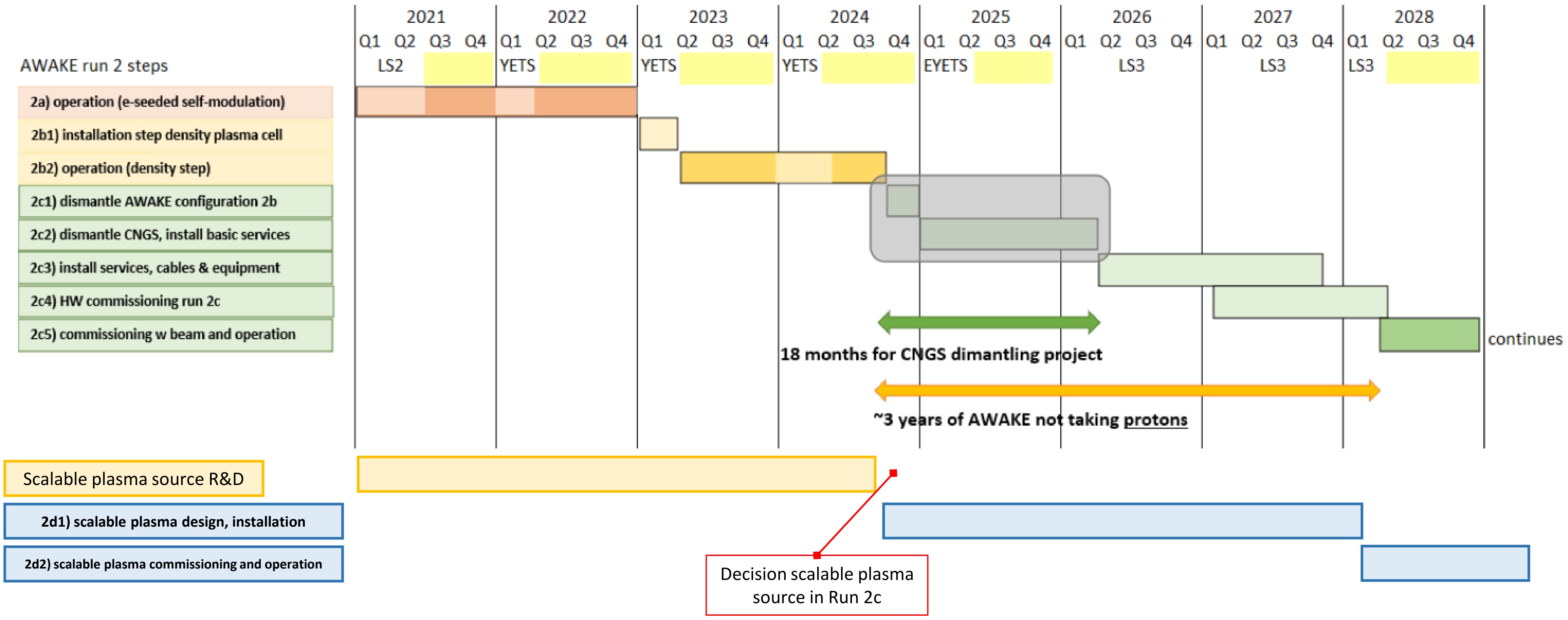
Summary of Scalable Plasma Source Internal Review

Edda Gschwendtner, CERN

AWAKE Collaboration Meeting, 4 – 6 October 2023

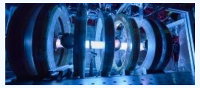
AWAKE Run 2 Timeline



Scalable Plasma Source R&D

1) R&D 2021-2024: Address physics and technical challenges

Helicon Plasma Source



Existing 1 m

- → **Demonstrate AWAKE nominal density**
- → First assessment of **axial plasma density uniformity (Nov 2021)**
- → Development of **plasma diagnostics** with high accuracy

Discharge Plasma Source

Existing 1.6 m

- → **Demonstrate AWAKE nominal density**
- → Development and test of **high reproducibility, low jitter pulsed power supplies** for ignition and heating
- → Study and optimize different **electrode materials/geometries**
- → Arc discharge plasma **simulations**
- → Development/**share of plasma diagnostics** with HPS

2) R&D 2021-2024 Address physics and technical challenges

Helicon Plasma Source

2.5 m unit module

- → Design and build **scalable tunnel-compatible prototype**
- → Tailor all required parameters to **achieve desired density x homogeneity**
- → Guarantee **stable and reproducible control and operation**
- → Trade off to scale properly address physics and technical challenges
- → Optimize with **extensive modeling** and plasma diagnostics deployment

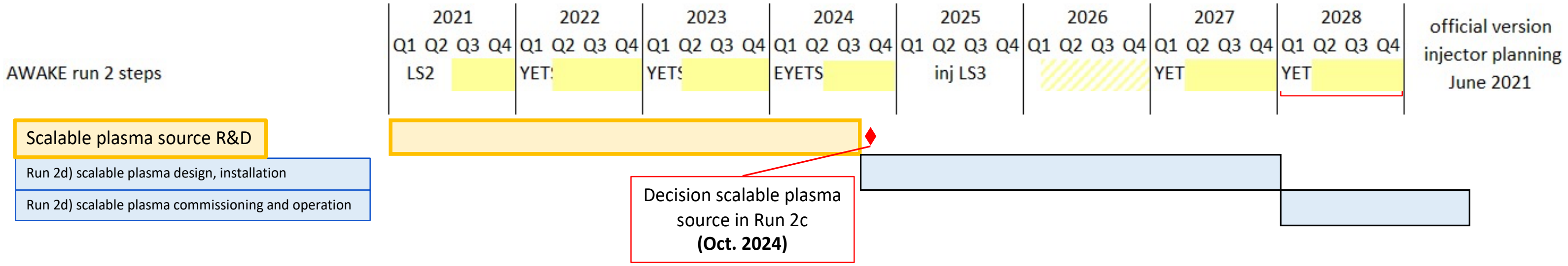
Discharge Plasma Source

2.5 m to 10 m unit module

- → Design and build **scalable tunnel-compatible prototype**
- → Tailor all required parameters to **achieve desired density x homogeneity**
- → Guarantee **stable and reproducible control and operation**
- → Test different common anode/cathode schemes for scalability
- → **Proof of principle possible YETS 2022/23 test in tunnel 2a and 2b**

Scalable Plasma Sources: From R&D to Tunnel

2) Implementation 2025-2028 (readiness for Run 2c)



Decision end 2024: three scenarios, cost-neutral:

1. **Further studies** needed: ➔ keep baseline of Rb vapour source as 2nd plasma source ➔ scalable sources in Run 2d
2. **Decision for discharge source** in Run 2c: ➔ save ~800kCHF (700kCHF DPS – 1400 kCHF for 2nd laser for 2nd Rb vapour source)
3. **Decision for helicon plasma source** in Run 2c: 2300kCHF HPS, save ~1400kCHF for 2nd laser, get contributions from institutes

Option 2) or 3): + 1 fellow + 3.2FTE.yrs (2025-2028)

4x 2.5 m modules = **10 m tunnel plasma cell**

HPS: ~2.3MCHF

1x 10 m or 2x5 m or 4x 2.5 m modules = **10 m tunnel plasma cell**

DPS: ~0.7MCHF

→ Build test and document the tunnel 10m prototype cell and diagnistcs in dedicated surface infrastructure
→ Prepare tunnel integration/facilitites/interface/control, installation and commissioning

Scalable Plasma Source Internal Review, 29 Aug 2023

Charge to the reviewers (AWAKE management board):

- How can the progress to achieve the deadline for end 2024 be improved?
- What are the consequences if we can’t meet the deadlines?
- How can we focus the investment?

Charge to the presenters:

- What is the committment of the different institutes?
- What is the state of the art?
- Uniformity, density, reproducibility, industrialisation, status of diagnostics, etc…
- How do you organize yourself?
- workforce, budget, resources
- R&D at CERN vs R&D at institutes
- What’s your plan?

Scalabla Plasma Source Internal Review

Tuesday 29 Aug 2023, 09:00 → 17:00 Europe/Zurich

6/R-012 - conference room (CERN)

2023-08-29-Charge....

Videoconference Scalabla Plasma Source Internal Review — Join — 6/R-012

09:00 → 09:10 **Introduction** 10m

09:10 → 09:25 **AWAKE status overview and budget for plasma sources R&D** 15m

Speaker: Edda Gschwendtner (CERN)

2023-08-29-plasma... 2023-08-29-plasma...

09:30 → 09:45 **Run 2c physics requirements/parameters** 15m

Speaker: Patric Muggli (Max Planck Institute for Physics)

PSRAug2023Muggli...

09:50 → 10:10 **Coffee/Tea Break** 20m

10:10 → 10:25 **DPS at CERN** 15m

Speaker: Alban Sublet (CERN)

20230829_PlasmaS... 20230829_PlasmaS... 20230829_review_D...

10:30 → 10:45 **DPS at IST** 15m

Speaker: Nelson Lopes (IST)

2023_08_29_meetin...

10:50 → 11:05 **DPS at IC** 15m

Speakers: Zulfikar Najmudin (Imperial College), Zulfikar Najmudin

AWAKE_DPSreview_... AWAKE_DPSreview_...

11:05 → 12:00 **Discussion** 55m

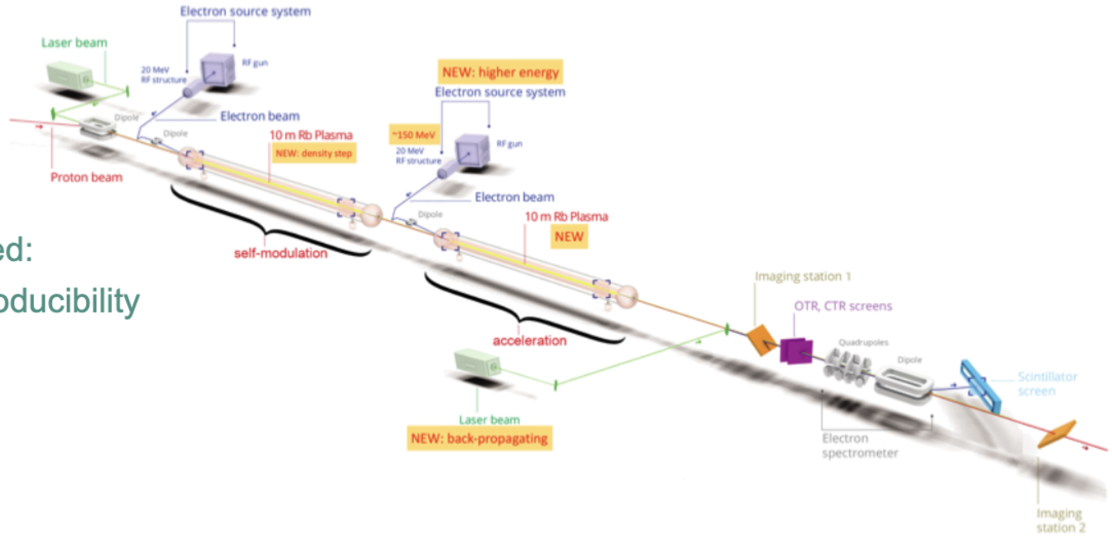
12:00 → 13:30	**Lunch**			1h 30m
13:30 → 13:45	**HPS at CERN**	**Speaker**: Alban Sublet (CERN)	20230829_PlasmaS... ; 20230829_PlasmaS... ; 20230829_review_H...	15m
13:50 → 14:05	**HPS at Wisconsin**	**Speaker**: Oliver Schmitz (University of Wisconsin Madison (US))	UWMadison_AWAK... ; UWMadison_AWAK...	15m
14:10 → 14:25	**HPS at Lausanne**	**Speaker**: Christine Stollberg (EPFL - Ecole Polytechnique Federale Lausanne (CH))	2023-08-29_AWAKE... ; 2023-08-29_AWAKE...	15m
14:30 → 14:45	**HPS at Greifswald**	**Speaker**: Olaf Grulke		15m
14:50 → 15:30	**Discussion**	**Speaker**: All		40m
15:30 → 16:00	**Coffee/Break**			30m
16:00 → 16:30	**Panel Closed Session**			30m
16:30 → 17:00	**Panel recommendation and close-out**			30m

Patric

MAX-PLANCK-INSTITUT FÜR PHYSIK

AWAKE

REQUiREMENTS: ALL



✧In all cases, with two sources, need:
- ✧mutual adjustment and reproducibility

✧Choice:
- ✧fall back for Run 2c: Rb+Rb
- ✧all other options …
- ✧Run 2d …

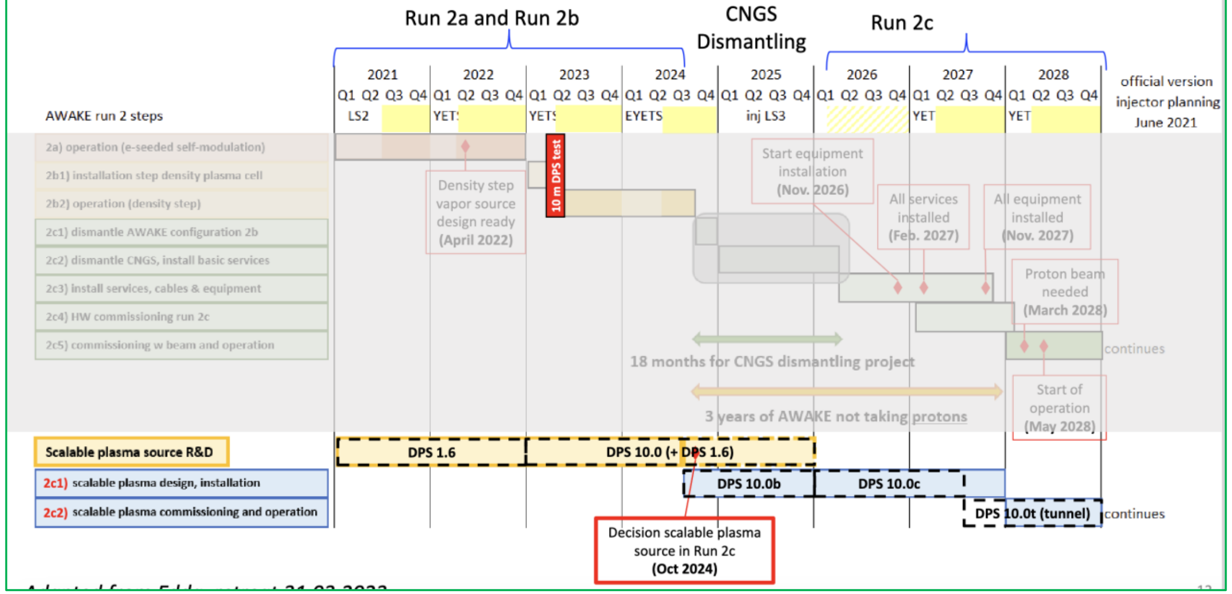
✧Need measurements or estimates of:
- ✧density uniformity
- ✧reproducibility/adjustment

✧Expert opinion as to the likelihood that the source will meet the requirements, short of knowledge

✧Commitment to make it work as best as possible

© P. Muggli

DPS for run 2c → timeline



DPS, CERN, Alban

Summary

1. Unique opportunity to test the DPS with protons during AWAKE first run in May 2023
   - ✓ very successful with a lot of learning and results (still under processing)
2. Physics aspects addressed together with institutes towards uniformity measurement at CERN until end 2024
3. Distributed tasks among institutes with pulse generator specialty at IST and transverse diagnostics at ICL.
4. Well defined program for next 2 years at institutes and CERN
5. Weekly meeting for follow-up
6. Will Increase feedback to the project by further participations/presentations at AWAKE TB/collaboration meetings

Plan (IST short term <Q4 2024)

DPS, IST, Nelson

Main goal

… demonstrate a path for possible use of DPS(s) in Run 2C

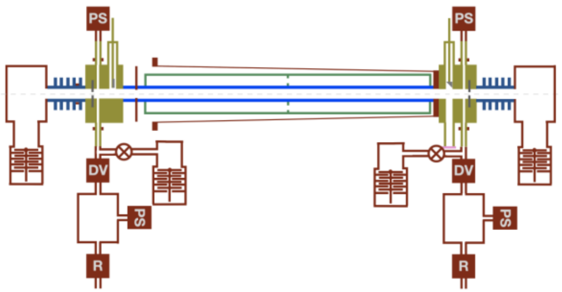
How to demonstrate we are one track ?

Successfully test a Run 2C partial tube

IST plan constrained by

… ongoing work

… funding cycle



Commitments

DPS, IC, Zulfikar

- Plasma discharge lab with working 200 A, 8 kV, 1 m discharge
- Longitudinal interferometer based on ns fibre laser
  - time evolution of plasma (resolution << 1 µs)
  - radial uniformity (< 1% of ambient)
- Transverse interferometer using fibre laser
  - Longitudinal inteferometry (< 1% of ambient)
- Transverse deflectometery using fibre laser
- Transverse spectroscopy (imaging spectrometer)
- Development of high accuracy power supply for discharge (< 0.1% ambient)
- Simulating discharge development

HPS, CERN, Alban

CERN AWAKE project, Coordination Package 8: Plasma Sources R&D
- Coordination of HPS and DPS experiments at CERN
- Periodic follow-up meetings
- Report in project team meeting
- Source design, development, operation within AWAKE requirements
- Adaptation to AWAKE tunnel infrastructures

Max-Planck-Institut für Plasmaphysik

- In charge of institute Work Package for the HPS R&D
- Launched the helicon plasma cell study ~ 2009 (PPA09 conference)
- 1m HPS setup designed/build/operated at IPP and moved to CERN
- Reference plasma diagnostic (CO2 interferometer)
- Development of MW cut-off frequency "monitoring" diagnostic

EPFL

- Development Thomson Scattering for axial density profile
- Helicon wave physics and simulation, RF and plasma simulations
- RAID test setup at EPFL-SPC + alternative resonant antenna design

College of Engineering, University of Wisconsin-Madison

- Diagnostics: Laser Induced Fluorescence and emission spectroscopy
- RF coupling and impact on density formation and profile
- Particle balance to identify sources and sinks causing anisotropies
- MAP (Madison AWAKE prototype) as sister experiment to HPS for extrapolation to longer cell, qualify diagnostics and test bed for optimization concepts towards AWAKE goals

3

HPS campaigns

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

Since 2023 new Jr. fellow at CERN to work on HPS operation/test (RF) and preparation of 2.5 m prototype setup

→ See institutes slides for results and plans.

Next campaigns:

1. Install LIF and restart TS → October/November 2023
2. In parallel 1st LIF campaign with calibration based on TS for particle flows and density measurement
3. 2nd LIF campaign to determine first axial profile in January 2023
4. Determine axial density profile with TS on HPS 1.0 → begin 2024
5. Second trial with MW cut-off diagnostic → spring 2024
6. *(TS with DPS in 169 laser room → June 2024)*
7. 3rd LIF campaign → fall 2024

HPS 2.5 next device at CERN, 2.5 m long cell

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

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

→ Tailor all required parameters to **achieve desired density x homogeneity**

→ Optimize with extensive **modelling** and plasma **diagnostics** deployment

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

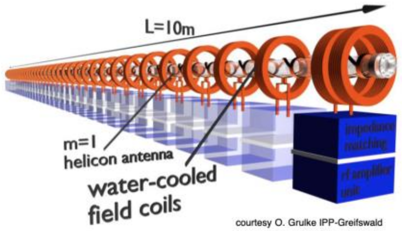
→ Installation in large 169/R-026 room (+ extend laser room)

→ Implement learnings from HPS 1.0b and MAP devices

Then (> 2025): scale-up to 10 m by building 3 additional modules

Timeline:

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



Summary of results at CERN and at Institute

- **CERN**
  - Installed and partially commissioned LIF diagnostic for density measurement
  - Plan was established to use Thomson Scattering as calibration in 11/2023
  - Fast LIF for comprehensive LIF particle balance measurement ongoing
  - Contributions to device optimization on RF setup
  - Provided and installed fast gas valve for local gas fueling
- **At UW Madison**
  - Designed, built and commissioned MAP as test bed for HPS development
  - Demonstrated role of radial density gradient in RF coupling characteristics, which informs the axial coupling of single antenna plasmas
  - COMSOL model (with static background density) developed and tested on experimental MAP findings, available for use in design process
  - LIF based density measurement tested and expanded, next step is to reach 10^{20} m^{-3} range
  - Basis of fast LIF (1ms time resolution) demonstrated, system is being procured and will be tested at MAP, including software lock-in amplifier for fast sampling
  - Impact on tube diameter on plasma density in a 2m long, homogenous magnetic fields can be investigated

AWAKE

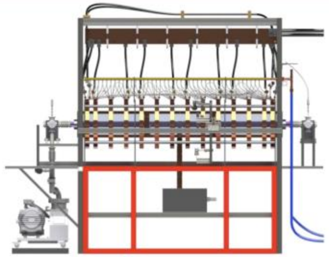
College of Engineering
UNIVERSITY OF WISCONSIN-MADISON

4

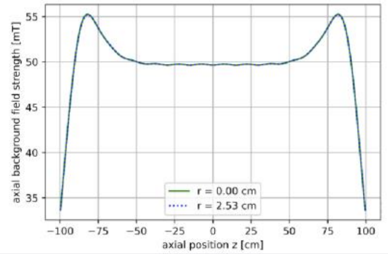
HPS, Wisconsin, Oliver

Overview of the Madison AWAKE Prototype (MAP)

MAP Features and Specifications	
Plasma dimensions	5.2 cm inner diameter, 2.1 m long (HPS-like, twice the length)
Magnetic field	50 mT in center, 54 mT at ends
Available RF power	one 10 kW antenna at 13.56 MHz, 3x10 kW available
Current Diagnostics	passive spectroscopy, RF comp. Langmuir probe, LIF
In development	heterodyne interferometry, 3-axis Mirnov probes
Steady state capability	water cooled magnets, RF generators and soon antennas



[M. Granetzny et al., PSST (2023) submitted]



5

This is our commitment to AWAKE:

EPFL

1) Diagnostics:
Measurement of electron density (homogeneity) in the HPS (and in the DPS) by **Thomson Scattering**

2) Contribution to design of HPS 2.5:
Address design criteria for HPS 2.5 by **simulations** of helicon wave propagation and expected density profiles for different configurations: experiment radius, antenna distance, alternative antenna design

3) Theory:
Deeper understanding of helicon physics, i.e. mode propagation and power deposition, to inform design decisions on HPS 2.5

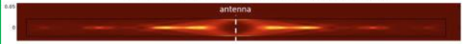
HPS, EPFL, Christine

2) Design of HPS 2.5

EPFL

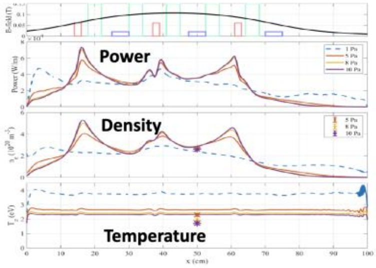
Date	Objective	ppm	comment
2022	**Simulations of helicon wave propagation** in non-homogenious plasma for HPS 1.0	0.5	
01/2023	Development of **1D power-and-particle balance** simulations for HPS 1.0 with ring antennas & reproduction of currently available experimental data	1	
08/2023	Preliminary simulations of optimized experimental conditions for HPS 1.0 at a given density → **estimated homogeneity of 'ideal' HPS 1.0**	0.5	

Power deposition 1 antenna (ring)



Power deposition 3 antennas

$$\int_0^{R_p} r Q_{wave}(r,z)\, dr$$



11

Summary

→ Very useful to get the different institutes all together!
→ Great summaries of all the activities!

Close-Out

1) How can the progress to achieve the deadline for end 2024 be improved?

- Share diagnostics
- Spend more time at CERN
- Focus on the needs of AWAKE experiment at CERN for external collaborations.

2) What are the consequences if we can't meet the deadlines?

- Weakens the credibility for long-term application.
- Use Rubidium source for Run 2c
- Continue studies for Run 2d

3) How can we focus the investment?

- Share, create a community, exchange information.
- Use all the same baseline for each plasma source type/diagnostics/… , be guided by CERN installation
- Documentation, profit from industry
- Dedicated TB or regular presentations in TB