Assessment of ITER LFS Reflectometer System

Presented by

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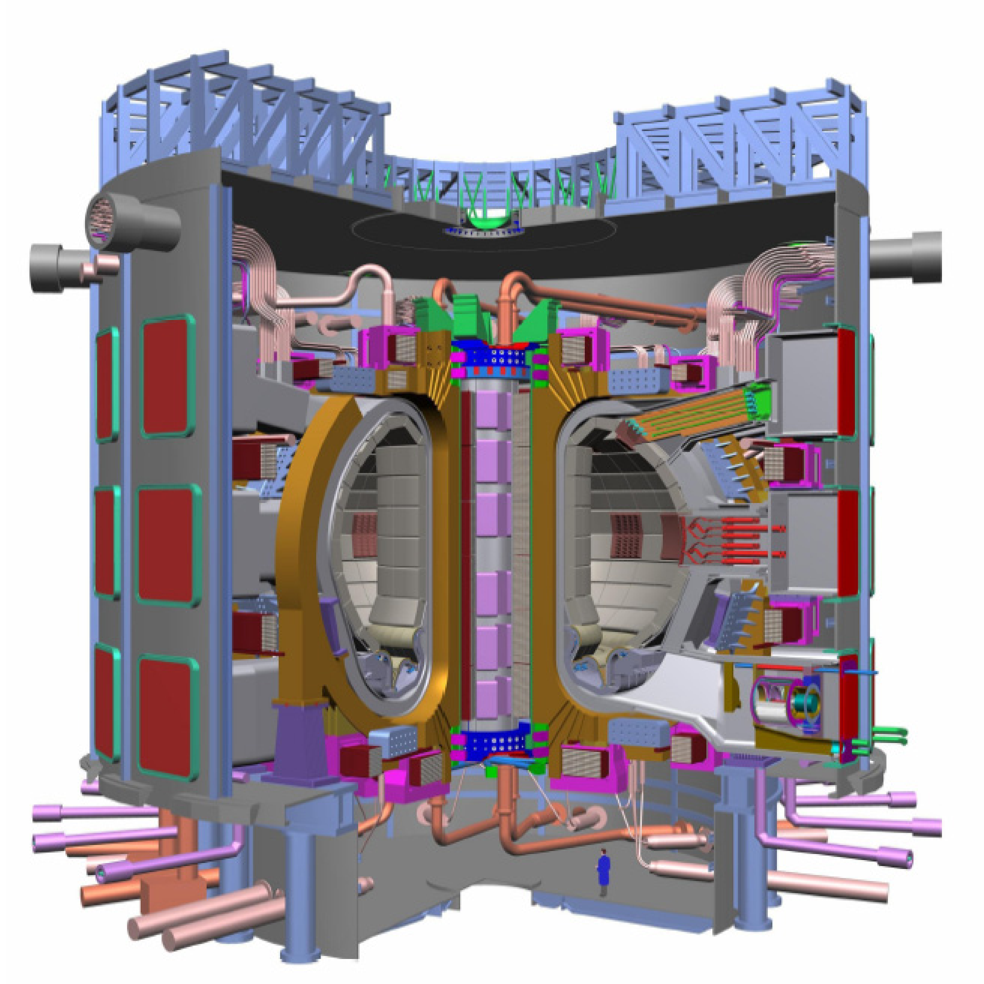


12th Meeting of ITPA Topical Group on Diagnostics
PPPL, 3/26/2007

Assigned U.S. IPO tasks for the LFS reflectometer assessment

1. **Review the reference design** and characterize the range of radial coverage for a number of appropriate ITER operating scenarios, **including relativistic effects** on cutoffs and absorption.

2. **Optimize** the choice of **frequency ranges and polarizations** to best satisfy the measurement requirements for **density profile measurements**. Also assess the impact of these choices on the measurement of other plasma parameters.

   Optimization should be done under the **constraint** that the **maximum number of waveguide runs is twelve**.

3. Assess the **cost and benefit of combined LFS reflectometer/ECE** operation and the impact on the front-end design of the US components in this plug.

4. Assess the **cost and benefit** of the use of two of the horn pairs for **Doppler reflectometry**, again under the **constraint** that the **maximum number of waveguide runs is twelve**.

Assessment is *preliminary* and clearly *more work is needed*

Measurement priorities

After discussions with ITER Central Team and the RWG my understanding of the ITER measurement priorities are as follows:

(1) Profile in the scrape-off and gradient regions.

- Note that this would extend well into the LFS core plasma for peaked density profiles.
  - HFS reflectometer would typically NOT access this region for peaked profiles.
- **Profile measurement in gradient and SOL is "absolutely required"**
- Prioritization of other deliverables more flexible

(2) Monitor for MHD modes such as NTM, Alfven instabilities

(3) Plasma flow, turbulence

The above measurements, especially the profile capability, should be available for plasma magnetic axis height variations as large as ~40cm

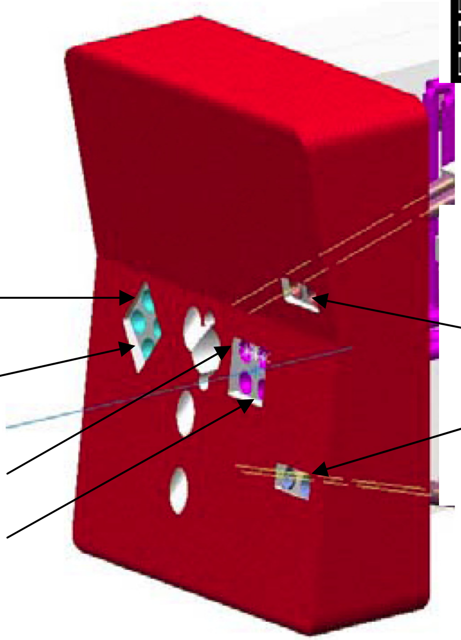
Front-end antenna configuration & optimization should be focused on meeting these prioritized requirements

Major concerns in LFS proposed design

- **In ITER, density profile measurement becomes strongly dependent on T_e !**
  - Little discussion to date. Need to assess density profile inversion sensitivity to uncertainties in knowledge of temperature profile. **Major issue.**
    - **NOTE**: O and X-mode cutoffs are modified **DIFFERENTLY**
    - **In some situations, this allows BOTH density & temperature profiles to be determined.**
- **How will up/down plasma position & shape variations be handled?**
  - Ray tracing indicates accommodating these variations represents a significant challenge
  - Optimize for edge pedestal? Core access required for peaked profiles. Also, highly desirable for Alfven waves, NTMs, etc. **HFS reflectometer cannot access this region for peaked profiles.**
- **What is the optimum front-end antenna configuration?**
  - Bi-static vs mono-static antenna configuration?
  - Bi-static preferred (no spurious reflections, directivity not an issue)
  - However, increases number of waveguides or requires combining O & X into same waveguides.
  - Mono-static employed extensively on ASDEX. Can we employ on ITER? Significant benefit !
    - Needs thorough demonstration at relevant frequencies.
- **How will measurement redundancy be achieved?**
  - O and X mode systems. Is this sufficient ?

Recent modifications to DDD antenna configuration
12 total waveguides – same as in DDD

- **Recently (May 2006) Dr. George Vayakis (ITER CT) updated the locations of the antennae to accommodate the more recent ITER configuration**



Antenna locations

System	Antenna	R	Z	theta	phi	Nom. Size (mm)	Picture
LFS, Doppler, Top	right	8475.5	939.6	195	0	89.5 circular	LFS
LFS, RH cluster	TOP_RIGHT	8497.8	529.7	180	0	89.5 circular	LFS
LFS, RH cluster	BOTTOM_RIGHT	8497.8	399.1	180	0	89.5 circular	LFS
LFS, Doppler	left	8470.0	151.0	165	0	89.5 circular	LFS

2 O-mode pairs **2** X-mode pairs

2 angled Doppler reflectometry pairs

Corrugated waveguide diameter ~64mm.

Tapered at plasma to ~90mm to accommodate lower frequencies.

Bi-static antenna arrangement assumed.

X –mode 76-220 GHz O-mode 15-155GHz

Note that proposed adjacent waveguides are separated by ~ 13cm

Located ~ 30cm from LCFS

More recent estimates indicate plasma magnetic axis height variation of ~40cm

Concerns regarding proposed antenna locations
- too close to LCFS

- **Proposed antennas are only 30cm away from LCFS**
  - X-mode reflection occurs well *outside* LCFS (i.e. required measurement in SOL)
- **The relatively large separation between the proposed bi-static antennas (13cm) will result in significant phase errors for reflections within SOL**
  - Simply a geometry issue - path length between transmit and receive antennas significantly larger than direct path assumed in inversion.
  - Proposed bi-static system would REQUIRE very low gain antennas (i.e. smaller diameter) simply to receive EH_{11} signal return.
  - Such antennas would have very large antenna patterns in plasma core guaranteeing a small signal return and potential acceptance of "exotic" ray paths. Background ECE ~ 1.6 10^{-7} W/GHz keV (~100μW in 30GHz bandwidth with Te~ 20keV)
- **The currently proposed antenna configuration is unacceptable**
- **Requires modification**
  - Locate antennas deeper into port plug – another 30cm probably sufficient
  - Move bi-static antennas closer together: reduces errors; allows use of higher gain antenna
  - Utilize mono-static configuration (discuss later)?

Reflectometry measurements in ITER are strongly dependent on temperature

- **High electron temperatures modify location of cutoff layers**

  G.J. Kramer et al, Nucl. Fusion **46** (2006) **“2D reflectometer modelling for optimizing the ITER low-field side X-mode reflectometer system”**

- **In ITER these modifications can be every large**
  - O and X mode cutoffs respond differently
  - X-mode RH cutoff has largest modifications

- **If relativistic effects are ignored, inversion of measured phase leads to <u>very large errors</u> (~35%).**

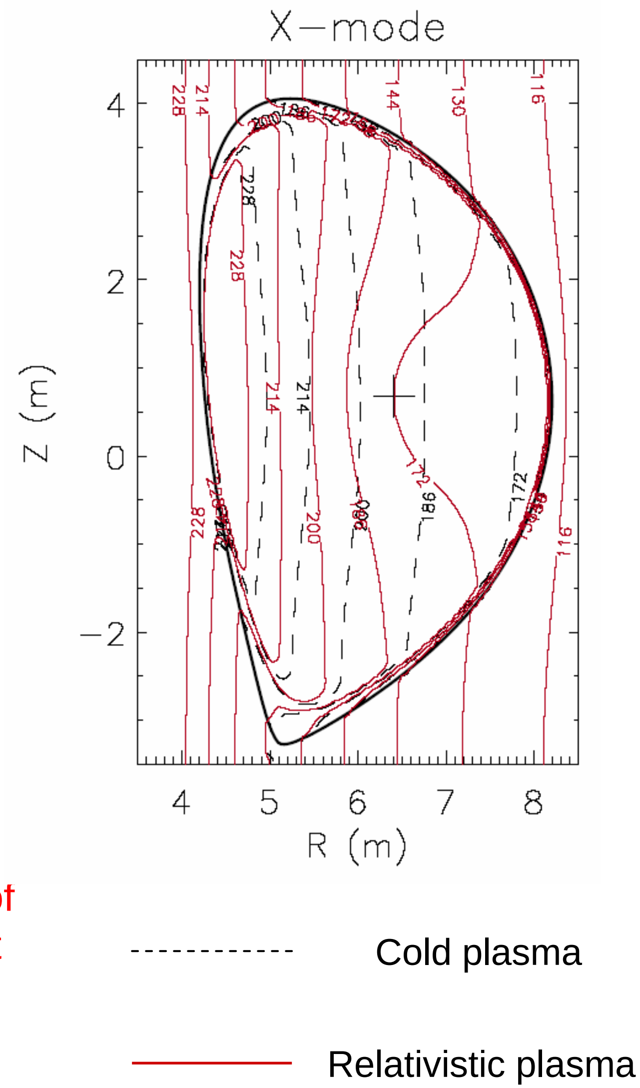
- **How do we resolve?**

  <u>Approach</u>

  - **First,** use independent measure of T_e profile in inversion procedure. Assess the effect of uncertainties in electron temperature measurement on inverted density profile

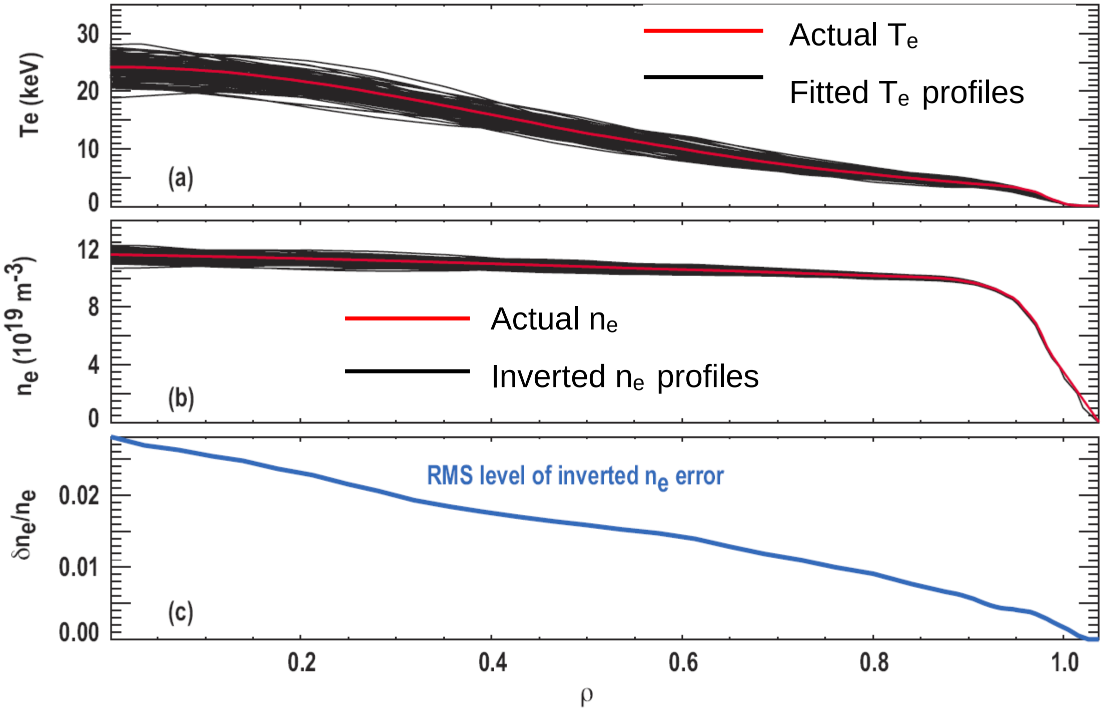
  - **Second**, in **peaked profiles & edge pedestal,** investigate use of data from both O and X mode cutoffs to obtain information about **BOTH density and temperature profiles.**

- **Concave nature of cutoff contour also affects wave propagation – addressed later via ray tracing**



How well do we need to know temperature profiles? - assessed via simulation

- Assume temperature measurement is limited by random error with uniform distribution up to max. ±30% (±10 % also studied)
- Apply error to 42 spatial measurement locations in the assumed profile
- Apply a spline fit (4 knots) to generate smoothed “temperature profile data”
- Use these temperature profiles in inversion procedure to obtain density profile
- Repeat 100 times to build up statistics and assess resultant RMS error in inverted density profile



Polevoi’s profiles (2005) assumed for these calculations – slightly peaked

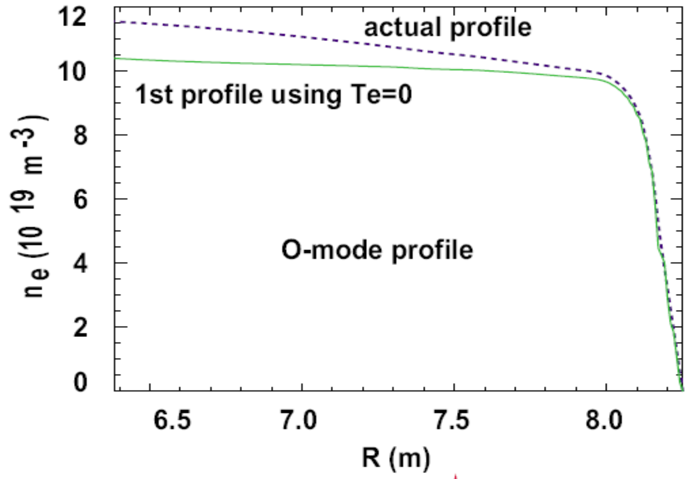
30% pk-pk random error applied to *local* electron temperature “measurement” leads to RMS error in the inverted density profile of < 3%

Accurate reconstruction of electron density profile is possible with reasonable knowledge of the electron temperature profile

However, errors in temperature DO translate to density

Reflectometry can determine both T_e and n_e profiles on ITER

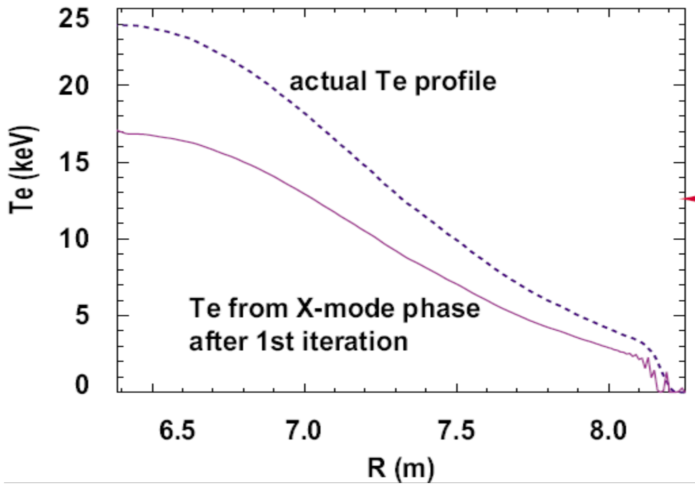
- no independent temperature information required



Step 1: assume Te=0 and invert O-mode phase to get density profile

Step 2: X-mode phase - now a function of ne and Te- is inverted to extract Te profile using O-mode density profile as input

Step 3: Te profile from X-mode inversion is now used as input for O-mode density profile and process is repeated



Relativistic effects very different for O and X-mode.

- **Peaked profile** allows access to plasma core for both O and X-mode

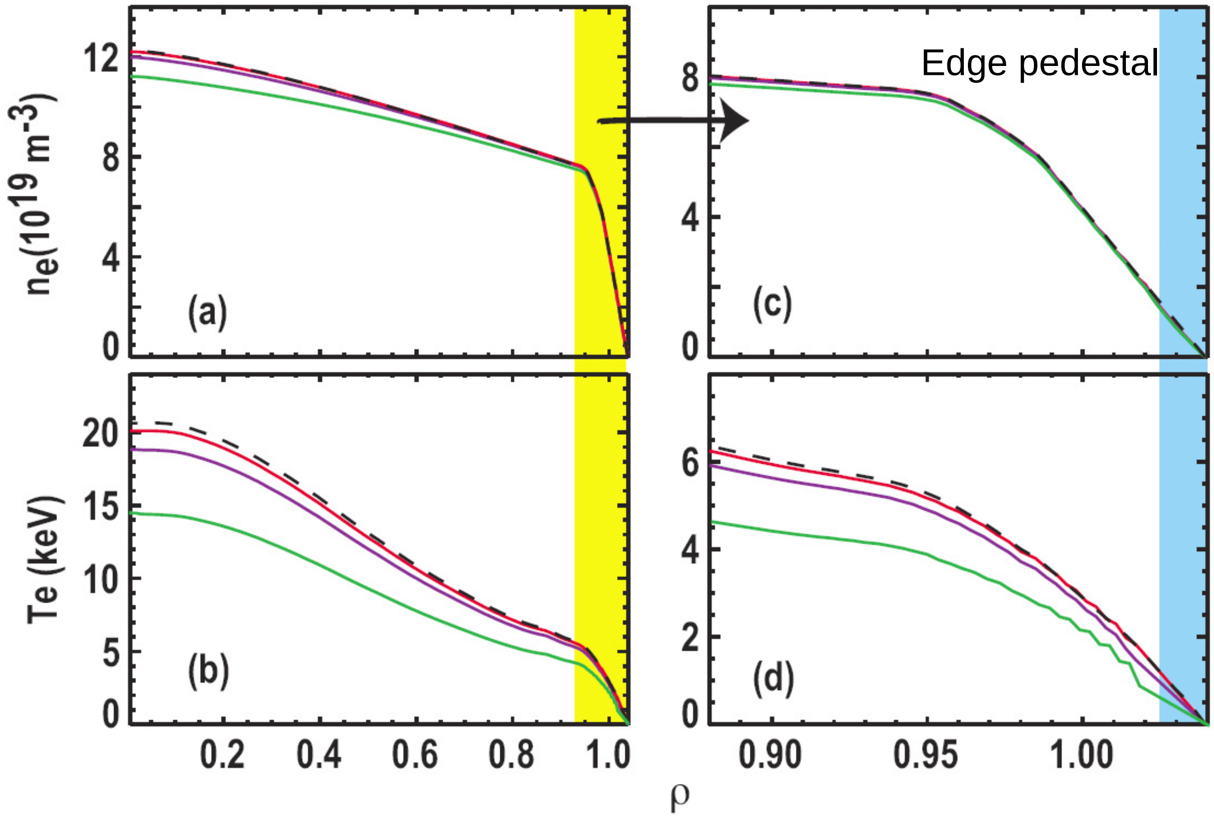
Use additional information to invert BOTH temperature and density profile.

- Inversion procedure illustrated.

-**Technique can also be applied to edge pedestal**

- **Planned demonstration on DIII-D**

Successful iterative inversion of BOTH temperature & density profiles simulated for ITER peaked profile



Simulation demonstrates that iterative inversion allows retrieval of BOTH electron temperature and density profiles

After **three** iterations agreement between input and inverted profiles are very good.

Further improvement with more iterations

Simulation assumes X-mode operation 110 -185GHz, O-mode 35-95GHz

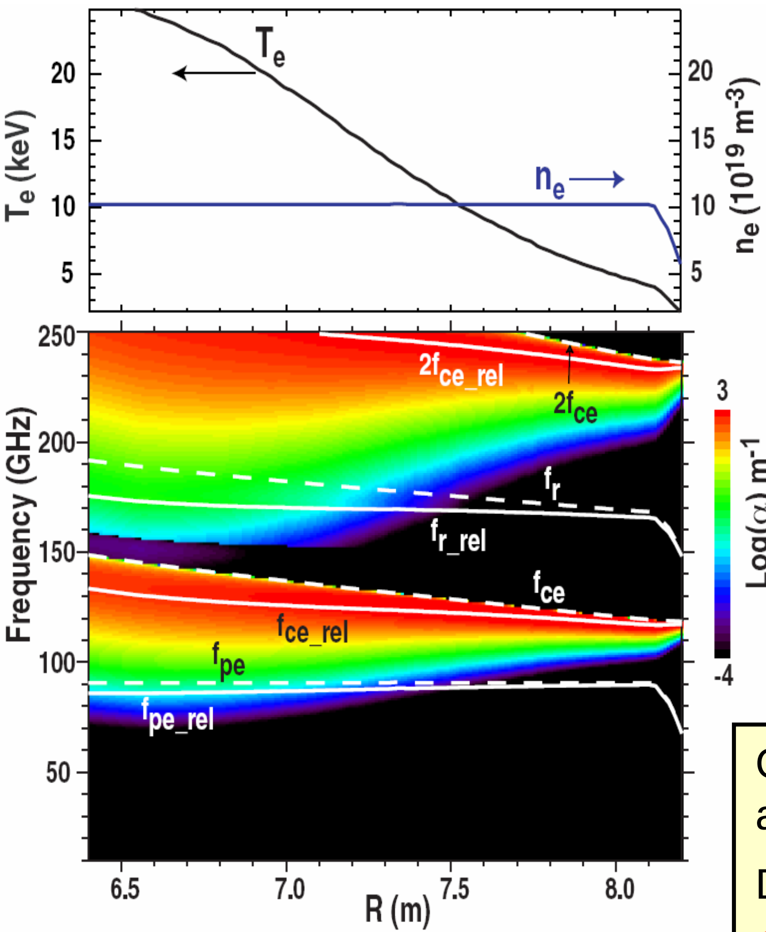
Since O-mode not available from 0-35GHz, calculated X-mode phase is used to invert density profile assuming Te = 0. Then O-mode phase (0-35GHz) is calculated using this profile and added to calculated O-mode phase 35-95 GHz

Simulation indicates good inversion of density and temperature profiles for core, gradient, and edge pedestal plasma. Plan demonstration on DIII-D

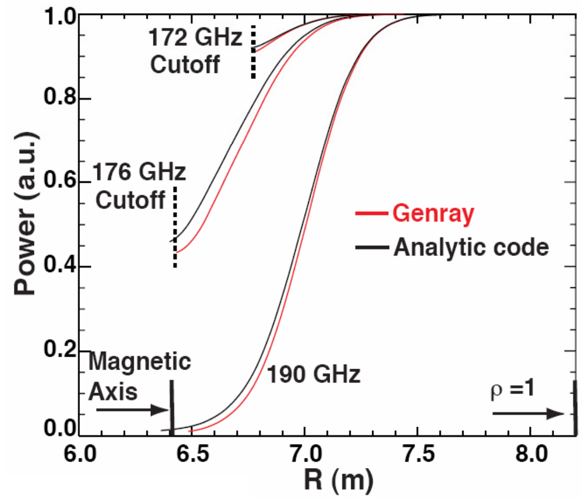
Core Accessibility limitations

Downshifting/broadening of cyclotron resonances causes increased absorption in ITER

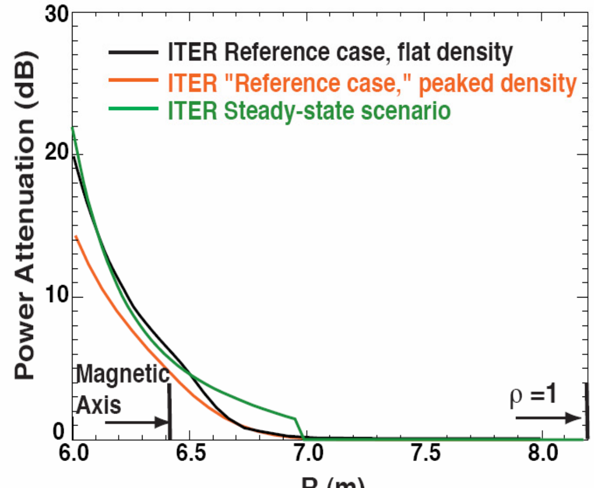
ITER Scenario 2



- Analytic approximation for cyclotron absorption (Batchelor, 1984) benchmarked to GENRAY relativistic calculation (for X-mode)
  - ITER reference case plasma



- Cyclotron absorption double pass loss only becomes significant close to plasma center



Good agreement between Genray and analytical calculation of absorption

Double pass absorption~ 5dB for ITER Scenario 2 profile

Core access not limited by absorption for Scenario 2

Need to assess for lower magnetic fields, higher densities and strongly peaked profiles which all serve to increase overlap.

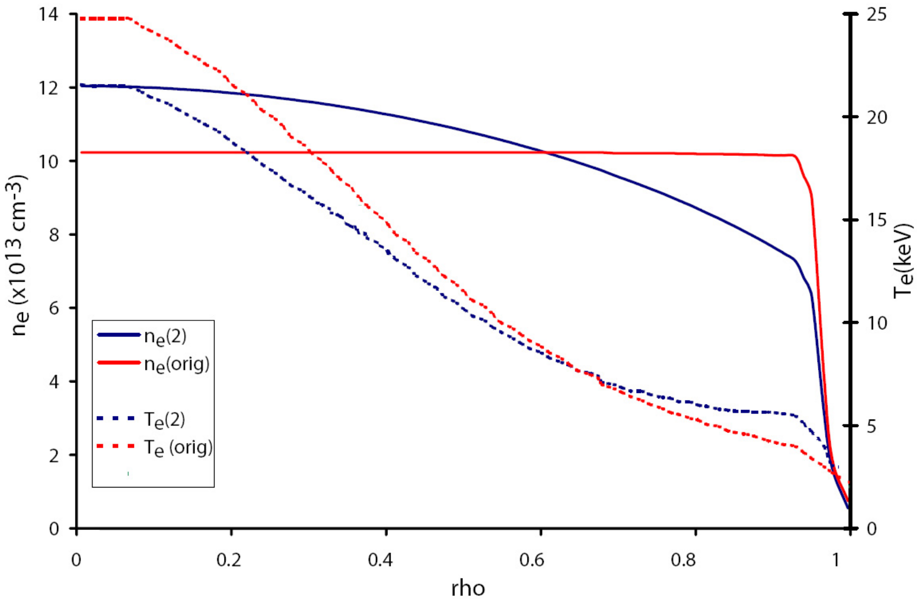
Effect of density peaking on gradient in cutoff frequencies

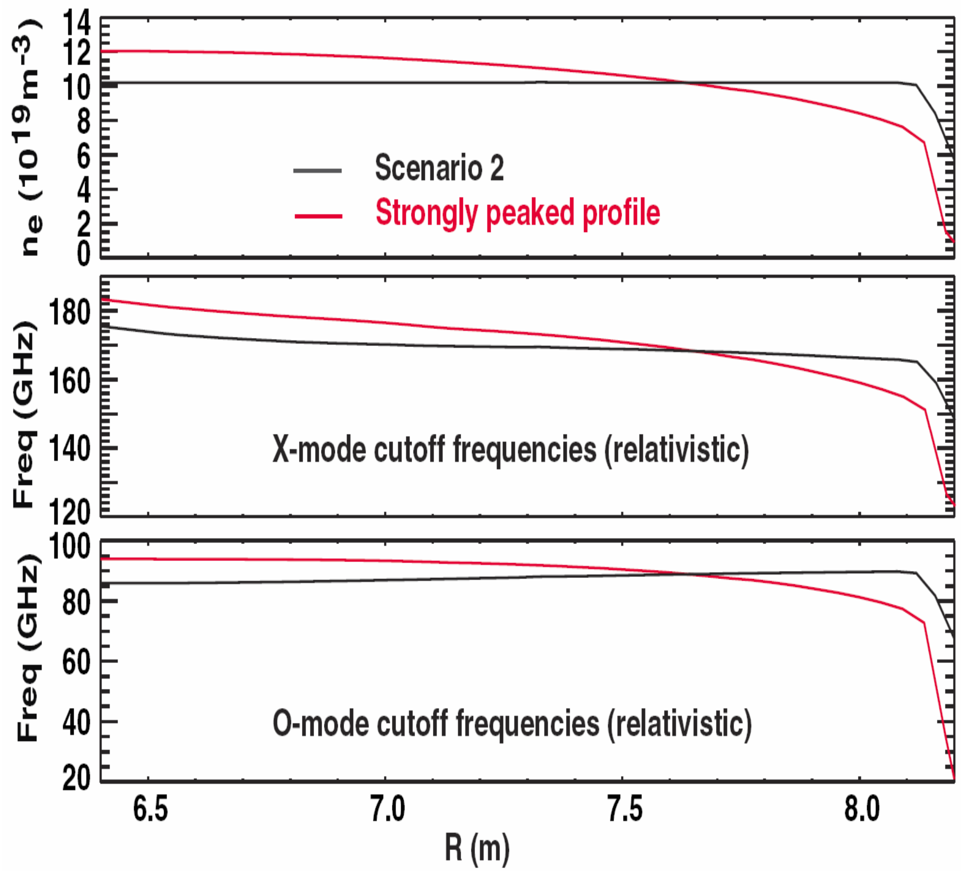
– **Full core access not possible with Scenario 2 flat profiles ; neither O or X-mode**

– **Significant density peaking projected for ITER.**

- See Weissen (EX8-4), Sips (EX1-1) IAEA 2006, Polevoi et al.Nucl. Fus. 2005.

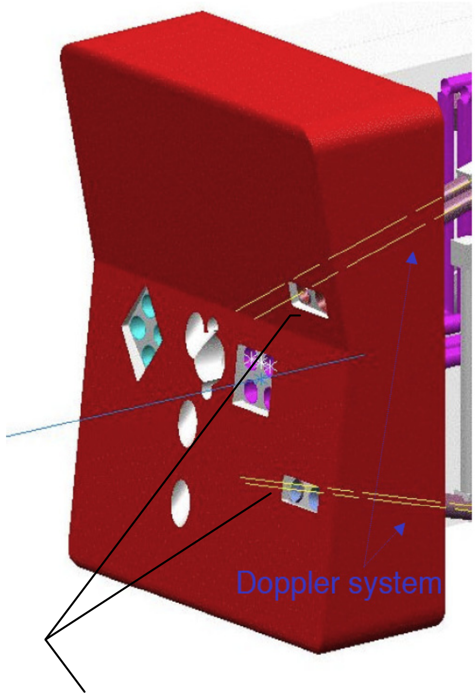
– **Opens up new possibilities**
– X-mode fully accessible
– O-mode partially core accessible



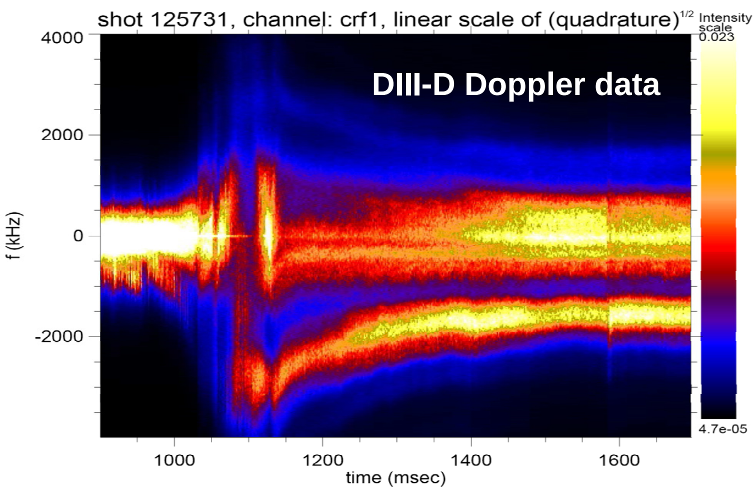


Peaked density profiles and lower electron temperatures will significantly increase core access in ITER for both O and X-mode propagation.

Current antenna concept (Vayakis 2006) suggests devoting two pairs (4 antennae) to Doppler reflectometry



Doppler antennas



- **Antennas are located on LFS - same general area as profile reflectometers**
- **Strawman design taken from ITPA presentations**
  - Not in DDD 5.5.f
  - 2 pairs antennae proposed
  - **15º launch angles**
- **Measures ExB turbulent flow.**
- **Demonstrated on multiple machines**
  - M. Hirsch, et al., PPCF (2001)
  - G. Conway, et al., PPCF (2004)
  - Recently DIII-D – L. Schmitz

- **Assess cost/benefit under constraint of maximum 12 waveguides**
- **Concerns**

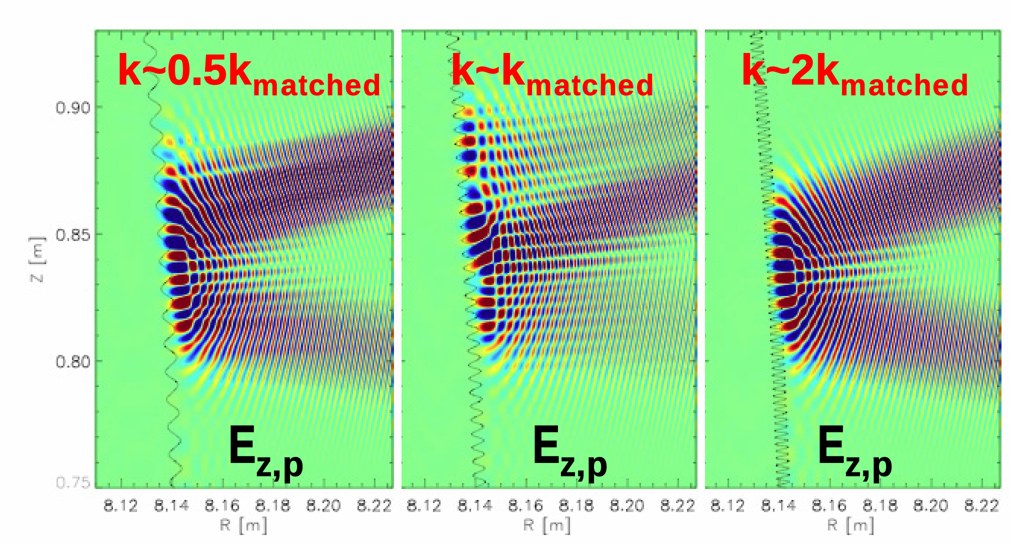
  - Proposed Doppler waveguide ***not useful for profile measurement***. **FOUR** waveguides assigned.

  - Measures turbulent flow NOT plasma flow. Represents a problem when toroidal rotation small.

  - Current design probes large turbulent k – may compromise measurement due to k-spectra decay

Full-wave calculations indicate Doppler response is peaked near predicted matched wavenumber, $k_{\tilde{n}}=2k_0 \sin(\theta_{tilt})$

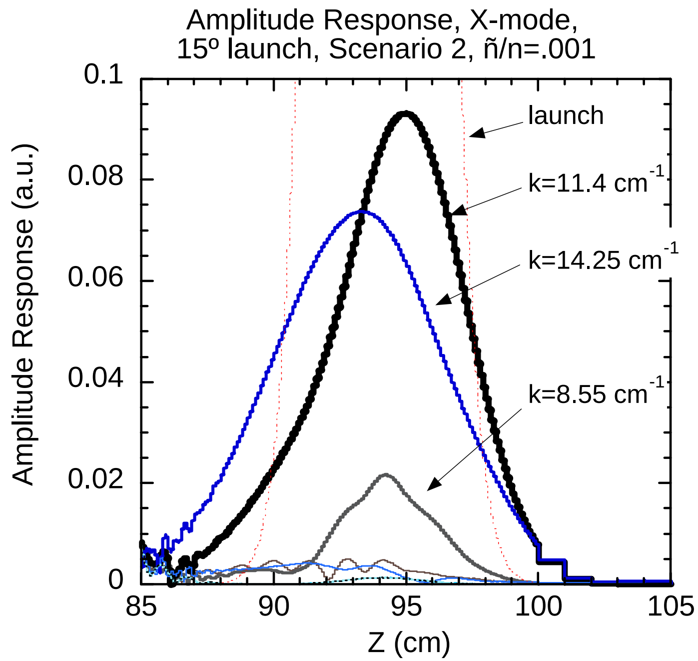
Perturbed $E_{z,p}$



- 15º launch angle, ITER Scenario 2
- Density perturbation indicated in contour plots by corrugated line near the cutoff location.
- **Backscattered signal** returns to launch antenna making it easily detected by **mono-static antenna arrangement**.

> Full wave code derived by S. Kubota (UCLA) from original version of H. Hojo, et al., RSI '04
> Uses full magnetic geometry
> 160 GHz, reflecting from pedestal

Response to different wavenumbers



Detection position is at antenna plane

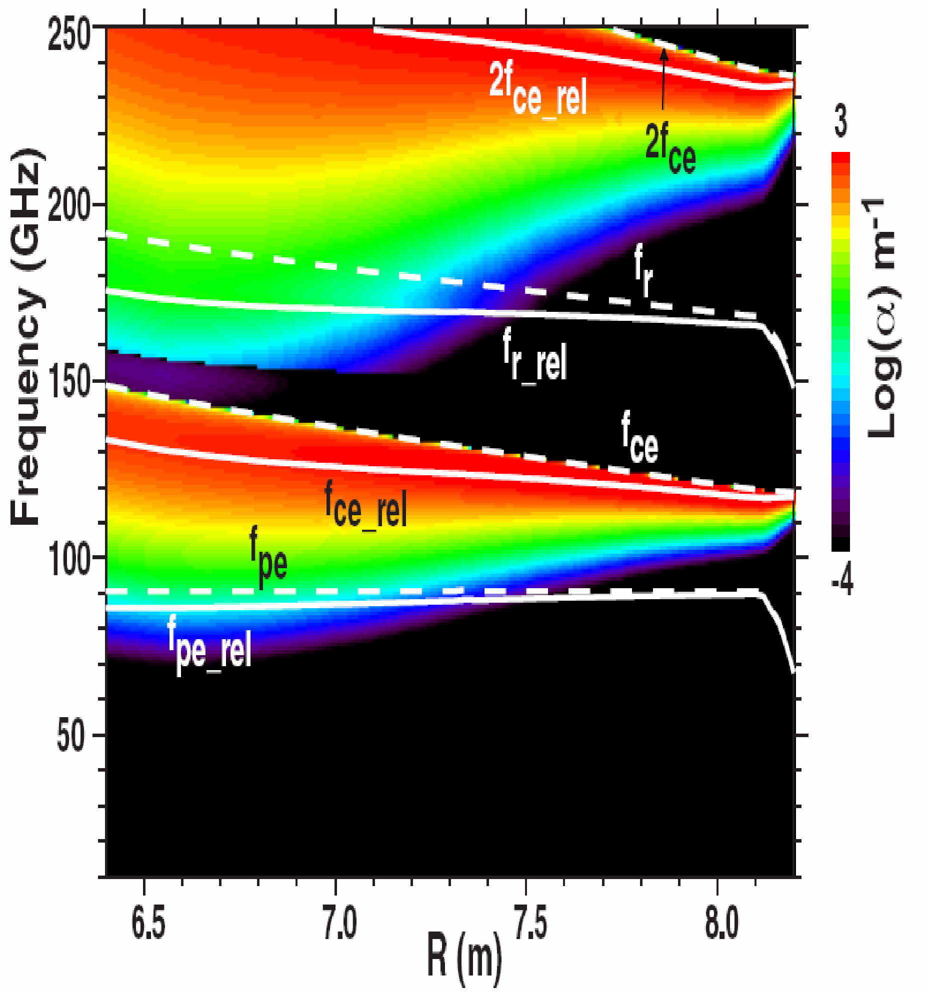
> Confirms that probed k would be large in ITER.
>
> Turbulence level decays rapidly at higher wavenumbers - detectability?.
>
> Rapid fall-off may also distort the inferred k.
>
> **Details of the turbulent k spectrum in ITER important at these larger k's**

Assessment of Doppler reflectometry

- **Doppler reflectometry can potentially provide important physics information related to ExB turbulent flow and intermediate wavenumber turbulence.**
  - The technique is still under active development – expect to see continued progress over the next few years.
- **However, a turbulent flow measurement is NOT equivalent to a plasma or ion flow measurement.**
  - Especially true in low rotation plasmas: could be small in ITER due to low input torque
  - Need clear indication that Doppler can satisfy ITER measurement requirement/need
- **The Doppler antennas, as envisaged, are <u>incompatible</u> with simultaneous density profile measurement**
  - **At this time could not commit 4 out of 12 antennas for Doppler.**
  - **Too risky with too little payoff – large launch angle <u>only</u> useful for Doppler .**
- **Doppler reflectometry is compatible with mono-static operation**

Integration of an ECE system into the LFS reflectometer
What are the benefits/costs?

- **Little detailed assessment performed so far.**

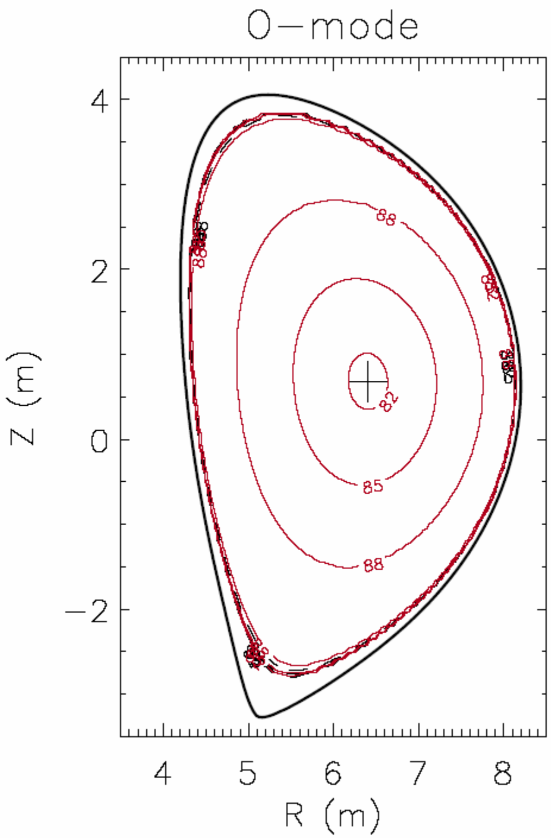


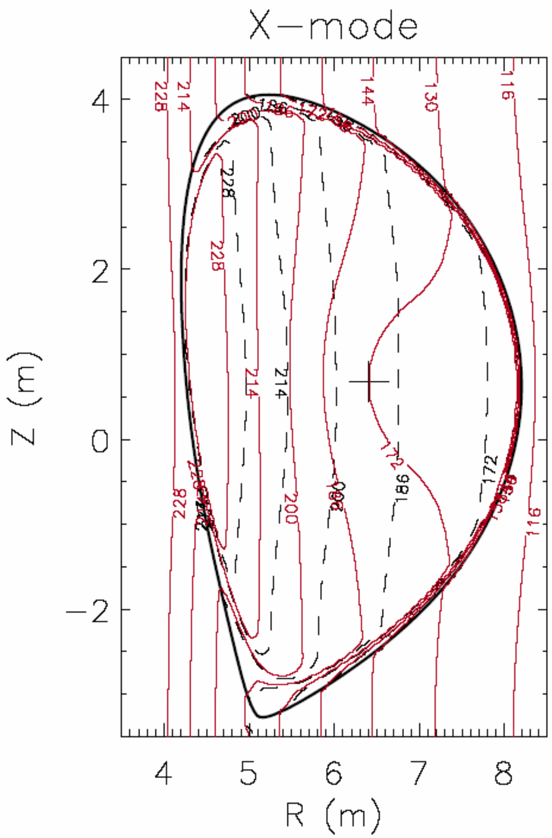
- Proposed corrugated waveguide for the LFS reflectometer operates from 50 to 200 GHz
- For Scenario 2 the fundamental cyclotron O-mode emission frequencies range from 120GHz up to ~200GHz
- This frequency range is supported by the proposed reflectometer corrugated waveguide.
  - Integrate with O-mode reflectometer system. No overlap in frequency space.
  - Use frequency diplexer (e.g. dichroic plate) to separate ECE from reflectometry

Preliminary assessment of integration of reflectometry/ECE

- **Integration of a limited (O-mode) ECE system into the LFS reflectometer appears a win-win situation.**
  - Little risk to O-mode reflectometry measurements.
  - Separate through lack of frequency overlap
  - Multiple radial views possible using proposed vertical antenna array
    - Poloidal mode number, etc.
- **Primary concern is lack of independent calibration via hot load**
  - For many applications this is not critical
    - Mode number identification, turbulence studies, etc.
  - Receiver system would be calibrated
    - Main concerns are windows and waveguide expansion
    - Reflectometer will monitor waveguide movement at end of guide
    - Presumably could also monitor changes in transmission properties.
- **Proposal is worthy of more detailed consideration**

Wave propagation studies via ray tracing





ITER Scenario 2 Flat profile, T_{eo} ~25keV.

Note the large X-mode concave cutoff contour created by flat density profile combined with large centrally peaked electron temperature.

Convex cutoff – defocusing

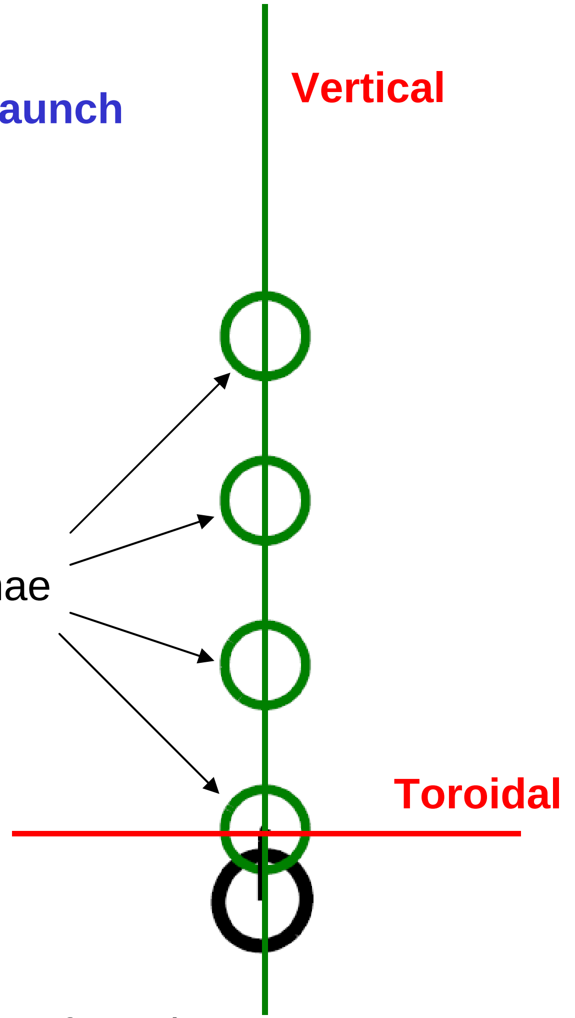
Concave cutoff – focusing

Investigate wave propagation via ray tracing

O-mode becomes strongly hollow

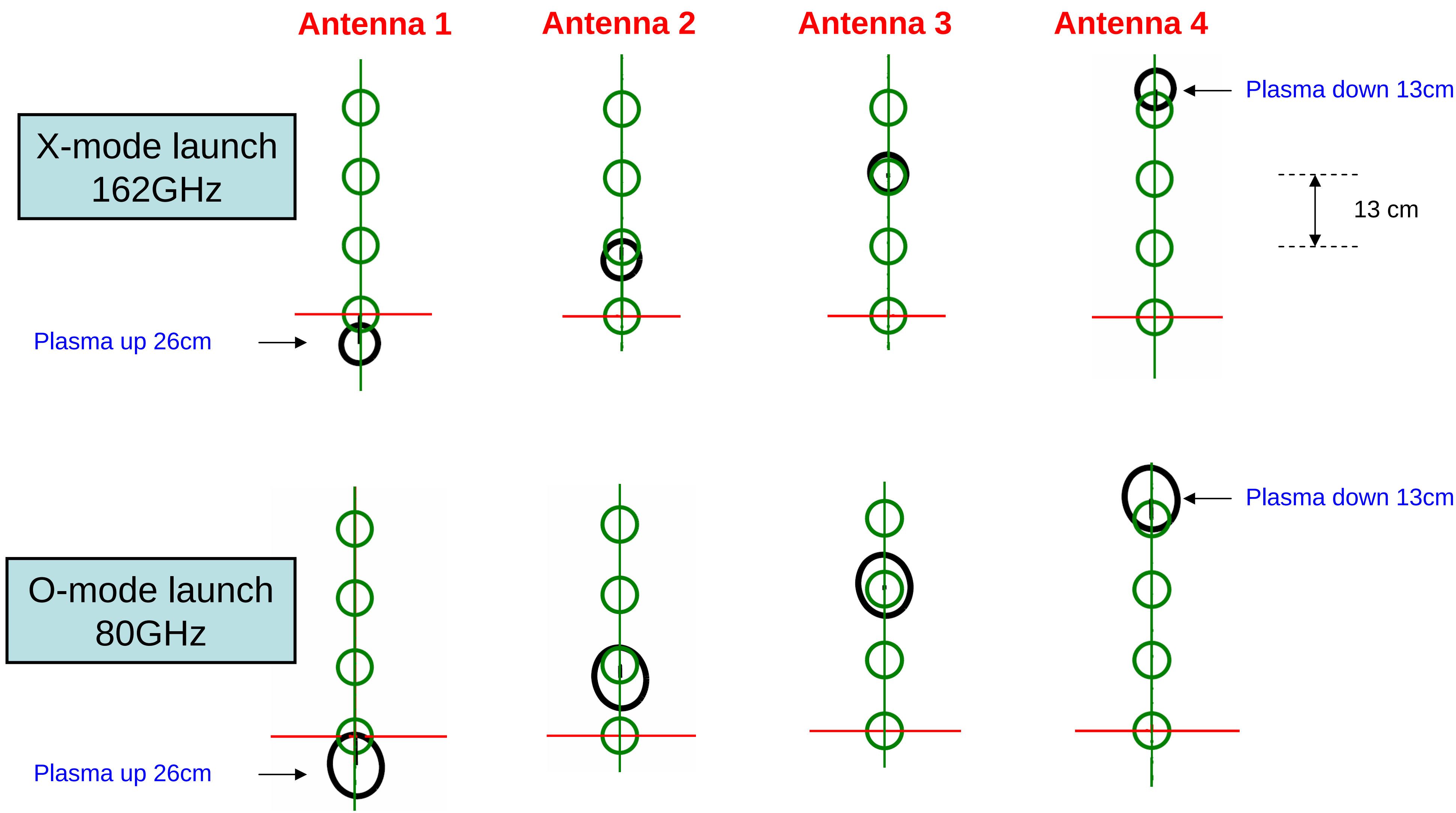
Red indicates <u>relativistic</u> cutoff contours – black: cold plasma

3-D , relativistic ray tracing (GENRAY) indicates concern regarding ITER antenna alignment



- Consider **vertical array** of **FOUR** antennas as shown
  - lower 2 antennae located vertically as proposed by Vayakis 2006.
  - **64mm diameter, 30cm from LCFS, 13cm separation**
- Radial view illustrates "footprint" of return beams (from $1/e^2$ launch) at antenna plane
- Genray calculates ray propagation for a cone of rays launched at LCFS. Following procedure is followed:
  (1) The beam waist ($W_0 = 1/e^2$ power radius) at the exit from the waveguide is calculated.
  (2) Assuming EH_{11} coupling to Gaussian mode, the expansion of the beam waist to the LCFS is calculated, as well as the spread angle.
  (3) Rays are then launched in GENRAY from the LCFS at the above angles and locations

O & X-mode launch: reflection from edge pedestal
- ray tracing illustrates effect of plasma up/down movement

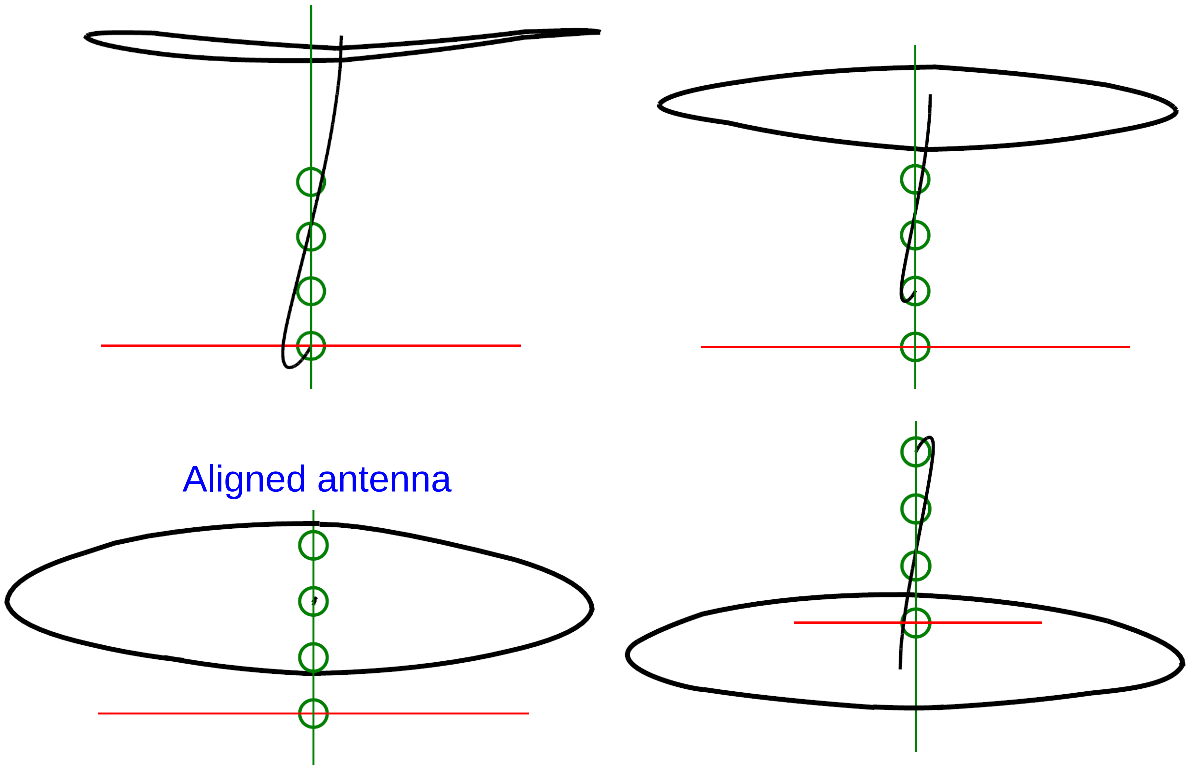


Antenna 3 close to magnetic axis - launch returns to same antenna

Difficult to avoid mono-static operation!

X-mode launch (177 GHz) from vertical array of antennas

DEEP Core plasma (r/a~ 0.1) ITER *Moderately peaked profile*



As can be seen, ray tracing indicates “exotic” propagation paths - except in the case of launch from antenna 3 which is aligned with magnetic axis.

Good alignment essential for core access – independent of whether antenna configuration is mono-static or bi-static.

Need multiple antennas

Ray tracing indicates that <u>meaningful</u> return signals from the core plasma requires an aligned antenna that must be able to accommodate plasma height variation.

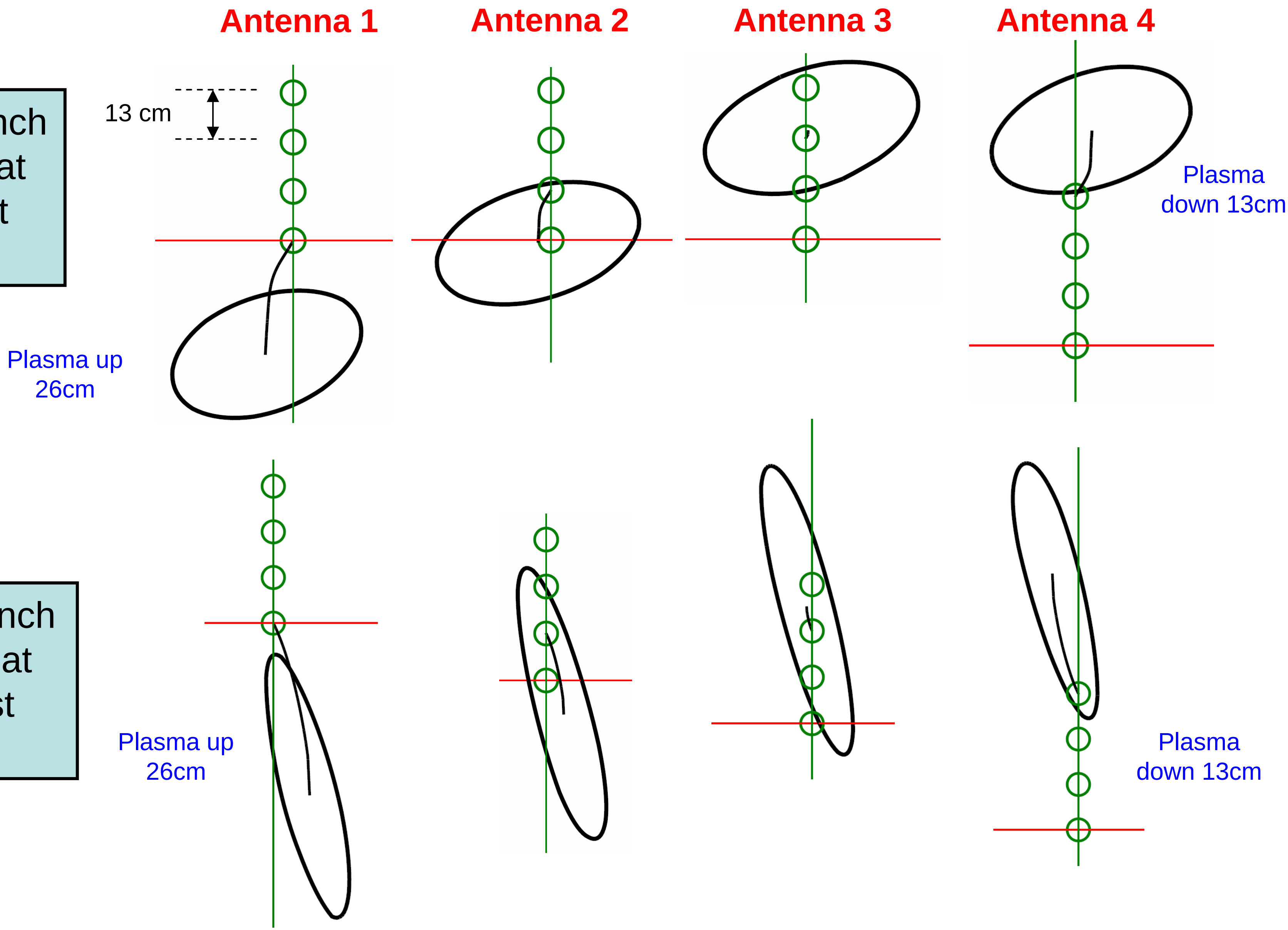
Receiving radiation with a low gain antenna using a misaligned launch would generate large errors in inversion for core plasma.

O & X-mode launch: reflection from core plasma

- ray tracing illustrates effect of plasma up/down movement

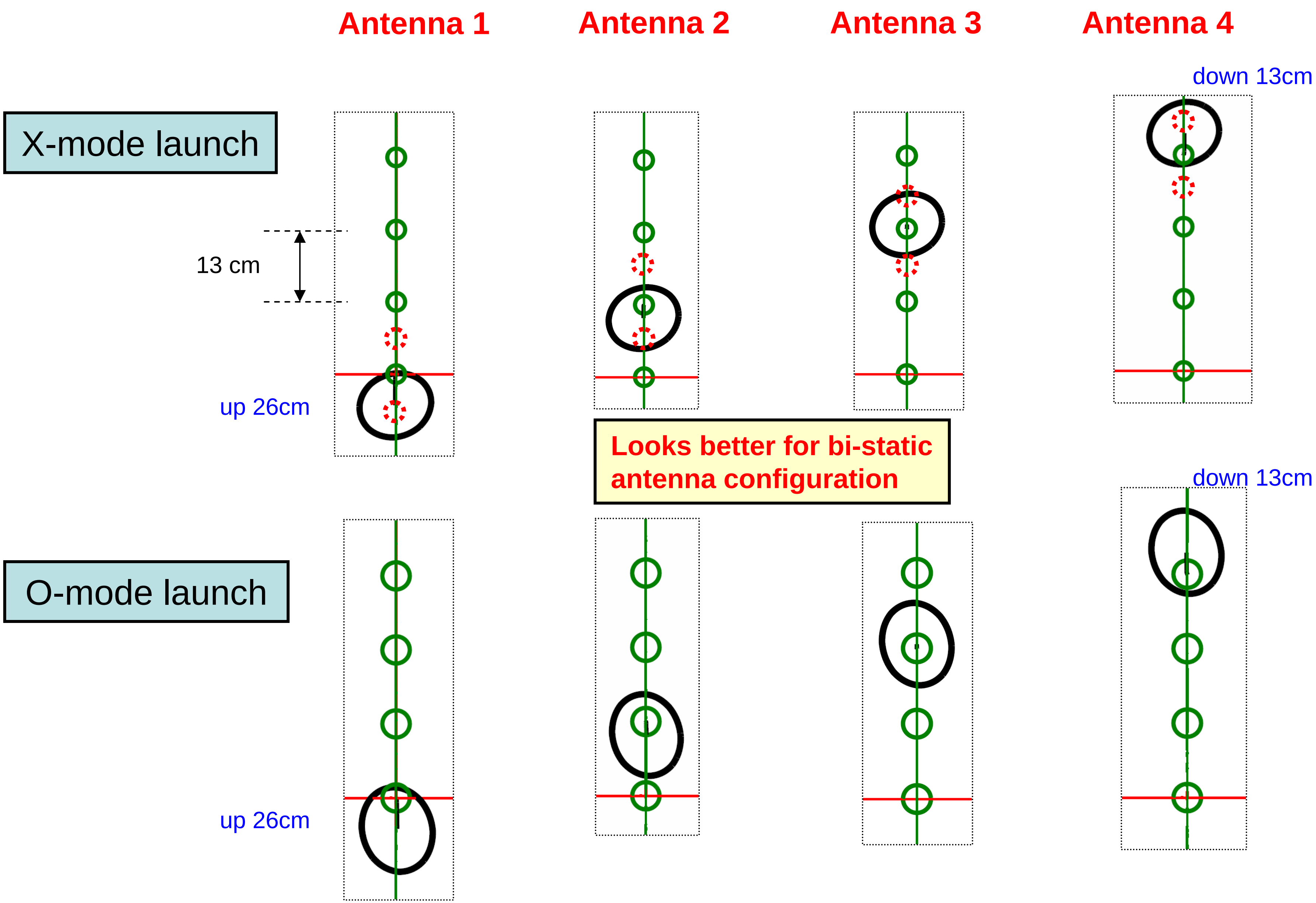
X-mode launch Reflection at 80cm past LCFS

O-mode launch Reflection at 50cm past LCFS



O & X-mode launch: reflection from edge pedestal

- waveguide reduced to 32mm for X-mode; 48mm for O-mode

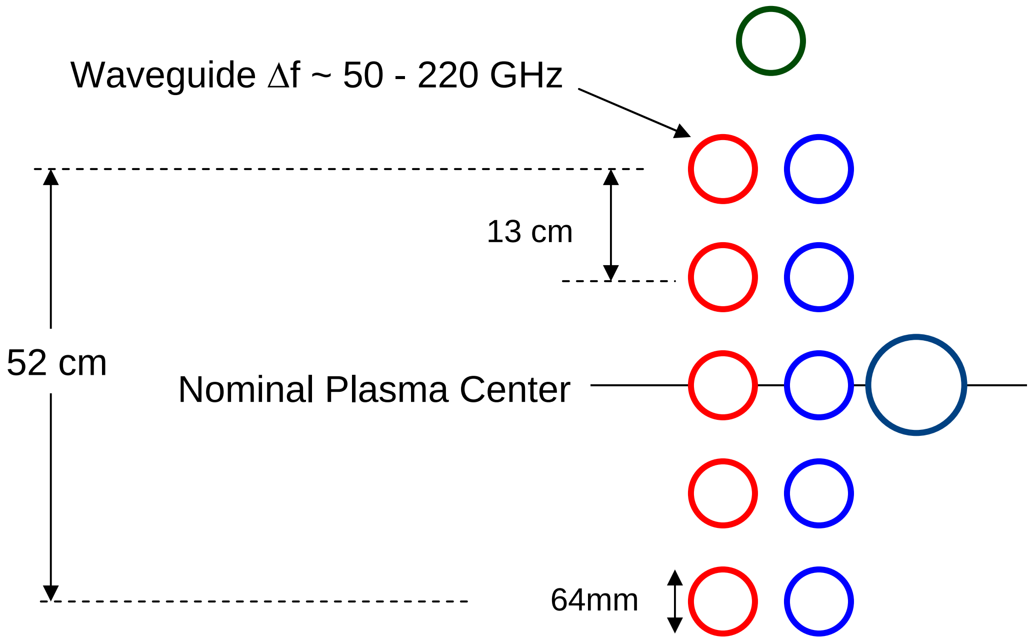


Initial conclusions re profile measurement on ITER

- **X-mode offers greatest potential**
  - **scrape-off and edge pedestal plasma**
  - **offers core access in weakly peaked profiles or low temperature plasmas**
  - waveguide frequency range 50-220 GHz. Initially, limit source frequency to ~75-170GHz
- **O-mode provides redundancy and added capabilities**
  - needs TWO different waveguides O-mode (15GHz - 60 GHz, 50 - 220 GHz)
  - source frequencies 15-60GHz and 50 -110GHz ($1.5 \times 10^{14} cm^{-3}$)
  - allows adequate measurement of edge pedestal profile, **provides profile redundancy**
  - **peaked profiles** allow O-mode access to the core and thereby **simultaneous measurement of both density and electron temperature profiles**
- **Ray tracing has shown that expected plasma height variations cannot easily be accommodated**
  - bi-static operation minimizes internal reflections, directivity not an issue
    - would **increase the number of required waveguides**
  - mono-static antenna, in addition to disadvantages, has significant potential advantages
    - increases use of waveguides! MHD, ECE, Alfven modes, turbulence, etc.
    - minimizes complicated ray trajectories resulting in more accurate inversion
    - allows thermal length variation of waveguides to be directly monitored

\- **Will return to optimum antenna configuration at end of talk**

Suggested mono-static antennae configuration for LFS reflectometer



Initial operating frequency range

- X-mode Δf ~ 75 - 170 GHz (64mm)
- O-mode 50 -110 GHz (64mm)
- O-mode 15 - 60 GHz (90mm)
- Doppler O or X-mode 50-170GHz (64mm)

Monostatic operation.

Independent O and X mode waveguides

- simpler X, O & ECE integration

Doppler:

Within context of maximum 12 waveguides would currently choose to have 1 Doppler antenna only. Optimum angle still needs additional careful consideration. Hirsch desires at least two waveguides

Plasma flow measurement - lower priority than profile, MHD, Alfven mode measurements.

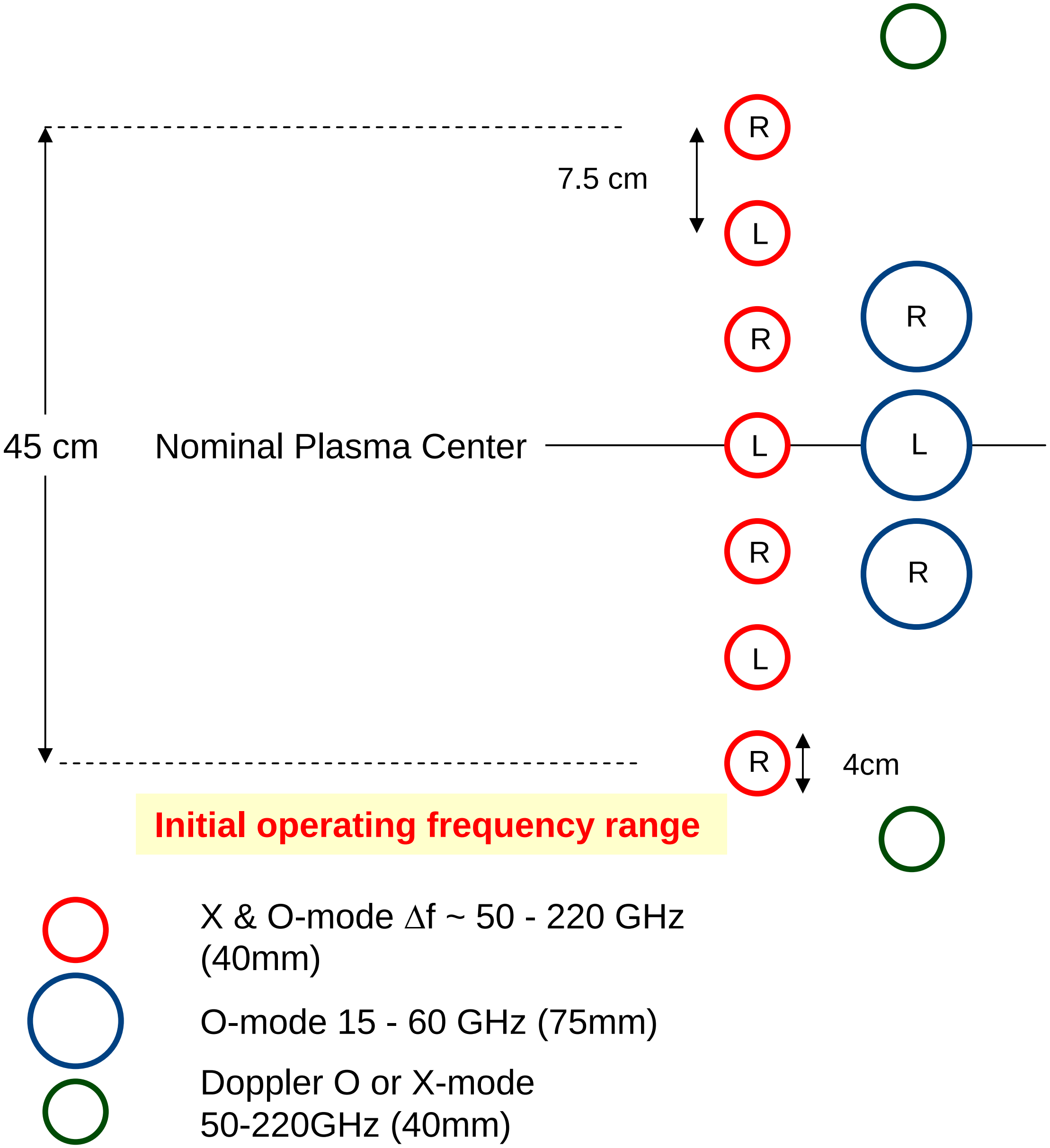
MHD, ECE, turbulence

Profile antenna are compatible with MHD, ECE and low-k turbulence measurements except for radial correlation.

Doppler antenna compatible with mono-static antenna

Major concern that spurious reflections will make phase measurement impossible

Possible bi-static antenna configuration requires integration of high frequency O and X mode



Employ smaller (lower gain) diameter antennas with smaller separation.

Integrate BOTH O and X mode into same waveguides

Should allow edge pedestal to be measured with minimal phase error

However, reduces received signal from core plasma and introduces large potential errors by accepting meandering ray paths

If core access is REQUIRED then careful study essential

Concerns regarding mono-static antenna configuration

- **Successful, but challenging, mono-static profile measurements have been performed at ASDEX for many years**

Issues

- **Directivity**
  - Mono-static operation normally requires use of a waveguide directional coupler (or equivalent) to redirect reflected radiation to receiver
  - These couplers typically reject the original launch power by < 40dB
    - If return power was 60dB down from the launch this might present a problem
    - Possible solution would be to employ a “quasi-optical” directional coupler or simple beamsplitter, BS, which would have the potential for much higher directivities
    - A simple mesh BS, or “leaky polarizer” would provide an effective coupler over a broad frequency range.
- **Spurious reflections along waveguide**
  - Reflections from overmoded guide, Brewster windows, miter bends into the EH_{11} mode would typically be very small. Needs careful design – especially miter bends.
  - Any significant reflections should be located such that any intermediate frequencies generated would be filtered. That is the reflection points should not match delay times similar to those expected from the plasma.
- **UCLA operates bi-static systems at DIII-D and NSTX !**
  - However, benefits offered by mono-static operation in ITER warrants a careful feasibility study before rejecting out-of-hand.

Conclusions

- **In ITER, density profile reflectometry becomes dependent on electron temperature due to relativistic effects**

  - Utilizing independent electron temperature profile information allows accurate density profile inversion.

  - In peaked profiles, and in the edge pedestal, a new inversion technique allows determination of BOTH electron density and temperature profiles.

- **Accessibility: absorption not a major problem.**

  - Absorption not a major problem for ITER Inductive and Hybrid scenarios

  - However, flat density profiles prevent access to core plasma at high temperatures (>25keV) due to relativistic modifications in cutoffs.

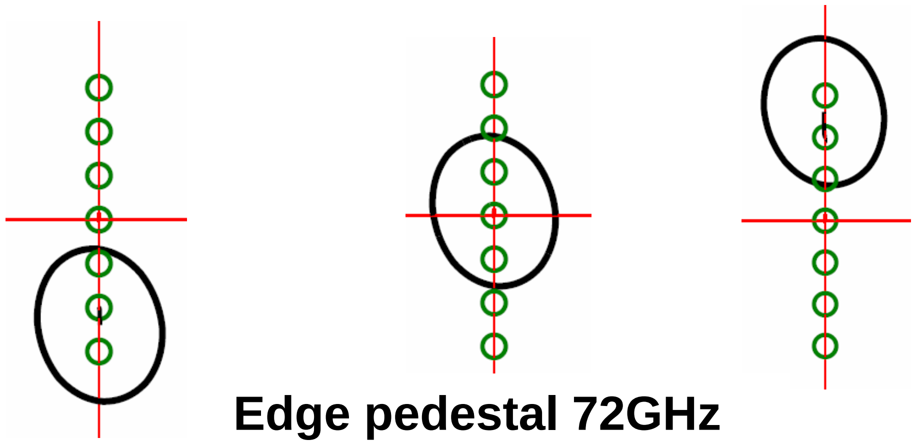
  - Operation at lower temperature and/or peaked density profiles provides full access (to center) for X-mode and partial access for O-mode.

Conclusions - continued

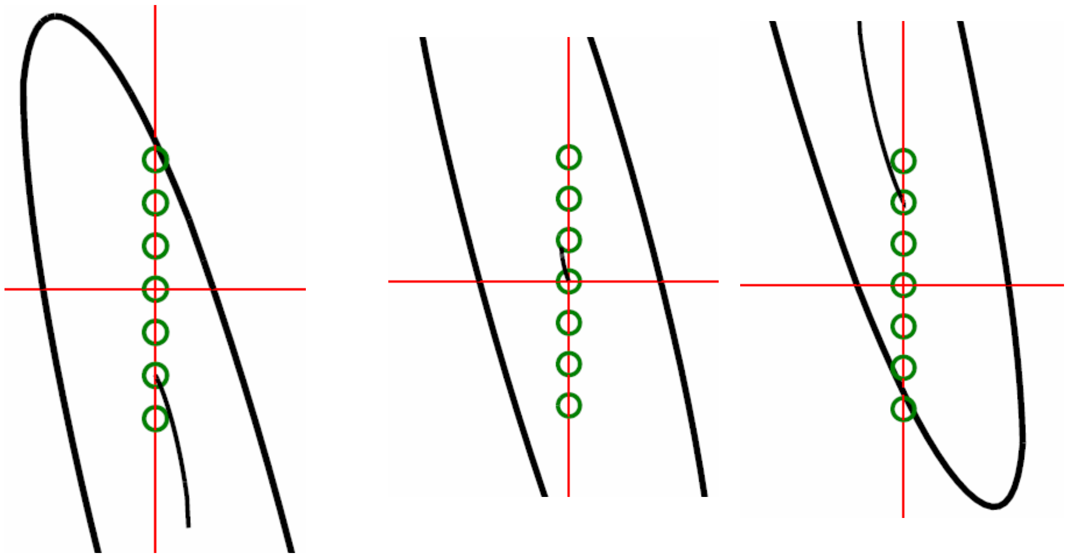
- **Ray tracing indicates that alignment is critically important**
  - Access to the core plasma requires method of retaining "alignment"
  - Within constraint of 12 waveguides mono-static vertical array is proposed consisting of both O and X mode polarizations.
    - **Such a configuration guarantees profile availability, while also being compatible with the study of MHD and turbulence.**
- **Installation of an O-mode ECE system integrated with a mono-static O-mode reflectometer appears practical – no frequency overlap.**
    - Complementary to primary ECE system - provides additional redundancy
    - Multiple radial views possible
    - Poloidal spot size sufficiently small in edge pedestal to study turbulent temperature fluctuations.
    - Important for MHD, Alfven mode studies. Toroidal/poloidal mode number determination.
- **Alignment concerns prevent deployment of FOUR-antenna Doppler system**
  - Proposed systems have maximum of TWO antennas allocated exclusively for Doppler
  - If Doppler determined to be a critical measurement could focus LFS system on the edge pedestal thereby freeing up additional waveguides. However, this threatens profile availability.
  - UCLA has rejected this option at this time.

O-mode launch: *- 40mm diameter waveguide, 75mm separation*

Antenna 1 **Antenna 2** **Antenna 3**



Edge pedestal 72GHz



Core plasma 50cm past LCFS 88.5GHz

Reflection from 50cm past LCFS has become very large

Received power too small?

Background ECE ~100μW for 30GHz bandwidth at 20keV.

Requires more detailed study

O-mode energy flow propagation