Update of the scalable plasma source program and plans

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Claudia Cobo, Louis Forrester, Zulfikar Najmudin (Imperial College London)

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Outline

AWAKE plasma sources

Plasma characterization

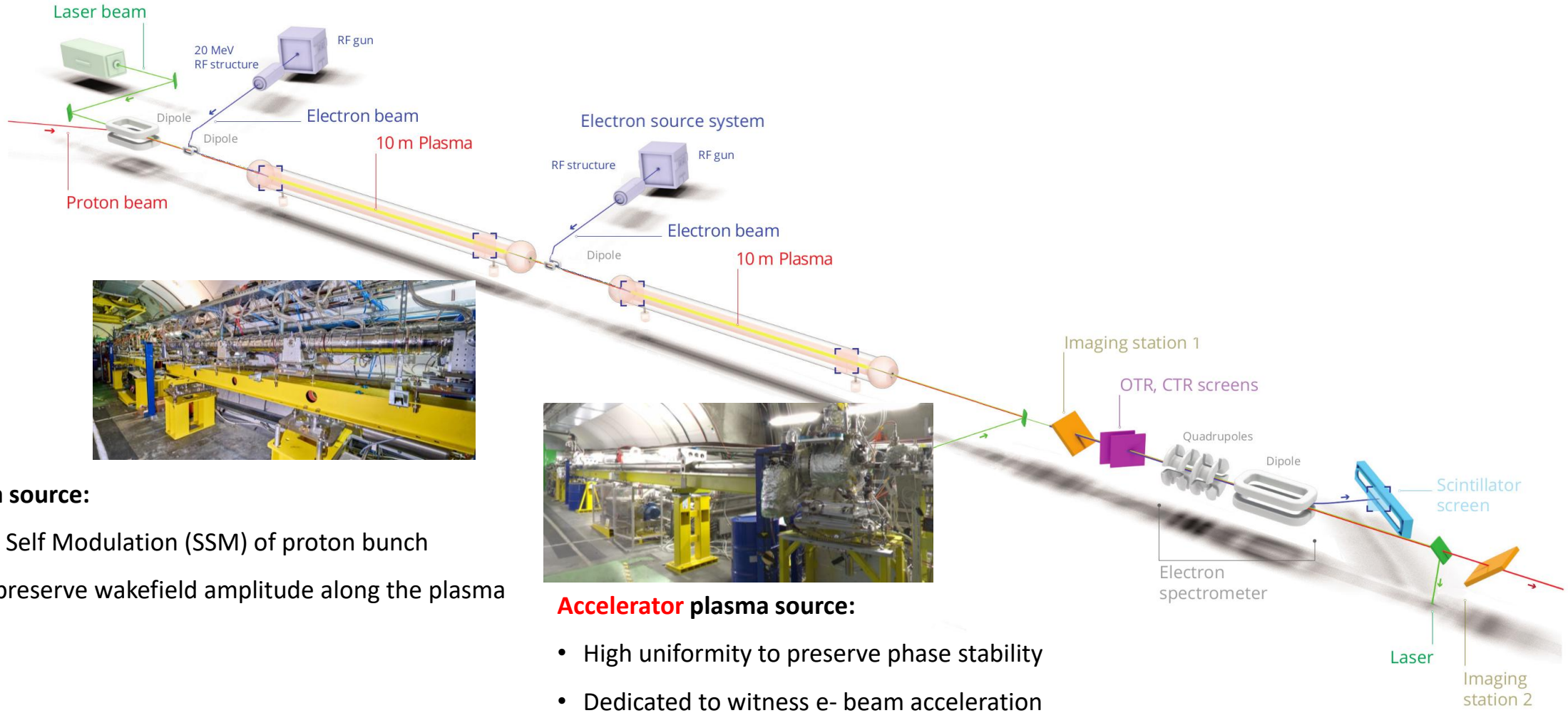
Towards scalability

Summary

AWAKE plasma sources

- 2029, after LS3 → **AWAKE Run 2c**

→ Two plasma sources: **laser ionized Rb vapor**



Modulator plasma source:

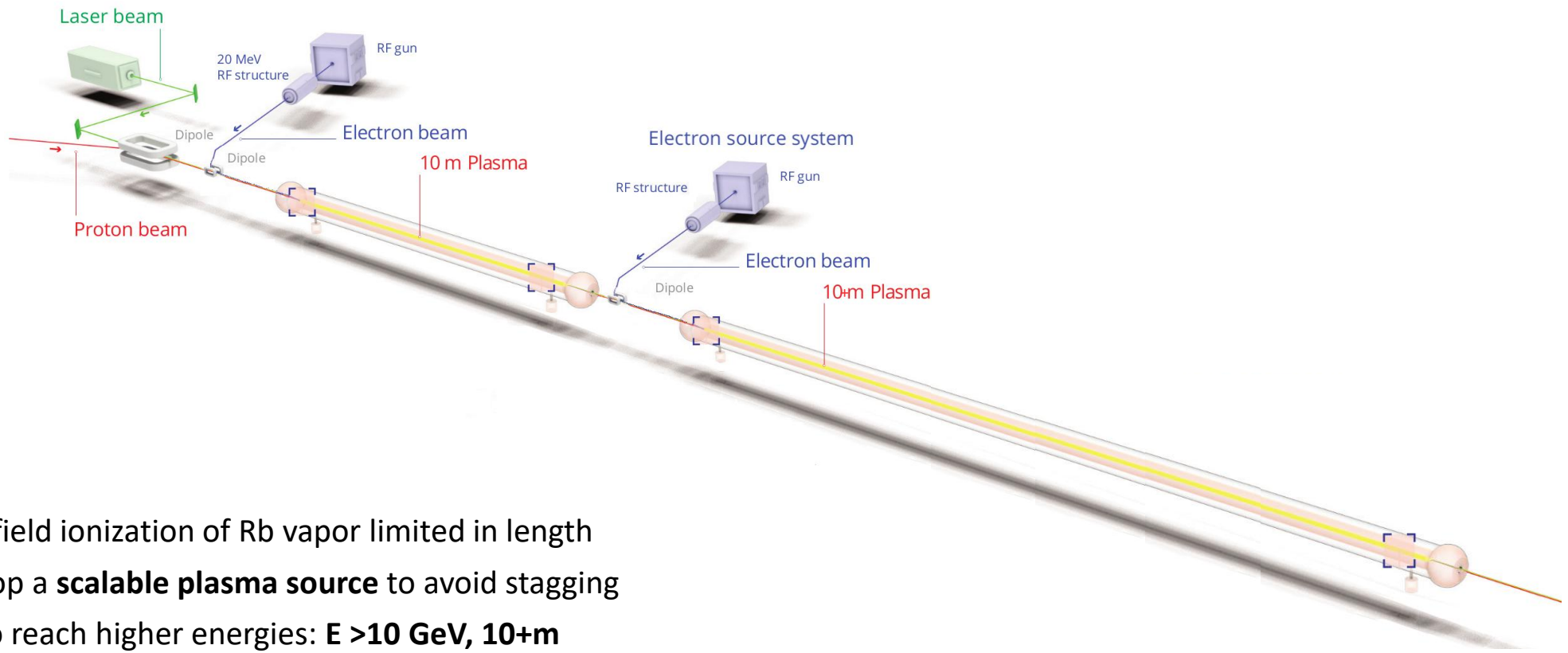
- Laser/e- Seeded Self Modulation (SSM) of proton bunch
- Density step to preserve wakefield amplitude along the plasma

Accelerator plasma source:

- High uniformity to preserve phase stability
- Dedicated to witness e- beam acceleration

AWAKE plasma sources

→ What's next: **scalability**, towards **AWAKE Run 2d**

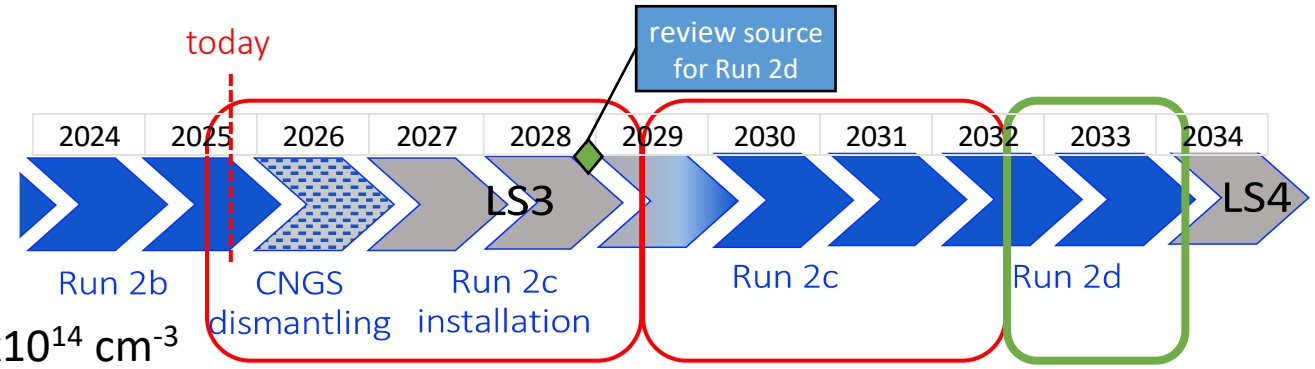


- Laser field ionization of Rb vapor limited in length
- Develop a **scalable plasma source** to avoid stagging
- And to reach higher energies: **E >10 GeV, 10+m**

→ **Dedicated R&D on scalable plasma source** to be ready for experiments in 2030s

Scalable plasma source R&D

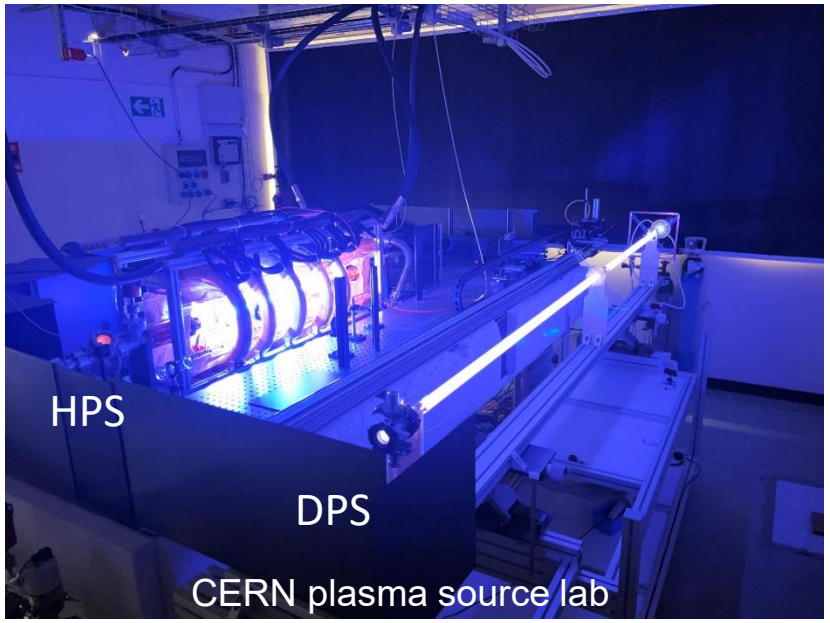
- R&D towards AWAKE Run 2d:
  - Helicon Plasma Source (HPS): RF-wave heated plasma
  - Discharge Plasma Source (DPS): pulsed DC discharge



- Challenge: achieve 0.25% plasma uniformity at $n_e = 7x10^{14}$ cm^{-3}

  → **focus on plasma diagnostics** and source design optimization

- Work in parallel on scalability and tunability:
  - For HPS: stacking RF-antenna/generators/coils → large investment
  - For DPS: stacking sources → challenging source design and electrical circuit



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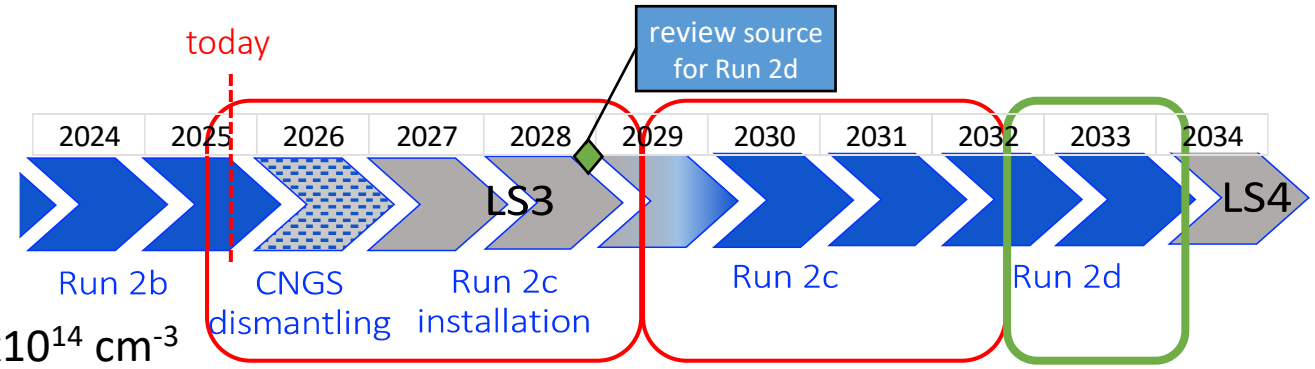

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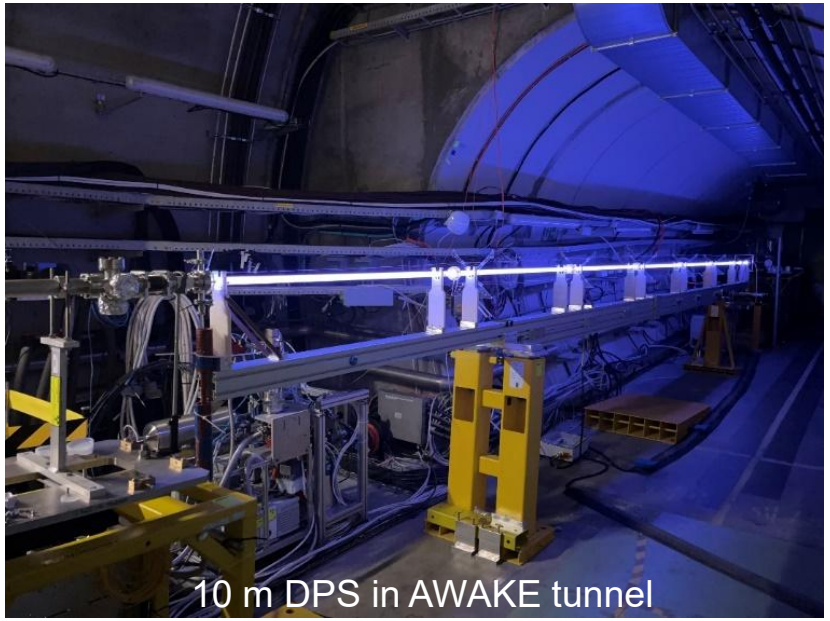
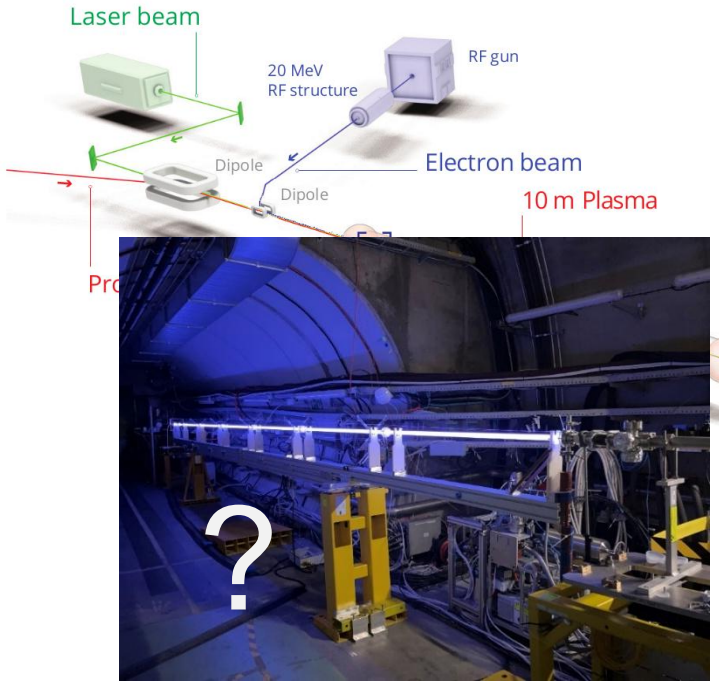

10 m DPS in AWAKE tunnel

- Milestones:
  1. May 2023 run: 10 m DPS in AWAKE → **SMI with DPS**/ion motion/filamentation/…
  2. End 2024/begin 2025: first density uniformity profile with 1 m HPS and 3 m DPS
  3. End 2025: Internal review whether scalable technology can already be used for Run 2c
  4. ~ 2028: Scalable Plasma Source review and decision for Run 2d scalable source

AWAKE plasma sources

- 2029, after LS3 → **AWAKE Run 2c**

→ Two plasma sources: **laser ionized Rb vapor** **and/or alternative scalable plasma source?**



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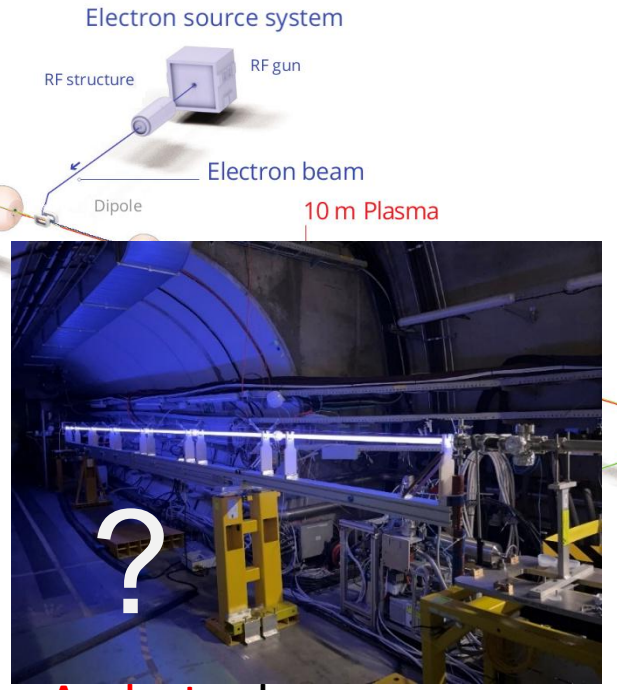

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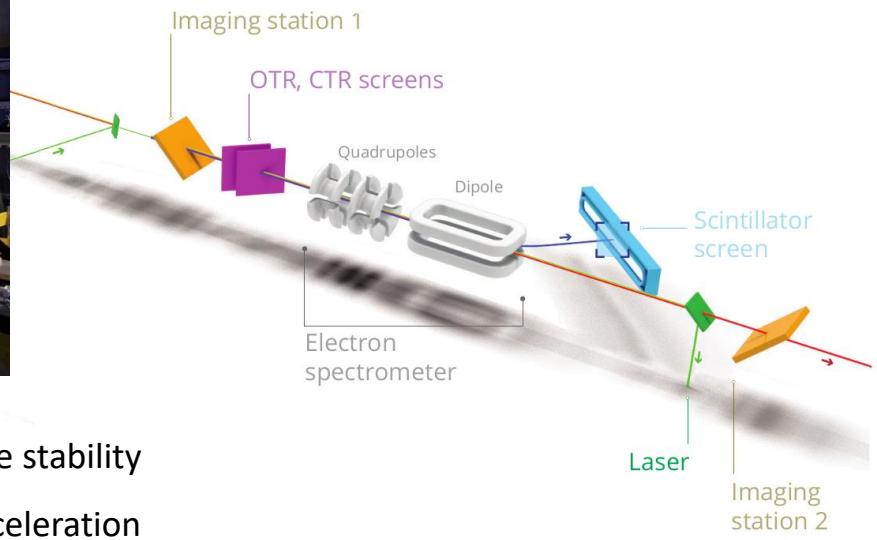

→ Schedule dedicated discussion/review to address this question (physics, design/engineering, timeline, resources…)

Plasma characterization: collaborative R&D effort

- Thomson scattering (TS), interferometry, helicon wave propagation modelling, **HPS + DPS** → EPFL
  - **Axial density profile along the HPS and DPS sources with TS**
  - Thomson scattering and modelling: 2024 *Plasma Phys. Control. Fusion* **66** 115011
  - Validation of mm-wave technique at CERN on both sources with 100 GHz heterodyne setup → **developing a 350-400 GHz setup at CERN**
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  - Development of a transverse multi-pass interferometry in parallel to the longitudinal one

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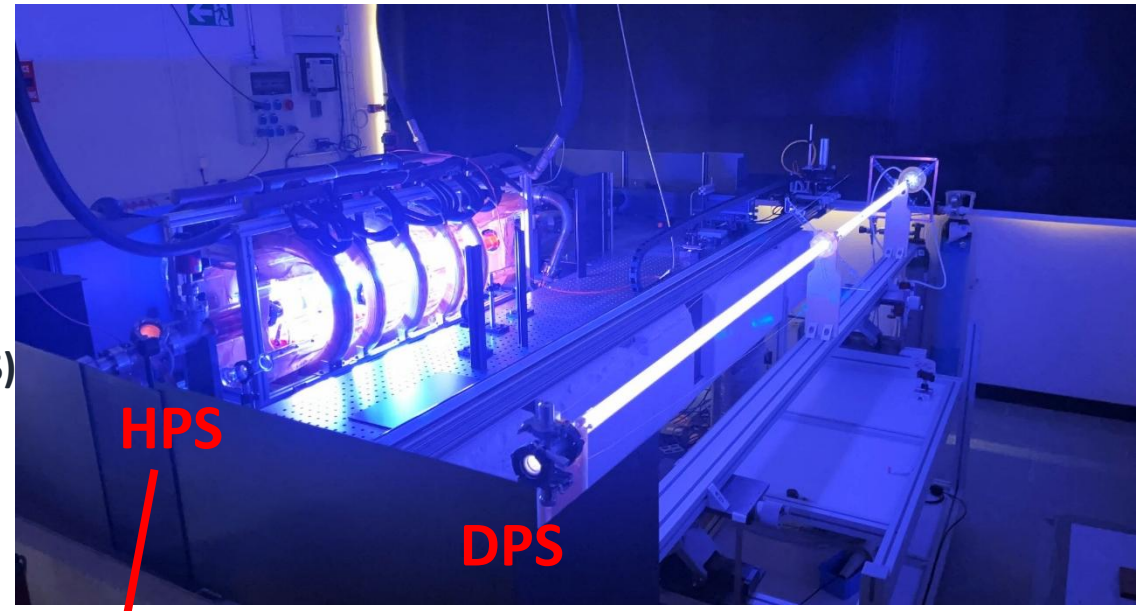
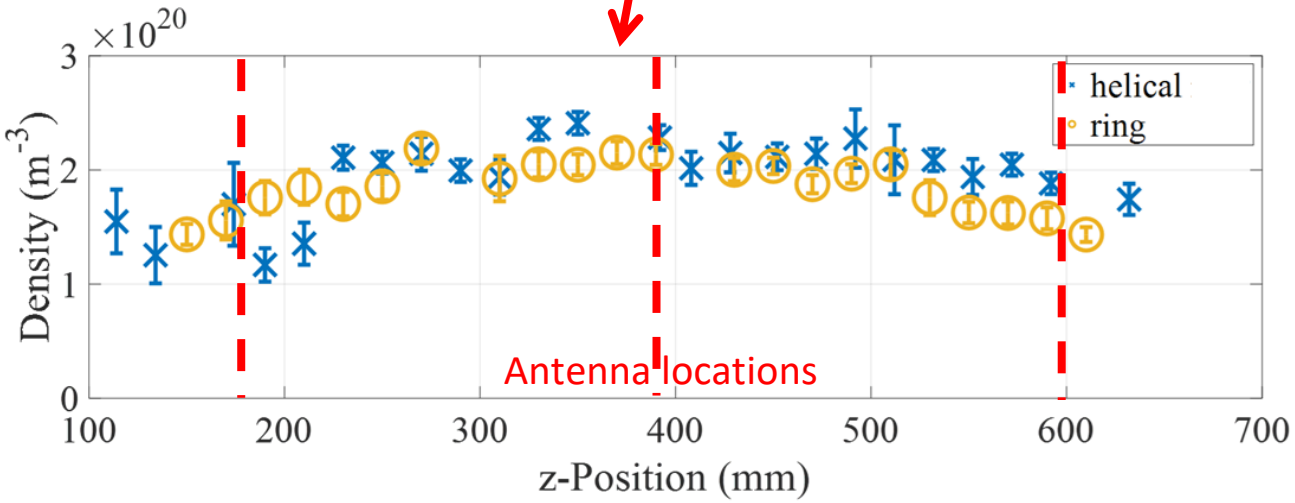
  - Development of a transverse multi-pass interferometry in parallel to the longitudinal one
- longitudinal interferometry, stability and scalability studies on **DPS**, source design → IST Lisbon
  - Pulsed-DC generator development and **current balancing scheme in view of scalability test**
  - High stability and reproducibility source

Axial density profiles: Thomson scattering

1 m Helicon Plasma Source (HPS)

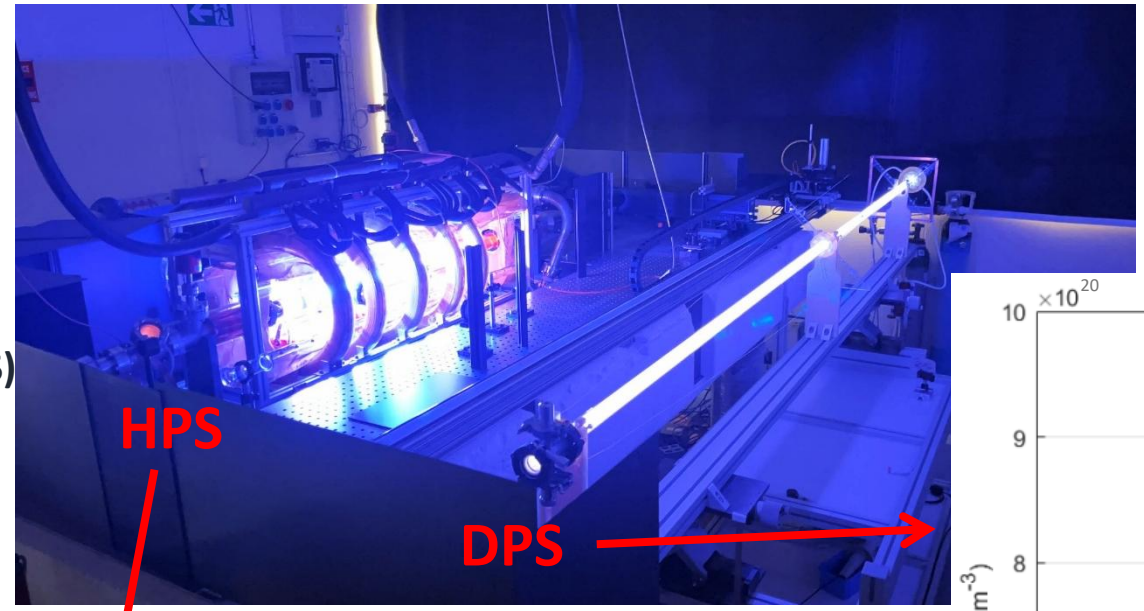
uniformity ± <11 %





Courtesy of Renat Karimov, EPFL-SPC

Axial density profiles: Thomson scattering



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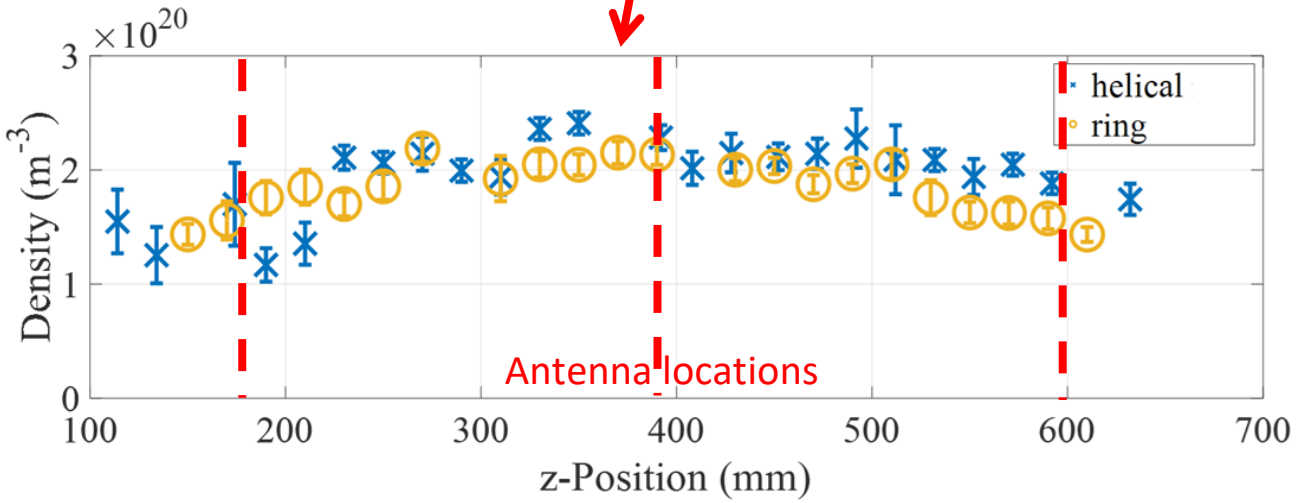
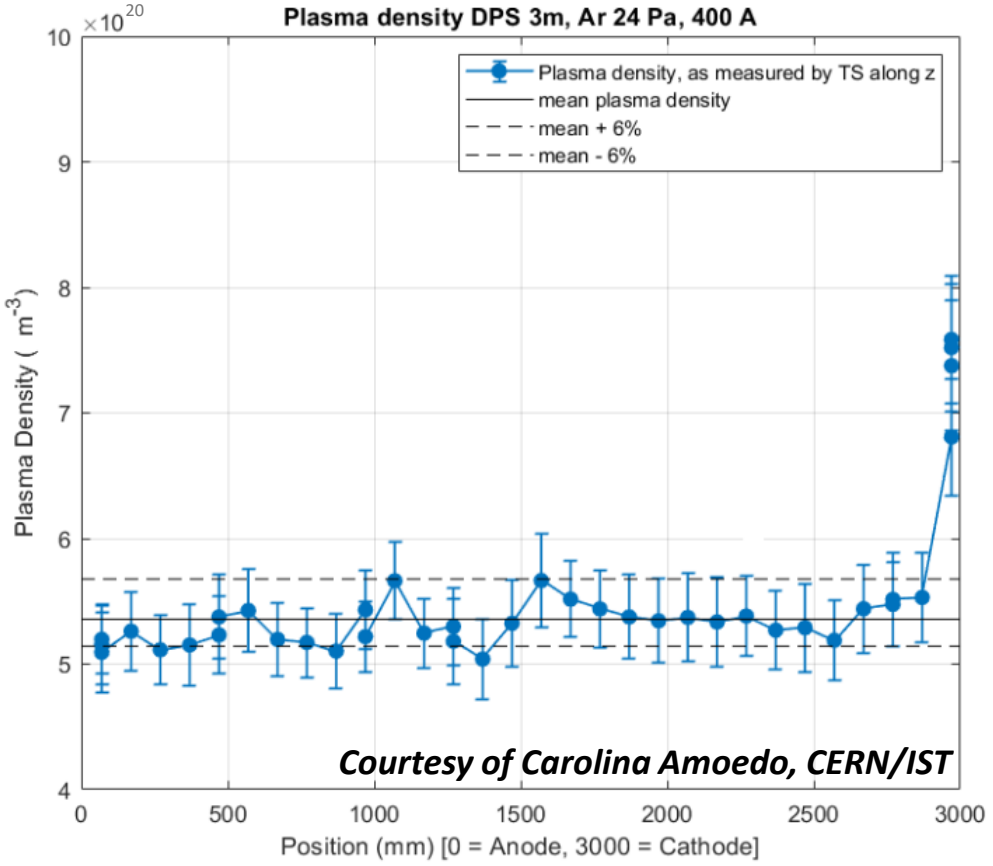


Courtesy of Renat Karimov, EPFL-SPC

3 m Discharge Plasma Source (DPS)

uniformity ± 6%

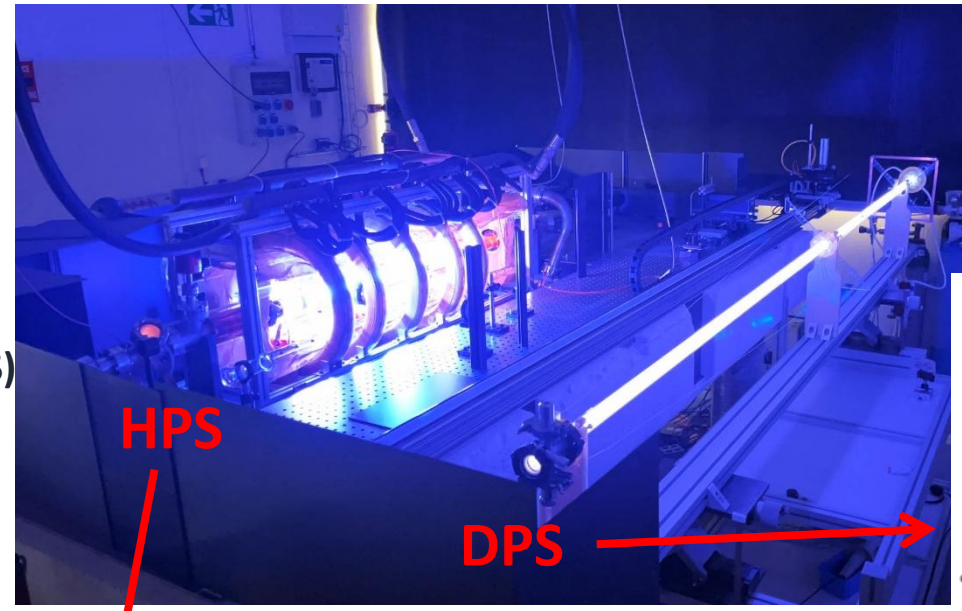


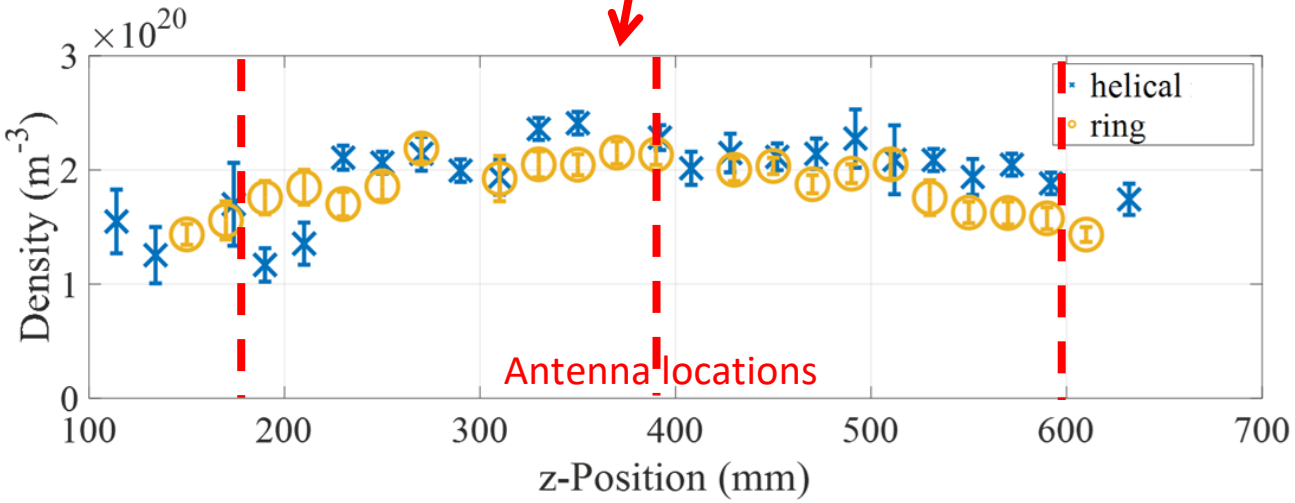
→ Reaching the limits of TS diagnostic capability!

Axial density profiles: Thomson

1 m Helicon Plasma Source (HPS)

uniformity ± <11 %





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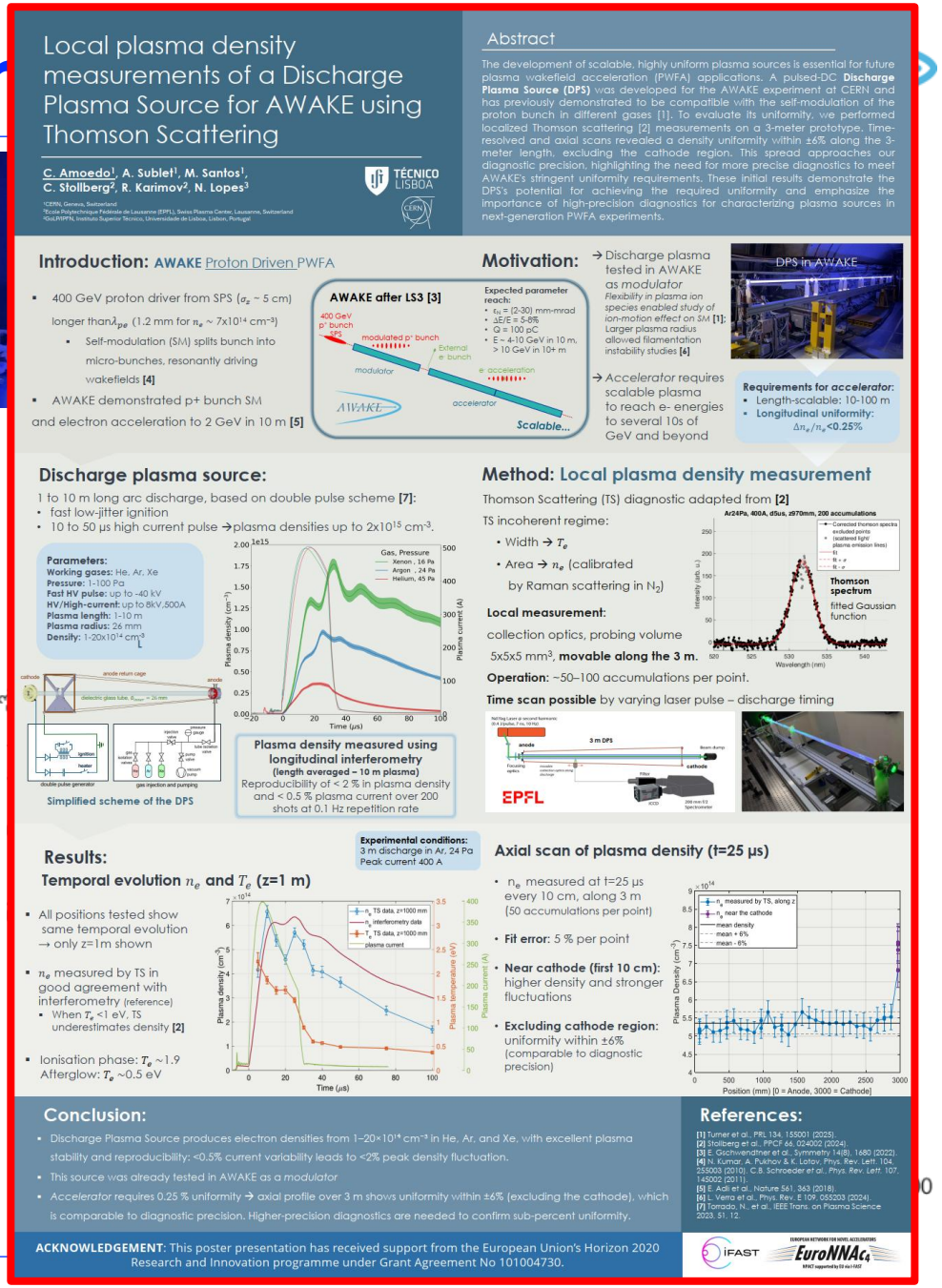

Local plasma density measurements of a Discharge Plasma Source for AWAKE using Thomson Scattering

C. Amoedo[1], A. Sublet[1], M. Santos[1], C. Stollberg[2], R. Karimov[2], N. Lopes[3]

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[2]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center, Lausanne, Switzerland
[3]GoLP/IPFN, Instituto Superior Tecnico, Universidade de Lisboa, Lisbon, Portugal

Abstract

The development of scalable, highly uniform plasma sources is essential for future plasma wakefield acceleration (PWFA) applications. A pulsed-DC **Discharge Plasma Source (DPS)** was developed for the AWAKE experiment at CERN and has previously demonstrated to be compatible with the self-modulation of the proton bunch in different gases [1]. To evaluate its uniformity, we performed localized Thomson scattering [2] measurements on a 3-meter prototype. Time-resolved and axial scans revealed a density uniformity within ±6% along the 3-meter length, excluding the cathode region. This spread approaches our diagnostic precision, highlighting the need for more precise diagnostics to meet AWAKE's stringent uniformity requirements. These initial results demonstrate the DPS's potential for achieving the required uniformity and emphasize the importance of high-precision diagnostics for characterizing plasma sources in next-generation PWFA experiments.

Introduction: AWAKE Proton Driven PWFA

- 400 GeV proton driver from SPS (σ_z ~ 5 cm) longer than λ_{pe} (1.2 mm for n_e ~ 7x10¹⁴ cm⁻³)
  - Self-modulation (SM) splits bunch into micro-bunches, resonantly driving wakefields [4]
- AWAKE demonstrated p+ bunch SM and electron acceleration to 2 GeV in 10 m [5]

AWAKE after LS3 [3]

Expected parameter reach:
- ε_N = (2-30) mm-mrad
- ΔE/E = 5-6%
- Q = 100 pC
- E ~ 4-10 GeV in 10 m, > 10 GeV in 10+ m

Motivation:

→ Discharge plasma tested in AWAKE as *modulator*
Flexibility in plasma ion species enabled study of ion-motion effect on SM [1]; Larger plasma radius allowed filamentation instability studies [6]

→ *Accelerator* requires scalable plasma to reach e- energies to several 10s of GeV and beyond

DPS in AWAKE

Requirements for *accelerator*:
- Length-scalable: 10-100 m
- Longitudinal uniformity: $\Delta n_e/n_e$<0.25%

Discharge plasma source:

1 to 10 m long arc discharge, based on double pulse scheme [7]:
- fast low-jitter ignition
- 10 to 50 µs high current pulse → plasma densities up to 2x10¹⁵ cm⁻³.

Parameters:
Working gases: He, Ar, Xe
Pressure: 1-100 Pa
Fast HV pulse: up to -40 kV
HV/High-current: up to 8kV,500A
Plasma length: 1-10 m
Plasma radius: 26 mm
Density: 1-20x10¹⁴ cm⁻³

Simplified scheme of the DPS

Plasma density measured using longitudinal interferometry (length averaged – 10 m plasma)
Reproducibility of < 2 % in plasma density and < 0.5 % plasma current over 200 shots at 0.1 Hz repetition rate

Method: Local plasma density measurement

Thomson Scattering (TS) diagnostic adapted from [2]

TS incoherent regime:
- Width → T_e
- Area → n_e (calibrated by Raman scattering in N_2)

Ar24Pa, 400A, d5us, z970mm, 200 accumulations

Thomson spectrum fitted Gaussian function

Local measurement:
collection optics, probing volume 5x5x5 mm³, **movable along the 3 m.**

Operation: ~50–100 accumulations per point.

Time scan possible by varying laser pulse – discharge timing

EPFL

Results:

Temporal evolution n_e and T_e (z=1 m)

Experimental conditions: 3 m discharge in Ar, 24 Pa Peak current 400 A

- All positions tested show same temporal evolution → only z=1m shown
- n_e measured by TS in good agreement with interferometry (reference)
  - When T_e <1 eV, TS underestimates density [2]
- Ionisation phase: T_e ~1.9 Afterglow: T_e ~0.5 eV

Axial scan of plasma density (t=25 µs)

- n_e measured at t=25 µs every 10 cm, along 3 m (50 accumulations per point)
- **Fit error:** 5 % per point
- **Near cathode (first 10 cm):** higher density and stronger fluctuations
- **Excluding cathode region:** uniformity within ±6% (comparable to diagnostic precision)

Conclusion:

- Discharge Plasma Source produces electron densities from 1–20×10¹⁴ cm⁻³ in He, Ar, and Xe, with excellent plasma stability and reproducibility: <0.5% current variability leads to <2% peak density fluctuation.
- This source was already tested in AWAKE as a *modulator*
- *Accelerator* requires 0.25 % uniformity → axial profile over 3 m shows uniformity within ±6% (excluding the cathode), which is comparable to diagnostic precision. Higher-precision diagnostics are needed to confirm sub-percent uniformity.

References:

[1] Turner et al., PRL 134, 155001 (2025).
[2] Stollberg et al., PPCF 66, 024020 (2024).
[3] E. Gschwendtner et al., Symmetry 14(8), 1680 (2022).
[4] N. Kumar, A. Pukhov & K. Lotov, Phys. Rev. Lett. 104, 255003 (2010). C.B. Schroeder et al., Phys. Rev. Lett. 107, 145002 (2011).
[5] E. Adli et al., Nature 561, 363 (2018).
[6] L. Verra et al., Phys. Rev. E 109, 055203 (2024).
[7] Torrado, N., et al., IEEE Trans. on Plasma Science 2023, 51, 12.

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→ C. Amoedo's poster prize and talk at EAAC2025

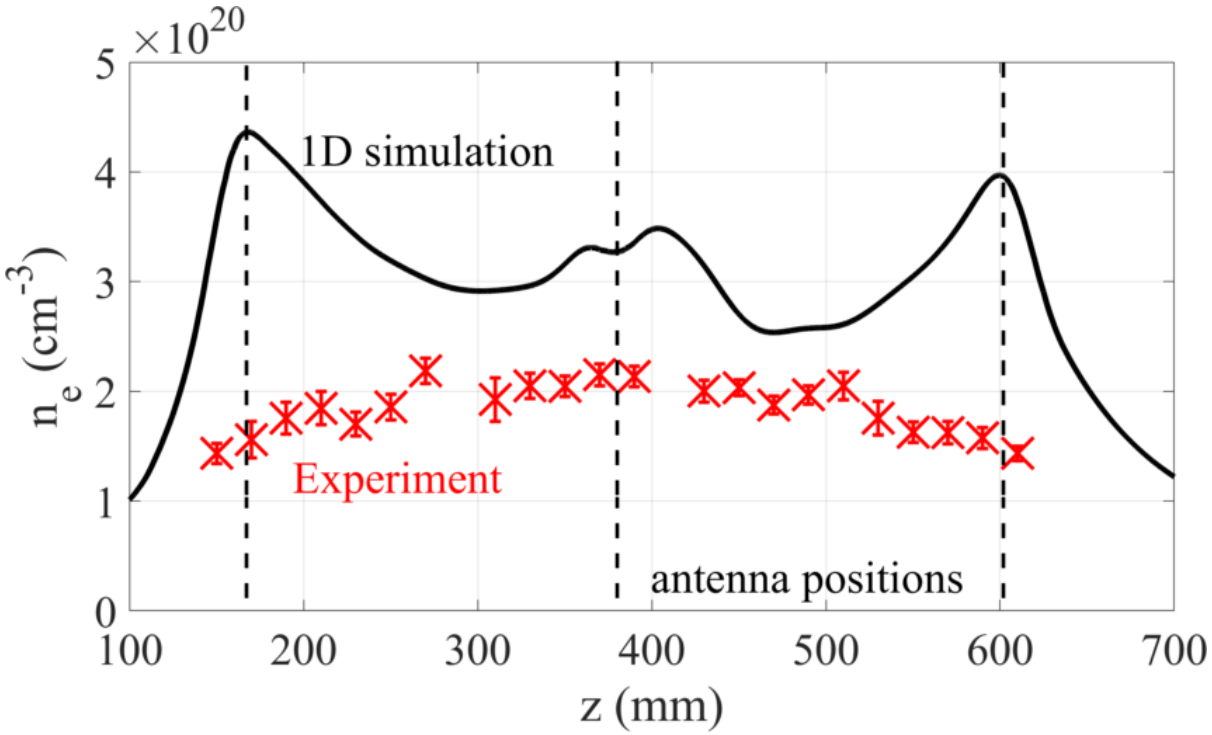
EPFL contributions 2025: Simulations

- **Detailed parameter scans** in different locations and **full axial scans** were obtained in the HPS by Thomson scattering in 2024
  → Valuable data for benchmarking simulations
- Some measurements contradict 1D power-particle balance model
  → Experimental homogeneity better than predicted while absolute density is lower

Improvement of simulations ongoing:

- Solving conjointly Maxwell's equations for antenna excitation and 2D transport equations for ambipolar diffusion
  → n_e, T_e, n_i, T_i, n_N, T_N
- Including neutral depletion
- Including electron-ion collisions (in addition to electron-neutral coll.)

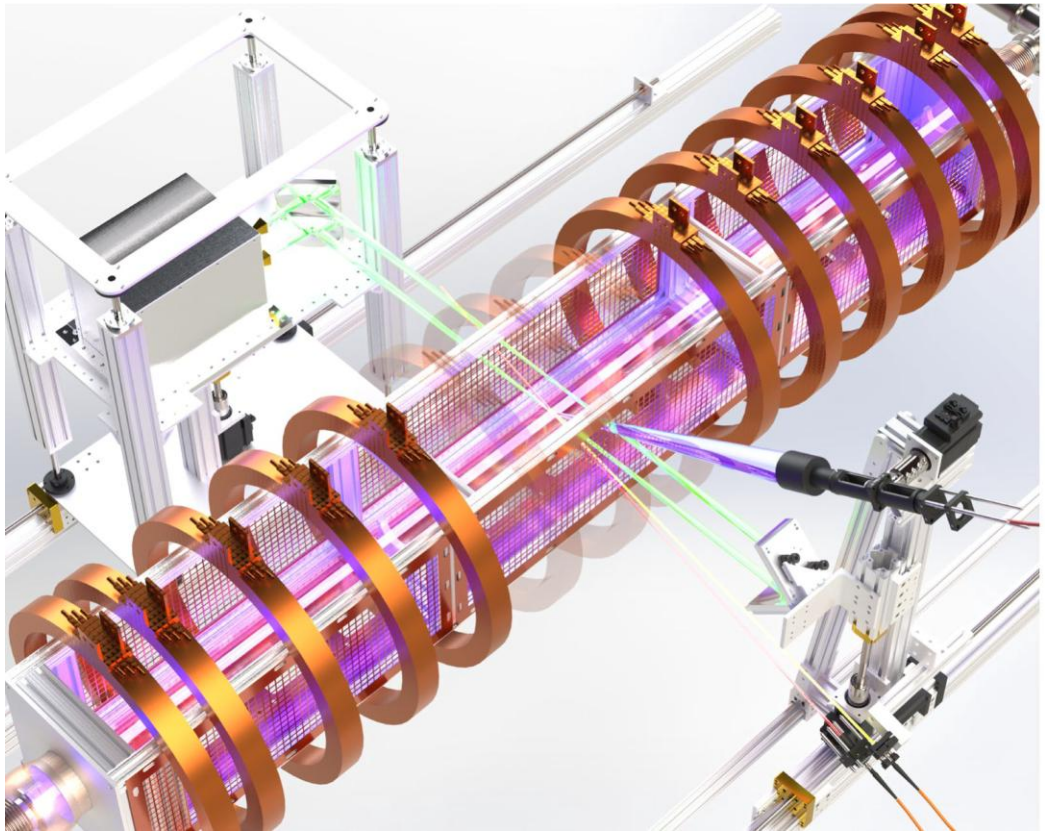
→ Investigation magnetic field confinement effects, antenna coupling, and density saturation at high power



Courtesy of Christine Stollberg, EPFL-SPC

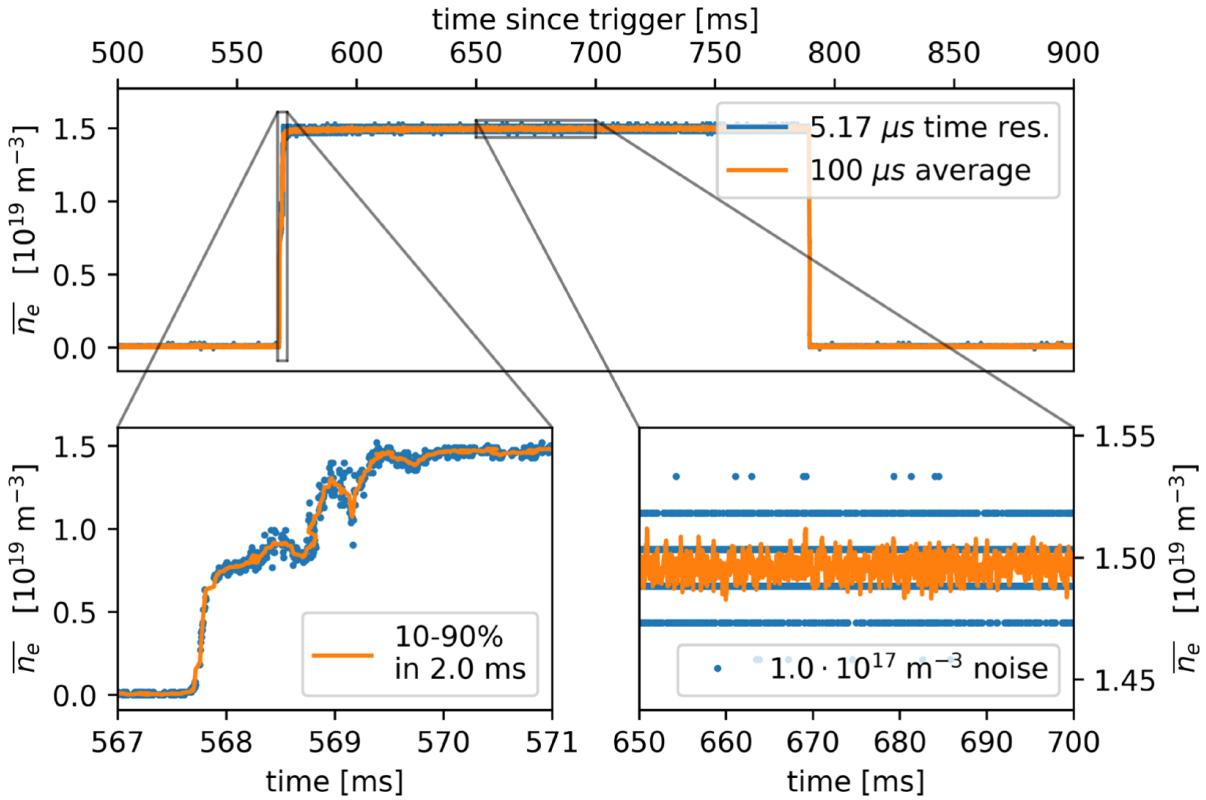
Stollberg et al. Plasma Physics and Controlled Fusion, 66 (11) 2024

mm-wave diagnostic on MAP setup



Madison AWAKE Prototype (MAP), *Phys. Plasmas* 32, 093507 (2025)

2.6 m long source, dual antennas, up to 10kW/antenna

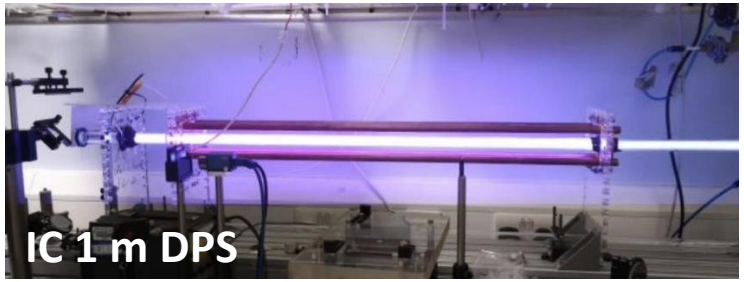


Density evolution over a 1.3 kW / 200 ms RF pulse (single antenna)
~ 0.7% noise level in steady state

→ *Rev. Sci. Instrum.* 96, 093510 (2025)

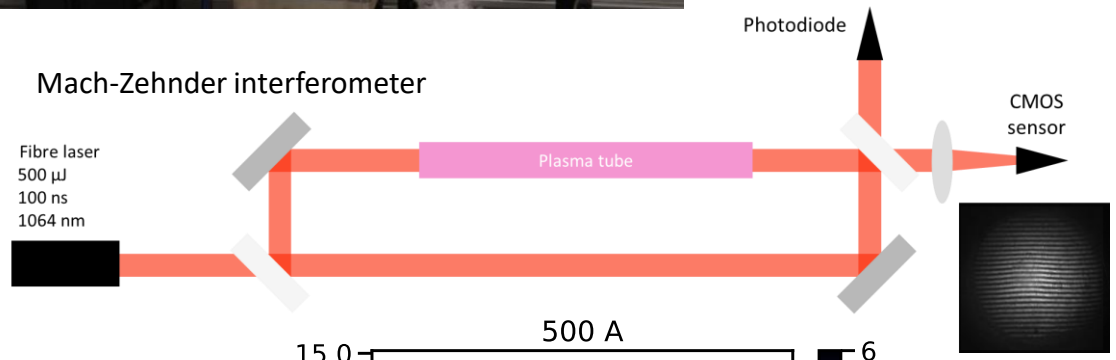
Courtesy of Marcel Granetzny, Univ. Wisconsin

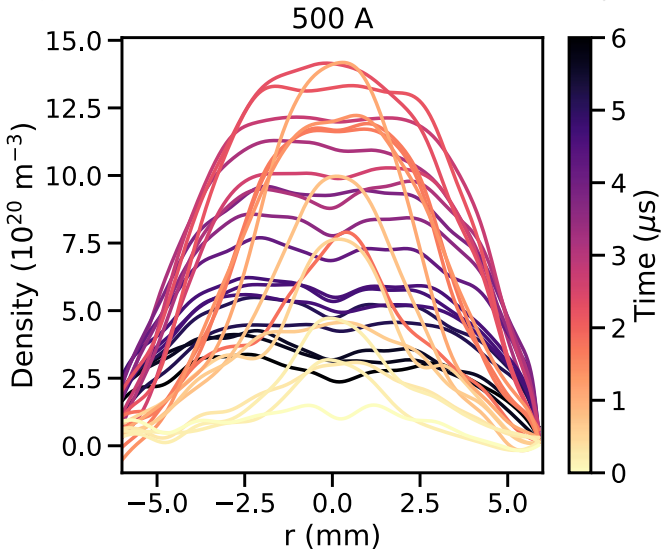
2D interferometry and plasma emission spectroscopy



Gas	Argon
Pressure	0.2 mbar
Voltage	8 kV

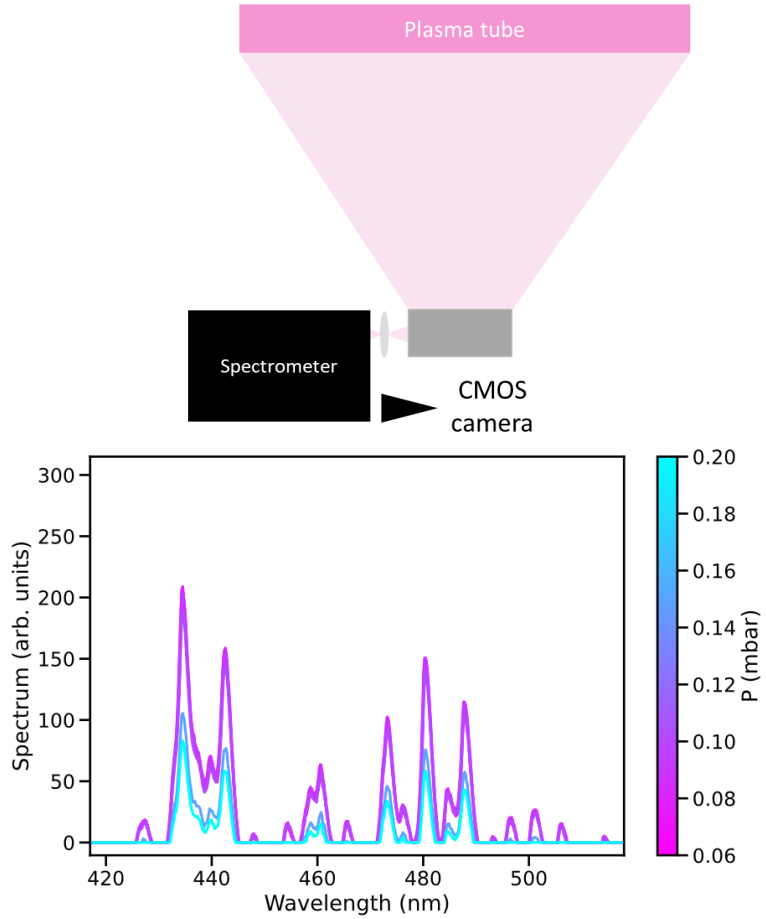
Mach-Zehnder interferometer





Bentham M300 Czerny-Turner spectrometer used to measure spectrum of plasma emission.

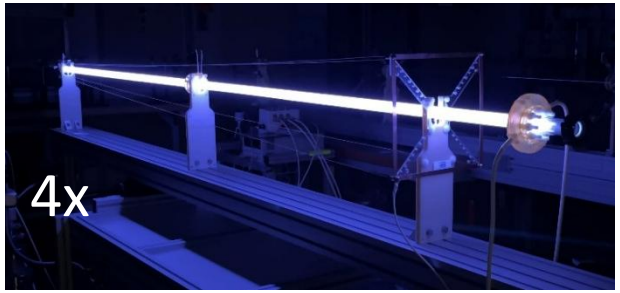
- Integrated over discharge pulse

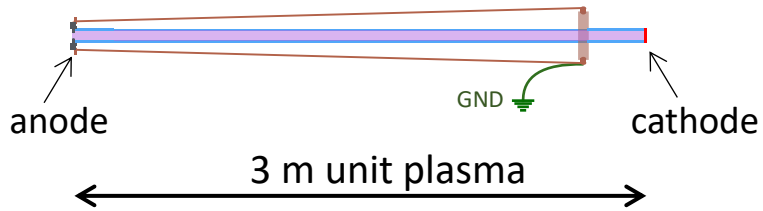


Plasma spectrum dominated by Ar II (singly ionised argon)

Towards scalability: DPS

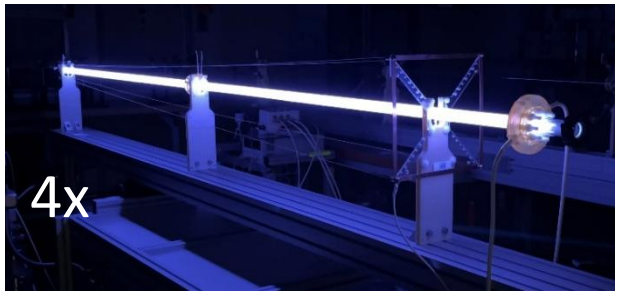
- **From 3 m unit plasma to 12 m plasma at CERN:**
  - Combine x4 the well characterized 3 m DPS source
  - Use existing shared cathodes and anodes
  - Use two sets of pulsed generators (used during May 2023 run) to power two twin plasmas

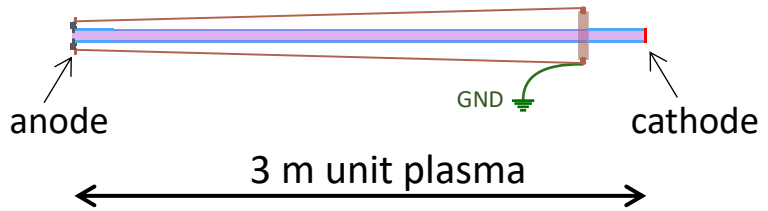


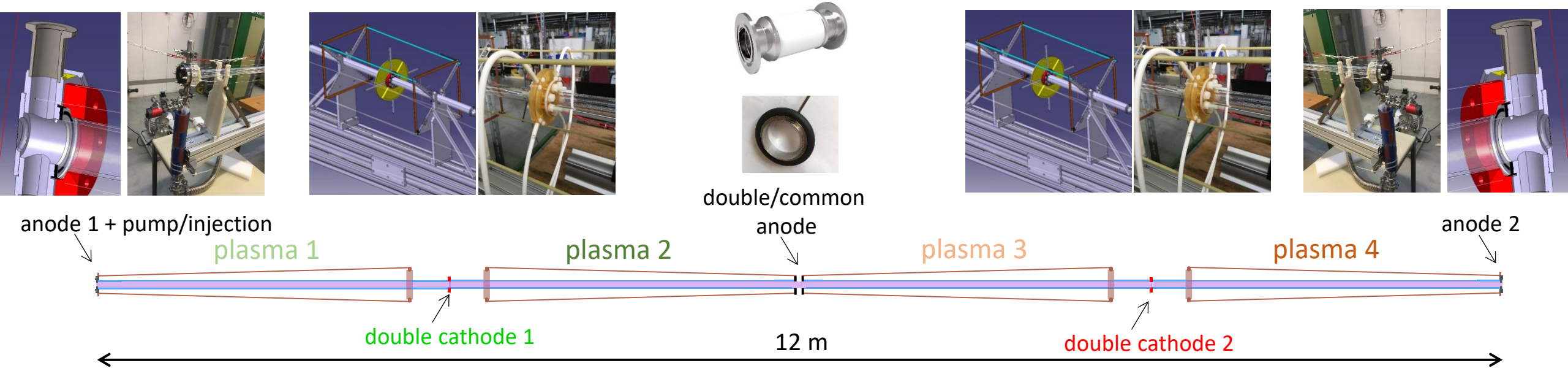


Towards scalability: DPS

- **From 3 m unit plasma to 12 m plasma at CERN:**
  - Combine x4 the well characterized 3 m DPS source
  - Use existing shared cathodes and anodes
  - Use two sets of pulsed generators (used during May 2023 run) to power two twin plasmas







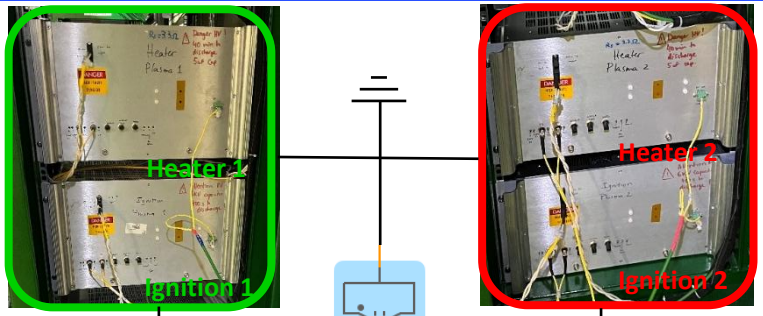
→ Planned for **end Nov. 2025 at CERN with venue of Nelson + Diogo and Miguel, 2 master students from IST**

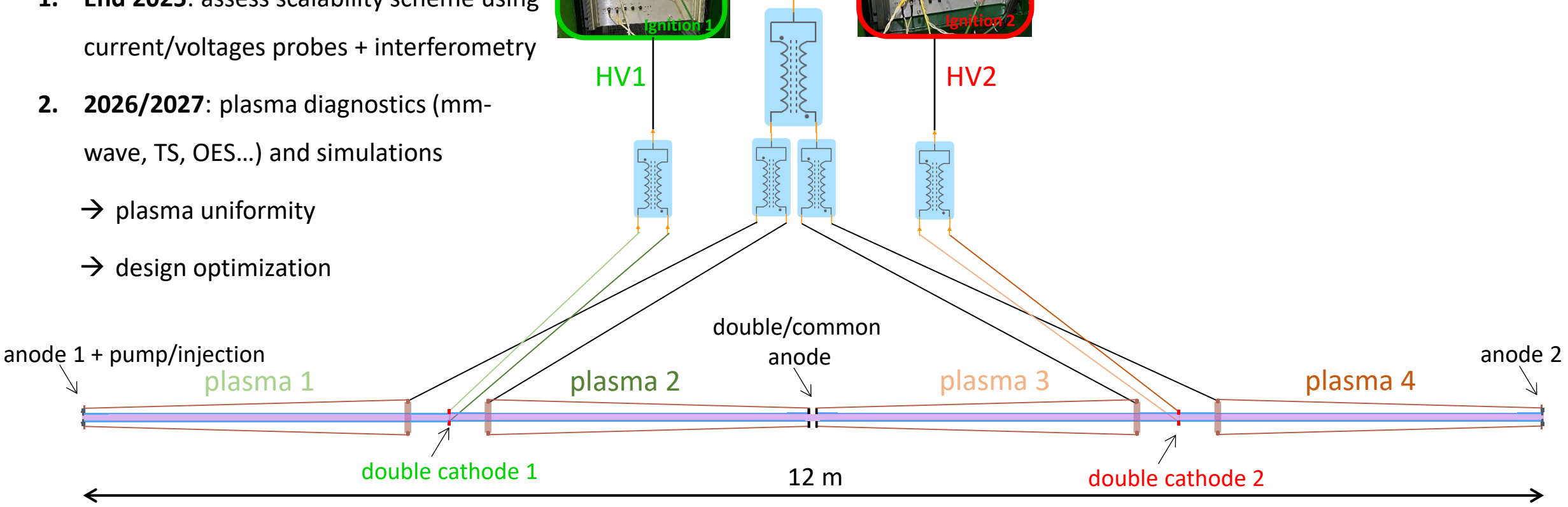
Towards scalability: DPS

- New current balancing modules (CBM) under design at IST → **magnetic chokes**
  1. **End 2025**: assess scalability scheme using current/voltages probes + interferometry
  2. **2026/2027**: plasma diagnostics (mm-wave, TS, OES…) and simulations

     → plasma uniformity

     → design optimization





Towards scalability: HPS

1. **On going**: HW consolidation of 1 m/3 antennas HPS at CERN

   → Based on RF-plasma expert measurements and recommendations from July 2025

   → RF-lines and RF-coupling optimization and monitoring

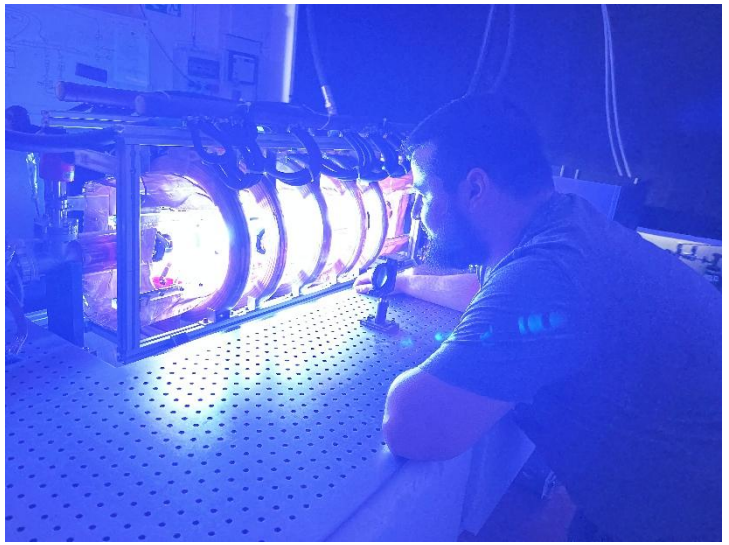
2. **End 2025/begin 2026**: test feasibility of 6 antennas on 1 m HPS at CERN

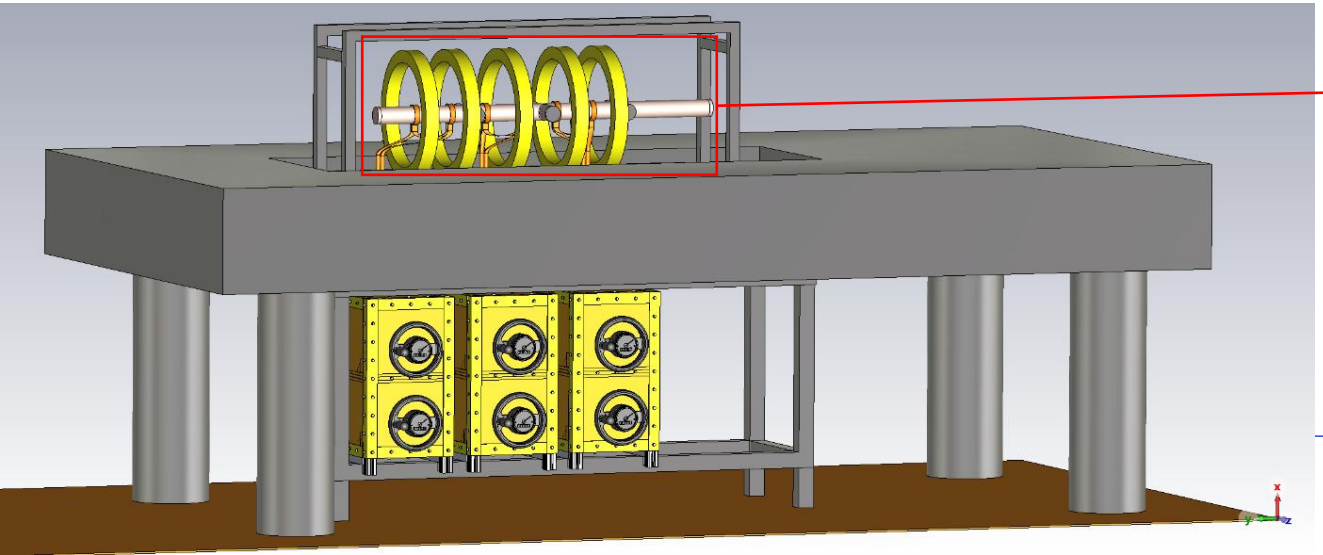
   → 3x 2 antennas in series powered by existing 3x RF-lines

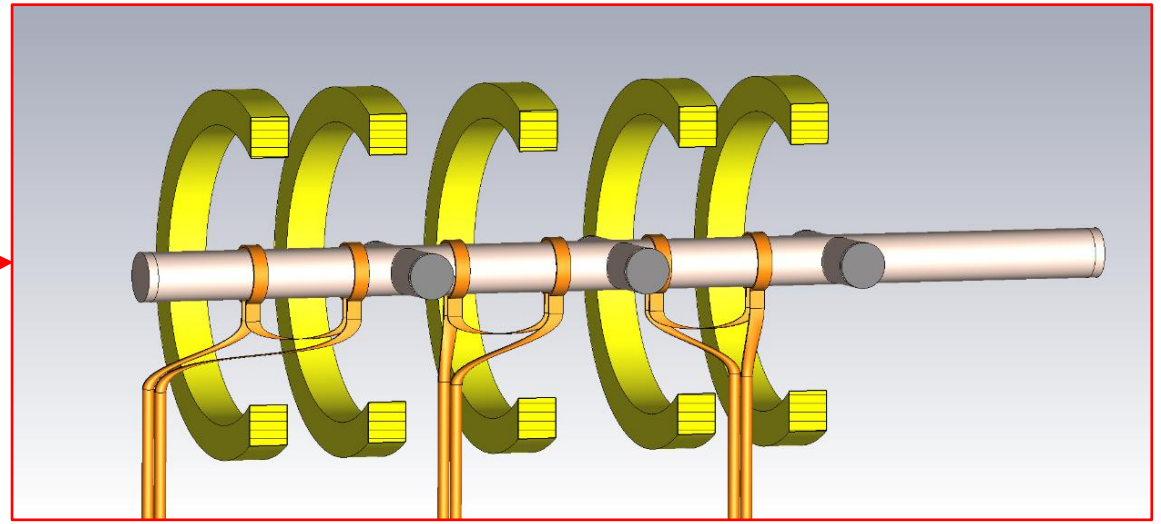
   → Keep same RF-power density (~ 30 kW/m):

   5 kW/antenna and half distance between antennas

3. **2026**: assess density uniformity (mm-wave, TS…)



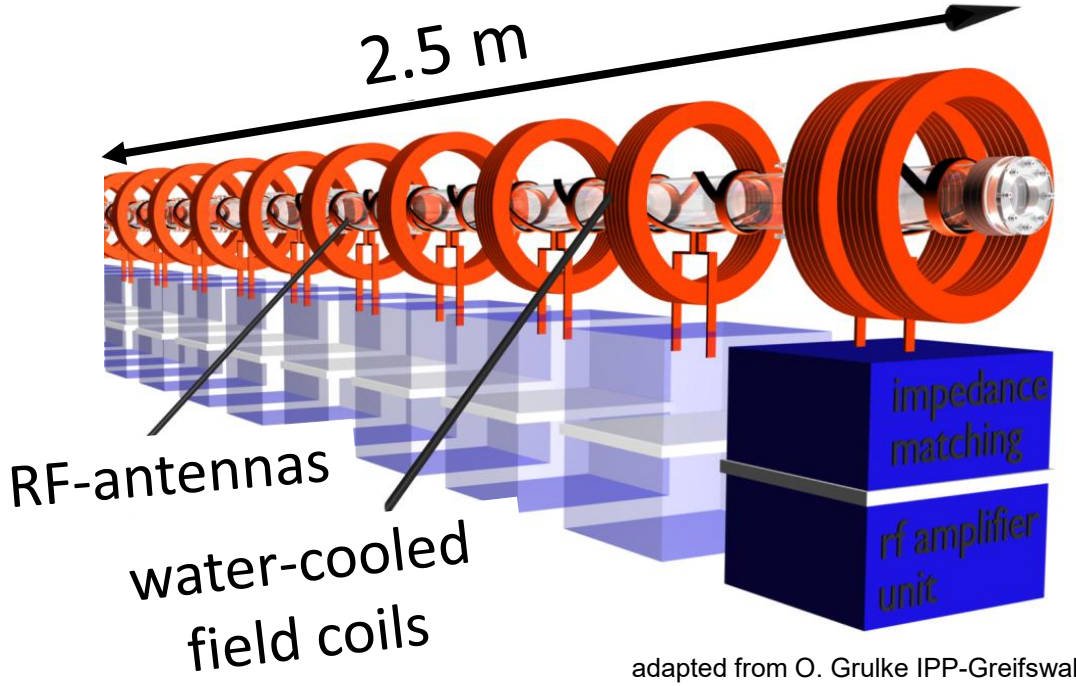




Courtesy of Miguel Santos

Towards scalability: HPS

4. **2026/2027**: Implement learnings from institutes
   - Design and build a ~ 2.5 m HPS module with ~ XX antennas at CERN
   - With optimal tube diameter and antenna shape/spacing
   - Procurement of RF-generators/matchboxes with frequency tuning for fast ignition, short pulses and high stability/reproducibility
   - Build and commissioning
   - Assess plasma uniformity



adapted from O. Grulke IPP-Greifswald

Summary

→ Time to schedule a review and decide if scalable technology can already be used for Run 2c

- On going collaborative effort with institutes to develop diagnostics and combine them to characterize the plasma
- Axial density profile on 1 m HPS: +/- 11% uniformity and 3 m DPS: +/- 6% uniformity → reaching the limits of diagnostic!
- Scalability tests to be gradually implemented starting with 12 m DPS test and 6-antennas HPS test
- Publications in the pipeline: the 2023 DPS run, HPS axial profile and DPS axial profile using Thomson scattering

Summary

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2024-2026 PhDs:

- 2 PhDs at University of Madison: Marcel Granetzny (May 2024) and Michael Zepp (October 2024)
- 2 PhD at IST/CERN: Nuno Torrado (July 2025) and Carolina Amoedo (due by end 2025/begin 2026)
- 1 PhD at EPFL-SPC: Renat Karimov (due by begin/mid-2026)

Thank you for your attention