Experimental Considerations

Diagnostics & Plasma Heating

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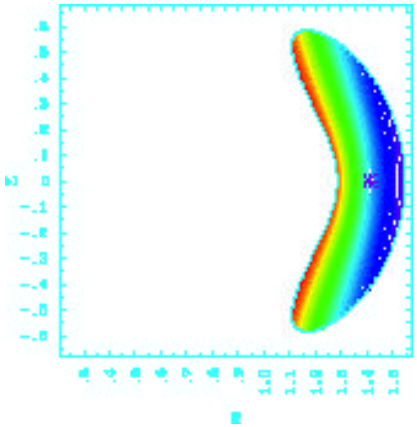
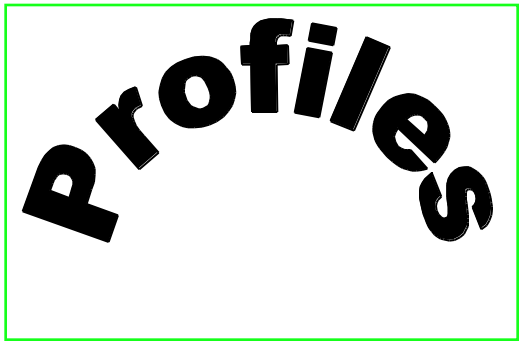
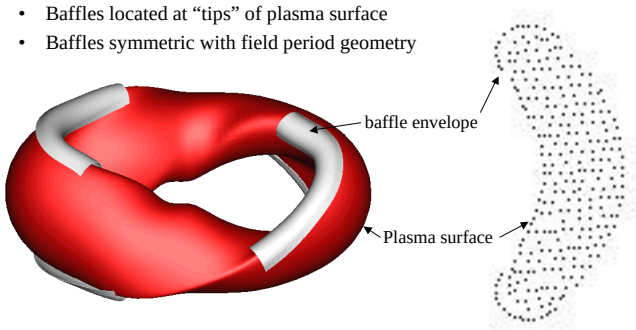
Diagnostic considerations

- **Requirements**
  - **VACUUM MAGNETIC GEOMETRY - Flexibility of configurations**
  - **MHD EQUILIBRIUM - Fragility of flux surfaces**
  - **BOOTSTRAP CURRENT - Effect on flux surfaces, internal modes**
  - **TRANSPORT- Profiles, Ion orbits**
  - **POWER BALANCE - Heating diagnostics**
  - **MHD INSTABILITY - Mode structure**
  - **PLASMA EDGE, DIVERTOR GEOMETRY - Edge plasma interactions**

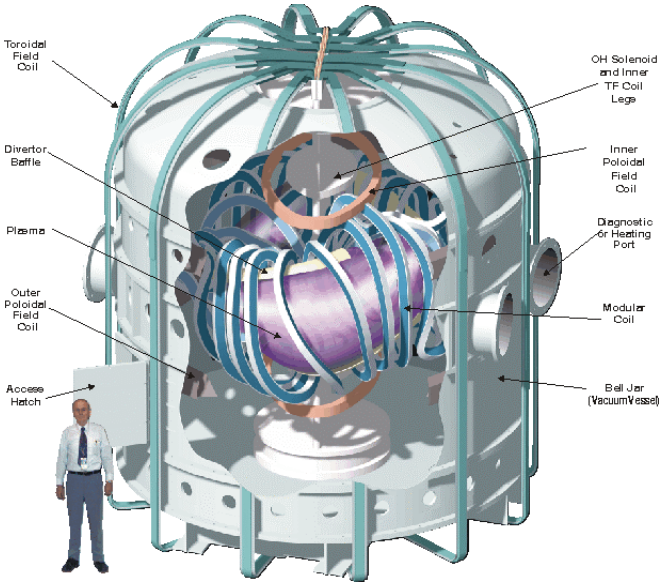






Diagnostic considerations

- **Strawman list of diagnostics based on NCSX list**
  - **Timing**
    - ✧ **Day 1 list, Phase I, Phase II, III**
    - ✧ **Need to start some efforts soon**
    - ✧ **Develop concepts on existing stellarators**
  - **Access**
    - ✧ **Vacuum vessel**
    - ✧ **Coils**



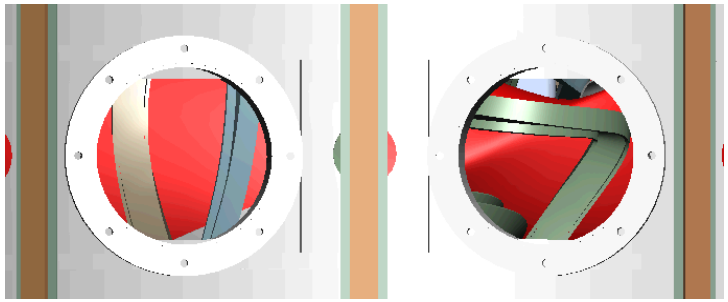
- **Sources**
  - **Existing at ORNL**
  - **Collaborator and ORNL supplied- Diagnostics from the US and International community (DIII-D, NSTX, etc.)**
  - **Collaborator required**
  - **New innovative diagnostics (use first on other experiments)**

QOS DIAGNOSTICS

black: Day 1, Phase I blue: Phase II, III red: Requires collaborators

PHYSICS AREA	CHARACTERISTICS	DIAGNOSTIC
VACUUM MAGNETIC GEOMETRY, FLEXIBILITY	starting/low beta geometry: dominant |B|components, ergodic regions, islands, aspect ratio, ellipticity, triangularity, helical axis, etc.	electron beam with fluorescent screen or rods low energy -- flux surfaces high energy -- lowest |B| components and energetic orbits
MHD EQUILIBRIUM, ROBUSTNESS OF FLUX SURFACES	finite-beta geometry: flux surfaces, magnetic axis shift, interior ergodic regions and magnetic islands	Soft X-ray detector Soft X-ray diode arrays YAG Thomson scattering, HIBP, Advanced island detection
BOOTSTRAP CURRENT	variation (reduction) with coil currents, effect on magnetic islands, ergodization of flux surfaces, and tearing modes	Rogowski coils, magnetic loops
POWER BALANCE	power deposition power losses	fast diamagnetic loop, Thomson scattering, reflectometer bolometers, spectroscopy fast ion loss cups, ECE/EBWE
TRANSPORT	electron density electron temperature profile ion temperature profile electric field	2-mm multi-channel interferometer ECE/EBWE, Thomson scattering spectroscopy, charge-exchange probes, spectroscopy, HIBP
MHD INSTABILITY	frequency spectrum, mode structure, correlations	high frequency magnetic probes soft X-ray array, Scattering diag.
PLASMA EDGE, DIVERTOR GEOMETRY	limiting aspect ratio, edge magnetic structure and islands, diverted flux bundle	Lang. probes, filtered CCD cameras, reflectometer, edge interferometer, IR camera, biased divertor plates

Diagnostic access

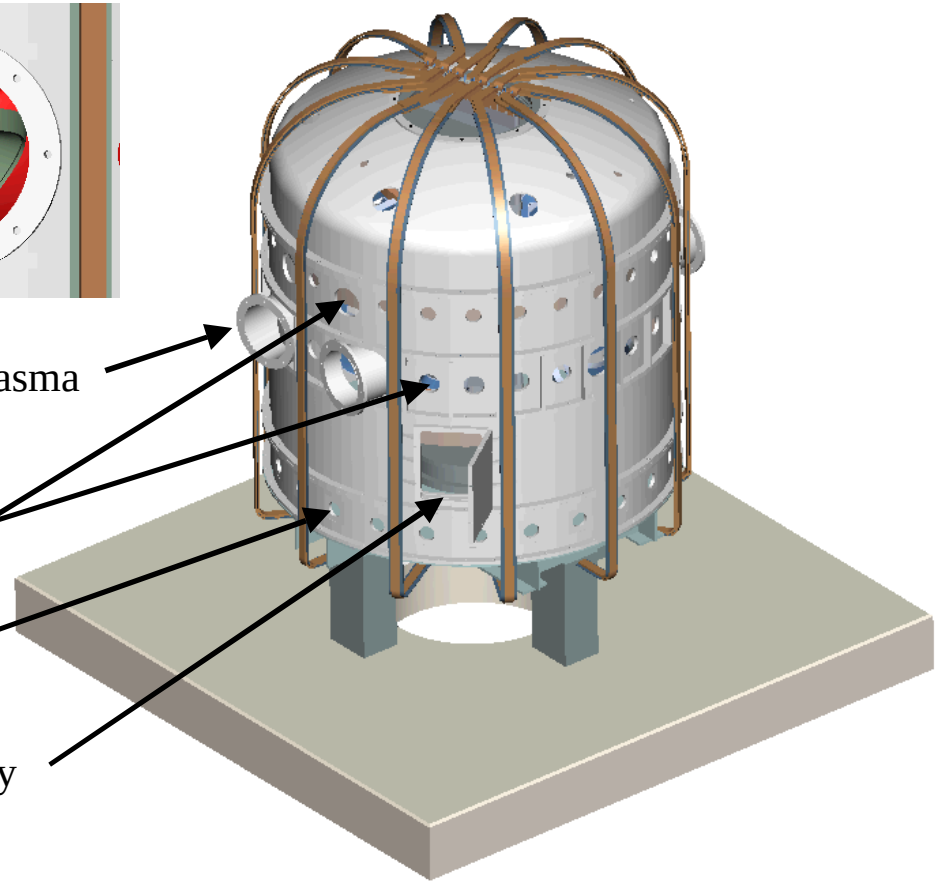


4 x 22” dia. ports, red (above) is plasma

18 x 8”, 6 x 12” , 23 x 6” ports

24 x 6” ports for coil leads,
coolant feeds, etc.

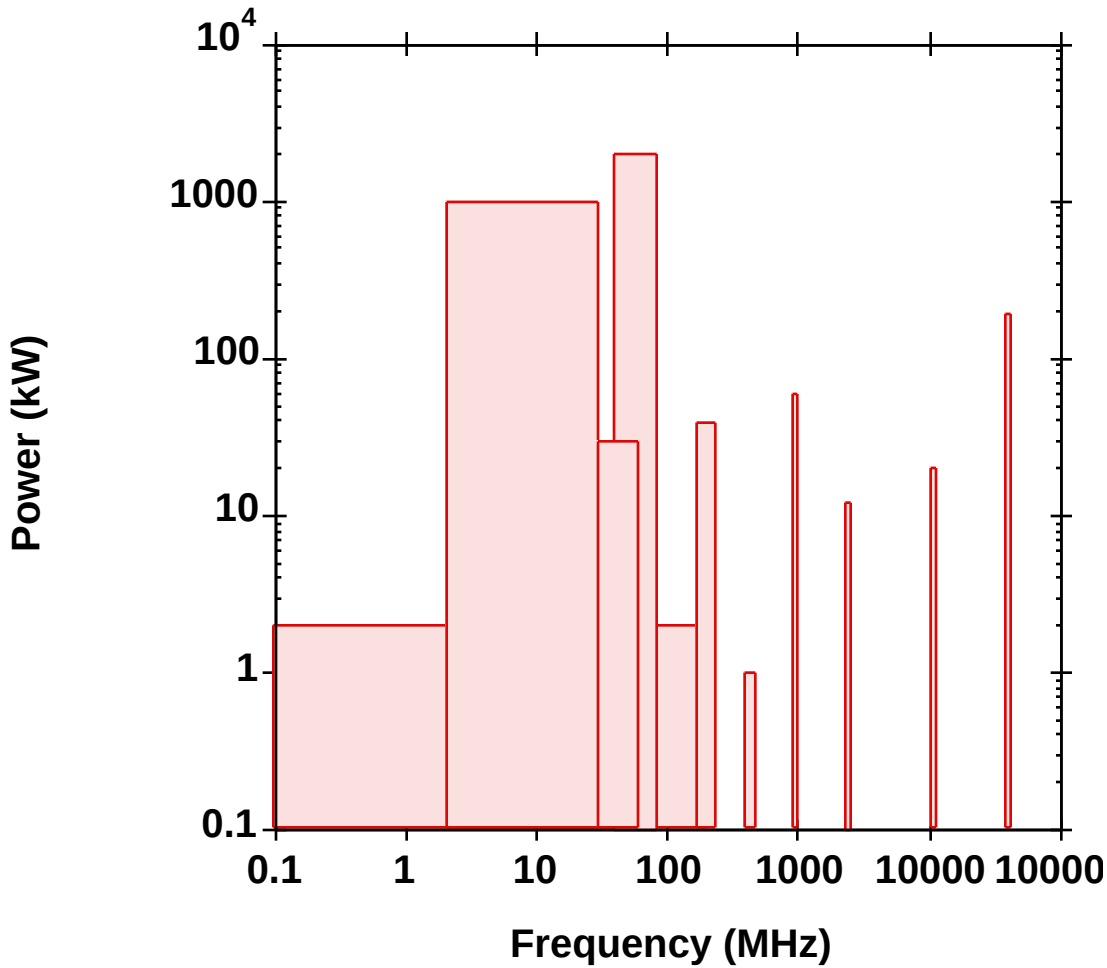
Manway



Plasma Heating Introduction

- QOS offer new opportunities in ICRF, ECH/EBW
  - What are the options?
  - What heating, current drive, profile, or flow control is desired?
- Worldwide ICRF and ECH experience on stellarators can be applied to QOS
- QOS has the access and conditions for ICRF, ECH and EBW
- Heating of bulk electrons and ions at high beta is achievable

Power and frequency ranges available



ICRF, ECH and LH Assets

ICRF

6-20 MHz	**2ea. 1MW ea. BBC transmitters**
40-80 MHz	**1ea. FMIT transmitter**

ECH/EBW

> 2MW ECH supply (pulsed) with 9 sockets/magnets

53 GHz	**3ea. 200kW ea.**
56 GHz	**1ea. 200kW ea.**
28 GHz	**4ea. 200kW ea. Suitable for EBW**
35 GHz	**1ea. 200kW ea.**

53 GHz 1MW is also possible from Russia ~500K

Lower Hybrid

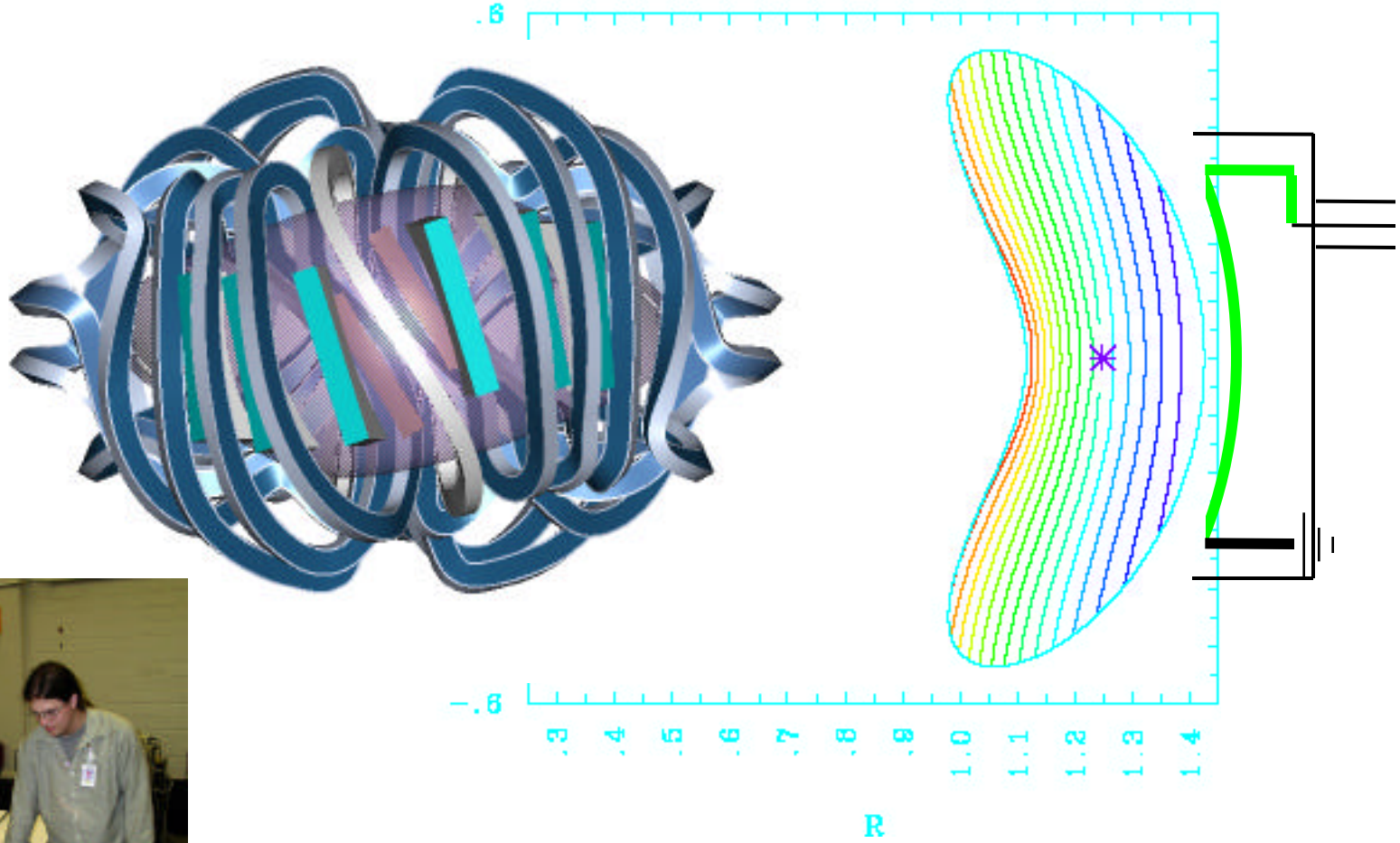
2.45 GHz 1MW (parallel electron heating)

915 MHz, 800 MHz ~100 KW

ICRF options in priority order

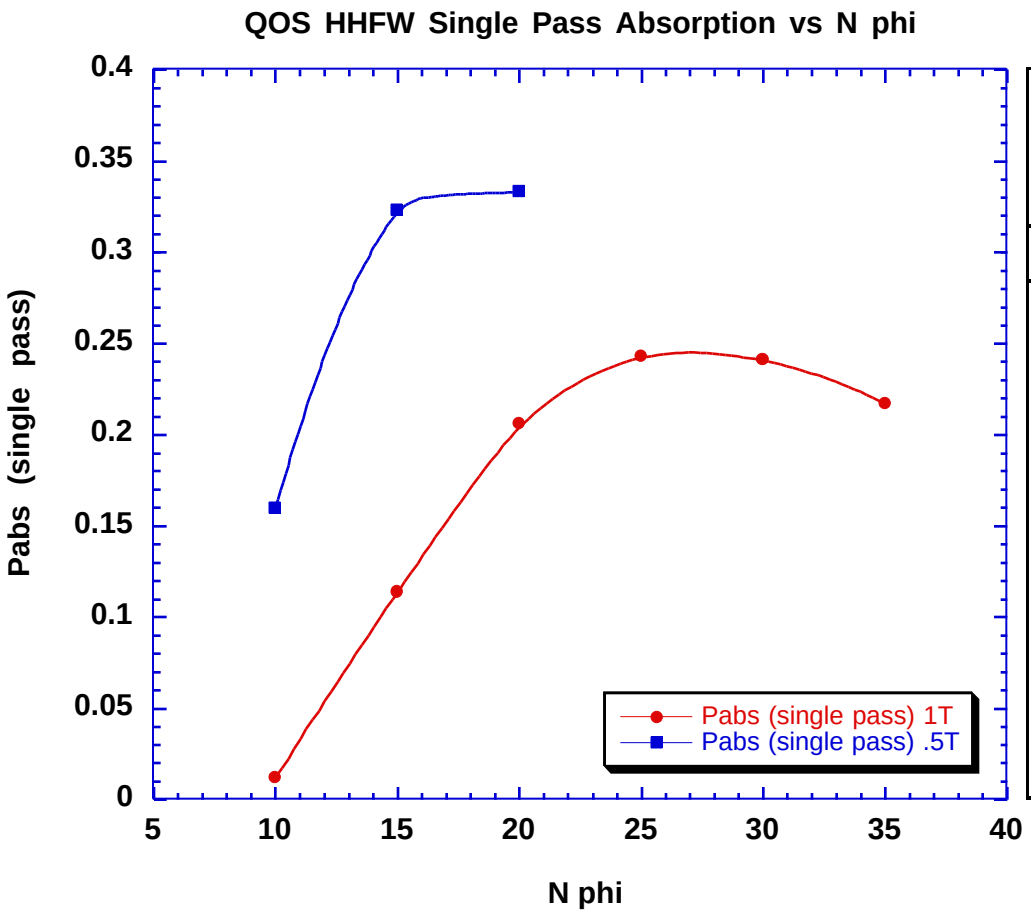
- **Direct electron or high harmonic heating (≥20 MHz)**
  - FW and HHFW bulk electron heating
- **Mode conversion heating (~ 15 MHz at 1.0 T)**
  - IBW mode conversion at two-ion hybrid resonance layer
  - bulk electron heating
- **Minority heating (~ 14 MHz at 1.0 T ; He majority, H minority)**
  - ~ 5 % minority (tail heating)
  - ~ 30 % minority (bulk ion heating)
- **Magnetic beach heating (< 14 MHz at 1.0 T)**
  - bulk ion heating
- **Current drive and flow control (≥20 MHz)**
  - FW and HHFW current drive
- **LH 2.45 GHz, 915 MHz, 800 MHz**

FW & HHFW and Minority heating



Low Field Side Antenna (NSTX style)

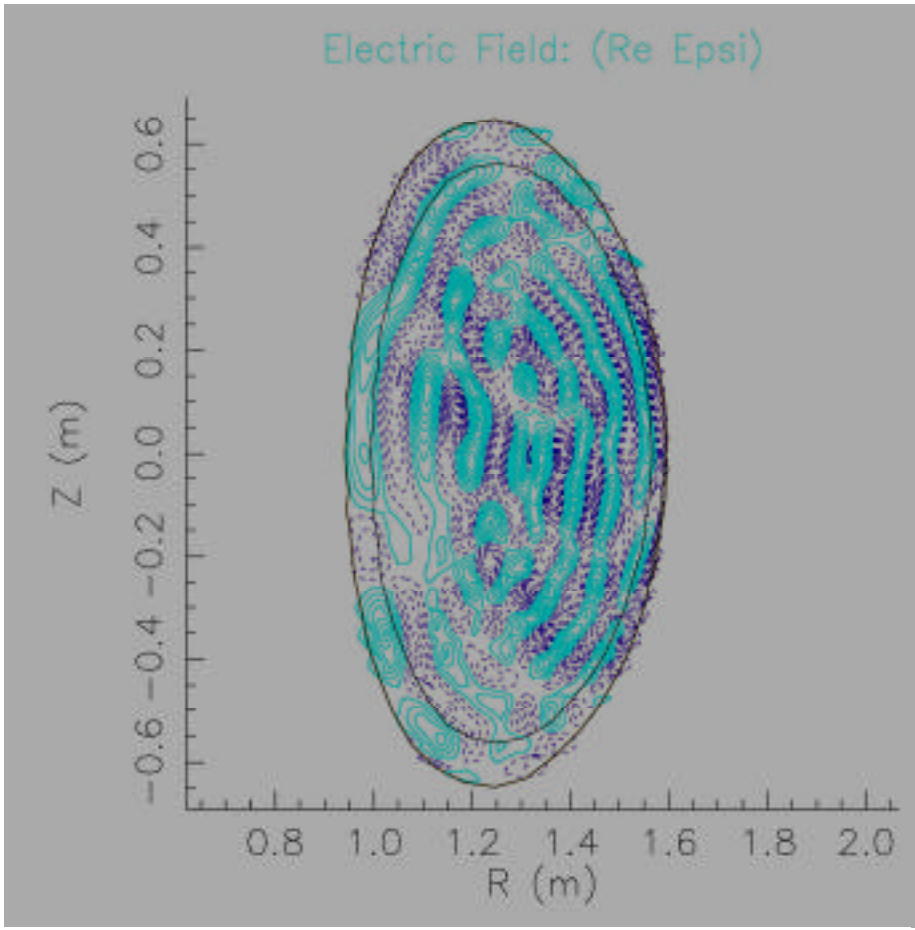
Single Pass Absorption Calculations for HHFW Look Promising

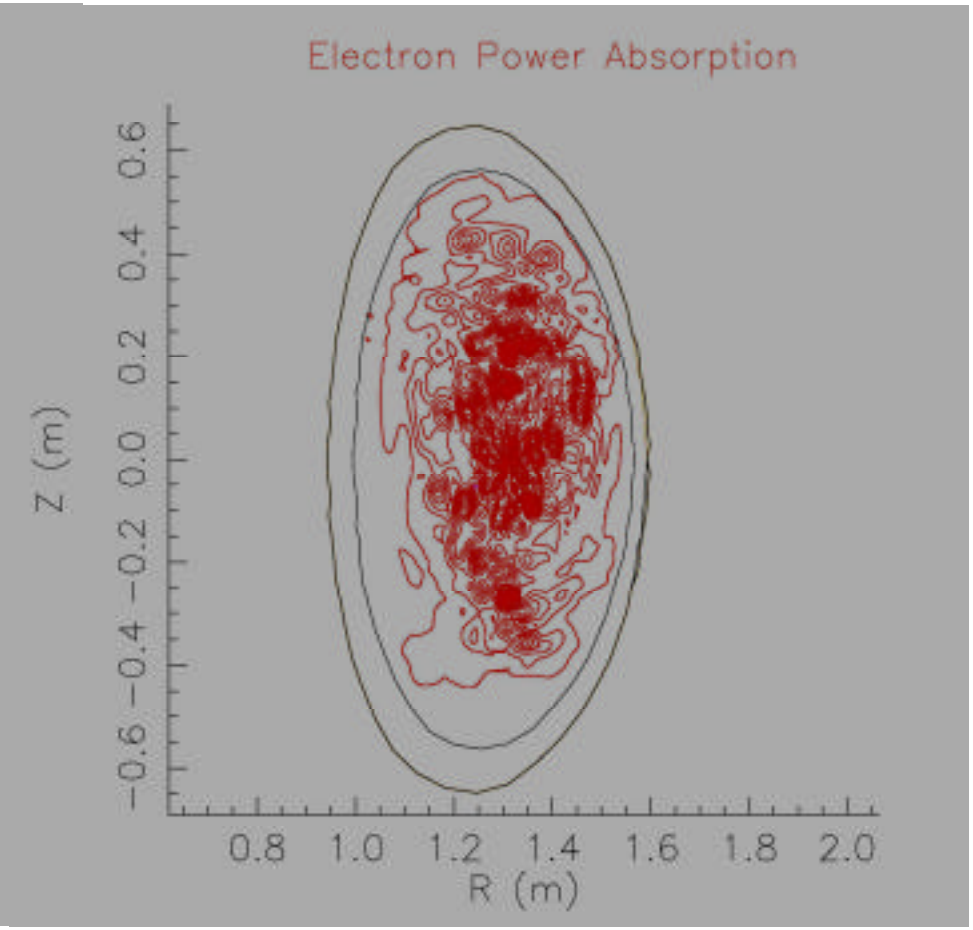


ECH power perpendicular electron heating	28 GHz 4 @ 300KW ea. 2nd 28	53 & 56 GHz 4 @ 200KW ea. 2nd 53
Parameter	**low**	**high**
B (T)	0.5	1.0
R (m)	0.83	0.83
a (m)	0.35	0.35
V_p (m^3)	1.78	1.78
P (MW)	1.0	0.5
n (10^{19} m^{-3})	0.45	1.8
$<\beta>$ (%)	1.5	1.02
τ_E (ms)	2.25	12.1
T_{e0} (keV)	3.1	2.1
T_{i0} (keV)	0.30	0.23

Jaeger

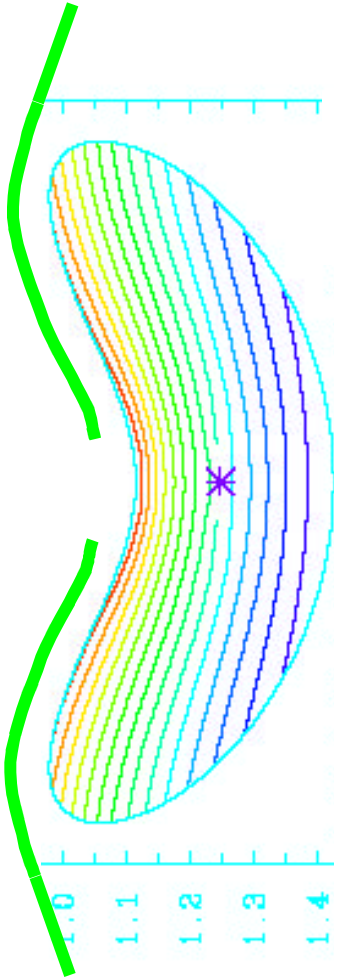
HHFW Absorption 1T 1% beta 60 MHz



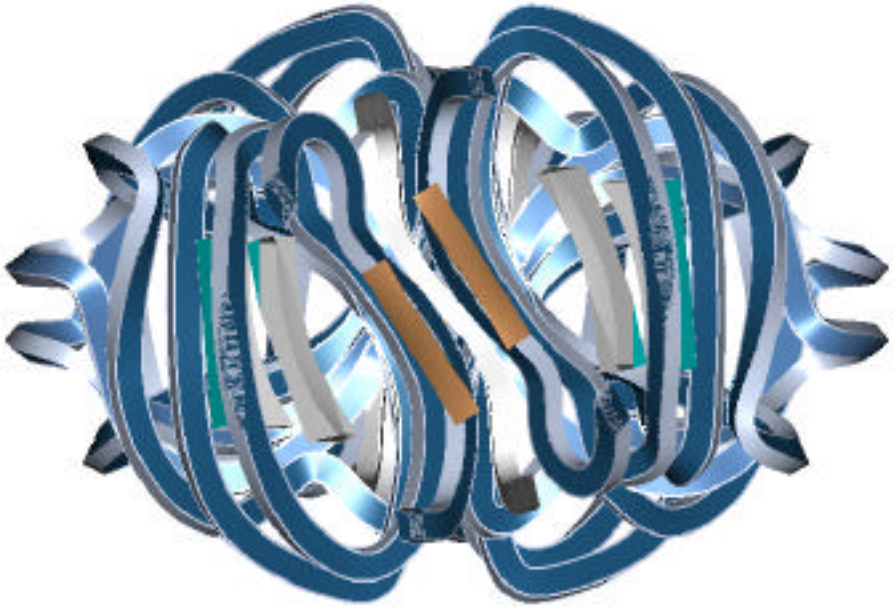


Fred Jaeger

Mode Conversion, Minority heating



Upper and lower single strap antennas



High Field Side Antenna (LHD/CHS Style)

Mode conversion heating of electrons and ions on CHS

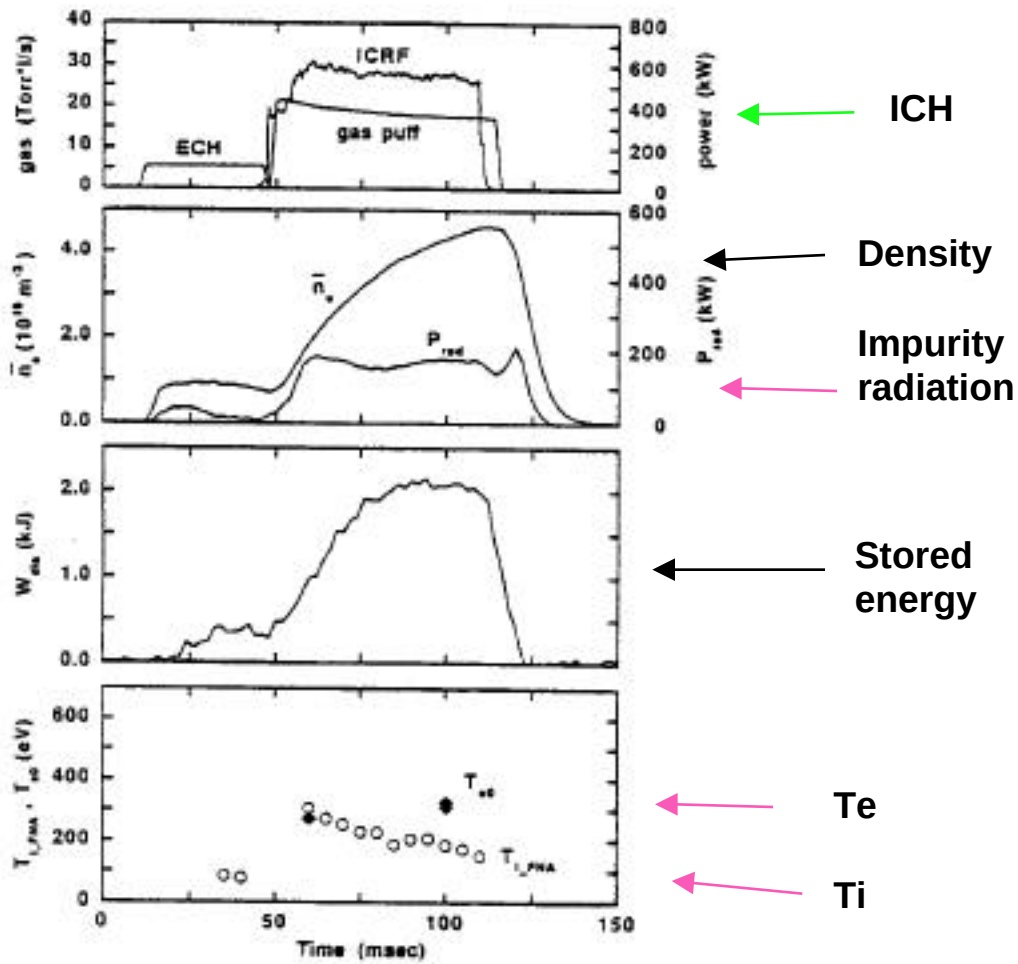
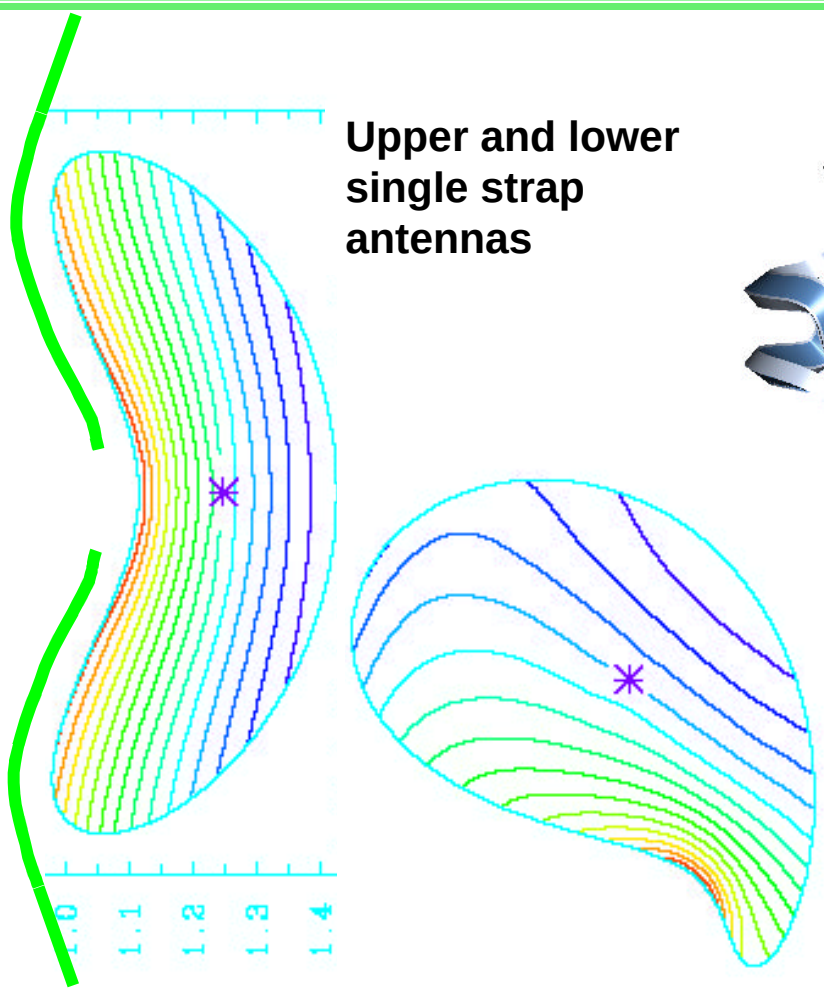
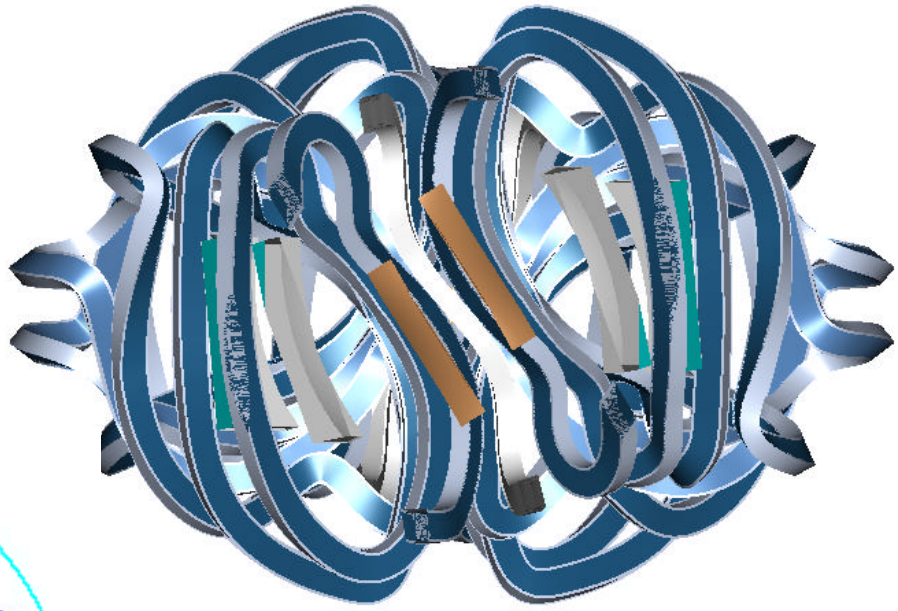


Fig. 3 Temporal evolution of plasma parameters for an ICRF heating experiment (#40991). Top column : gas puffing rate and input power. Second column : line averaged electron density and radiation loss. Third column : stored energy measured by a diamagnetic loop. Bottom column : electron and ion temperature measured by Thomson scattering and NPA, respectively.

Beach heating - similar to W7-AS



Upper and lower single strap antennas



ICRF propagates to lower field “beach” region

High Field Side Antenna (LHD/CHS or W7-AS Style)

Magnetic Beach heating on W7-AS

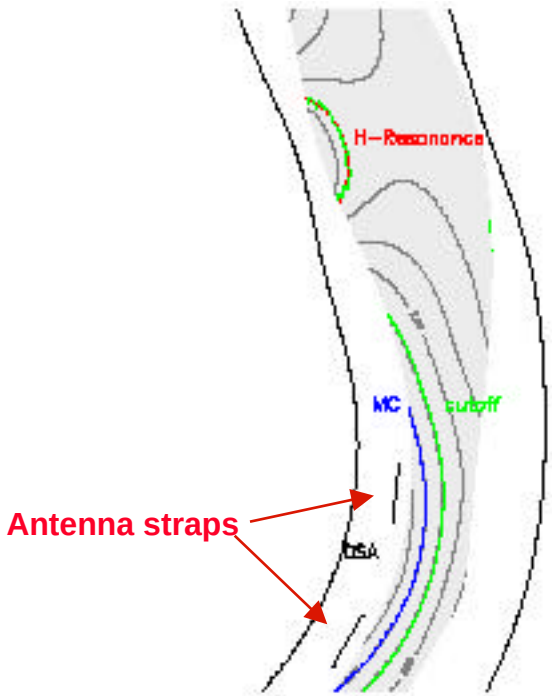


Figure 11: Horizontal cross-section with magnetic field contour lines of a half module in W7-AS for a mirror configuration with two ion hybrid resonance (MC) and associated cutoff. Mirror ratio $M=0.85$.

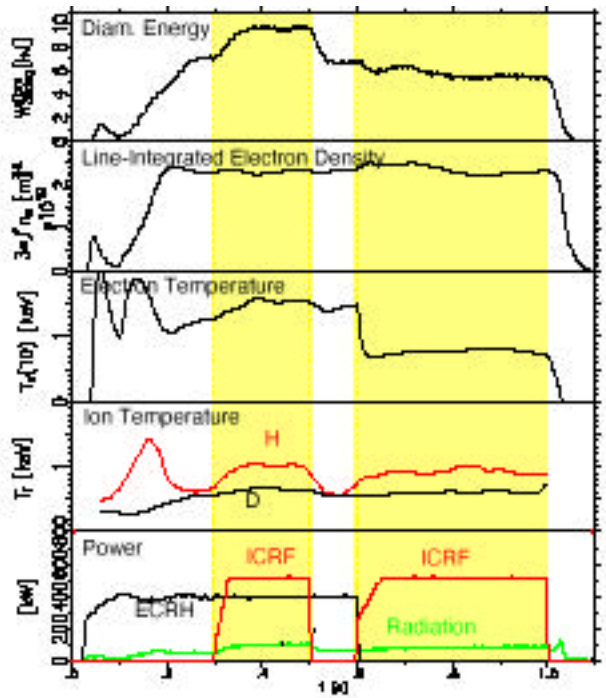
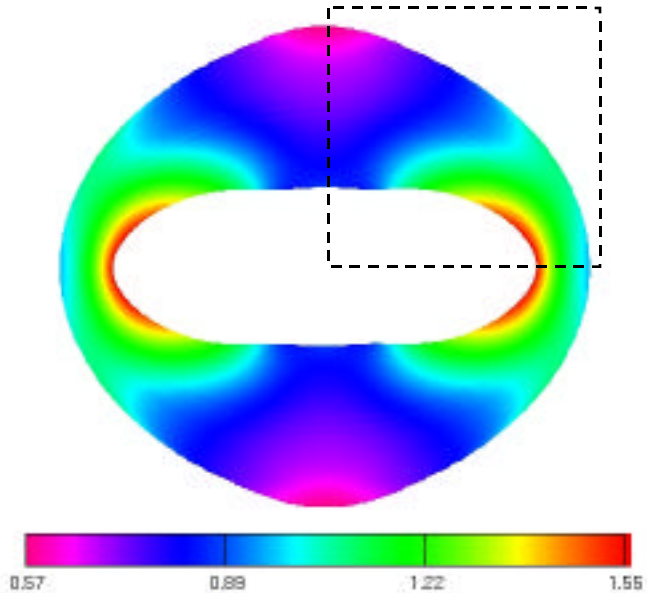


Figure 12: Example shot for magnetic beach heating.

Hartman, et al

Mod-B Contours midplane



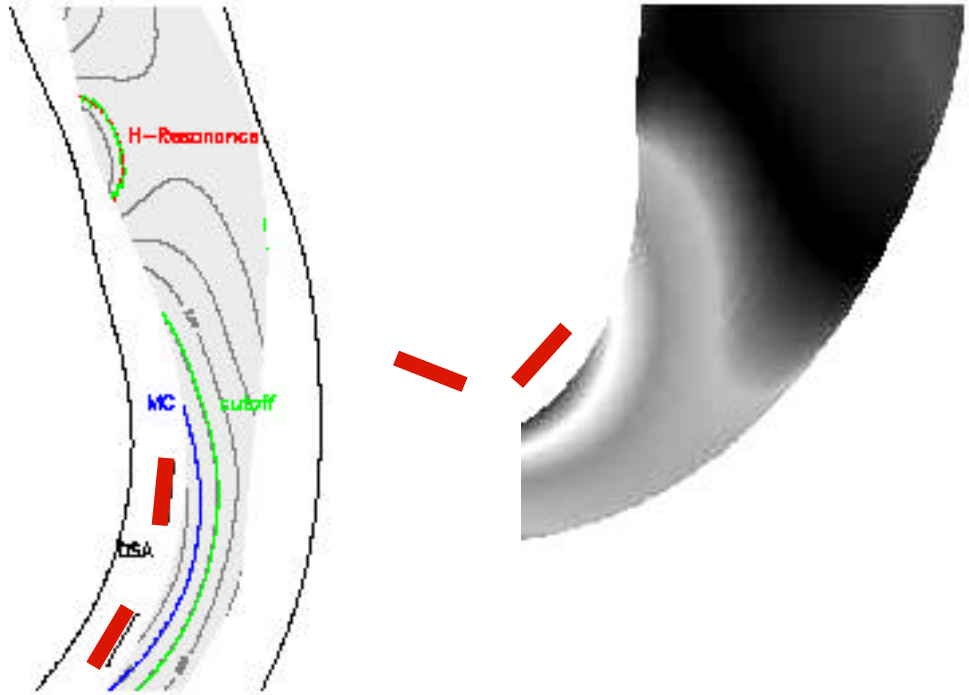
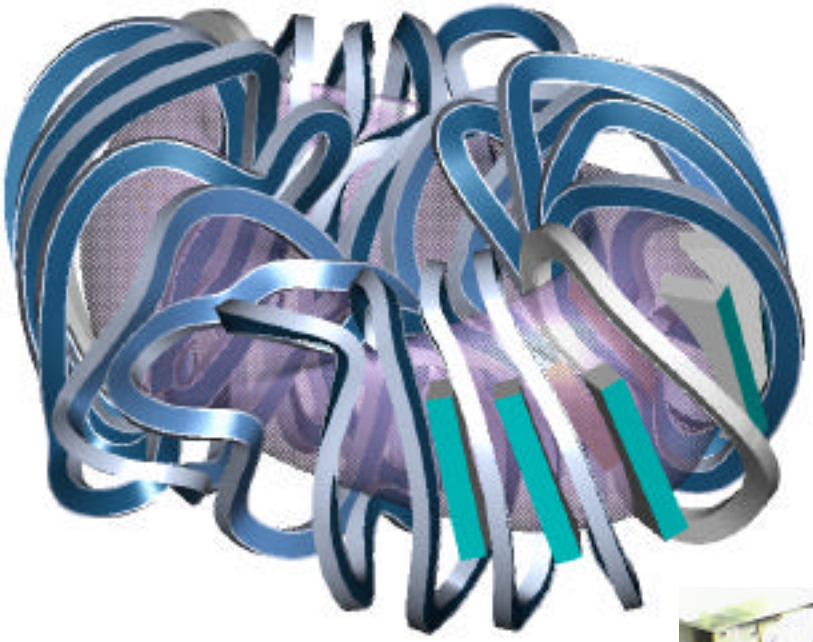
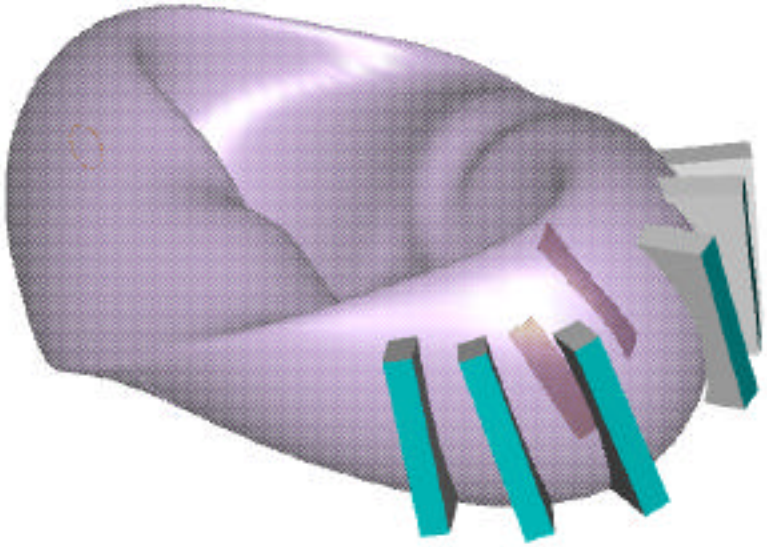
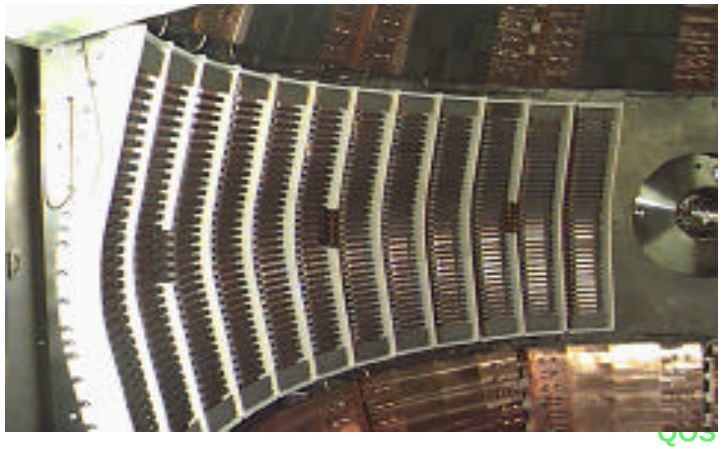


Figure 11: Horizontal cross-section with magnetic field contour lines of a half module in W7-AS for a mirror configuration with two ion hybrid resonance (MC) and associated cutoff. Mirror ratio $M=0.85$.

FW and HHFW array for current drive and flow control (NSTX style)







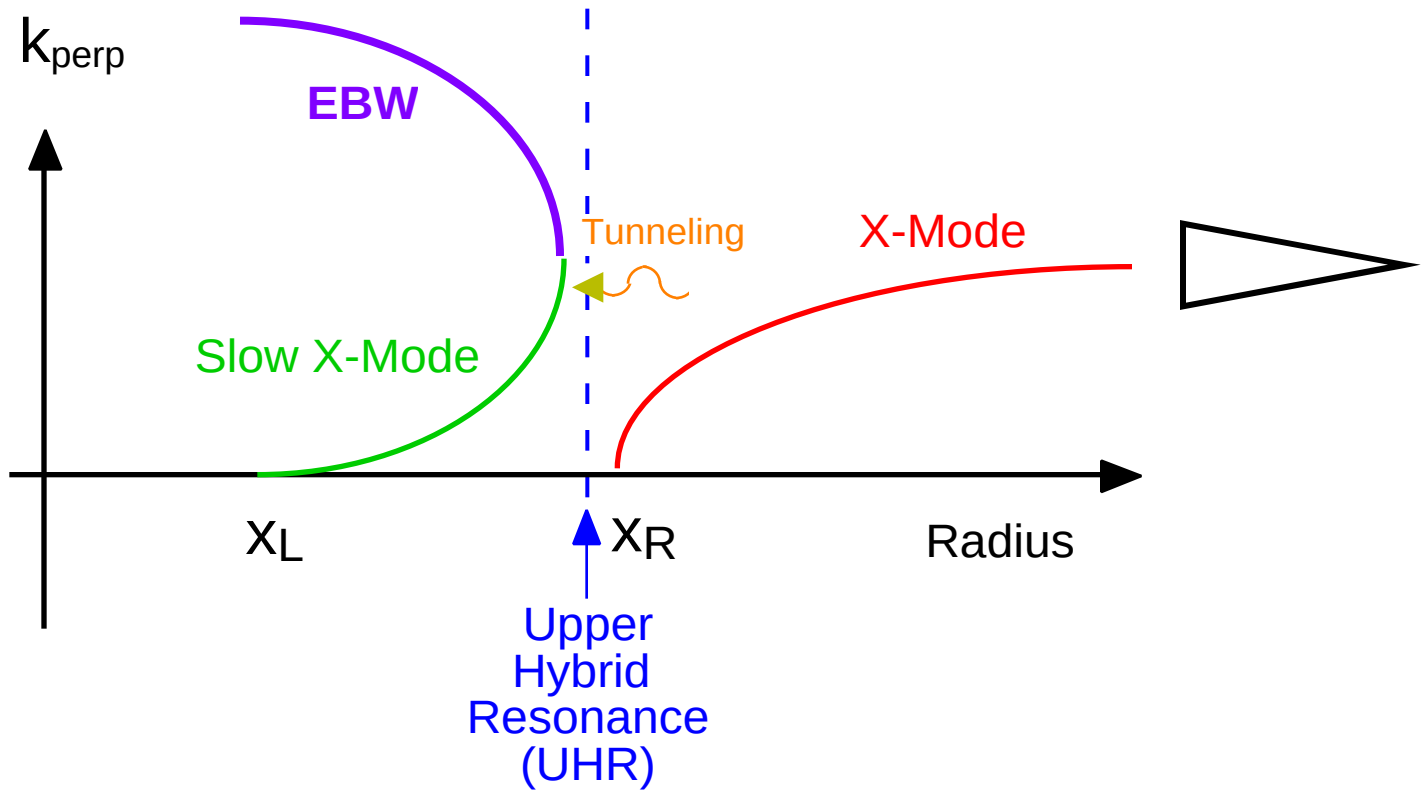
Motivation for Electron Bernstein Wave Emission Studies and Heating & Current Drive

- **High β plasmas with $\omega_{pe} >> \Omega_{ce}$ (NSTX) cannot use ECH, ECCD or ECE $T_e(R,t)$ diagnostics High β on QOS will also benefit from EBW**
- **Electron Bernstein waves (EBWs) can propagate in these "overdense" plasmas**
- **EBWs have high optical thickness at ECE resonances; τ ~ 1000 for QOS**
- **Potential for local heating, current drive and $T_e(R,t)$ diagnostic**
- **EBW emission can yield information about viability of EBW heating and current drive**

Fast X-Mode via Mode Conversion to EBW

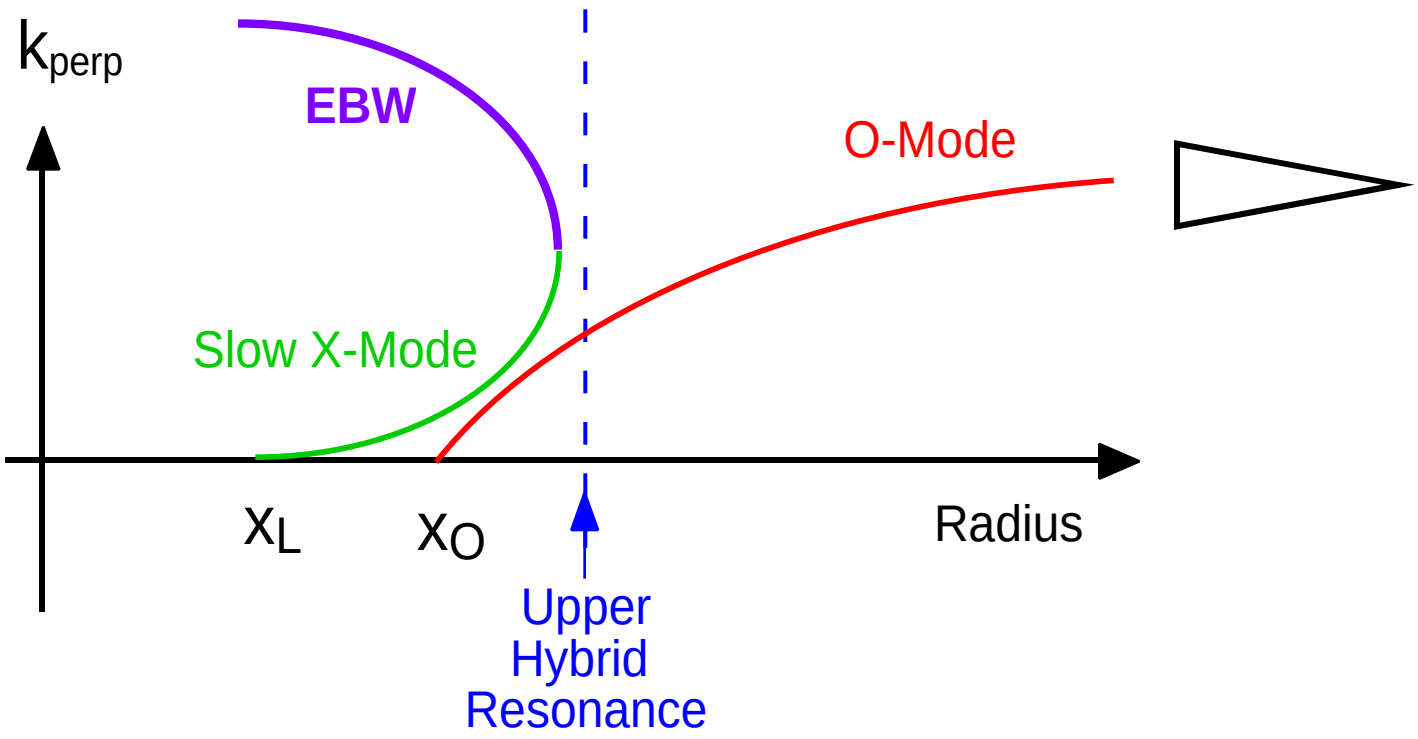
If L_n is steep at UHR, X-mode can tunnel through to the EBW mode

Heating is the reciprocal of the emission process

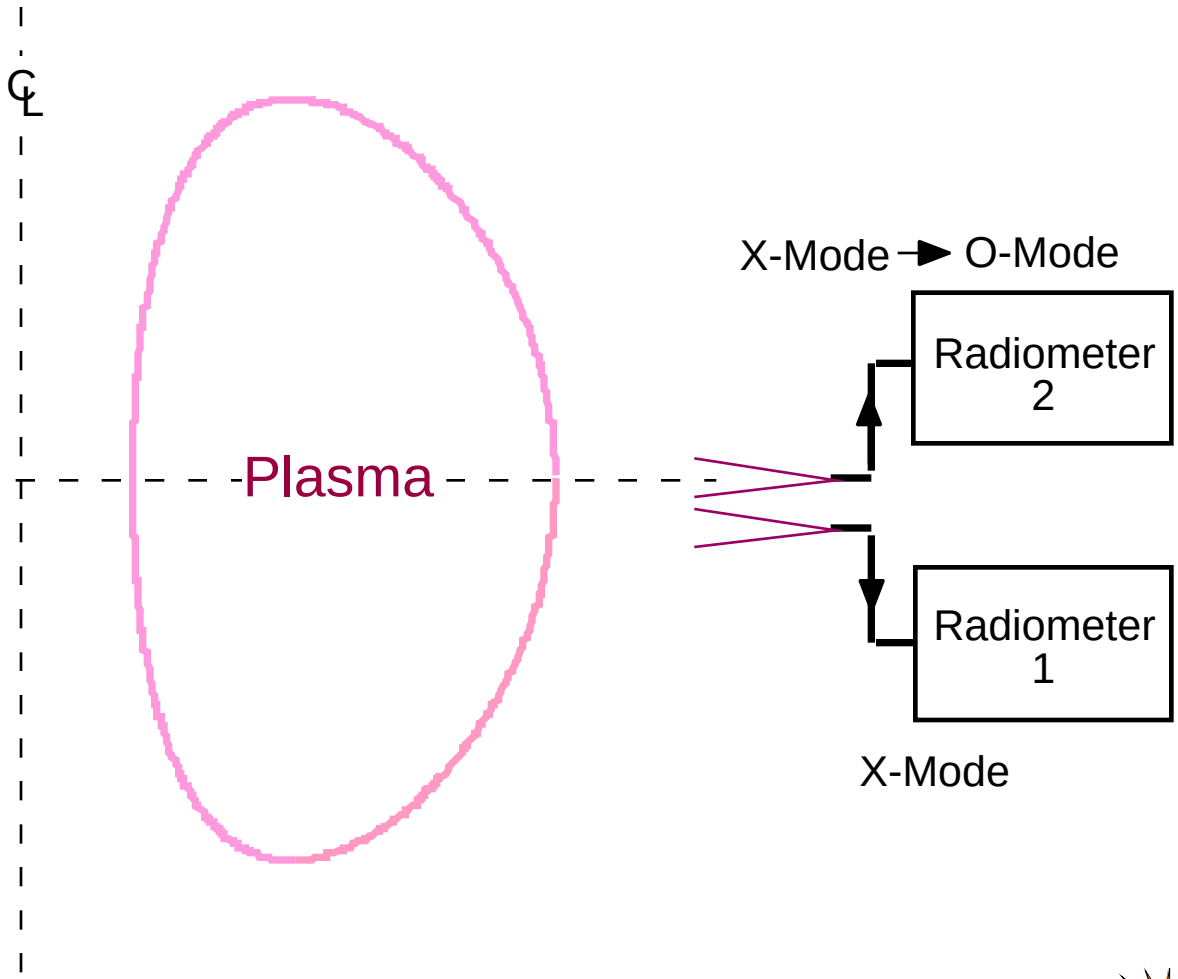


O-Mode to EBW Mode Conversion (O-X-B) Possible with Oblique Launch/View

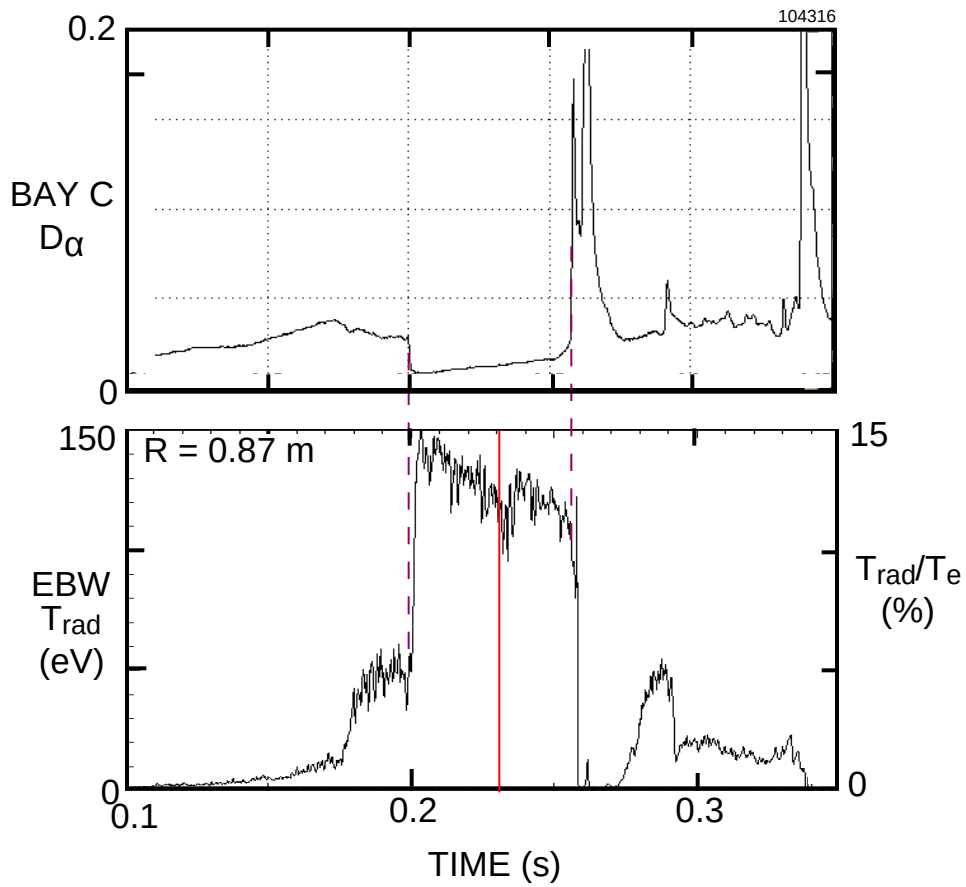
This mode conversion process studied by Laqua *et al.* on W7-AS stellarator



EBW Polarization Simultaneously Measured with Two Radiometers on NSTX

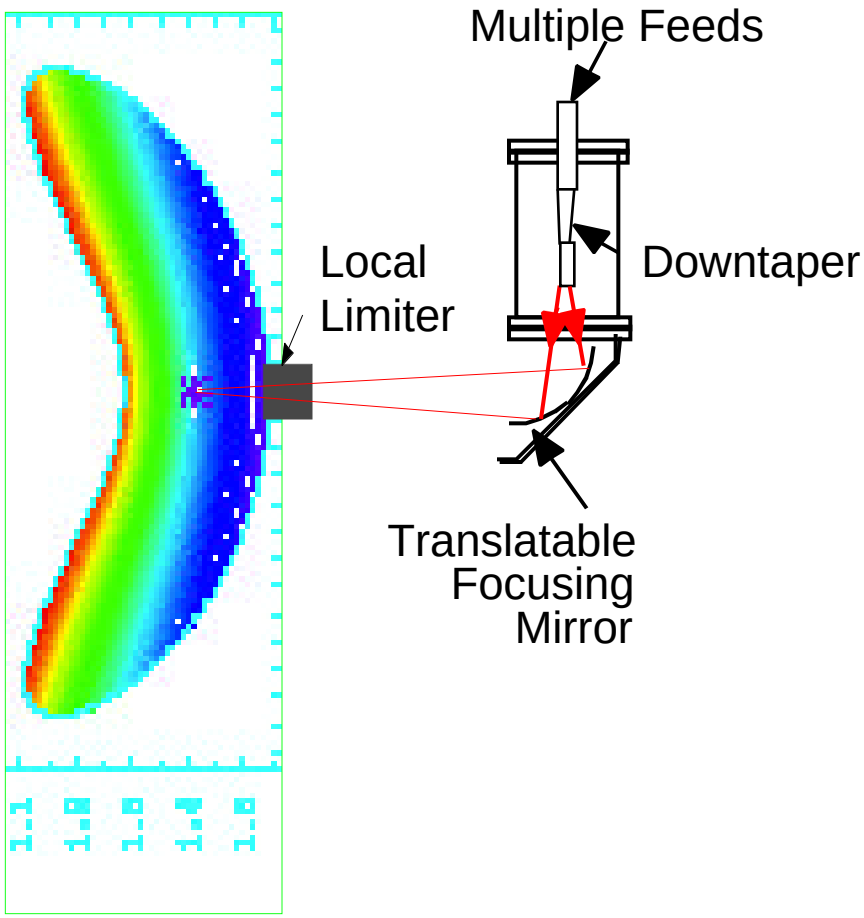


EBW Mode Conversion Efficiency Increases to 15% at L-H Transition, Consistent with Theory



- **Edge L_n ~ 1 cm from Thomson scattering implies EBW T_{rad}/T_e ~ 11% at 0.23 sec**

Conceptual layout of 28 GHz n// = 0 Launch EBW Antenna Located on QOS Midplane



- **Focusing mirror translated poloidally to vary $n_{//}$ at EBW resonance location**
- **Local limiter to define critical L_n for maximum X-EBW mode conversion**

ICRF and ECH/EBW Summary

- QAS & QOS offer new opportunities in ICRF, ECH/EBW
- ICRF is successful on similar sized stellarators
- Access and conditions for ICRF look favorable
  - Several possible ICRF antenna designs
    - High field side antennas may be possible similar to LHD/CHS, W7-AS
    - Low field side antennas similar to NSTX
  - HHFW, Mode conversion & magnetic beach heating look possible
- ECH will be a mainstay, EBW is a good high beta option
- Open issues
  - First pass absorption for ECH and ICRF
  - ICRF antenna size and directivity (?)
  - Outside or inside or both?
  - EBW coupling efficiency
  - LH frequency and port size
  - Others