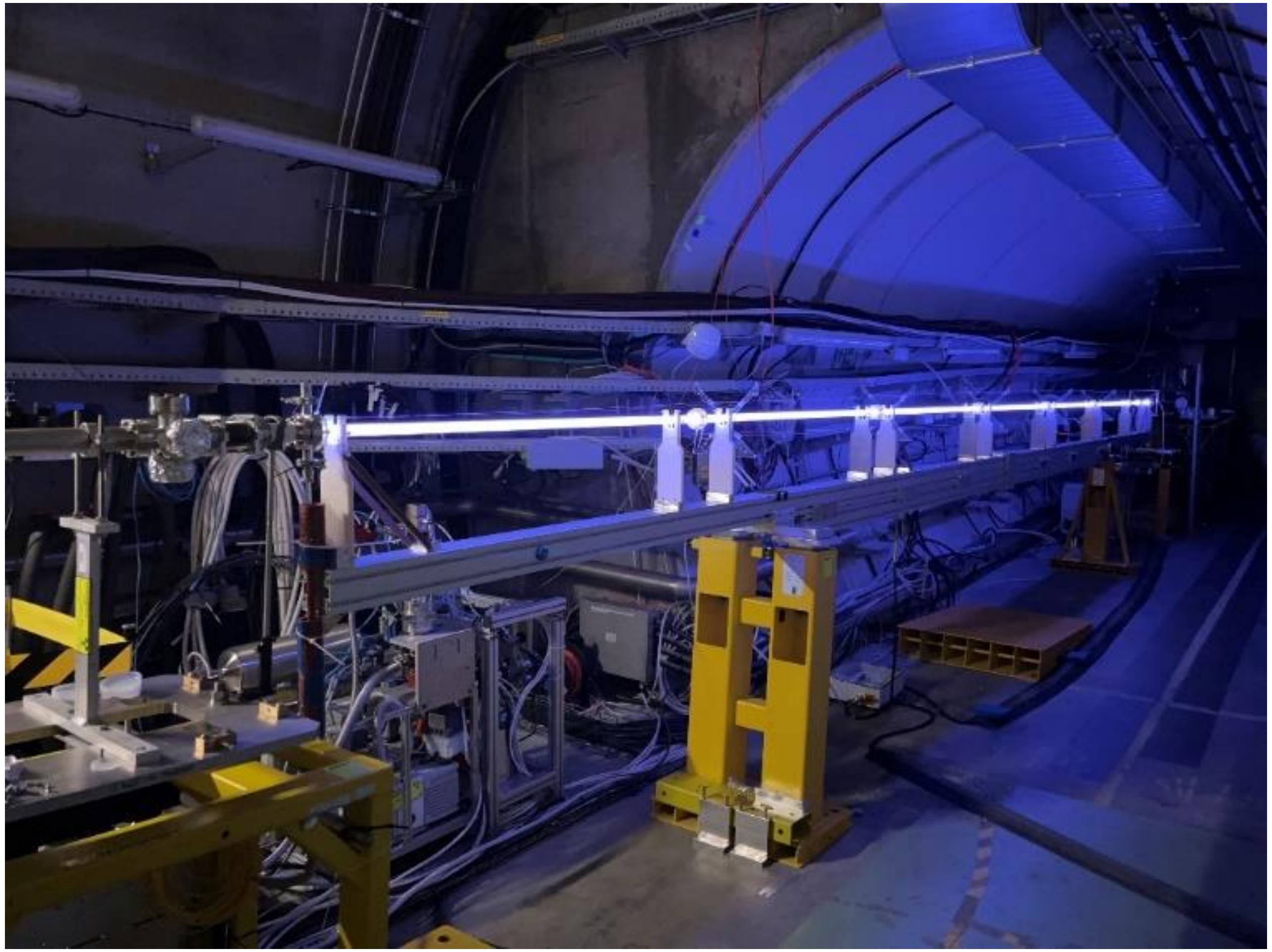
First test of a 10 m discharge plasma source with a proton beam in the AWAKE experiment



CERN
Technology Department
Vacuum, Surfaces & Coatings Group

TÉCNICO LISBOA

AWAKE

A. Sublet, C. Amoedo, N. Lopes, N. Torrado, J. Ferando Silva, P. Muggli, L. Verra, M. Turner, G. Zevi Della Porta, J. Pucek, M. Bergamaschi, A. Clairembaud, J. Mezger, F. Pannell, N. Z. van Gils, E. Gschwendtner, M. Taborelli, J. Farmer and the AWAKE Collaboration

6th EAAC, Elba, 17-23 September 2023

Outline

1. AWAKE project timeline
2. Scalable plasma sources R&D
3. Discharge Plasma Source (DPS) setup
4. DPS run with protons in the AWAKE experiment
5. Next: scalability x uniformity
6. Summary and perspectives

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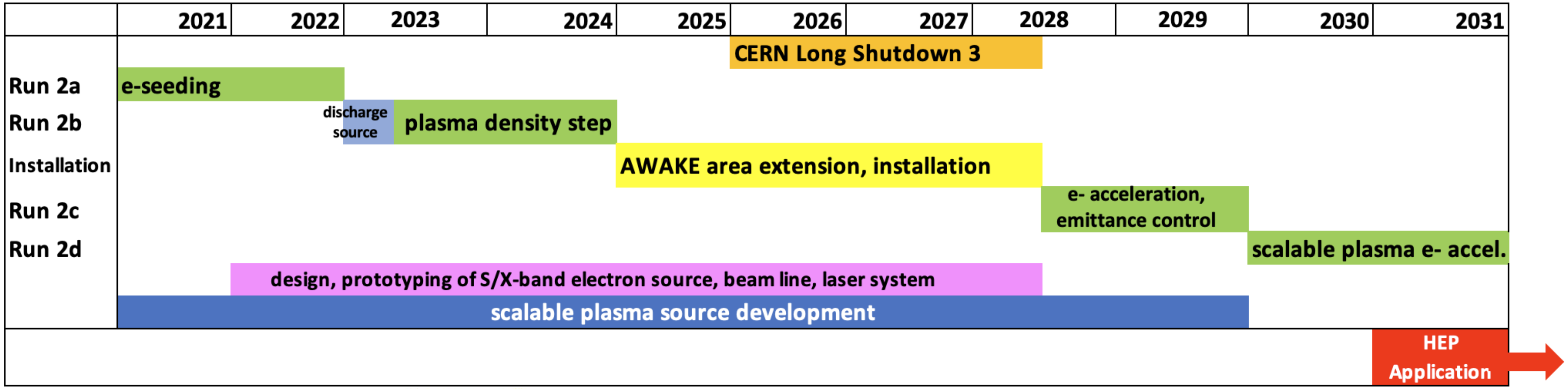
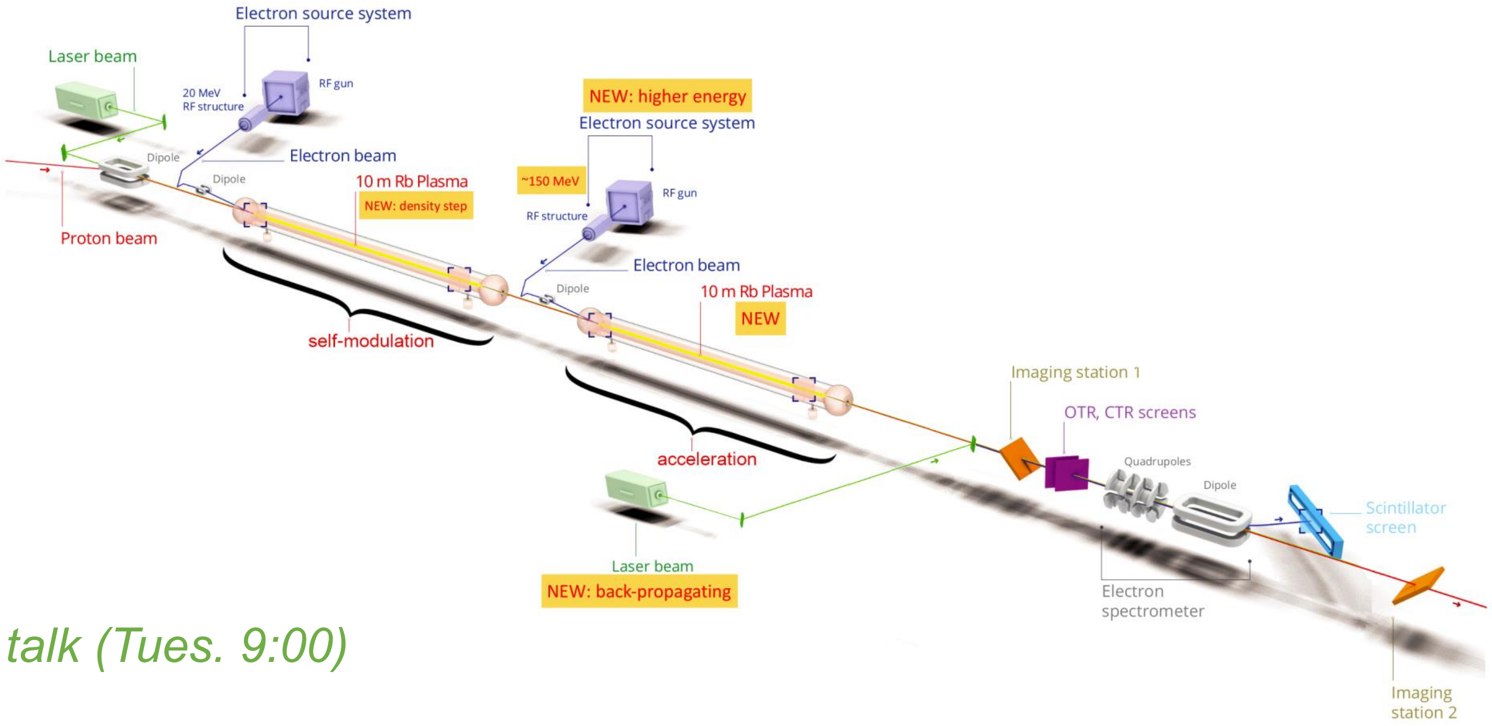
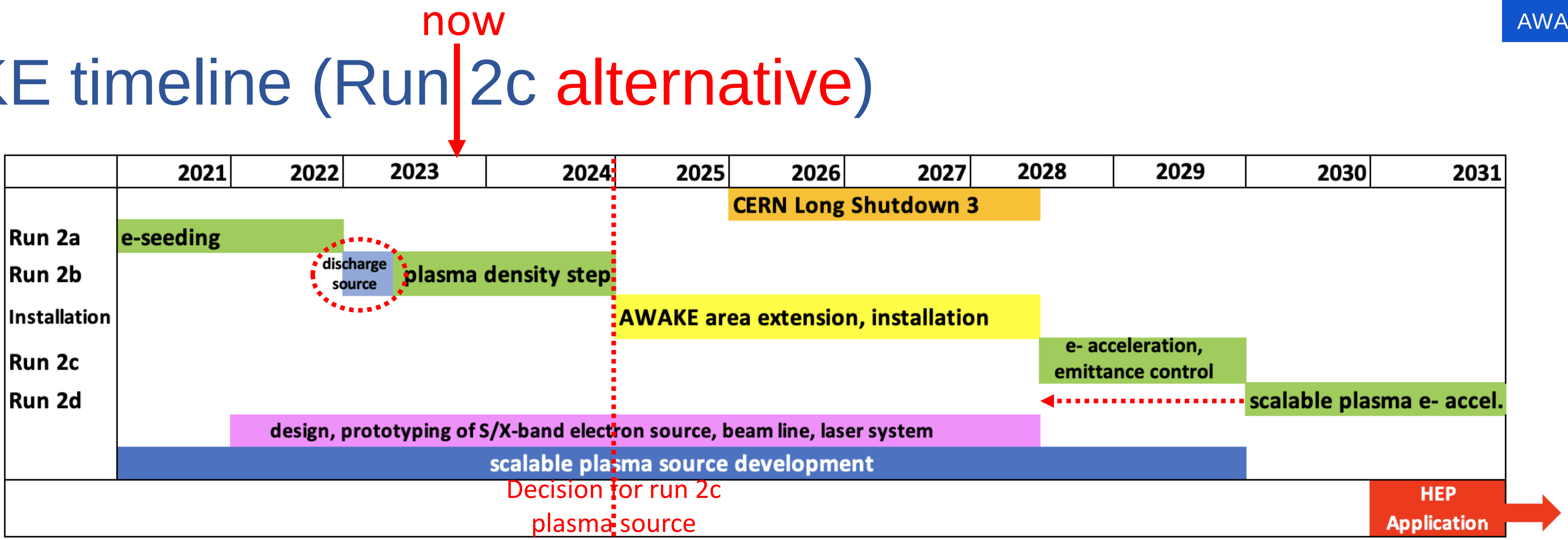
AWAKE timeline (Run 2c baseline)

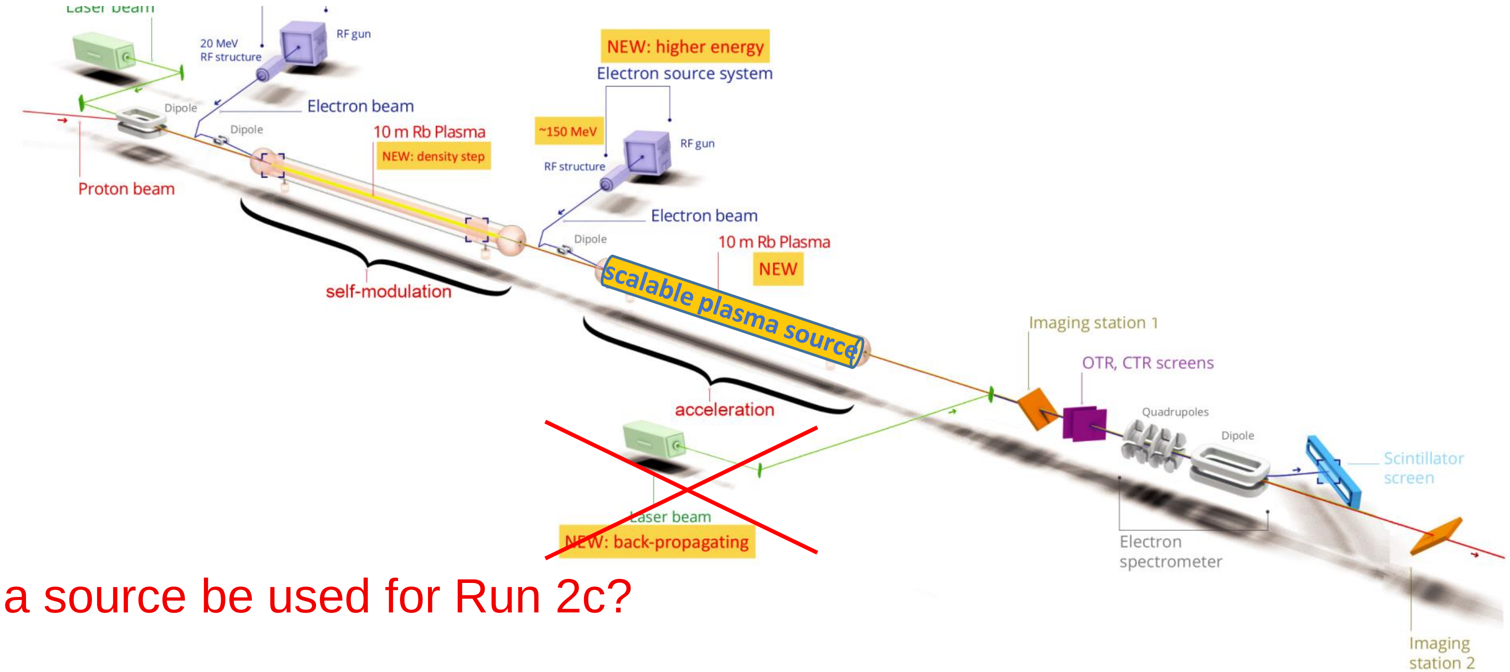




→ *See E. Gschwendtner's talk (Tues. 9:00)*

AWAKE timeline (Run 2c alternative)





→ Could a scalable plasma source be used for Run 2c?

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Scalable plasma sources R&D

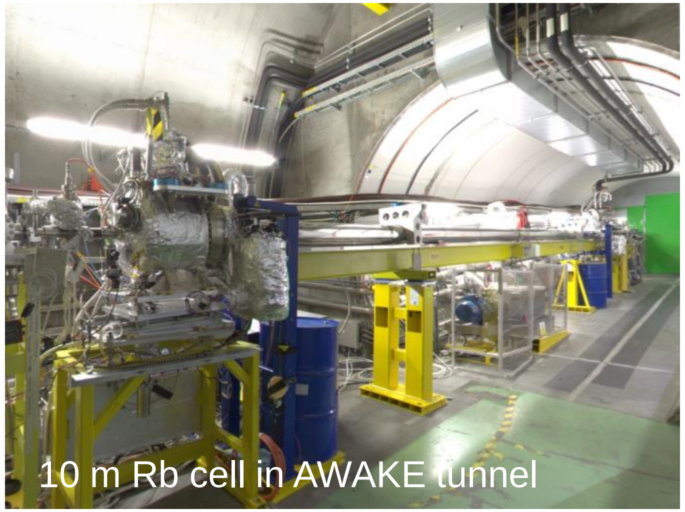
- Present AWAKE 10 m plasma source: Rb vapour ionized by TW laser

→ Limitation: laser pulse energy depletion for length > 10 m

→ Beyond 10 m, we need:

1. An efficient plasma production to reach high density/low temperature plasma
2. A modular approach that allows scalability

→ Two technologies identified and under study


10 m Rb cell in AWAKE tunnel

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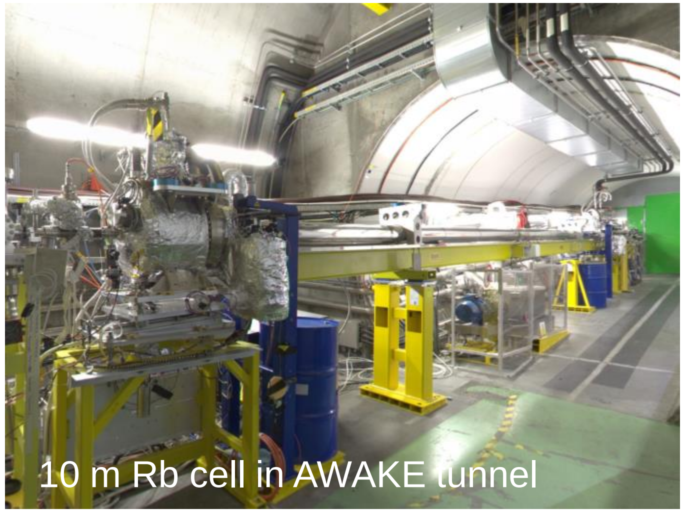

10 m Rb cell in AWAKE tunnel

Helicon Plasma Source (HPS)
→ RF wave heated plasma,
easily scalable but power demanding (RF + DC)

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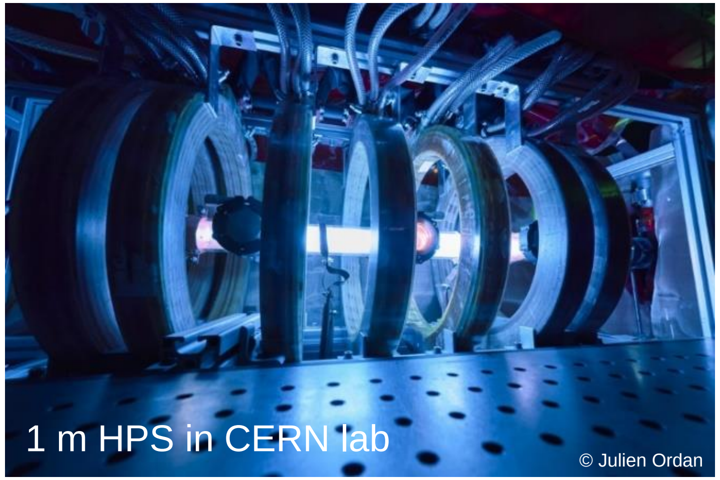
Max-Planck-Institut für Plasmaphysik

EPFL

College of Engineering, University of Wisconsin-Madison



1 m HPS in CERN lab

© Julien Ordan

Scalable plasma sources R&D

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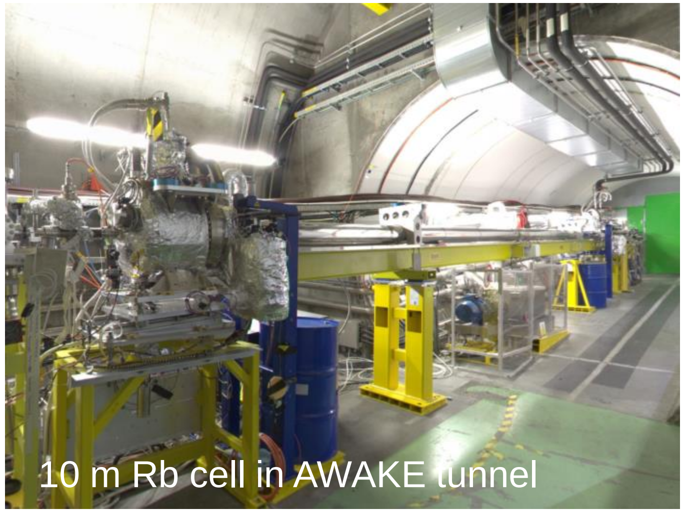

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CERN

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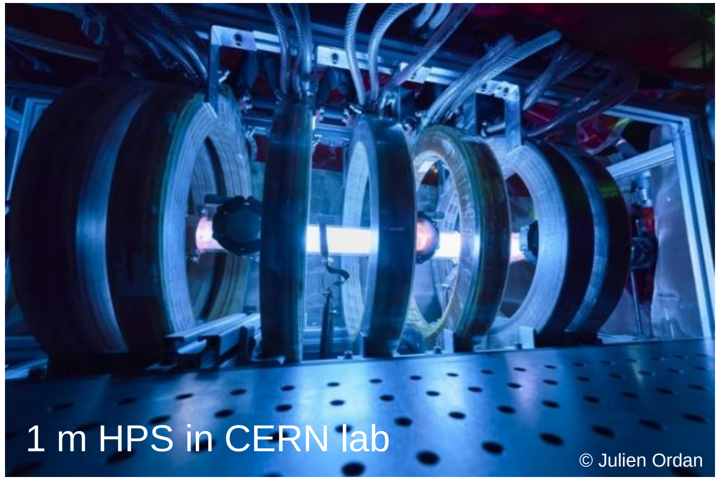
College of Engineering UNIVERSITY OF WISCONSIN–MADISON



1 m HPS in CERN lab

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Discharge Plasma Source (DPS)
→ pulsed-DC discharge,
simple and economic but more complex to scale-up

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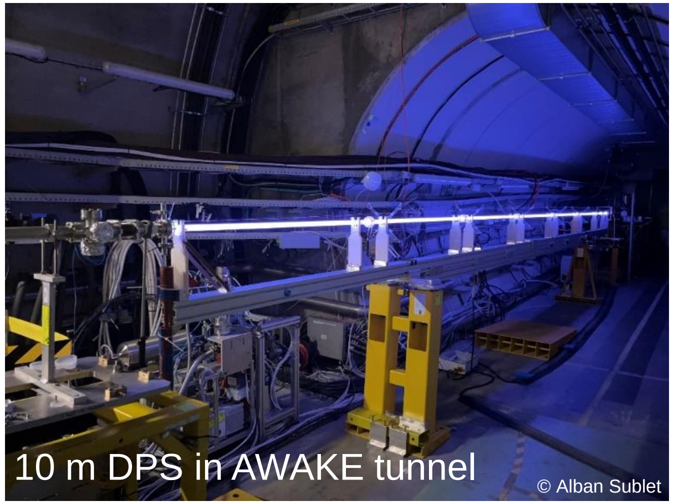
Imperial College London



10 m DPS in AWAKE tunnel

© Alban Sublet

Scalable source requirements

1. Reach AWAKE nominal plasma density ($7x10^{14}$ cm^{-3}) ☑
2. And **uniformity: 0.25% over 10 m**
3. Demonstrate scalability
4. Operate in a stable and reproducible way (power supplies, vacuum, gas injection, temperature, etc.)
5. Connect to existing source and beam lines (interfaces design, windows, density matching, etc.)

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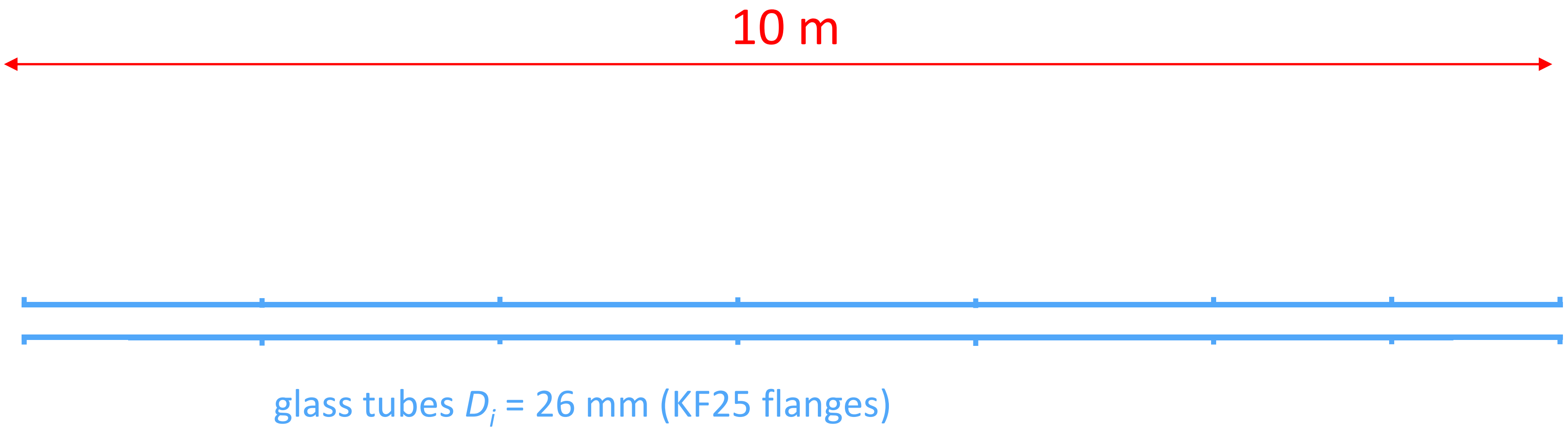
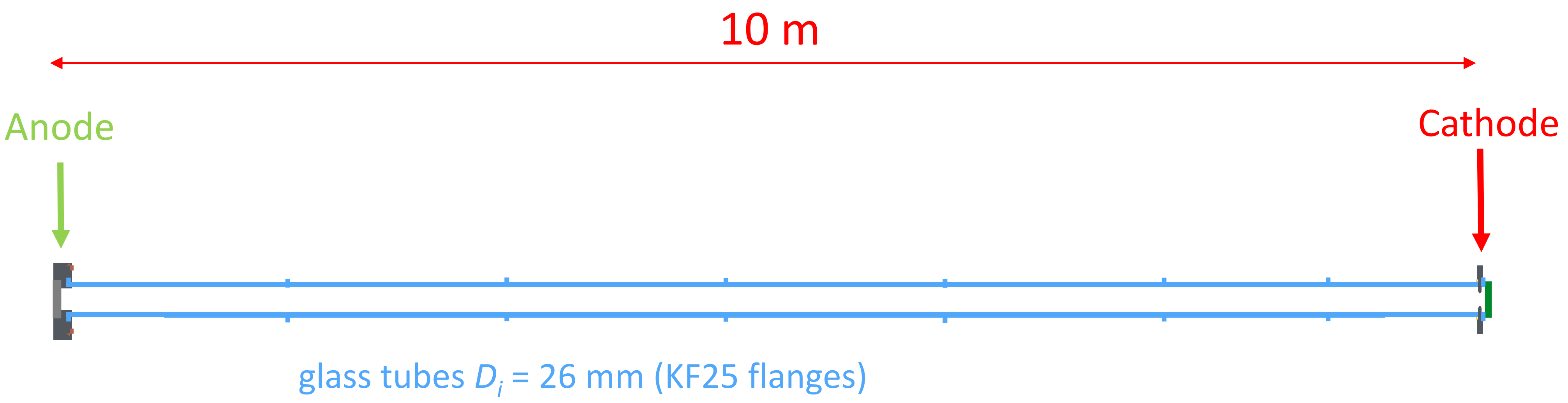
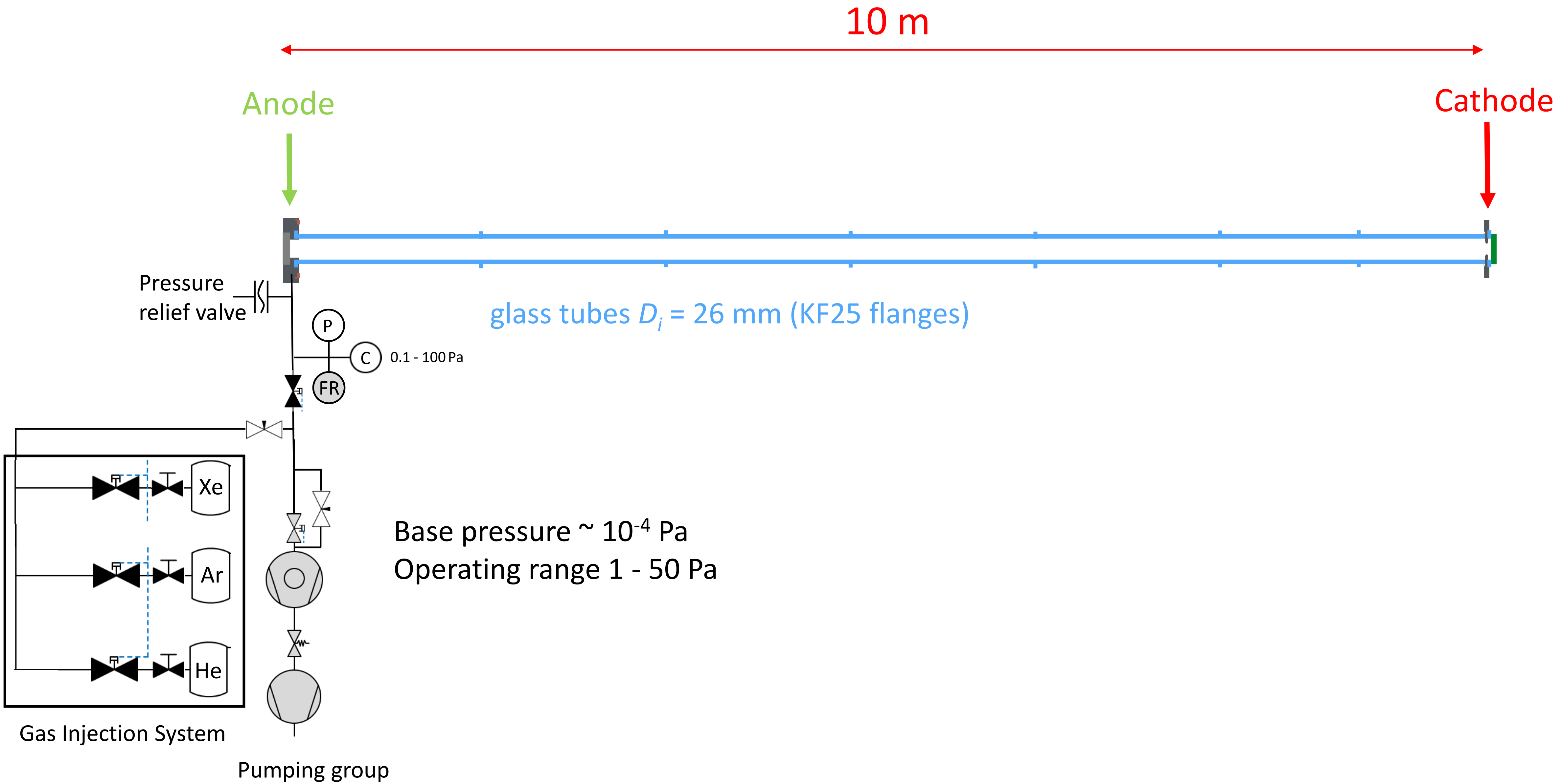
DPS 10 m schematic



DPS 10 m schematic

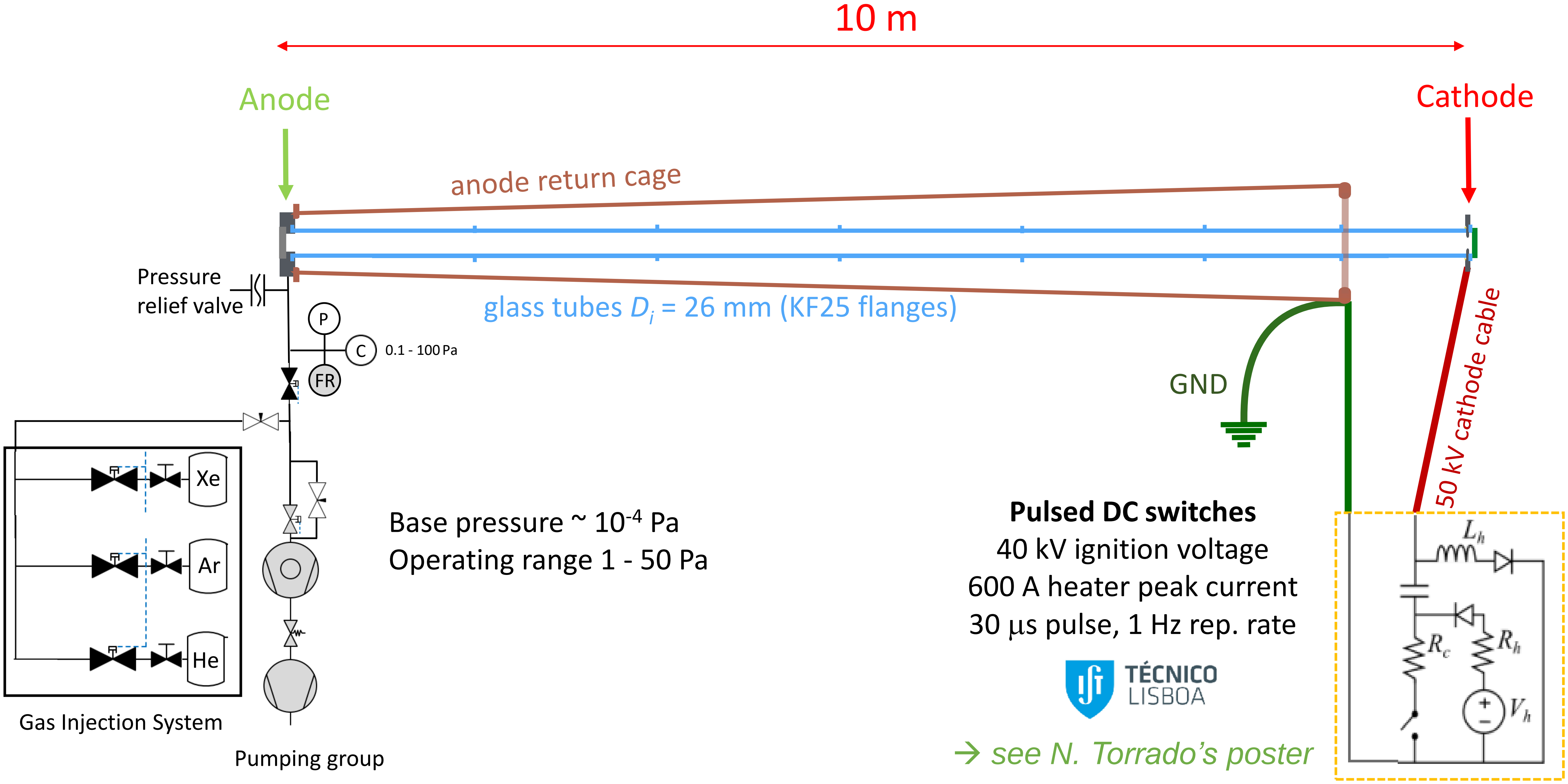


DPS 10 m schematic



Base pressure ~ 10^{-4} Pa
Operating range 1 - 50 Pa

DPS 10 m schematic



Base pressure ~ 10^{-4} Pa
Operating range 1 - 50 Pa

Pulsed DC switches
40 kV ignition voltage
600 A heater peak current
30 µs pulse, 1 Hz rep. rate

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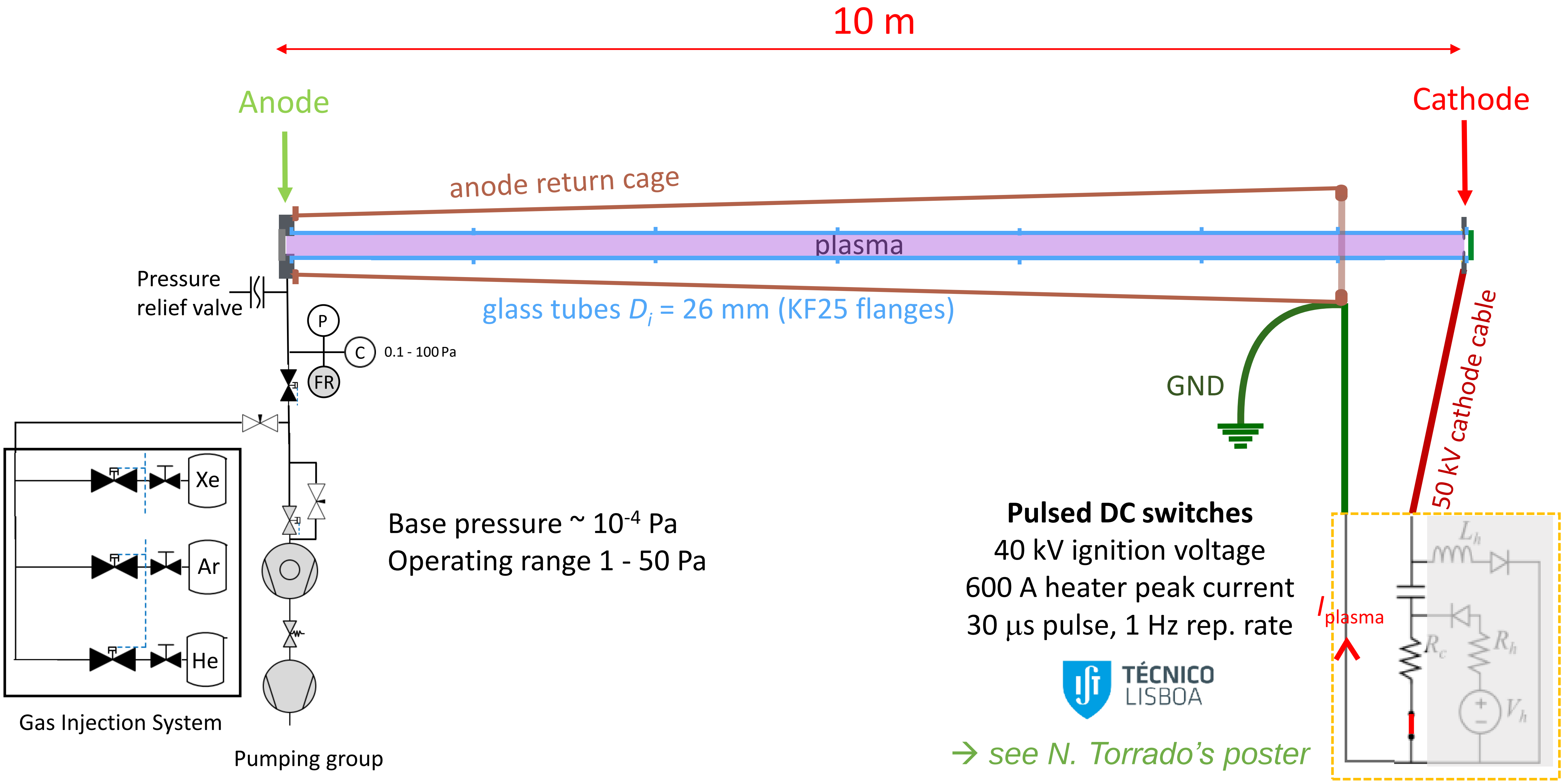
→ *see N. Torrado's poster*

DPS 10 m schematic



Base pressure ~ 10^{-4} Pa
Operating range 1 - 50 Pa

Pulsed DC switches
40 kV ignition voltage
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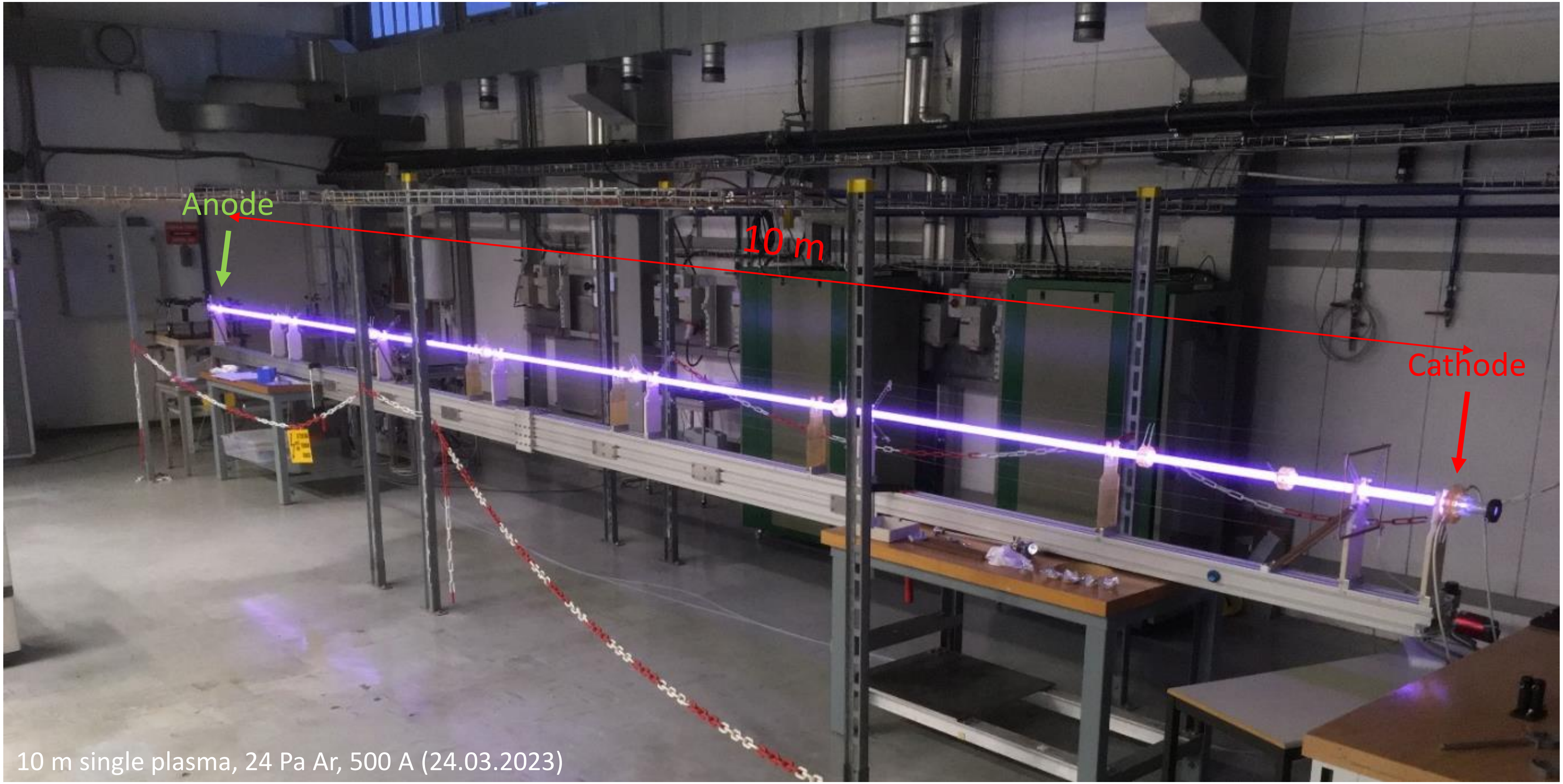
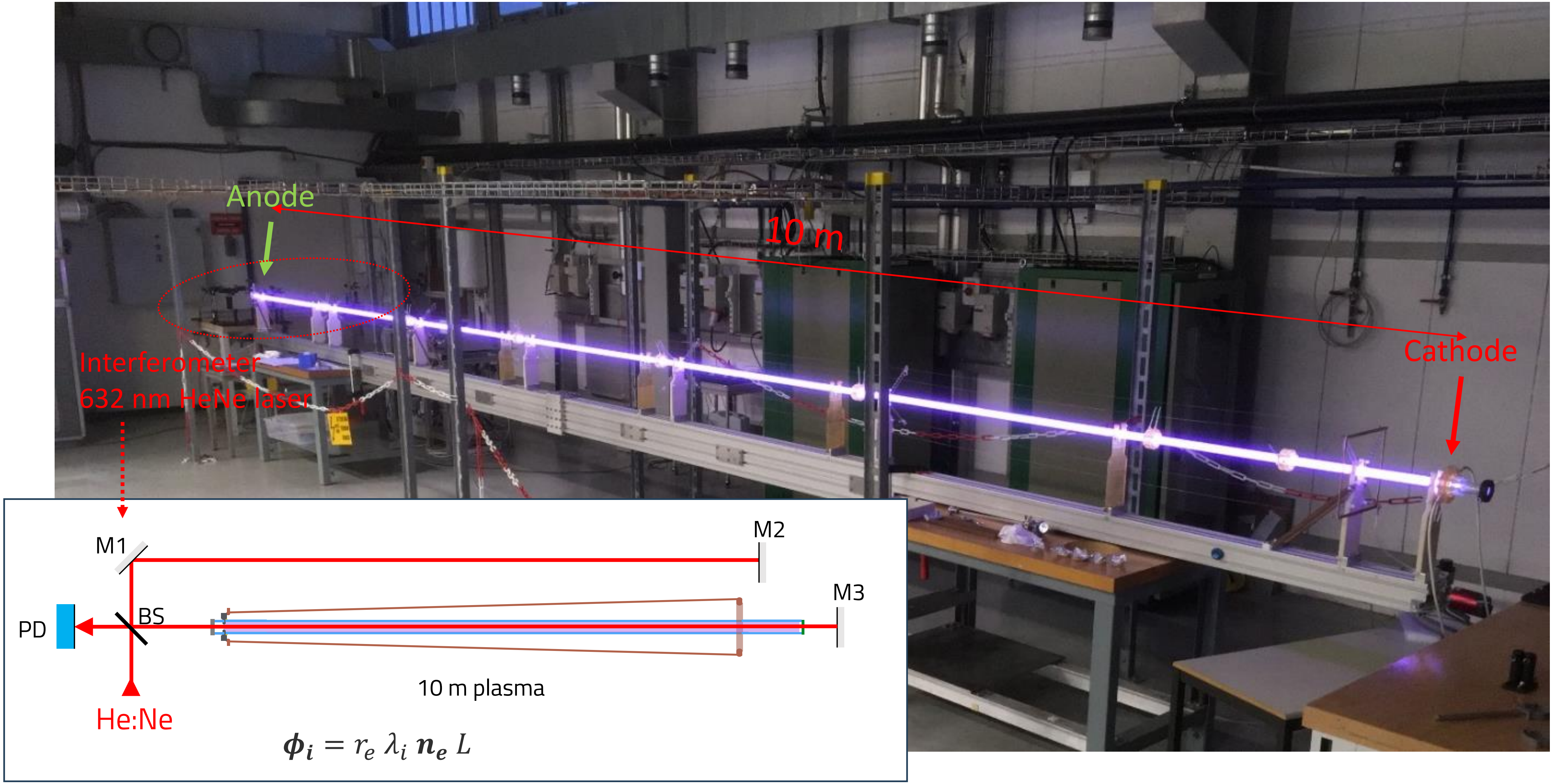
→ *see N. Torrado's poster*

DPS 10 m lab setup in CERN



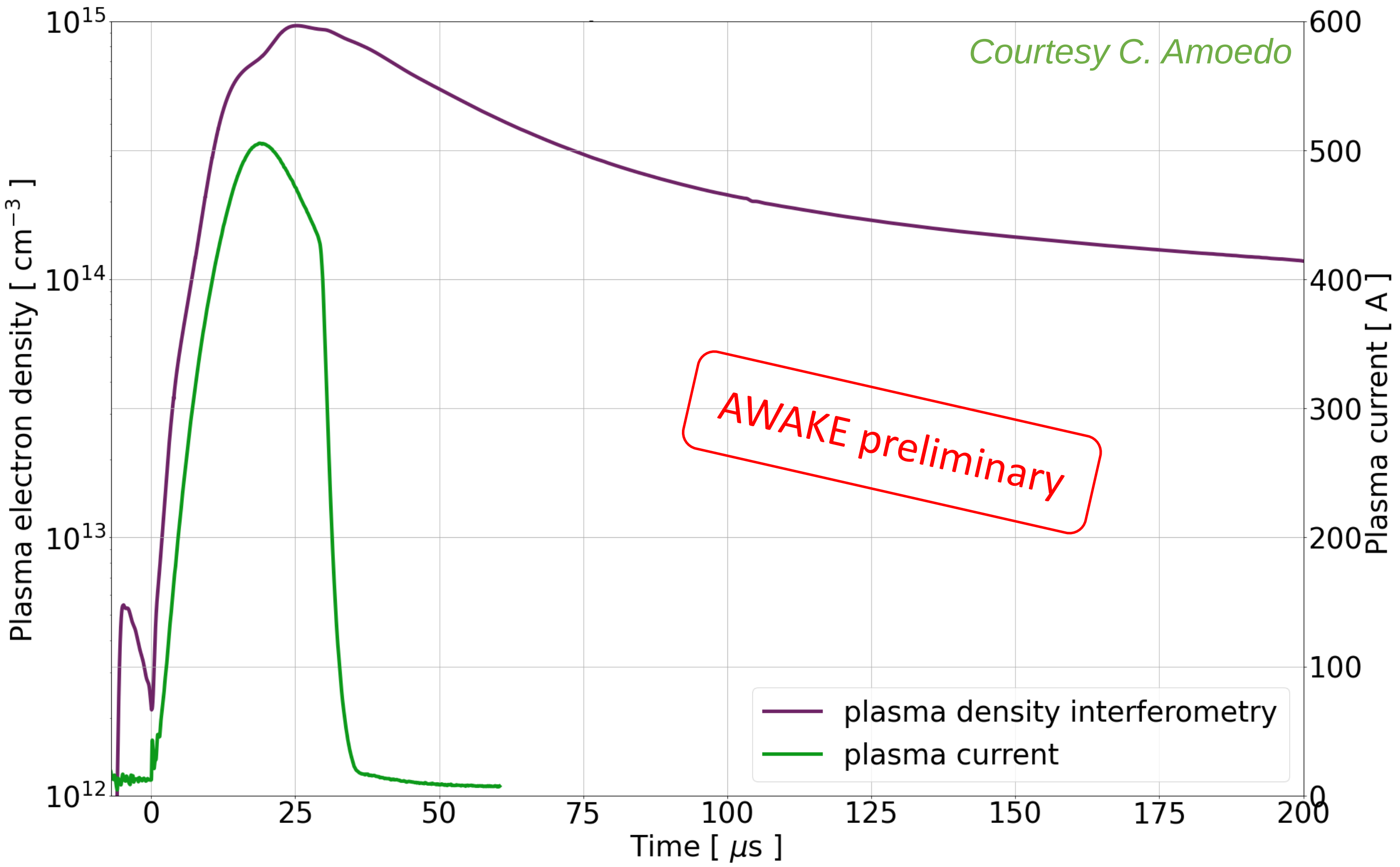
DPS 10 m lab → interferometry for longitudinally averaged density



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

DPS 10 m lab → interferometry for longitudinally averaged density

24 Pa Ar, 500 A, 10 m single plasma **lab interferometry**, 10 discharges average



→ AWAKE nominal density reached

→ Density span over one discharge ~ 1x10^{13} to 1x10^{15} cm^{-3}

→ see C. Amoedo's poster

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DPS run in the AWAKE tunnel → motivation

Why? → unique chance to test an alternative plasma source between AWAKE run 2a and 2b:

1. show that the propagation of a proton bunch in a DPS plasma results in the usual SMI signature *(see C. Amoedo's poster)*
2. determine the effect of plasma density and length L_0 (10 m single), L_1 (6.5 m), L_2 (3.5 m) and L_1+L_2, on SMI
3. assess the effect of the ion mass on the self-modulation along the proton bunch in Ar, He, Xe plasmas *(see M. Turner's talk)*
4. study Current Filamentation Instability (CFI) with wide proton bunch and high density plasma *(see L. Verra's talk)*

→ SMI only experiment: no laser and no electron beam, reduced constraint on axial uniformity

How?

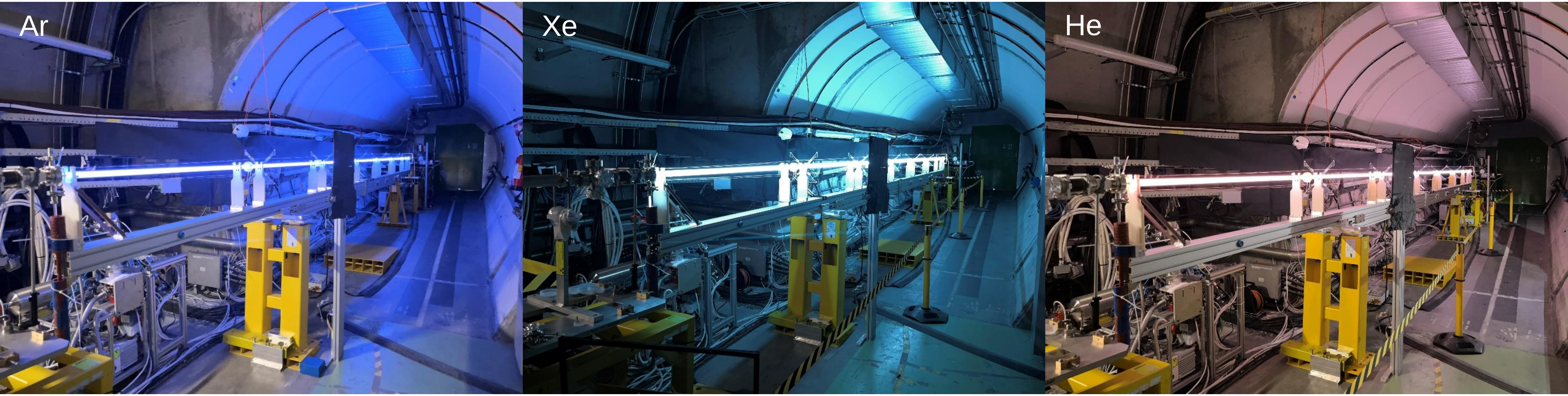
→ Profit from the flexibility of the DPS setup and parameters (glass tube, density, ion species, pressure, etc.) to achieve that.

→ Streak camera images to assess p+ bunch self-modulation frequency and plasma density, compare with lab interferometry

→ PMTs + cameras for plasma light measurements along the DPS

→ Screens for halo and current filamentation measurements

DPS run → operation



→ 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%

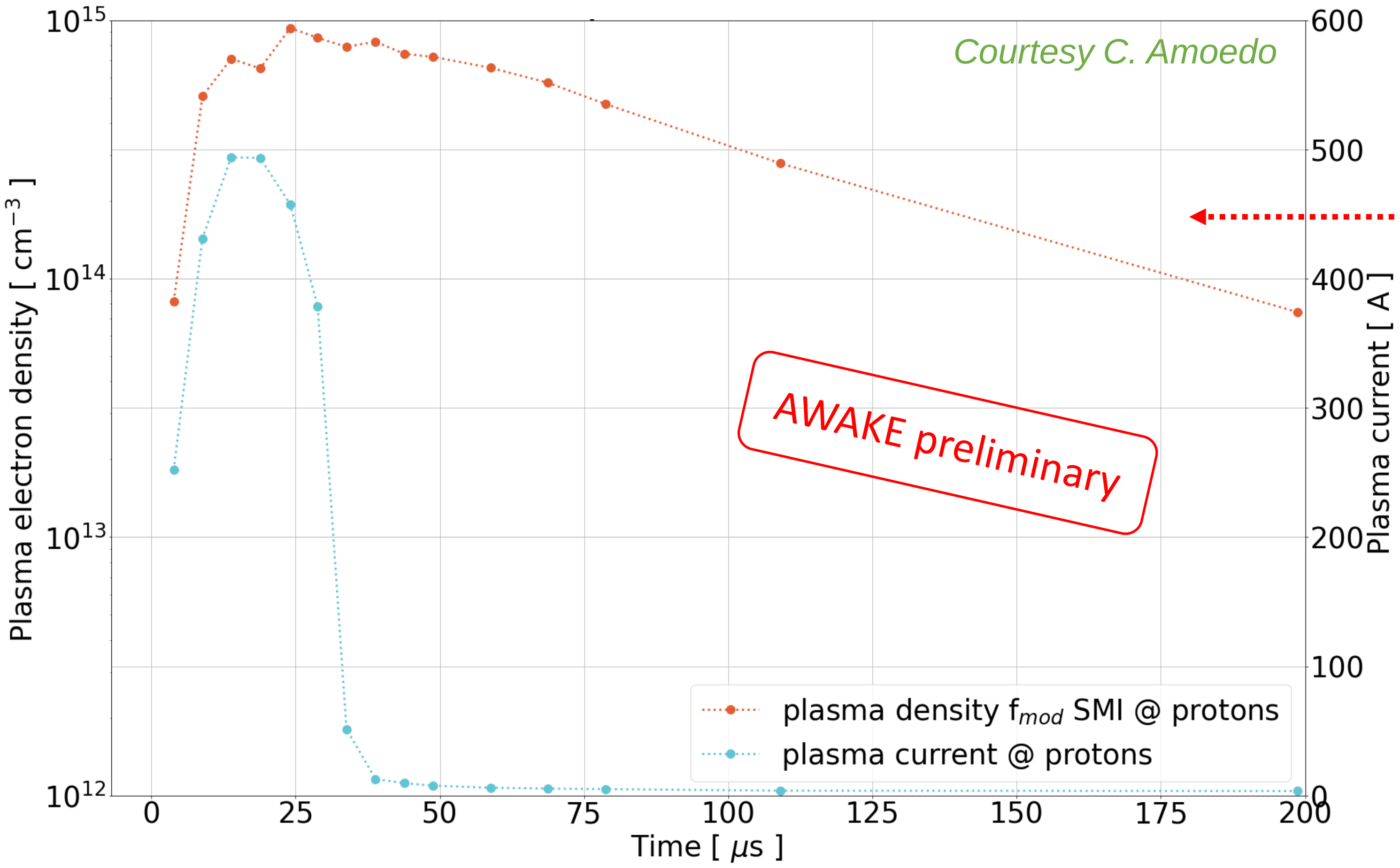
→ 3 plasma lengths (3.5/6.5/10 m) investigated

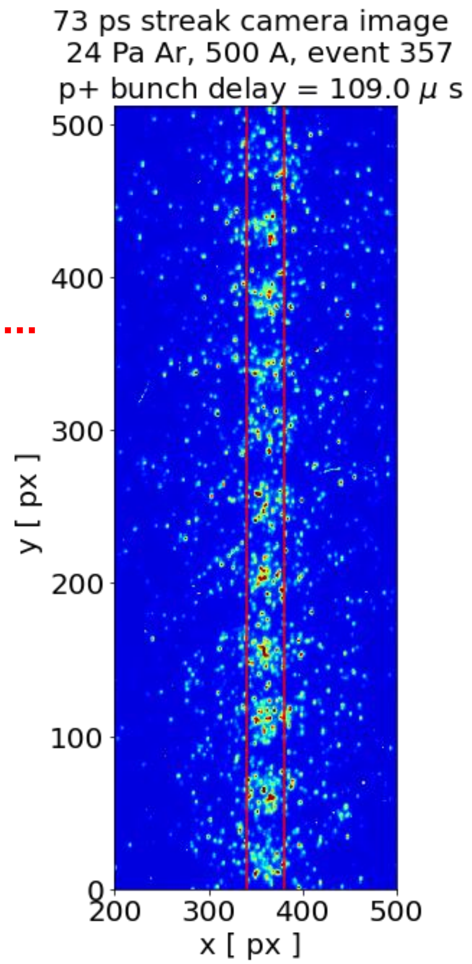
→ 3 gases: Ar/Xe/He at 5 pressures 8/16/24/30/45 Pa

→ density range spans over 2 orders of magnitude: 10^{13} - 10^{15} cm^{-3}

DPS run → proton self-modulation frequency measurement with streak camera

24 Pa Ar, 500 A, 10 m single plasma **density from proton SMI frequency**





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

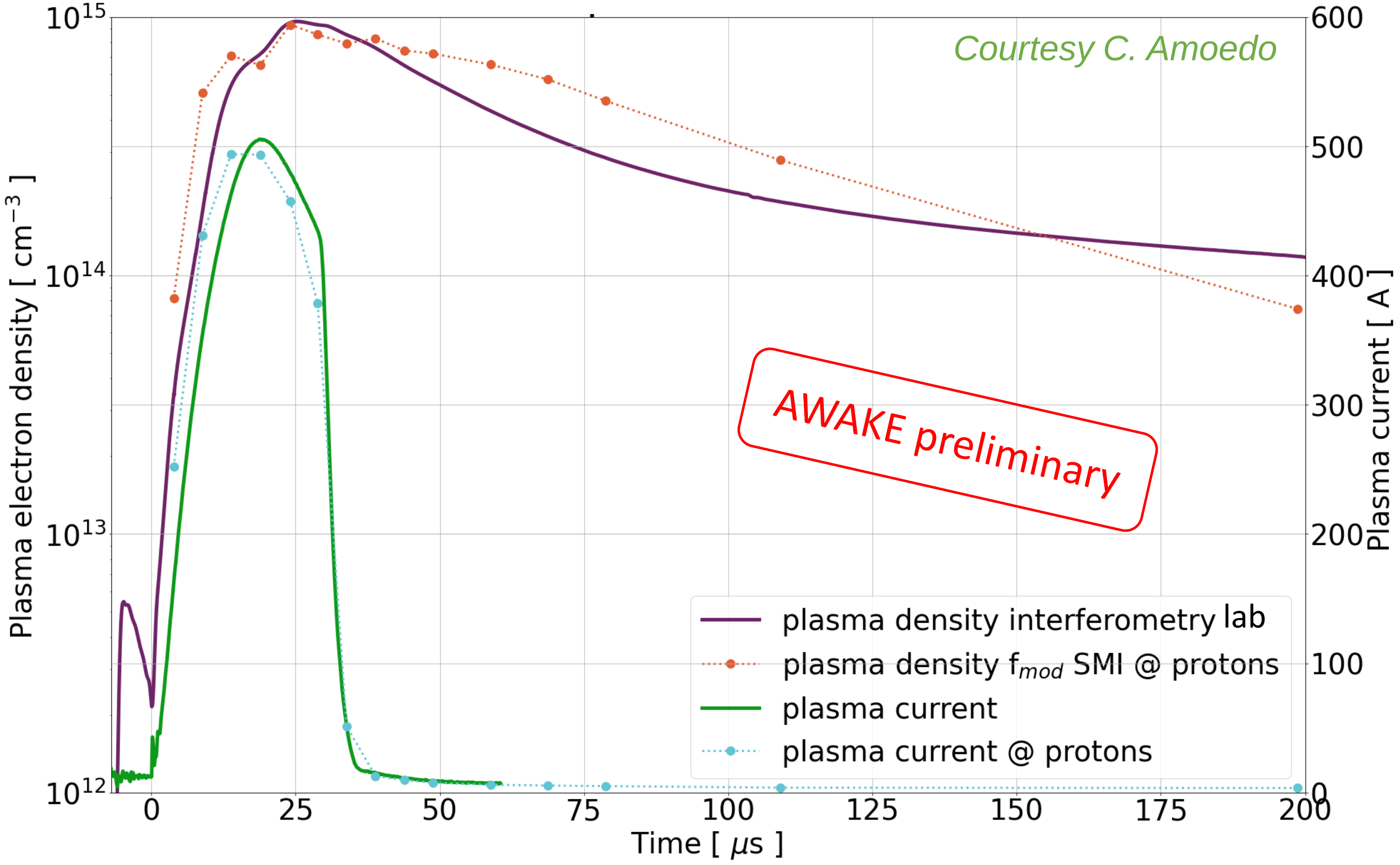
$$\omega_p^2 = \frac{n_e e^2}{\epsilon_0 m}$$

→ SMI observable with the DPS

→ Scanning through density by changing the delay between current pulse and proton bunch

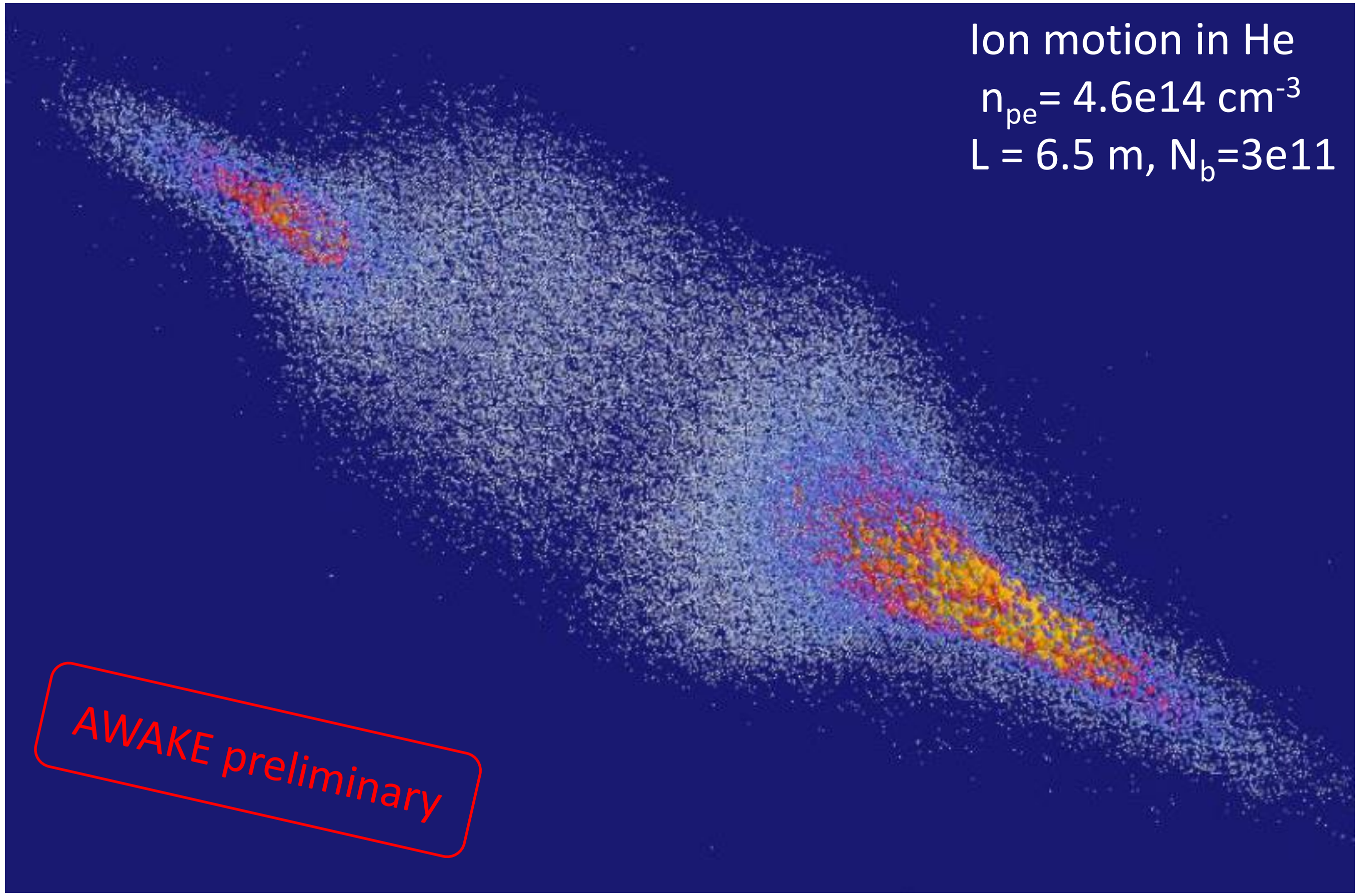
DPS run → benchmarking lab interferometry with proton self-modulation frequency

24 Pa Ar, 500 A, 10 m single plasma **density lab/tunnel comparison**



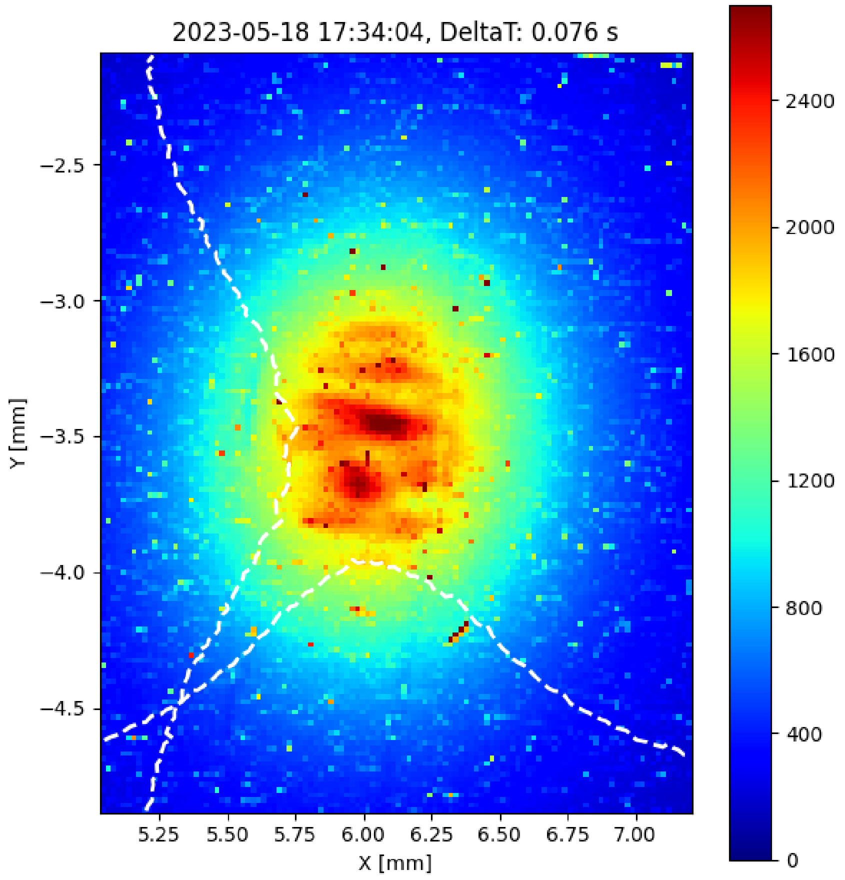
→ Good agreement between lab interferometry and density extracted from proton self-modulation frequency

DPS run → ion motion / CFI



→ *See M. Turner's talk*

Current filamentation instability (CFI)
wide p+ bunch in Xe at n_{pe} = 5.19e14 cm^{-3}



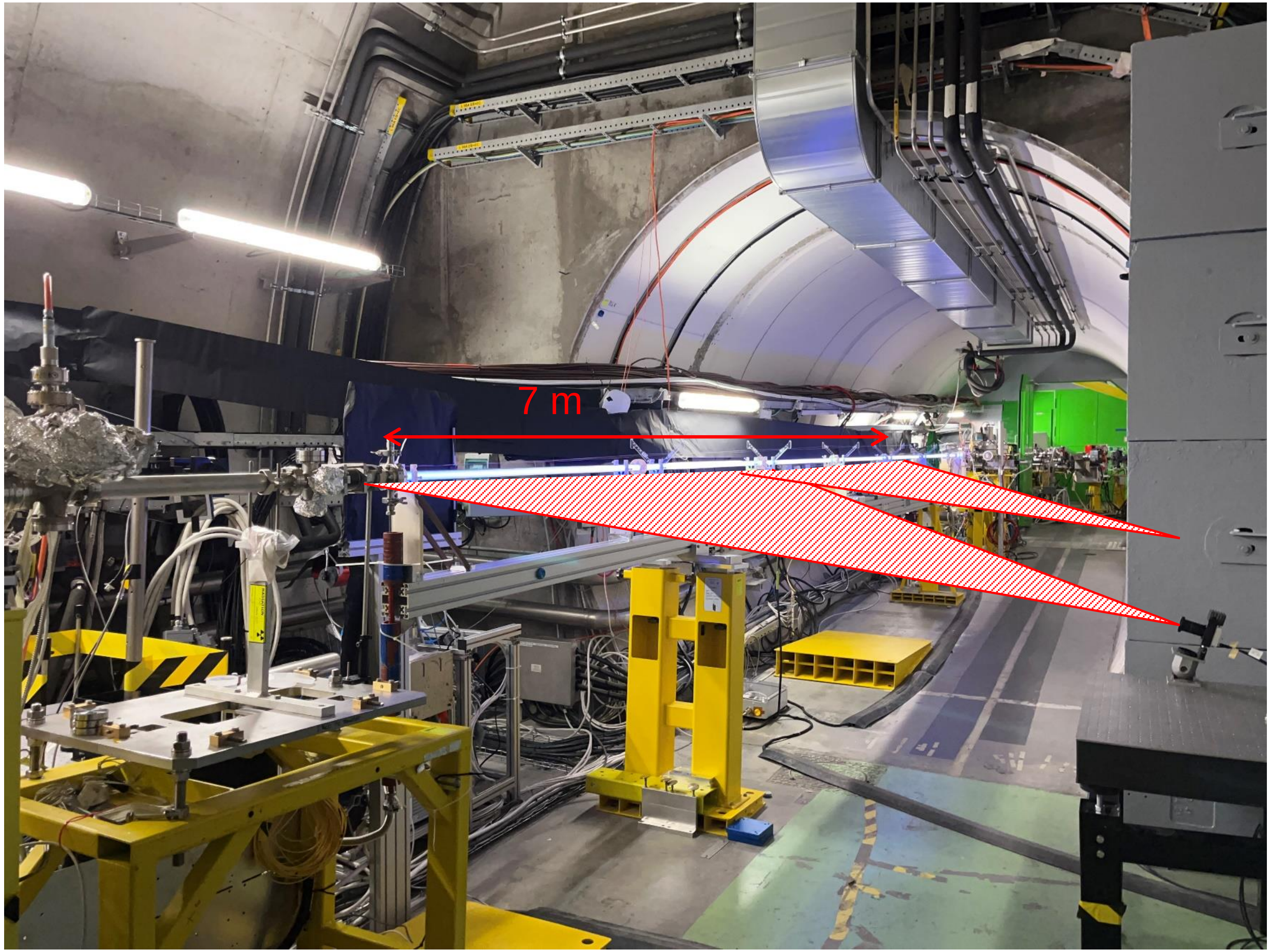
→ *L. Verra's talk*

DPS run → plasma light

- 2x CMOS camera

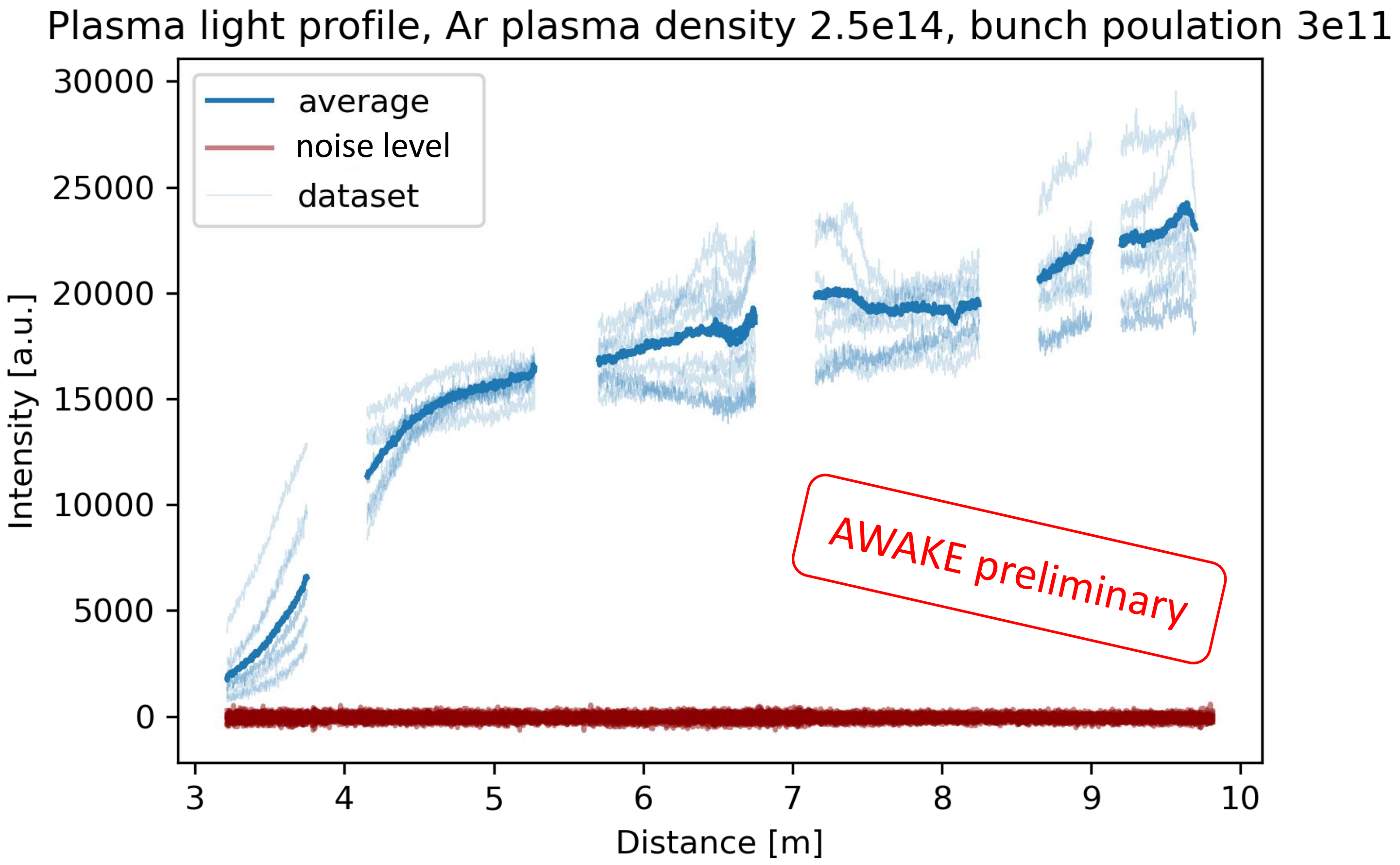
  (Basler boost boA5328 100cm)
- 1μs exposure time

DPS run → plasma light



- 2x CMOS camera
  (Basler boost boA5328 100cm)
- 1μs exposure time
- 7m field of view (2x 3.5 m), 2 m away from DPS
- Plasma only images taken in between two events with protons

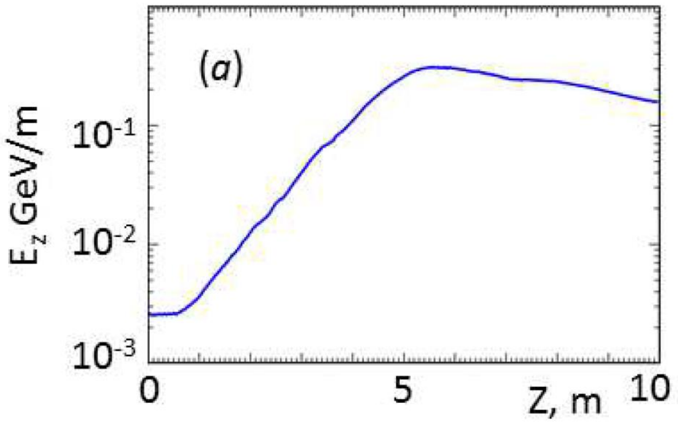
DPS run → plasma light



Courtesy J. Mezger

A. Pukhov, PRL107 145003 (2011)

ne = $7.76 \cdot 10^{14}$ cm^{-3}



→ Total light emitted, radially integrated, time and space resolved

→ Exponential growth, saturation → qualitatively matches simulation of wakefield amplitude

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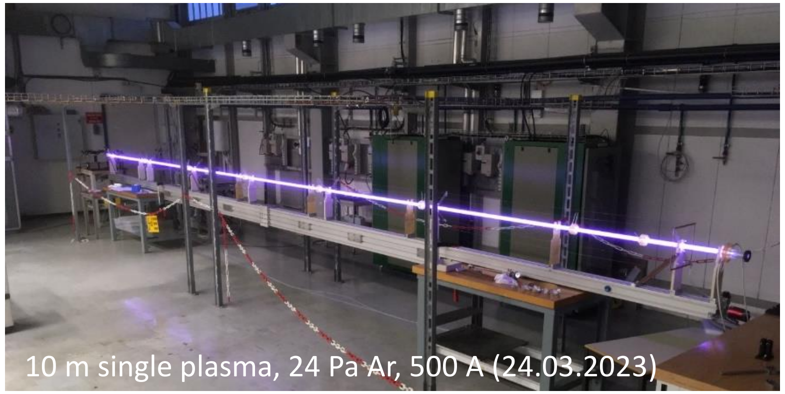
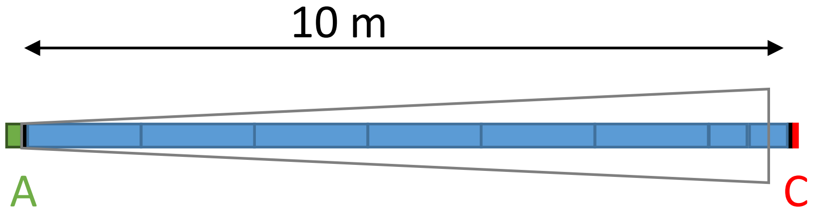
DPS → demonstrate scalability x uniformity

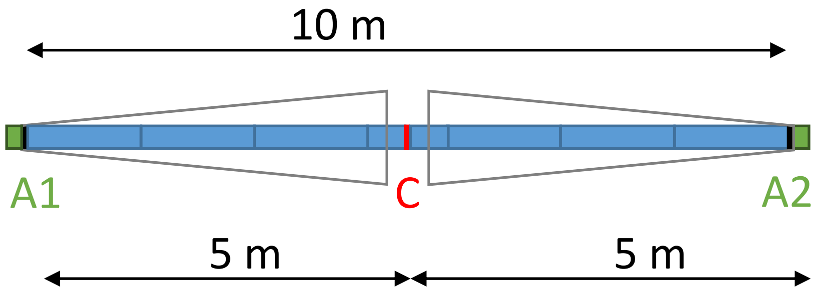


Long plasmas mostly for scalability, with longitudinal interferometry and microsecond cameras imaging the whole discharge:

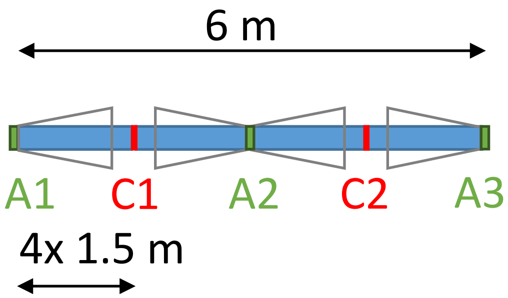
1. 10 m **single plasma** electrical measurement and characterization (Paschen curve, breakdown voltage...)



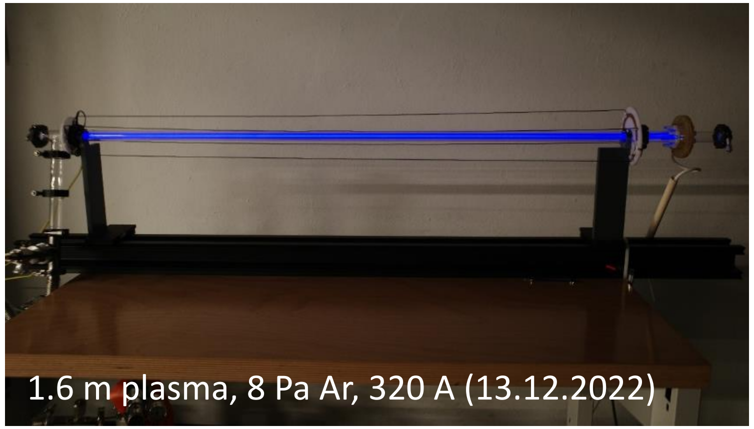
2. Symmetric **double plasma** (5 m + 5 m) with common cathode: A/C/A scheme and 1 or 2 pulse generators



3. **Quadruple plasma** (1.5 m + 1.5 m + 1.5 m + 1.5 m): A/C/A/C/A scheme with 2 pulse generators to test common anode and common cathodes and dedicated current balancing modules

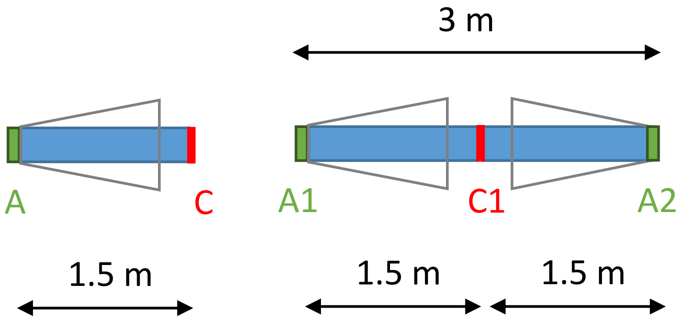


DPS → demonstrate scalability x uniformity

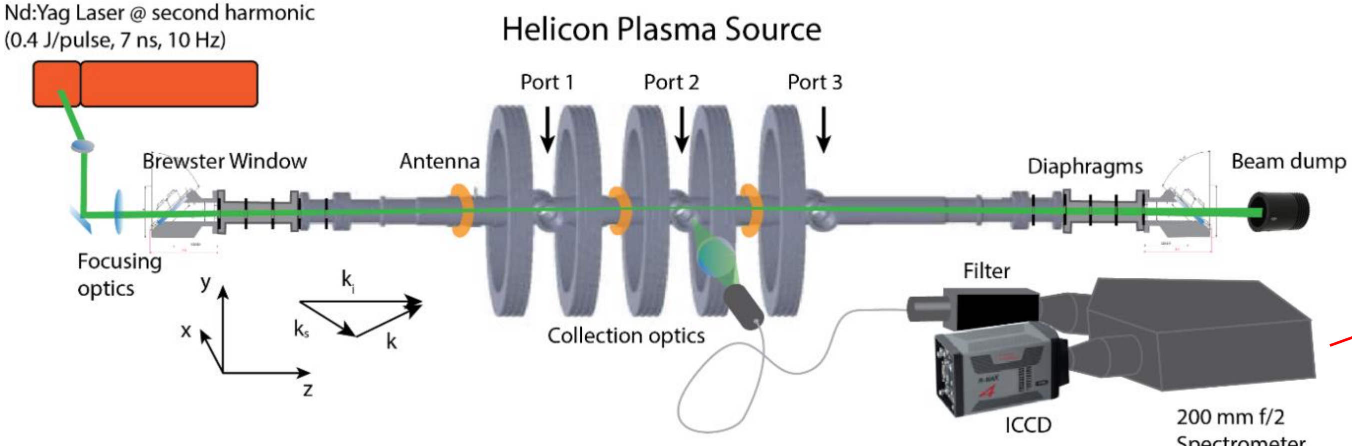


Short plasmas for longitudinal density uniformity measurements and scalability

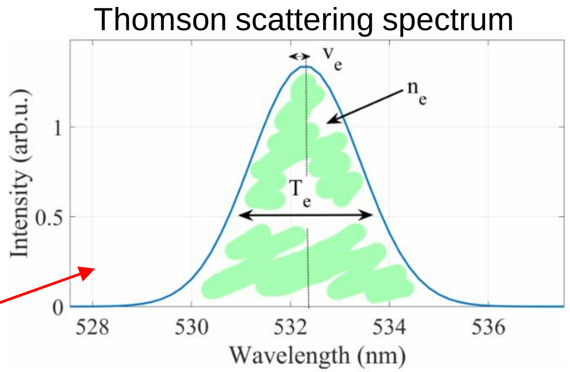
1. 1.5 m single and 1.5 m + 1.5 m double plasmas configurations:
   - plasma light and interferometry → benchmark with 10 m / 5+5 m plasma
   - prepare for Thomson scattering in HPS laser room → May 2024



2. **Thomson scattering** on DPS with EPFL-SPC → June 2024, TS/plasma light calibration for uniformity assessment, comparison with HPS



Courtesy Christine Stollberg, EPFL-SPC



- Operating regime: $1x10^{18}$ - $1x10^{21}$ m^{-3}
- Uncertainties: 0.1 eV and ~ 10% in density

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Summary

- Dedicated R&D program for scalable plasma sources for AWAKE: helicon and discharge plasma sources
- 10 m DPS designed, built and tested in the lab: interferometry to measure longitudinally averaged density
- Unique chance to install and operate a 10 m DPS with protons in the AWAKE tunnel btw run 2a and 2b
- Very stable operation of the DPS over 3 weeks with protons, allowing a large harvest of data thanks to its flexibility of operation and parameter range accessible (density/plasma lengths/gases/etc.)
- Proton bunch SMI observed with the DPS, lab interferometry in good agreement with density from p+ self-modulation + observation of ion motion, CFI, etc.
- Plasma light monitoring as a tool to investigate wakefield time/space evolution
- Scalable plasma sources R&D program continues in the lab with aim at density uniformity measurement by mid-2024 and scalability assessment → decision point end 2024 for AWAKE Run 2c plasma source