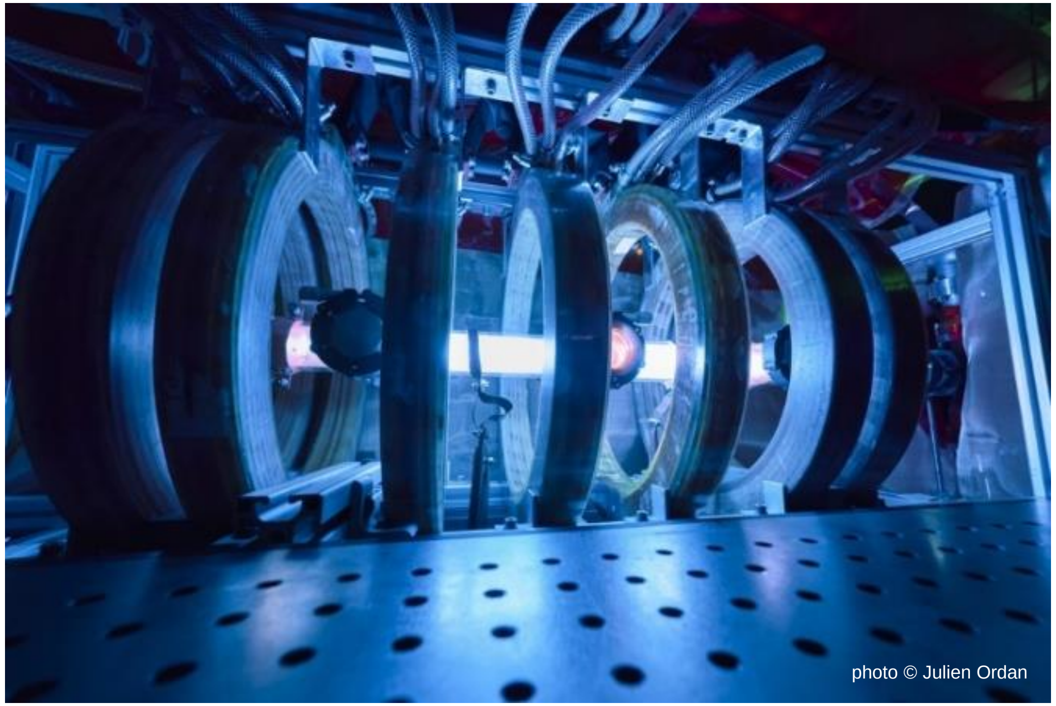
# Scalable plasma sources R&D program at CERN

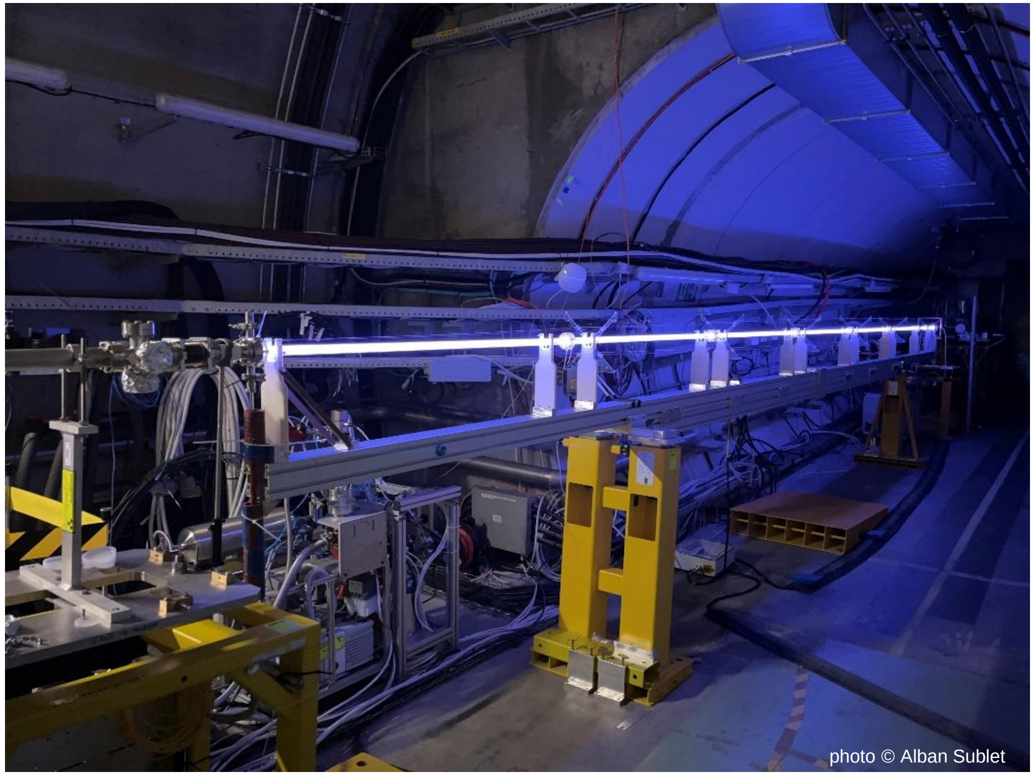
## Helicon Plasma Source (HPS)




Max-Planck-Institut für Plasmaphysik · EPFL · College of Engineering, University of Wisconsin–Madison

A. Sublet, M. Santos (CERN)
O. Grulke, B. Buttenschön, T. Windisch (IPP-Greifswald),
I. Furno, C. Stollberg, P. Guittienne, R. Karimov (EPFL-SPC),
O. Schmitz, M. Zepp, M. Granetzny, B. Elward (Univ. of Wisconsin),

## Discharge Plasma Source (DPS)




TÉCNICO LISBOA · Imperial College London

A. Sublet, C. Amoedo, (CERN)
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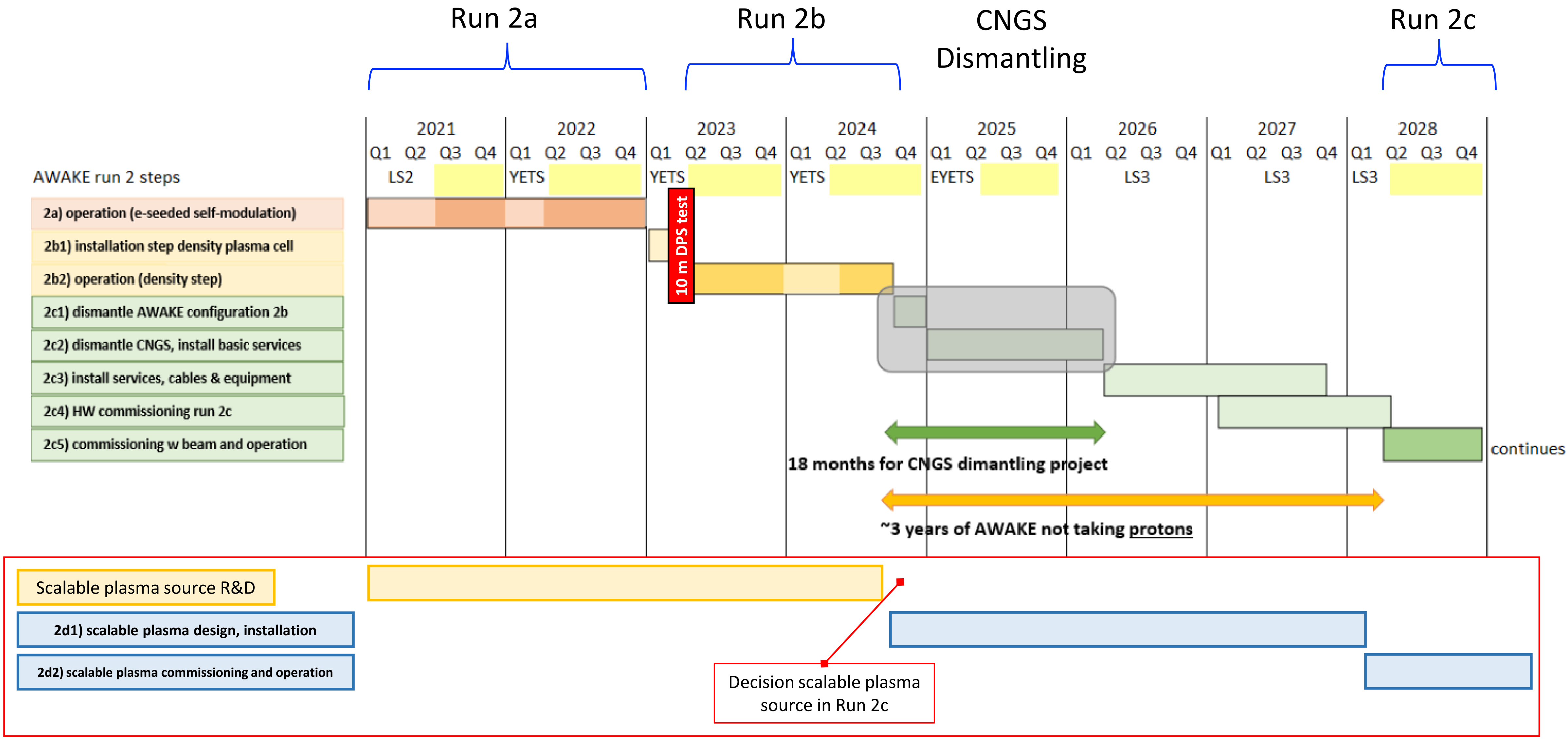
Z. Najmudin (IC-London),

AWAKE

# AWAKE Run 2 Global Schedule




*From Edda, 29.08.2023*

# Scalable plasma sources R&D: CERN mandate and budget

- **Goal: develop and build a scalable plasma source (10 m and beyond) to be installed in the AWAKE tunnel**

**CP8 CERN coordination Package: Plasma cell R&D**

**Mandate**: The coordination package leader, is responsible for the plasma sources test facilities, the interface between the CERN equipment in this area and the equipment/diagnostics delivered by the collaborating institutes.

| | Plasma cell R&D budget | 2022 | 2023 | 2024 | 2025 | Total |
|---|---|---|---|---|---|---|
| | **Material [kCHF] (BC 98715)** | **201** | **516** | **346** | **0** | **1063** |
| DPS | MtoP [kCHF] (PhD Carolina) | 50 | 100 | 100 | 50 | 300 |
| DPS | MtoP [kCHF] (PhD Nuno) | 0 | 24 | 0 | 0 | 24 |
| HPS | MtoP [kCHF] (Jr. fellow Miguel) | 0 | 100 | 110 | 110 | 320 |
| | **Total [kCHF]** | **251** | **740** | **556** | **160** | **1707** |

## WP14 Helicon Plasma Source @ CERN

Collaborating institutes:

- IPP-Greifswald (Olaf Grulke)
- EPFL-SPC (Ivo Furno)
- University of Wisconsin, Madison (Oliver Schmitz)

→ Helicon source, plasma diagnostics, helicon wave physics, …

## WP15 Discharge Plasma Source @ CERN

Collaborating institutes:

- IST-Lisbon (Nelson Lopes)
- IC-London (Zulfikar Najmudin)

→ plasma diagnostics, power supplies and sources designs, …

# HPS @ CERN


Max-Planck-Institut für Plasmaphysik

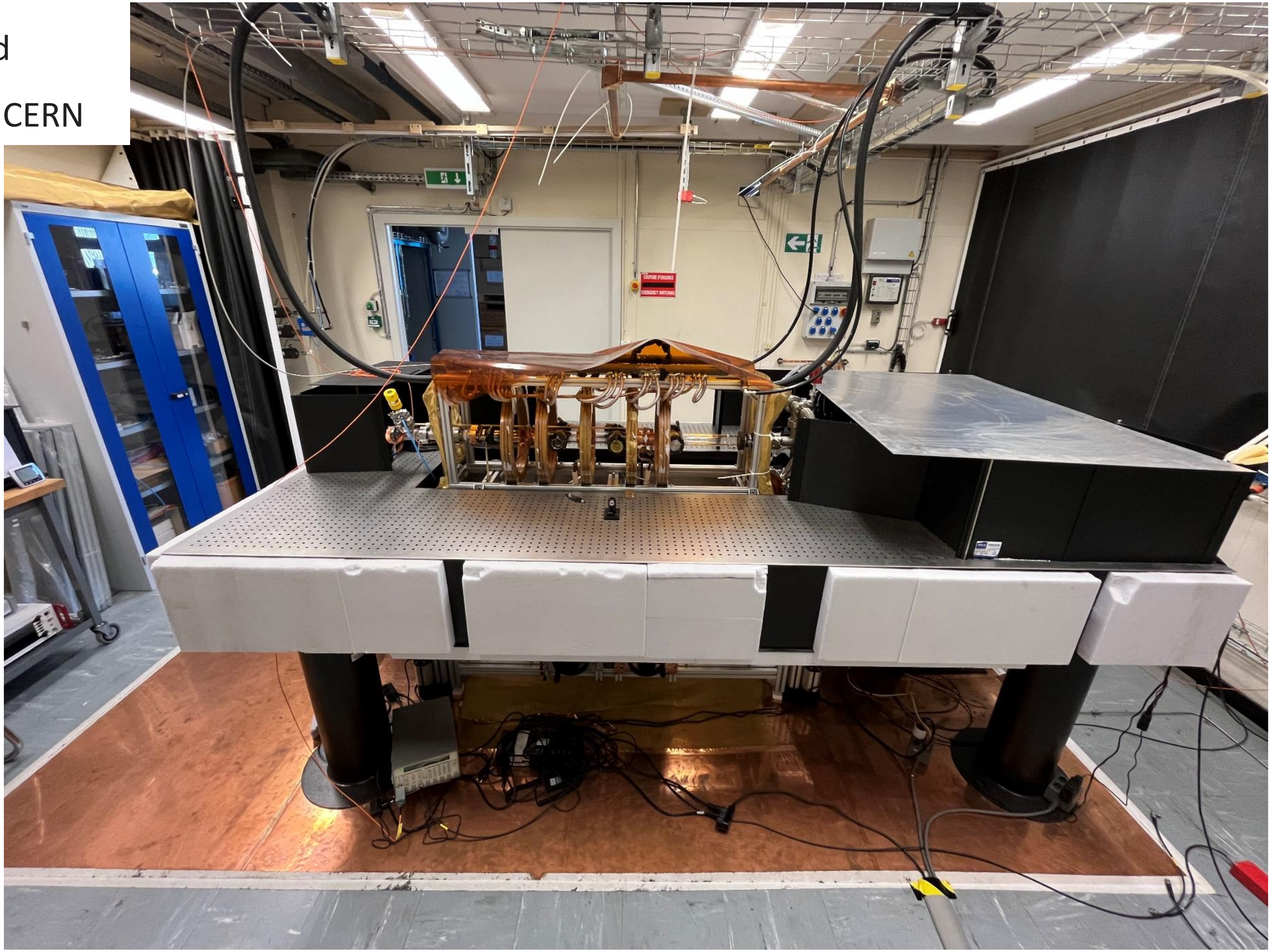
EPFL

College of Engineering
UNIVERSITY OF WISCONSIN–MADISON

# HPS 1.0 setup in CERN premisses (169/R-024 lab)

From IPP Greifswald

Installed in 2019 at CERN



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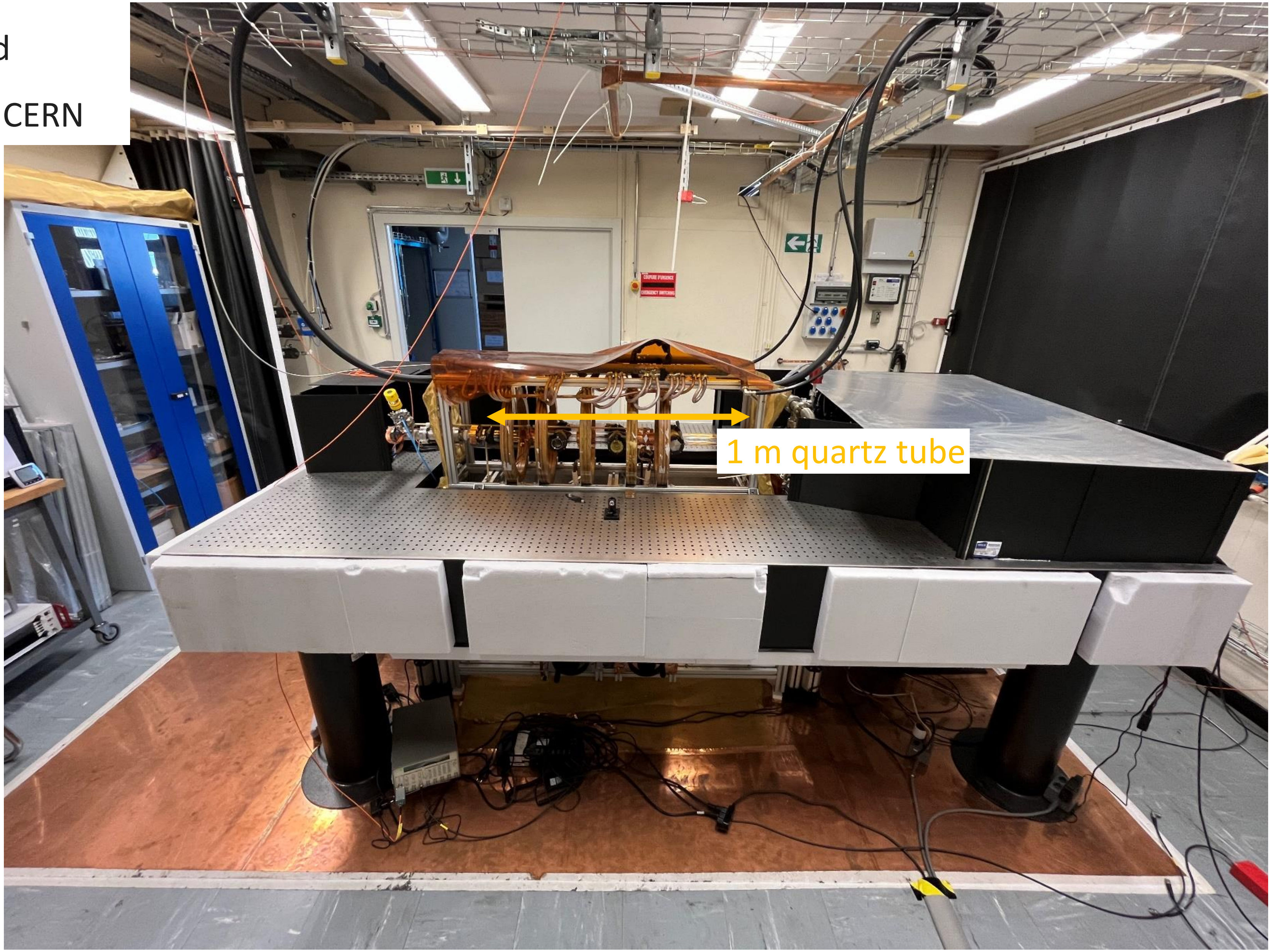


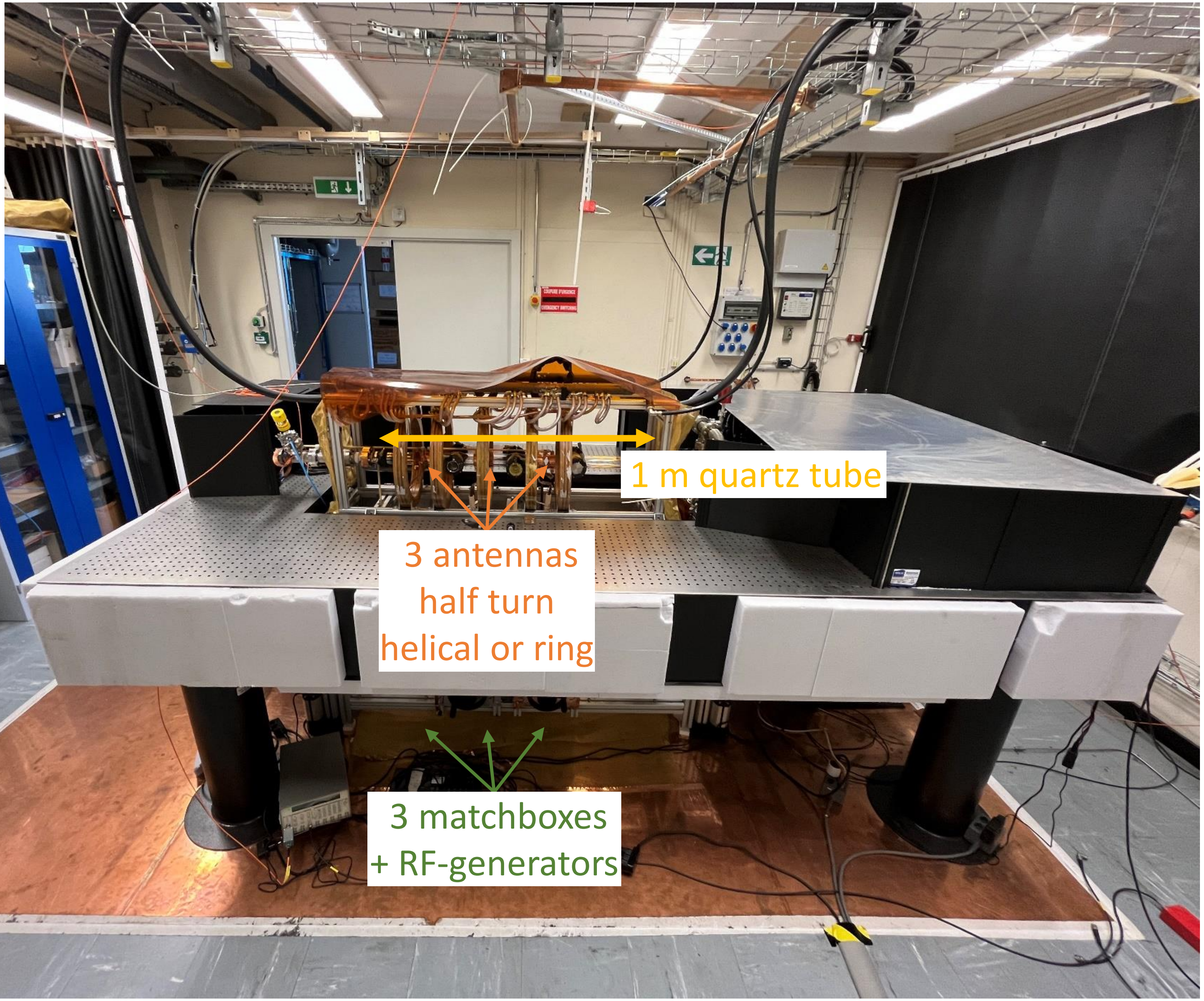
# HPS 1.0 setup in CERN premisses (169/R-024 lab)

From IPP Greifswald

Installed in 2019 at CERN

pulsed RF → 5 ms at 10 Hz

up to 10 kW/antenna



# HPS 1.0 setup in CERN premisses (169/R-024 lab)

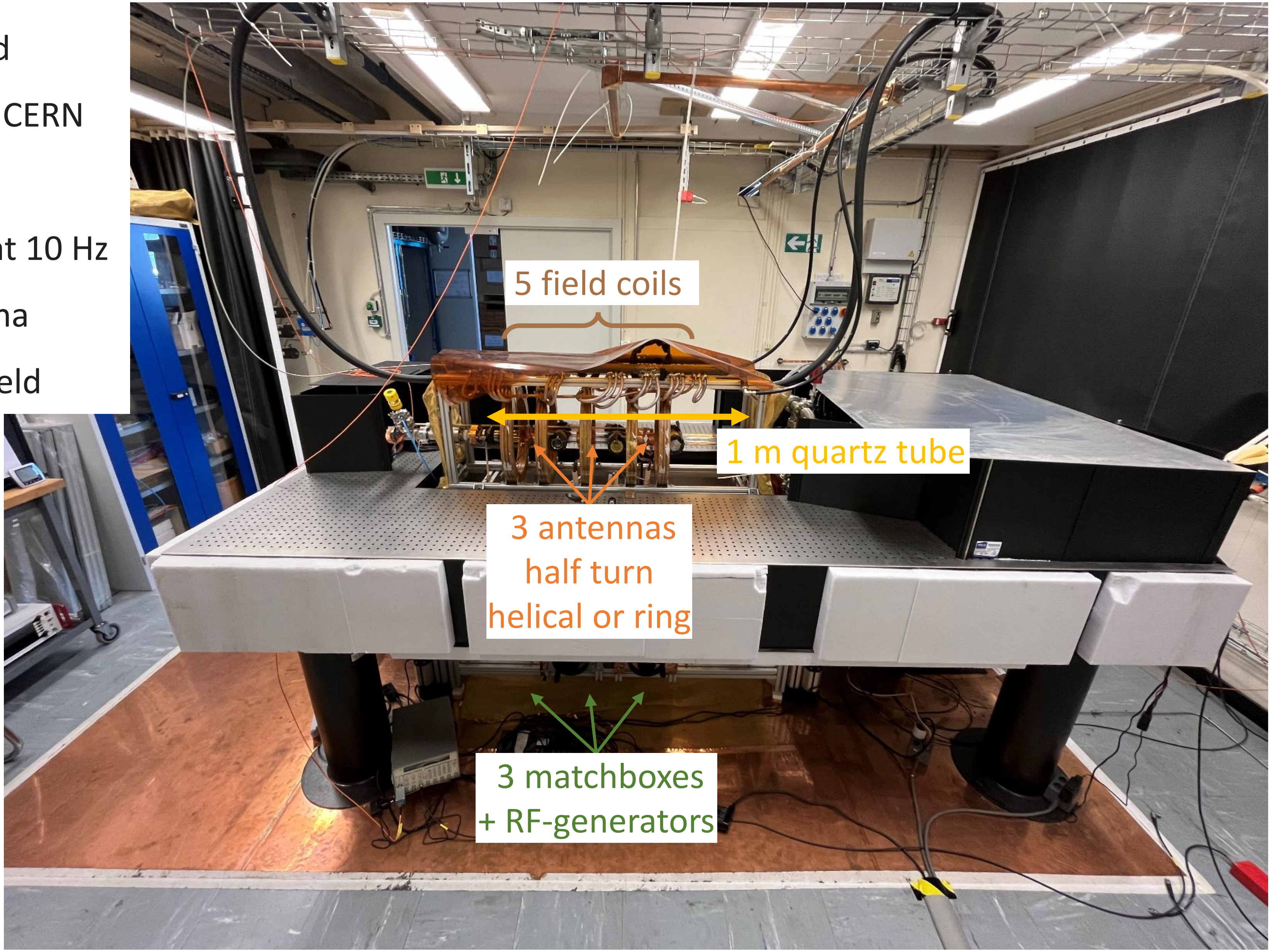
From IPP Greifswald

Installed in 2019 at CERN

pulsed RF → 5 ms at 10 Hz

up to 10 kW/antenna

up to ~ 130 mT B-field



# HPS diagnostics

Nominal e- density
→ obtained at IPP

Uniformity < 10%
in non-uniform B-field

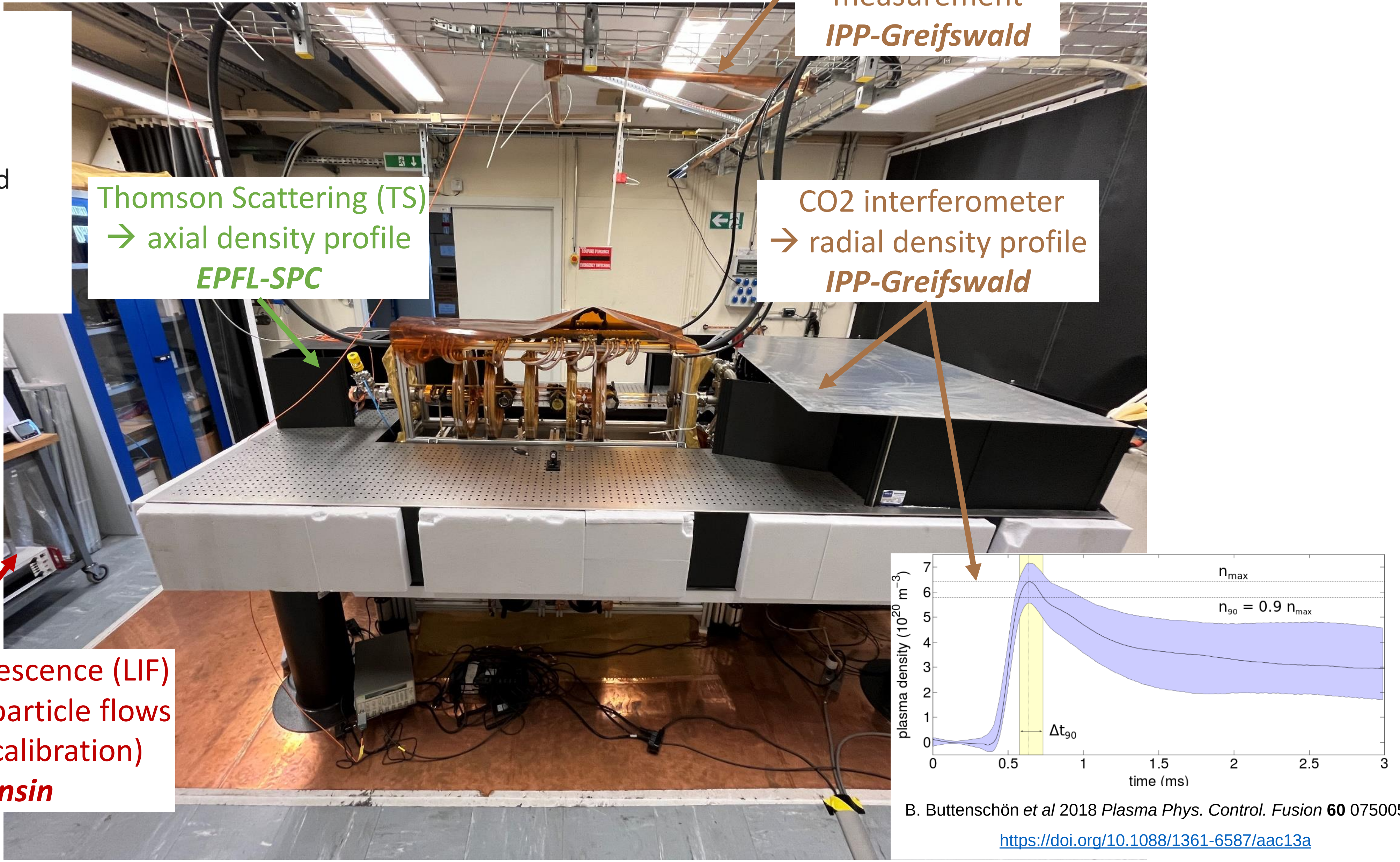
Reproducibility to be assessed

MW
→ cut-off density measurement
***IPP-Greifswald***

Thomson Scattering (TS)
→ axial density profile
***EPFL-SPC***

$CO_2$ interferometer
→ radial density profile
***IPP-Greifswald***

Laser Induced Fluorescence (LIF)
→ axial neutral/ion particle flows and density (with calibration)
***Univ. Wisconsin***




B. Buttenschön *et al* 2018 *Plasma Phys. Control. Fusion* **60** 075005
https://doi.org/10.1088/1361-6587/aac13a

# HPS campaigns

Regular 3-4 campaigns per year with visiting institute, technical and experimental

Since Feb. 2023 new Jr. fellow (Miguel V. Do Santos) at CERN → HPS operation, RF optimization and preparation of 2.5 m prototype setup.

<u>Next campaigns</u>:

1. Finalise LIF installation and restart TS → calibration, particle balance, TS uniformity setup, November 2023
2. 2nd LIF campaign to determine first axial profile in January 2024
3. Determine axial density profile with TS on HPS 1.0 → begin 2024
4. Second trial with MW cut-off diagnostic → spring 2024
5. *(TS with DPS in 169 laser room → June 2024)*
6. 3rd LIF campaign → fall 2024

# HPS 1.0 issues/limitation of 1 m setup

- ○ Non-uniform B-field, large coils/cooling efficiency → limited by available coils/design
- ○ RF-generators aging: update/repair/refurbishment required → currently 2 out of 3 at Hüttinger for repair
- ○ RF noise → GND scheme, cable routing, …
- ○ Manual matching → ok for 3 antennas, more challenging beyond…
- ✓ Antenna arcing → mitigated in June 2023 campaign (mostly) by installing ceramic breakers at both ends (like at IPP)

→ Need for a more stable/uniform setup and longer to continue R&D and assess scalability:

→ **2 steps, implementation in between campaigns**

1. **HPS 1.0b upgrade**
2. **HPS 2.5, scalable module of 2.5 m**

# HPS 1.0b → fix issues and improve HW

Goal = **short term** upgrade of existing system to **assess axial uniformity before end 2024**

- Get uniform B-field, add/upgrade coils to get to < 1% uniformity over 1 m → Until spring 2024
- RF-generators → get 3 generators upgraded, possibly purchase a 4$^{th}$ one to operate 4 antenna/m → pending
- RF noise mitigation for diagnostics → install Faraday screen around the tube, pending
- Ground scheme → short ground path to building GND (~ 6 m instead of 30 m) to be installed by end October
- Matching → use available match boxes with position indicators + “live” Smith chart (Miguel) → almost ready
- Test of a pulsed only RF power amplifier module → spring 2024

# HPS 2.5 next device at CERN, 2.5 m long cell

Goal: Design and build a **scalable** module as **tunnel-compatible prototype**

→ **Trade off scale** to address physics and technical challenges

→ Implement learnings from HPS 1.0b, RAID and MAP devices (Oliver's talk)

→ Optimize according to **modelling** and plasma **diagnostics** outcomes

→ **Use new pulsed-RF (matchless?) generators and DC coils setup**

→ Guaranty stable and reproducible **control and operation**

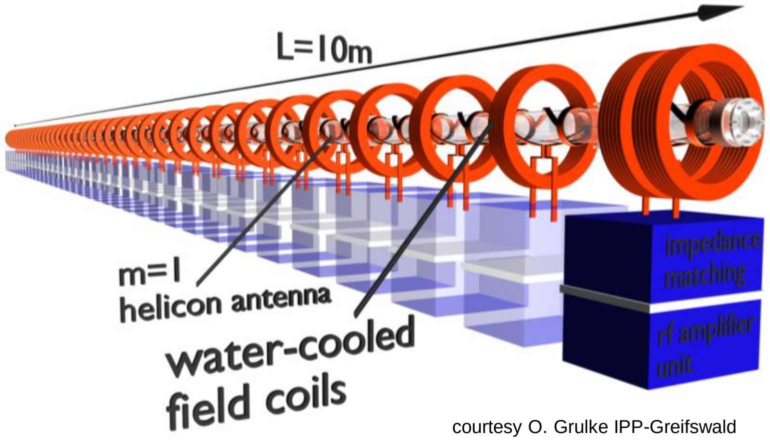
→ Installation in large 169/R-026 room (+ extend laser room)

> 2025: scale-up to 10 m → build 3 additional modules

**2.5 m unit module**

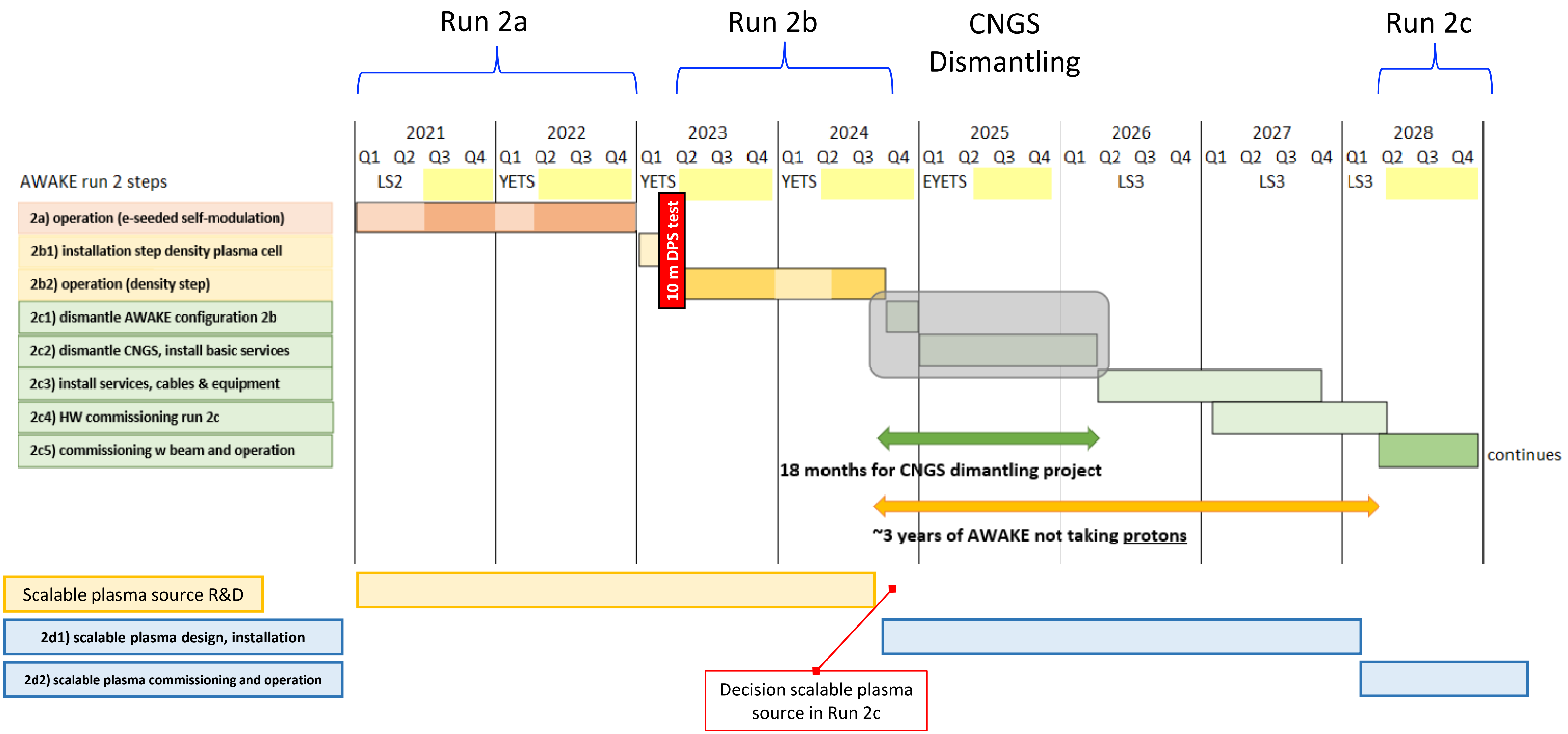
Timeline (2.5 m unit module):

1. Specifications → fixed by begin 2024
2. Procurement → spring/summer 2024
3. Delivery → end 2024
4. Installation and start of operation → begin 2025



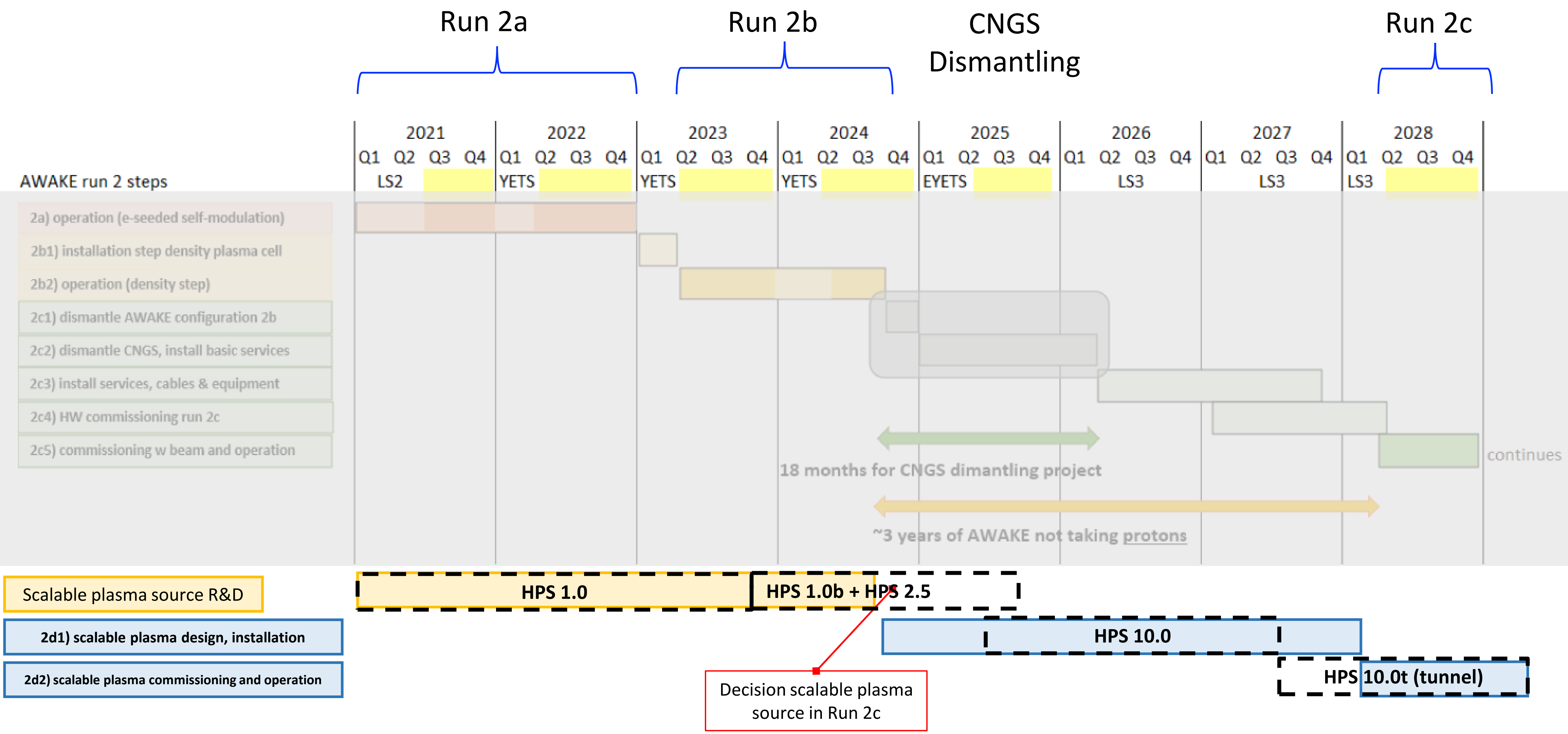

courtesy O. Grulke IPP-Greifswald

# AWAKE Run 2 Global Schedule




*From Edda, 29.08.2023*

# HPS for run 2c → timeline

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# DPS @ CERN

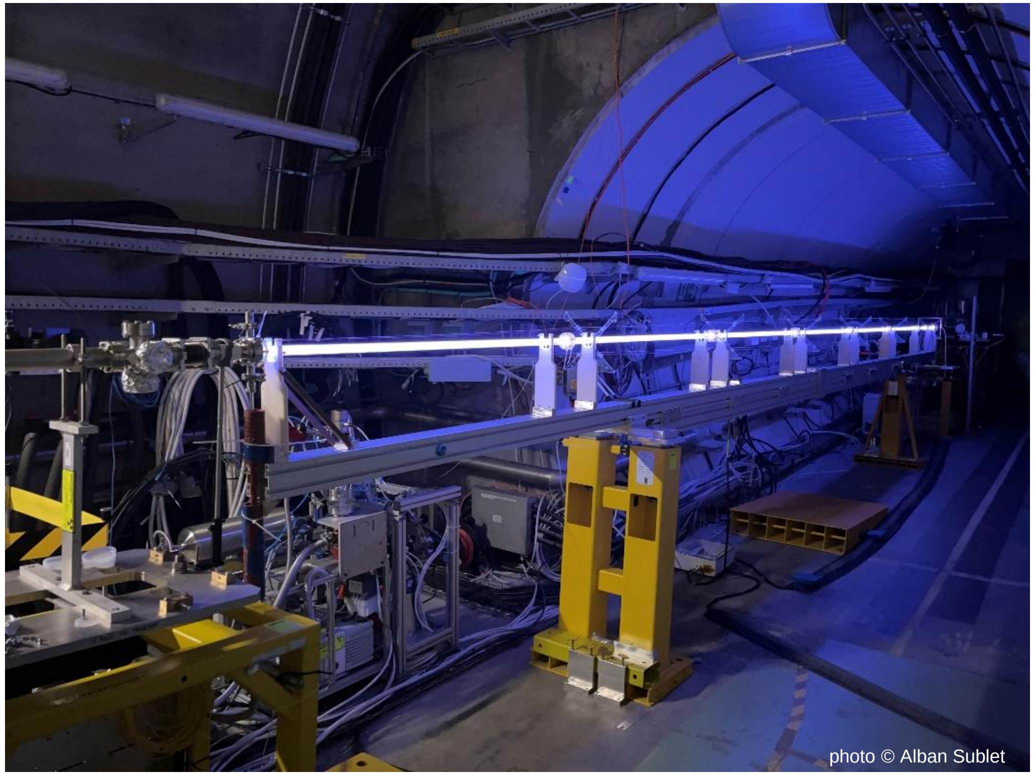
photo © Alban Sublet

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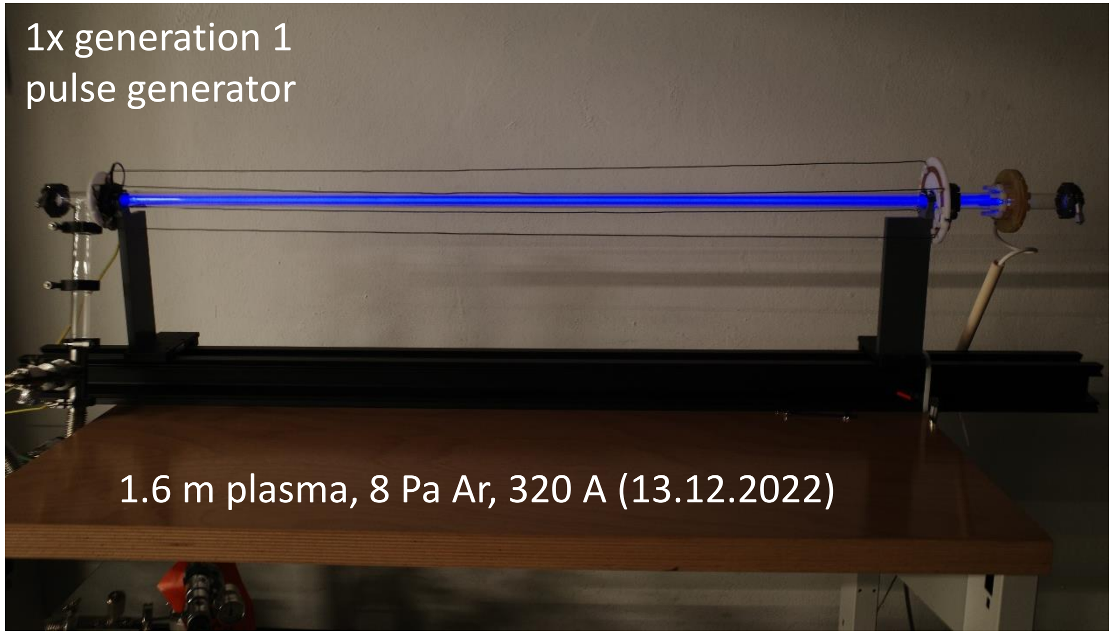
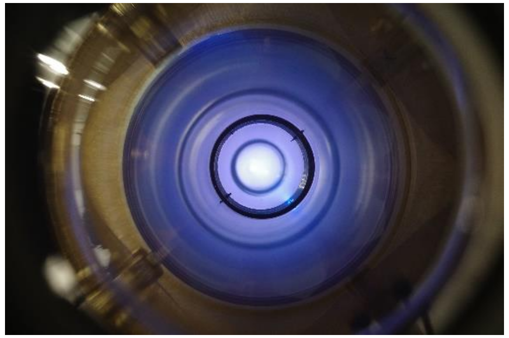
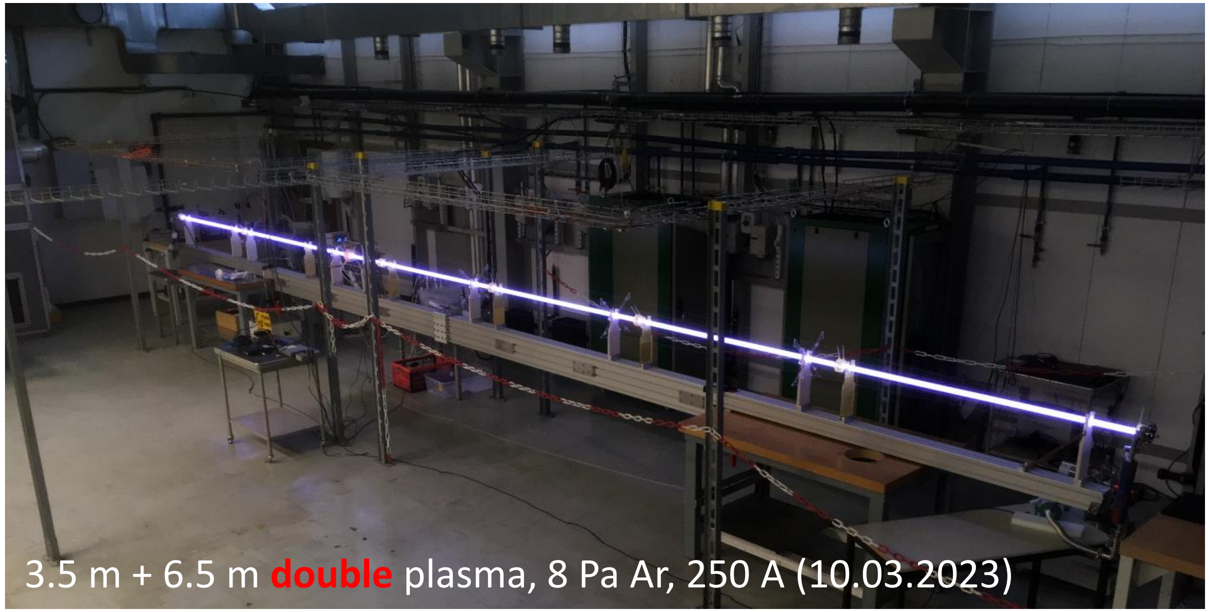
# DPS 1.5 and DPS 10.0 setup in CERN premisses (101/1-015)

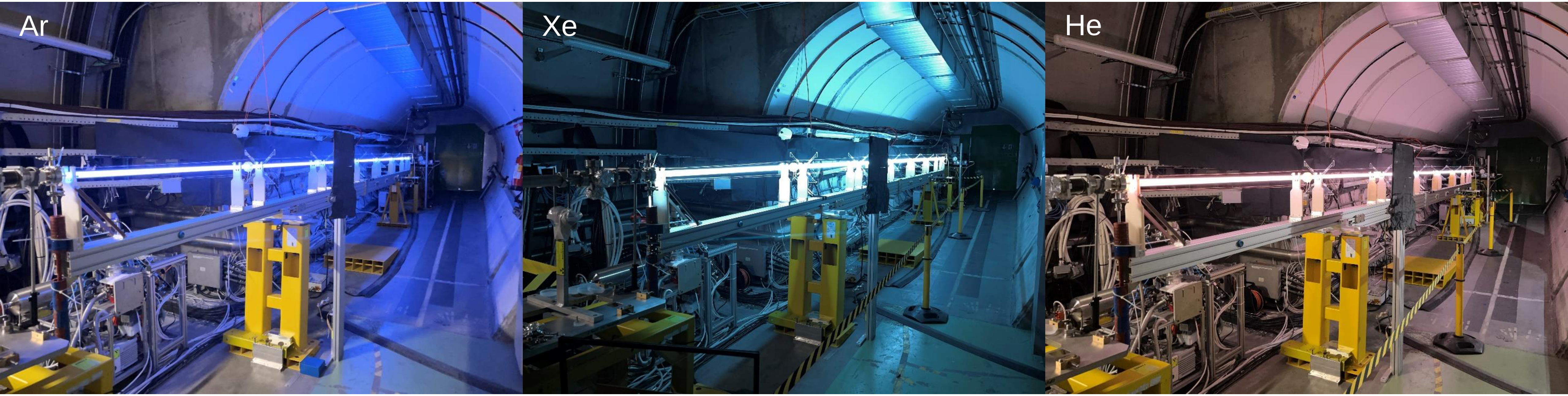


→ Both systems can operate in parallel in the 101 lab

# DPS 10.0 setup in the tunnel → AWAKE May run




**Unique chance to test the DPS during first AWAKE run in May 2023!**

→ Overall, very smooth operation of the DPS, tunnel remote control system ready

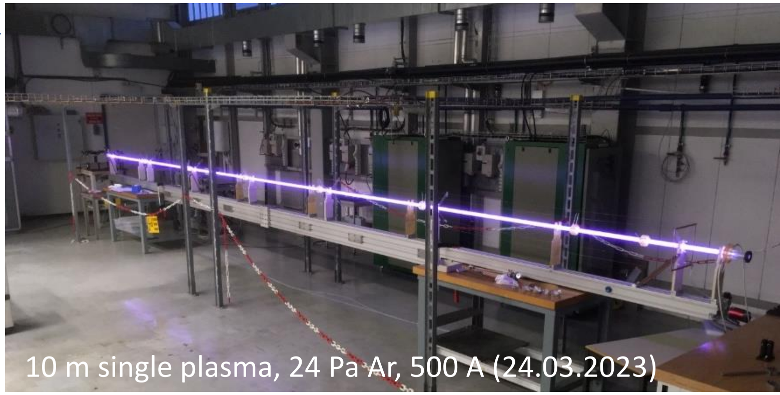
→ ~ 22000 discharges over 3 weeks, peak current stability < 1 % with ~20 ns maximum jitter (Nuno's talk)

→ 3 gases: Ar/Xe/He at 5 pressures 8/16/24/30/45 Pa and 3 plasma lengths (3.5/6.5/10 m)

→ density range span over 2 orders of magnitude: $2x10^{13}$ to $2x10^{15}$ $cm^{-3}$

→ proof of principal with SMI measurement, benchmarking with interferometry (Carolina's talk) and several data set recorded to study ion motion (Marlene's talk), current filamentation instability (Livio's talk), plasma light, hosing, etc.

# DPS 10.0 CERN program → uniformity x scalability

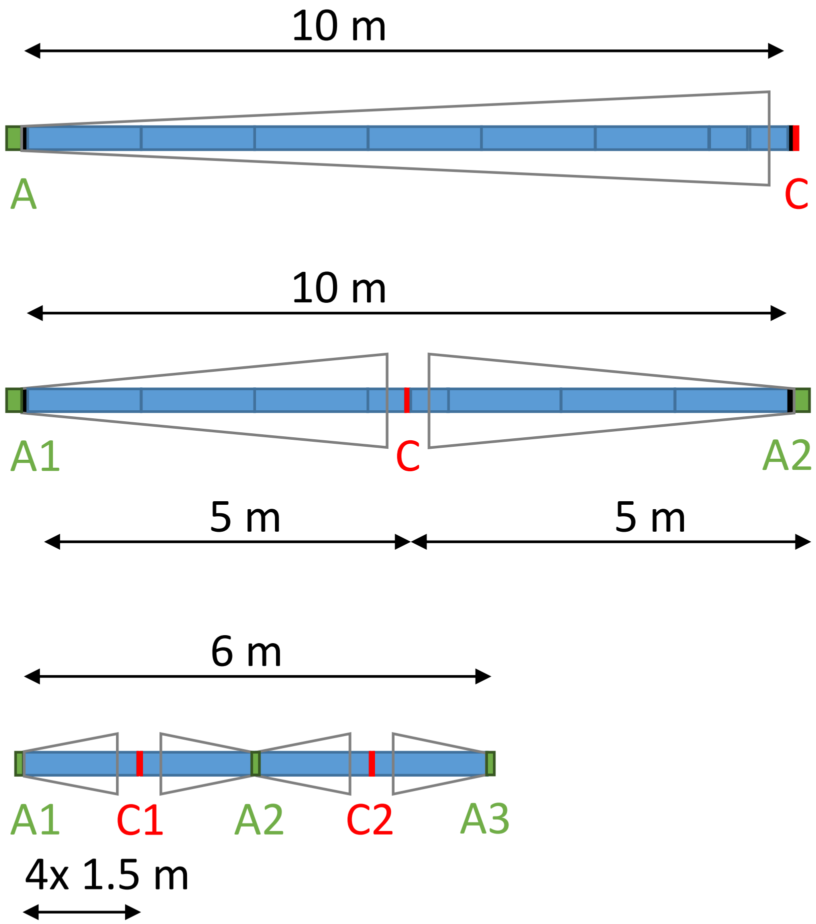



Long plasmas mostly for scalability, with longitudinal interferometry, μs cameras imaging and electrical characterisation:

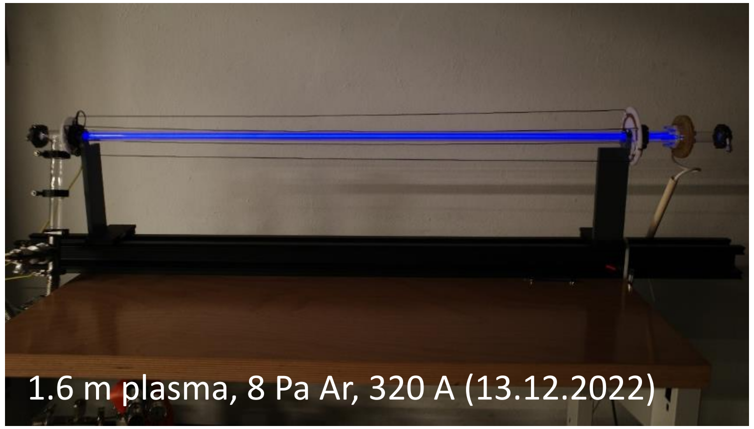
1. **Single plasma** (10 m), complete datasets, time/space/spectral resolved imaging of the whole plasma (until end 2023)

2. **Double plasma** (5 m + 5 m) with common cathode: A/C/A scheme and 1 or 2 pulse generators (begin 2024)

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 (mid 2024)

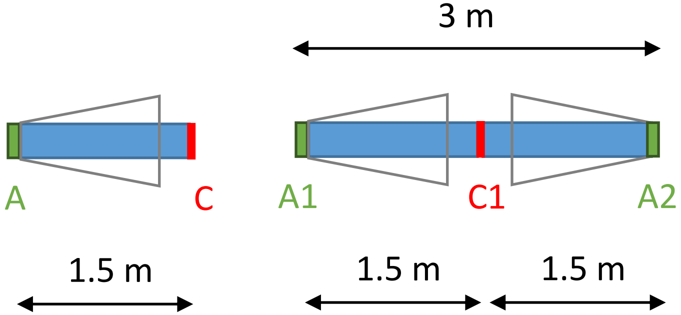


# DPS 1.5 CERN program → uniformity x scalability



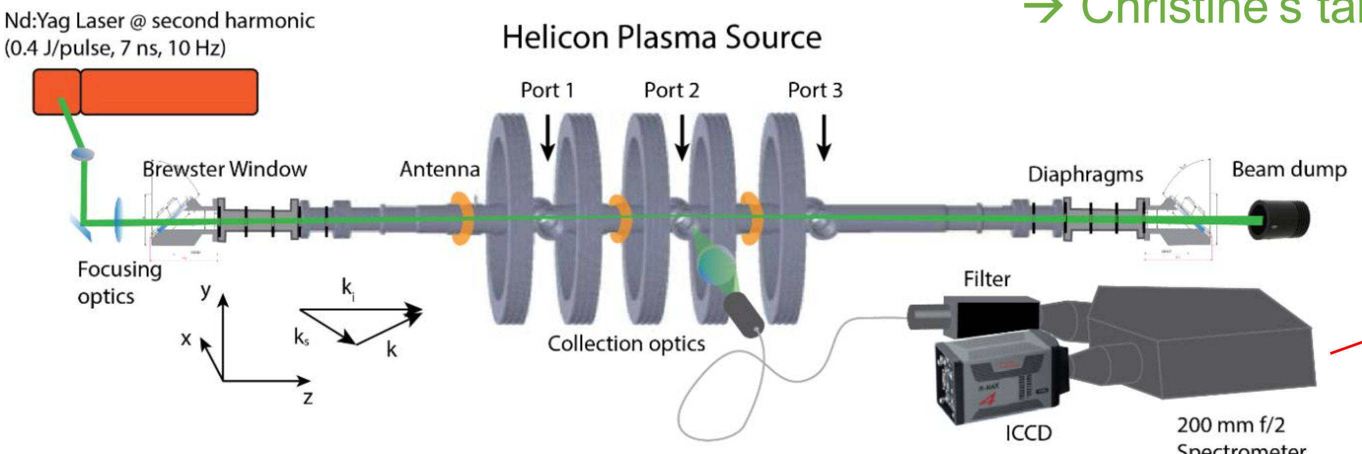

<u>Short</u> plasmas for longitudinal density uniformity measurements and scalability

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

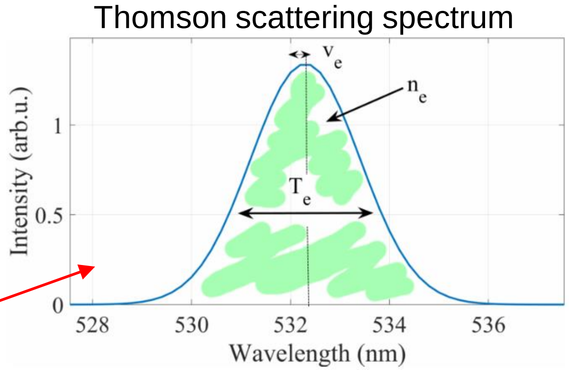



2. **Thomson scattering** on DPS with EPFL-SPC → June 2024, TS/plasma light for uniformity assessment, comparison with HPS

→ Christine's talk

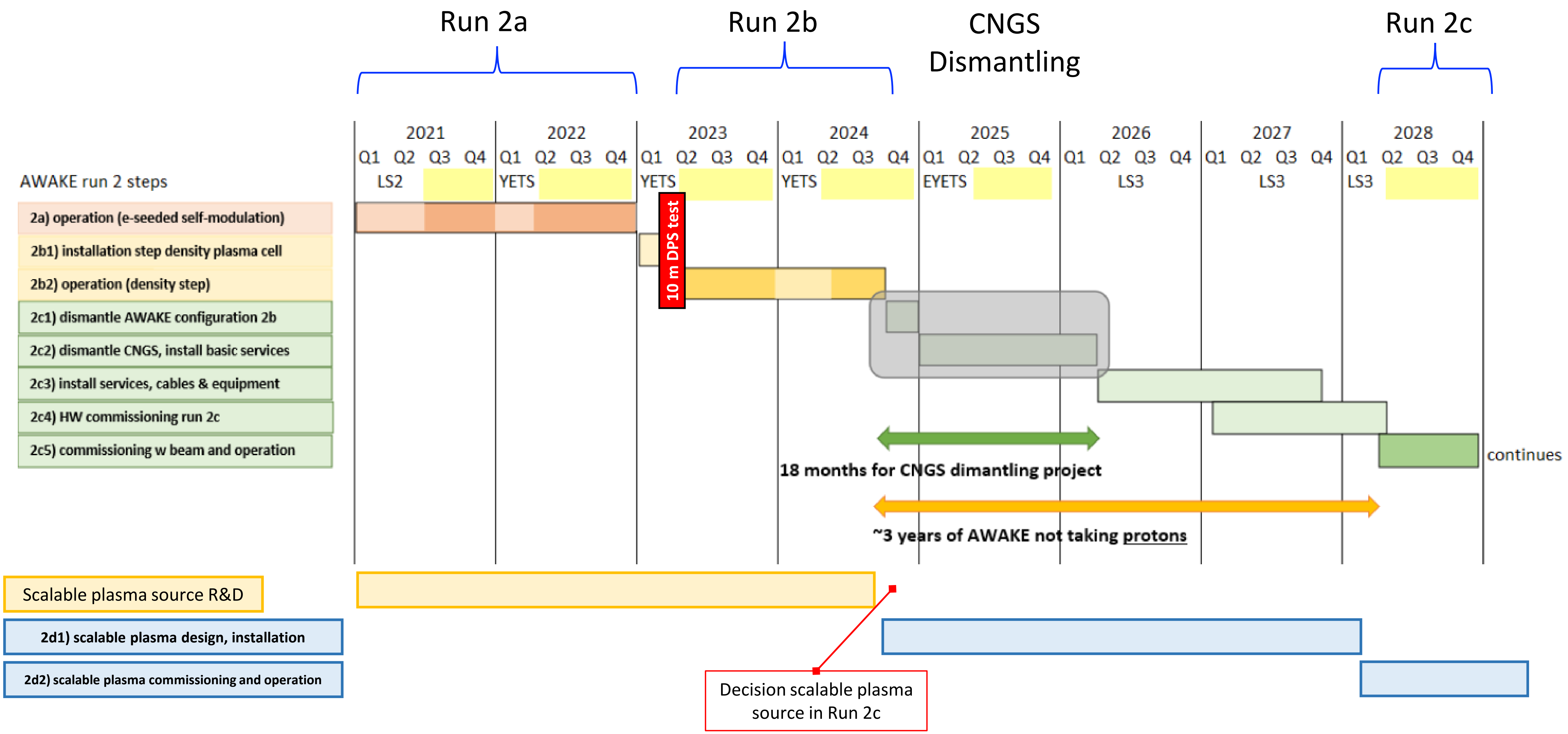



*Courtesy Christine Stollberg, EPFL-SPC*




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

# AWAKE Run 2 Global Schedule

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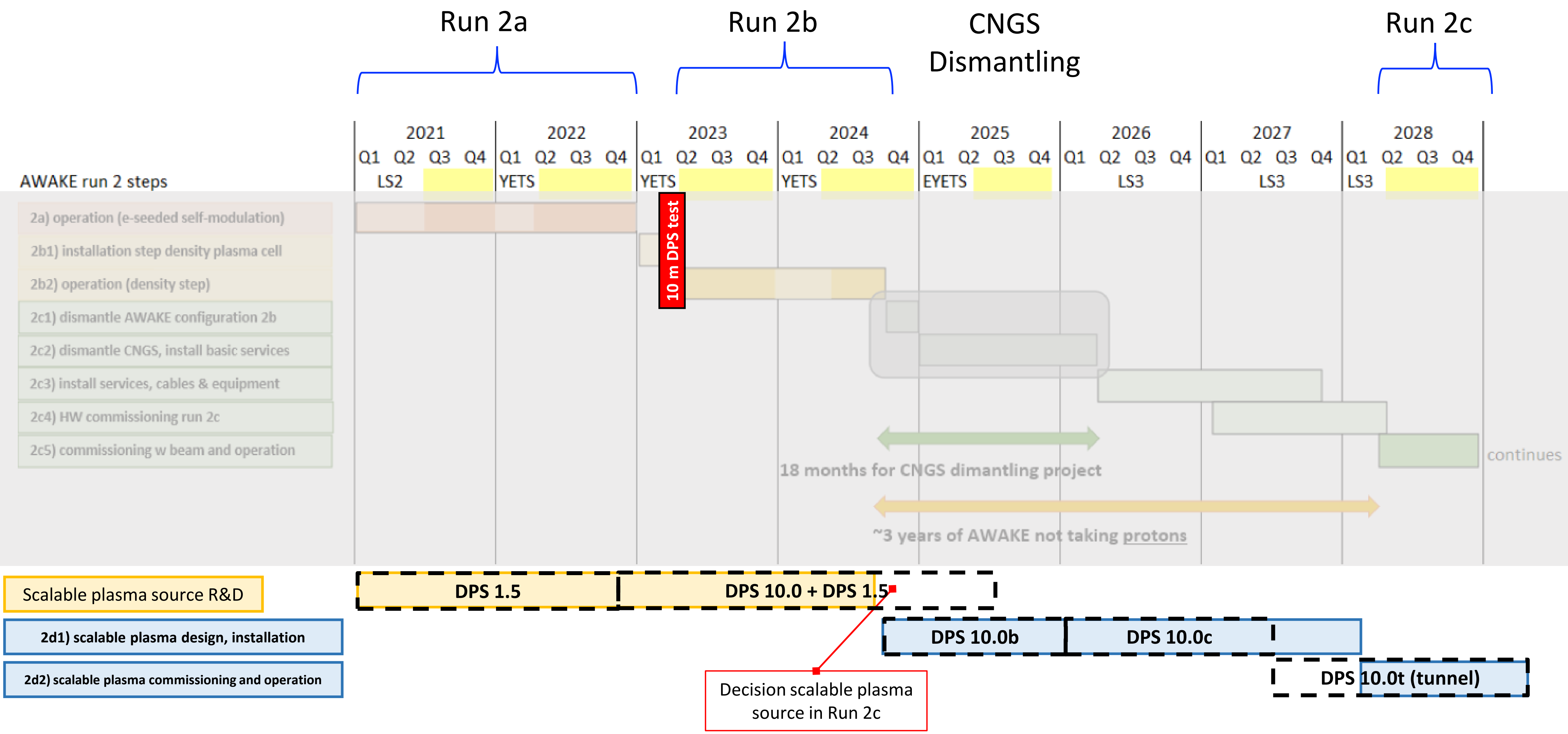
# DPS for run 2c → timeline

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# Run 2c technical challenges for plasma sources (HPS/DPS)

Beyond plasma density uniformity and scalability, specific challenges of life in the AWAKE tunnel:

1. Pulse RF/DC generator/long cable/tube diameter/antenna/electrodes → design optimization for tunnel operation, industrialisation of pulse generators and components → specifications/documentation/know-how transfer/spare units
2. Vacuum/pressure/flow profile/interfaces/windows/beam orifice (gas injection, temperature control, pumping...)
   → addressed by CERN + institutes expertise (see Nelson's talk)
3. Plasma source: Which one, where? self-modulator and/or accelerator?
4. Density requirements beyond 10 m → density step/ramp to correct dephasing?
5. Tunnel operation/timing: proton/plasma delay range?, plasma current/beam(s) interactions? Plasma trigger delays along the scalable source? Earth magnetic field shielding? …
6. Tunnel plasma diagnostic(s)

→ Deserves dedicated studies in parallel to on going sources R&D

# Summary

- Dedicated scalable plasma sources R&D program launched at CERN, in spring 2019 for the HPS and in summer 2020 for the DPS, in collaboration with 5 institutes in total
- Both sources reached the AWAKE nominal density, but both are lacking uniformity and scalability assessment
- Several HW issues on the HPS still to be fixed
- Physics aspects addressed together with institutes towards uniformity measurement at CERN until end 2024
- Unique opportunity to test the DPS with protons during AWAKE first run in May 2023
- Decision point end of 2024 between the 3 sources candidates for run 2c (Rb/HPS/DPS)
- Set of technical challenges common to all plasma sources to be addressed in parallel, in view of Run 2c
- R&D MUST continue on both scalable sources in parallel to keep maximum options open until all AWAKE requirements are fulfilled