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

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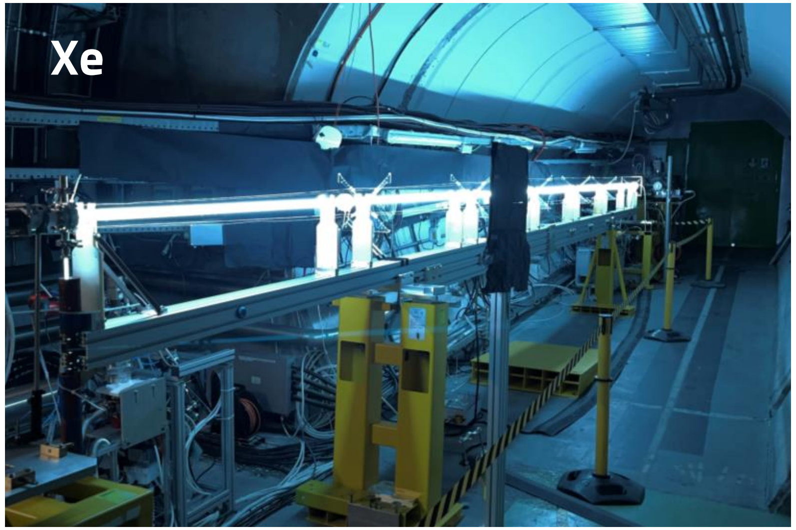
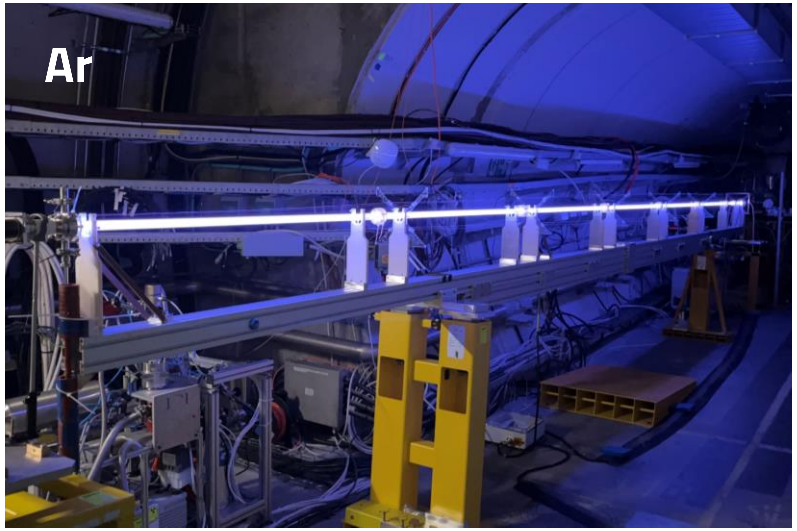
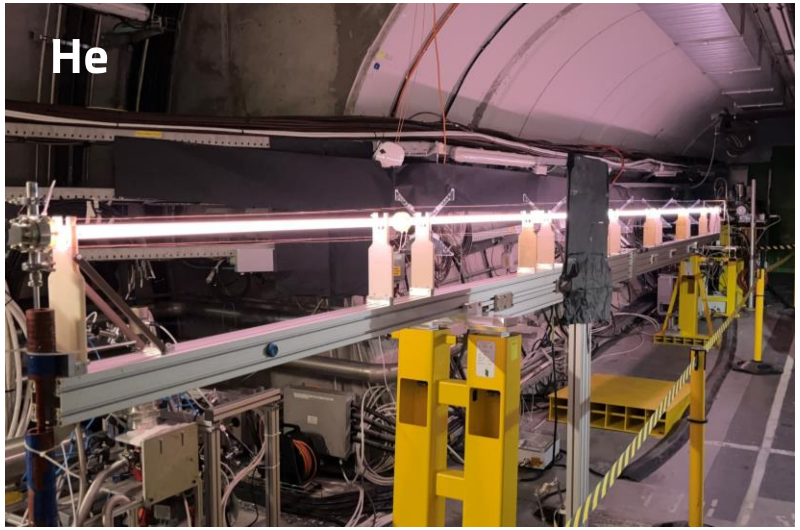
G. Zevi Della Porta[1,4], J. Pučeк[1], M. Bergamaschi[4], A. Clairembaud[4], J. Mezger[4], F. Pannell[5],
N. Van Gils[6], E. Gschwendtner[1], M. Taborelli[1], A. Sublet[1] *and the AWAKE Collaboration*

AAC'24 Workshop
22/07/2024

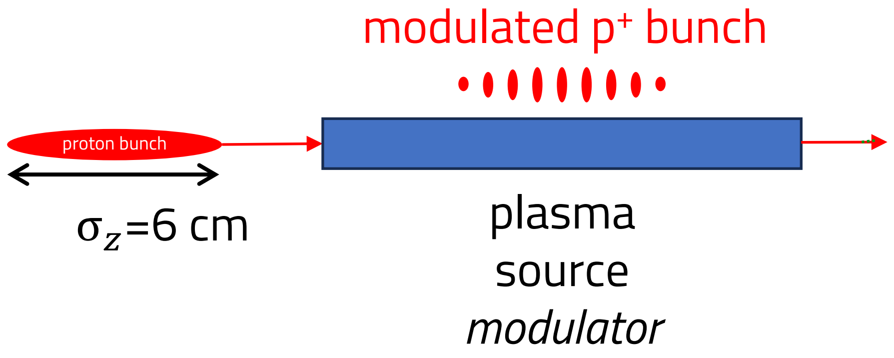






[1]CERN, Geneva, Switzerland, [2]GoLP/IPFN, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal, [3]INESC-ID, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal, [4]Max Planck Institute for Physics, Munich, Germany, [5]UCL, London, United Kingdom,[6]University of Groningen, Groningen, Netherlands,[*]Present Address: INFN Laboratori Nazionali di Frascati, 00044 Frascati, Italy

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



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

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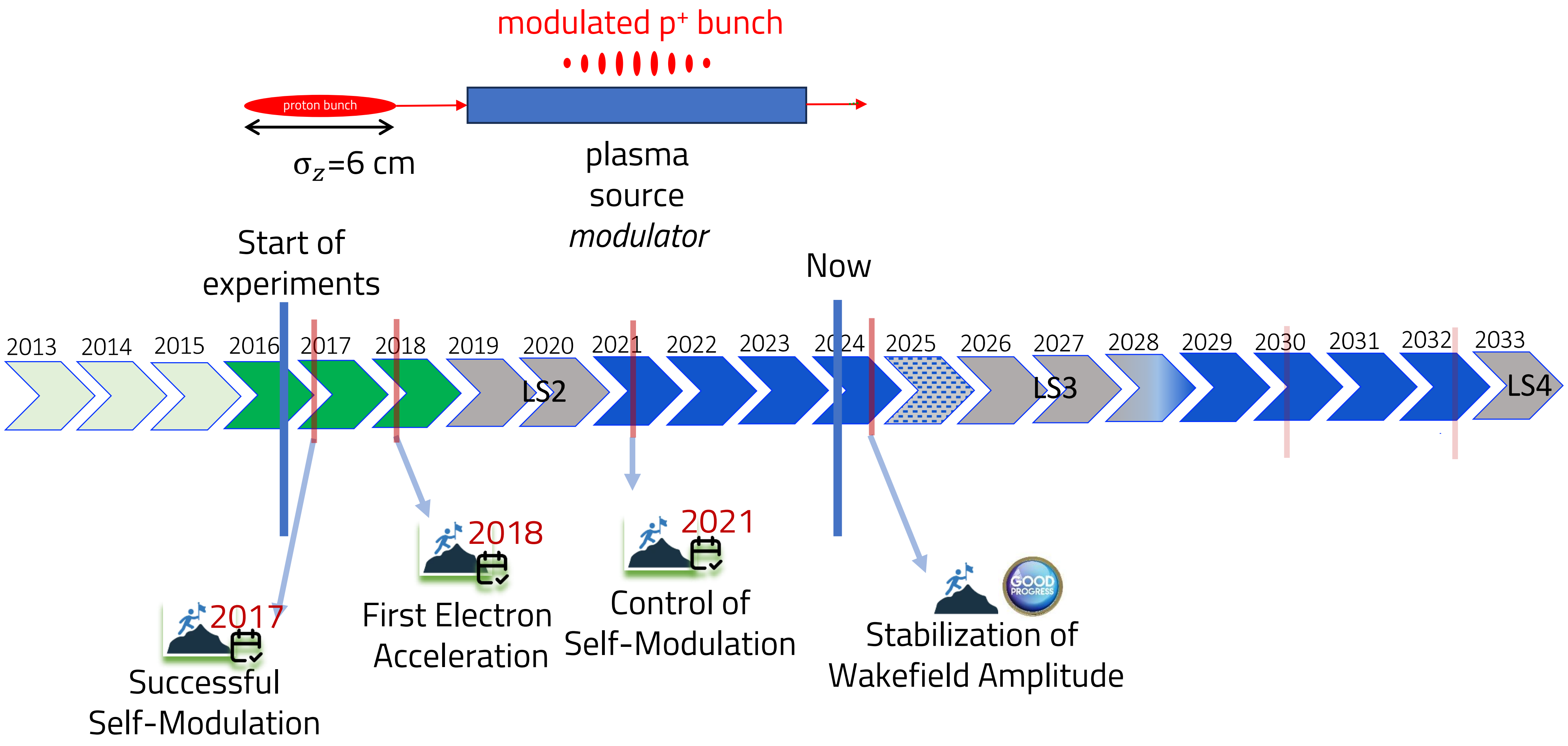

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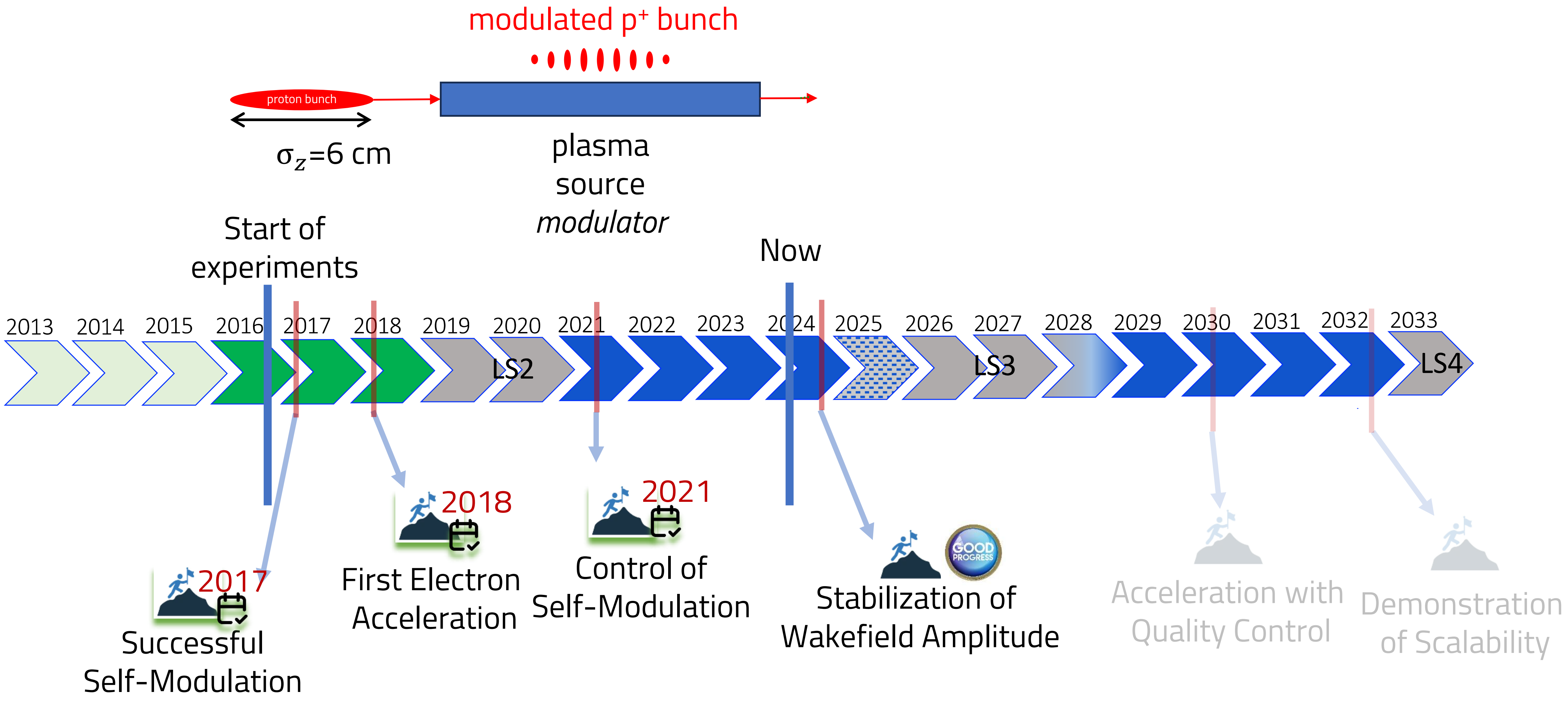

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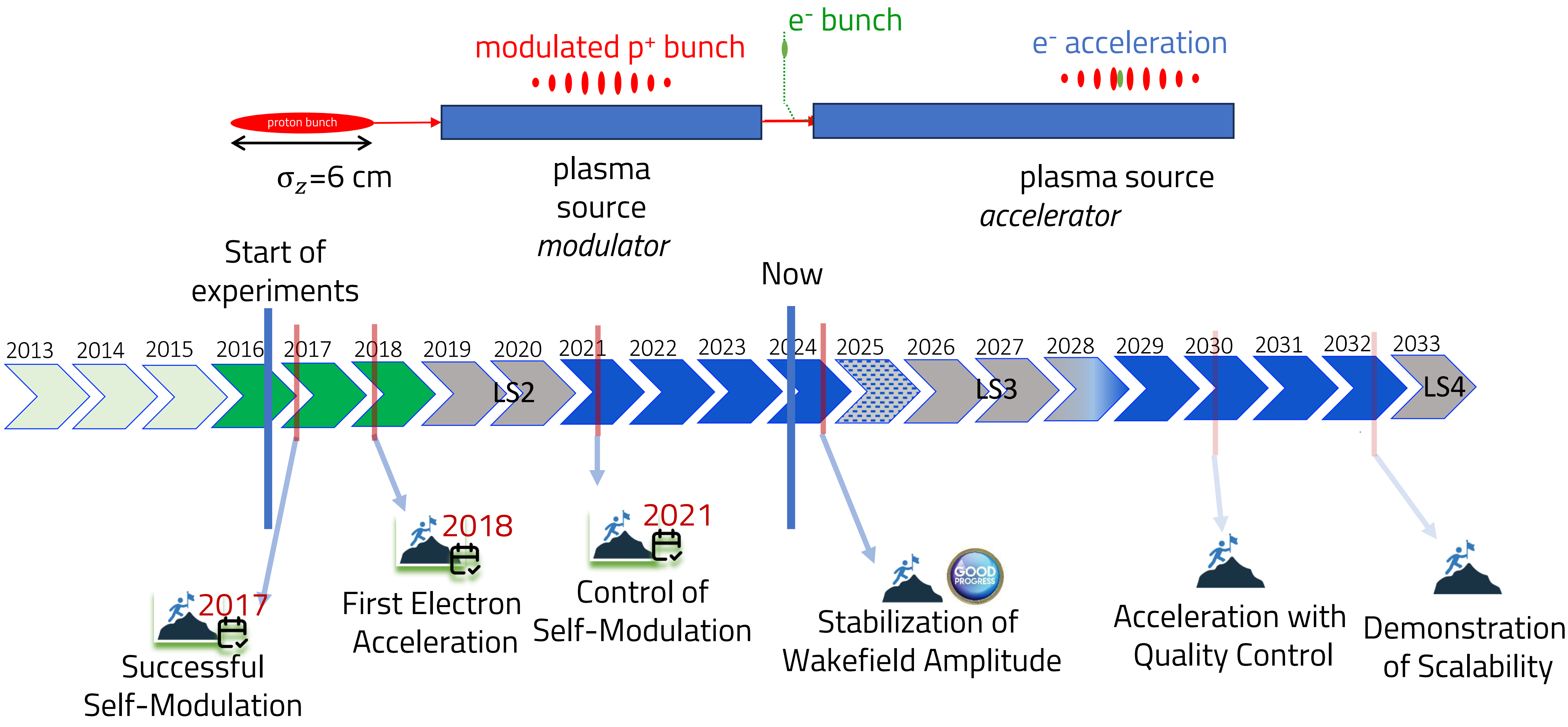

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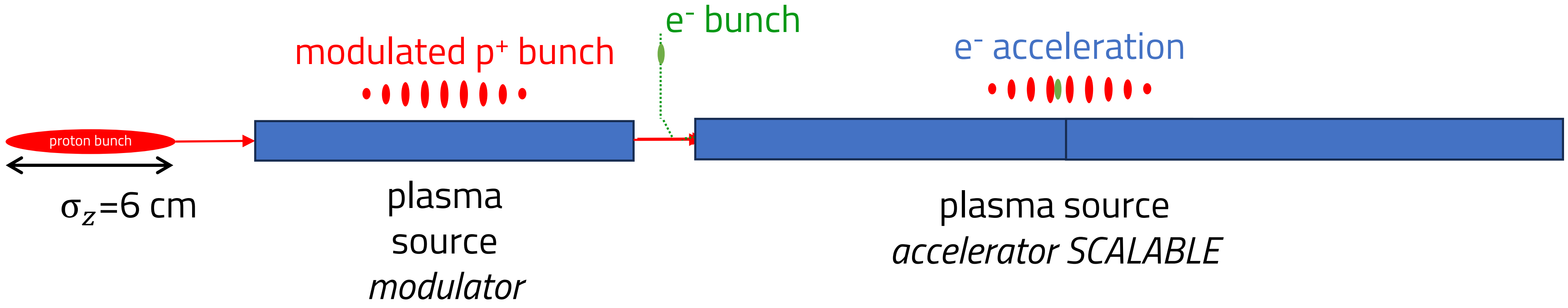
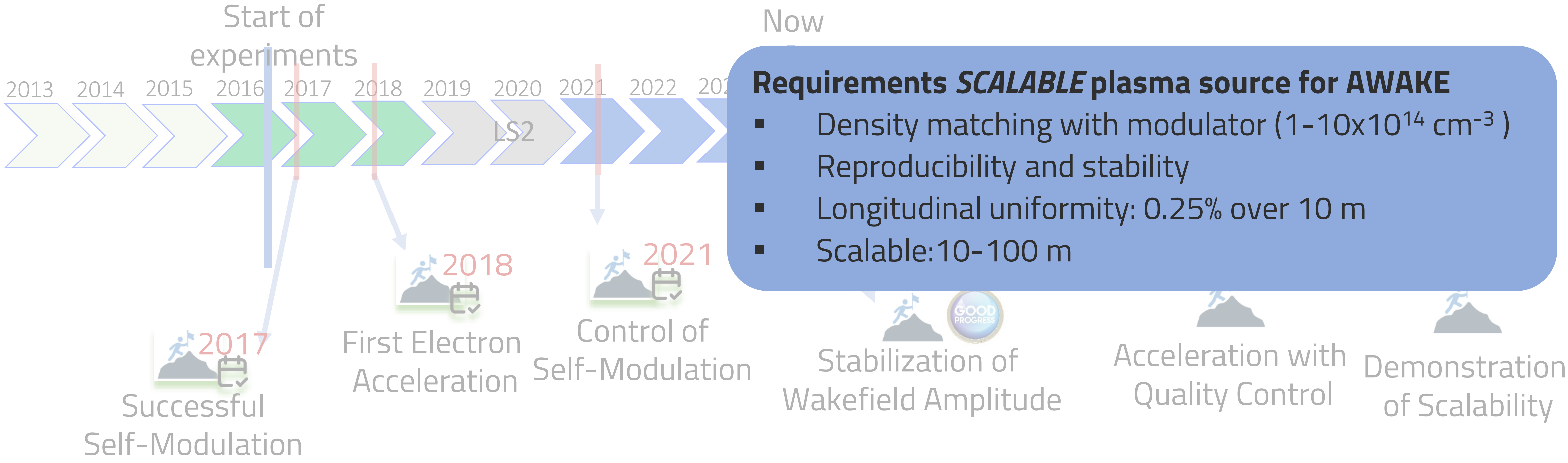


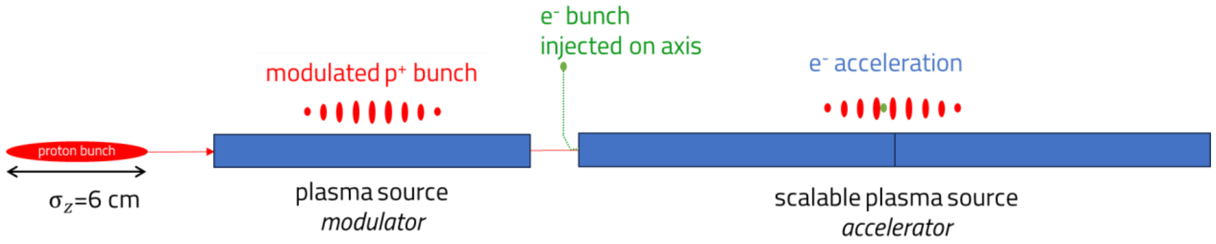


Requirements *SCALABLE* plasma source for AWAKE

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

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

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

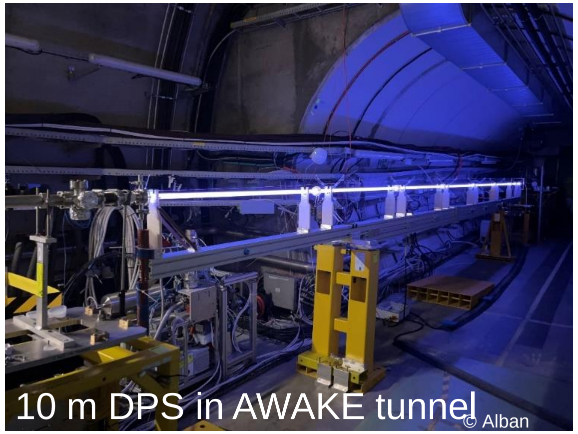


Requirements scalable plasma source for AWAKE

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

Discharge Plasma Source (DPS)

→ pulsed-DC discharge

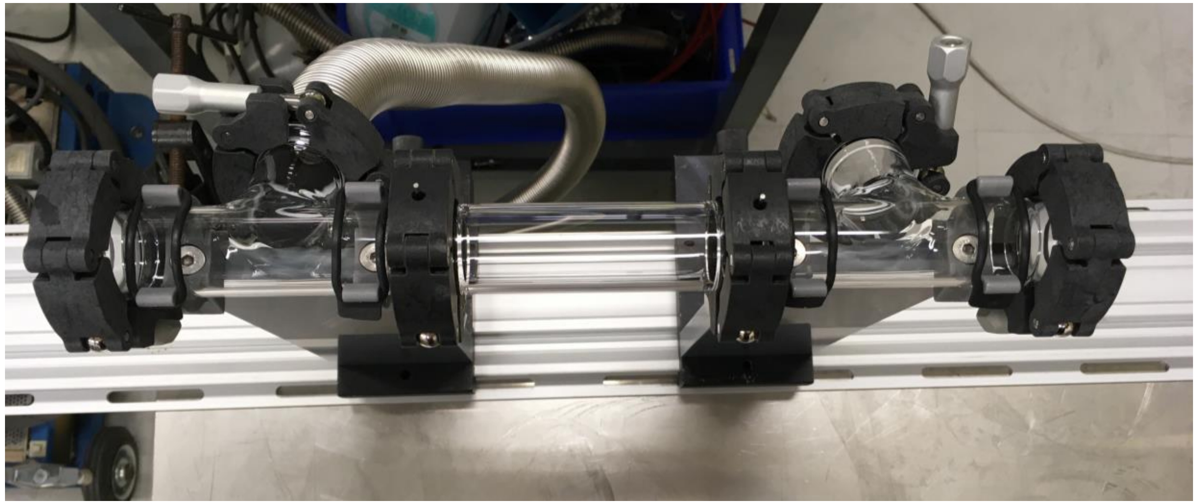


CERN

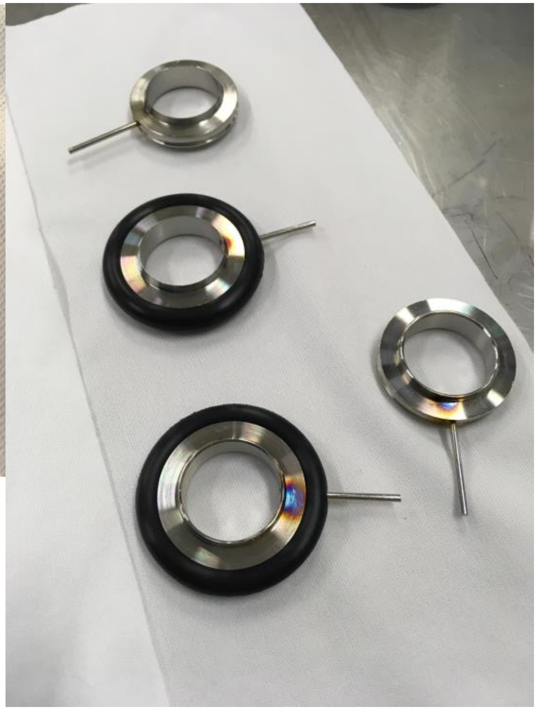
TÉCNICO LISBOA

Imperial College London

Start by 10 cm...

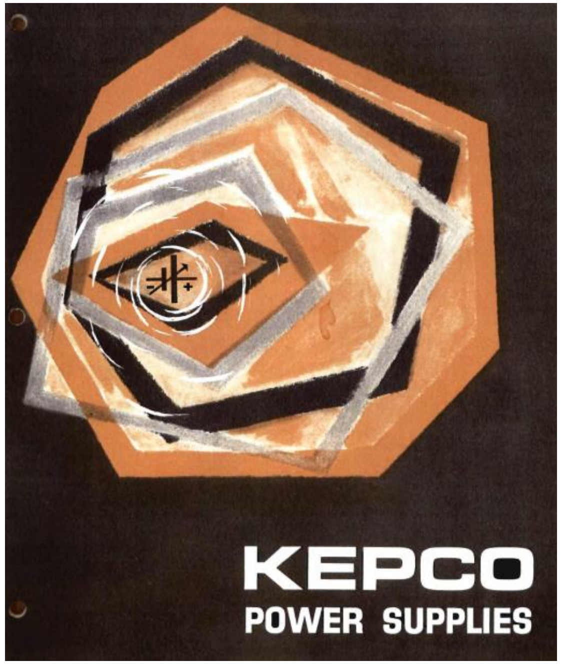


Glass tube
+ gas + vaccum



Some electrodes

Catalogue of power suplies



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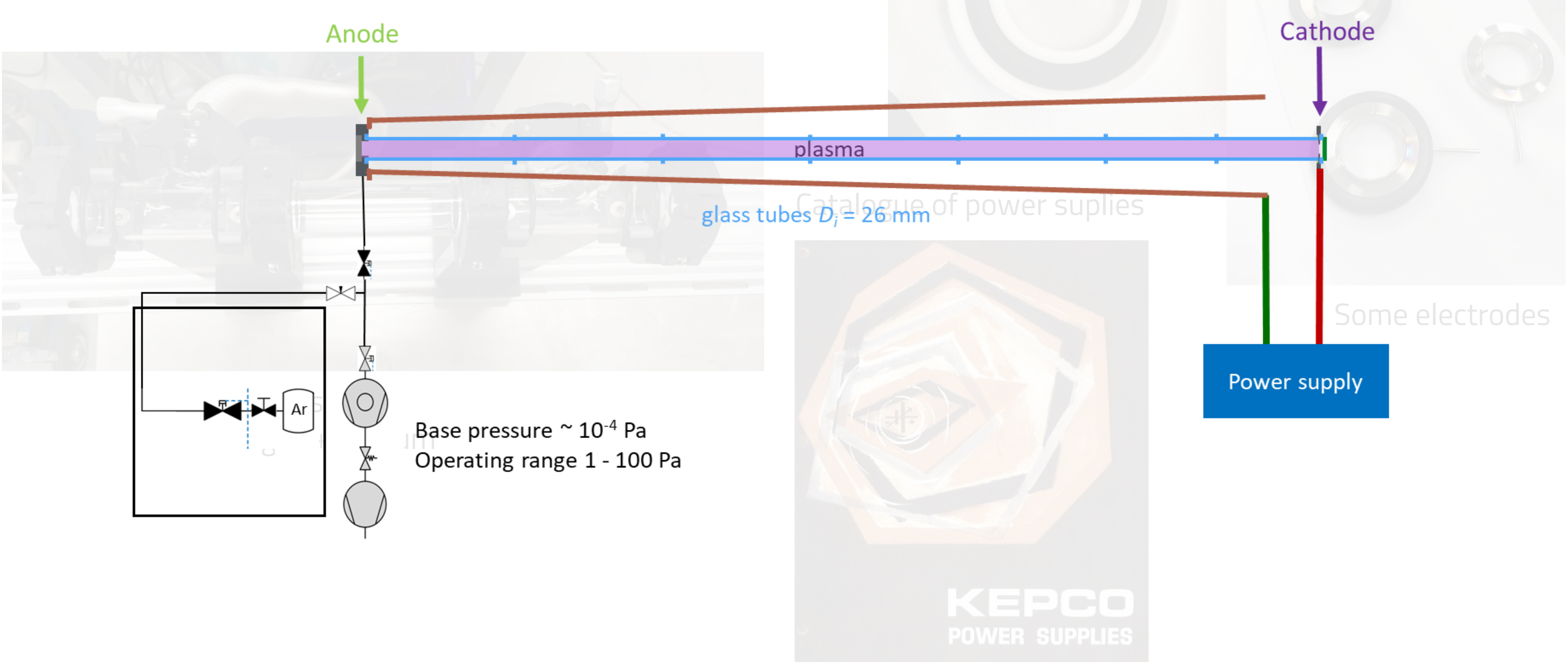
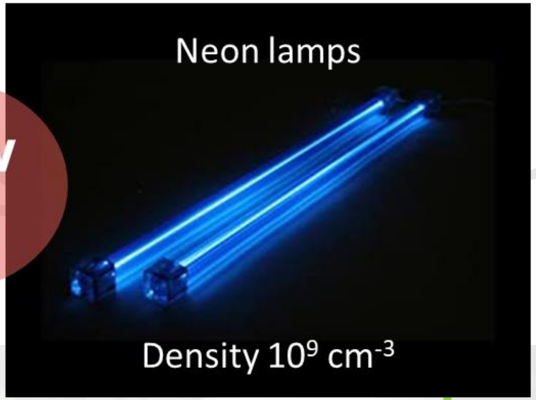
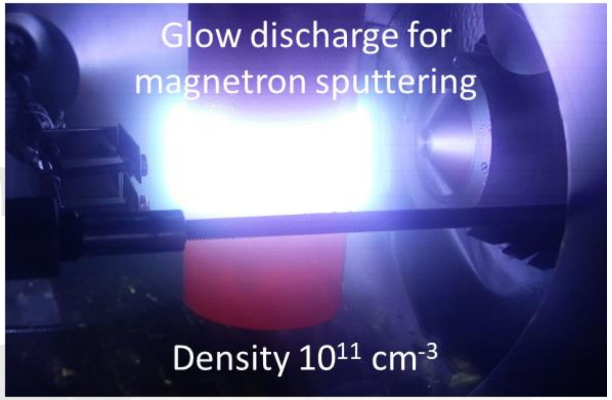
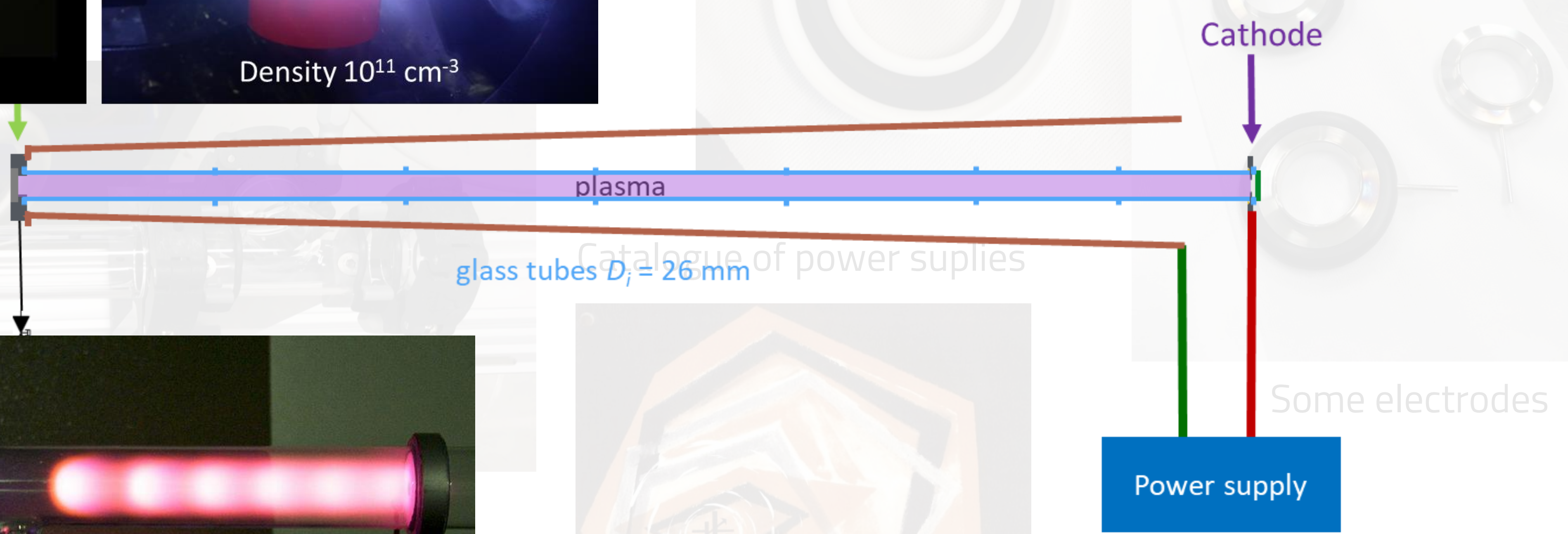


glow
mA







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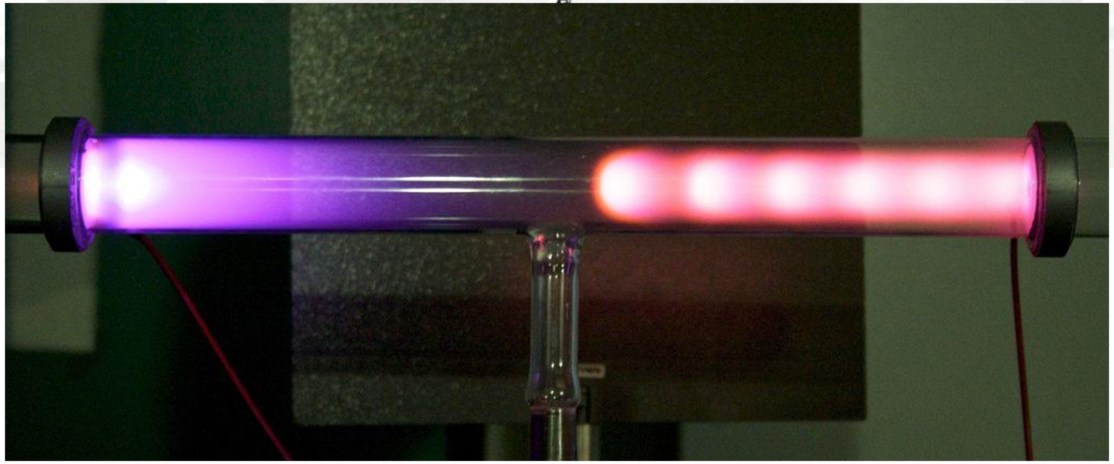
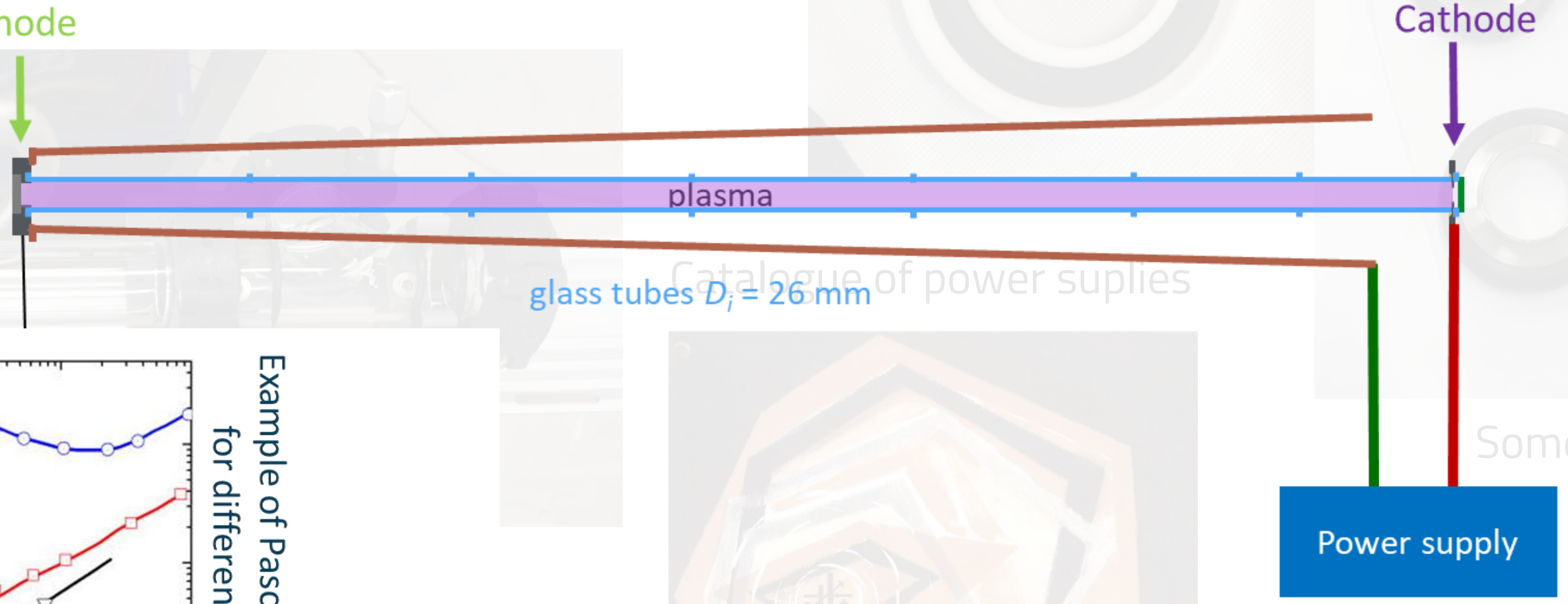


Example electrical glow discharge

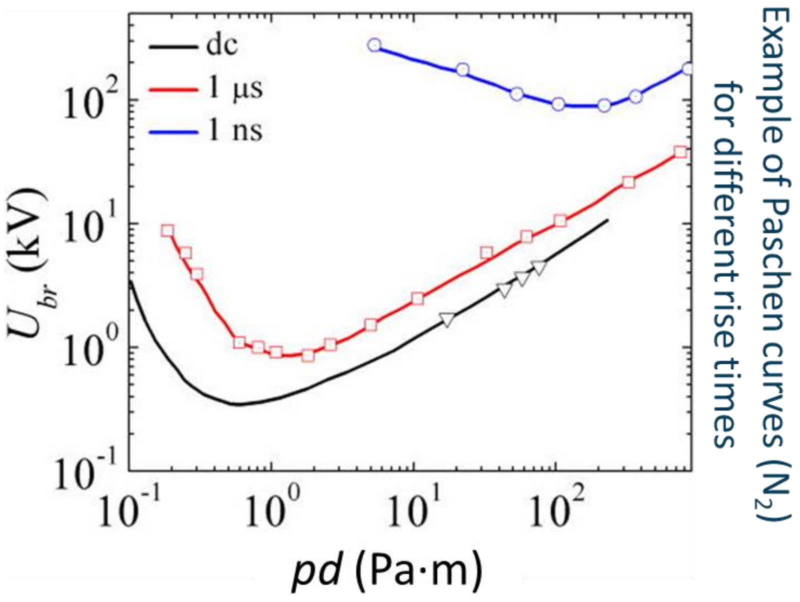
- Densities are not high enough → unless arc regime
- Plasma is not uniform enough → unless pulsed to μs

Start by 10 cm…



Catalogue of power suplies

Some electrodes

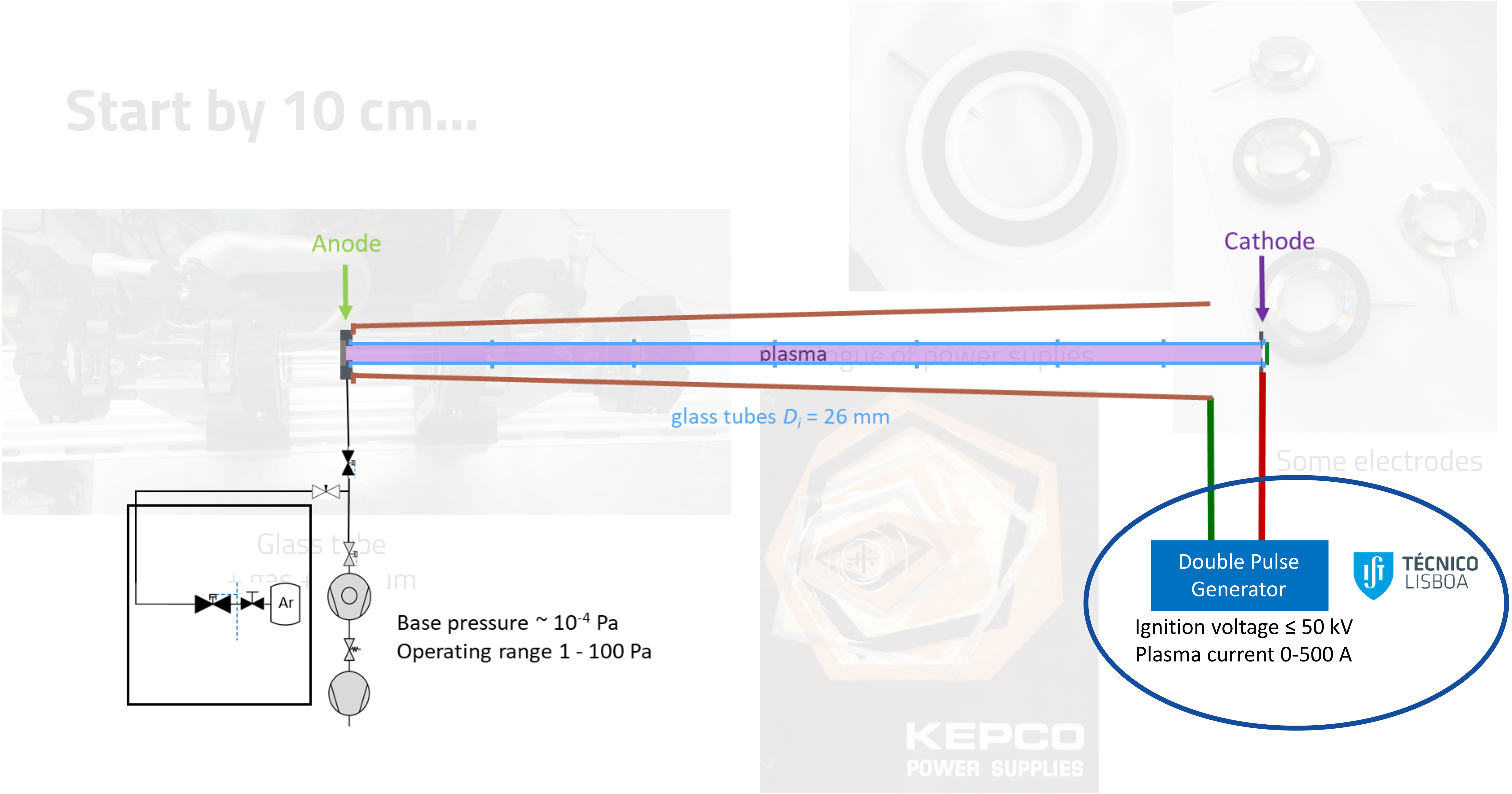


Example of Paschen curves (N_2) for different rise times

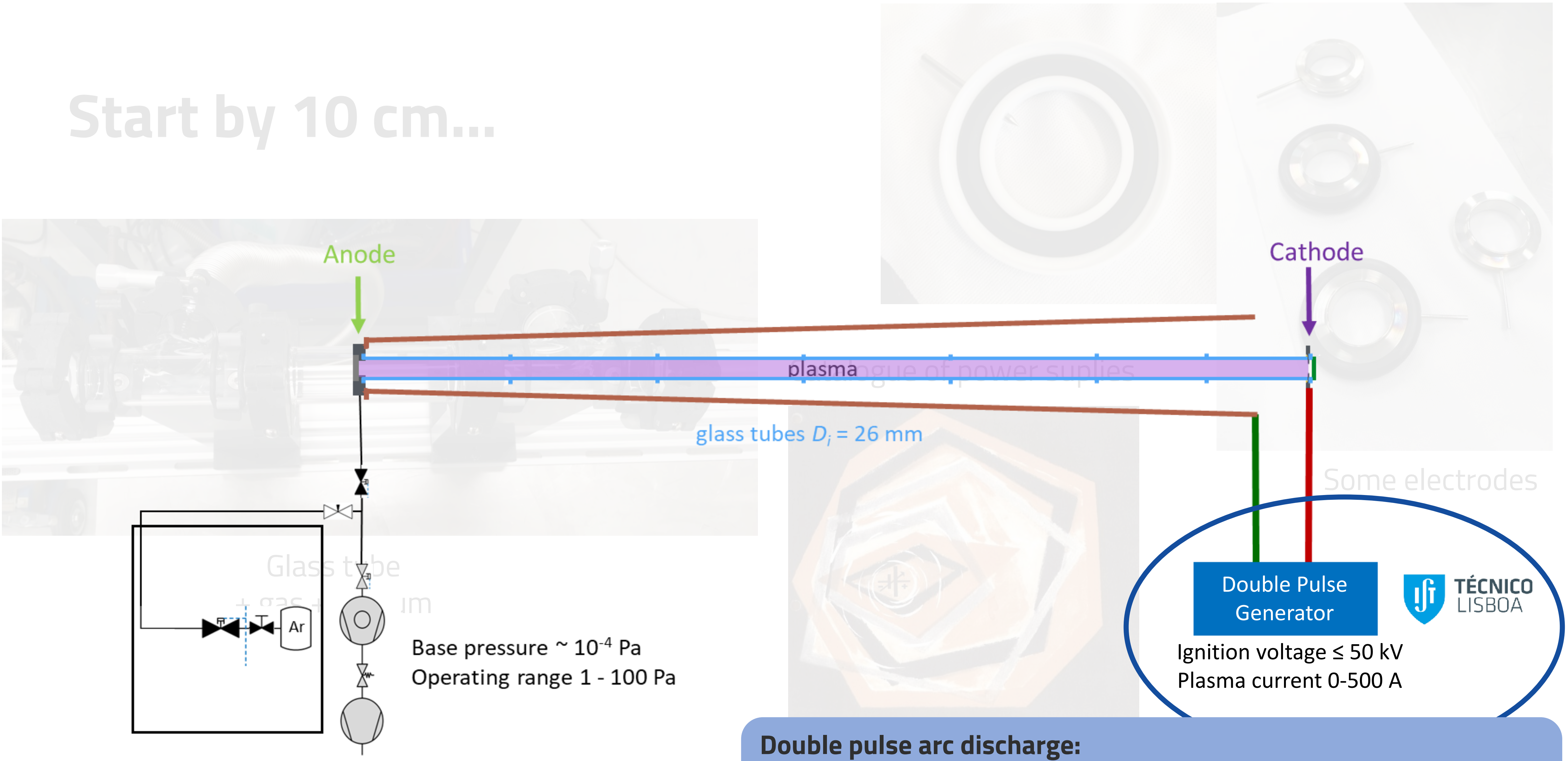
Levko et. al, Phys. Plasmas 26 (2019)

- Densities are not high enough → unless arc regime
- Plasma is not uniform enough → unless pulsed to μs
- **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...

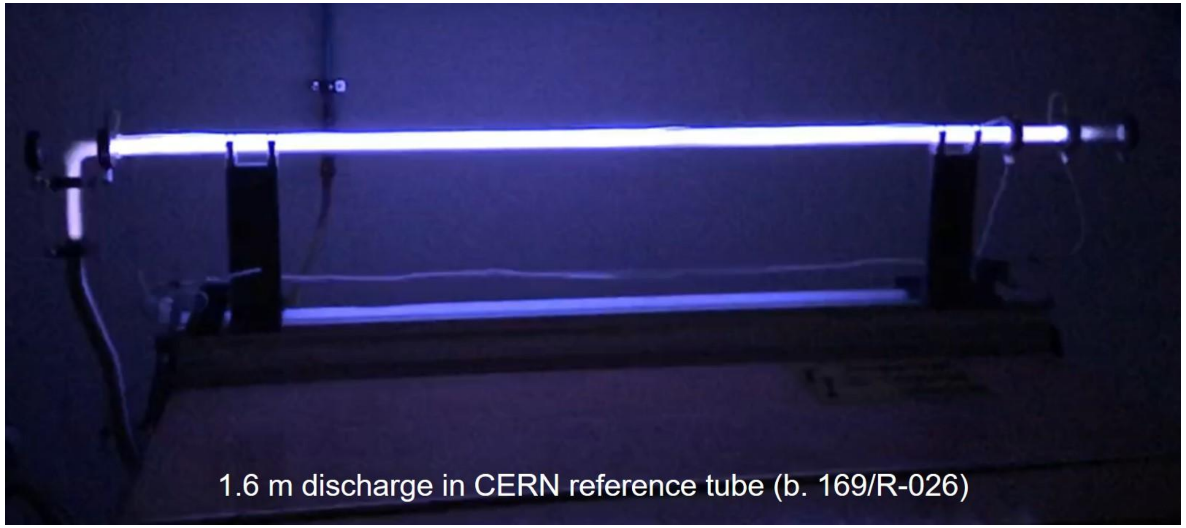


Double pulse arc discharge:

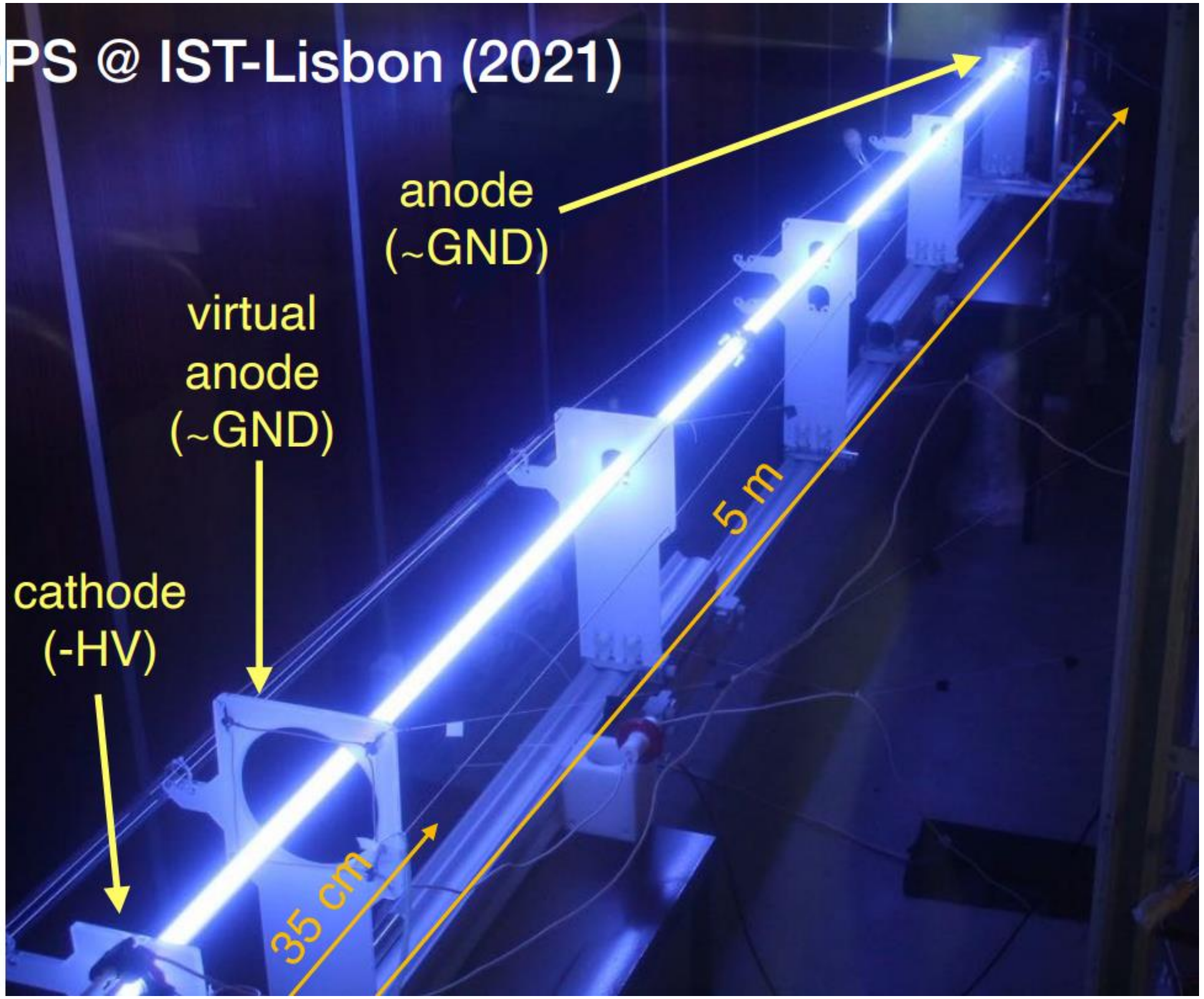
1) high voltage ignition → jitter <20 ns in plasma ignition
2) 10 to 50 μs high current pulse → achieve high plasma densities

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

Scaling up

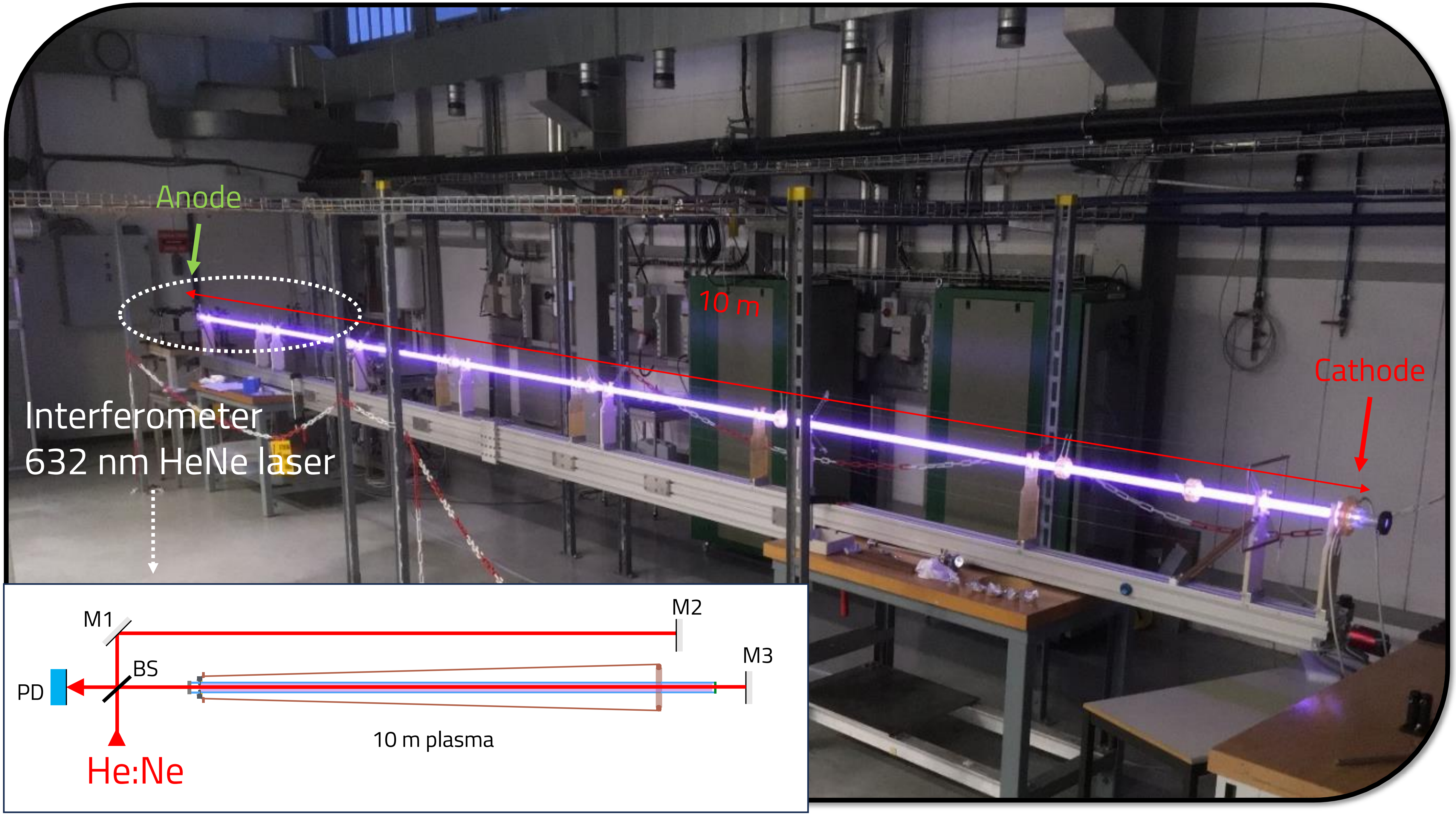

1.6 m discharge in CERN reference tube (b. 169/R-026)

AWAKE DPS @ IST-Lisbon (2021)



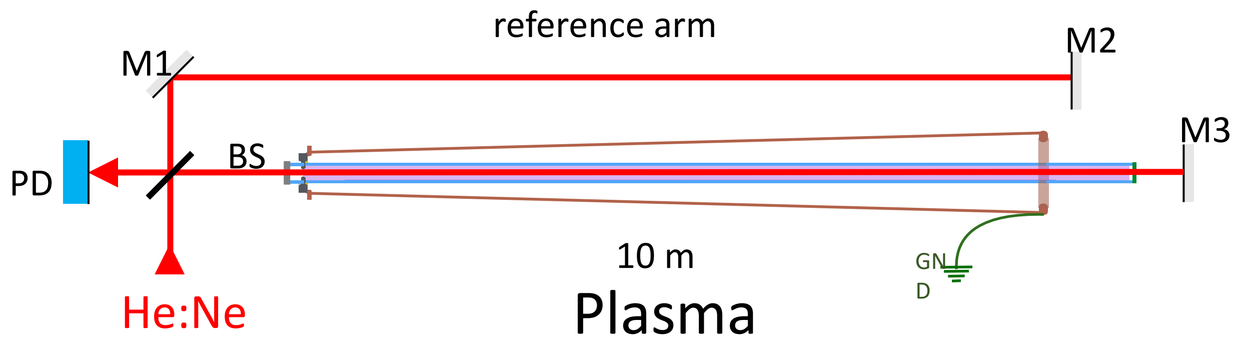
empty lab - June 2022 - to do a 10 m DPS

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


Anode
10 m
Cathode
Interferometer
632 nm HeNe laser
M1
M2
M3
BS
PD
10 m plasma
He:Ne

Plasma density diagnostic

Longitudinally integrated interferometry

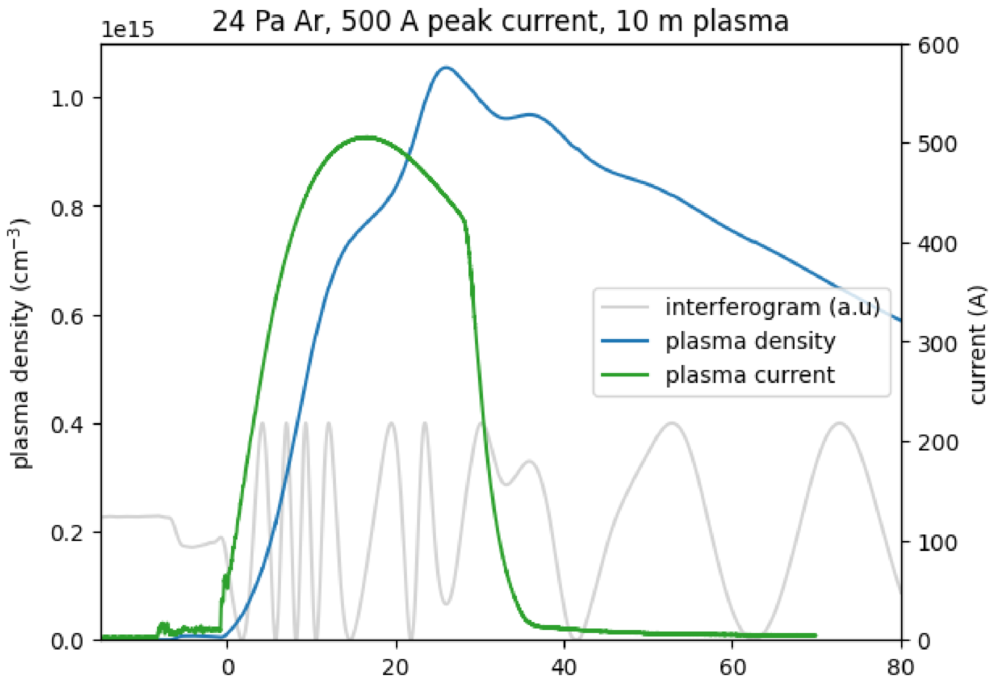


- ► Michelson interferometer
- ► Measurement arm (plasma) adds a phase shift ϕ_i proportional to the plasma density n_e:

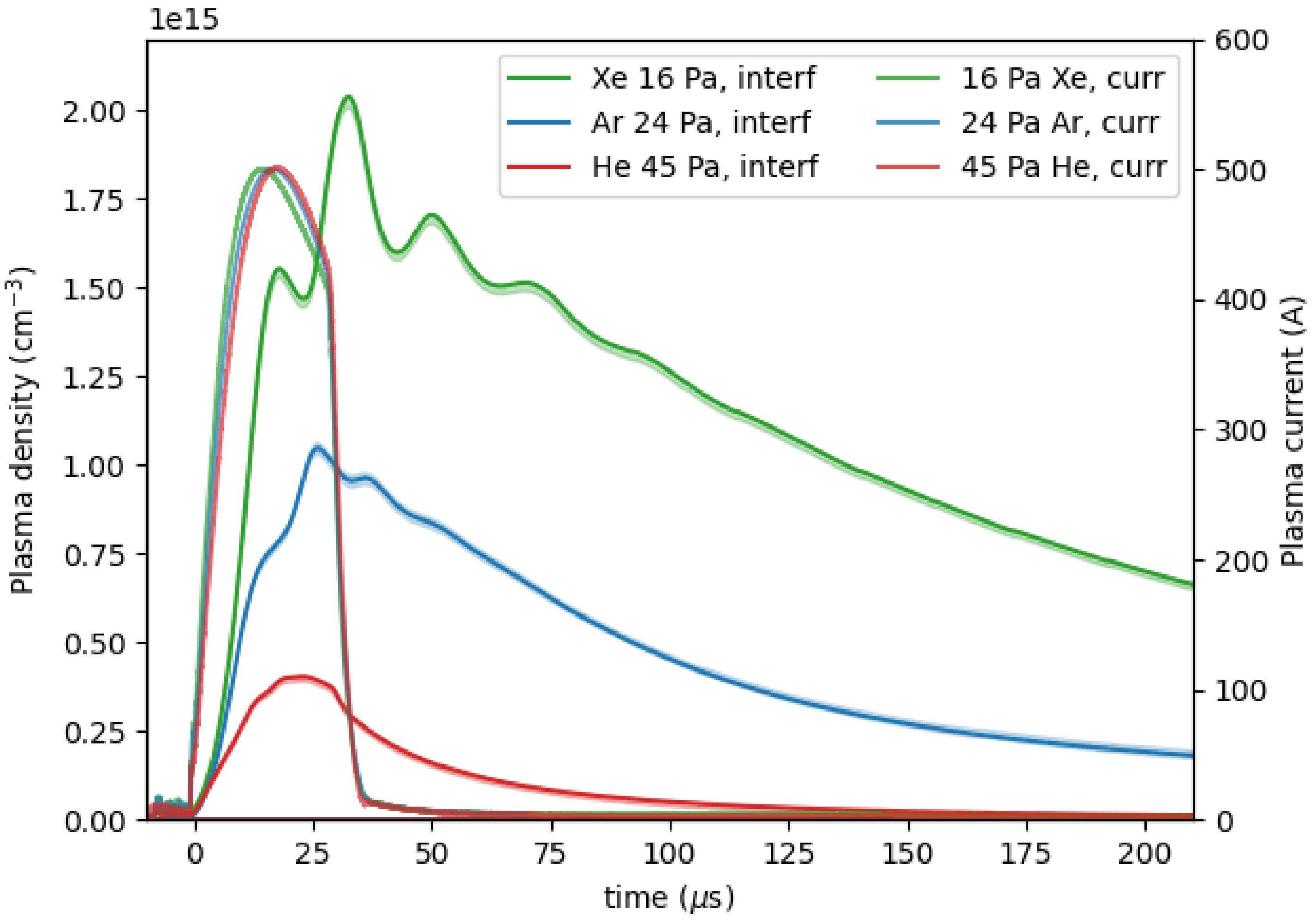
$$\phi_i = \frac{n_e}{r_e \lambda_i L}$$

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.

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

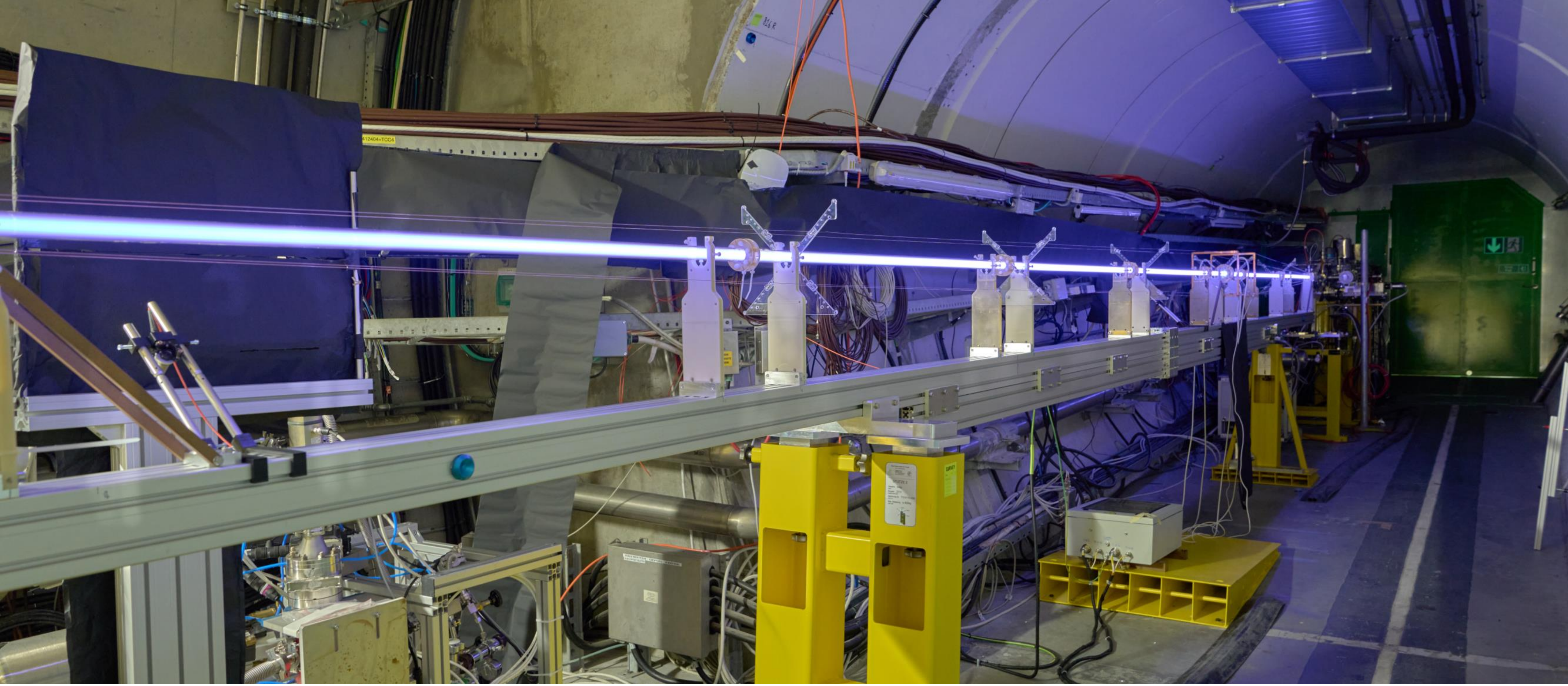


► **Time-evolution of the plasma density, line integrated over the 10 m**



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

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



Discharge Plasma Source

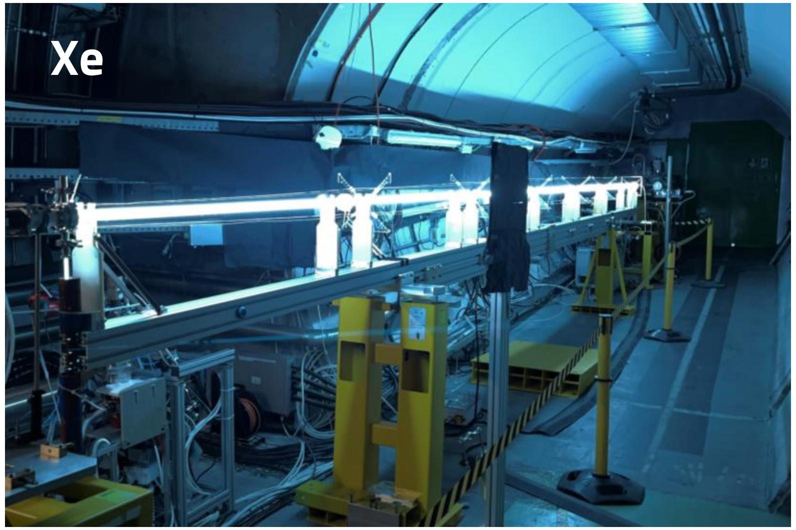
(3 Weeks of p+ beamtime in 2023)

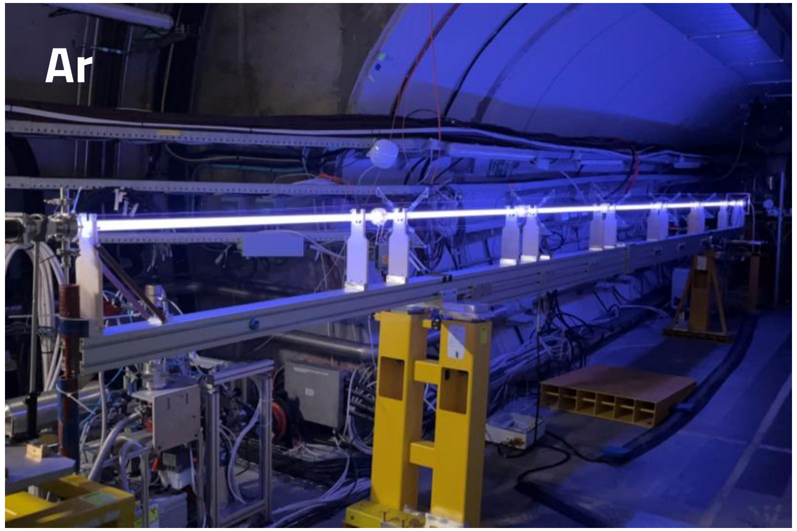
10 m DPS in AWAKE

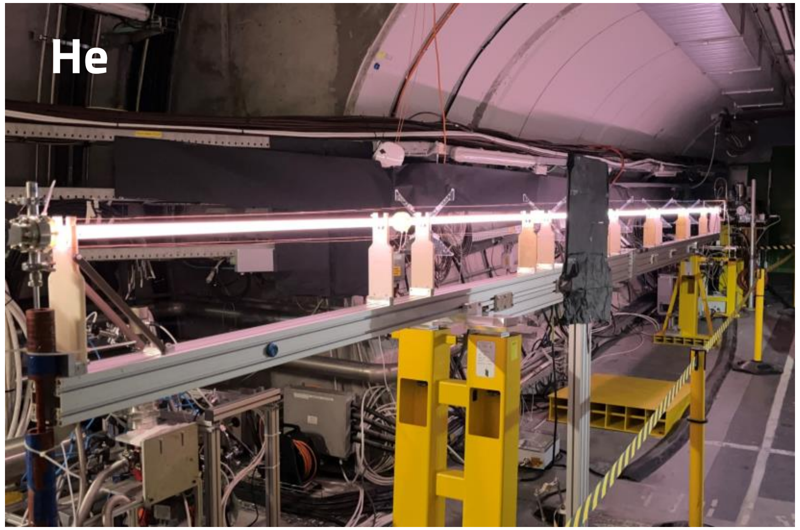
→ unique chance to test an alternative plasma source in AWAKE:

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%





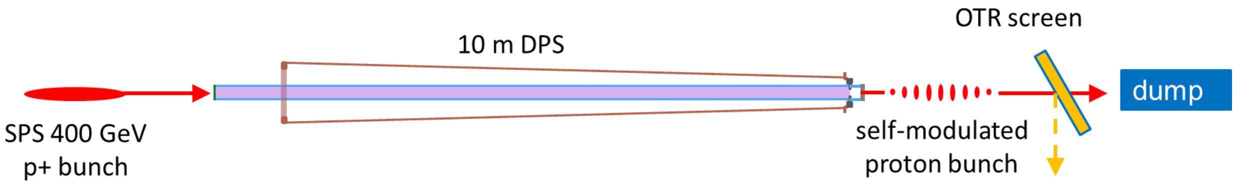


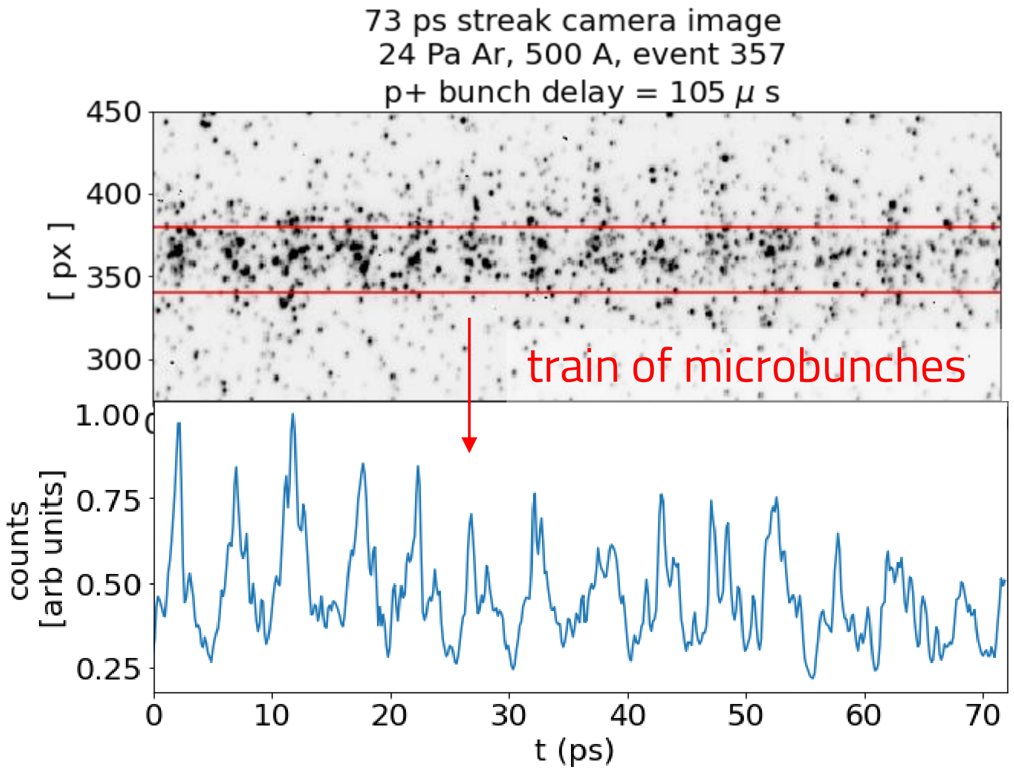
10 m DPS in AWAKE

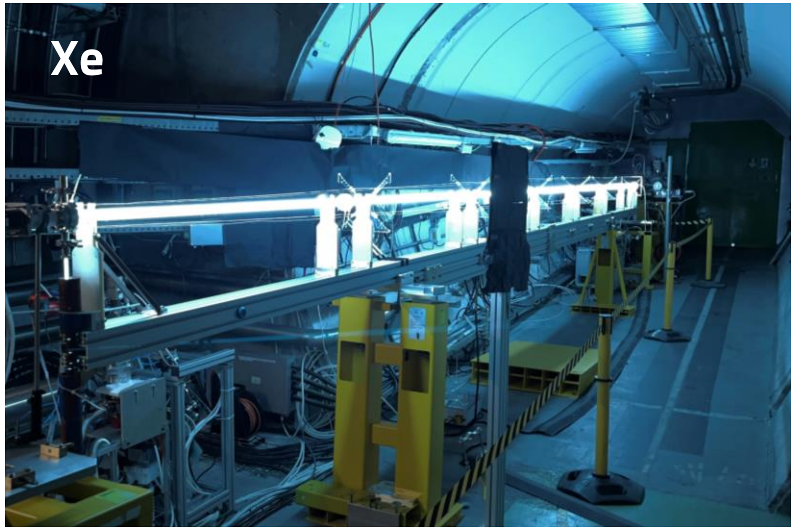
→ **unique chance to test an alternative plasma source in AWAKE:**

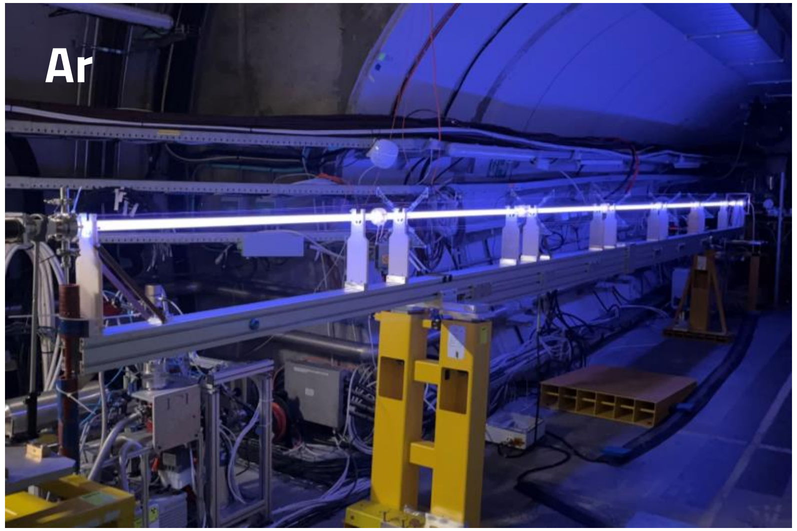
1. demonstration of operation of DPS source in AWAKE

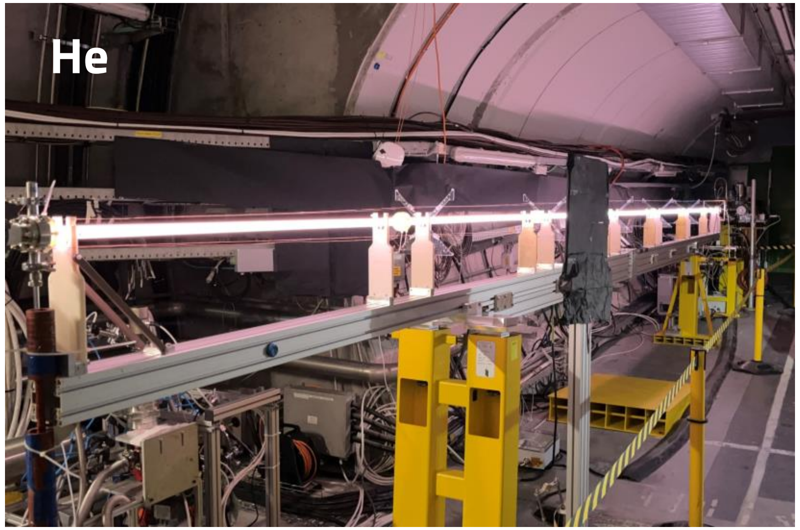
2. **Self Modulation Instability (SMI) ?**







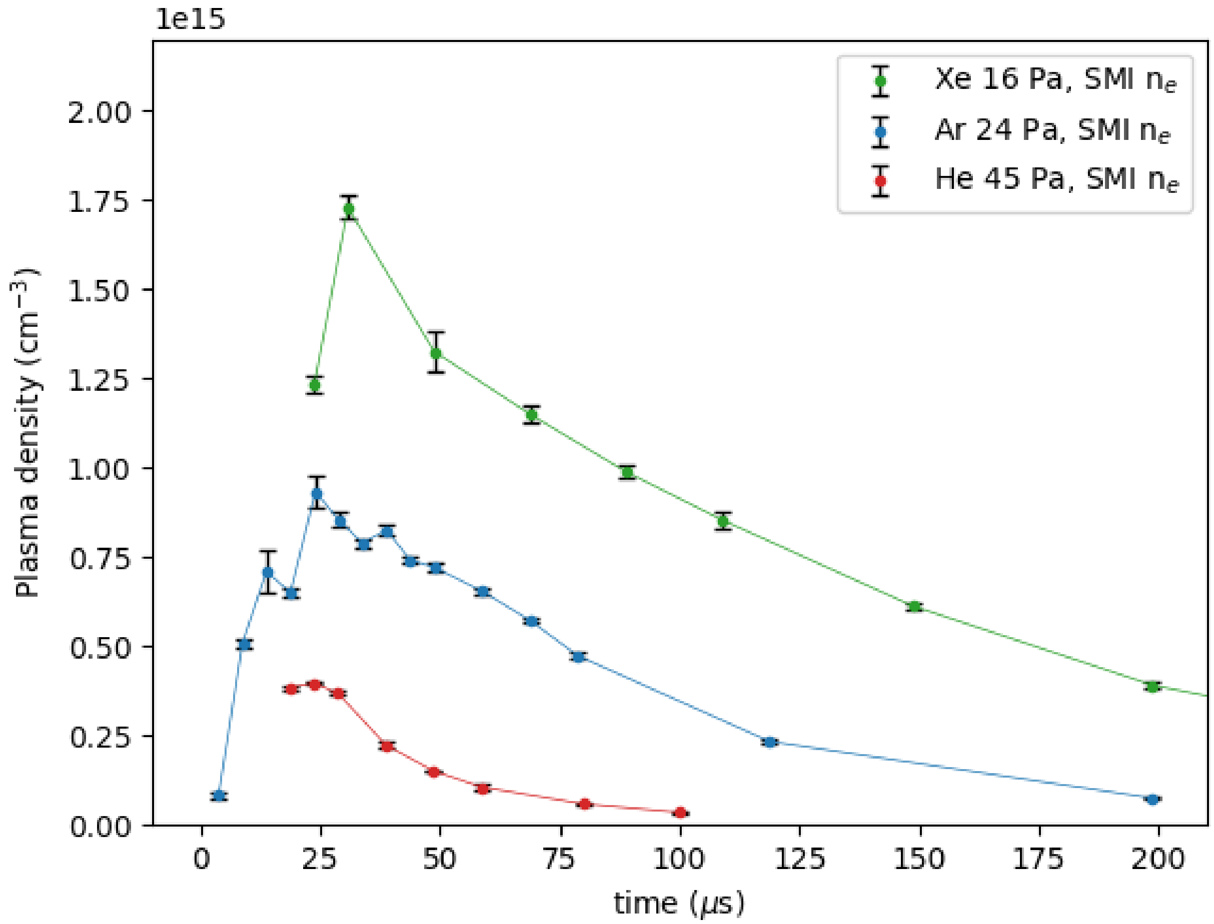




Plasma electron density calculated from modulation frequency of p+ bunch

→ **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

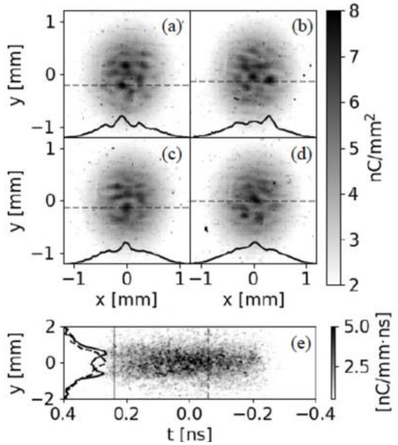


10 m DPS in AWAKE

→ 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

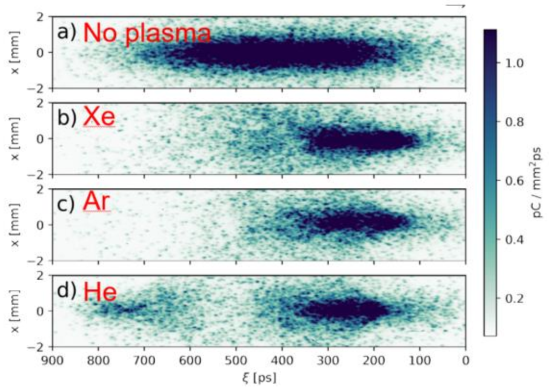


→ Wide plasma allowed to study the filamentation instability

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

→ **Next talk by L.Verra**

Ion Motion

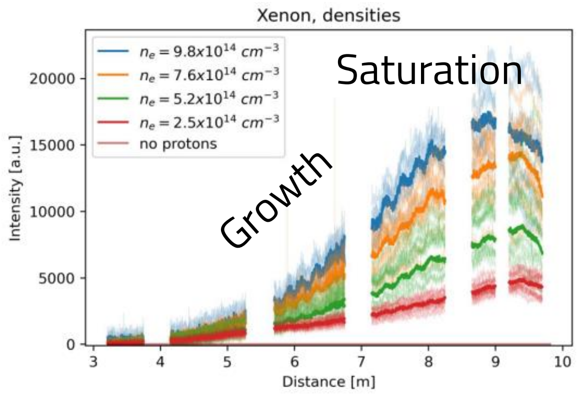


→ Flexibility in plasma ion species allowed to study the effect of ion motion on wakefields

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- 20x10^{14} 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.**

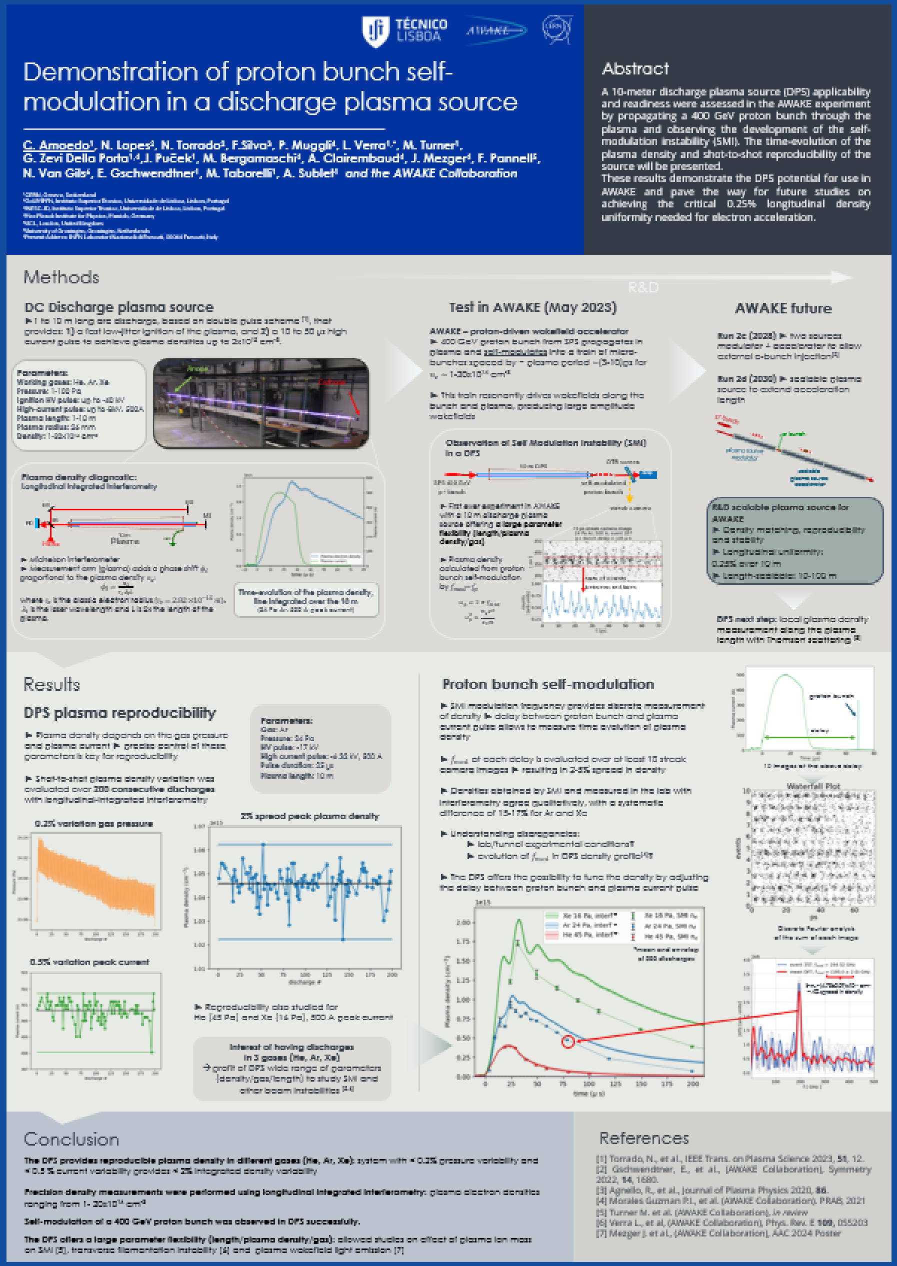
- The DPS offers a **large parameter flexibility (length/plasma density/gas)** allowing studies on effect of plasma ion mass on SMI, transverse filamentation instability and plasma wakefield light emission

Requirements scalable plasma source for AWAKE

- ✓ Density matching with modulator (1-10x10^{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

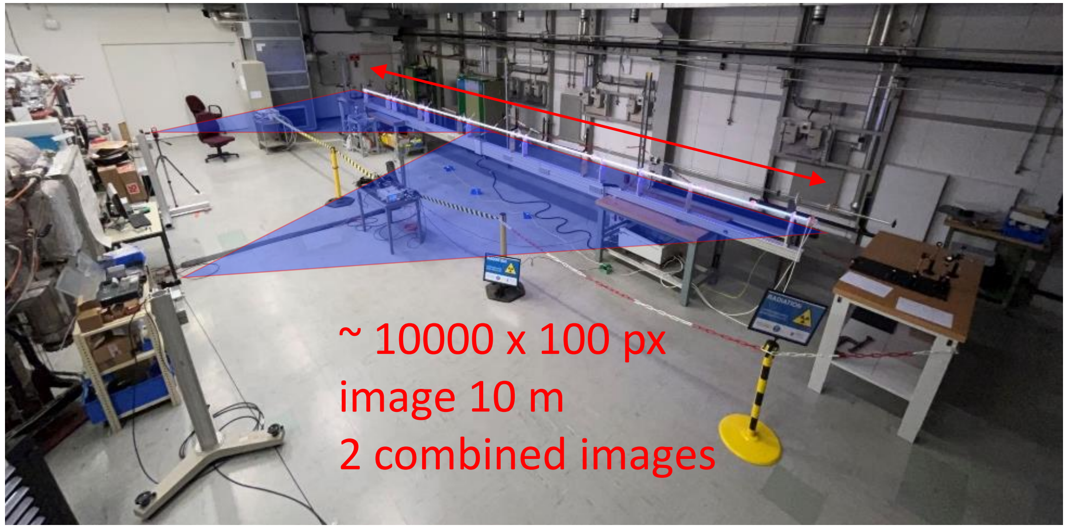
→ **Poster**

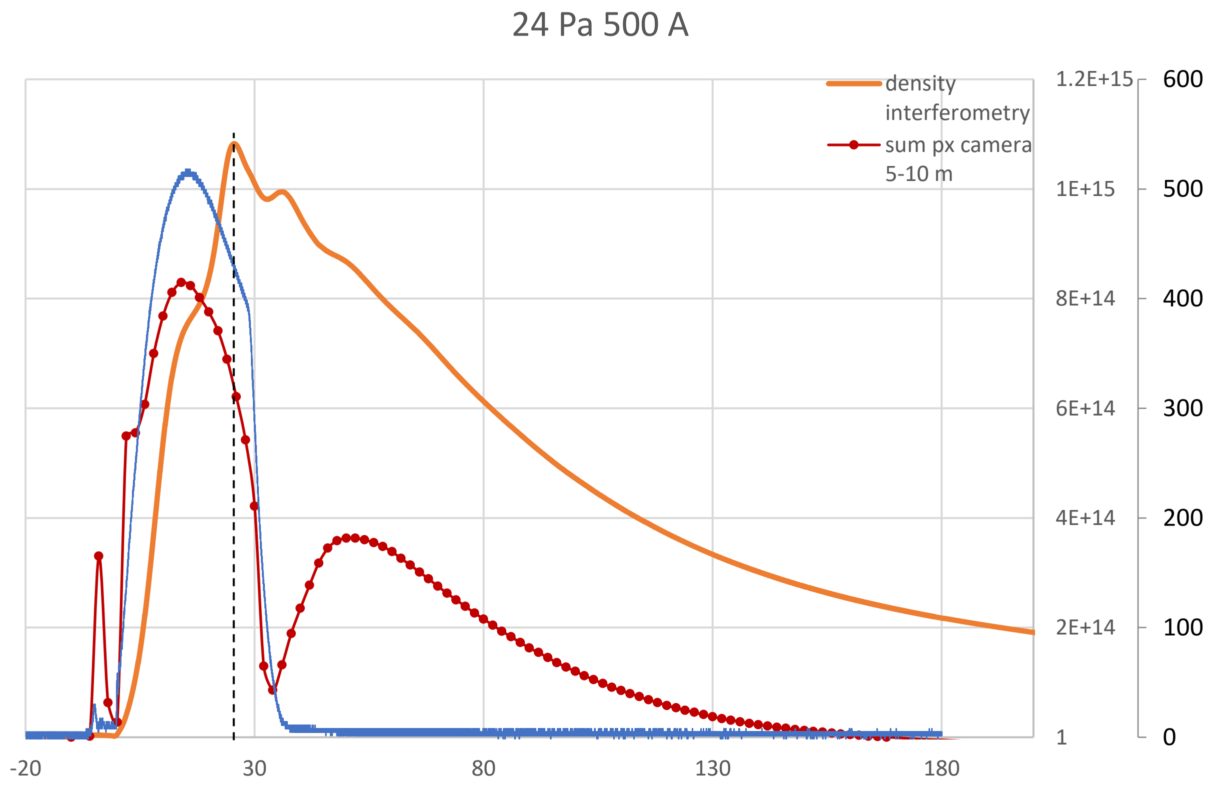


Next steps

10 m prototype: plasma light imaging → µs time-scan discharge

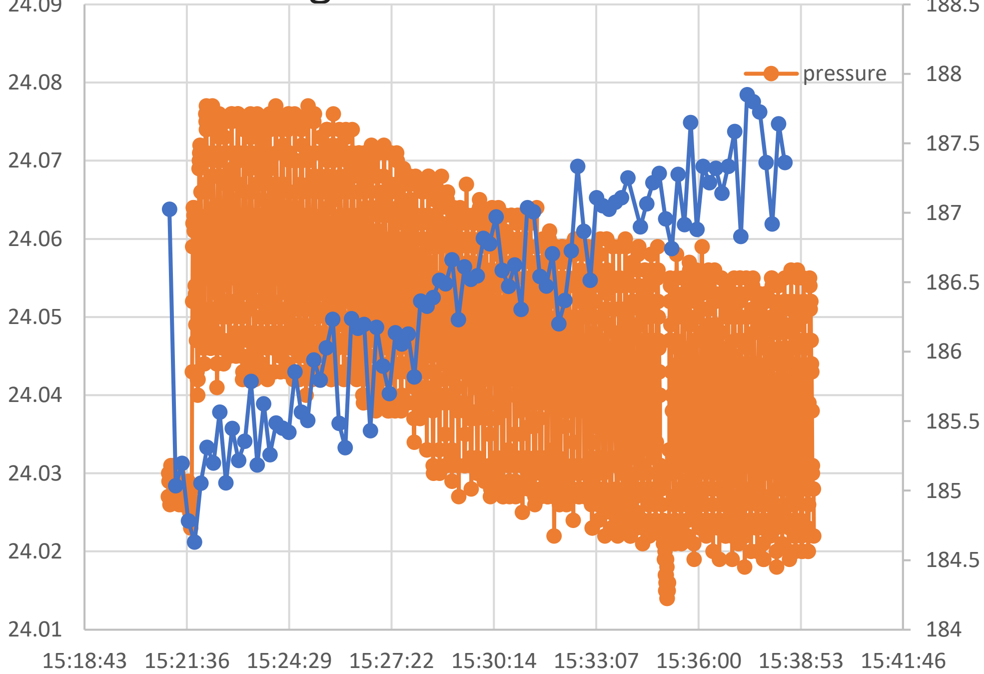
(1 µs exposure time)





peak density: mean of all pixels of the image

(100 discharges) → raw data (no correction)

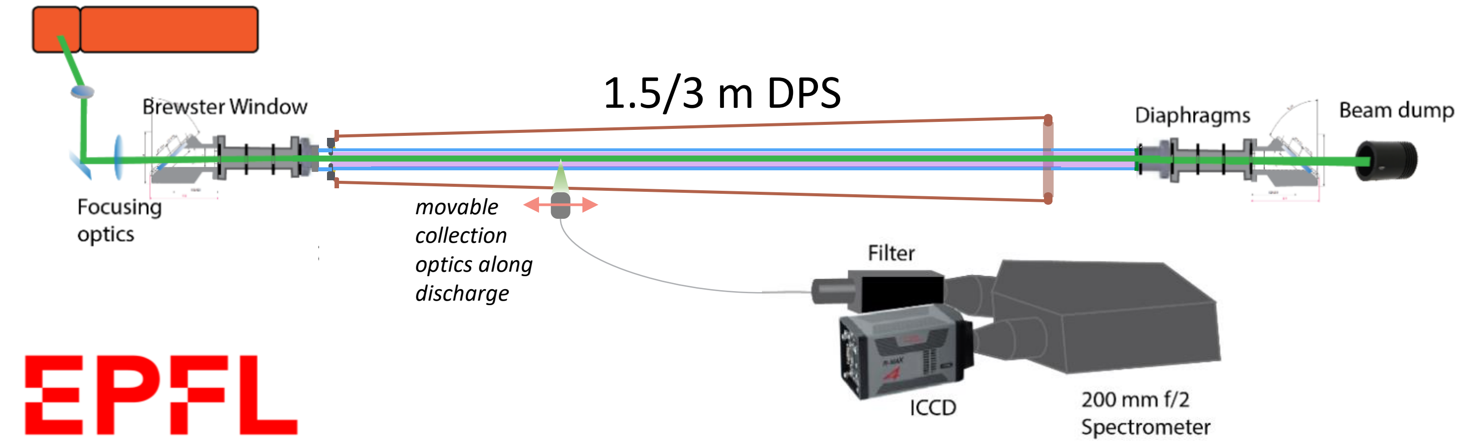


Next steps

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

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

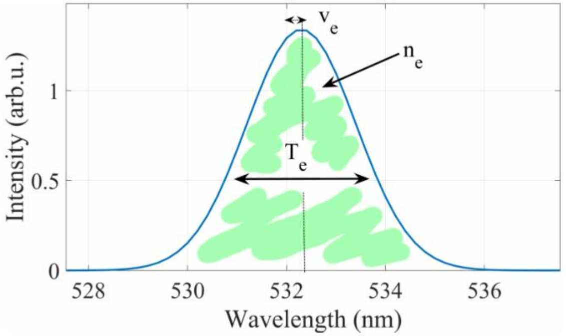
→ time-scan: repeat scan at different laser-discharge delays



EPFL

Courtesy Christine Stollberg, EPFL-SPC

Thomson scattering spectrum



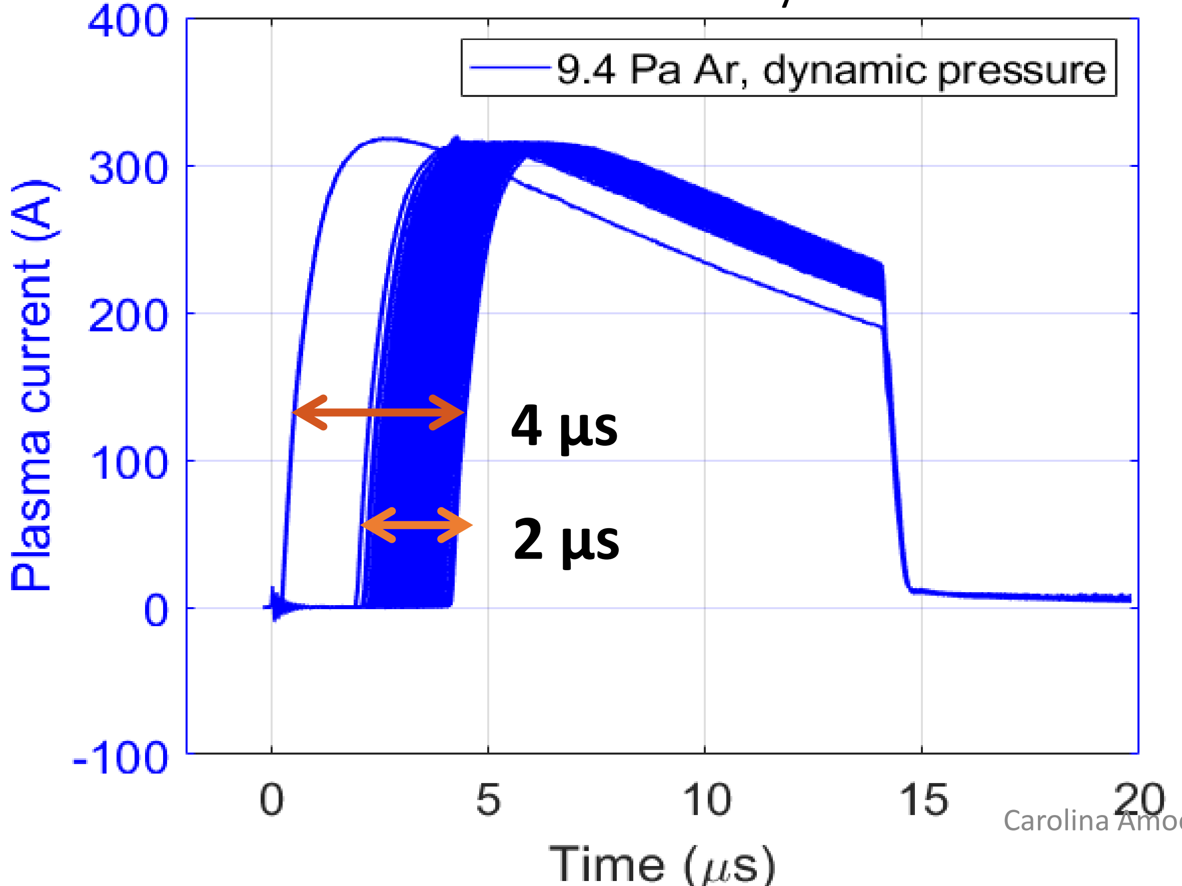
- Operating regime: 1×10^{18} - 1×10^{21} m^{-3}
- Uncertainties: 0.1 eV and ~ 10% in density

DPS 1.6 m prototype

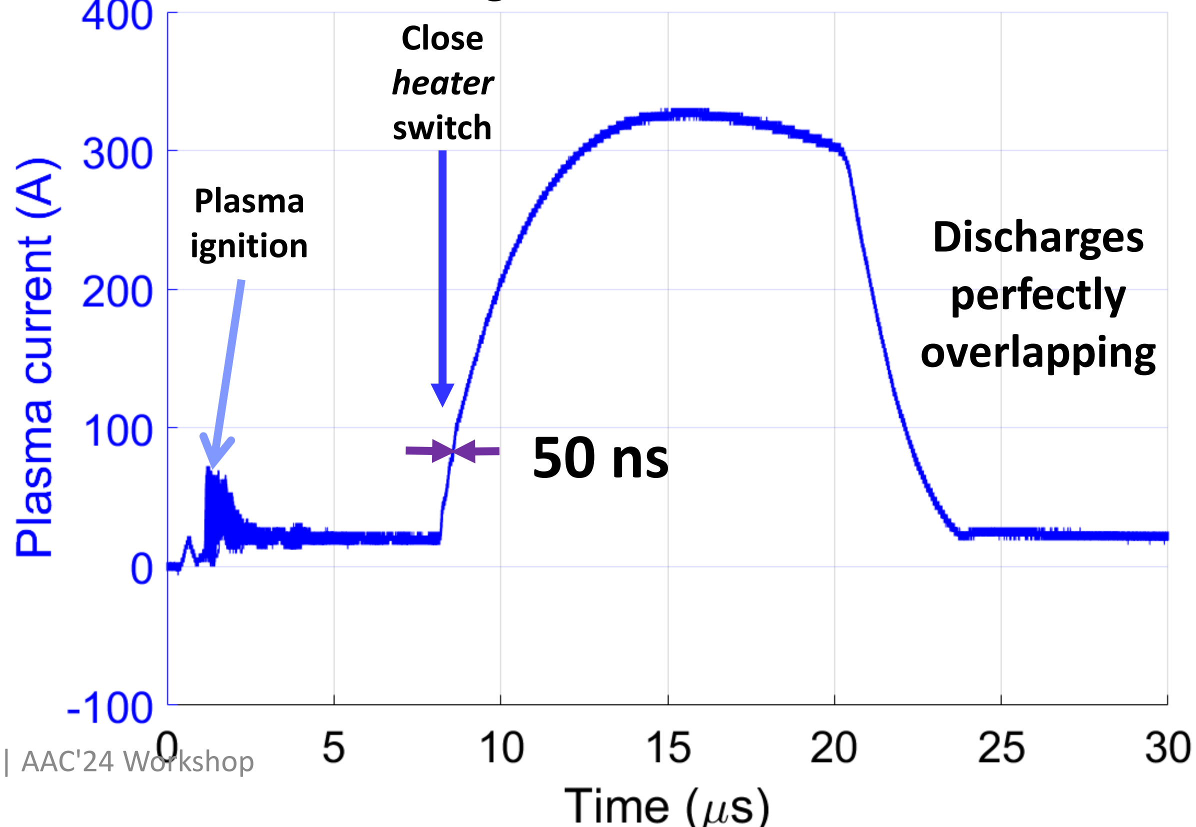
Double pulse discharge

- 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**

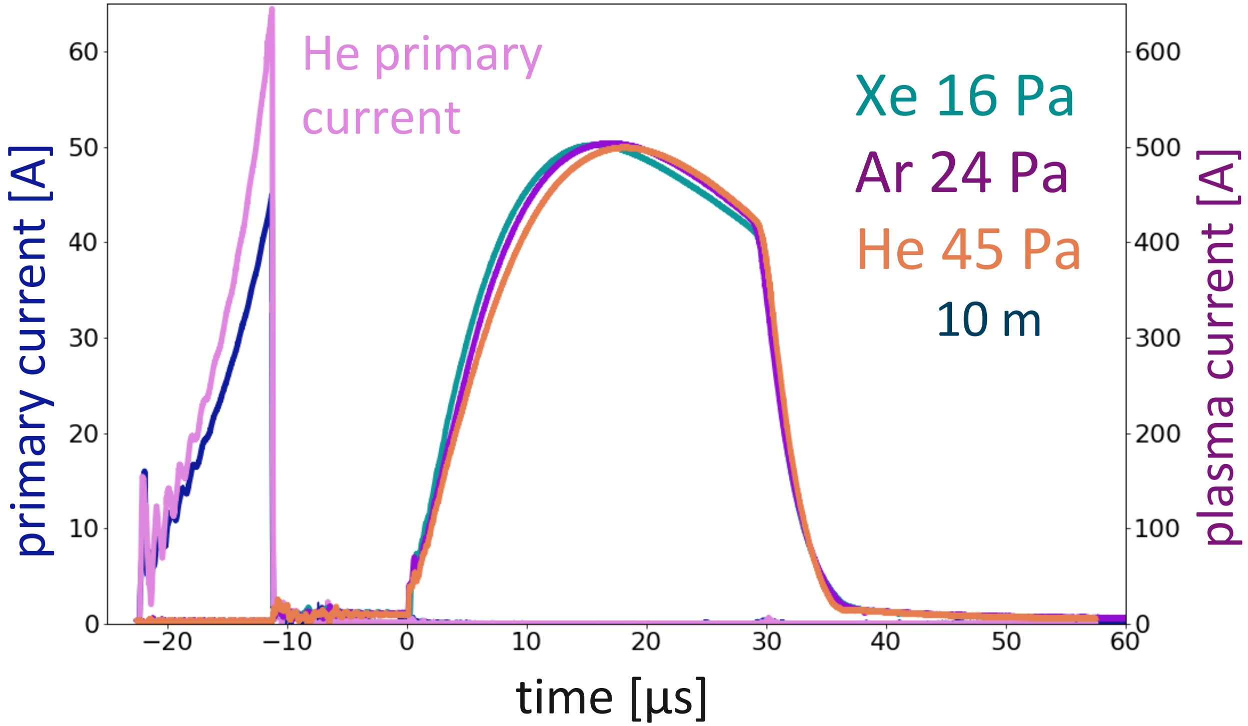


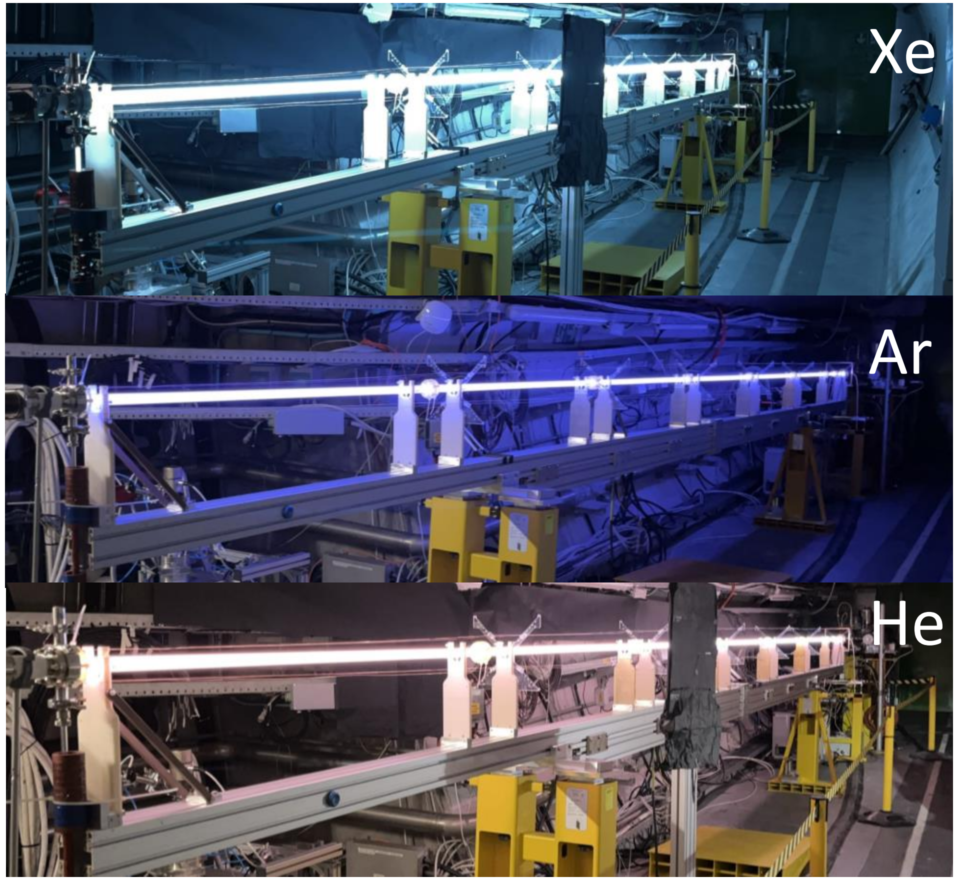
Ignition + heater



May 2023 proton run

Operation range – Gases



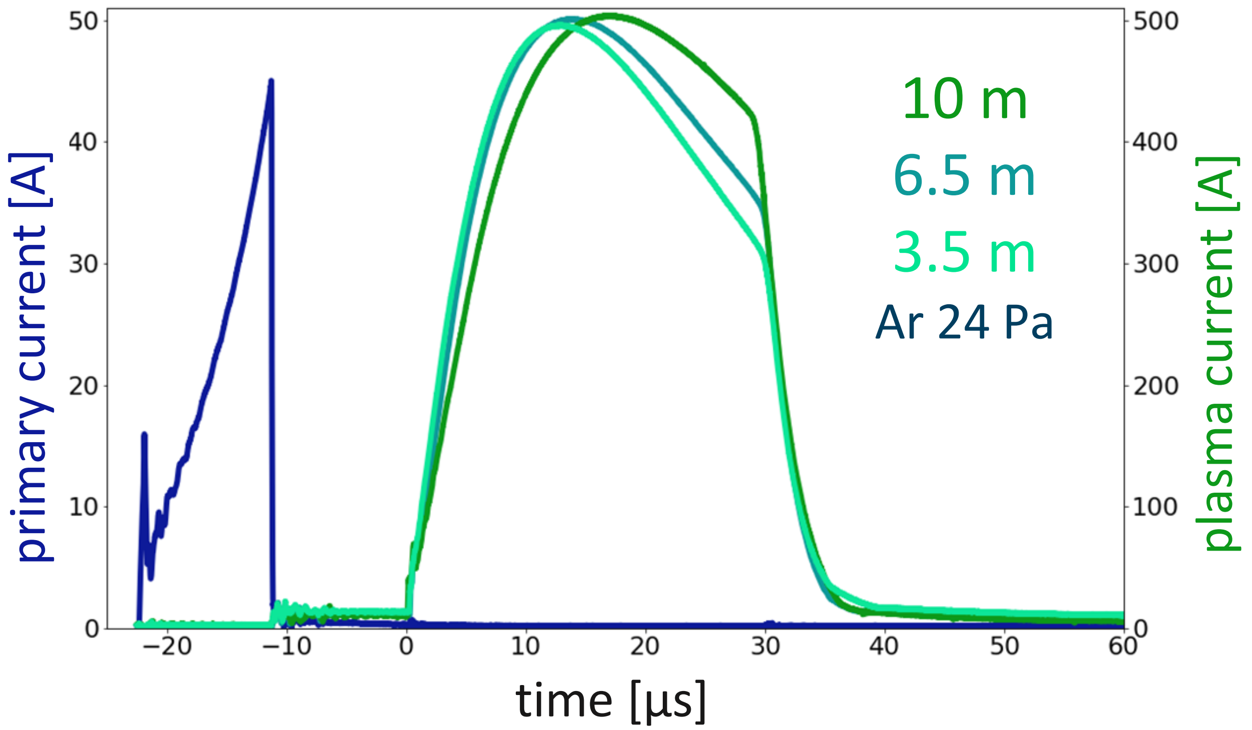


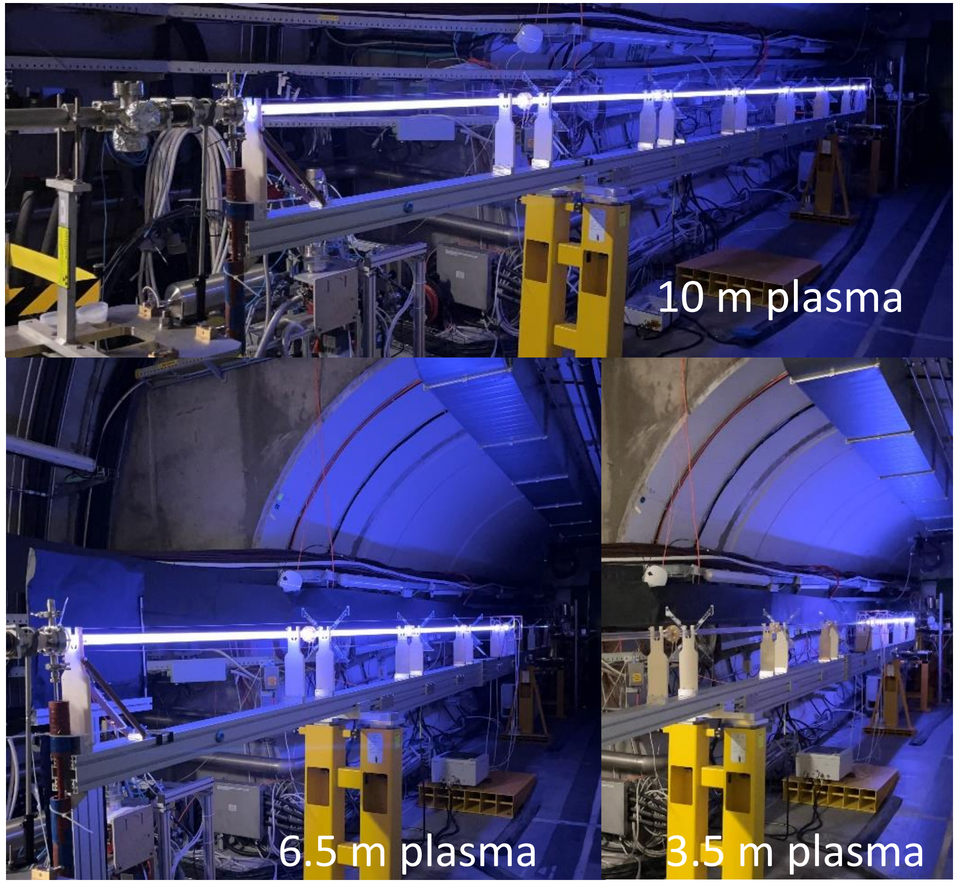
The pulse generators reach the target currents in all three gases

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

May 2023 proton run

Operation range – Length





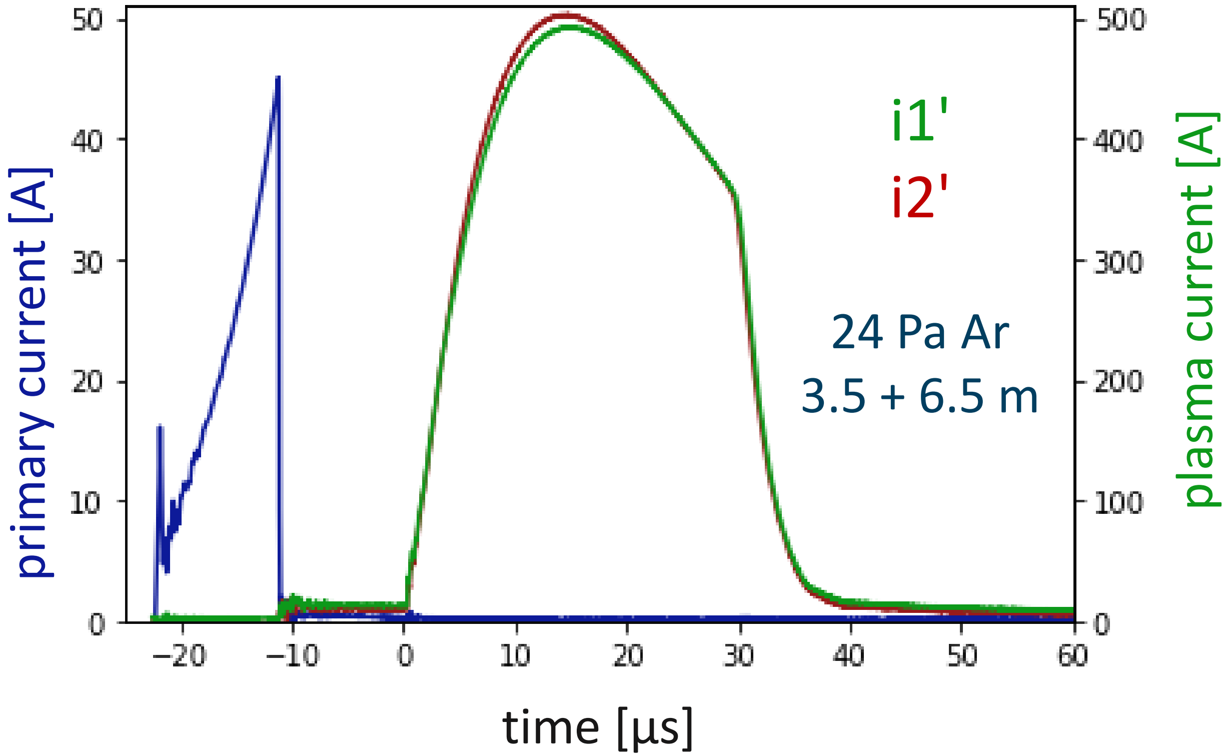
The pulse generators reach the target currents in all three gases and lengths

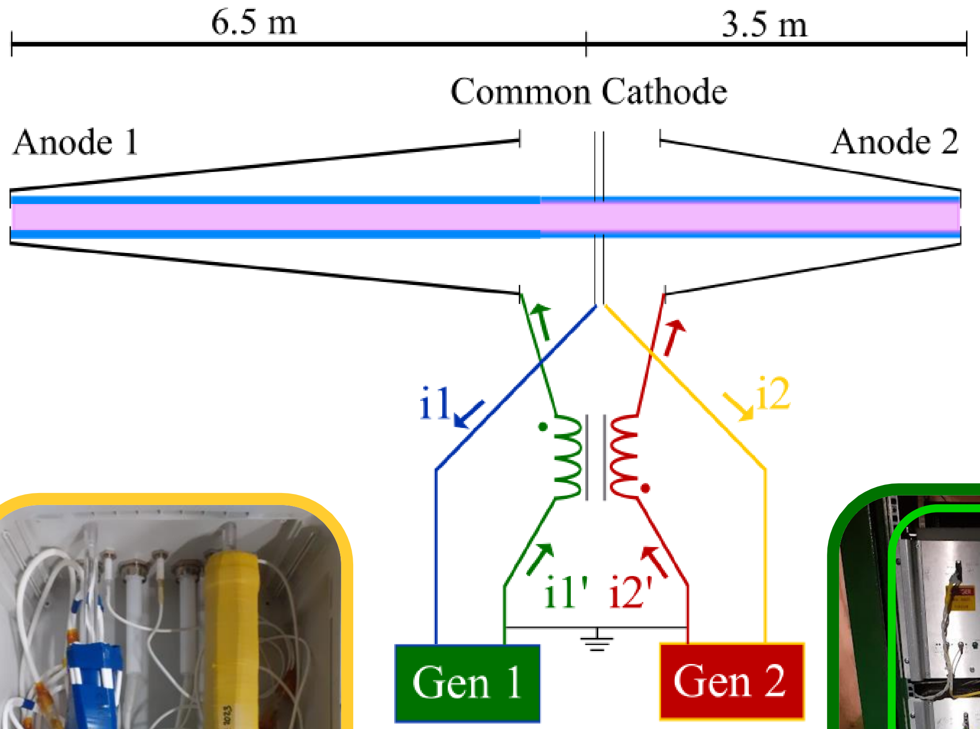
Gas affects mostly the ignition voltage required, leading to a higher primary current for He

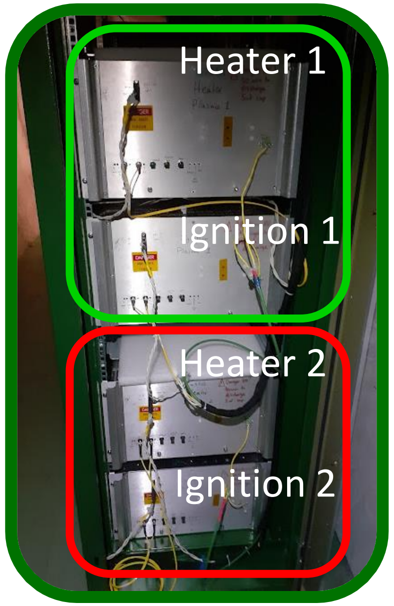
Plasma length affects the load impedance, thus causing differences in the pulse shape

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