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

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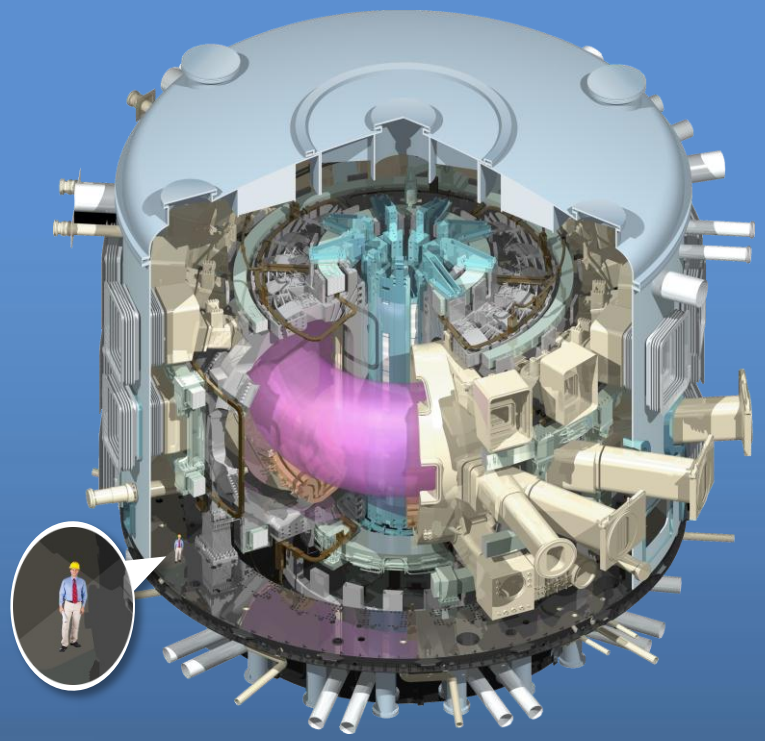
and the IPFN Microwave and ASDEX Upgrade Teams

## OUTLINE

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

# Motivation



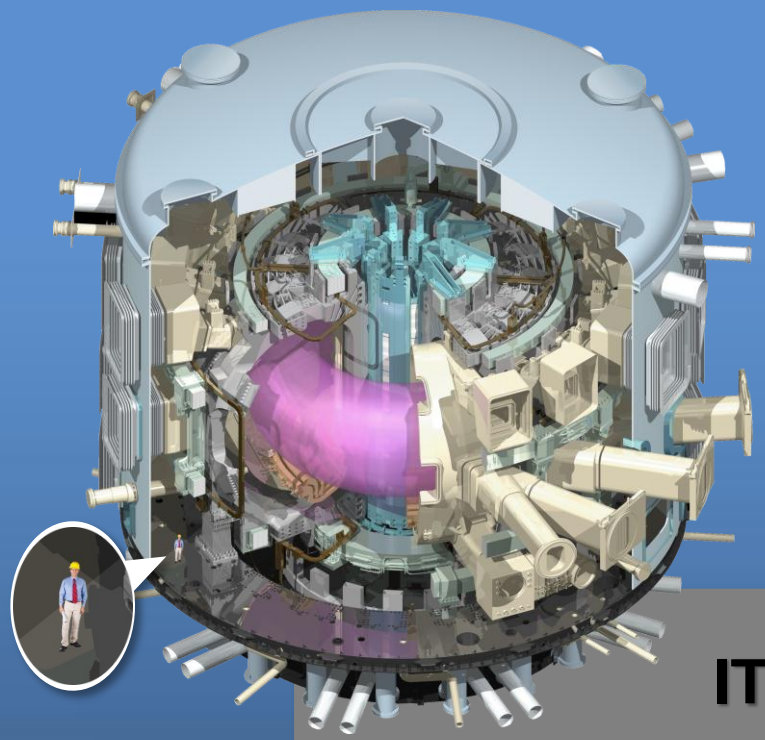
In future fusion reactors, fast neutrons and radiation emitted by D-T fusion plasmas may affect magnetic sensors.

**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.**

# Motivation



**ITER is a**

**16 billion €**

**Machine !**

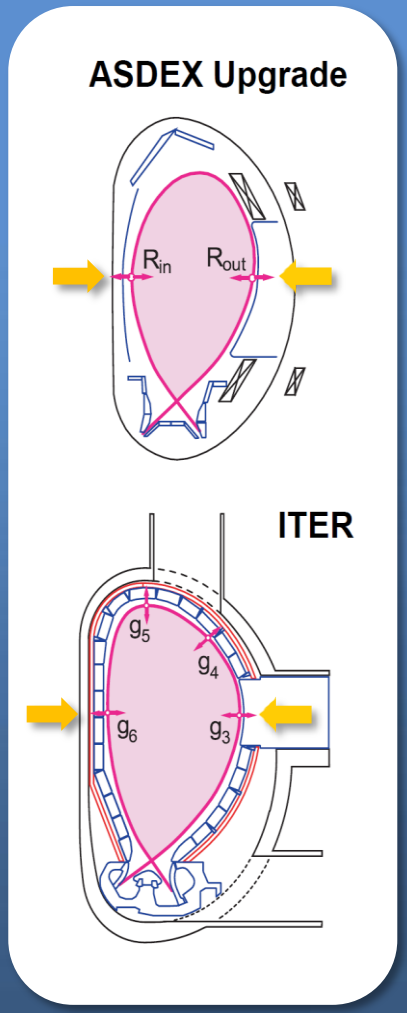
**ITER**

- 5.3 T magnetic field
- 15 MA of plasma current
- 500 MW of fusion power
- **150 million ºC**

**Position control of the plasma column is very**

**Critical**

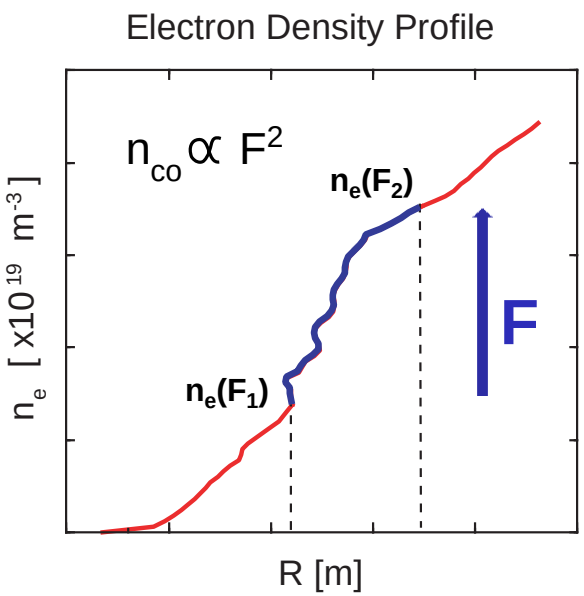
# Demonstration on ASDEX Upgrade

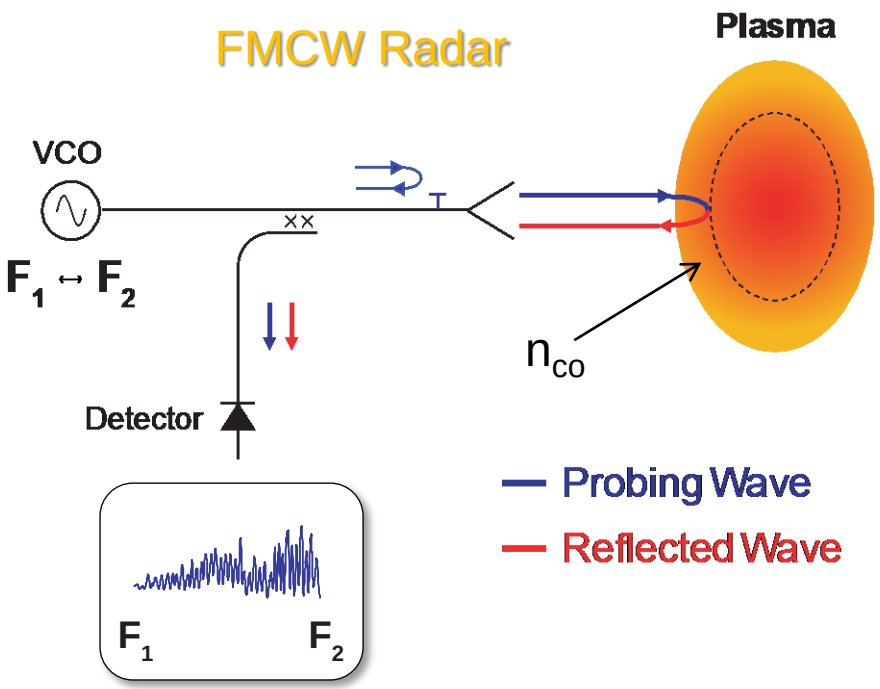



**ASDEX Upgrade** provides a unique test bed for this demonstration:

- **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



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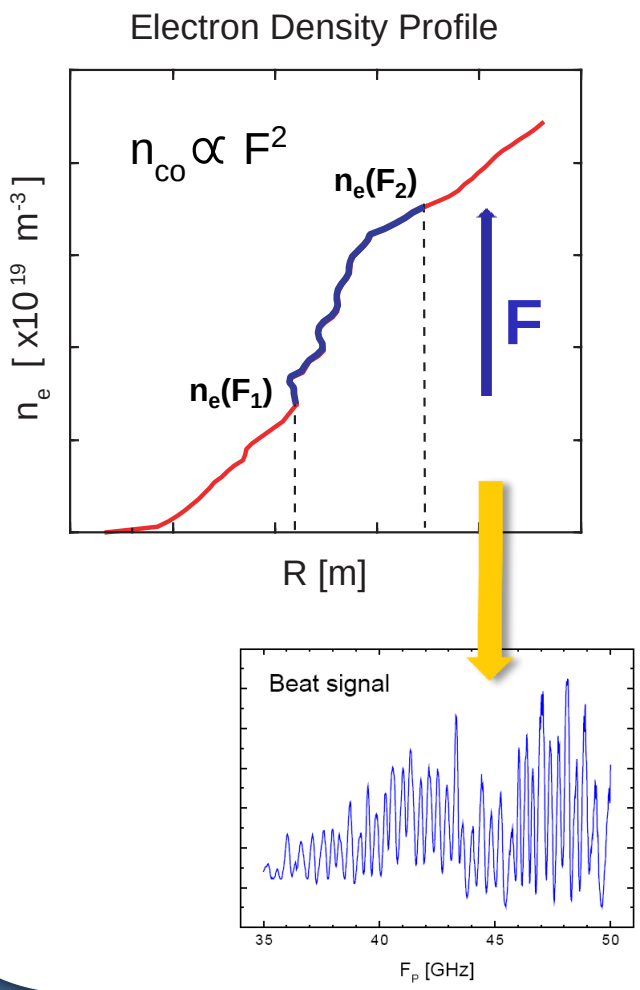


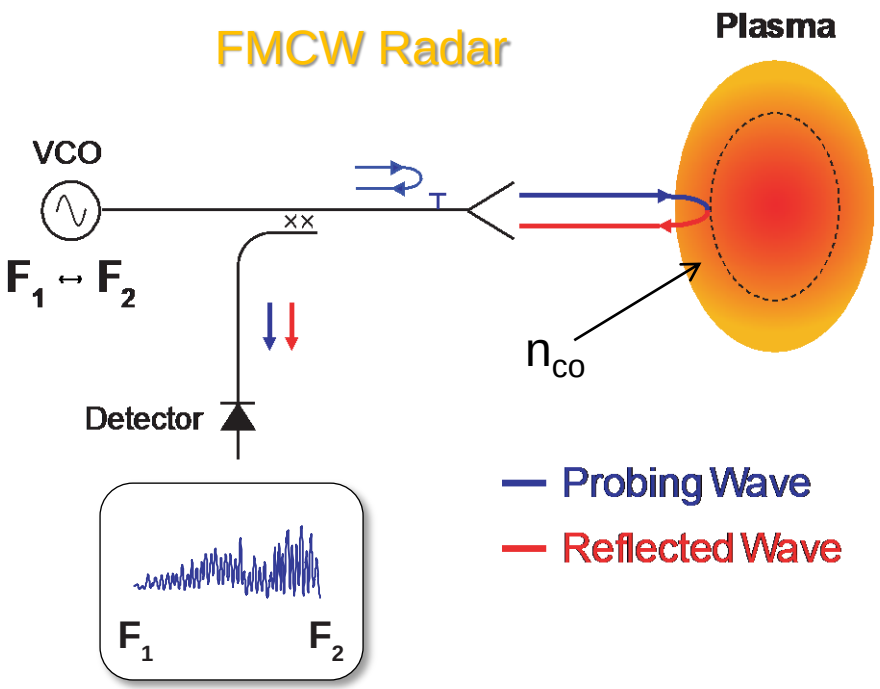

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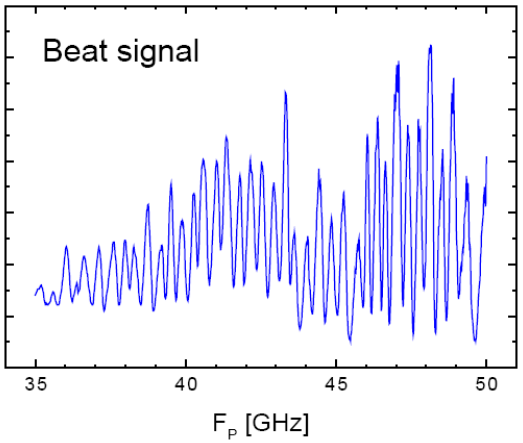
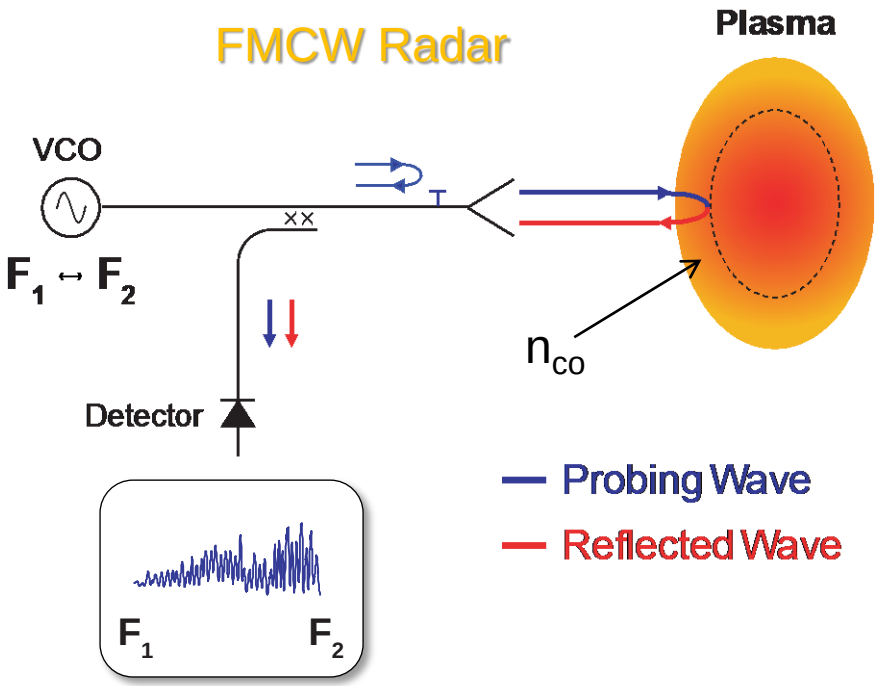



Up to
**1 GHz/µs**

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



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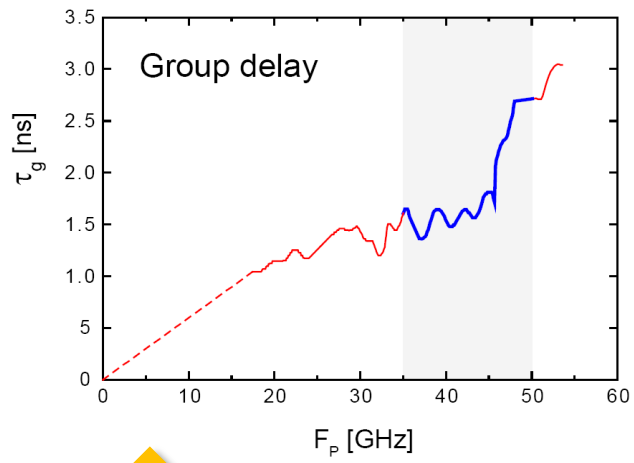
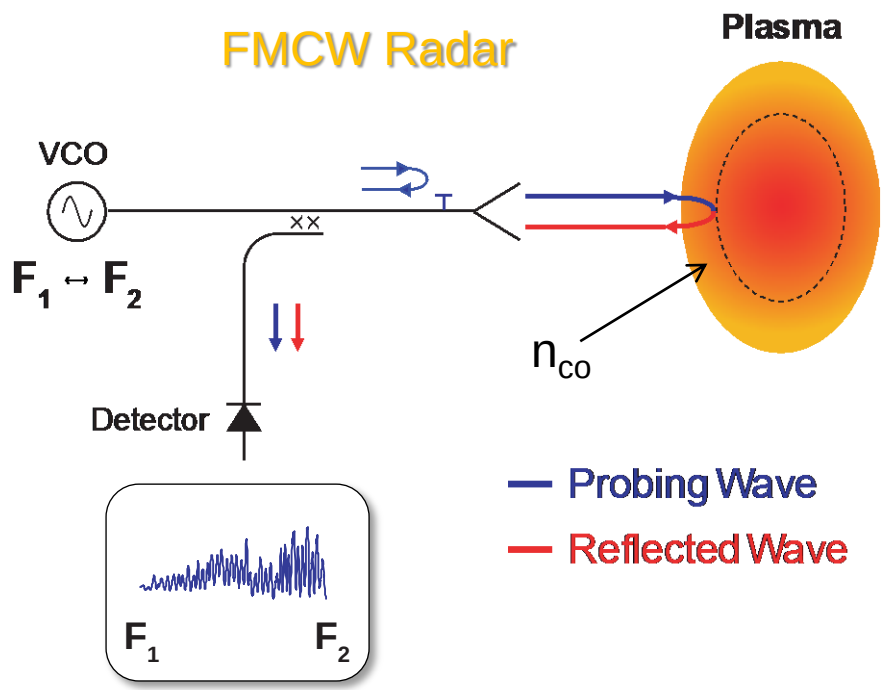
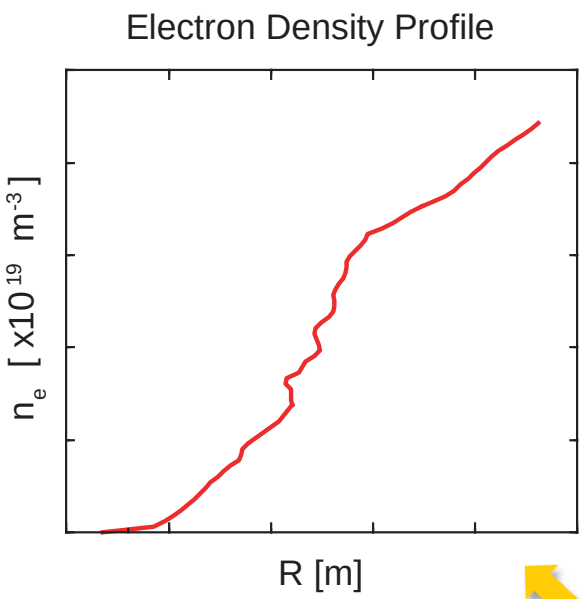
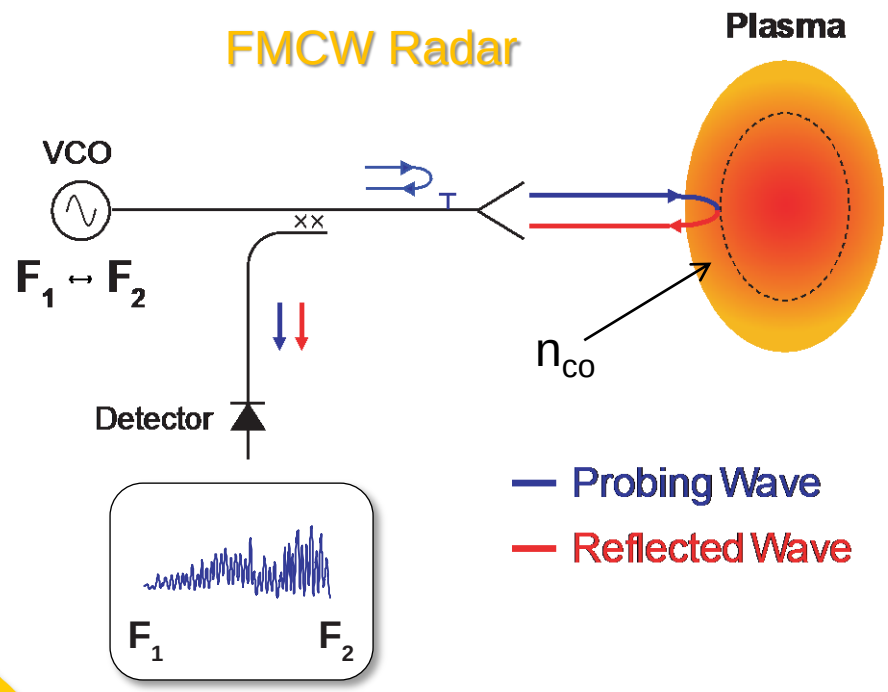



$$\tau_g(f) = f_b(t)\,(df/dt)^{-1} \Rightarrow R_{co}(F_{co}) = \frac{c}{\pi}\int_0^{F_{co}} \frac{\tau_g(f)}{\sqrt{F_{co}^2 - f^2}}\,df$$

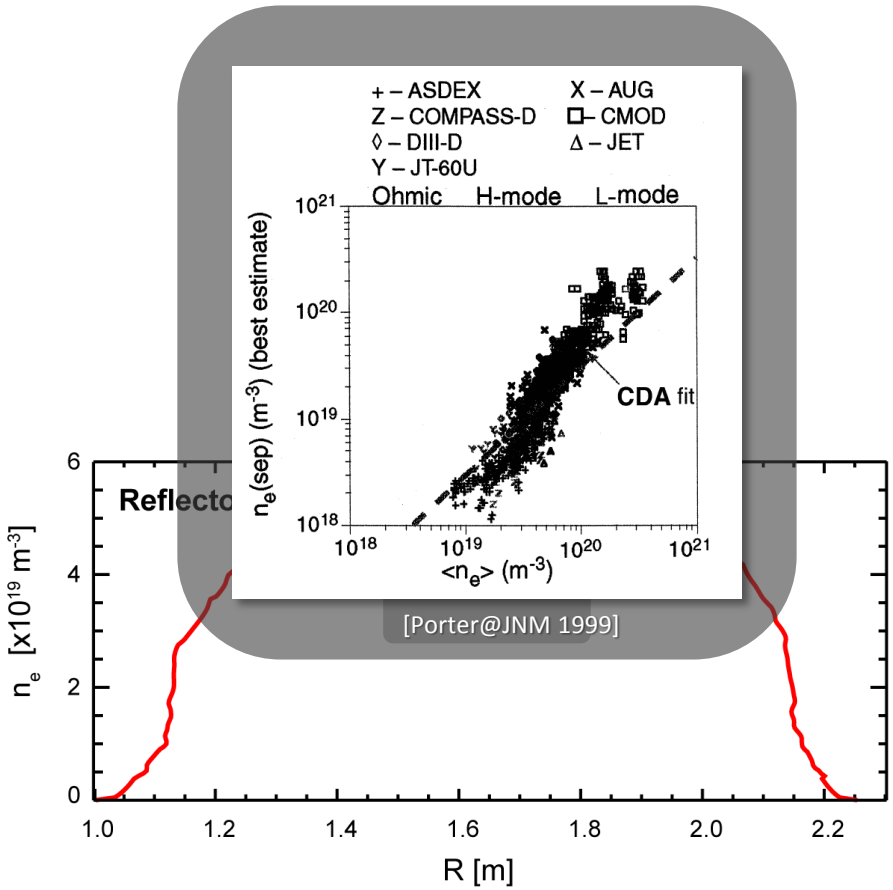
# Reflectometry density measurement

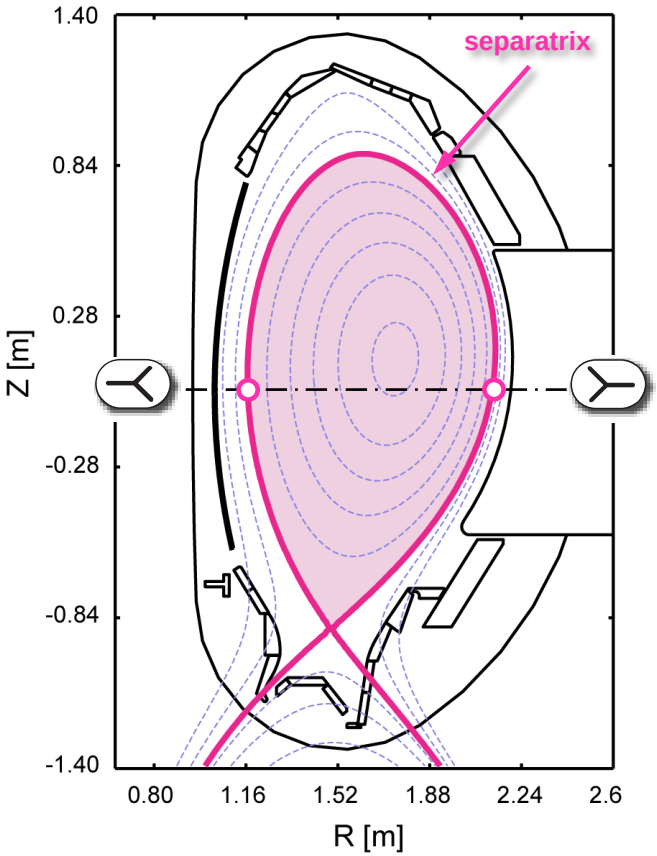



$$R_{co}(F_{co}) = \frac{c}{\pi}\int_0^{F_{co}} \frac{\tau_g(f)}{\sqrt{F_{co}^2 - f^2}}\,df$$

# Position control with reflectometry



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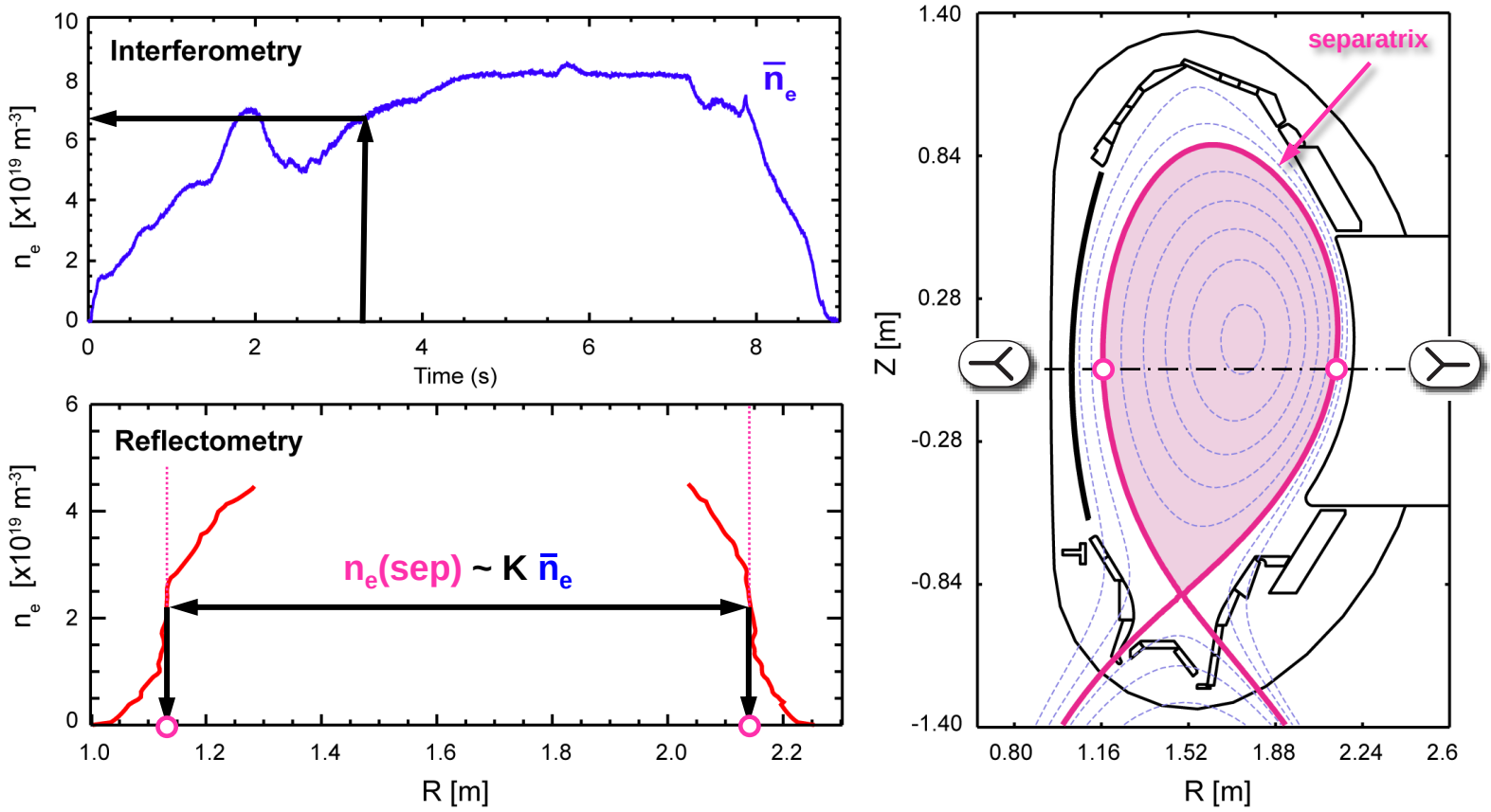
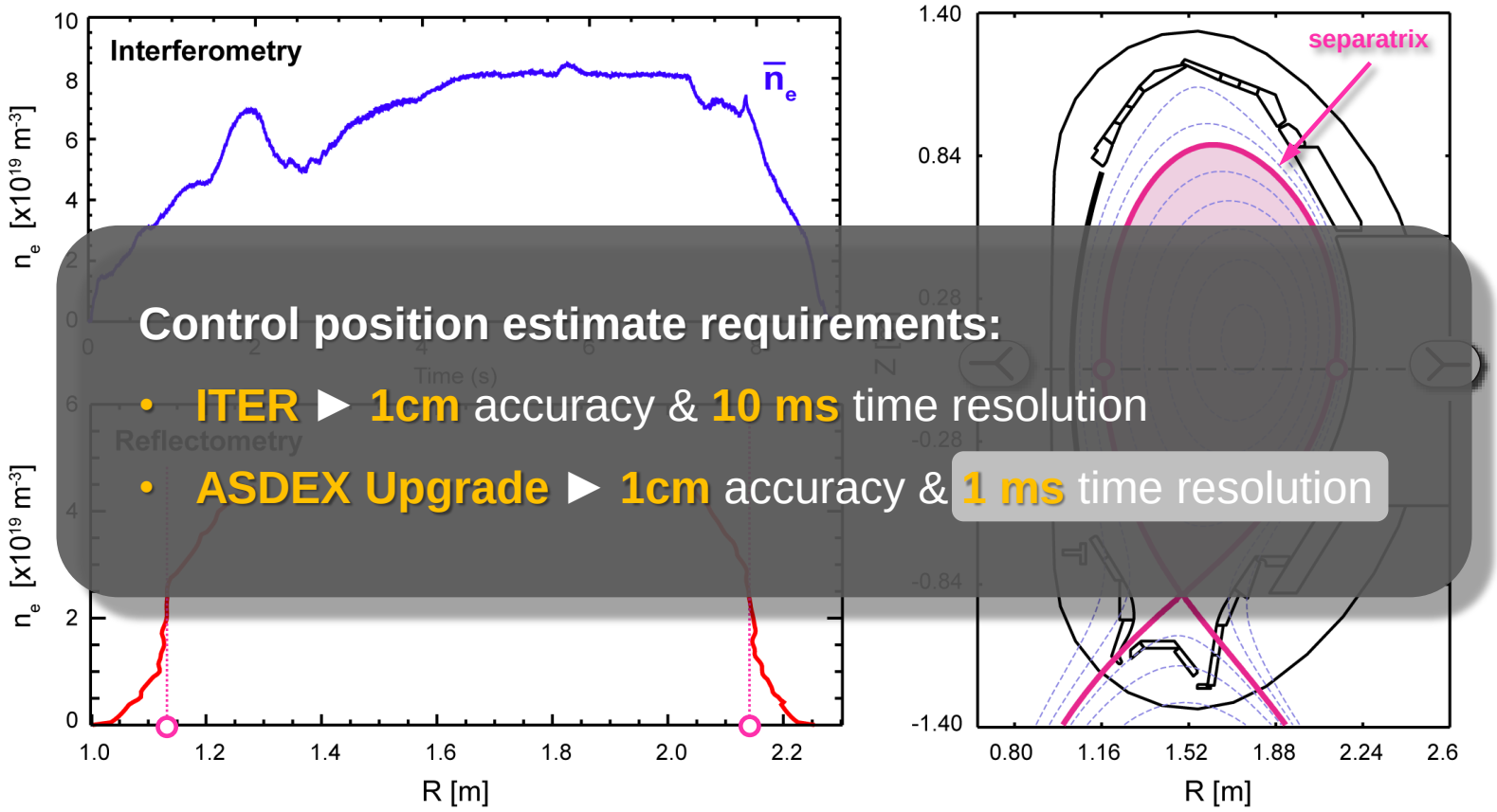


# Position control with reflectometry



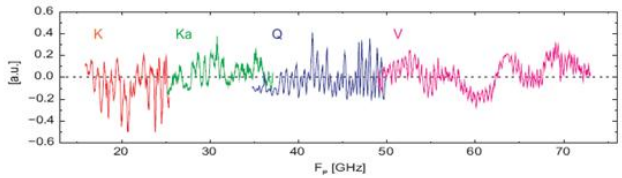

**Control position estimate requirements:**

- **ITER** ► **1cm** accuracy & **10 ms** time resolution
- **ASDEX Upgrade** ► **1cm** accuracy & **1 ms** time resolution

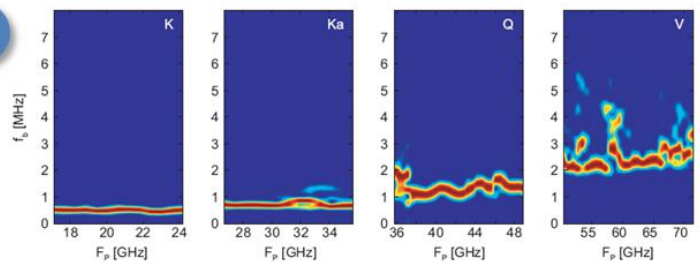
# Real-time data processing algorithms

## Group delay estimation procedure

1



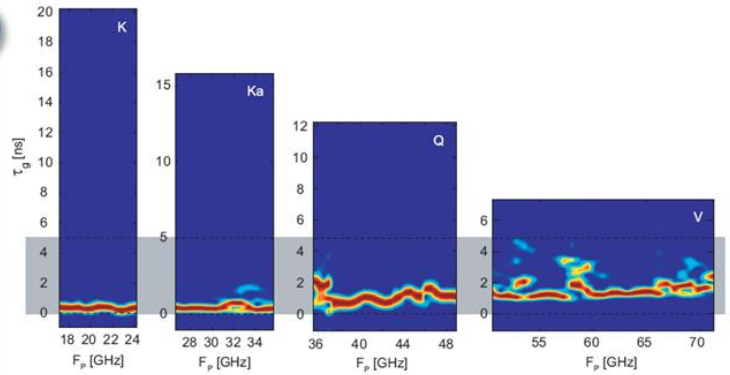

2



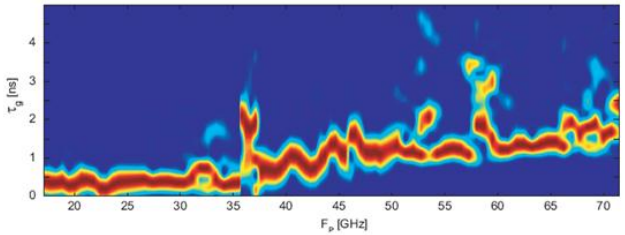

2 → 3

$$\tau_g(t) = f_b(t)\left(\frac{\Delta F_p}{\Delta T}\right)^{-1} - \tau_{corr}$$

3

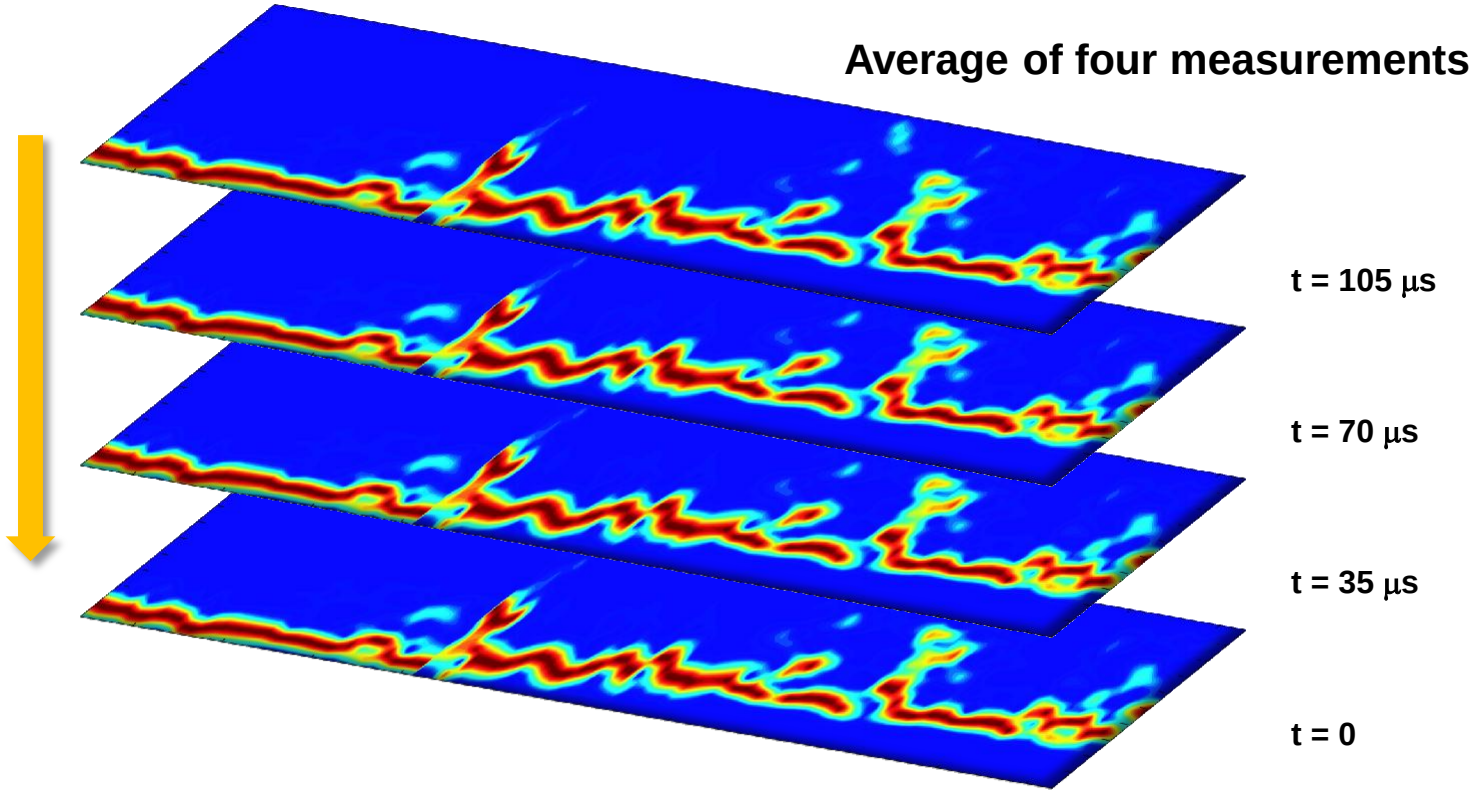



4



# Real-time data processing algorithms

## Group delay estimation procedure



# Real-time data processing algorithms

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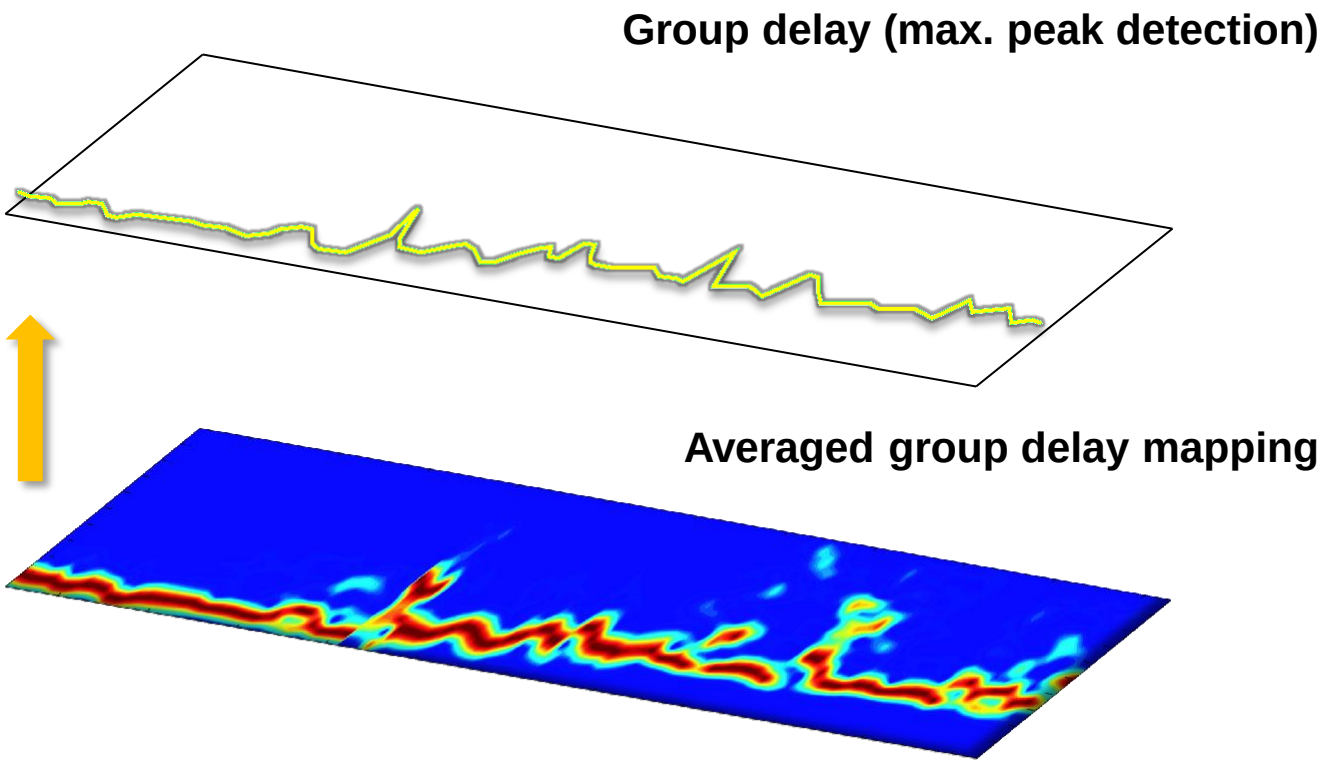
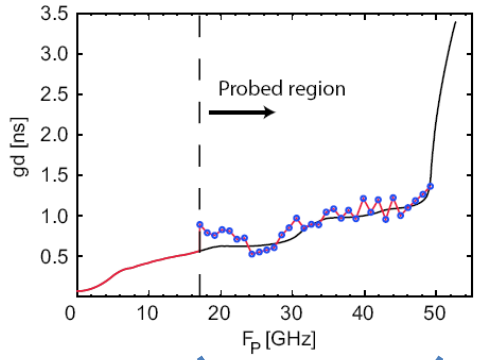


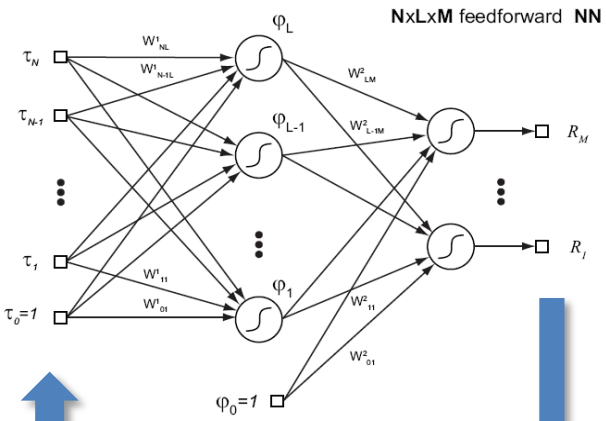
# Real-time data processing algorithms

## Profile calculation

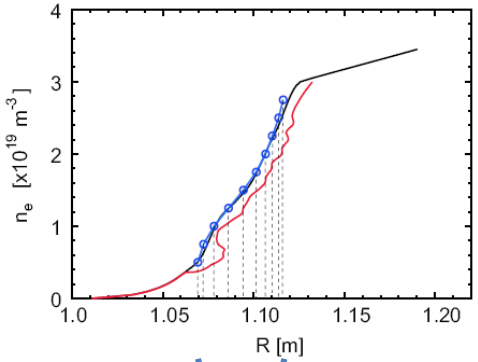
**NN Input**




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

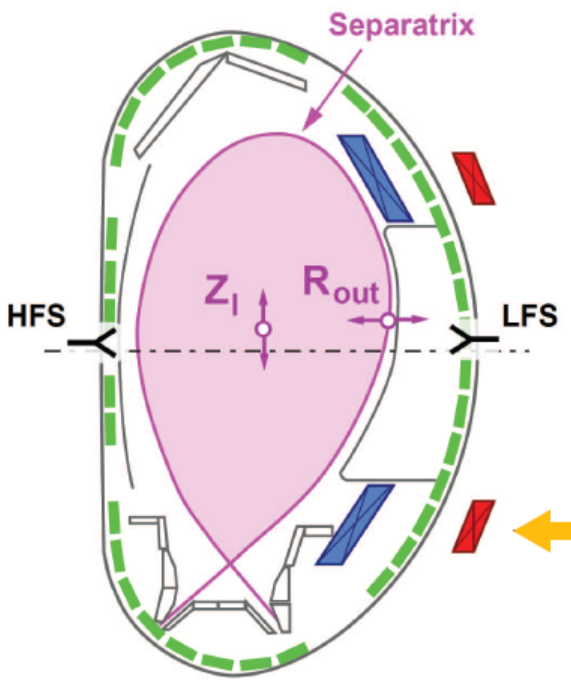


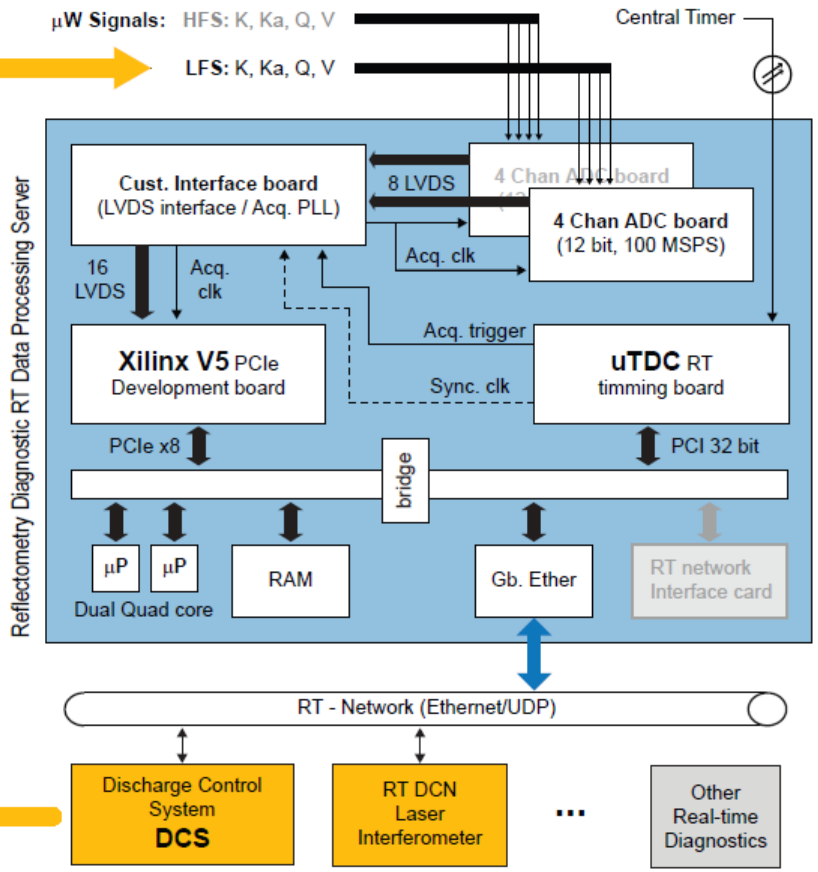

**NN Output**



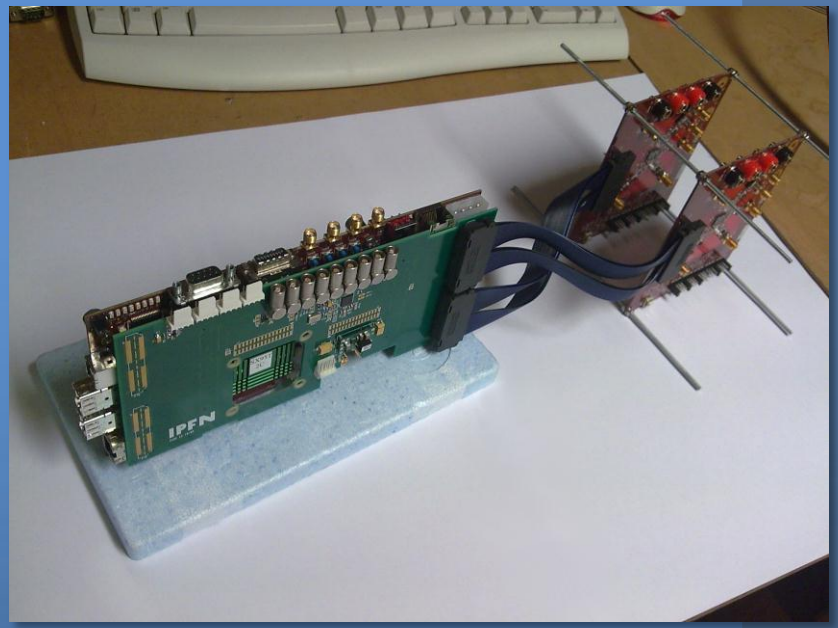

**M** radial positions corresponding to M fixed density layers

# Real-time diagnostic / system integration



# RT data acquisition & processing system





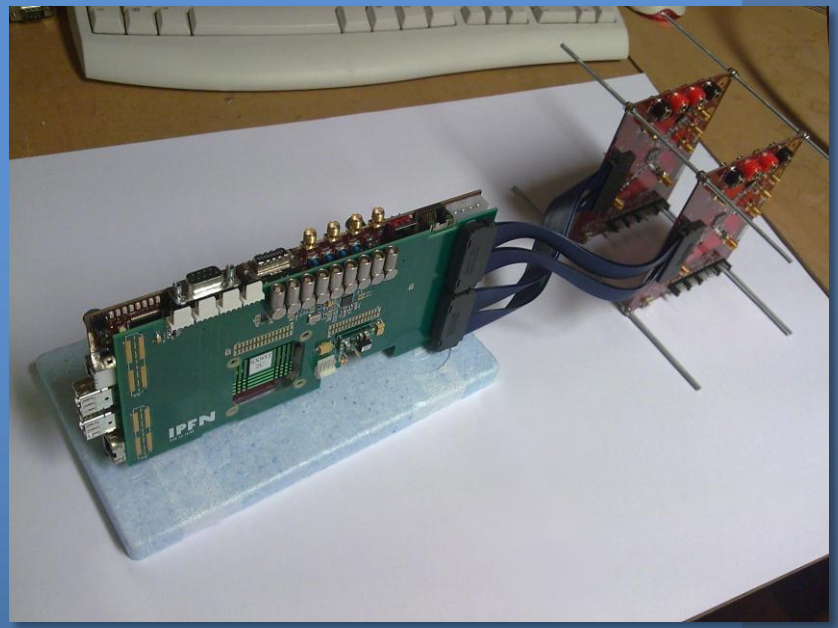
**Custom designed DAS**

- **8 channel, 12-b, 100 MSPS**
- **PCIe 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**

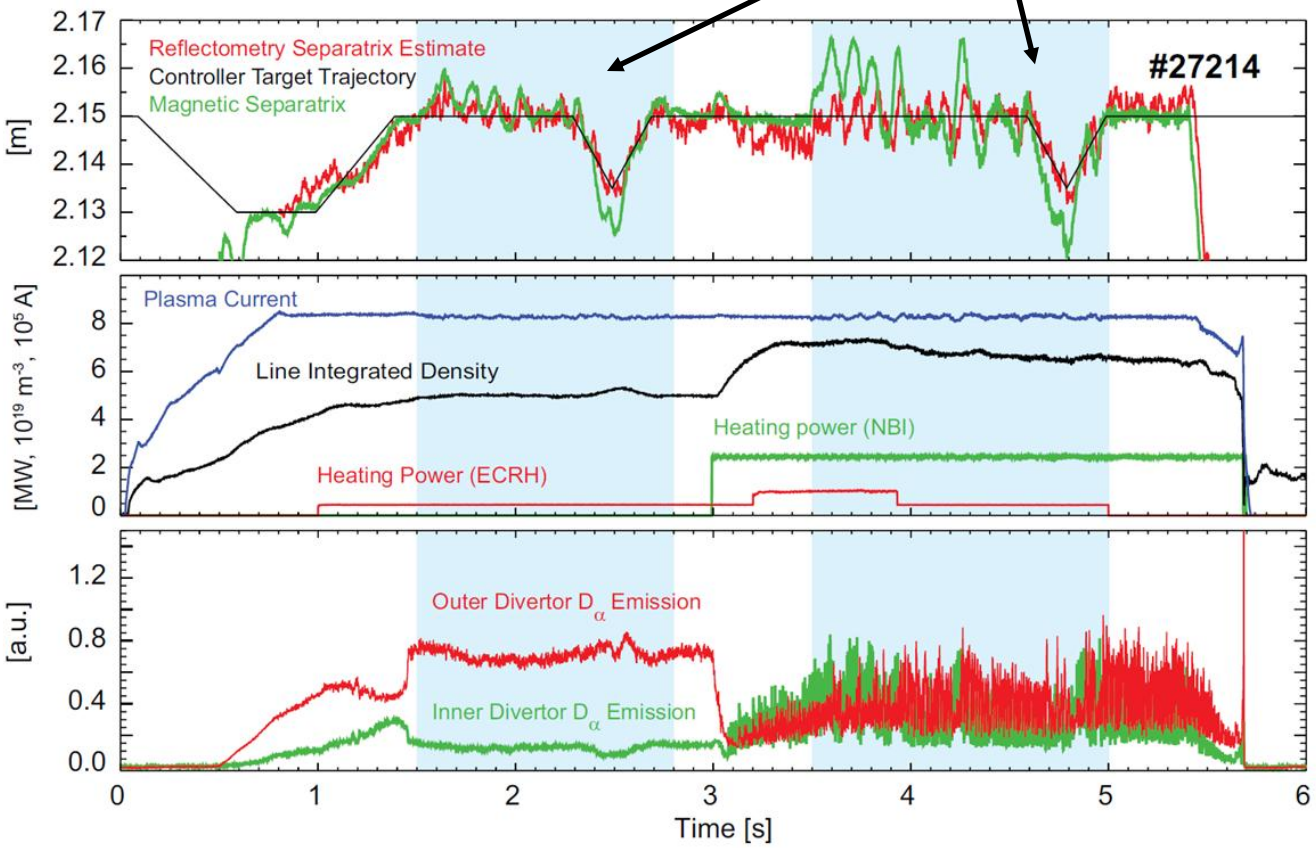
- **Calculate In & out profiles and separatrix position in < 400μs**

  **(4 dedicated/segregated cores)**

- **Satisfy control cycle timings**
  **1 ms rate & 1 ms latency**
  **(acquisition to actuation)**

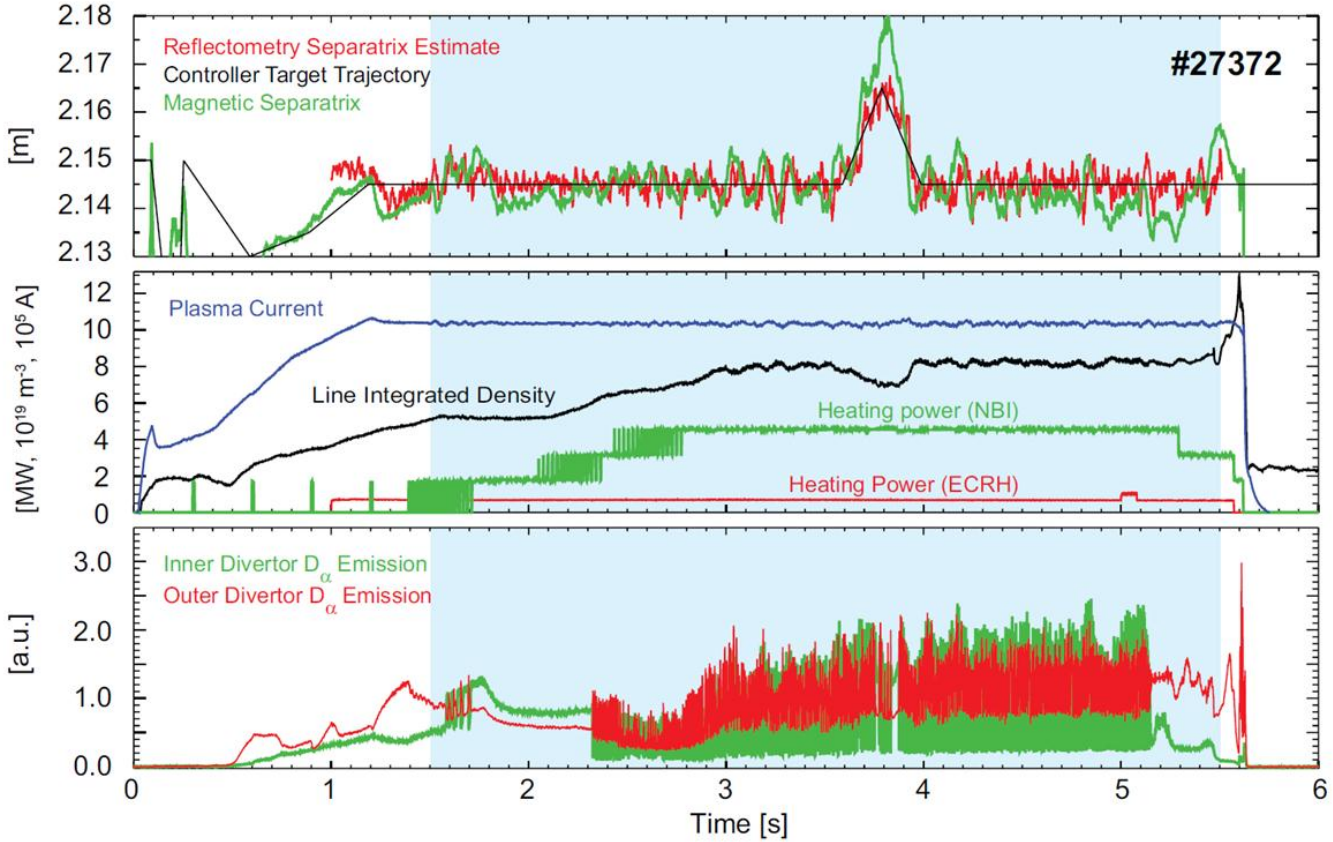
# Demonstration results - discharge #27214

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  a fusion plasma.

- **IPFN** posesses **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)