Demonstration of proton bunch self-modulation in a discharge plasma source

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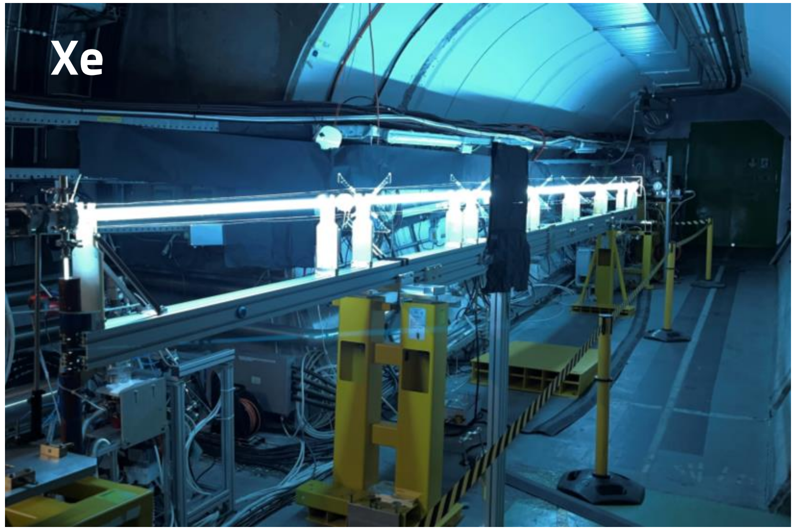
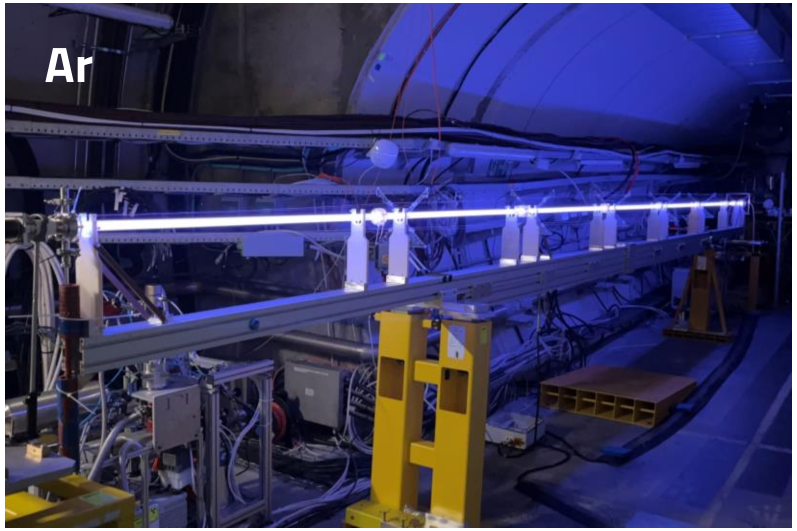
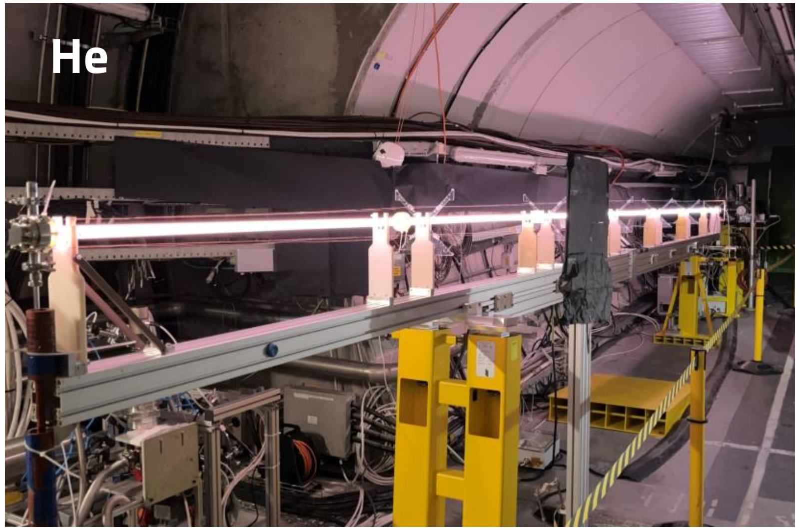
G. Zevi Della Porta[1,4],J. Pušek[1], M. Bergamaschi[4], A. Clairembaud[4], J. Mezger[4], F. Pannell[5],
N. Van Gils[6], E. Gschwendtner[1], M. Taborelli[1], A. Sublet[1] *and the AWAKE Collaboration*

AAC'24 Workshop
22/07/2024







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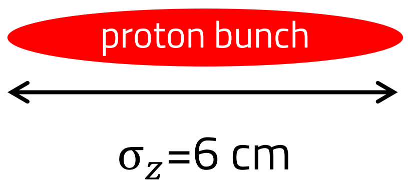
AWAKE → **A**dvanced Proton Driven Plasma **WAK**efield **E**xperiment

Drives wakefields in plasma with a **proton bunch** (p^+)

- ► CERN SPS proton bunch (400 GeV): **proton bunch length is ~6 cm**

To effectively excite wakefields:

► Driver bunch length ~ plasma wavelength (~ 1.2 mm for $n_e \sim 7\text{x}10^{14}\ \text{cm}^{-3}$)



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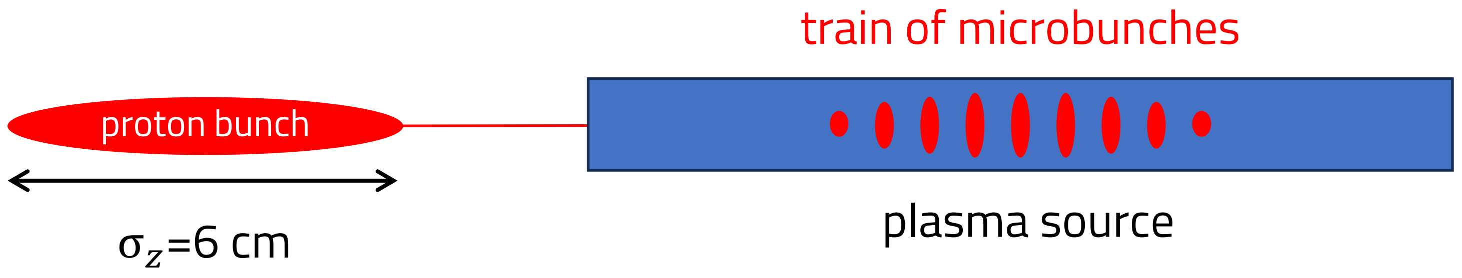
Self-Modulation Instability (SMI): Initial (transverse) 'seed' wakefields

Modulates the proton bunch into micro-bunches spaced ~ plasma wavelength



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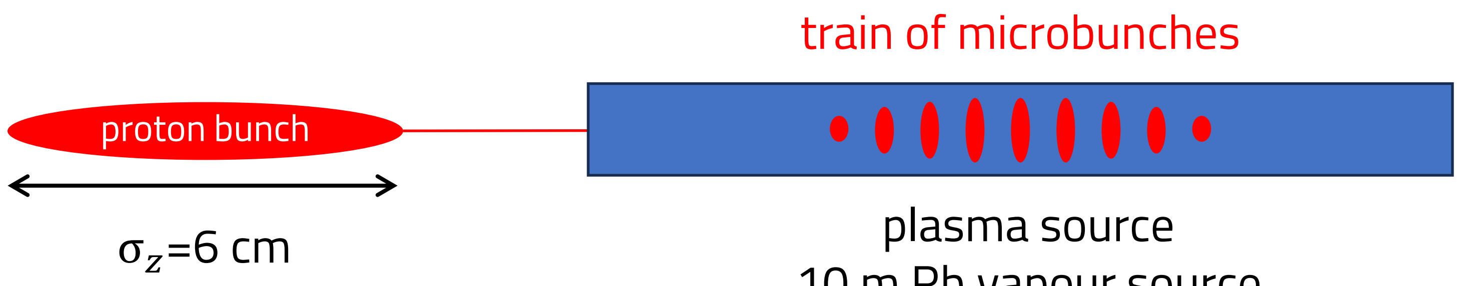
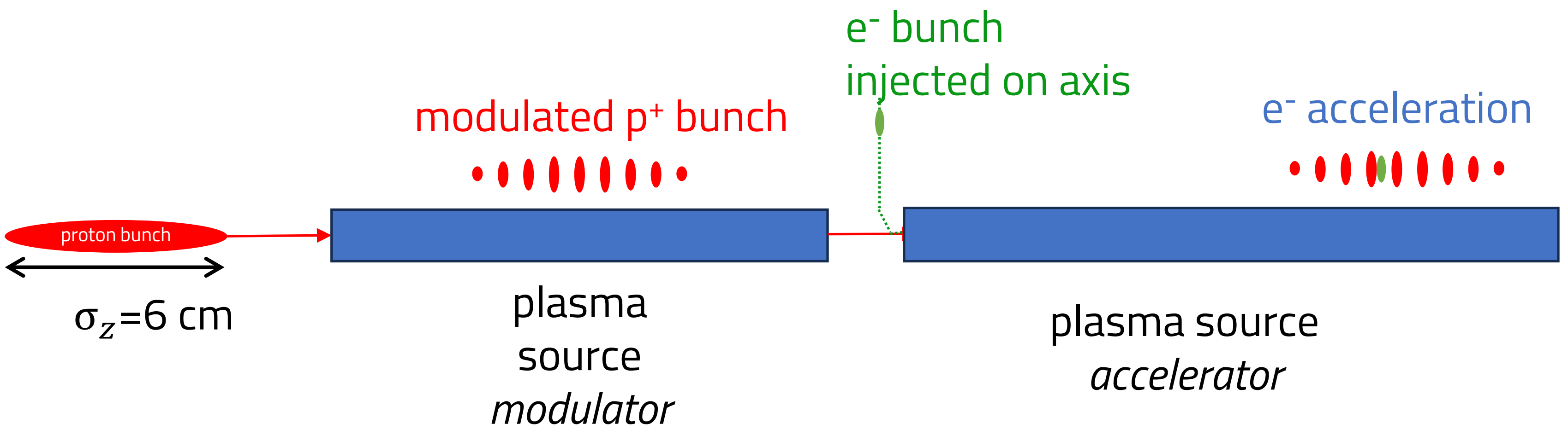


Milestones achieved by AWAKE so far

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

Currently: upgrade Rb vapour source (stabilization of Wakefield Amplitude)

Next in AWAKE



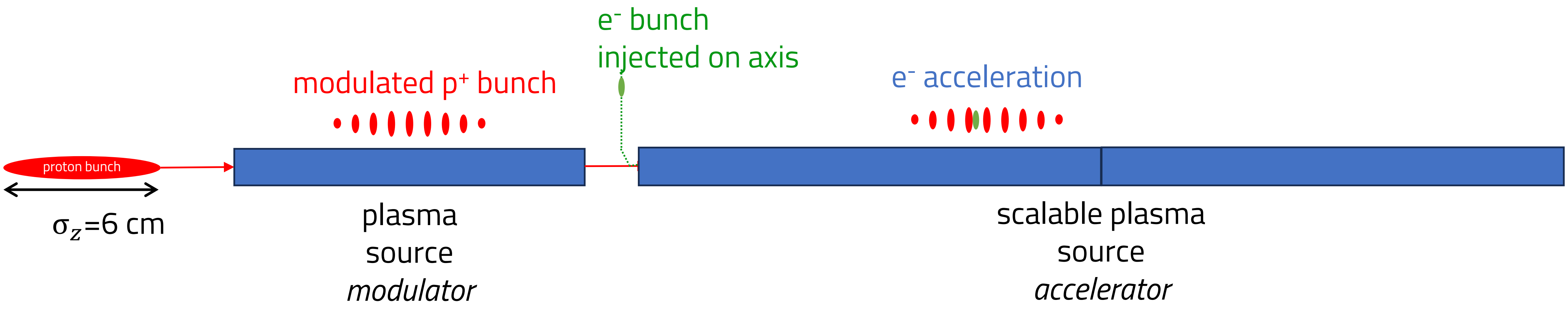
Run 2c (2028) ▶ two sources *modulator* + *accelerator* to allow external **e-bunch injection**[2]

Requirements *accelerator* plasma source for AWAKE

- Density matching with modulator (1-10x10^{14} cm^{-3})
- Reproducibility and stability
- Longitudinal uniformity: 0.25% over 10 m

[2] Gschwendtner, E., et al., (AWAKE Collaboration), Symmetry 2022, **14**, 1680.

Next in AWAKE



Run 2c (2028) ▶ two sources *modulator* + *accelerator* to allow external e-bunch injection[2]

Run 2d (2030) ▶ scalable plasma source to extend acceleration length

▼

R&D scalable plasma sources for AWAKE

Requirements scalable plasma source for AWAKE

- Density matching with modulator (1-10x10^{14} cm^{-3})
- Reproducibility and stability
- Longitudinal uniformity: 0.25% over 10 m
- Length-scalable: 10-100 m

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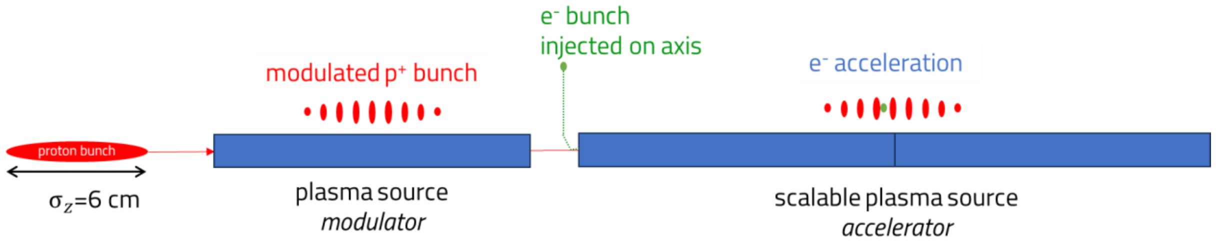
Next in AWAKE

R&D scalable plasma source for AWAKE



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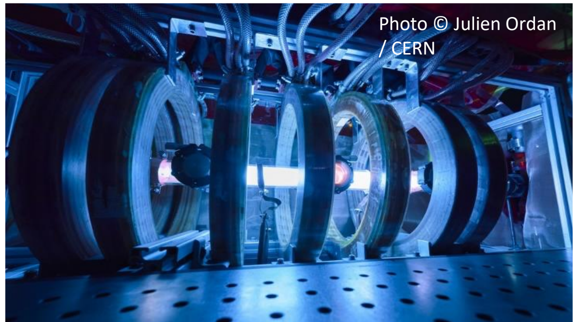
Helicon Plasma Source (HPS)

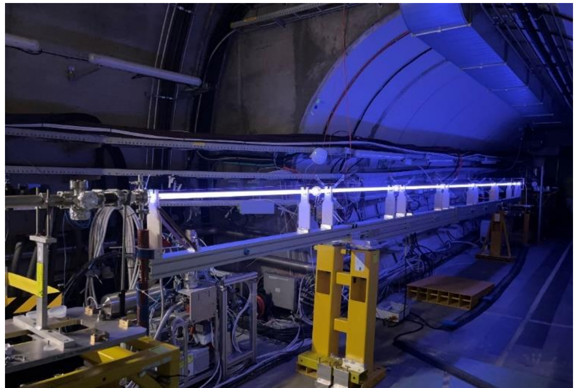
→ RF wave heated plasma



1 m helicon plasma cell from IPP-Greifswald @ CERN

Discharge Plasma Source (DPS)

→ pulsed-DC discharge



10 m DPS in AWAKE tunnel

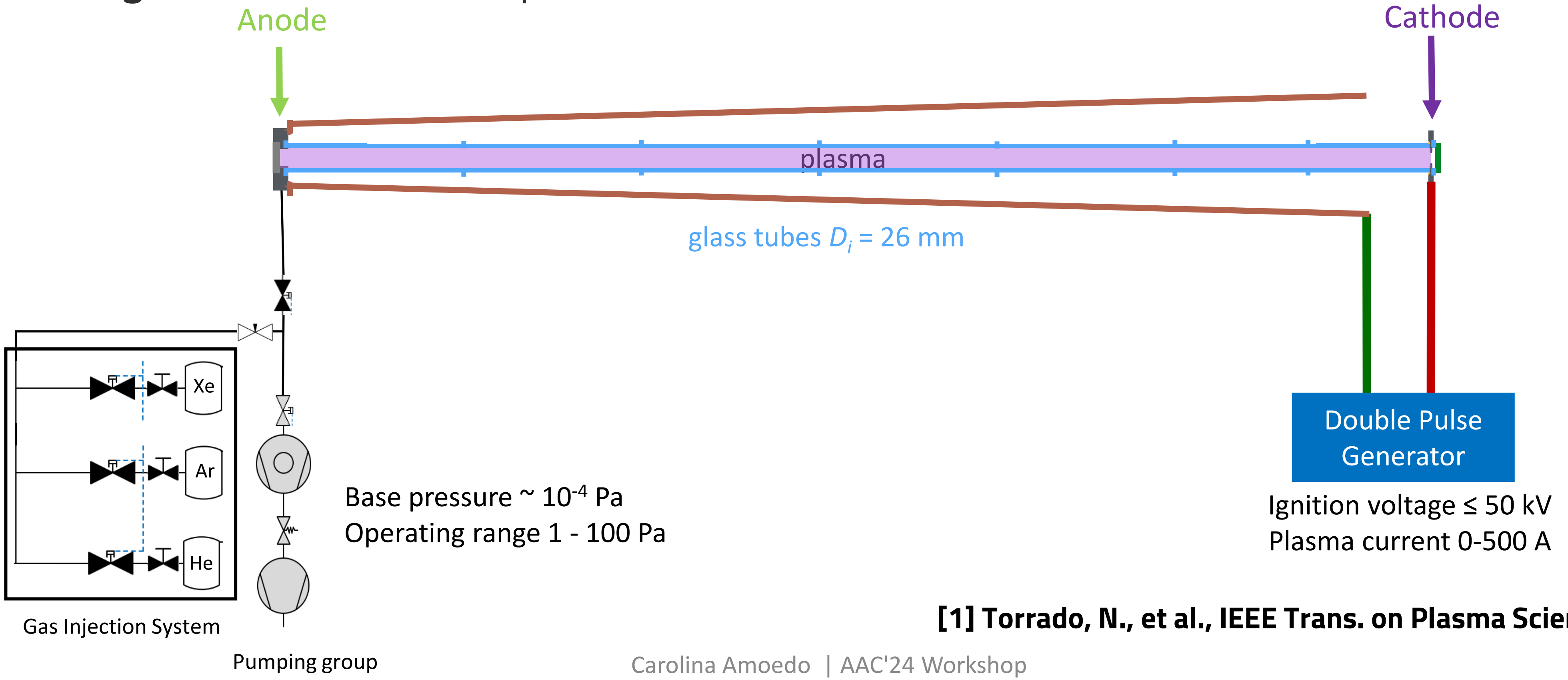
CERN

TÉCNICO LISBOA

Imperial College London

Discharge plasma source (DPS)

- **Double-pulse arc pulsed discharge** [1]
  1) high voltage ignition → jitter <20 ns in plasma ignition
  2) 10 to 50 μs high current pulse → achieve plasma densities up to 2×10^{15} cm^{-3}
- **1 to 10 m long plasmas** **(so far)**
- **Different gases:** He/Ar/Xe at low pressure (1-100 Pa)



TÉCNICO LISBOA

[1] Torrado, N., et al., IEEE Trans. on Plasma Science 2023, 51, 12.

Discharge plasma source (DPS)

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  1) high voltage ignition → jitter <20 ns in plasma ignition
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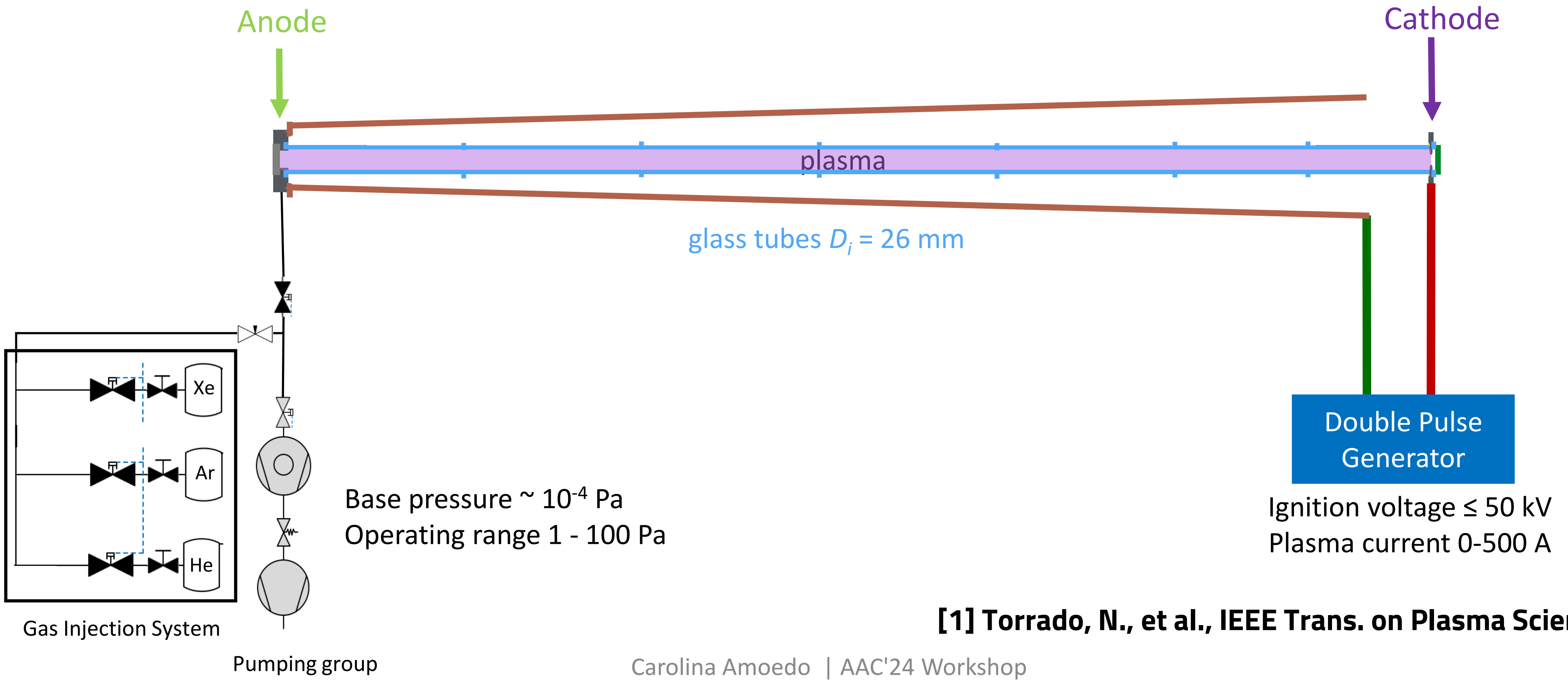
- **1 to 10 m long plasmas → scalability:** series of discharges: common electrodes + current balancing magnetic circuits
- **Different gases:** He/Ar/Xe at low pressure (1-100 Pa)



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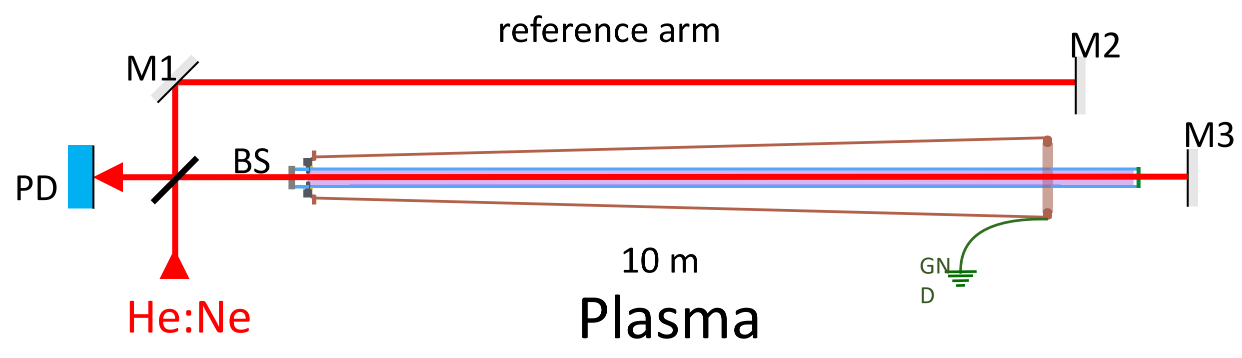
[1] Torrado, N., et al., IEEE Trans. on Plasma Science 2023, 51, 12.

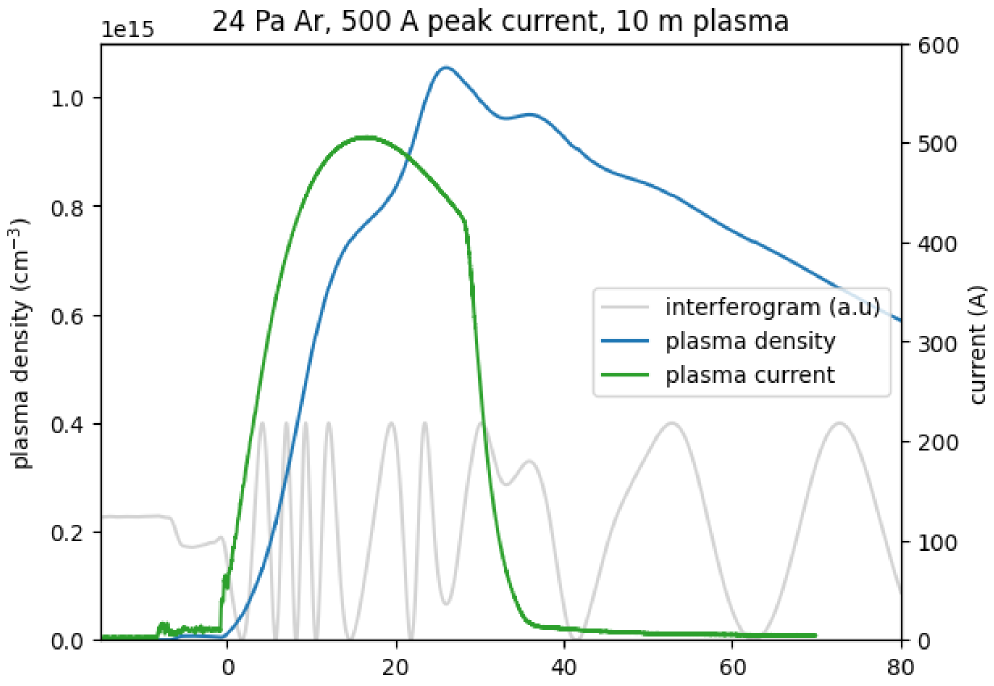
10 m single plasma, 24 Pa Ar, 500 A (24.03.2023)

Plasma density diagnostic

Longitudinally integrated interferometry

Parameters:
Gas: Ar
Pressure: 24 Pa
HV pulse: -17 kV
High current pulse: -6.32 kV, 500 A
Pulse duration: 25 µs
Plasma length: 10 m





▶ Michelson interferometer
▶ Measurement arm (plasma) adds a phase shift ϕ_i proportional to the plasma density n_e:

$$\phi_i = \frac{n_e}{r_e\,\lambda_i L}$$

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

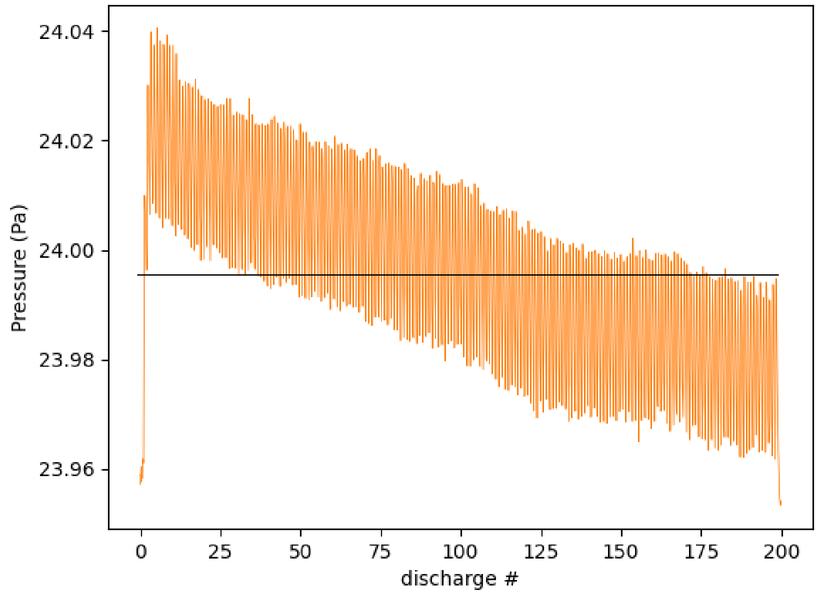
▶ Time-evolution of the plasma density, line integrated over the 10 m

DPS plasma density reproducibility

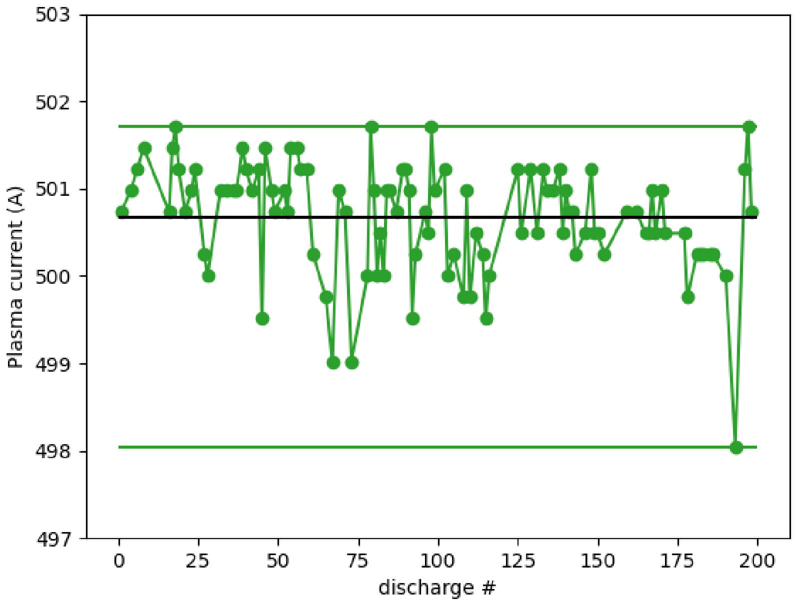
Parameters:
Gas: Ar
Pressure: 24 Pa
HV pulse: -17 kV
High current pulse: -6.32 kV, 500 A
Pulse duration: 25 μs
Plasma length: 10 m

▶ **200 consecutive discharges @ 0.1 Hz** (similar to rep rate at AWAKE 2 extractions per SPS cycle)

0.2% variation gas pressure



0.5% variation peak current

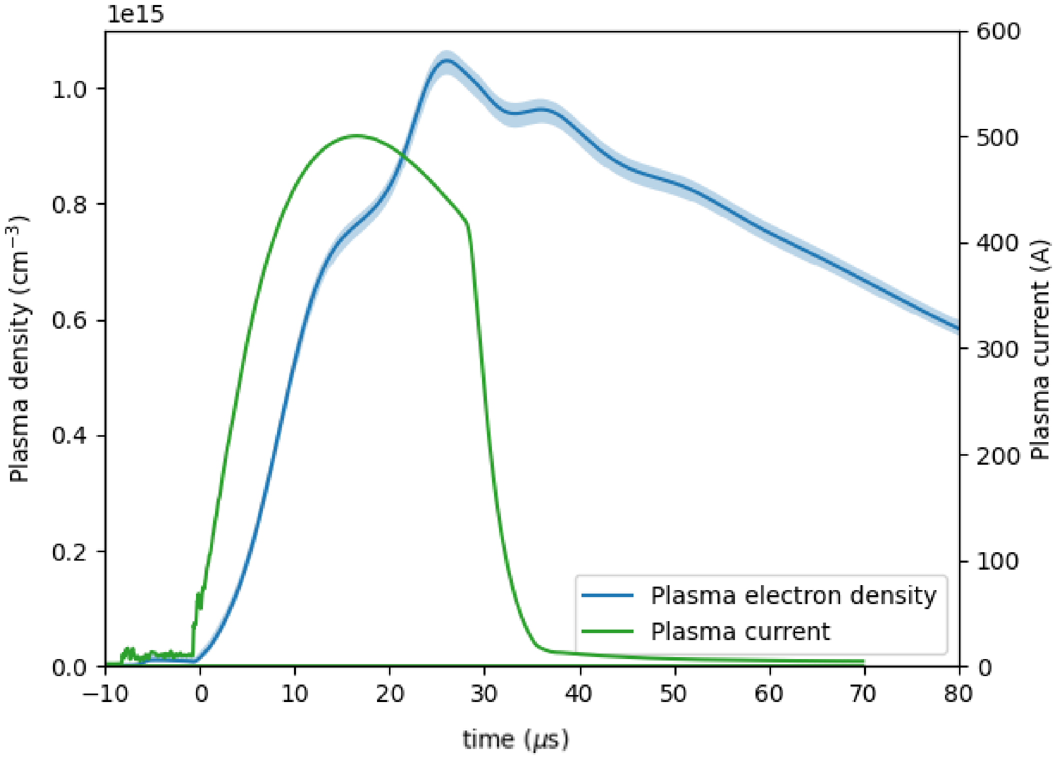


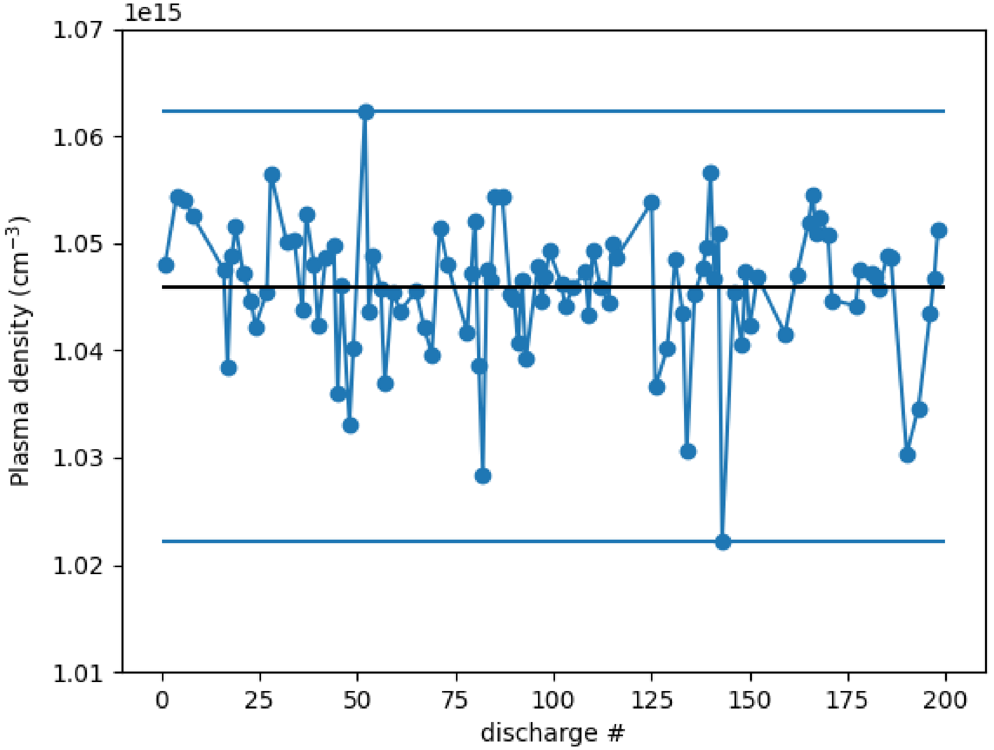
▶ precise control of these parameters is key for reproducibility

DPS plasma density reproducibility

► Shot-to-shot plasma density variation was evaluated over **200 consecutive discharges** with longitudinal-integrated interferometry

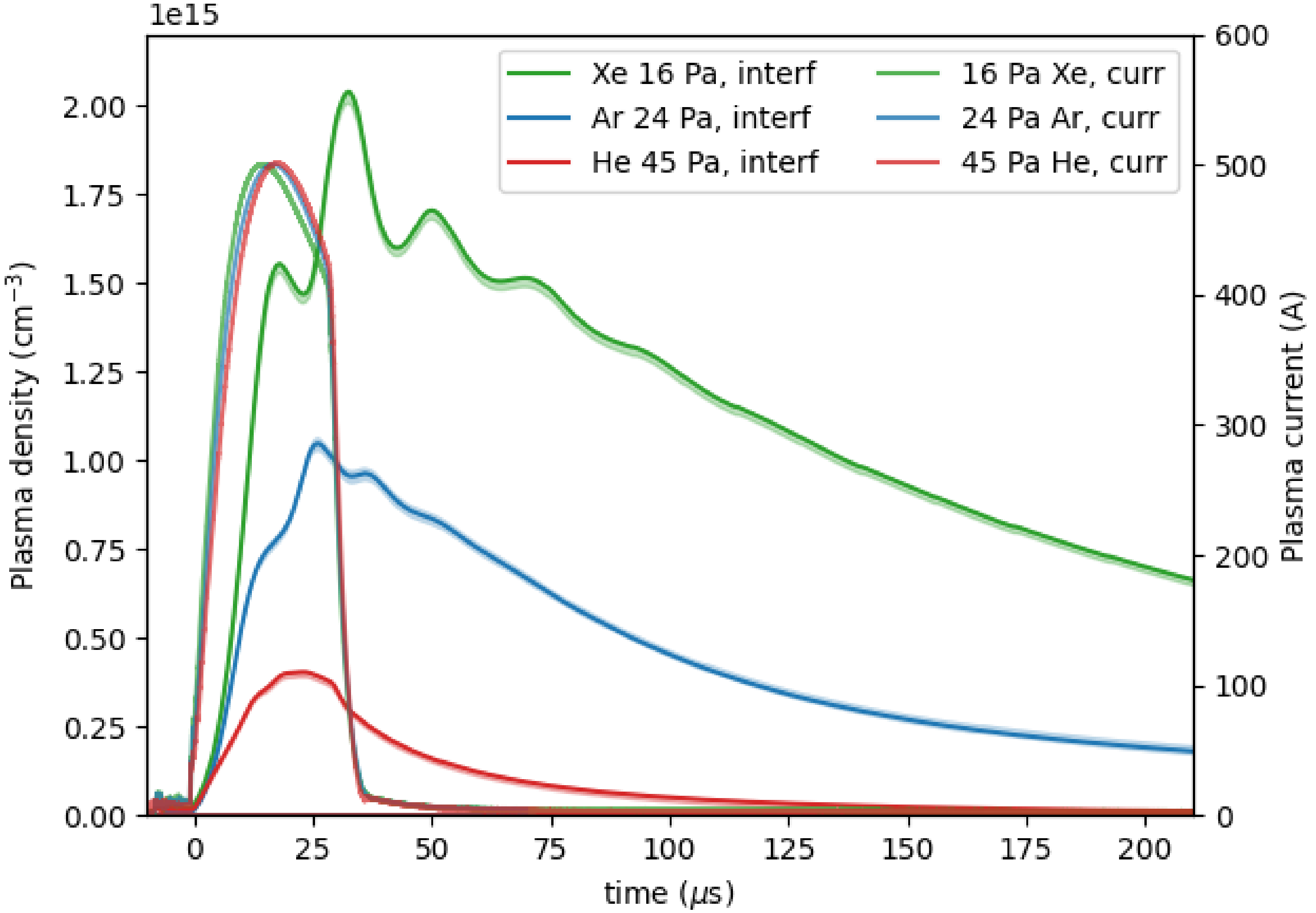
Parameters:
Gas: Ar
Pressure: 24 Pa
HV pulse: -17 kV
High current pulse: -6.32 kV, 500 A
Pulse duration: 25 μs
Plasma length: 10 m





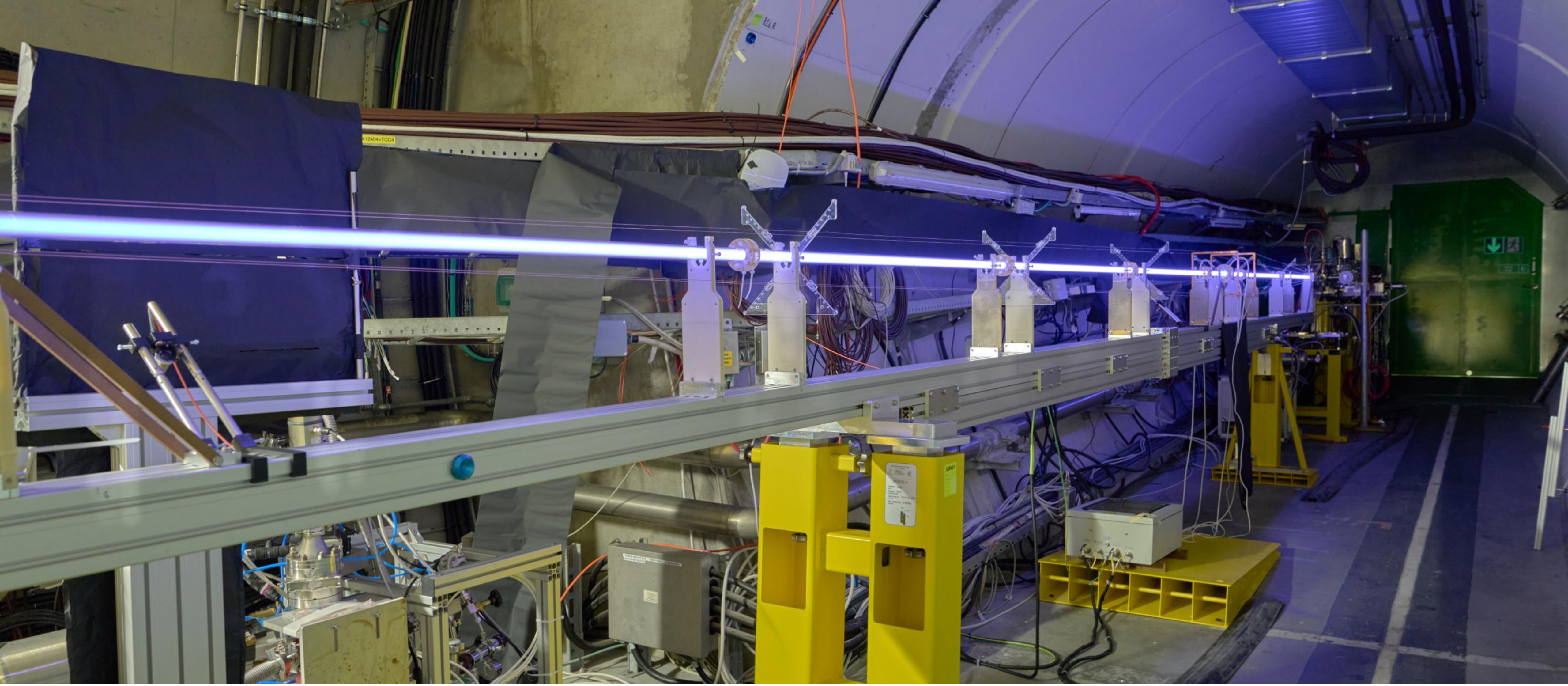
► <2% plasma peak density variability

DPS flexibility - 3 gases



► Reproducibility also studied for He (45 Pa) and Xe (16 Pa), 500 A peak current

► DPS wide range of parameters **(density/gas/length)**



Discharge Plasma Source

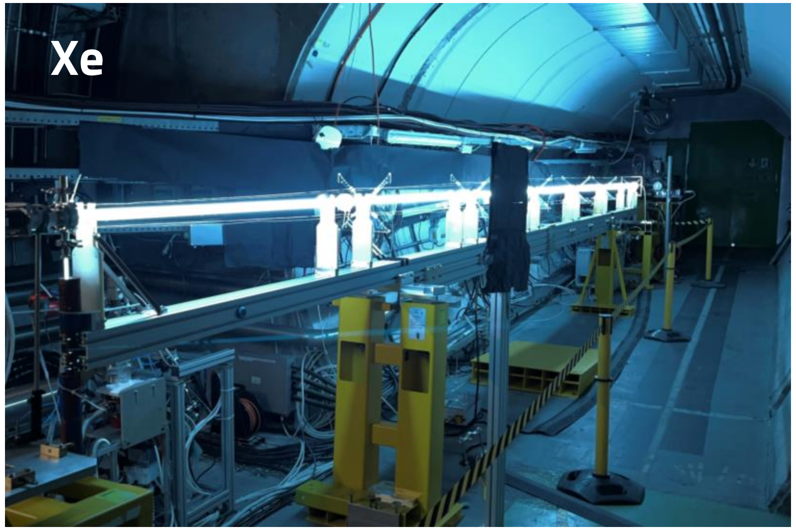
(3 Weeks of p+ beamtime in 2023)

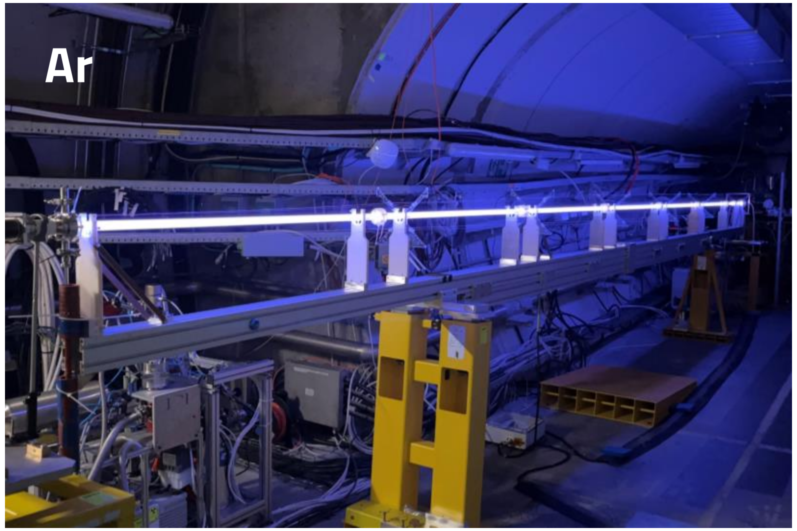
10 m DPS in AWAKE

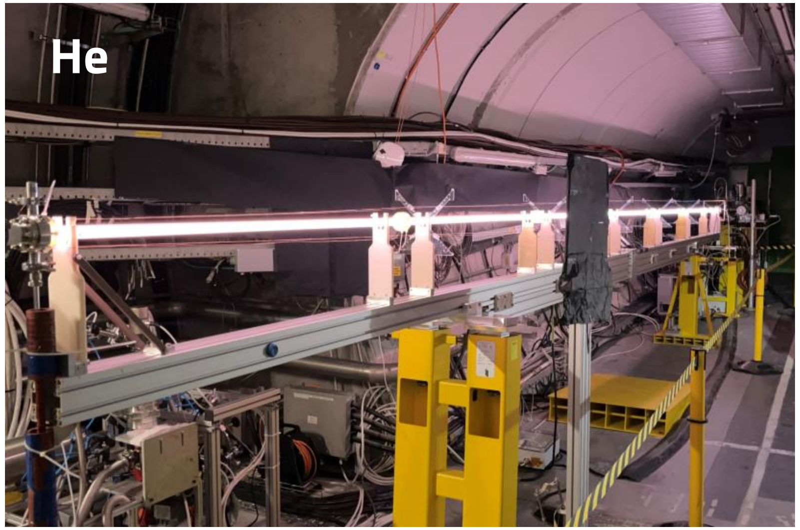
→ unique chance to test an alternative plasma source in AWAKE:

1. demonstration of operation of DPS source in AWAKE

- Over 3 weeks of run with protons, very smooth operation of the DPS
- ~ 22000 discharges produced, with current pulse ~ 20 ns maximum jitter and current amplitude stability < 1%



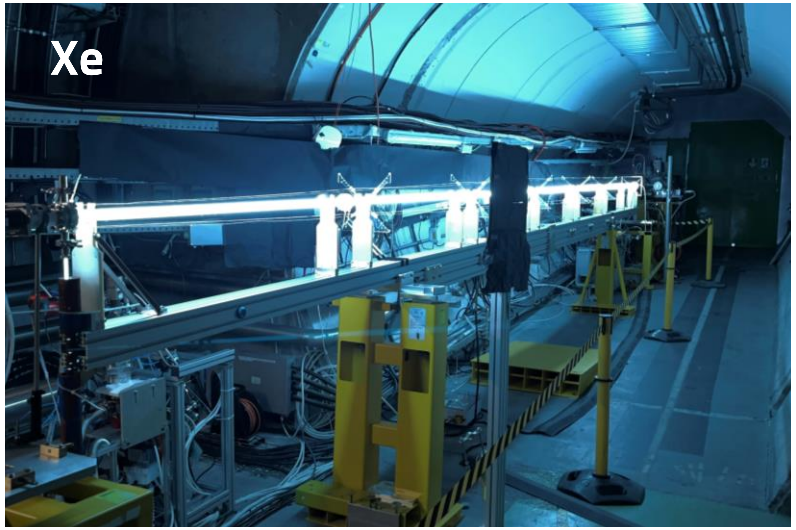


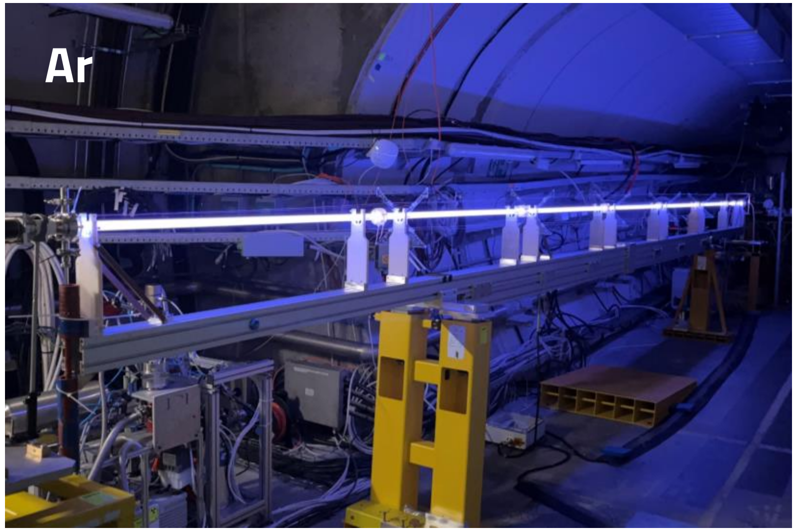


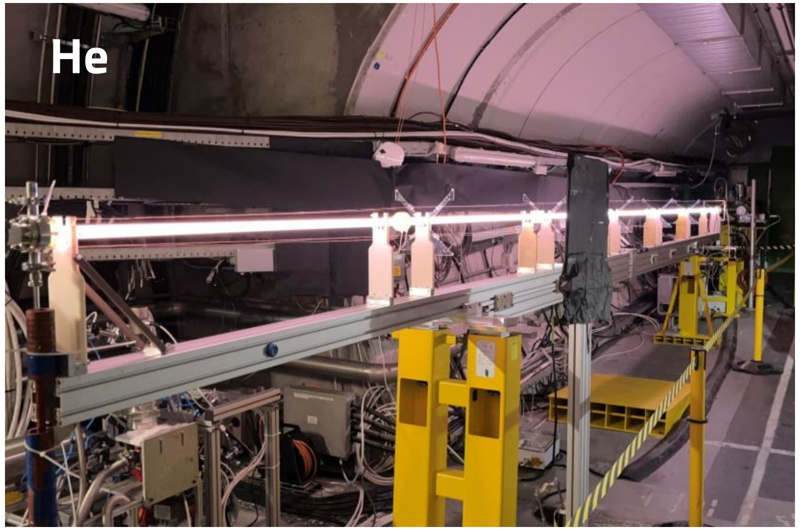
10 m DPS in AWAKE

→ unique chance to test an alternative plasma source in AWAKE:

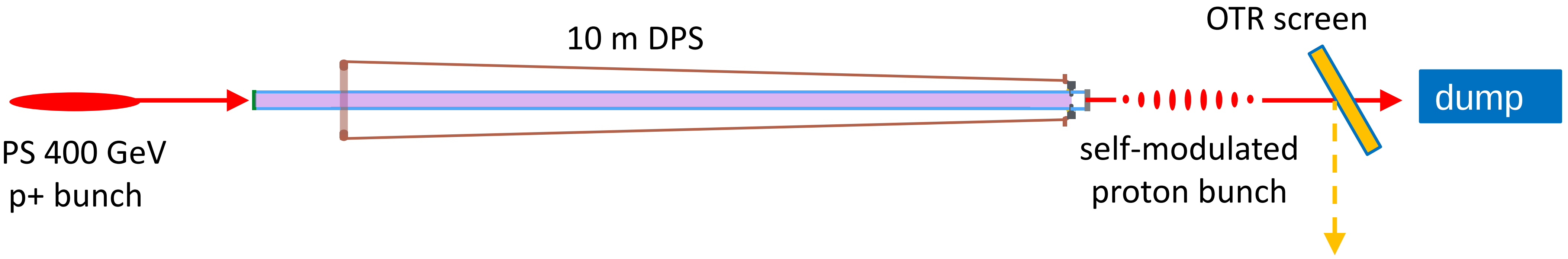
1. demonstration of operation of DPS source in AWAKE
2. **Self Modulation Instability (SMI) signature ?**
3. Study the effect of plasma density/length/gas on SMI

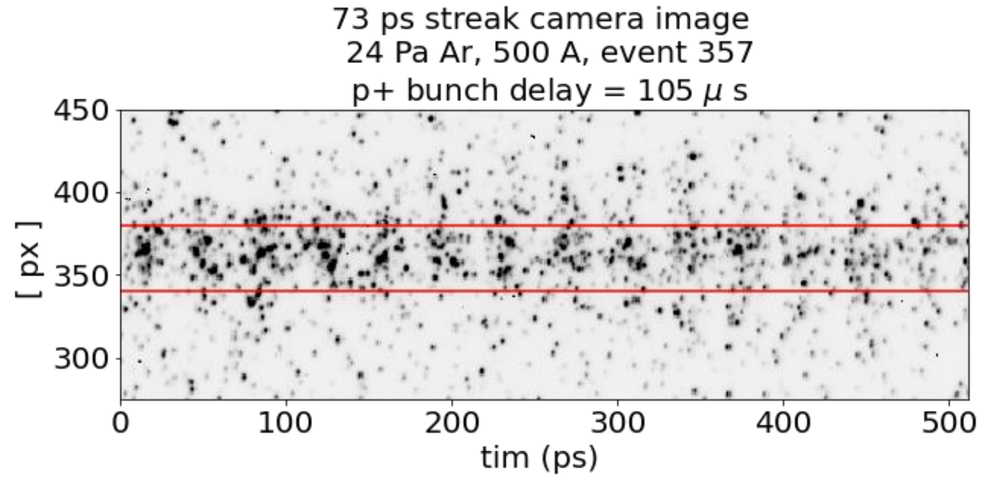






Streak camera observation of modulation of the p+ bunch

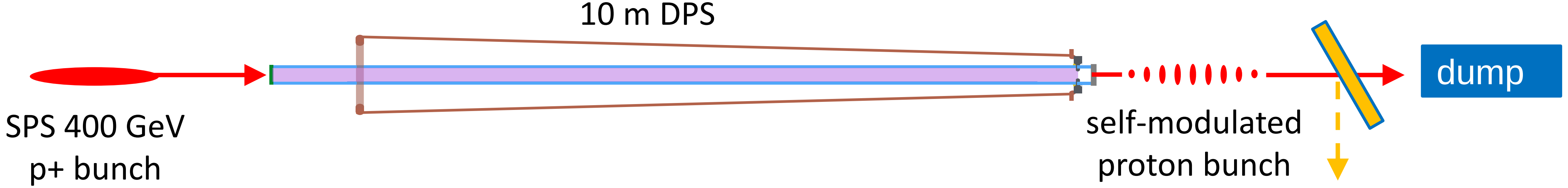




- ▶ Proton bunch propagating through DPS plasma
- ▶ Non-seeded self-modulation
- ▶ Time-resolved images of the bunch density distribution

▶ usual Self Modulation Instability (SMI) signature with the DPS !

Streak camera observation of modulation of the p+ bunch

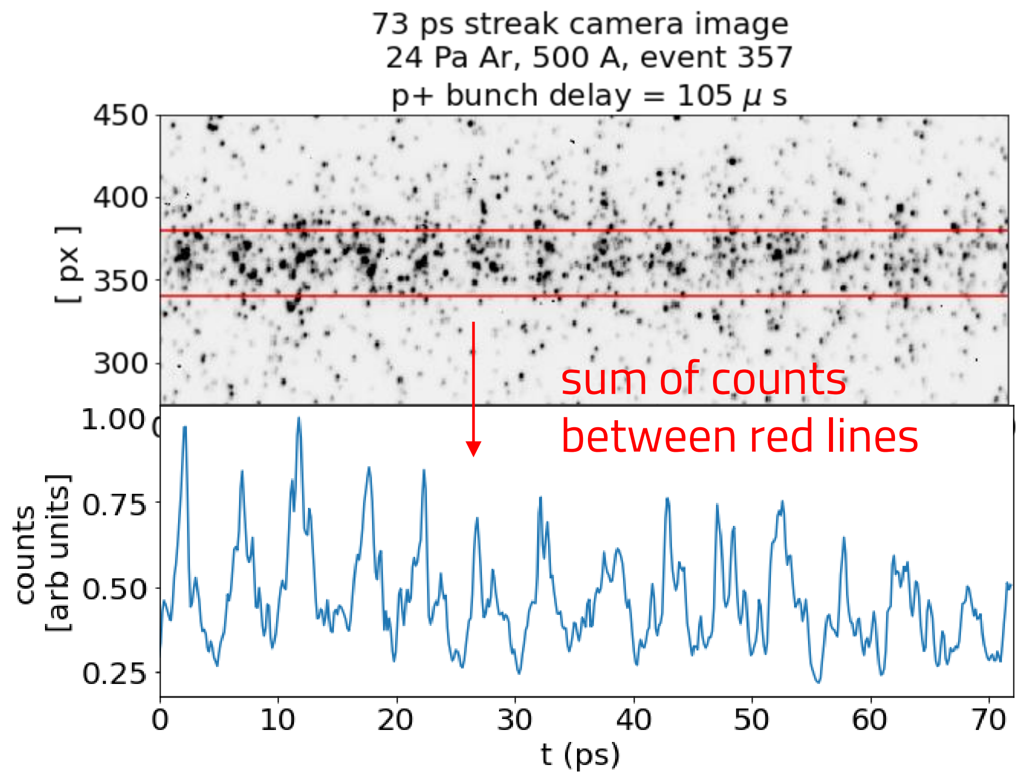


► Plasma density calculated from proton bunch self-modulation frequency

$$f_{mod} \sim f_p$$

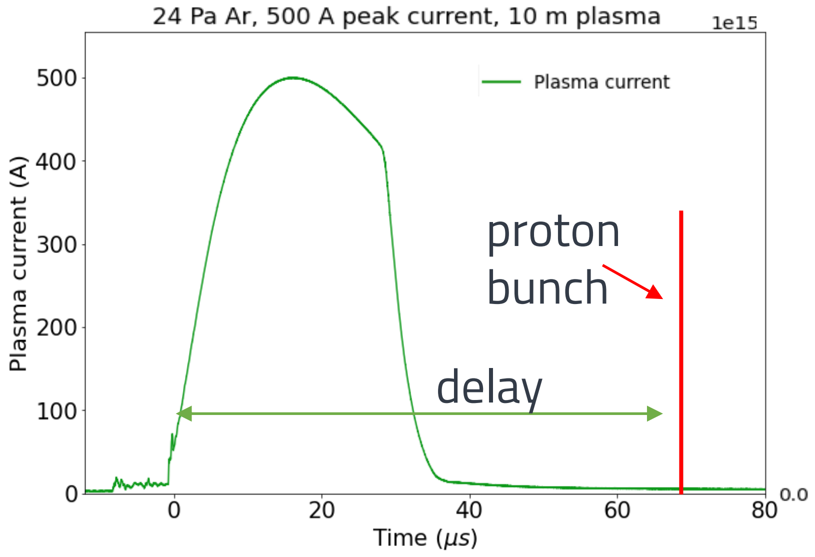
$$\omega_p = 2\,\pi\, f_{mod}$$

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



DPS at AWAKE

→ Time delay between time the discharge and the p+ bunch → discrete measurement of density (in time)



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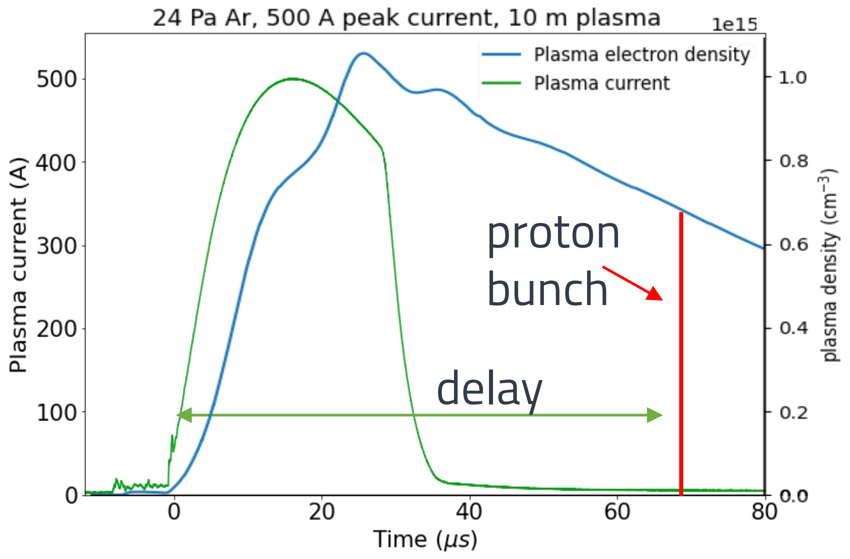

DPS at AWAKE

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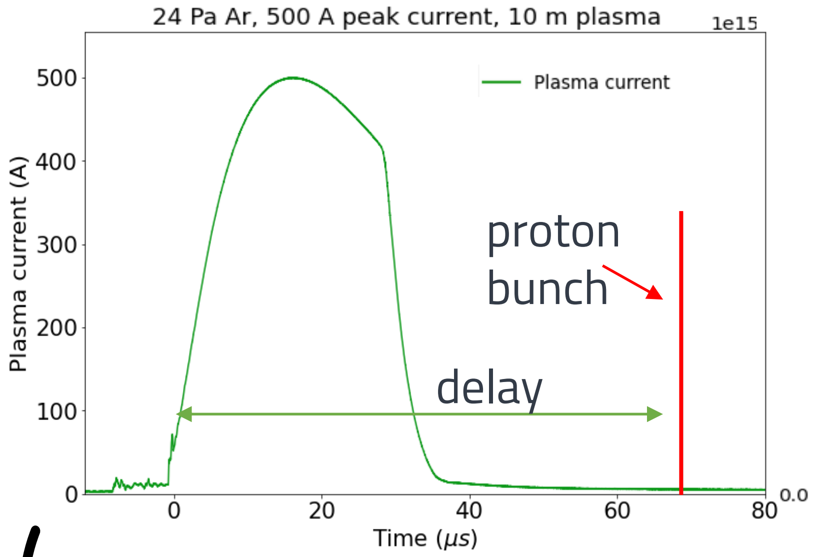
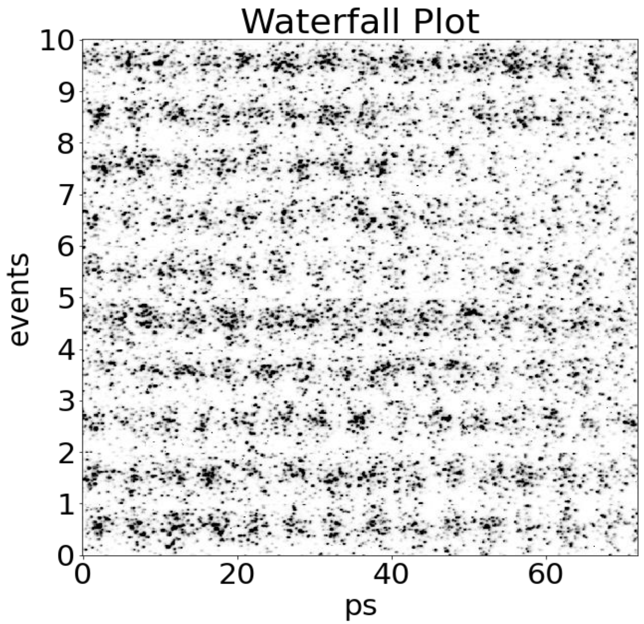
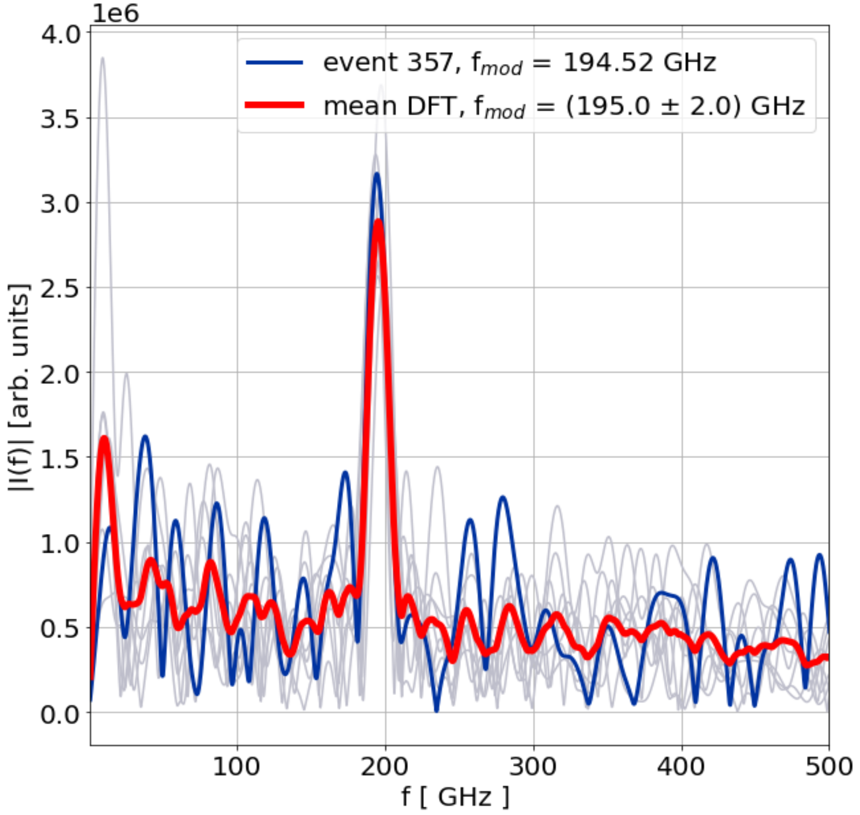


10 events per delay



f_{mod}



► $n_e(t=70\mu s)=(4.73\pm0.09)\times10^{14}$ cm^{-3}

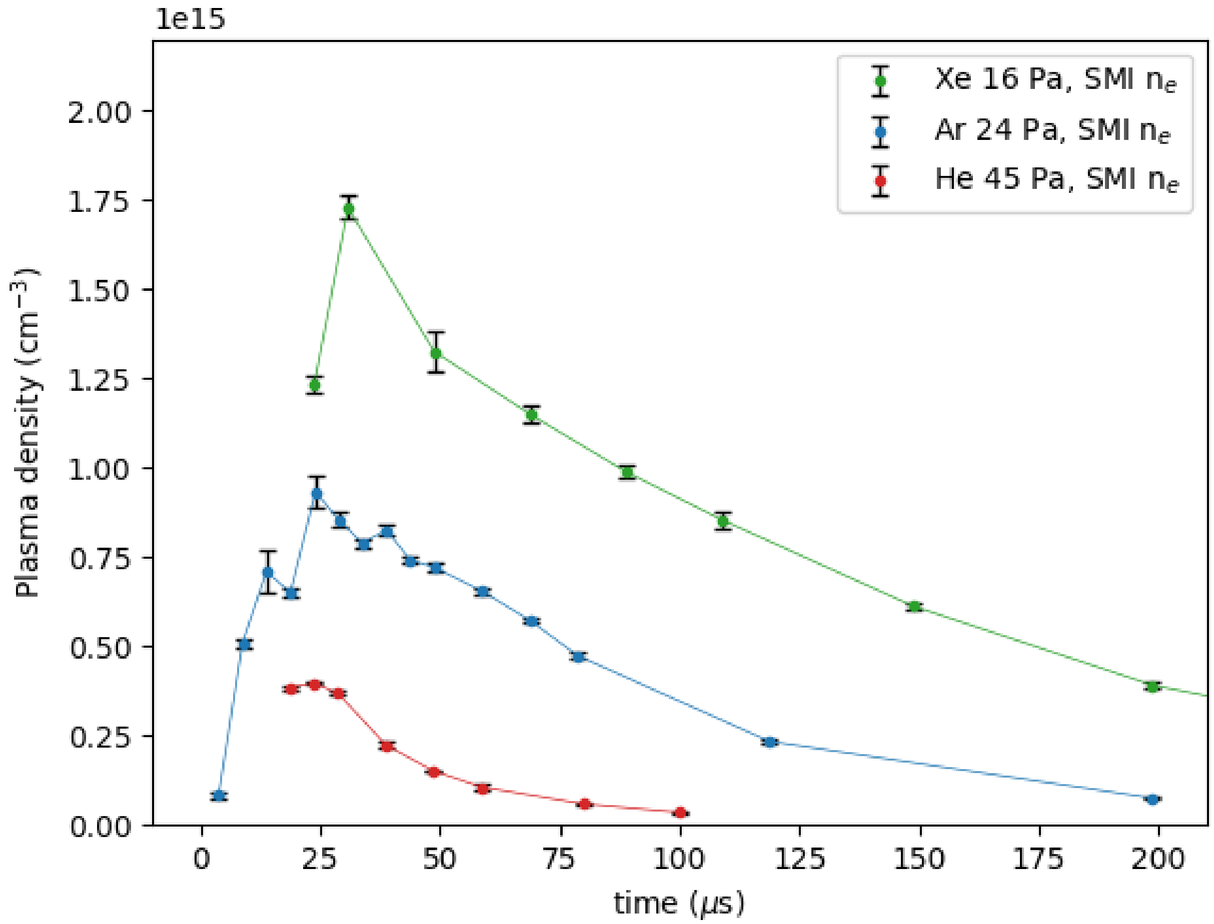
~ 4% spread in density

Plasma electron density calculated from modulation frequency of p+ bunch

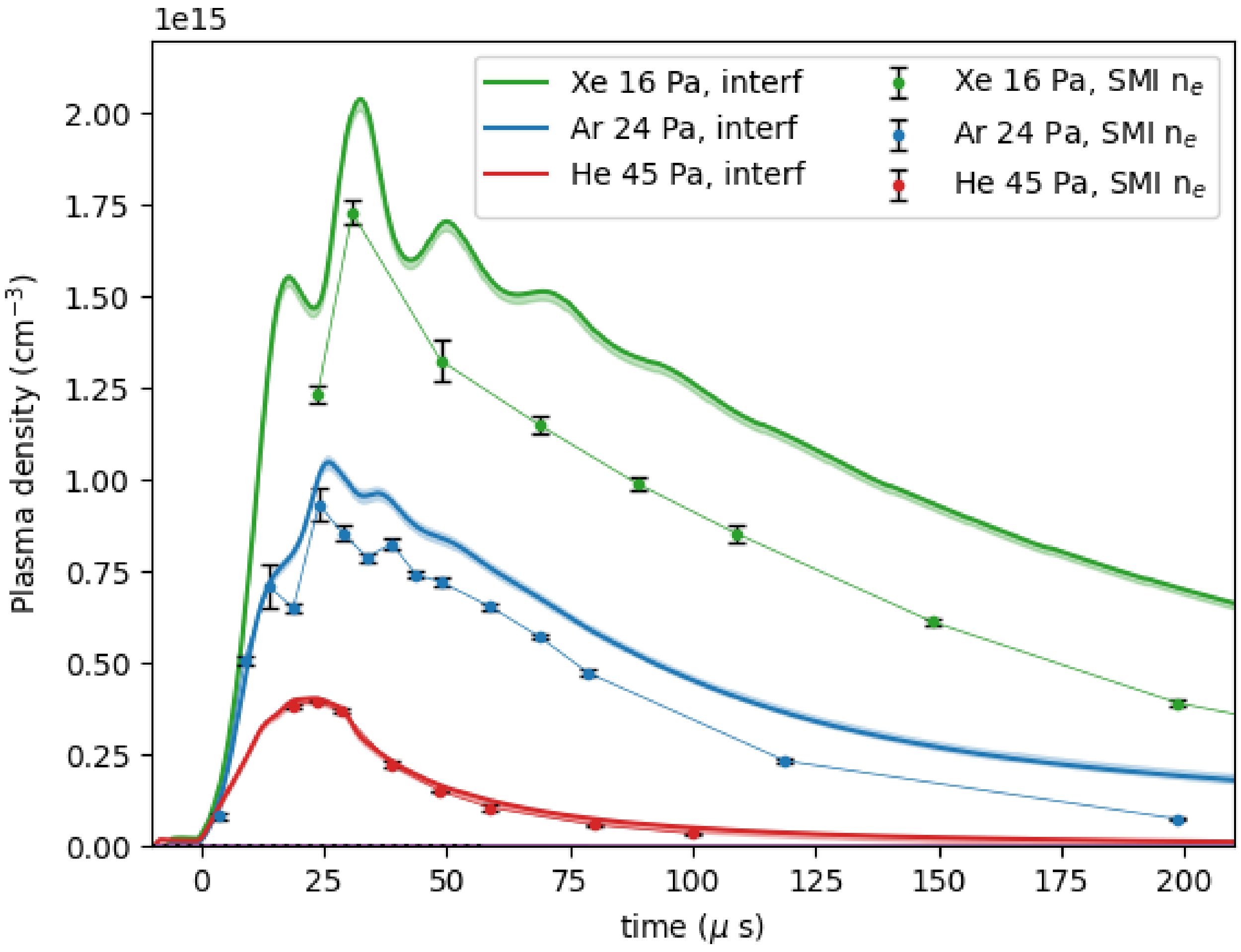
→ **Time evolution of the DPS plasma density**

for 3 gases: He, Ar, Xe

▶ **easy way of changing density**
(requirements of R&D for scalable plasma sources)



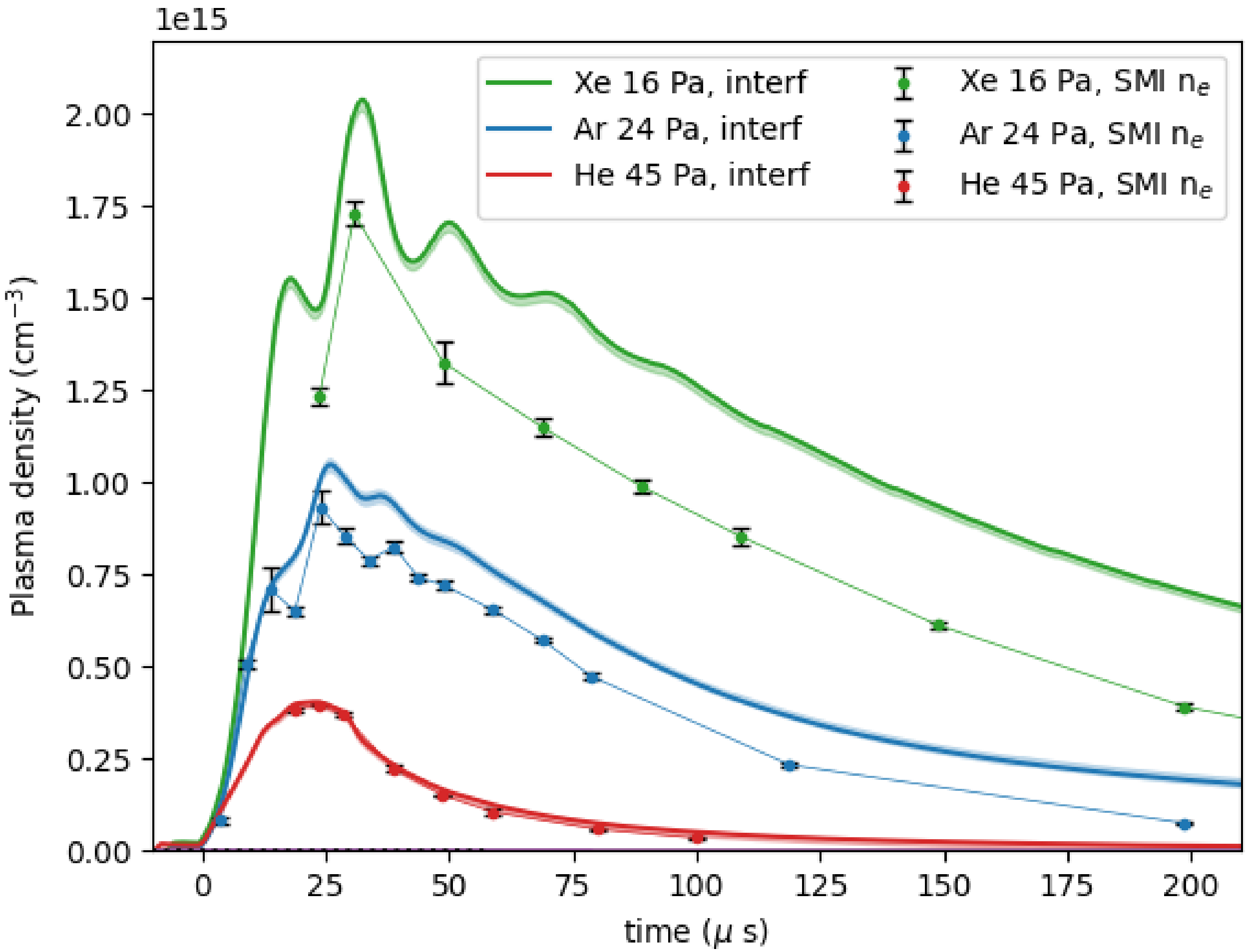
Comparison n_e from modulation frequency and lab interferometry



- **Agree qualitatively**
  with a systematic difference of 15-17% for Ar and Xe

[4] Morales Guzman P.I., et al. (AWAKE Collaboration). PRAB, 2021

Comparison n_e from modulation frequency and lab interferometry



- ▶ **Agree qualitatively** with a systematic difference of 15-17% for Ar and Xe
- ▶ Understanding discrepancies
  - ▶ **Two very different measurements**
    - ▶ best effort to match exact same lab/tunnel experimental conditions (gas/current)
    - ▶ in case of radial density profile: are p+ bunch/laser probing the same point?
    - ▶ f_{mod} can differ from f_p depending on the longitudinal plasma density profile[4]

▶need of plasma uniformity measurement

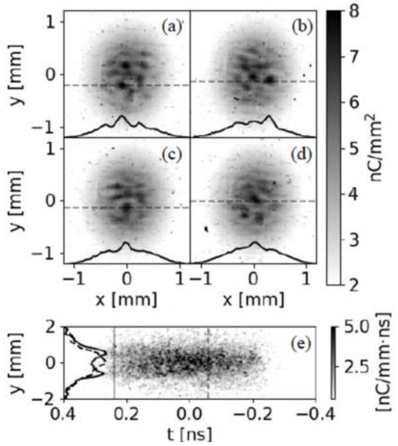
[4] Morales Guzman P.I., et al. (AWAKE Collaboration). PRAB, 2021

10 m DPS in AWAKE

→ unique chance to test an alternative plasma source in AWAKE:

1. demonstration of operation of DPS source in AWAKE
2. Self Modulation Instability (SMI) signature
3. Physics Studies enabled by the DPS

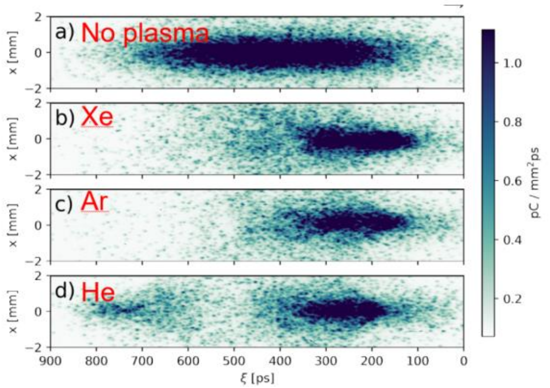
Filamentation Instability



→ Wide plasma allowed to study the filamentation instability

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

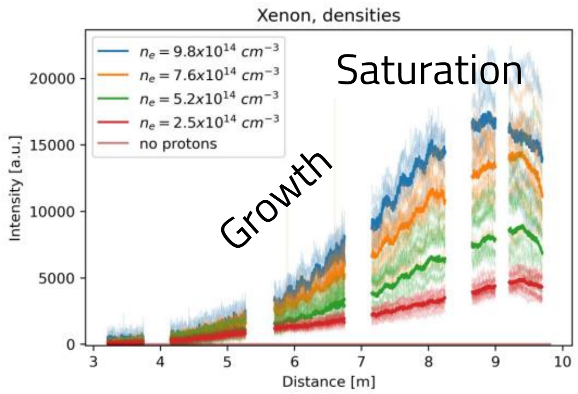
Ion Motion



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

M. Turner et al., submitted

Plasma Light



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

→ **Next talk by L.Verra**

→ **Plenary talk, Thu 9:00, by M. Turner**

→ **Poster, Tuesday, by J. Mezger**

Conclusion

- **The DPS provides reproducible plasma density in different gases (He, Ar, Xe):** system with
< 0.2% pressure variability and < 0.5 % current variability provides <u>< 2% integrated peak density variability.</u>

- Precision density measurements were performed using longitudinal integrated interferometry: **plasma electron densities ranging from 1- 20x10^{14} cm^{-3} .**
  - <u>Next step</u>**:** local plasma density measurement with Thomson scattering <u>(this fall)</u>

- **Self-modulation of a 400 GeV proton bunch was observed in DPS successfully.**

- The DPS offers a **large parameter flexibility (length/plasma density/gas)** allowing studies on effect of plasma ion mass on SMI, transverse filamentation instability and plasma wakefield light emission

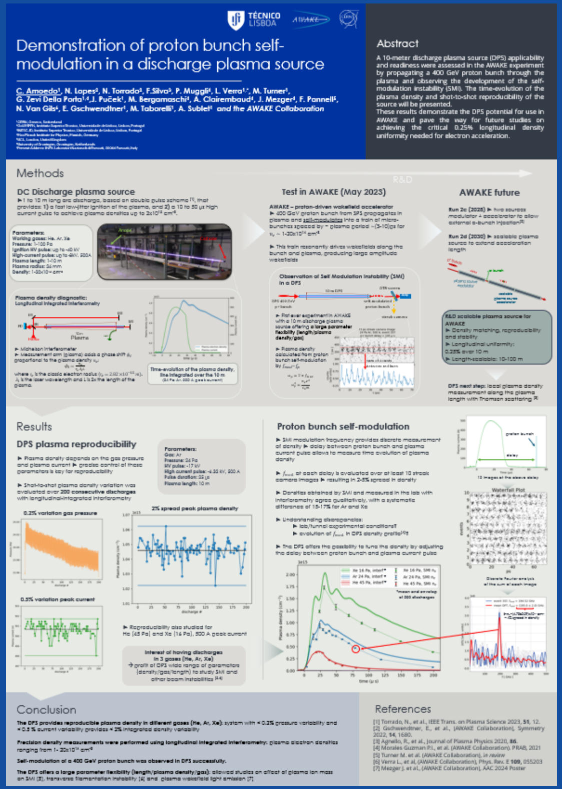
Requirements scalable plasma source for AWAKE

- ✓ Density matching with modulator (1-10x10^{14} cm^{-3})
- ✓ Reproducibility and stability
- ▪ Longitudinal uniformity: 0.25% over 10 m → **Next steps**
- ▪ Length-scalable: 10-100 m → **Preliminary test: plasmas 3.5 + 6.5 m** →

**[1] Torrado, N., et al.,
submitted IOP Conference Series 2024**

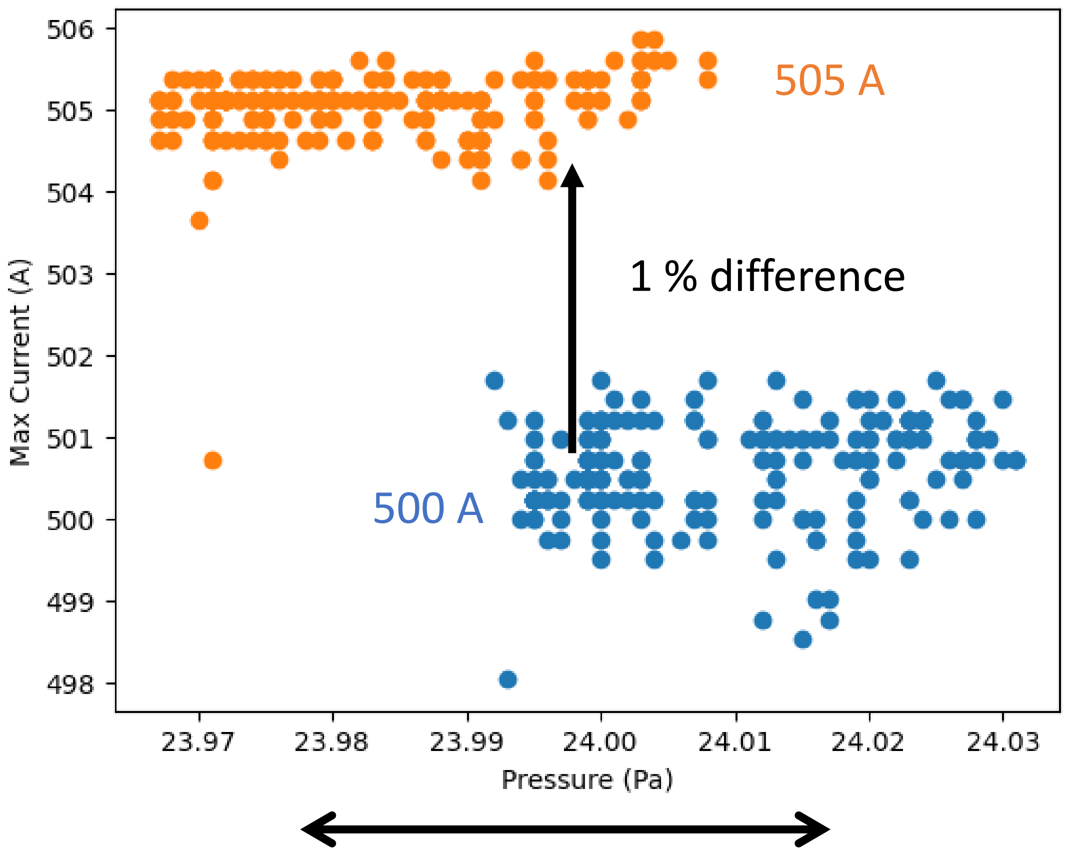
Thank you for your attention

→ **Poster session Tuesday**

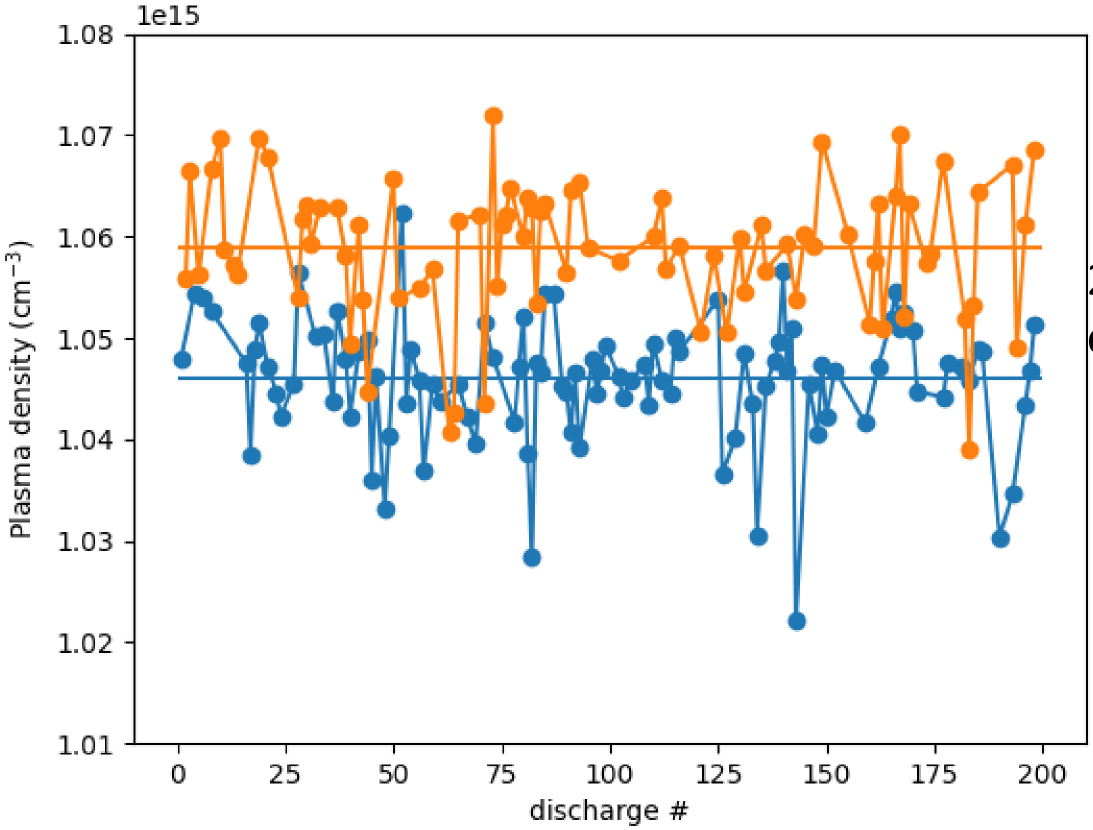


Sensitivity DPS to peak current

Parameters:
Gas: Ar
Pressure: 24 Pa
HV pulse: -17 kV
High current pulse: -6.32 kV, 500 A
Pulse duration: 25 µs
Plasma length: 10 m



spread pressure (0.2 %)

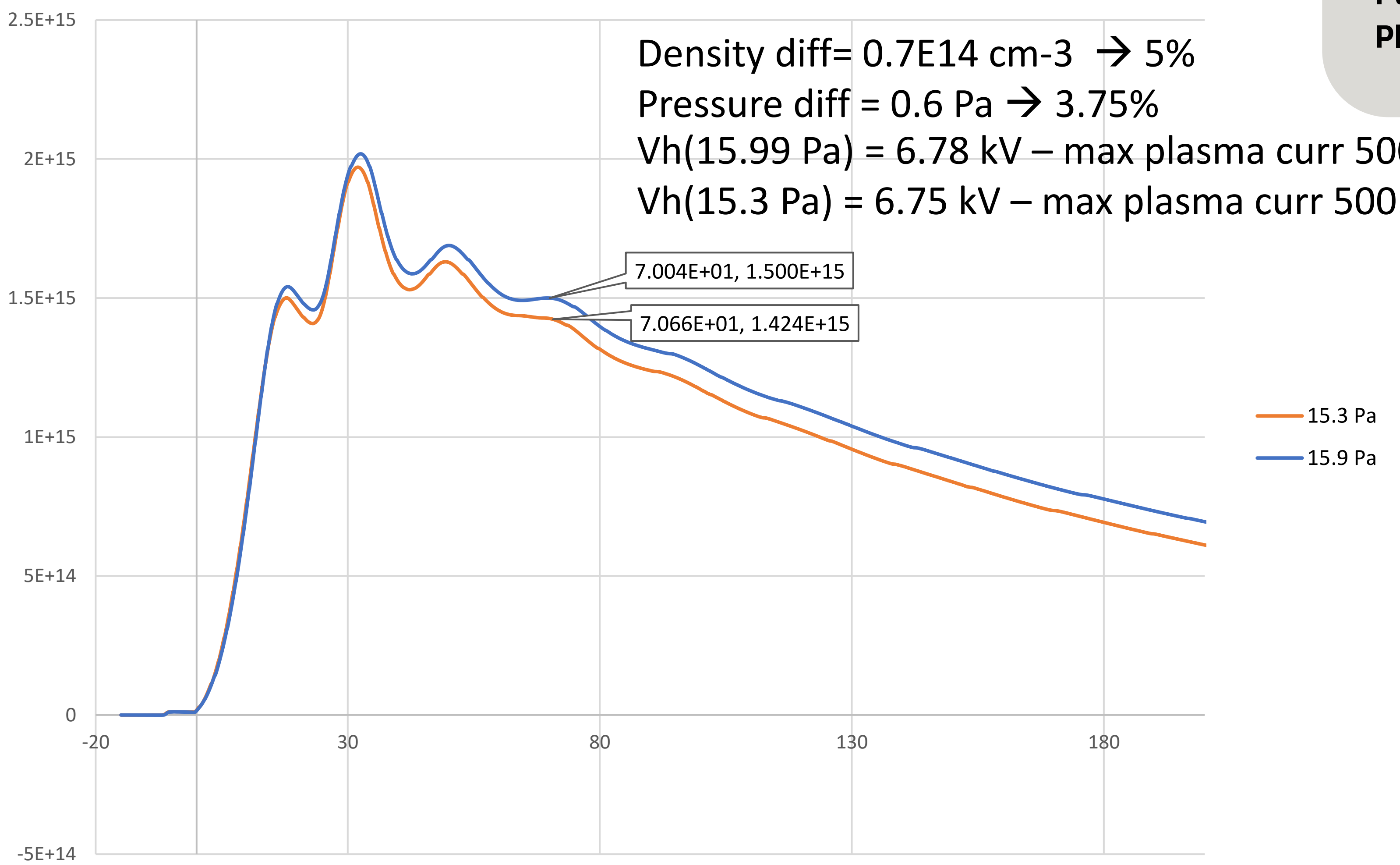


2 % increase density

Sensitivity DPS to density

Parameters:
Gas: Xe
Pressure: 16 Pa
HV pulse: (primary) 3kV
High current pulse: -6.75 kV**,** 500 A
Pulse duration: 25 μs
Plasma length: 10 m

Density diff= 0.7E14 cm-3 → 5%
Pressure diff = 0.6 Pa → 3.75%
Vh(15.99 Pa) = 6.78 kV – max plasma curr 500.7 A
Vh(15.3 Pa) = 6.75 kV – max plasma curr 500.2 A

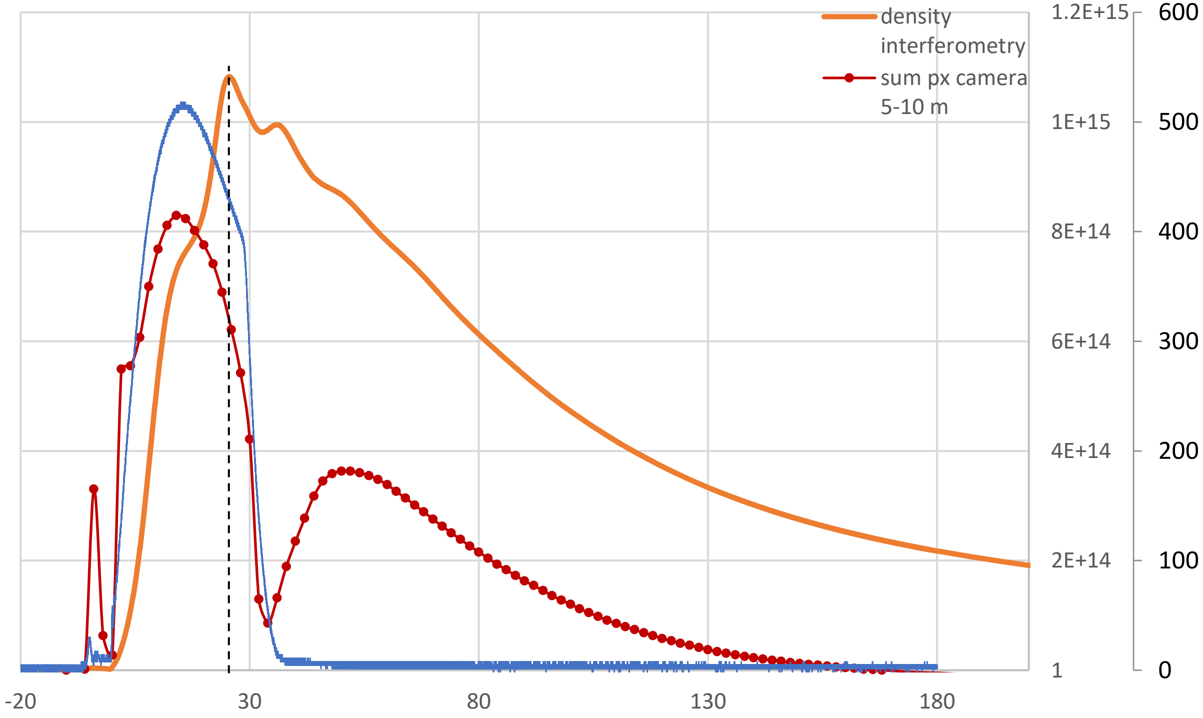


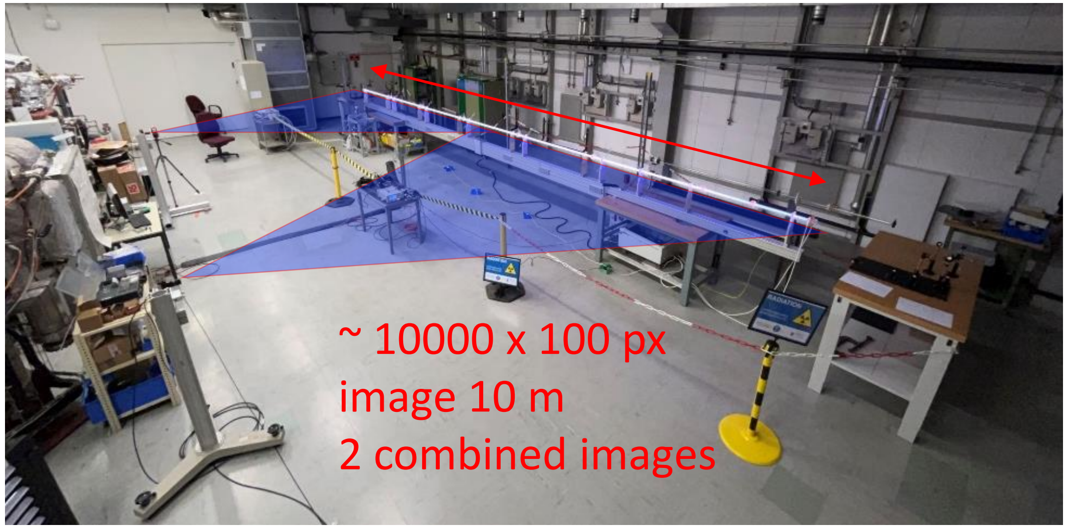
Next steps

<u>10 m prototype:</u> plasma light imaging → μs time-scan discharge

(1 μs exposure time)

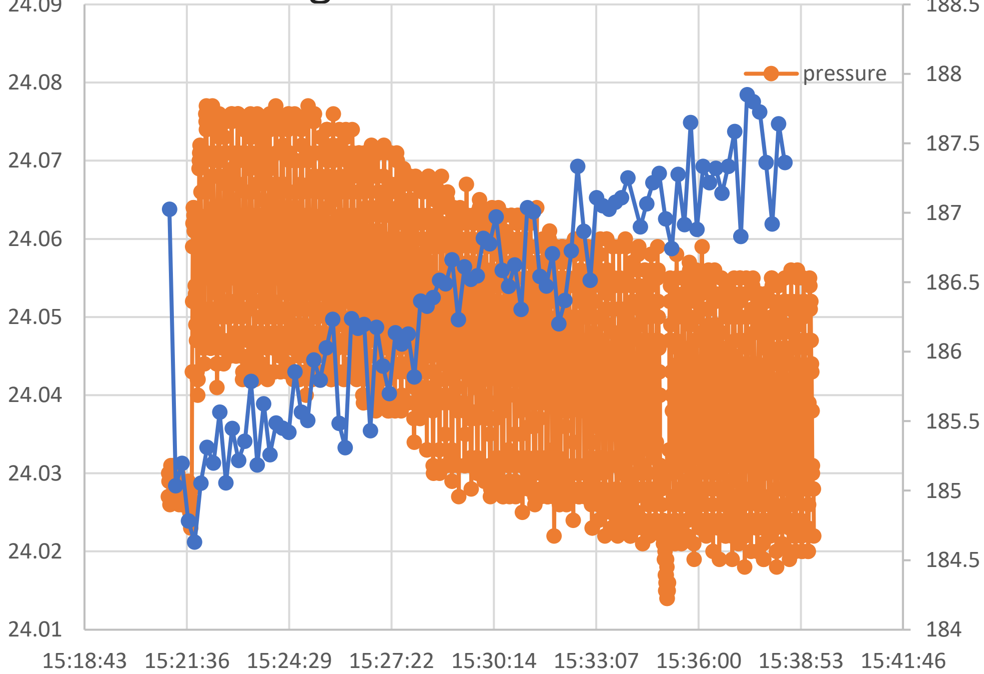
24 Pa 500 A





peak density: mean of all pixels of the image

(100 discharges) → raw data (no correction)

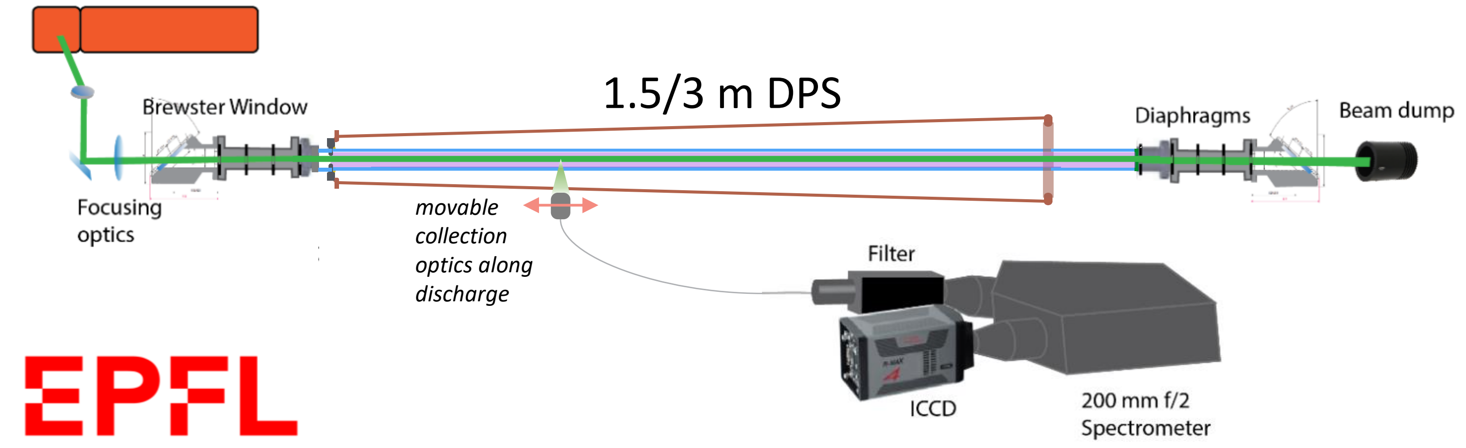


Next steps

1. **Thomson scattering on DPS:** Fall 2024

→ **local** plasma density measurement along the source (at a specific point in time)

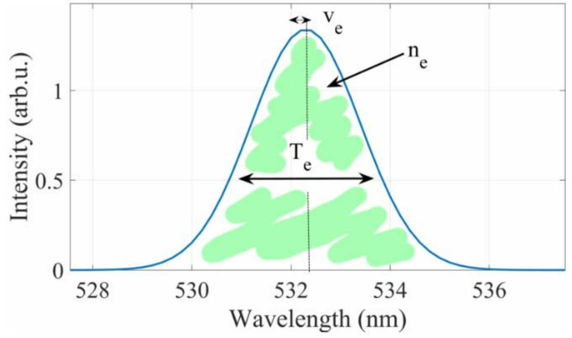
→ time-scan: repeat scan at different laser-discharge delays



EPFL

Courtesy Christine Stollberg, EPFL-SPC

Thomson scattering spectrum



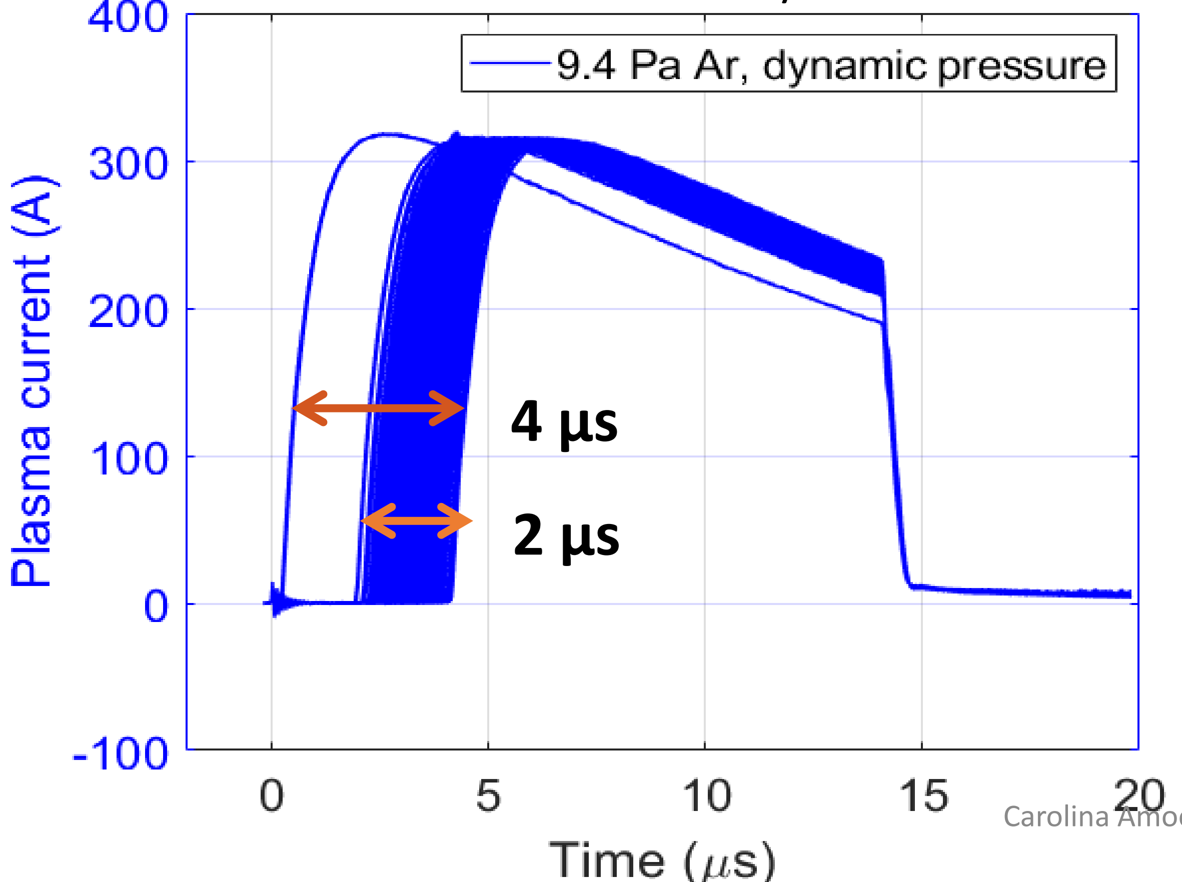
- Operating regime: 1×10^{18} - 1×10^{21} m^{-3}
- Uncertainties: 0.1 eV and ~ 10% in density

DPS 1.6 m prototype

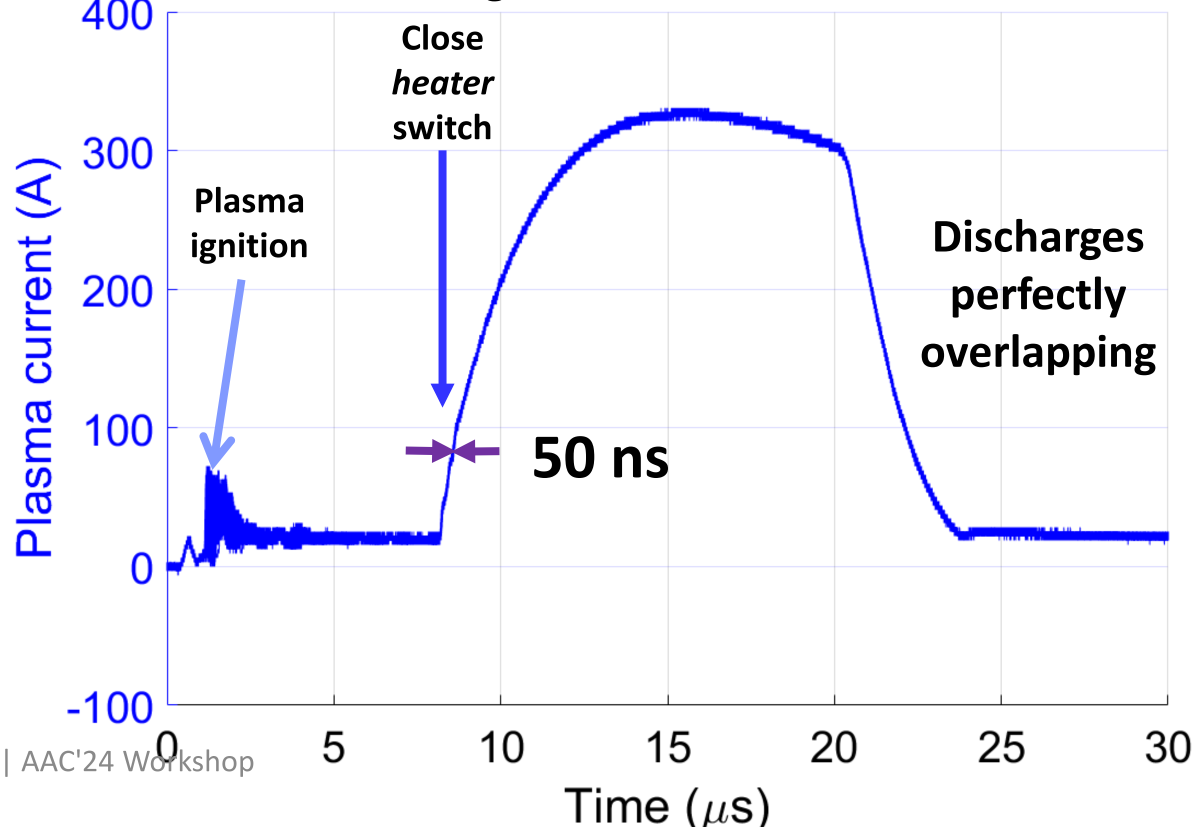
Double pulse discharge

- 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

Heater only

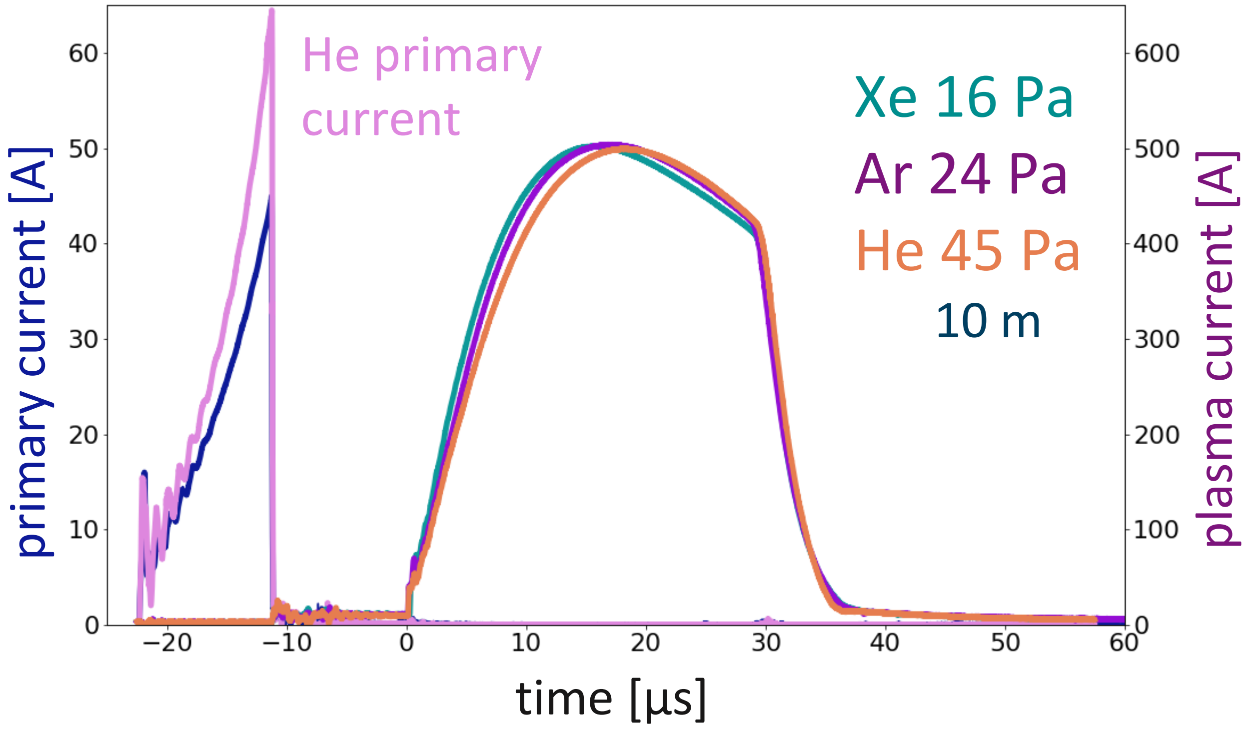


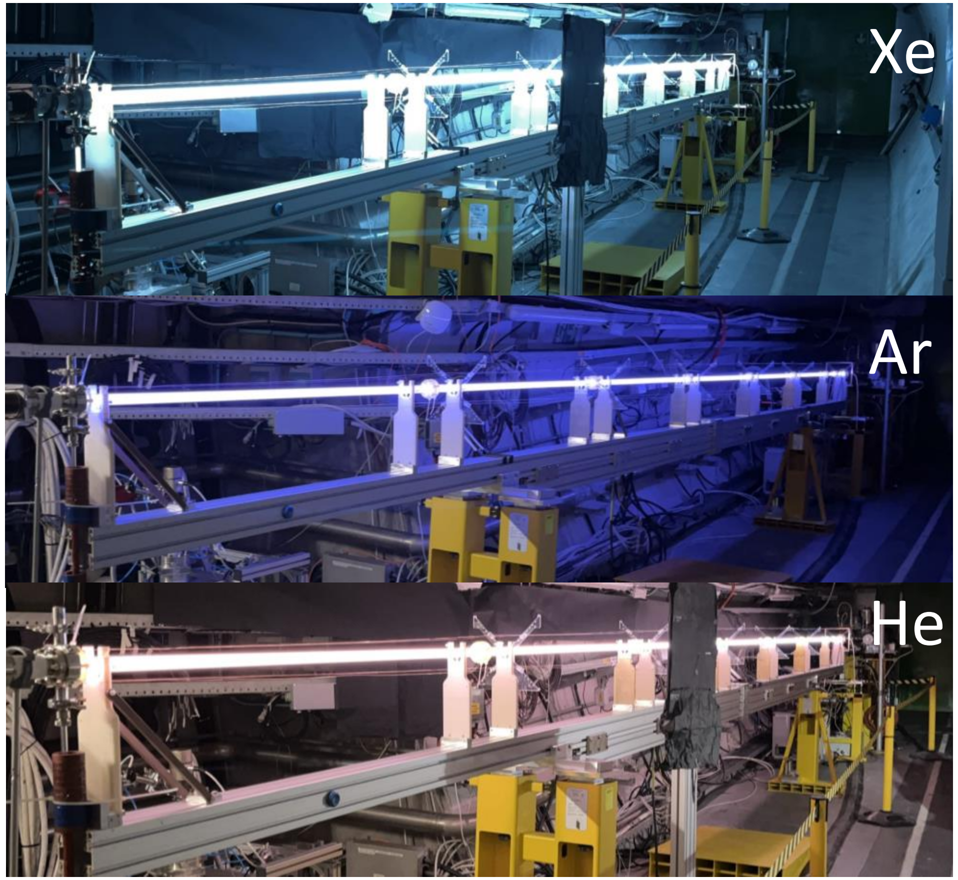
Ignition + heater



May 2023 proton run

Operation range – Gases



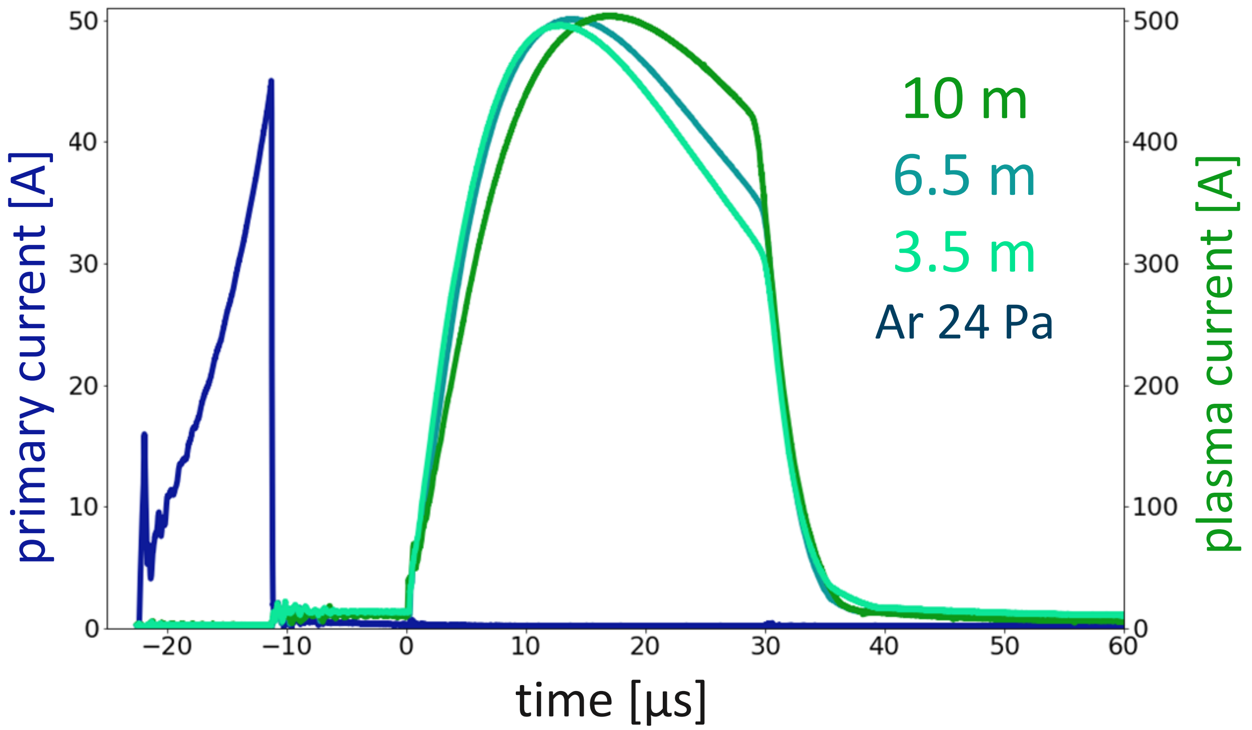


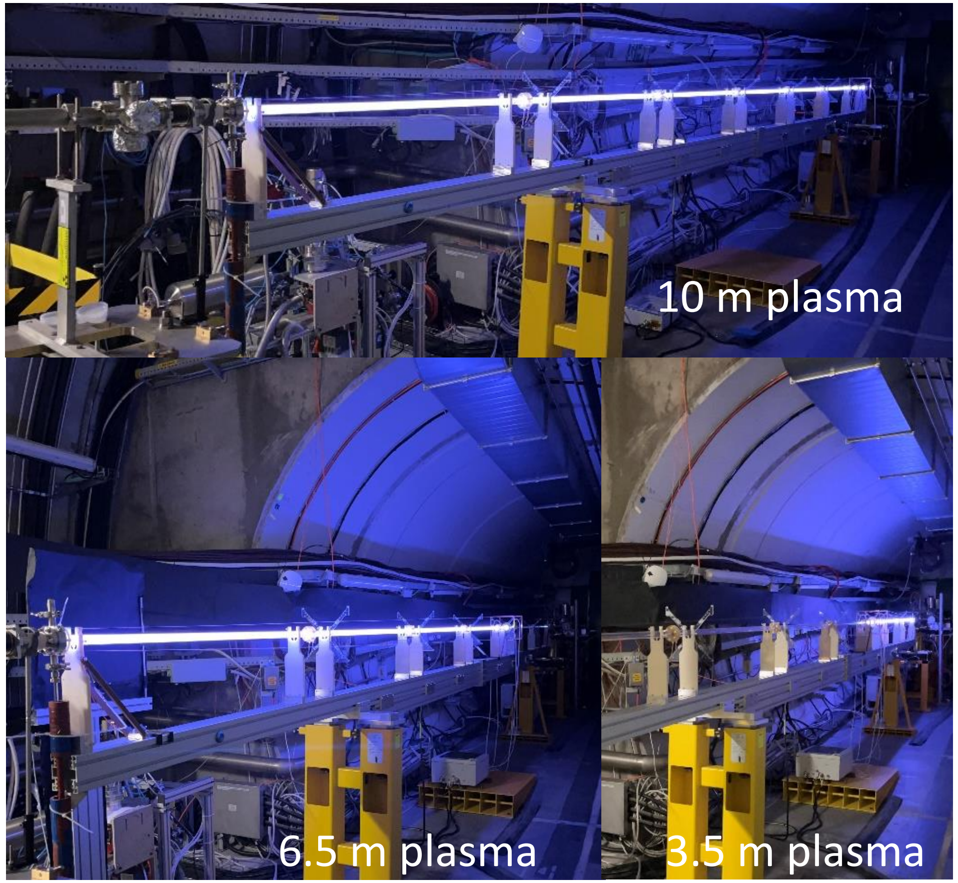
The pulse generators reach the target currents in all three gases

Gas affects mostly the ignition voltage required, leading to a higher primary current for He

May 2023 proton run

Operation range – Length





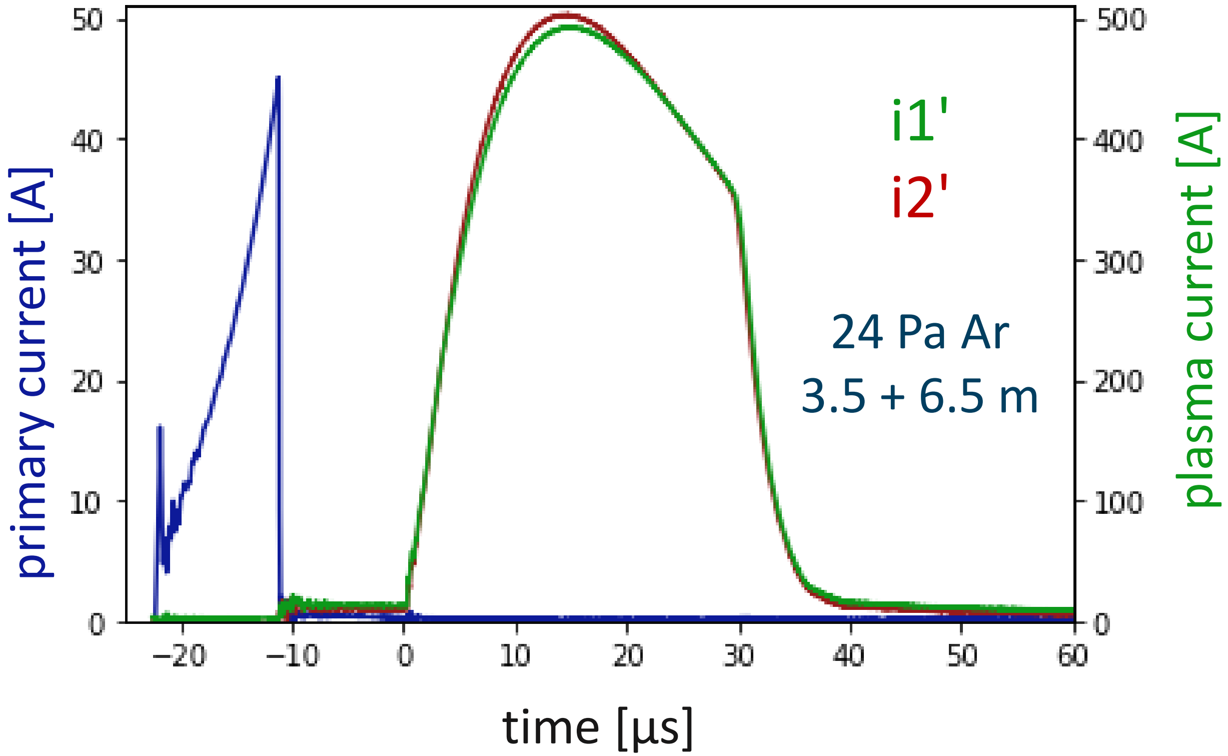
The pulse generators reach the target currents in all three gases and lengths

Gas affects mostly the ignition voltage required, leading to a higher primary current for He

Plasma length affects the load impedance, thus causing differences in the pulse shape

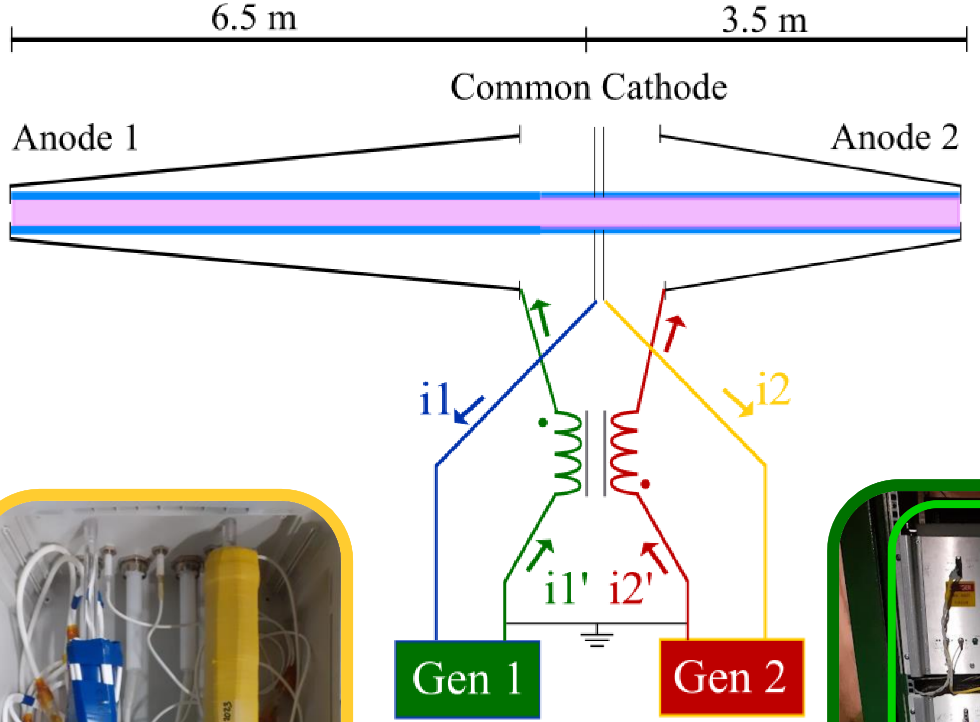
May 2023 proton run

Operation range – Double plasma



The double plasma current is equalized by a current balancing module: a high-current and small leakage inductance magnetic choke

The high-frequency impedance of each winding adjusts, forcing current symmetry between both plasmas



Tested in the AWAKE tunnel delivering symmetric currents, even with asymmetric plasma lengths