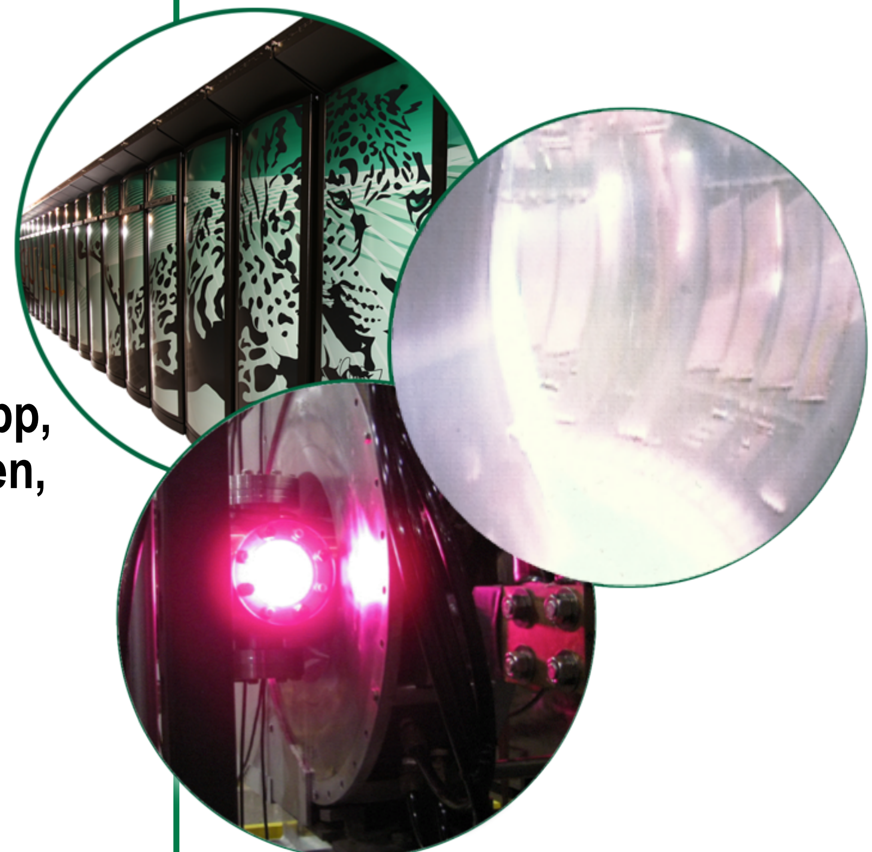
The ORNL High-Flux Helicon Source and PhIX



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VLT Conference Call

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U.S. DEPARTMENT OF ENERGY

Fusion Energy Division
OAK RIDGE NATIONAL LABORATORY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Outline

- Introduction
- The Physics Integration eXperiment (PhIX) – a step towards an RF-based Plasma-Material Test Station (PMTS)
- The ORNL High Flux Helicon Plasma Generator
  - Design
  - Full power and long pulse operation with He
  - Operation with D
- Conclusions and Future Work

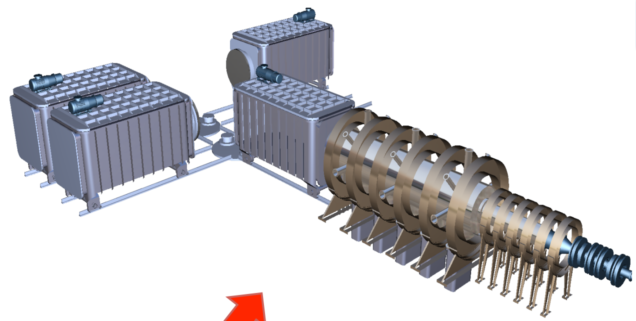
Introduction

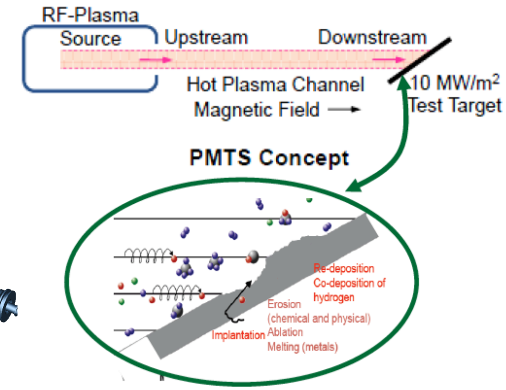
- Linear plasma facilities are a valuable adjunct to tokamaks for the study of Plasma Materials Interface (PMI) phenomena of interest for ITER and DEMO
- Advantages include
  - Cost effectiveness
  - Easy access for diagnostics and samples
  - Well controlled plasma parameters – ability to focus on specific mechanisms and processes
  - Long pulse and high temperature issues can be addressed in the near term
  - Possibility for testing materials not easily handled in most tokamaks (e.g., Be, materials with neutron damage)
- Ultimate goal: develop PMI linear facility based on a high performance, flexible rf plasma source
  - Electrodeless
    - lack of internal metallic electrodes minimizes contamination of samples by impurities
  - Low maintenance, intrinsically CW
  - Combination of helicon plasma generator with additional EC and IC heating provides wide range of possible source parameters, with light ion (H, D, He) plasmas, without biasing
    - $n_e = 0.1 – 3 \times 10^{19}\ m^{-3}$
    - $T_e = 3 – 50$ eV
    - $T_i = 1 – 200$ eV
  - Low power and pumping requirements ($P_{rf} \leq 0.5$ MW, ≥ 50% ionization efficiency)

Introduction (cont.)

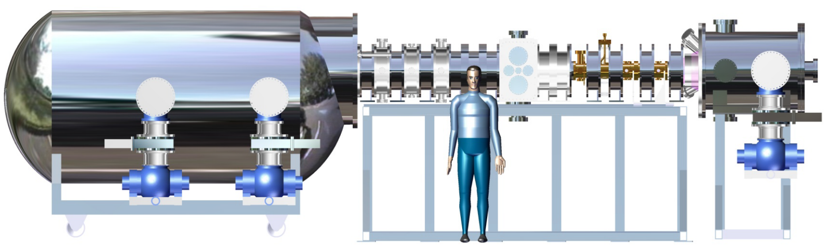
- As one step in development, a high power (100 kW), large plasma diameter (12cm), high field (0.7 T mirror) helicon plasma generator has been tested.
- Record power density helicon plasma (for pulse length > 1 ms): 100 kW, volume ~ 10^4 cm^3 = 10 MW/m^3 achieved – and with antenna outside vacuum to minimize impurities
- Record densities for low-Z ions: 6 X 10^{19} m^{-3} (He), 4.5 X10^{19} m^{-3} (D) to-date. Broad profiles observed, and high densities also seen beyond mirror
- Reached stationary state for RF-plasma-fueling-wall recycling system in 80 ms pulses (limited to prevent Langmuir probe self-emission and damage)
- Inertially cooled system has been operated up to 20 s at reduced power

Development stages for a Linear RF-Based PMTS



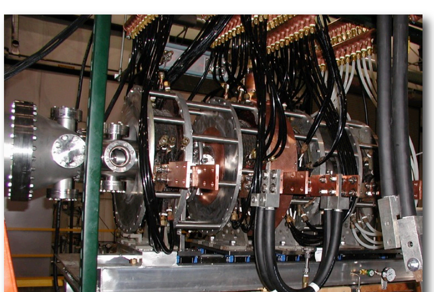


- **Linear RF-Based PMTS**
  - Steady state operation
  - Heat flux up to 20 MW/m^2 (note: perpendicular)
  - Particle flux ≥ $10^{23}/(m^2\text{-}s)$
  - 10 cm diameter target region
  - $|B|$ = 1 T at target



- **PHISX (Prototype High Intensity Source eXperiment)**
  - Short pulse prototype high intensity rf-based plasma source
  - 100 kW helicon power + 100 kW ECH + 30 – 200 kW ICH
  - Plasma transport region separates source from target
  - Incorporates tungsten targets and baffles, SS expansion chamber (collaboration with ASIPP)

- **Helicon rf plasma generator**



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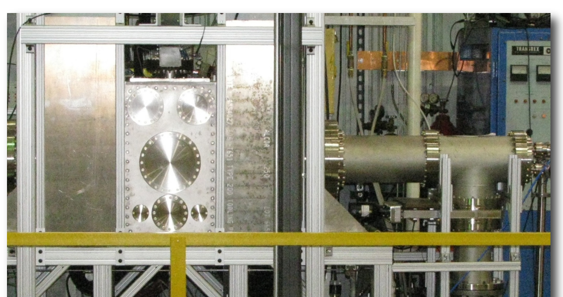
- **Linear ECH/EBW test stand**



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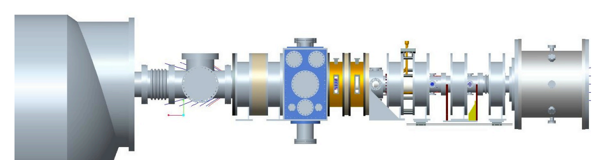
- **PhIX (Physics Integration eXperiment**



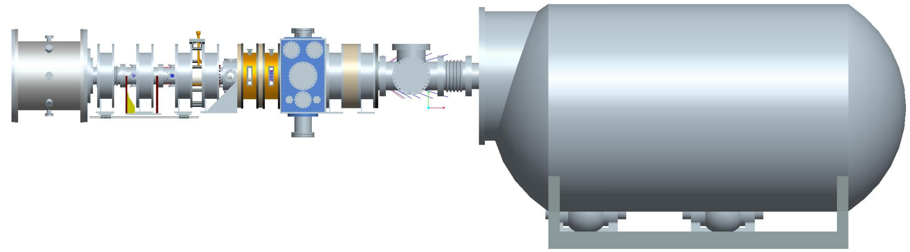
- Under construction
- Internally funded (ORNL LDRD)

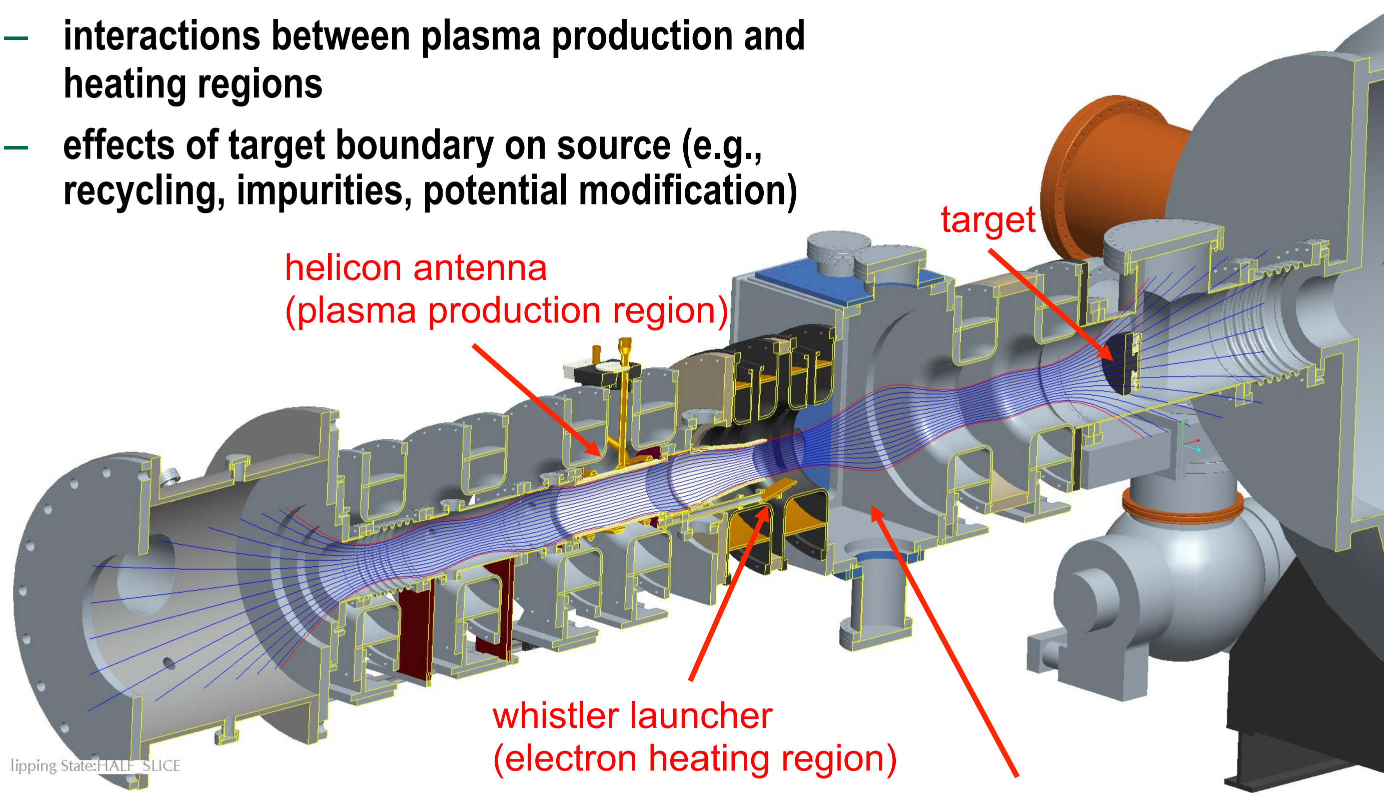
Whistler / EBW and Helicon Experiments

Whistler / EBW **Helicon**

PhIX (Physics Integration eXperiment)

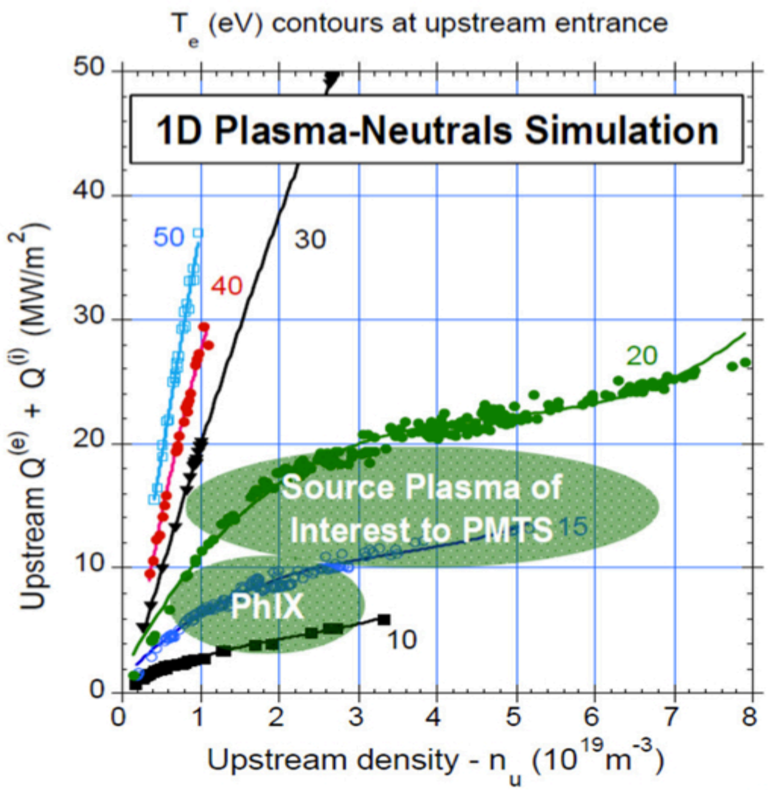
- Investigation of production (rf-helicon) and heating of an overdense plasma by whistler and electron Bernstein waves (EBW), including:
  - ionization cost, gas utilization efficiency
  - electron heating efficiency
  - interactions between plasma production and heating regions
  - effects of target boundary on source (e.g., recycling, impurities, potential modification)





Required parameters for PhIX based on ECH requirements, 1-D simulation

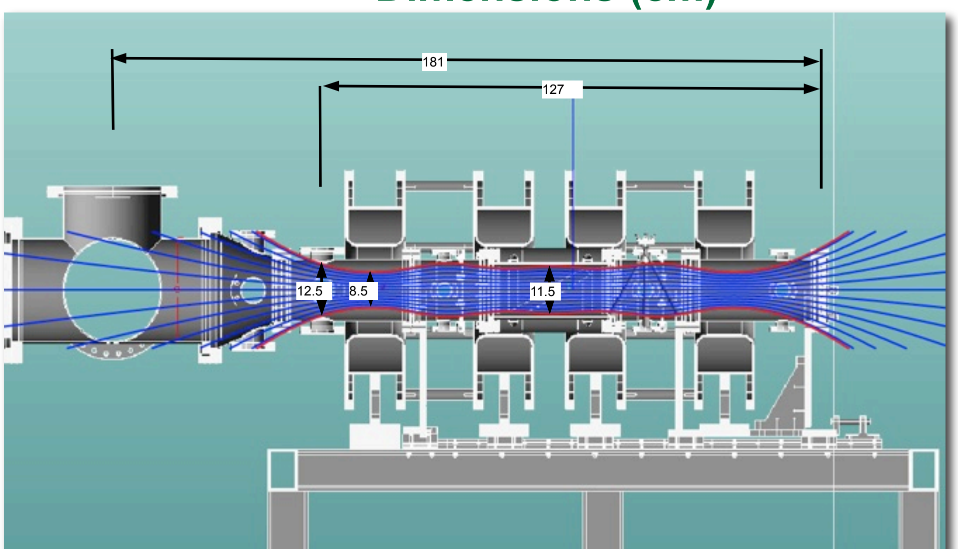
- Maximum |B| in PhIX ~ 0.9 T
  - Allows whistler/EBW heating with available microwave sources at 15 and 18 GHz
- Source outlet density target for PhIX in range 1 - 3 X 10^{19} m^{-3} - well within overdense regime for heating at $\omega = \omega_{ce}$
- Helicon operation must be compatible with these requirement for high |B| and high n_e

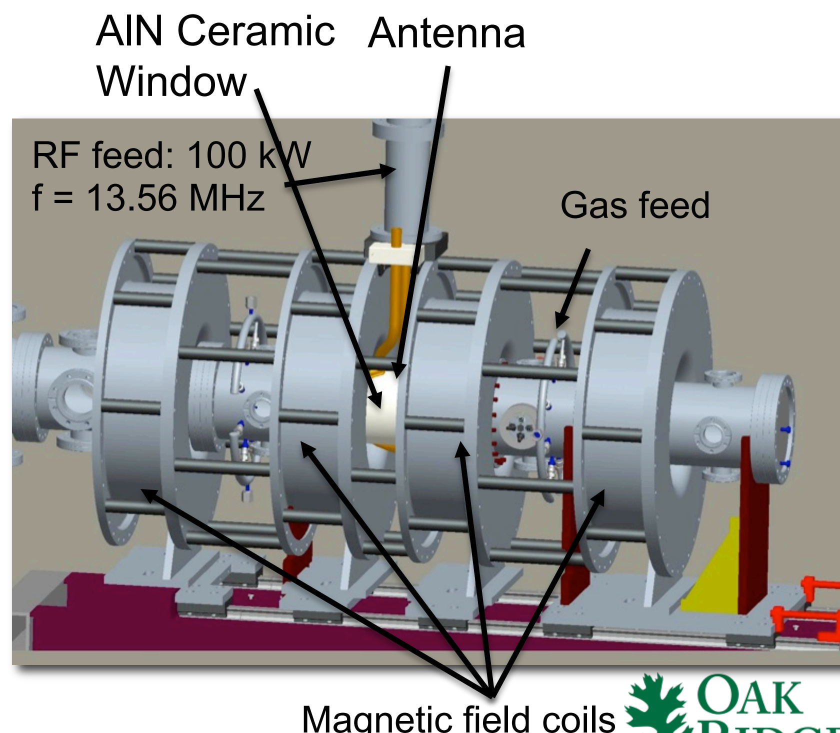


Goals for helicon plasma generator

- Operate with $|B_{max}|$ compatible with ECH (> 0.64 T)
- Plasma densities in the range 1 - 6 X 10^{19} / m^3

Dimensions (cm)





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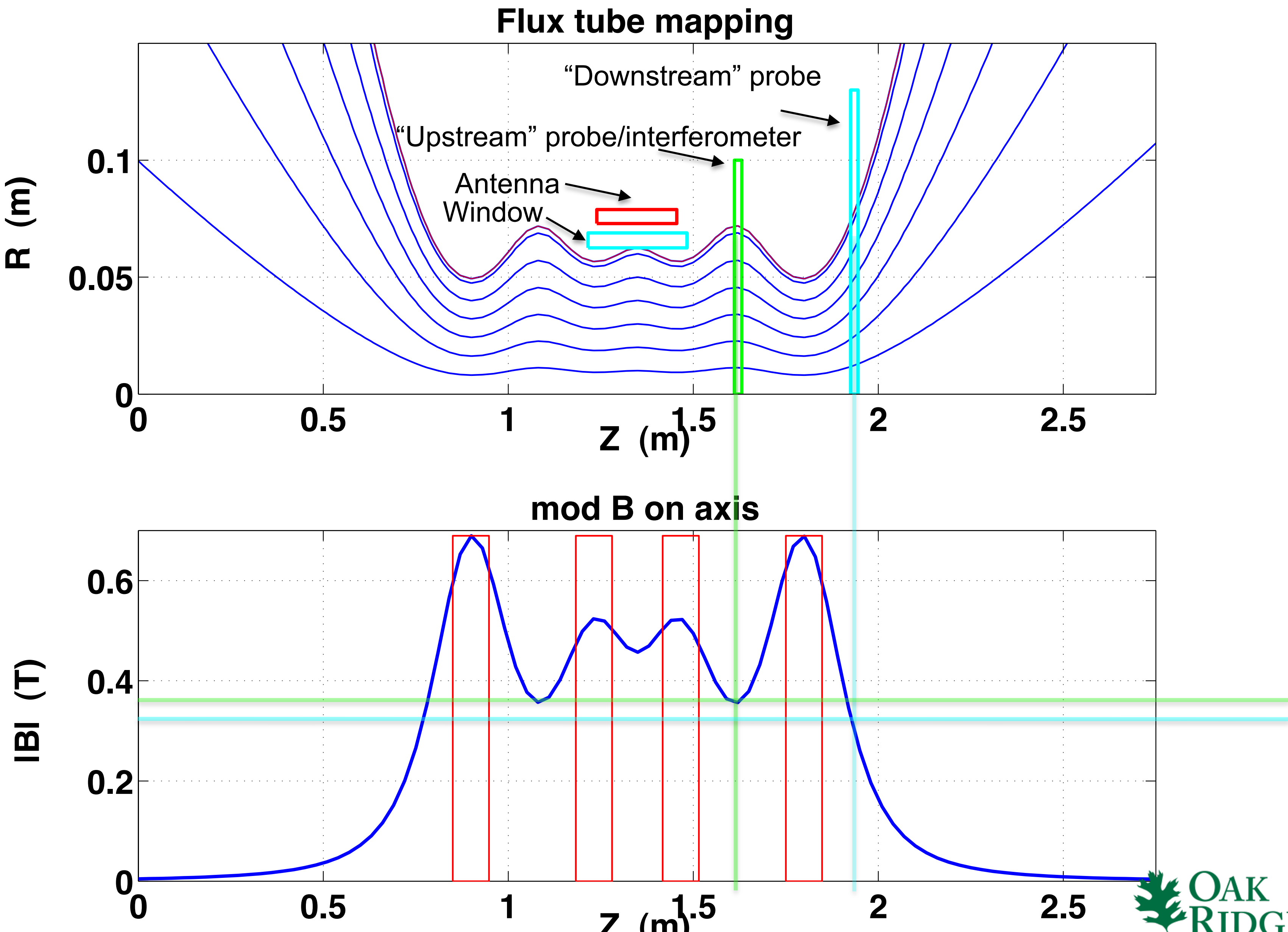
Magnetic field profile for highest |B| operation



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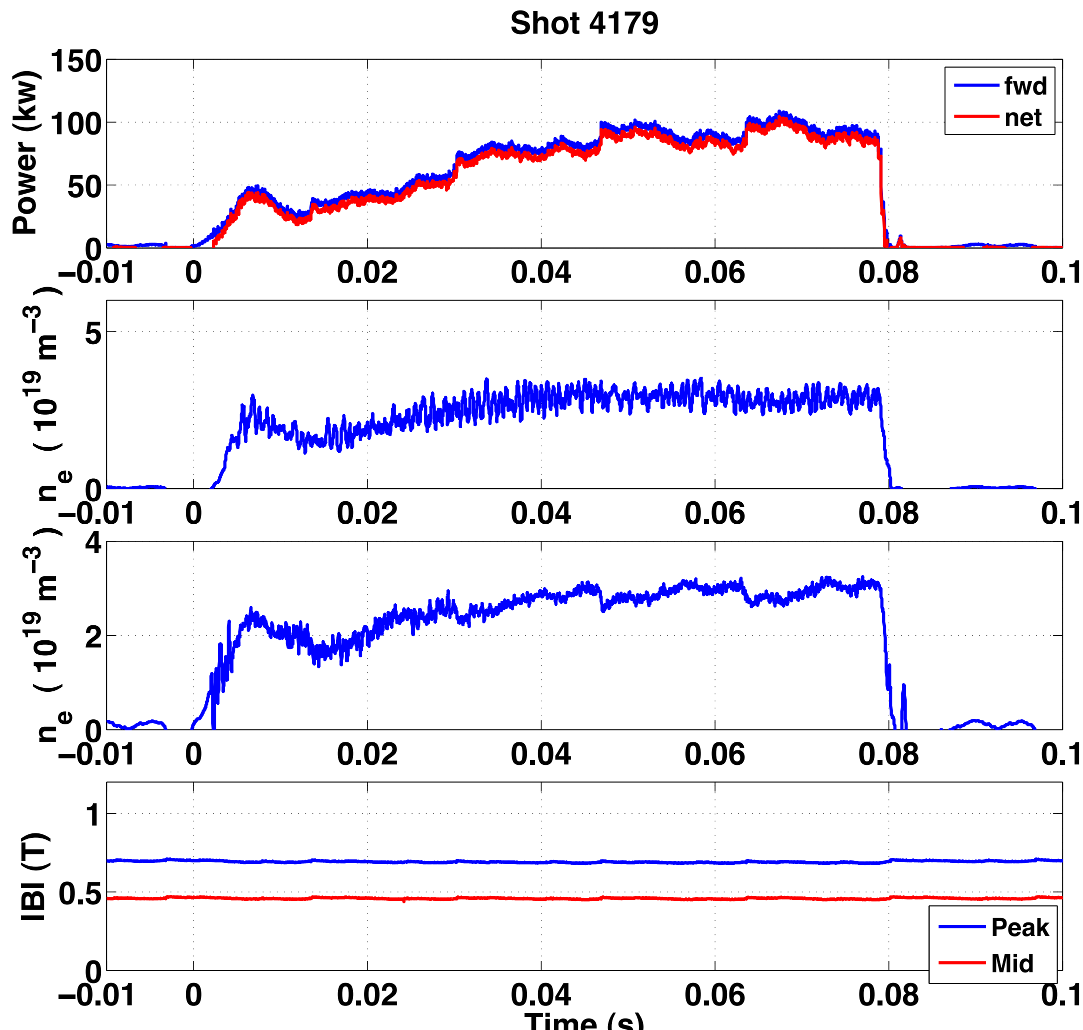
Results of Helium Operation

- Reliable 100 kW operation achieved with upstream density up to ~ 6 X 10^{19} m^{-3}, downstream density > 3 X 10^{19} m^{-3}
- Reliable operation at 0.7 T at mirror peak, 0.5 T at antenna, at 100 kW
- Could operate at higher peak field with upgraded power supplies
- Magnetic field scaling data obtained at ~ 100 kW power

Highest |B| case

- Mirror ratio ~ 1.3, He gas, prefill pressure 20 – 50 mtorr



Power

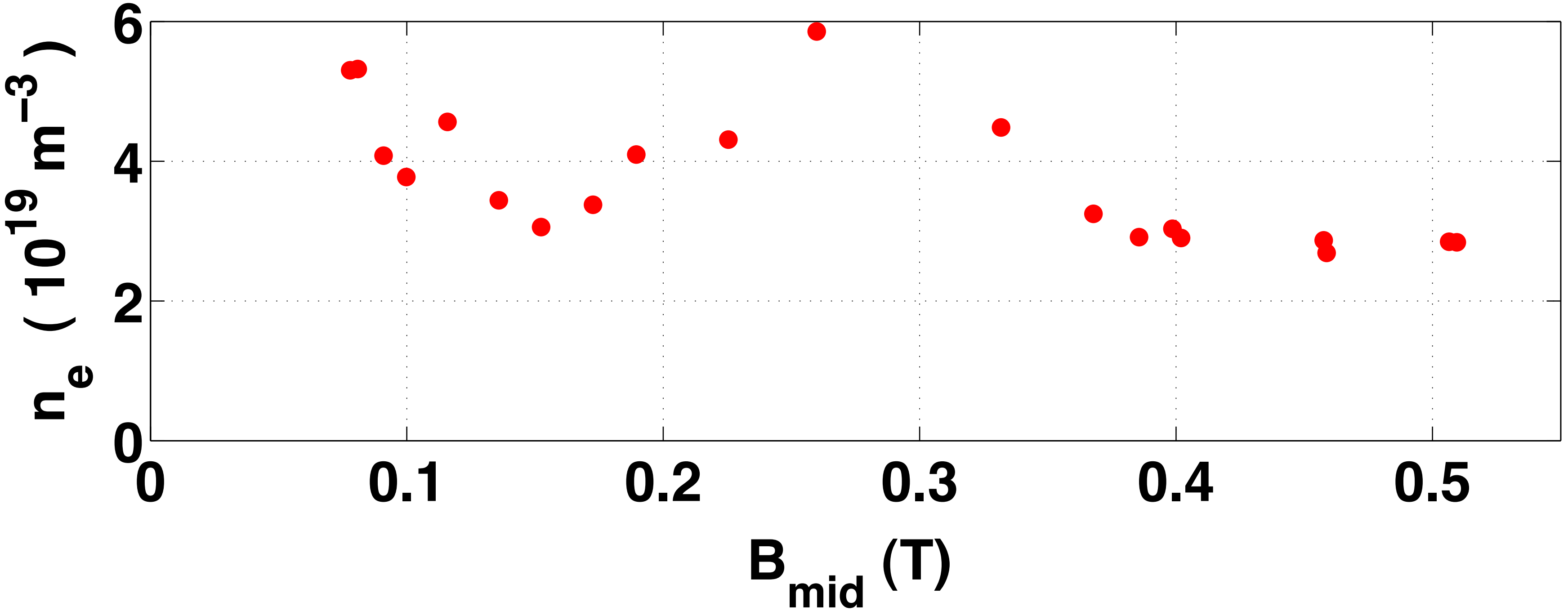
n_e (upstream)
(radius = 2 cm)

n_e (downstream)
(radius = 2 cm)

||B| at mirror peak
and antenna

High density is achieved over a wide range of |B| at the antenna

- For data shown, current on outer magnets held at highest value possible, current on inner magnets is varied
- Input power ~ 100 kW, He gas



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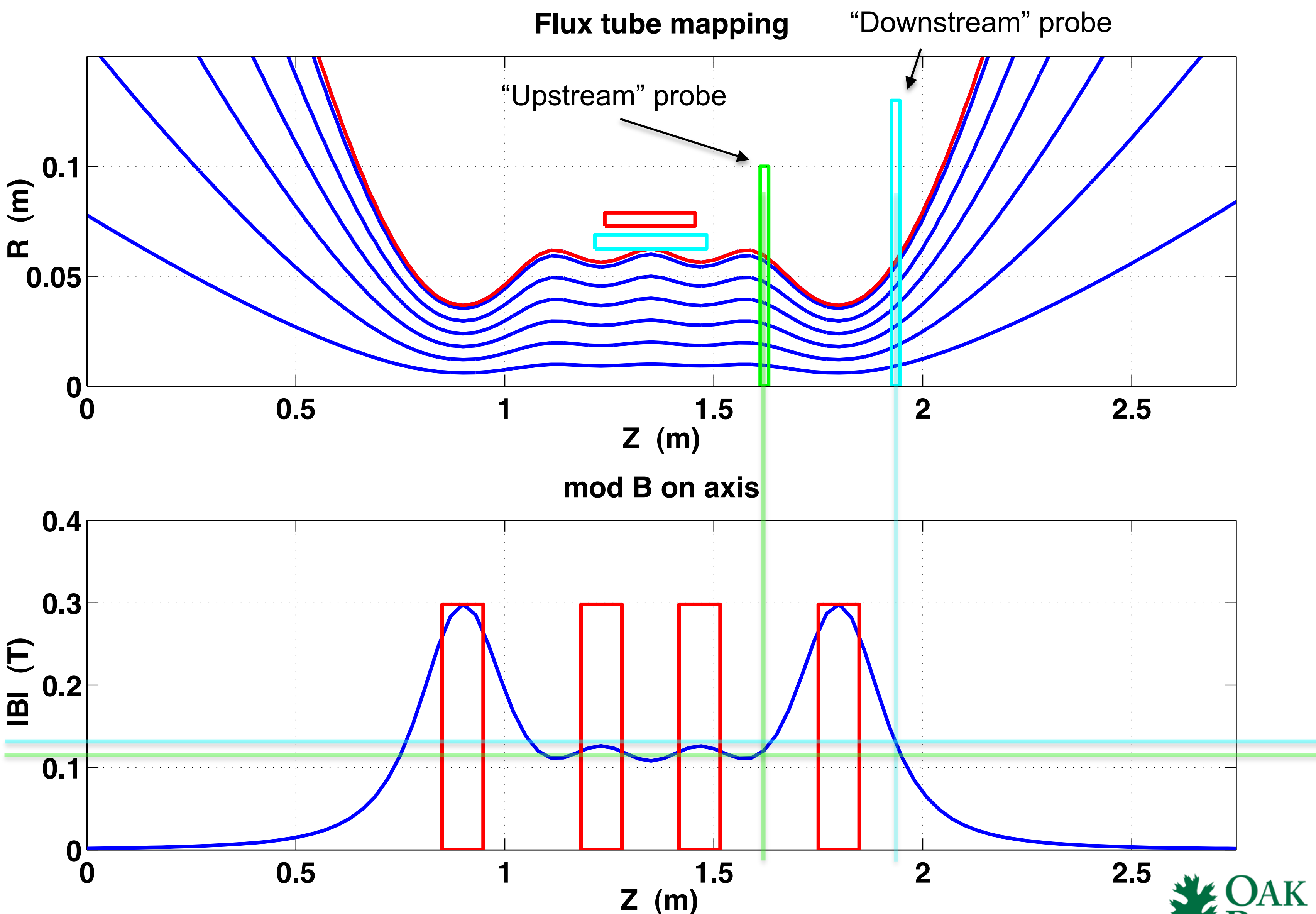
Deuterium operation

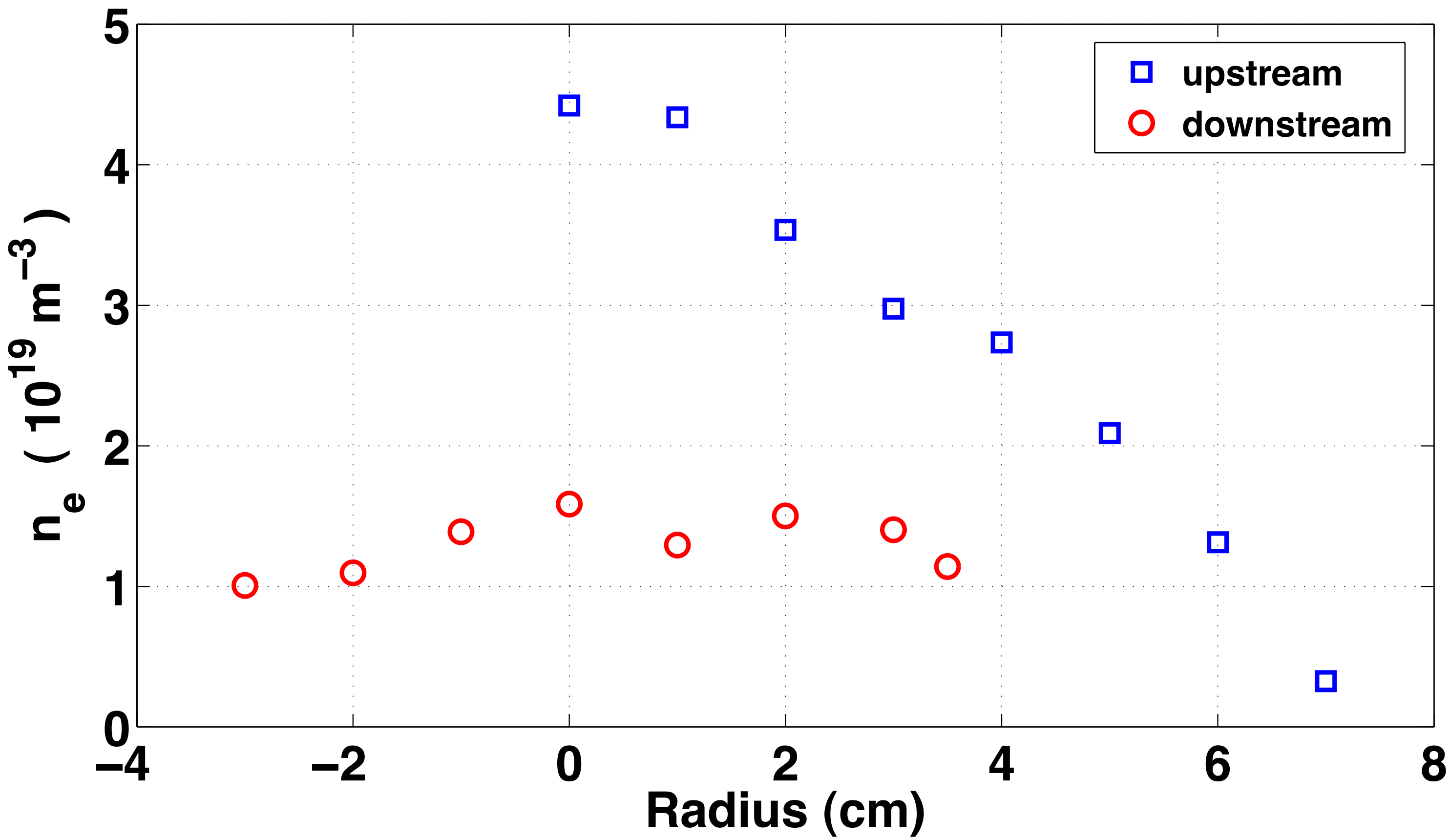
- $n_e > 4 \times 10^{19}$ m^{-3} achieved with $|B|$ at antenna ~ 0.12 T, B_{max} = 0.3 T, rf power = 70 kW
- Stable match achieved
- Loading appears adequate, better than for He

|B| profile for D operation



C1 = 1800 amps C2 = 530 amps C3 = 530 amps C4 = 1800 amps

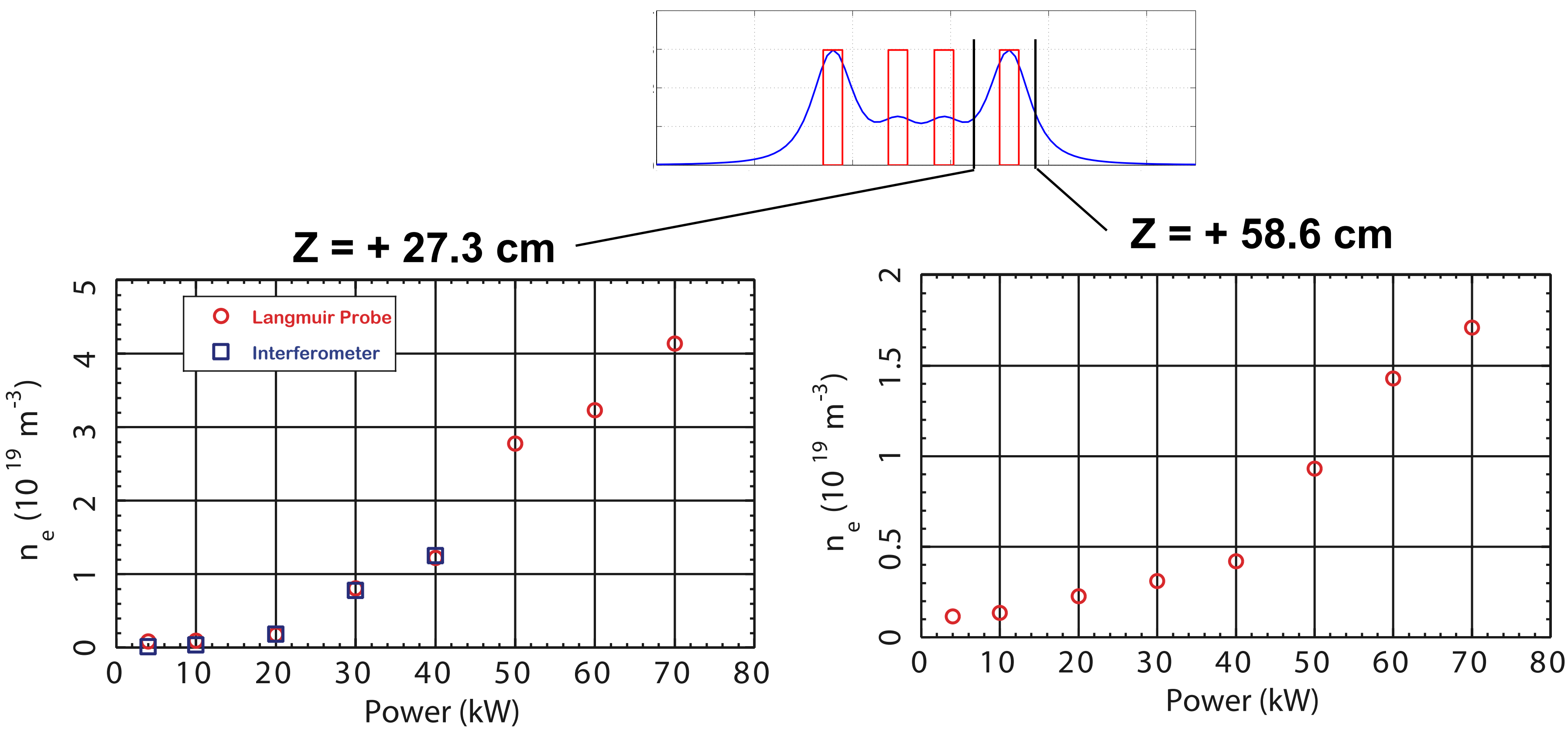
Upstream and downstream radial profiles from ion saturation current



Power = 70 kW, D gas flow = 1200 sccm

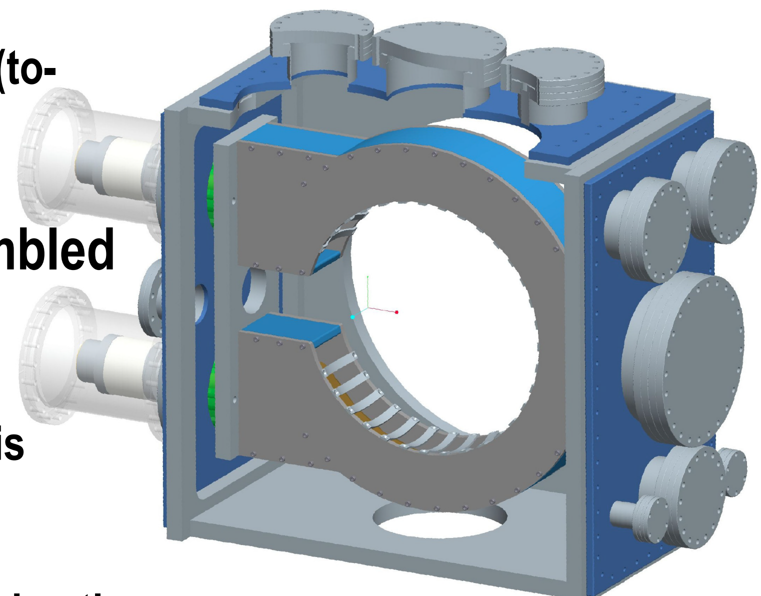
D plasma density scaling with power

- Suggests that higher density achievable at higher power



Conclusions / Future work

- Routine operation has been demonstrated at highest achievable |B| and available power (100 kW) with He gas
  - Upstream n_e up to 6 X 10^{19} m^{-3}
  - Downstream n_e to 3 X 10^{19} m^{-3}
  - T_e in range 4 – 10 eV (measured with rf compensated probe)
- Operation at power levels to 70 kW have routinely been demonstrated with D
  - Lower |B| than with He: $|B_{max}|$ = 0.3 T, $|B_{mid}|$ = 0.12 T (to-date)
  - n_e > 4 X 10^{19} m^{-3}
- Helicon and ECH Experiments will be disassembled and combined into PhIX
  - Operation expected to resume in August 2012
  - Modeling with SOLPS, GENRAY, and EMS-2D codes is underway for development of optimized operating scenarios
  - Will also be used as a testbed for investigation of rf sheath interactions and fields in front of antenna

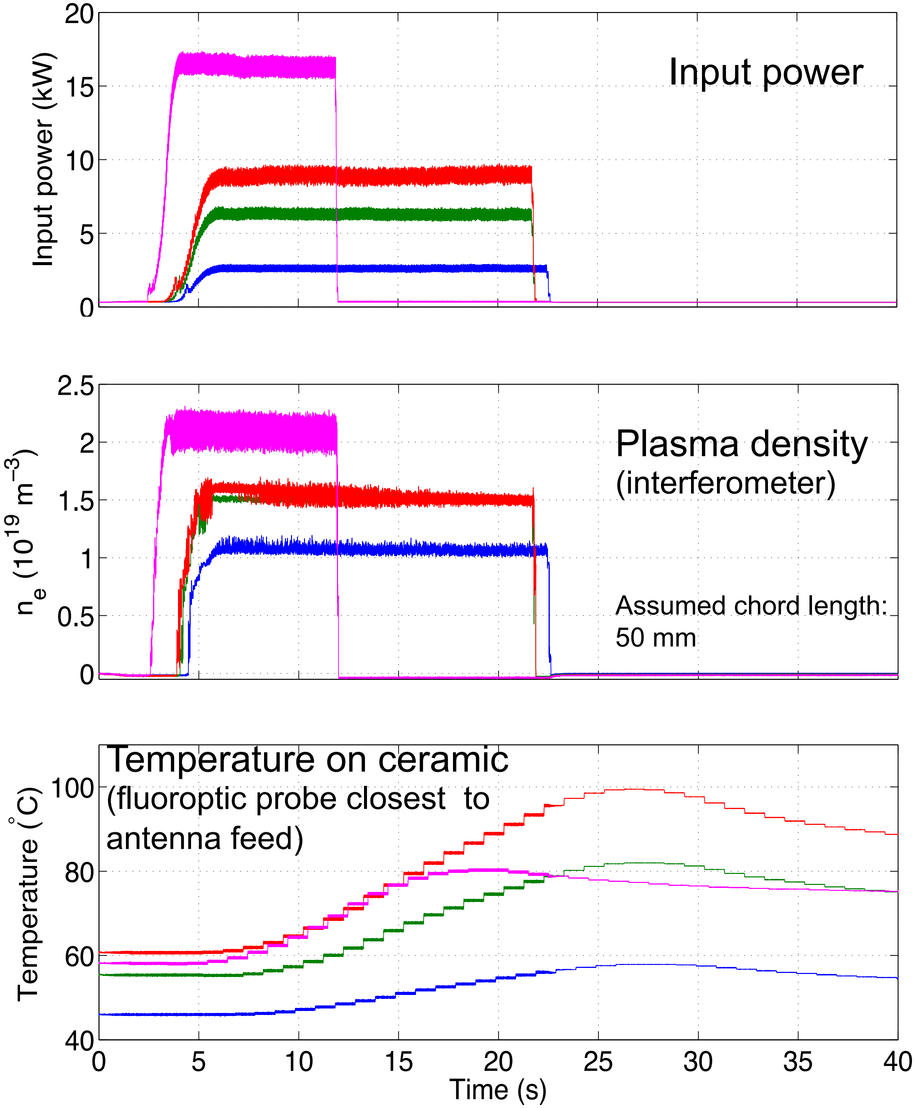


ICH test antenna for PhIX

Backup

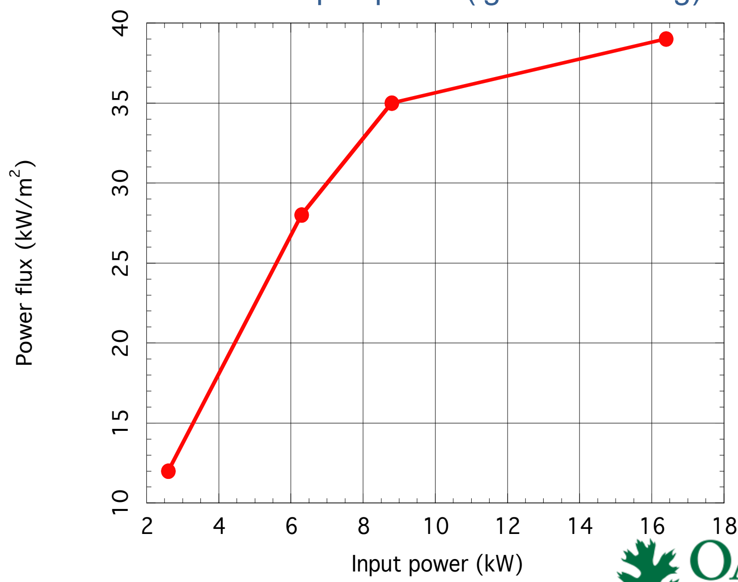
Long pulses achieved, plasma density and rate of temperature rise on ceramic for varying input power levels determined (power limited due to lack of cooling)

- **Measured directly with Fluoroptic™ probes in contact with ceramic**



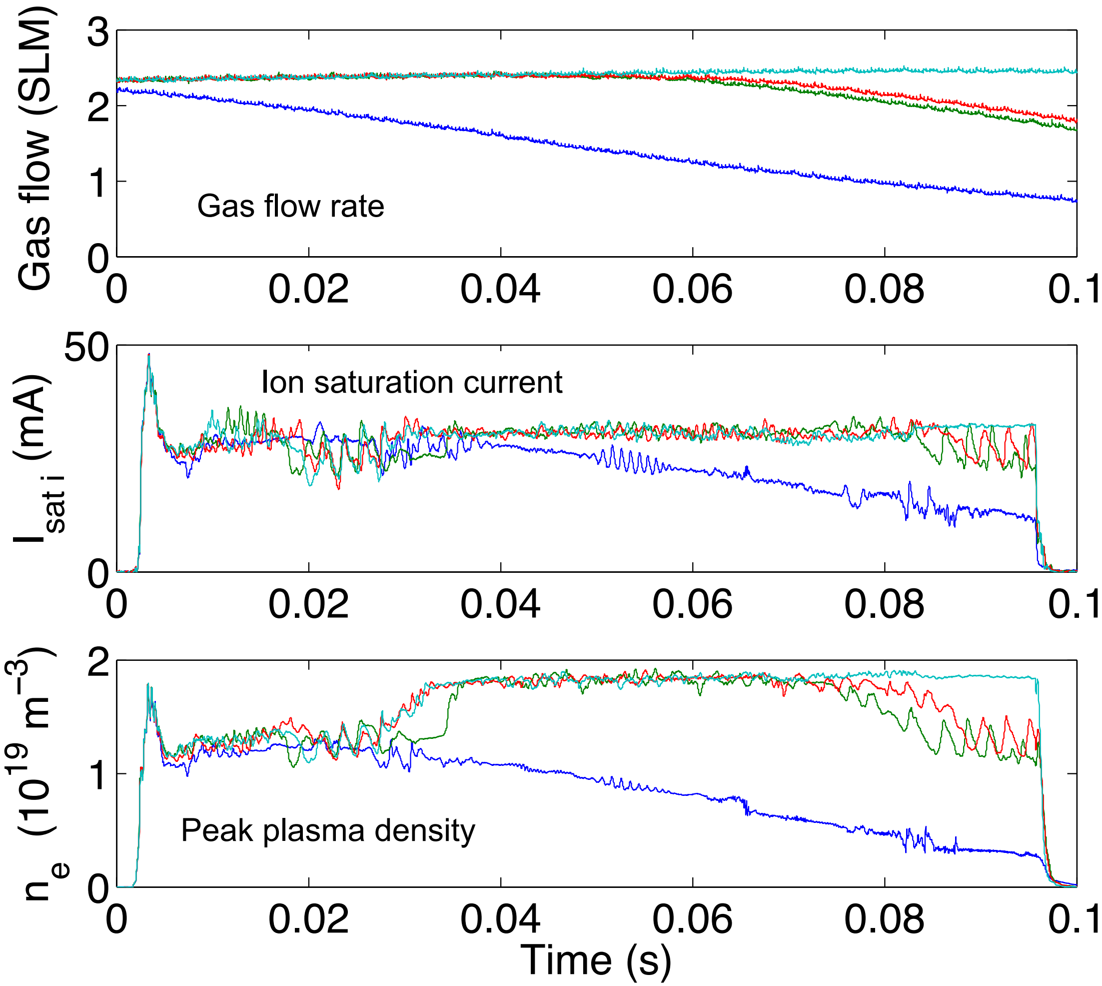
- **Experimental conditions:**
  - **Gas: He**
  - **Gas flow: 110 sccm**
  - **B at antenna: ~ 0.1 T**
  - **Mirror ratio: ~ 2**

Local heat flux from rate of temperature rise on fluoroptic probe (ignores cooling)

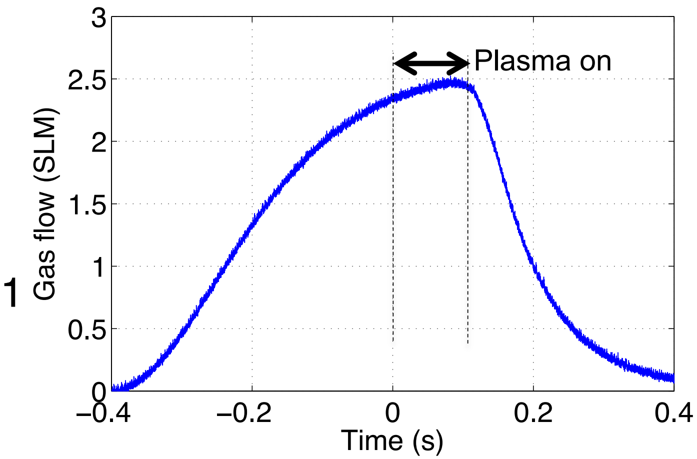


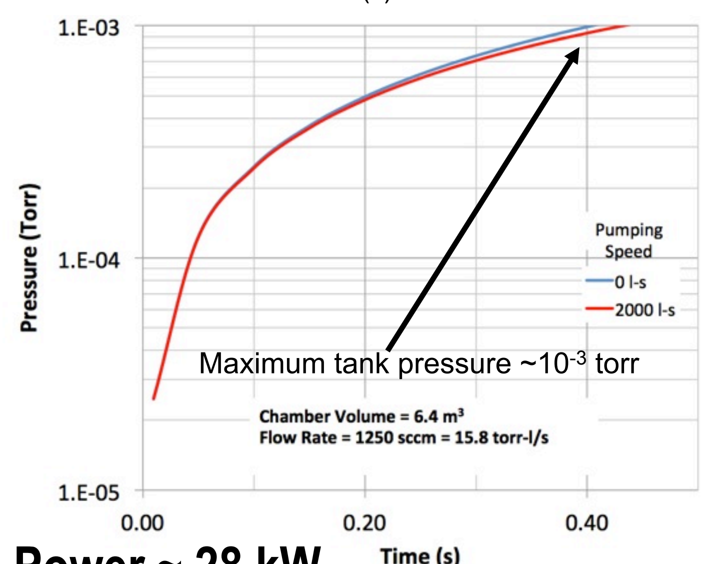
$N_e \sim 2 \times 10^{19} m^{-3}$ has been achieved with He, downstream pressure ~ 10^{-3} Torr

- **Probe current and plasma density for varying gas time profiles**



- **Example gas flow vs time**





- **RF Power ~ 28 kW**