Microwaves used for the first time in the position control of a fusion machine

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OUTLINE

- Motivation
- FMCW Radar in the feedback loops
- Required R&D
- Demonstration results
Motivation

In future fusion reactors, fast neutrons and radiation emitted by D-T fusion plasmas may affect magnetic sensors.

An alternative approach to magnetic sensor based plasma position control is essential for ITER long pulse operation!

Reflectometry is one of the few diagnostics with potential to perform position measurements in real time (proposed 1997).

This novel application of reflectometry needed to be demonstrated in the present fusion devices.
ITER is a 16 billion € Machine!

Position control of the plasma column is very Critical.

- 5.3 T magnetic field
- 15 MA of plasma current
- 500 MW of fusion power
- 150 million °C
Demonstration on ASDEX Upgrade

ASDEX Upgrade provides a unique test bed for this demonstration:

- **ITER relevant** configuration and plasma regimes.
- Unique O-mode (non-magnetic) **FMCW Radar** capable of probing the **inner and outer** plasma edge gap, equivalent to ITER control gaps $g_3$ and $g_6$. 
Reflectometry density measurement

$n_{co} \propto F^2$

Electron Density Profile

$\frac{n_e}{n_e(F_1)}$

$\frac{n_e(F_2)}{}$

F

R [m]

$F_1 \leftrightarrow F_2$

vco

Detector

FMCW Radar

Plasma

$n_{co}$

Probing Wave

Reflected Wave

$n_e [x10^{19} \text{ m}^{-3}]$

$e_0(F_1)$

$e_0(F_2)$
Reflectometry density measurement

Electron Density Profile

\[ n_c \propto F^2 \]

\[ n_e(F_1) \quad n_e(F_2) \]

R [m]

FMCW Radar

Detector

\[ F_1 \rightarrow F_2 \]

\[ F_1 \quad F_2 \]

Probing Wave

Reflected Wave

Electron Density Profile

\[ n_e [x 10^{19} \text{ m}^{-3}] \]

Beat signal

FMCW Radar

Plasma

vco

\[ F_1 \rightarrow F_2 \]

Detector

Probing Wave

Reflected Wave

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Reflectometry density measurement

$$\tau_g(f) = f_b(t) \frac{df}{dt}^{-1}$$

FMCW Radar

Beat signal

Up to 1 GHz/µs
Reflectometry density measurement

\[ \tau_g(f) = f_b(t) \frac{df}{dt}^{-1} \]

\[ R_{co}(F_{co}) = \frac{c}{\pi} \int_0^{F_{co}} \frac{\tau_g(f)}{\sqrt{F_{co}^2 - f^2}} df \]
Reflectometry density measurement

Electron Density Profile

\[ R = \text{R [m]} \]

\[ n_e [x10^{19} \text{ m}^{-3}] \]

\[ F_{\text{MCW Radar}} \]

**Plasma**

\[ n_{co} \]

**Probing Wave**

**Reflected Wave**

\[ R_{co}(F_{co}) = \frac{c}{\pi} \int_{0}^{F_{co}} \frac{\tau_g(f)}{\sqrt{F_{co}^2 - f^2}} df \]

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Position control with reflectometry
Position control with reflectometry

Interferometry

Reflectometry

$n_e(\text{sep}) \sim K \bar{n}_e$
Position control with reflectometry

Control position estimate requirements:

- **ITER** ► 1 cm accuracy & 10 ms time resolution
- **ASDEX Upgrade** ► 1 cm accuracy & 1 ms time resolution
Real-time data processing algorithms

Group delay estimation procedure

\[ \tau_g(t) = f_b(t)(\frac{\Delta F_p}{\Delta T})^{-1} - \tau_{corr} \]
Real-time data processing algorithms

Group delay estimation procedure

Average of four measurements

\[
t = 0 \\
t = 35 \text{ ms} \\
t = 70 \text{ ms} \\
t = 105 \text{ ms}
\]
Real-time data processing algorithms

**Group delay estimation procedure**

Group delay (max. peak detection)

Averaged group delay mapping
Real-time data processing algorithms

Profile calculation

**NN Input**

- Probed region

**NN Output**

- $N$ radial positions corresponding to $M$ fixed density layers

$N \tau_g(f)$ values evaluated at $N$ fixed probing frequencies

$N \times L \times M$ feedforward NN

Profile calculation
Real-time diagnostic / system integration
RT data acquisition & processing system

Custom designed DAS

- 8 channel, 12-b, 100 MSPS
- **PCle** 1.1 x8 bus (DMA capable)
- Sustained DMA transfers of **1.272 GB/s** (measured)
- Data packet tagging (48 bit timestamping & frame count)

RT data processing host

- Dual quad-core Xeon server (Intel Xeon E5450 @ 3.0 GHz)
- **openSuse Linux** (vanilla kernel with RT_PREEMPT patches)
RT data acquisition & processing system

With this system we were able to

• Maximize time available for computation & communication
  DMA transfers finish 1 μs after last sample is acquired

• Calculate In & out profiles and separatrix position in < 400μs
  (4 dedicated/segregated cores)

• Satisfy control cycle timings
  1 ms rate & 1 ms latency
  (acquisition to actuation)
Demonstration results - discharge #27214

Reflectometry control during separate L and H-mode phases
Demonstration results - discharge #27372

Continuous reflectometry control during L, L-H and H-mode phases
Final thoughts

- **First successful demonstration** of an alternate non-magnetic procedure to control the position of a fusion plasma.

- **IPFN** possesses **worldwide recognized competence** in the domains of reflectometry diagnostic design and exploitation, control and data acquisition.

- A consortium led by the IPFN team **won the 8.5 M€ contract** for the **design of the ITER Plasma Position Reflectometer**, in the frame of an international call launched by Fusion for Energy (F4E).
Final thoughts

“A fusion reaction is about four million times more energetic than a chemical reaction such as the burning of coal, oil or gas. While a 1,000 MW coal-fired power plant requires 2.7 million tons of coal per year, a fusion plant of the kind envisioned for the second half of this century will only require 250 kilos of fuel per year, half of it deuterium, half of it tritium.”

(from www.iter.org)