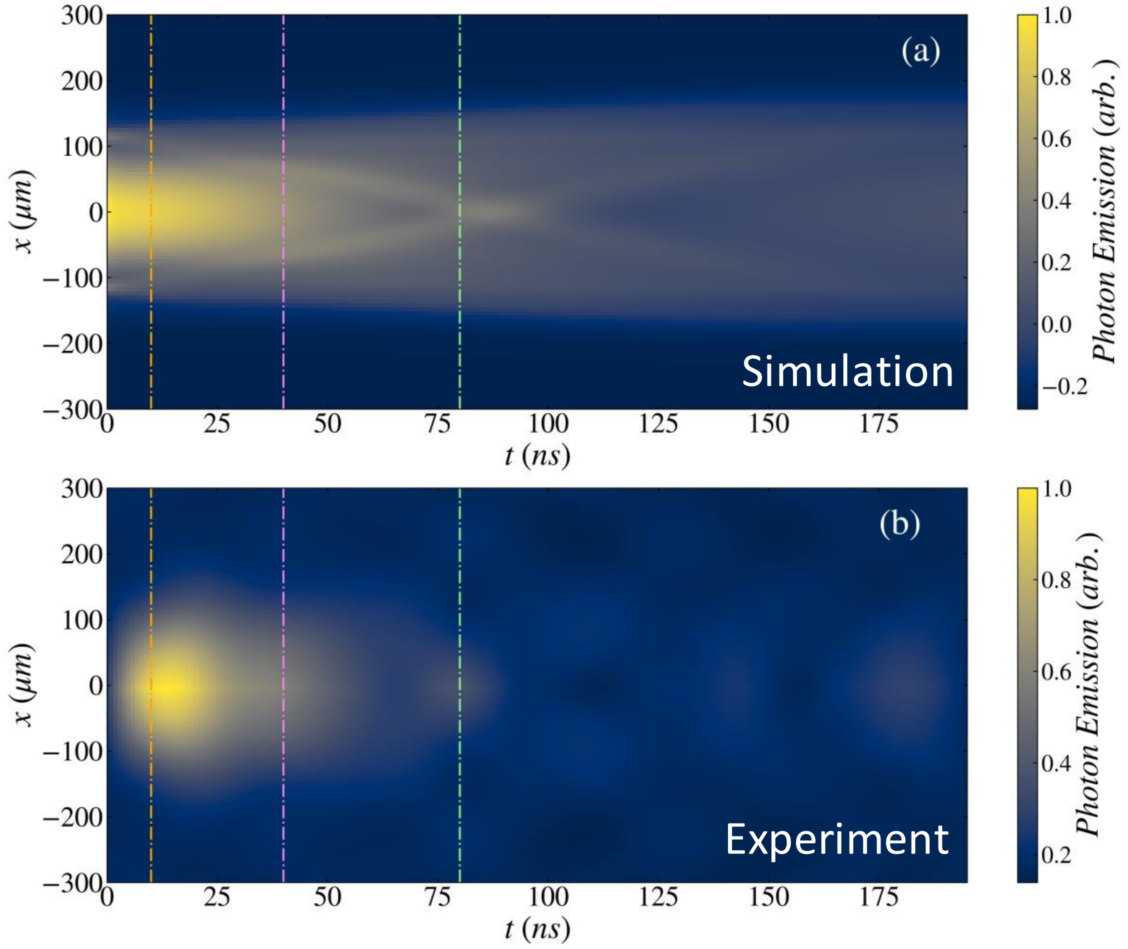
Figure (a)
The images have been summed over the laser/plasma axial dimension. The columns are sorted and aligned based on their total intensity within ROI.

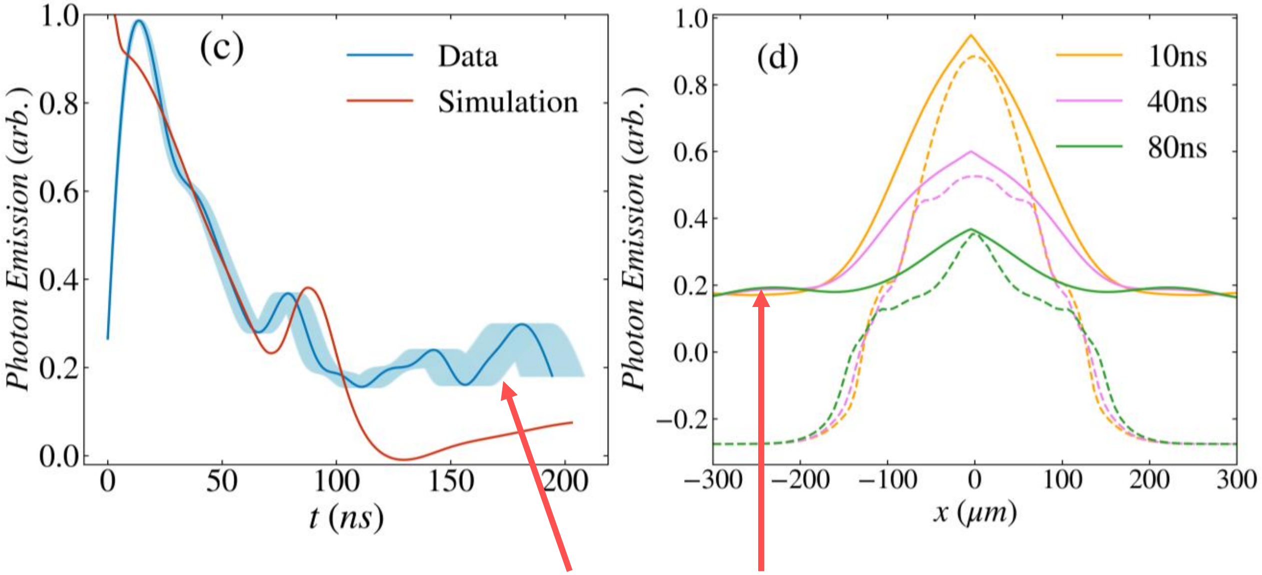
Figure (b)
A Gaussian (low-pass) filter is applied to (a) and each column is subtracted from the next column, yielding time-resolved photon emission pattern.



We demonstrate the ability to achieve O(1 ns) time resolved imagery of the plasma light emission using a cost-effective GigE CMOS camera.

Plasma Light Decay Dynamics Exp. vs Sim.





Experimental noise level

An **inverse Abel transform** is used to convert from the horizontally integrated glow pattern to retrieve the radial light intensity pattern.

The temporal evolution of the simulated and experimentally observed plasma light emission show good agreement.

Experimental Results

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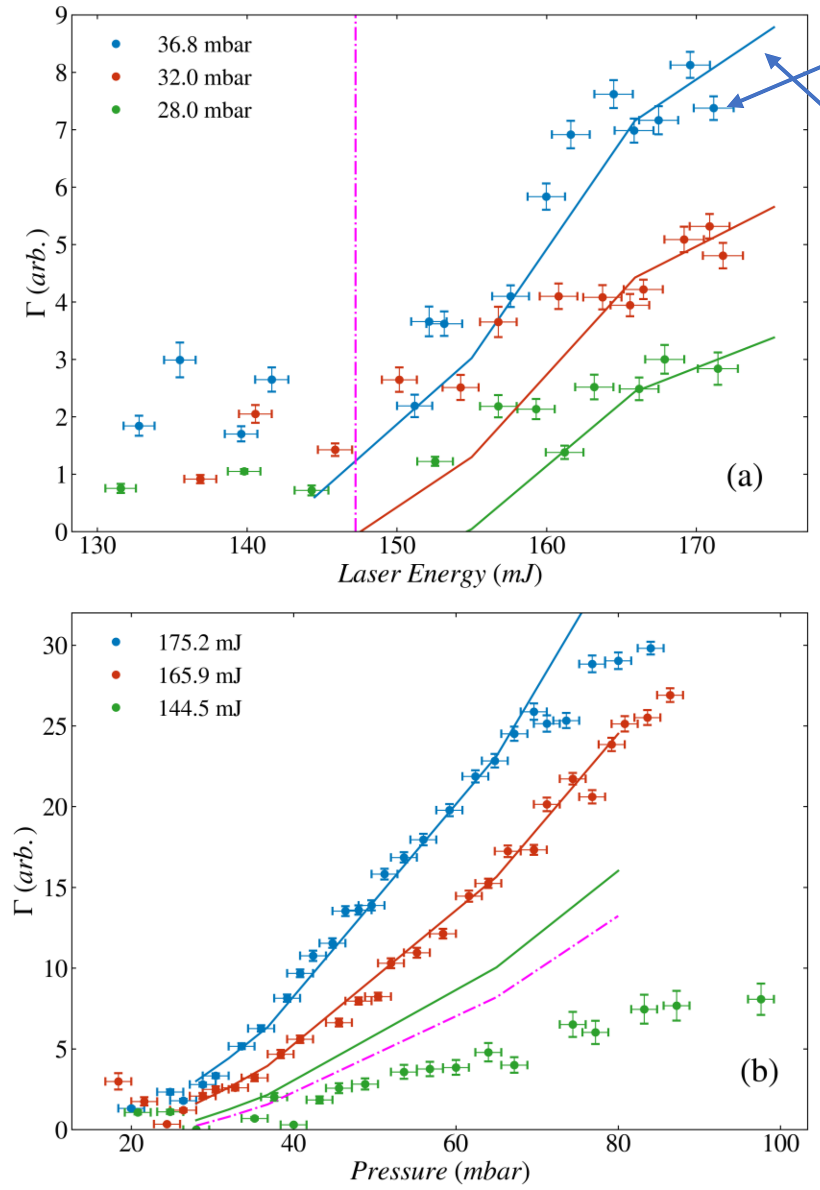


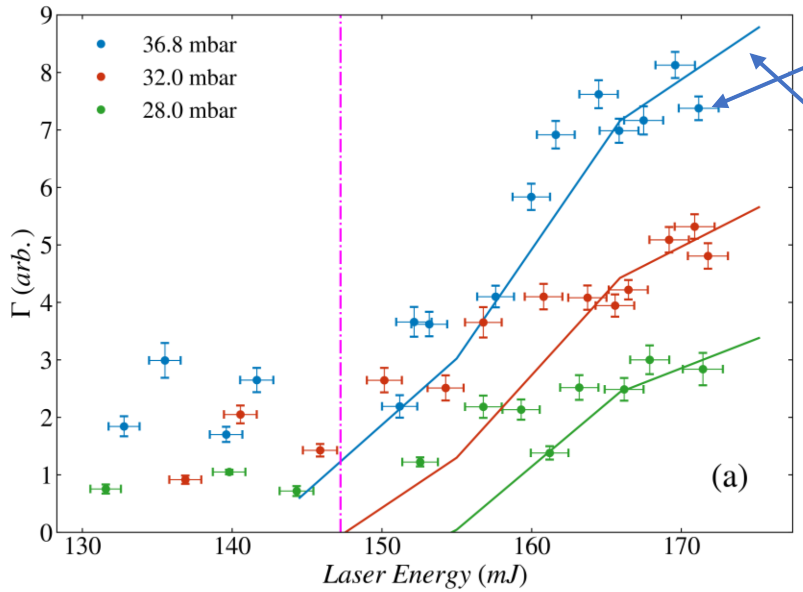
Experimental data

On-axis, time-integrated light emission:

$$\Gamma = \int_0^\infty n_e(x=0, y=0) < \upsilon_{en}(x=0, y=0) > dt$$
$$= C n_0^2 \sqrt{R\, k_B T_0} \exp(-K_{th}/(R\, k_B T_0)),$$

The experimental data show remarkable agreement with our simple prediction of the peak light emission scaling as a function of the initial plasma parameters

Experimental Results



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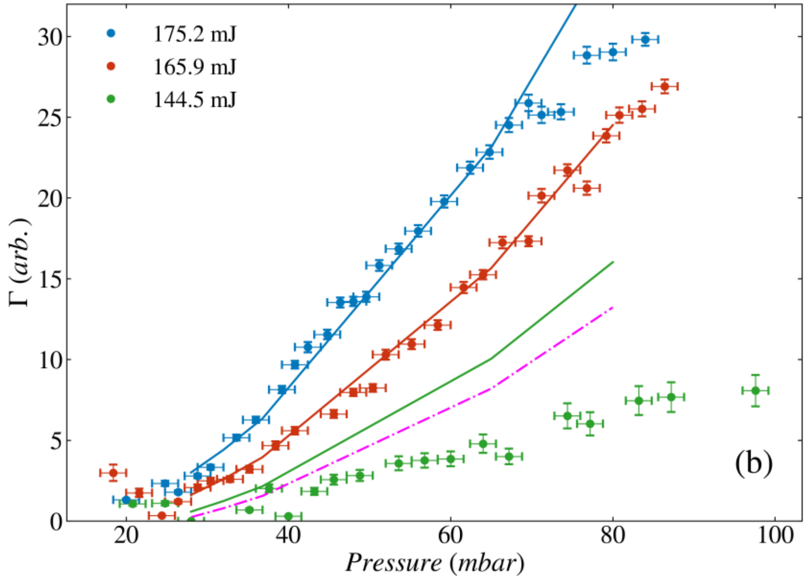

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The experimental data show remarkable agreement with our simple prediction of the peak light emission scaling as a function of the initial plasma parameters

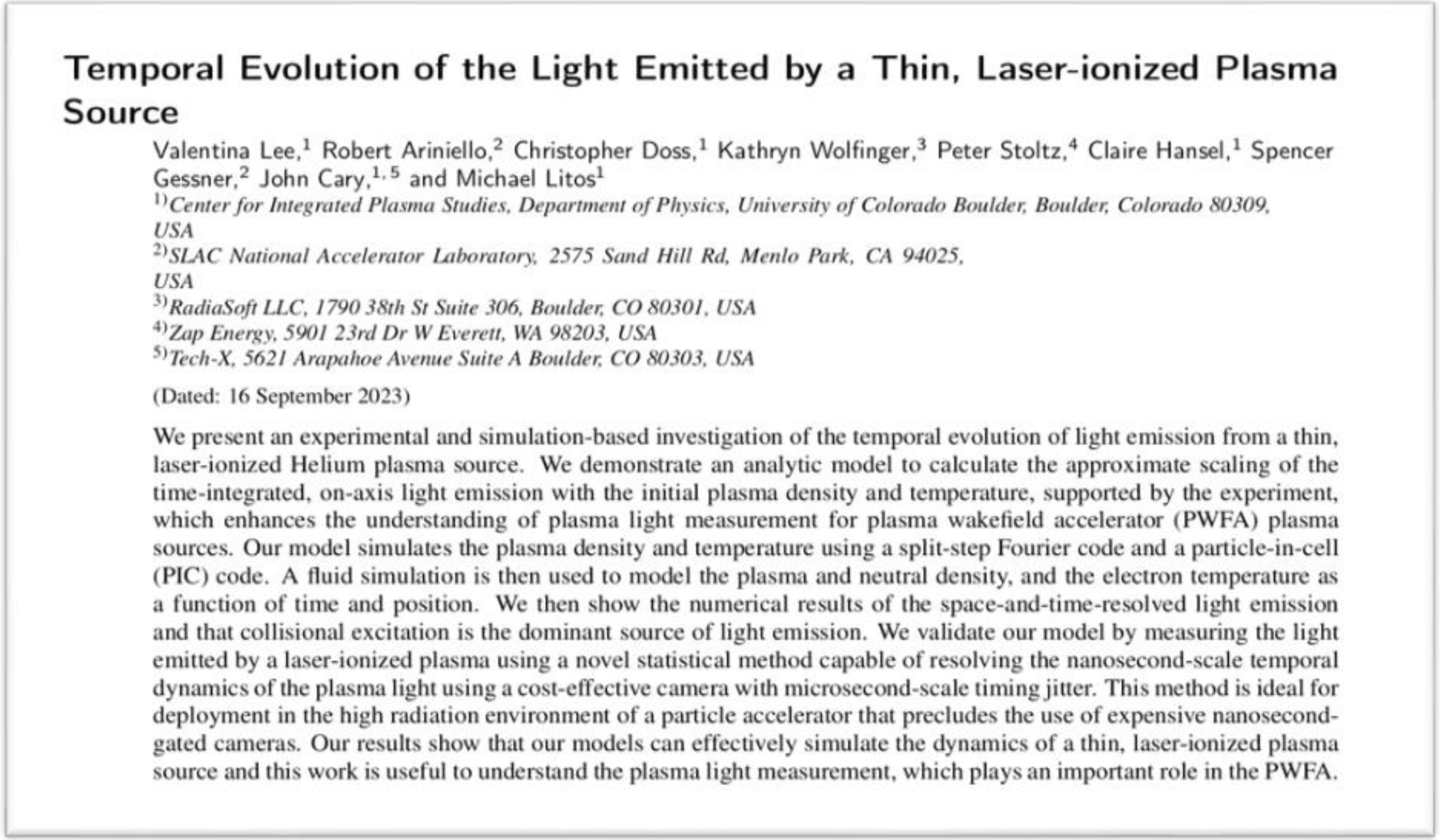
Summary

- We demonstrated an experimental comprehension of the decay process of the plasma light emitted from a laser-ionized PWFA-like plasma source, supported by numerical simulations.
- Collisional excitation dominants the photon emission process in a helium PWFA plasma.
- We presented a novel statistical approach for measuring the temporal evolution of plasma light with ns resolution using a GigE CMOS camera and use the laser as the fiducial signal.
- We showed that a simple, semi-analytical model can accurately predict the scaling of the peak photon emission density with the initial plasma (gas) density and temperature.

Advances in understanding the plasma light emission process of PWFA-like plasma sources and enhances their utility as diagnostic tools in PWFA experiments.

See more details on arXiv: 2309.10723

Preprint



Temporal Evolution of the Light Emitted by a Thin, Laser-ionized Plasma Source

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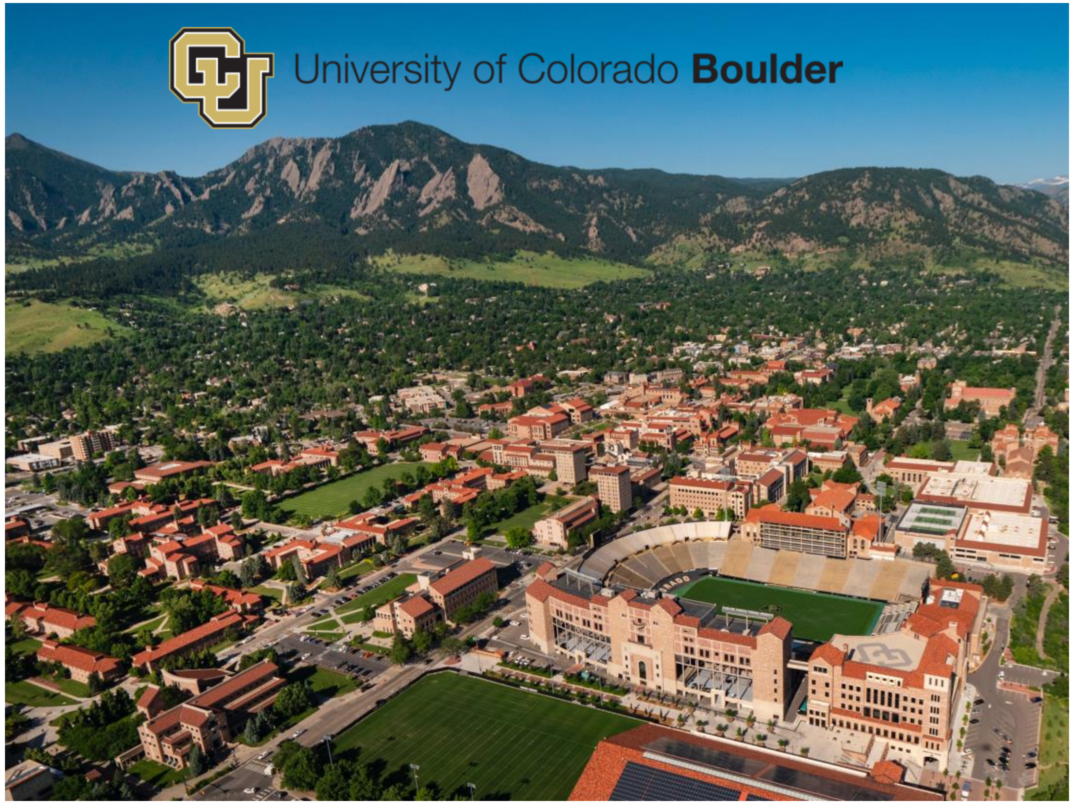
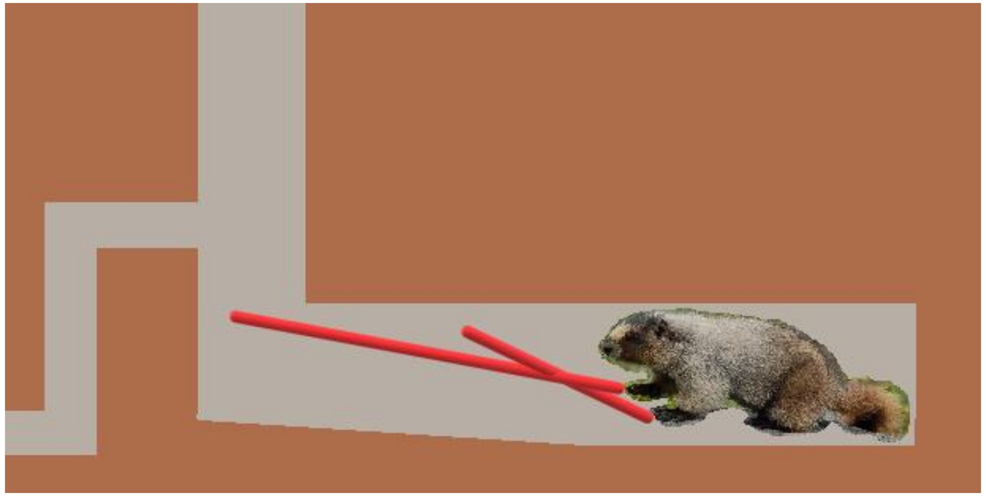
(Dated: 16 September 2023)

We present an experimental and simulation-based investigation of the temporal evolution of light emission from a thin, laser-ionized Helium plasma source. We demonstrate an analytic model to calculate the approximate scaling of the time-integrated, on-axis light emission with the initial plasma density and temperature, supported by the experiment, which enhances the understanding of plasma light measurement for plasma wakefield accelerator (PWFA) plasma sources. Our model simulates the plasma density and temperature using a split-step Fourier code and a particle-in-cell (PIC) code. A fluid simulation is then used to model the plasma and neutral density, and the electron temperature as a function of time and position. We then show the numerical results of the space-and-time-resolved light emission and that collisional excitation is the dominant source of light emission. We validate our model by measuring the light emitted by a laser-ionized plasma using a novel statistical method capable of resolving the nanosecond-scale temporal dynamics of the plasma light using a cost-effective camera with microsecond-scale timing jitter. This method is ideal for deployment in the high radiation environment of a particle accelerator that precludes the use of expensive nanosecond-gated cameras. Our results show that our models can effectively simulate the dynamics of a thin, laser-ionized plasma source and this work is useful to understand the plasma light measurement, which plays an important role in the PWFA.

See preprint on arXiv: 2309.10723

Thank You for Your Attention





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