EAAC2025

AWAKE

– EAAC 2025 –
Measurement of the radius of a plasma column in presence of a relativistic proton bunch

Lucas Ranc (1)

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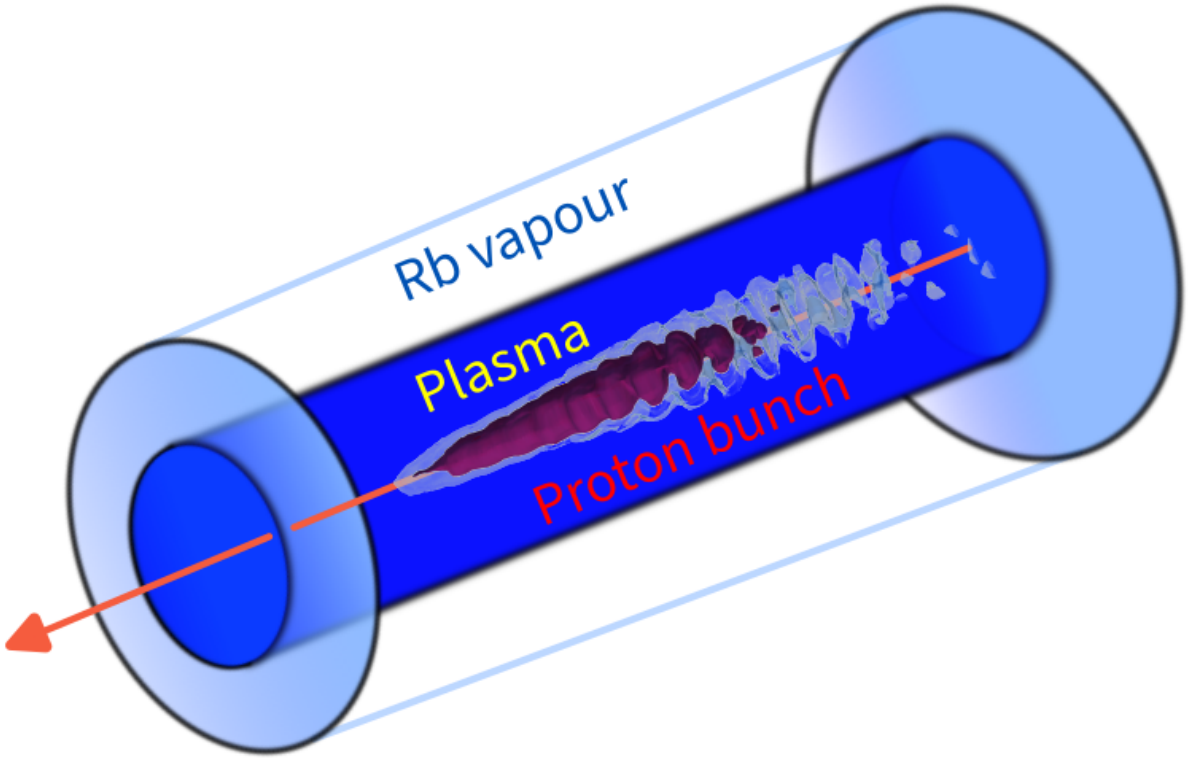
(4) UCL, London, UK

MAX-PLANCK-INSTITUT FÜR PHYSIK

Content

- Introduction
- Evaluation and estimation of the plasma parameters
- Results
  - Experimental overview
  - Physics studies
- Summary & Outlook

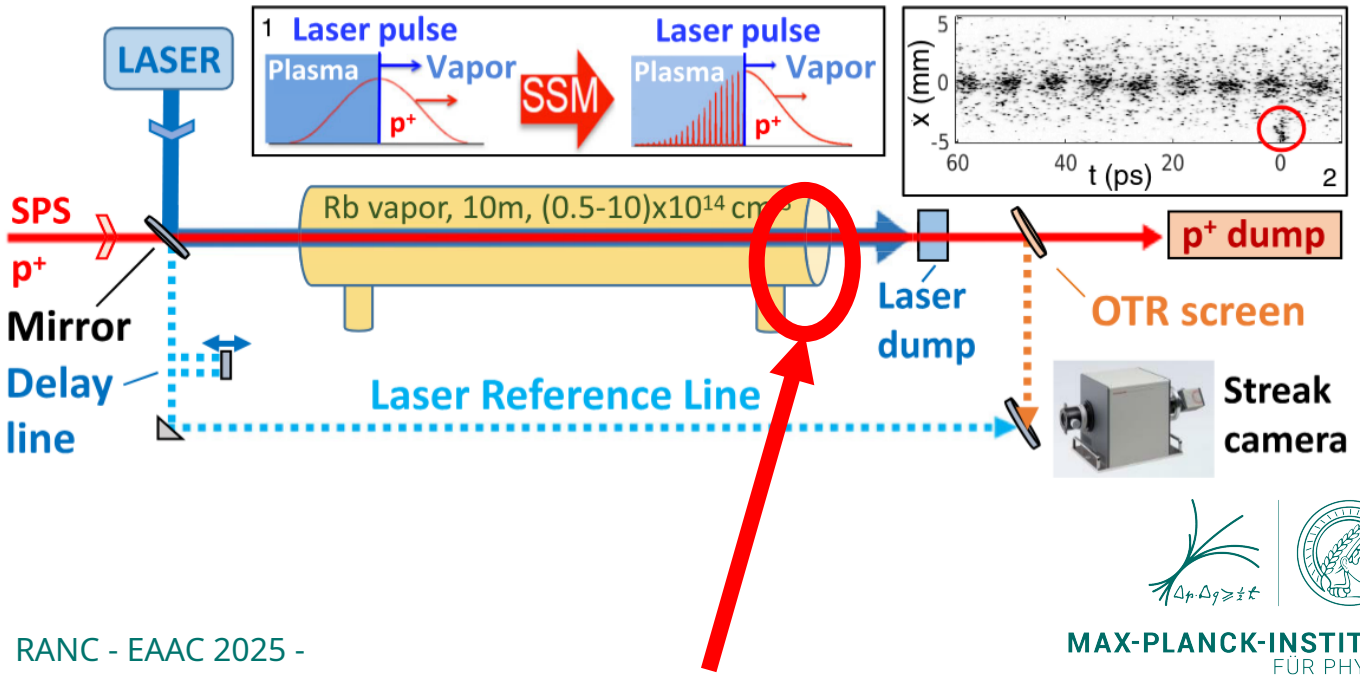


Introduction

- AWAKE Experiment : accelerate electrons to GeV scale in the wakefield of proton micro-bunches
- Accelerating medium: Rubidium: 10 m long-plasma, 1e14 − 1e15 cm^{-3} density
- Ionized Rb vapor using a Ti:Sapphire TeraWatt Laser at 780 nm at resonance, 120 mJ, 120 fs

- Experimental motivation of the present study:
  Determine the plasma characteristics via Schlieren Imaging

- Characterization of plasma column:
  Experimental quantification of plasma's:
  - **Transverse size**
  - **Edge sharpness**
  - Adequate homogeneity
  - Rb atomic transitions properties
  - …



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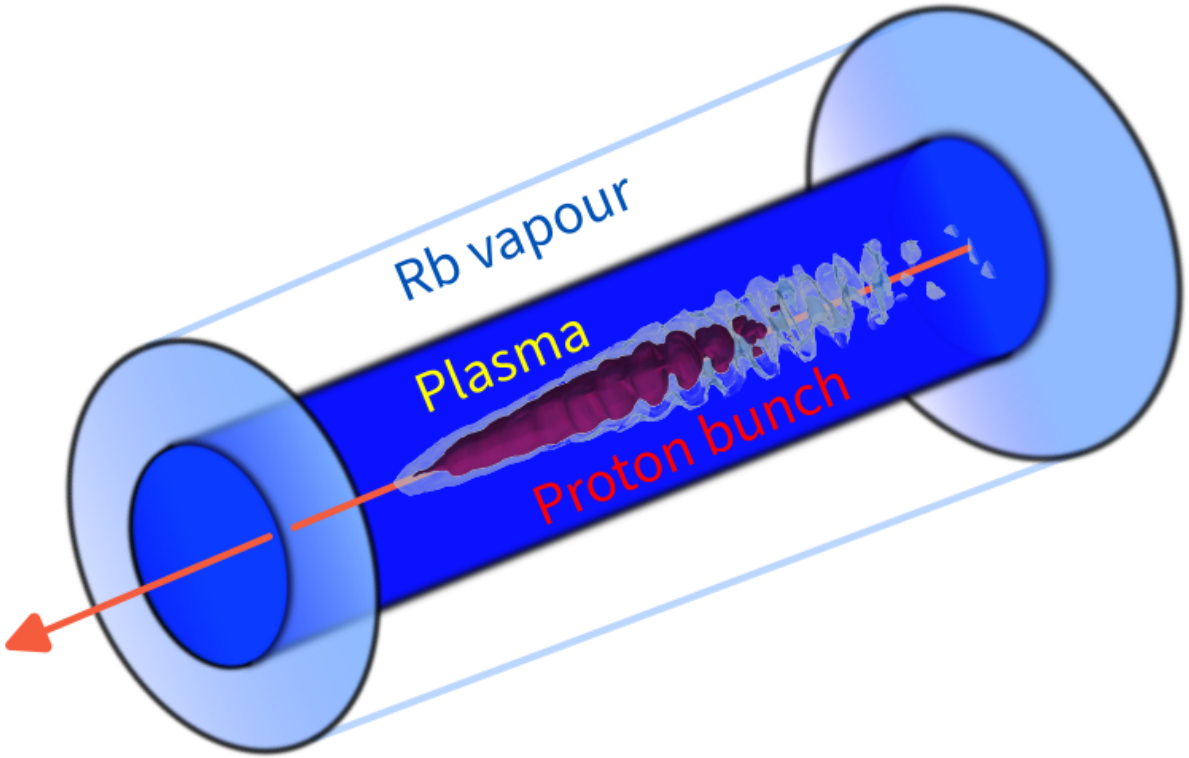
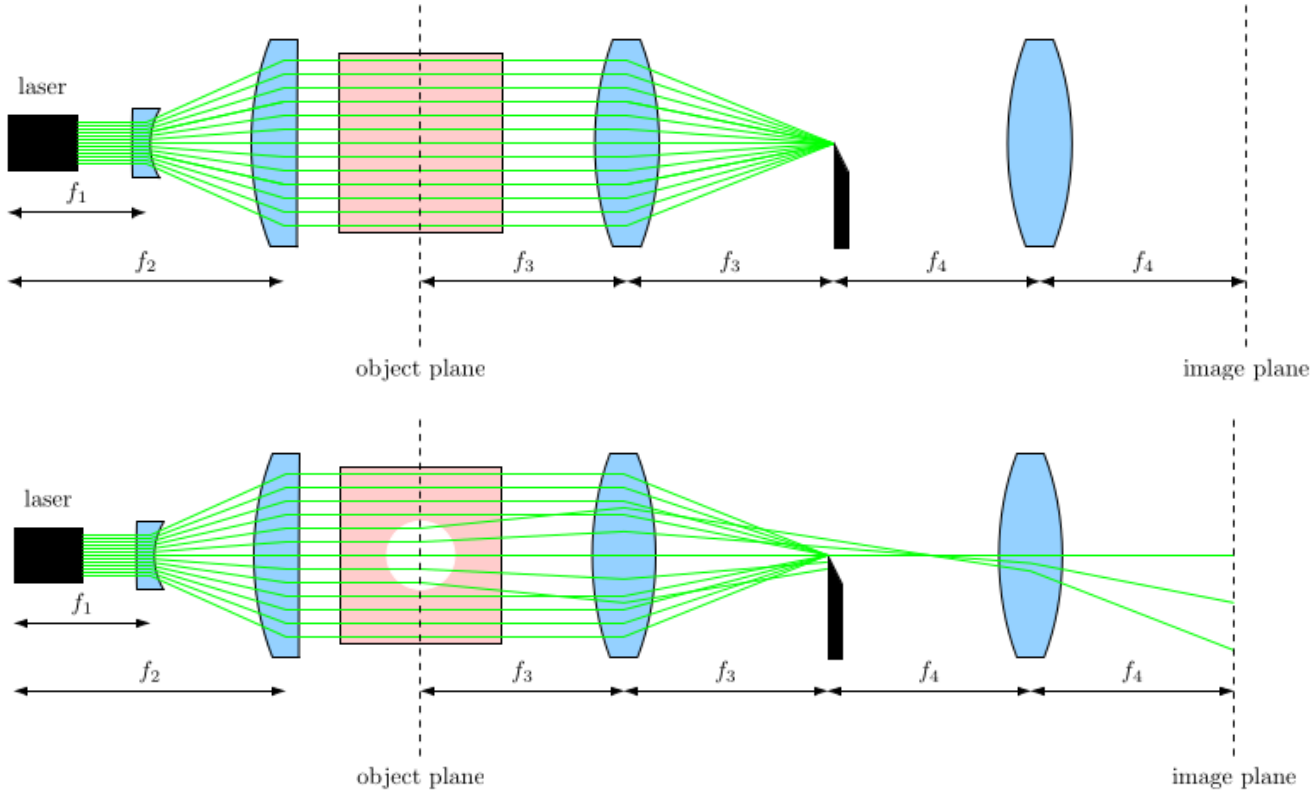


Evaluation of the plasma

Schlieren Imaging

- Sharp edges & transverse size
  - Optical technique sensitive to small variations in the refractivity
  - Fourier filtering optical system
- Without plasma
  - no signal – mask filters the probe beam completely
- With Plasma
  - high frequency components pass through the mask.



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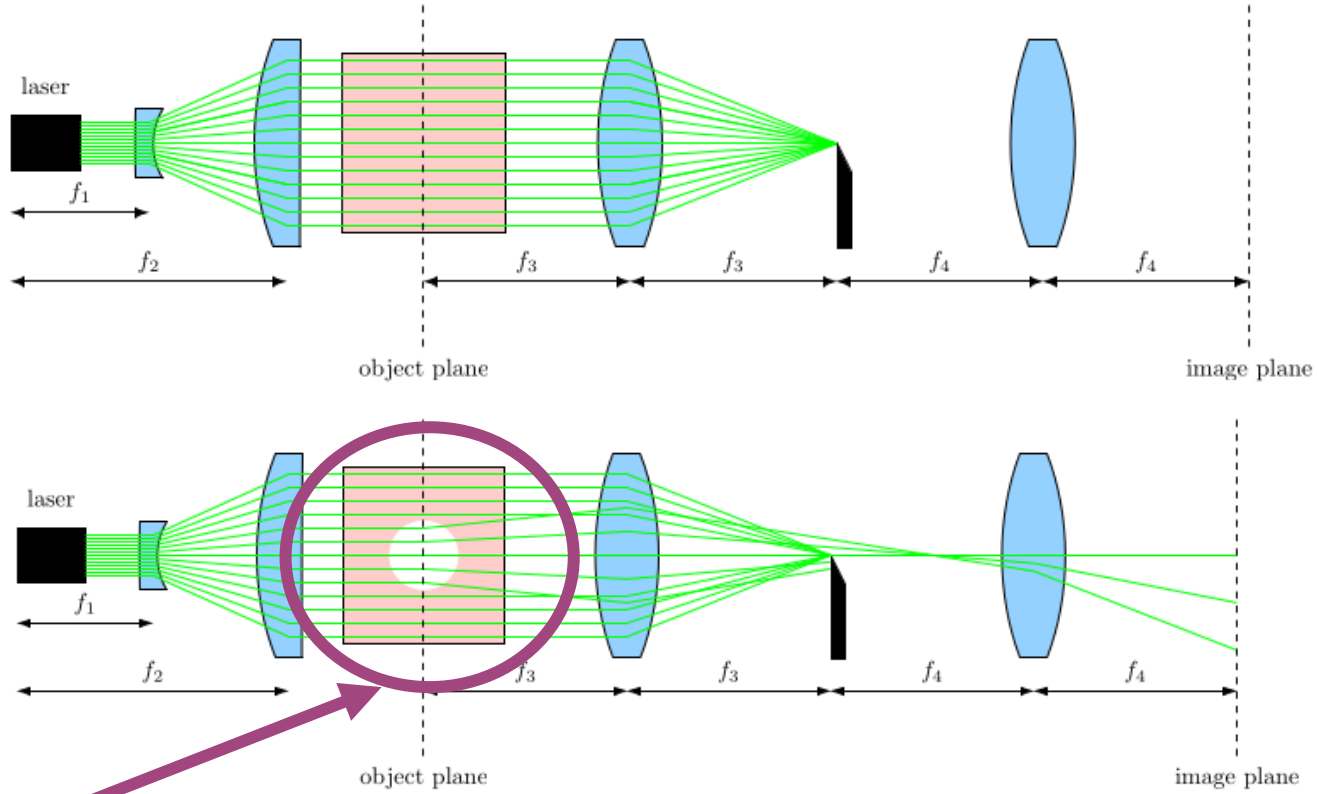

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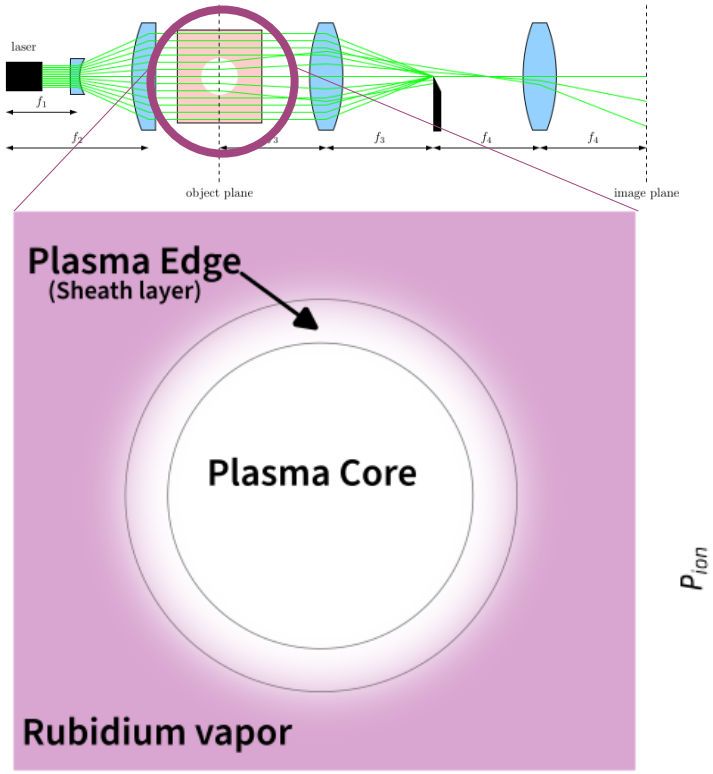
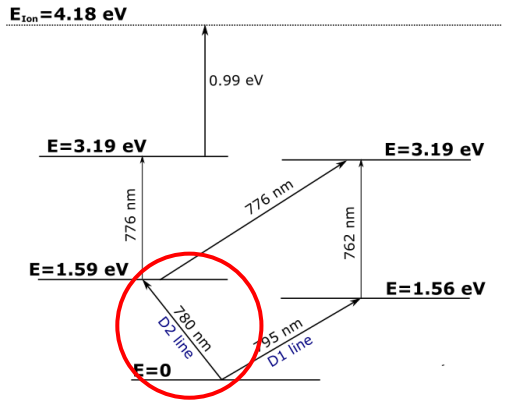
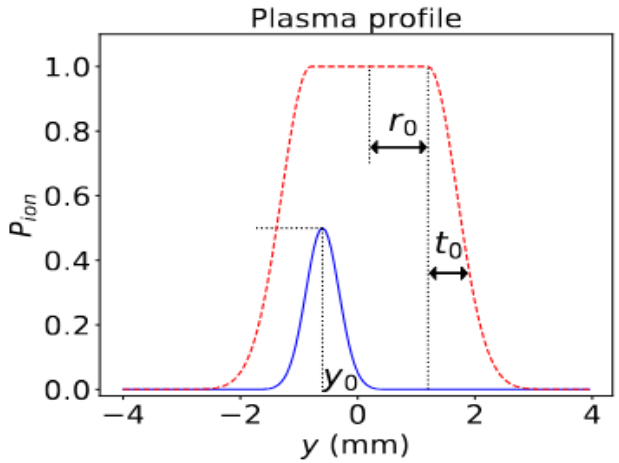






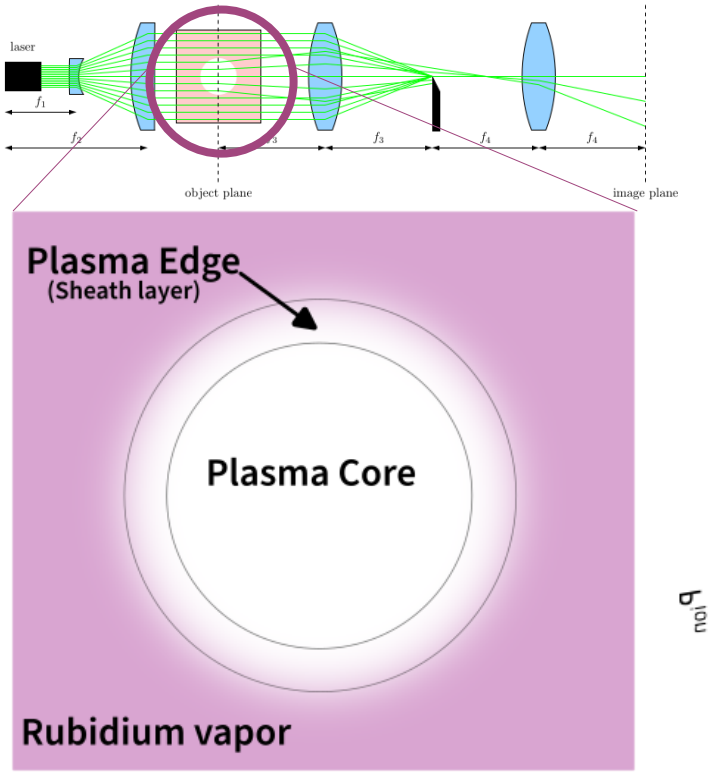
1) Plasma creation: TW laser pulse removes the single valence electron with a Prob.~1
2) Facilitated by λ_0 780 nm ($\Delta\lambda$=10nm) resonant with the D2 transition (780.241 nm) of Rb at ground state
3) Density low 1e14 cm^{-3} → low peak intensity ~10^{12}W/cm^2 → below threshold of self-focusing
4) The plasma medium is transparent
5) We image the missing ground state Rb atoms

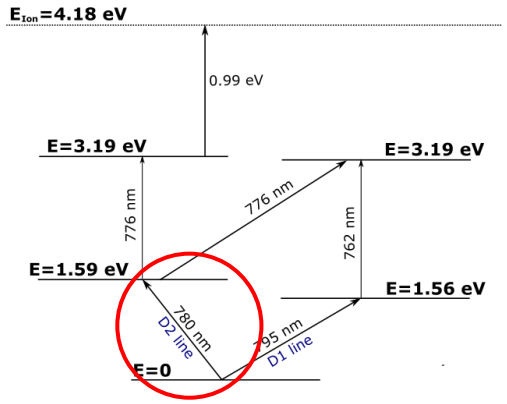
The plasma profile can be modeled as

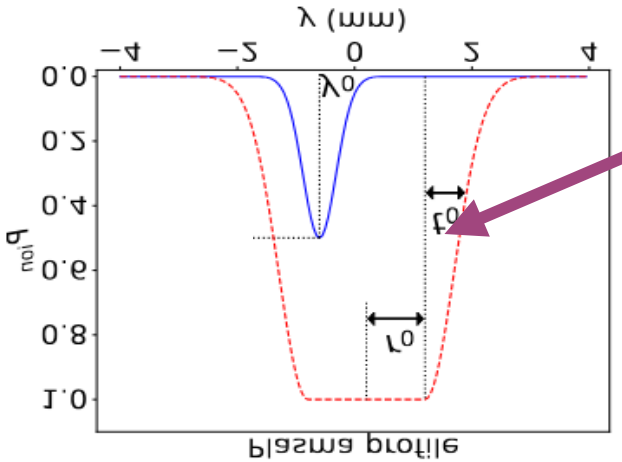
- A Plasma Core : plateau of maximum ionization r< r_0
- A Plasma Edge; sheath layer with t0 : characteristic length of the transition region.

Evaluation of the plasma

Schlieren Imaging







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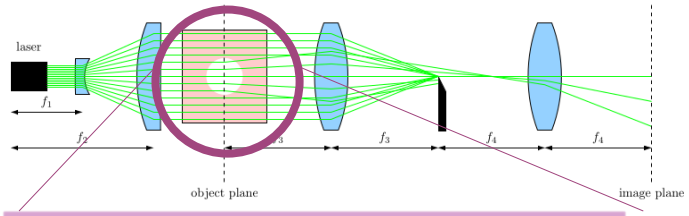
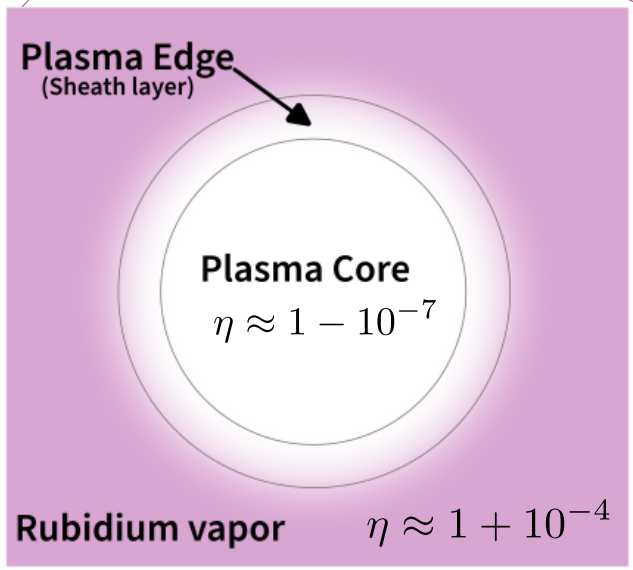
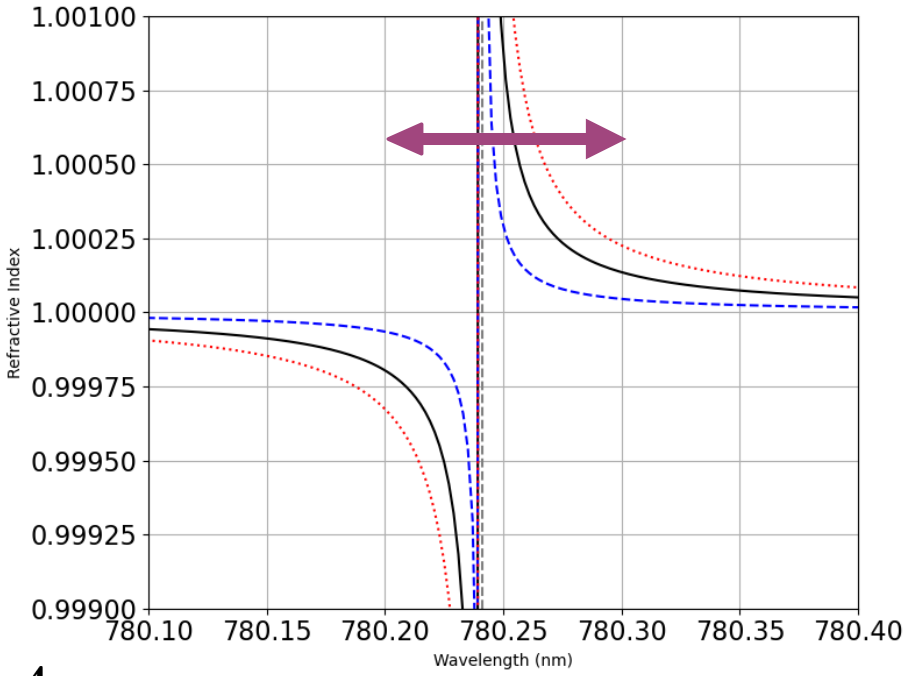




$$n_{vapor} = \sqrt{1 + \chi(\omega)}$$

$$\chi(\omega) = \frac{Ne^2}{\varepsilon_0 m_e \omega_0^2} \cdot \frac{f}{\omega_0 - \omega - i\gamma}$$

$$\eta_{\text{plasma}} = \sqrt{1 - \left(\frac{\omega_p}{\omega_L}\right)^2}$$

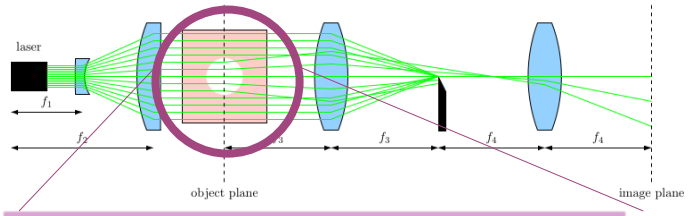


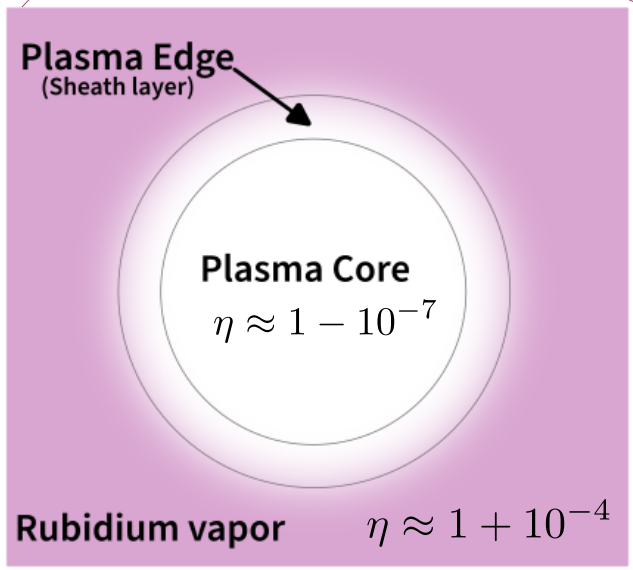
- Small change of refractivity
- Index of refrac. of the Rb vapor
- Need to choose the probe laser
  - Broadening: The higher the density the stronger the absorption
  - De-tuning the probe → small Δn

$$\Delta\eta \approx 10^{-4}$$

Evaluation of the plasma

Schlieren Imaging





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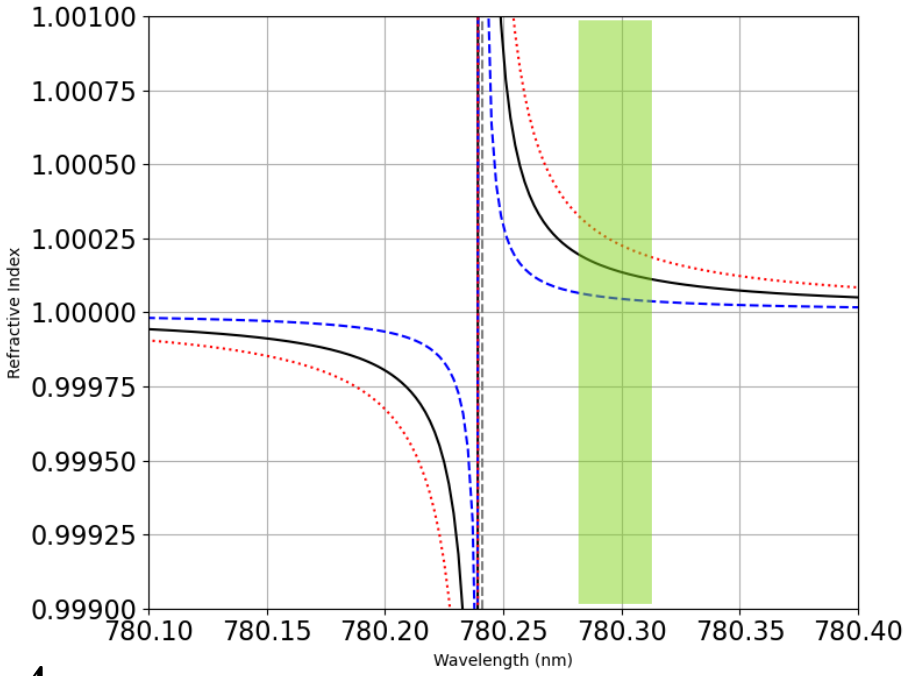

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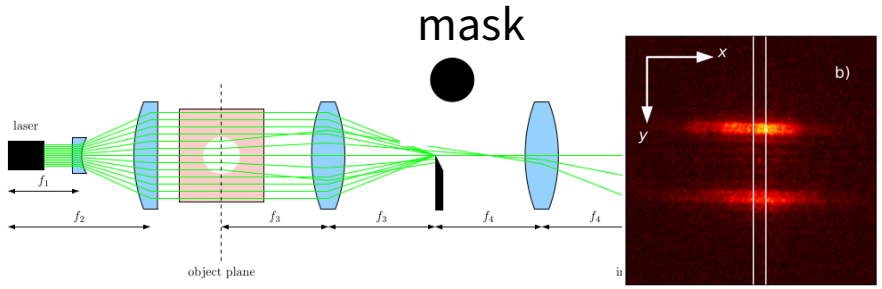
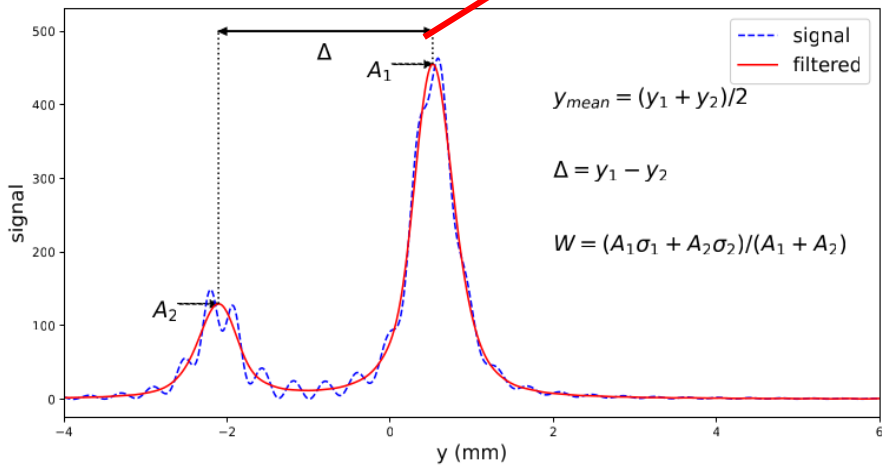
Evaluation of the plasma

Schlieren Imaging – past results



- Obtain line-out
- Frequency filter
- Peak finding



=> Derive Δ, W peak width

$$\Delta = M_{12} r_0 t_0 + M_1 r_0 + M_2 t_0 + B$$

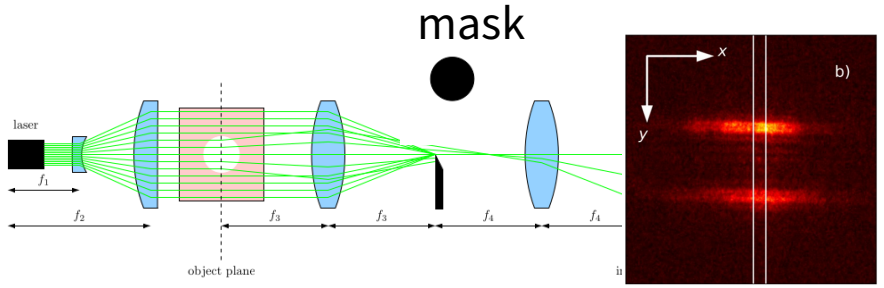
$$W = Q_{12} r_0 t_0 + Q_1 r_0 + Q_2 t_0 + P$$

=> We can estimate the set {y0, **r0, t0**}

G. Demeter, et al. Optics & Laser Technology 168, 109921 (2024).

Evaluation of the plasma

Schlieren Imaging – past results



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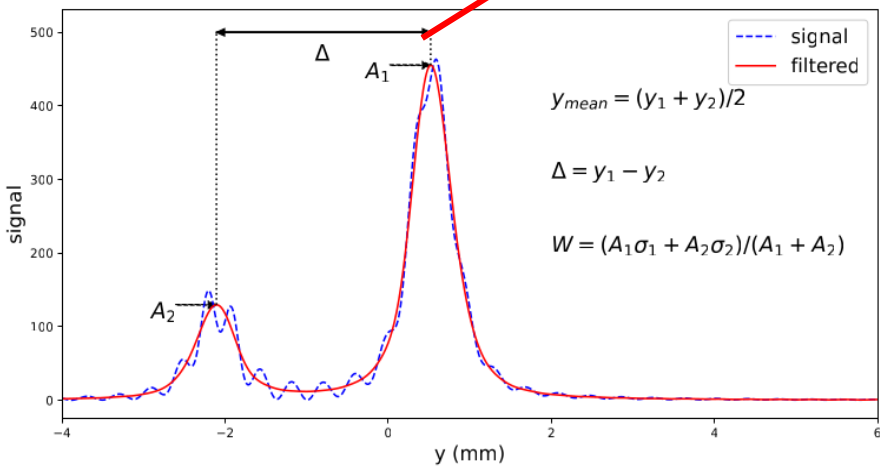
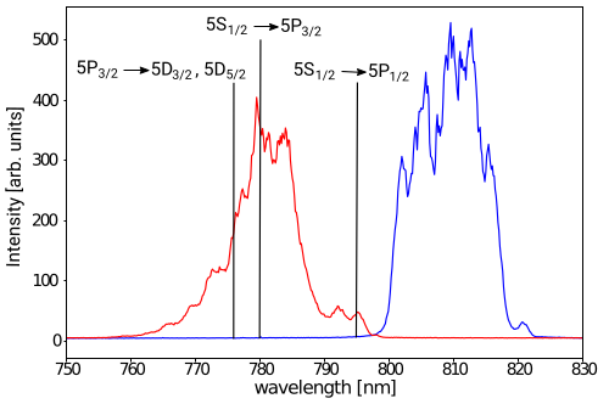
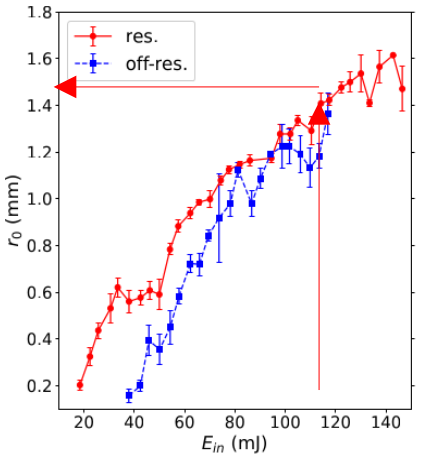
Ex: on-resonant and off-resonant ionizing pulses



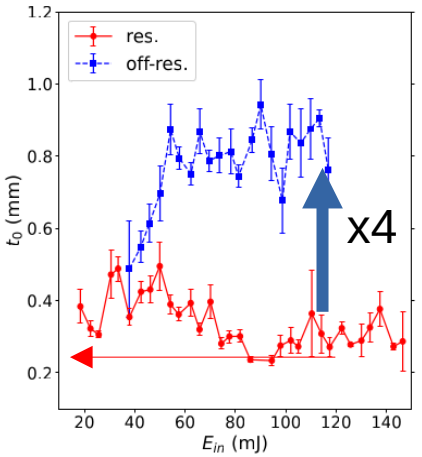
spectrum



Core radius



Transition extent



$$5\times \quad \sigma_r \leq \frac{c}{\omega_{pe}} \simeq 200\ \mu m$$

Evaluation of the plasma

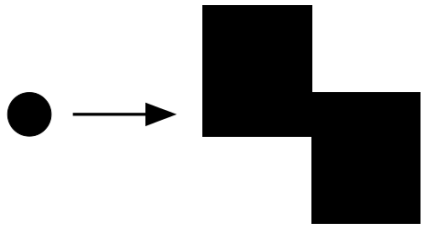
Schlieren Imaging – past results

- Successful design developed allowing:
  - evaluation of the plasma transverse size using Schlieren Imaging
  - estimation r_0 and sheath t_0 using a model

✔ Confirmed on-resonant ionizing laser at 780 nm of the Rubidium vapor and compatible for AWAKE

❖ To use it during the experiment – Limitations:

- removed to let other diagnostic
- Radiation compatible setup needed
- Plasma column constant along x direction of view. 1D → Cylindrical optics
- Mask adjustable on translation stage, precision movement for a higher signal amplitude and signal filtering less distorting.
- Tunable Probe wavelength with an active locking: “ideal” wavelength is different for each density



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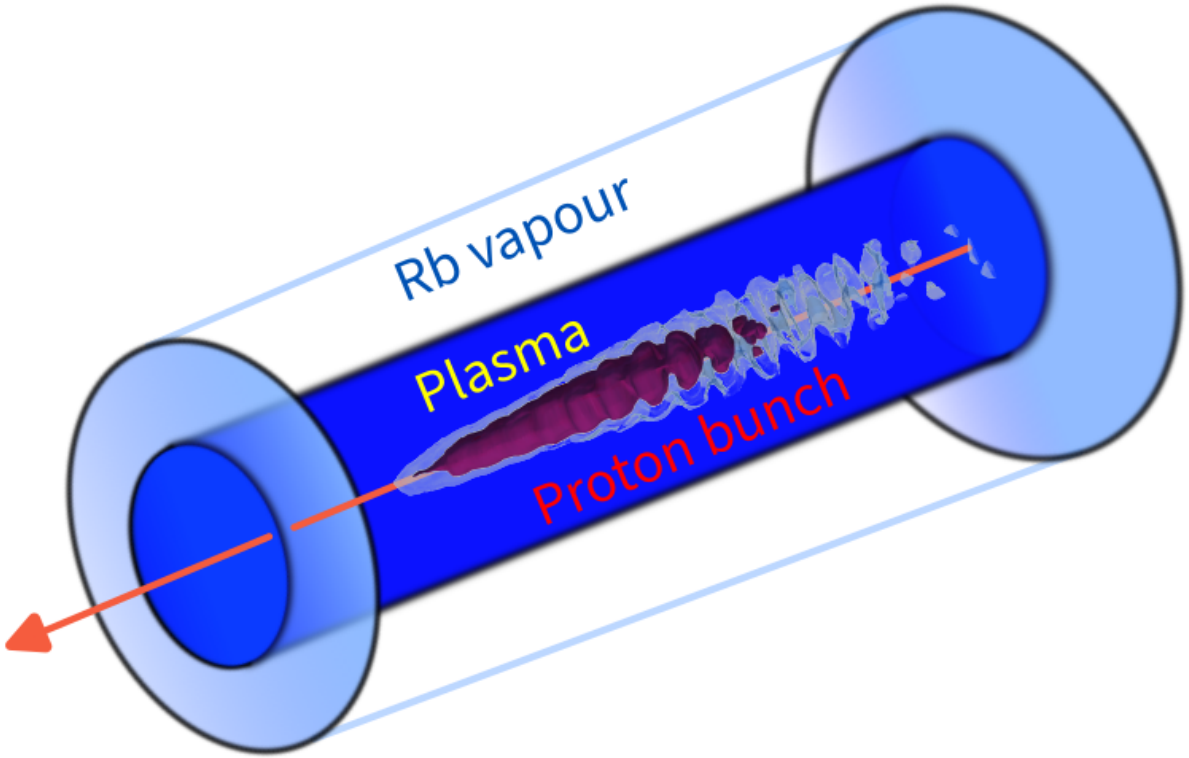
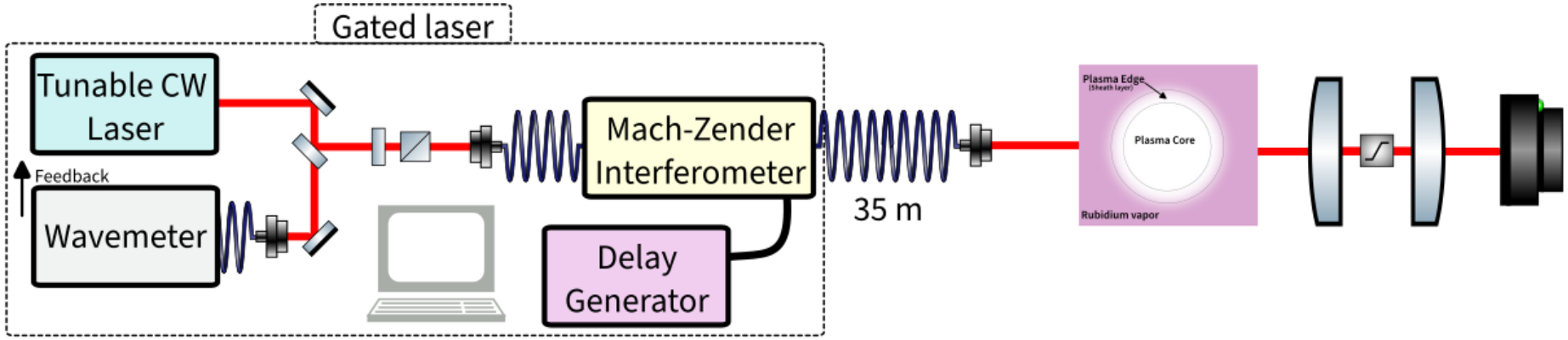
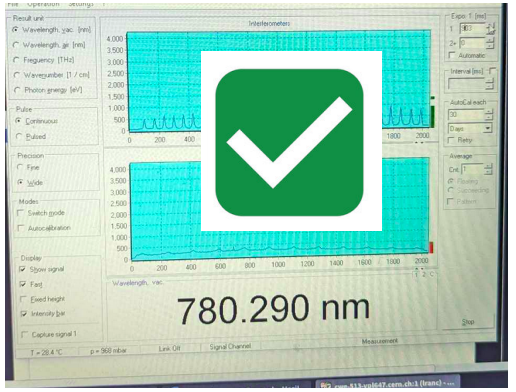


Experimental upgrade

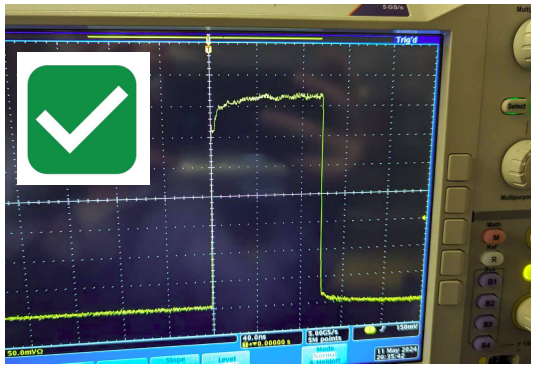


(Probe Laser) Gated system:

- Precise **stabilization** of the probe **wavelength** using the **wavemeter**
- Coupling a MZI modulator and a Delay Generator enables the control of the **exposure** duration
- Coupled in a 35-m-long optical fiber (radiation free)

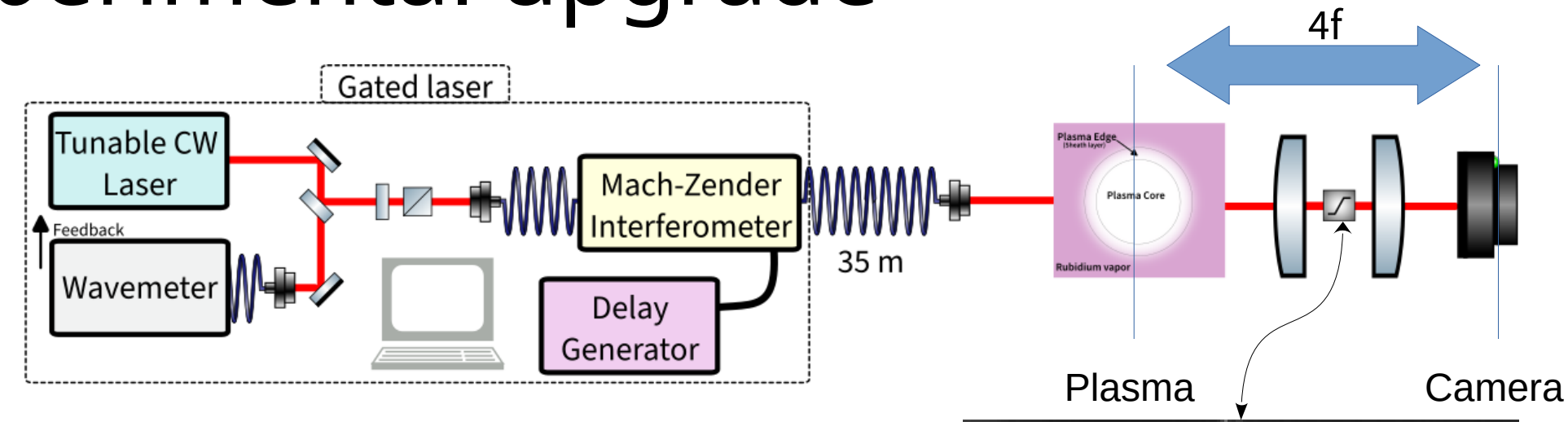


Wavemeter Control



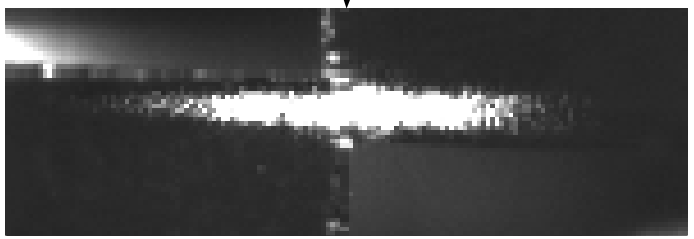
Example of Exposure: 100ns

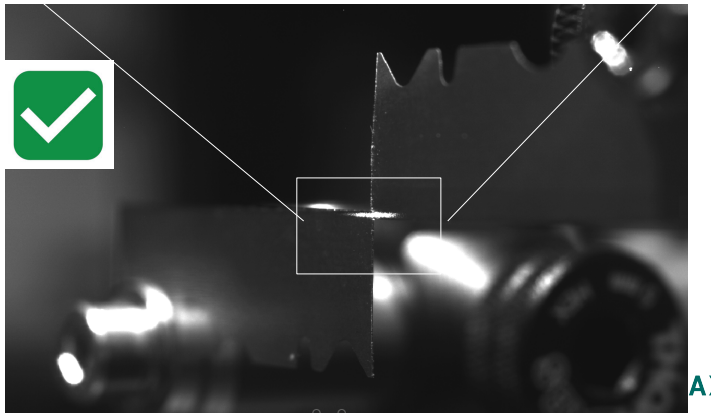
Experimental upgrade



<u>Schlieren optical system:</u>

- Cylindrical optics
- Knife edge mask with 5D alignment precision
- Camera Basler 2us
  (instead of Andor Intensified Cam)





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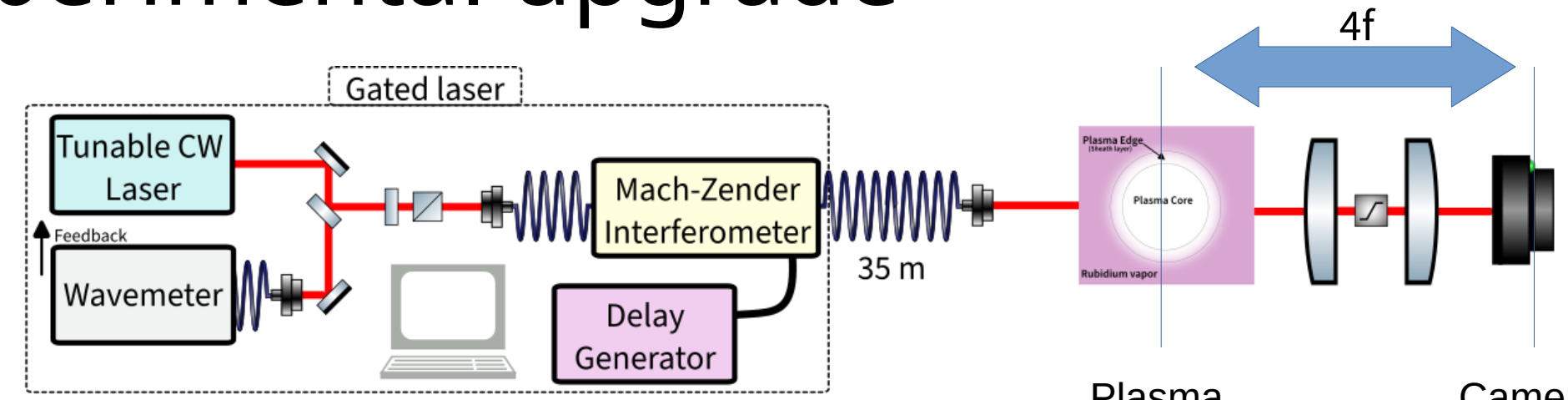
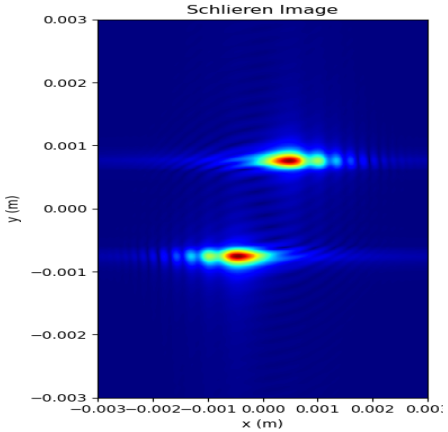
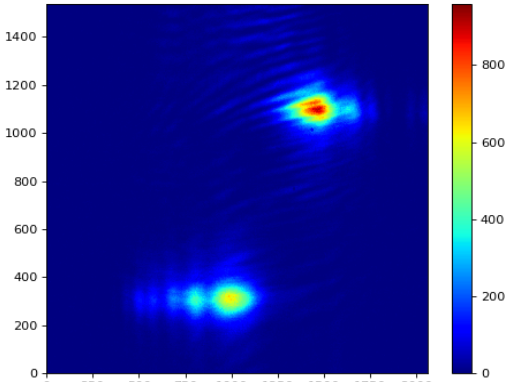


Fourier optics simulation comparison with the experiment

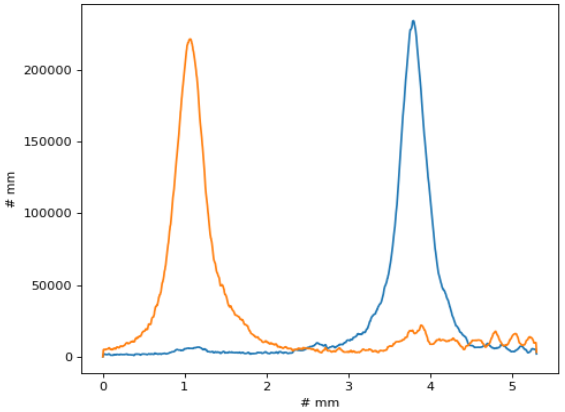
simulation



experiment



Line-out optimized

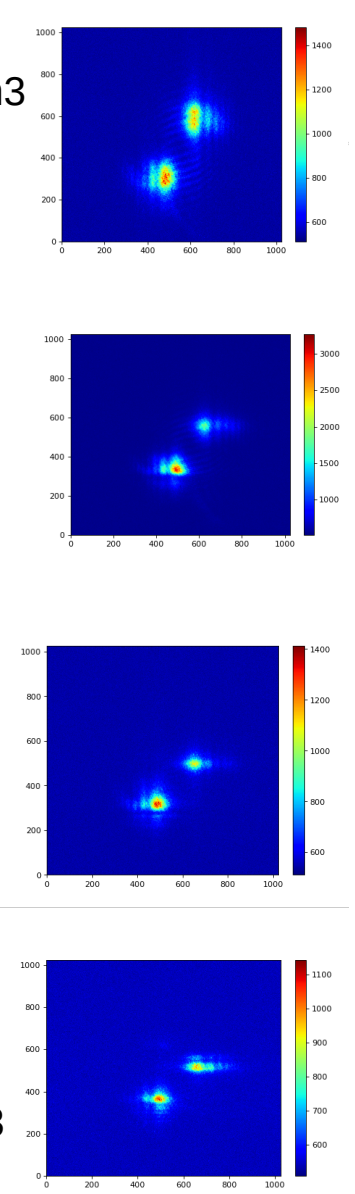


Very good agreement and spatial separation obtained

Experimental Validation

- Achievements:
  - ✔ Validation of the re-designed gated laser system
  - ✔ Able to evaluate the full range of the Rubidium vapor source
  - ✔ Suitable remote control setup

1.8e14/cm3

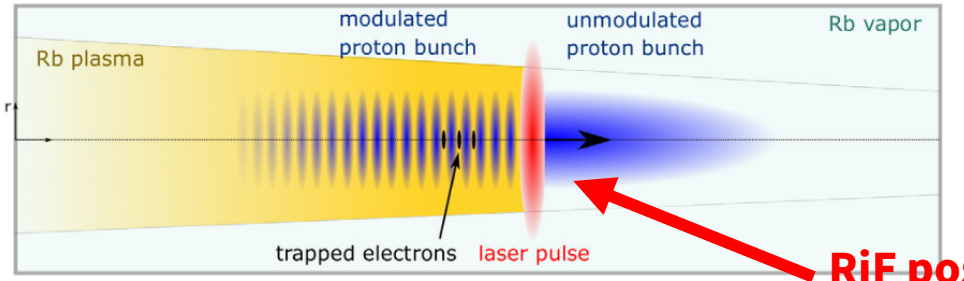


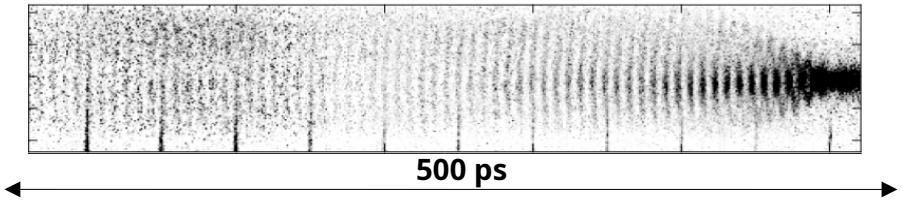
9.5e14/cm3

Experimental overview in AWAKE context

- **Long p+ bunch** propagating in plasma is **<u>subject</u>** to **Self-Modulation** (SM) instability.
- **Transform** driver bunch into a **train of shorter bunches** with a periodicity λ_{pe}.
-

→ The micro-bunch train can then resonantly excite large amplitude wakefields.

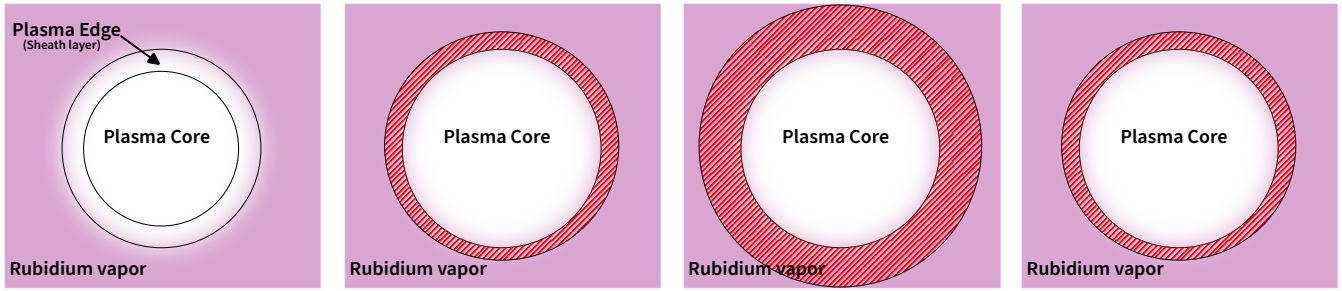




RiF position = Δ (laser vs proton bunch centroid)

- **→ <u>Proposed measurement:</u> Measure the plasma transverse size asf of RiF position**

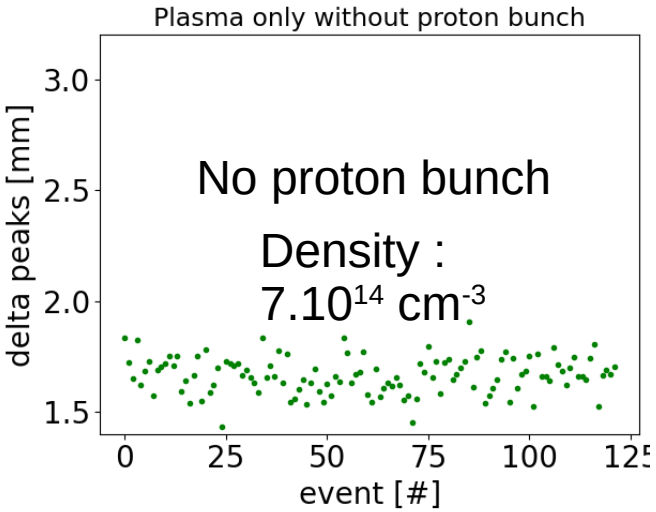
RiF position

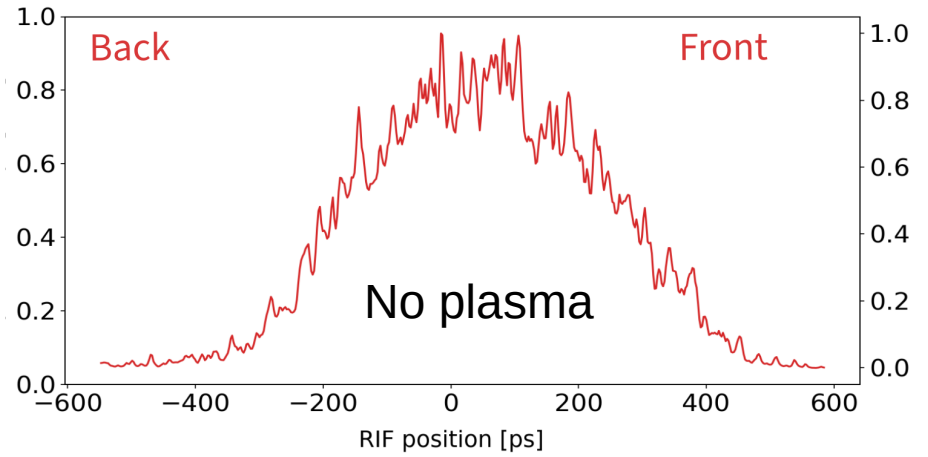


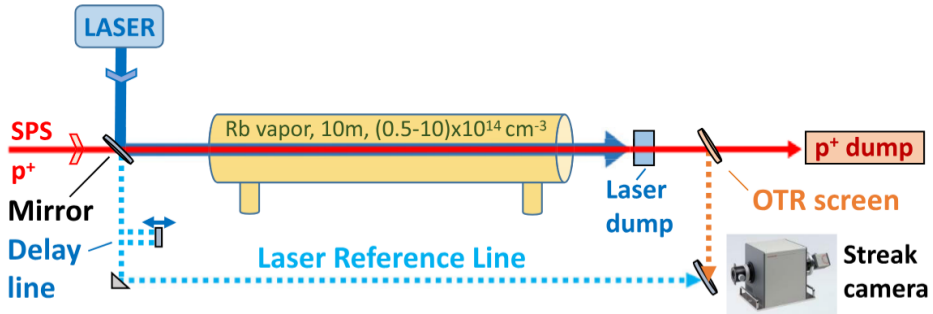
Plasma transverse size asf of RiF position

Initial conditions

1) Plasma without protons
2) Proton bunch no plasma (profile obtained using a streakcam)







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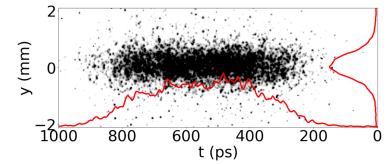
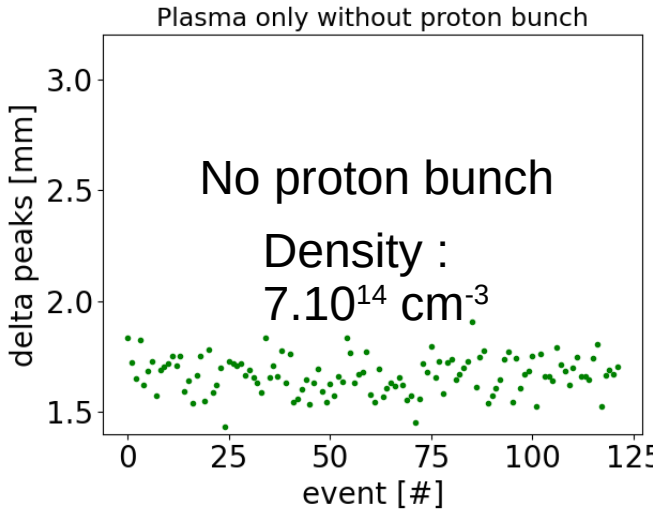
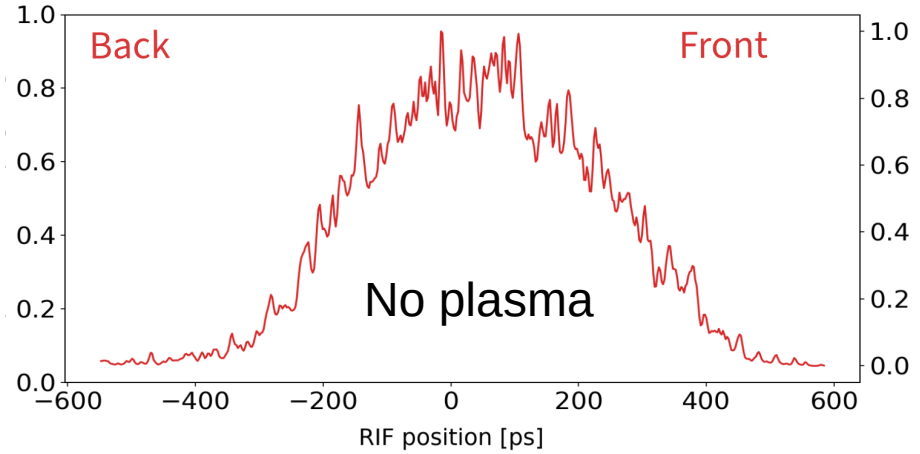
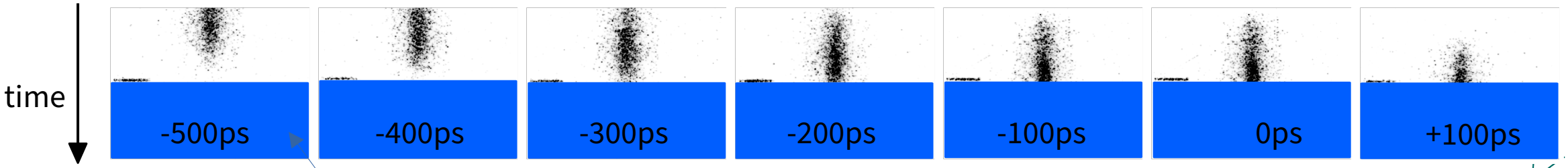
   (profile obtained using a streakcam)

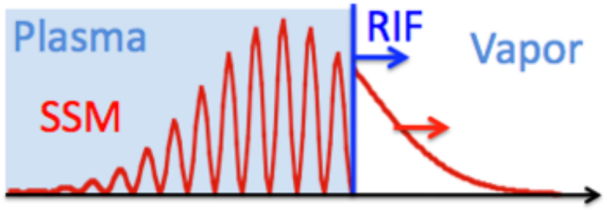


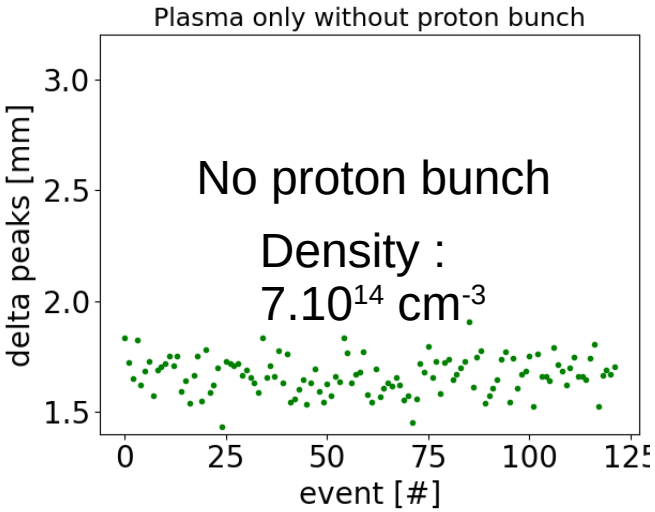


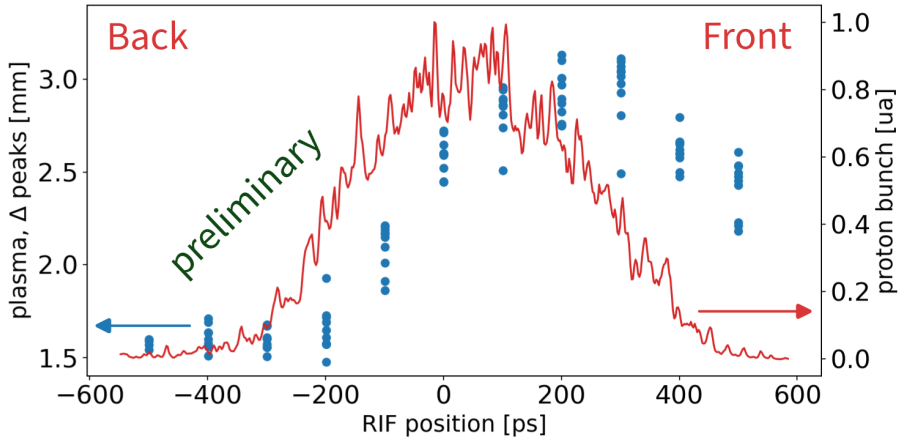




Plasma transverse size asf of RiF position

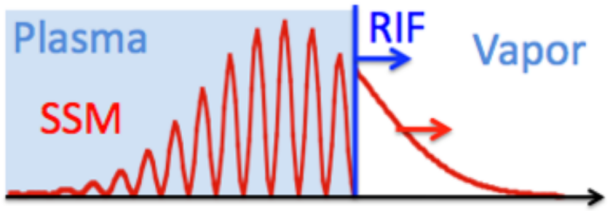


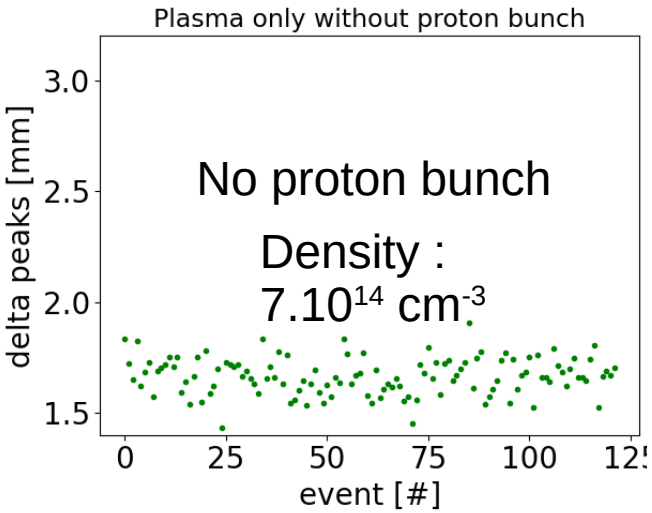


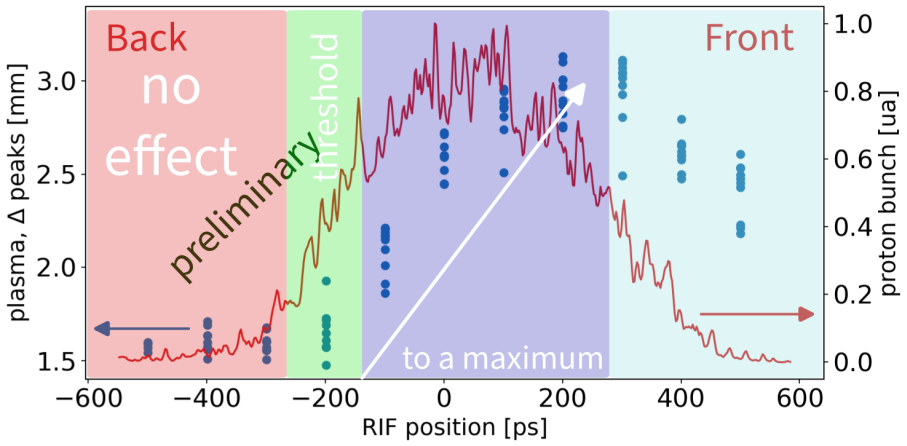


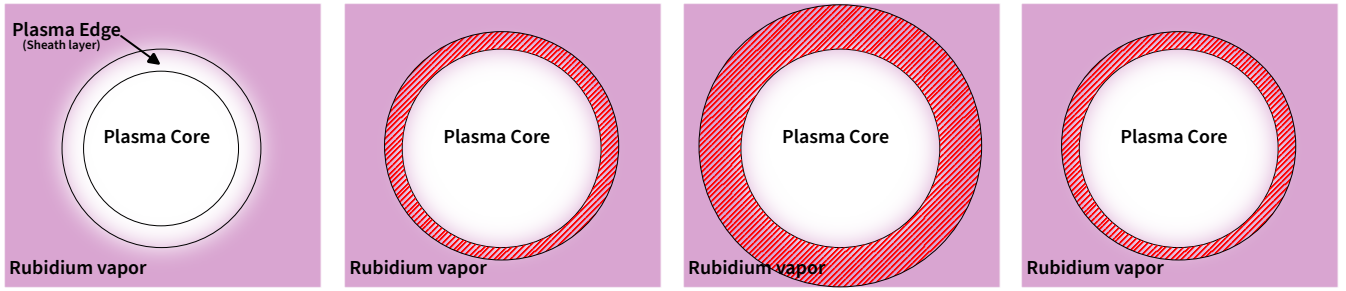
Plasma transverse size asf of RiF position

1) No significant seed to ionize the outer ground state Rb
2) A threshold
3) Significant halo formation

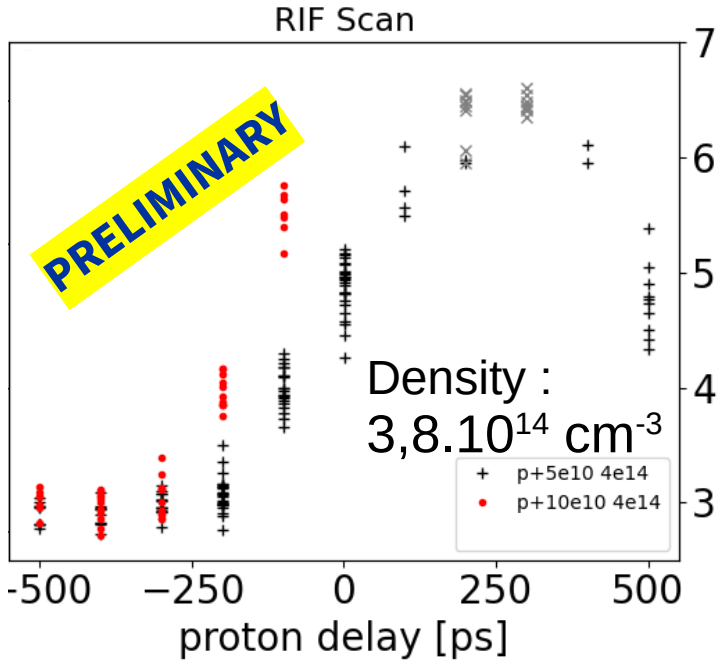








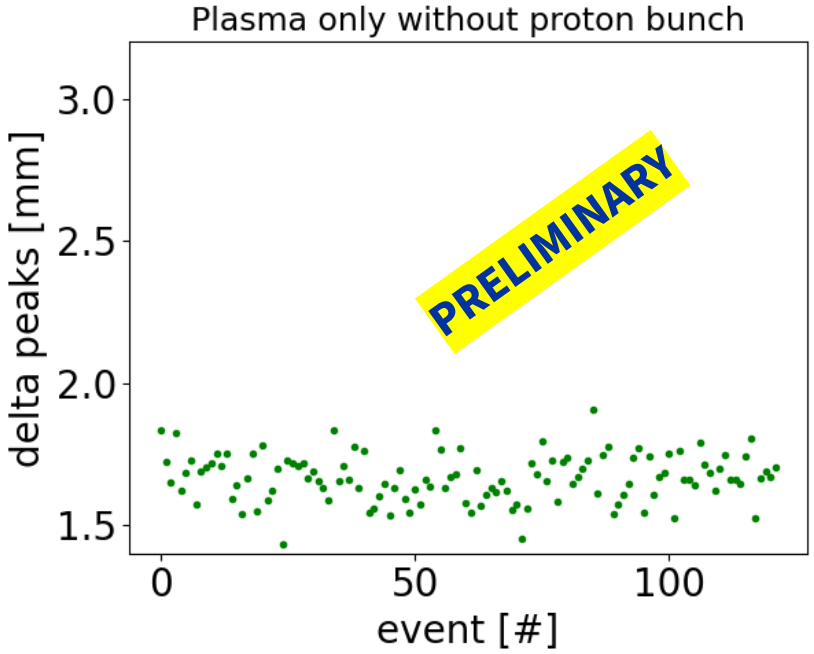
Plasma transverse size asf of RiF position

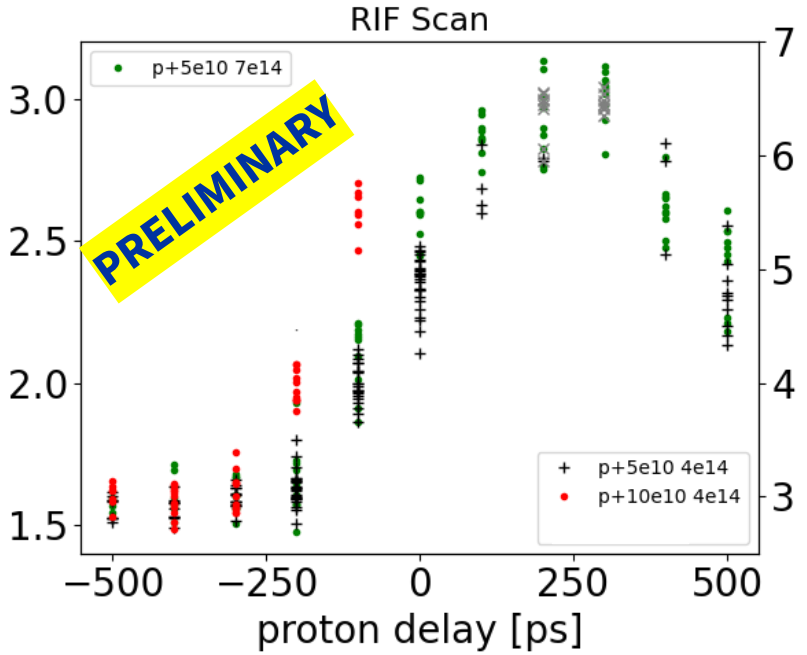


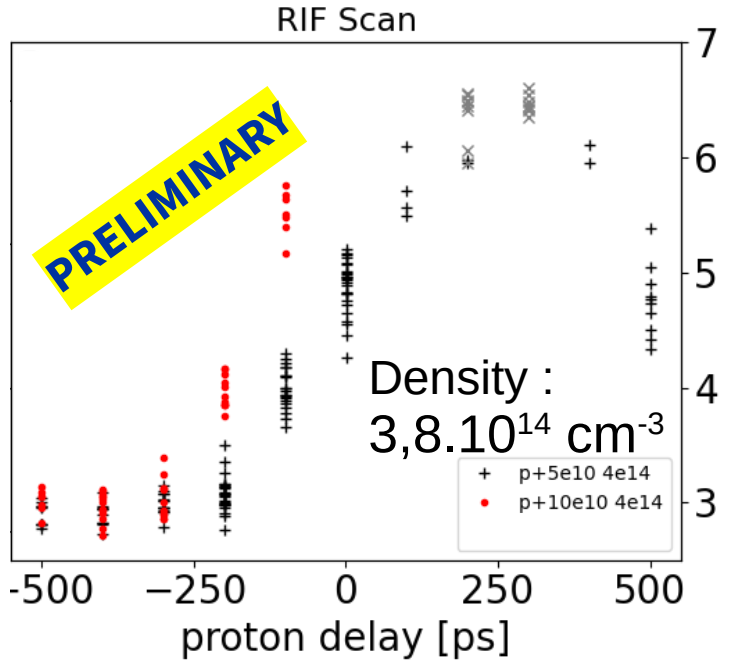
At half the density:

Behavior is essentially comparable

Plasma transverse size asf of RiF position







Earlier halo formation
When doubling the
Proton bunch population

At half the density:
Behavior is essentially comparable

Summary

- Successful design developed allowing:
  - evaluation of the plasma transverse size using Schlieren Imaging
  - estimation r_0 and sheath t_0 using a model

✔ Commissioned plasma radius for the AWAKE experiment and compatible for the current runs and for the future runs configurations
✔ Confirmed on-resonant ionizing laser at 780 nm of the Rubidium vapor
✔ Validation of an inline monitoring plasma diagnostic
✔ Observed a plasma halo formation

❖ Outlook
- Continue the data analysis : 1 day out of 6 weeks of run
- Refine the fit models
- More in depth simulations to link the energy deposited in the plasma

Thank you for your attention

MAX-PLANCK-INSTITUT
FÜR PHYSIK