Characterization of the Mini-RFTF Hydrogen Helicon Source

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Outline

- Goals of the ORNL helicon program
- Description of the helicon source
- Review of previous results
- Recent developments

Goals for the light ion helicon source studies at ORNL

- **Compare damping mechanisms for regimes $\omega_{RF} \dot{} \omega_{LH}$, $\omega_{RF} \ddot{} \omega_{LH}$ (ω_{LH} = lower hybrid frequency)**
- **Investigate plasma production in the region of the lower hybrid frequency**
- **Upgrade the EMIR code for improved modeling of the helicon geometry**
- **Investigate antenna coupling and plasma production using a phased array**
- **Measure neutral density profiles**

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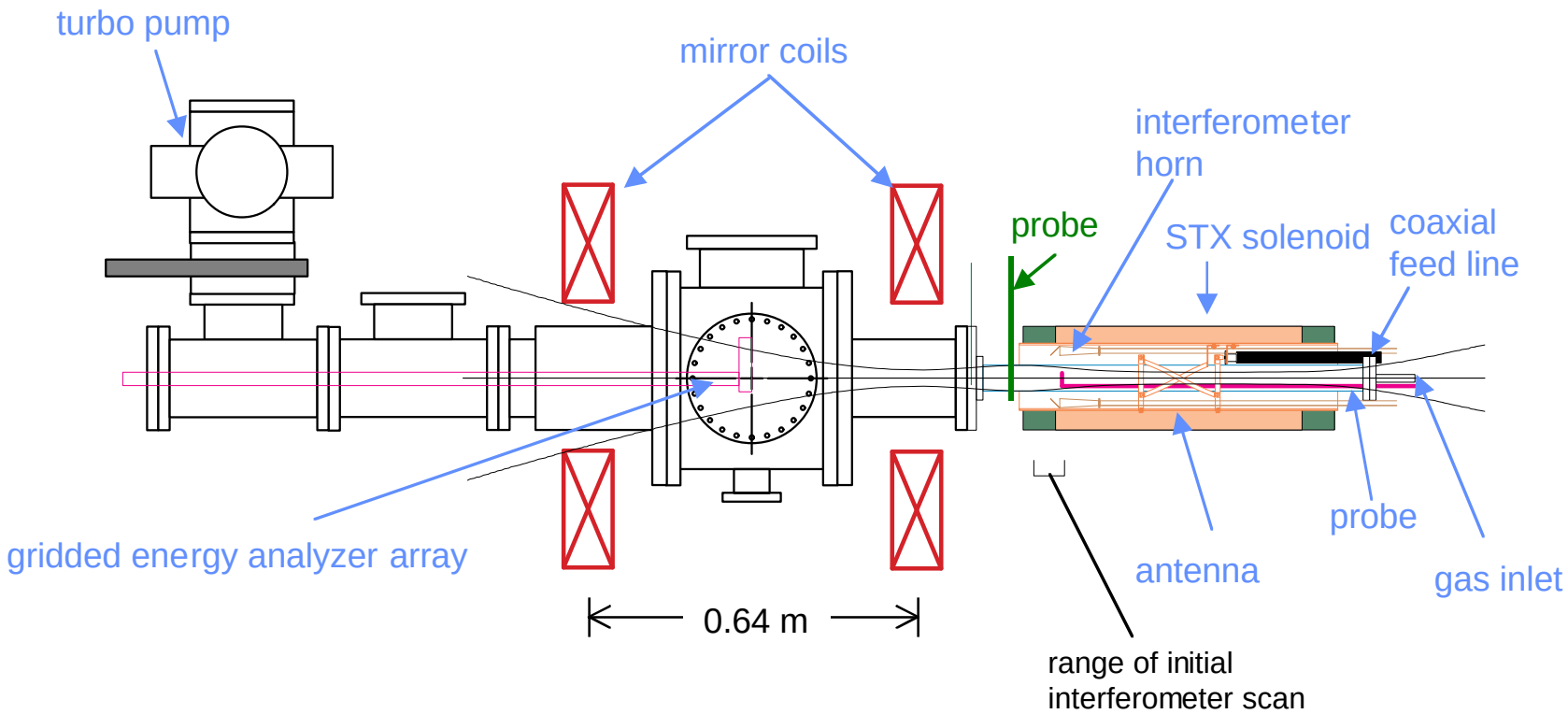
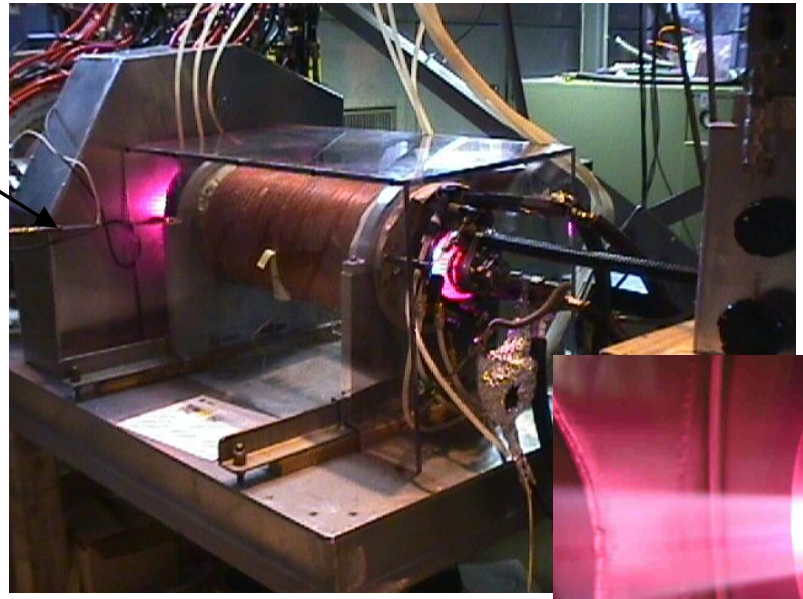
Mini-RFTF with STX solenoid

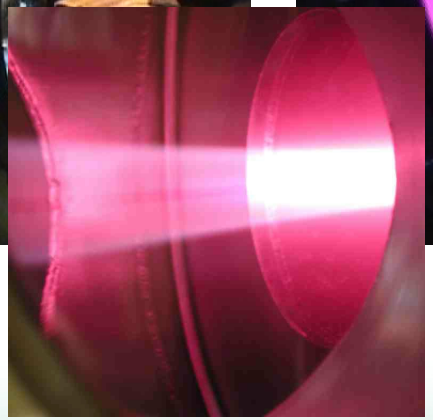


Hydrogen plasma operation

EXHAUST END VIEW

Langmuir probe





SIDE VIEW

Outline

- Goals of the ORNL helicon program
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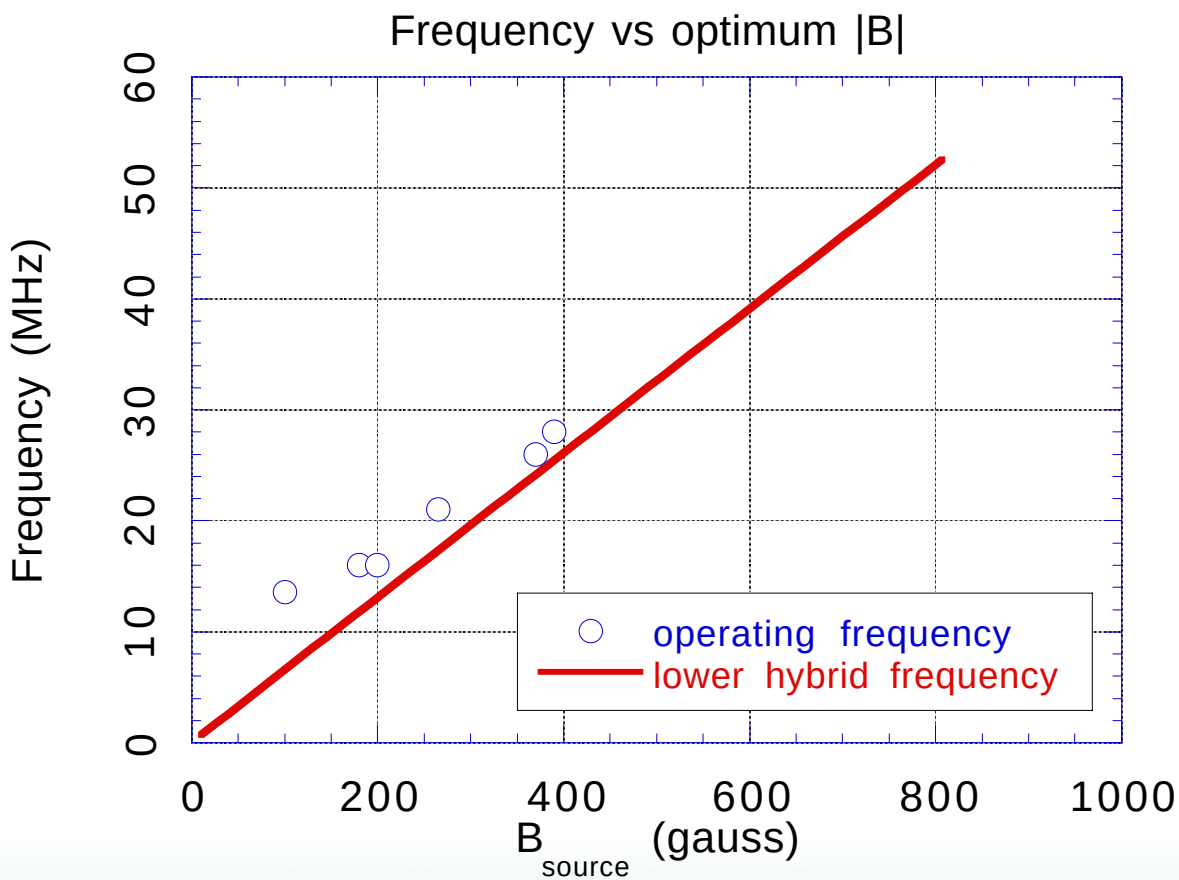
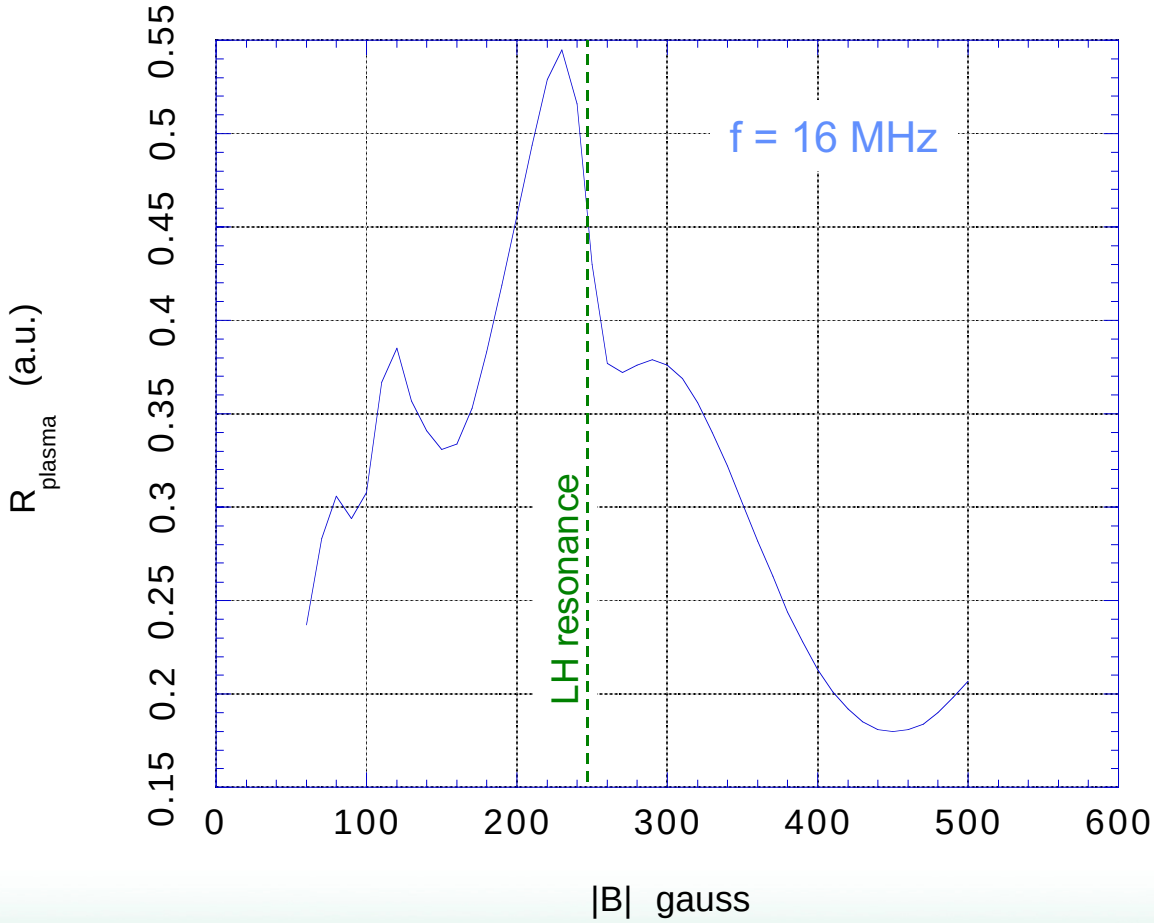
Recent results from the ORNL helicon source

- High density helium plasmas achieved at high |B|
  - n_i = 1.6 × 10^{19} m^{-3} produced with ω_{RF}/ω_{LH} = 0.25 (f =13.56 MHz) at 1300 W
  - also good results for $\omega_{RF} \ddagger \omega_{LH}$ (usual helicon regime)
- High density hydrogen plasmas
  - $n_i \ddagger 7 \times 10^{18}$ m^{-3} for 1300 W input power at 16 MHz
  - low field helicon mode - low source | B| with ω_{RF} slightly higher than ω_{LH}
  - downstream peak in |B| produced by mirror coil
- RF modeling gives qualitative agreement with results

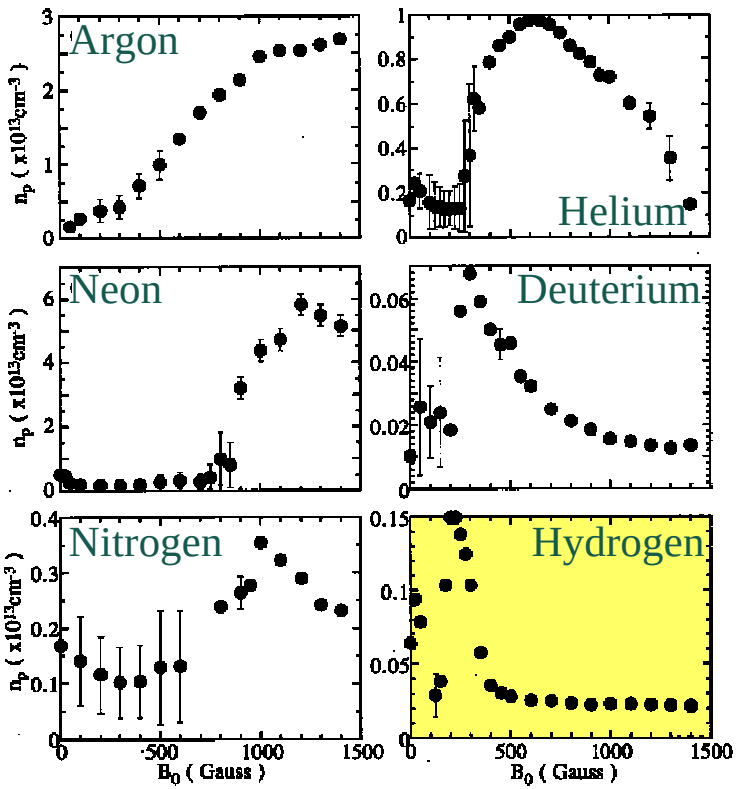
Ion densities above 10^{18} m^{-3} are only achieved with ω_{RF} slightly above ω_{LH}



The ANTENA code also indicates highest power absorption for |B| when $\omega_{RF} \approx \omega_{LH}$



This hydrogen behavior has also been seen by others (at lower peak density)



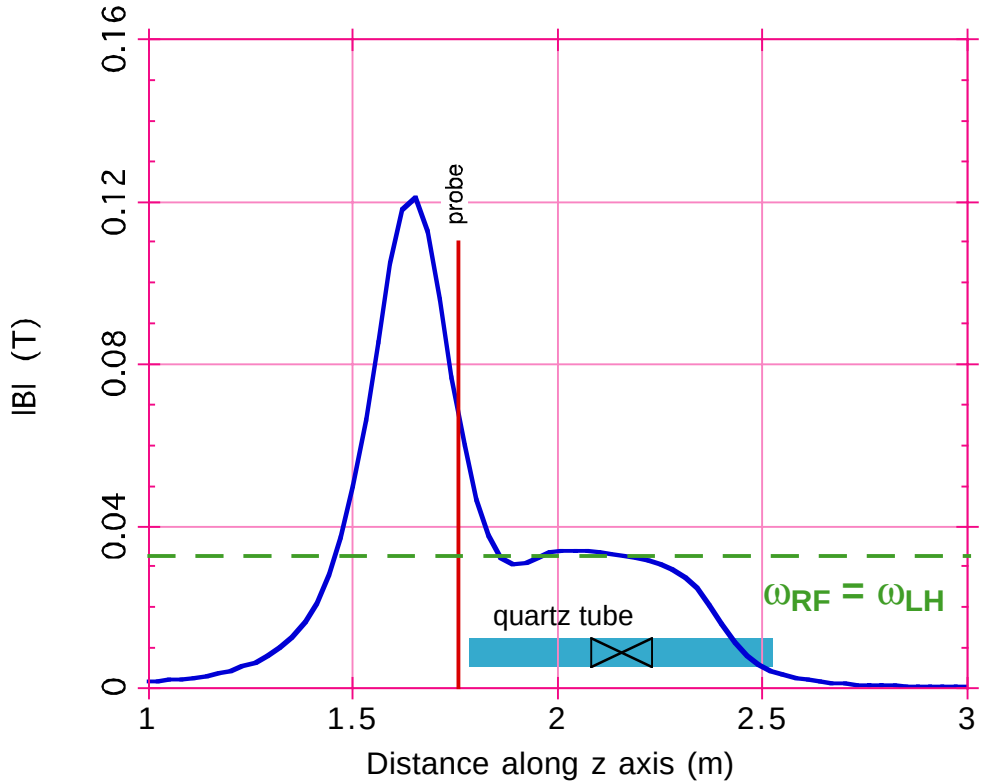
f = 13.56 MHz
P = 3 kW

- The density peak at the lower hybrid resonance weakens as the ion mass increases

Y. Sakawa, T. Takino, and T. Shoji, Phys. Plasmas **6**, Dec. 1999, p. 4759

Magnetic field strength profile for high density hydrogen operation has low |B| in source with downstream peak in |B|

- Example shown is for optimum operation at f = 21 MHz
- Low |B| in helicon source: $\omega / \omega_{LH} \sim 1$
- Peak in field downstream from source improves confinement



What is the damping mechanism in high density (‡ 10^{19} m^{-3}) helicon plasmas?

- **Theory:**
  - —**Landau damping produces non-Maxwellian electron distribution, but careful investigations have not seen this.**
  - —**Nonlinear damping mechanisms relying on spatially varying E require low collisionality.**
  - —**Collisional damping is much higher for short wavelength modes (TG modes for $\omega >> \omega_{LH}$) than long wavelength helicon modes, but these do not propagate for $\omega < \omega_{LH}$.**
- **Our experimental observations:**
  - —**For helium, high plasma density is achieved for a wide range of |B| values, $\omega << \omega_{LH}$, ω - ω_{LH}, and $\omega >> \omega_{LH}$.**
  - —**Sharply peaked profiles suggest efficient central power deposition.**
- **Conclusion:**
  - —**Collisional damping of helicon wave can be effective. This may require high neutral pressure.**

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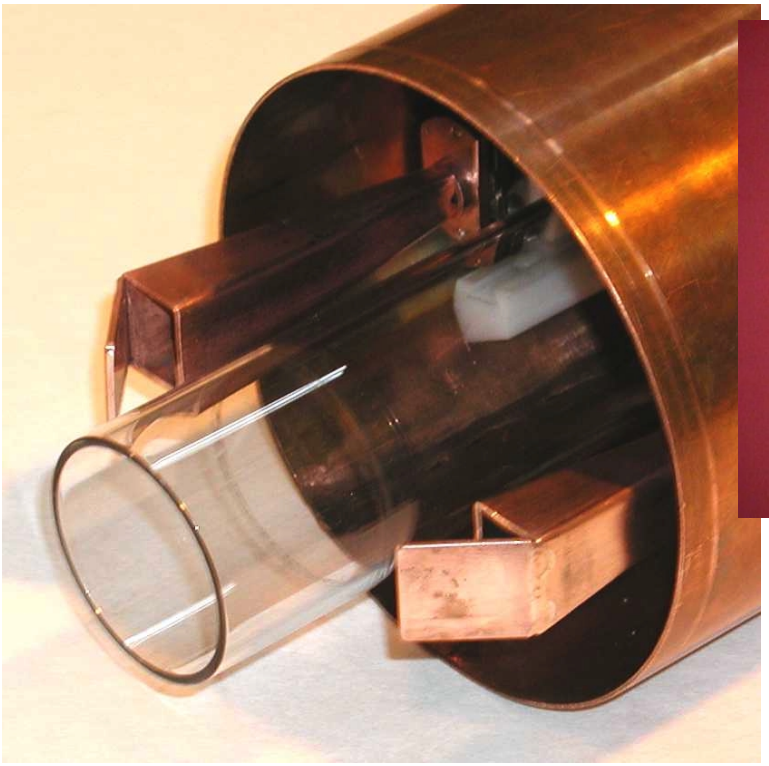
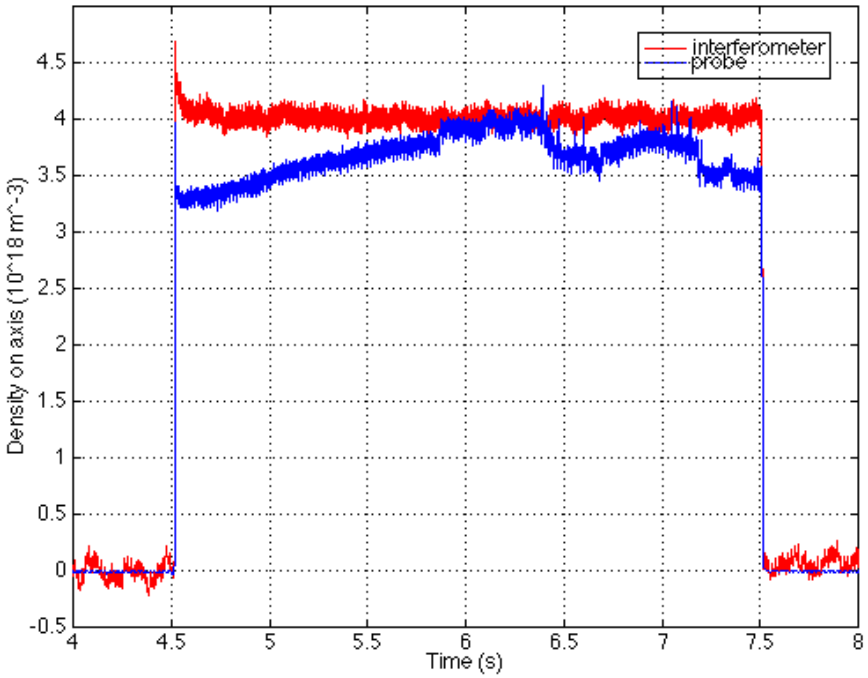
Closeup view of the axially scannable interferometer horns and gridded energy analyzer array



Good agreement is obtained between interferometer and Langmuir probe data

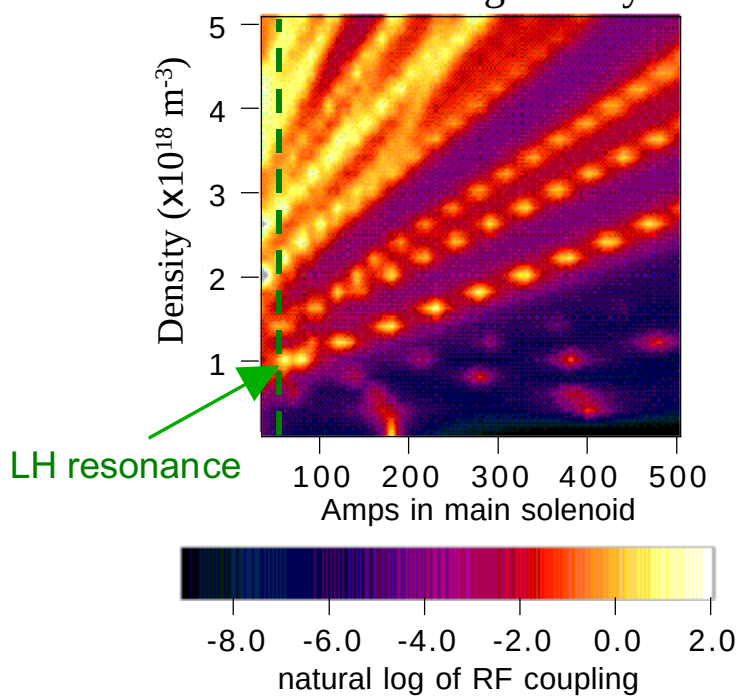
- Hydrogen plasma produced by 1.8 kW at 21 MHz
- A triangular density profile is assumed for the interferometer data
- An electron temperature of 6 eV is assumed for the Langmuir probe analysis



Magnetic field scans at fixed frequency show the difficulty of high field operation

- EMIR code calculations for hydrogen plasma at 13 MHz
- Large variations in antenna coupling are caused by changes in density and |B|
  - Density is proportional to input power, but very nonlinear
  - Circuit must tolerate large mismatch during transients to final operating point
  - Coupling is independent of density only at low |B| (approaching the lower hybrid resonance)

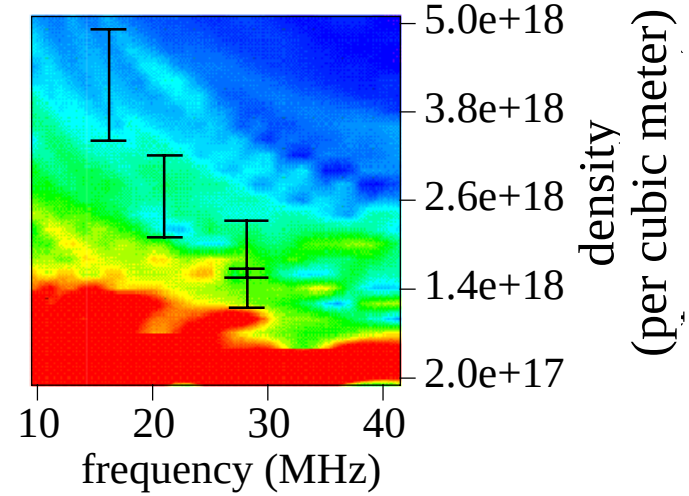
13 MHz launch into H plasma for Mini-RFTF geometry

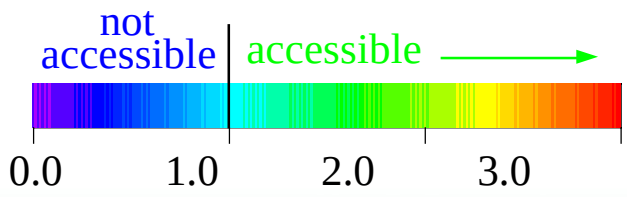


Downstream leakage may be an issue in Mini-RFTF

- **Power balance of absorption upstream of 0.5 m with antenna Joule losses and downstream leakage**
  - **Electrons downstream of 0.5 m are impeded by an increasing magnetic field**
  - **There is very little neutral gas downstream of 0.5 m, so no ionization occurs**
  - **Upstream, most field lines terminate on the quartz tube**

Downstream helical launch with coils adjusted to maintain constant f/B





Additional work in the near term

- Optimize gas utilization efficiency and plasma production efficiency
- Optimize propellant injection through use of diffuser plates, gas plenums, etc.
- Determine the effect of insulating and conducting boundaries
- Investigate performance with various antenna geometries, especially phased dual half-turn configuration
- Compare operation with hydrogen and deuterium
- Examine the importance of slow waves to efficient helicon operation by measuring wave damping lengths, varying neutral density, etc.

Summary

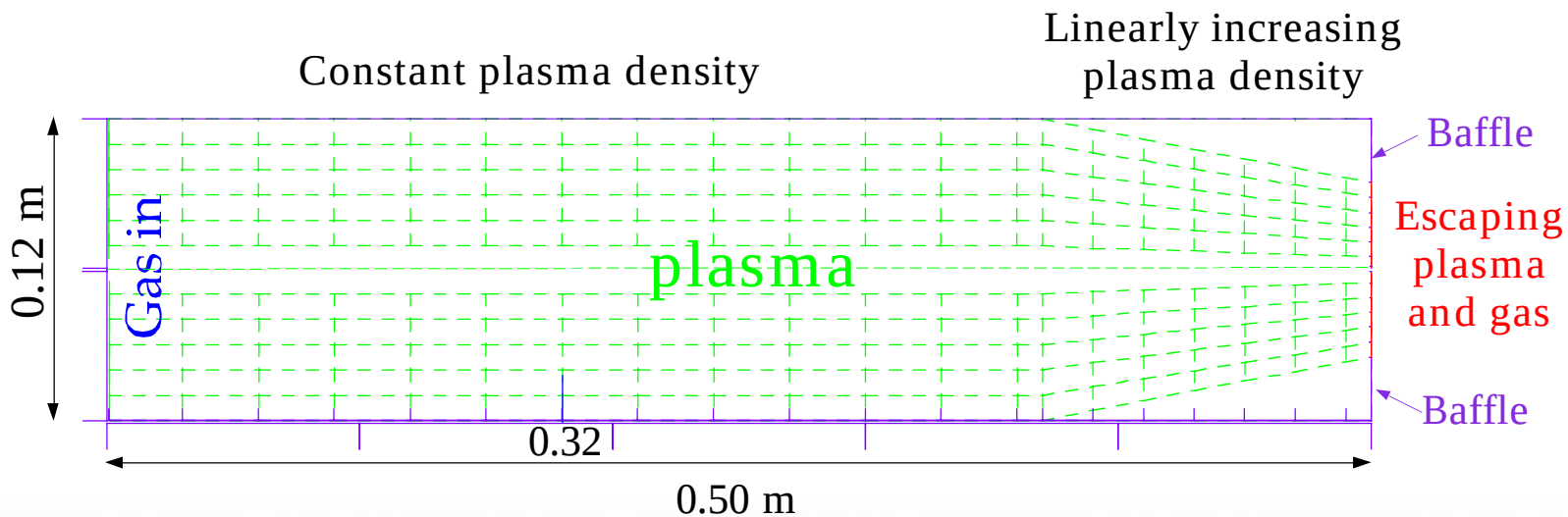
- High densities in the 10^{19} m^{-3} range have been achieved for both hydrogen and helium plasmas in the ORNL Mini-RFTF helicon source
- From source |B| scans, there is a peak in density seen for source operation with $\omega_{RF} - \omega_{LH}$
- In the case of helium, high density operation has also been demonstrated for high |B| with $\omega_{RF} = 0.25\ \omega_{LH}$ at the midplane of the source, and for low |B| with $\omega_{RF} > \omega_{LH}$
- Similar behavior is predicted by the ANTENA code
- There is a decline in density with frequency observed experimentally, even though f/B is held constant. This behavior is reproduced qualitatively by the EMIR code

Abstract

Helicon plasma sources typically use radio frequency waves in the 1 to 50 MHz range and can produce high plasma densities with high ionization efficiency. However, their operation depends sensitively on the magnetic field geometry and strength, as well as the driving frequency, especially when light diatomic gases are used. The helicon source on Mini-RFTF at ORNL has been operated with both hydrogen and helium gas fill. The primary emphasis at the present is on hydrogen operation as the plasma source for a VASIMR engine. Diagnostics include a microwave interferometer, Langmuir probes, and a gridded energy analyzer. Results of hydrogen operation with a helical antenna at frequencies below and above the lower hybrid frequency will be presented and compared with theoretical predictions using the EMIR code, which allows for axial as well as radial variations in the plasma parameters. Experimental observations indicate that axial variations can strongly influence the operational range of the helicon, and the behavior is further complicated by non-linear power coupling to cavity modes that also depend on axial variations in the system.

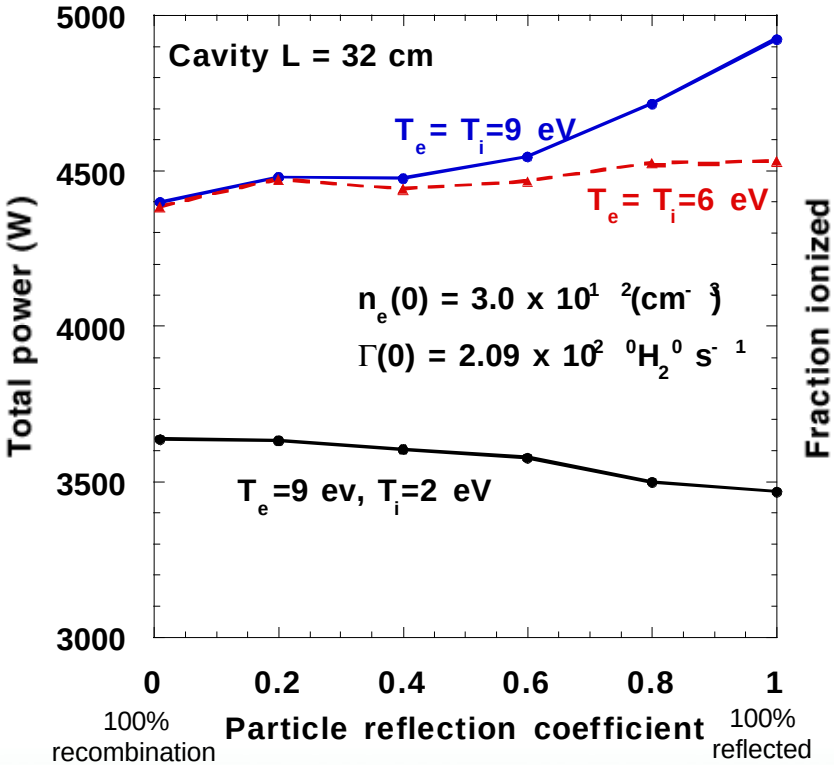
DEGAS RTD-like geometry

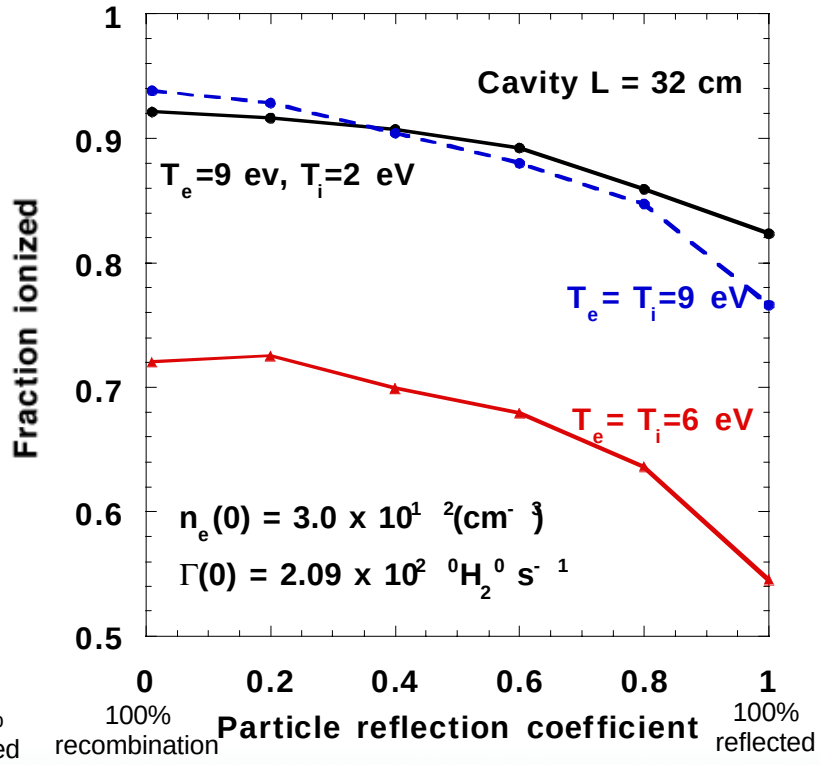
- **Plasma parameters specified**
  - —Parabolic radial profile
  - —Constant density axially up to magnetic choke
  - —Linearly increasing density ∝ |B| in magnetic choke



DEGAS modeling of RTD-like geometry is very encouraging

- >90% stream ionization with ~4KW RF possible
- Surface recombination better than H reflection





Future modeling possibilities

- Model experiments at ASPL, ORNL
  - —Set up appropriate geometries
  - —Build database for Helium
- Improve surface properties database for H
  - —May require experiments for RF appropriate materials
- Geometry optimization for VX- 10 and VF- 10
  - —Tube length and baffle requirements
  - —Ionization and power efficiencies
- Integrated plasma model
  - —Consistent RF power deposition
  - —Consistent electrostatic potential, density, Ti, and Te