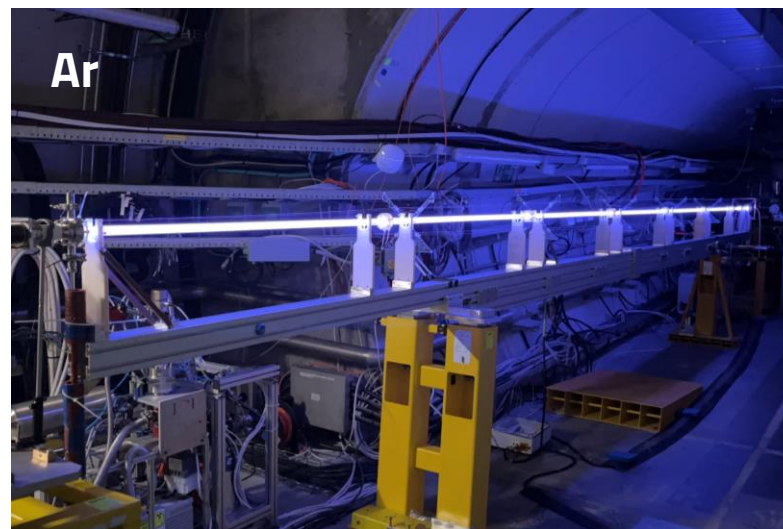
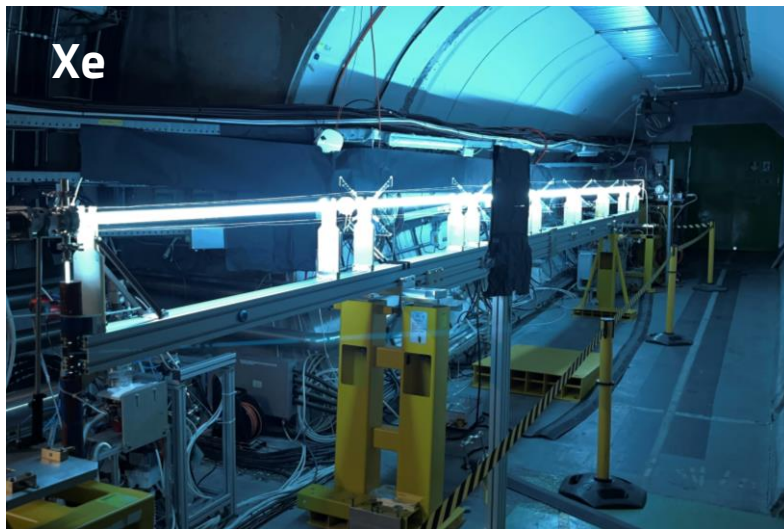


# Demonstration of proton bunch self-modulation in a discharge plasma source

Carolina Amoedo<sup>1</sup>,  
N. Lopes<sup>2</sup>, N. Torrado<sup>2</sup>, F. Silva<sup>3</sup>, P. Muggli<sup>4</sup>, L. Verra<sup>1\*</sup>, M. Turner<sup>1</sup>,  
G. Zevi Della Porta<sup>1,4</sup>, J. Puček<sup>1</sup>, M. Bergamaschi<sup>4</sup>, A. Clairembaud<sup>4</sup>, J. Mezger<sup>4</sup>, F. Pannell<sup>5</sup>,  
N. Van Gils<sup>6</sup>, E. Gschwendtner<sup>1</sup>, M. Taborelli<sup>1</sup>, A. Sublet<sup>1</sup> and the AWAKE Collaboration

AAC'24 Workshop  
22/07/2024



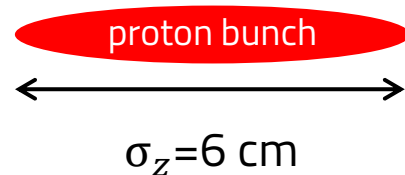
# **AWAKE** → Advanced Proton Driven Plasma **WAKE**field **E**xperiment

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 ( $\sim 1.2$  mm for  $n_e \sim 7 \times 10^{14} \text{ cm}^{-3}$ )



# AWAKE → Advanced Proton Driven Plasma WAKEfield Experiment

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

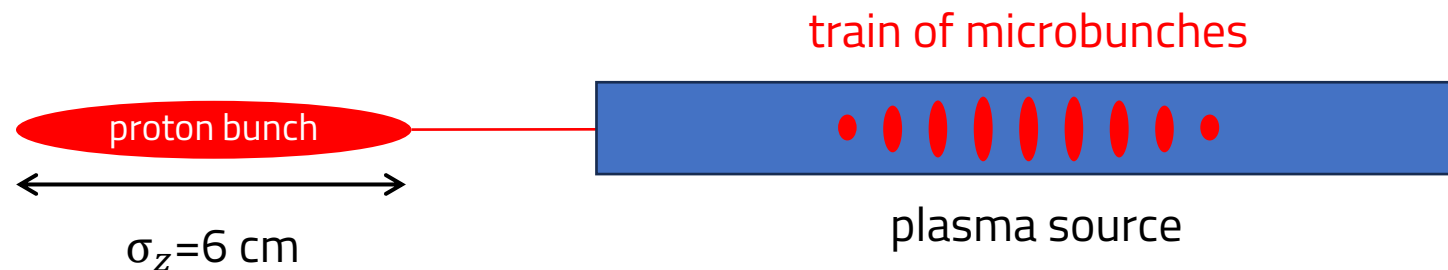
- ▶ CERN SPS proton bunch (400 GeV): **proton bunch length is ~6 cm**

**To effectively excite wakefields:**



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

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



# AWAKE → Advanced Proton Driven Plasma WAKEfield Experiment

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

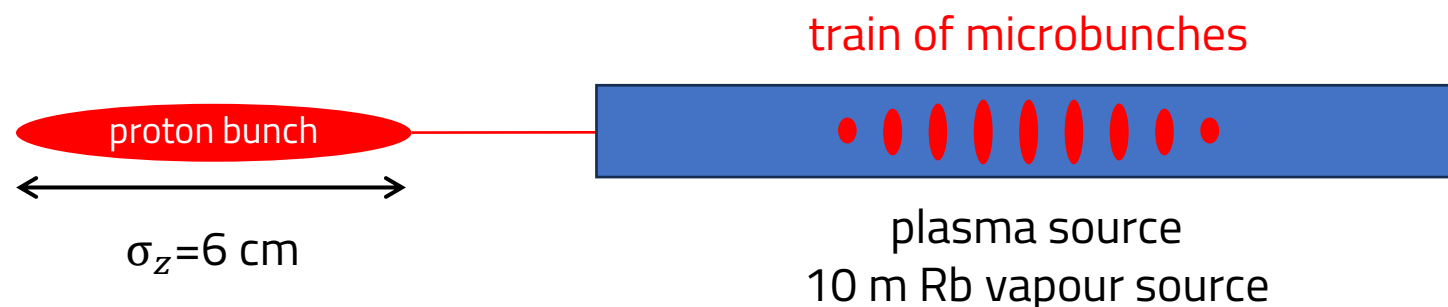
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To effectively excite wakefields:



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

Modulates the proton bunch into micro-bunches spaced  $\sim$  plasma wavelength

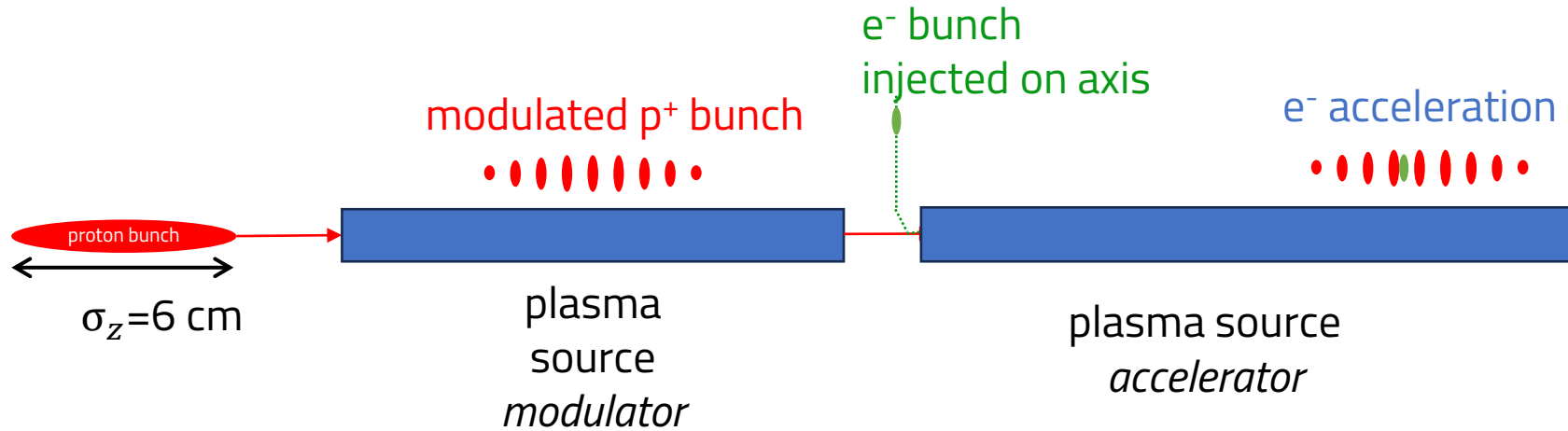


## Milestones achieved by AWAKE so far

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

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

# Next in AWAKE



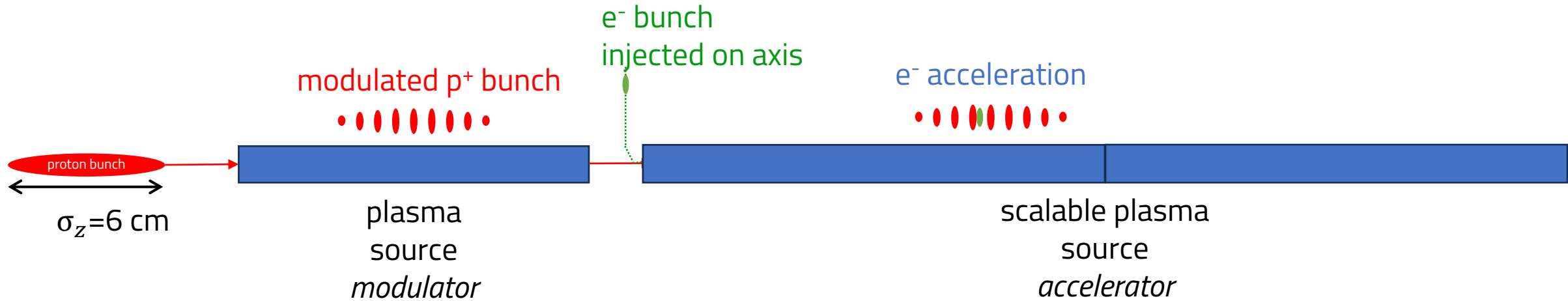
**Run 2c (2028)** ► two sources *modulator* + *accelerator* to allow external **e-bunch injection**<sup>[2]</sup>

## Requirements *accelerator* plasma source for AWAKE

- Density matching with modulator ( $1-10 \times 10^{14} \text{ cm}^{-3}$ )
- 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<sup>[2]</sup>

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



## R&D scalable plasma sources for AWAKE

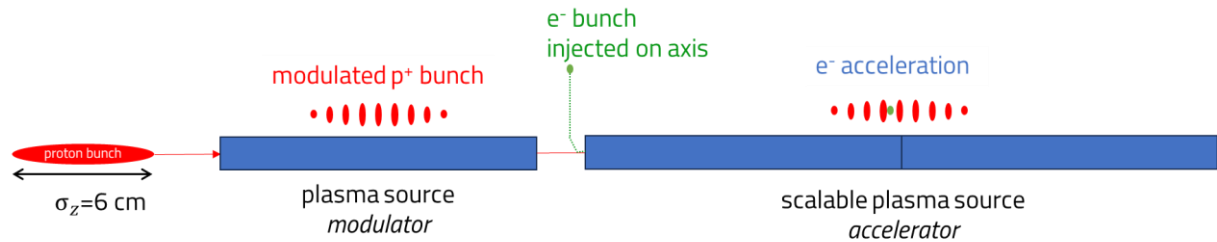
### Requirements scalable plasma source for AWAKE

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

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

# Next in AWAKE

## R&D scalable plasma source for AWAKE

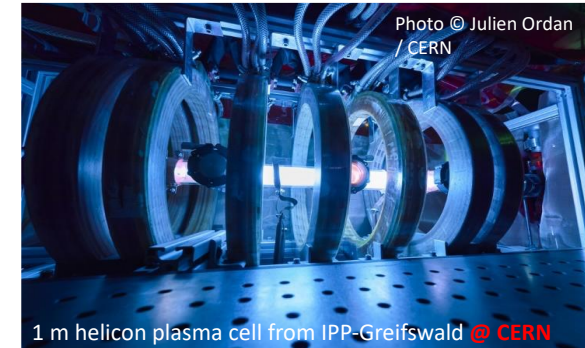


### Requirements scalable plasma source for AWAKE

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

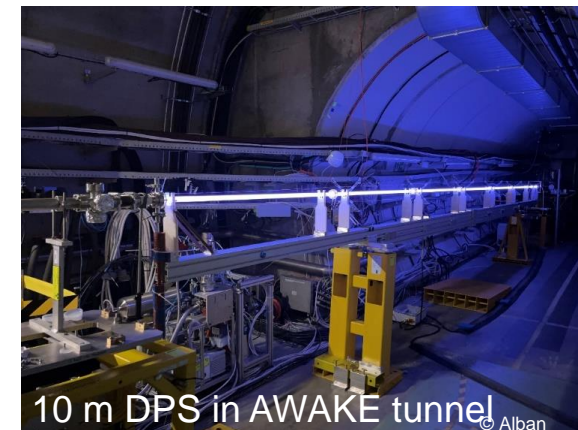
### Helicon Plasma Source (HPS)

→ RF wave heated plasma



### Discharge Plasma Source (DPS)

→ pulsed-DC discharge



Imperial College London



# Discharge plasma source (DPS)

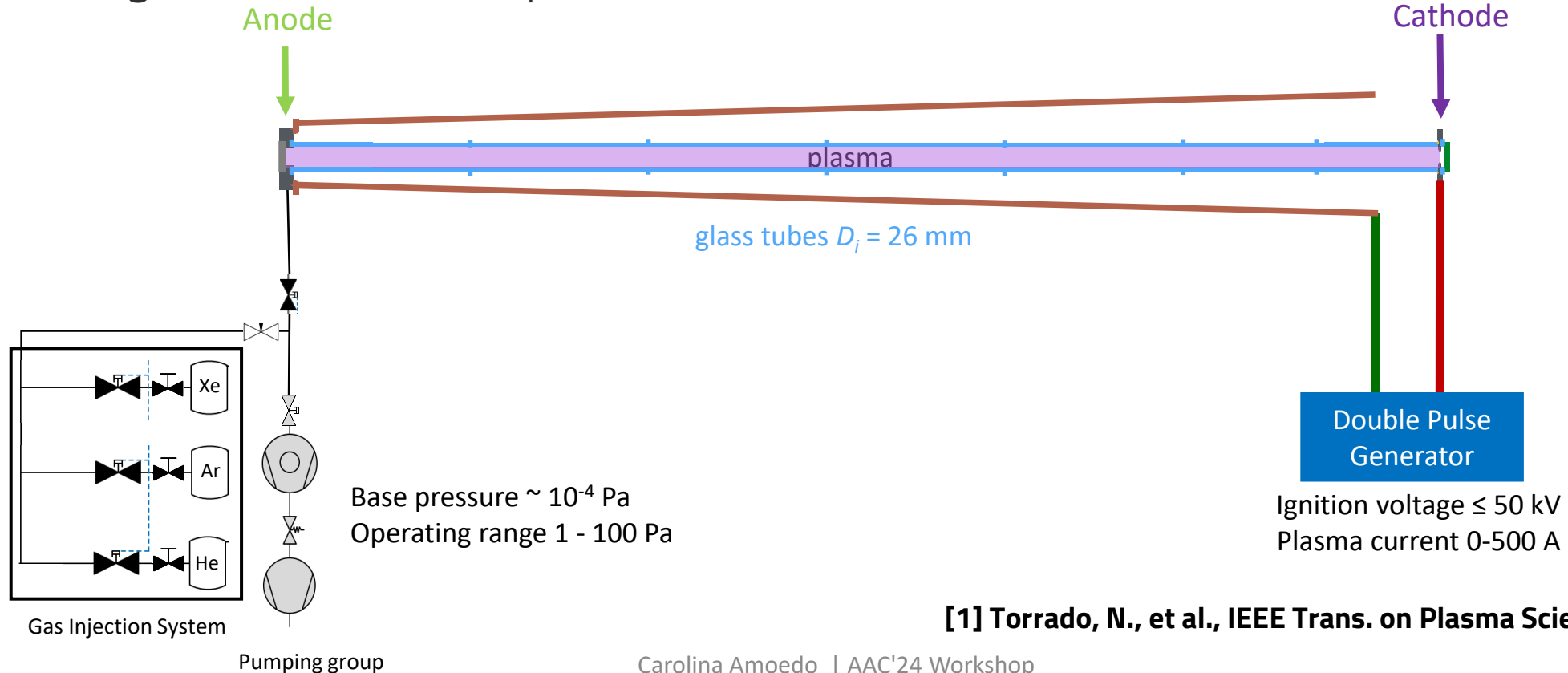
## ► Double-pulse arc pulsed discharge <sup>[1]</sup>

1) high voltage ignition → jitter < 20 ns in plasma ignition

2) 10 to 50 μs high current pulse → achieve plasma densities up to  $2 \times 10^{15} \text{ cm}^{-3}$

## ► 1 to 10 m long plasmas (so far)

## ► Different gases: He/Ar/Xe at low pressure (1-100 Pa)



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



# Discharge plasma source (DPS)

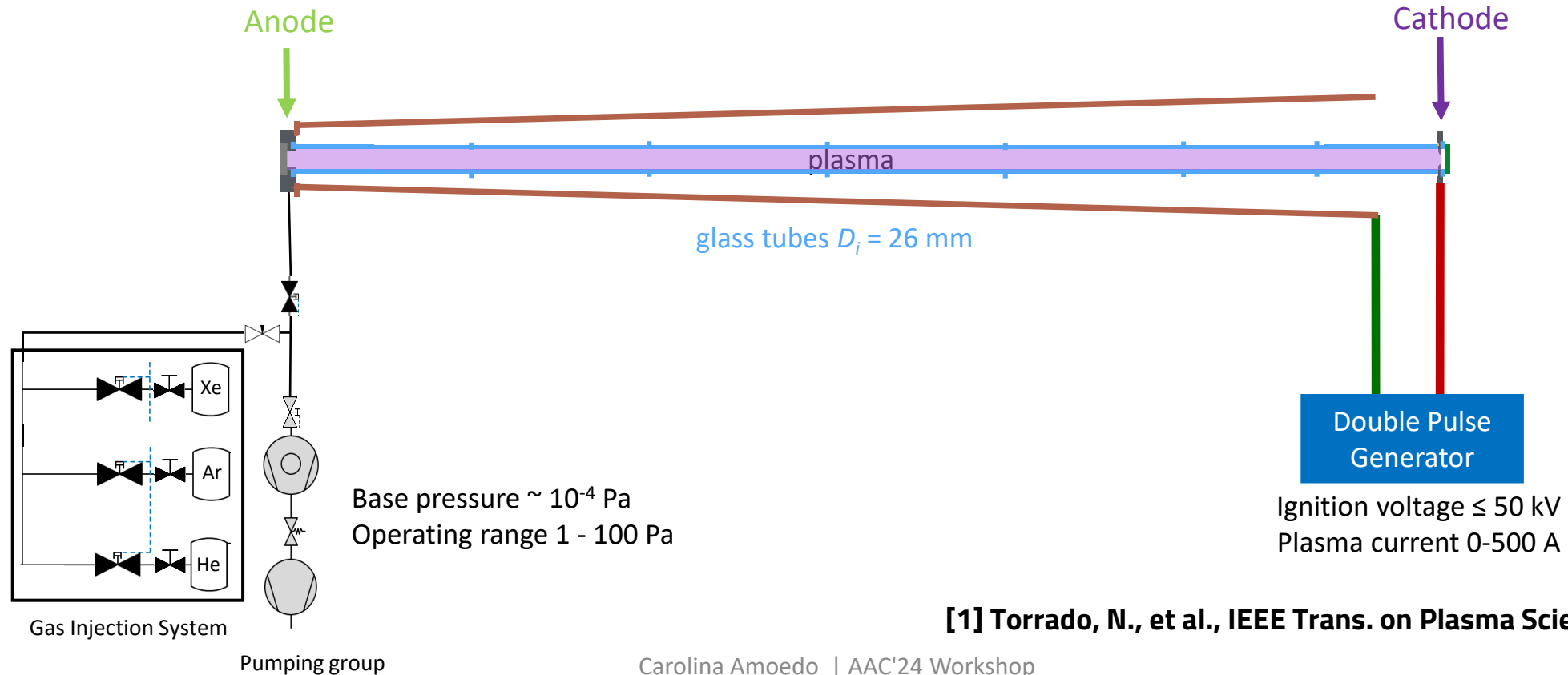
## ► Double-pulse arc pulsed discharge<sup>[1]</sup>

1) high voltage ignition → jitter < 20 ns in plasma ignition

2) 10 to 50 μs high current pulse → achieve plasma densities up to  $2 \times 10^{15} \text{ cm}^{-3}$

► **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)





Anode



10 m

Cathode



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

# Plasma density diagnostic

## Longitudinally integrated interferometry

### Parameters:

Gas: Ar

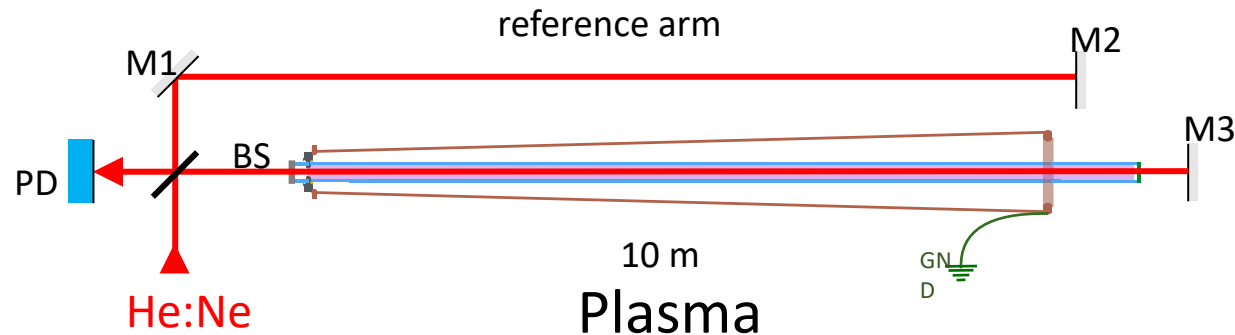
Pressure: 24 Pa

HV pulse: -17 kV

High current pulse: -6.32 kV,  
500 A

Pulse duration: 25  $\mu$ s

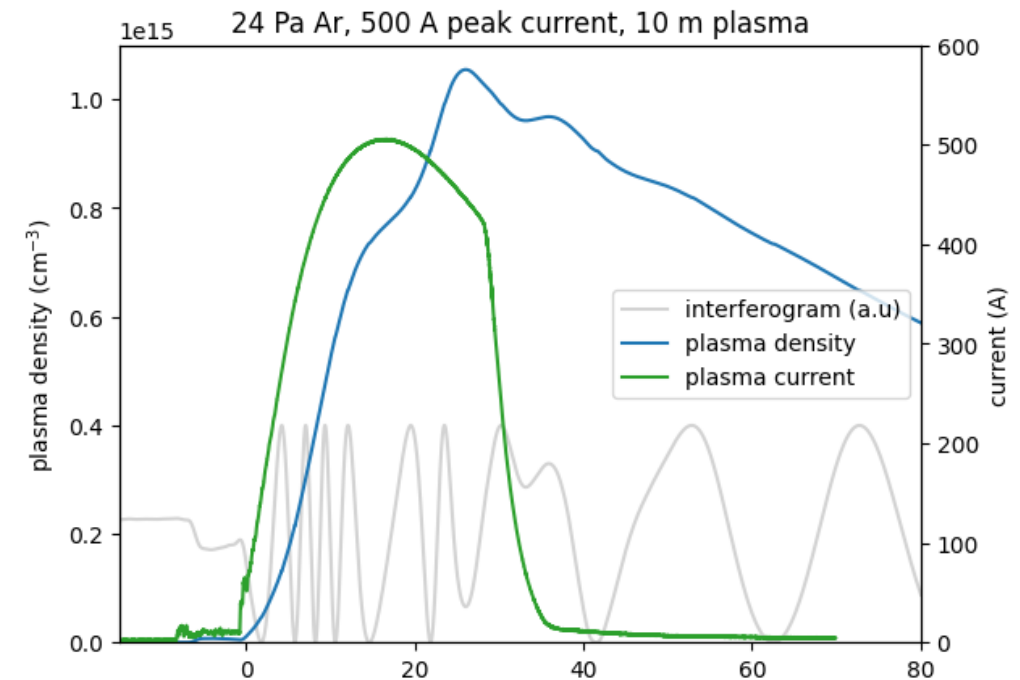
Plasma length: 10 m



- ▶ Michelson interferometer
- ▶ Measurement arm (plasma) adds a phase shift  $\phi_i$  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 ( $r_e = 2.82 \times 10^{-15} \text{ m}$ ),  $\lambda_i$  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

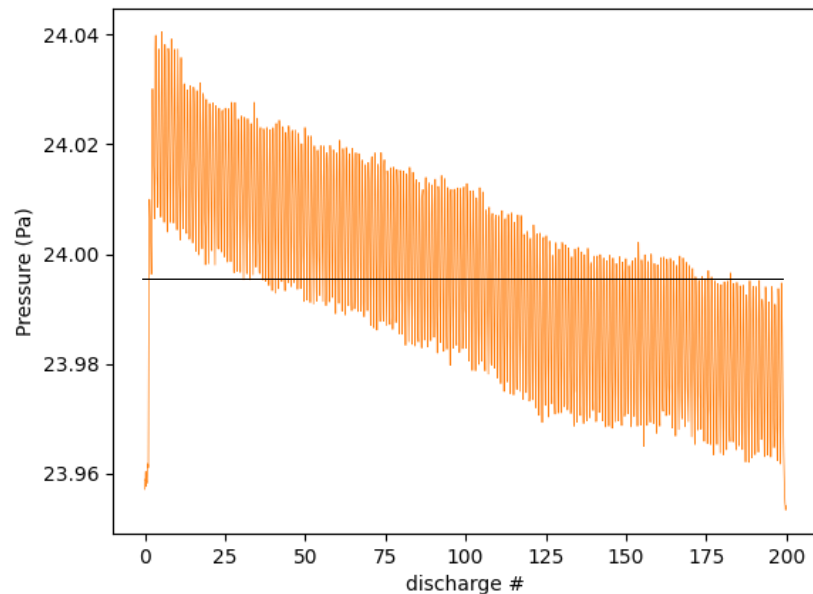
**High current pulse:** -6.32 kV, 500 A

**Pulse duration:** 25  $\mu$ s

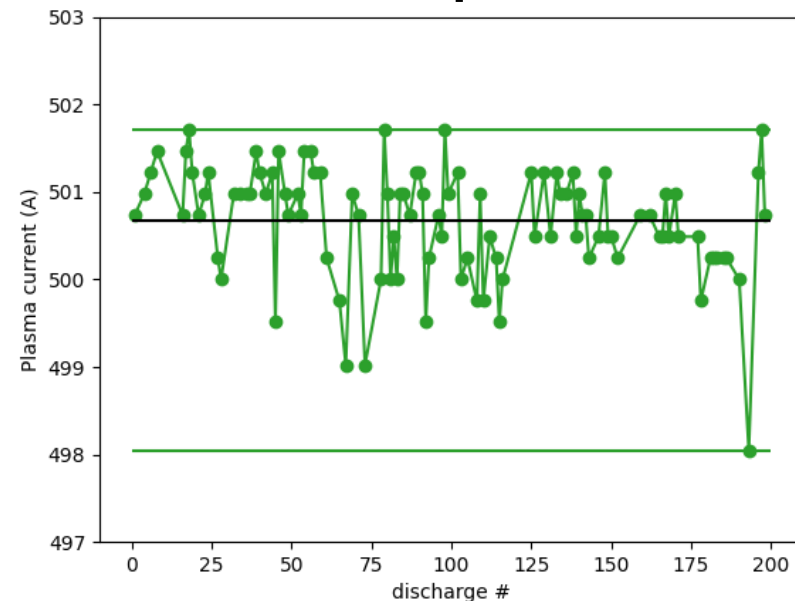
**Plasma length:** 10 m

► **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

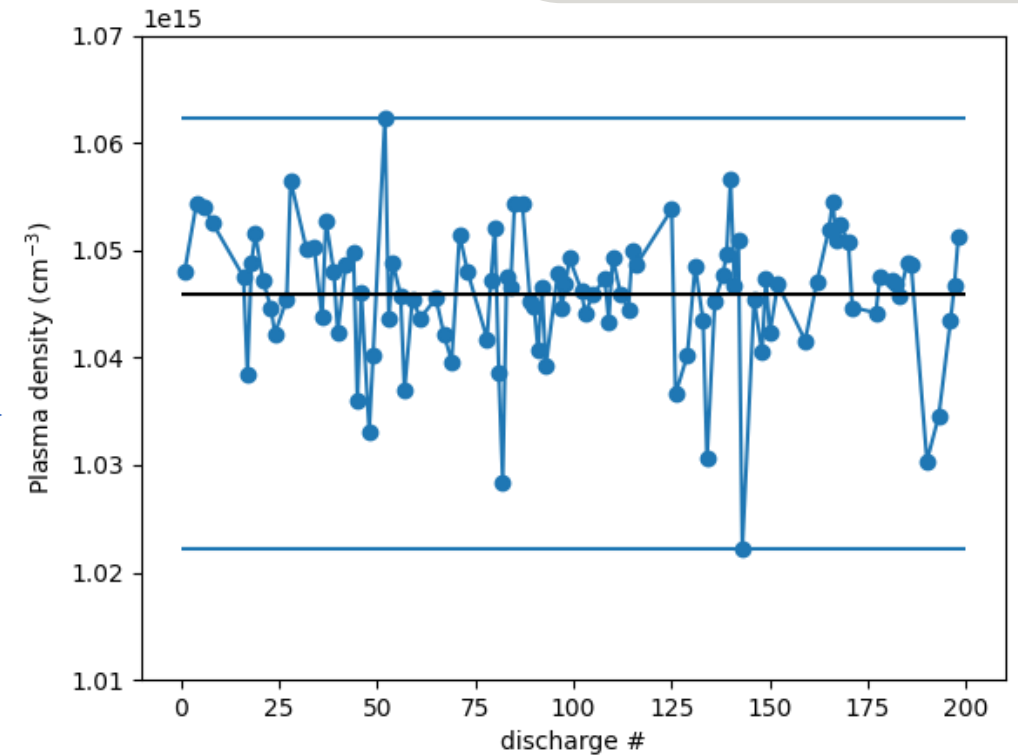
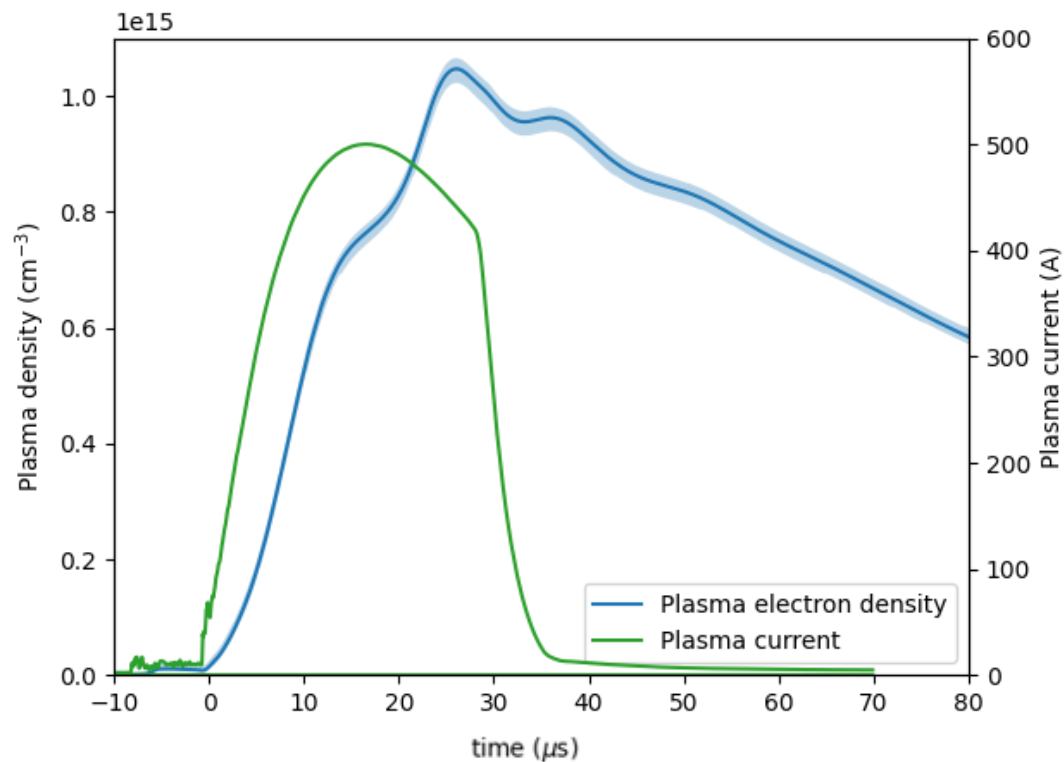
**Pressure:** 24 Pa

**HV pulse:** -17 kV

**High current pulse:** -6.32 kV, 500 A

**Pulse duration:** 25  $\mu\text{s}$

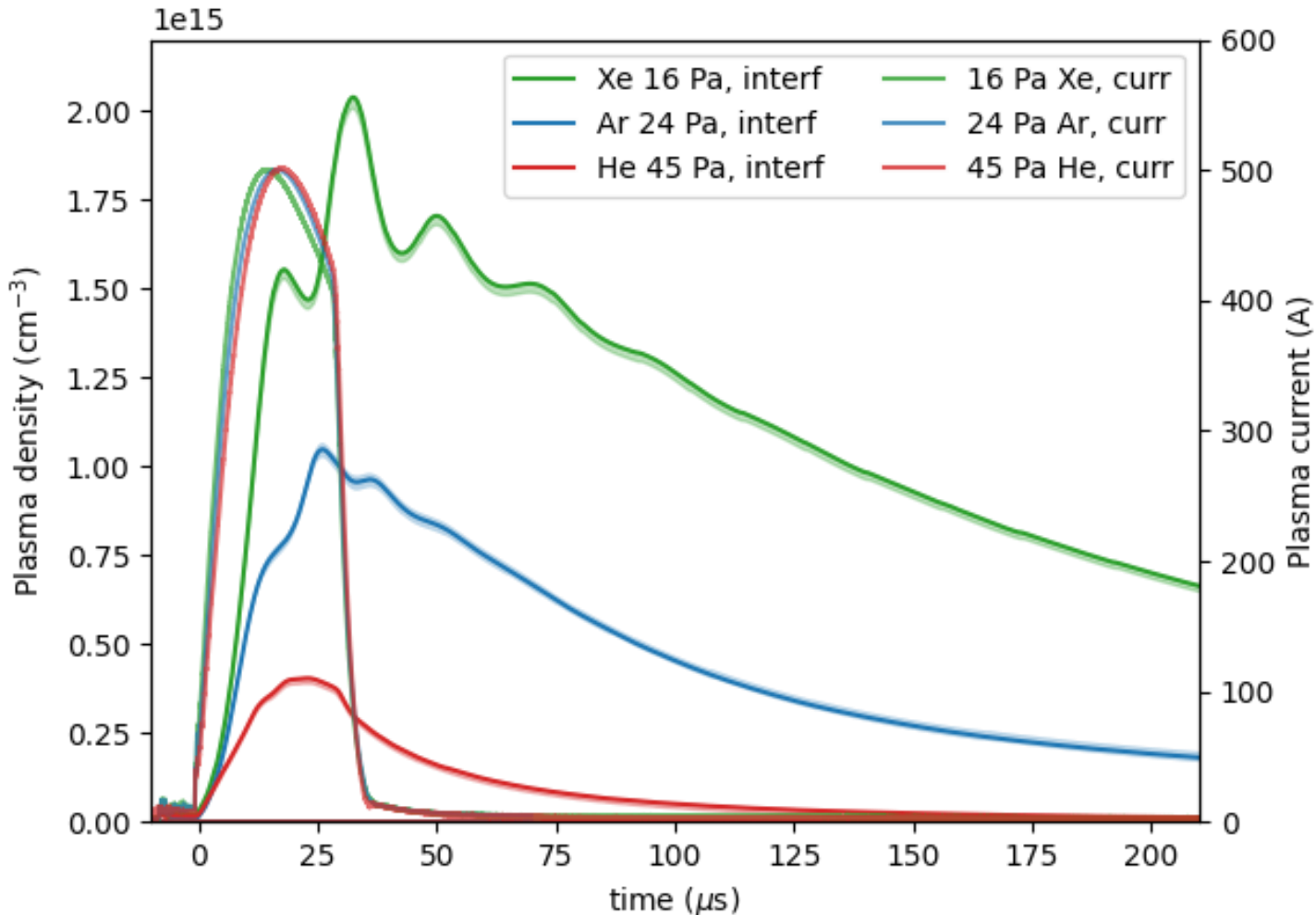
**Plasma length:** 10 m



► **<2% plasma peak density variability**

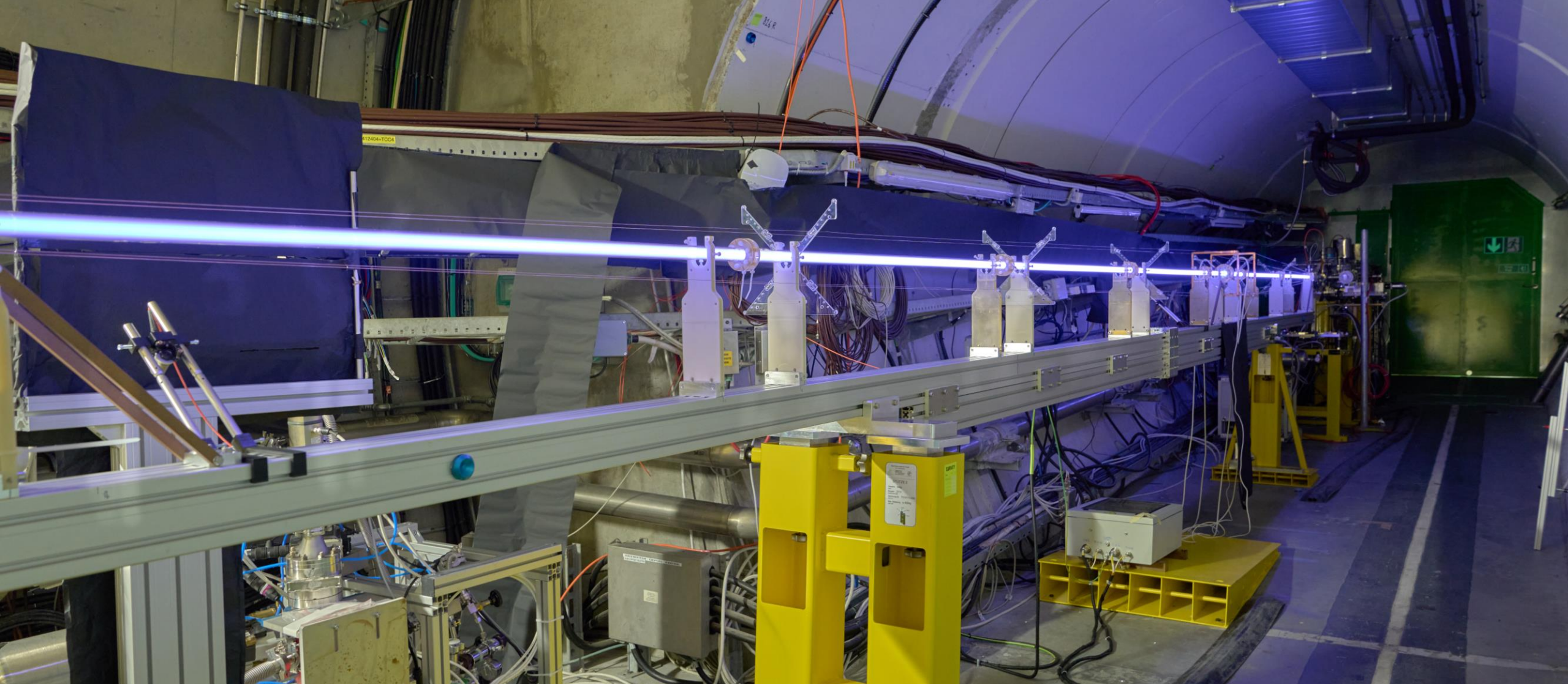


# DPS flexibility - 3 gases



► 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)





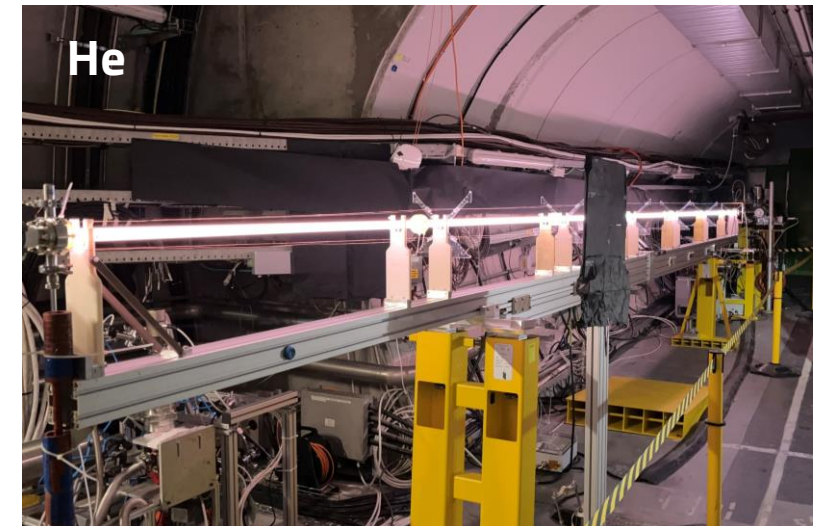
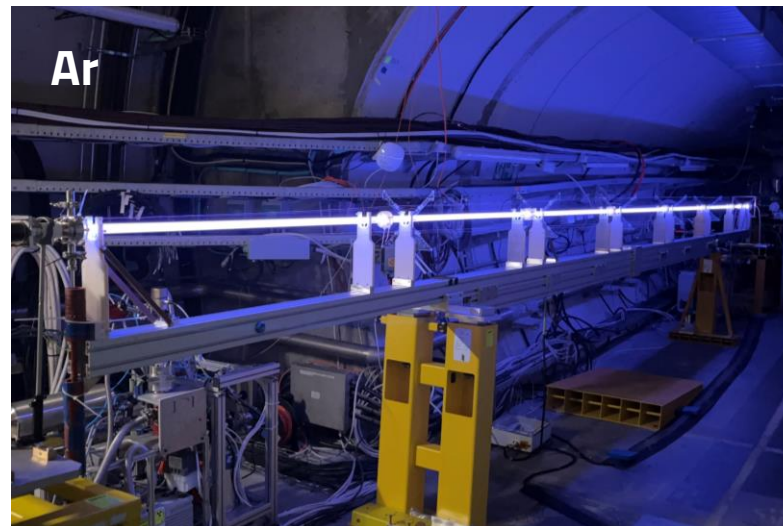
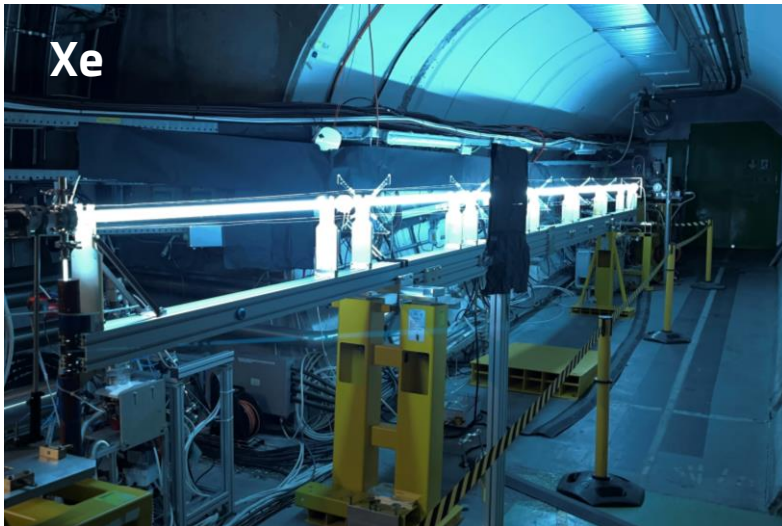
# 10 m DPS in AWAKE

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

1. demonstration of operation of DPS source in AWAKE



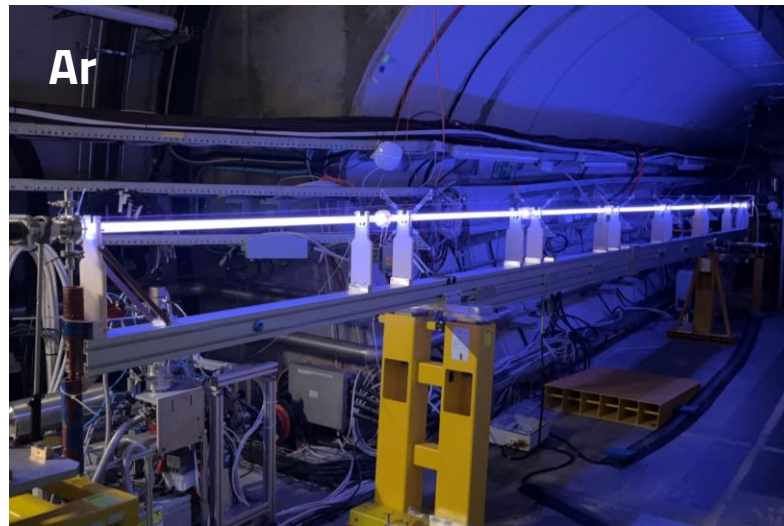
- Over 3 weeks of run with protons, very smooth operation of the DPS
- ~ 22000 discharges produced, with current pulse ~ 20 ns maximum jitter and current amplitude stability < 1%



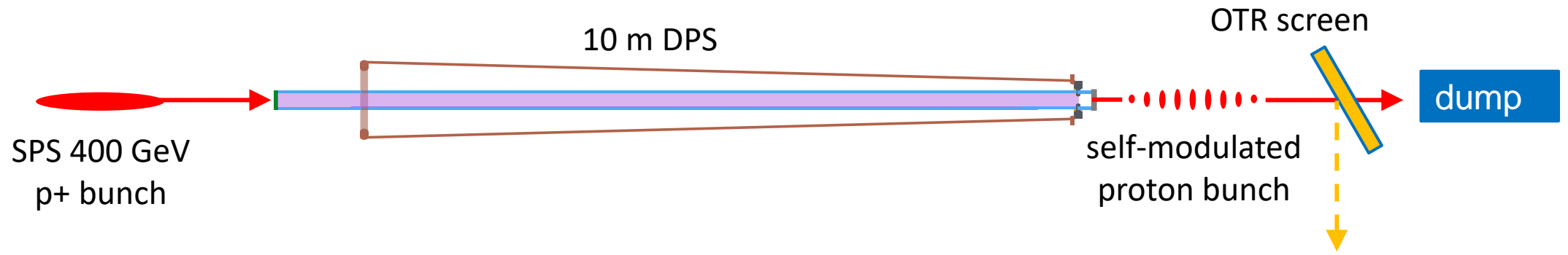
# 10 m DPS in AWAKE

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

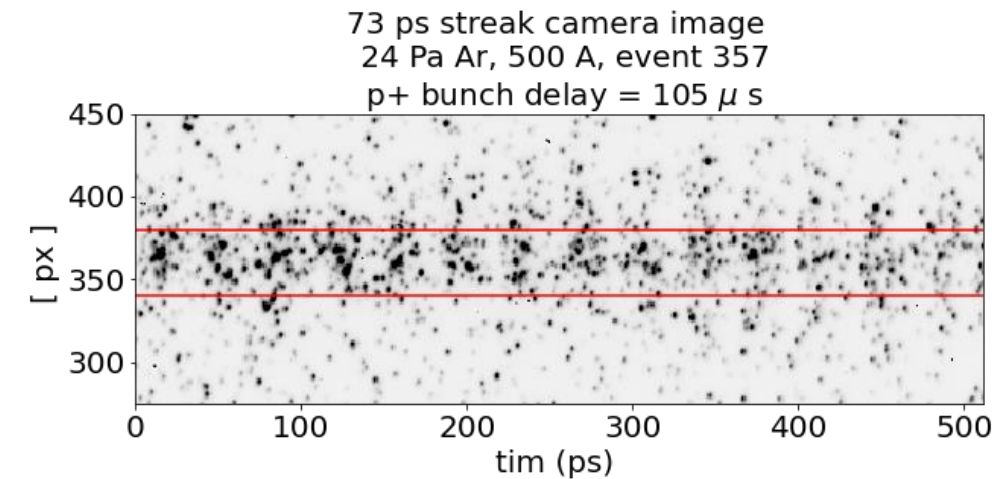
1. demonstration of operation of DPS source in AWAKE
2. **Self Modulation Instability (SMI) signature ?**
3. Study the effect of plasma density/length/gas on SMI



# 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

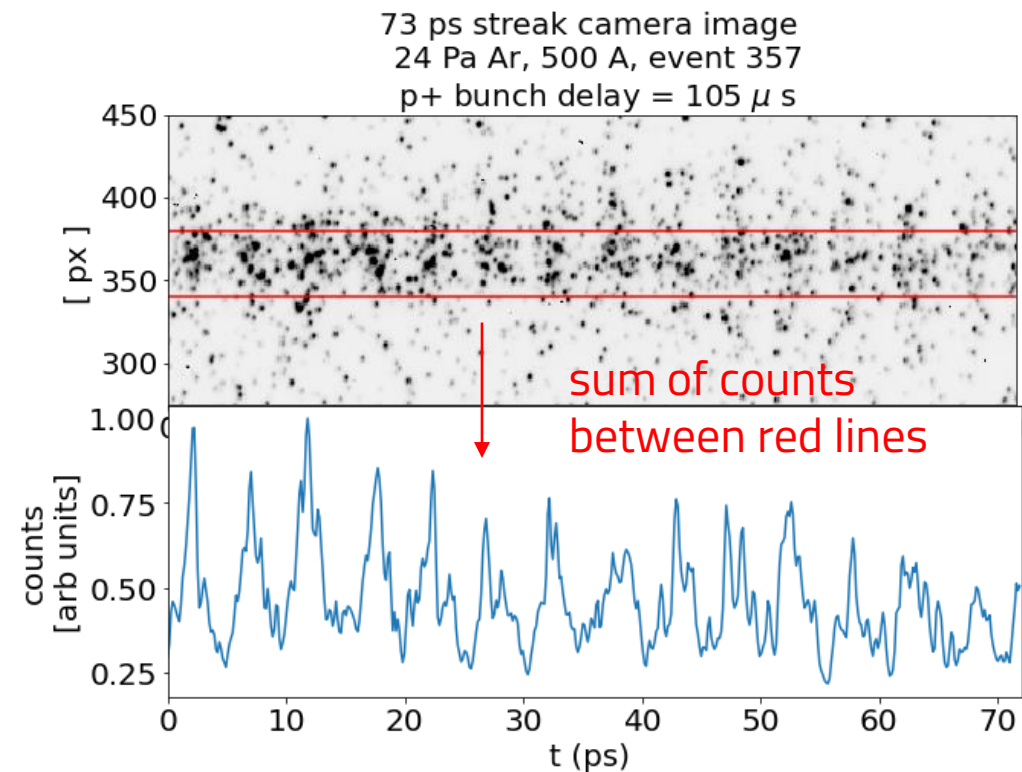


- Plasma density calculated from proton bunch self-modulation frequency

$$f_{mod} \sim f_p$$

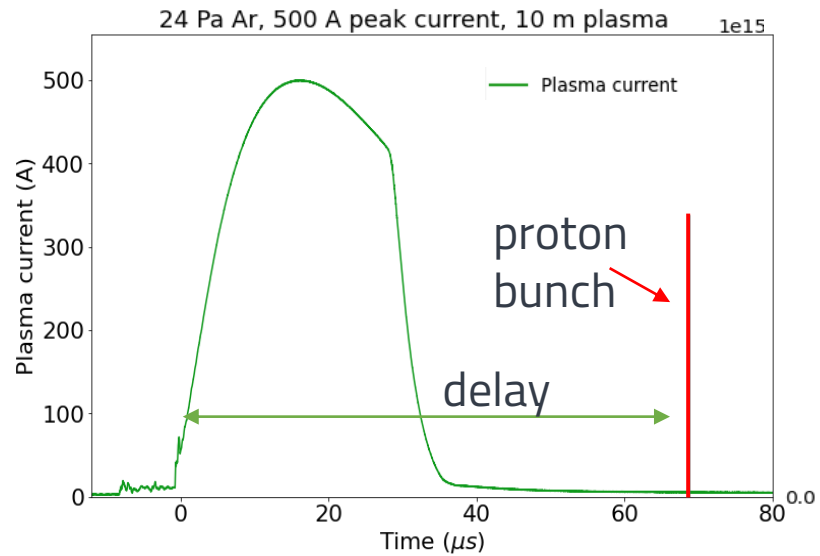
$$\omega_p = 2 \pi f_{mod}$$

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



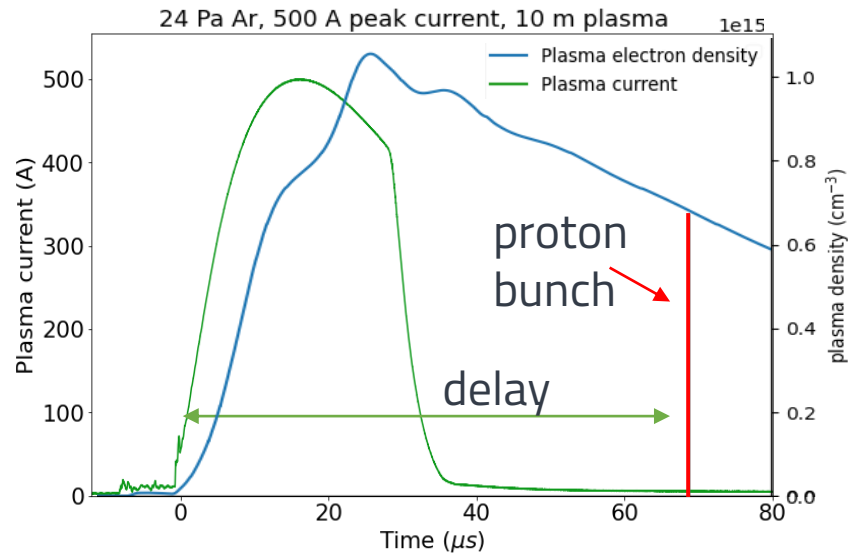
# DPS at AWAKE

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



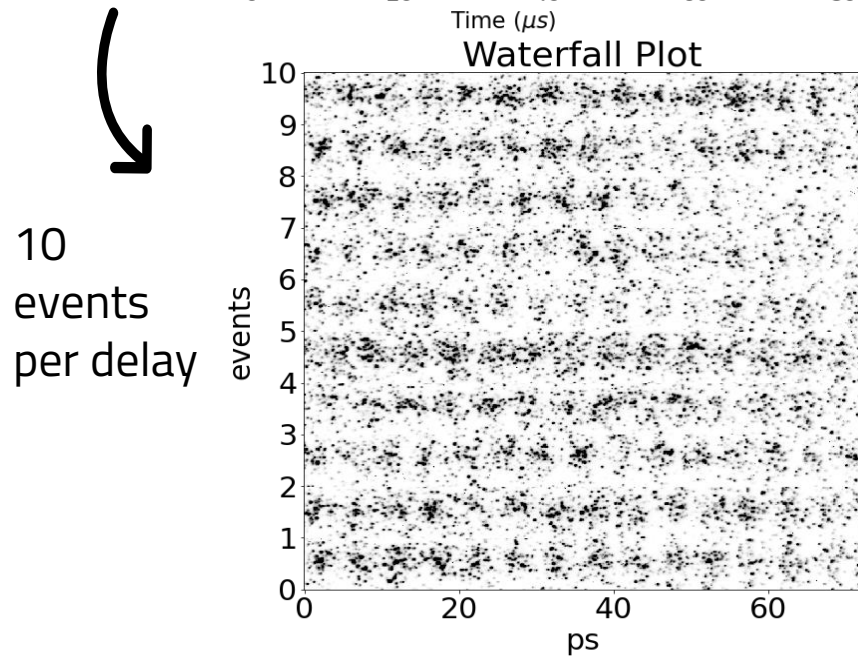
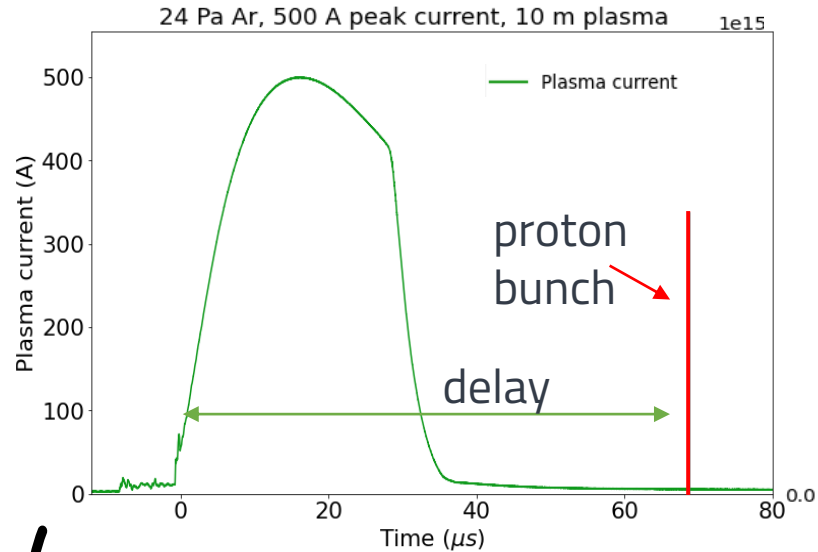
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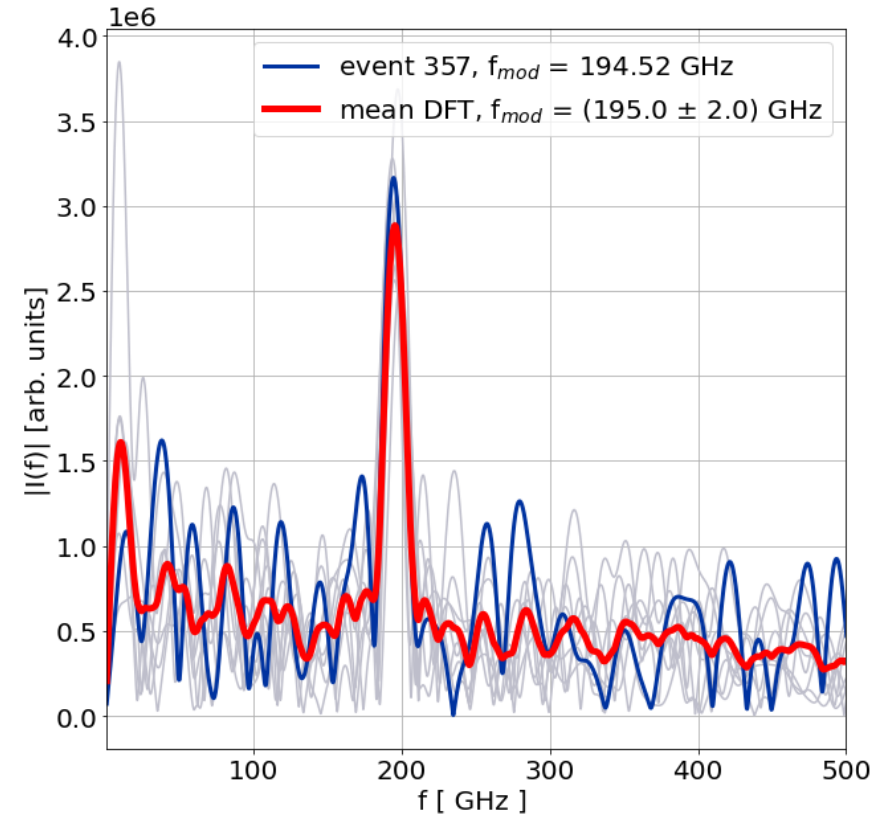


# DPS at AWAKE

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



$f_{mod}$



►  $n_e(t=70\mu\text{s}) = (4.73 \pm 0.09) \times 10^{14} \text{ cm}^{-3}$   
~ 4% spread in density

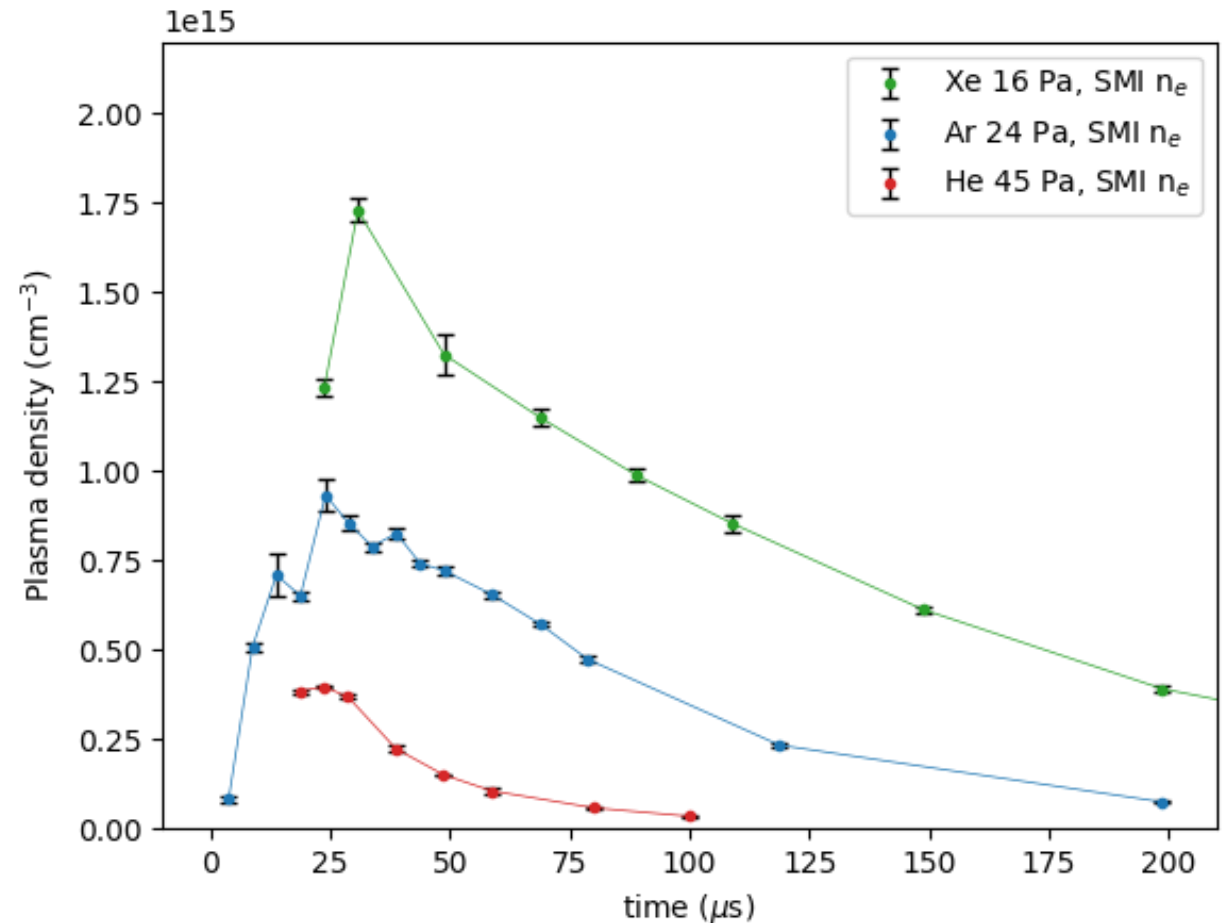


# Plasma electron density calculated from modulation frequency of p+ bunch

→ Time evolution of the DPS plasma density

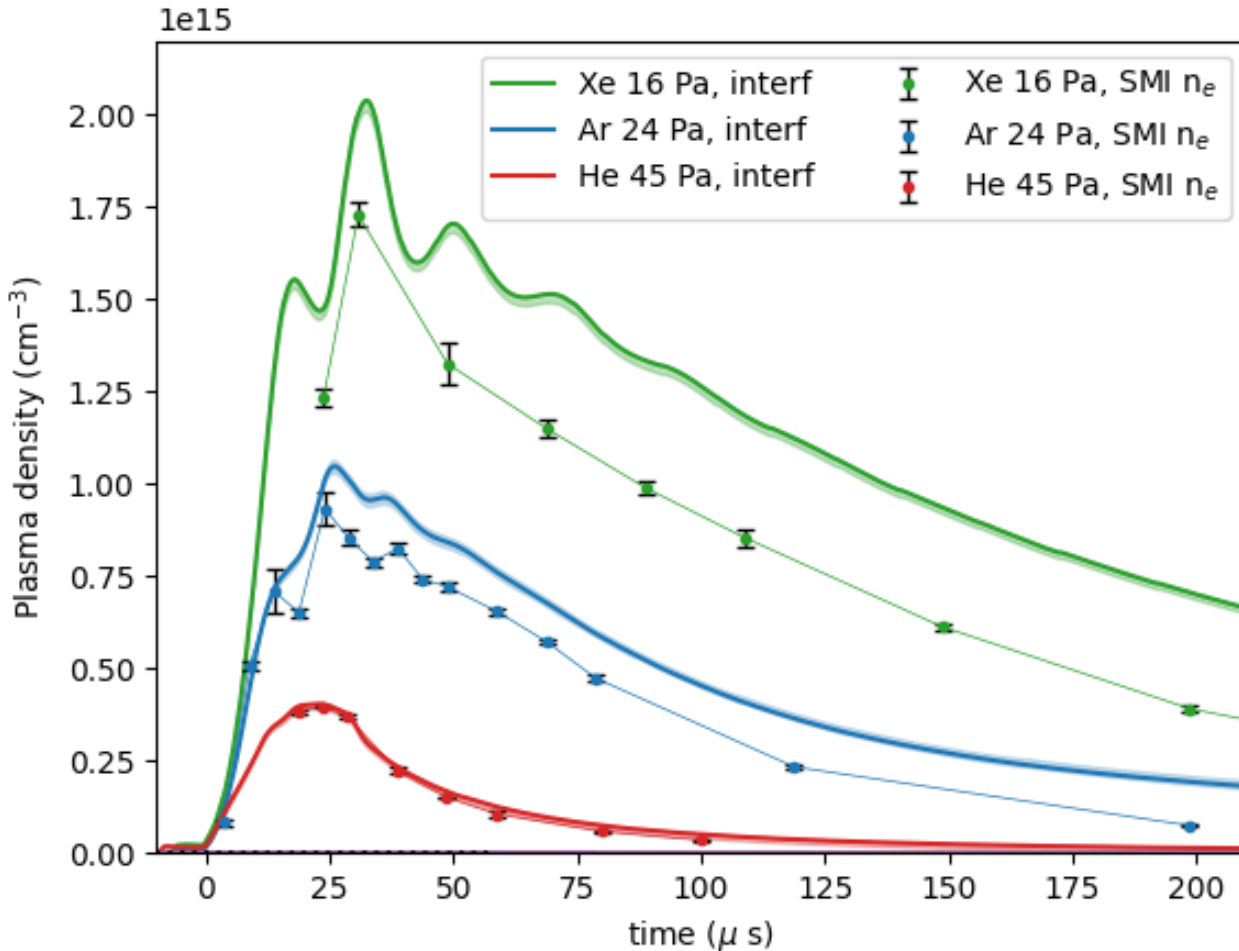
for 3 gases: He, Ar, Xe

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

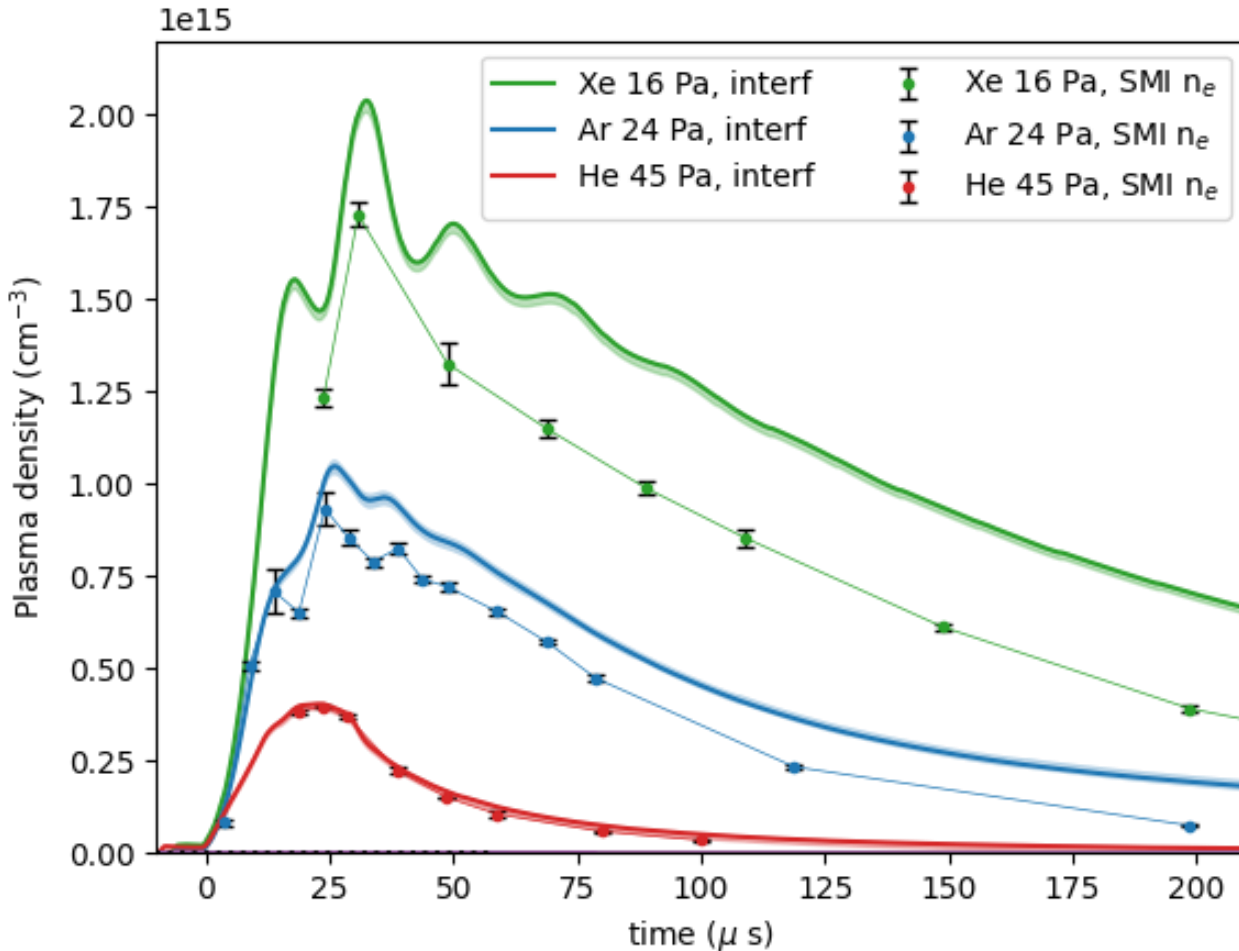


# Comparison $n_e$ from modulation frequency and lab interferometry

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



# 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<sup>[4]</sup>

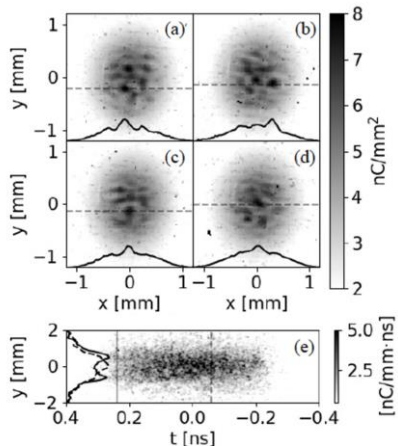
▶ **need of plasma uniformity measurement**

# 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

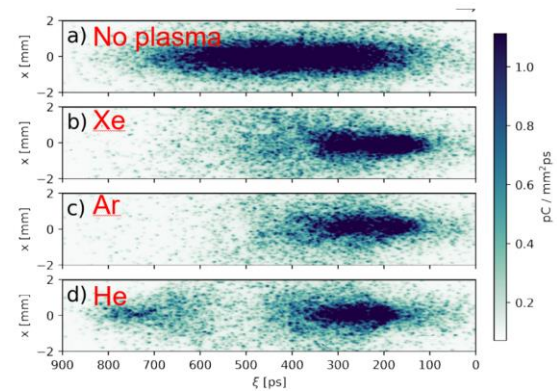


→ Wide plasma allowed to study the filamentation instability

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

→ Next talk by L.Verra

## Ion Motion

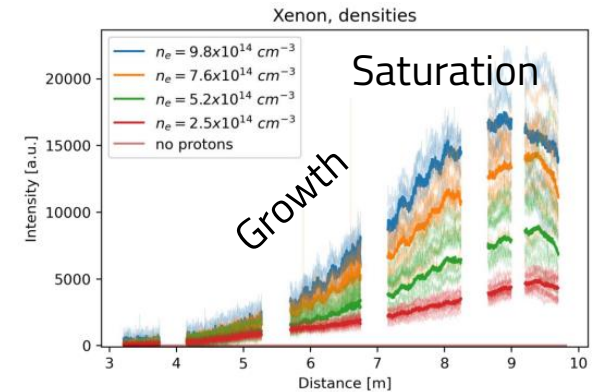


→ Flexibility in plasma ion species allowed to study the effect of ion motion on wakefields

M. Turner et al., submitted

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

## Plasma Light



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

→ 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 < 2% integrated peak density variability.
- ▶ Precision density measurements were performed using longitudinal integrated interferometry: **plasma electron densities ranging from 1- 20x10<sup>14</sup> cm<sup>-3</sup> .**
  - ▶ Next step: local plasma density measurement with Thomson scattering (this fall)
- ▶ **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<sup>14</sup> cm<sup>-3</sup> )
- ✓ 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

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

**Abstract**

A discharge plasma source (DPS) applicability and maturity were assessed in the AWAKE experiment by producing a low current bunch through the source and observing the development of the self-modulation instability (SMI). The dependence of the plasma density and shot-to-shot reproducibility of the source were presented. These results demonstrate the DPS potential for use in AWAKE and pave the way for future studies on softening the critical B20% longitudinal density uniformly needed for electron acceleration.

**Methods**

**DC Discharge plasma source**

- 10.7 m long and designed based on electrostatic shielding, total pressure 13 mbar (no other gases in the plasma), and B2 is 16 to 20 μm (high current pulse to source plasma operates up to 2000 A/cm<sup>2</sup>)

**Parameters**

- Operating gas: Ar, Xe
- Pressure: 13 mbar
- Current: 1000 A
- High current pulse: 10 to 20 μm
- Plasma length: 10 m
- Electron density: 10<sup>21</sup> cm<sup>-3</sup>
- Beam: 1000 pA

**Plasma density reproducibility**

Longitudinal self-modulation

**AWAKE future**

Run 2a (2023) → This source module is essential to allow external bunch injection

Run 2b (2023) → A suitable plasma source to ensure separation length

**600 kV DC discharge plasma source for AWAKE**

- Current: 1000 A
- Pressure: 13 mbar
- Electron density: 10<sup>21</sup> cm<sup>-3</sup>
- Beam length: 10 m

**DPS next step: local plasma density measurement using the plasma length with Protonium scattering**

**Test in AWAKE (May 2023)**

AWAKE - proton-driven relativistic accelerator

- in 2023, proton bunch from DPS propagates in plasma and **self-modulates** into a train of micro-bunches spaced by ~ 2.5 cm (one  $\lambda_{pe}$  for  $\gamma_p = 1.02017$ )

in the next experiments, drive resonances along the bunch and plasma, producing large amplitude wakefields

**AWAKE future**

Observation of Self-Modulation Instability (SMI) in a DPS

- For new experiments, AWAKE will use a **discharge plasma source**
- Self-modulation instability (SMI) will be observed
- Self-modulation instability (SMI) will be observed

**Results**

**DPS plasma reproducibility**

- Plasma density depends on the gas pressure and plasma current. In practice, current is fixed and pressure is varied.
- Discharge plasma density reproducibility was evaluated over 200 consecutive discharges with longitudinal reproducibility improvement.

**Parameters**

- Current: 1000 A
- Pressure: 13 mbar
- Electron density: 10<sup>21</sup> cm<sup>-3</sup>
- Beam length: 10 m

**25% variation gas pressure**

**25% spread peak plasma density**

**25% variation peak current**

**Reproducibility also studied for Xe (14 Pa) and Xe (16 Pa), 800 A peak current**

**Effect of having discharges at 3.3 pA (Xe, Ar, Xe)**

**Current of DPS does not depend on pressure (beam length) to avoid SMI and other vacuum instabilities**

**Proton bunch self-modulation**

- Self-modulation instability produces periodic measurement of density (Δ) along between proton bunch and plasma current pulse which is measure time evolution of plasma density
- $\Delta_{SMI}$  of approx 0.05 is observed over of beam 10 cm (proton bunch length) resulting in 0.25% spread in density
- Currents extracted by SMI are measured in the test with independent optical diagnostics, with a systematic difference of 13-17% for Ar and Xe
- Longitudinal reproducibility
- Self-modulation experimental separation
- Evolution of  $\Delta_{SMI}$  in DPS source quality
- The DPS offers the possibility to tune the density by adjusting the ratio between proton bunch and plasma current pulse

**Conclusion**

The DPS provides reproducible plasma density in different gases (Ar, Xe) system with ~ 25% pressure variability and ~ 25% current variability, providing ~ 25% reproducibility variability.

Proton density measurements were performed using longitudinal integrated interferometry, plasma current densities ranging from 1 to 2000 A/cm<sup>2</sup>.

Self-modulation of a 800 GeV proton bunch was observed in DPS experiments.

The DPS offers a large parameter flexibility (length, plasma density, gas), allowing studies on softening the critical B20% longitudinal density uniformly needed for electron acceleration.

**References**

- Torales, N., et al., IEEE Trans. on Plasma Science 2023, 51, 13.
- Compostelli, C., et al., AWAKE Collaboration, Summary 2022, 44, 1680.
- Spinks, S., et al., Journal of Plasma Physics 2022, 86.
- Morales-Guerra, M., et al., AWAKE Collaboration, PRAS, 2023.
- Torales, N., et al., AWAKE Collaboration, in review.
- Wang, L., et al., AWAKE Collaboration, Phys. Rev. Lett. 1999, 105, 2013.
- Wang, L., et al., AWAKE Collaboration, AWAKE 2023, 10.

# Sensitivity DPS to peak current

## Parameters:

Gas: Ar

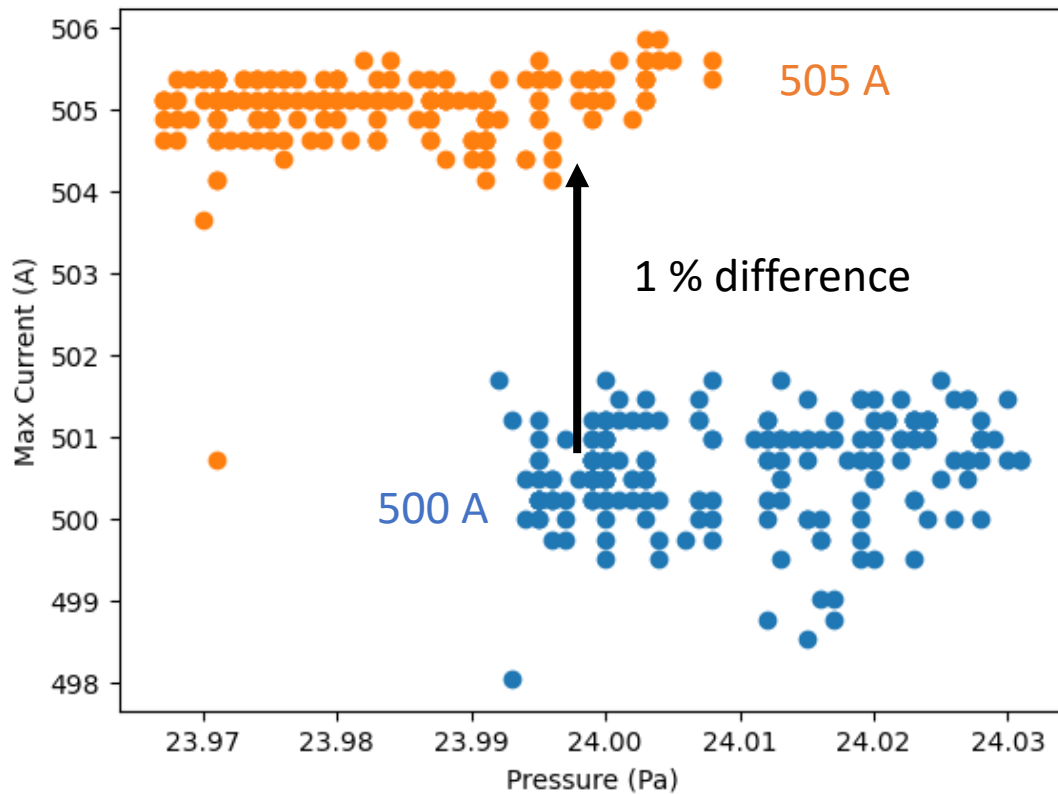
Pressure: 24 Pa

HV pulse: -17 kV

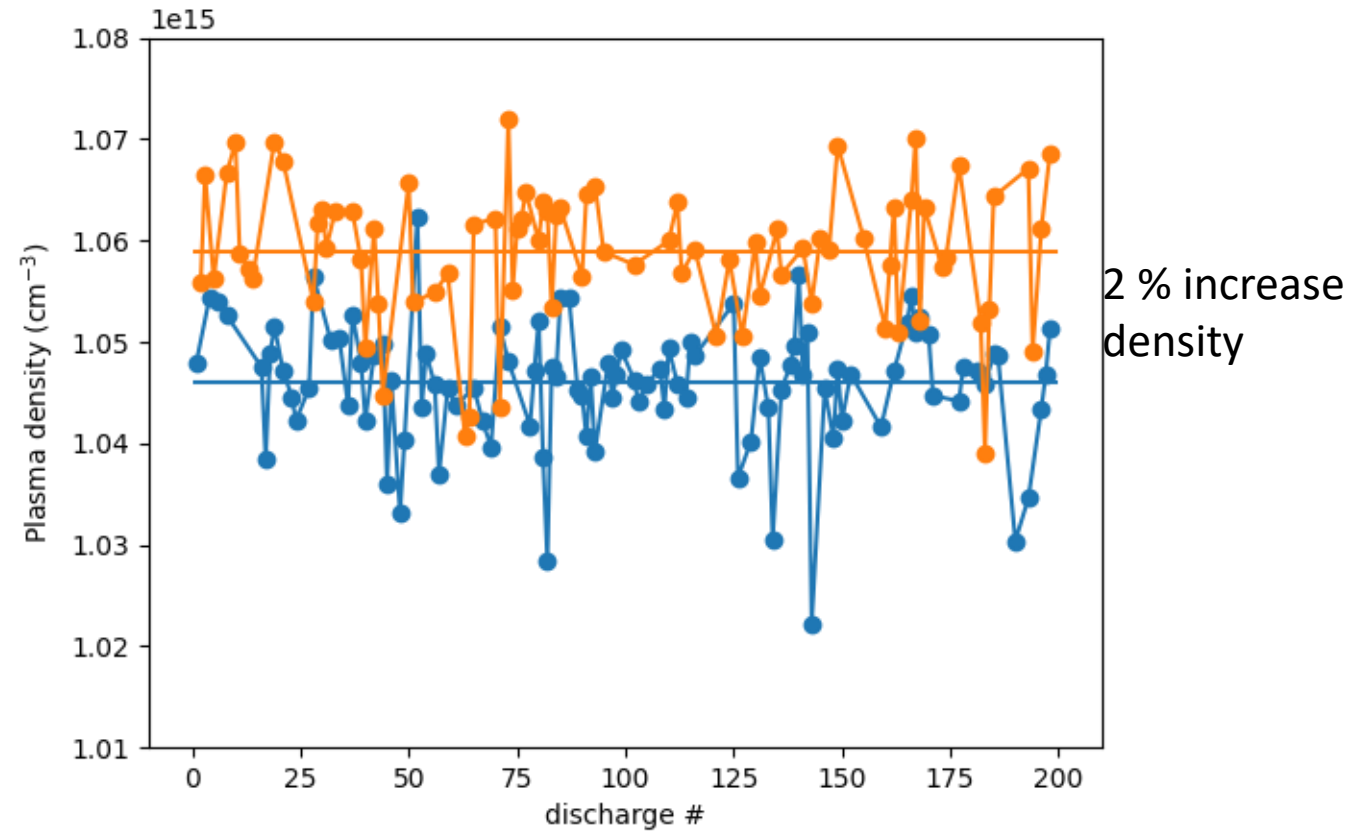
High current pulse: -6.32 kV, 500 A

Pulse duration: 25  $\mu$ s

Plasma length: 10 m



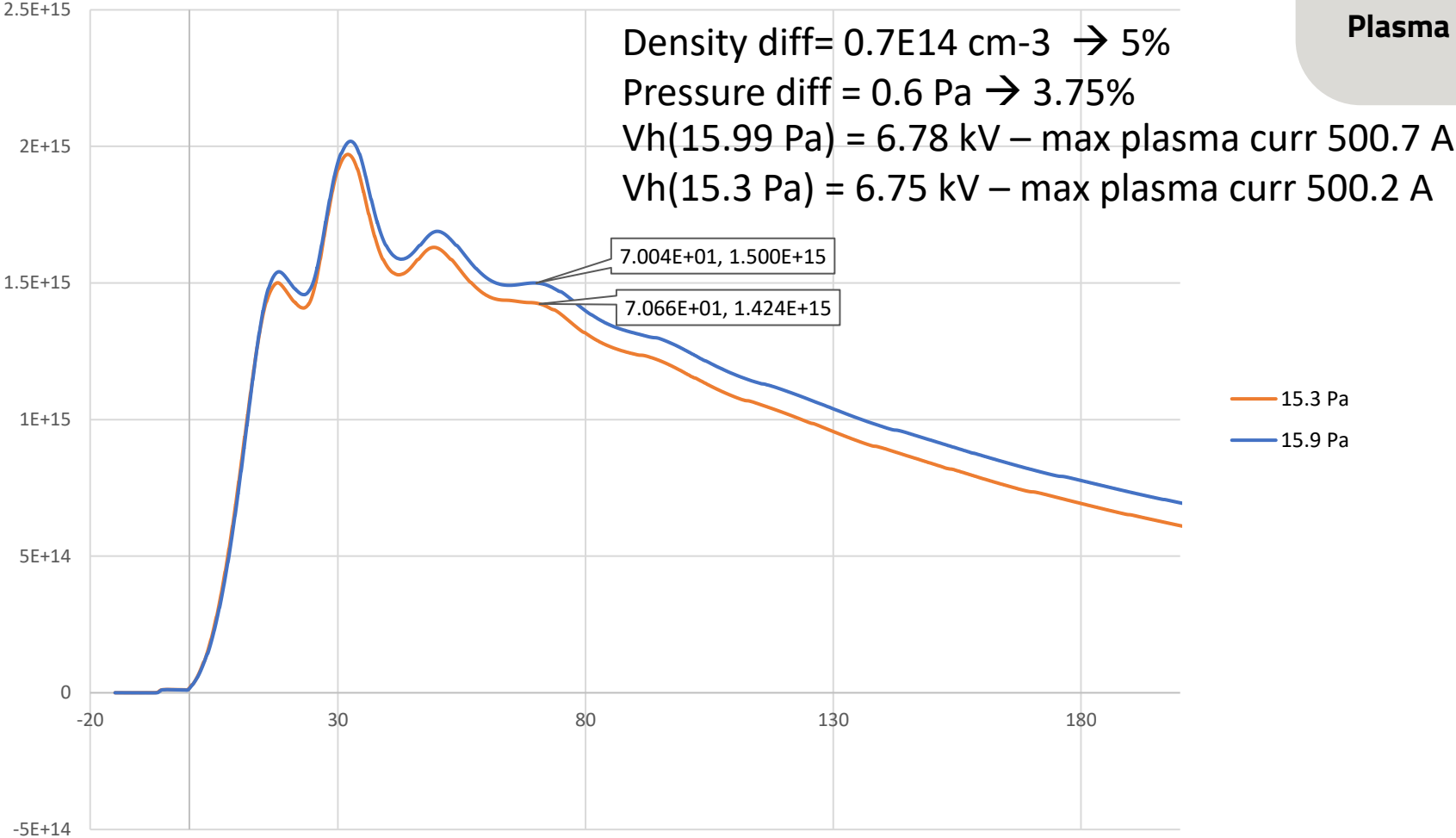
← spread pressure (0.2 %) →





# 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  $\mu$ s  
**Plasma length:** 10 m



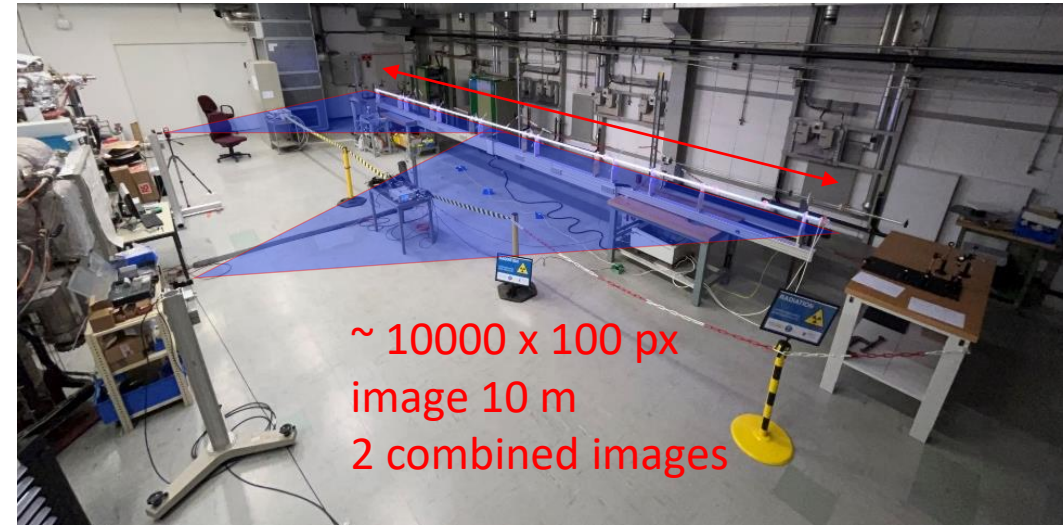
# Next steps

10 m prototype: plasma light imaging  $\rightarrow$   $\mu$ s time-scan discharge

(1  $\mu$ s exposure time)

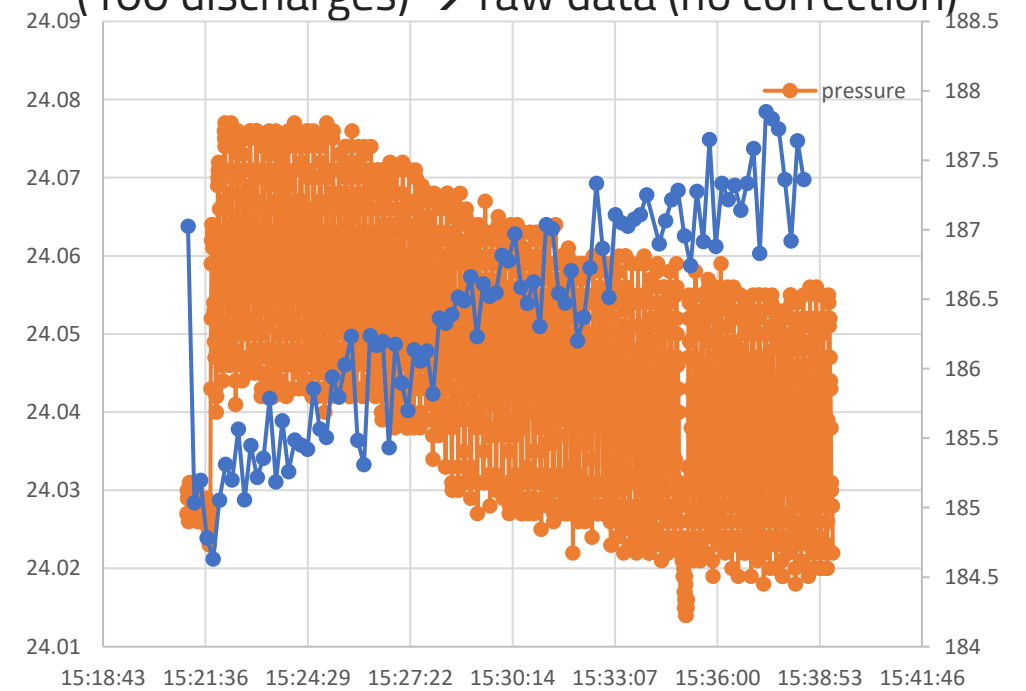
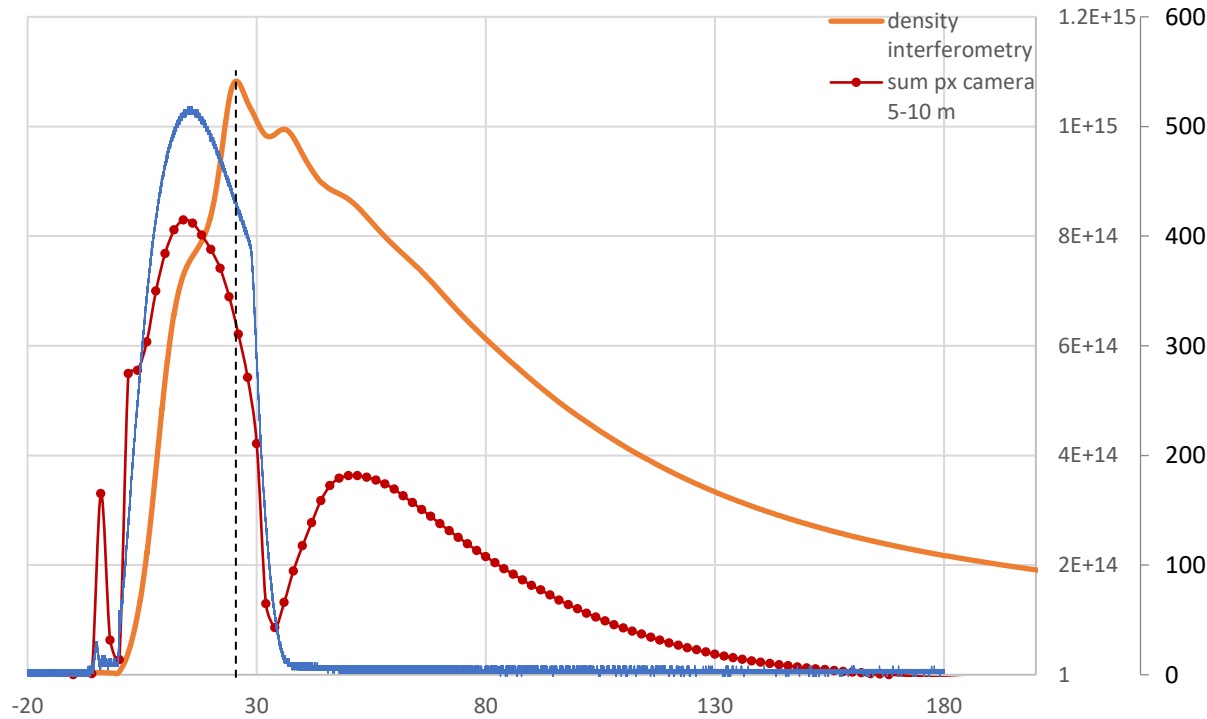


24 Pa 500 A



peak density: mean of all pixels of the image

(100 discharges)  $\rightarrow$  raw data (no correction)



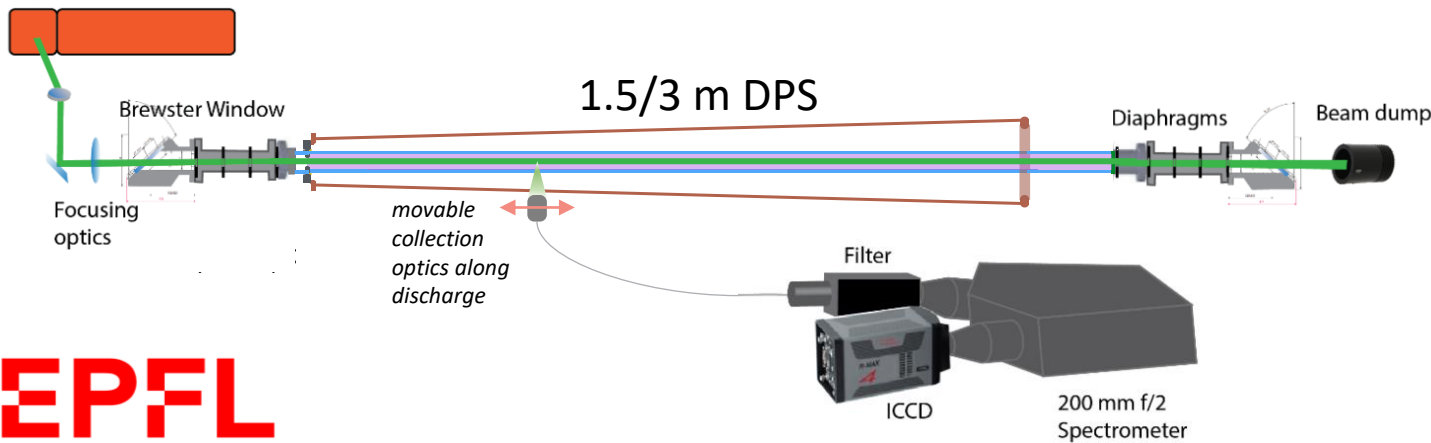
# Next steps

## 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

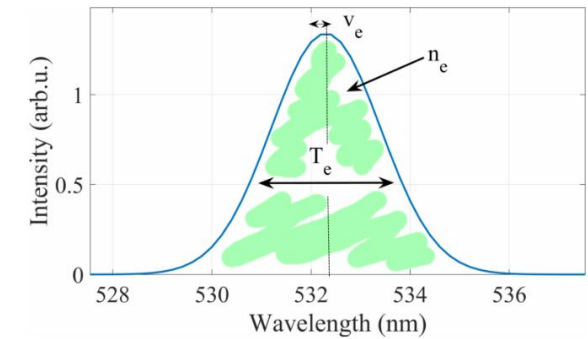
Nd:Yag Laser @ second harmonic  
(0.4 J/pulse, 7 ns, 10 Hz)



**EPFL**

Courtesy Christine Stollberg, EPFL-SPC

Thomson scattering spectrum

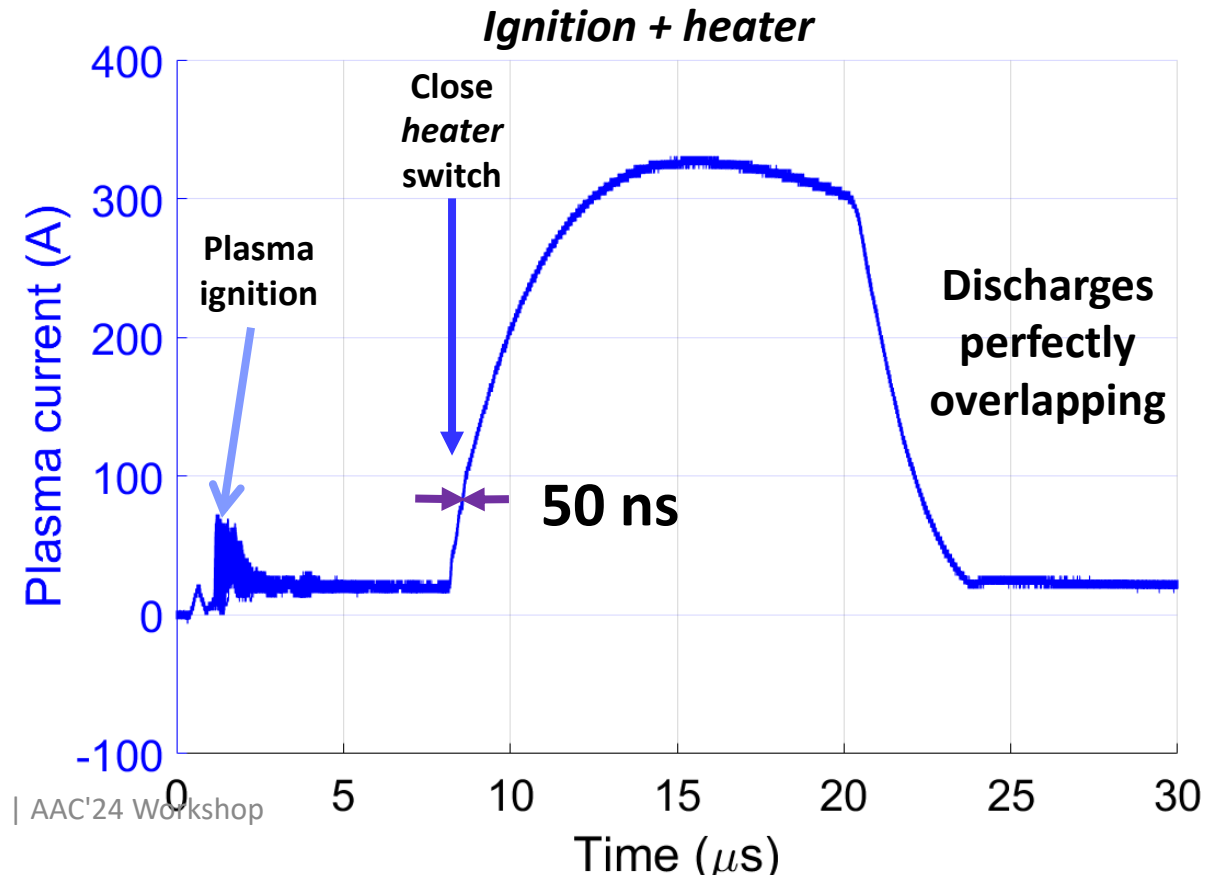
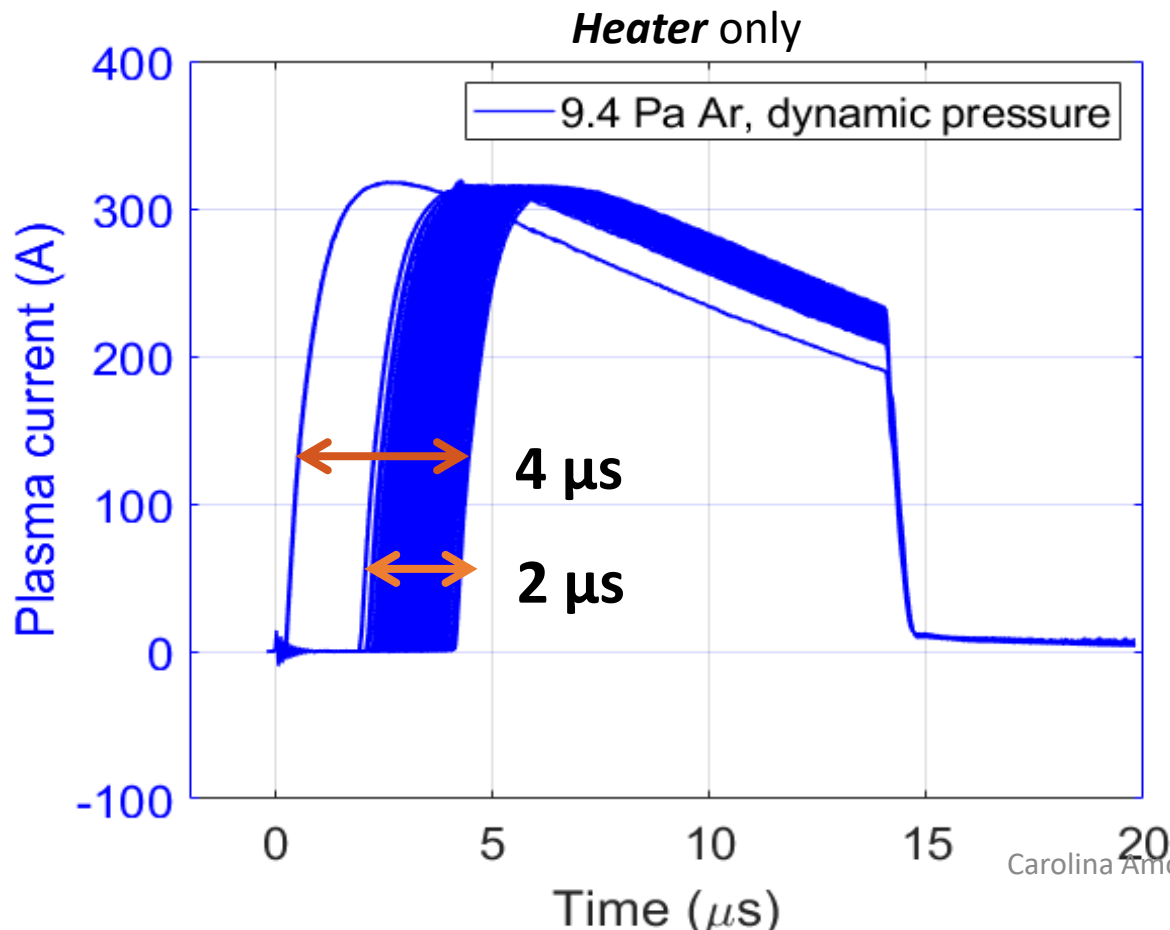


- Operating regime:  $1 \times 10^{18} - 1 \times 10^{21} \text{ m}^{-3}$
- Uncertainties: 0.1 eV and  $\sim 10\%$  in density

# DPS 1.6 m prototype

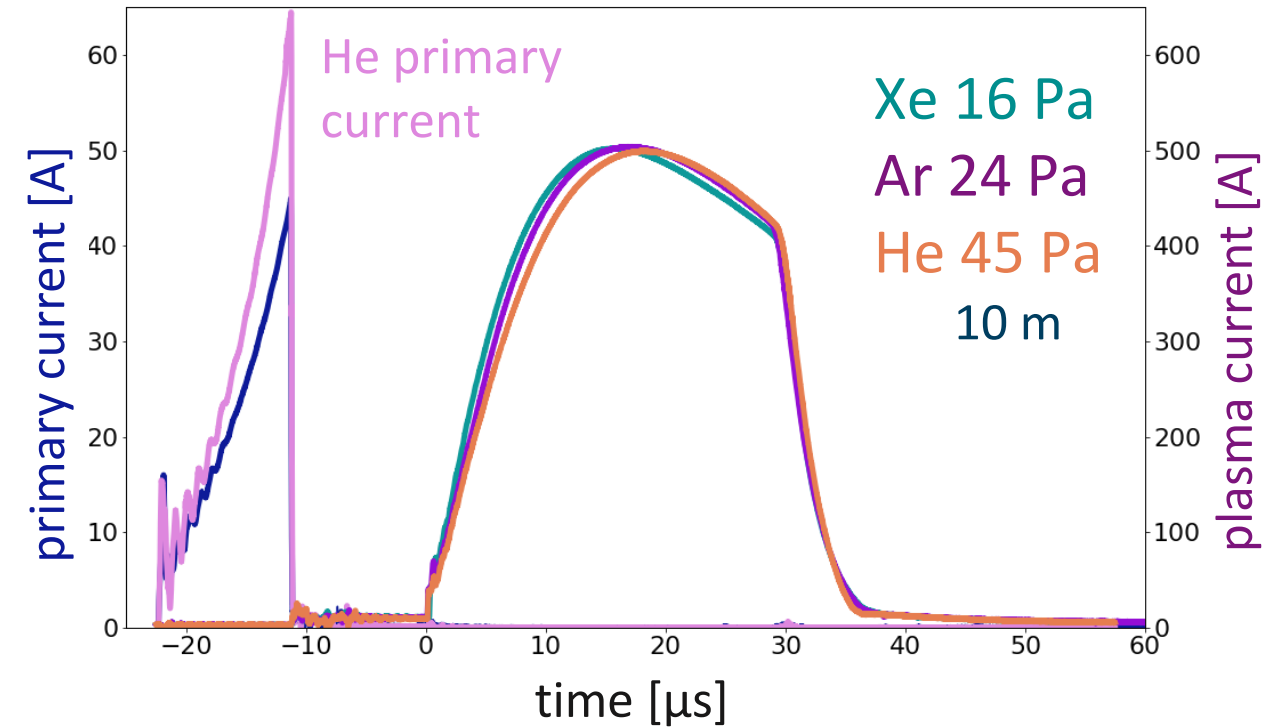
## Double pulse discharge

- 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



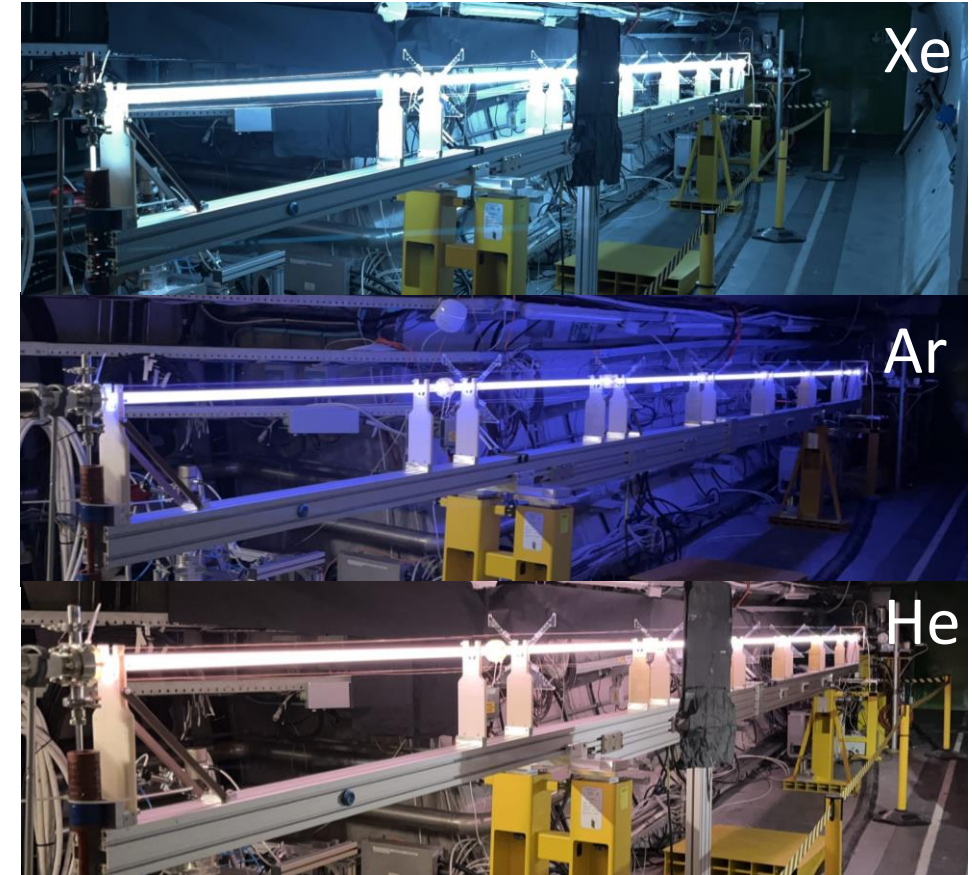
# May 2023 proton run

## Operation range – Gases



The pulse generators reach the target currents in all three gases

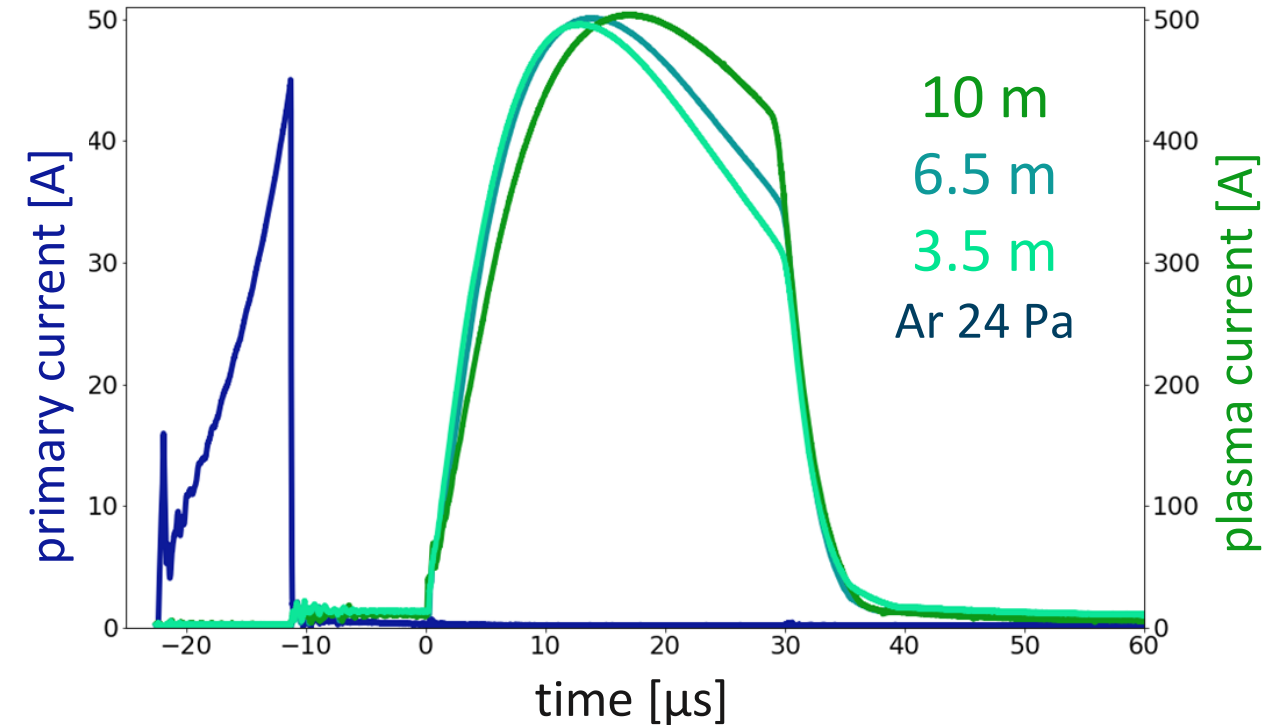
Gas affects mostly the ignition voltage required, leading to a higher primary current for He





# May 2023 proton run

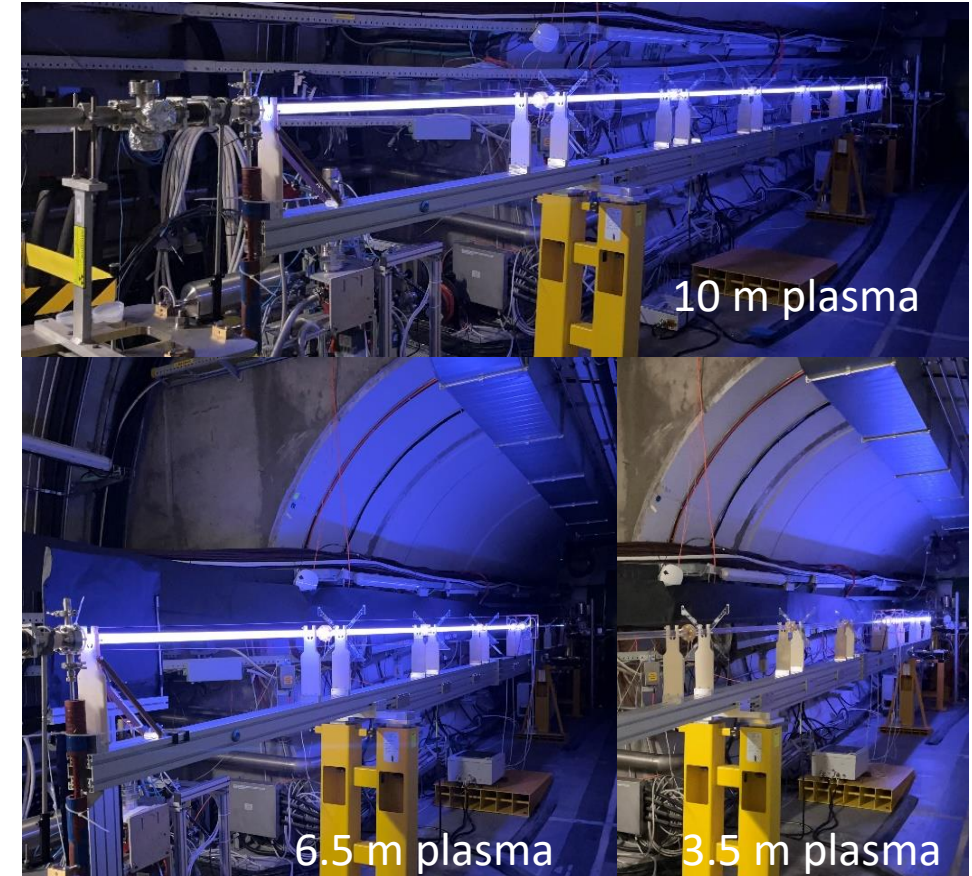
## Operation range – Length



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

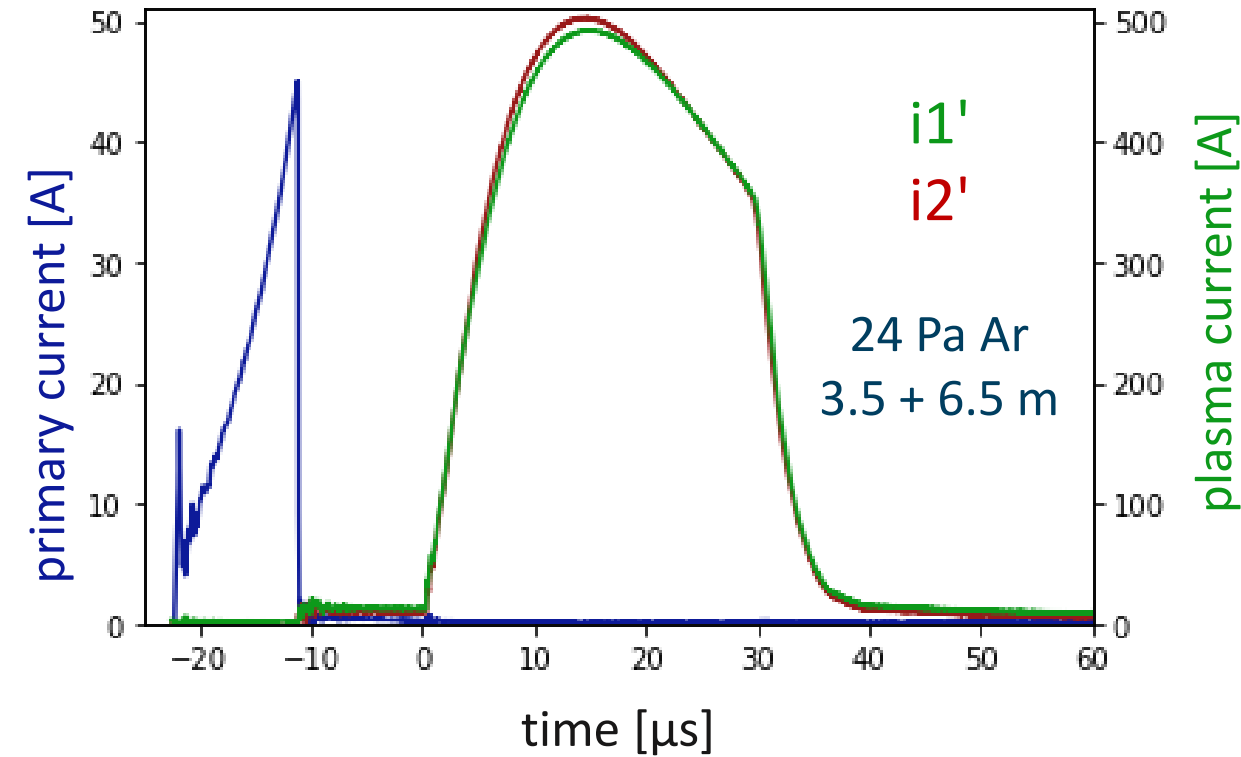
Gas affects mostly the ignition voltage required, leading to a higher primary current for He

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



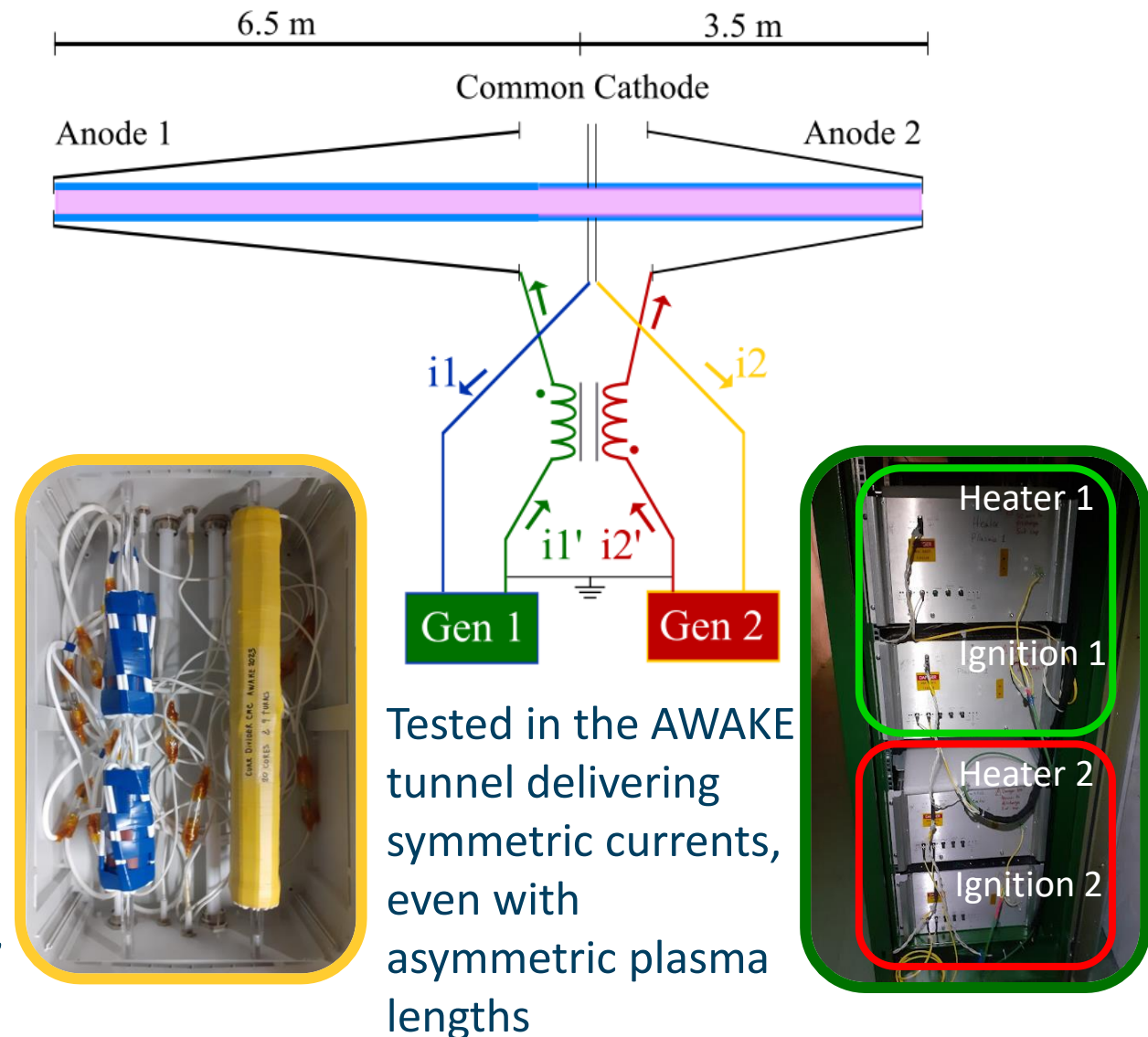
# May 2023 proton run

## 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