Proton Beam Self-Modulation Instability in a DC Discharge Plasma Source at AWAKE

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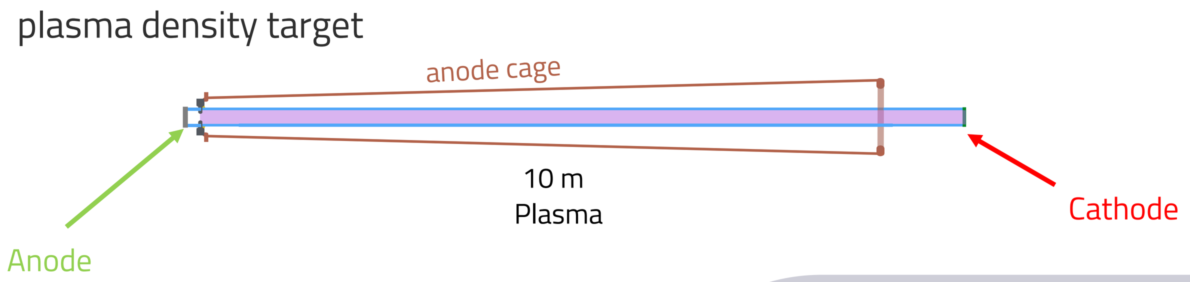
Alternative plasma sources for AWAKE

- AWAKE (the Advanced WAKefield Experiment) explores plasma wakefield acceleration of electrons, using proton bunch as driver.
- AWAKE requires plasma sources capable of reaching **densities of 1 to 10x10^{14} cm^{-3}**, and that allow extending the acceleration **length from tens to hundreds of meters**, beyond the limit of the present laser-ionised rubidium vapor plasma source [1].

DC Discharge Plasma Source (DPS) is based on[2]:

- **Double-pulse arc discharge** produced between two electrodes at the extremities of long dielectric tubes, filled with Ar/Xe/He at low pressure:
  - The ignition pulse (up to 40 kV) establishes a low-current plasma (~10 A)
  - The heater pulser allows for a **high current (up to 600 A)** to achieve the plasma density target

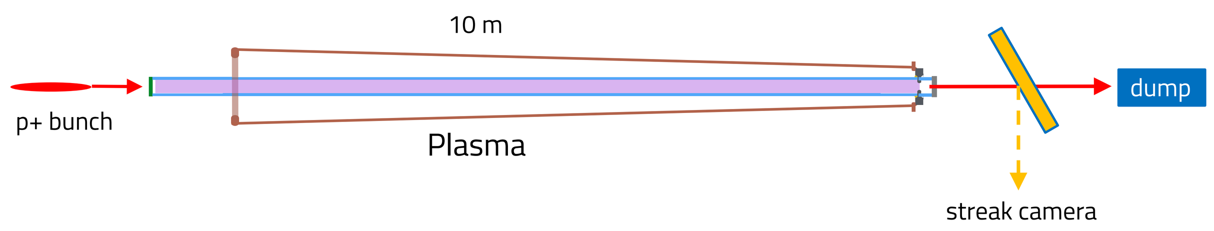


10 m single plasma, 24 Pa Ar, ignition+heating 500 A, ~30 us pulses

DPS tests with protons in AWAKE, 2023

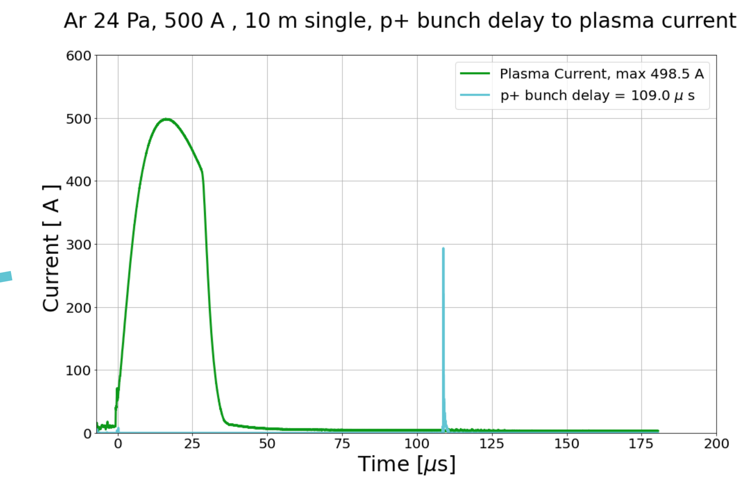
Why?

- Unique opportunity to test an alternative plasma source → important for AWAKE run 2c and beyond [3]
- show that the propagation of a proton bunch in a DPS plasma results in the usual **self modulation instability (SMI)** signature
- SMI with different lengths: 10 m single, 6.5 m, 3.5 m and 6.5+3.5 m
- SMI with different gases: He, Ar, Xe, to assess the effect of increasing ion mass
- reaching densities > 1x10^{15} cm^{-3} to study Current Filamentation Instability (CFI)

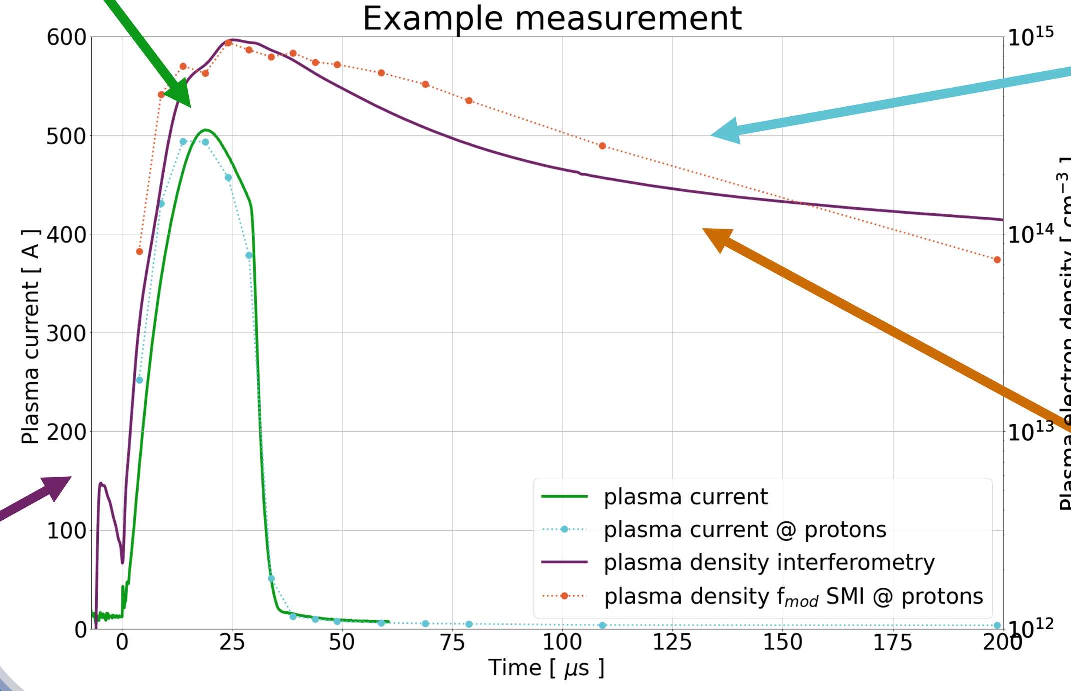


How?

- delaying the plasma main current (heater) with respect to the passage of the 400 GeV proton bunch → scan different densities

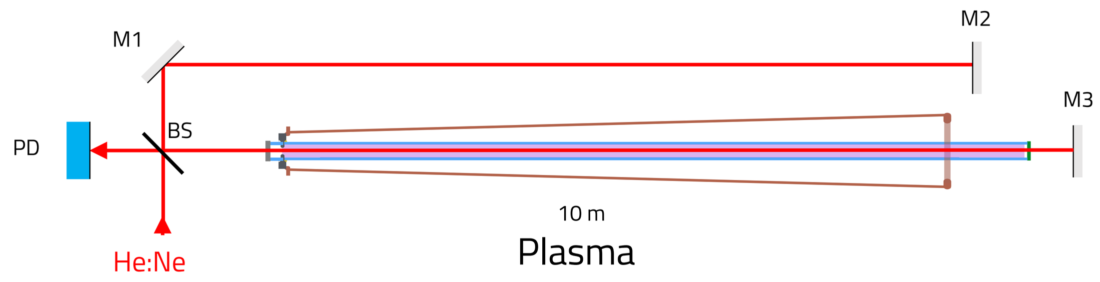


Benchmark interferometry plasma density with SMI modulation frequency



Longitudinally integrated interferometry

Time-resolved density measurement

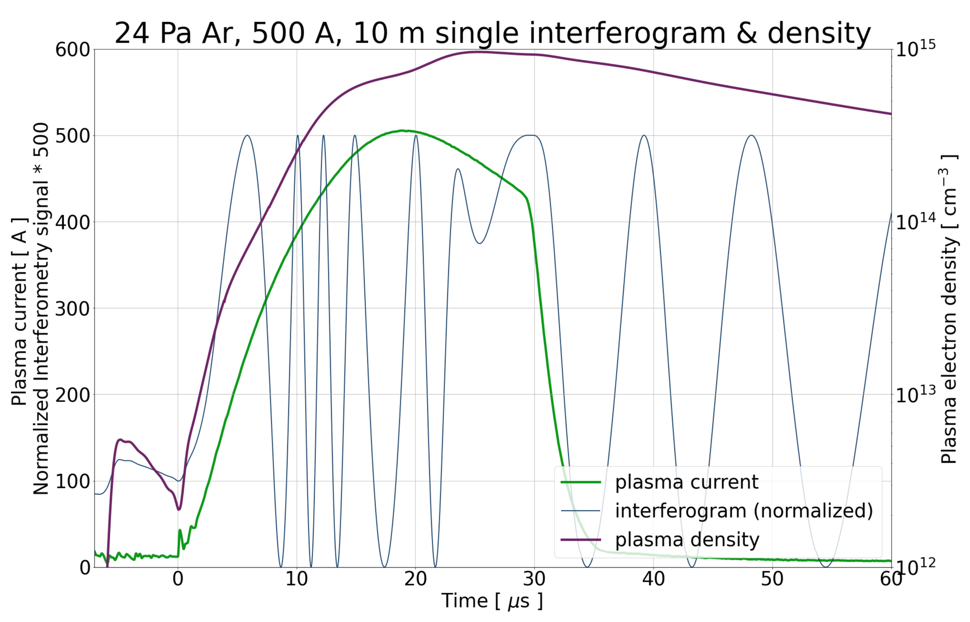


Phase shift ϕ_i added by a plasma density n_e given by

$$\phi_i = r_e\, \lambda_i\, n_e\, L$$

where r_e is the classic electron radius ($r_e = 2.82 \times 10^{-15}\ m$) and L is 2x the length of the plasma

From PD **interferogram** to plasma density

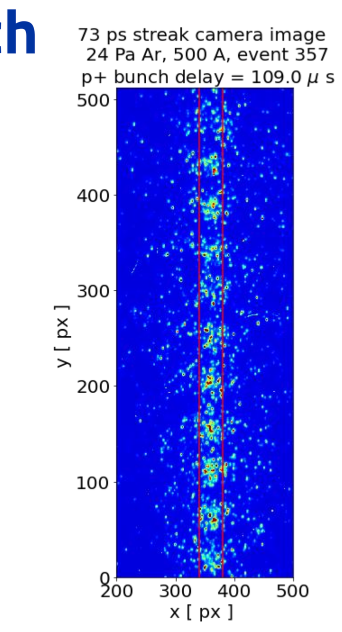


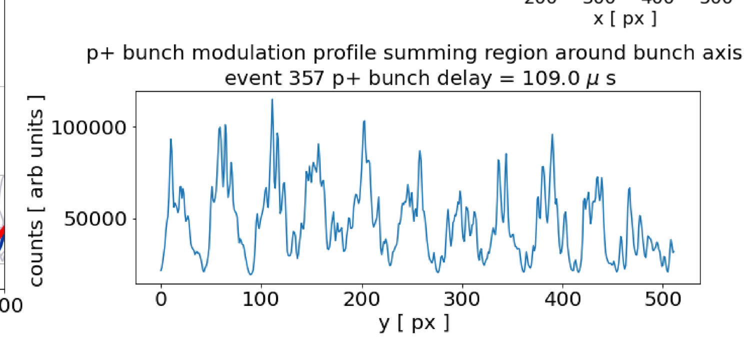
Frequency modulation of the p+ bunch

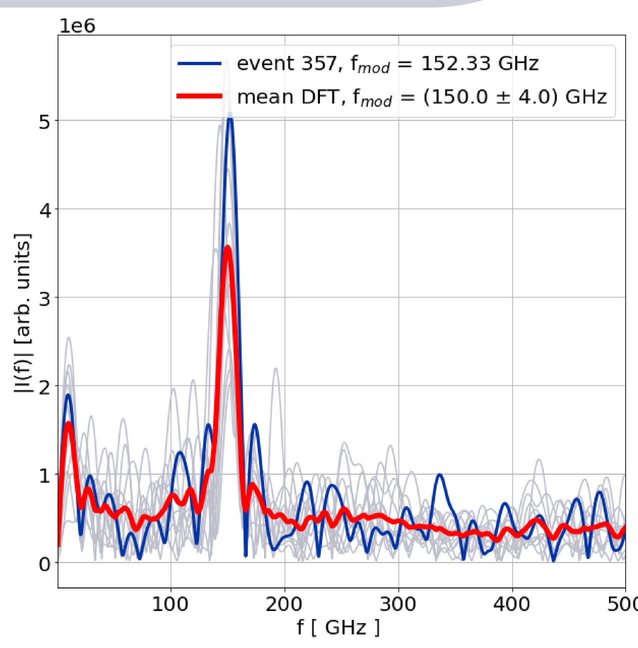
Time-resolved image of the p+ bunch charge density distribution in a 180 μm-wide slice, near the propagation axis of the bunch.

$$f_{mod} = 2\,\pi\,\omega_p$$

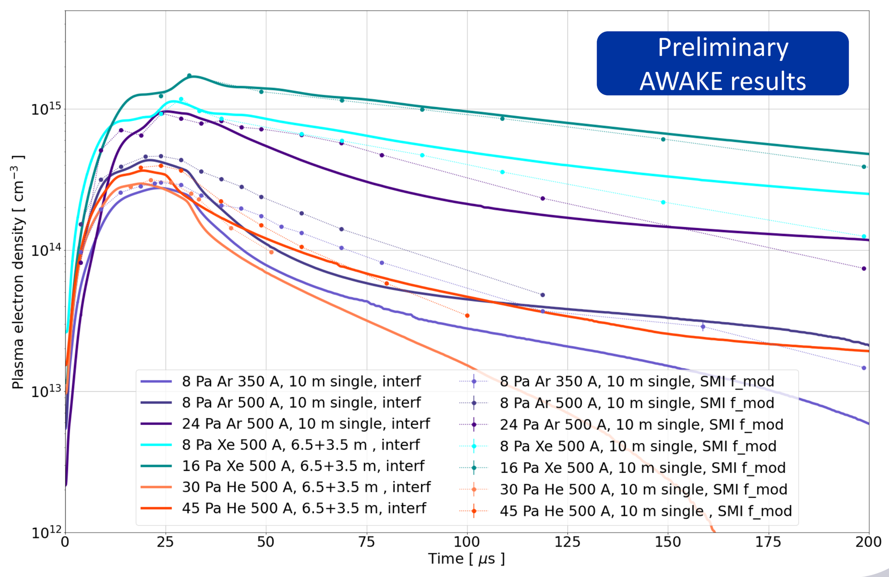
$$\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m}$$







Benchmark interferometry with SMI density for **all the conditions tested**



References:
[1] P Muggli *et al.* (AWAKE Collaboration), 2018 Plasma Phys. Control. Fusion 60, 014046 (2018)
[2] N. Torrado *et al.*, IEEE Transactions on Plasma Science (2023. submitted)
[3] E. Gschwendtner, *et al.* (AWAKE Collaboration), Symmetry 2022, 14(8), 1680

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Conclusion

- The usual SMI signature was observed with the DPS
- Interferometry lab measurements in good agreement density obtained with SMI
- Variety of SMI and CFI studies were possible thanks to the DPS flexibility of operation with different plasma lengths/gases/densities