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

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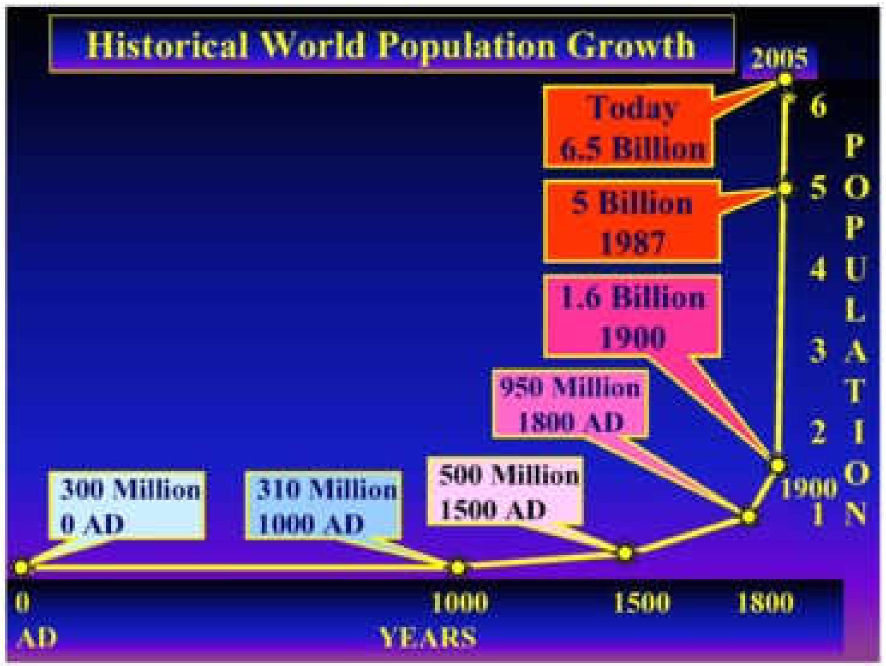
Quick overview

- 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 CO_2-free energy sources
  - Exploding energy requirements of a growing, wealthier world population



Energy Crisis

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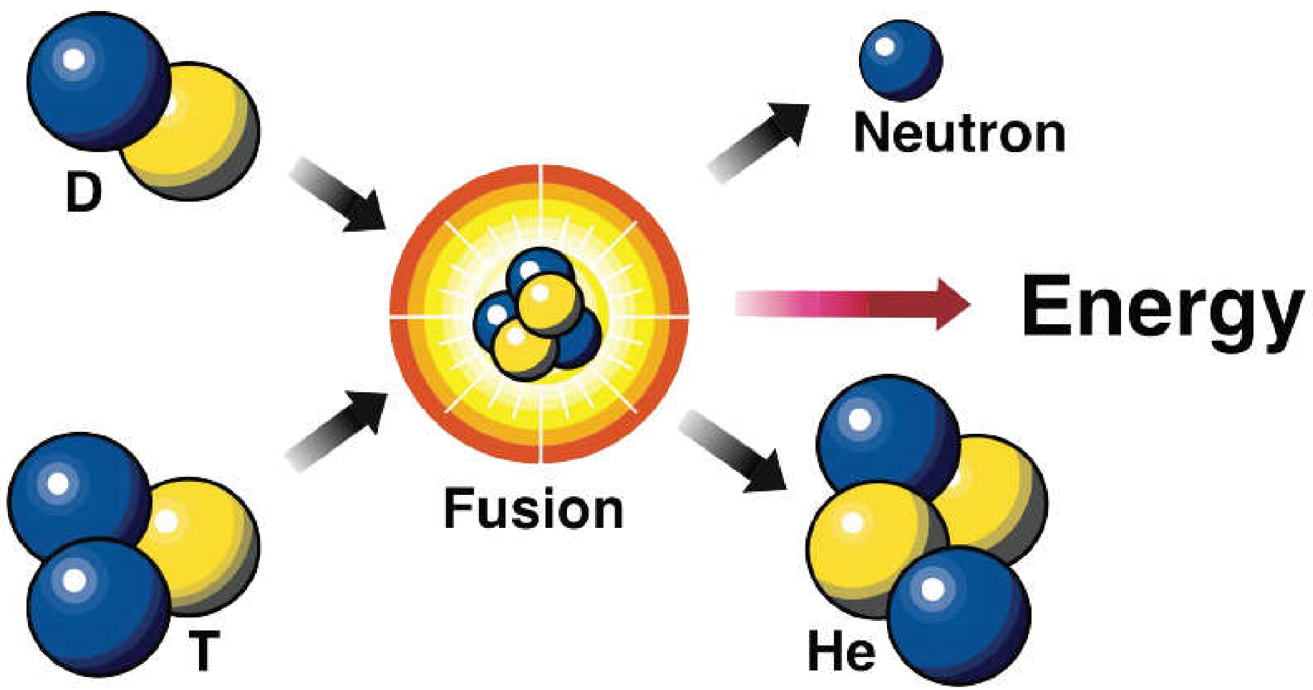
  - Global warming

Energy Crisis

- Need for new CO_2-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

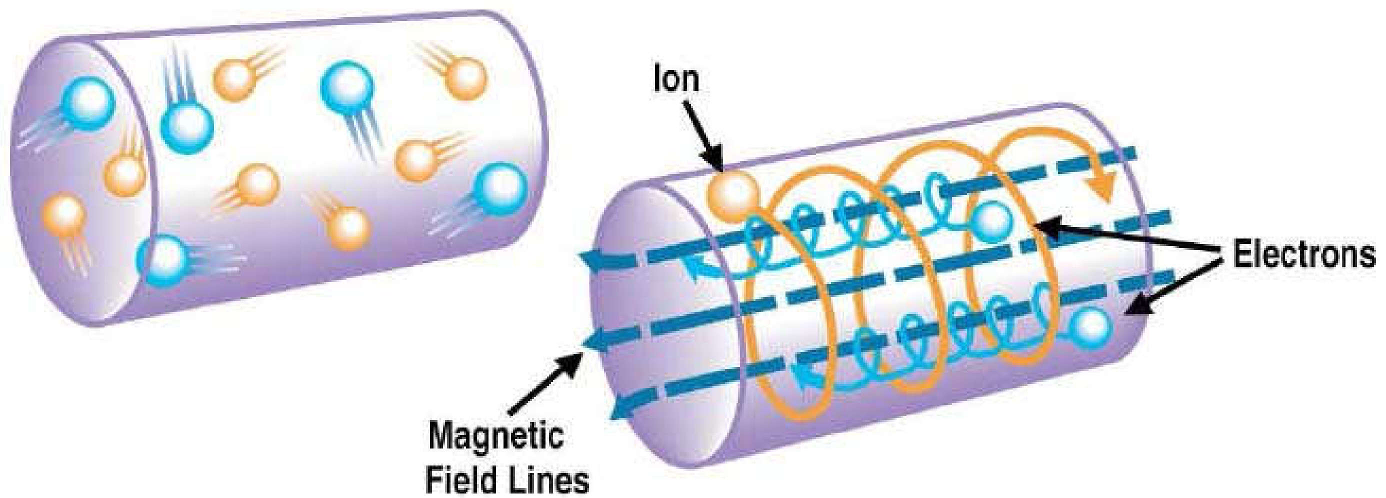


Requirements for Fusion?

- Lawson criterion: energy produced must exceed energy lost

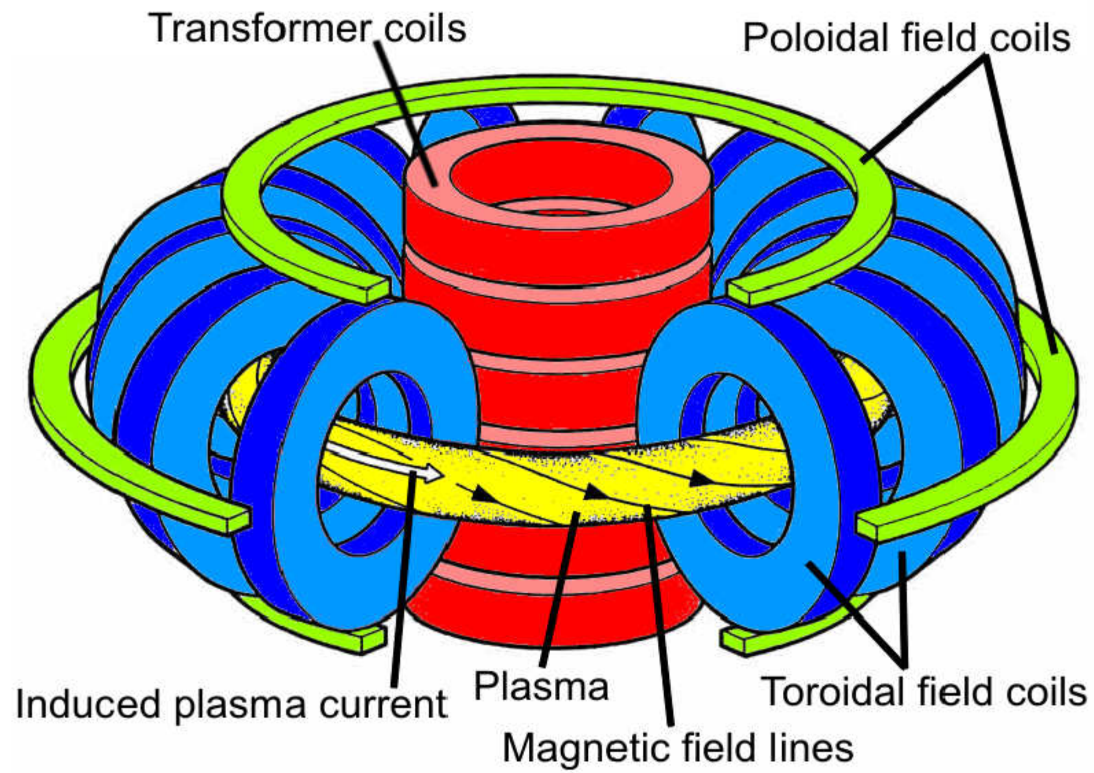
$$n\ T\ \tau_E > \text{critical value}$$

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



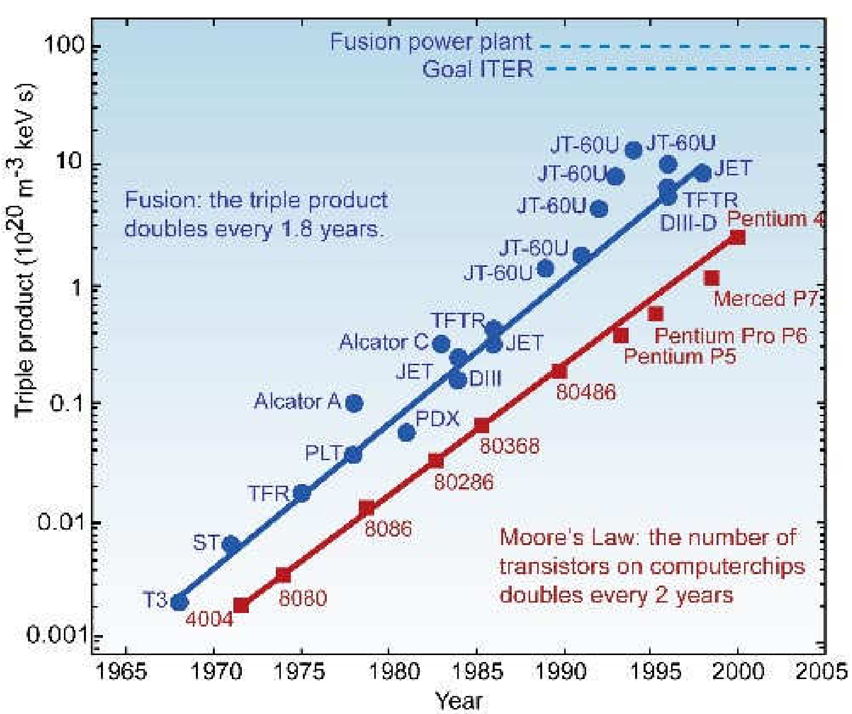
Magnetic confinement

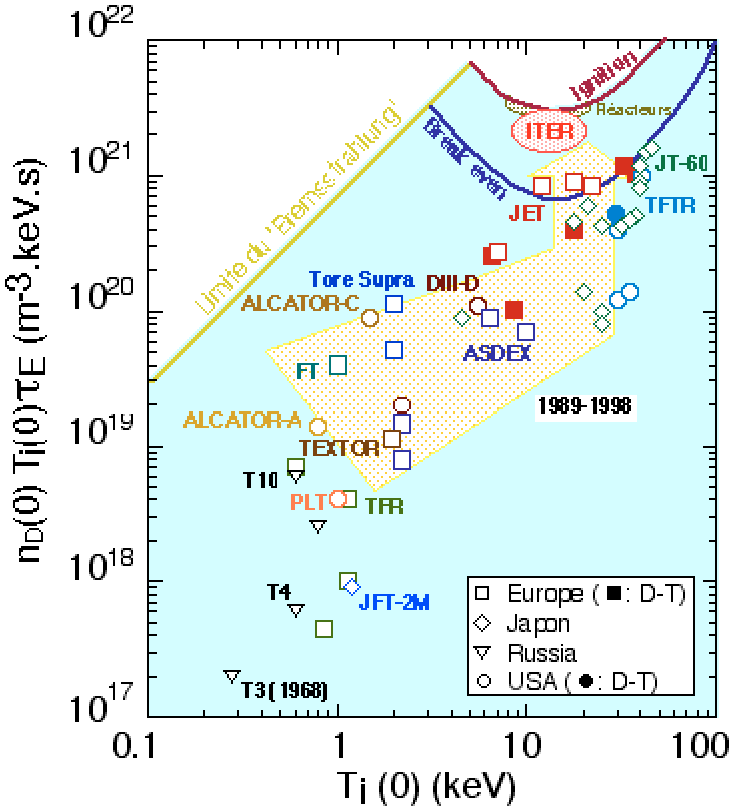
- Bend magnetic field lines into a torus to prevent end-losses: the TOKAMAK



Tokamak achievements

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

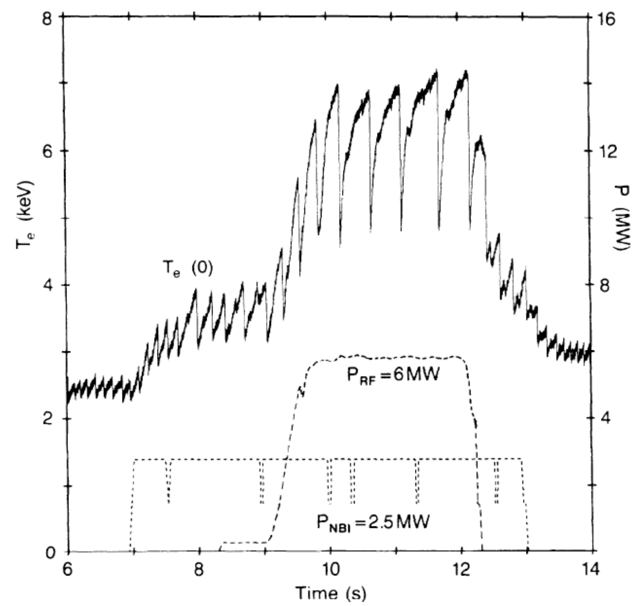


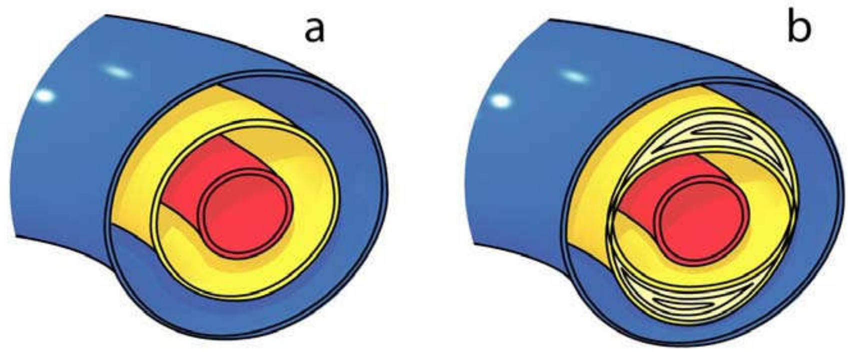


There is a catch: instabilities

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

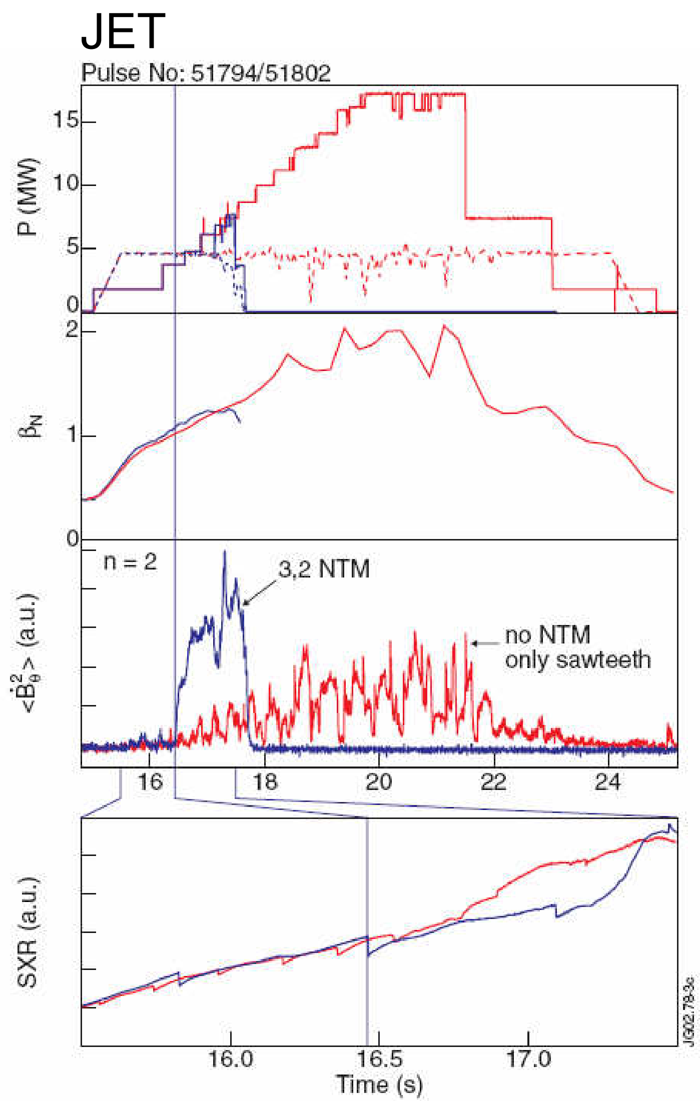
- These need to be controlled





The need for MHD instability control

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



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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

DIII-D

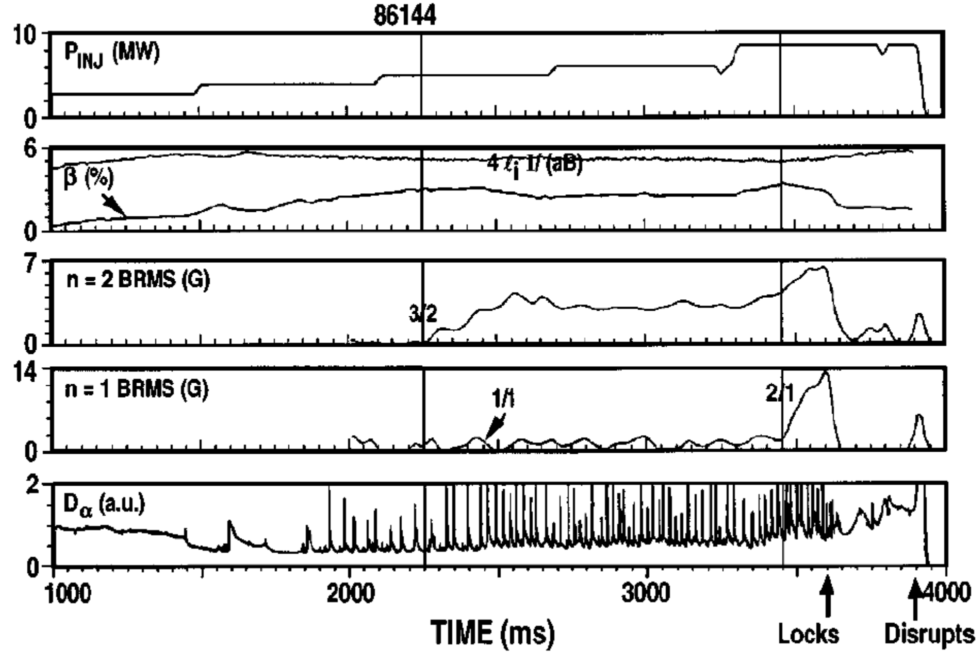


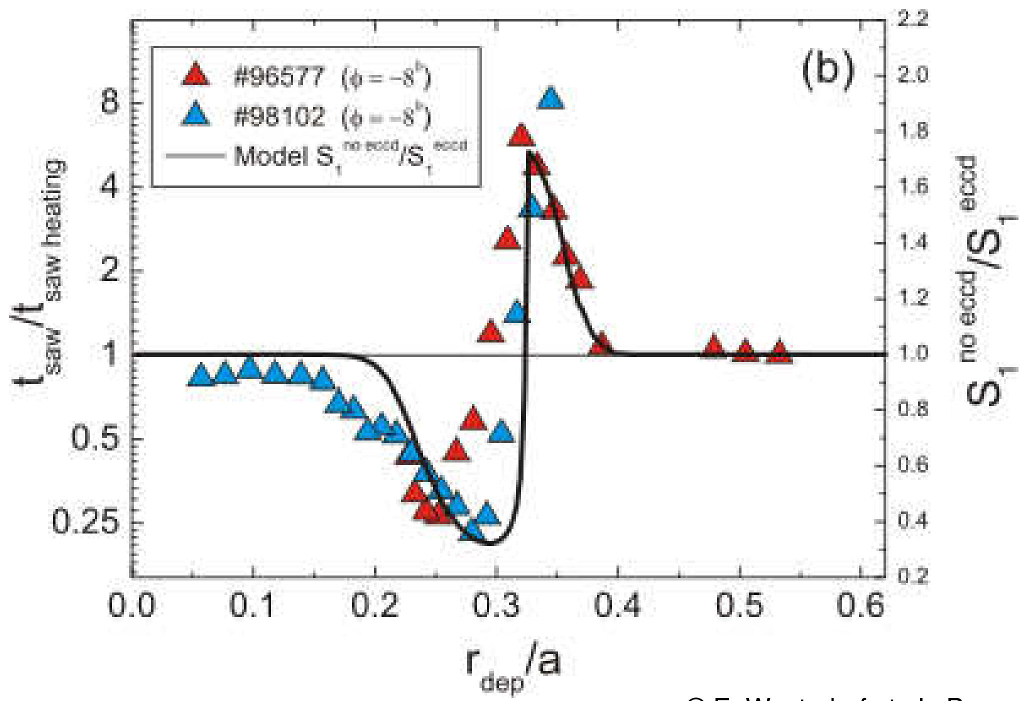
FIG. 1. Typical time history of the neoclassical modes. In this DIII-D discharge #86144, a 3/2 mode is excited at $t=2250$ ms and induces a saturation of β. At $t=3450$ ms, a 2/1 mode grows to a large amplitude until it locks and triggers a disruption. The computed ideal limit for this case is $\beta_N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

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



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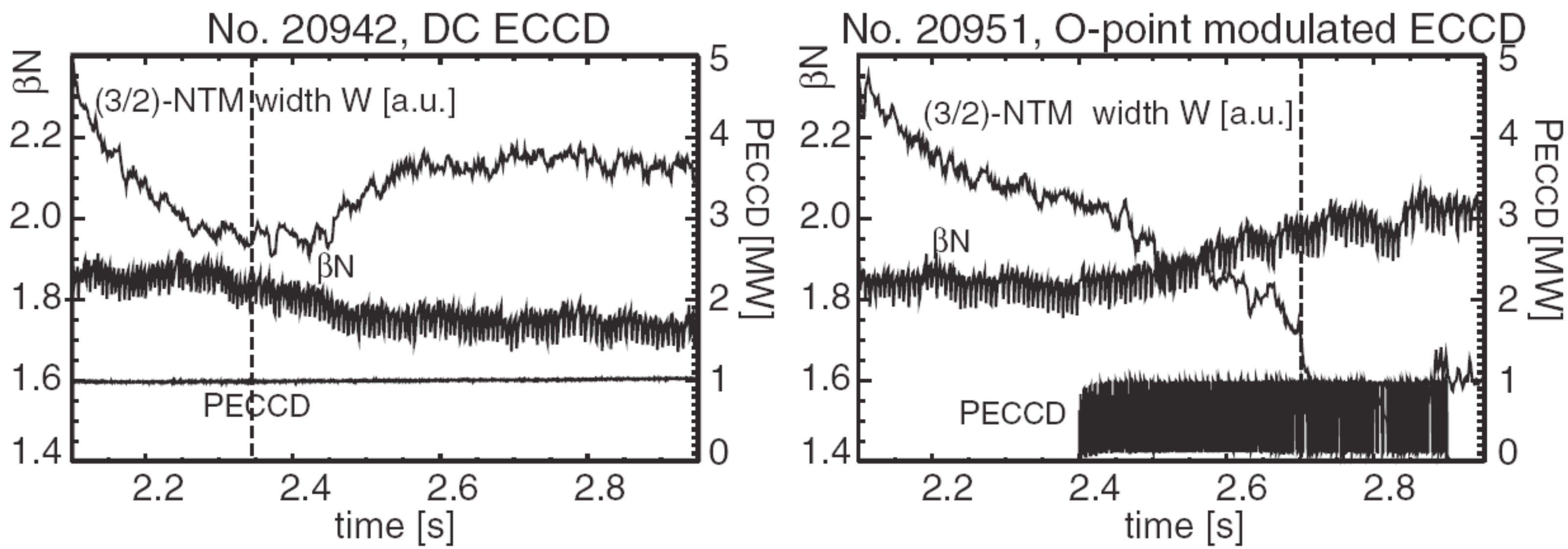
The need to control ECRH localization

- 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



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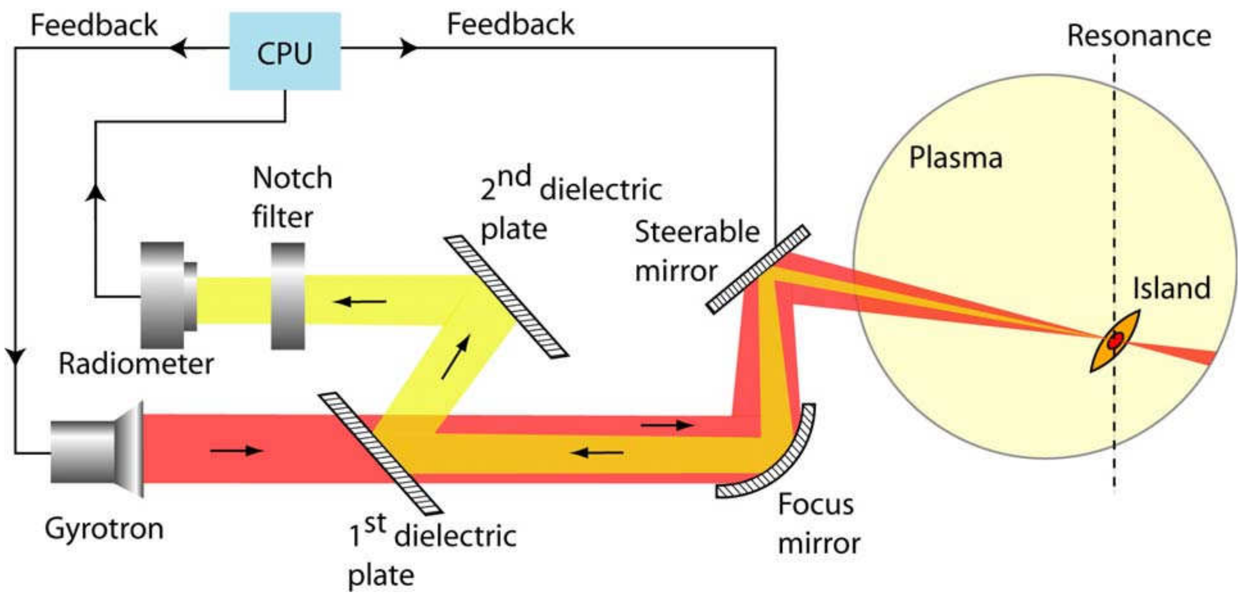
Diagnostic requirements for feedback controlled power deposition

- 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

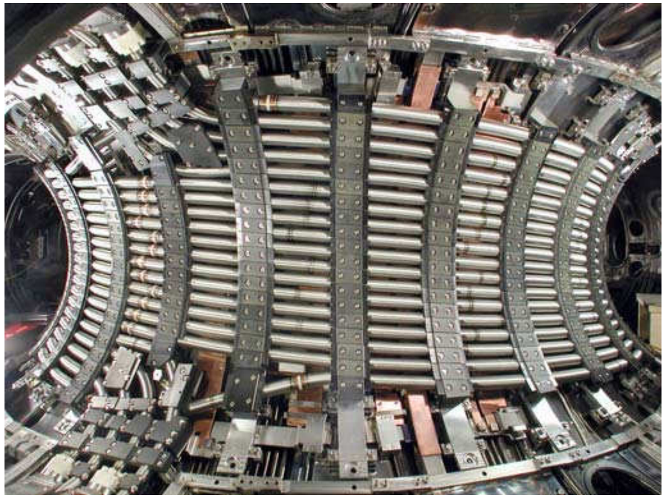
on the gyrotron frequency

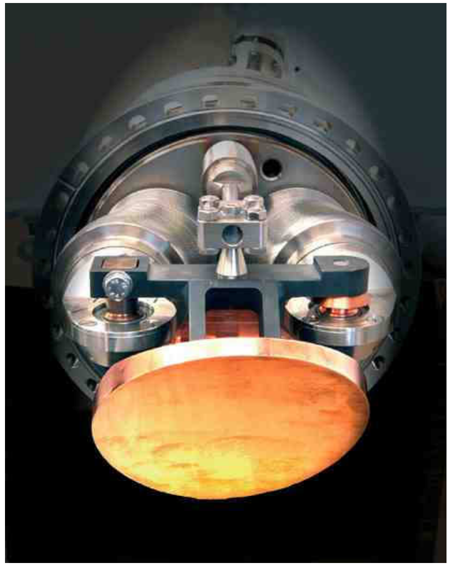
ensures power deposition on top of it

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

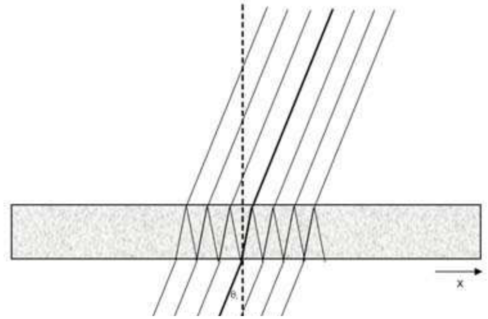
TEXTOR system design

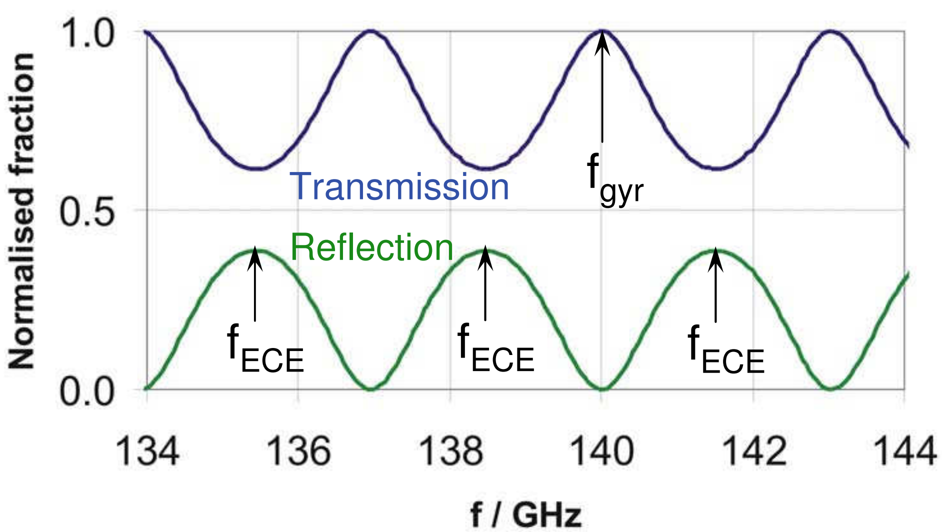




Implementation in Quasi Optical environment

- 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

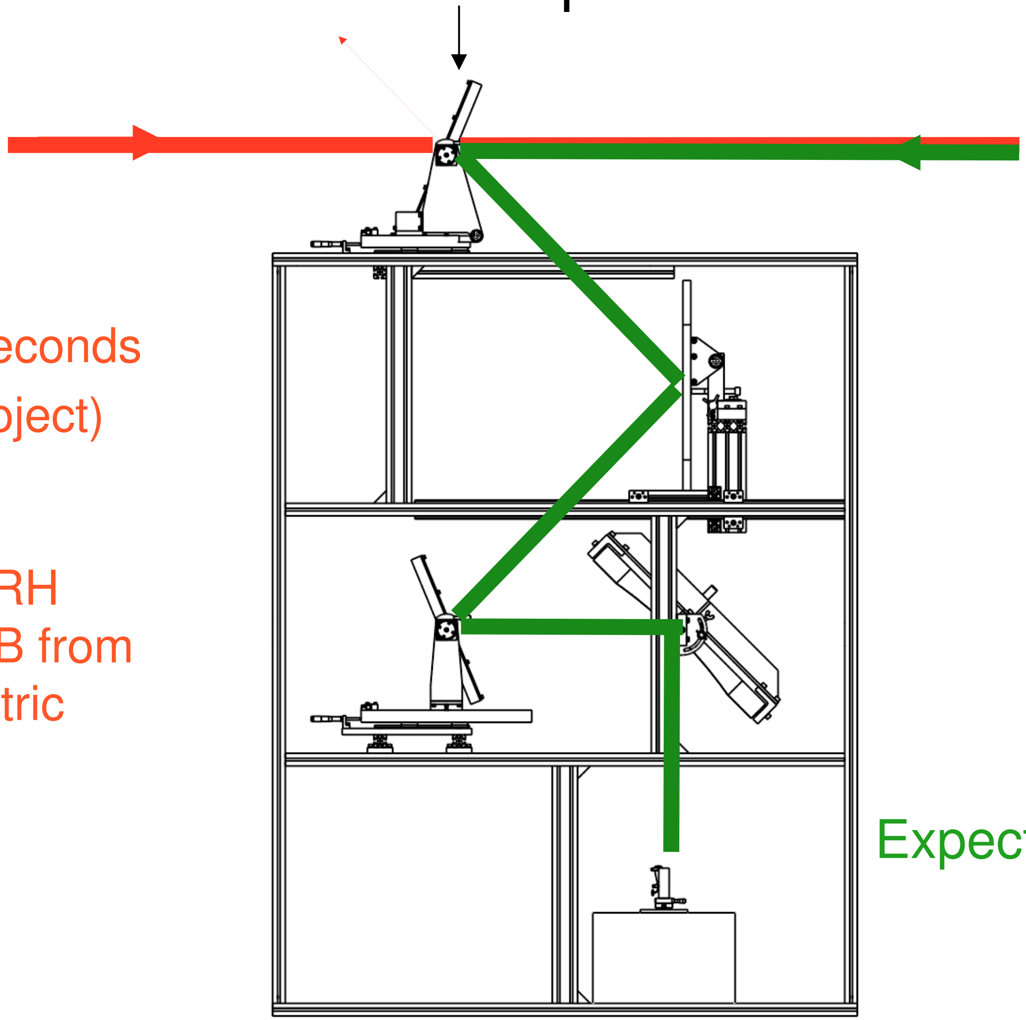
ECRH from gyrotron

140 GHz

800 kW, 10 seconds

(3 s for FB project)

Reflected ECRH down by 50 dB from the two dielectric plates

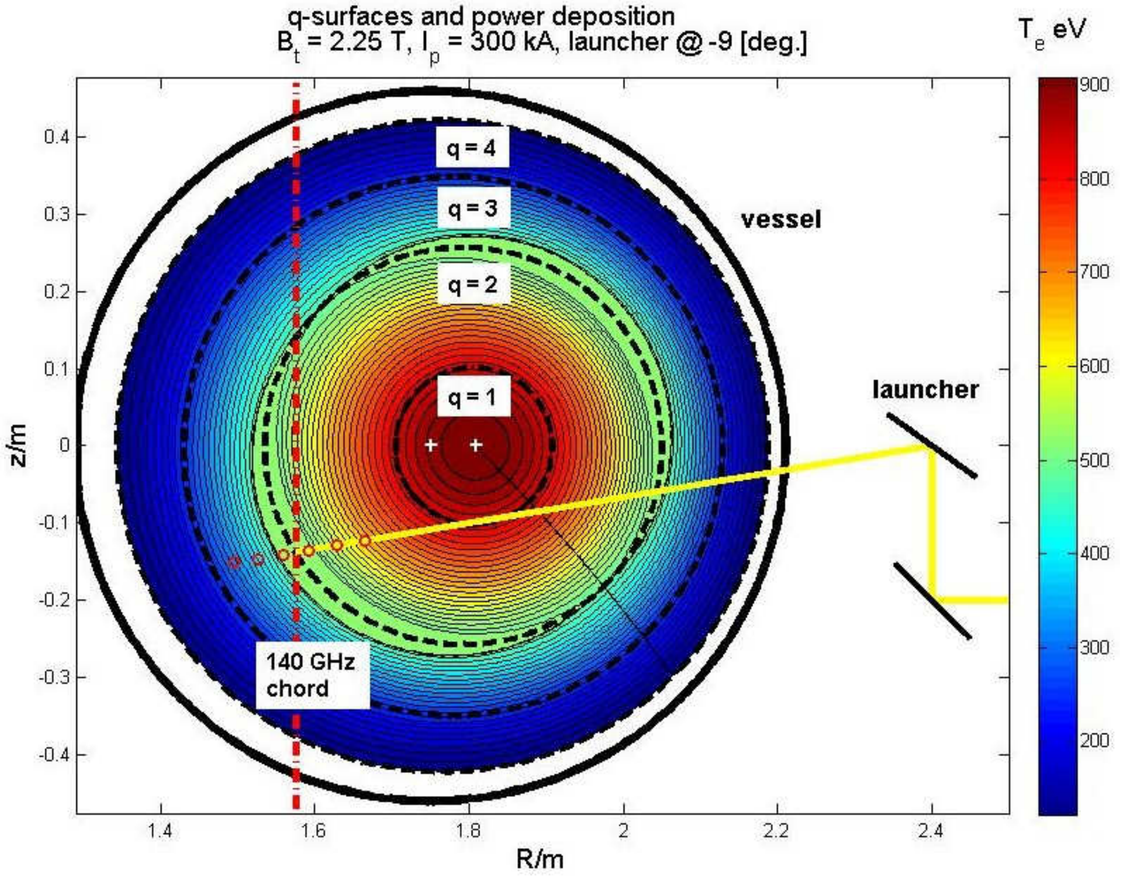


ECE from plasma

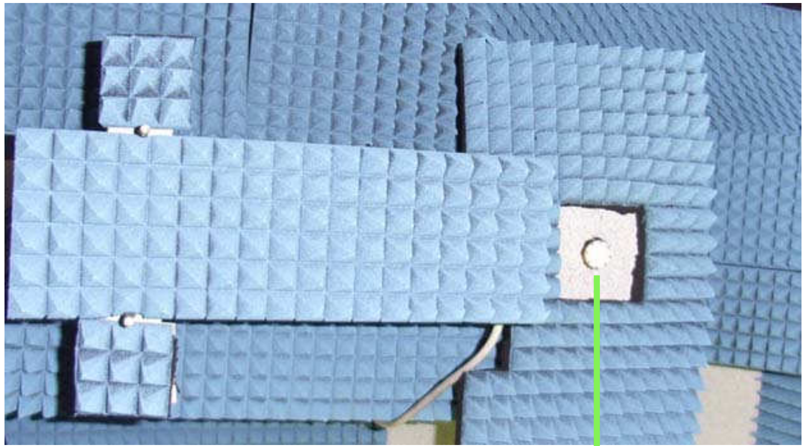
Expected ECE ~ 100 pW

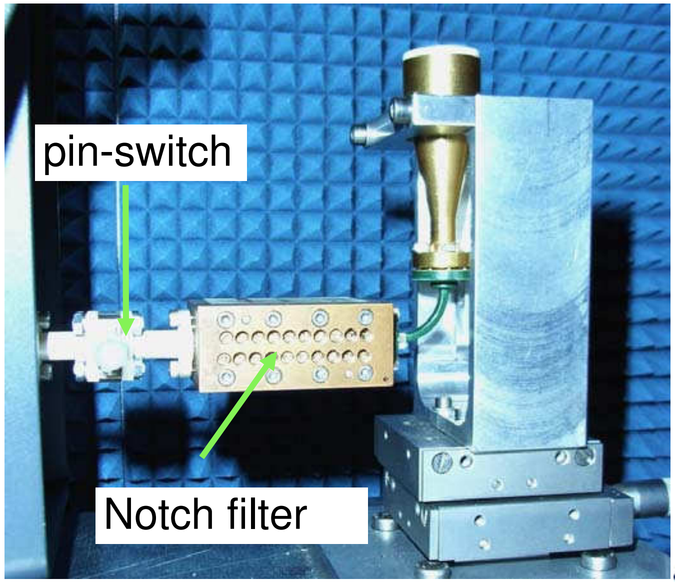
Geometry in plasma of final system

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



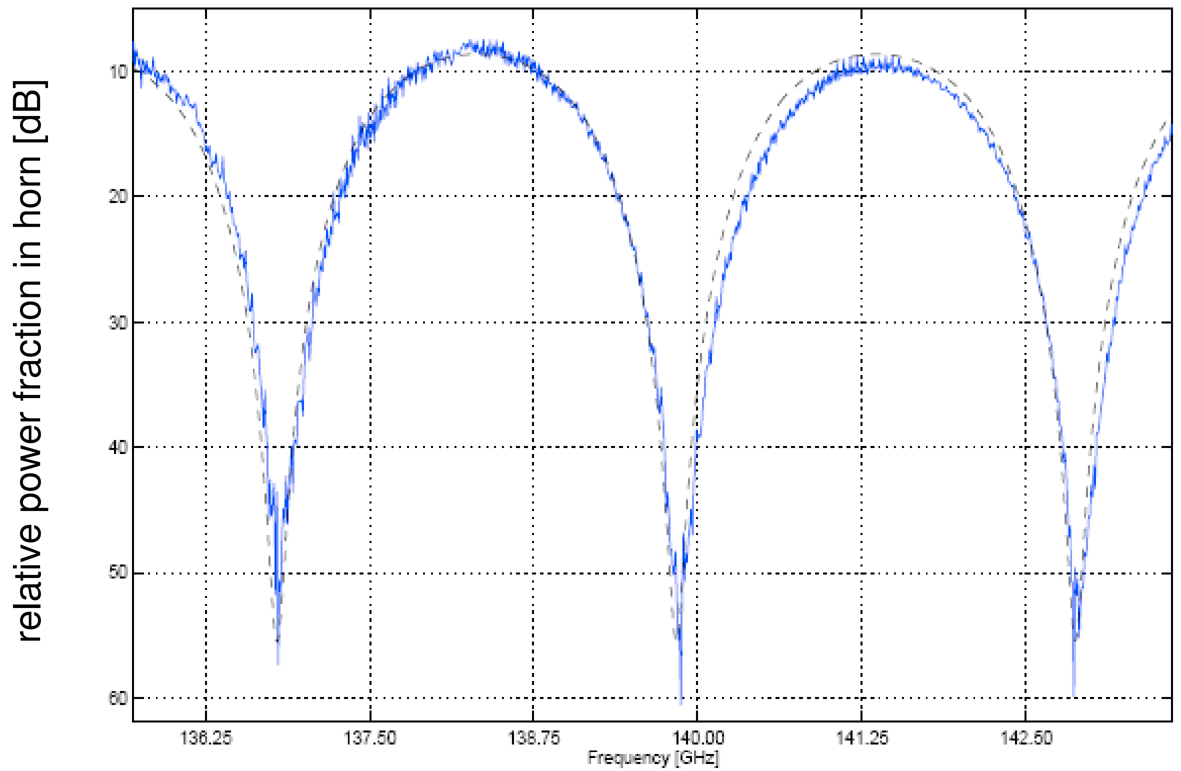
System as constructed and implemented





Acceptance tests: low power

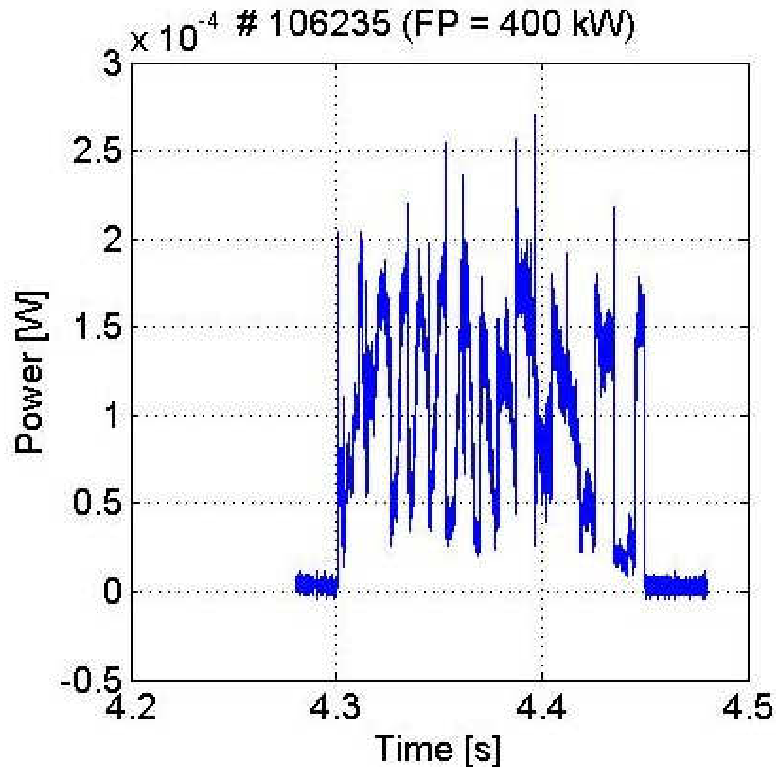
- Lab tests confirm 50 dB suppression of gyrotron component by the two dielectric plates



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:

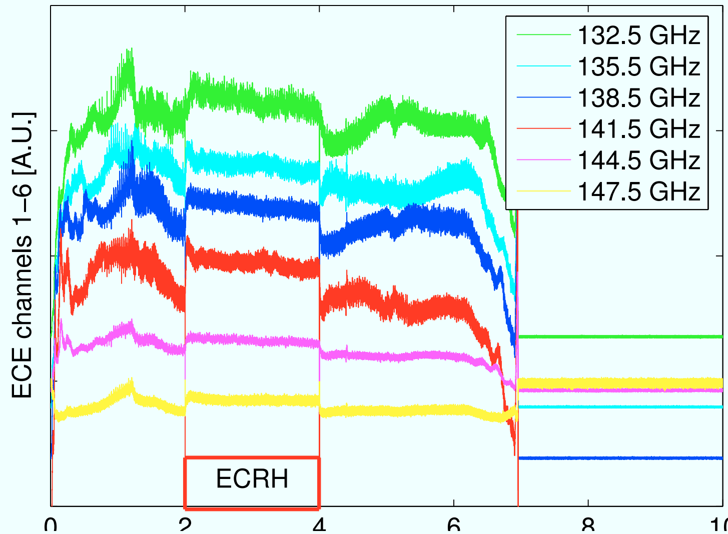
B_ϕ = 2.3 T

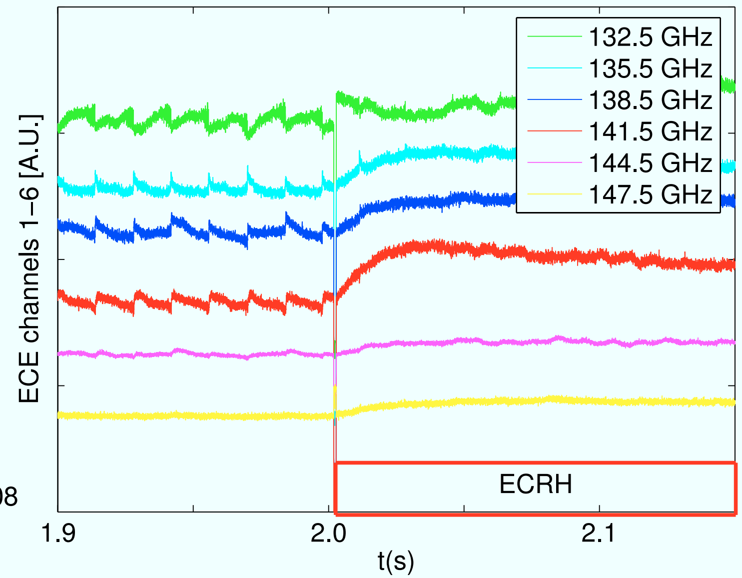
I_p = 300 kA

400 kW co-ECCD

Sawtooth inversion clearly visible between 132.5 and 135.5 GHz

ECRH outside q=1 sawteeth stabilized





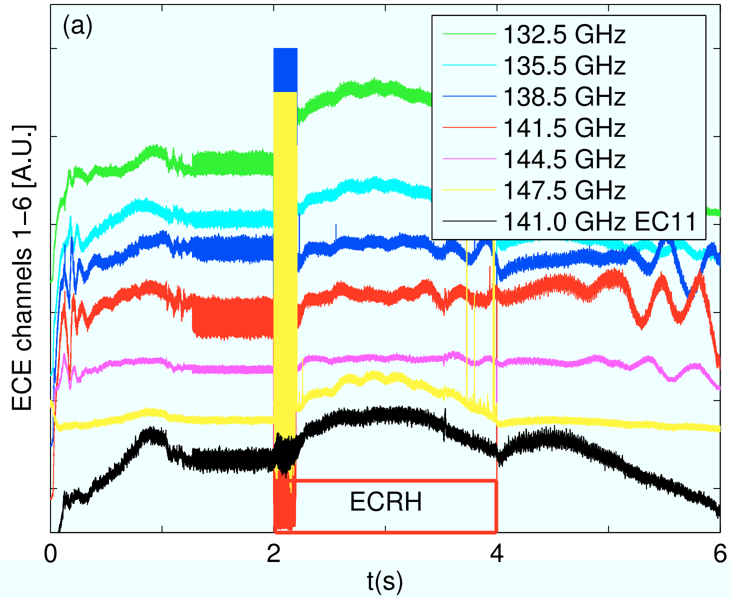
Discharge with tearing mode

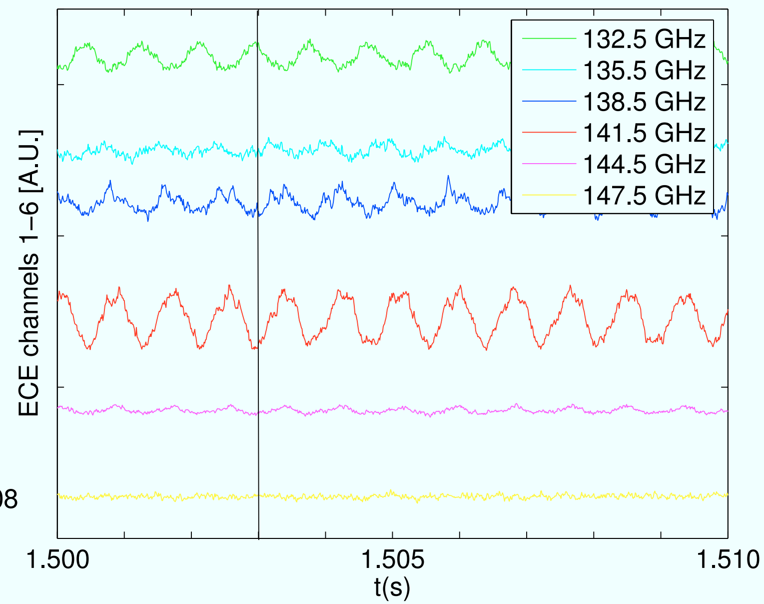
107125 Plasma conditions:
B_ϕ = 2.25 T
I_p = 300 kA
400 kW co-ECCD (ϕ = -10°)
Elevation scan -15° to +15°

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 if island





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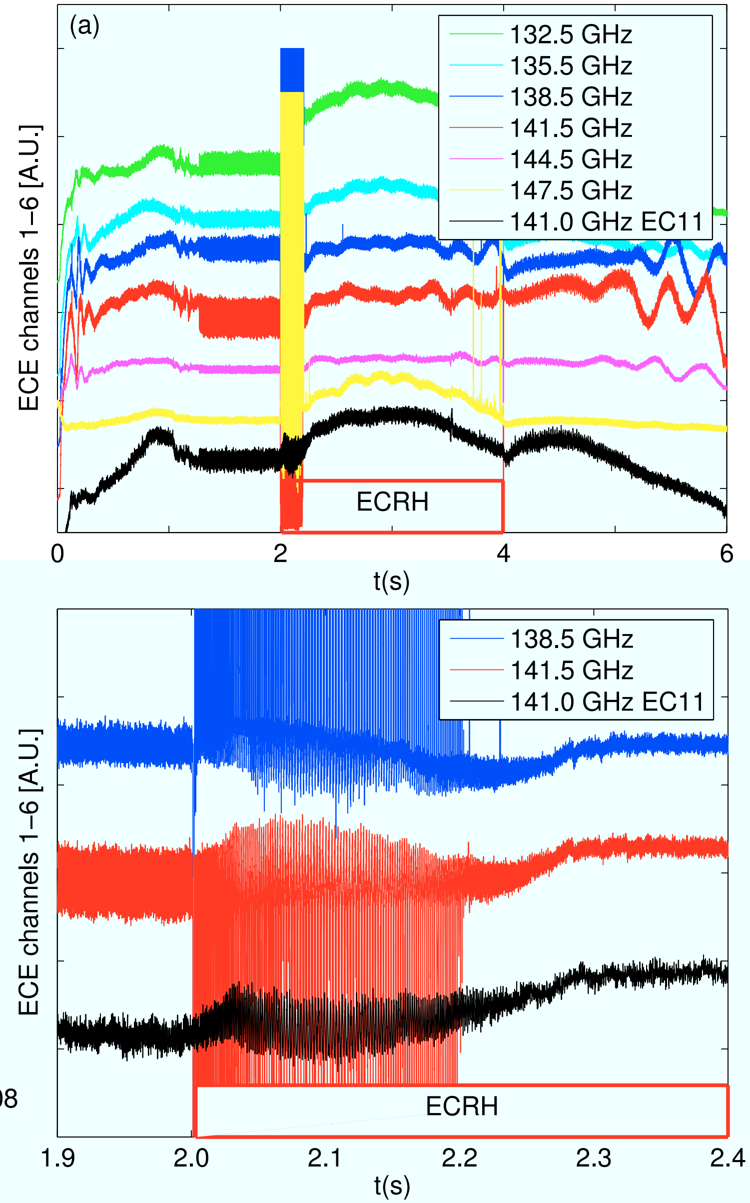

Discharge with tearing mode

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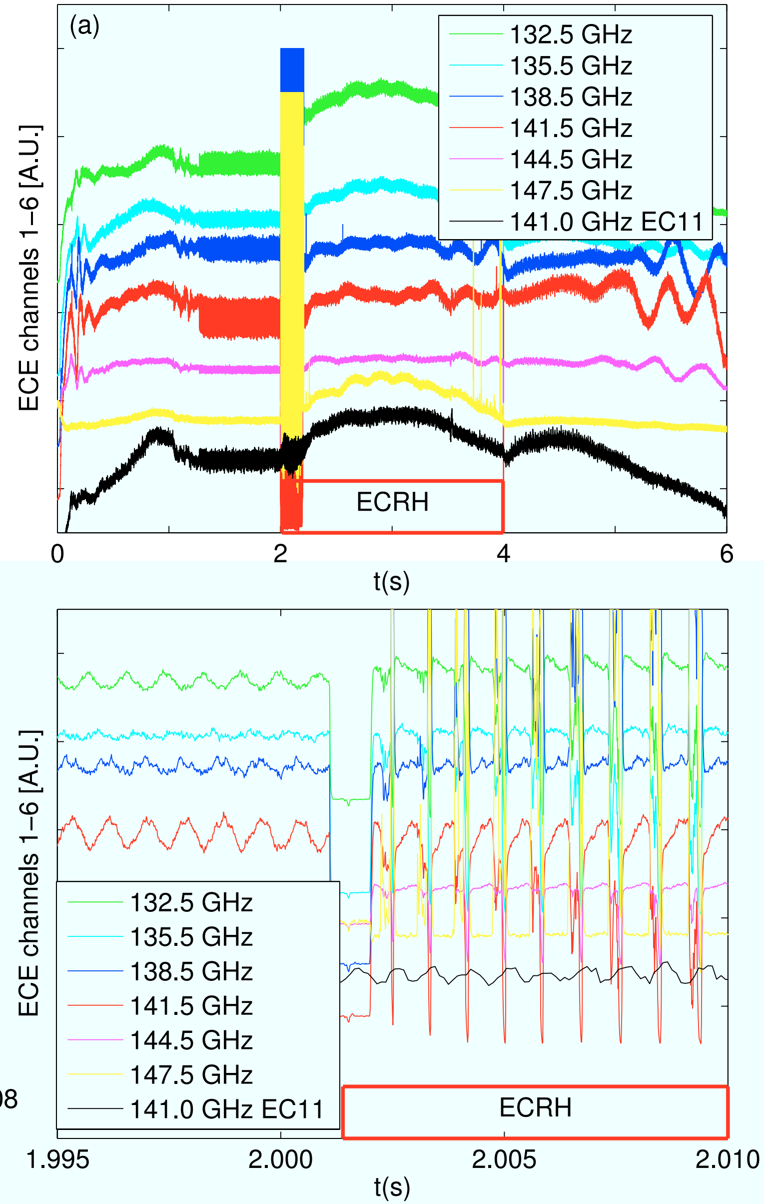
I_p = 300 kA
400 kW co-ECCD (ϕ = -10°)
Elevation scan -15° to +15°

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

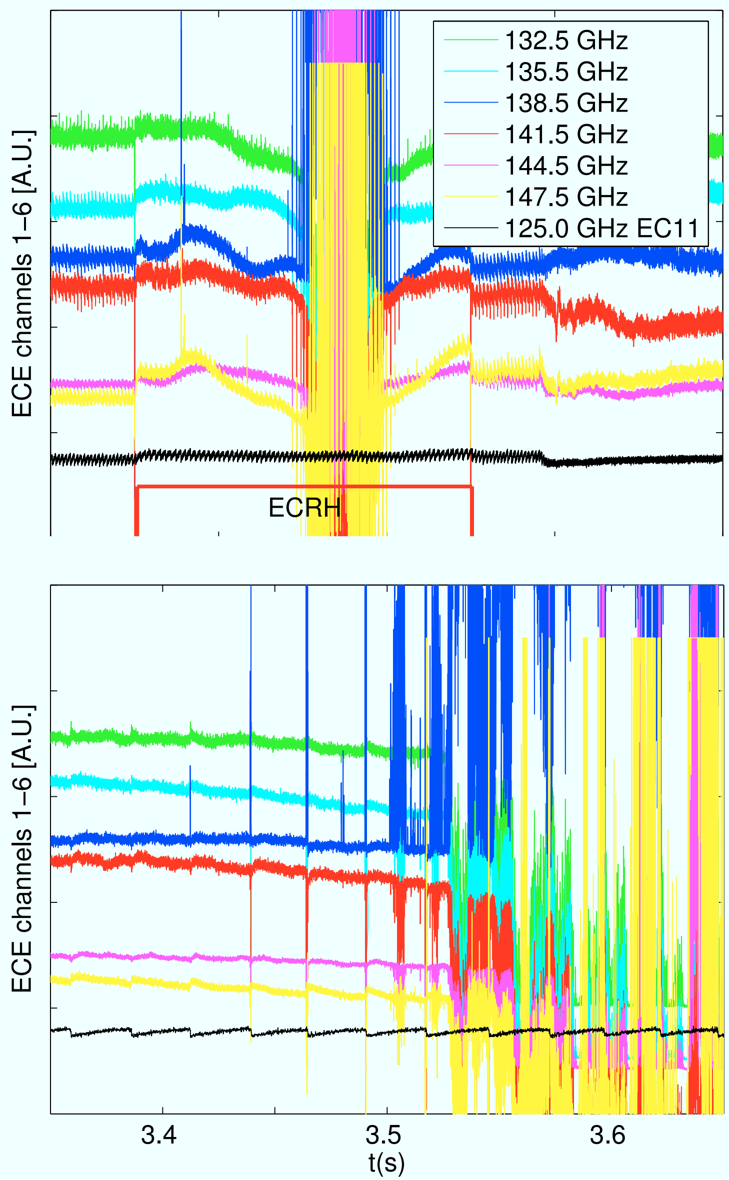
Strong perturbations in
presence of islands:
in phase with island rotation



Perturbations also in absence of tearing mode

- Example 107015
- 2.25 T, 300 kA
- Sawtoothing discharge
- 400 kW ECRH
  toroidal injection angle
  scan -10º to +10º

- Perturbations:
- at sawtooth crash?
- in limited range around
  perpendicular injection f
  = [-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, …

IMΦ

Thank you

for your attention !