

FOM-Institute for Plasma Physics Rijnhuizen
Association Euratom-FOM, Trilateral Euregio Cluster

The TEXTOR line-of-sight ECE system for feedback controlled ECRH power deposition



TRILATERAL
EUREGIO CLUSTER



E. Westerhof

With contributions from:

M. de Baar, B.A. Hennen, J.W. Oosterbeek, W.A. Bongers,
A. Bürger, S.B. Korsholm, S.K. Nielsen, P. Nuij, D.J. Thoen, M. Steinbuch,
and the TEXTOR-Team

Quick overview

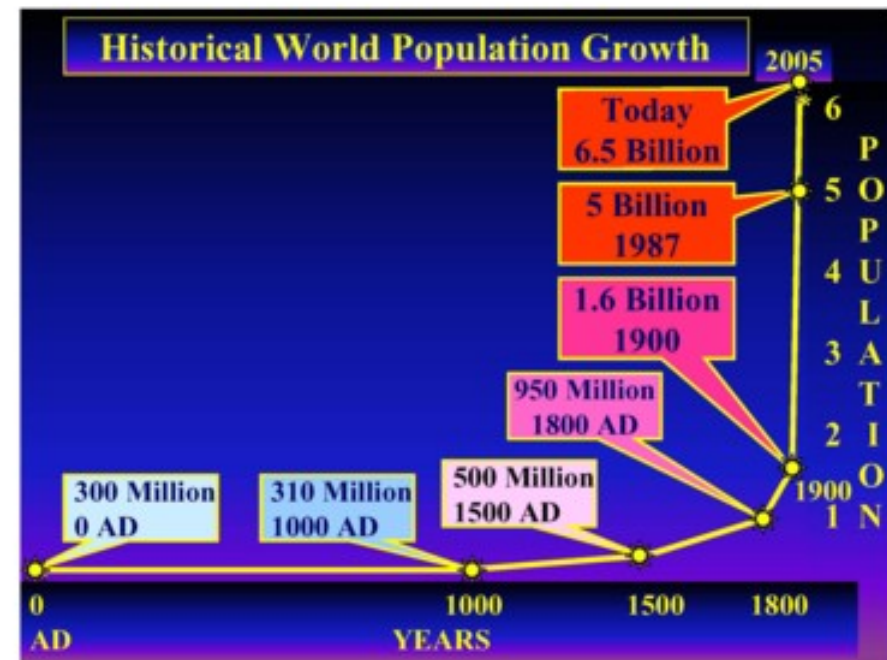


- Background
 - Nuclear Fusion
 - Control of fusion plasmas
 - Feedback control of MHD instabilities
 - Feedback control of ECRH power deposition
- Inputs for power deposition control
 - Where should the power go?
 - Where is the power going?
- Solution by line-of-sight ECE
 - TEXTOR system design
 - TEXTOR results
- What comes next

Energy Crisis



- Need for new CO₂-free energy sources
 - Exploding energy requirements of a growing, wealthier world population



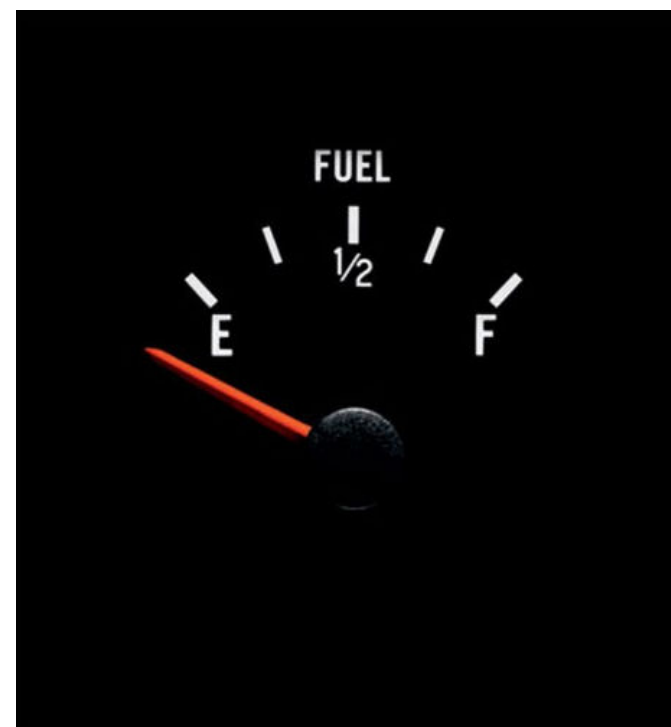
- Need for new CO₂-free energy sources
 - Exploding energy requirements of a growing, wealthier world population
 - Global warming



Energy Crisis



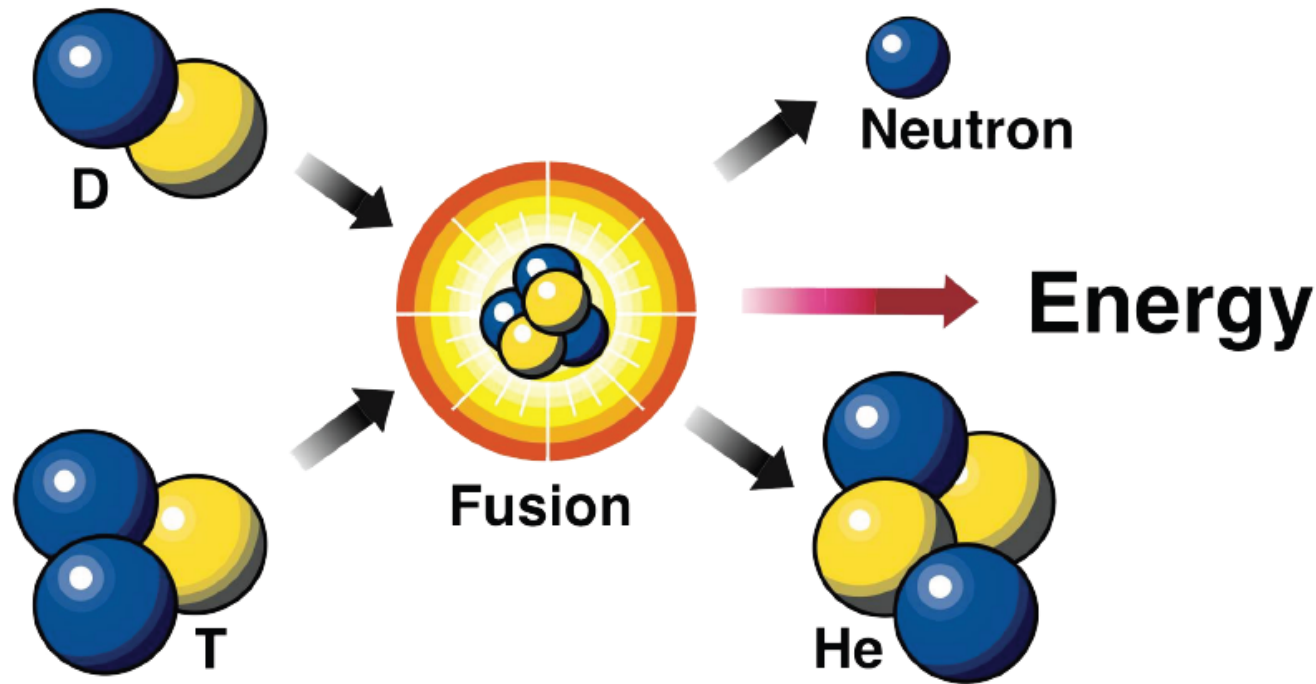
- Need for new CO₂-free energy sources
 - Exploding energy requirements of a growing, wealthier world population
 - Global warming
 - Limited oil supplies
 - Rising oil prices



Nuclear Fusion



- A relatively clean, safe, and virtually limitless source of energy



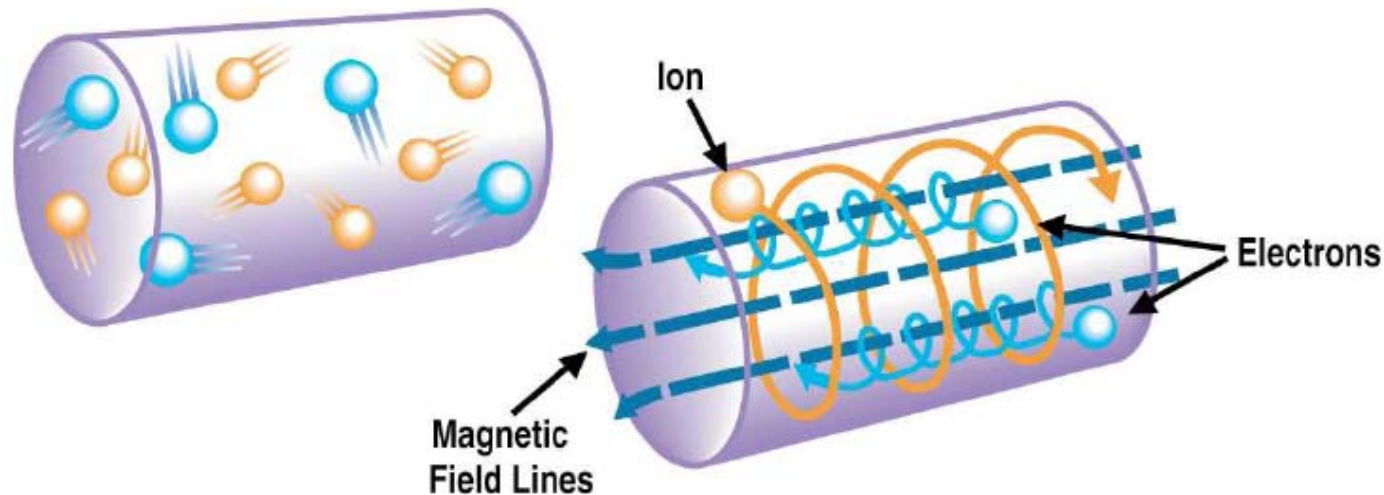
Requirements for Fusion?



- Lawson criterion: energy produced must exceed energy lost

$$n T \tau_E > \text{critical value}$$

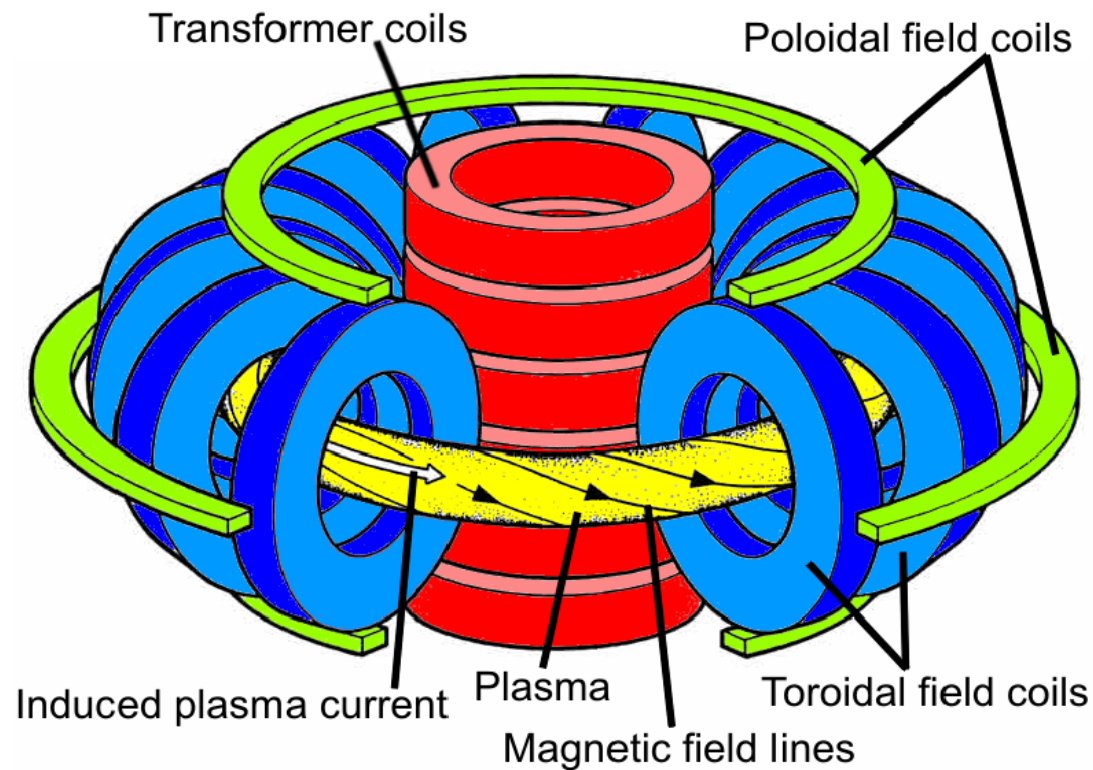
- High density
- High temperature: plasma
- High confinement time: magnetic confinement



Magnetic confinement



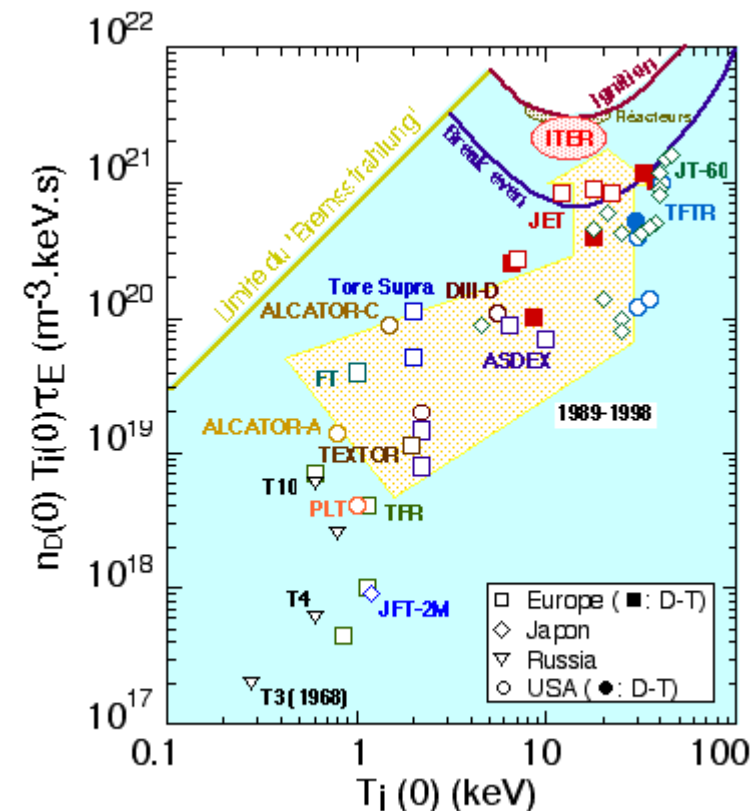
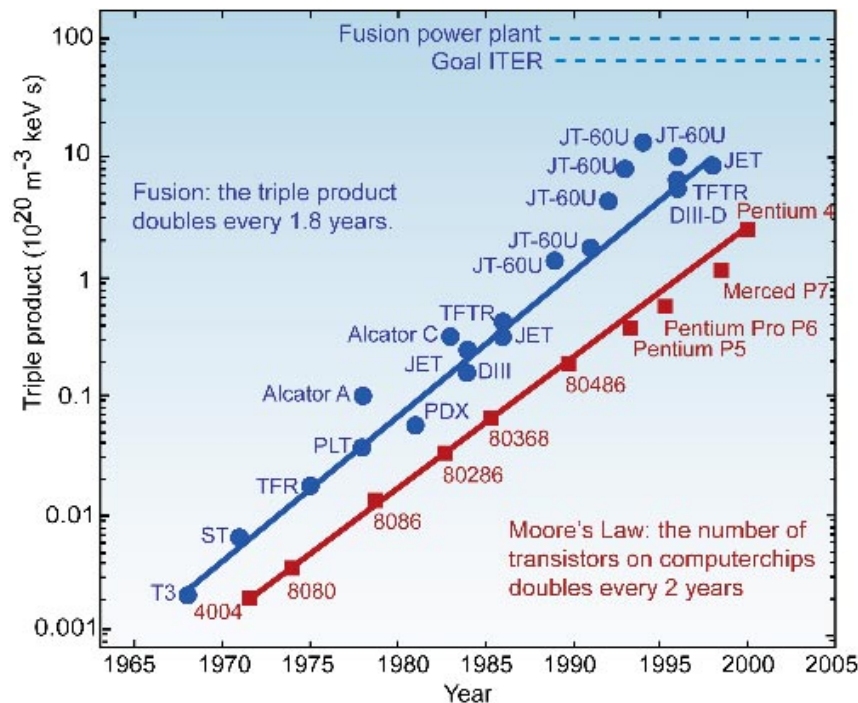
- Bend magnetic field lines into a torus to prevent end-losses: the TOKAMAK



Tokamak achievements



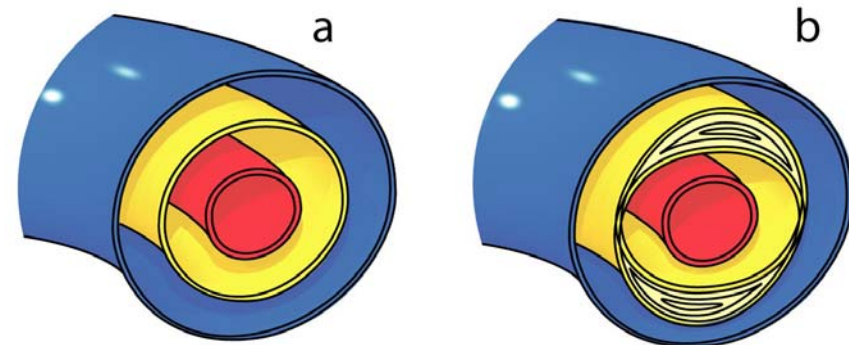
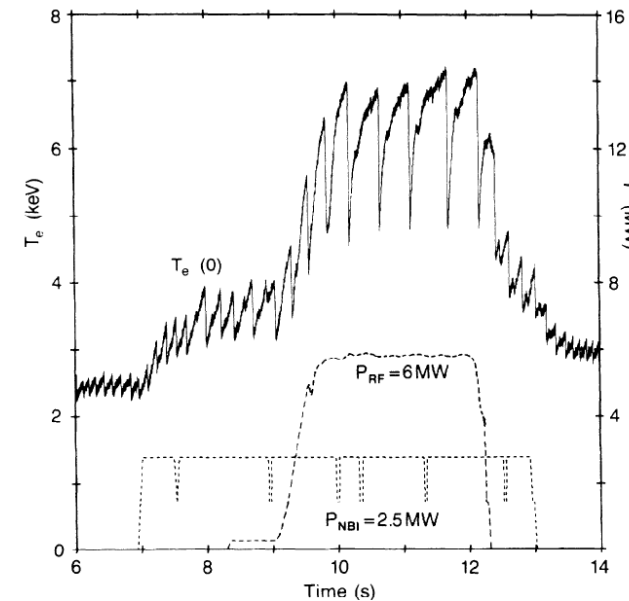
- The achieved fusion triple product $nT\tau$ has been increased dramatically over the years and is approaching the values required for a reactor



There is a catch: instabilities



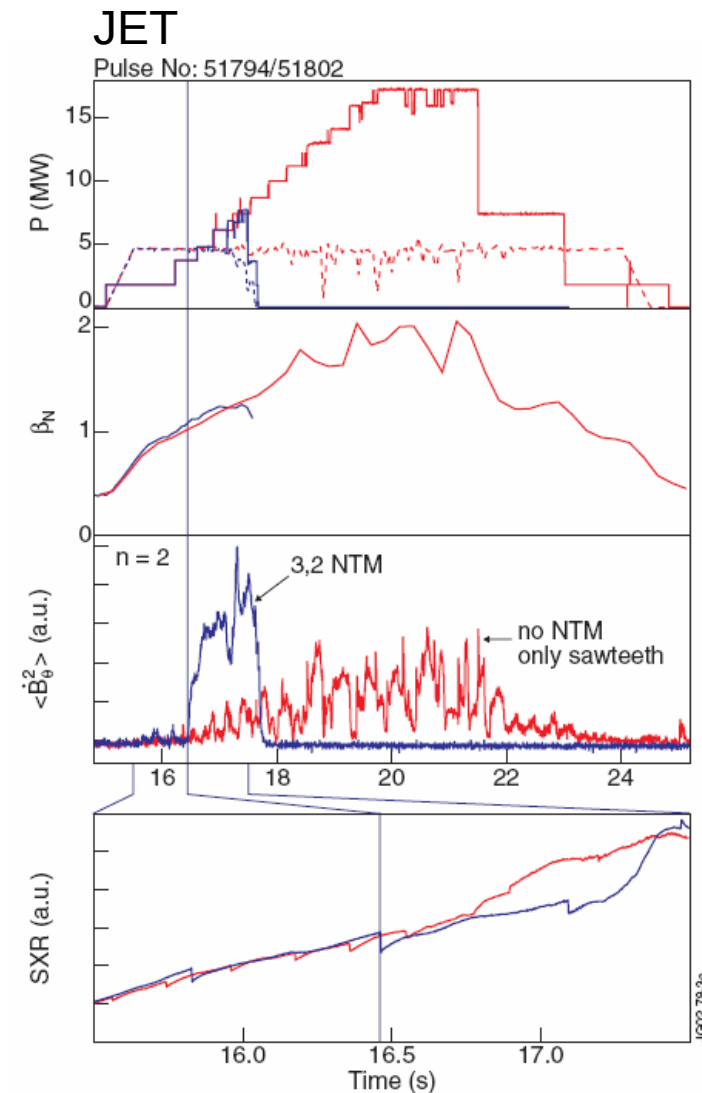
- Core relaxations oscillations: sawteeth
- Magnetic islands created by the neoclassical tearing modes (NTMs)
- And many others
- These need to be controlled



The need for MHD instability control



- Sawteeth
 - limit central pressure
 - trigger NTMs
 - redistribute fusion alphas and He-ash

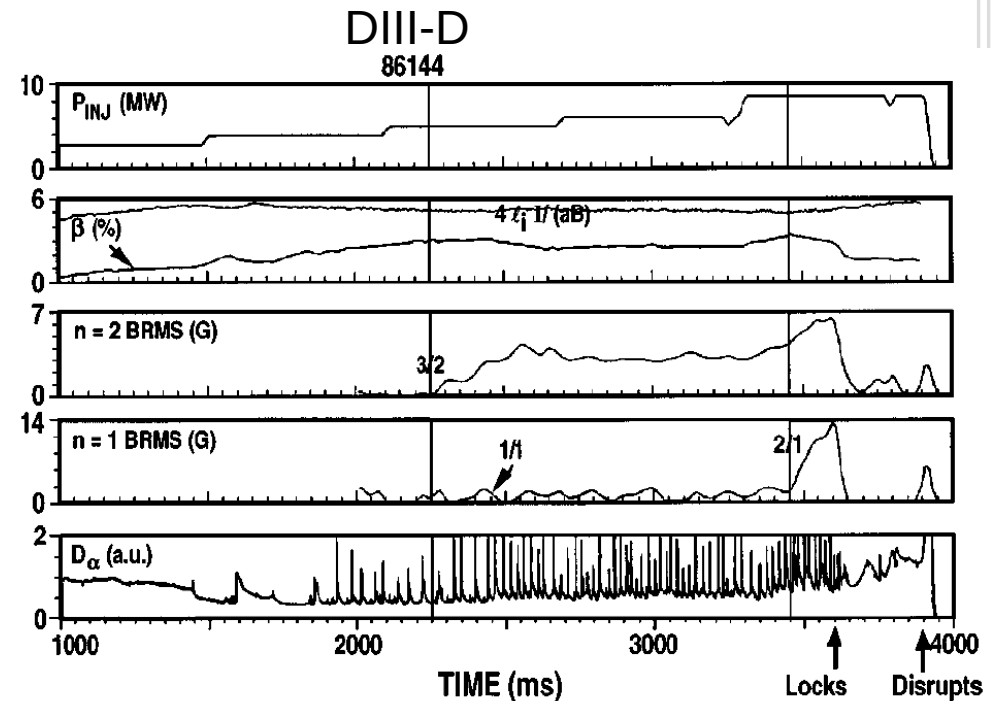


© E. Westerhof et al., Nucl. Fusion 42 (2002) 1324
O. Sauter et al., Phys. Rev. Letters 88 (2002) 105001

The need for MHD instability control



- Neoclassical Tearing Modes (NTMs)
 - deteriorate confinement
 - cause disruptive discharge termination



© O. Sauter et al., Phys. Plasmas 4 (1997) 1654

FIG. 1. Typical time history of the neoclassical modes. In this DIII-D discharge #86144, a $3/2$ mode is excited at $t=2250$ ms and induces a saturation of β . At $t=3450$ ms, a $2/1$ mode grows to a large amplitude until it locks and triggers a disruption. The computed ideal limit for this case is $\beta_N \approx 3.4$.

Control by Electron Cyclotron waves

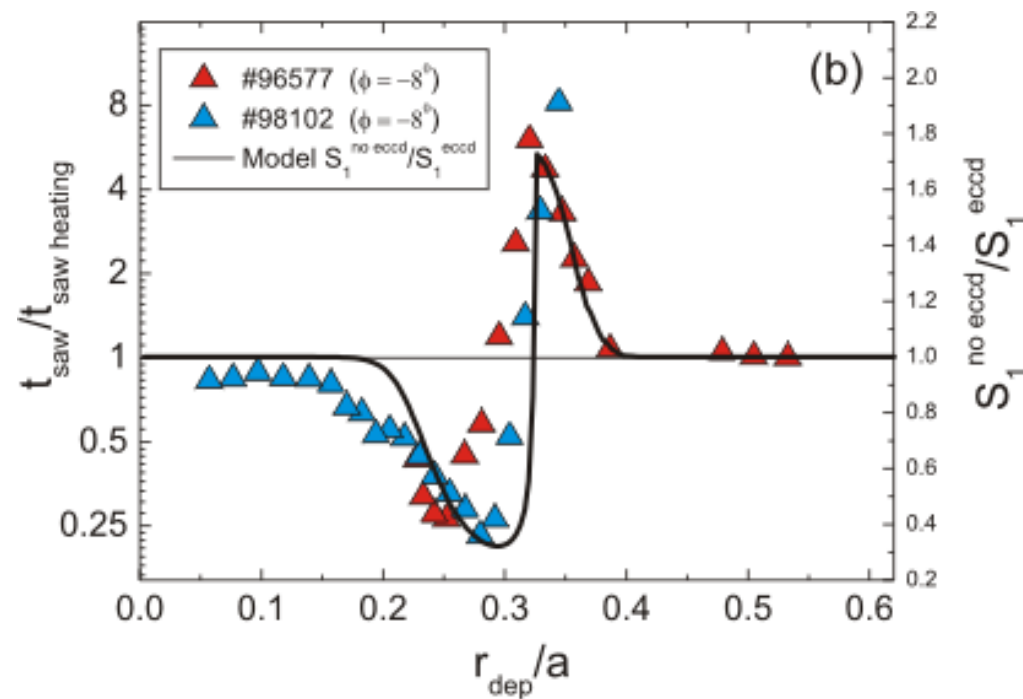


- Control requires fine manipulation of current density and pressure profiles
- Fits best with properties of ECRH/ECCD
 - mm waves in the 100 GHz range
 - Allows use of narrow focused wave beams
 - Launched directly from vacuum into plasma
 - Localized power deposition at EC resonance
 - All power deposited in a few 10 cm^3

The need to control ECRH localization



- Effect of ECRH on sawteeth and NTM depends strongly on localization
 - co-ECCD for sawtooth period control in TEXTOR

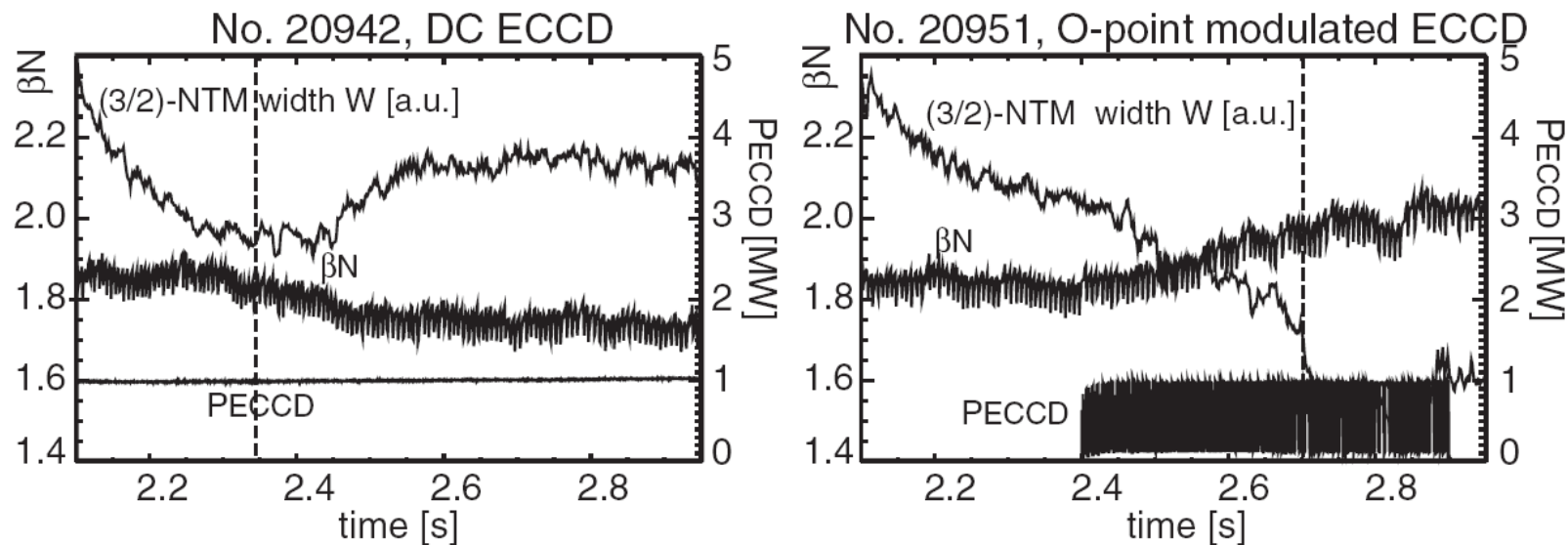


© E. Westerhof et al., Proceedings EC14 2006

The need to control ECRH localization



- Effect of ECRH on sawteeth and NTM depends strongly on localization
 - (modulated) ECCD for 3/2 NTM control in AUG
 - B_T -ramp to achieve localization
 - Advantage of modulation with O-point rotation



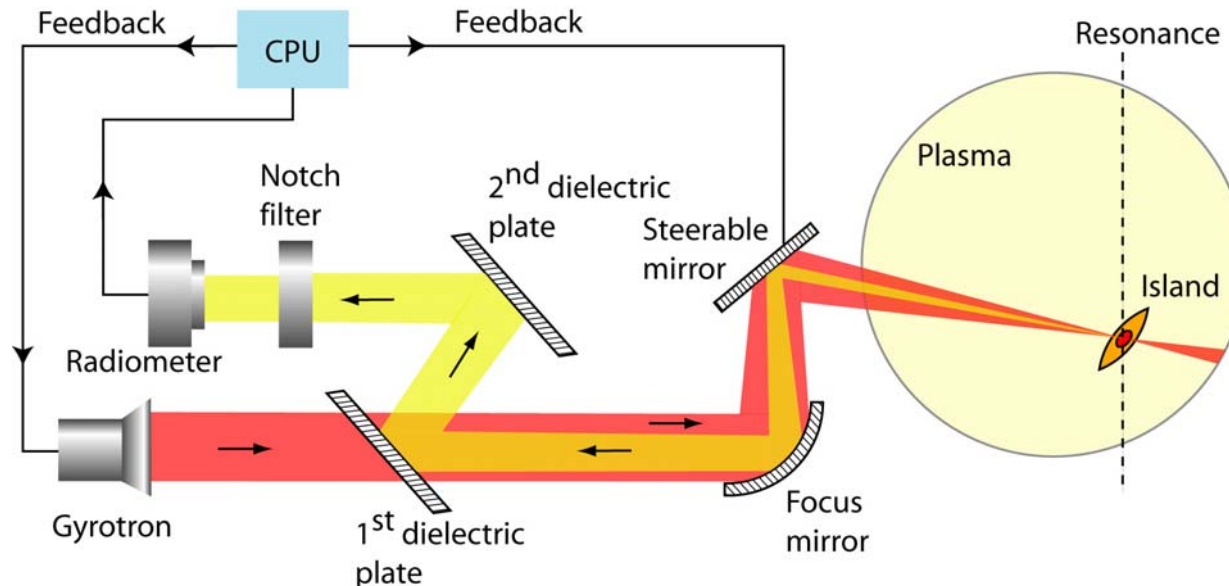
© M. Maraschek et al., Phys. Rev. Letters 98 (2007) 025005

Diagnostic requirements for feedback controlled power deposition



- Measurement of required position
 - Sawtooth inversion radius
 - Rational surface of NTM
- Measurement of achieved position
 - ECRH power localization
 - Alternatively predicted from ray-tracing
 - Requires plasma equilibrium and profile data

Single system solution: line-of-sight ECE



Single system for mode detection & ECRH steering

Principle: localizing it ...

in the ECE spectrum

on the gyrotron frequency

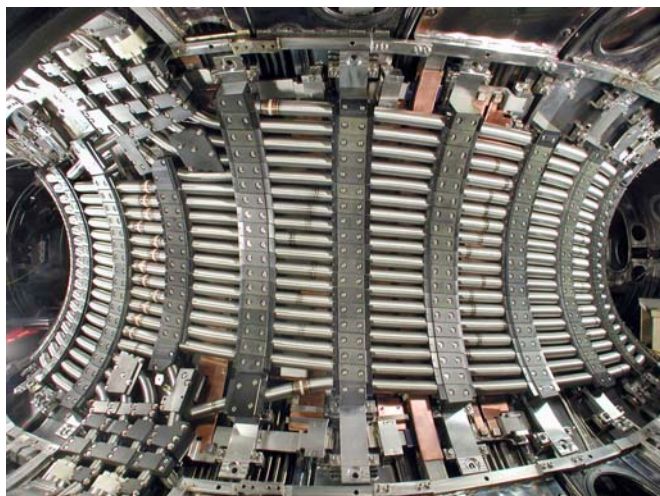
ensures power deposition on top of it

Major technical challenge for inline ECE



- To separate the ~ 1 MW gyrotron radiation from the ~ 100 pW expected ECE power at the radiometer
 - 20 .. 50 mW of power can destroy radiometer
 - Requires a 130 dB rejection of the gyrotron component to level ECRH and ECE components at the input of the mixer

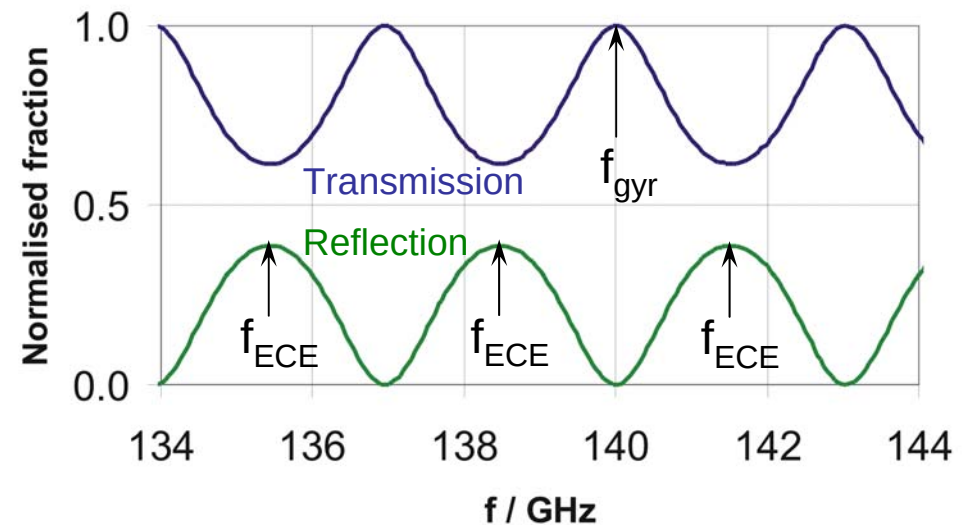
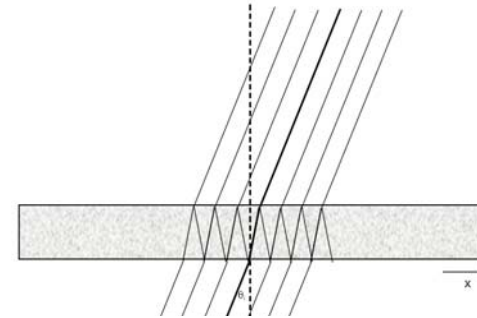
TEXTOR system design



Implementation in Quasi Optical environment



- Frequency Selective Coupler based on the Fabry-Pérot principle
- Constructive interference for transmitted waves at gyrotron frequency
- Constructive interference of reflected waves at ECE frequencies
- Destructive interference for reflected gyrotron waves



Spacing of ECE channels determined by thickness of plate

Trade off between ECE resolution and losses through plate absorption

Final design of in-line ECE optics



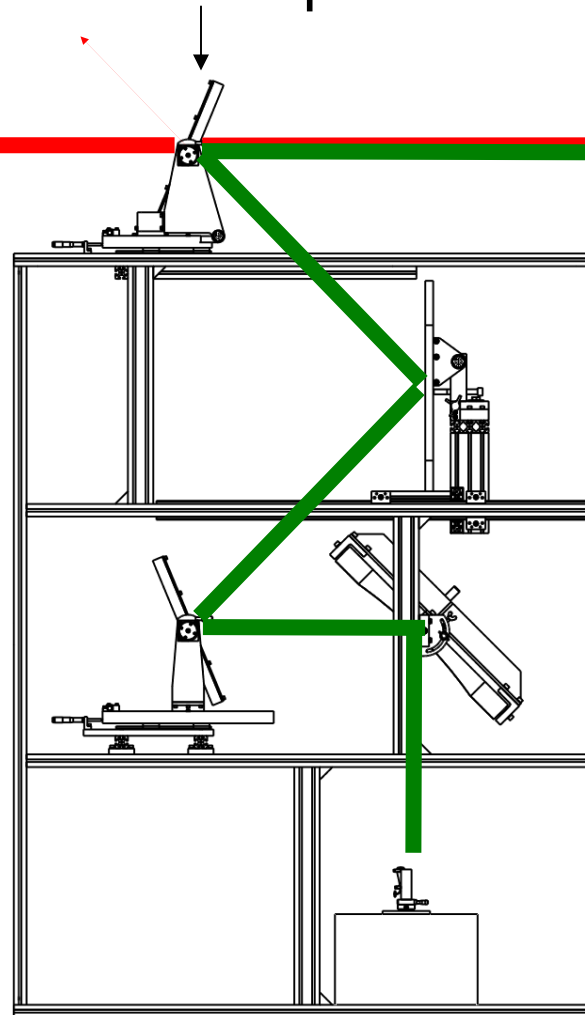
25.75 mm thick dielectric plate in 96 mm waist

ECRH from
gyrotron

140 GHz
800 kW, 10 seconds
(3 s for FB project)

Reflected ECRH
down by 50 dB from
the two dielectric
plates

ECE from
plasma

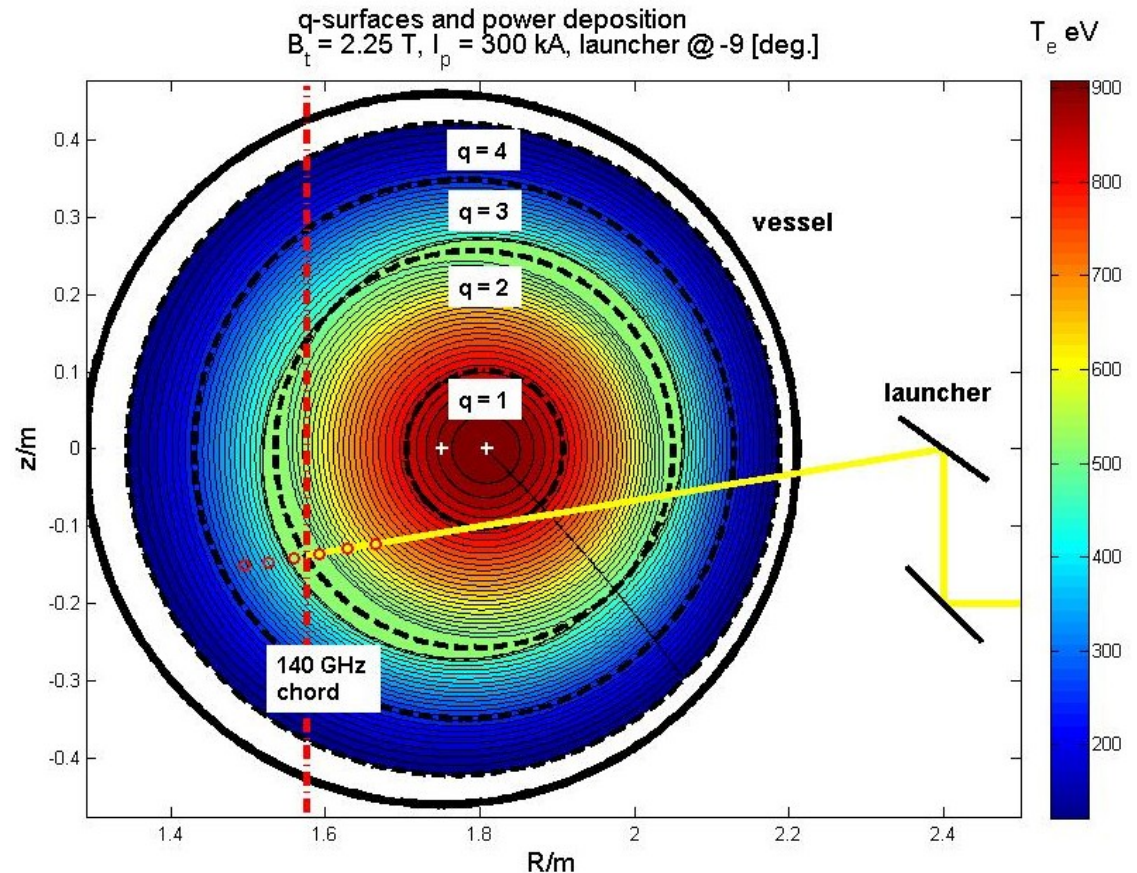


Expected ECE ~ 100 pW

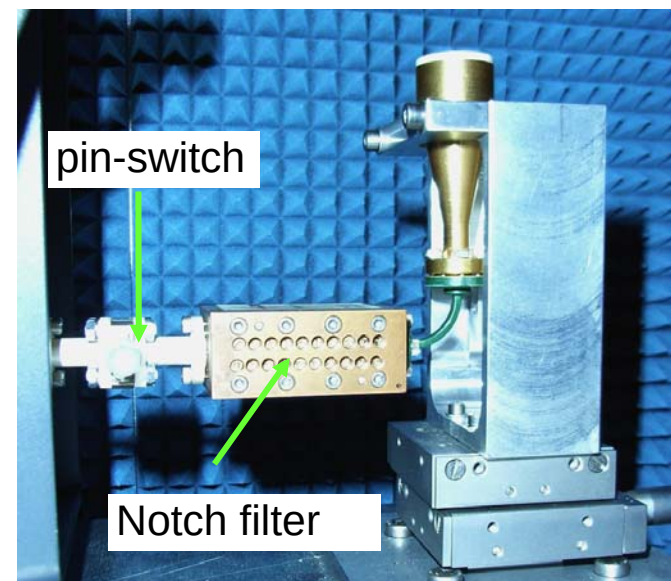
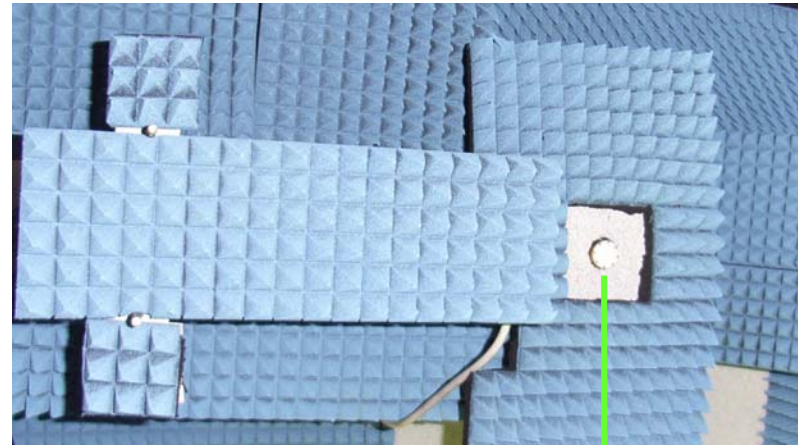
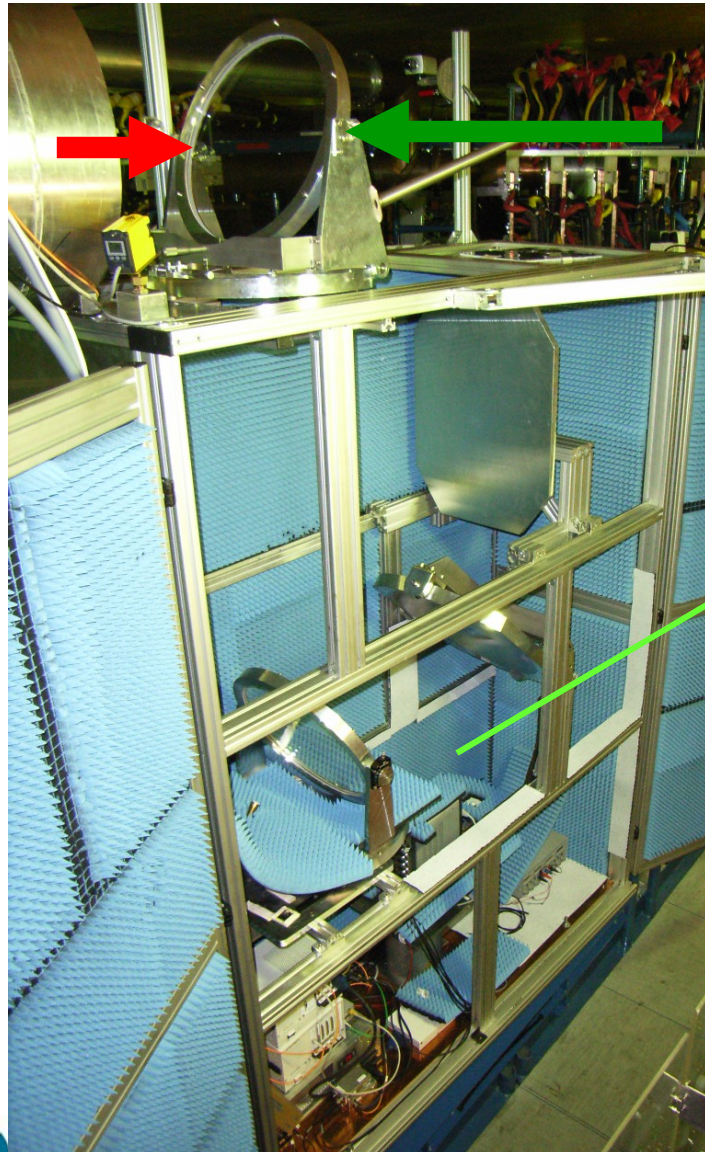
Geometry in plasma of final system



- 6 ECE channels spaced 3 GHz
– 132.5, ..., 147.5 GHz
- Each channel 500 MHz wide
- Larger coverage by varying of launcher elevation



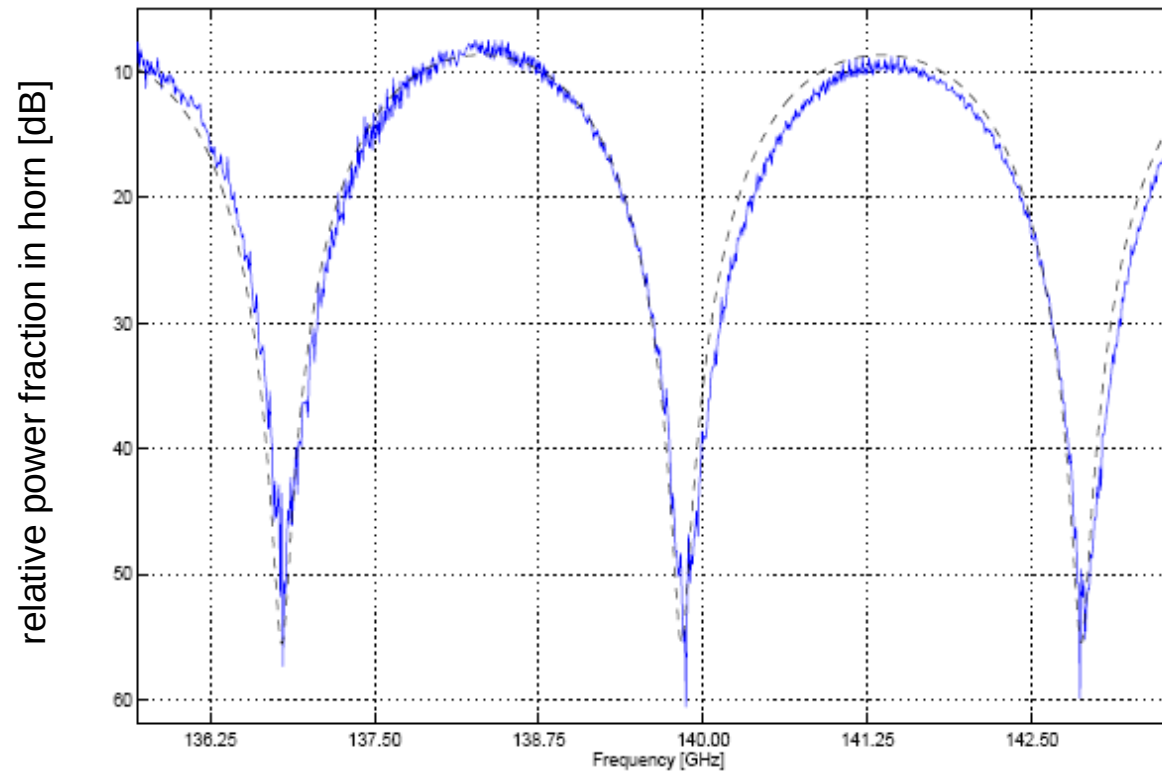
System as constructed and implemented



Acceptance tests: low power



- Lab tests confirm 50 dB suppression of gyrotron component by the two dielectric plates

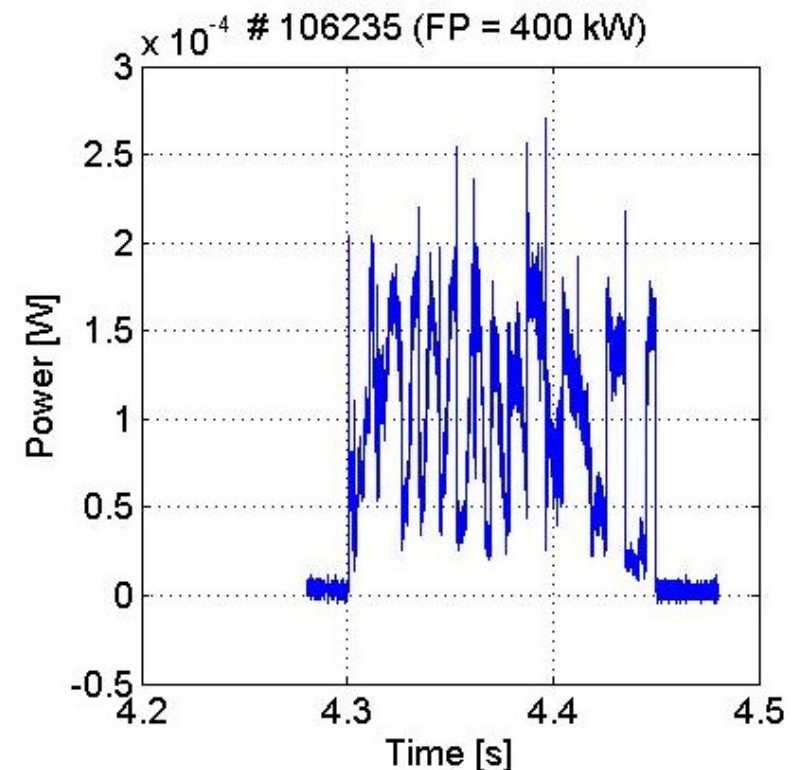


Acceptance tests: high power



- plate angle tuned to optimum of 21.8° .
- heating up of plate
22 K/s for 400 kW ECRH
- caloric measurement of reflected power
700 W for 400 kW ECRH
- stray radiation at horn antenna < 1 mW !

Stray radiation



Conclusion: System meets specifications

Experimental results: discharge with sawteeth



106913 Plasma conditions:

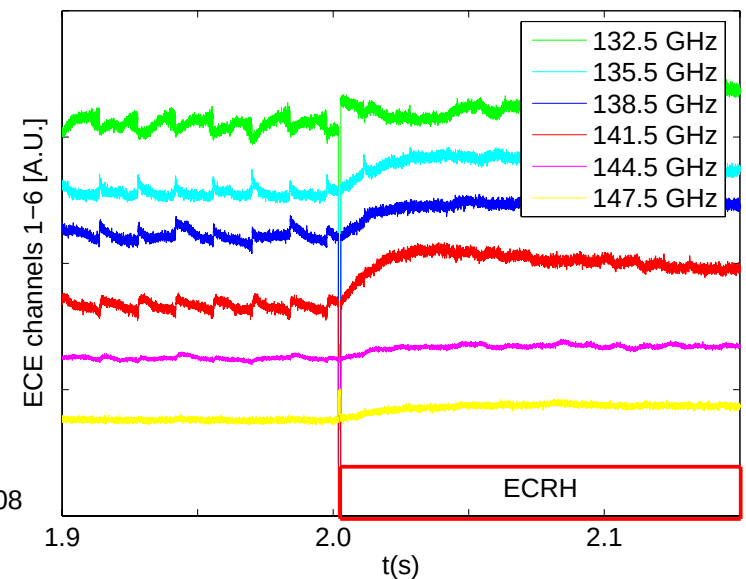
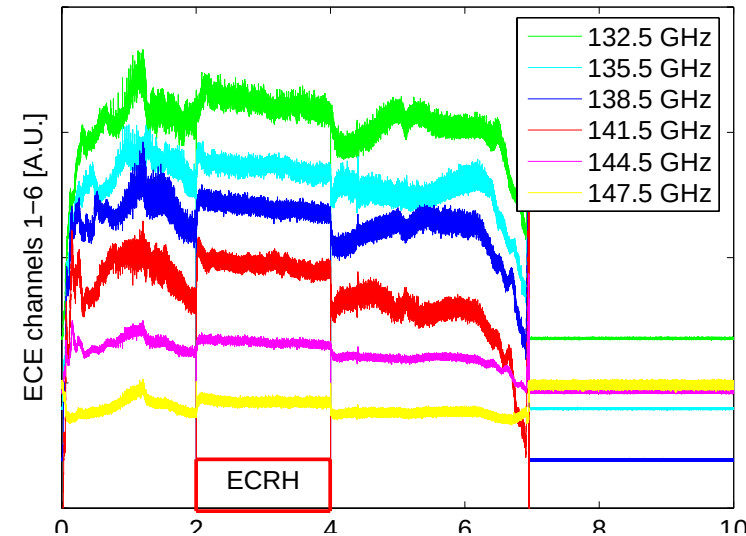
$B_\phi = 2.3 \text{ T}$

$I_p = 300 \text{ kA}$

400 kW co-ECCD

Sawtooth inversion clearly visible between 132.5 and 135.5 GHz

ECRH outside $q=1$ sawteeth stabilized



© J.W. Oosterbeek et al., Proceedings EC15 2008



Discharge with tearing mode



107125 Plasma conditions:

$B_\phi = 2.25$ T

$I_p = 300$ kA

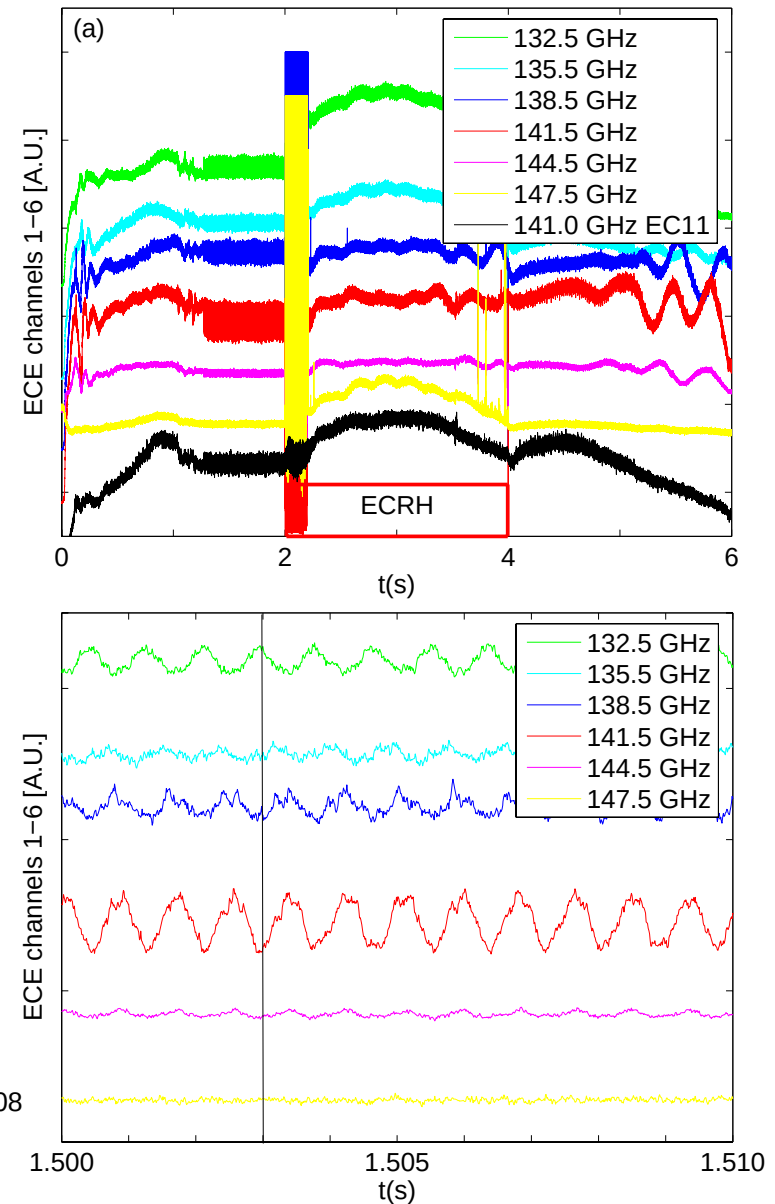
400 kW co-ECCD ($\phi = -10^\circ$)

Elevation scan -15° to $+15^\circ$

ECRH outside r_s at start of scan:
phase reversal from 132.5 to 138.5

Mode stabilized early in scan
when r_{EC} approaches r_s

Strong perturbations in
presence of island



© J.W. Oosterbeek et al., Proceedings EC15 2008



Discharge with tearing mode



107125 Plasma conditions:

$B_\phi = 2.25$ T

$I_p = 300$ kA

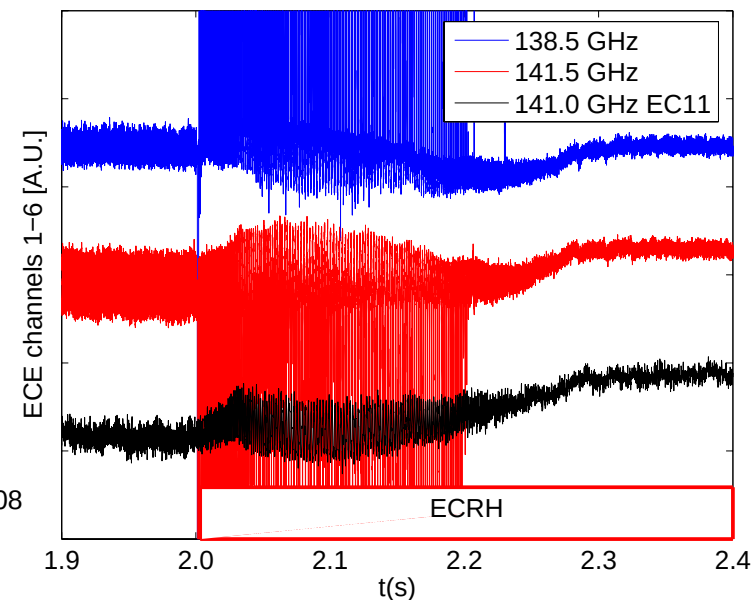
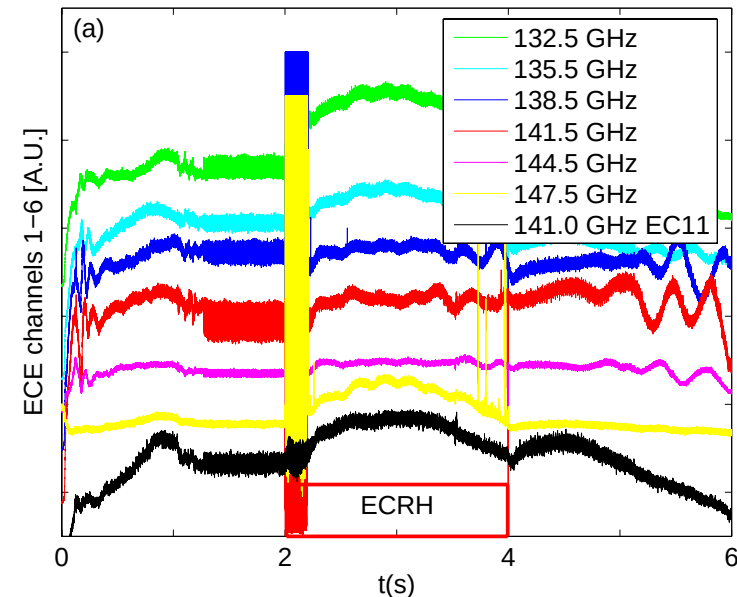
400 kW co-ECCD ($\phi = -10^\circ$)

Elevation scan -15° to $+15^\circ$

ECRH outside r_s at start of scan:
phase reversal from 132.5 to 138.5

Mode stabilized early in scan
when r_{EC} approaches r_s

Strong perturbations in
presence of island



© J.W. Oosterbeek et al., Proceedings EC15 2008



Discharge with tearing mode



107125 Plasma conditions:

$B_\phi = 2.25$ T

$I_p = 300$ kA

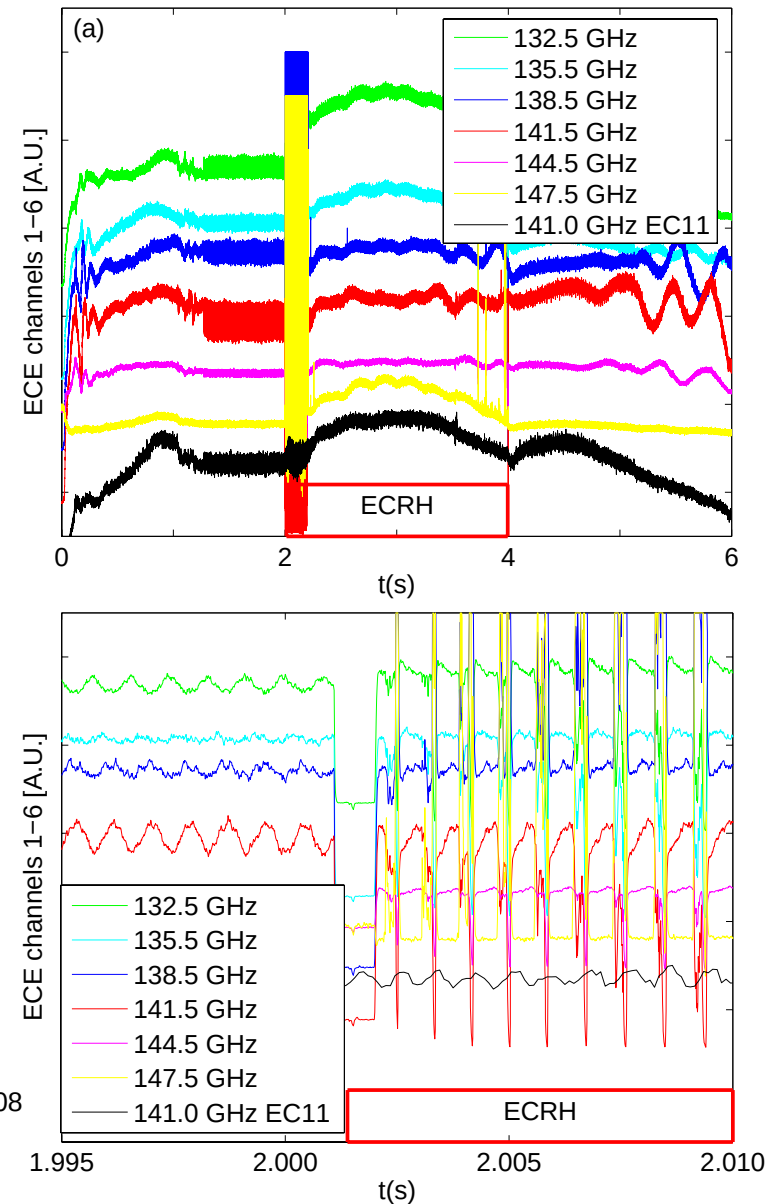
400 kW co-ECCD ($\phi = -10^\circ$)

Elevation scan -15° to $+15^\circ$

ECRH outside r_s at start of scan:
phase reversal from 132.5 to 138.5

Mode stabilized early in scan
when r_{EC} approaches r_s

Strong perturbations in
presence of islands:
in phase with island rotation



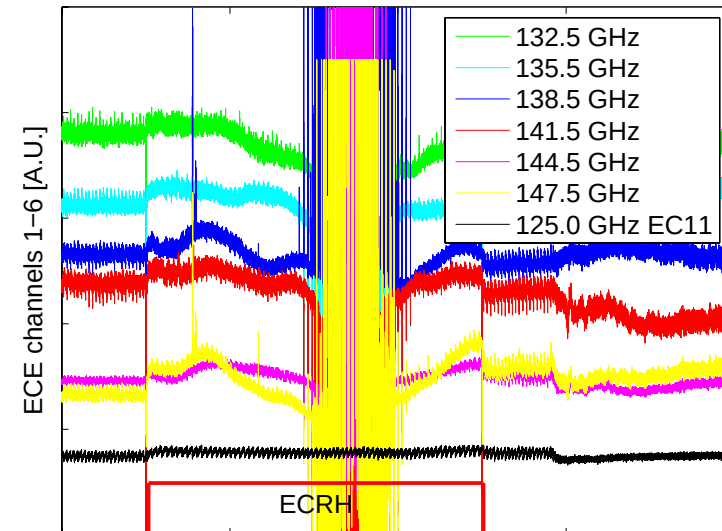
© J.W. Oosterbeek et al., Proceedings EC15 2008



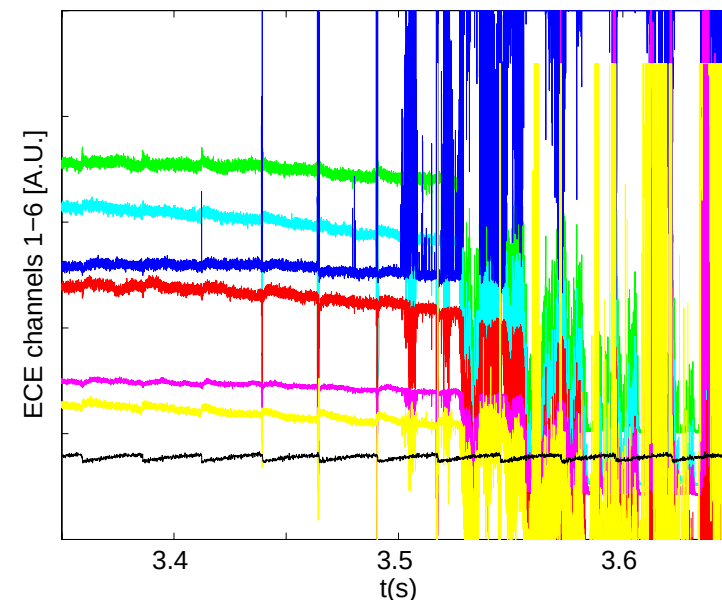
Perturbations also in absence of tearing mode



- Example 107015
- 2.25 T, 300 kA
- Sawtoothing discharge
- 400 kW ECRH
toroidal injection angle
scan -10° to $+10^\circ$



- Perturbations:
- at sawtooth crash?
- in limited range around perpendicular injection
= $[-0.5 : +5.5]$



In summary



- MHD control in fusion plasmas requires feedback control ECRH power deposition
- In-line ECE diagnostic for integrated mode detection, phase tracking and ECRH launcher steering developed and tested
- New phenomenon of back-scattered ECRH radiation has been uncovered
 - Around perpendicular propagation
 - For any propagation angle in case of presence of magnetic islands

What comes next



- Implementation of in-line ECE in feedback loop for NTM or sawtooth period control
- Physics studies of back-scattered ECRH in in-line ECE diagnostic
- Development of CW wave guide compatible frequency selective couplers for in-line ECE
 - AUG, ITER, ...
 - FADIS, ...

Thank you
for your attention !

