Length-scalable discharge plasma source for AWAKE

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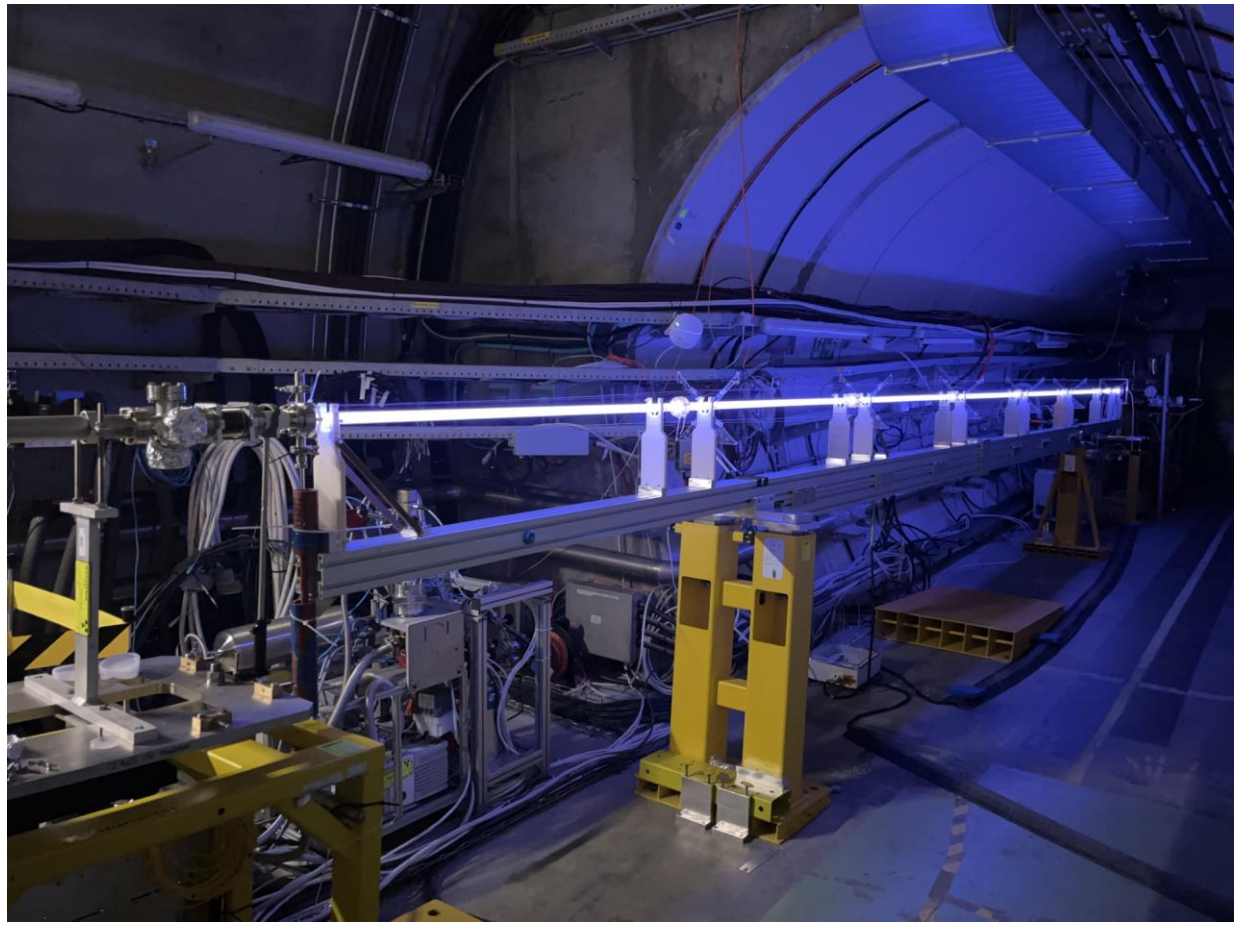


CERN/FIS-TEC/0017/2019

CERN/FIS-TEC/0034/2021

PRT/BD/152341/2021

AWAKE: Advanced proton-driven plasma **WAKE**field acceleration

Wakefield acceleration: driver creates a wakefield in a plasma where electrons can be accelerated

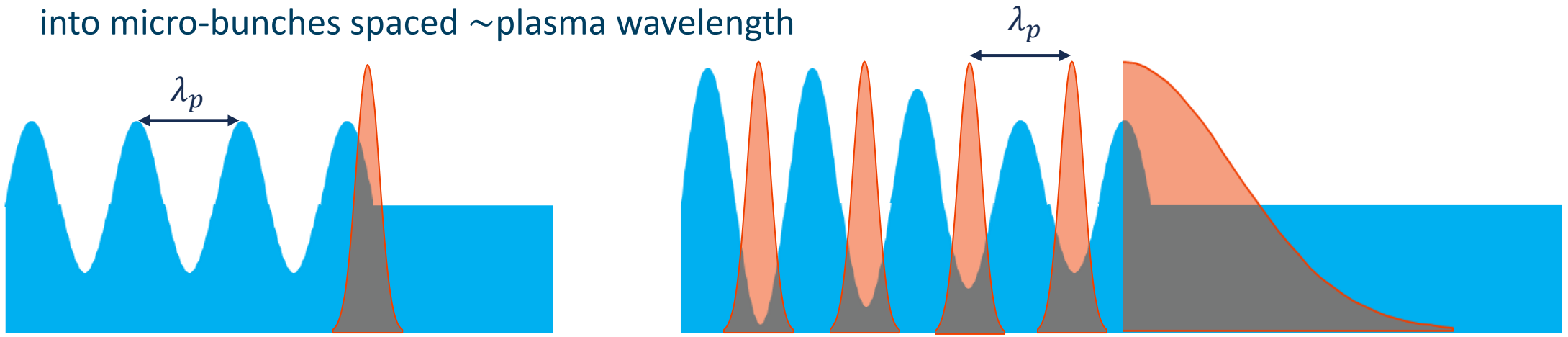
AWAKE use high energy drivers – CERN SPS proton bunch $400\ \mathrm{GeV/c}$: hundreds of GeV of energy gain

SPS proton bunch lengths is $\sim 6\ \mathrm{cm}$ – larger than the plasma wavelength ($\sim 1.2\ \mathrm{nm}$ or $n_e \approx 7 \times 10^{14} \mathrm{cm}^{-3}$)

Self-modulation instability (SMI) modulates the proton bunch into micro-bunches spaced ~plasma wavelength

Milestones achieved by AWAKE so far

- Successful self-modulation (2017)
- First electron acceleration (2018)
- Seeded self-modulation (2021)



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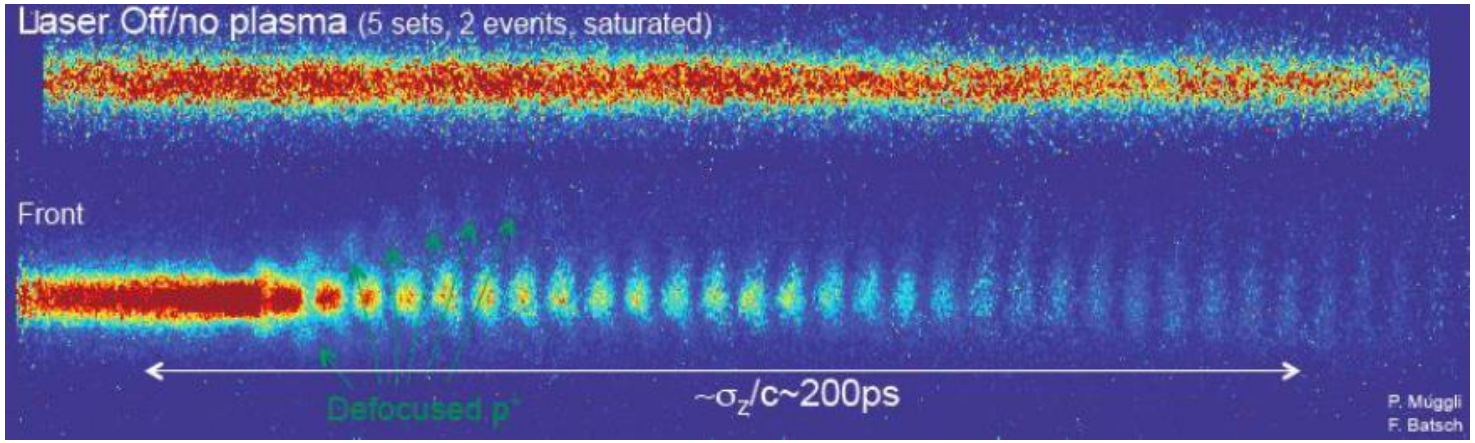


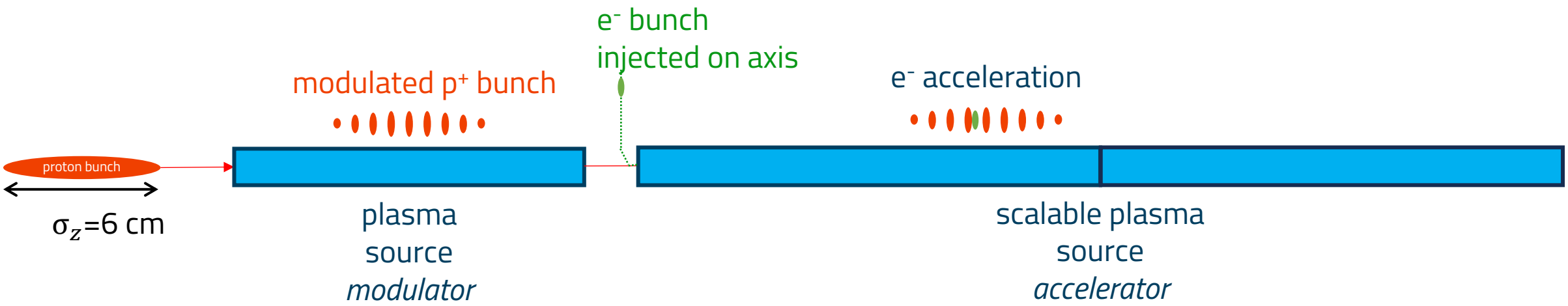
proton beam propagation

AWAKE: Advanced proton-driven plasma **WAKE**field acceleration

Next steps

- Two sources *modulator* + *accelerator* to allow external electron bunch injection
- **Scalable plasma source** to extend acceleration length

Requirements scalable plasma source
- Plasma electron density 1-10x10^{14} cm^{-3}
- Reproducibility
- Longitudinal uniformity: 0.25% over 10 m
- Length-scalable: 10-100 m



Length Scalable Plasma Sources

Possible solution: **Discharge Plasma Source**

- Current density 1000 A/mm^2
- Fast plasma ignition (1-2 µs) and current reproducibility (<1%)
- Long plasma sections (10 m) and series assembly with common electrodes

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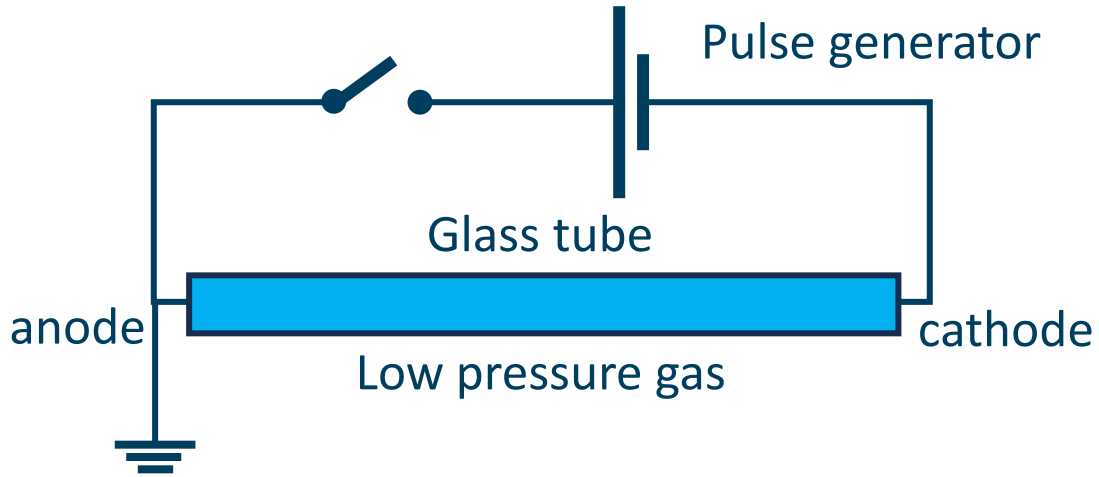
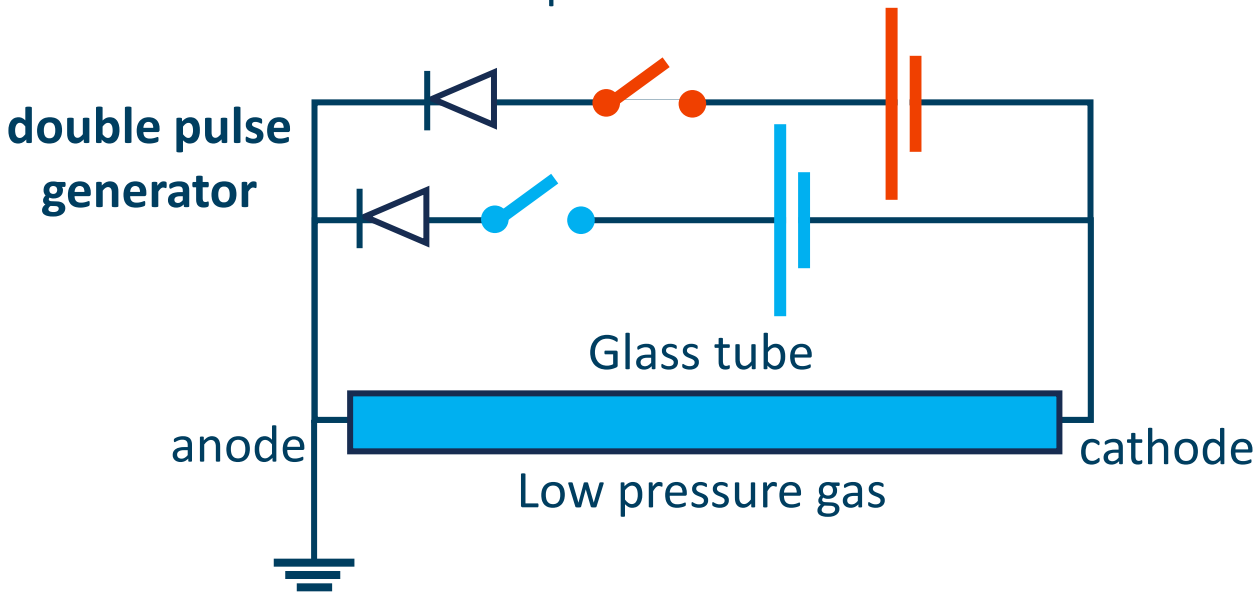
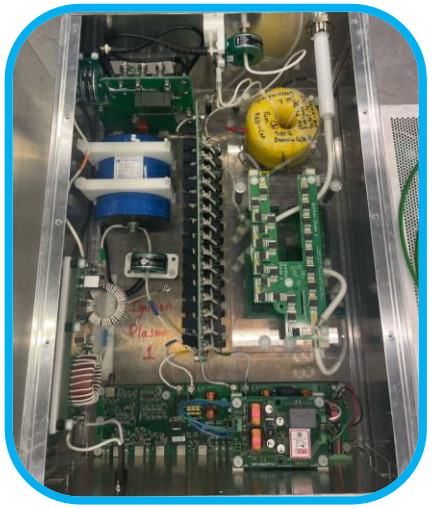


Discharge Plasma Source (DPS)

Challenges

- AWAKE densities and the uniformity targets demand high current plasma – around 500 A
- 10 m plasma lengths and µs-fast ignition demands over 20 kV voltage pulse
- Combining a single pulse with about 20 kV and 500 A results in 10 MW of power





→ Double-pulse solution:
High-voltage **ignition pulse**
High-current **heater pulse**

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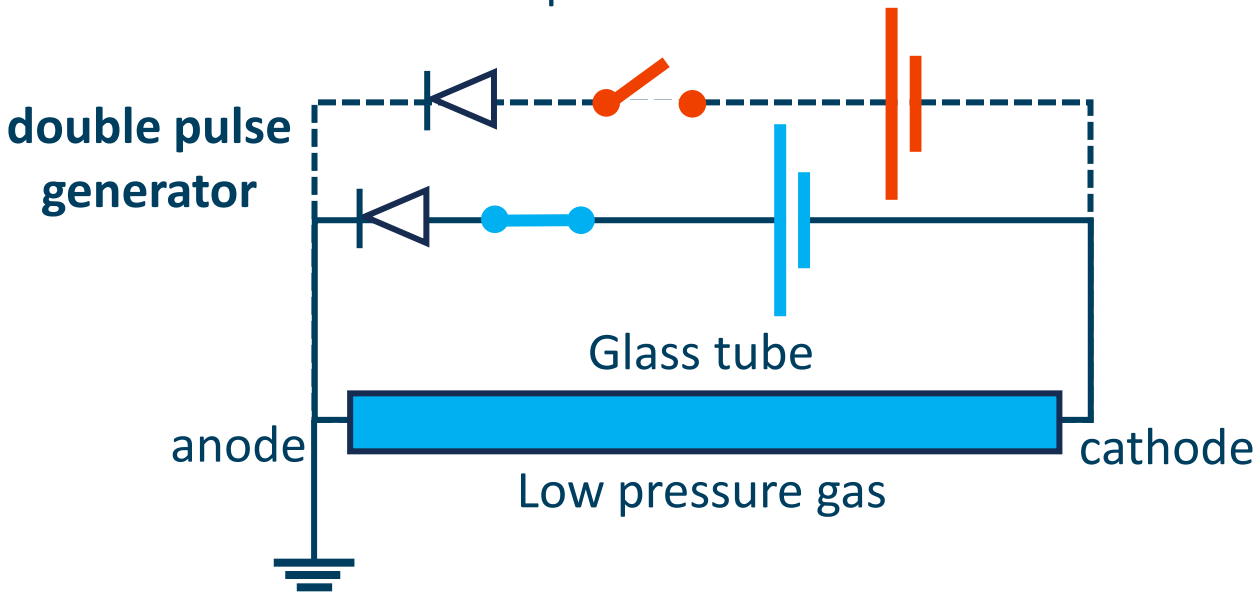

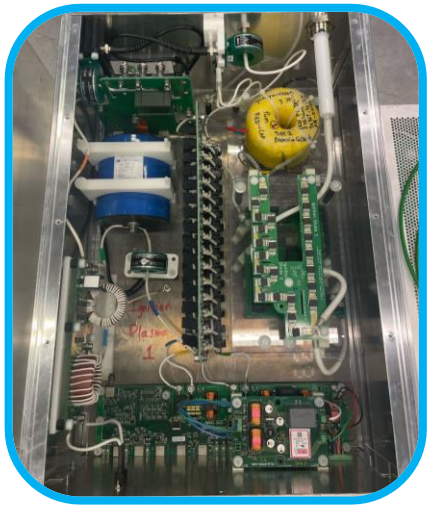

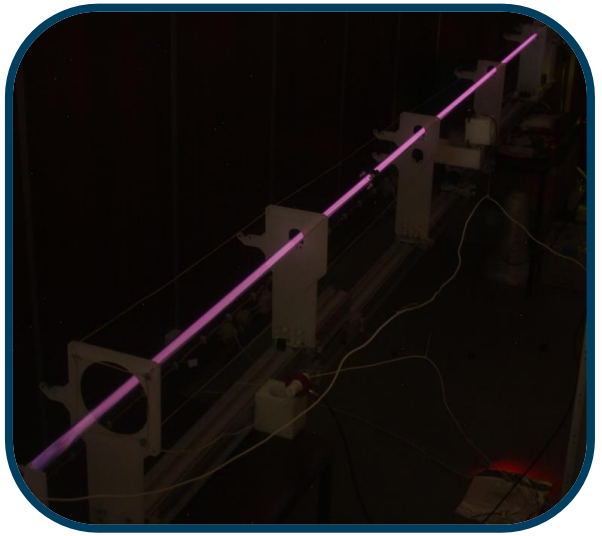

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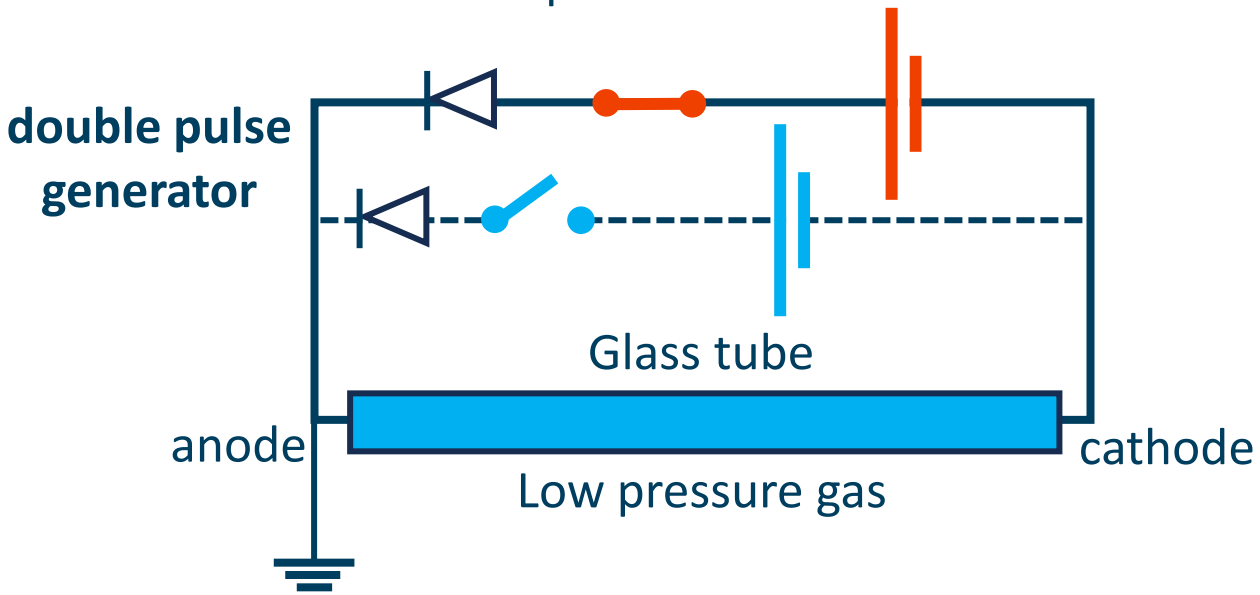
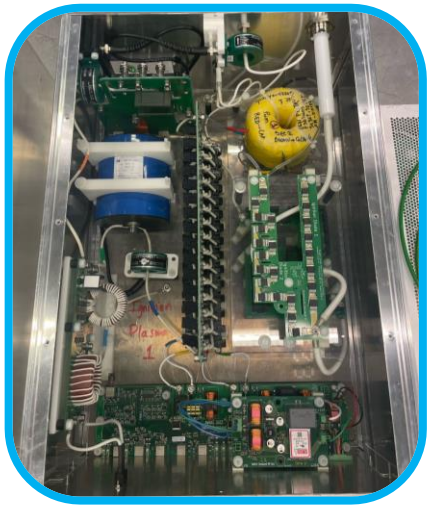
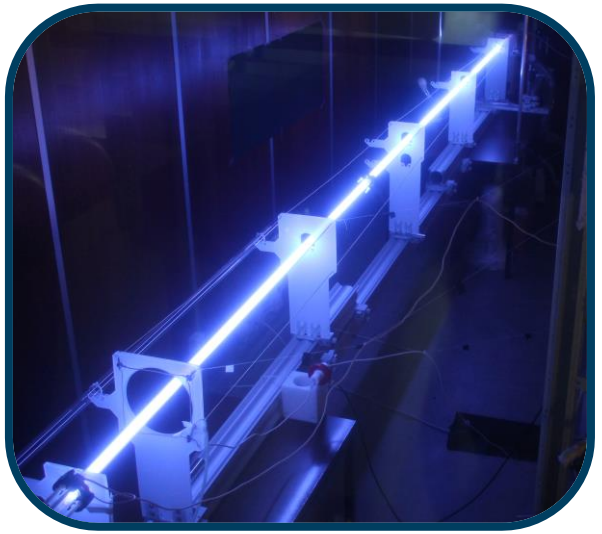
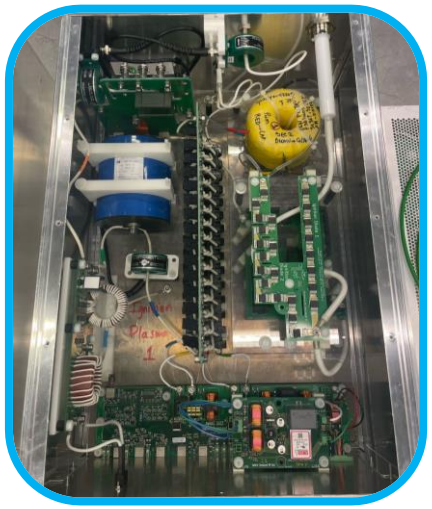


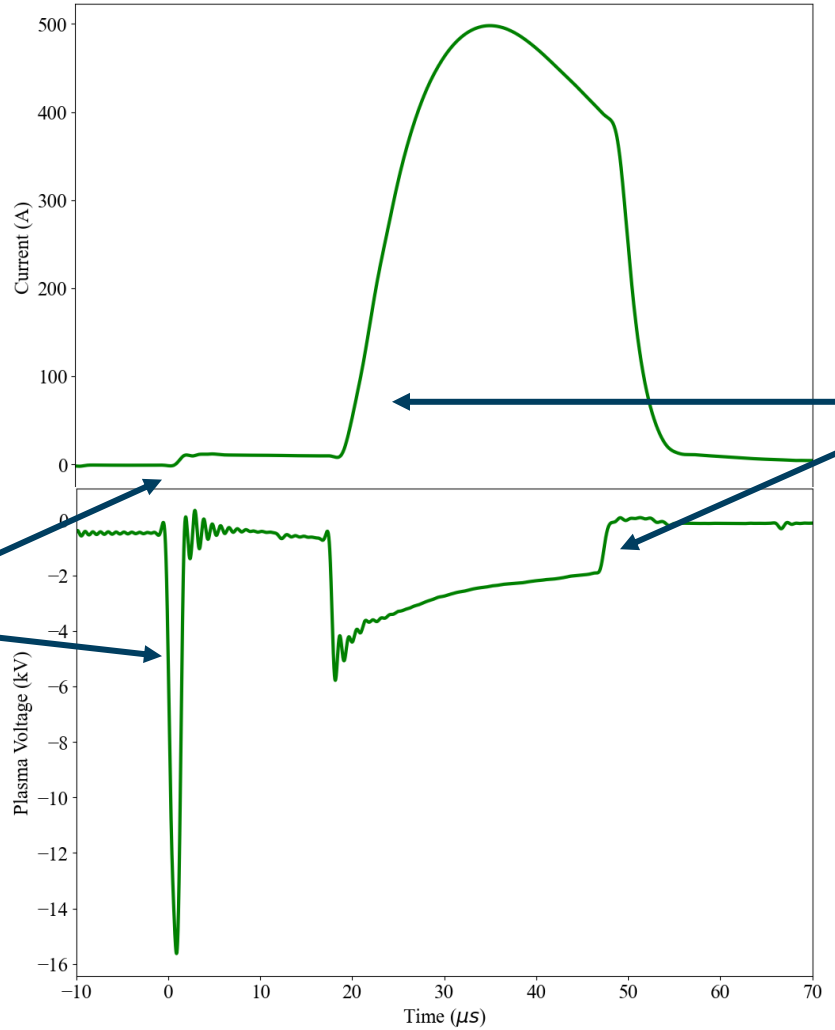




Discharge Plasma Source (DPS)

Double Pulse Generator





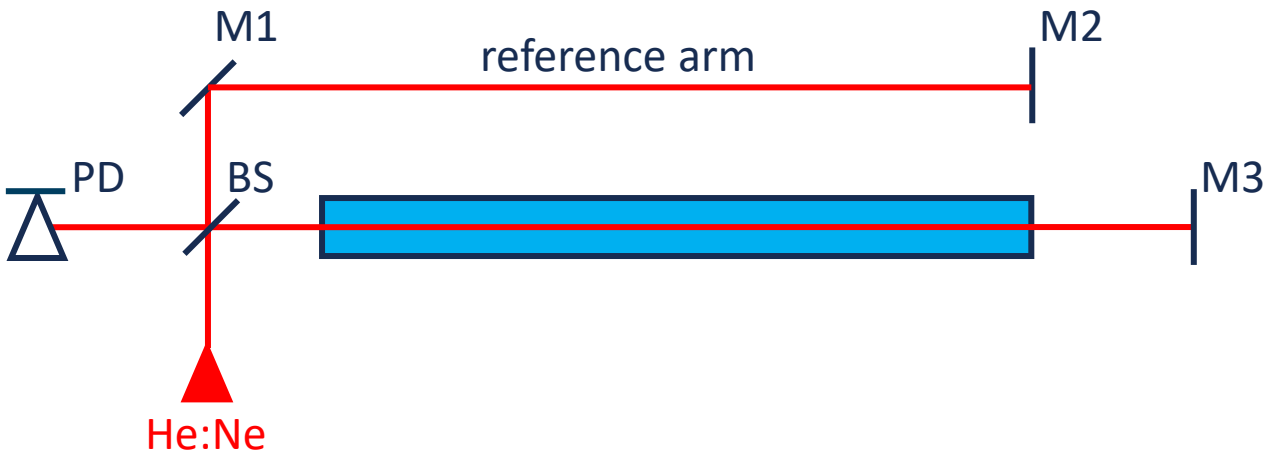
Heater pulse
High current pulse (500 A) to increase plasma density
Takes advantage of the low impedance established

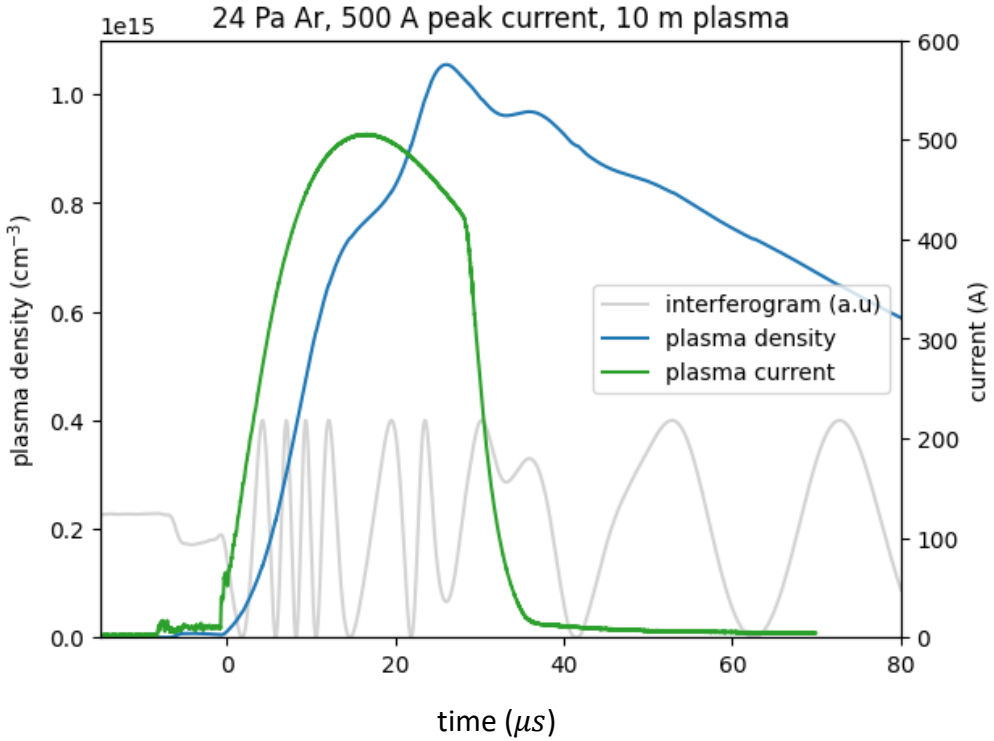
Ignition pulse
Fast rising high-voltage pulse (up to 20 kV) to ignite the plasma
Establishes low-current (20 A) arc

Discharge Plasma Source (DPS)

Density diagnostics

Michelson interferometer





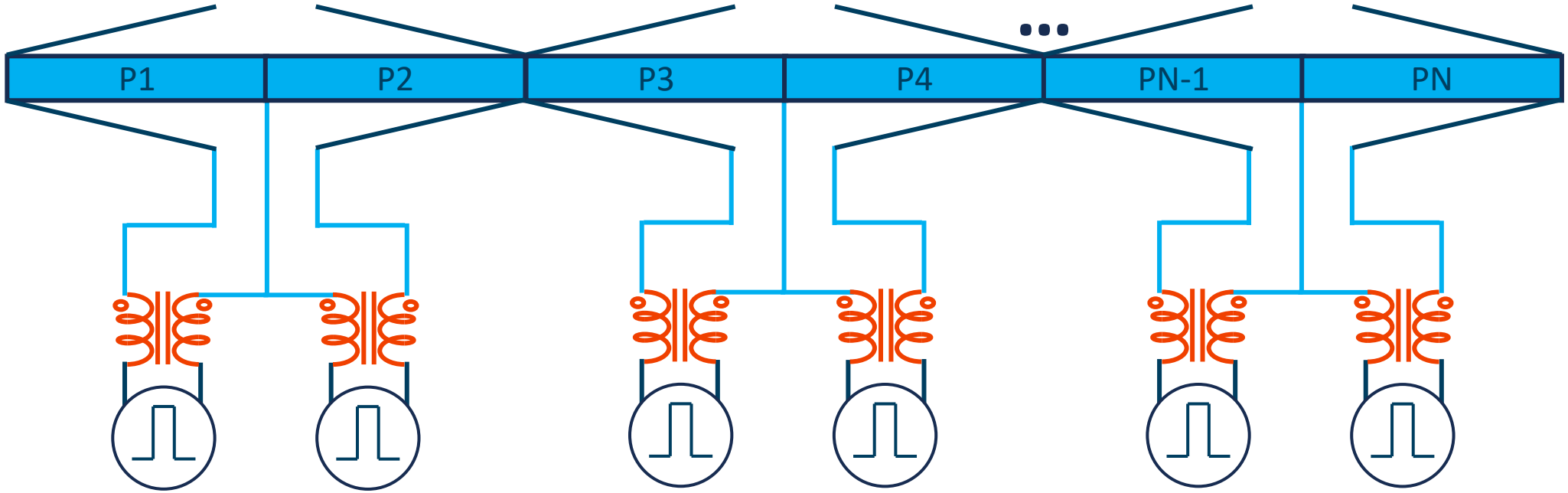
Measurement arm (plasma) adds a phase shift ϕ_i proportional to the plasma density n_e

$$\phi_i(t) = \frac{1}{r_e \lambda_i} \int n_e(t) dx$$

Time-evolution of the plasma density, line integrated over the 10 m

Discharge Plasma Source (DPS)

Length scalable plasmas



Length scalability obtained by connecting multiple plasma sections with common electrodes

Coupled inductors force current symmetry between the electrodes of each section

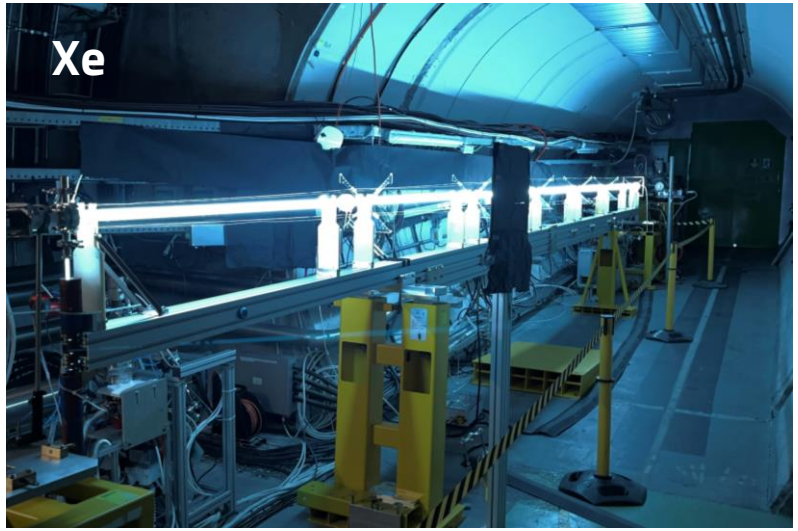
Discharge Plasma Source (DPS)

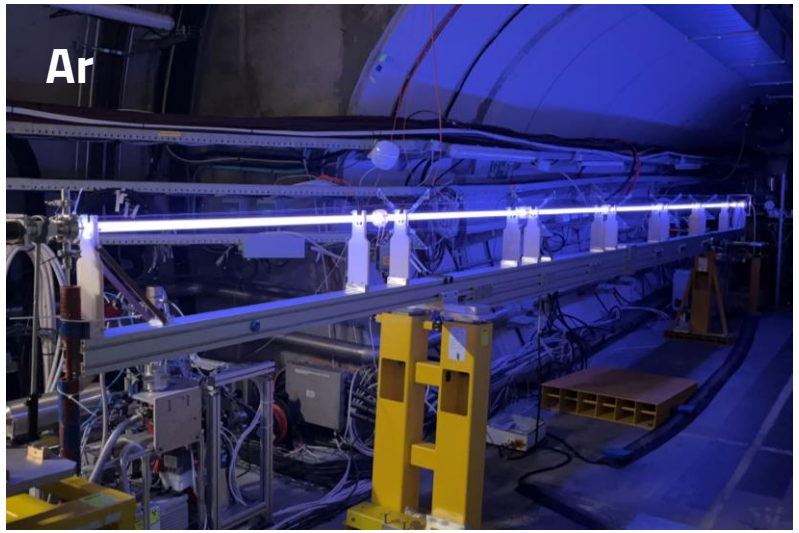
DPS in the AWAKE

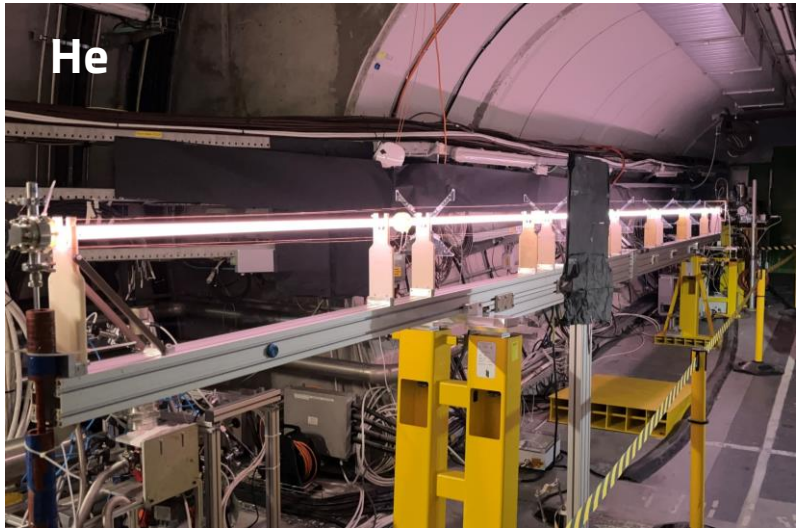
Diagnostics showed that the DPS was technologically ready for installation

Operated for three weeks with proton beams in AWAKE (May 2023)

A chance to test an alternative plasma source and profit from its operation range







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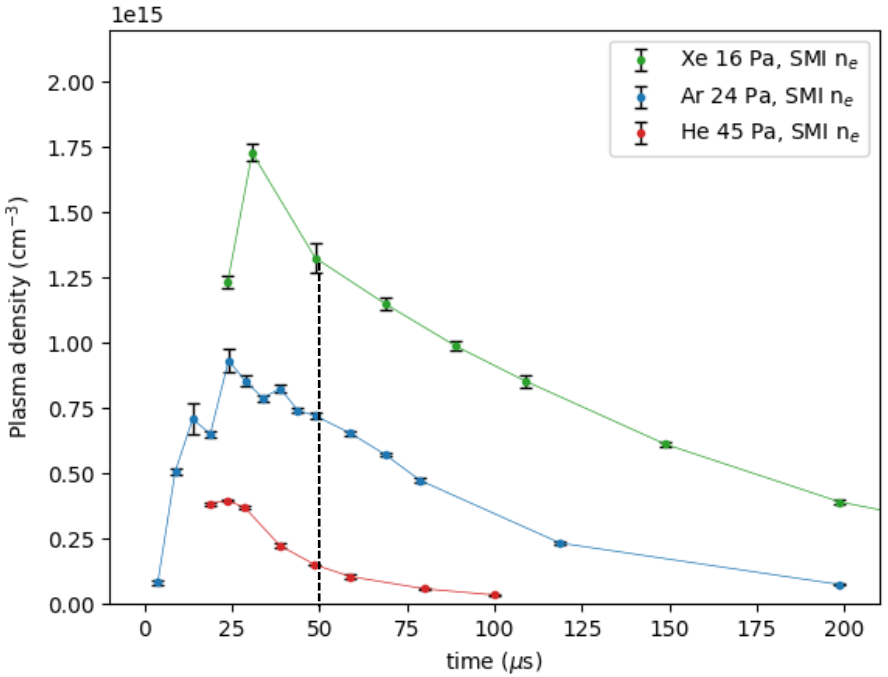
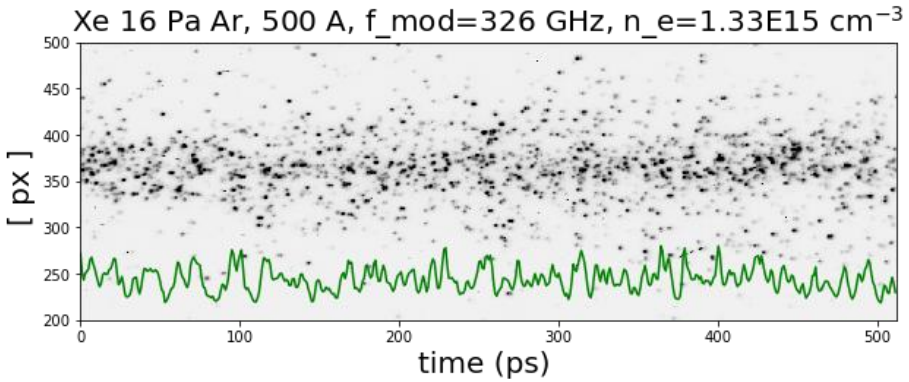
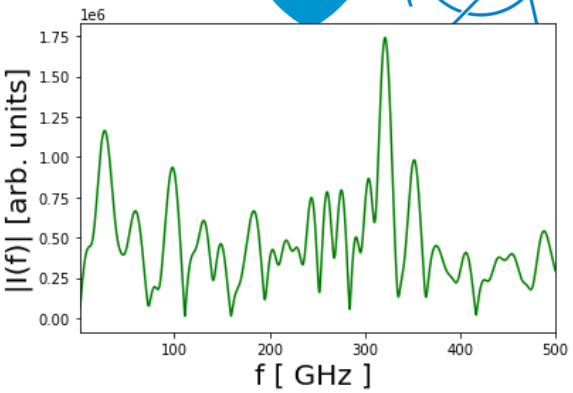
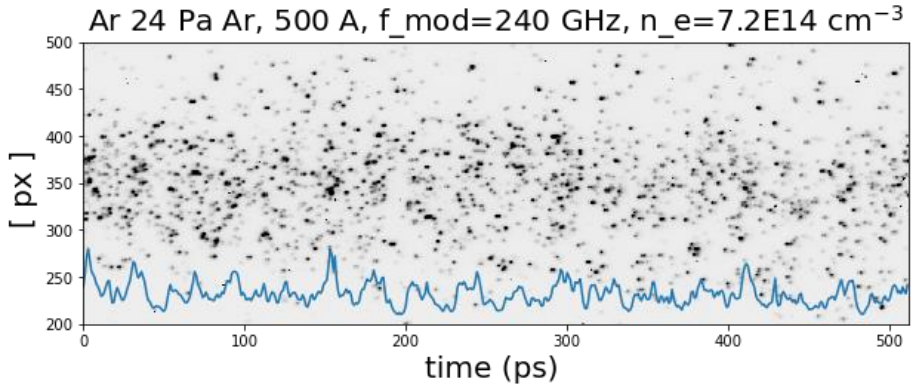
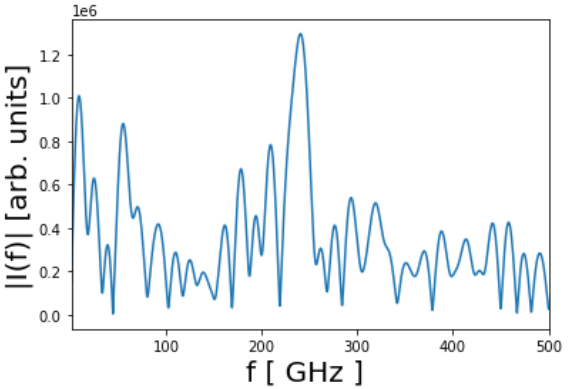
DPS in the AWAKE

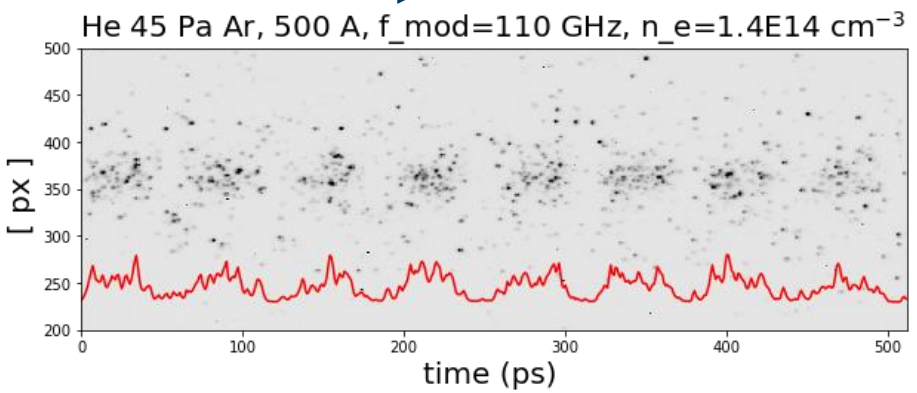


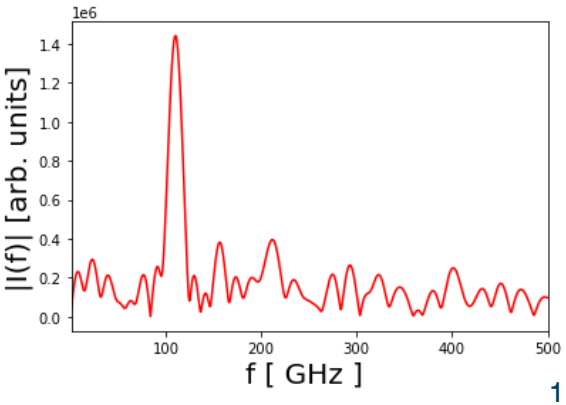












Self Modulation Instability (SMI) signature – demonstration of the applicability of DPS in AWAKE

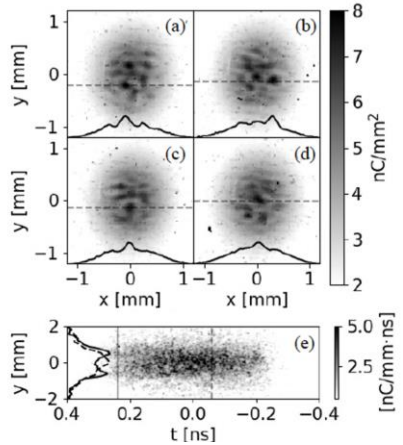
C. Amoedo, *in preparation*

Discharge Plasma Source (DPS)

DPS in the AWAKE

DPS operation range allowed a variety of plasma wakefield physics' studies

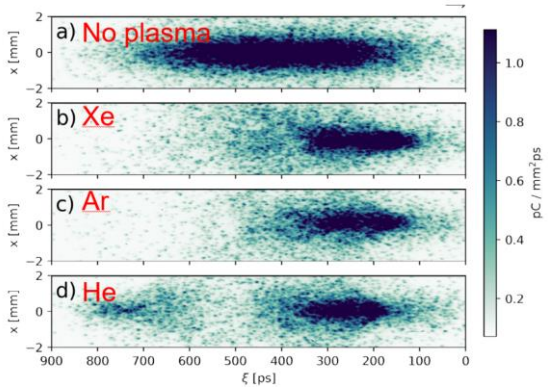
Filamentation Instability



Wide plasma allowed to study the filamentation instability

L. Verra et al., PRE **109, 055203 (2024)**

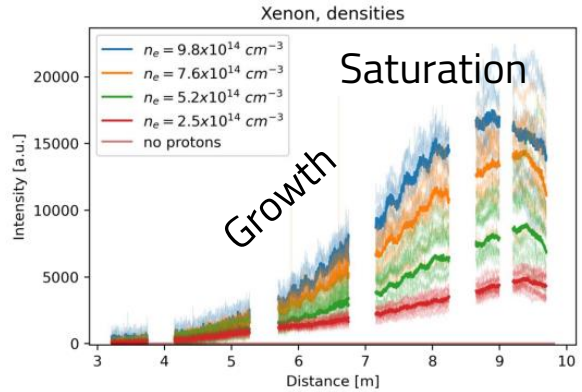
Ion Motion



Flexibility in plasma ion species allowed to study the effect of ion motion on wakefields

M. Turner et al., *in review*

Plasma Light



Monitoring of plasma light allowed insight into wakefield growth due to SMI

J. Mezger

Conclusion

The Discharge Plasma Source:

is a novel plasma source based on electric gas discharges
generates uniform plasmas from µs-pulse high-voltage and high-current discharges
single plasmas have been studied successfully with 10 m set-ups
scalability can be achieved by connecting plasma sections in series