Update of the ECH/ EBW LDRD Project

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FEST Seminar

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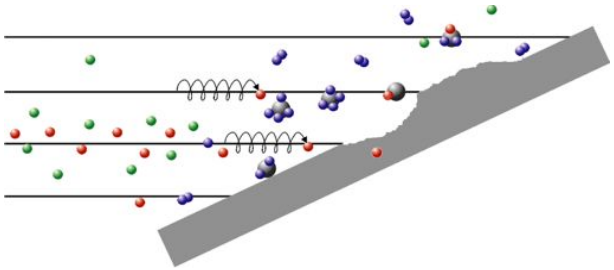
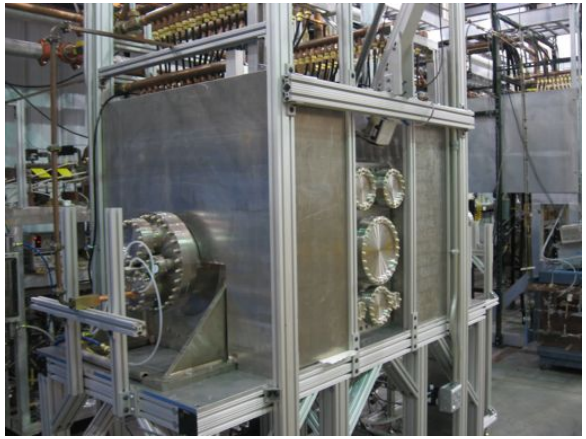
U.S. DEPARTMENT OF ENERGY

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

Agenda

- Motivation and Significance
  - Plasma Material Interface (PMI) research issues
  - New high plasma heat flux facility for PMI research and internal component testing
  - Plasma electron heating for producing required heat flux: subject of this research
  - Produce environment for antenna testing
- Experimental apparatus
- Plasma operation results
- Modeling approach
- Plans for antenna physics and technology testing
- Summary and future work





The requirements for PFCs in ITER and follow on Demonstration Reactors (DEMO) are demanding

ITER conditions: Pulsed, Low T, C, Be, W

Plasma Interaction in Divertor

- $n_e = 10^{21}\ m^{-3}$
- T_e = 1-10 eV
- $\Gamma_{D,T} > 10^{23}\ m^{-2}\ s^{-1}$
- $q_{div} > 20\ MW/m^2$

DEMO conditions:

Similar to ITER with:

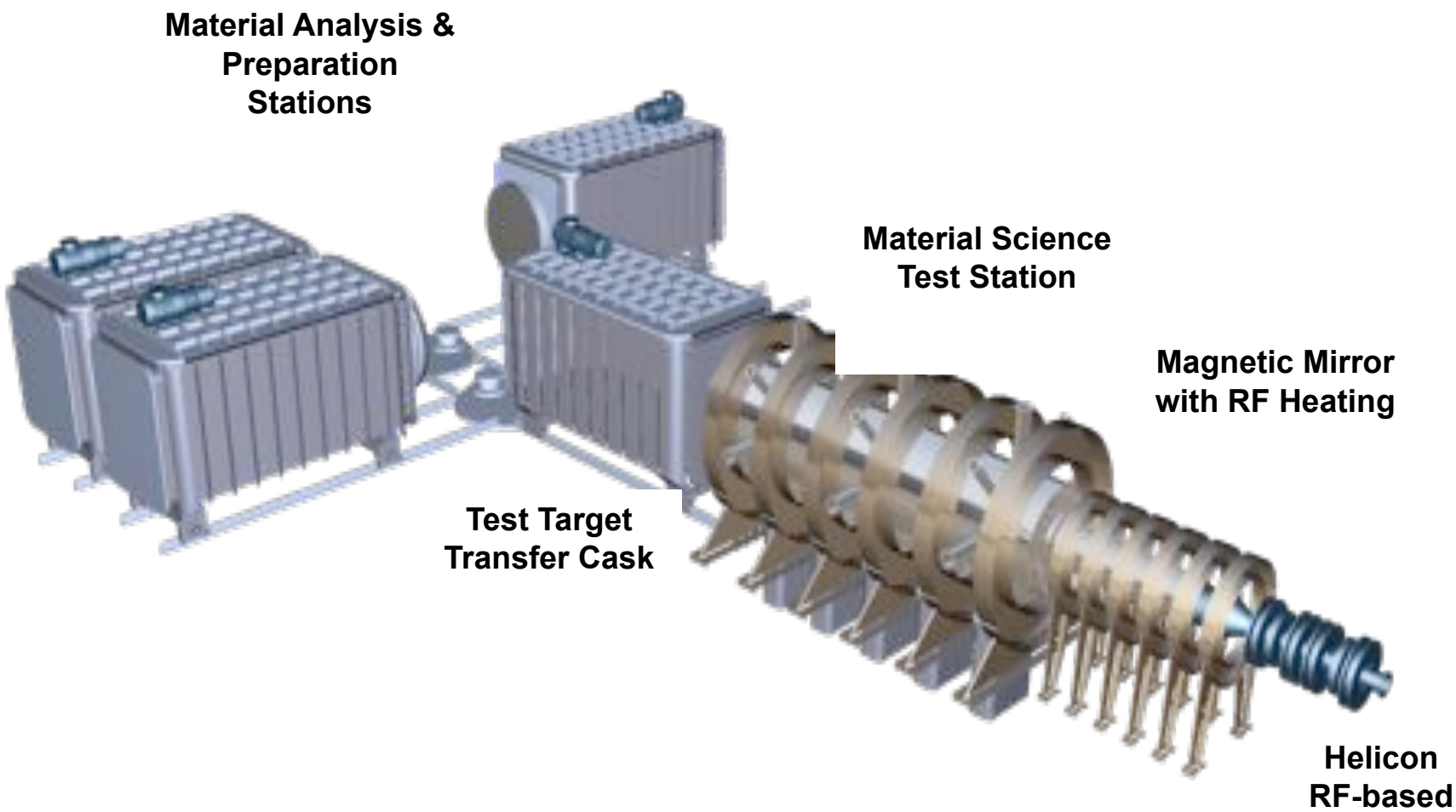
- **Steady-state**
- **elevated temperature (600 C cooling)**
- **Refractory metals**
- **Neutron irradiation (up to 100 dpa)**

Parameter range is inaccessible in present tokamaks and PMI experiments

Dedicated Facilities are needed for Plasma Material Interface Research

- Dedicated laboratory experiments/test stands have several advantages over full complexity of a tokamak for doing PMI research:
  - Cost effective
  - Well-diagnosed due to better diagnostic access
  - Long pulse(>100 s) or CW [100 sec tokamaks aren't available yet]
  - Well controlled: ability to focus on specific mechanisms and processes
  - Long pulse and high temperature issues can be addressed much sooner than on current fusion devices
- A new PMI research facility, based on a helicon plasma source, would add to the capability of existing linear devices, providing particle fluxes > $10^{23} m^2 s^{-1}$, heat fluxes ≥ 20 MW/m^2, steady state operation, and eventual capability for irradiation of neutron damaged materials
- Additional heating of the electrons and ions is needed to produce the desired plasma heat flux
- Electron heating of over-dense plasmas is a main focus of this research

Concept for a long-pulse PMI Test Stand

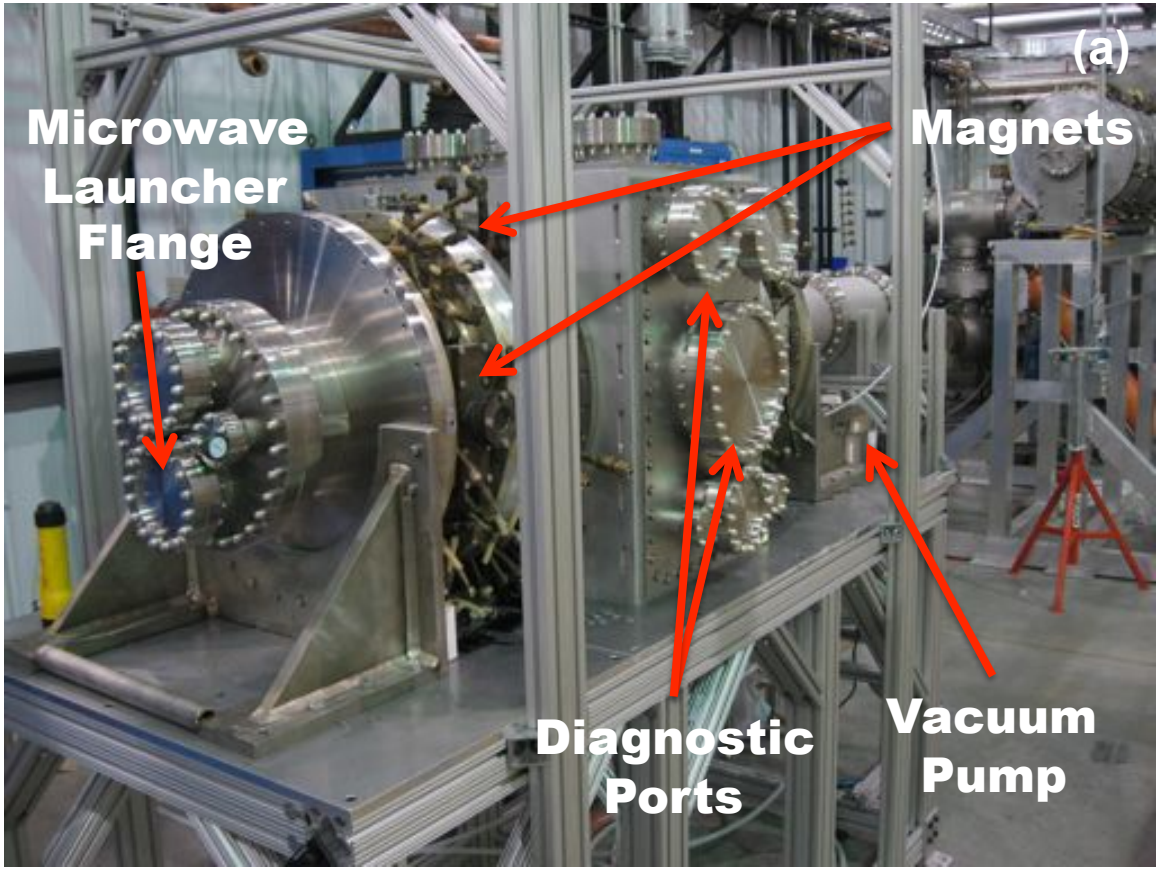


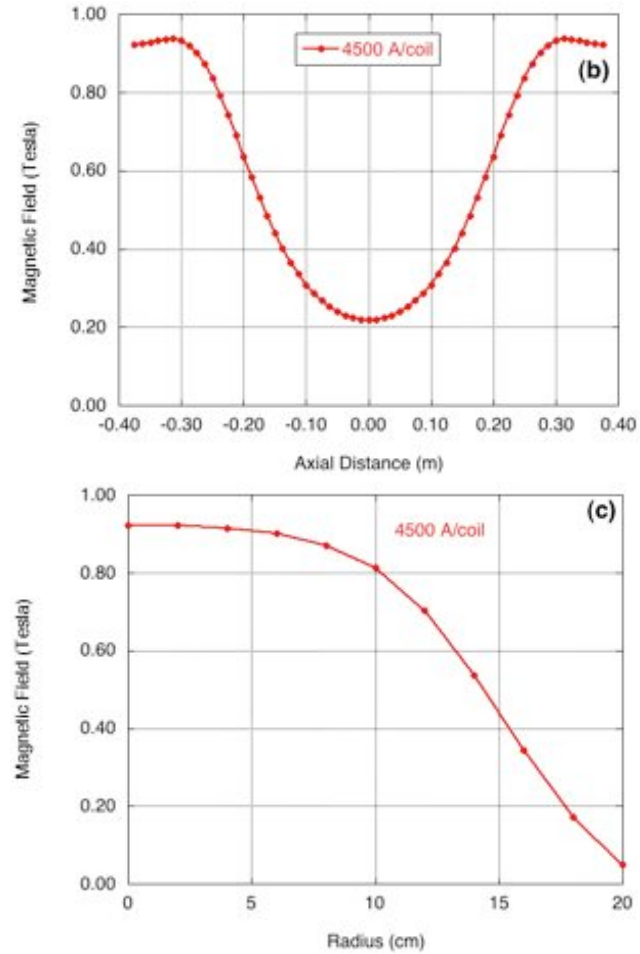
Long-term goal is to build this facility at ORNL

Research Goals

- Primary goal: Demonstrate electron heating physics in high density plasmas:
  - Create a target plasma with density $>10^{12}/cm^3$ with an 18 GHz klystron
  - Couple to an **over-dense plasma** at 6 GHz using whistler waves and/ or EBW waves ($n_c \approx 4.5x10^{12}/cm^3$)
  - Measure plasma parameters with several diagnostics and use ray-tracing modeling to understand wave propagation
- Secondary goal: Provide a magnetized plasma environment for RF physics and technology development:
  - Build a simple single-strap antenna with a single-tier Faraday shield (similar in concept to one NSTX antenna segment)
  - Study near-field antenna plasma interactions
  - Use diagnostics to measure plasma parameters, ion energies, and electric field structure: compare to optical emission measurements of the dynamic Stark effect (Elijah Martin's thesis work and Chris Klepper)
  - Test arc detection methods, private vacuum, capacitor concepts, etc.

Experimental Apparatus

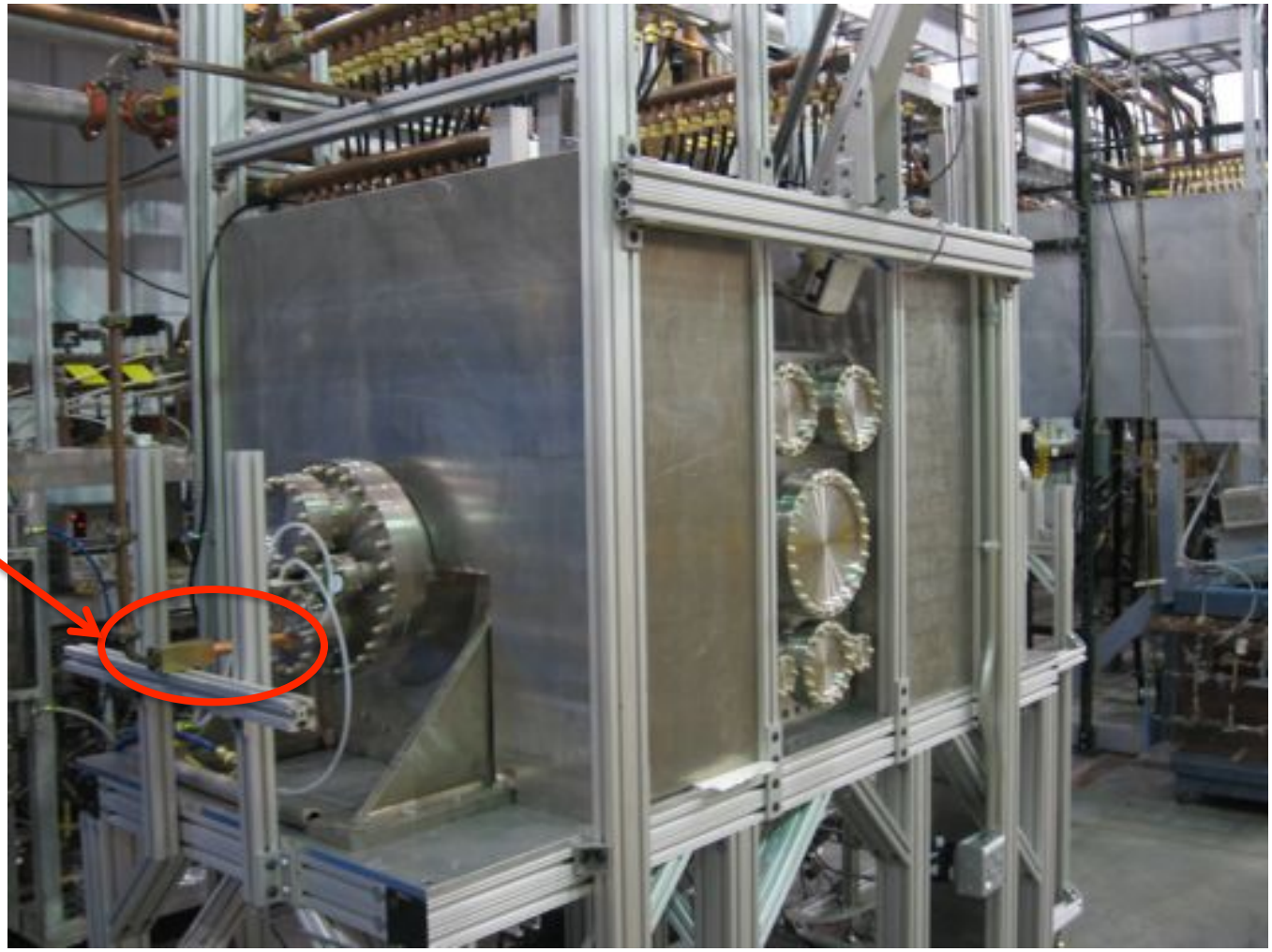




- The experiment consists of a central vacuum chamber (41 cm x 66 cm x 66 cm) surrounded by two solenoid magnet pairs (4 total EBT magnets)
- Central magnetic field of 0.92 Tesla at 4500 amps of current through each magnet

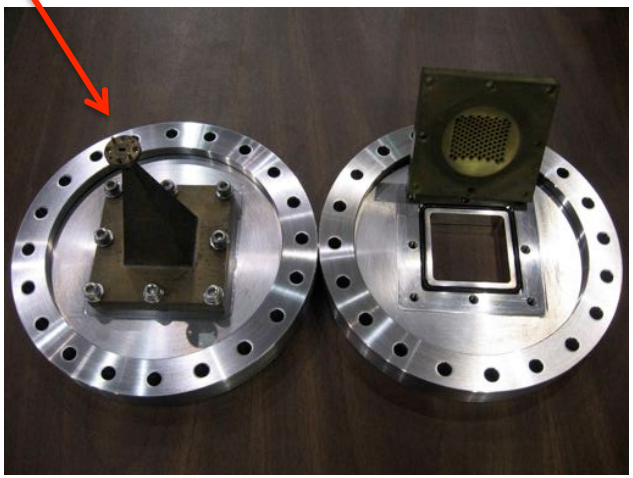
Recent experimental configuration

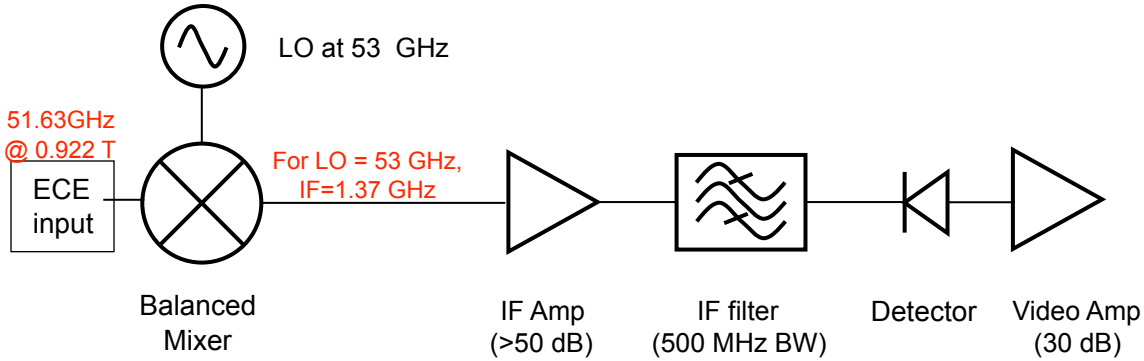
18 GHz Whistler launch microwave input



Plasma Diagnostics

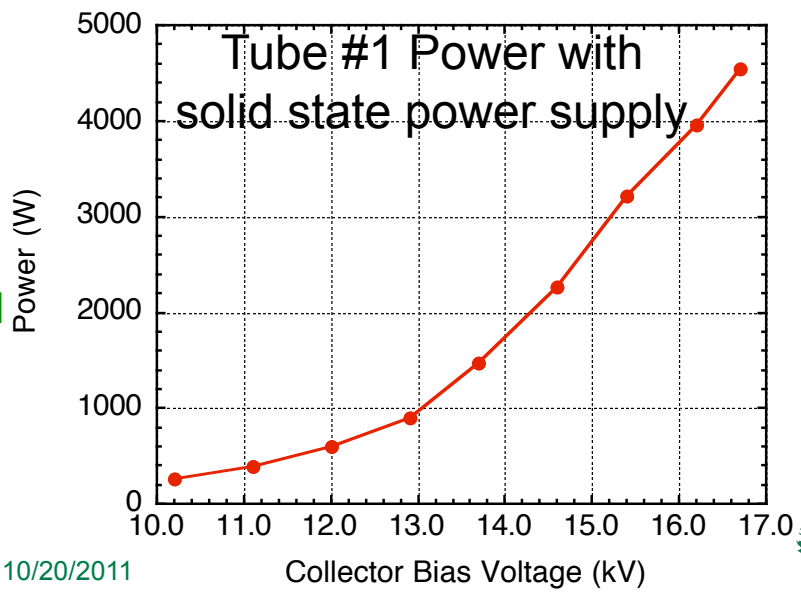
- Several diagnostics are being used to characterize the plasma:
  - Langmuir probe for plasma density and temperature measurements (radial scan)
  - Microwave interferometer for central plasma density measurement
  - Retarding field analyzer for ion energy (plasma potential) measurement (coming soon)
  - Electron Bernstein wave emission (EBE) and electron cyclotron emission (ECE) radiometers for electron temperature measurement and coupling efficiency (did not have time to commission and use)





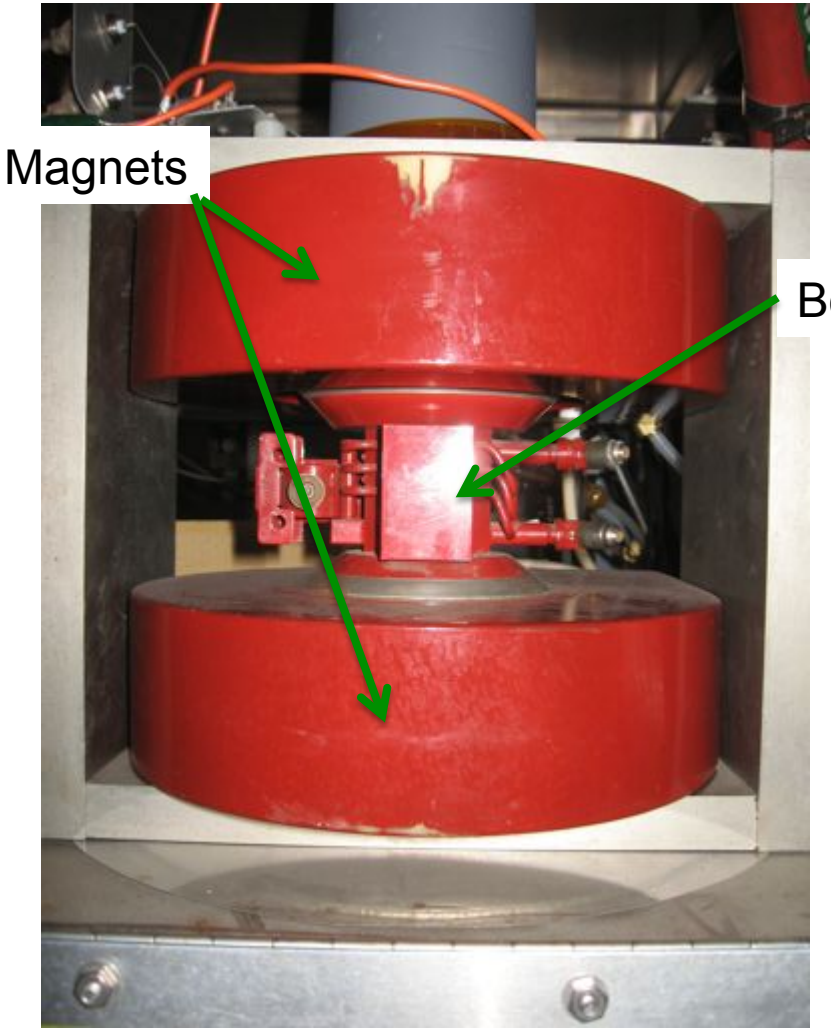
Available Microwave Power Supplies

- Initial tests were made with a 1500 W 2.45 GHz source at lower magnetic field (875 gauss magnetic field) using an O-mode launcher
- Normal operations at higher power levels are at 18 GHz (0.64 Tesla): 18 GHz klystrons available (used on EBT at ORNL in the early 1980s)
- 18 GHz output power was limited by available DC power supplies
  - Tubes are rated at 20.5 kV and 3.5 amperes to produce an output power of 15 kW
  - First tests have been made with an available compact solid-state power supply that has been modified to produce 16.9 kV at 3.0 amperes
  - Result: One tube produced 4.5 kW and another one produced 2.5 kW at the lower voltage
- Two options were pursued to increase the 18 GHz output power:
  - Operate in a depressed collector configuration: bias the body up to 4 kV
  - **Resurrect a Cober power supply rated at 25 kV at 4 amperes: got up to 8 kW**
- Additional coupling with a 3 kW 6 GHz source: EBW and Whistler

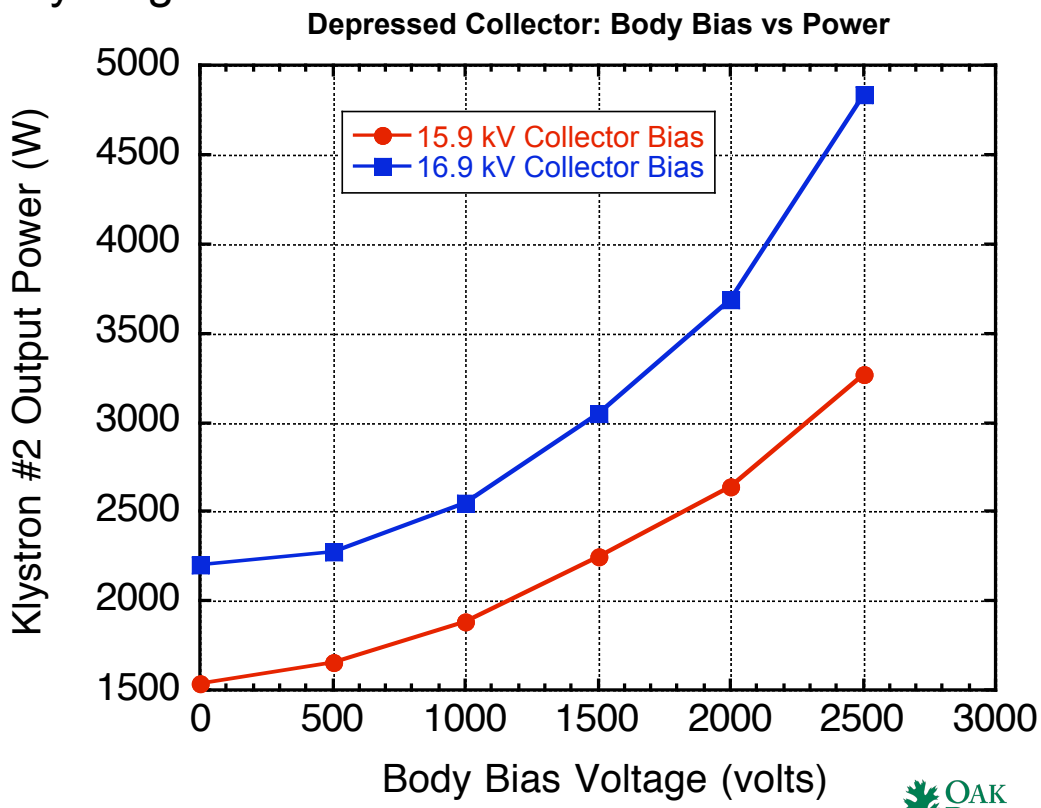


Depressed Collector Klystron Operation

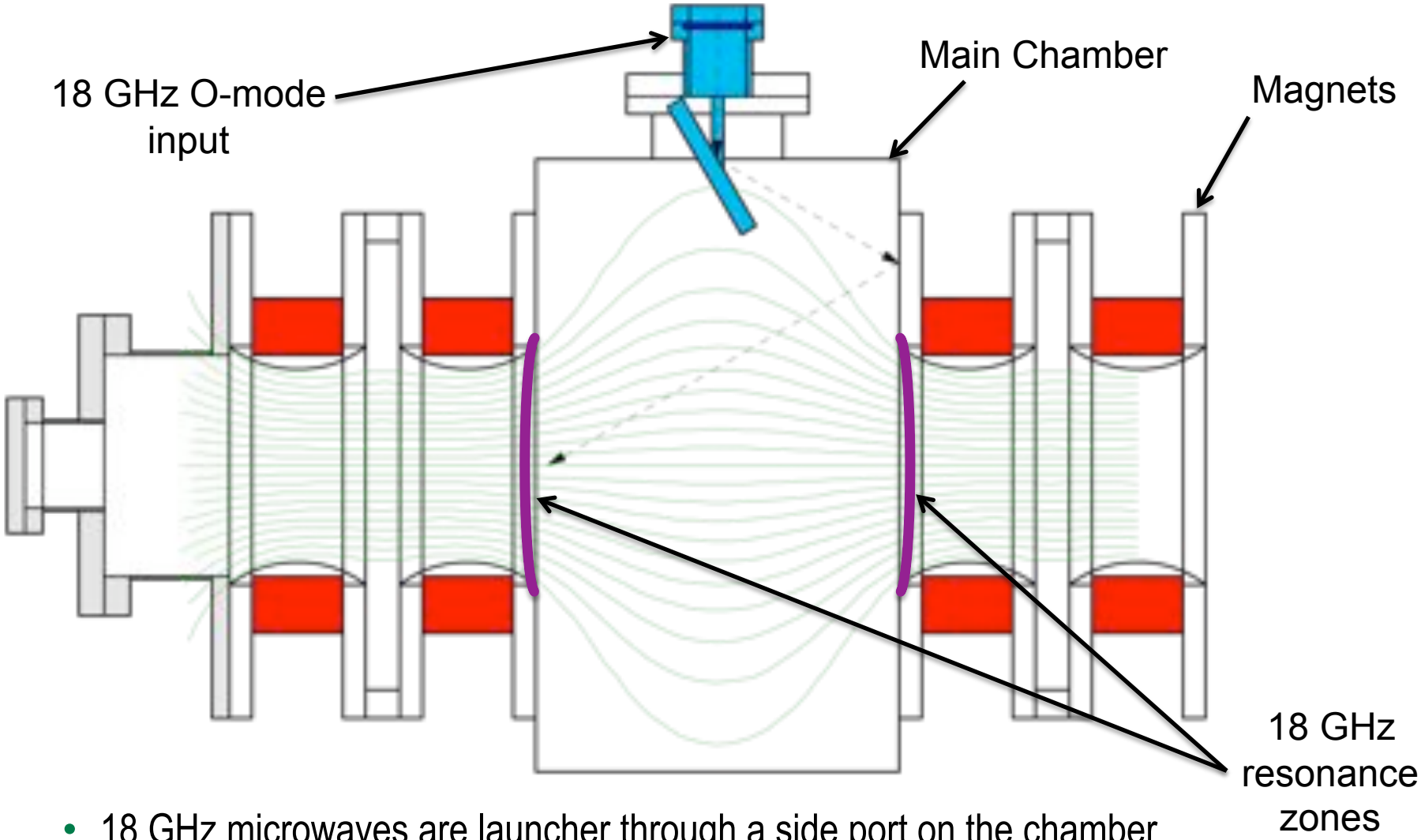
15 kW 18 GHz Klystron



- Electrically isolate the body region of the klystron
- Bias with a 3 kV, 200 mA power supply
- Result: increased from 2.5 kW to 4.5 kW

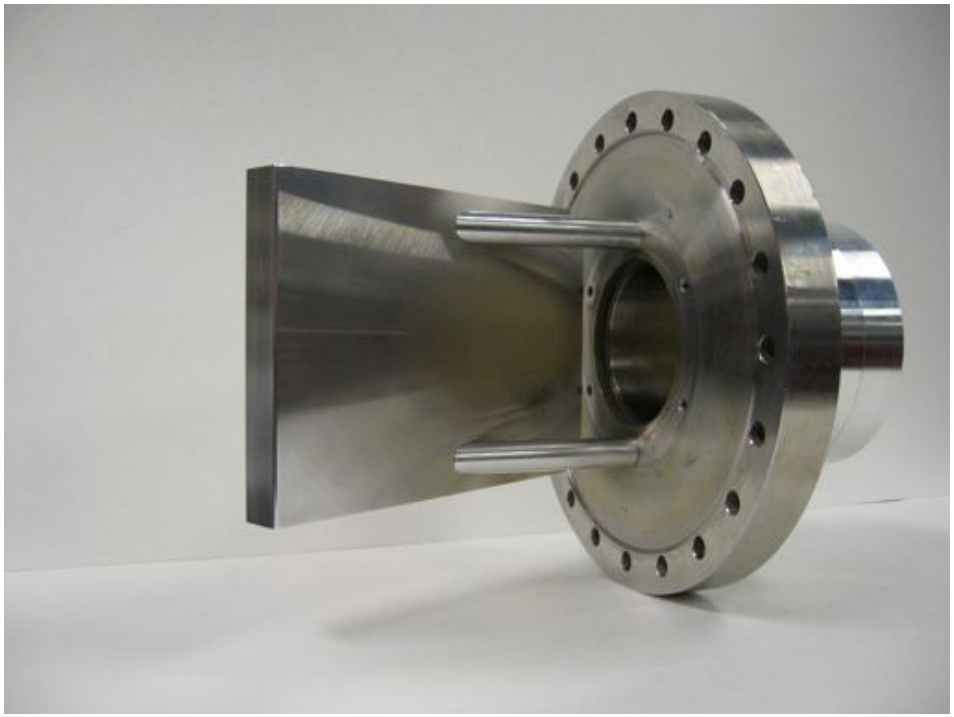


18 GHz O-mode launcher is used to create the target plasma



- 18 GHz microwaves are launcher through a side port on the chamber
- A reflector directs the beam off the chamber wall to the resonance zone

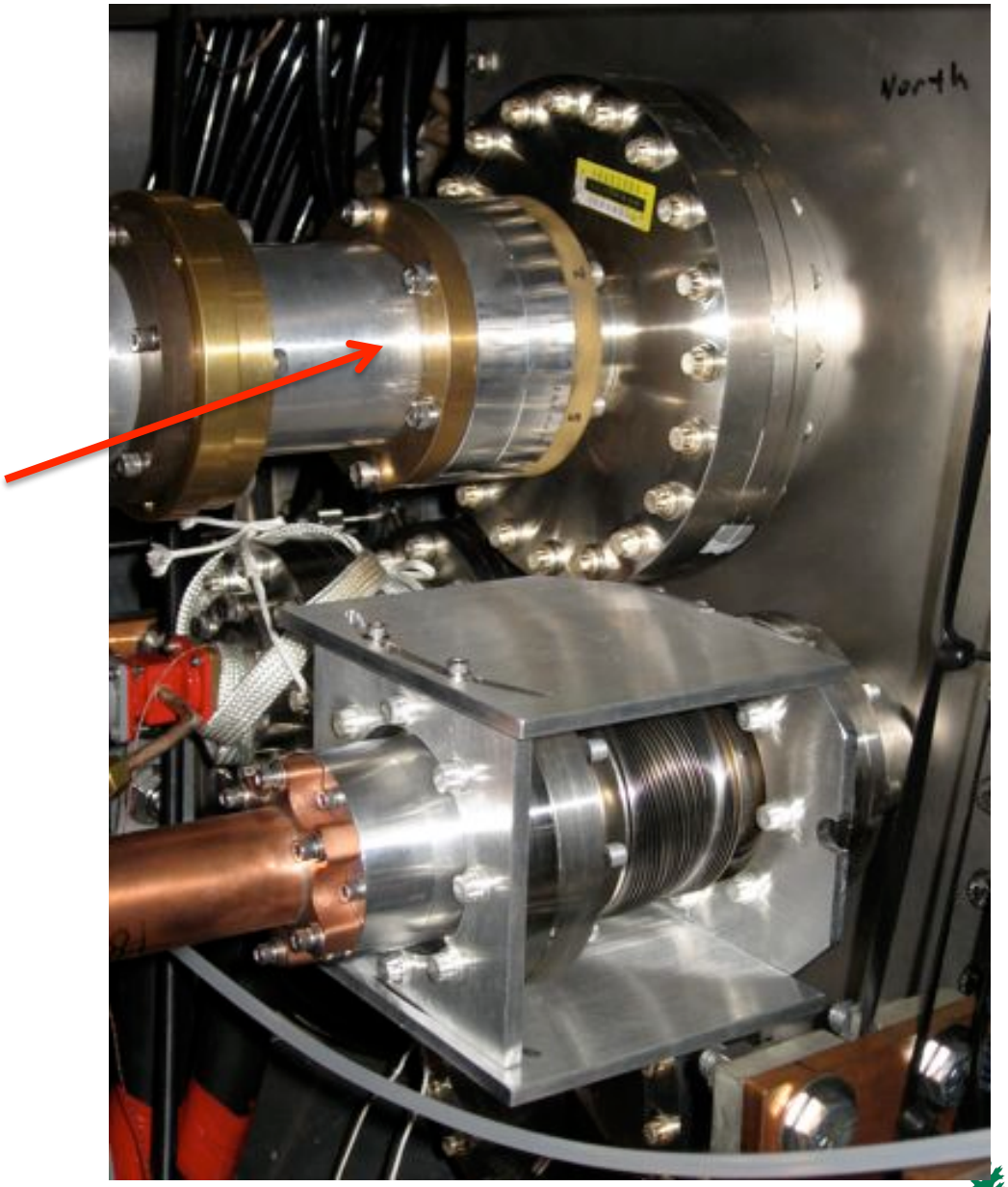
18 GHz High Power O-mode Launcher



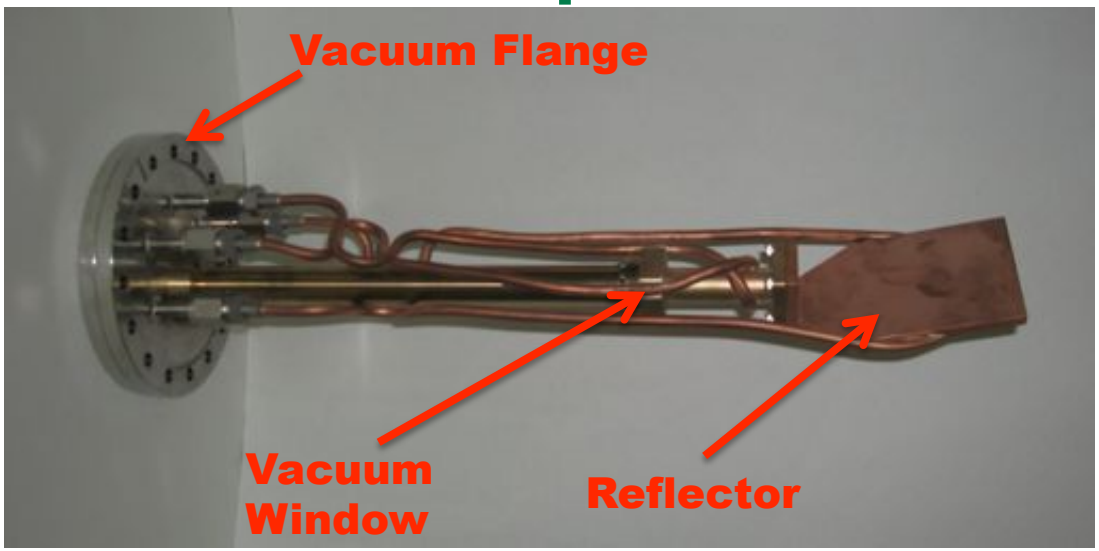
- **Mounted on back barn-door flange on the main chamber**
- **Uses an alumina disc as the vacuum break**

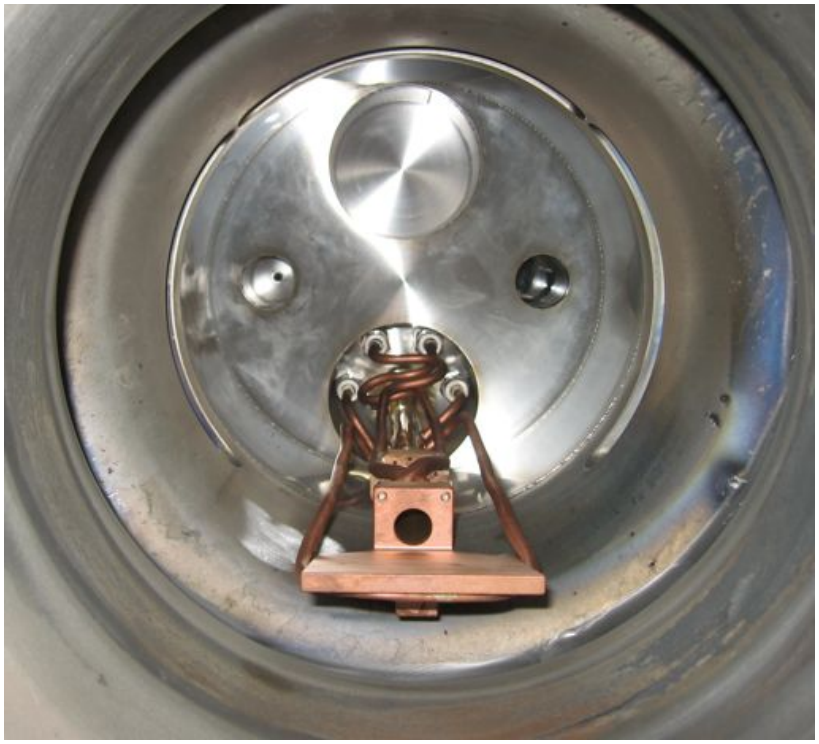
Launcher on Chamber

18 GHz O-mode launcher is mounted on one of the large side ports on the main chamber



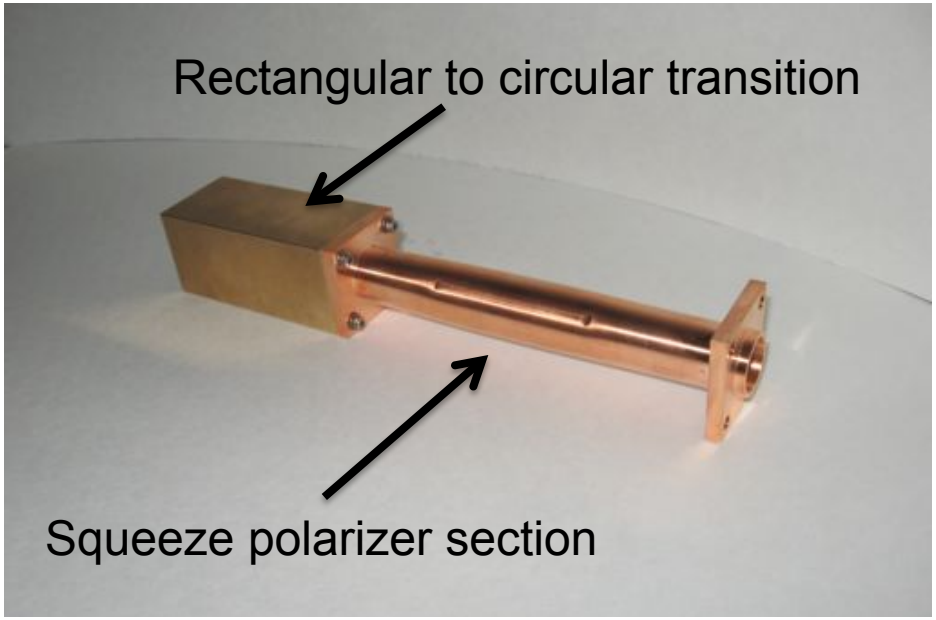
Whistler Wave Microwave Launcher Development at 18 GHz and 6 GHz

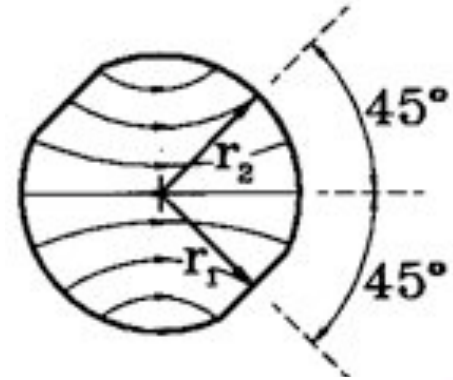




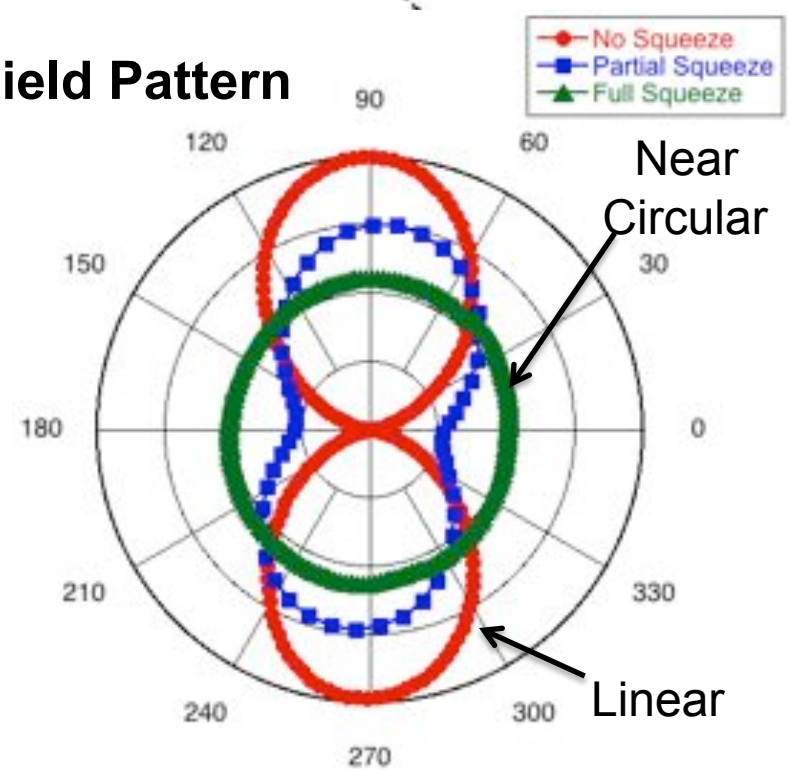
- Whistler wave launch needs to be from the high field side (right hand circularly polarized wave)
- The microwave vacuum window must be located within the high-field region and consists of a quartz window with dual helicoflex seals
- The reflector plate directs the microwaves to the center of the resonance zone and also acts as a limiter to keep plasma out of the waveguide

A Squeeze polarizer is used to produce a circularly polarized wave



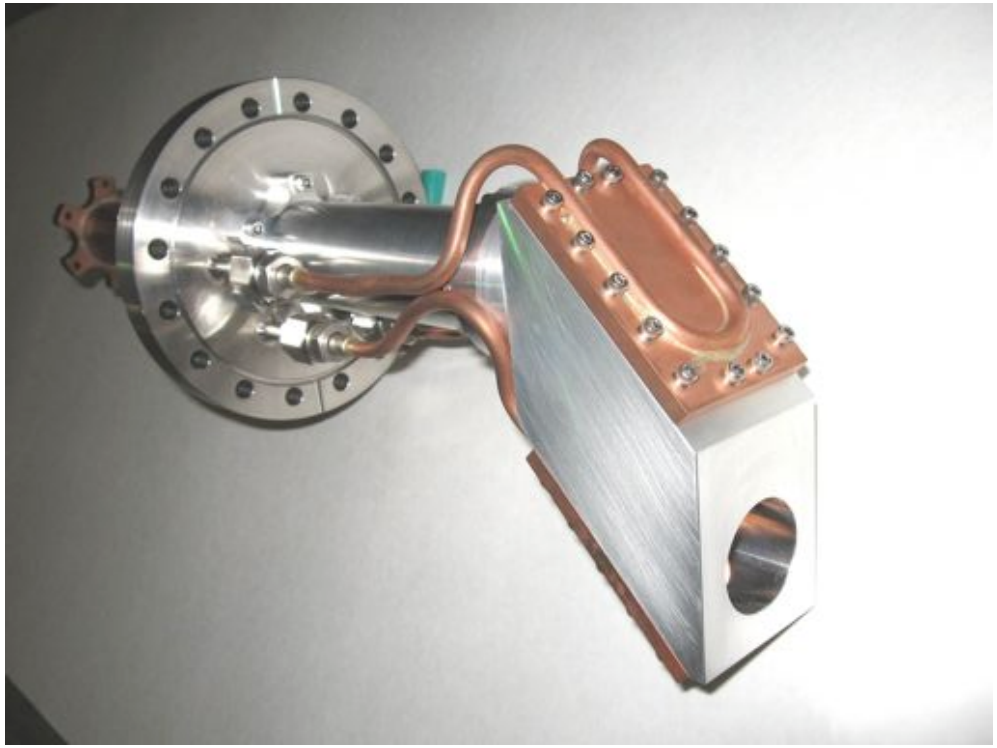


Field Pattern



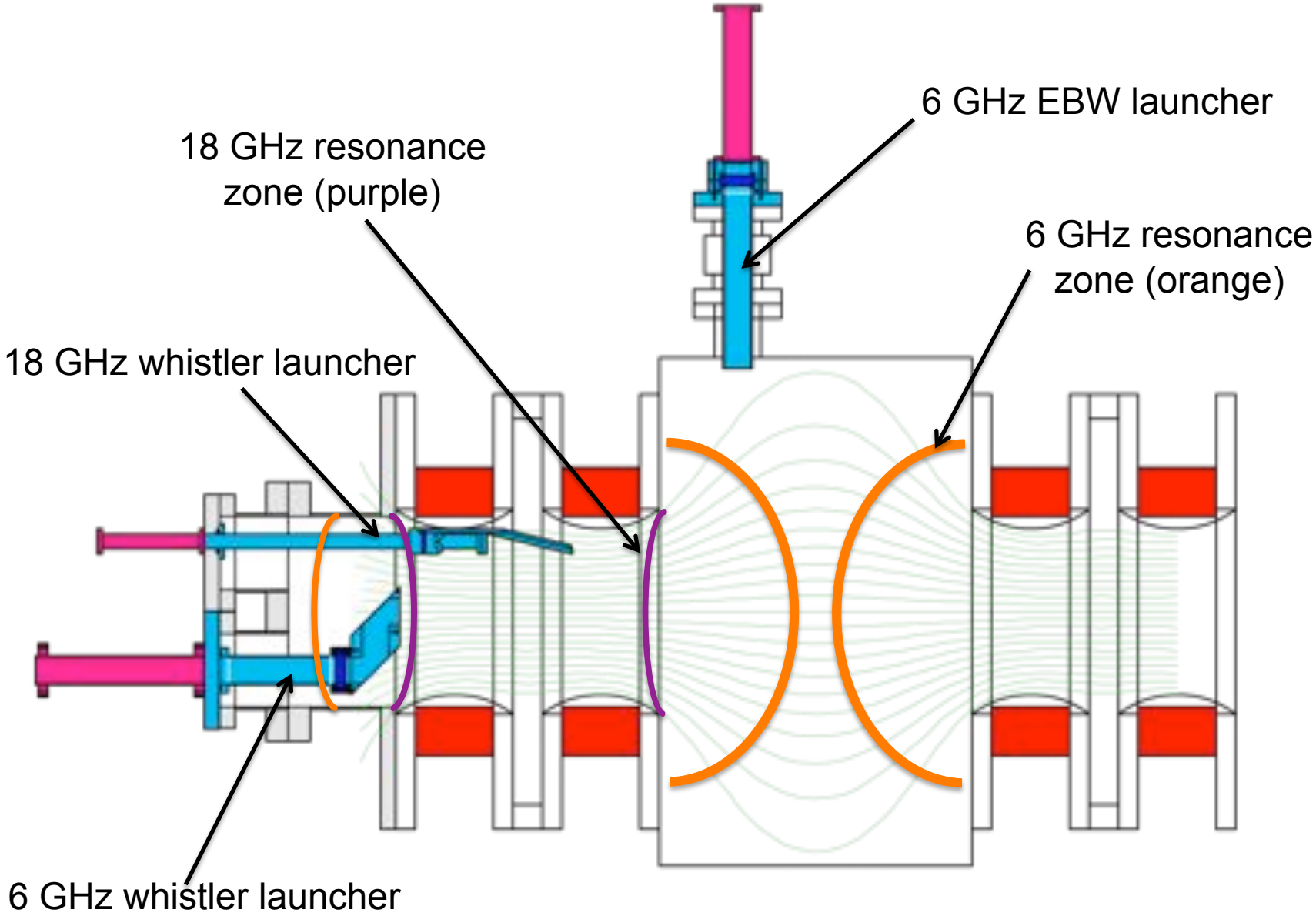
- A section of circular waveguide is "squeezed" at a 45 degree angle to create a radial perturbation
- The wave is split into two equal-amplitude linearly polarized waves and will propagate at two different phase velocities
- A 90 degree phase shift is achieved after a sufficient distance (8-9 cm) to create a circularly polarized wave
- Ref: T.H. Chang, et al., Rev. Sci. Instrum. 70, 1530 (1999)

6 GHz whistler wave Launcher



- **Wave is close to circularly polarized at the launcher output**
- **Uses a double mitre-bend to keep plasma off the vacuum window**
- **Note: window must be in the high-field region of the magnets to launcher the whistler wave**

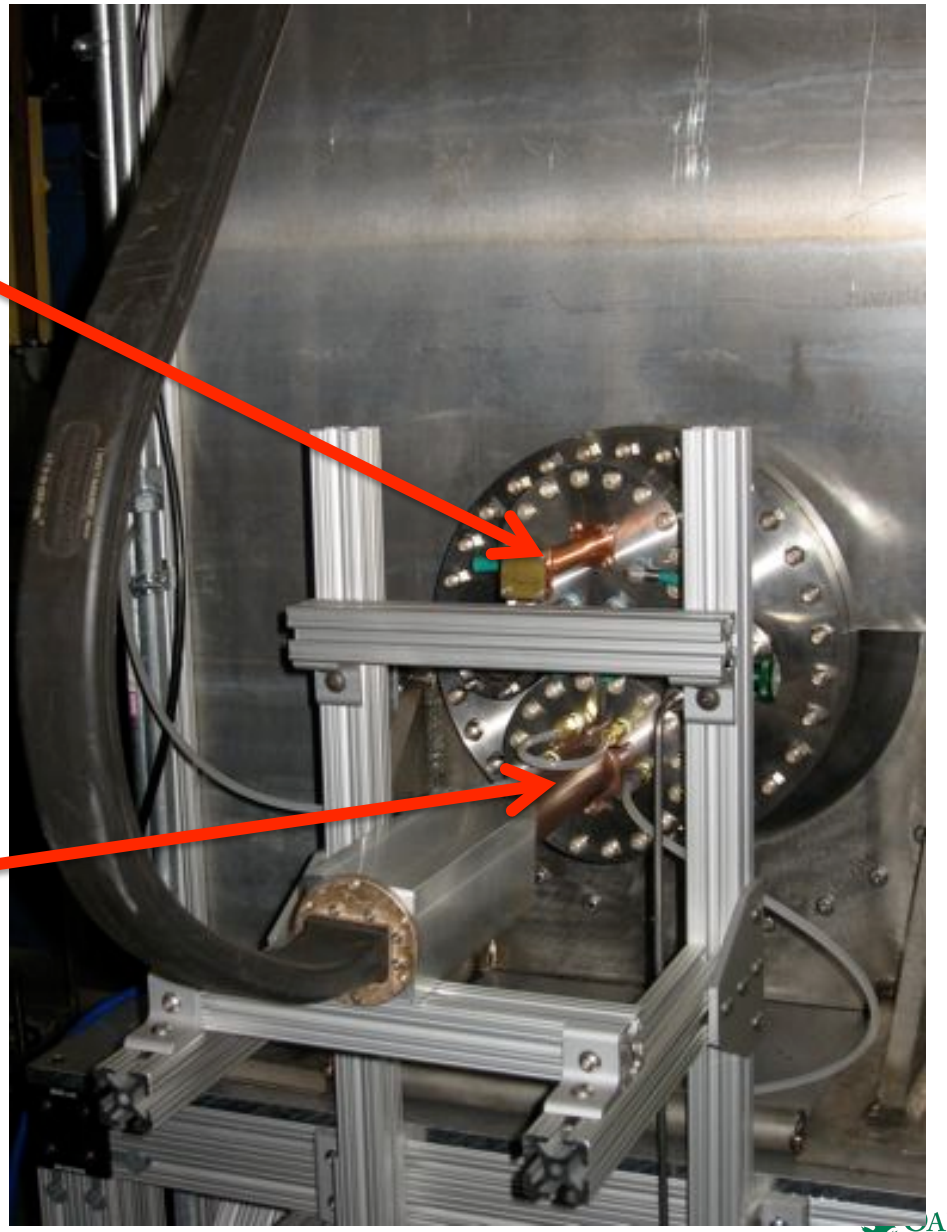
Location of launchers on Chamber



Whistler Launchers on Chamber

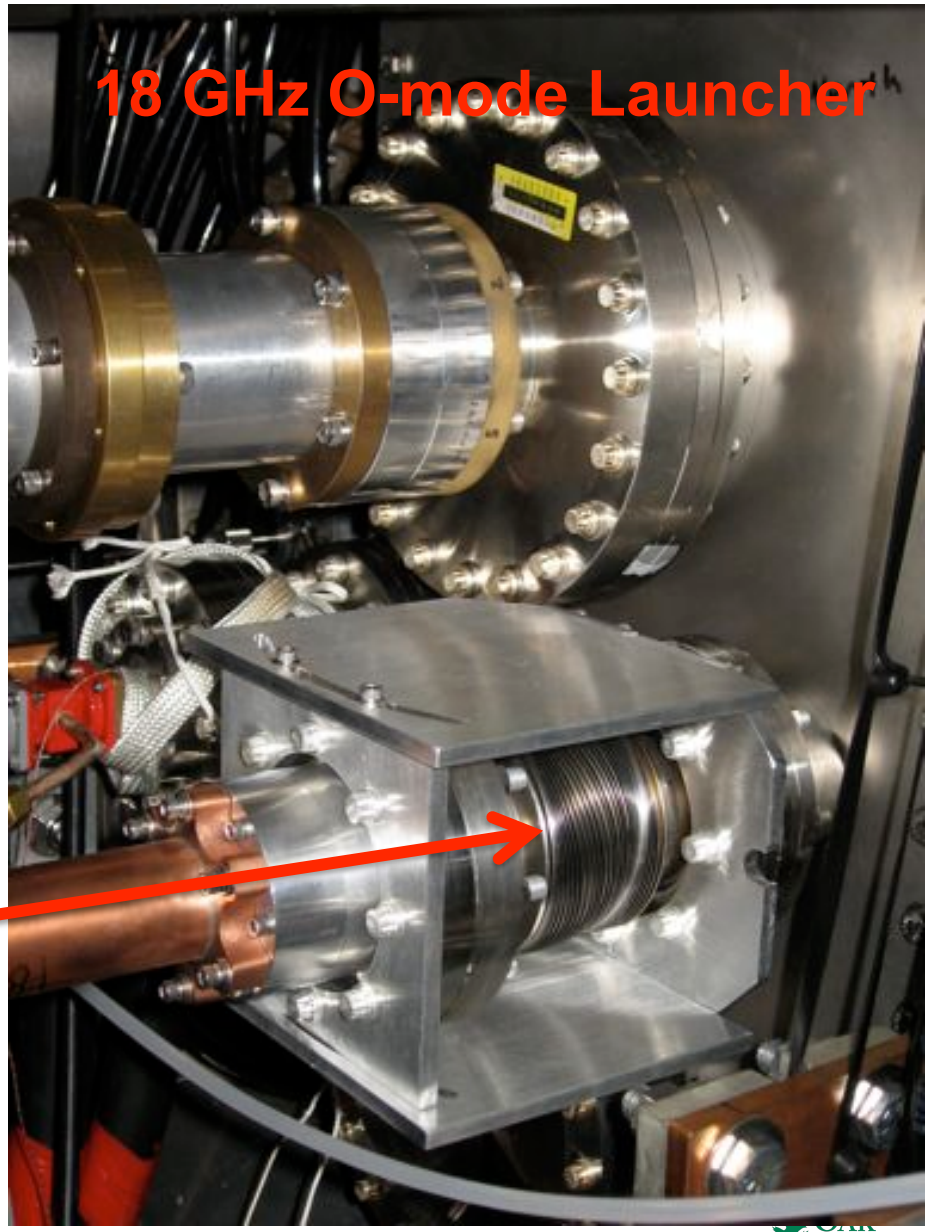
18 GHz Whistler Launcher

6 GHz Whistler Launcher



6 GHz EBW Launcher

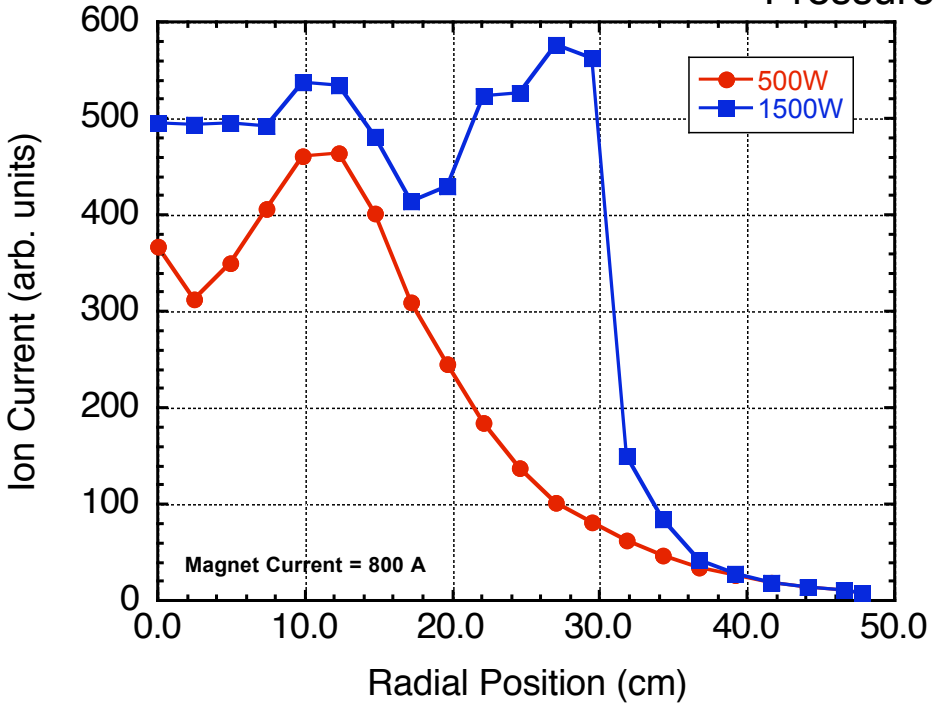
- Coupling to the electron Bernstein wave requires a double-mode conversion process:
  - EBWs are electrostatic plasma waves that propagate only in plasma
  - Requires conversion from O-mode to X-mode to the Bernstein mode (OXB)
- Efficient coupling to EBWs requires that the microwaves be launched at an optimum angle with respect to the magnetic field
  - The launcher is mounted on a bellows flange so that the launch angle can be varied +/- 8 degrees

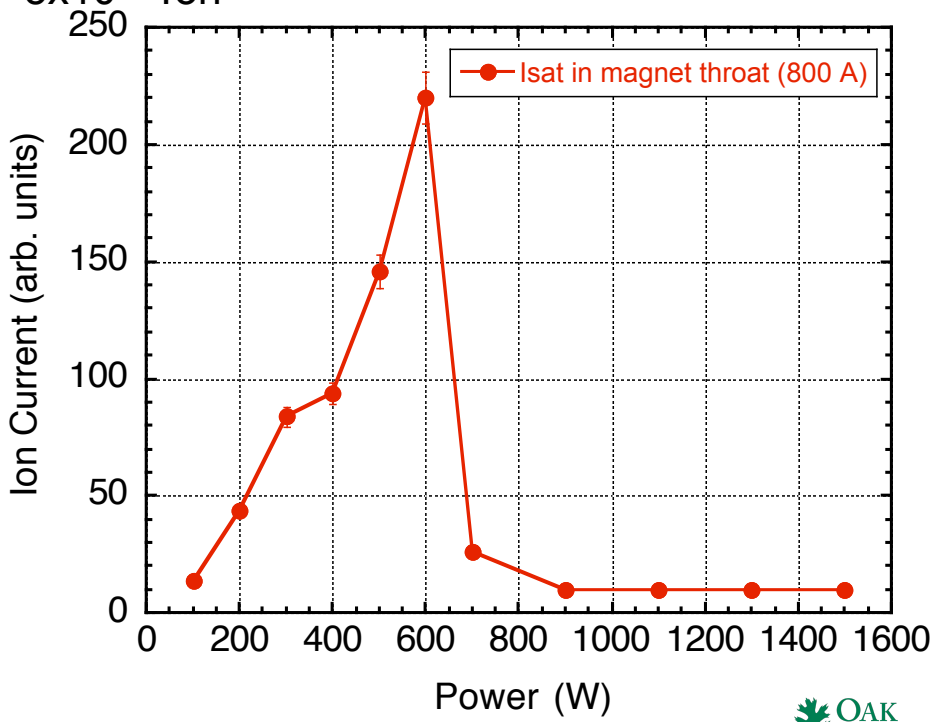


Initial plasma operation for system commissioning

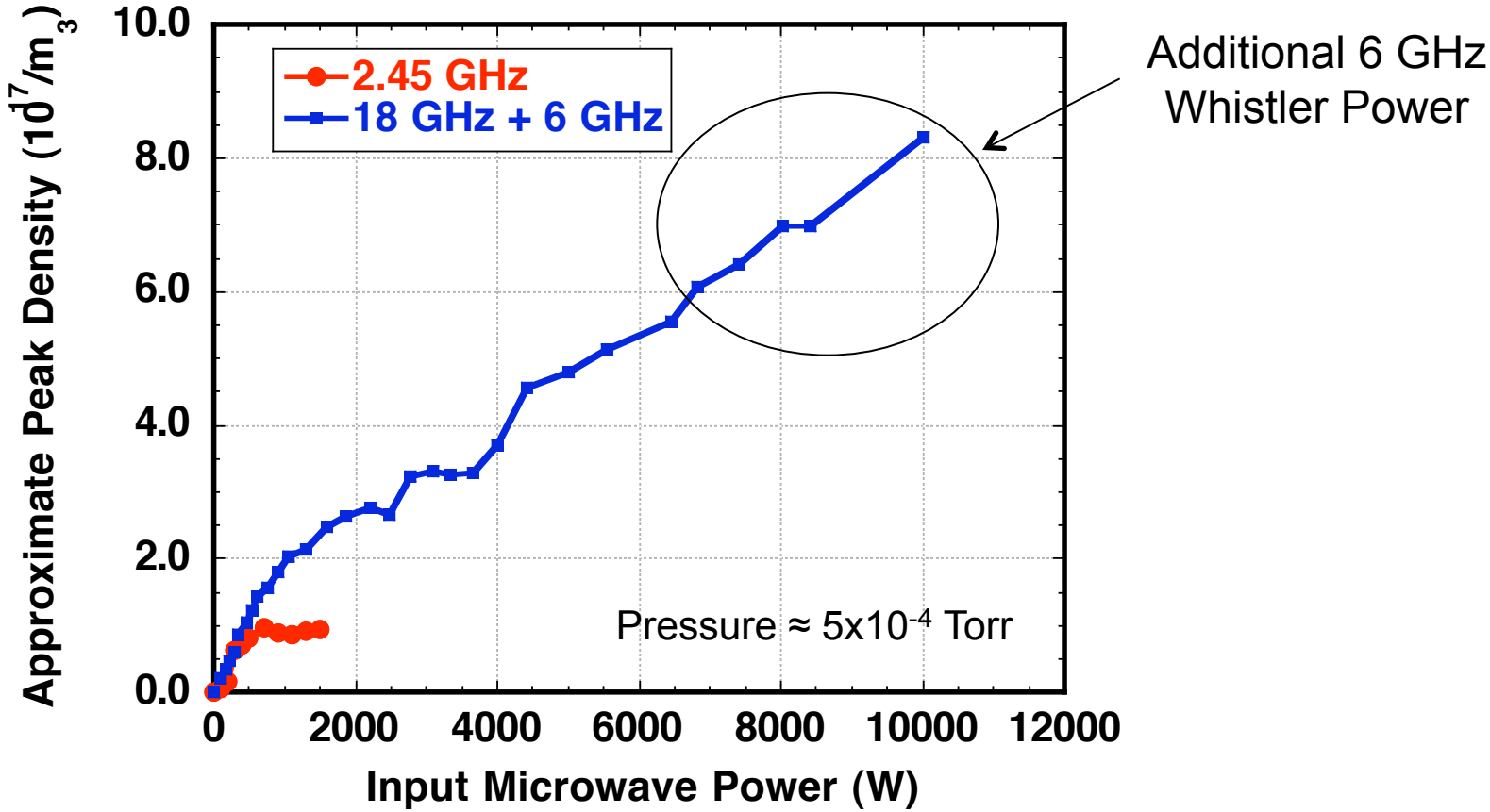
- Initial commissioning tests were made with low-field O-mode launch at 2.45 GHz at modest field (0.1 Tesla)
- As expected, the density was limited to the plasma cutoff density of ~$8 \times 10^{10}/cm^3$ as the microwave power was increased (as shown by the interferometer)
  - The plasma was confined to the central chamber after the plasma density approached the cutoff density

Pressure ≈ 5×10^{-4} Torr



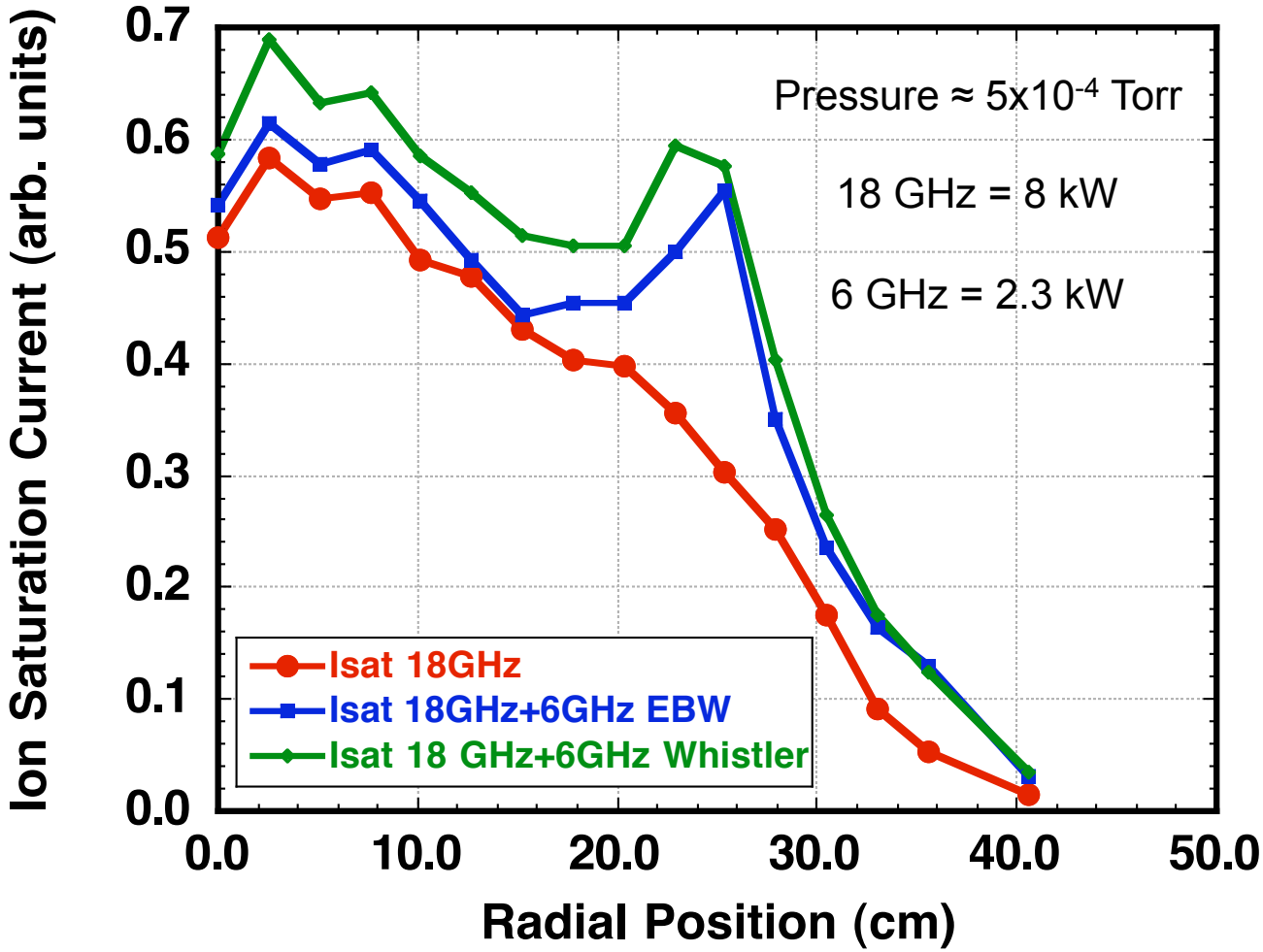


Plasma operation at 18 GHz



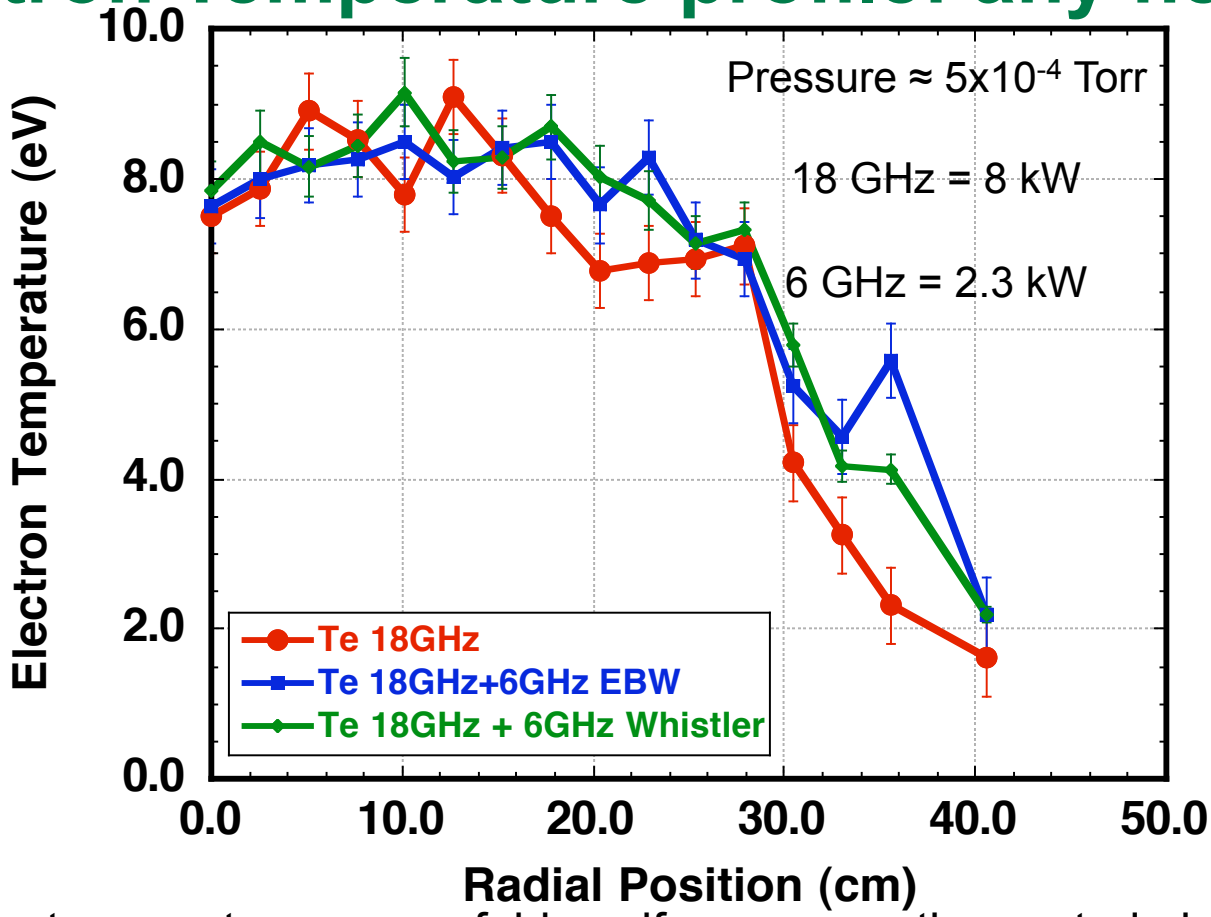
- While the peak plasma density was limited in the low-field side O-mode launch at 2.45 GHz, no density limitation has been observed for high-field launch at 6 GHz or 18 GHz
- A peak density of > 8x10^{11}/cm^3 has been observed so far: still power limited (need more 18 GHz power)

Plasma density profile



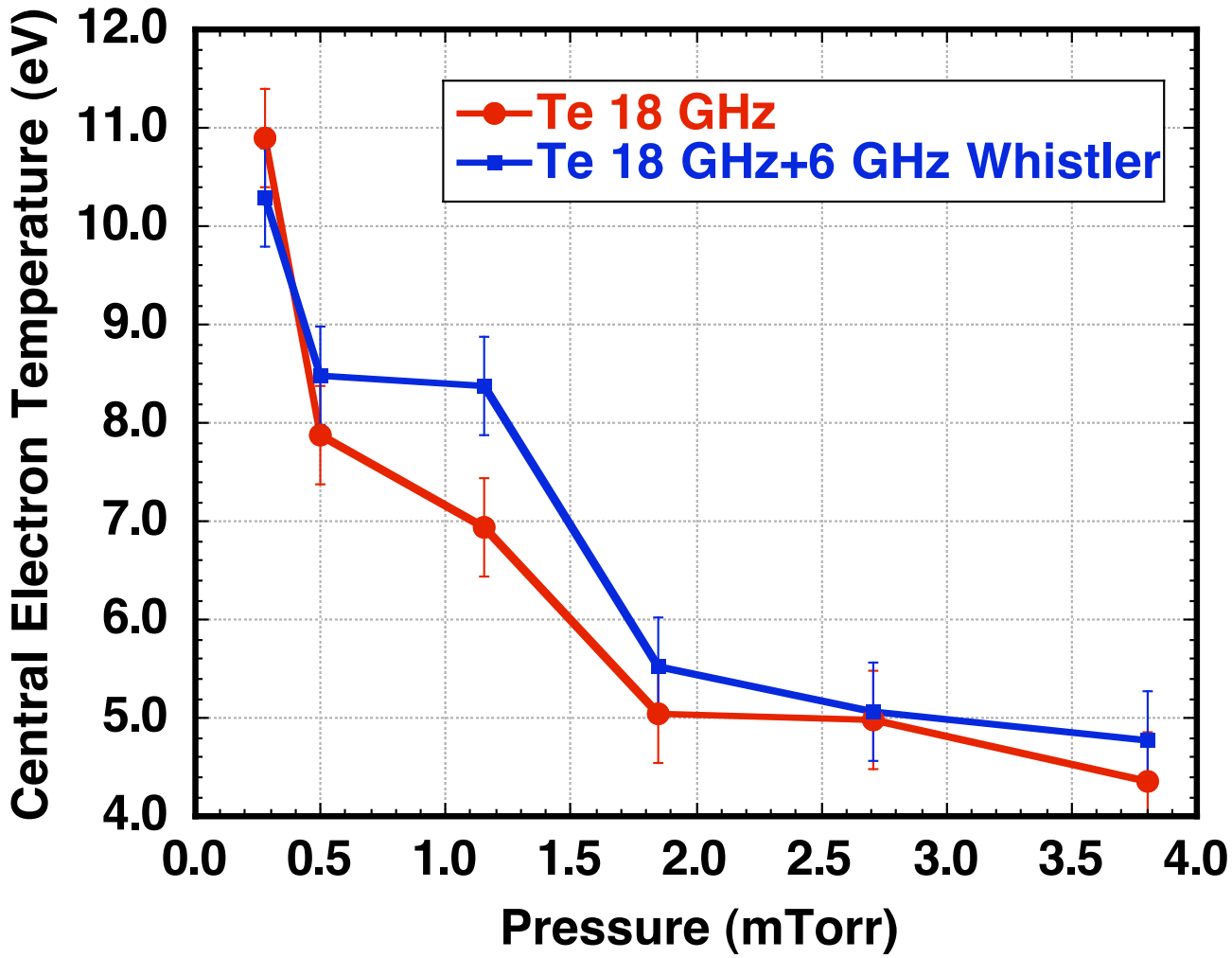
- A centrally peaked profile is seen for 18 GHz alone
- The edge density increases with the addition of 6 GHz EBW or whistler waves: power deposition at the near-by resonance zone may be the reason

Electron Temperature profile: any heating?



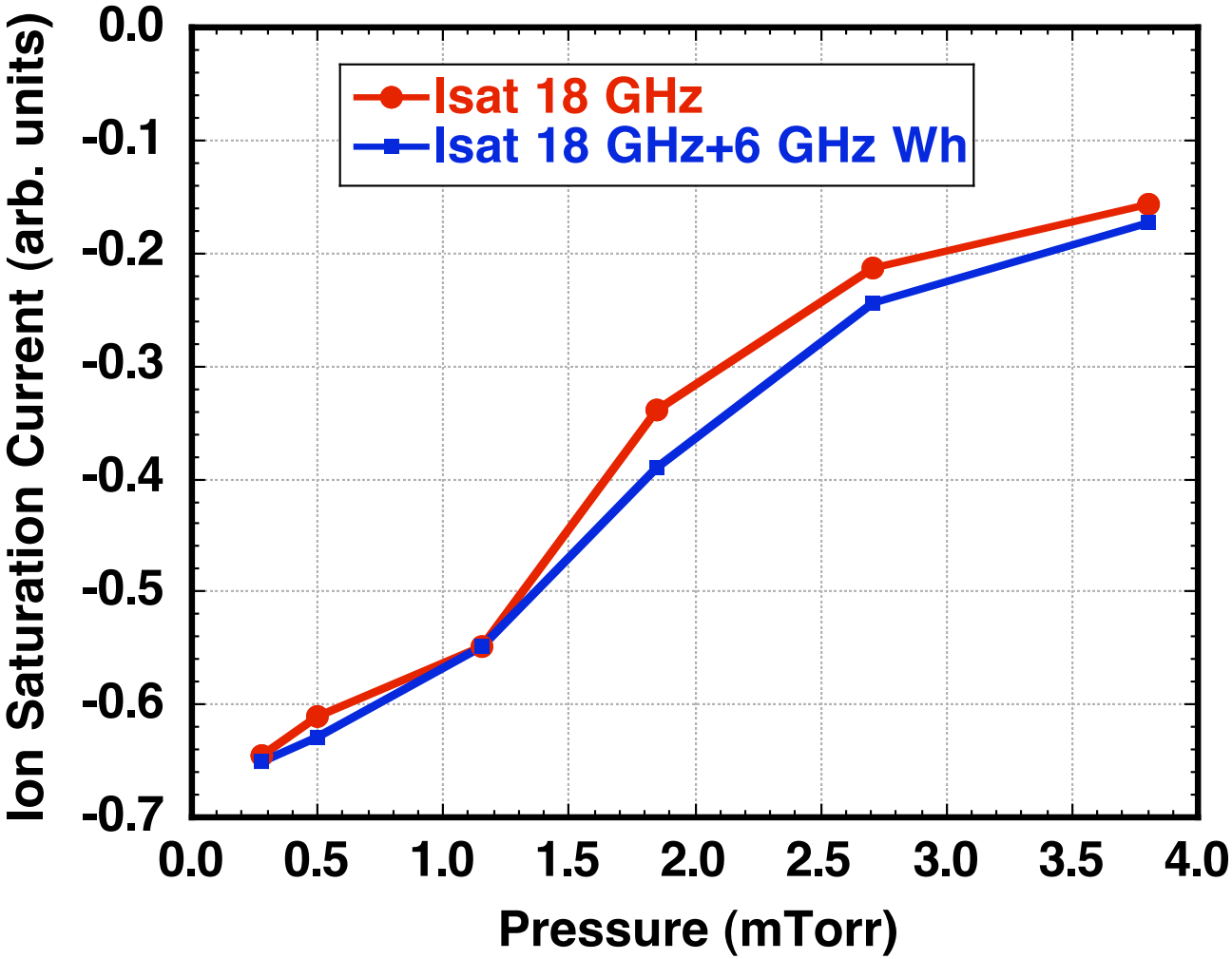
- The electron temperature seems fairly uniform across the central plasma
- There is a hint of electron heating in the 20-25 cm range, but error bars are on the same order as the temperature difference (same area as density rise)
- Optical emission measurements in He may help to answer the question
- Note: earlier preliminary results showing Te increase where due to electronics problems, but the experimental conditions need to be repeated to verify

Electron temperature increases at lower pressures



- The electron temperature increases at lower pressures
- Indicates the need for pressure control in future experiments, such as PhiX (LDRD-3)

Plasma density increases at lower pressures

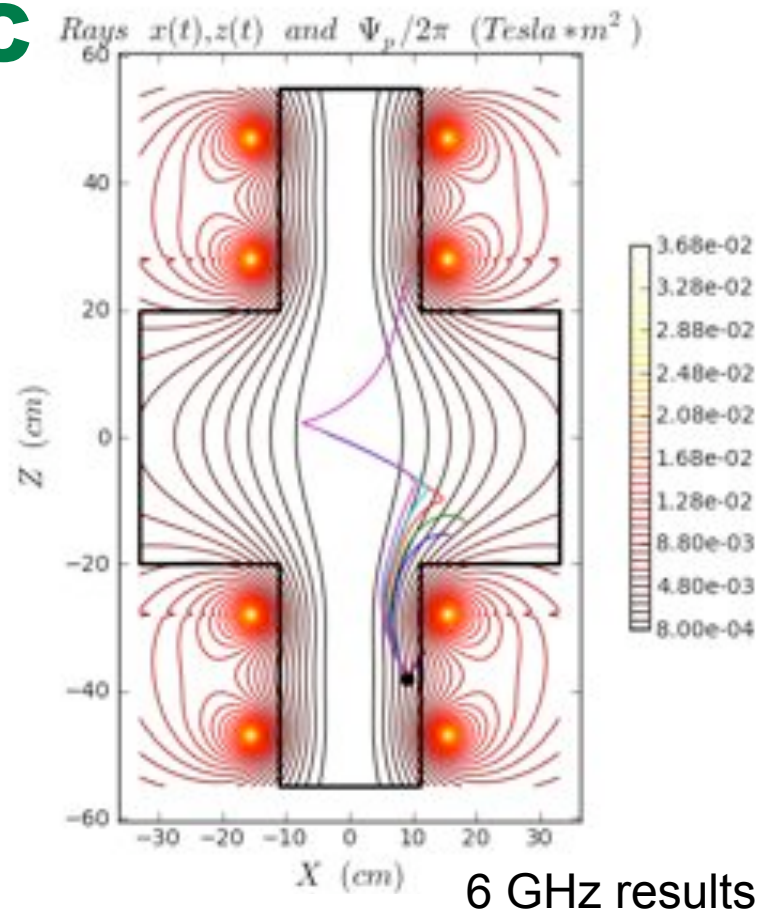


- Most results shown to date are at 0.5 mTorr Hydrogen
- Slightly higher densities at lower pressures, but the higher electron temperature is more important for coupling to the helicon plasma

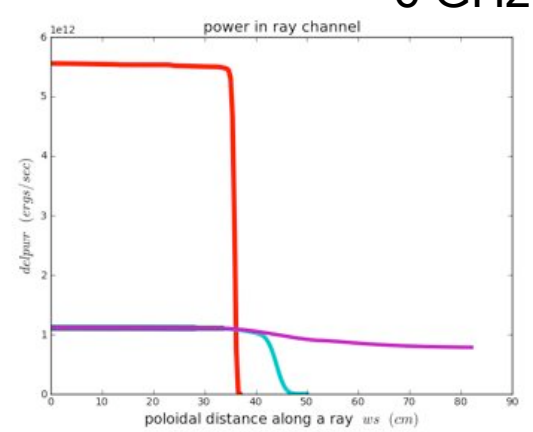
Wave propagation is being studied with GENRAY-C

- The GENRAY code has been modified to operate in a Cartesian framework*
- Initial modeling has begun for both whistler and EBW waves
  - Parabolic density profile with a peak density of 1-4 x10^{12}/cm^3
  - Electron temperature 8 eV
  - Both 6 GHz and 18 GHz considered
- Results here show wave absorption at the 6 GHz cyclotron layer for side launch waves

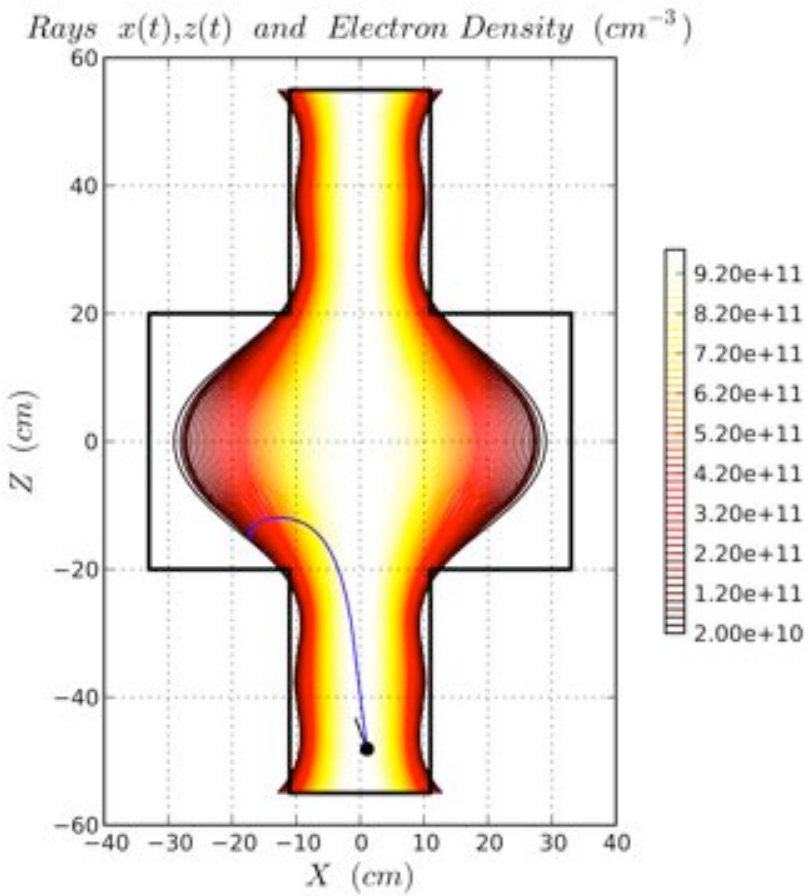
*R.W. Harvey and Y.V. Petrov, CompX

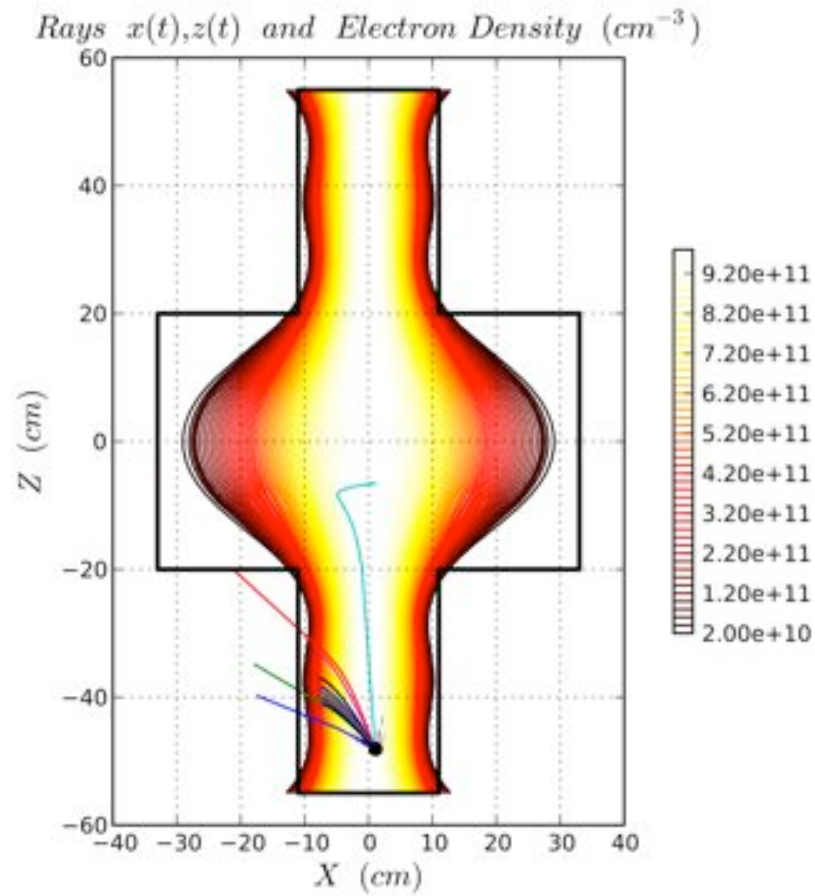


6 GHz results



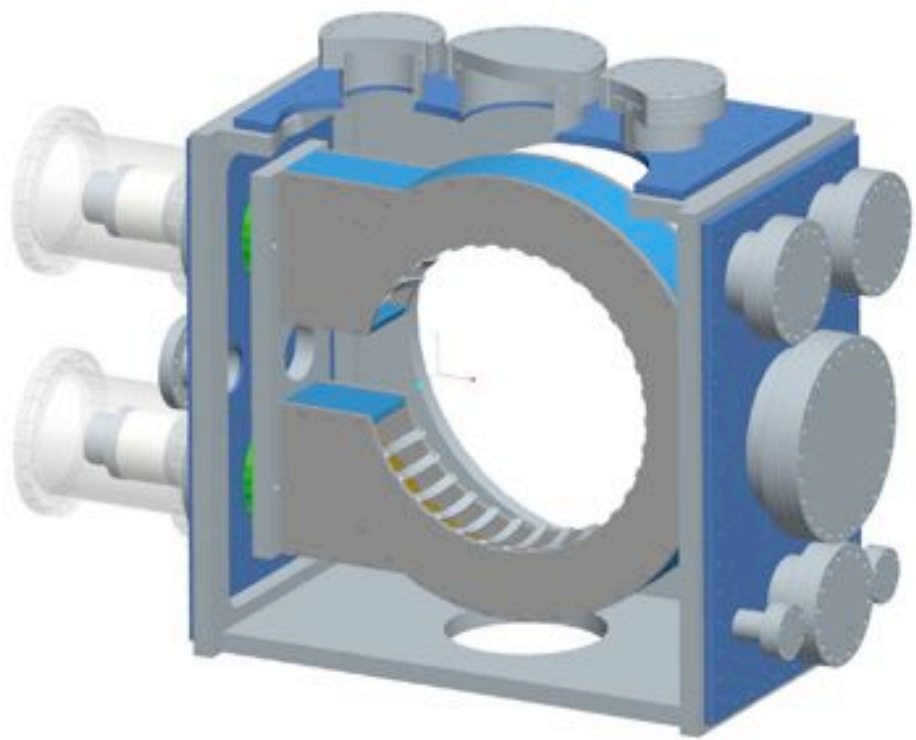
Whistler wave absorption is along the 6 GHz resonance zone





- See Steffi's poster at APS for more details

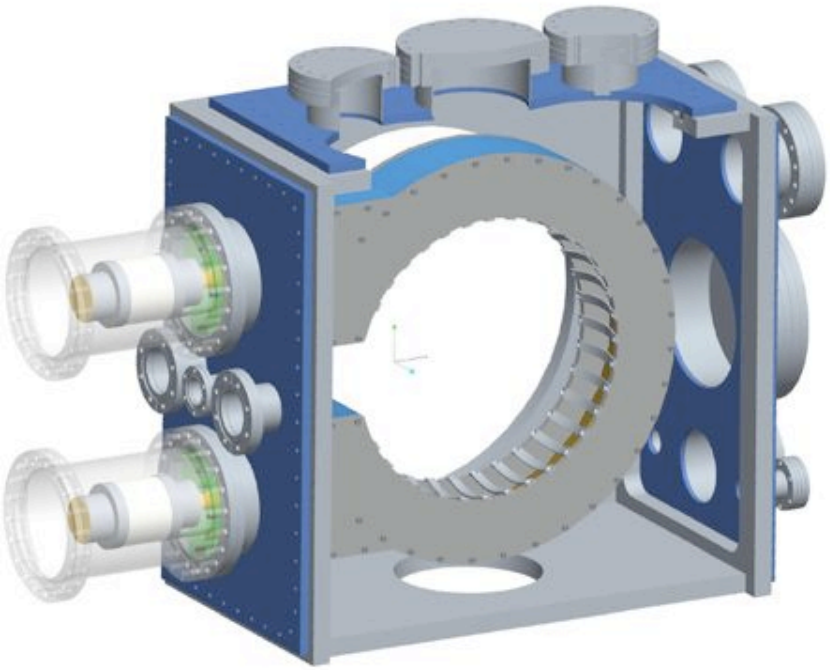
A mock-up antenna will be used to study antenna-plasma interactions

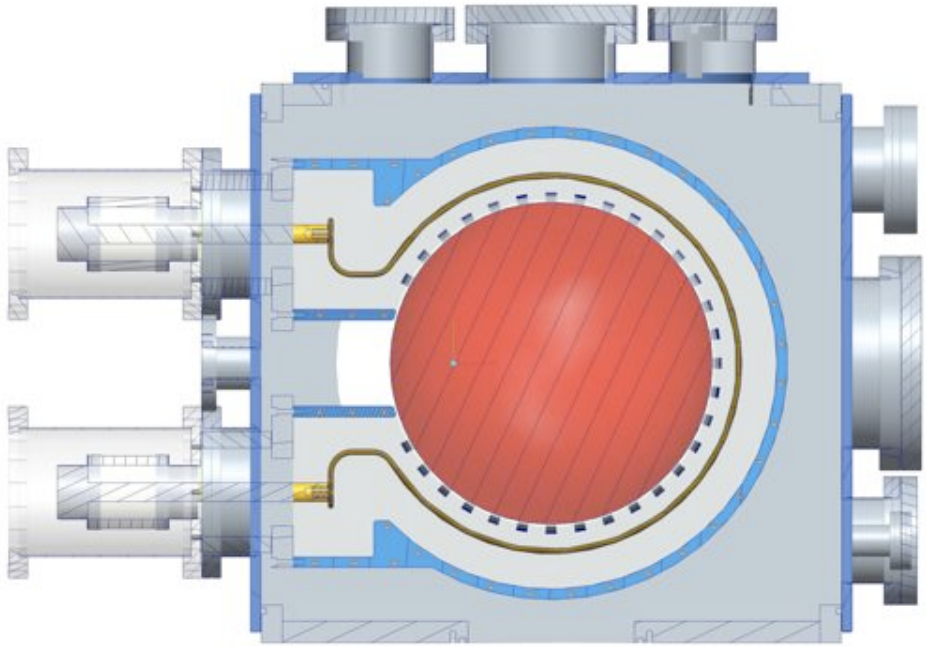


- Single current strap (copper)
- Single-tier Faraday shield (conformal to magnetic field)
- Copper-plated stainless steel structure

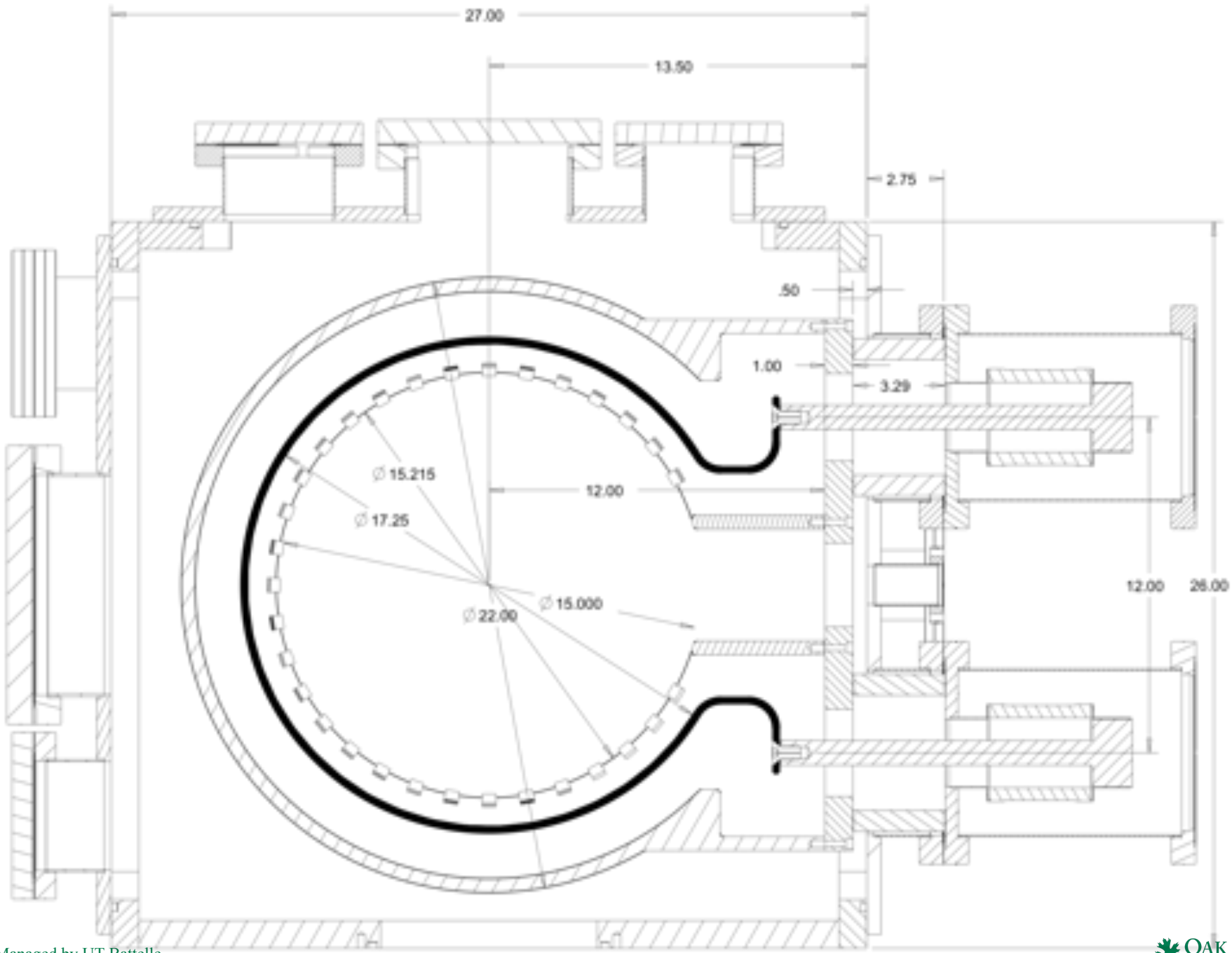
- A simple antenna will be placed in the central chamber with excellent diagnostic access
- Magnetic field geometry is well defined
- Magnetic field at antenna is 1-2 kG and plasma density 1-2x10^{12}/cm^3 (similar to NSTX)
- Many diagnostics will be used to measure near-field RF sheaths and will be compared to optical Stark measurements

A mock-up antenna can also be used to study other RF technology issues





- Arc detection, localization, and protection (GUIDAR, optical techniques, low-impedance arcs, etc.)
- Private vacuum vs. chamber vacuum
- Multi-strap antennas (capacitor concepts, too)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Summary and Future Work

- The science of the plasma material interface is a critical issue that needs to be addressed for fusion energy using dedicated research facilities for conducting the needed research
- A linear PMI research facility can provide the required plasma flux of >20 MW/m^2, but additional electron heating is needed
- This research addresses the need for electron heating in over-dense plasmas using microwaves via the whistler wave and/or the electron Bernstein wave
- Plasma operation in over-dense plasmas has started
  - Over-dense plasma heating at 6 GHz has been demonstrated
  - Next step is the PHiX LDRD experiment, where the helicon source experiment will be combined with the ECH heating experiment
- The experiment provides a magnetized plasma environment for antenna physics and technology testing
  - Mockup antenna has been designed and will soon be fabricated
  - Initial operation will focus on studying near-field plasma interactions