An assessment of reflectometry imaging


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Overview

- Conventional reflectometry is an extremely powerful diagnostic with multiple measurement capabilities – well suited to both existing and next-step fusion devices.

- What are the motivations for pursuing microwave imaging in plasmas?
  - Suggestions that conventional reflectometry is significantly flawed and often produces erroneous results. Series of papers by Mazzucato, Munsat, et al.
  - It is believed that imaging can correct these errors and thereby extend operational range.
  - Secondary goal of creating 2-D images of plasma turbulence to compare with simulation codes

- Imaging, as currently proposed, introduces access and other limitations that make it difficult to usefully apply – particularly on next-step devices.

- These constraints seem certain to reduce the operational range inherent in the imaging concept. Great care has to be taken interpreting images. Need to focus on detailed quantitative comparison.

- This talk provides a brief overview of measurement capabilities of conventional reflectometry. It contrasts phase measurements with the simple homodyne detection.

- A simpler approach to microwave imaging is also described which allows a clear assessment of the potential benefits and difficulties of “imaging”.
2-D Images - Not ALL images are equal!

- Great care has to be taken in the interpretation of “images”
- Focus should be to obtain quantitative information
- There already exist a number of “imaging” diagnostics
  - Gas puff imaging; beam emission spectroscopy, electron cyclotron emission imaging
  - Reflectometry imaging has also been proposed: what will these images represent?

Are these images similar? What do they represent?

Understand the details or you may draw incorrect conclusions.
• First, it has been suggested that microwave reflectometry “imaging” is essential, even when viewing a single location.

• Second, there is a desire to produce 2-D “images” of plasma turbulence to connect to computer simulations.

  “The difficulty arises from the fact that when the plasma permittivity fluctuates perpendicularly to the direction of propagation of the probing wave, the spectral components of the reflected field propagate in different directions. This can result in a complicated interference pattern on the detector plane, from which it is difficult to extract any information about the plasma fluctuations. In essence, the measurement of the fluctuations is limited by the fluctuations themselves.”

  “In this technique, large-aperture optics at the plasma edge are used to collect as much of the scattered wavefront as possible and optically focus an image of the cutoff layer onto an array of detectors, thus restoring the integrity of the phase measurement.”


Preliminary microwave imaging data on TEXTOR

Illustrates microwave imaging system installed on TEXTOR

Also shown are the I/Q plots as cutoff layer moves through image plane (6 cm difference).

New data run is planned in near future at TEXTOR.

Note the size of the optical system and the nature of the spectrum.

Munsat et al. , Plasma Physics & Controlled Fusion, March 2003

Munsat et al. , Review of Scientific Instruments
Basic homodyne configuration for reflectometry measurements

- Typical “homodyne” reflectometer system suitable for density profile measurement
- Systems that are somewhat more complicated are necessary for measurement of turbulent correlation length, magnetic field strength measurement, etc.
- However, these systems are easily integrated into both existing and next-step fusion plasmas – no detector array required close to plasma.
**Conventional reflectometry is extremely versatile and powerful**

- **Well-suited to burning plasma environment**
  - Sensitive hardware can be remotely located. *Essential that high quality low-loss waveguide be installed - ITER.*
  - Contributing operationally and scientifically to numerous fusion devices world-wide.
  - Planned for ITER – we, as a community, should promote the expansion of the measurement capabilities employed on ITER. Concern that many “optical” diagnostics may fail prematurely.

- **Can perform multiple tasks**
  - **Demonstrated capabilities:**
    - density profiles: simultaneous use of O and X mode propagation increases spatial coverage (Wang et al)
    - turbulent correlation lengths (rhodes et al)
    - magnetic field strength – O-X mode correlation reflectometry (Gilmore et al., Kramer)
    - rf waves including Alfvén modes (J.H. Lee et al)
  - **Sensitive, local, turbulence measurement with high bandwidth**
    - Accuracy regarding determination of density fluctuation levels not clear- via imaging?
  - **Future possibilities**
    - magnetic field tilt angle: correlate along field line – experiment initiated on NSTX (Kubota et al)
    - ExB flow – partially demonstrated. Various techniques. (UCLA – Rhodes+ others)
    - density fluctuation level: for many reasons not easy, even with “imaging” - results have been published from TFTR and JT-60 – are they still valid?
    - etc?
Demonstrated measurement capabilities

Density profiles

Turbulent correlation lengths

Magnetic field strength: Dual-mode (O-X mode) reflectometry

TABLE 1. Example comparisons of $|\theta|$ measured by O-X correlation reflectometry with values from EFIT reconstructions under various conditions in NSTX.

| Shot  | Time range (ms) | Condition | $B_{\text{major}}$ on axis (T) | Reflectometer cutoff major radius (cm) | $l_\perp$ (cm) | $|\theta|$ at cutoff from ERL (T) | Swept channel ($O/X$) | $|\theta|$ at cutoff from O-X reflectometer (T) |
|-------|-----------------|-----------|-------------------------------|----------------------------------------|----------------|----------------------------------|---------------------|-----------------------------------------------|
| 106360| 170–220         | Ohmic     | 0.45                          | 121                                    | 27             | 0.39                             | O                   | 0.38±0.015                                    |
| 106387| 170–220         | NBI, L mode | 0.40                         | 147                                    | 5              | 0.26                             | O                   | 0.25±0.015                                    |
| 108250| 250–300         | NBI+rf, L mode | 0.35                      | 151                                    | 6              | 0.30                             | X                   | 0.30±0.014                                    |
| 108270| 250–300         | NBI+rf, L mode | 2.45                      | 151                                    | 8              | 0.32                             | X                   | 0.31±0.015                                    |
| 108723| 475–550         | NBI, L mode | 0.425                        | 146                                    | 6              | 0.35                             | X                   | 0.35±0.017                                    |
| 108727| 300–350         | NBI, L mode | 0.50                         | 147                                    | 8              | 0.39                             | X                   | 0.39±0.012                                    |
| 108727| 375–450         | L mode     | 0.50                         | 149                                    | 5              | 0.39                             | X                   | 0.39±0.015                                    |
| 108728| 225–300         | H mode     | 0.55                         | 147                                    | 3              | 0.39                             | X                   | 0.39±0.015                                    |
Comparison of correlation reflectometry with Langmuir probes.

Comparison performed in a laboratory magnetized plasma – the LAPD device at UCLA.

Note that the reflectometry measurements were performed using X-X, O-O and X-O modes of operation.

• Homodyne correlation reflectometry was found to accurately measure turbulent radial correlation lengths, under the conditions studied.

See also: “Dual mode ordinary–extraordinary correlation reflectometry for magnetic field and turbulence measurements” M. Gilmore et al, RSI Vol 72 (1), 293-300, (Jan 2001)
Comparison of correlation functions of amplitude, phase and homodyne signals with Langmuir probes.

Comparison performed on a linear magnetized plasma.

"Dual mode ordinary–extraordinary correlation reflectometry for magnetic field and turbulence measurements"
M. Gilmore et al, RSI Vol 72 (1), 293-300, (Jan 2001)
Large amplitude density fluctuations can cause the phase to become indeterminate. This leads to $1/f^2$ spectra and incorrect determination of correlation length.

The homodyne spectrum remains consistent with probe data - correlation lengths remain in agreement. It should be noted that the cutoff layer is located well beyond the so-called “diffraction distance” defined by Mazzucato et al.

Removal (if possible) of phase “jumps” recovers both a spectra and correlation function that agree well with Langmuir probe data.

However, it is clear that, without correction, contaminated reflectometry PHASE data is unusable.

Homodyne data does not apparently suffer from this problem.
Comparison of reflectometer homodyne and phase fluctuation spectrum with Langmuir probe in CCT tokamak.

Comparison of Langmuir probe and homodyne reflectometry spectra in high fluctuation plasma

Data from CCT: “Signal amplitude effects on reflectometer studies of density turbulence in tokamaks”, T L Rhodes et al. Plasma Physics and Controlled Fusion

Homodyne spectrum agrees well with Langmuir probe

Again, the phase spectrum clearly fails at high fluctuation levels.
It appears that analysis of “homodyne” data can produce accurate measurements of a wide range of parameters even when analysis of phase data fails. Note that the homodyne signal is simply the electronic output from a millimeter-wave mixed - it is not equivalent to a calculated complex amplitude.

Examples of validated homodyne measurements include the following:

- Density profiles
- Turbulent correlation lengths
- Magnetic field strength
- General spectral properties
- Magnetic field pitch angle – not demonstrated fully.

Measurement of density fluctuation level

- Difficult to relate a homodyne signal to fluctuation level.
- Would seem to require a phase measurement.
- Can “imaging” fix this problem?
- Should note that even if phase is known determination of fluctuation levels is nontrivial.
- Much remains to understand. Needs careful comparison in a controlled experiment.
Existing approach to microwave imaging in plasmas

UC Davis-PPPL approach to microwave imaging

• In this approach the local oscillator and illumination sources are distinct. This makes an assessment of the imaging properties in a plasma difficult.

• Note that the quasi-optical system is designed to “match” the plasma cutoff layer so that the reflected power is directed towards the “imaging” detector array. What happens when the plasma is shifted vertically? After all the plasma is part of the “optical system”.
Restrictions associated with microwave reflectometry imaging

- **Imaging approach requires a very large view of plasma together with a large optical system close to boundary of machine.**
  - Reduces access for alternative diagnostics. Existing fusion devices such as spherical tori have limited port space.
  - Heat load concerns will prevent installation on some higher performance, longer pulse plasmas.

- **Imaging optics have to be ”matched” to shape and location of cutoff layer.**
  - The plasma is a dielectric medium and therefore part of the imaging optics.
  - This represents a problem in plasmas where the shape is varied significantly. e.g. double null, single upper null, single lower null, etc.
  - Imaging properties will be blurred significantly. Imaging properties will be lost.

- **In ITER the proposed imaging optics would have to be close to plasma edge (blocking access). In addition, detector array would have to be inside vacuum close to optics!**
2-D imaging requires simultaneous operation at multiple frequencies

- This will be very difficult to achieve. No demonstration yet: next step.
- Generation of image using a swept source "might" be possible but is not desirable.

Great care has to be taken to avoid contamination due to multiple reflections both from the optics and from the imaging array.

- This is a particularly difficult problem when multiple frequencies are involved.

Optical aberrations represent a significant problem

- Small angular deflections (e.g. caused by refraction) can, due to aberrations, result in an image where pixels are interchanged and the image distorted. The greater the demagnification of the image the greater this problem becomes. In ITER the image distance will be very large increasing the required demagnification to detector array.
An alternative approach to microwave imaging

Launch distinct rf frequencies from adjacent horns e.g. 50 and 50.1 GHz.

If cutoff layer coincides with image plane reflected/scattered radiation returns to the launch horn (?)

As the layers separate expect reflected/scattered radiation to become distributed amongst adjacent horns.
Radiation “imaged” at identical radii, but at distinct poloidal or toroidal locations.

When the cutoff layer coincides with the image location the reflected radiation should return to the original horn. **Power returning to horn is measurable.**

However, when there is a image mismatch, radiation will be received by multiple horns. **This is measurable.**

The optical “imaging” properties of the system in the plasma can therefore easily be checked. **This is important and is not possible in current microwave imaging systems.**

Detection at the IF frequency of ~100MHz allows quadrature detection and determination of phase. Since the homodyne signal would also be available, this would allow direct comparison for correlation length determination, etc.

Multiple spatial locations can be probed radially, poloidally and toroidally. **This allows the possibility for flow measurement, poloidal spectrum determination, etc. Measurement of ECE emission simultaneously is also possible.**

Plans underway to install system on DIII-D. 2-D simulation of simplified system also will be investigated in collaboration with Gerrit Kramer/Raffi Nazikian PPPL.
**Summary**

- **Standard homodyne reflectometry is a very powerful diagnostic capable of a wide range of measurements in both existing and future burning plasmas**
  - Demonstrated measurement capabilities include density profile, turbulent correlation length, magnetic field strength, etc.
- **Visualization of turbulence is being pursued via a number of techniques including microwave reflectometry. Great care has to be taken interpreting these images. MIR also viewed as essential by some to expand operational range.**

- **However, it should be recognized that microwave imaging reflectometry has significant potential limitations.**
  - Port accessibility: not suitable for burning plasma application
  - The fact that the plasma itself is part of the optical imaging system. Plasma shapes are constrained to match the imaging system. Depth of focus limitations.
  - Multi-frequency operation required for 2-D image – non-trivial.

- **A simplified, alternative, approach to microwave imaging has been proposed that allows quantitative assessment both in a controlled laboratory environment as well as in a fusion plasma. This novel approach should further our understanding of microwave reflectometry and introduce new measurement capabilities.**

- **The technique is potentially applicable to burning plasmas - no detector arrays close to plasma.**