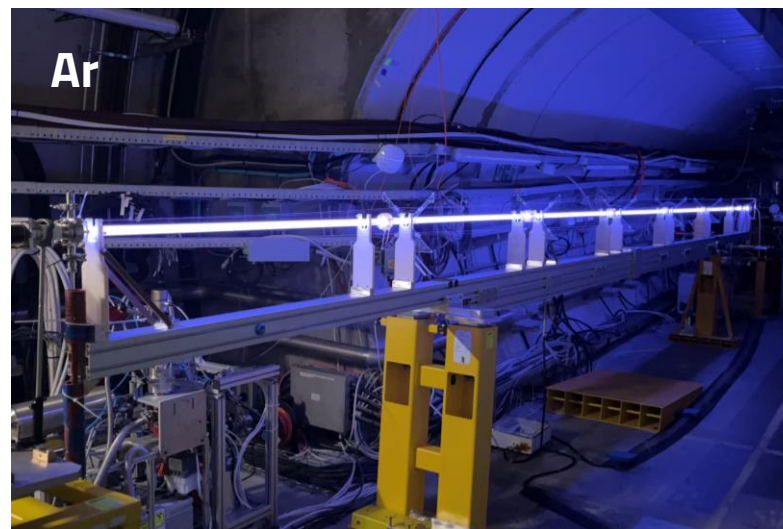
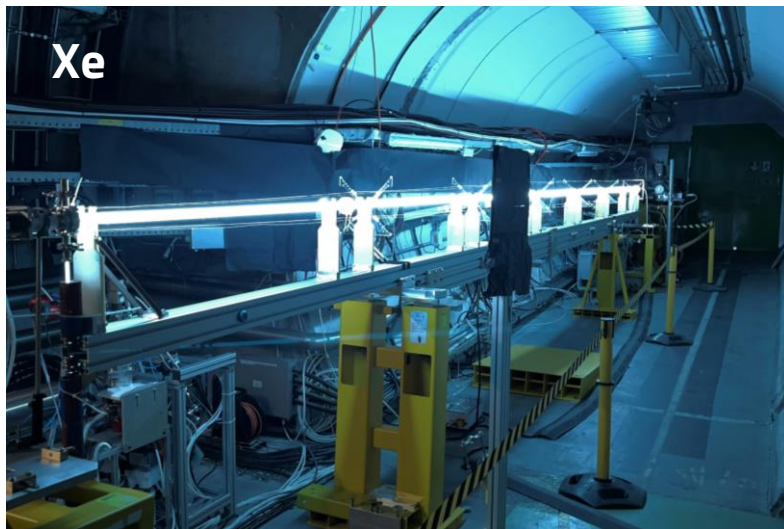


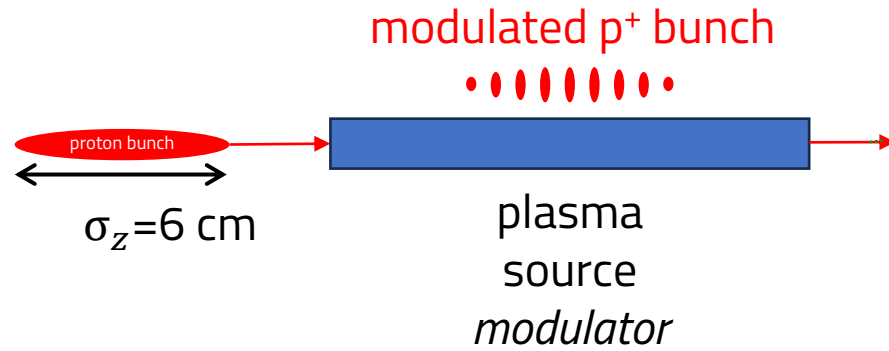
# Demonstration of proton bunch self-modulation in a discharge plasma source

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

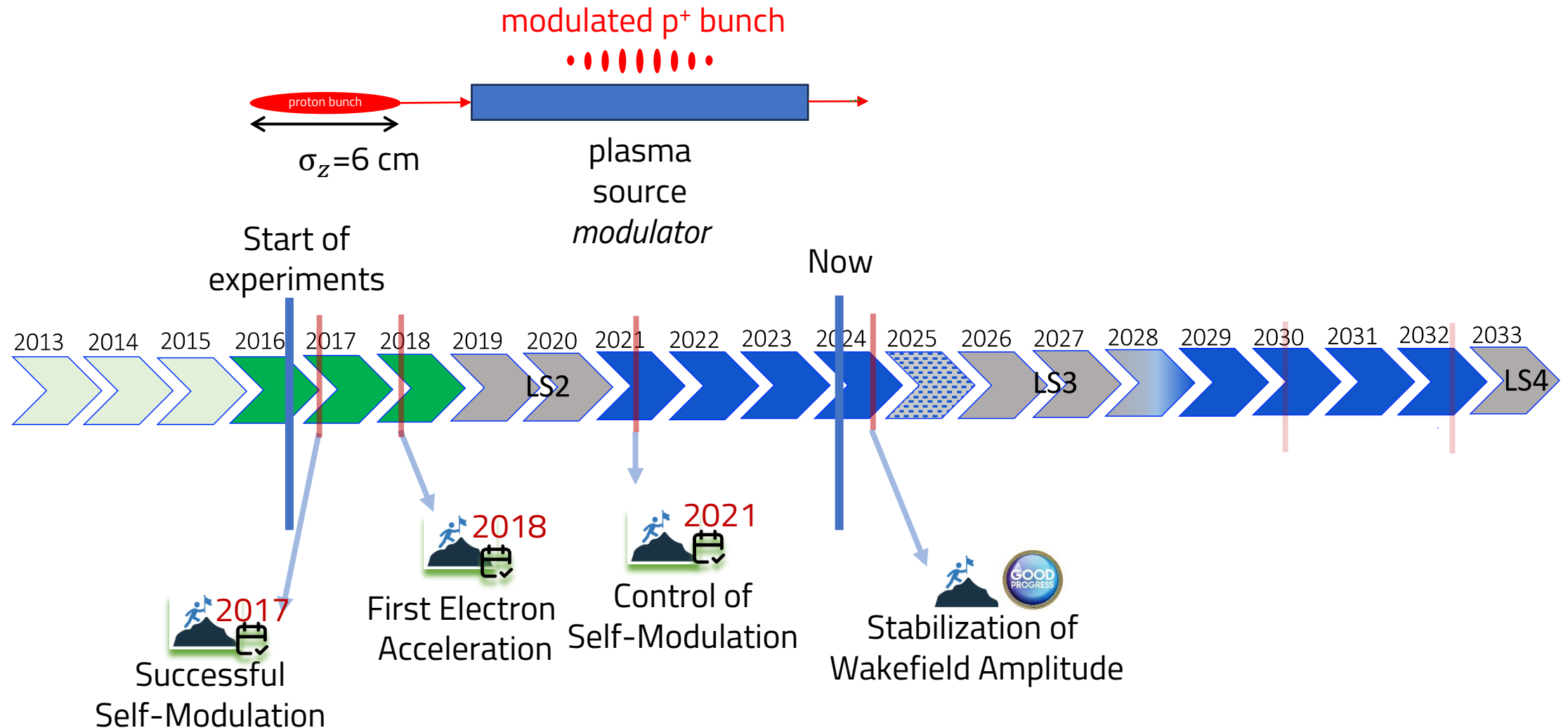
AAC'24 Workshop  
22/07/2024



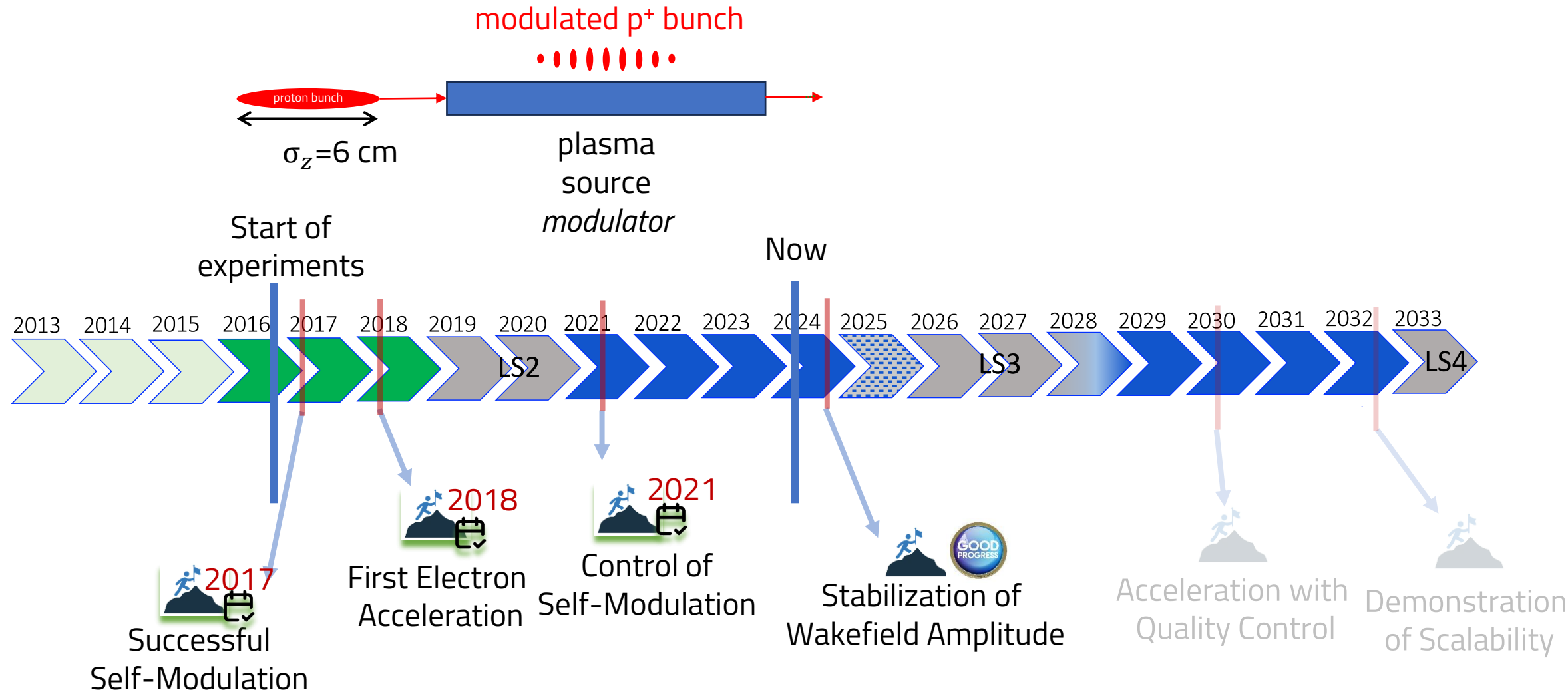
# AWAKE → Proton Driven Plasma **WAKE**field Experiment



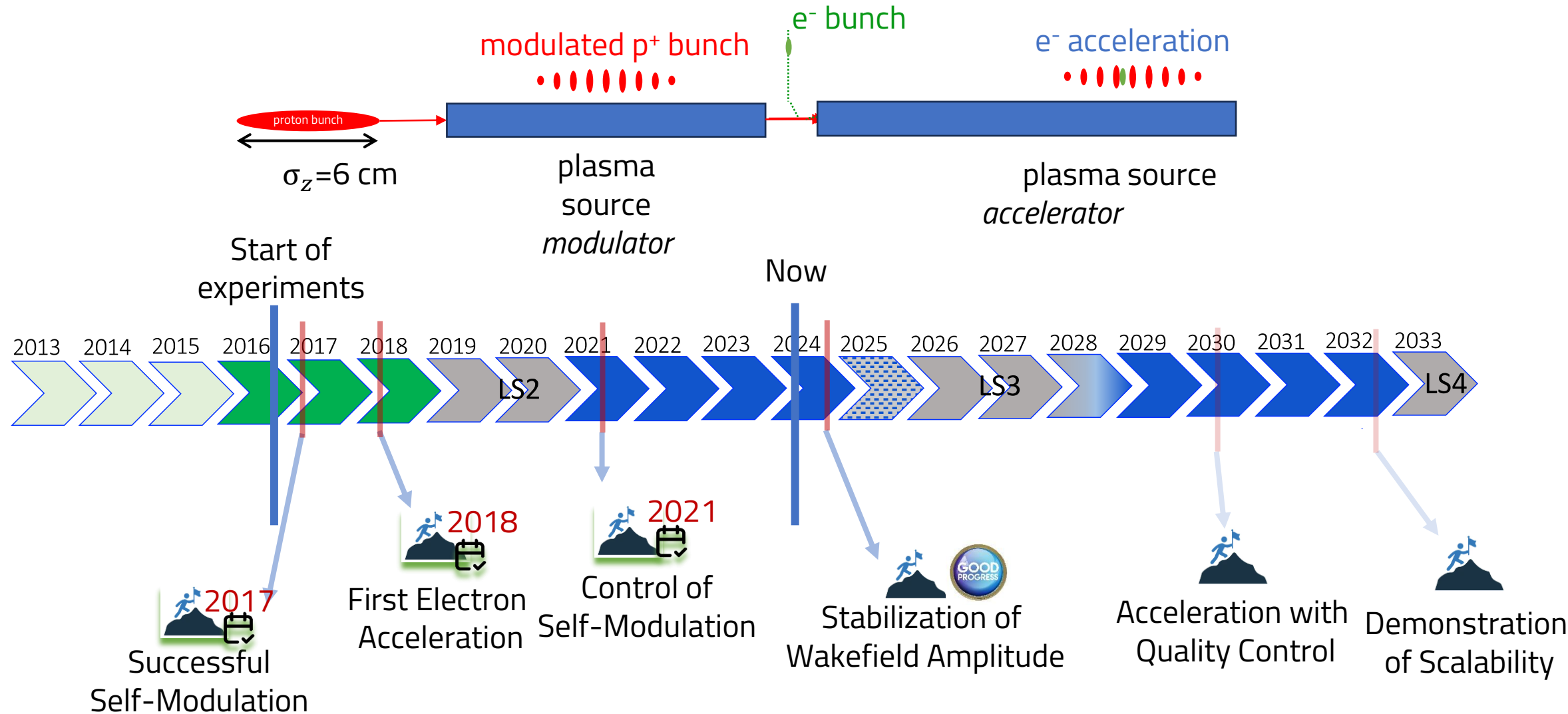
# AWAKE → Proton Driven Plasma **WAKE**field **E**xperiment



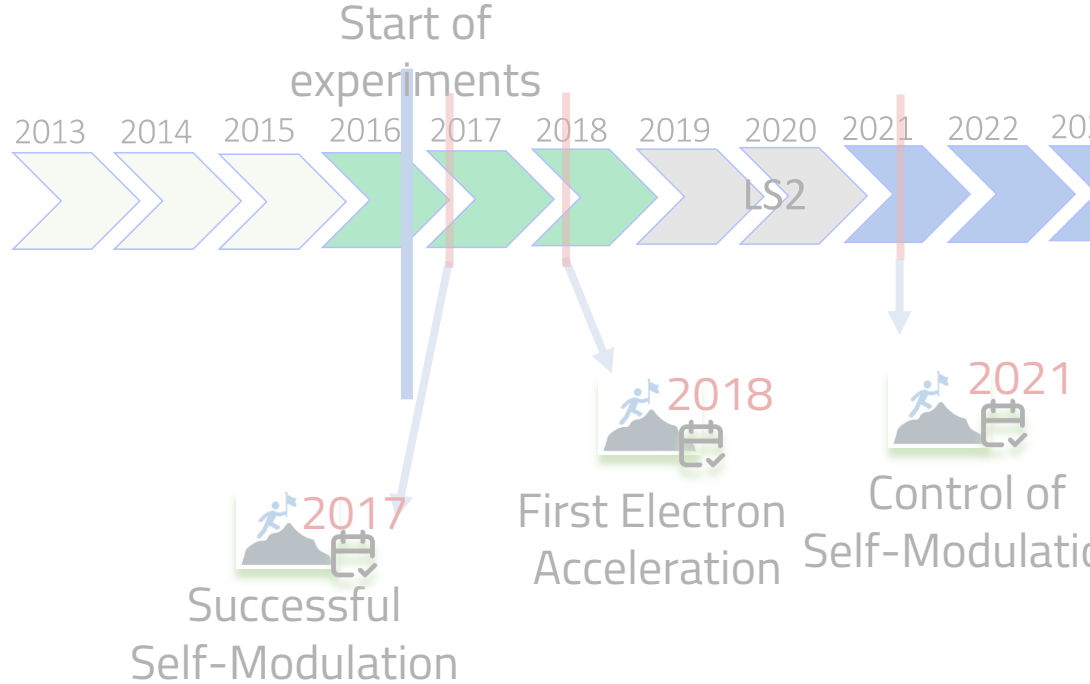
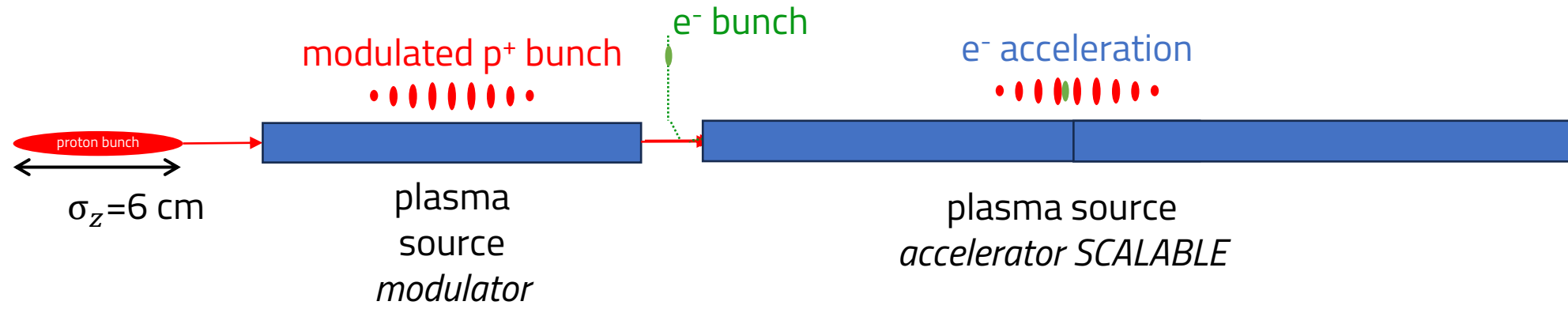
# AWAKE → Proton Driven Plasma **WAKE**field **E**xperiment



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



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



Now

**Requirements *SCALABLE* plasma source for AWAKE**

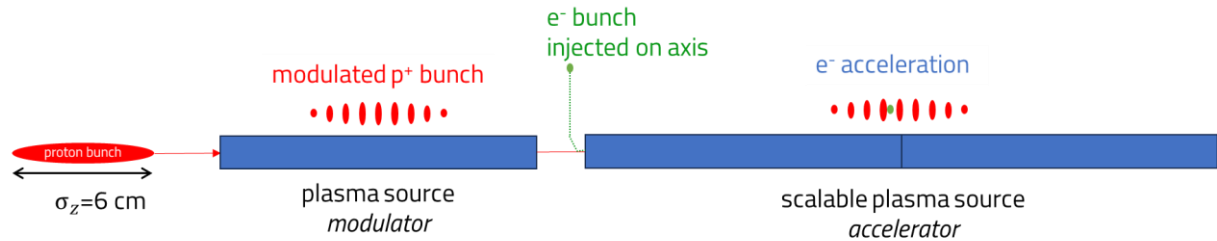
- Density matching with modulator ( $1-10 \times 10^{14} \text{ cm}^{-3}$ )
- Reproducibility and stability
- Longitudinal uniformity: 0.25% over 10 m
- Scalable: 10-100 m

Stabilization of Wakefield Amplitude

Acceleration with Quality Control

Demonstration of Scalability

# How to do 10s to 100s of meters of plasma?

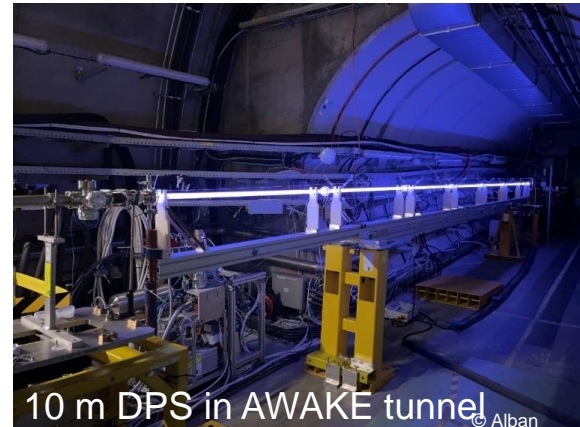


## Requirements scalable plasma source for AWAKE

- 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

## Discharge Plasma Source (DPS)

→ pulsed-DC discharge



10 m DPS in AWAKE tunnel © Alban



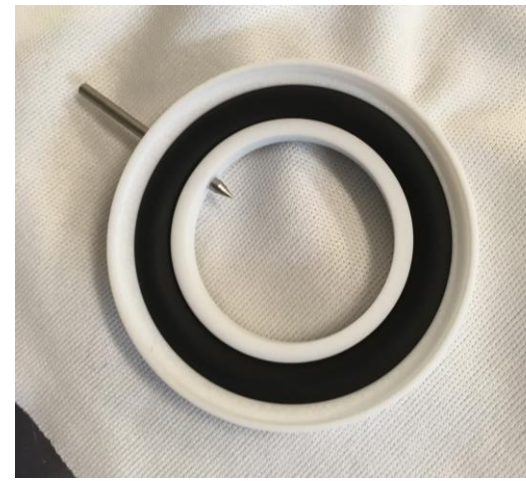
Imperial College  
London



# Start by 10 cm...

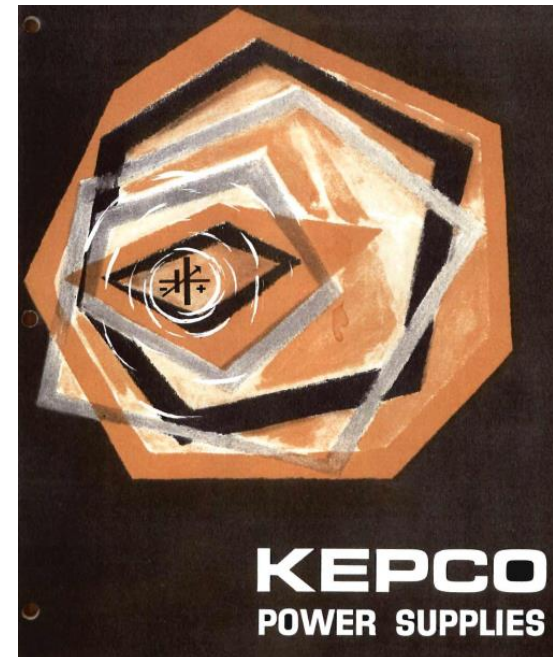


Glass tube  
+ gas + vacuum



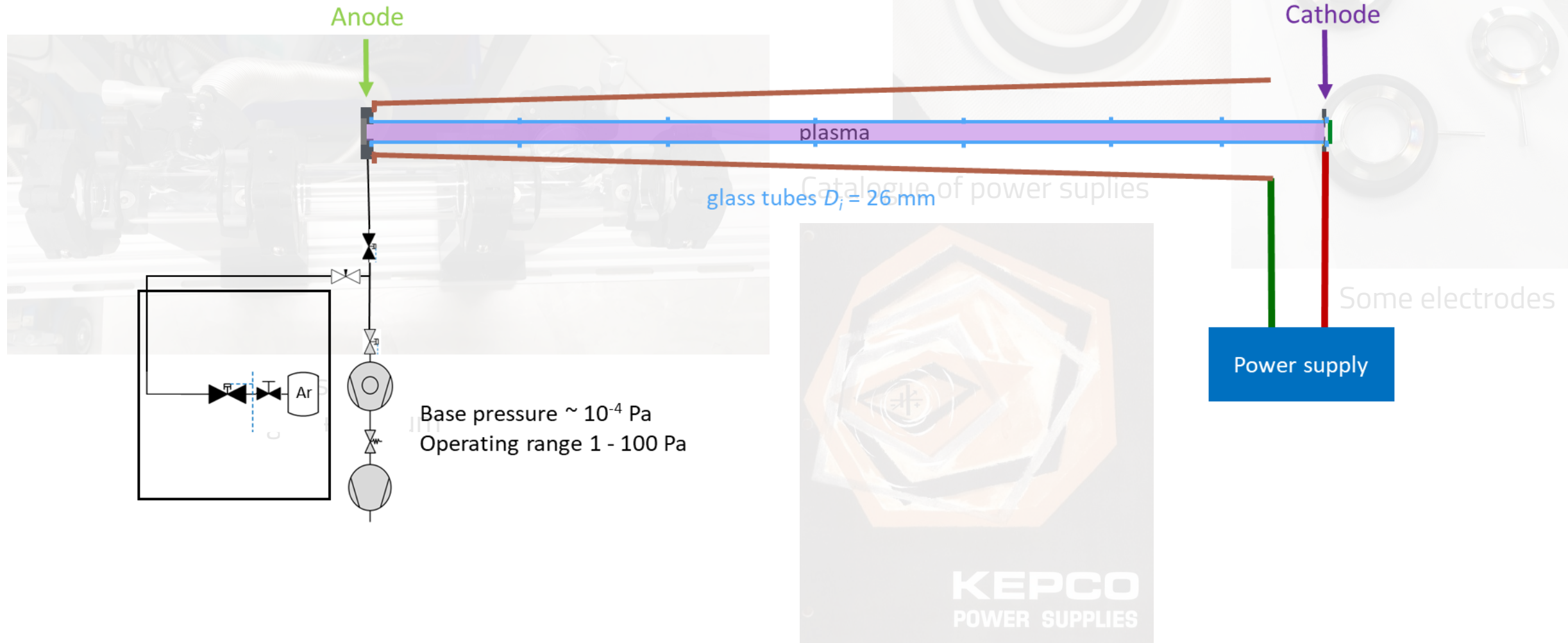
Some electrodes

Catalogue of power supplies

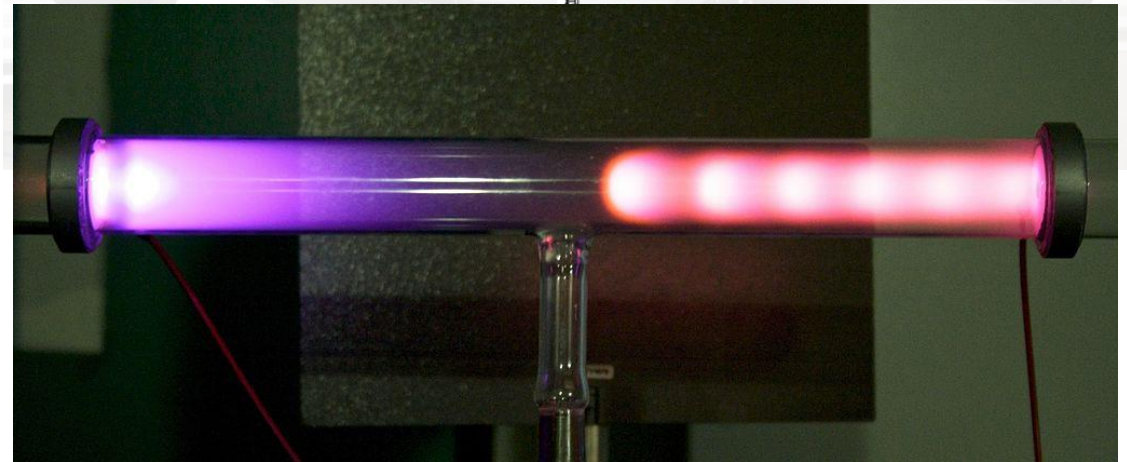
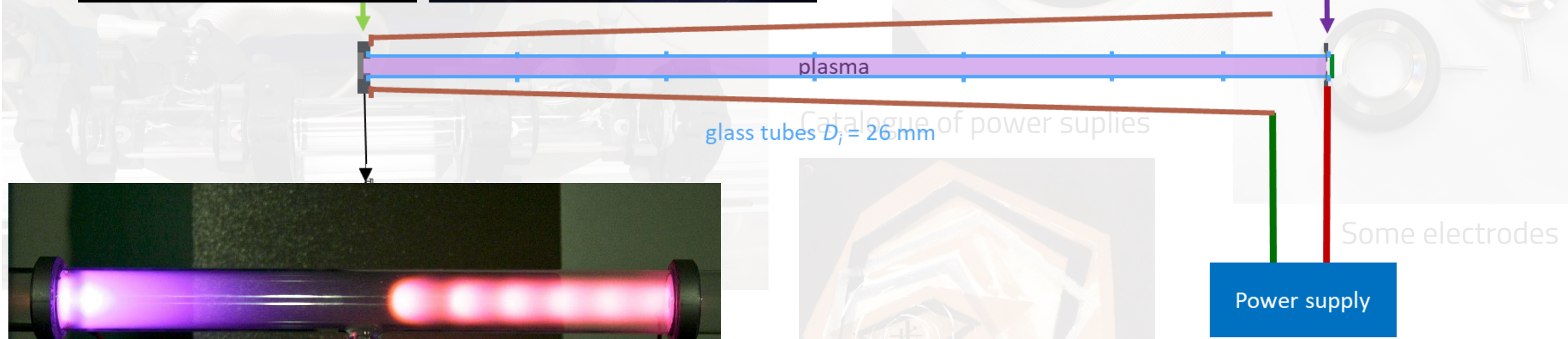
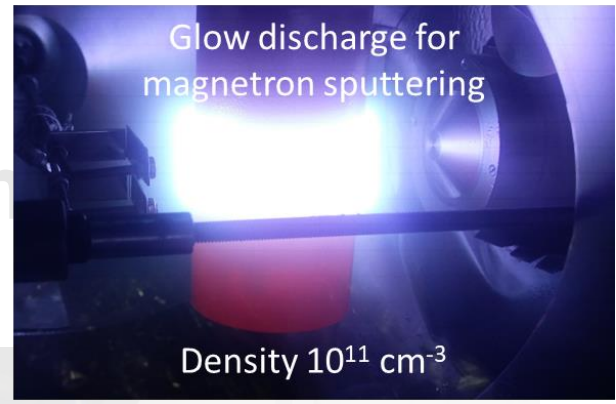
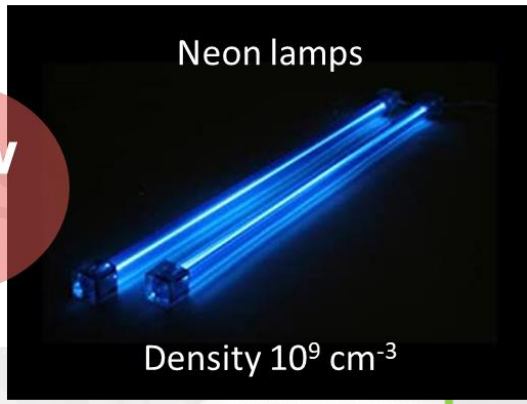




# Start by 10 cm...



glow  
mA

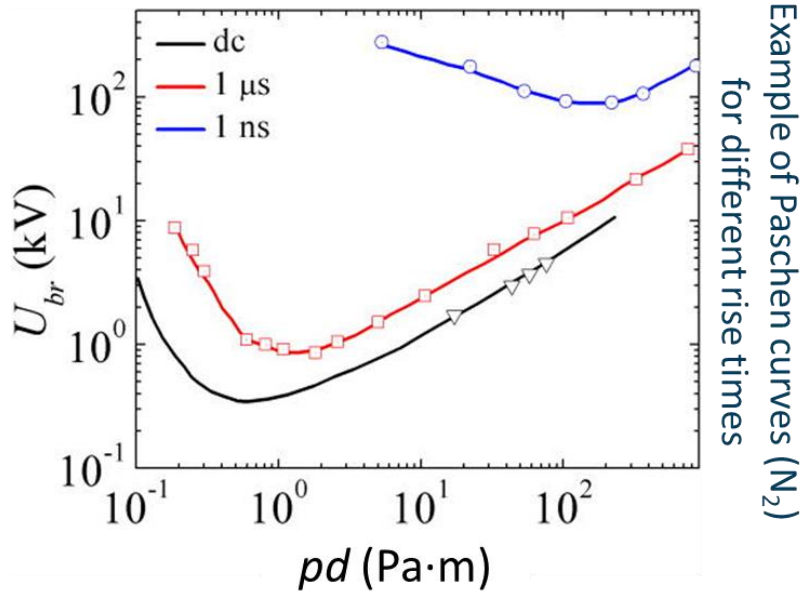
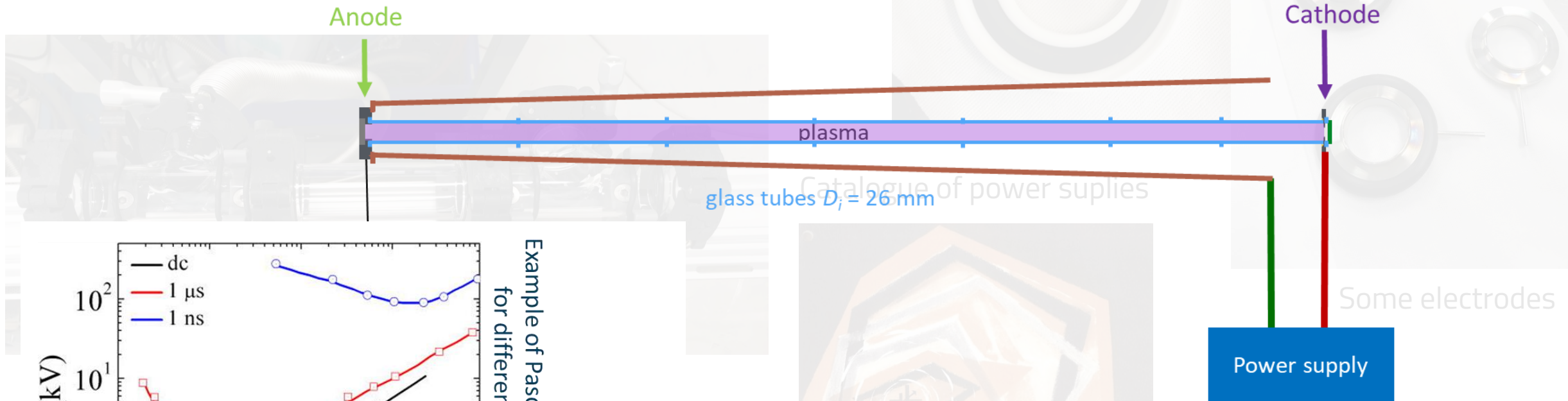


Example electrical glow discharge

- Densities are not high enough → unless arc regime
- Plasma is not uniform enough → unless pulsed to  $\mu\text{s}$



# Start by 10 cm...

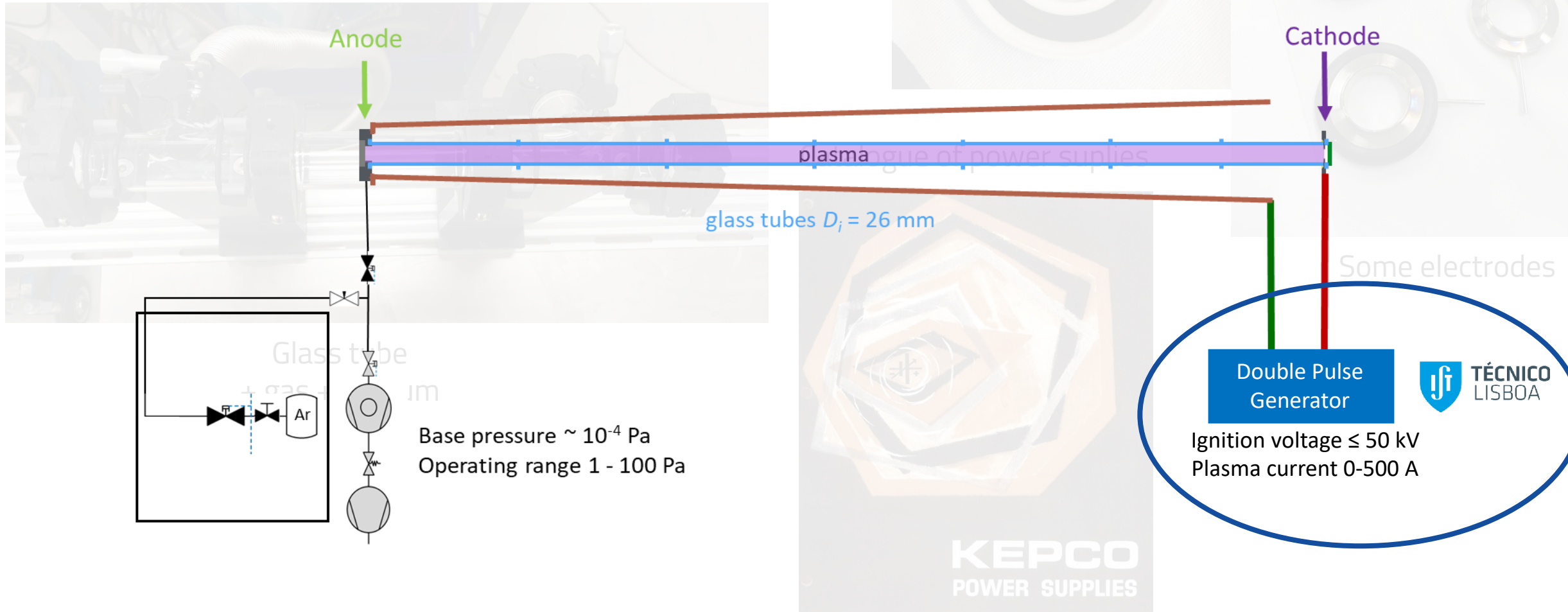


Levko et. al, Phys. Plasmas 26 (2019)

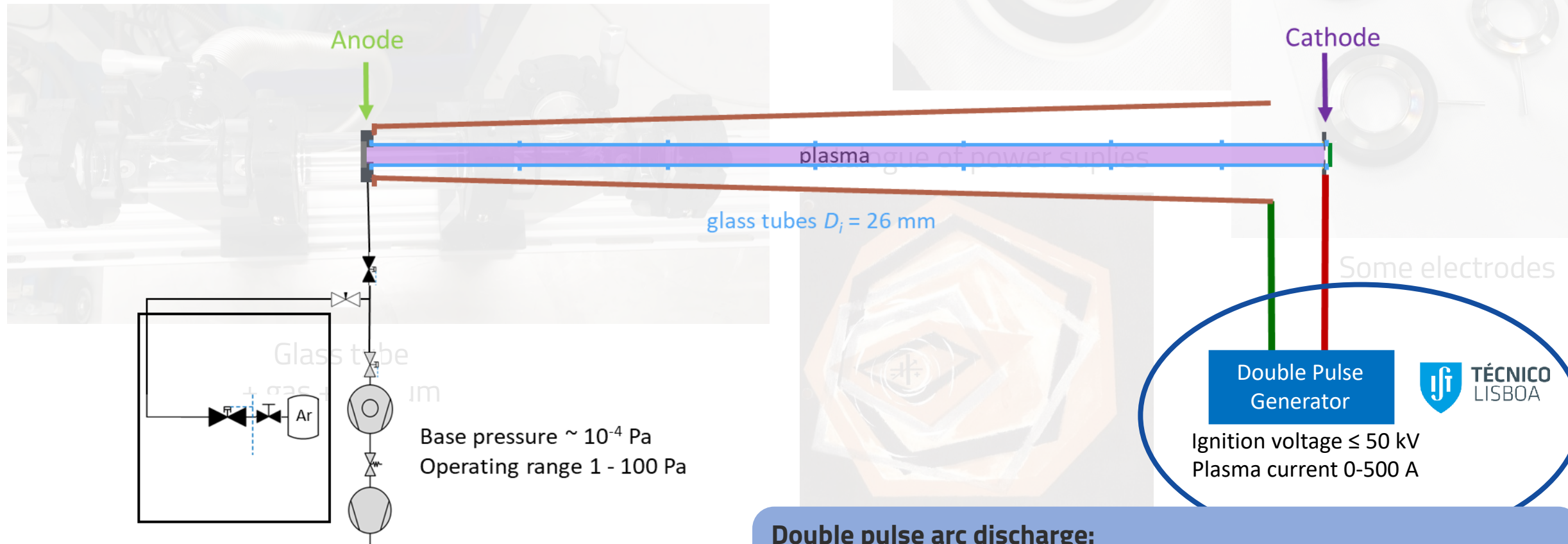
- Densities are not high enough → unless arc regime
- Plasma is not uniform enough → unless pulsed to  $\mu s$
- **Ignition is not reproducible enough** → unless fast ignition
- **10 m of plasma are not possible** → unless very HV



# Start by 10 cm...



# Start by 10 cm...

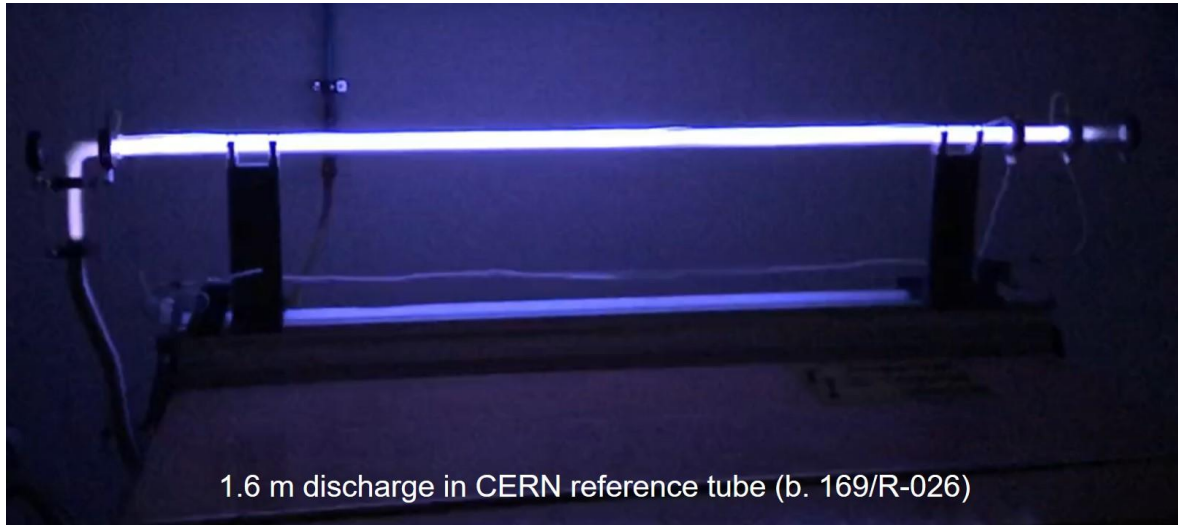


## Double pulse arc discharge:

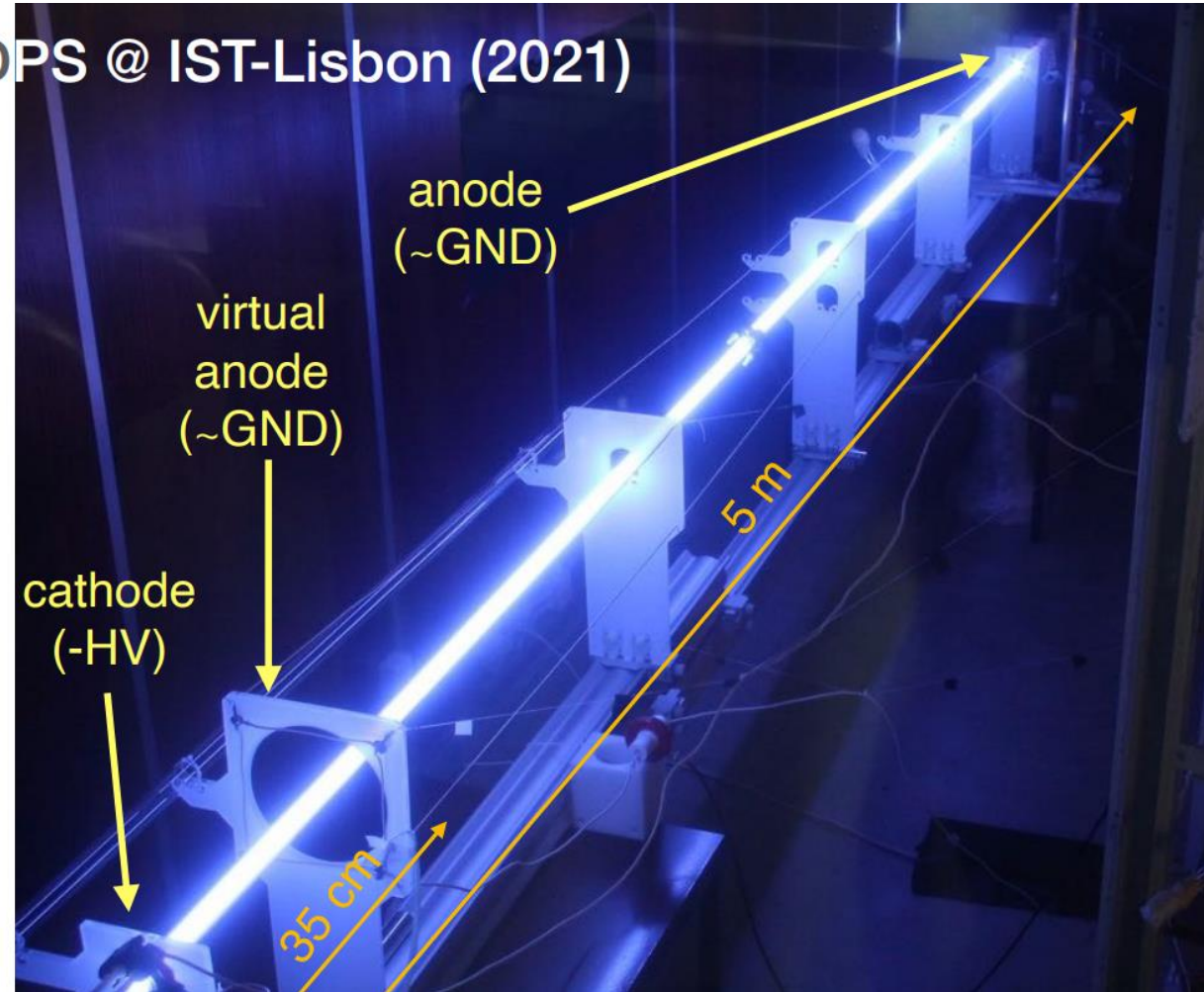
- 1) high voltage ignition  $\rightarrow$  jitter  $< 20$  ns in plasma ignition
- 2) 10 to 50  $\mu$ s high current pulse  $\rightarrow$  achieve high plasma densities



# Scaling up



AWAKE DPS @ IST-Lisbon (2021)







**empty lab - June 2022 - to do a 10 m DPS**





Anode



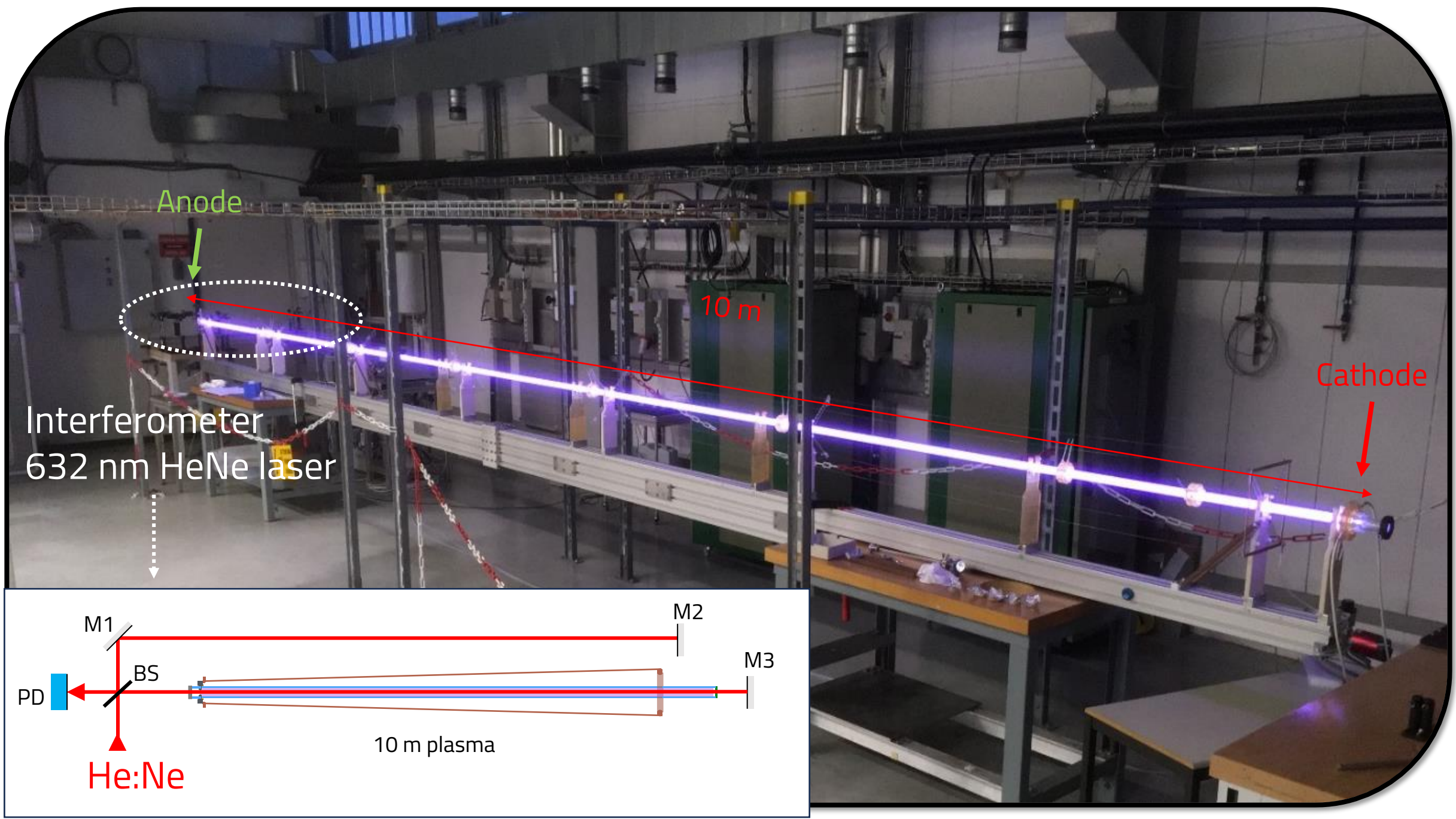
10 m

Cathode



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



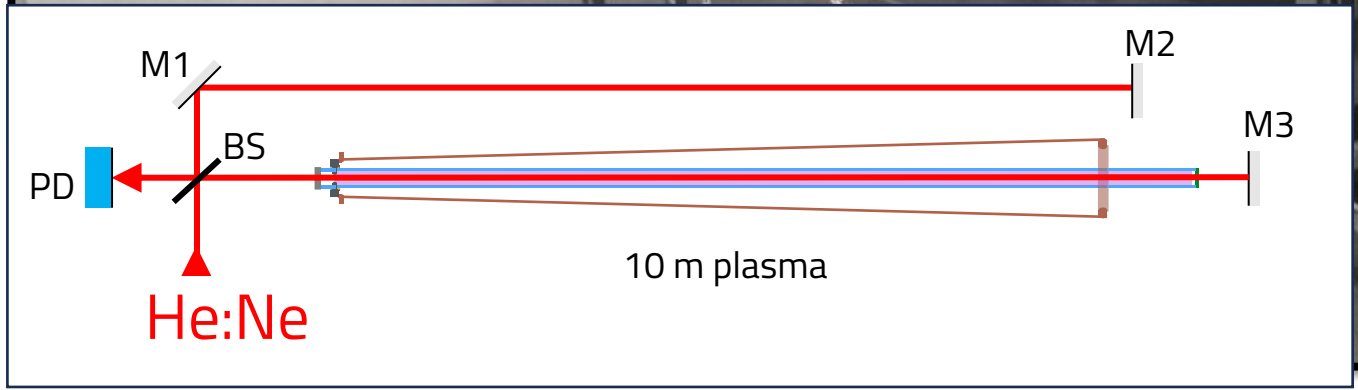


Anode

10 m

Cathode

Interferometer  
632 nm HeNe laser



# Plasma density diagnostic

## Longitudinally integrated interferometry

### Parameters:

Gas: Ar

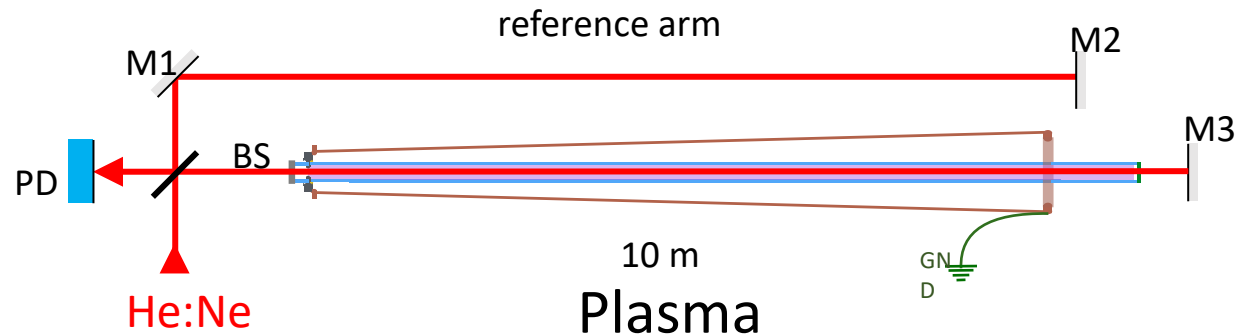
Pressure: 24 Pa

HV pulse: -17 kV

High current pulse: -6.32 kV,  
500 A

Pulse duration: 25  $\mu$ s

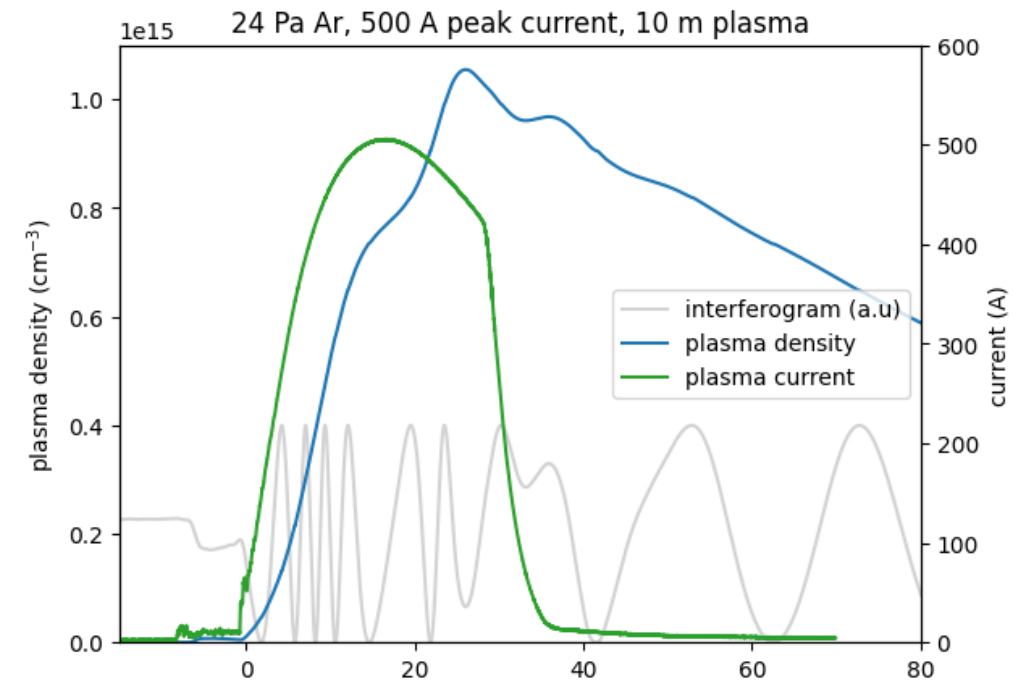
Plasma length: 10 m



- ▶ Michelson interferometer
- ▶ Measurement arm (plasma) adds a phase shift  $\phi_i$  proportional to the plasma density  $n_e$ :

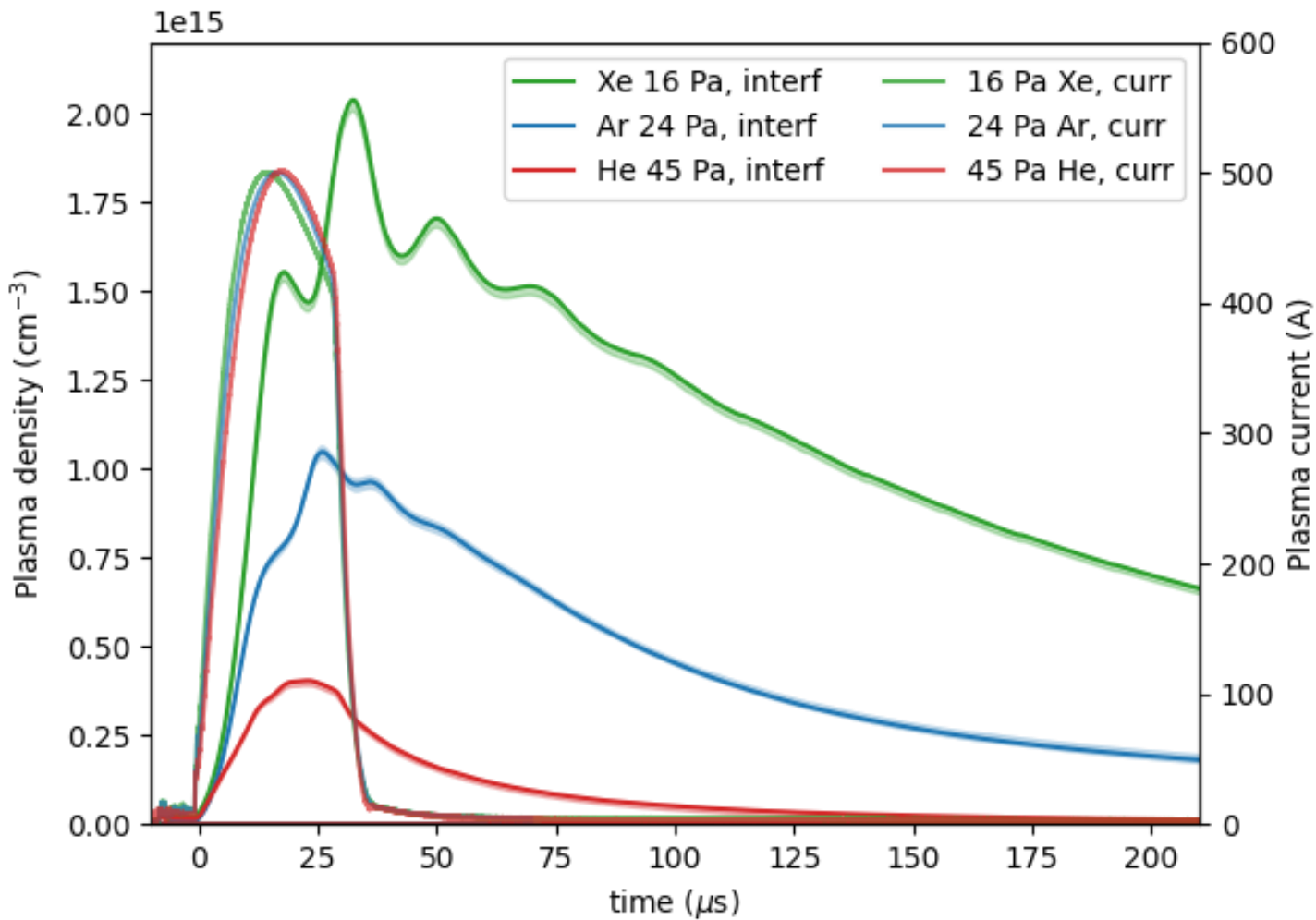
$$\phi_i = \frac{n_e}{r_e \lambda_i L}$$

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.



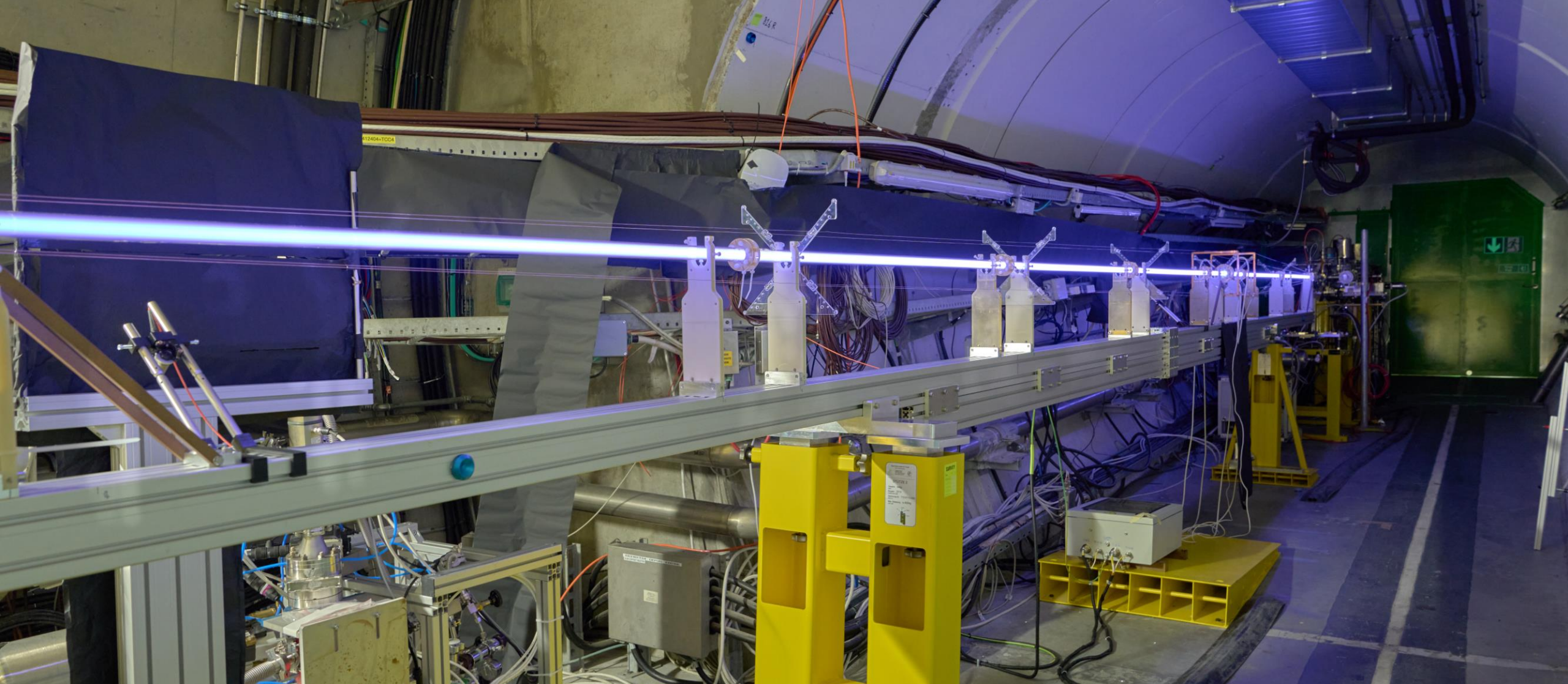
- ▶ Time-evolution of the plasma density, line integrated over the 10 m





► **Reproducible plasma density in different gases (He, Ar, Xe):**  
 < 0.2% pressure variability and  
 < 0.5 % current variability  
 provides < 2% integrated peak density variability.

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



**Discharge Plasma Source**  
(3 Weeks of p+ beamtime in 2023)





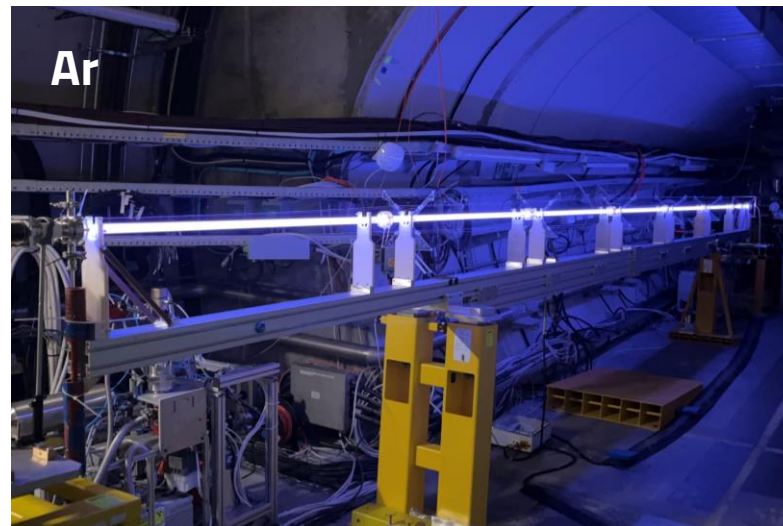
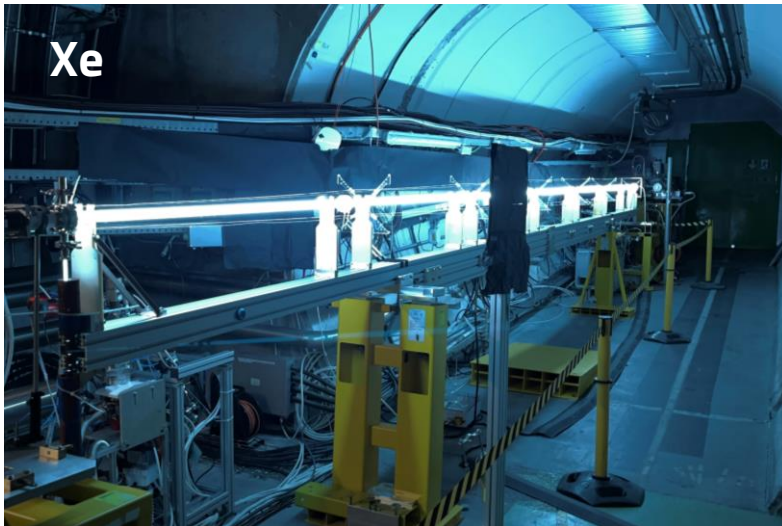
# 10 m DPS in AWAKE

→ 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%

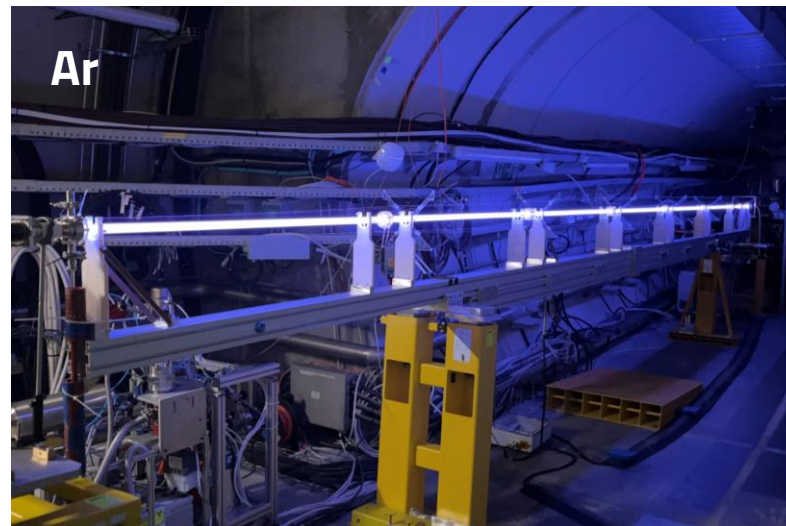
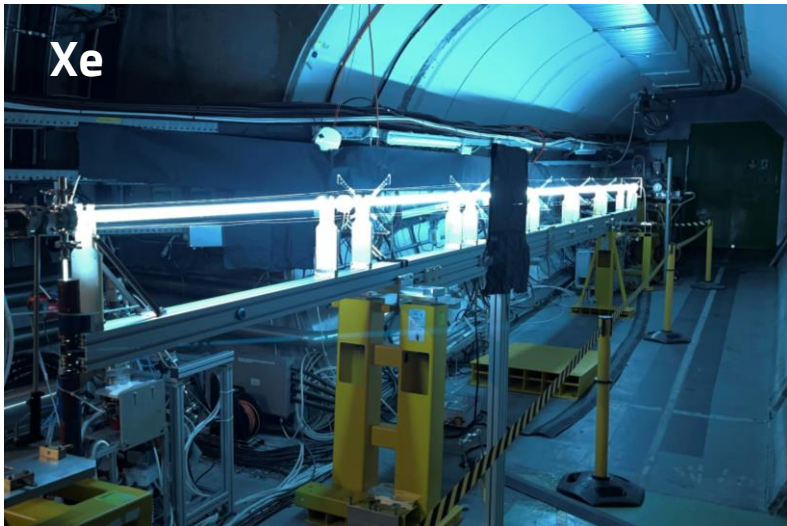
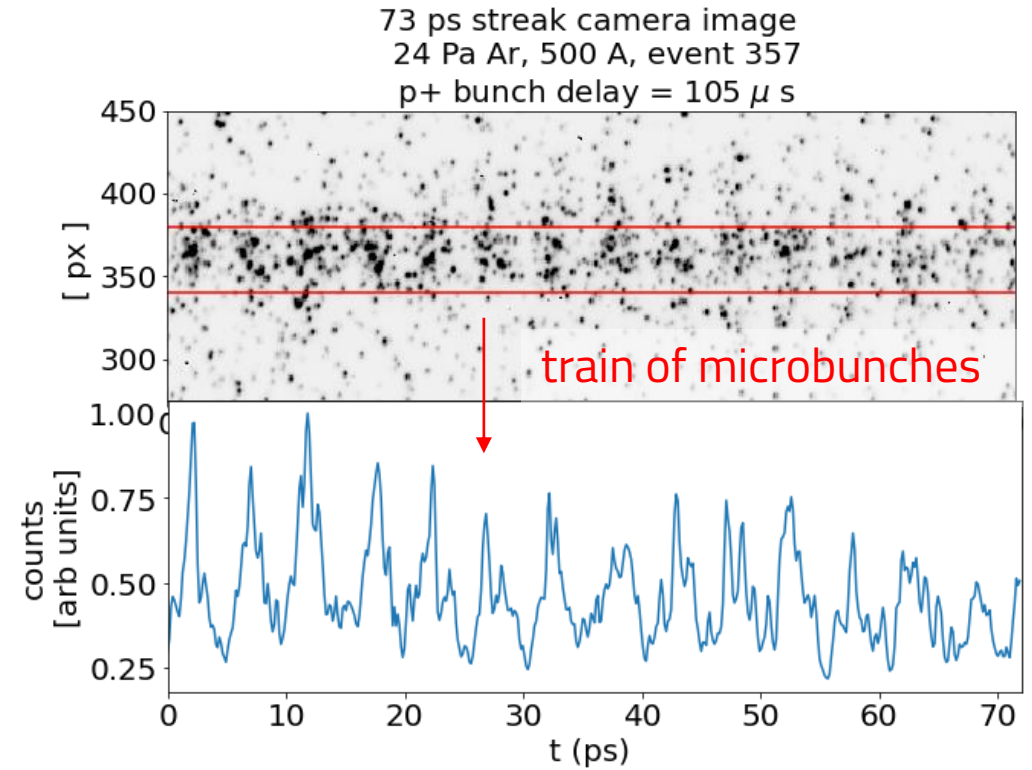
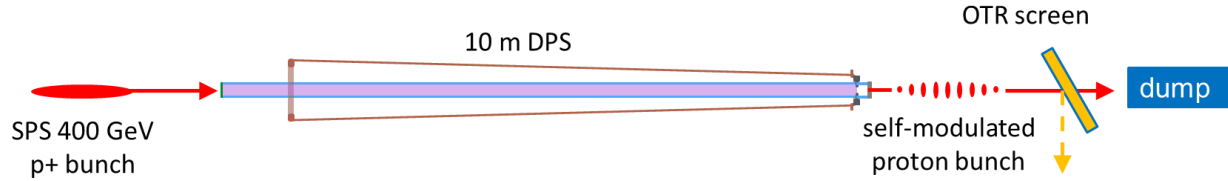


# 10 m DPS in AWAKE

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

1. demonstration of operation of DPS source in AWAKE

2. Self Modulation Instability (SMI) ?

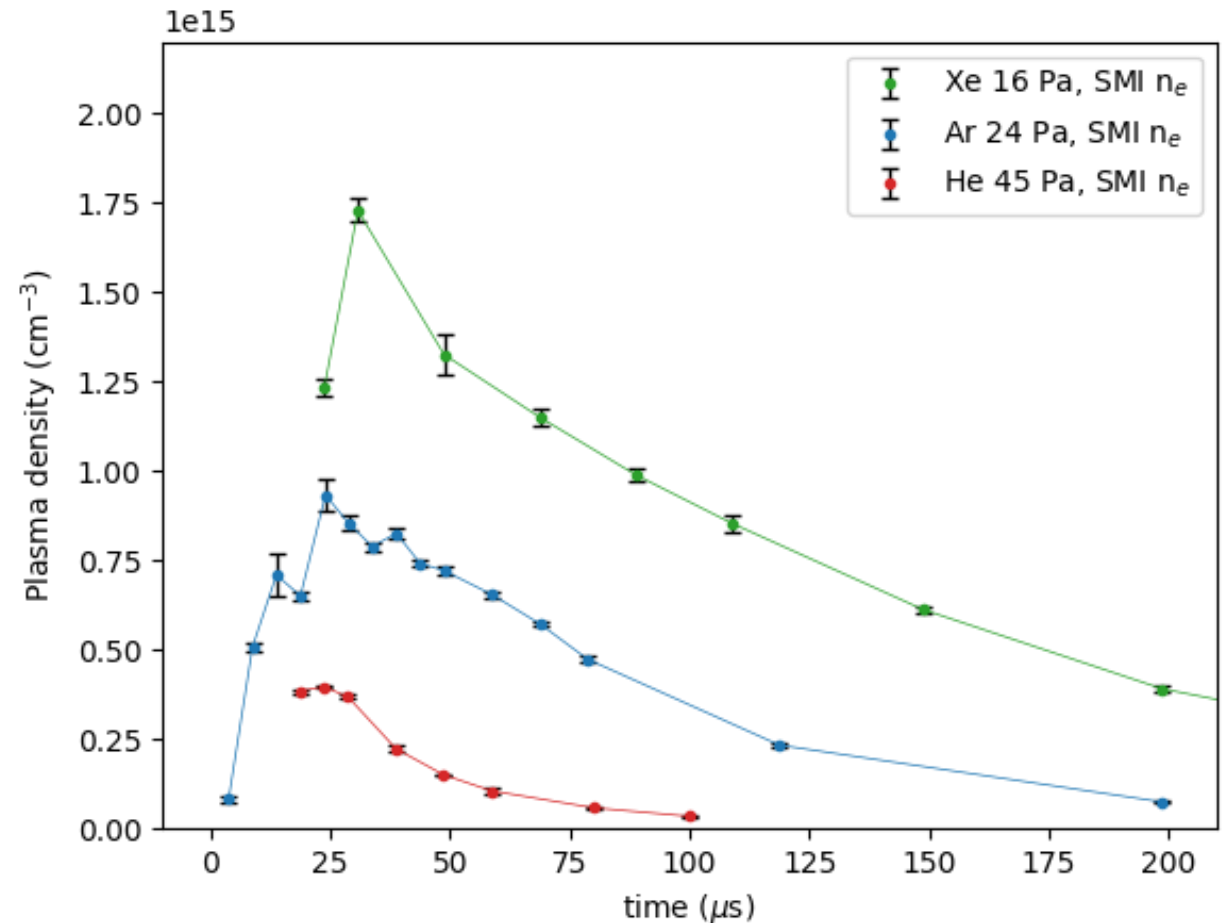




# Plasma electron density calculated from modulation frequency of p+ bunch

→ Proton bunch at different delays with respect to the discharge → probe SMI in different plasma densities

- ▶ easy way of changing density
- ▶ recover the time evolution of the discharge plasma density



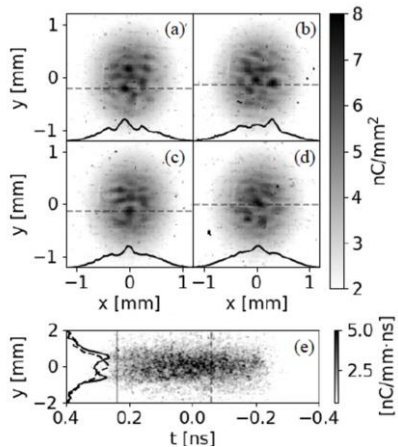


# 10 m DPS in AWAKE

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

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

## Filamentation Instability

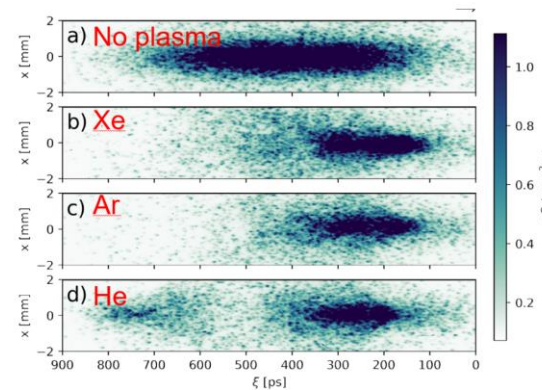


→ Wide plasma allowed to study the filamentation instability

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

→ Next talk by L.Verra

## Ion Motion

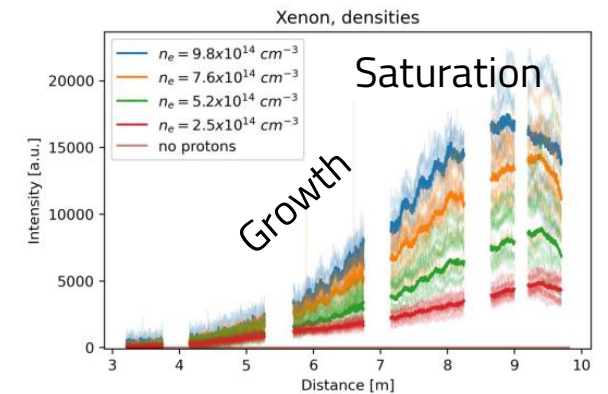


→ Flexibility in plasma ion species allowed to study the effect of ion motion on wakefields

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-  $20 \times 10^{14} \text{ cm}^{-3}$** .
  - ▶ 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 ( $1-10 \times 10^{14} \text{ cm}^{-3}$ )
- ✓ 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

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

C. Amoedo<sup>1</sup>, N. Lopes<sup>2</sup>, N. Torrado<sup>3</sup>, F. Silva<sup>3</sup>, P. Muggli<sup>4</sup>, L. Verra<sup>5</sup>, M. Turner<sup>6</sup>, G. Zevi Della Porta<sup>4</sup>, J. Puček<sup>1</sup>, M. Bergamaschi<sup>1</sup>, A. Clairembaud<sup>1</sup>, J. Mezzetti<sup>1</sup>, F. Pannelli<sup>1</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

<sup>1</sup>STFC, Central Laser Unit, 100Burslem Road, Coventry CV4 9EF, UK  
<sup>2</sup>STFC, Central Laser Unit, 100Burslem Road, Coventry CV4 9EF, UK  
<sup>3</sup>STFC, Central Laser Unit, 100Burslem Road, Coventry CV4 9EF, UK  
<sup>4</sup>STFC, Central Laser Unit, 100Burslem Road, Coventry CV4 9EF, UK  
<sup>5</sup>STFC, Central Laser Unit, 100Burslem Road, Coventry CV4 9EF, UK  
<sup>6</sup>STFC, Central Laser Unit, 100Burslem Road, Coventry CV4 9EF, UK

**Abstract**  
 A 10-meter discharge plasma source (DPS) applicability and readiness were assessed in the AWAKE experiment by propagating a 400 GeV proton bunch through the plasma and observing the development of the self-modulation instability (SMI). The time-evolution of the plasma density and shot-to-shot reproducibility of the source will be presented. These results demonstrate the DPS potential for use in AWAKE and pave the way for future studies on achieving the critical 0.25% longitudinal density uniformity needed for electron acceleration.

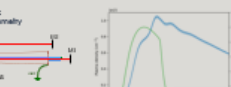
## Methods

**DC Discharge plasma source**  
 1) 1 to 10 m long dc discharge, based on double pulse scheme [1], that provides: 1) a fast low/short ignition of the plasma, and 2) a 10 to 50  $\mu$ s high current pulse to achieve plasma densities up to  $2 \times 10^{19}$  cm<sup>-3</sup>.

**Parameters:**  
 Working gases: He, Ar, Xe  
 Pressure: 1-10 Pa  
 Ignition HV pulse: up to 40 kV  
 High current pulse: up to 40V, 200 A  
 Plasma length: 1-10 m  
 Plasma radius: 25 mm  
 Density: 1-20x10<sup>19</sup> cm<sup>-3</sup>



**Plasma density diagnostic:**  
 Longitudinal integrated interferometry



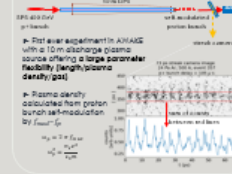
**Mach-Zehnder interferometer**  
 Measurement arm (plasma) adds a phase shift  $\Delta\phi$ , proportional to the plasma density  $n_p$ :  
 $\Delta\phi = \frac{2\pi}{\lambda} \int n_p dz$   
 where  $\lambda$  is the probe electron wave ( $\lambda_p = 2.00 \times 10^{-10}$  m),  $z$  is the laser wave length and  $L$  is the length of the plasma.



## Test in AWAKE (May 2023)

**AWAKE - proton-driven wakefield accelerator**  
 400 GeV proton bunch from DPS propagates in plasma and self-modulates into a train of micro-bunches spaced by  $\sim$  plasma period  $\sim$  (3-10)  $\mu$ s for  $n_p \sim 1-20 \times 10^{19}$  cm<sup>-3</sup>  
 This train resonantly drives wakefields along the bunch and plasma, producing large amplitude wakefields

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



## R&D

### AWAKE future

- Run 2c (2023)  $\rightarrow$  two sources modulator + accelerator to allow external e-bunch injection
- Run 2d (2025)  $\rightarrow$  scalable plasma source to extend acceleration length

**R&D scalable plasma source for AWAKE**  
 Density matching, reproducibility and stability  
 Longitudinal uniformity: 0.25% over 10 m  
 Length-scalable: 10-100 m

**DPS next step:** local plasma density measurement along the plasma length with Thomson scattering [8]

# Thank you for your attention

$\rightarrow$  Poster

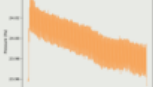
## Results

### DPS plasma reproducibility

Plasma density depends on the gas pressure and plasma current. Greater control of these parameters is key for reproducibility.  
 Shot-to-shot plasma density variation was evaluated over 200 consecutive discharges with longitudinal integrated interferometry.

**Parameters:**  
 Gas: Ar  
 Pressure: 2.0 Pa  
 HV pulse: -17 kV  
 High current pulse: 4.22 kV, 200 A  
 Pulse duration: 25  $\mu$ s  
 Plasma length: 10 m

#### 0.25% variation gas pressure



#### 2% spread peak plasma density



#### 0.5% variation peak current

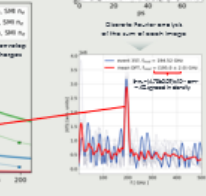
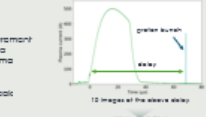
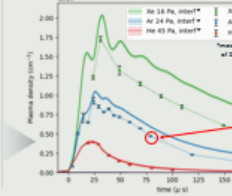
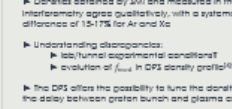


Reproducibility also studied for He (2.0 Pa) and Xe (1.6 Pa), 200 A peak current

Interest of having discharges in 3 gases (He, Ar, Xe)  
 $\rightarrow$  profit of DPS wide range of parameters (density/gas/length) to study SMI and other beam instabilities [4]

### Proton bunch self-modulation

SMI modulation frequency provides discrete measurement of density. Delay between proton bunch and plasma current pulse allows to measure time evolution of plasma density.  
 $t_{mod}$  of each delay is evaluated over at least 10 streak camera images, resulting in 0.2% spread in density.  
 Densities obtained by SMI and measured in the lab with interferometry agree qualitatively, with a systematic difference of 1.5-1.7% for Ar and Xe.  
 Understanding discrepancies:  
 Lab/tunnel experimental conditions  
 evolution of  $t_{mod}$  in DPS density profile  
 The DPS offers the possibility to tune the density by adjusting the delay between proton bunch and plasma current pulse



## Conclusion

The DPS provides reproducible plasma density in different gases (He, Ar, Xe) system with  $\sim$  0.2% pressure variability and  $\sim$  0.5% current variability provides  $\sim$  2% integrated density variability.  
 Plasma density measurements were performed using longitudinal integrated interferometry; plasma electron densities ranging from  $1-20 \times 10^{19}$  cm<sup>-3</sup>.  
 Self-modulation of a 400 GeV proton bunch was observed in DPS successfully.  
 The DPS offers a large parameter flexibility (length/plasma density/gas) allowed studies on effect of plasma on mass on SMI [8], transverse filamentation instability [4] and plasma vorticity light emission [7].

## References

- [1] Torrado, N., et al., IEEE Trans. on Plasma Science, 2023, 51, 12.
- [2] Gschwendtner, E., et al., AWAKE Collaboration, Symmetry, 2022, 14, 1680.
- [3] Agnello, R., et al., Journal of Plasma Physics, 2021, 86.
- [4] Morales-Guerron, P., et al., AWAKE Collaboration, PRF, 2021.
- [5] Turner, M., et al., AWAKE Collaboration, in review.
- [6] Verra, L., et al., AWAKE Collaboration, Phys. Rev. E, 2019, 100, 055203.
- [7] Mezzetti, J., et al., AWAKE Collaboration, AAC, 2024 Poster.

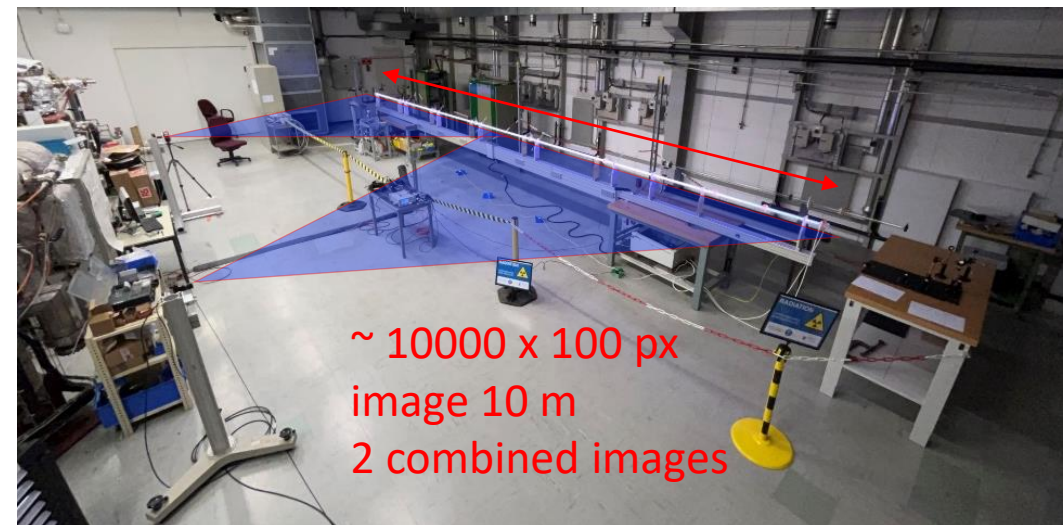
# Next steps

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

(1  $\mu$ s exposure time)

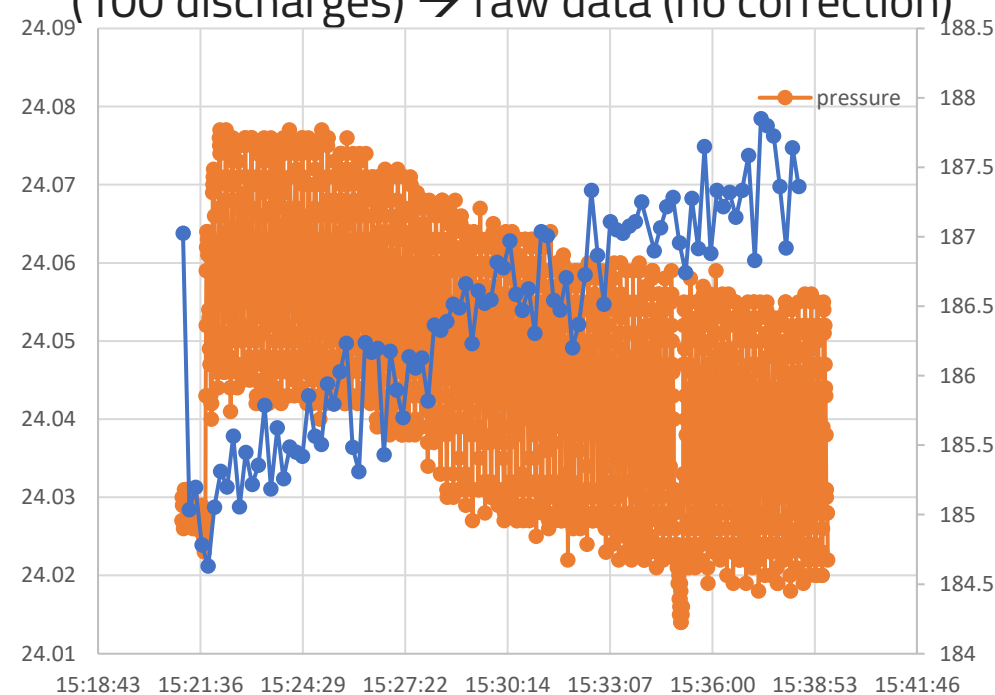
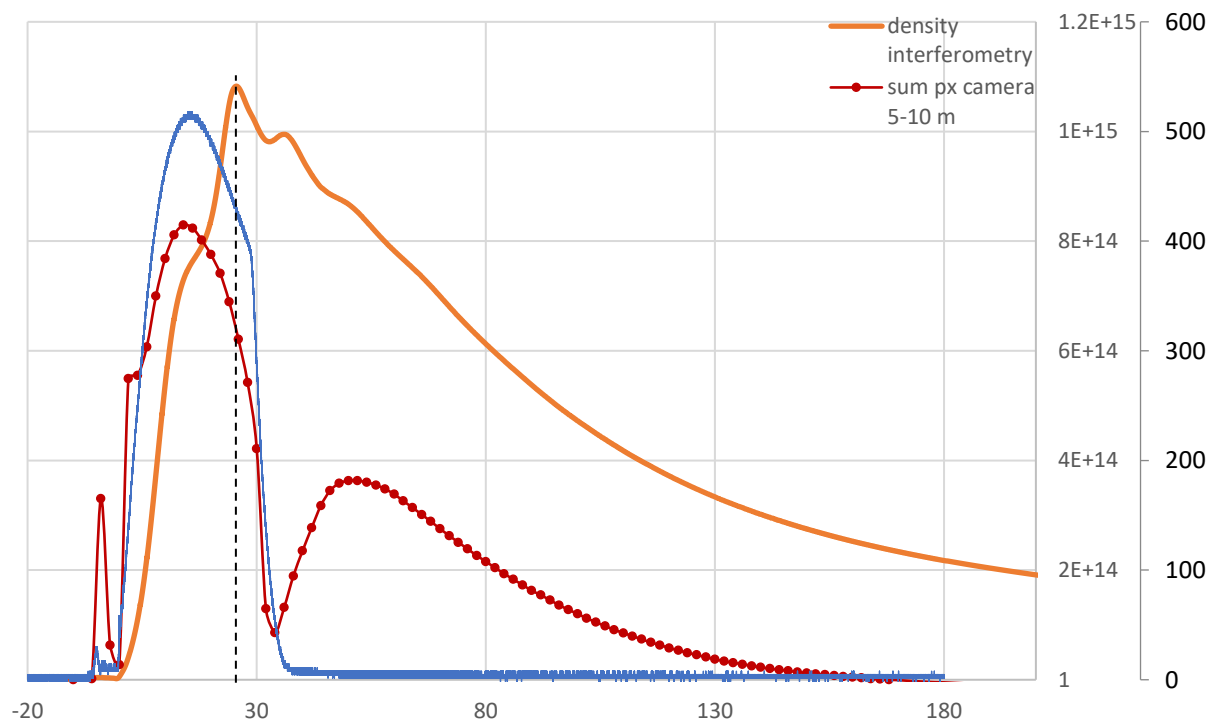


24 Pa 500 A



peak density: mean of all pixels of the image

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

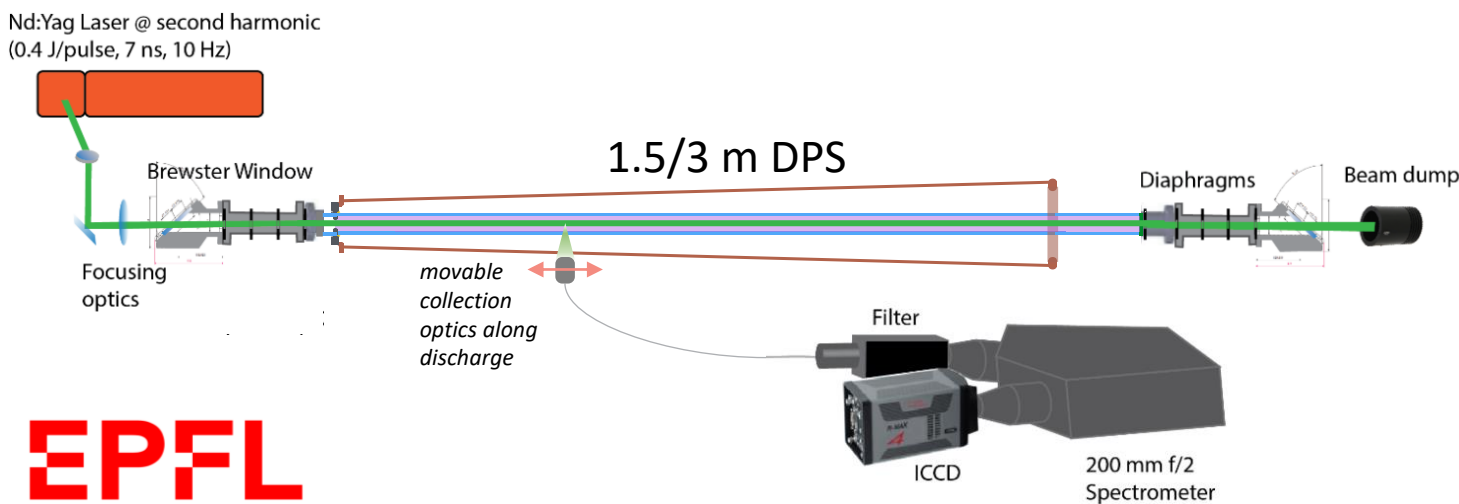


# Next steps

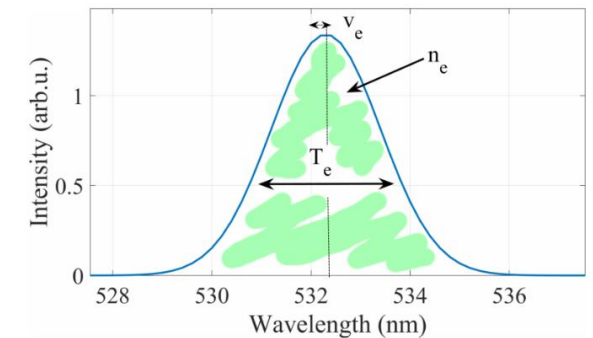
## 1. Thomson scattering on DPS: Fall 2024

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

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



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

**EPFL**

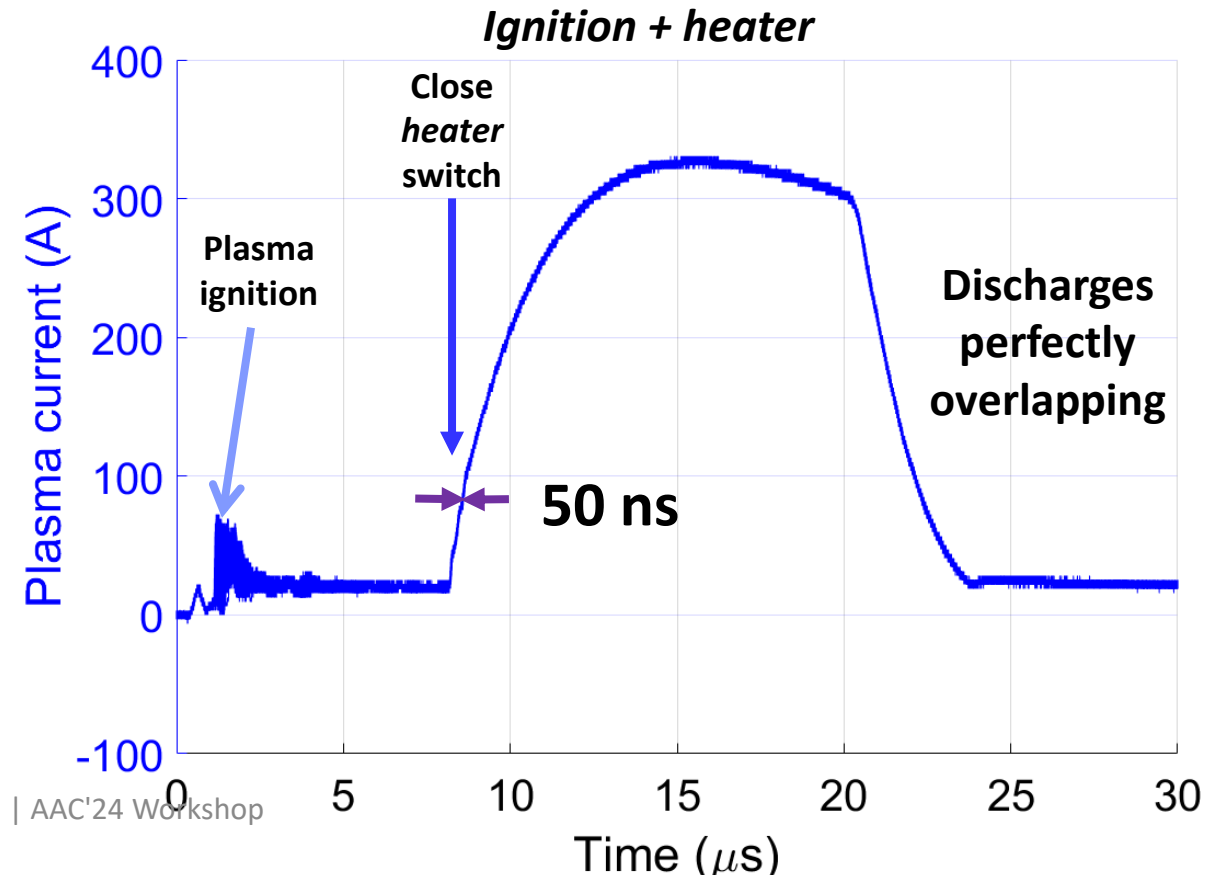
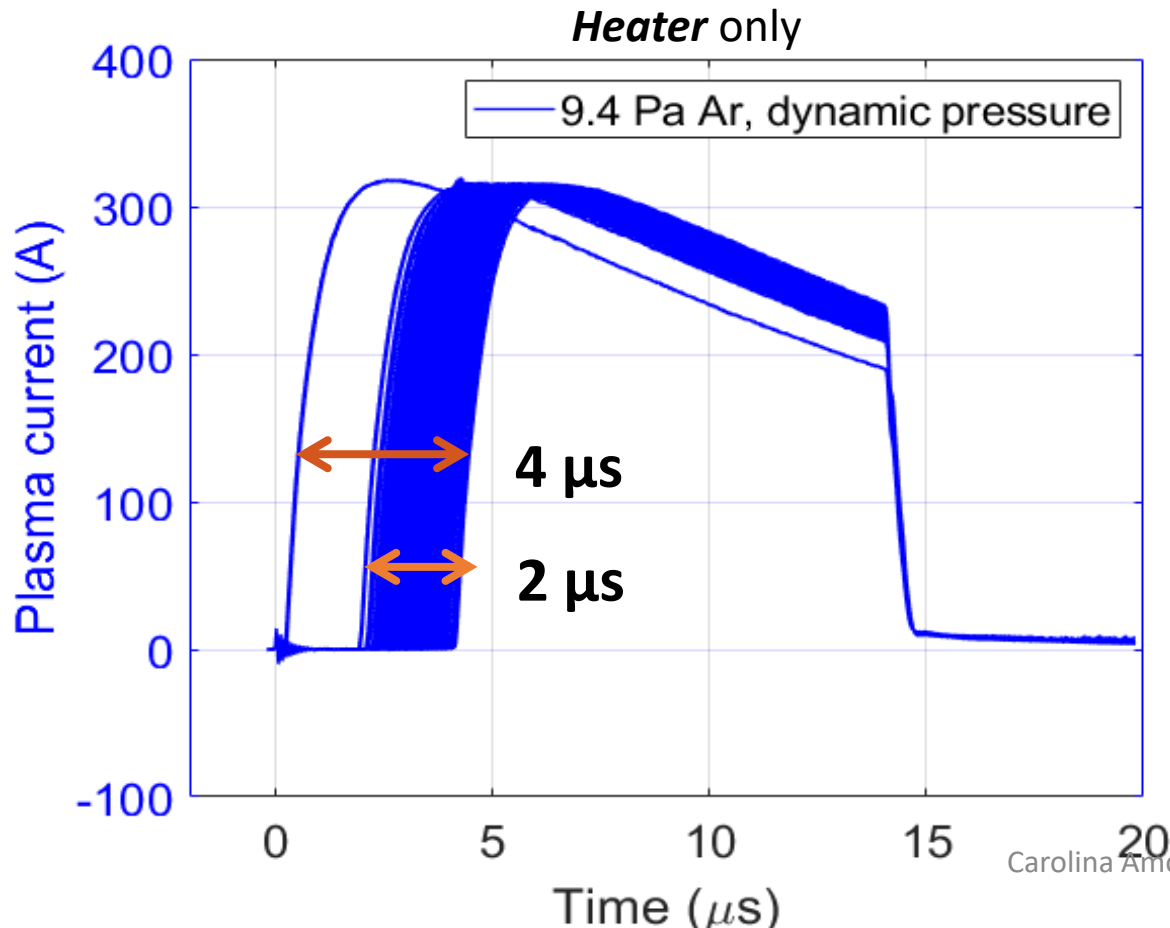
Courtesy Christine Stollberg, EPFL-SPC



# DPS 1.6 m prototype

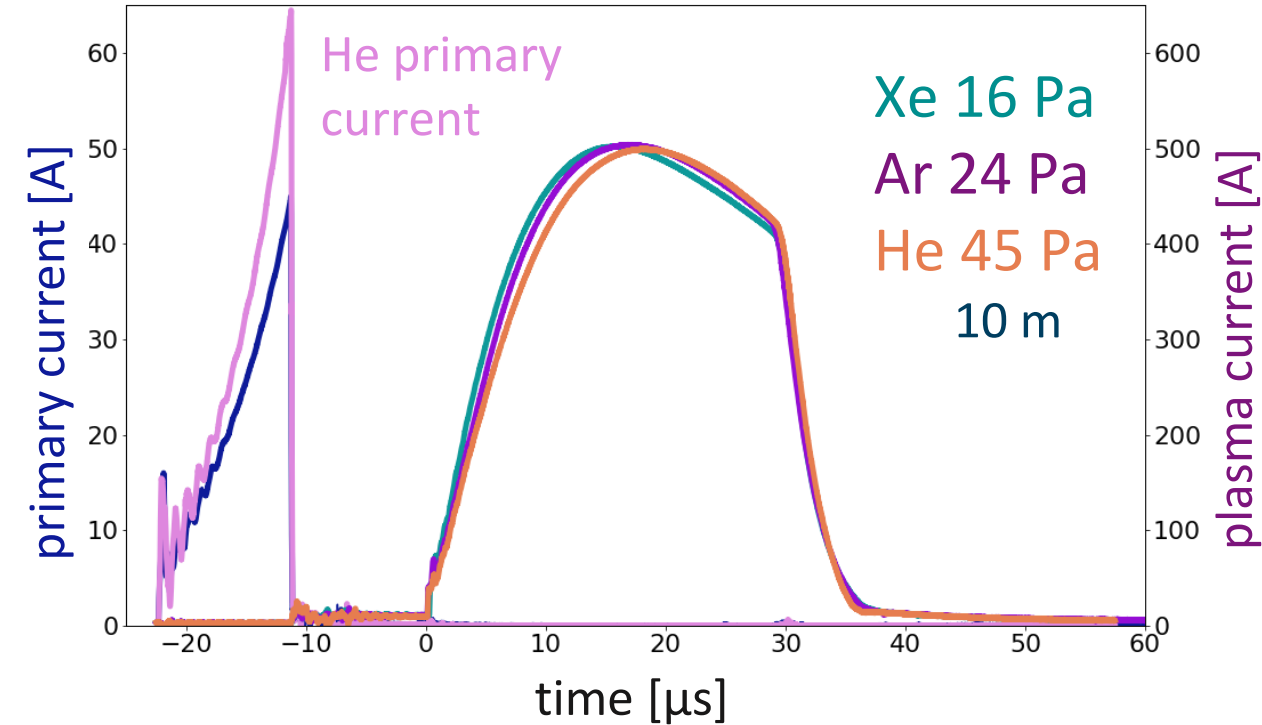
## Double pulse discharge

- 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



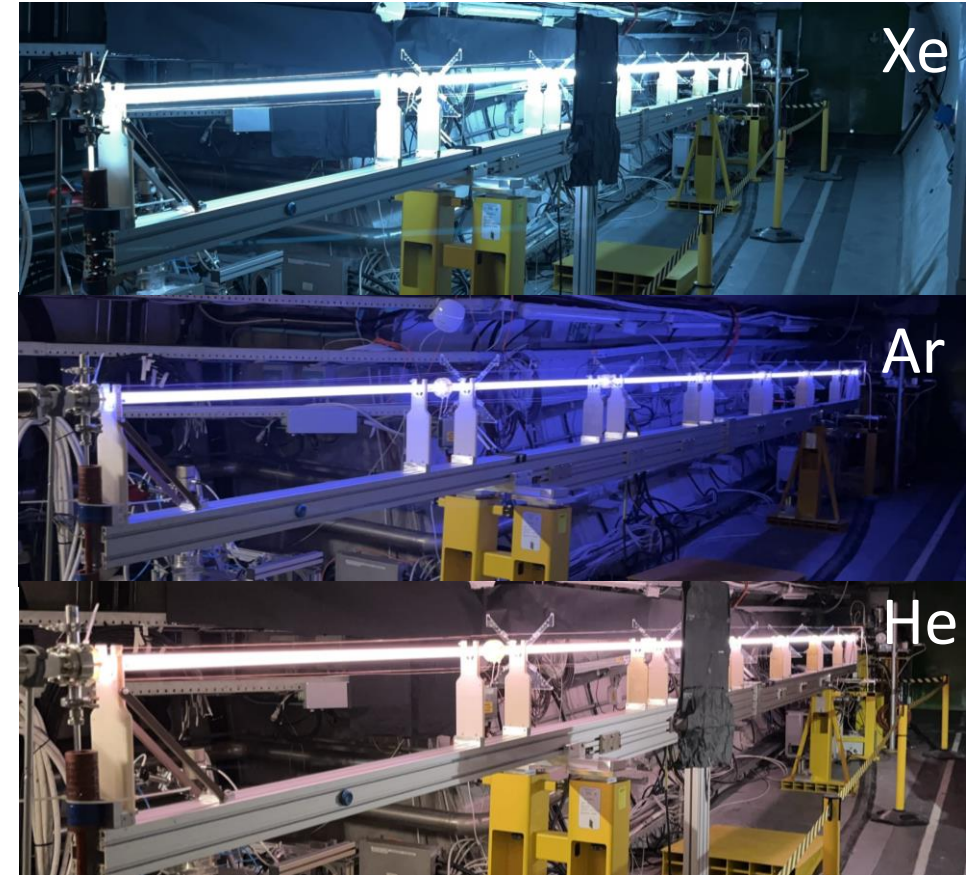
# May 2023 proton run

## Operation range – Gases



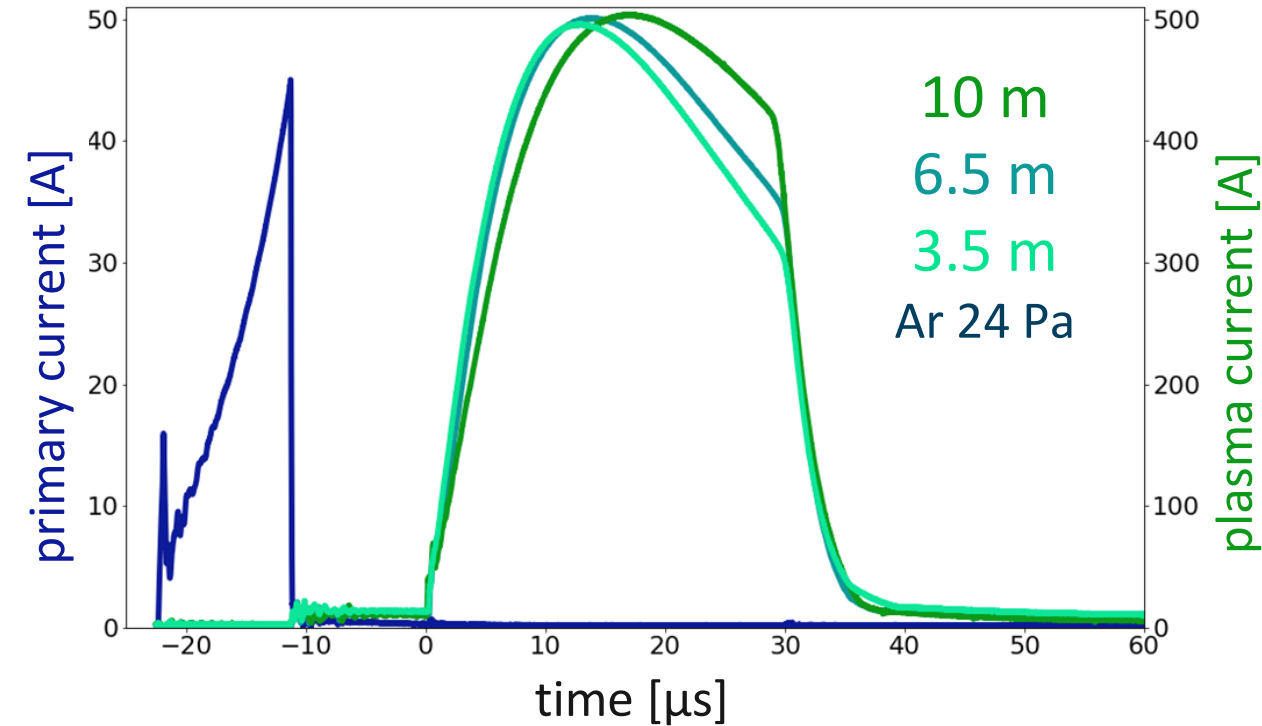
The pulse generators reach the target currents in all three gases

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



# May 2023 proton run

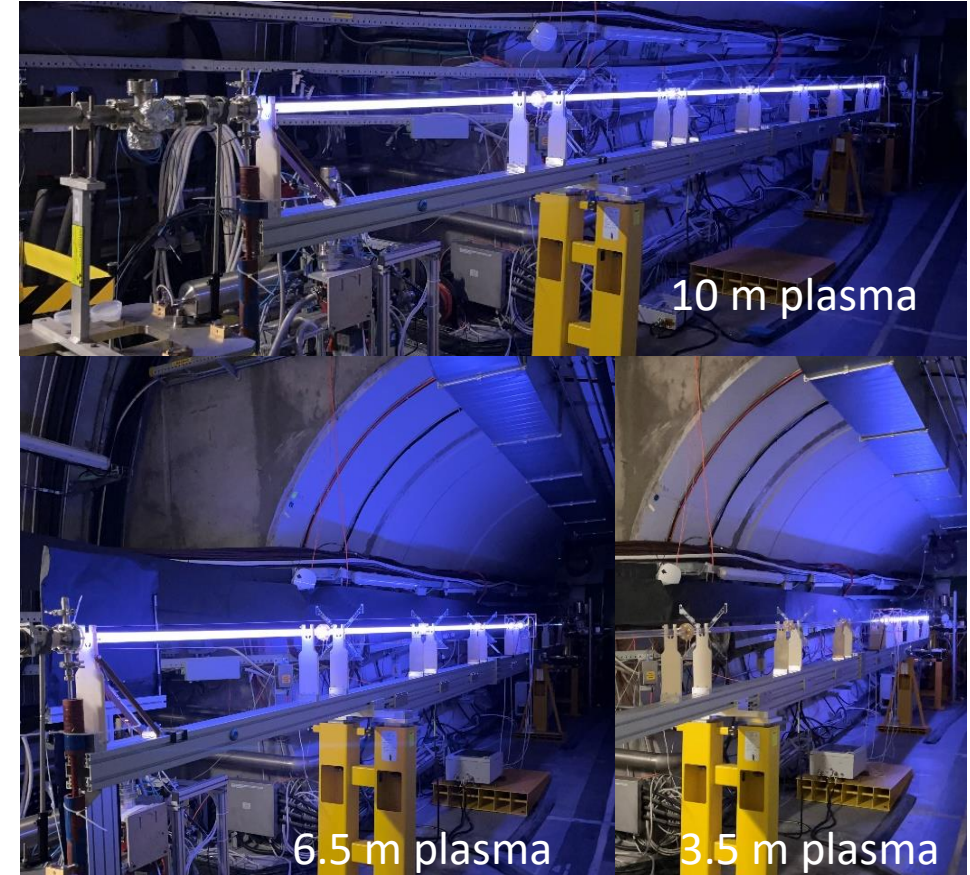
## Operation range – Length



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

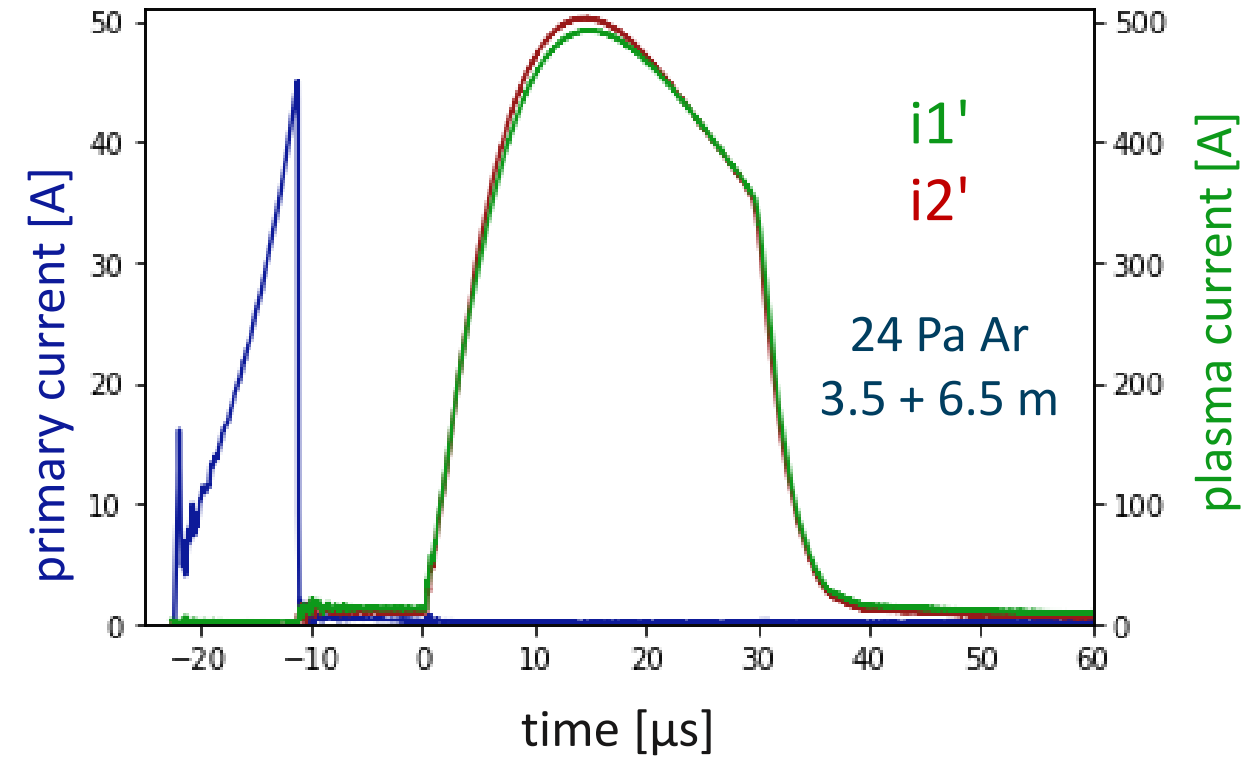
Plasma length affects the load impedance, thus causing differences in the pulse shape





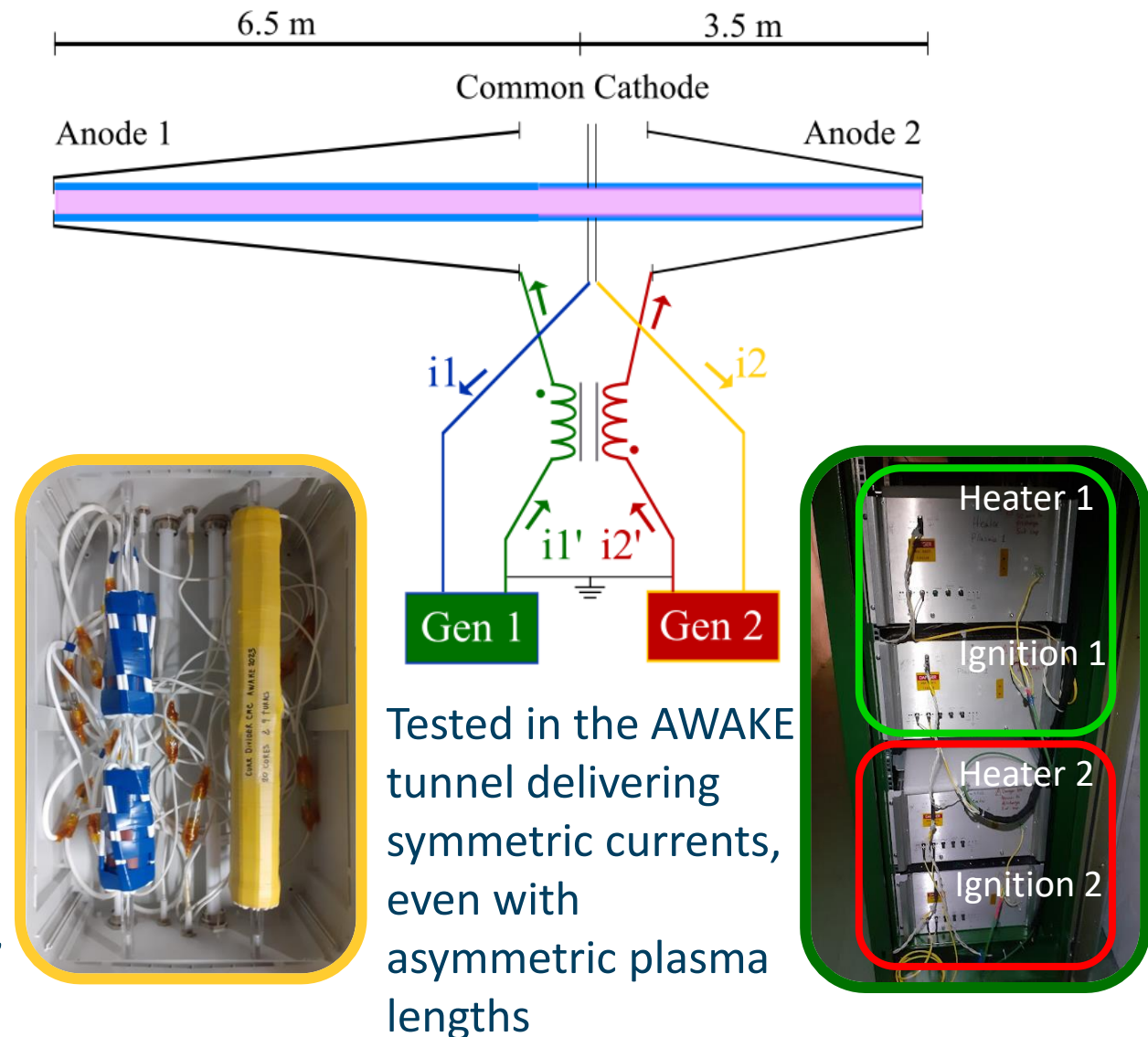
# May 2023 proton run

## 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