Advanced Density Profile Reflectometry; the State-of-the-Art and Measurement Prospects for ITER

by
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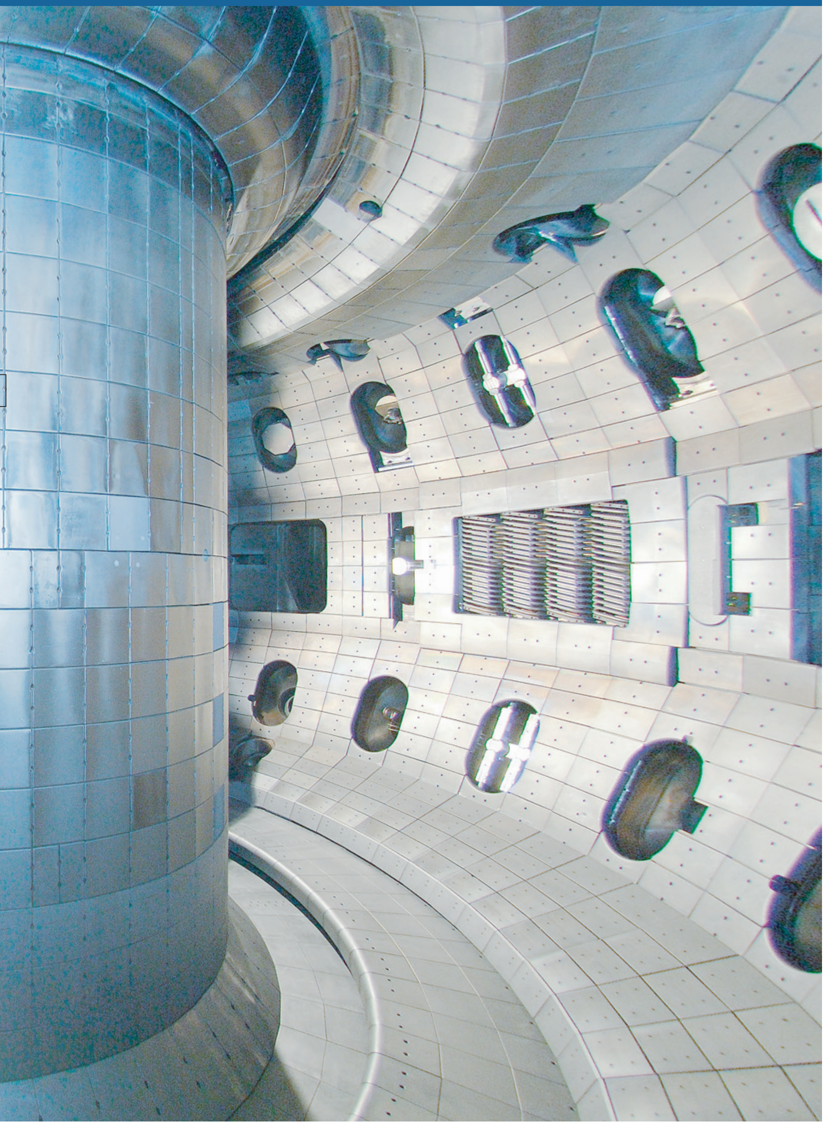

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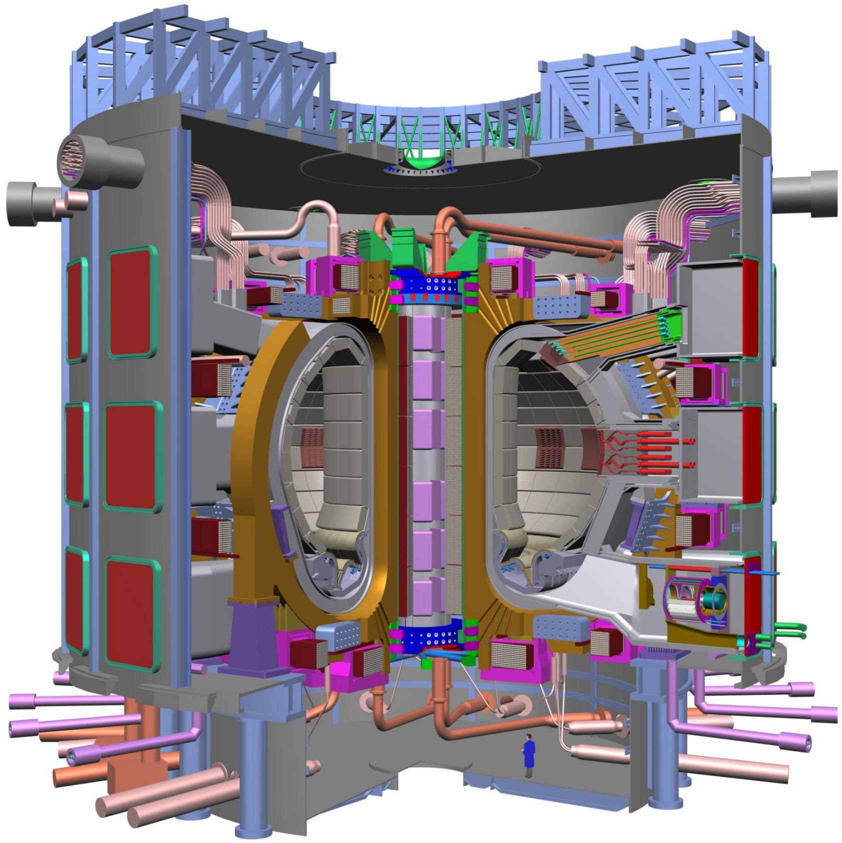
Outline

- Introduction - why use reflectometry, basic principles
- Technology has transformed ability to make high quality density profile measurements via reflectometry
  - High performance solid-state sources and frequency multipliers
  - Improved data acquisition and data analysis capabilities
- New set of measured density profiles from DIII-D and NSTX, illustrating current performance levels
  - Achieved spatial and temporal resolution are in-line with ITER targets
- Challenges and issues for basic feasibility of reflectometer density profile measurements on ITER
  - e.g. cyclotron absorption, cutoff downshift/flattening, refraction
  - Core measurements on ITER may be more feasible than previously thought
- Summary

Why profile reflectometry? - High resolution measurements, and reactor compatible

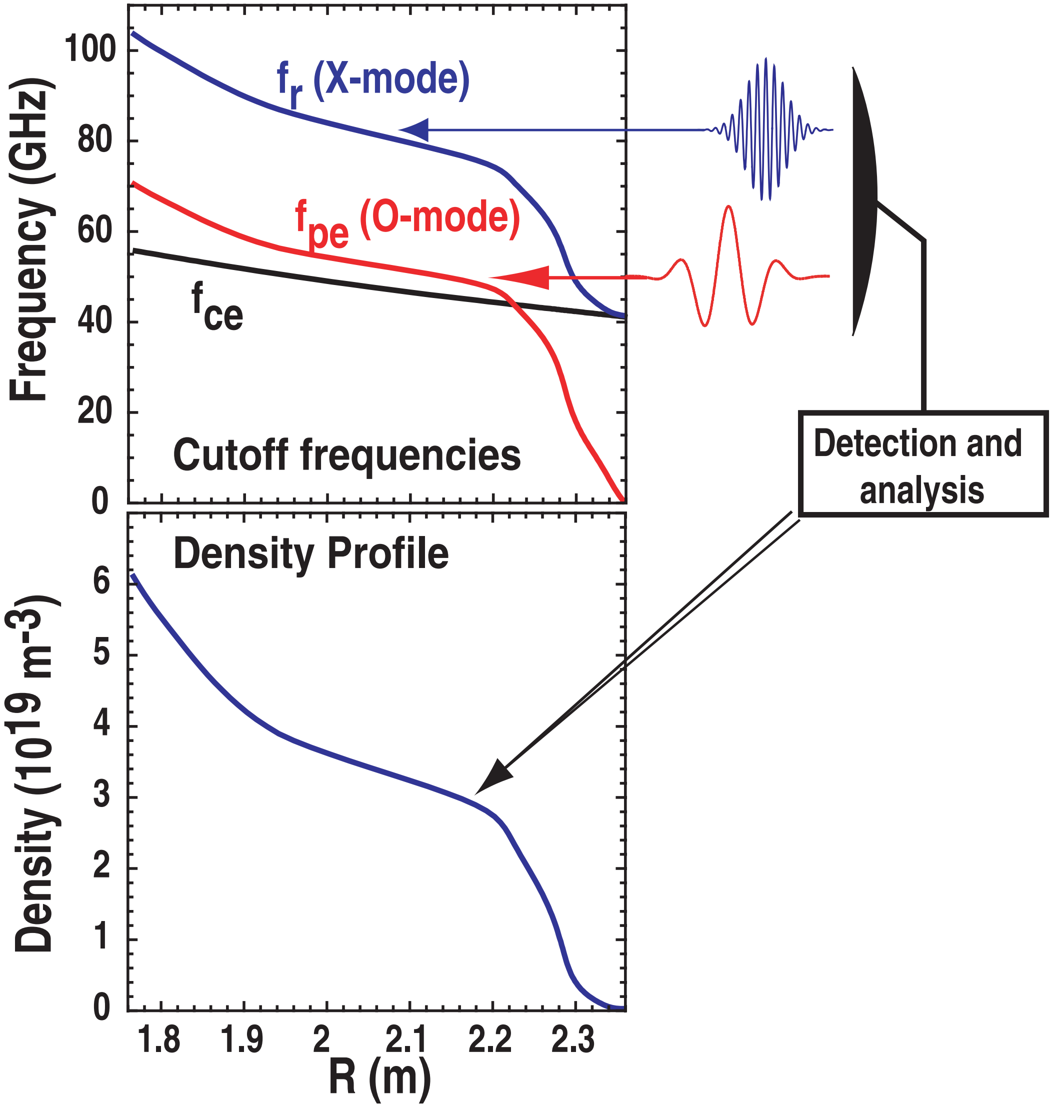
- For physics studies on current devices, reflectometry offers unique combination of high temporal and spatial resolution
  - Systems on DIII-D, NSTX, AUG, TS, etc.
  - DIII-D and NSTX results presented here
- Second major driver is desire to use microwave diagnostics on ITER, where optical diagnostics face serious challenges
  - Reflectometry is reactor compatible in terms of:
    - Tolerance of mirror imperfections
    - Radiation resistance
    - Mechanical robustness
    - Modest access requirements
- US is currently responsible for the main (low field side) profile reflectometer on ITER



ITER

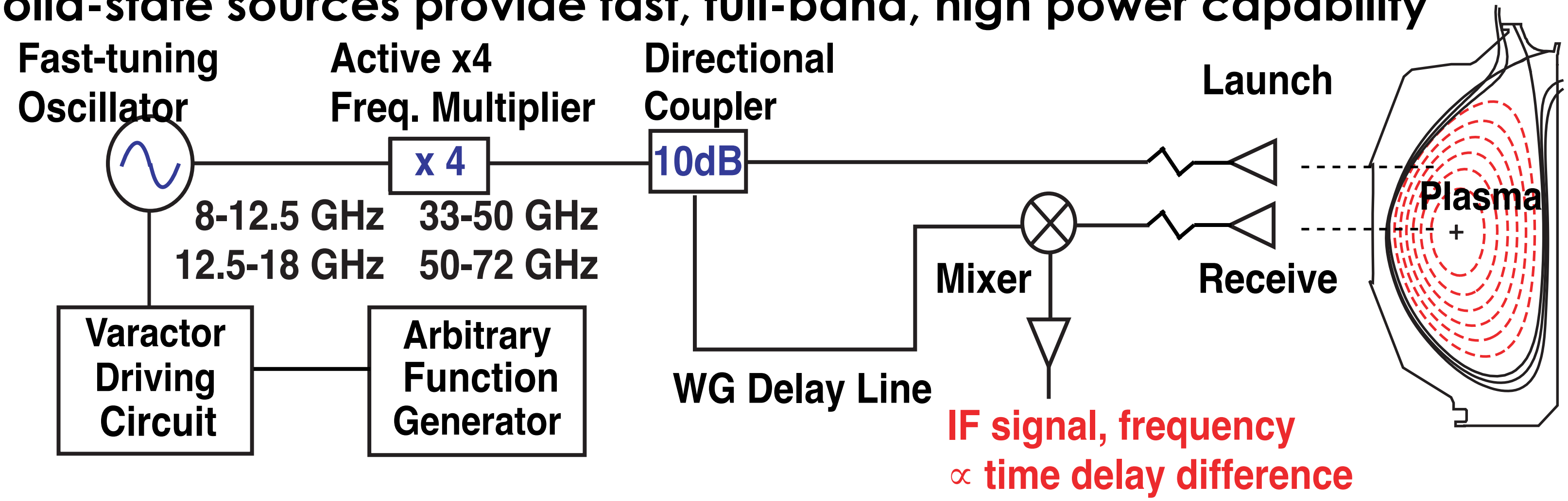
Profile reflectometry is a radar-like technique to measure the electron density profile

- **Measure time/phase delay to plasma cutoff layer, using radar techniques**
  - Two cutoffs available:
    - O-mode (E‖B), f_{pe}
    - X-mode (E⊥B), f_r
- **Two requirements for profile measurements:**
  - Probing frequency must cover density profile to be measured
  - Cutoff frequency profile must have finite gradient
- **For fusion plasmas, cutoff frequencies typically lie in range from 10-200 GHz**

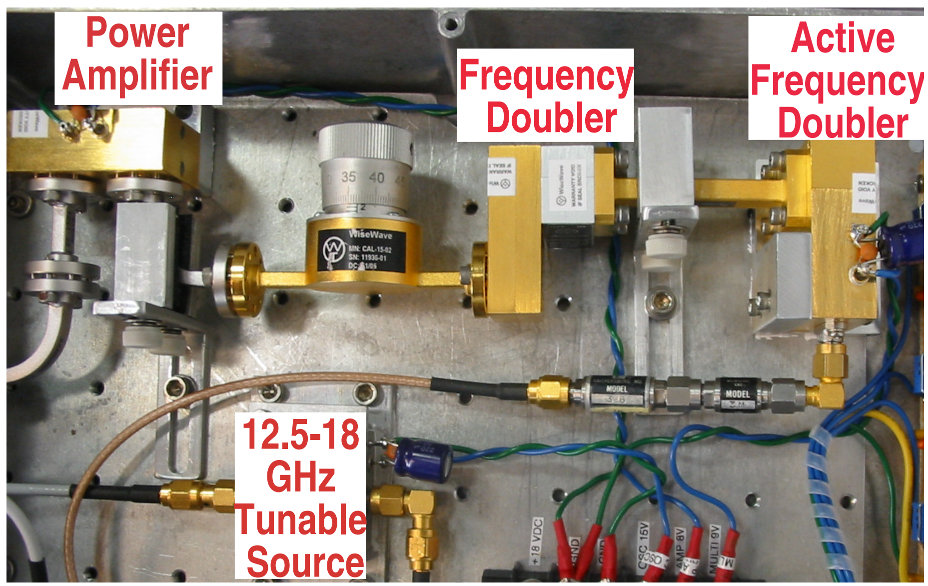


Solid-state microwave sources now provide fast, full-band frequency sweep capability on DIII-D

- Use continuous broadband frequency swept techniques (FM-CW radar)
- Solid-state sources provide fast, full-band, high power capability

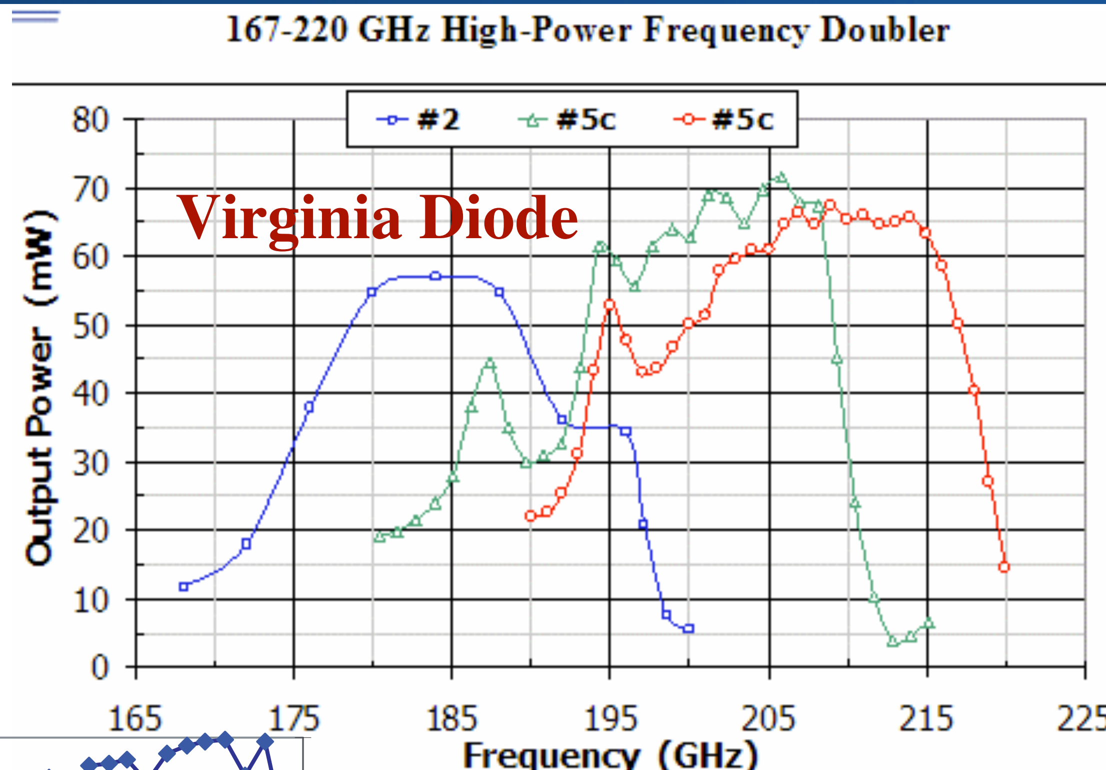


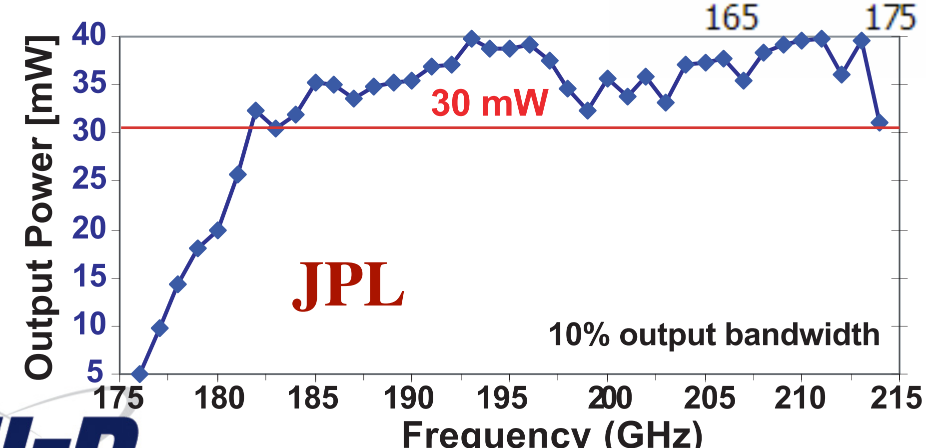
- Solid-state 50-72 GHz source, full-band sweep time ~10 μs, with 16-18 dBm, 45-65 mW power



Solid-state sources exist for higher frequency measurements, as required for ITER

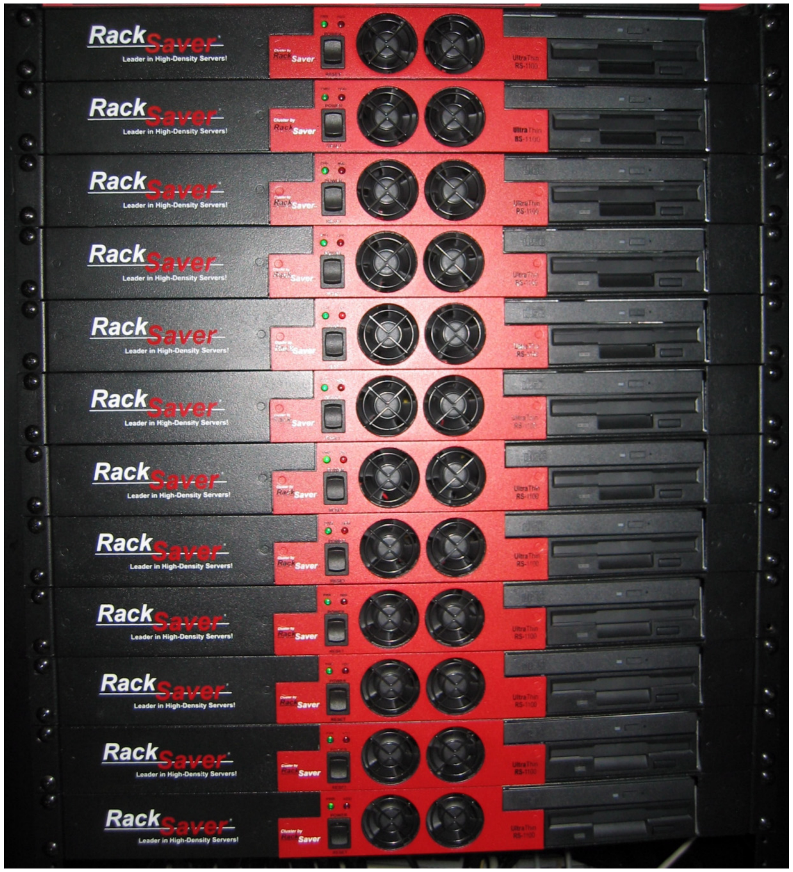
- Tore Supra and JET currently have solid-state profile systems to 155/160 GHz
- Maximum frequency required on ITER may be ~200 GHz (less than previously thought)
- Solid-state sources with >30 mW power currently exist to 200 GHz





Automatic, between-shot profile analysis enabled by multi-processor cluster on DIII-D

- Flexible digital signal processing similar to conventional radar, but with addition of profile inversion and other steps required for plasmas
  - Digital complex demodulation used to extract phase/time delay
  - Range resolution filtering and phase delay smoothing
  - Profile inversion from phase data
- 10 processors (photo) provide between-shot profile analysis
- Analysis of profiles measurements every 5 ms throughout a 5 s discharge takes ~4-5 min.
- Rapid growth in this technology, which can be expected to continue over next decade



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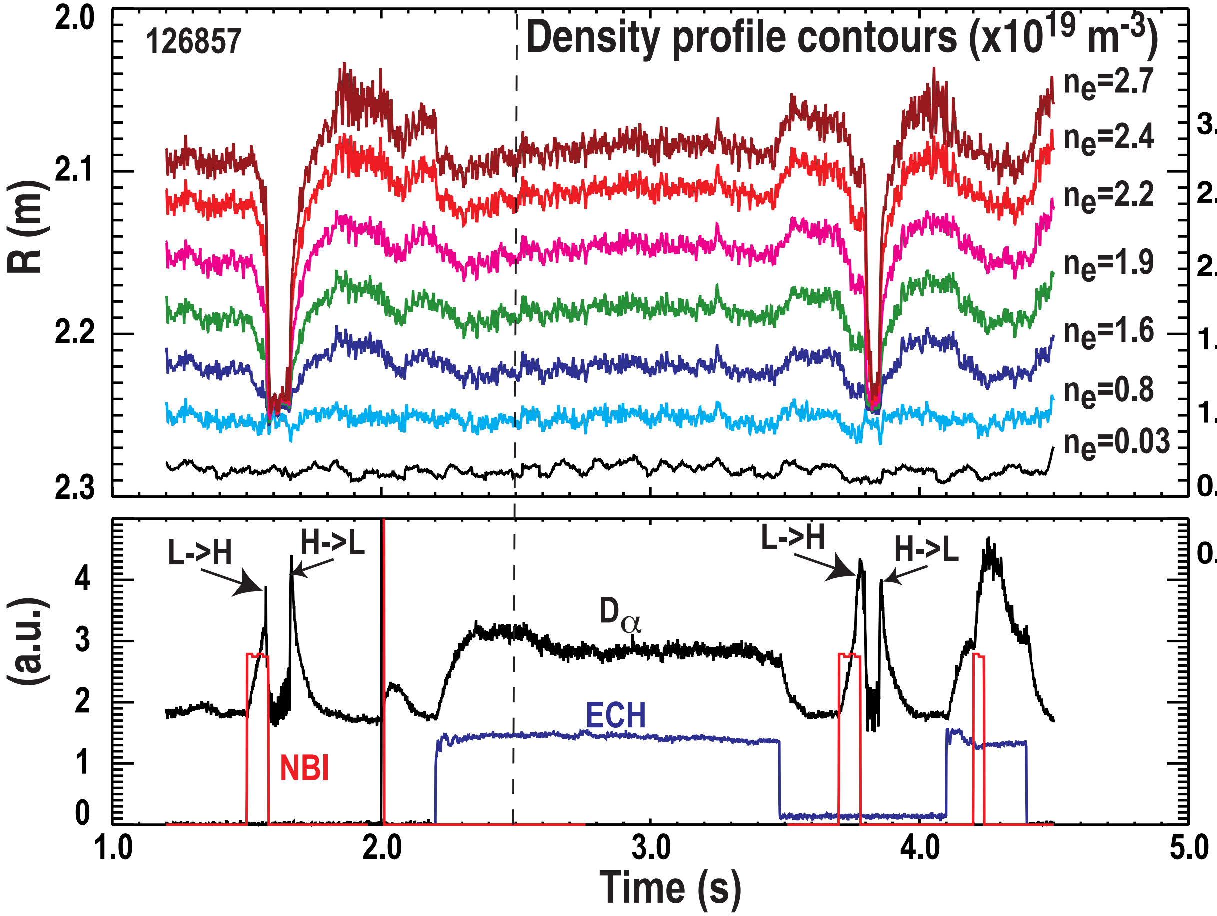
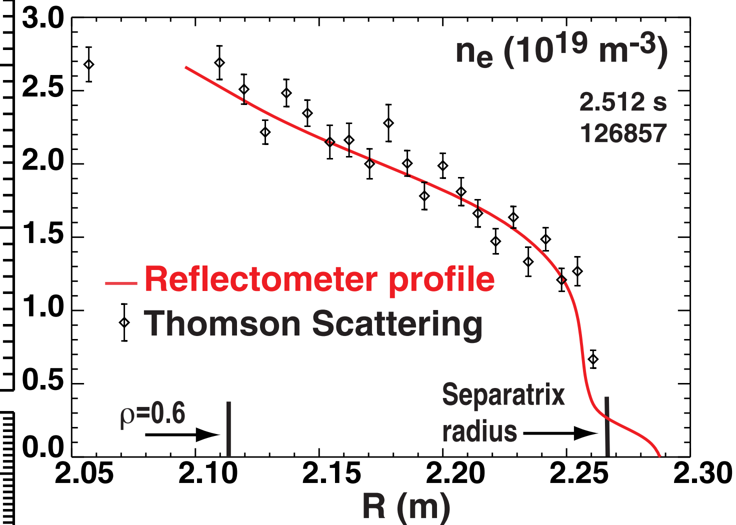
Example of fully-automatic DIII-D profile analysis with 1 ms time resolution, for duration of >3 s

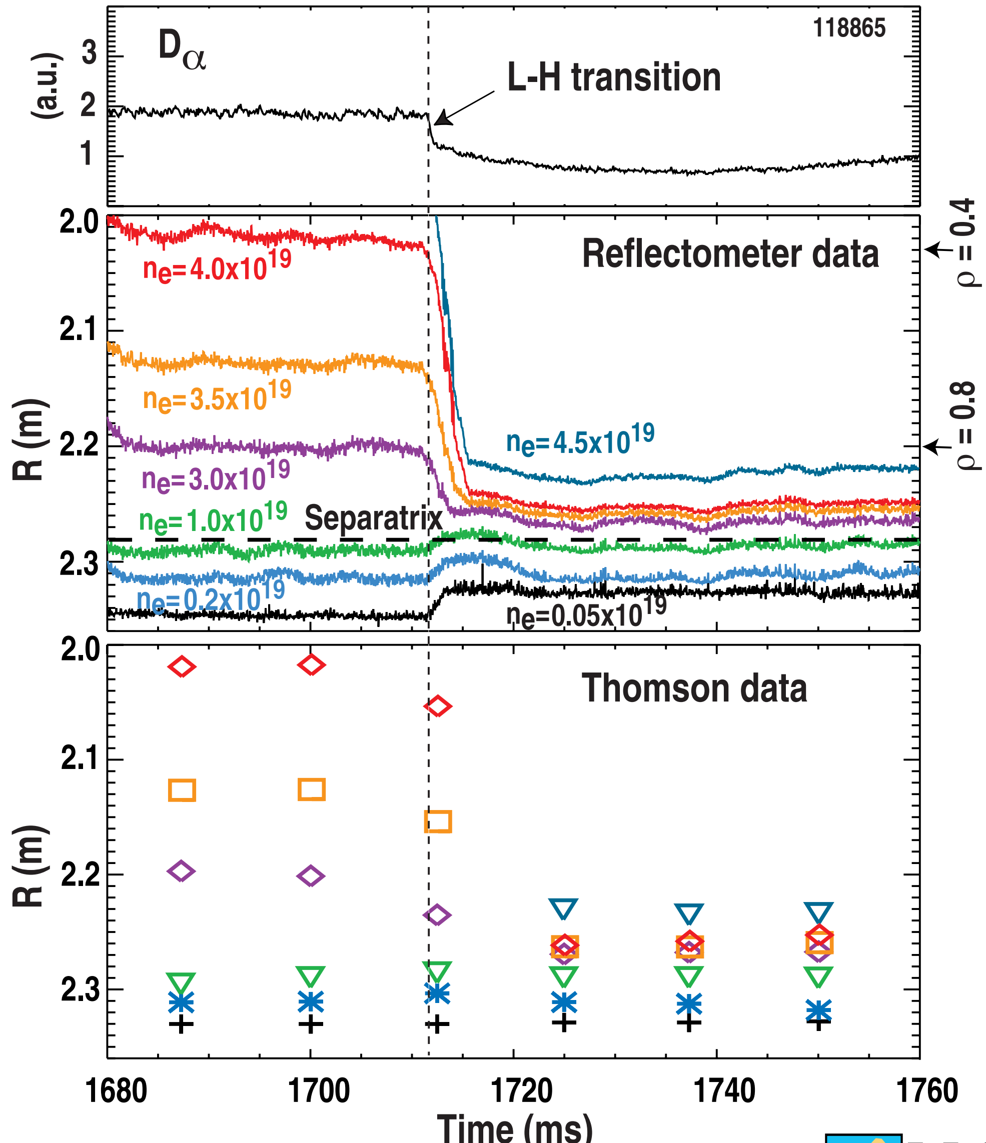
- **Example of ECH heated plasma with transient L-H transitions at NBI blips**





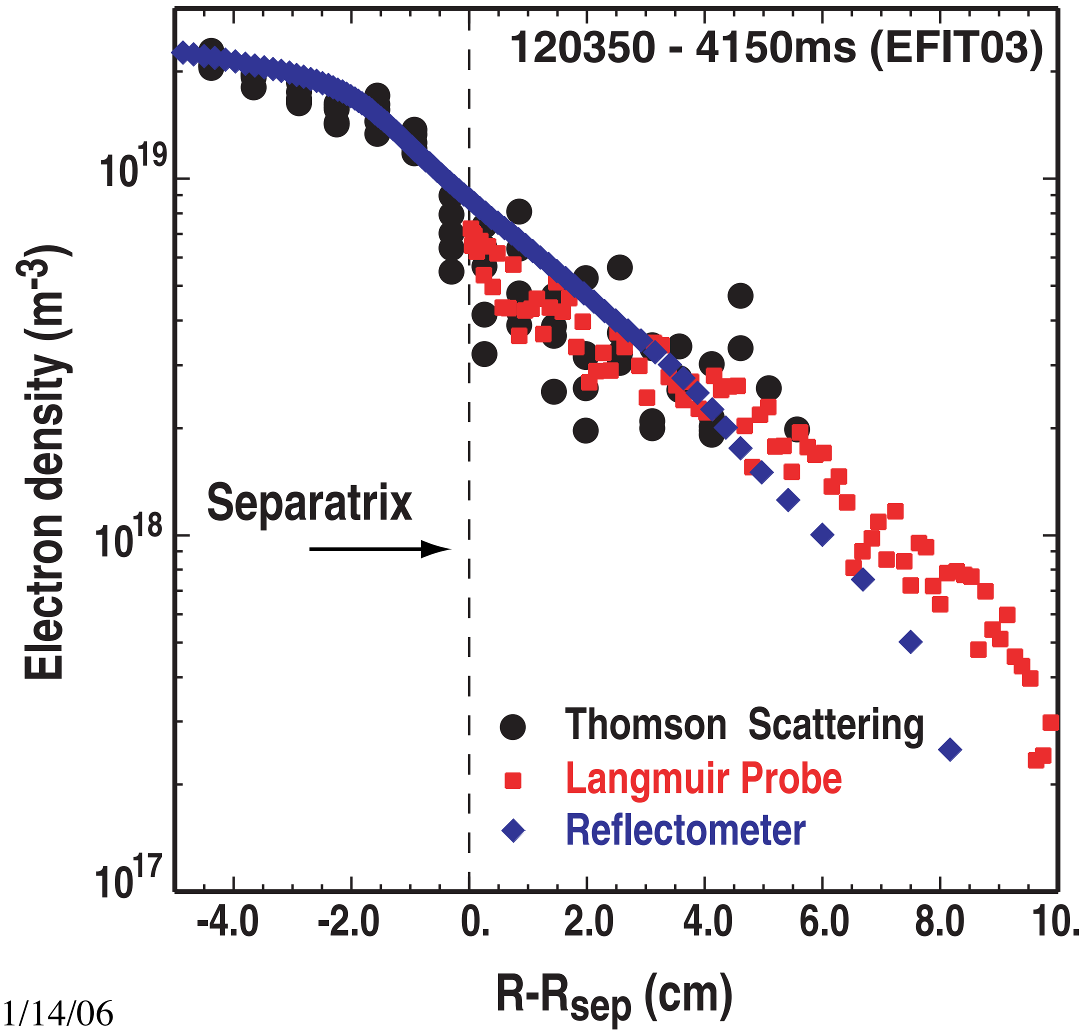
Very high time resolution is available, e.g. 25 μs (40 times previous example)

- **Profiles with 25 μs time resolution are available continuously for up to 2.5 s, limited only by data acquisition system**
  - 10 μs time resolution demonstrated
  - Standard DIII-D TS repetition rate is 12.5 ms
- **Example of profile data across L-H transition**



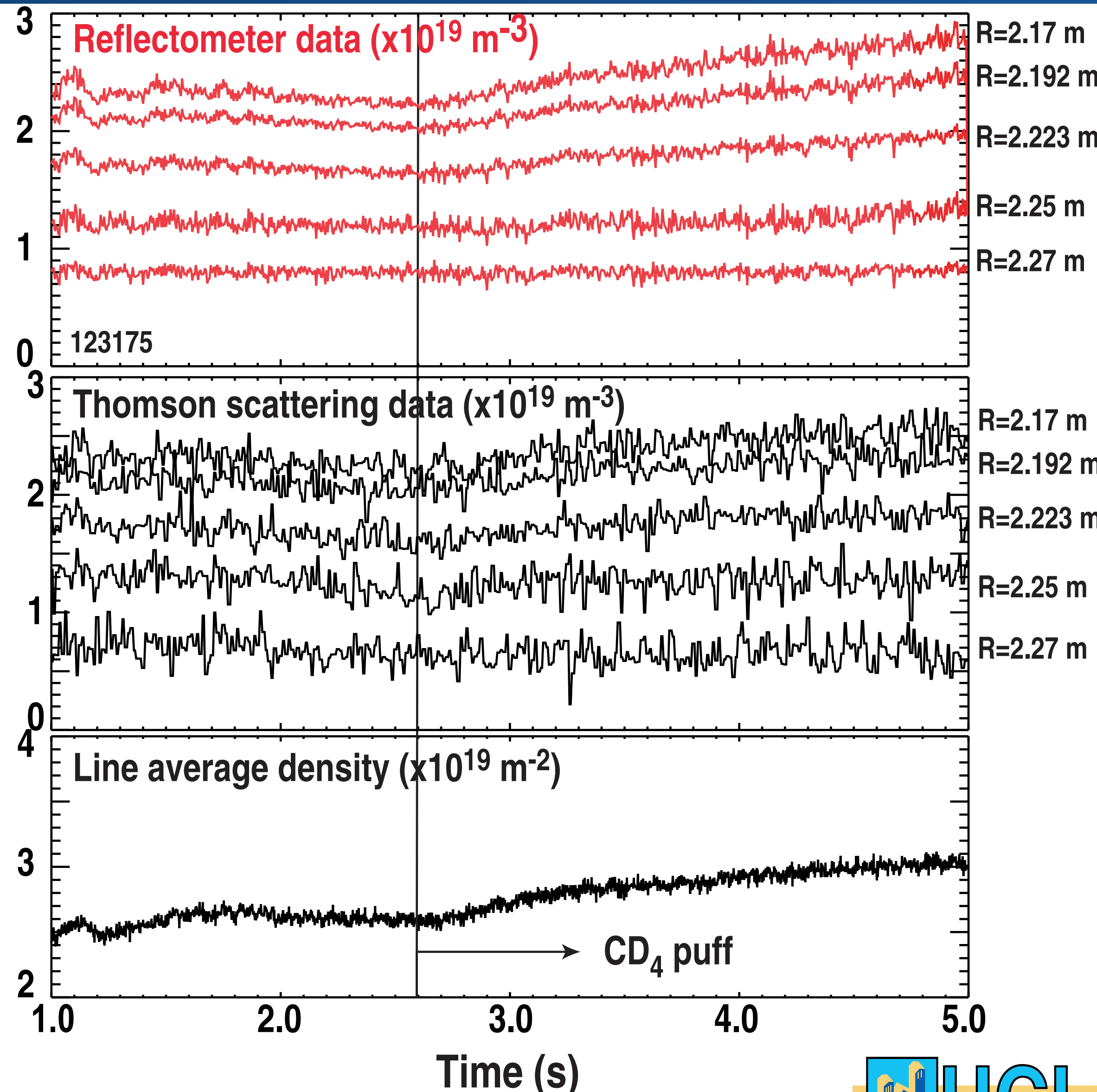
Excellent agreement found between reflectometer and other diagnostics in edge

- **Excellent agreement between three independent measurements**
  - Reflectometry, Thomson scattering (TS), reciprocating Langmuir probe measurements

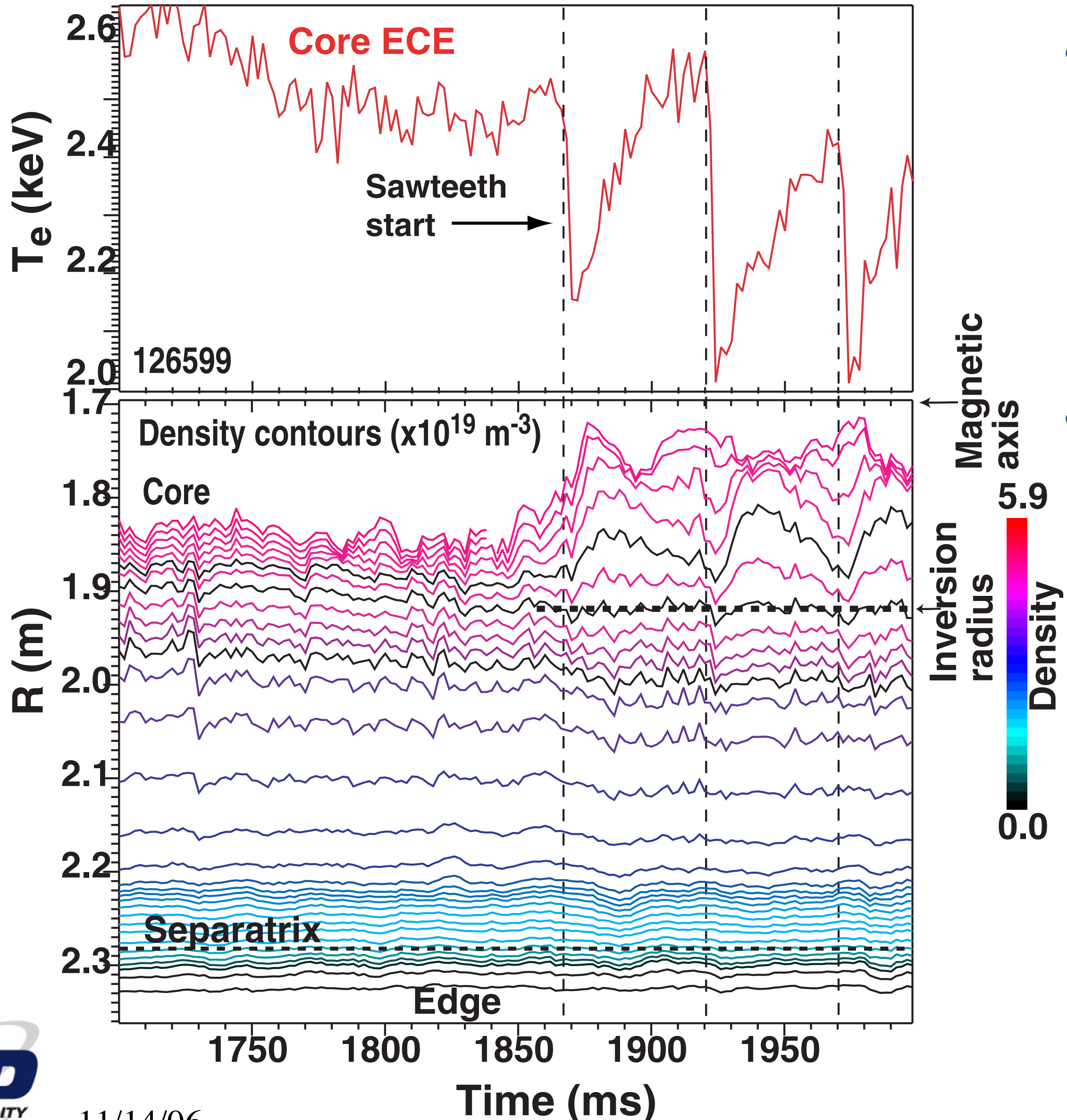


Reflectometer measurements have high precision

- **Direct comparison of reflectometer and Thomson data over same spatial and temporal range**
  - **Reflectometer with 5 ms and TS with 12.5 ms repetition rate**
  - **Less jitter on reflectometer data**
- **Reflectometer data are from automatic between-shot analysis**



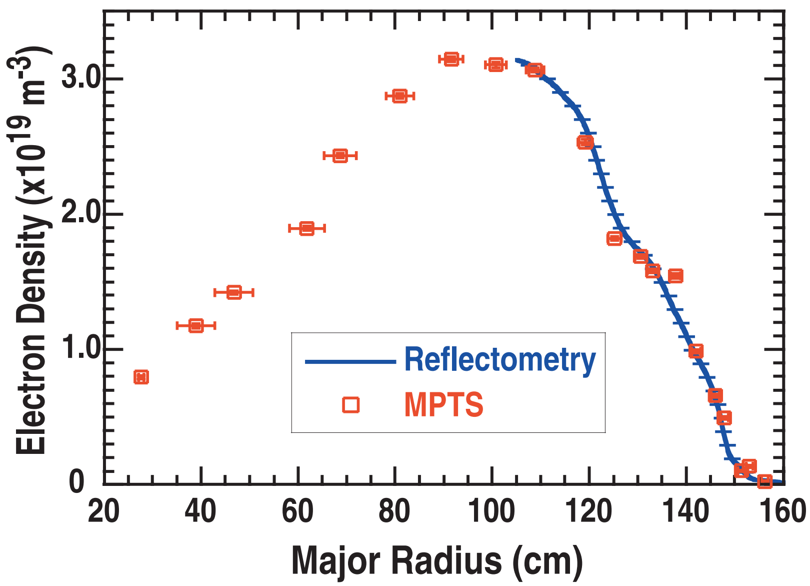
Core density profile modulation by sawteeth directly observed on DIII-D

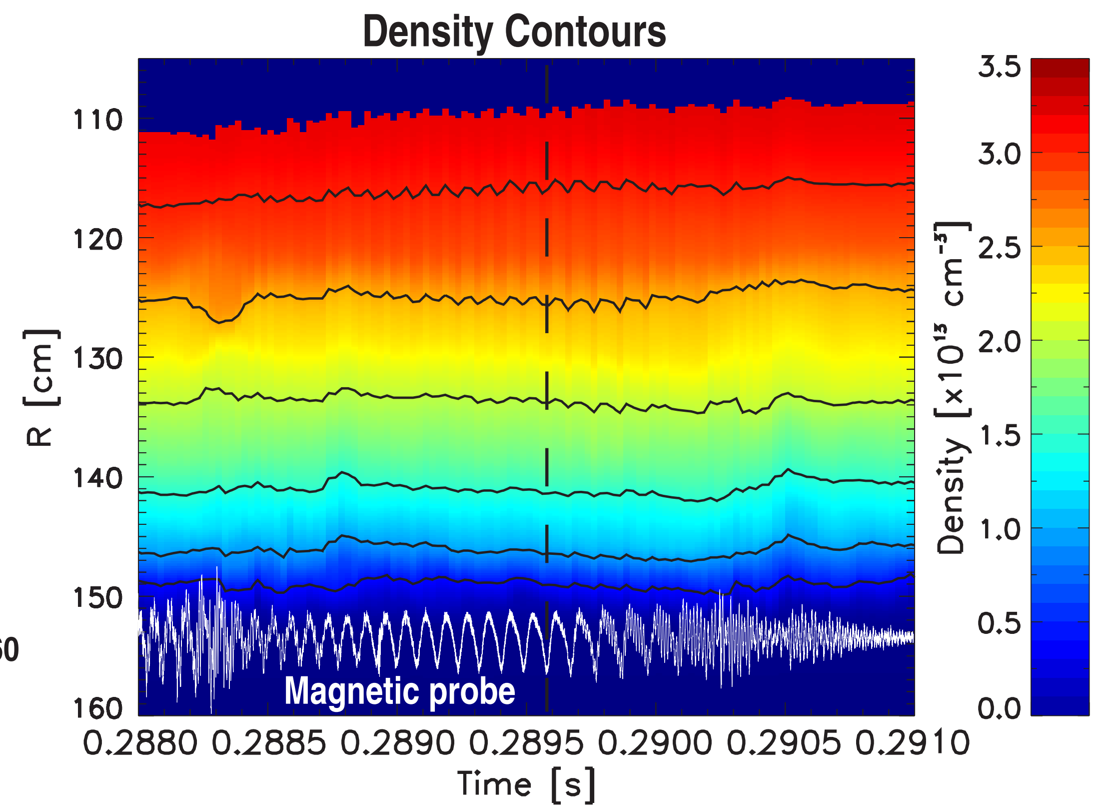


- Steep, ITB-like profiles in L-mode plasma relax when sawteeth start
  - 5 ms time resolution
- Also observed on Tore Supra, Sabot, EPS 2006

Core profile modulation by fast ion driven coherent modes directly observed on NSTX

- ~10 kHz energetic particle driven mode, with larger profile modulation in core than in edge
  - 25 μs time resolution
- Potential to provide mode structure and displacement measurements





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DIII-D and NSTX data provide proof-of-principle demonstration of ITER performance targets

- Current DIII-D performance levels over density range of 0-6.4x10^{19} m^{-3} are:
  - Spatial resolution:
    - ~0.4 cm at edge (twice rms jitter) (ITER target 0.5 cm)
    - ~2 cm in core (ITER target a/30~6.7 cm)
  - Time resolution:
    - 25 μs typical, 10 μs demonstrated (ITER target is 10 ms for core and edge)
  - Has proved capable of resolving edge H-mode pedestal, evolution through ELMs, ITBs, etc.

- Measurements are important for ITER, which seeks proof-of-principle demonstration of target performance levels on current devices

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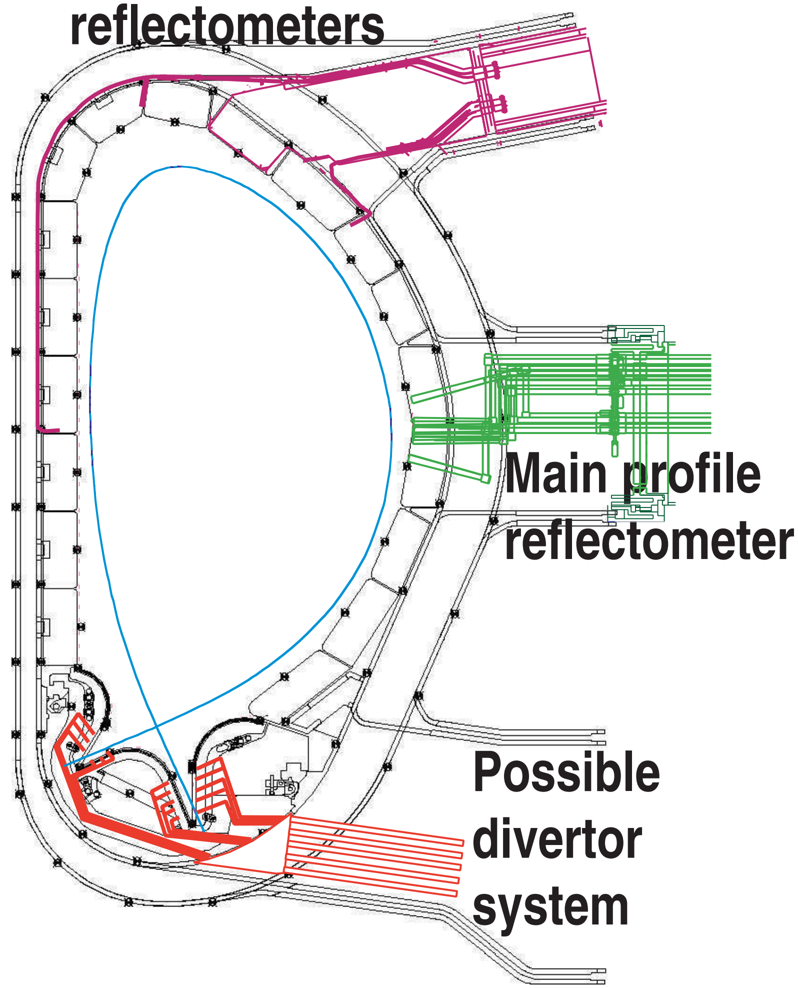
Reflectometry is intended to provide multiple plasma control and physics capabilities on ITER

- **Reflectometry on ITER will address a wide range of needs (Vayakis et al, NF 2006), using multiple systems, e.g.**
  - Density profile
  - Plasma position control
  - Plasma rotation
  - H-mode pedestal physics
  - MHD and EPMs
- **Main profile reflectometer design calls for core and edge profile measurements with:**
  - Density range of 0-3x10^{20} m^{-3}
    - >2.5 times Greenwald density (Propose to reduce to ~0-1.8x10^{20} m^{-3})
  - O-mode measurements from 15-150 GHz
  - X-mode from 75-250 GHz (reduce to ≤200 GHz)
  - 6 waveguide/antenna pairs



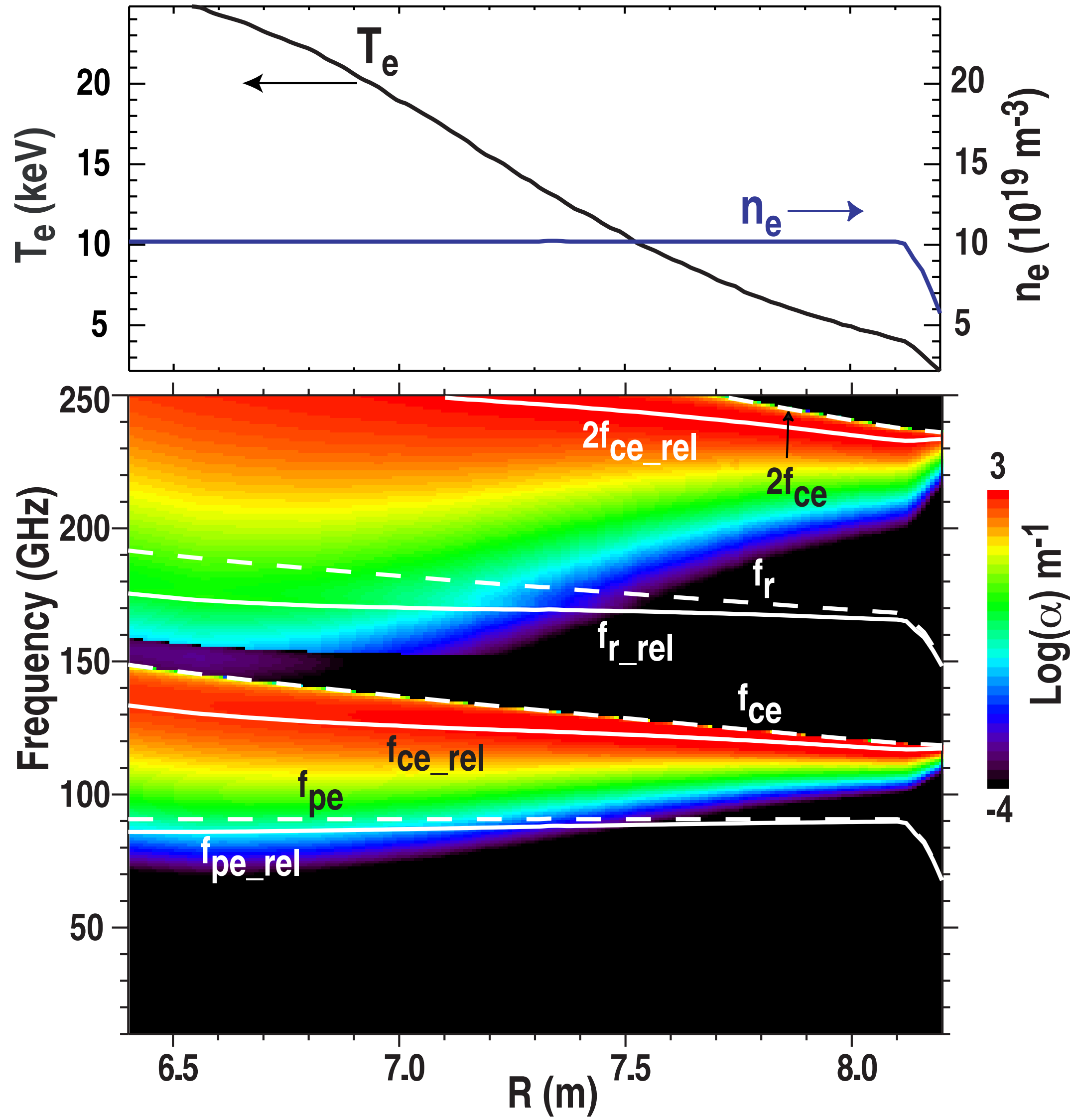
ITER presents new challenges and issues for feasibility of reflectometer profile measurements

- In plasma core, measurement access to cutoffs is affected by multiple relativistic effects:
  - Downshift and flattening of cutoffs
  - Absorption at downshifted and broadened cyclotron layers
  - 3-D refraction affects
- In the pedestal, relativistic effects are smaller than in core:
  - Pedestal measurements should be similar to measurements on current tokamaks
  - In general edge measurements easier to make than core, e.g. lower frequencies, etc.

- Conclusions from this study:
  - Refraction and time/phase delay variation due to cutoff curvature may be greatest limits on core measurements
  - Antenna arrangement needs to account for refraction - propose linear array configuration
  - Propose to reduce target measurement range to ~0-1.8x10^{20} m^{-3}

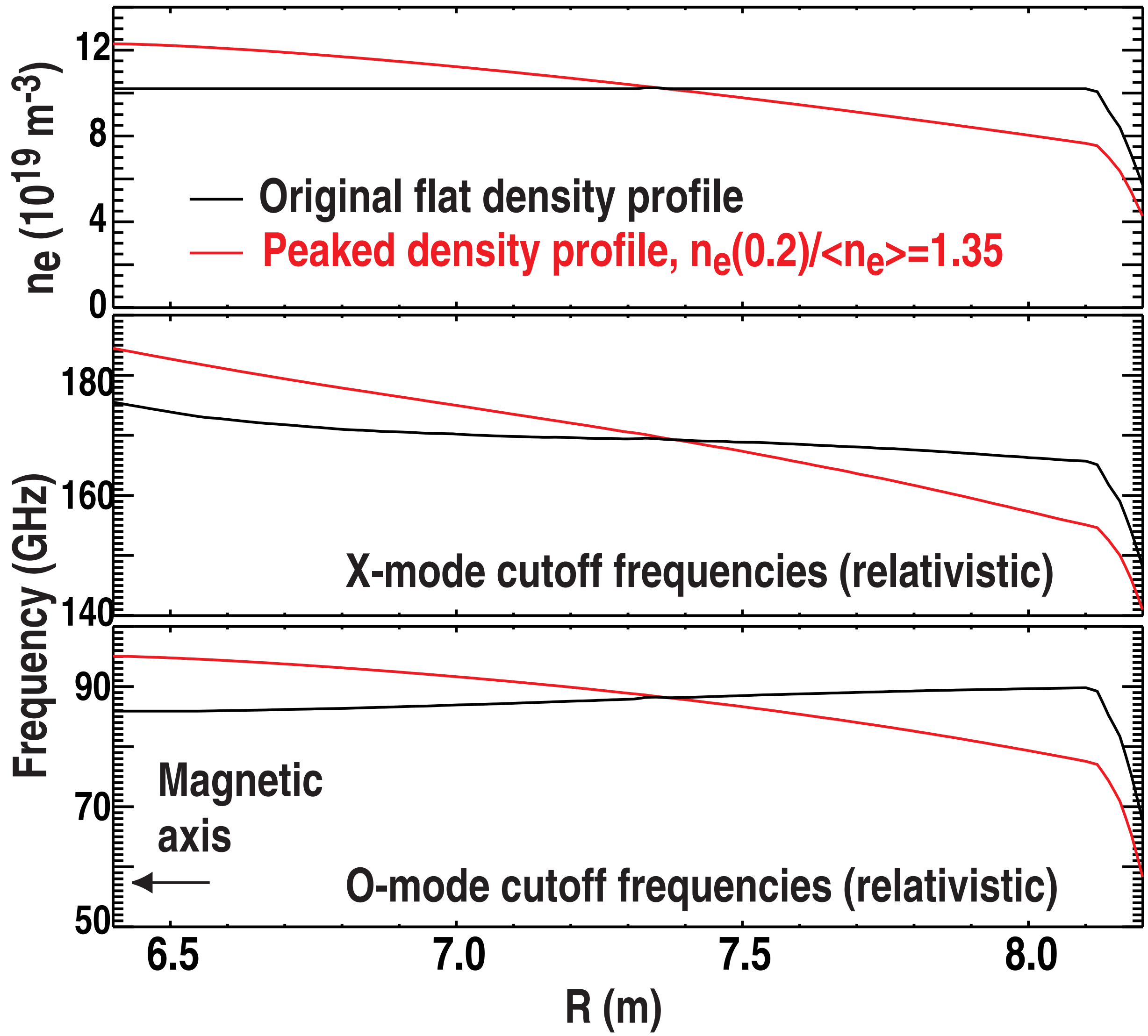
Access to cutoffs on ITER is affected by multiple relativistic effects

- **Calculations for ITER base case of ELMy H-mode operation (Scenario 2)**
- **Relativistic downshift/flat density profile makes cutoff profiles flat to hollow**
- **Cyclotron layers are also downshifted, leading to potential absorption problems**



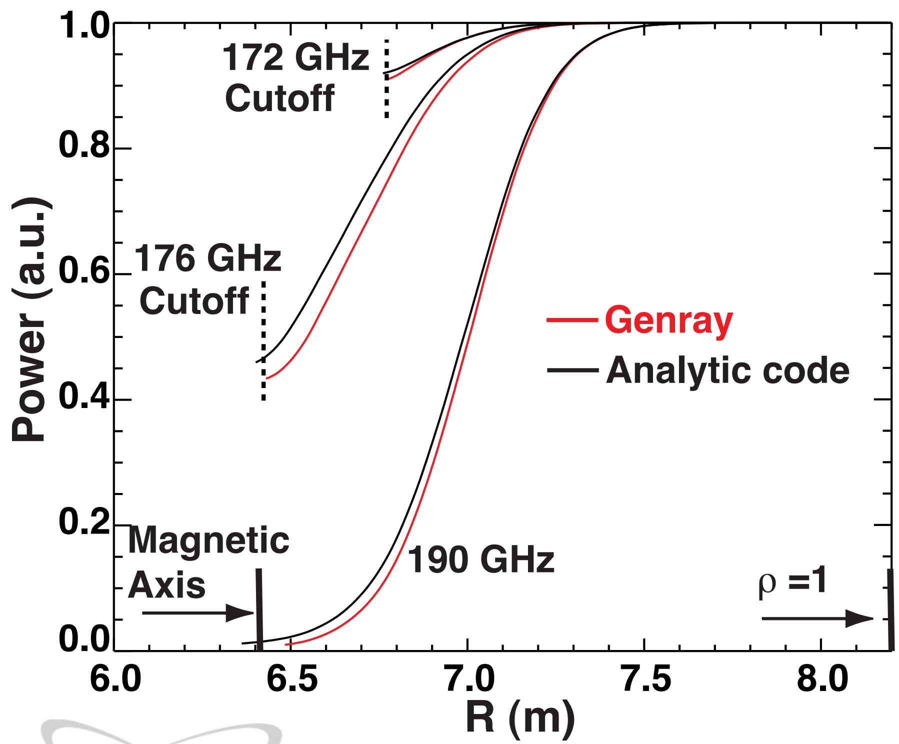
However, density peaking currently predicted for ITER will allow core measurements

- Latest predictions for ITER (Weisen, IAEA 2006) based on AUG/JET results predict $n_e(0)/\langle n_e \rangle \geq 1.35$ for ITER
- Even modest density peaking makes both O- and X-mode measurements viable
  - Creates gradient in cutoff frequency
  - Example for modified ITER reference case, keeping constant pressure and line density

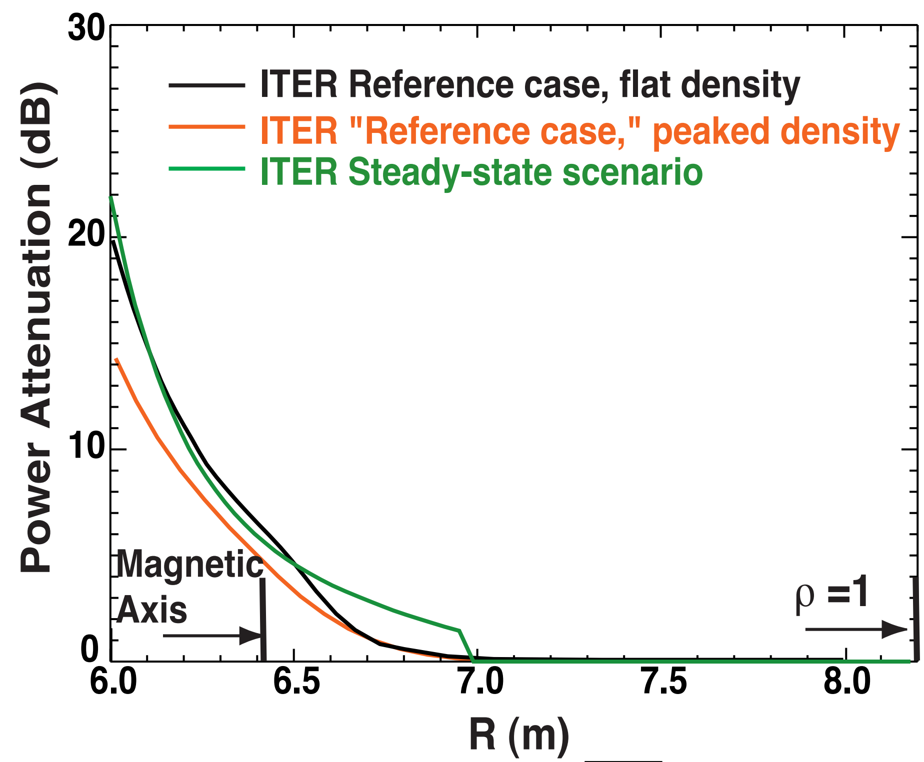


Cyclotron absorption may not be significant limitation on ITER, except close to plasma center

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

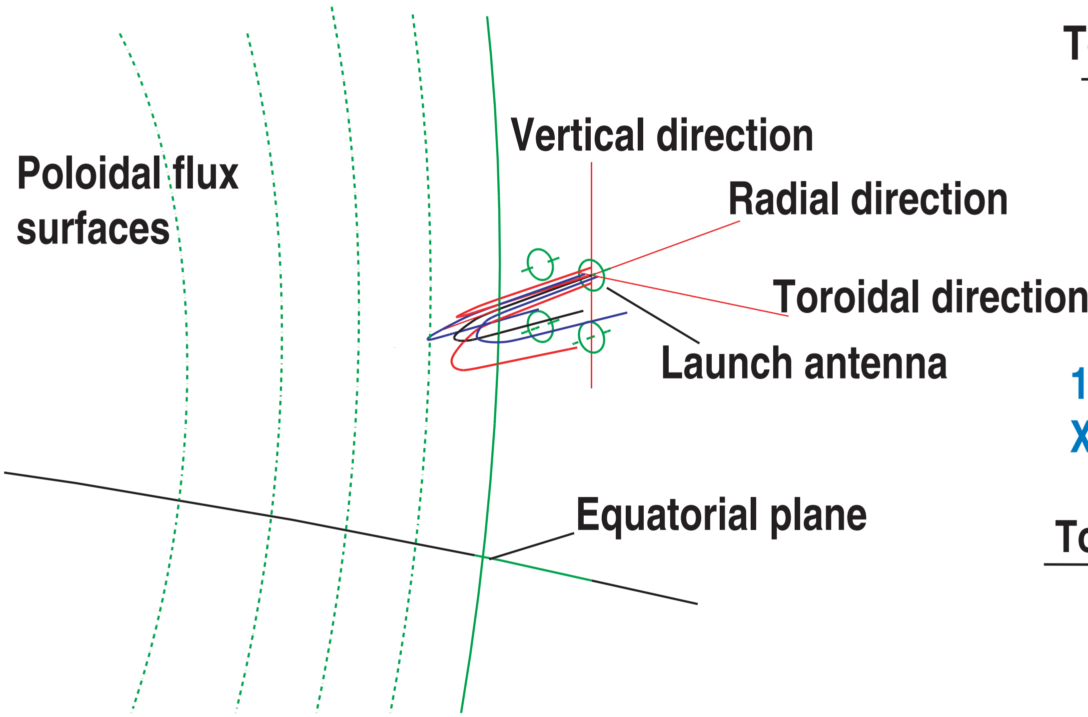


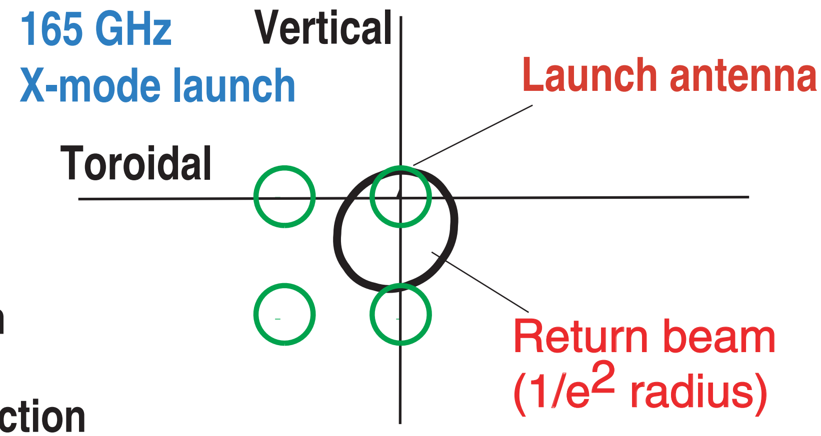
- Cyclotron absorption double pass loss only becomes significant close to plasma center

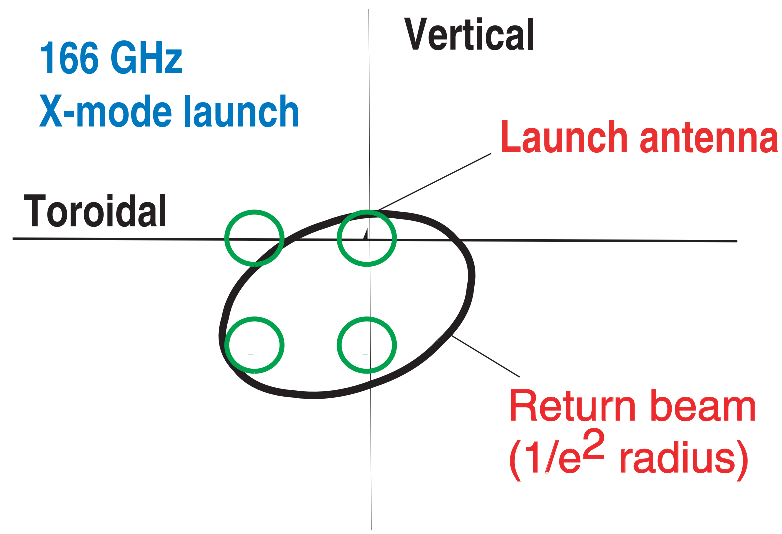


3-D relativistic ray tracing for ITER using GENRAY (Harvey, CompX) shows large refraction on ITER

- **Substantial toroidal and poloidal offsets, even from edge**

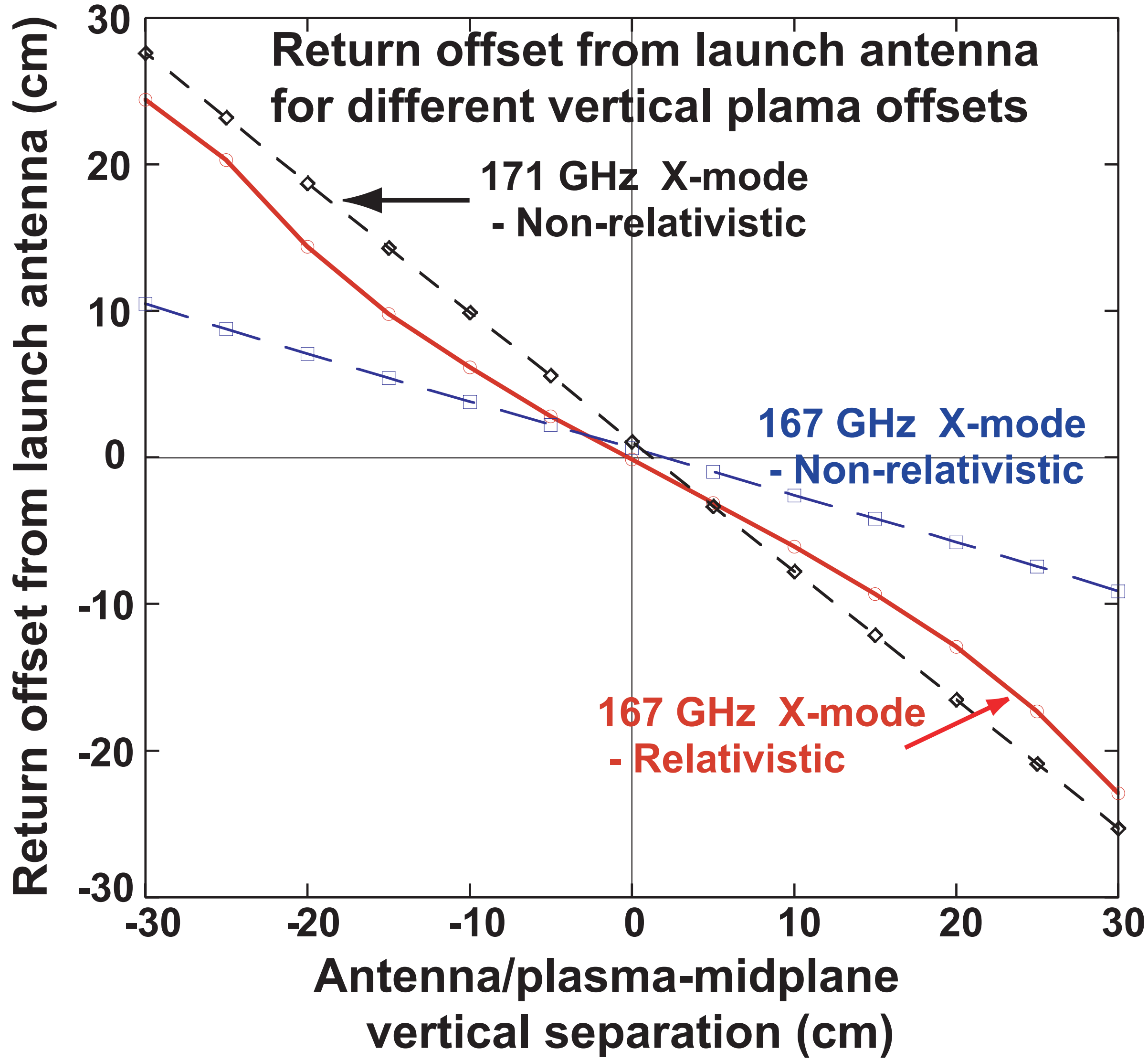






Tilted poloidal antenna array required to cope with refraction offsets for various shapes/positions

- X-mode refraction shown (substantially larger for O-mode)
- Solution is to rearrange ITER antennas in linear poloidal array
  - Also advocated by Kramer et al., NF 2006, from 2-D full-wave calculations
- Refraction and variable time/phase delay from cutoff curvature may be greatest limits on core measurements



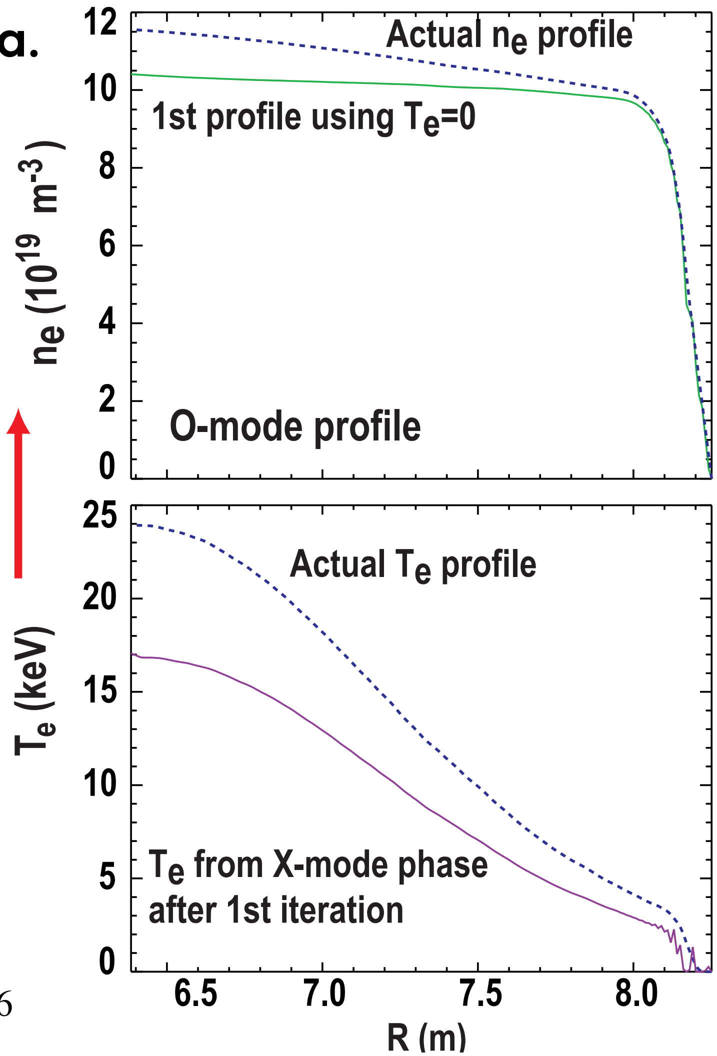
Reflectometry can determine T_e and n_e profiles on ITER if density is measured using two different cutoffs

- **Need to know T_e to determine n_e profile on ITER. However, due to different T_e sensitivities, can determine T_e and n_e if profile measurements made with two cutoffs. Perfect reconstruction possible with ideal data.**

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

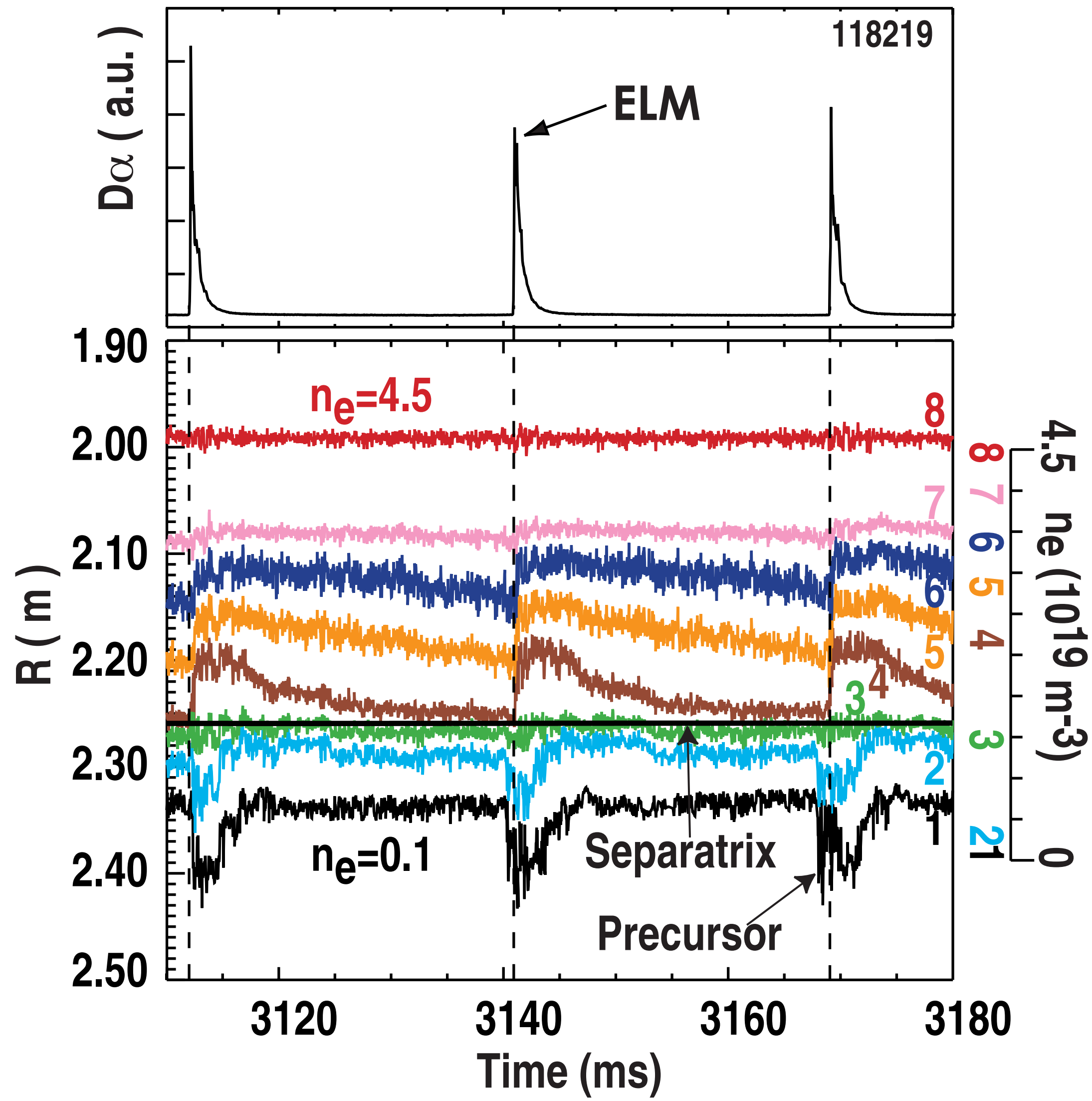
Step 2: X-mode phase - now a function of ne and Te- is inverted to extract Te profile using O-mode density profile as input

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



Edge pedestal profiles can be measured by reflectometry on ITER

- Edge measurements on ITER will not have problem with cutoff flattening or absorption
  - T_e and refraction corrections will be needed
- Pedestal measurements will be critical on ITER
  - ELMs, wall interaction, performance, stability, H-mode operation
- Example of pedestal measurements on DIII-D, with 25 μs time resolution through three ELM cycles with high spatial resolution



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Summary

- **Technological advances have transformed performance of reflectometer systems for measurement of electron density profiles**
  - Broadband, solid-state fast-sweep mm-wave sources
  - Improved data acquisition/analysis with use of parallel processing for between-shot profile analysis

- **Spatial and temporal resolution of current DIII-D measurements provides proof-of-principle demonstration of ITER target values**
  - Increases confidence in achieving targets on ITER

- **Edge pedestal measurements should be possible on ITER. Core measurements should also be possible if density profile is peaked**
  - Refraction and time/phase delay variation due to cutoff curvature may be greatest limits on core measurements
  - Propose linear array configuration to account for refraction
  - Other issues need further study, e.g. turbulence effects, waveguides, etc.