UW Madison contribution to AWAKE – HPS review input

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AWAKE Collaboration Meeting

2023-10-06

Overview of UW Madison focus and commitments with resources

- **UW Madison team focuses on relation of plasma density formation and radio-frequency (RF) coupling at own institution and CERN**
- **Funding basis:** new grant by National Science Foundation (starting 09/2023 - 08/2025) following two previous funding cycles geared towards helicon physics and high-density plasma sources, discretionary funding available from UW Madison
- **Resources:**
  - Two Ph.D. students (both dissertators, i.e. 100% research) focusing on (1) RF coupling vs. plasma formation and (2) Particle balance and density formation fully funded
  - PI commitment of 2 months/year fully funded
  - Undergraduate student effort, 6 months per year full time, fully funded
  - Instrumentation Engineer, 4 months/year funded
  - Materials and Supplies for MAP operation fully funded

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Deliverables towards HPS qualification

- **Deliver axial density measurement based on Laser Induced Fluorescence (LIF)** (PhD M. Zepp), joined CERN and UW Madison investment into hardware was done, system was partially commissioned
- **Establish LIF based quantification of the particle balance and invent methods to counteract possible localized sources and sinks for particles that can cause density anisotropies** (PhD M. Zepp), joined CERN and UW Madison investment into hardware was done, system was commissioned, UW Madison provided fast gas valve for local gas sourcing
- **Contribute to antenna optimization and axial phase coupling of antennas that support a homogeneous density profile** (PhD M. Granetzny), based on MAP experiments
- **Provide and run COMSOL 2D RF model**, including neutral particles and local ionization to extrapolate findings for AWAKE cell design (PhD M. Granetzny, post doc)
- **Provide MAP as test bed for diagnostics, methods and to investigate length scaling aspects in homogeneous magnetic field at comparable power density**, can contribute to design and setup of HPS 2.5 module as testing ground and for fast exploration of basic features

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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

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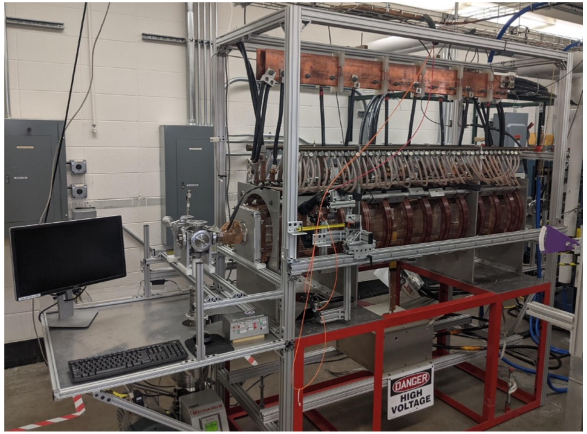
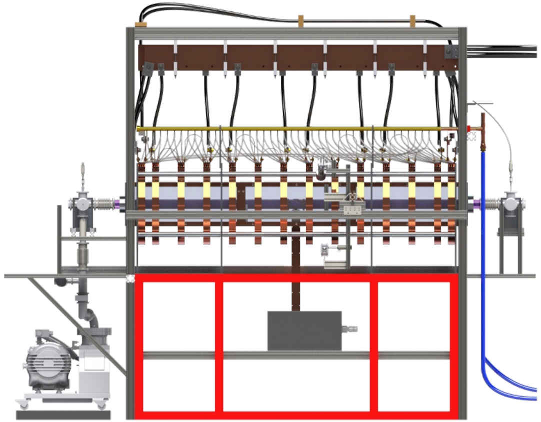
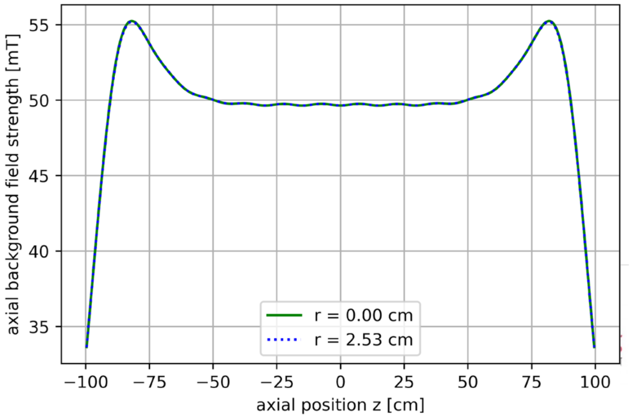
Overview of the Madison AWAKE Prototype (MAP)

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



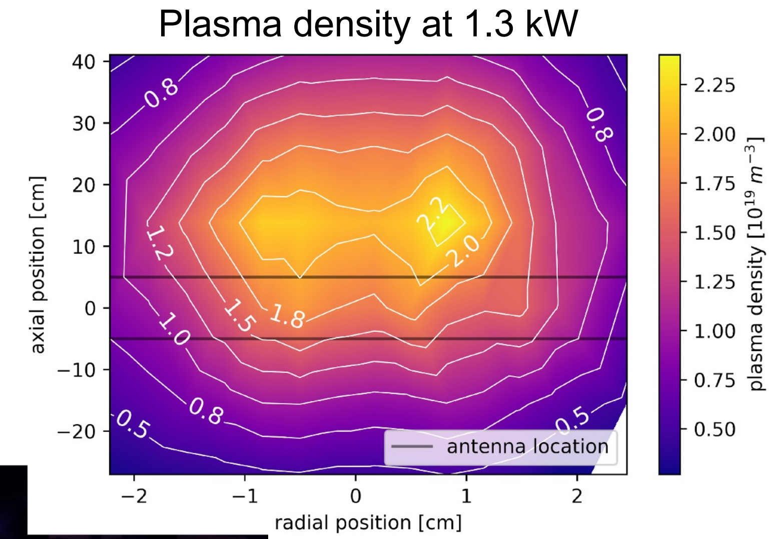


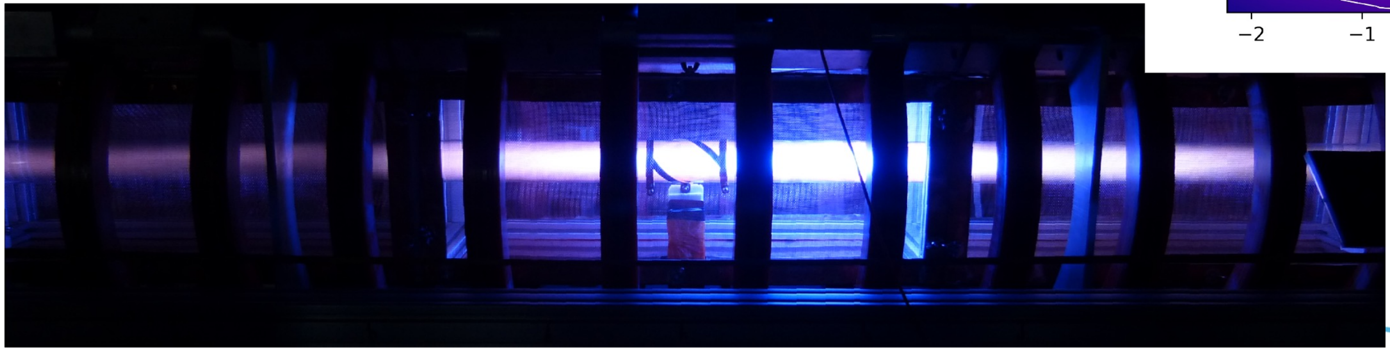
[M. Granetzny et al., PSST (2023) submitted]



Current performance of MAP and path towards AWAKE densities

- Reliably operational, including LIF density measurement
- Typically run at 1 Pa (10^{-2} mbar), 1.3 kW or 10 kW pulsed
- Bright blue core argon plasma
- Strongly directional discharge, in agreement with model
- Cold ions at 200 – 400 meV
- **Plasma densities up to 2.3×10^{19} m^{-3}** (expected to scale with power and expand into axial direction)
- **High-power operation with one antenna at 10kW accomplished, 3 total being commissioned**

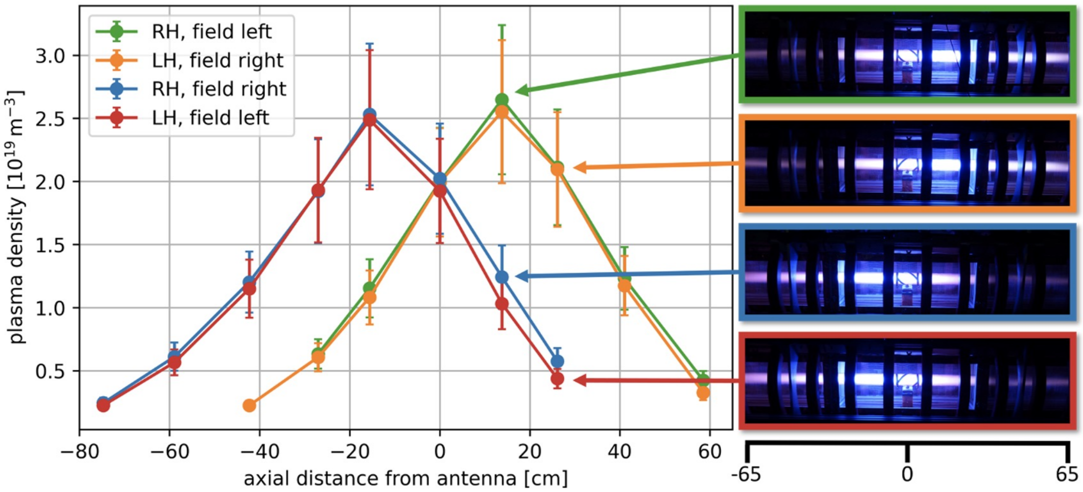




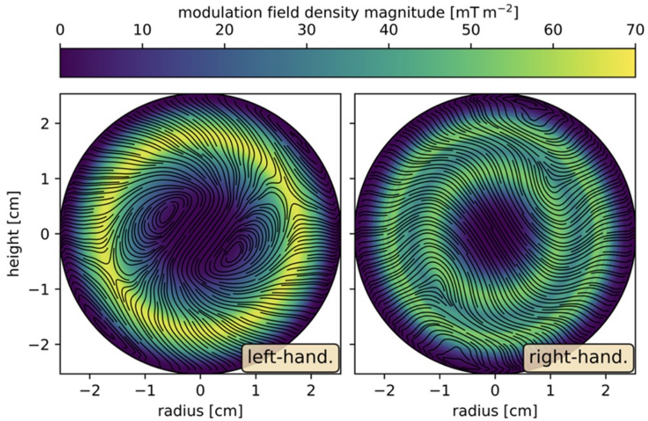
[M. Granetzny et al., PSST (2023) submitted]

First time demonstration and explanation of forward directionality of helicon plasma in homogeneous magnetic field

- **Alignment of RF helicity with magnetic field yields favorable coupling and hence higher density**



- **Due to azimuthal shear currents induced by the radial density gradient**



$$\delta \nabla \times \nabla \times \boldsymbol{B} \mp k \nabla \times \boldsymbol{B} + k_w^2 \boldsymbol{B} = \mp \frac{i\mu_0}{n}\frac{\partial n}{\partial r} j_r \hat{\boldsymbol{z}}$$

- **This is an important finding towards antenna stacking and optimization of plasma coupling for homogenous density profile**

[M. Granetzny et al., PoP Letter (2023), in review]

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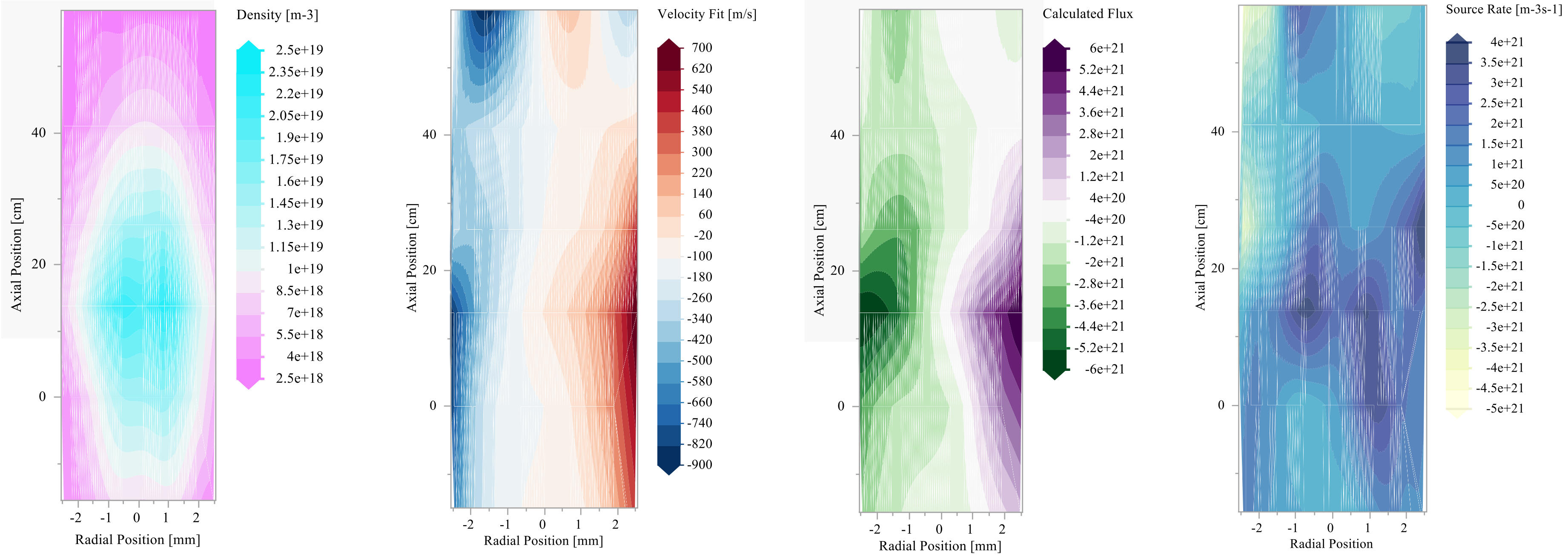
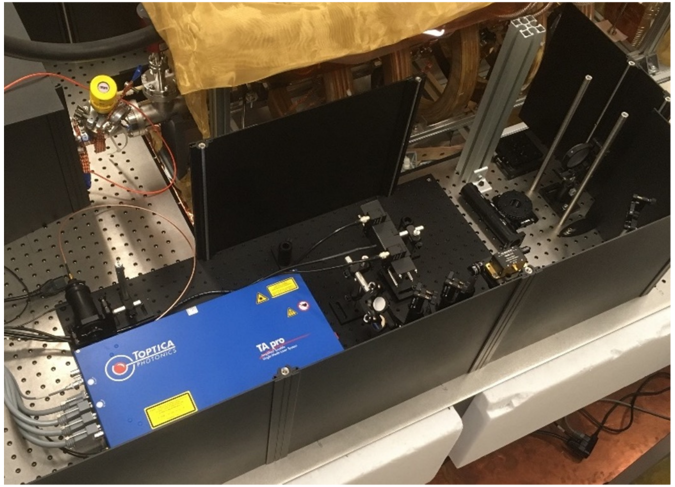
LIF is a versatile density and particle source measurement at MAP



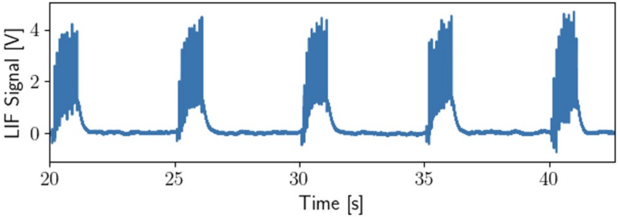
- Flux: $\boldsymbol{\Gamma = nV}$, source rate: $\boldsymbol{S = \frac{d\Gamma}{dr}}$
- **Indicates local particle source at highest density point, which implies that homogenous density profile relies on homogenous particle source**
- LIF can also measure neutrals, for characterization of neutral depletion
- With appropriate calibration, error is ~2% at 1.3 kW, likely decreasing at higher density

A LIF setup was established at the HPS cell - initial results in a nutshell

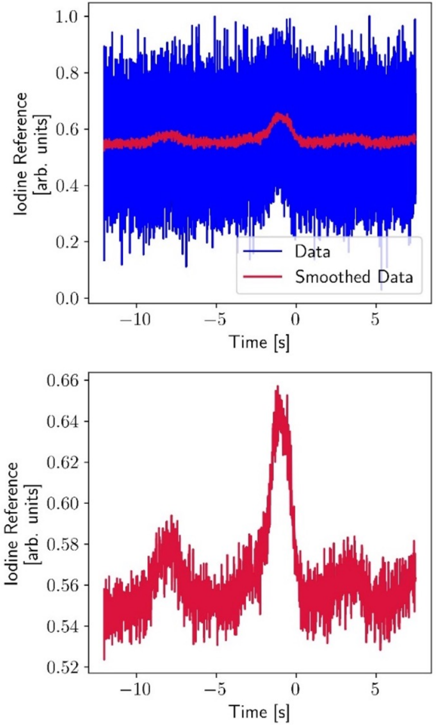
- LIF setup on optical table at CERN



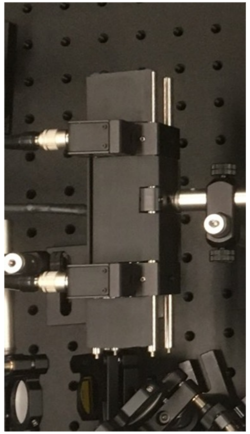
Significant noise on signal needs to be reduced



- Iodine absorption spectrum indicates correct laser frequency tuning, laser is very easy to tune



Iodine Reference Cell



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Plan at CERN towards density profile qualification

- **November 2023:**
  - Complete commissioning of LIF
  - Use Thomson scattering data as calibration reference
  - Establish axial density measurement and support campaigns

- **Early 2024:**
  - Align for axial measurements
  - Document axial density profile with LIF at one power level

- **2024:**
  - Document axial density profile to high power domain
  - Install fast LIF for source distribution measurement
  - Adjust fueling scheme to homogenize axial source distribution

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Plan at UW Madison MAP device towards density profile qualification

- **Step 1: 08-11/2023:**
  - Have established pulsed RF mode (30 ms pulses) up to 10kW
  - Document density in MAP for one antenna up to 10kW
  - Stepwise increase of power and measurement of peak density
  - Document axial density profile in preferential forward direction with LIF and interferometer (as soon as available), option to add water cooling to antenna ready

- **Step 2: 12/2023-02/2024:**
  - Mount second antenna and operate up to at least 8kW per antenna in pulsed mode
  - Document axial density profile between antennas and optimize antenna distance w.r.t. density homogeneity

- **Step 3: 03-07/2024:**
  - Mount third antenna and operate up to at least 8kW per antenna in pulsed mode
  - Document axial density profile between antennas and optimize antenna distance w.r.t. density homogeneity
  - Option to replace vacuum vessel with smaller diameter tube to investigate impact on density performance versus larger diameter setup, to benchmark results of EPFL simulated parameter scan

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Summary

- UW Madison has developed diagnostics to measure the axial density features and contributed to identifying means to optimize RF setup towards high density homogeneity
- MAP is available as a versatile test bed with twice the length of the CERN HPS cell at (soon) comparable power density, a smaller diameter tube can be tested for the compact HPS setup
- A flexible COMSOL model was developed and will be validated against dedicated fluctuating magnetic field measurements, already available for extrapolation
- The physics findings have enabled to take more informed decisions about axial coupling of antennas and their impact on the density profile, further detailed measurements are planned and the MAP experimental plan is prioritized towards this goal
- The integration with the CERN HPS effort through the LIF diagnostic activity and modeling contributions can support the rapid decision making.