Overview of scalable plasma source R&D for the AWAKE project at CERN

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Nuno Torrado, Nelson Lopes (IST-Lisbon)

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

Carolina Amoedo, Miguel Santos, Alban Sublet (CERN)

EAAC2025

Outline

Scope and challenges of scalable plasma source R&D

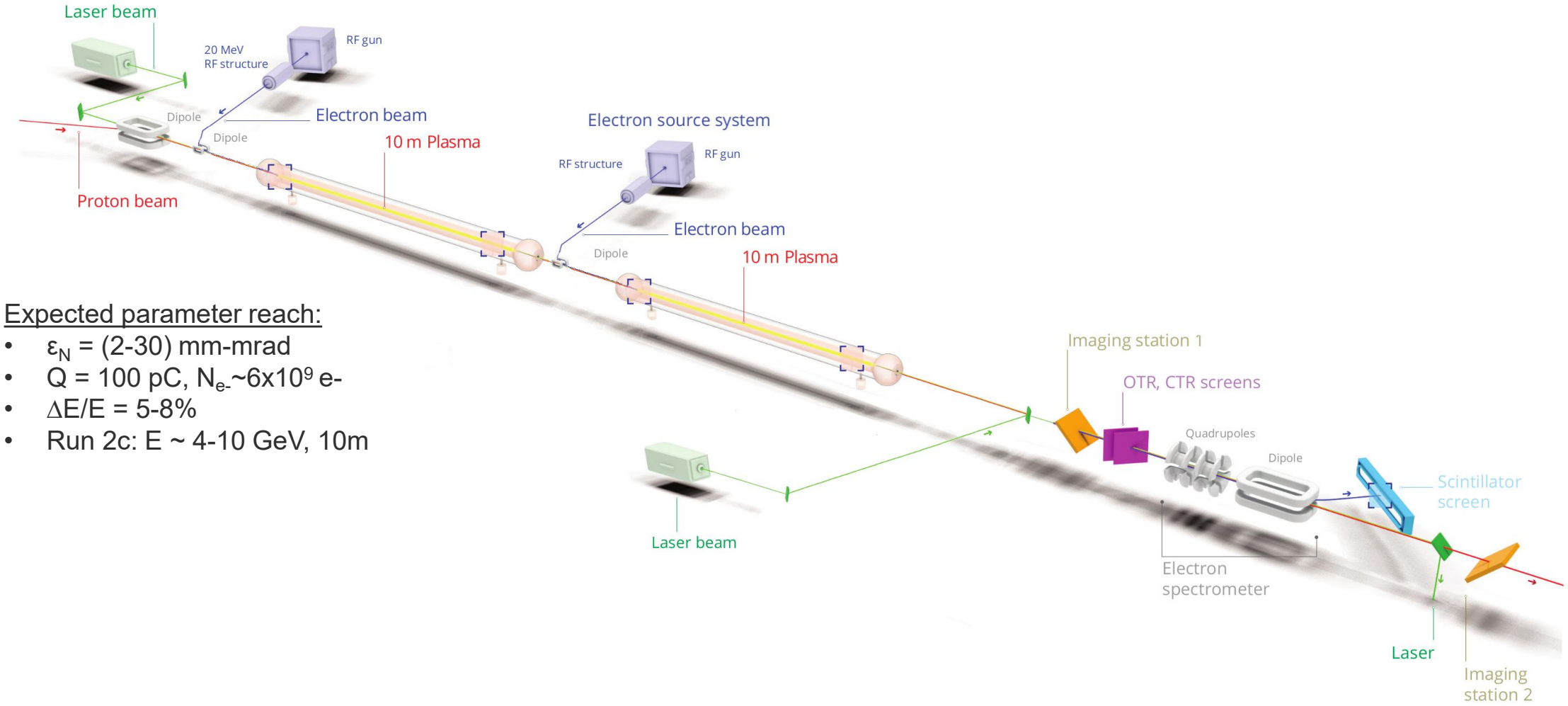
Diagnostics and plasma characterization

Towards scalability for AWAKE Run 2d

Summary

AWAKE plasma sources

- 2029, after LS3 for HL-LHC preparation → **AWAKE Run 2c**
- **Goals**: external injection of e- witness beam, preserved beam quality and acceleration



Expected parameter reach:

- ε_N = (2-30) mm-mrad
- Q = 100 pC, N_{e-}~6×10^9 e-
- $\Delta E/E$ = 5-8%
- Run 2c: E ~ 4-10 GeV, 10m

→ E. Gschwendtner presentation (current talk in Biodola)

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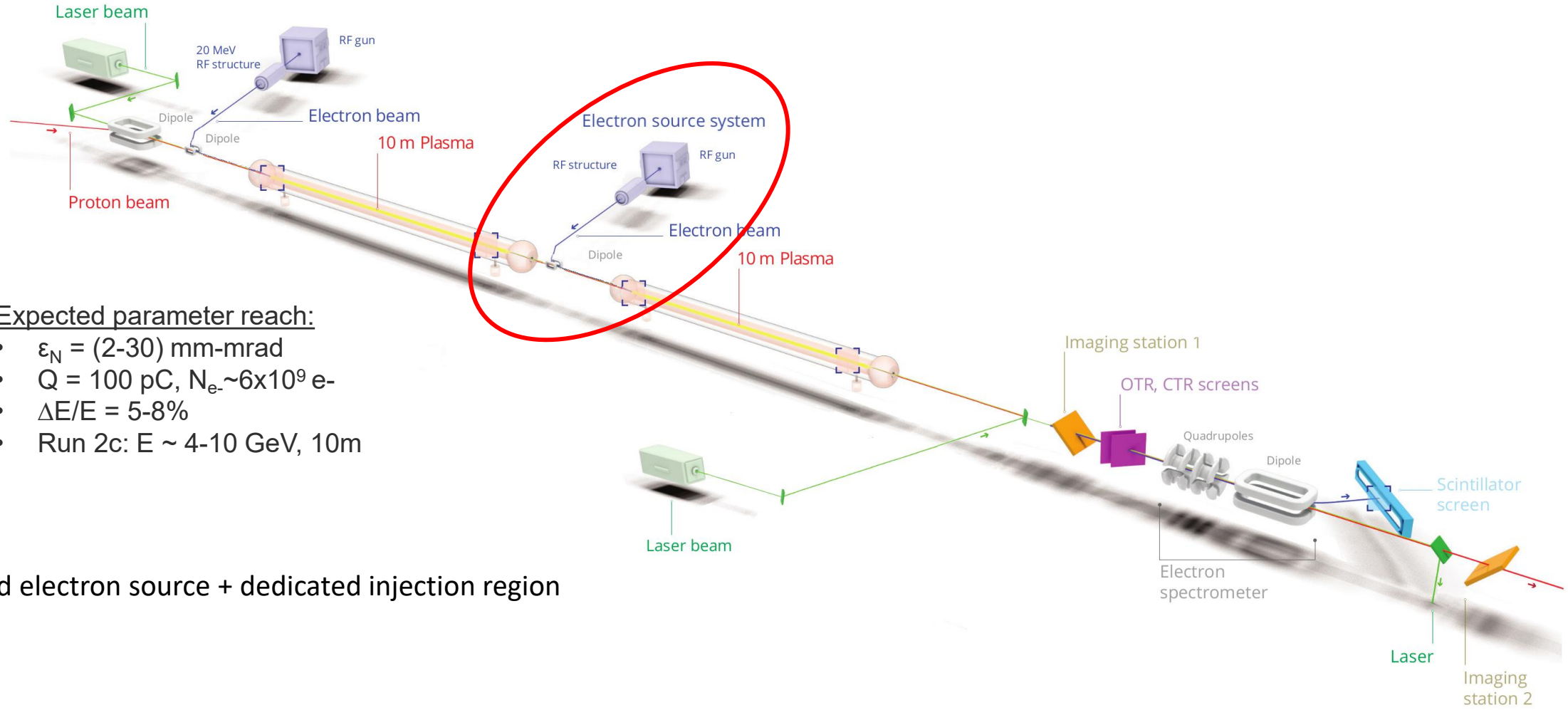

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→ Second electron source + dedicated injection region

→ S. Doebert presentation and E. Belli presentation (Monday session)

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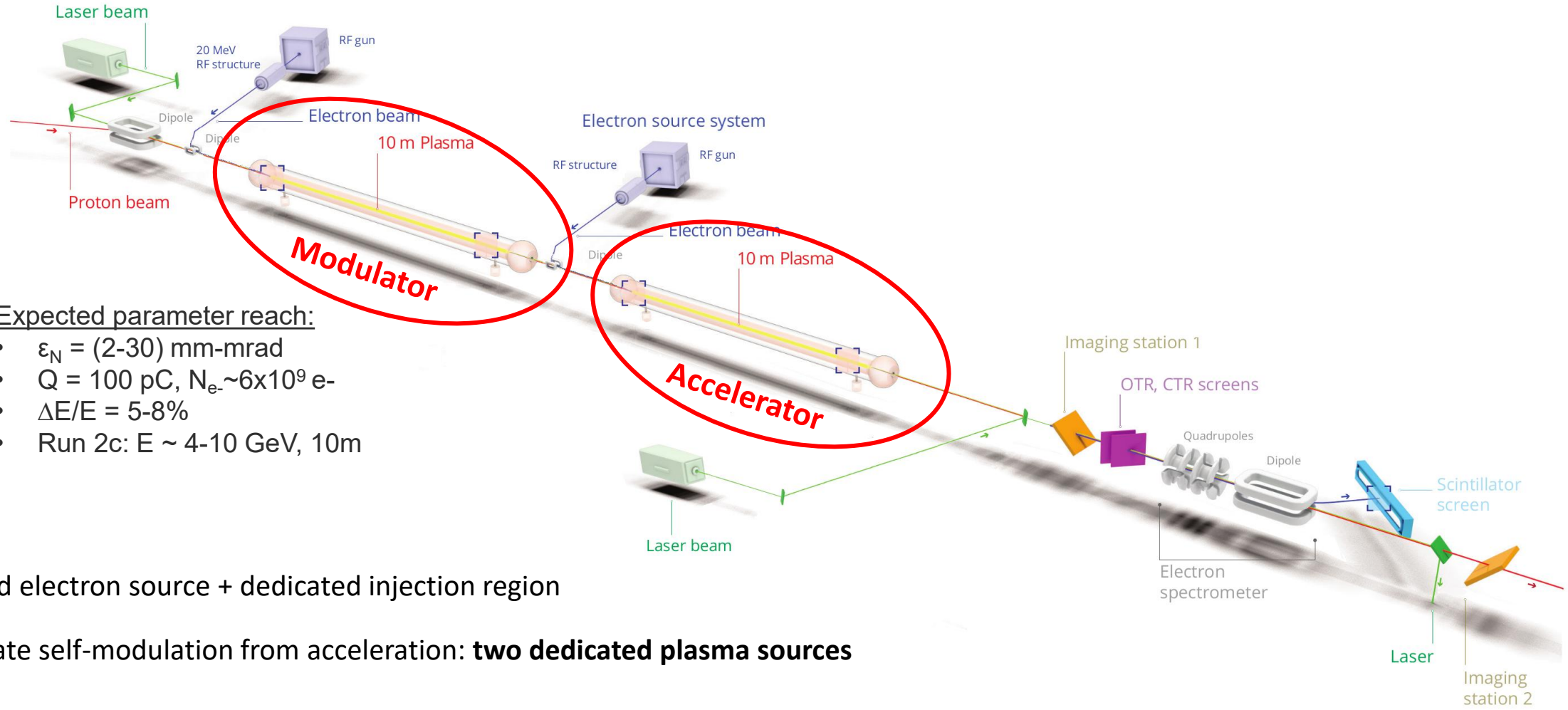

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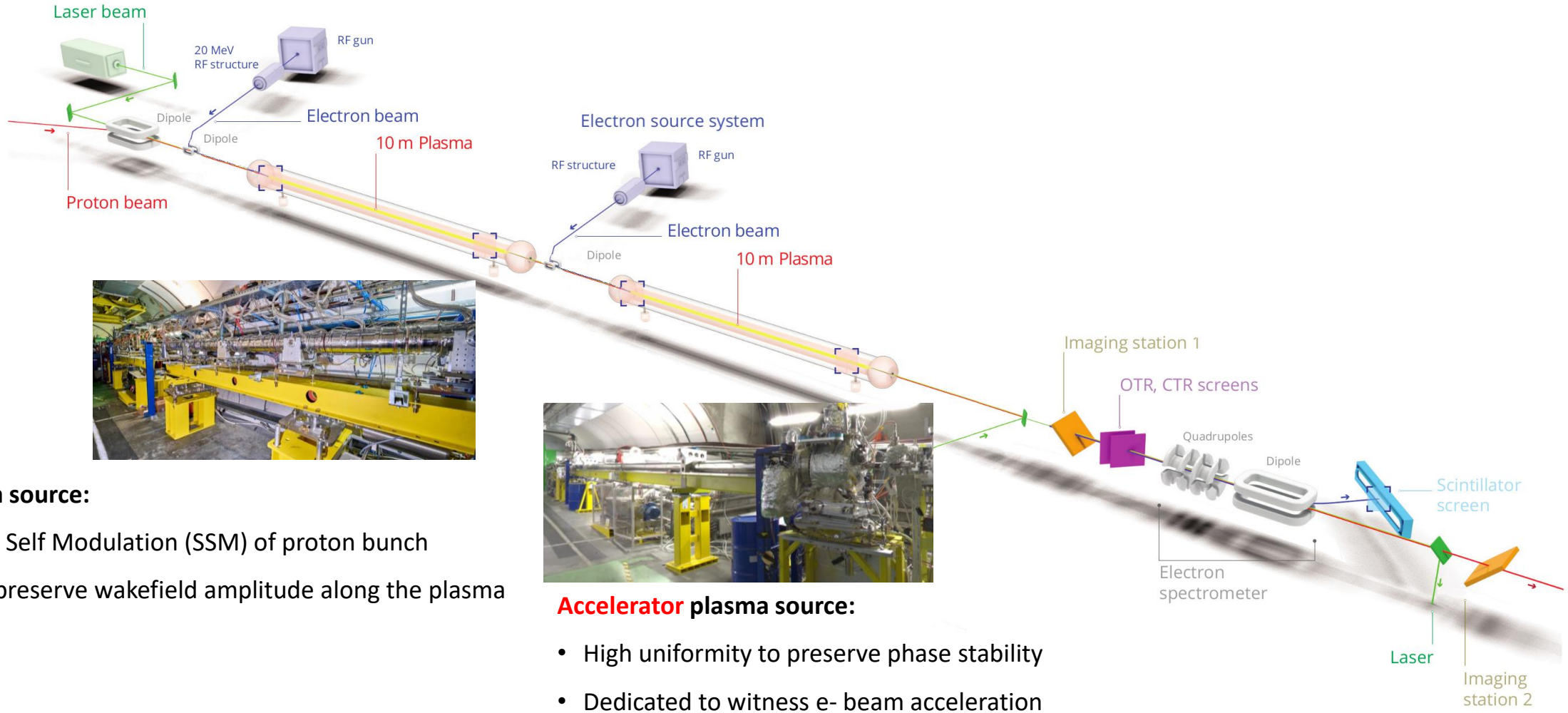
→ Second electron source + dedicated injection region

→ Separate self-modulation from acceleration: **two dedicated plasma sources**

AWAKE plasma sources

- 2029, after LS3 for HL-LHC preparation → **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

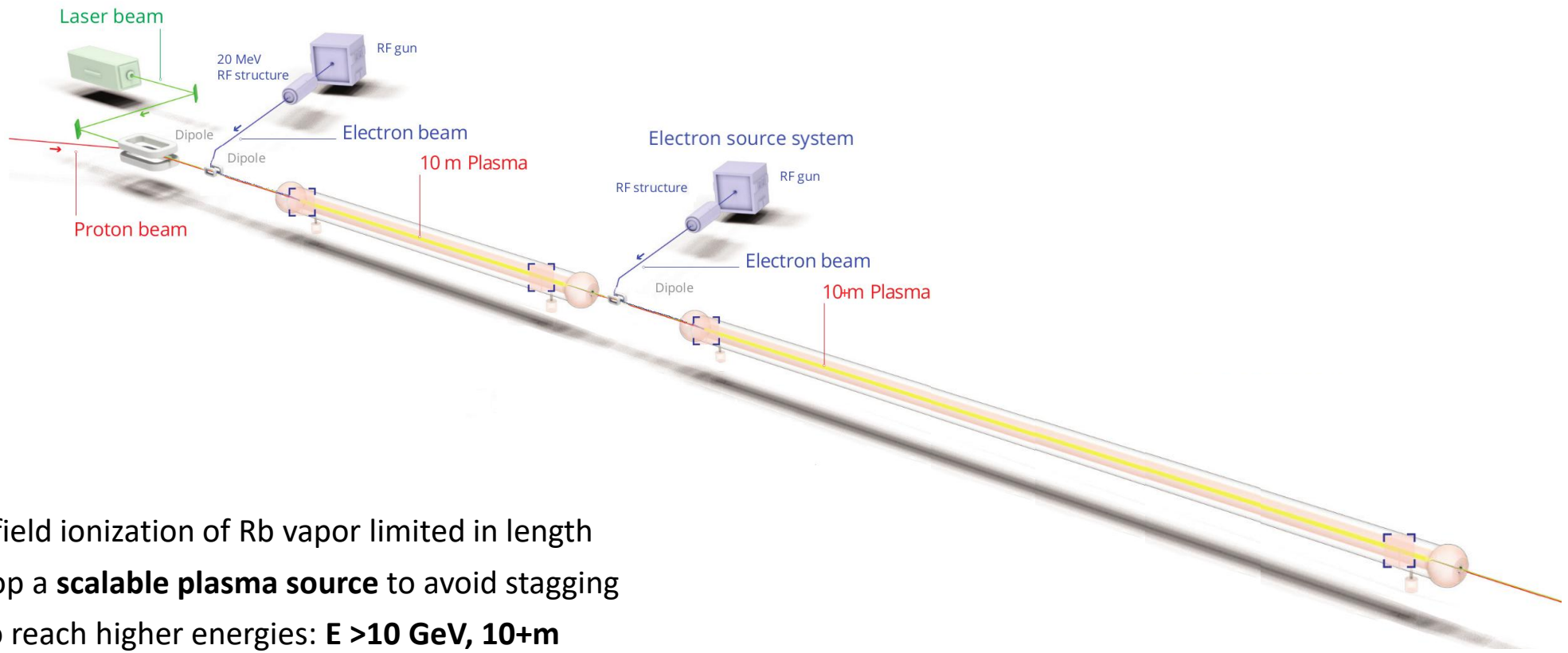
Accelerator plasma source:

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

→ M. Bergamaschi presentation (previous talk)

AWAKE plasma sources

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

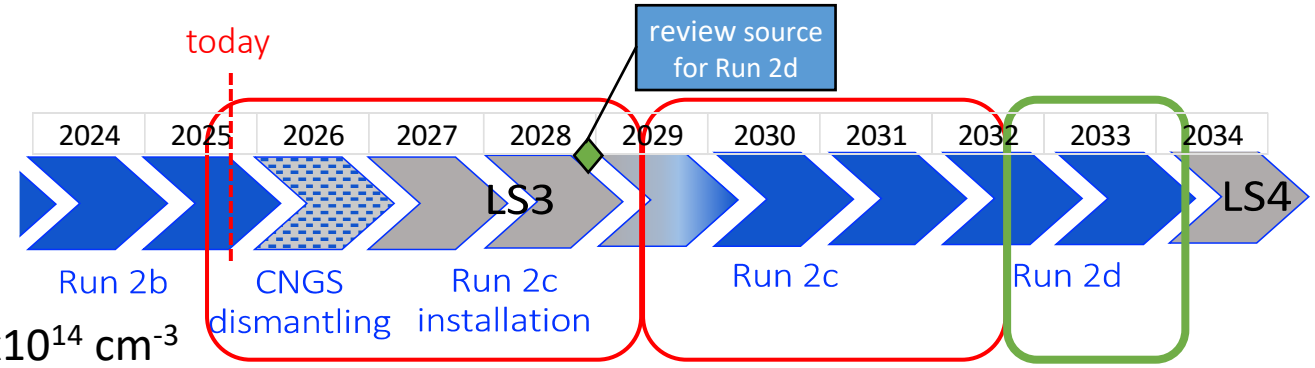


- Laser field ionization of Rb vapor limited in length
- Develop a **scalable plasma source** to avoid stagging
- And to reach higher energies: **E >10 GeV, 10+m**

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

Scalable plasma source R&D

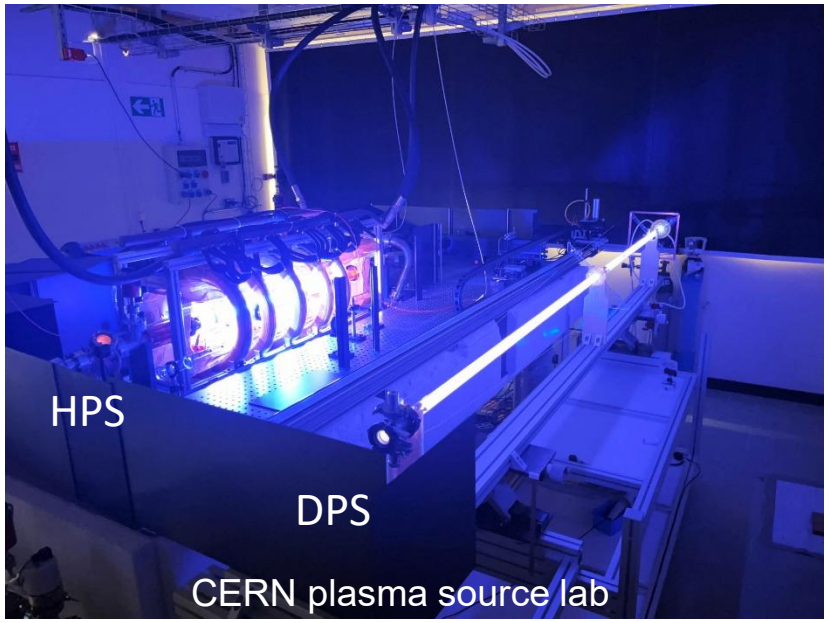
- R&D towards AWAKE Run 2d:
  - Helicon Plasma Source (HPS): RF-wave heated plasma
  - Discharge Plasma Source (DPS): pulsed DC discharge



- 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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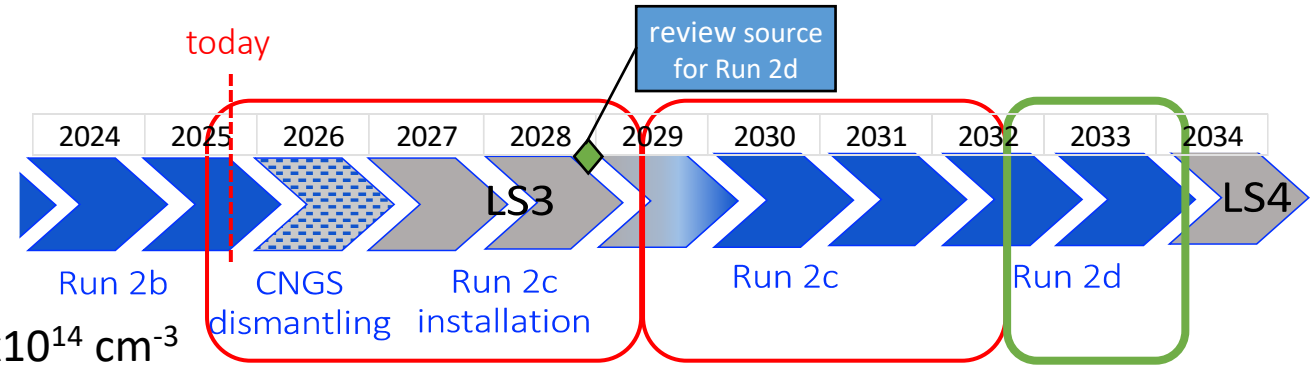

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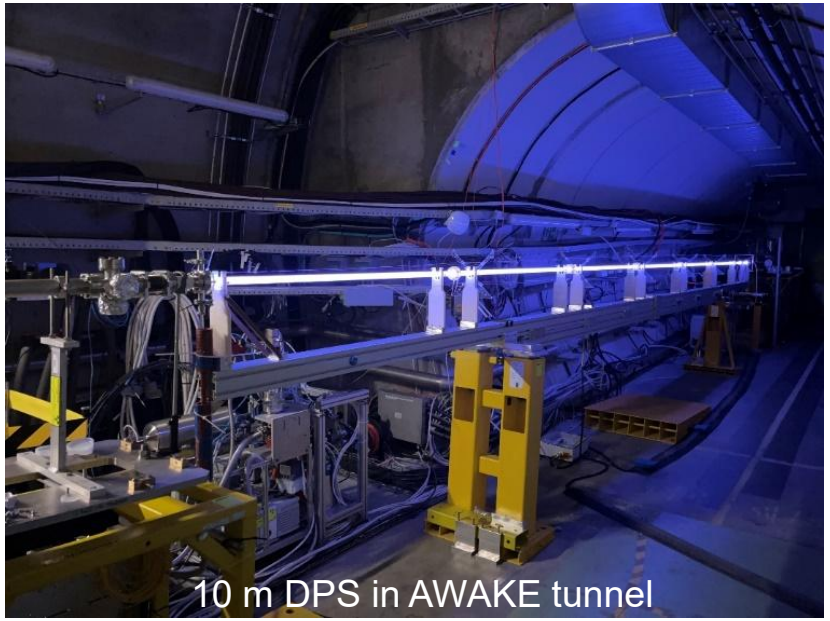
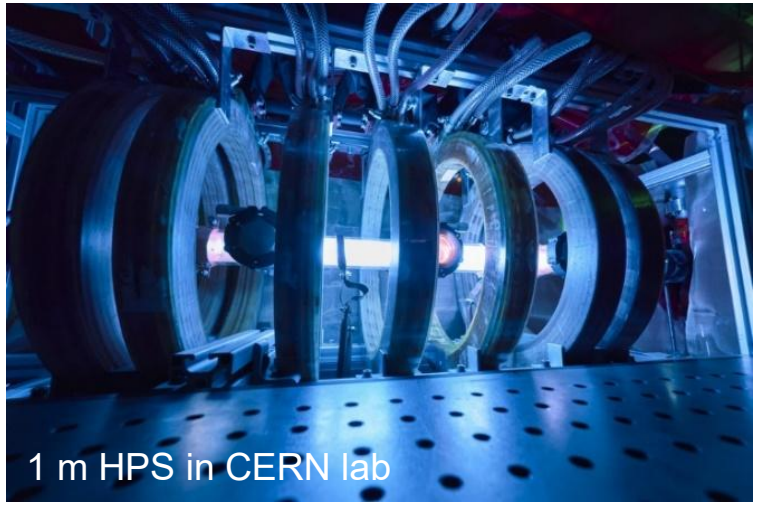


- Milestones:

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

Scalable source technologies

Helicon Plasma Source (**HPS**)
→ RF wave heated plasma, pulsed 10 Hz rep. rate



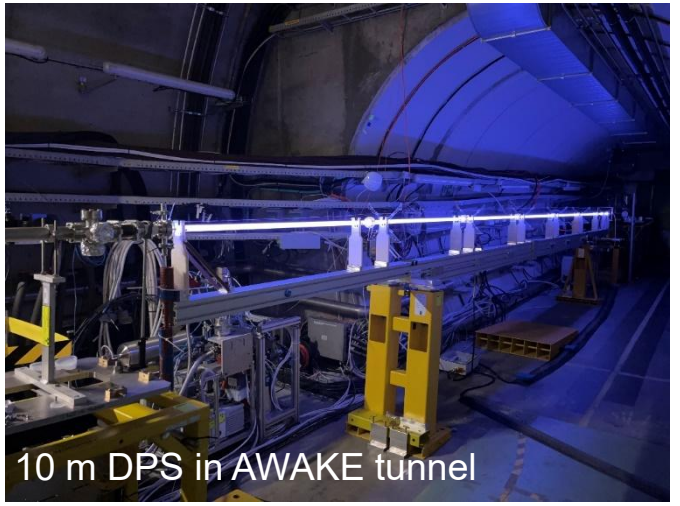
CERN
MAX PLANCK INSTITUTE FOR PLASMA PHYSICS
EPFL
College of Engineering UNIVERSITY OF WISCONSIN-MADISON

Low frequency EM waves along B-field

+ Intrinsically length scalable

- Complex physics, requires B-field, density challenging, homogeneity

Discharge Plasma Source (**DPS**)
→ pulsed-DC discharge, 1 Hz rep. rate



CERN
TÉCNICO LISBOA
Imperial College London

Pulsed high voltage discharge

+ Relatively simple setup, very flexible, density scalable

- Length scalability, homogeneity

B Buttenschön *et al* 2018 *Plasma Phys. Control. Fusion* **60** 075005

Collaborative effort R&D

- Thomson scattering, IR and millimetre wave interferometry on **HPS and DPS** → EPFL, MPP and CERN
  - **Axial density profile along the sources with TS:** 2024 *Plasma Phys. Control. Fusion* **66** 115011
  - Validation of mm-wave technique across the plasma tube on both sources with 100 GHz heterodyne setup → developing a 350-400 GHz setup
  - Transverse IR interferometry on HPS and longitudinal interferometry on DPS

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  - **Transverse line average and time resolved density measurements: arXiv:2503.11009**
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- Longitudinal (2D) + transverse interferometry and optical emission spectroscopy on **DPS** → Imperial college
  - **Spectroscopy over 1 m long plasma** to assess spectral emission longitudinal uniformity and potentially derive Te and ne from line ratio
  - Time resolved radial profile (averaged over length) of plasma density: radial plasma dynamic
  - Development of a transverse multi-pass interferometry in parallel to the longitudinal one

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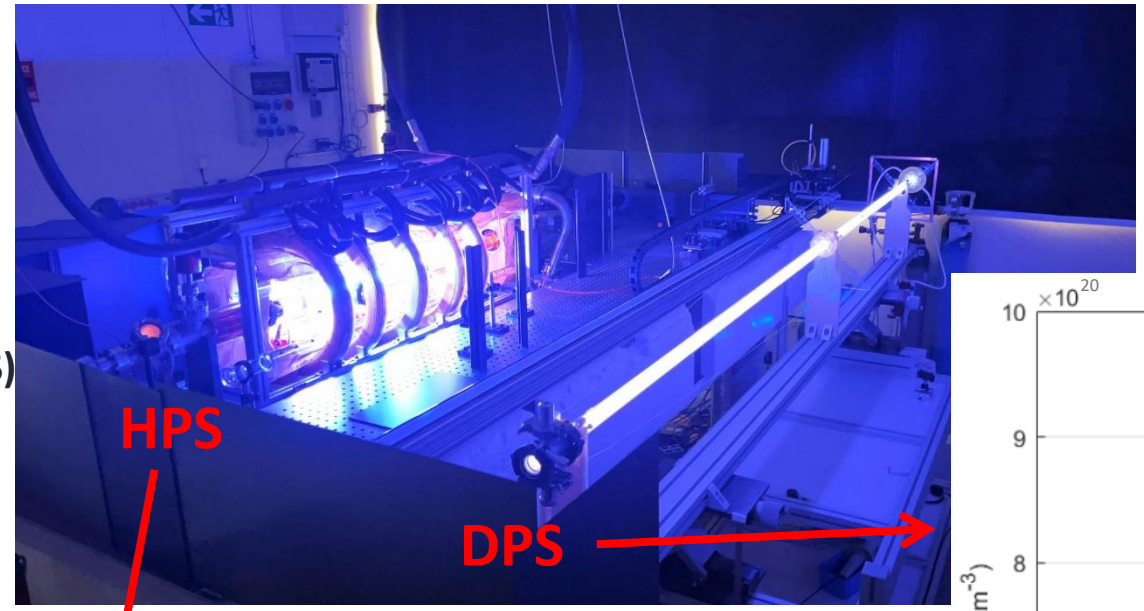
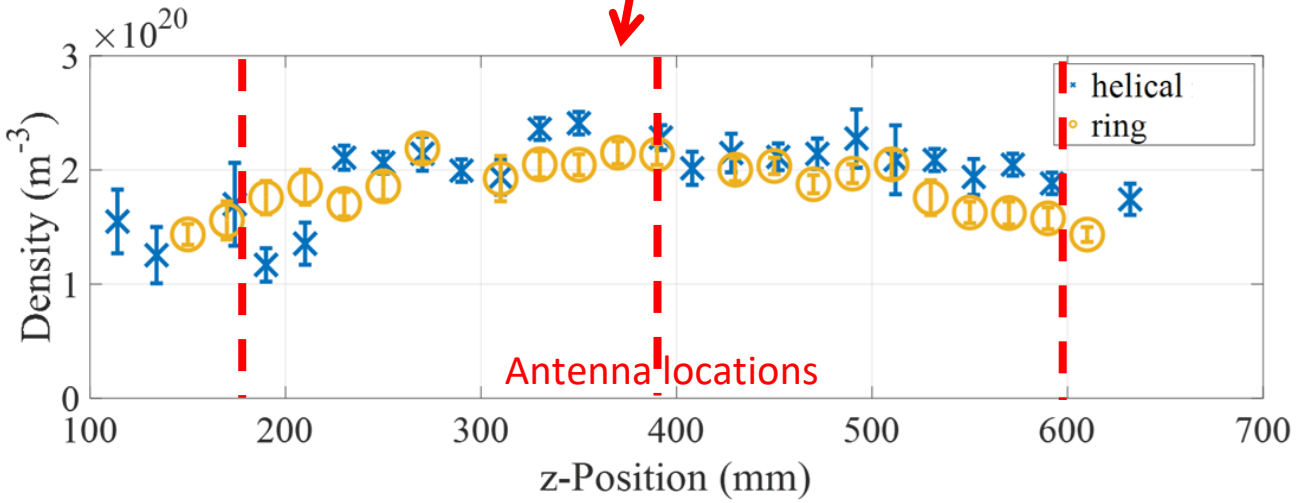
  - Time resolved radial profile (averaged over length) of plasma density: radial plasma dynamic
  - Development of a transverse multi-pass interferometry in parallel to the longitudinal one
- longitudinal interferometry and stability studies on **DPS**, source design → IST Lisbon
  - Pulsed-DC generator 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)

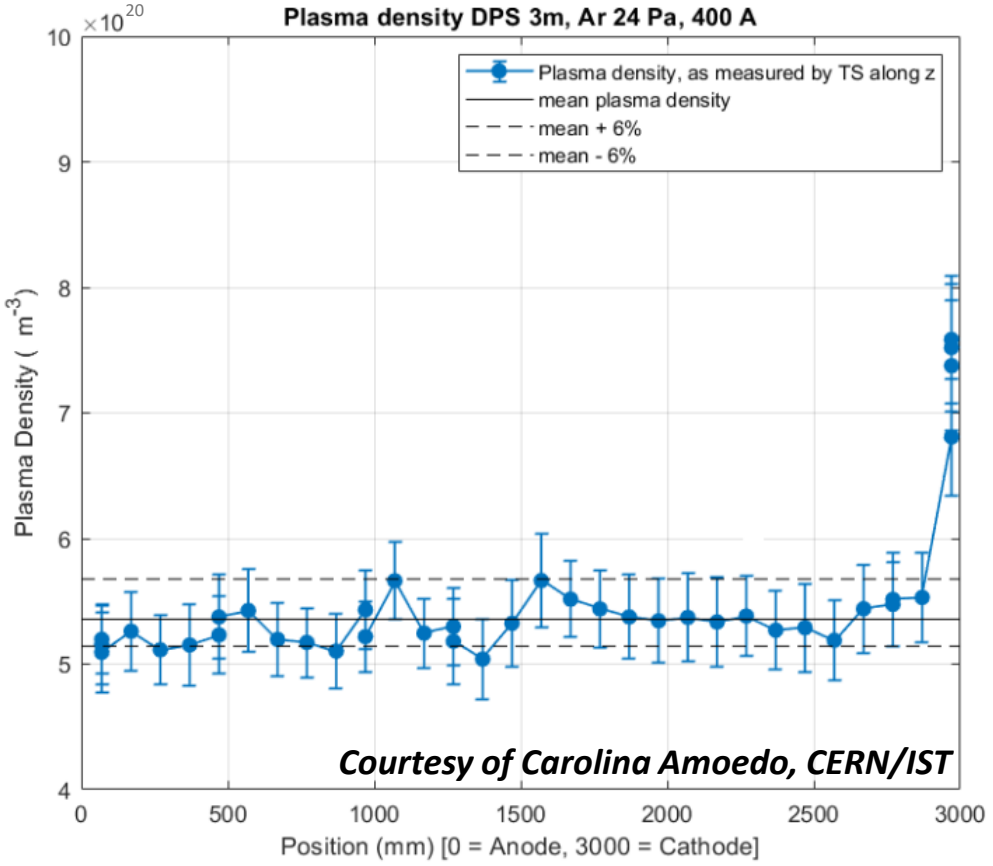
uniformity ± <11 %



Courtesy of Renat Karimov, EPFL-SPC

3 m Discharge Plasma Source (DPS)

uniformity ± 6%



→ Reaching the limits of TS diagnostic capability!

Axial density profiles: Thomson scattering

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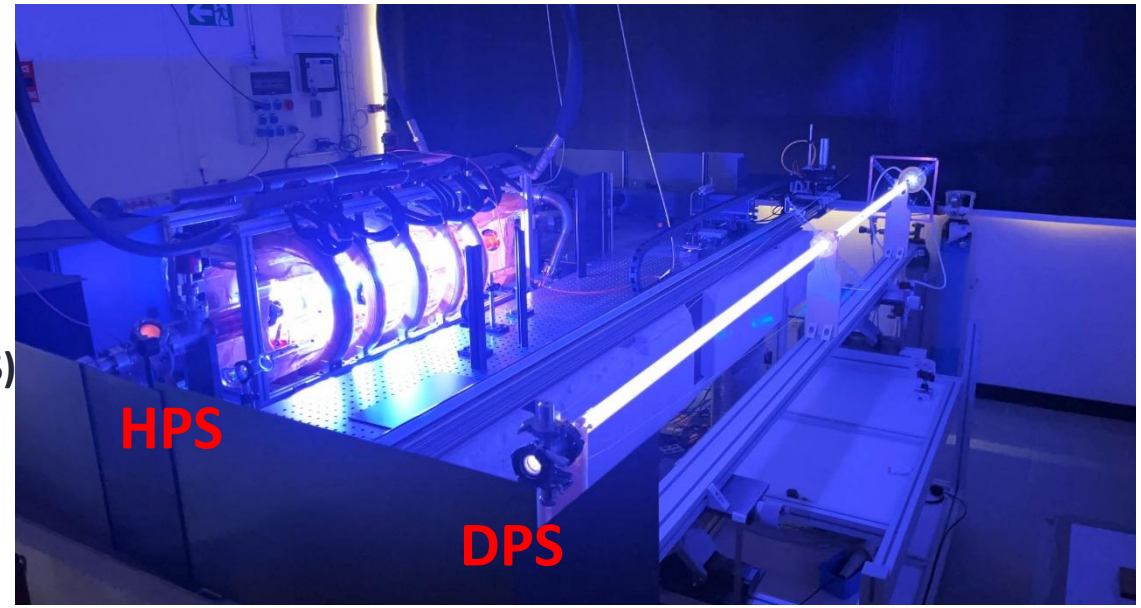


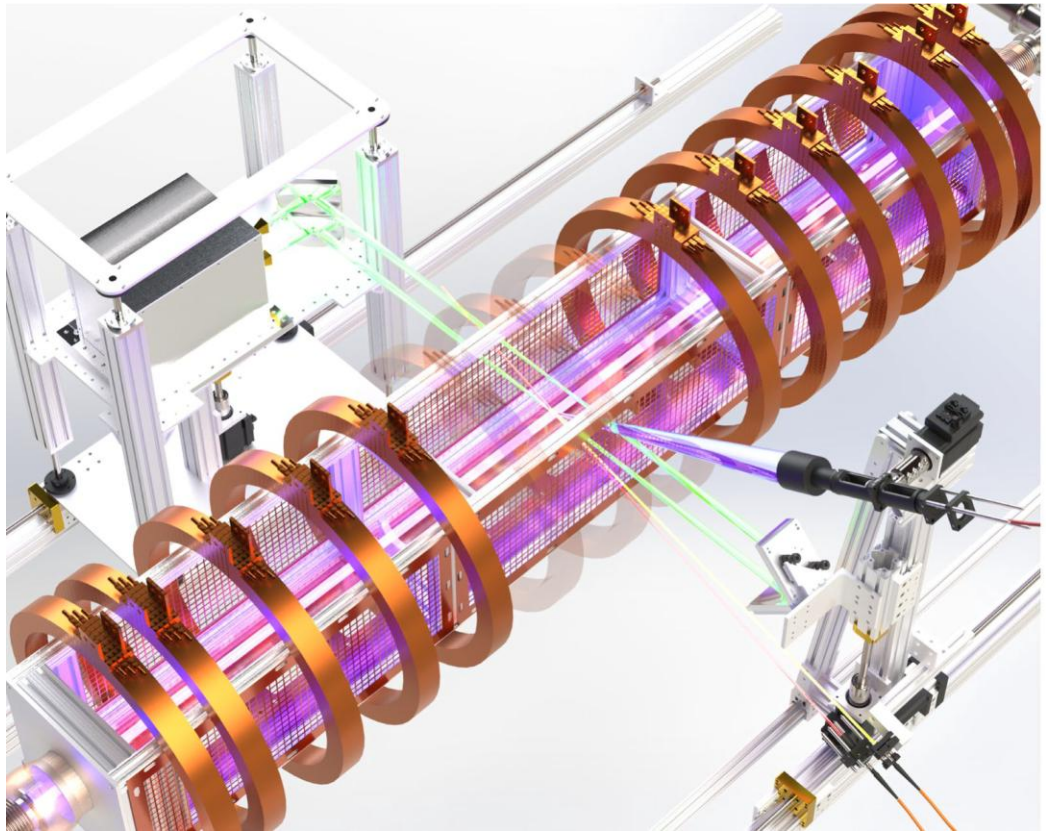
3 m Discharge Plasma Source (DPS)

uniformity ± 6%

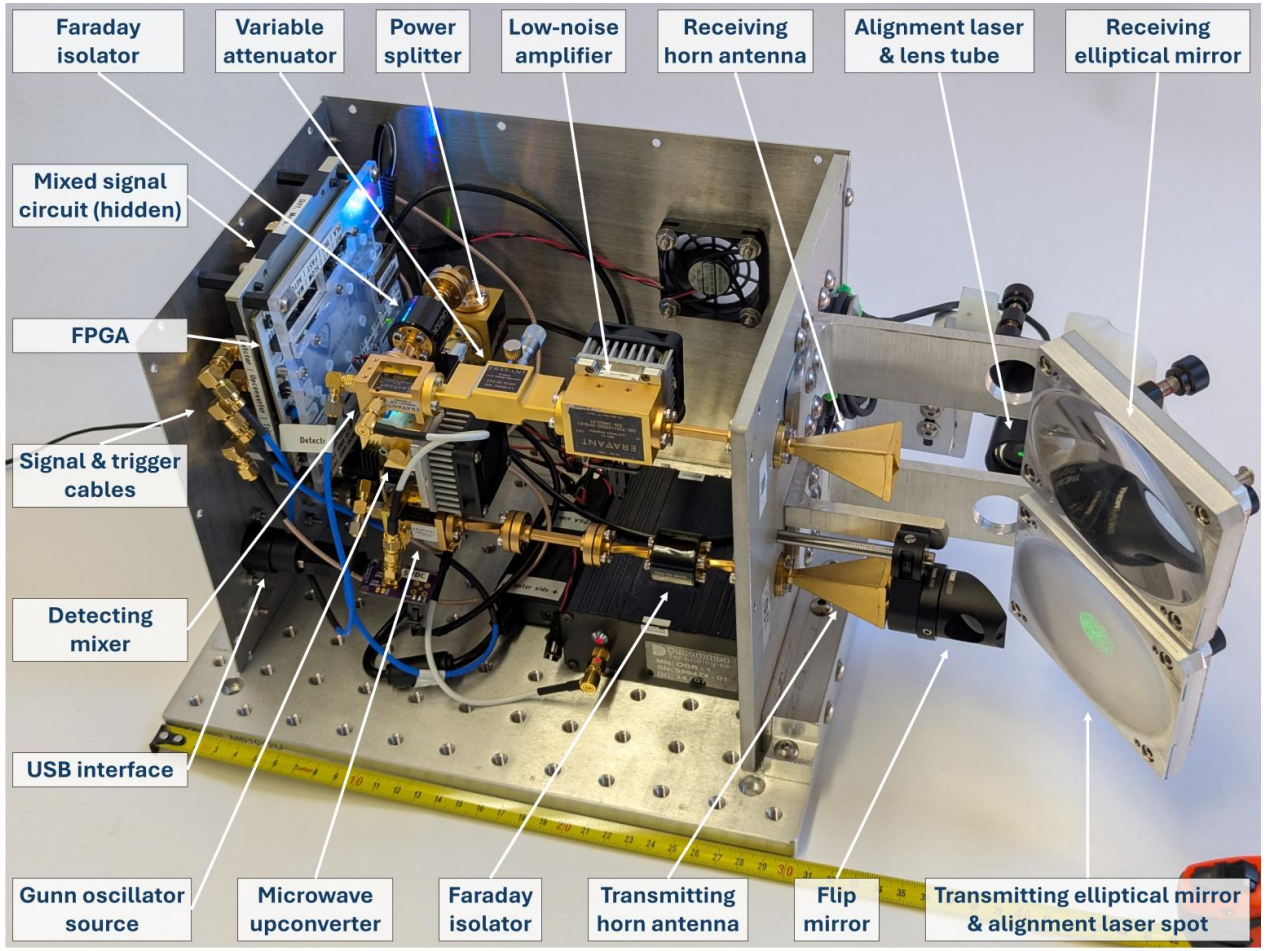
→ Reaching the limits of TS diagnostic capability!

→ C. Amoedo's poster (Tuesday session)

mm-wave diagnostic on MAP setup

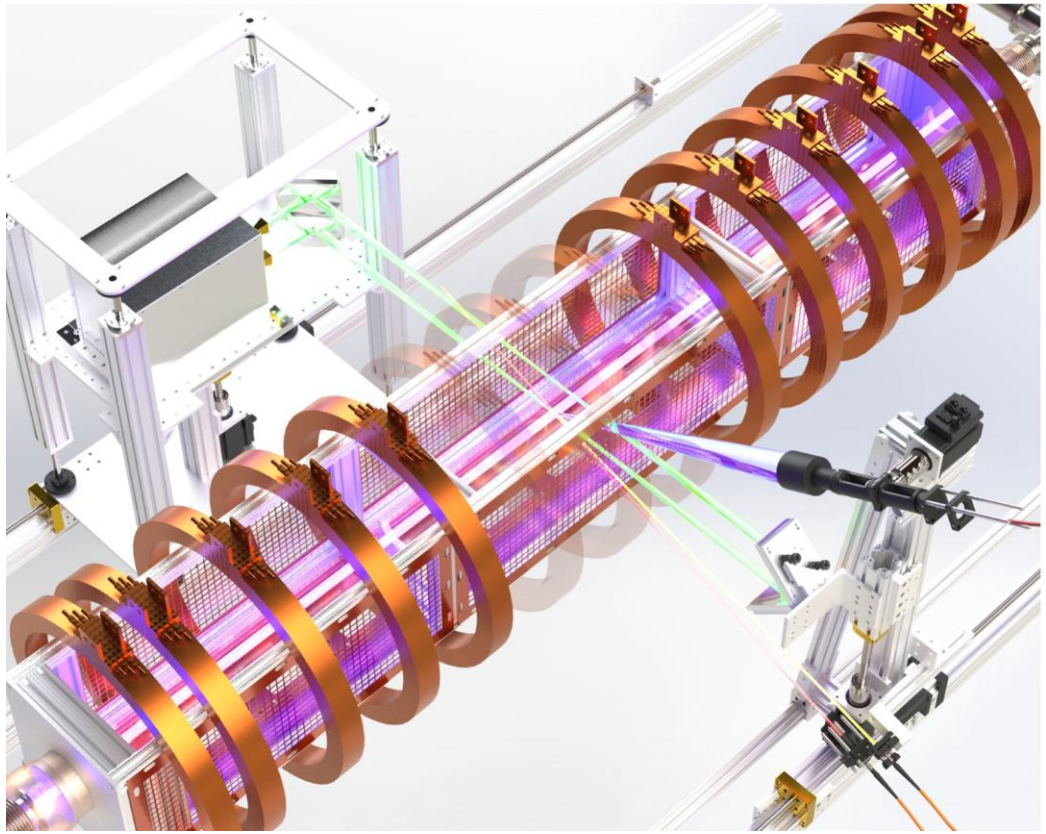


2.5 m Madison AWAKE Prototype (MAP), *Phys. Plasmas* 32, 093507 (2025)



105 GHz heterodyne interferometer setup

mm-wave diagnostic on MAP setup



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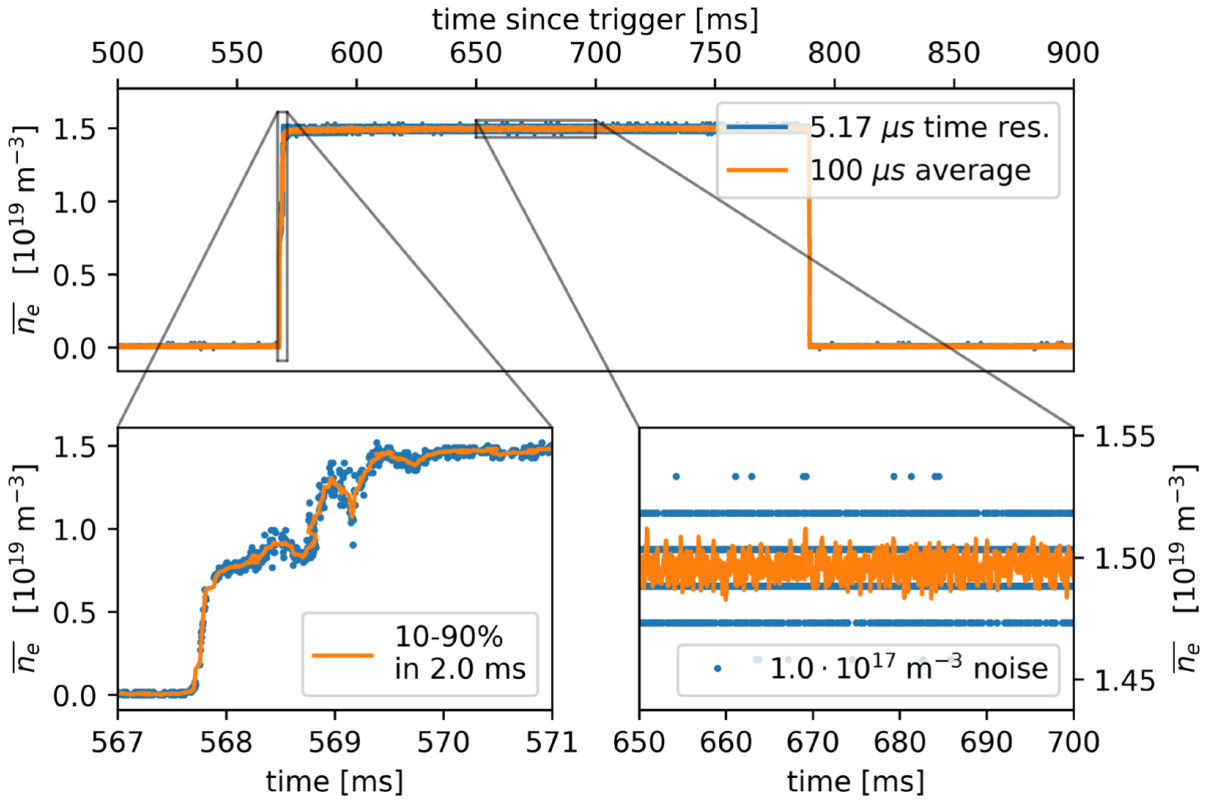


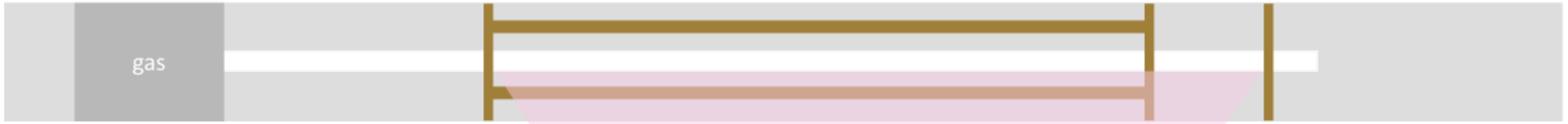
Density evolution over a 1.3 kW / 200 ms RF pulse (single antenna)
~ 0.7% noise level in steady state

Courtesy of Marcel Granetzny, Univ. Wisconsin

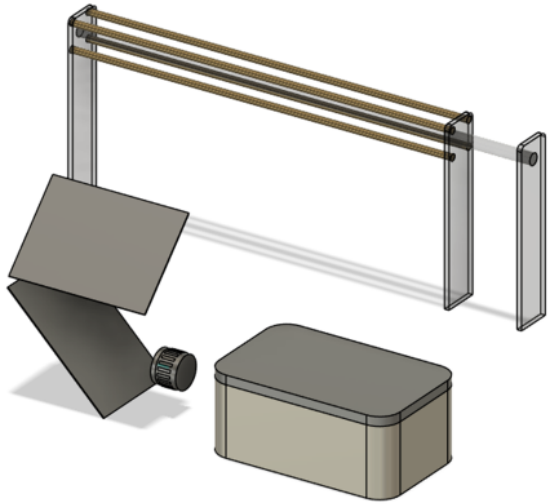
→ *Rev. Sci. Instrum.* 96, 093510 (2025)

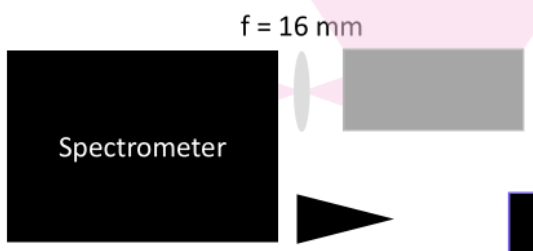
Plasma emission spectroscopy

Plasma Emission Spectroscopy

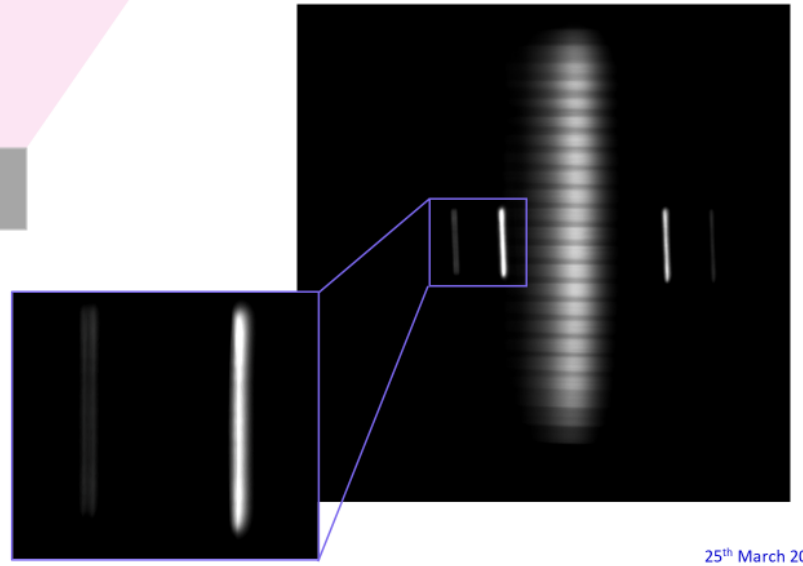


Bentham M300 Czerny-Turner spectrometer used to measure spectrum over 1 m tube





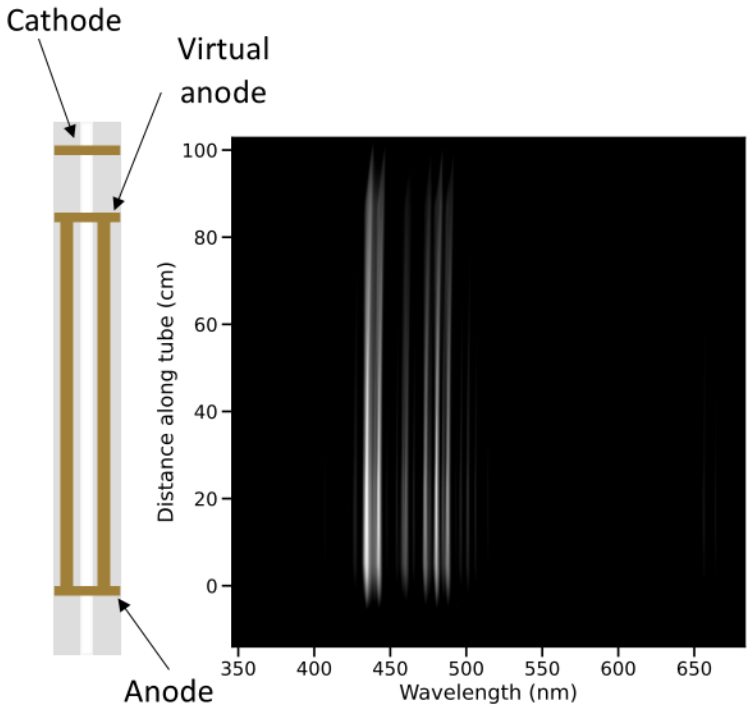
Calibration with mercury lamp + green LED strip
< 2nm spectral resolution
~10 cm spatial resolution

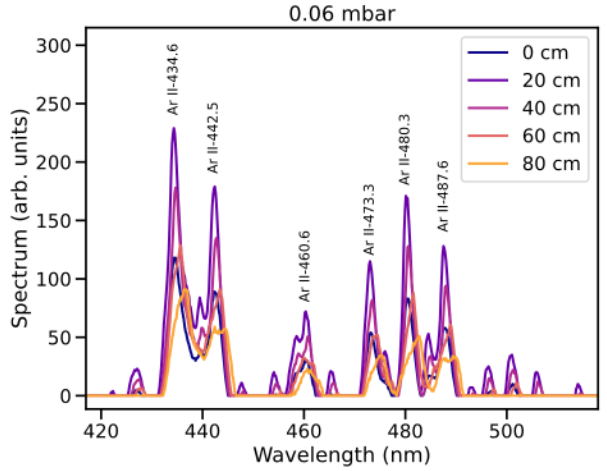


Plasma emission spectroscopy

Plasma Emission Spectroscopy

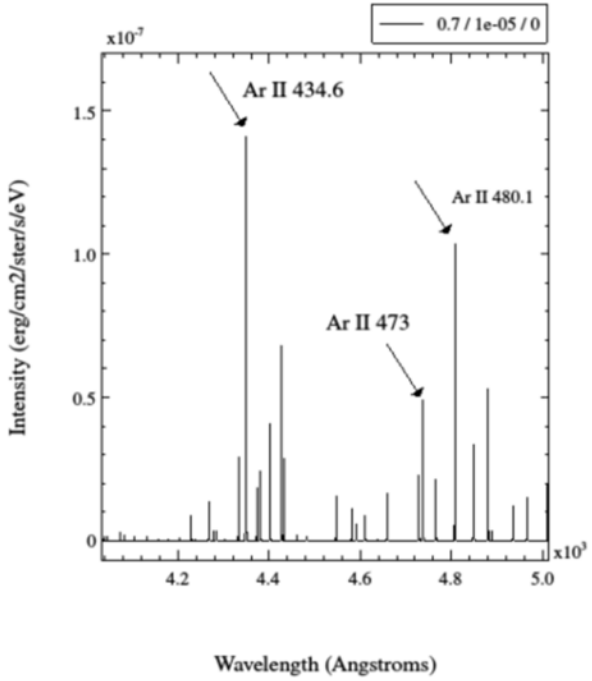
Uniformity Measurements





- Experimental spectra comparable to PrismSPECT simulations
- Primarily Ar II (singly ionised Ar)

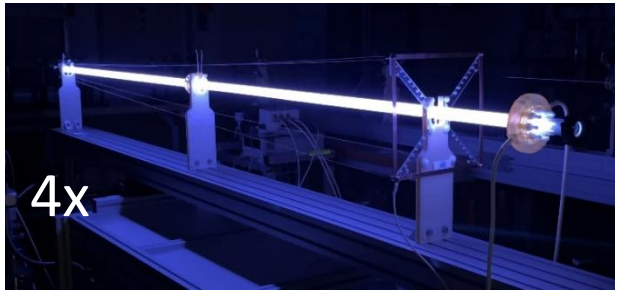
Preliminary

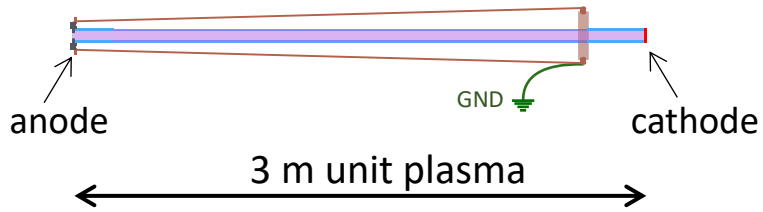


Towards scalability: DPS

- From 3 m unit plasma to 12 m plasma at CERN:
  - x4 duplicate the well characterized 3 m source
  - Use existing shared cathodes and anodes
  - Use two sets of pulsed generators to power two twin plasmas
  - With current balancing modules in between to equalize currents

→ Planned for **end 2025**





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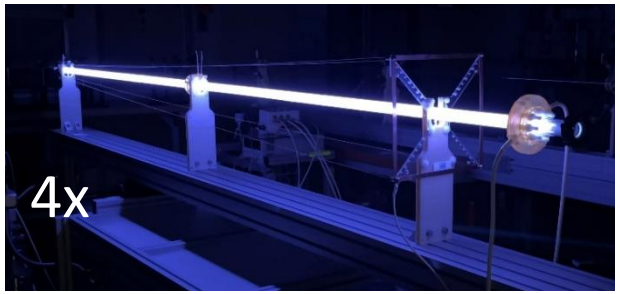

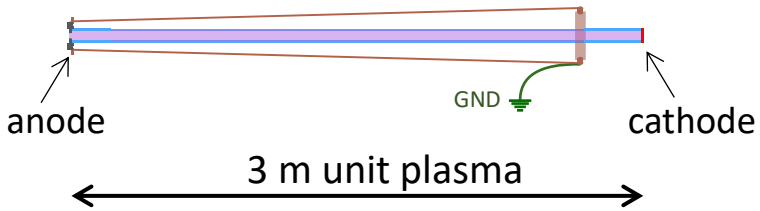

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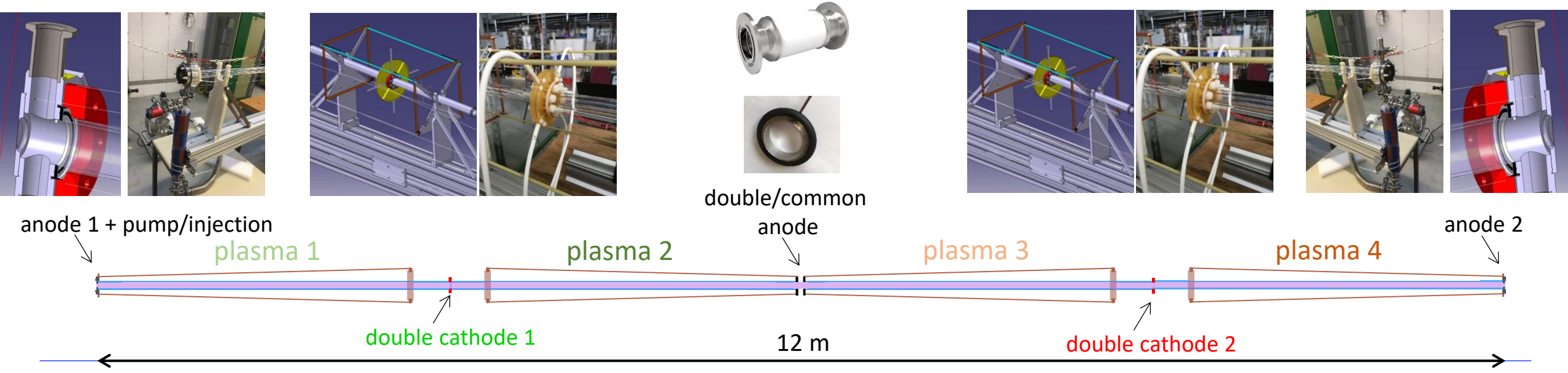
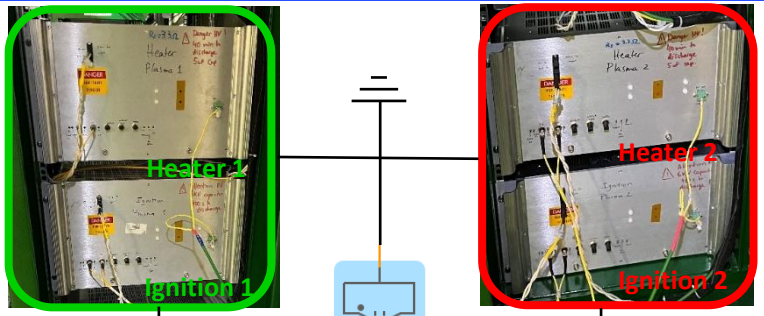
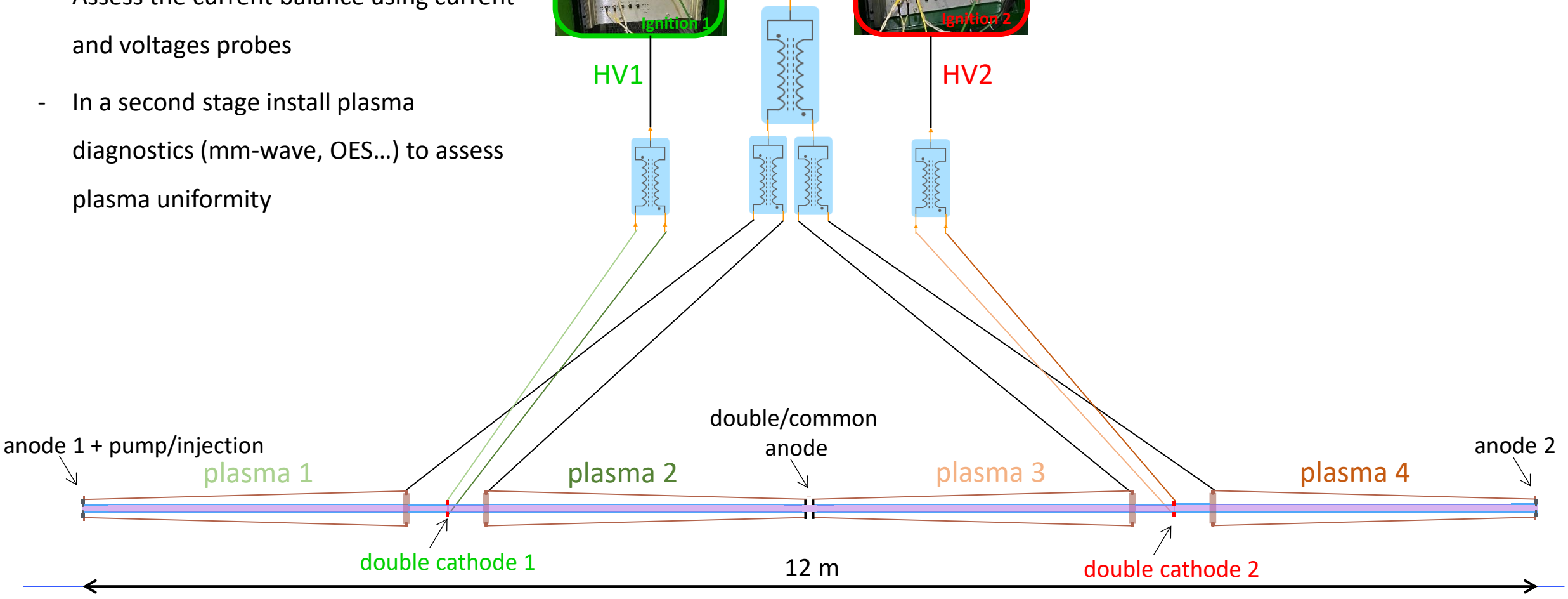


Towards scalability: DPS

- New current balancing modules (CBM) designed by IST → **magnetic chokes**
  - Assess the current balance using current and voltages probes
  - In a second stage install plasma diagnostics (mm-wave, OES…) to assess plasma uniformity

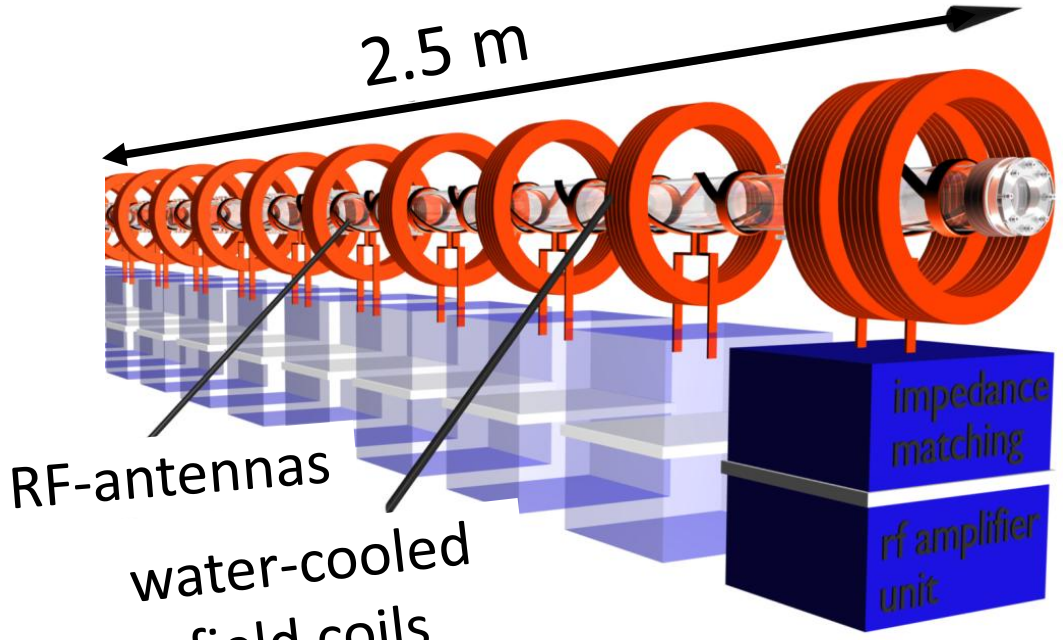




Towards scalability: HPS

- Implement all the learnings from institutes/CERN R&D:
  - Design and build a ~ 2.5 m unit module with ~ 10 antennas at CERN
  - With optimal tube diameter and antenna shape/spacing (inputs from Univ. Wisconsin/EPFL)
  - Procurement of RF-generators/matchboxes with frequency tuning for fast ignition, short pulses and stability/reproducibility
  - RF/plasma-coupling diagnostics
  - Install plasma monitoring diagnostics (mm-wave, OES…)

→ Planned for 2026/2027



adapted from O. Grulke IPP-Greifswald

Summary

- Dedicated scalable plasma source R&D program focused on helicon and discharge plasma sources
- 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!
- MAP HPS transversely average density measured by mm-wave with 0.7% noise level
- Scalability tests to be gradually implemented starting with 12 m DPS by the end of 2025

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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 of 2025)
- 1 PhD at EPFL-SPC: Renat Karimov (due by begin/mid-2026)