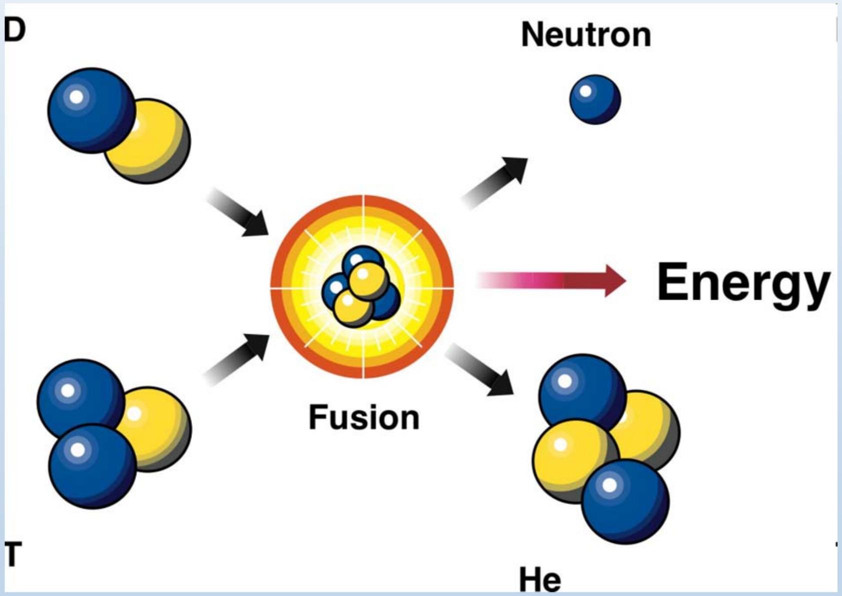
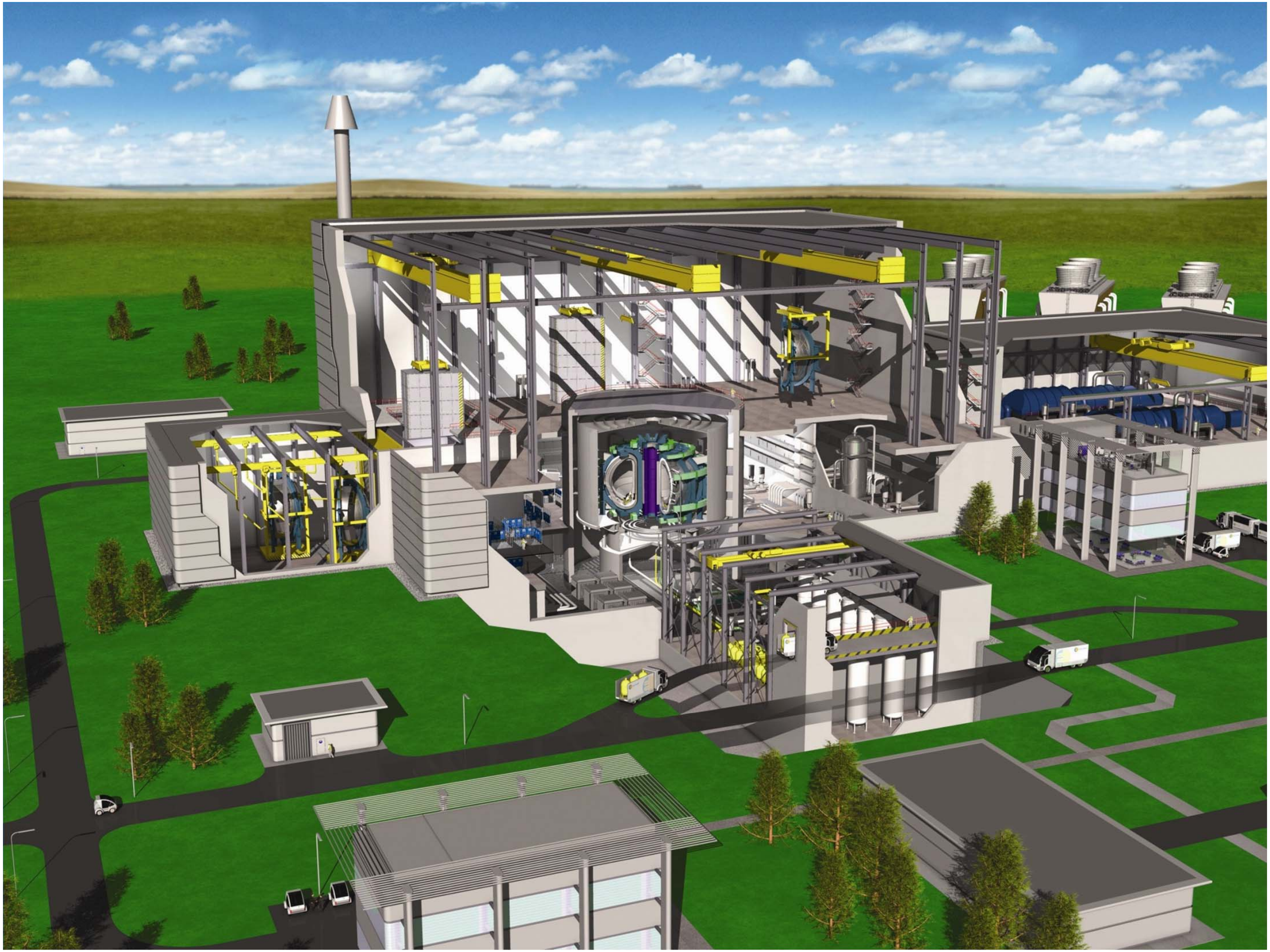
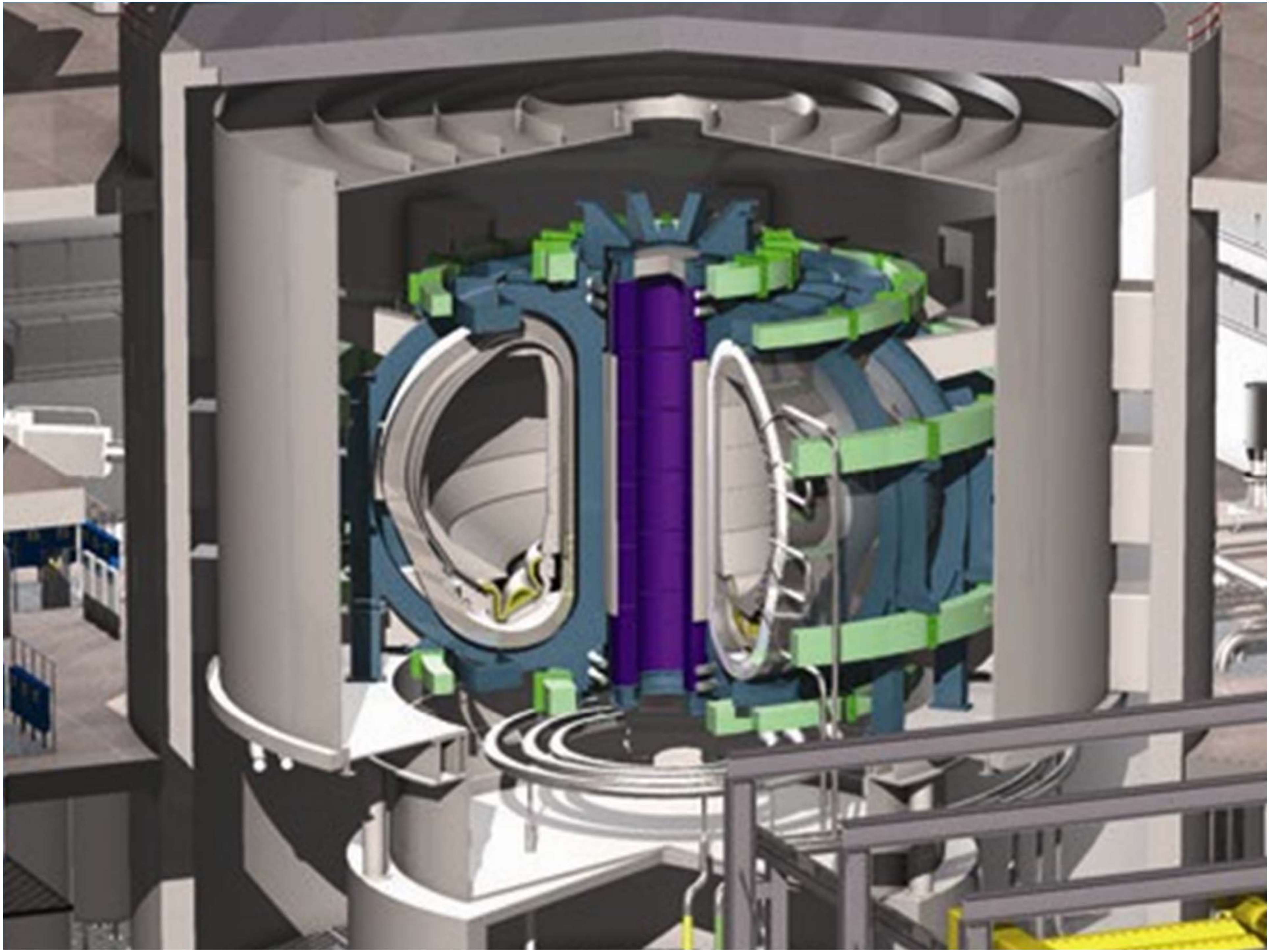
Control of a burning fusion plasma:

a multi-disciplinary scientific challenge

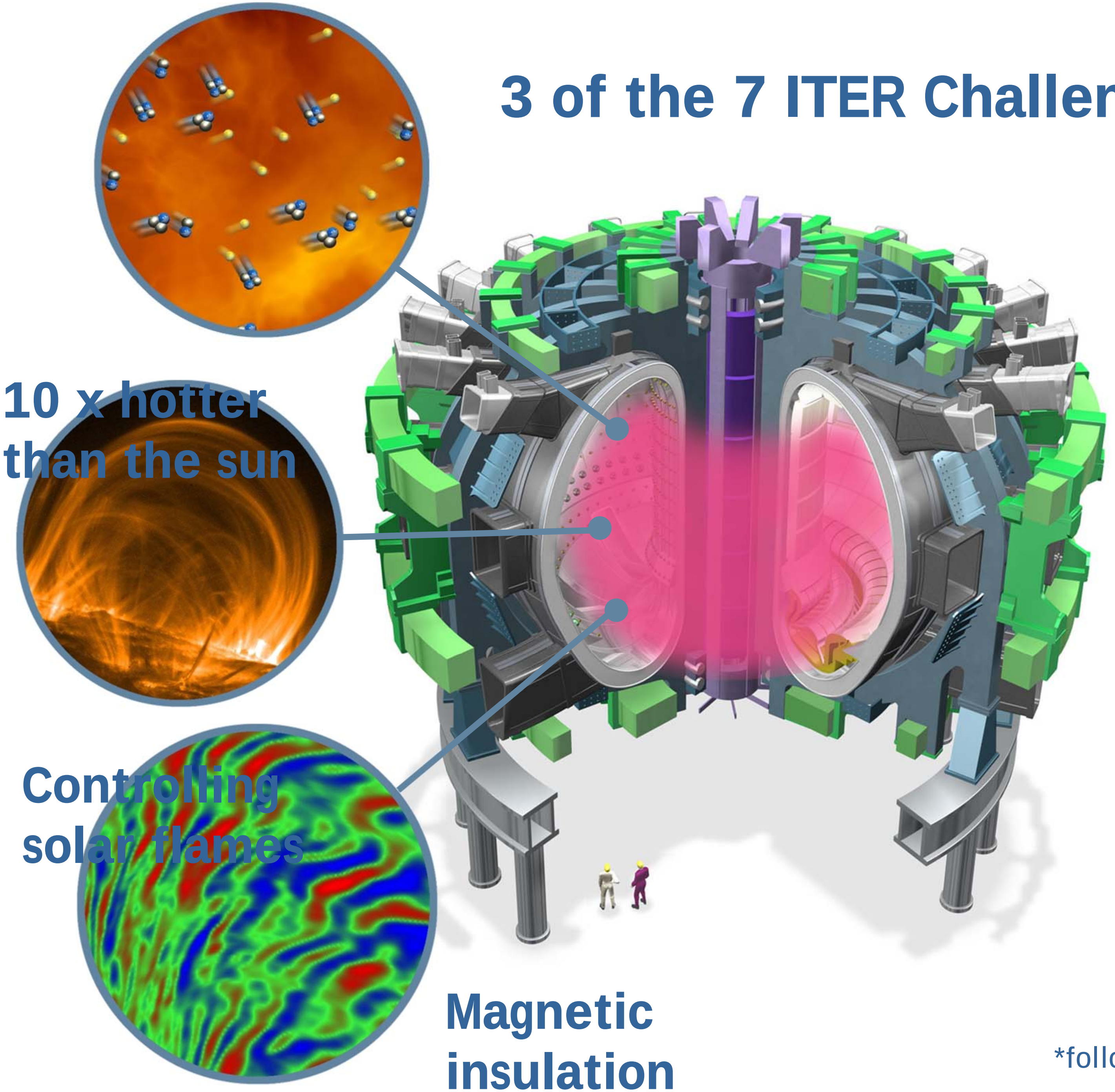


Tony Donné





3 of the 7 ITER Challenges*



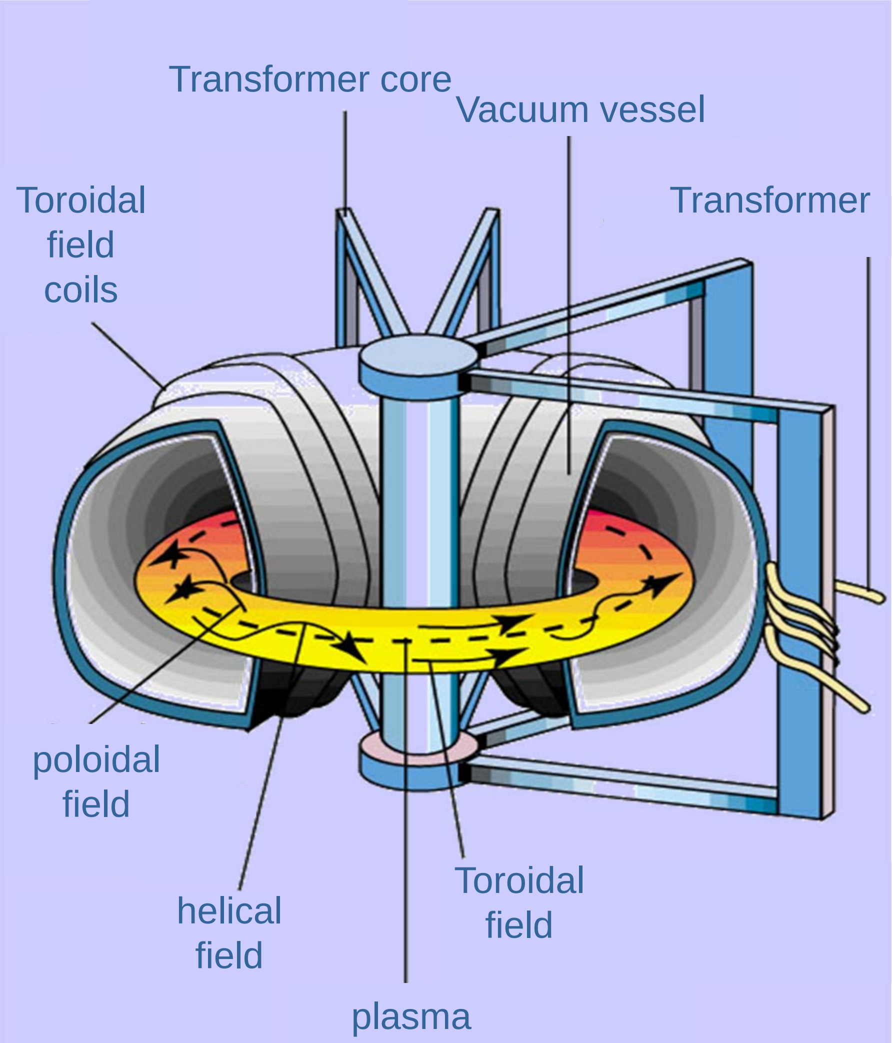
10 x hotter than the sun

Controlling solar flames

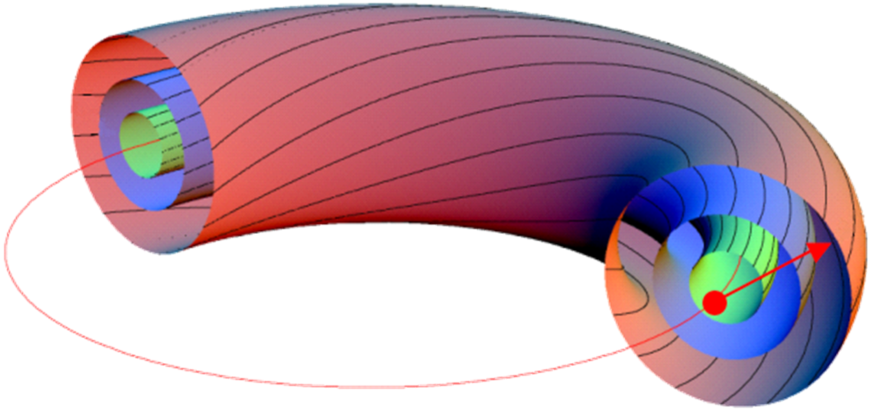
Magnetic insulation

*following Lopes Cardozo

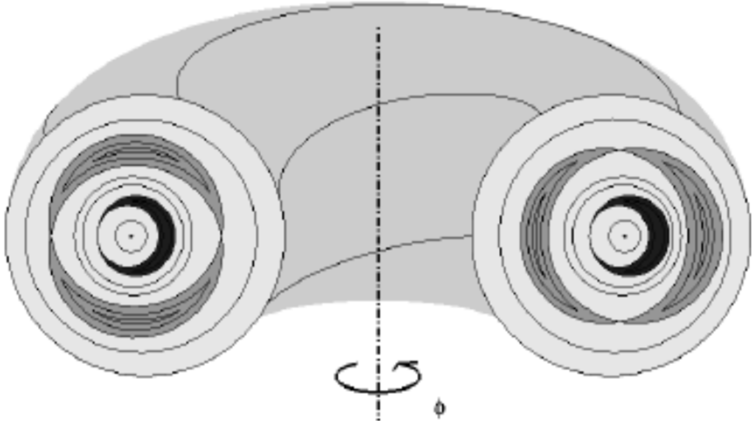
Tokamak



Ideal: Nested flux-surfaces

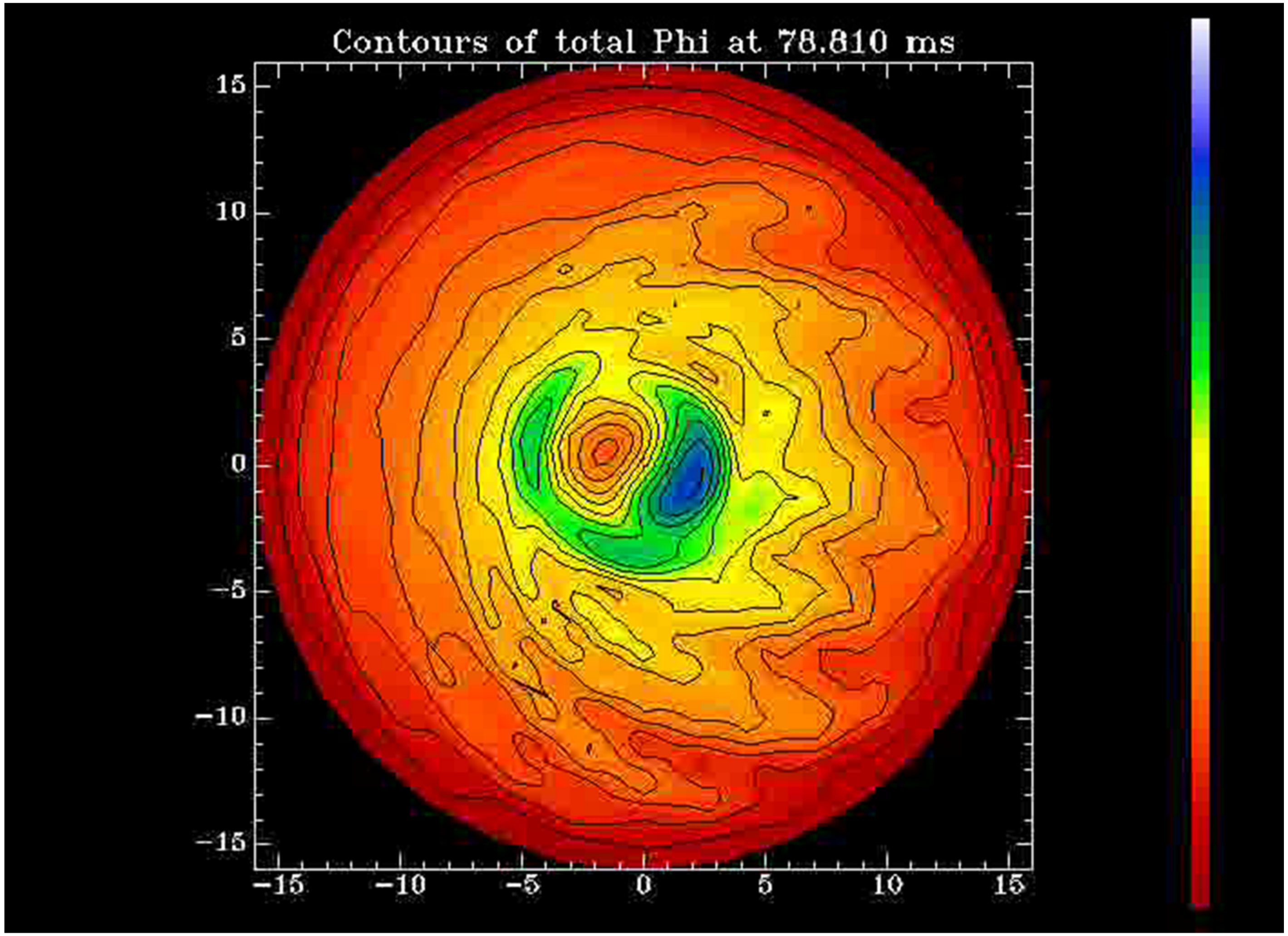


In practice: Many instabilities



Magneto-hydrodynamics: The theory to describe plasma and instabilities

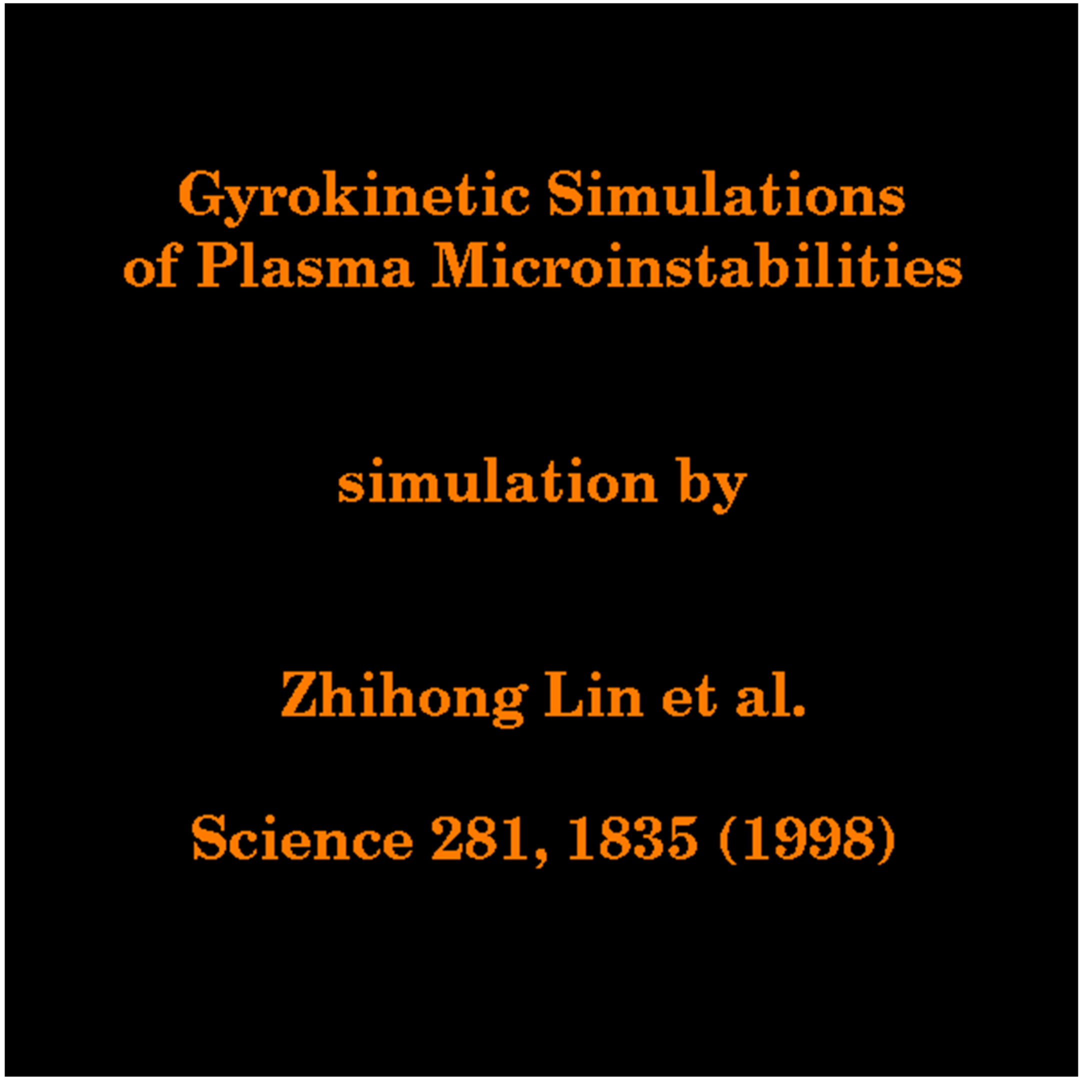
Fusion plasmas are highly structured



Modelling of cold pulse experiment

E. Min, PhD thesis

Hot magnetized plasmas are highly structured



Gyrokinetic Simulations
of Plasma Microinstabilities

simulation by

Zhihong Lin et al.

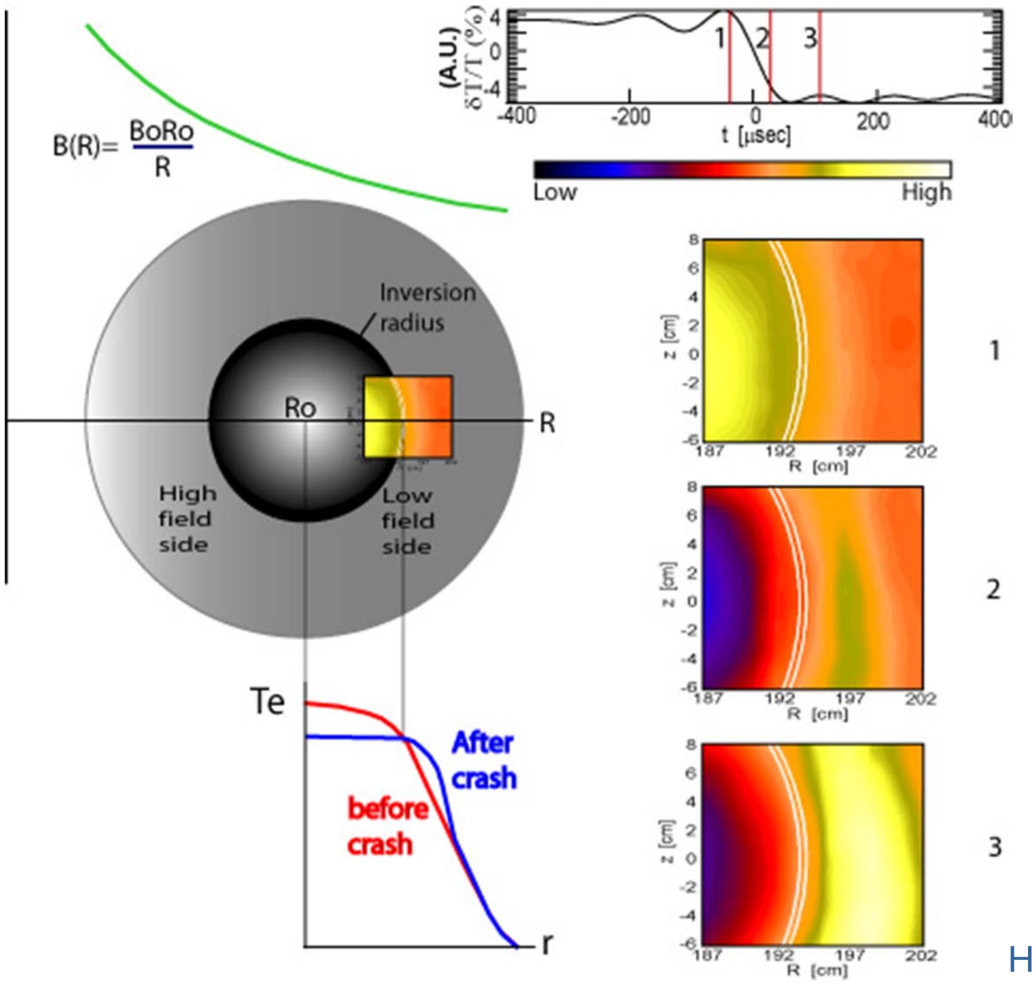
Science 281, 1835 (1998)

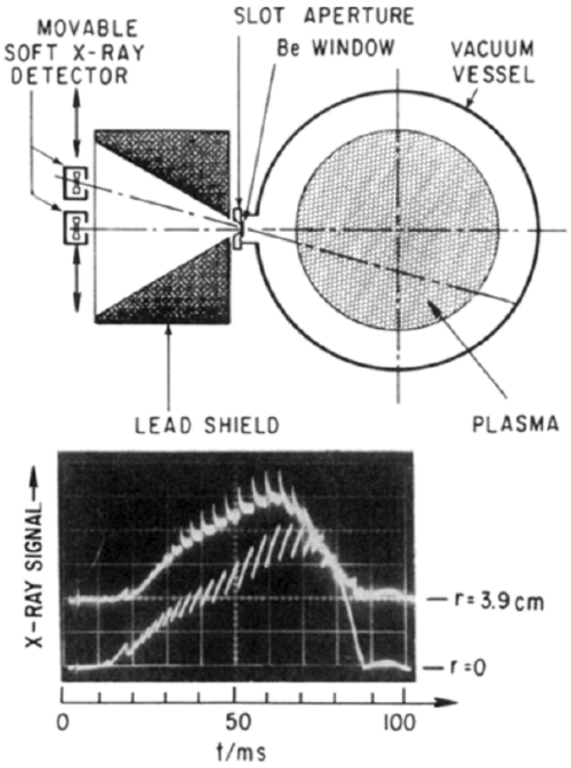
Obtaining a fundamental understanding of basic processes

The sawtooth instability

> In theory there is no difference between theory and practice.
> However, in practice there is.
>
> Lars Sonneveldt, Thesis TU Delft

2D ECE Imaging

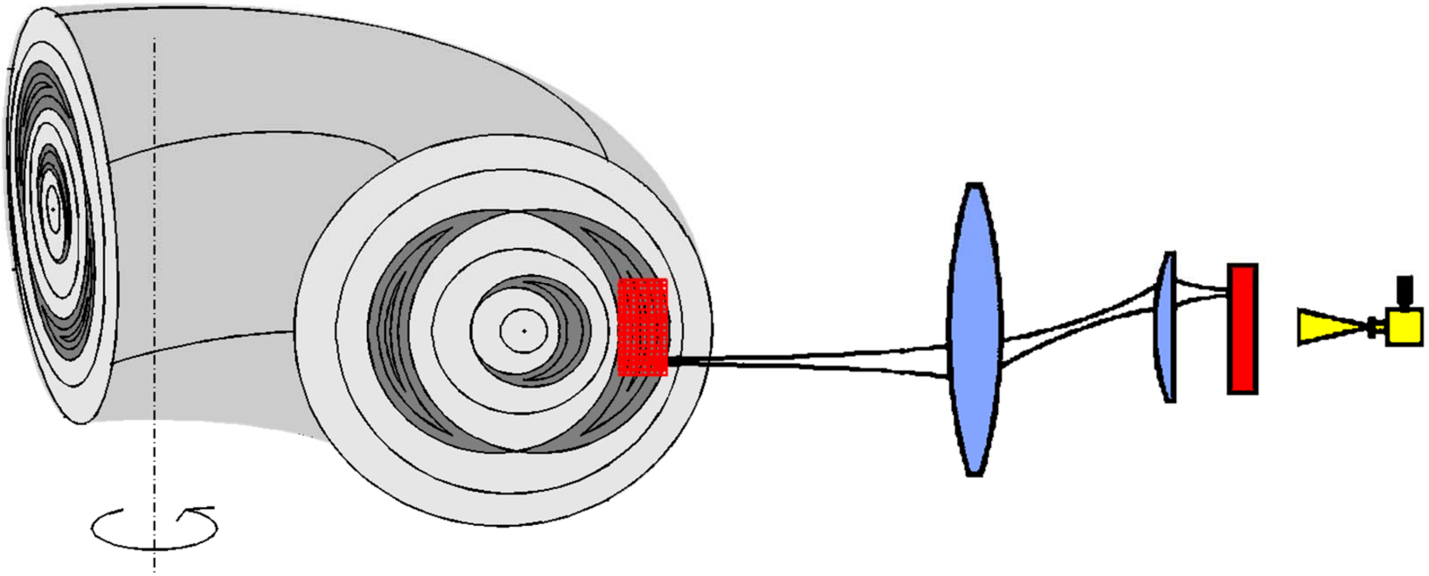




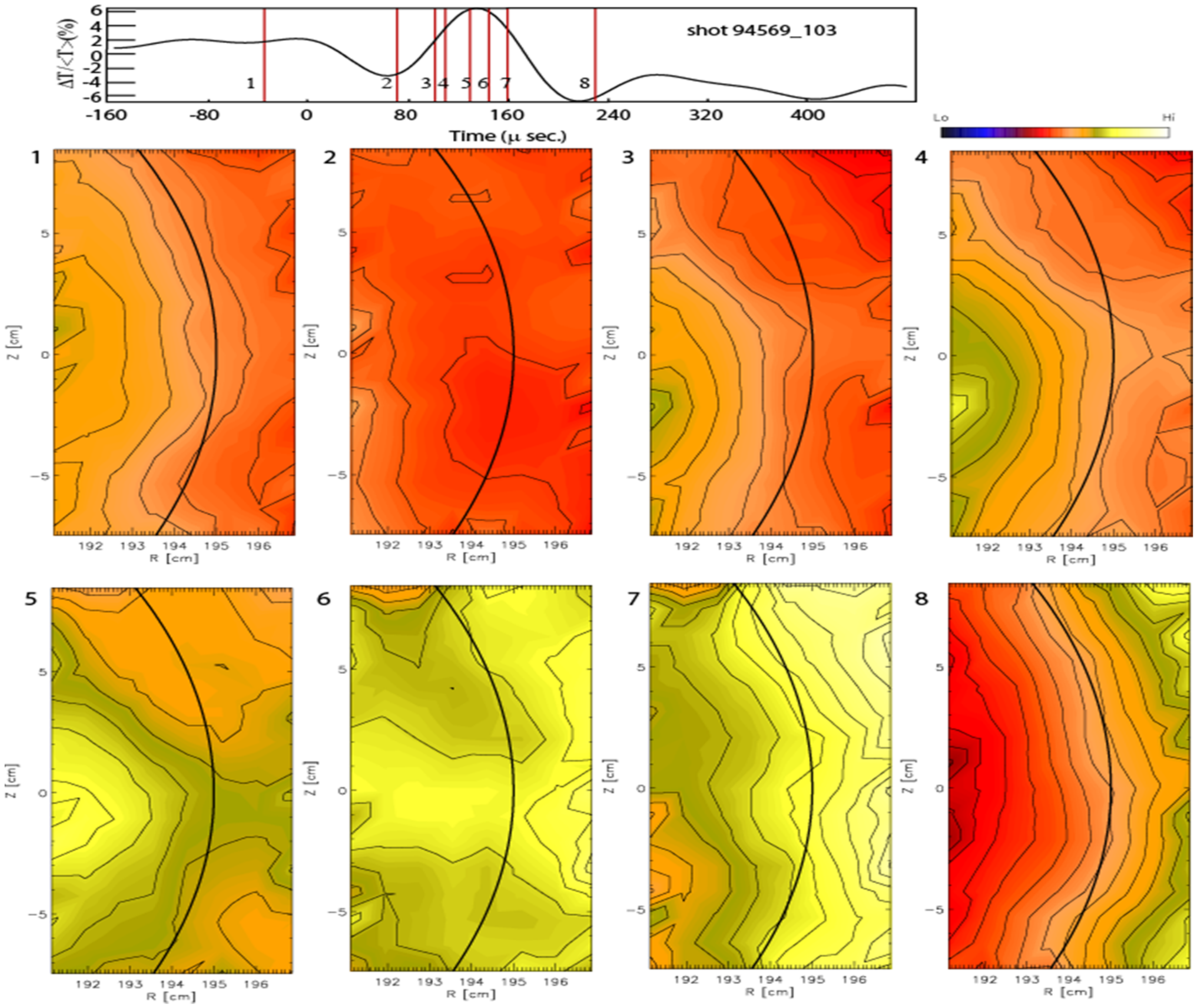
H. Park et al., Phys. Rev. Lett. **96** (2006) 195003
H. Park et al., Phys. Rev. Lett. **96** (2006) 195004
H. Park et al., Phys. Plasmas **13** (2006) 055907

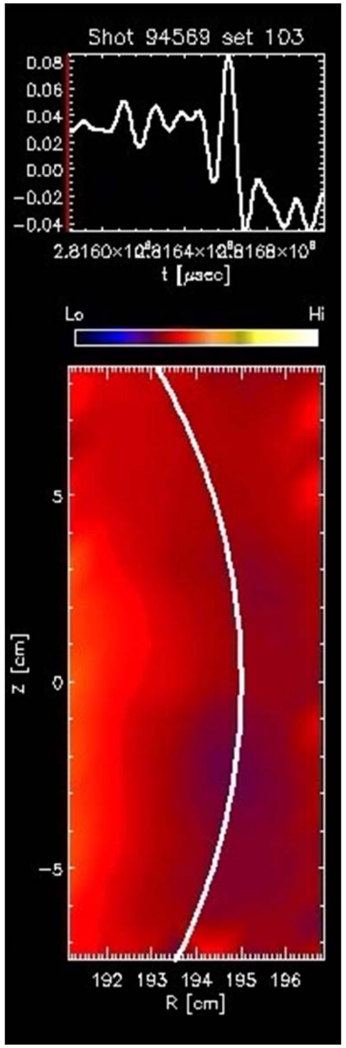
2D ECE Imaging

- 2D microwave camera
  - ECE-Imaging → electron temperature
  - Collaboration with UC-Davis, PPPL (& Postech, Korea)
  - Visualization of structures:
    - 3 PRL's on sawtooth crash, tearing mode suppression



A Rijnhuizen specialty: sawtooth control

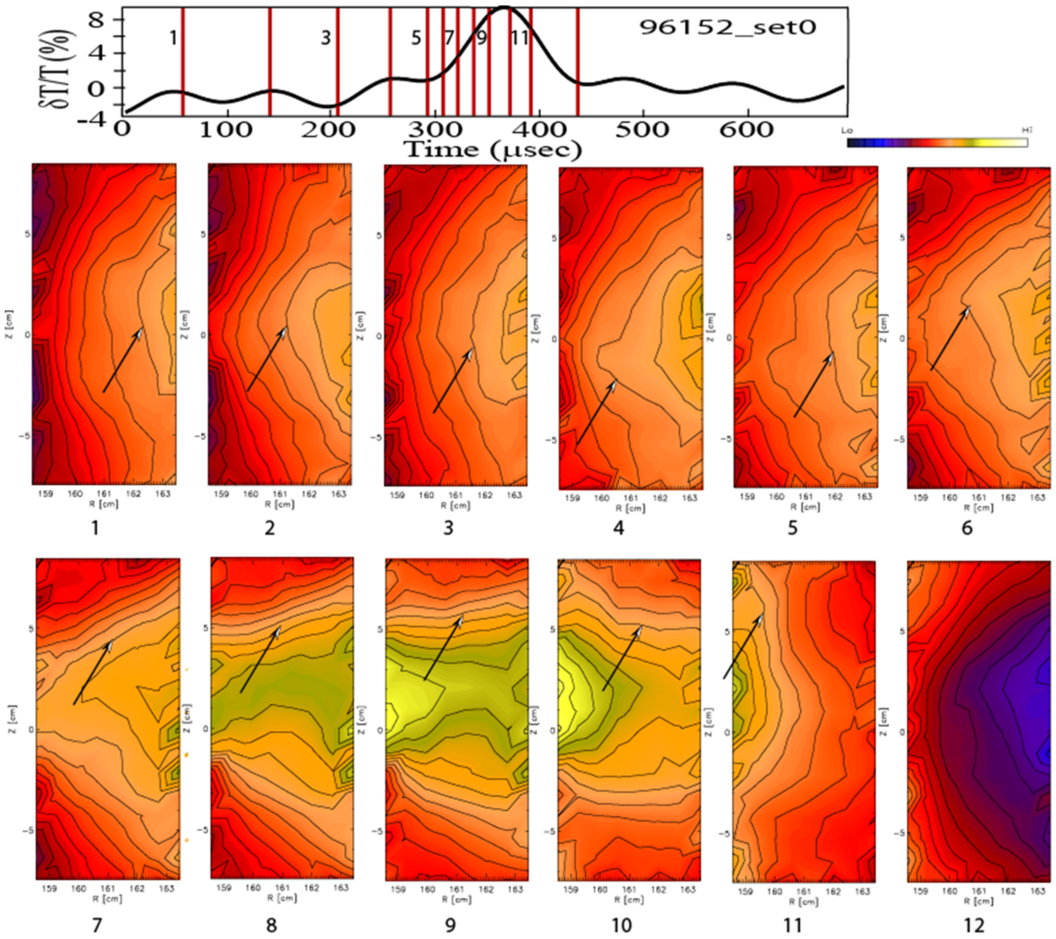




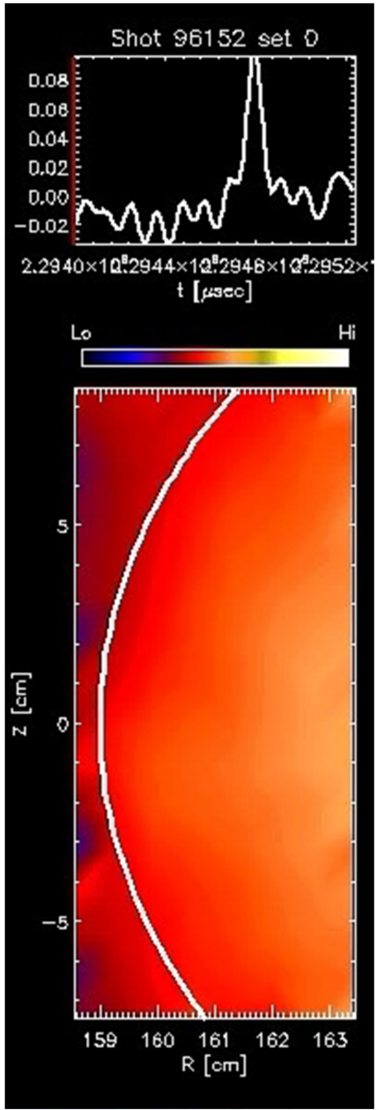
H. Park, N. Luhmann, A.J.H. Donné et al., Phys. Rev. Lett. 96 (2006) 195003
H. Park, A.J.H. Donné et al., Phys. Rev. Lett. 96 (2006) 195004

View of crash of sawtooth at HFS

- Crash is local in poloidal plane (~10 cm opening)
  - Crash is observed everywhere in high field side
  - A few attempts (pointed T_e contours near the mid-plane) are made before the final puncture (#6 & #7)

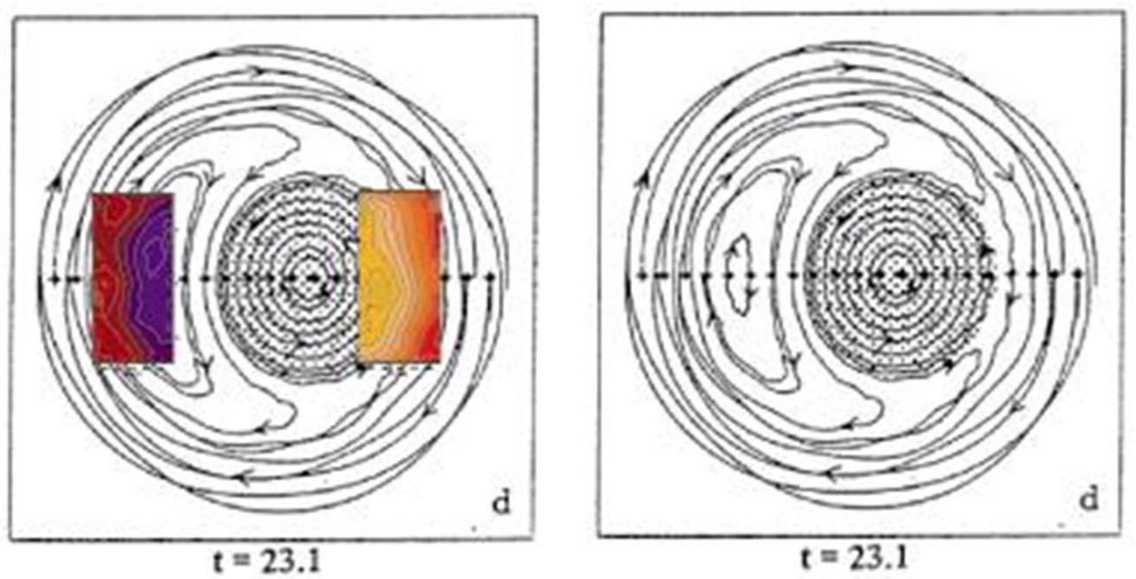


Radial speed
(4 cm/15 µsec=
2.7 x10^5 cm/sec)



Comparison with full reconnection model

- Remarkable resemblance between 2-D images of the hot spot/Island and images from the matured stage of the simulation result of the full reconnection model (Sykes et.al.)

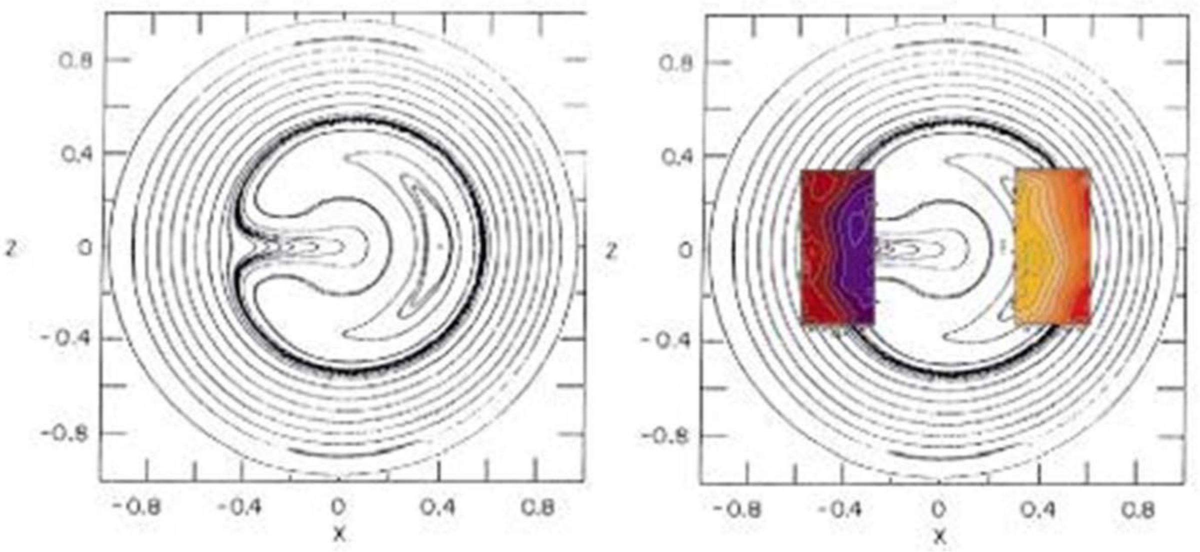


Simulation result of the full reconnection model from A. Sykes and Wesson:
Formation of island indicates reconnection at the low field side.

H. Park et al.,
Phys. Rev. Lett. **96** (2006) 195004

Comparison with the quasi-interchange model

- No clear resemblance between 2-D images of hot spot/island and projected images from the quasi-interchange model
- This model does not require any type of magnetic field reconnection

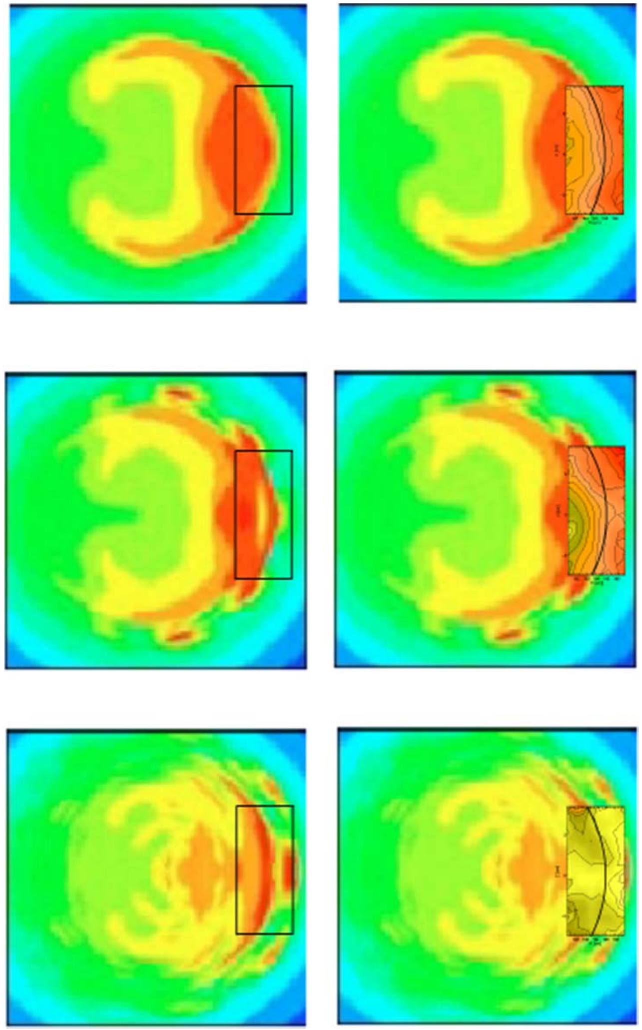


H. Park et al.,
Phys. Rev. Lett. **96** (2006) 195004

Comparison with ballooning mode model at LFS

- Similarities
  - Pressure finger in early stage of simulation at low field side (middle figure) is similar to those from 2-D images (“a sharp temperature point”)
  - Reconnection zone is localized in the toroidal plane (1/3 of the toroidal direction is opened)
- Differences
  - Heat flow is highly collective in experiment and stochastic process of the heat diffusion is clear in simulation.

Simulation results from Nishimura et.al. Plasma condition (β_p ~0.4 and β_t ~2 %) is similar to the experimental results



H. Park et al., Phys. Rev. Lett. **96** (2006) 195004

First dual array data (~400 ch. KSTAR) 10/15/2010

Plasma parameters

B(T) = 2T

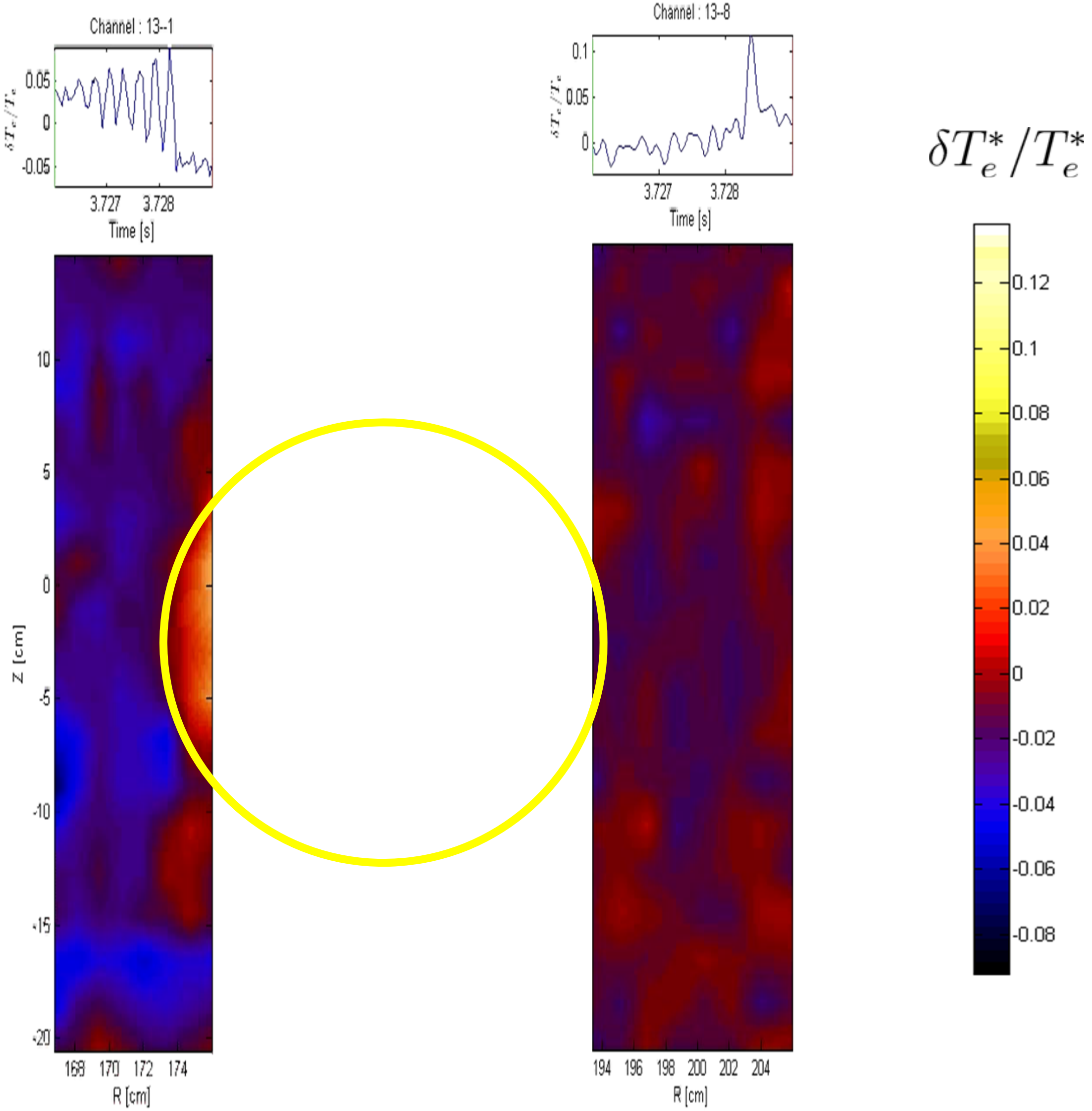
I(P) = 300 kA

T(0) ~ 1 keV

Ne(0) ~2.5x10^{13} cm^{-3}

ECH ~300kW, 0 - 0.4sec
ICRF ~150kW, 2 - 3sec
NBI (?), 2 - 3sec.

Plasma rotation speed ~ 50km/s

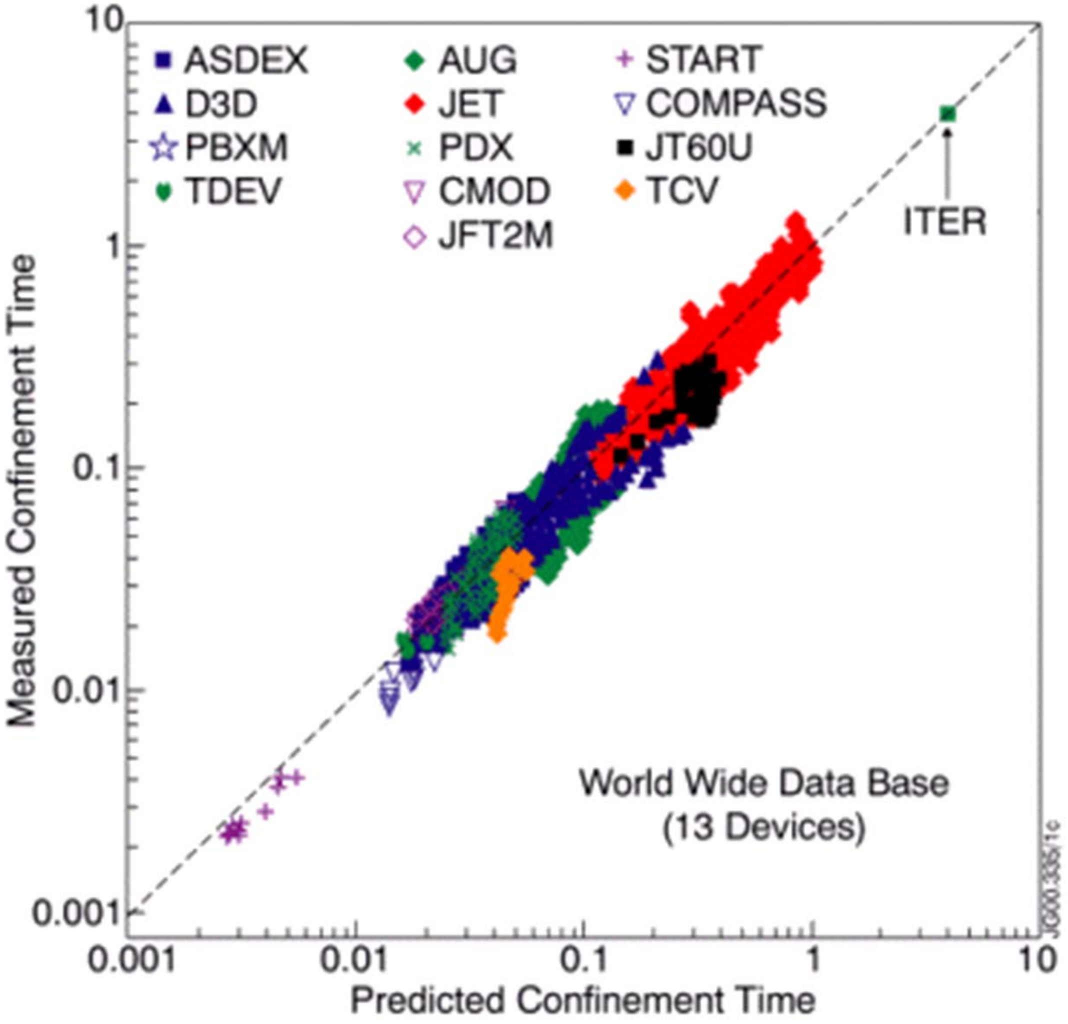


Is understanding needed for control?

- Even though the detailed physical processes (esp. turbulence) taking place in a tokamak plasma are not fully understood we can control the plasma.

- A better understanding could lead to improvements in control and performance.

Scaling laws

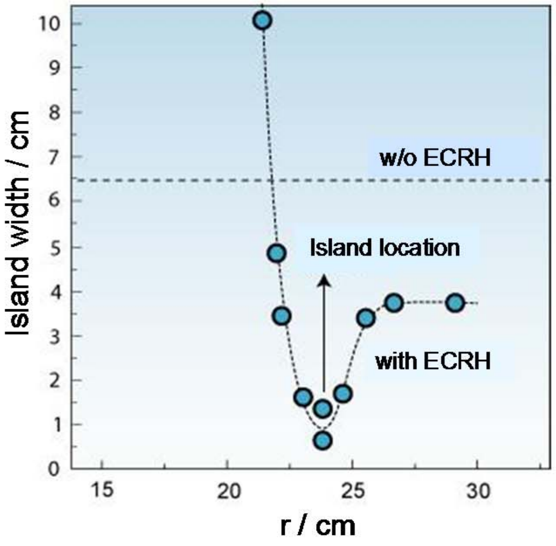


Control of plasma instabilities

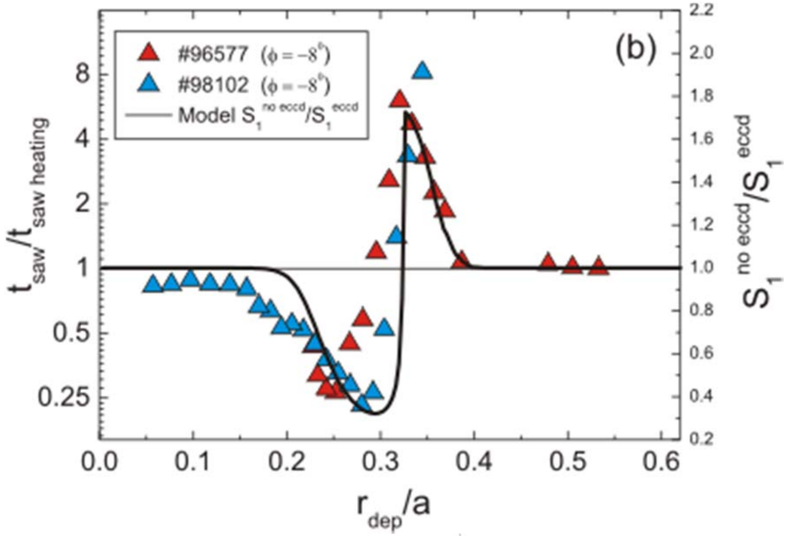
Electron Cyclotron Resonance Heating
& Current Drive

Experiments with predefined launcher

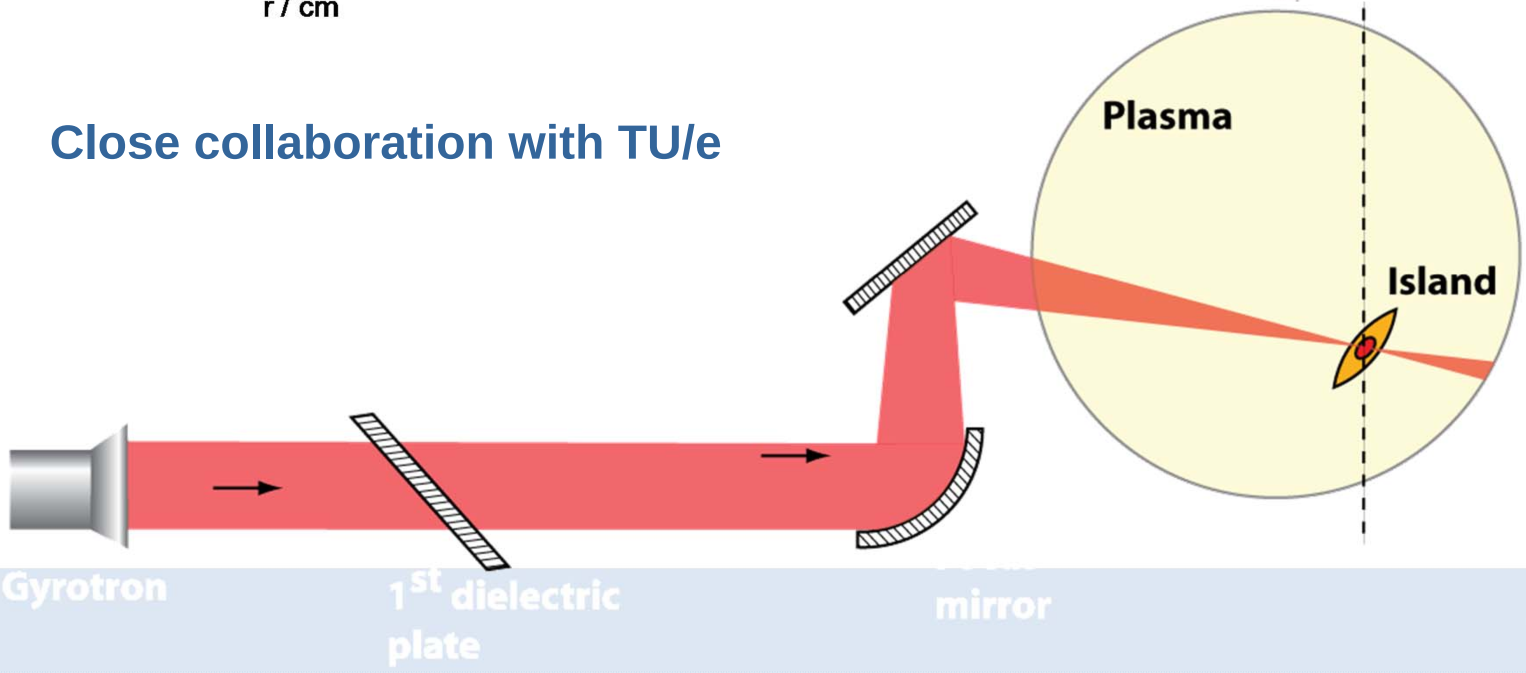
m = 2 suppression in TEXTOR



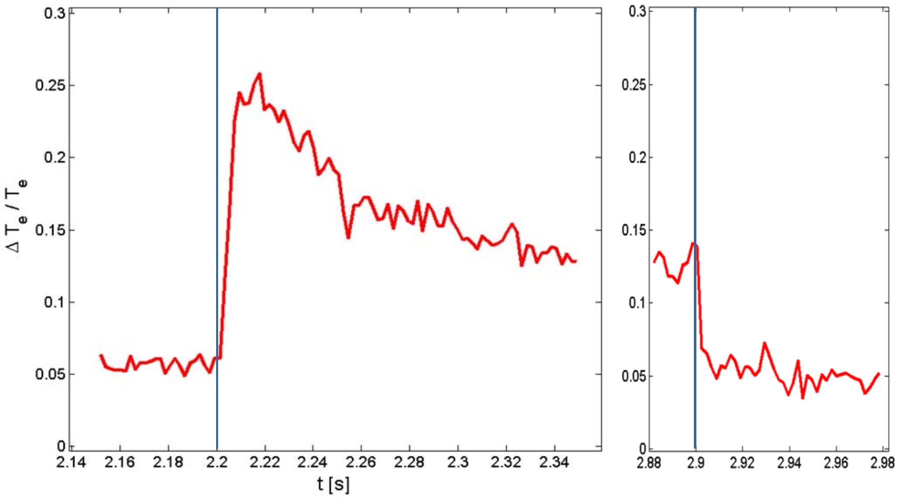
Sawtooth (de)stabilisation in TEXTOR

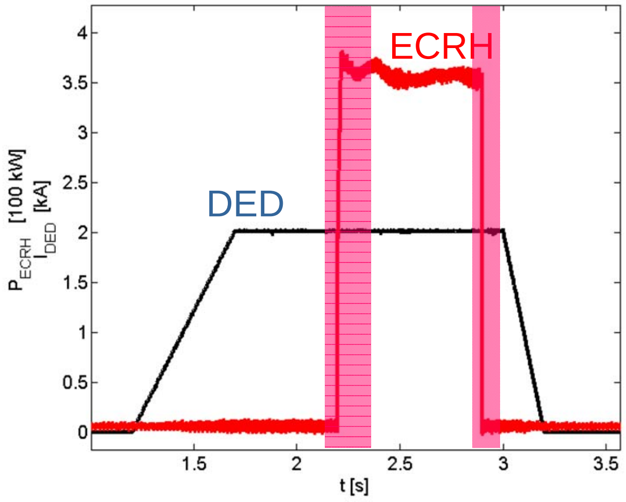


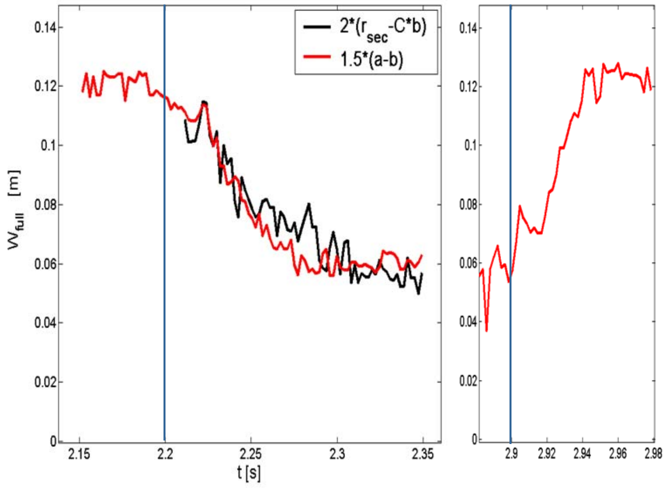
Close collaboration with TU/e



Control of Neoclassical Tearing Modes in TEXTOR







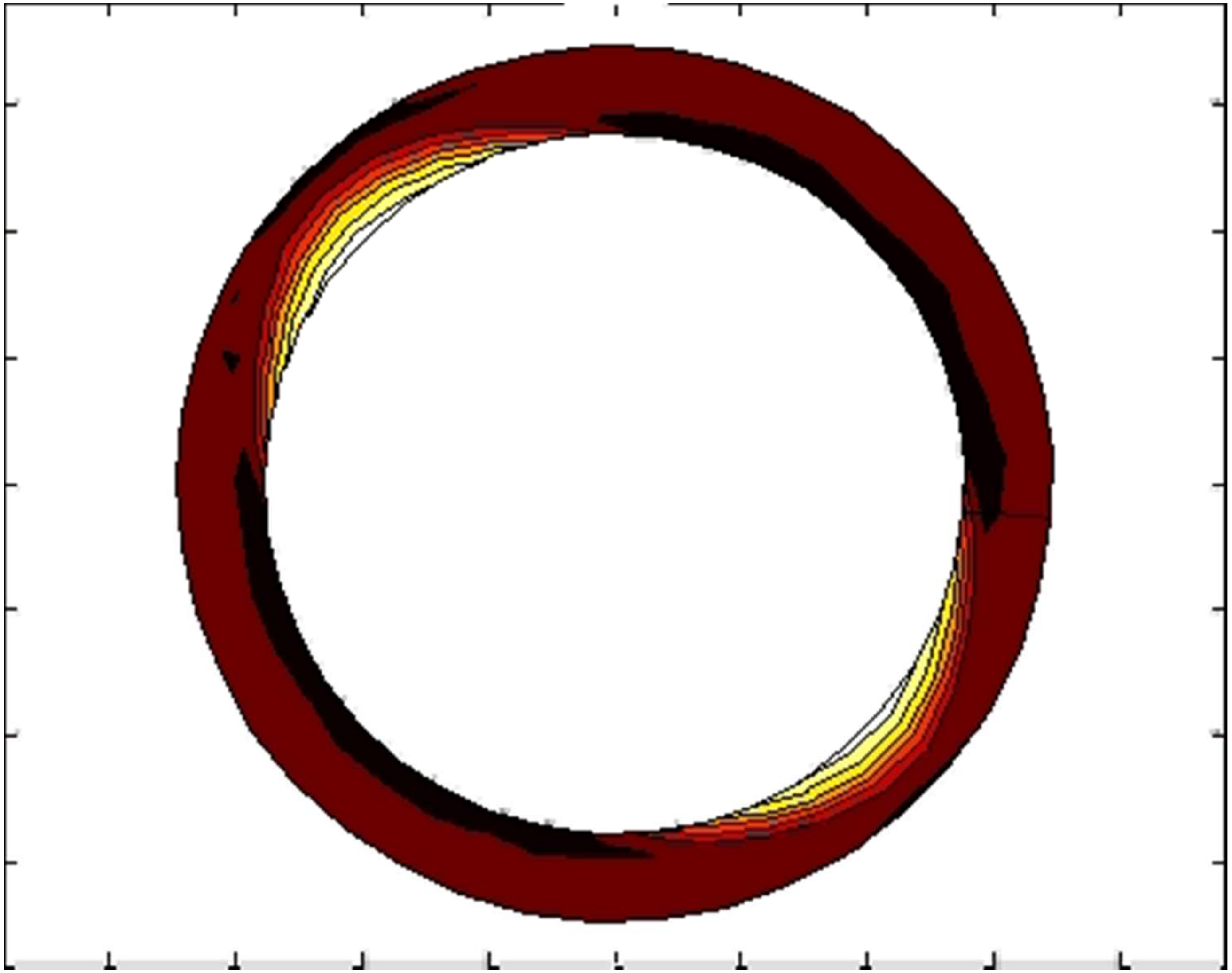
2 step process:

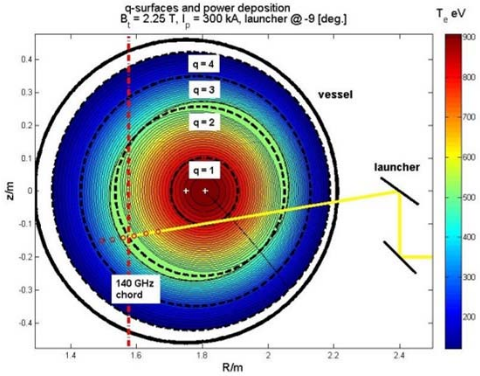
- Heating
- Suppression

I. Classen,
Phys. Rev. Lett. 98 (2007) 035001

Control of Neoclassical Tearing Modes in TEXTOR

(#99183: 400kW ECRH)



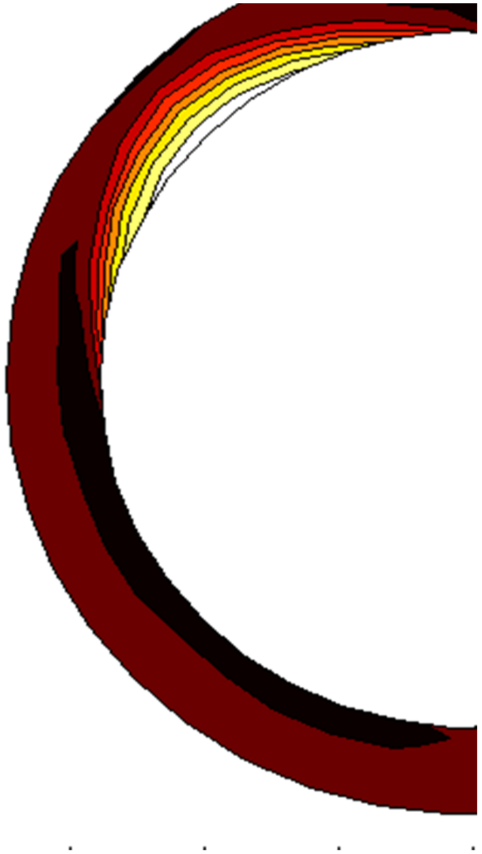


Every frame 1 rotation period (2ms)

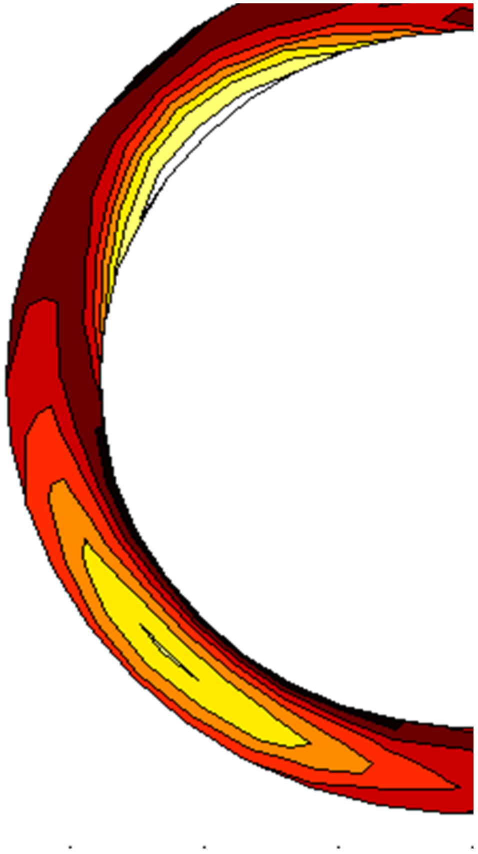
Total movie 200 ms

I. Classen,
Phys. Rev. Lett.
98 (2007) 035001

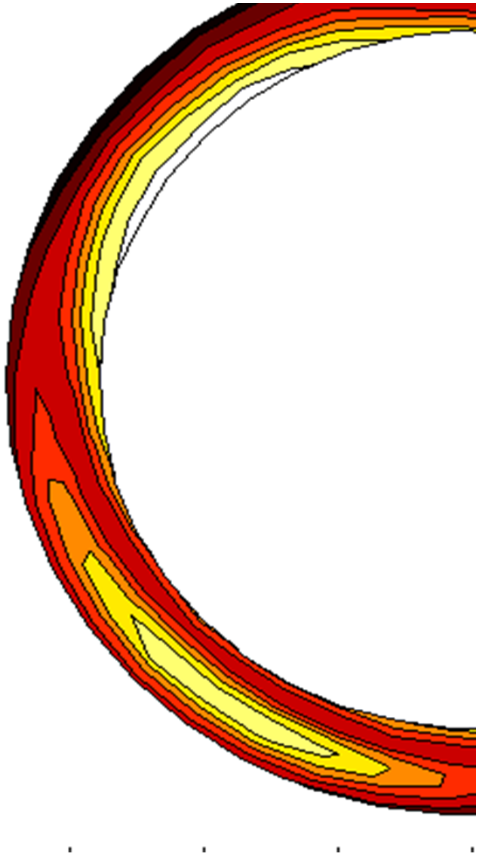
Time evolution of the island



Initially flat island ➔



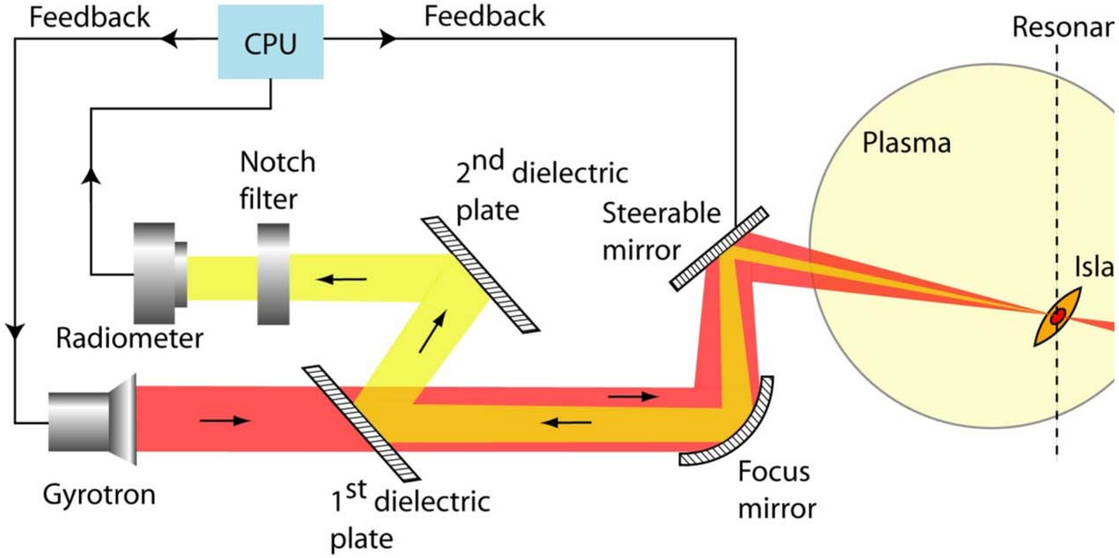
ECRH heated ➔

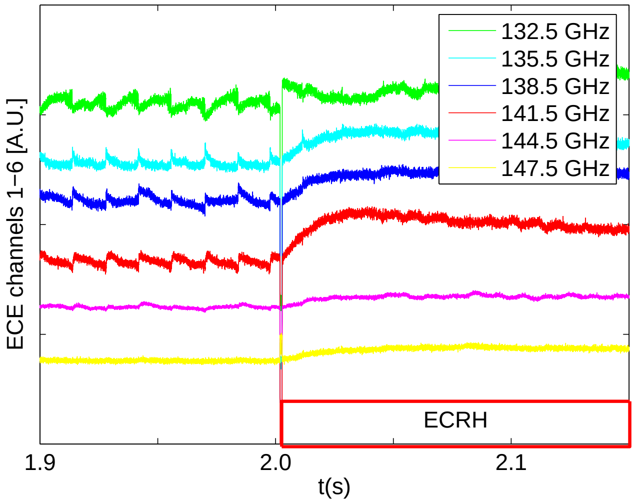


Suppressed

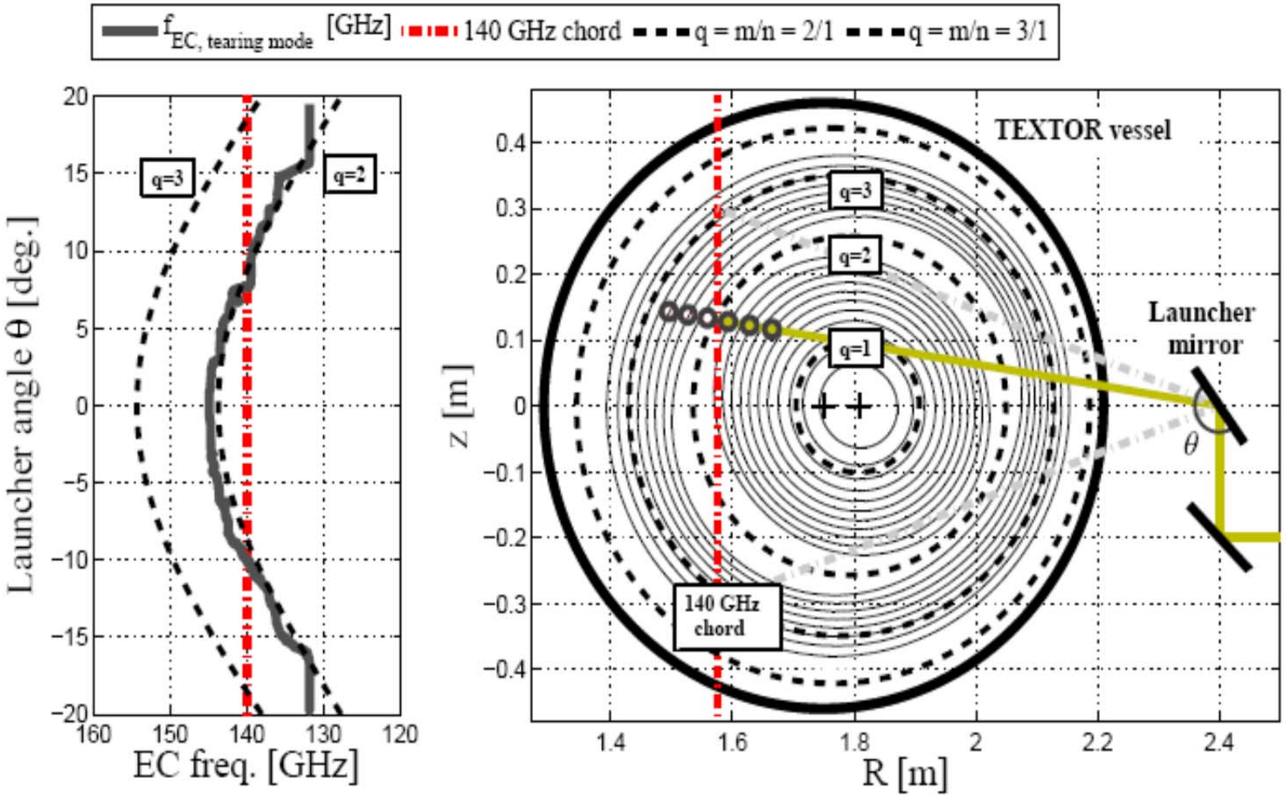
Optimized MHD control system: In-line ECE

- Sensor and actuator in a single system
- Proof-of principle experiment on TEXTOR (within TEC)
- NanoWatt signal level in MegaWatt environment

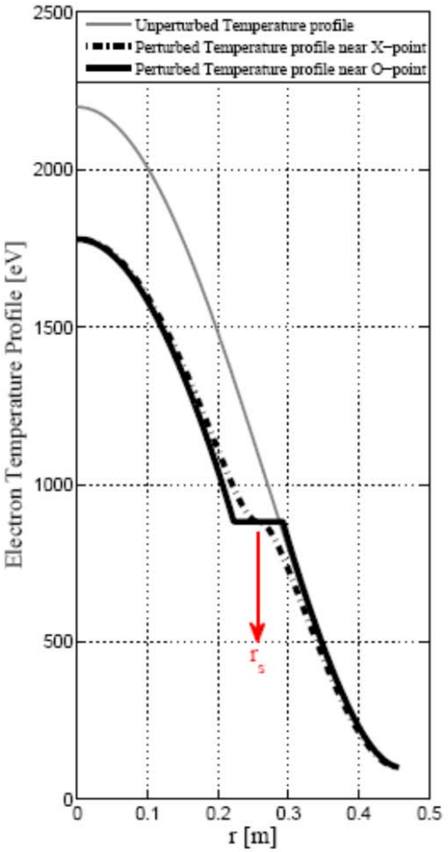


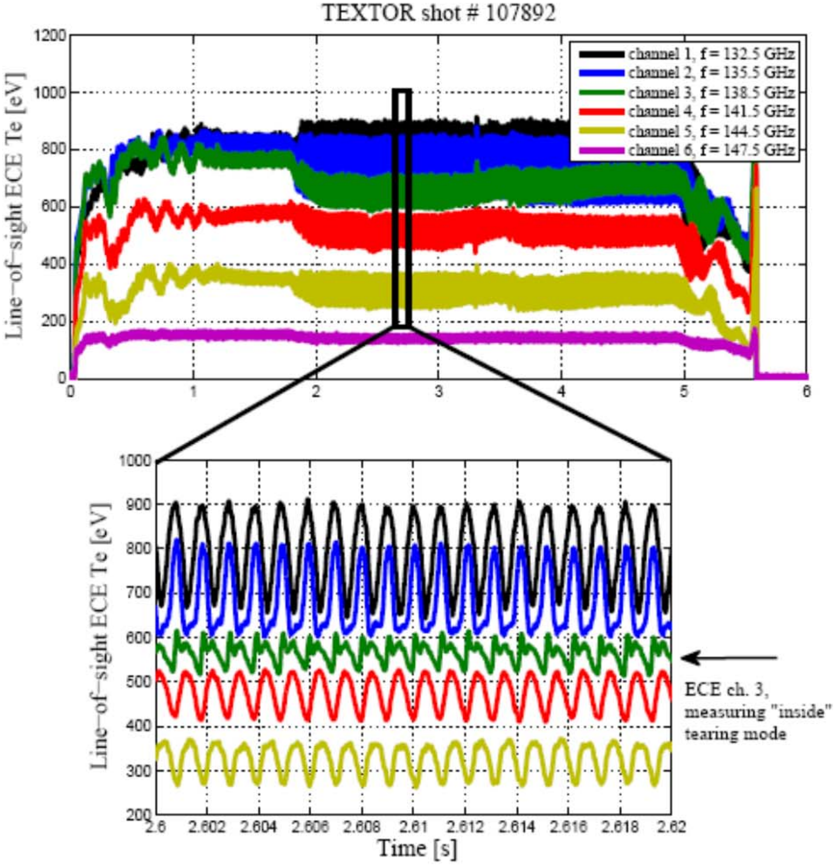


Searching the resonance



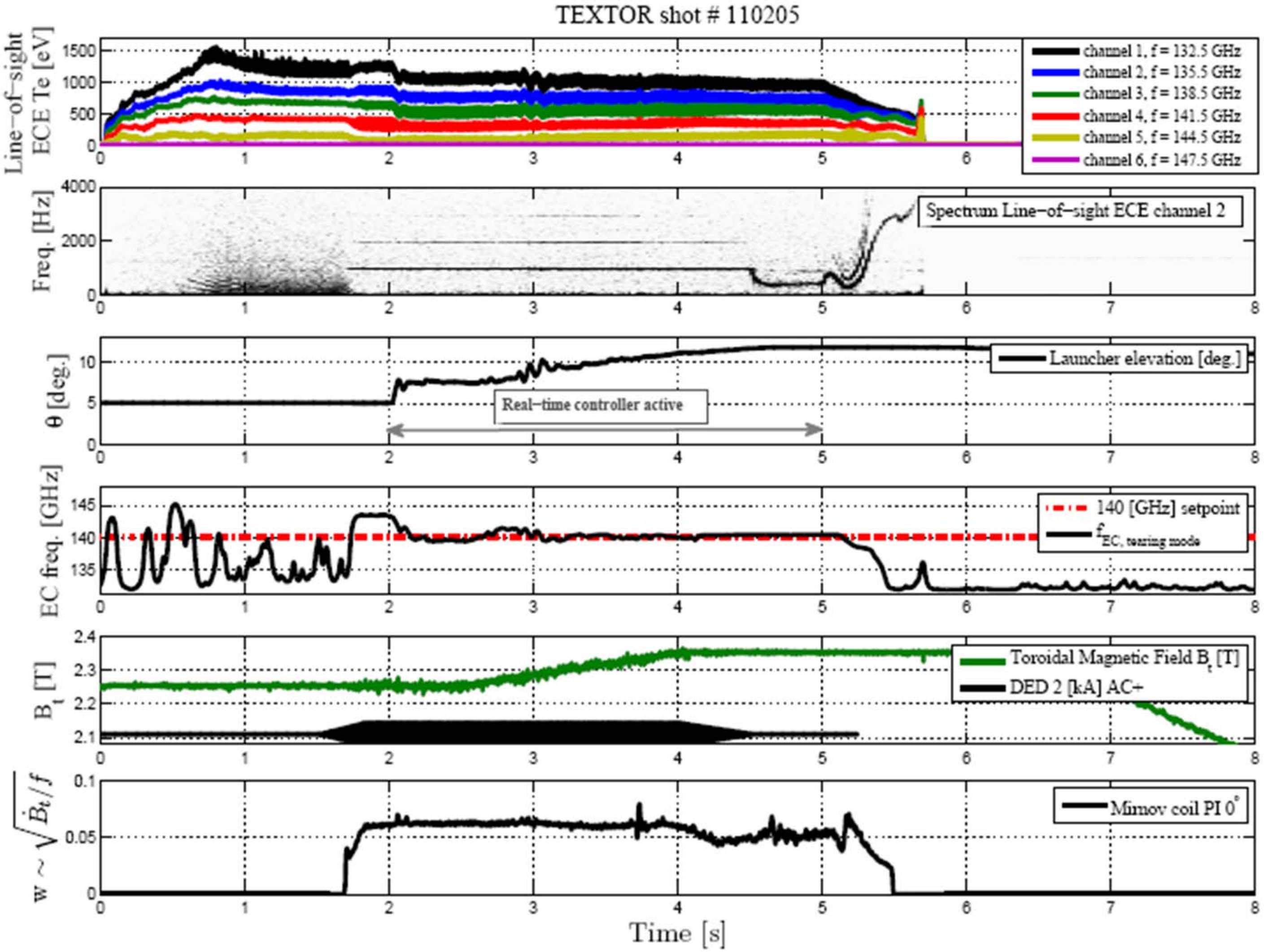
Temperature perturbations due to NTM



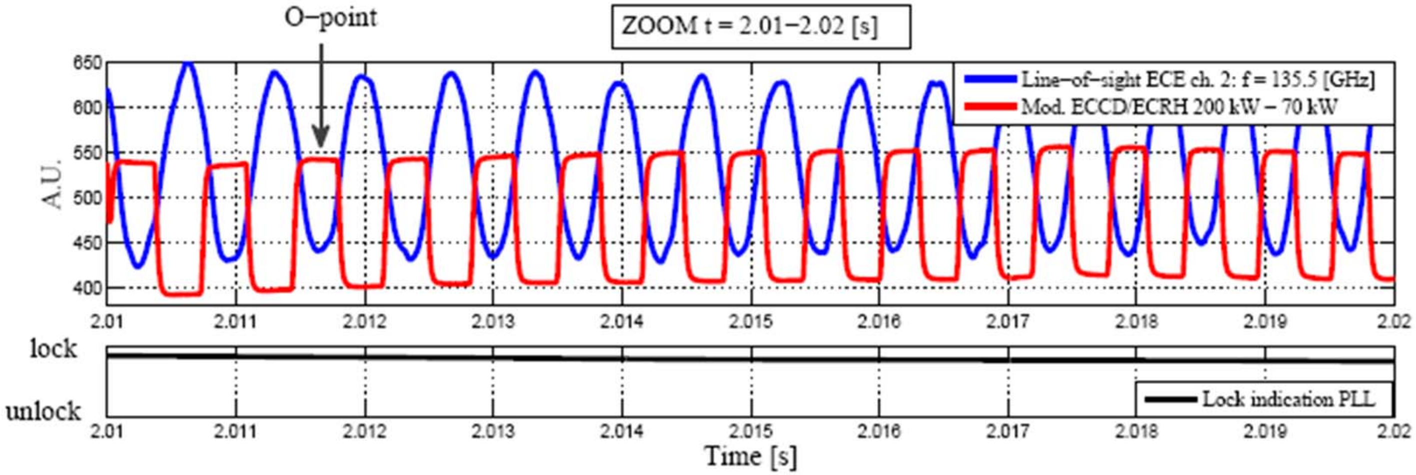


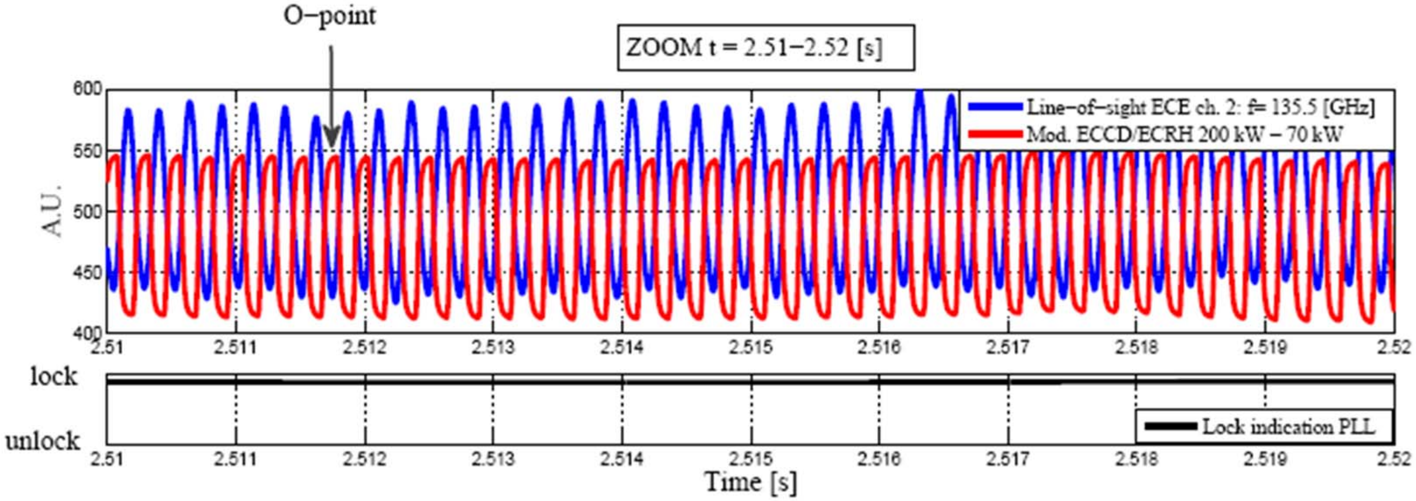
(NTM = Neoclassical Tearing Mode)

System tracks a moving NTM



System tracks O-point of island





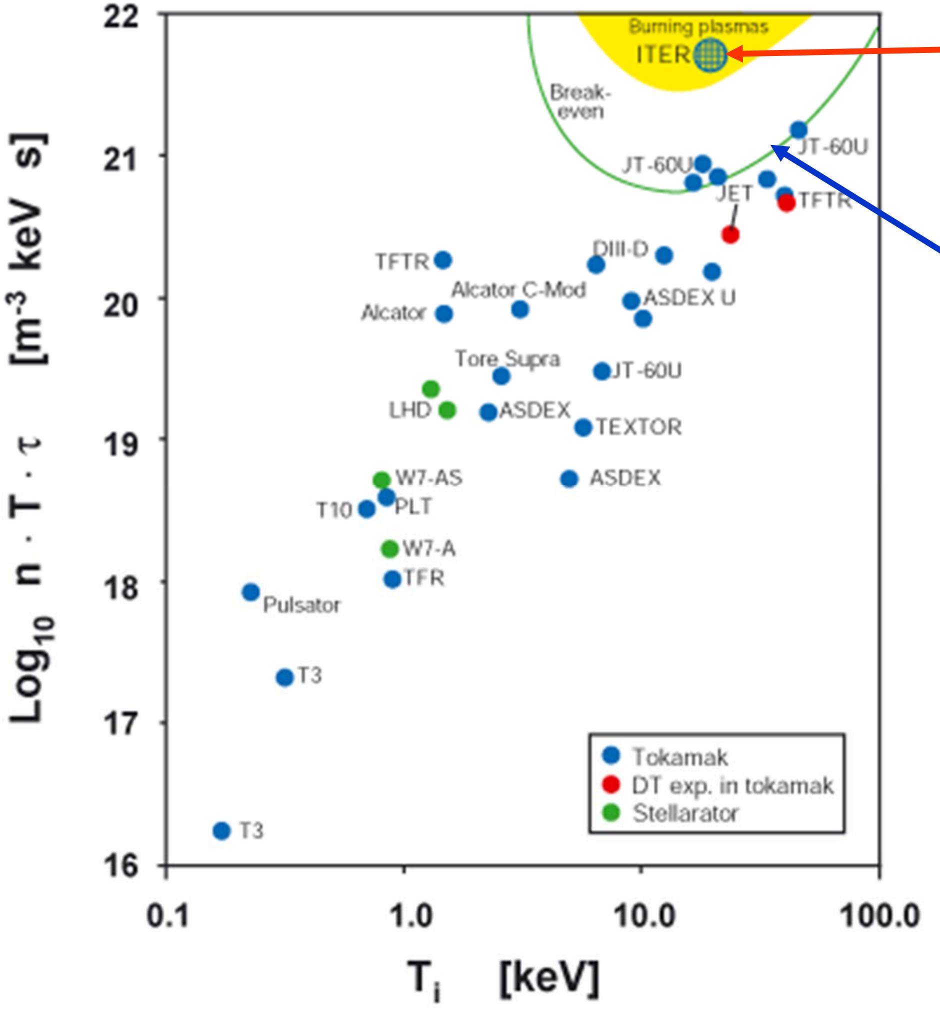
How to control a burning plasma

Dominant alpha heating

Fast particle instabilities

ITER: Net energy amplification

d + t → He (3.5 MeV) + n (14 MeV)



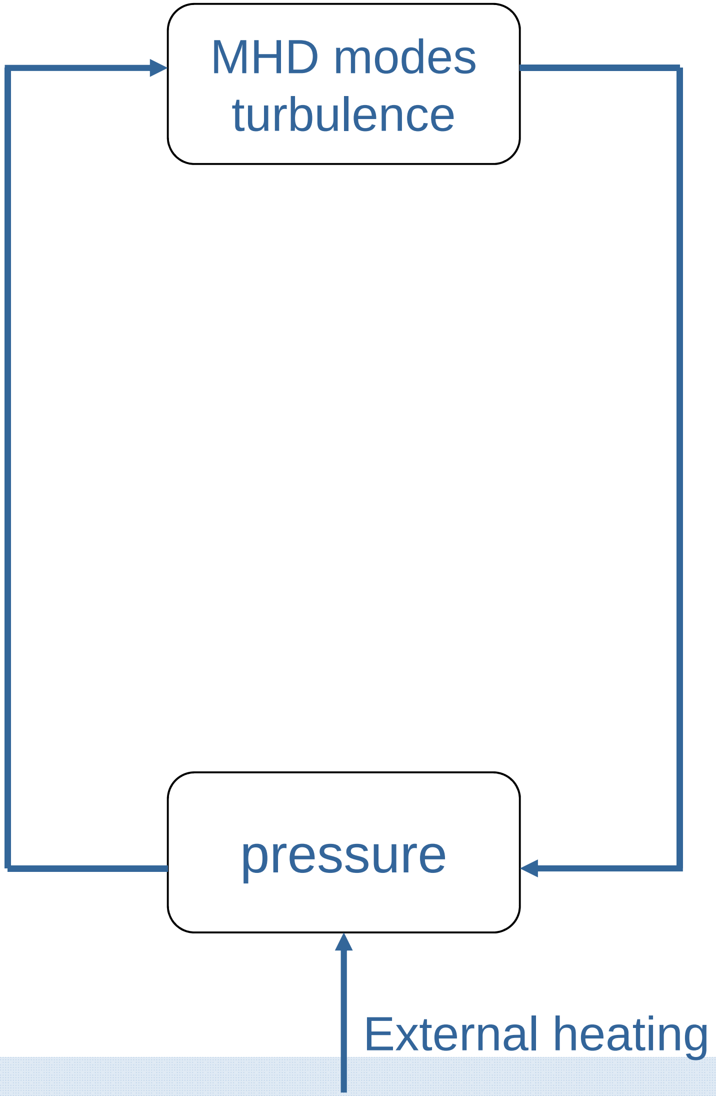
ITER:
$Q = P_{fusion}/P_{input} \sim 10$
Alpha particles have enough power to heat the plasma
(Q > 5: burning plasma)

Present devices:
$Q = P_{fusion}/P_{input} \sim 1$
Only 20% of power stays in plasma

Control of MHD modes in present plasmas

MHD modes largely controlled via pressure profile

Main actuator:
external heating


MHD modes turbulence

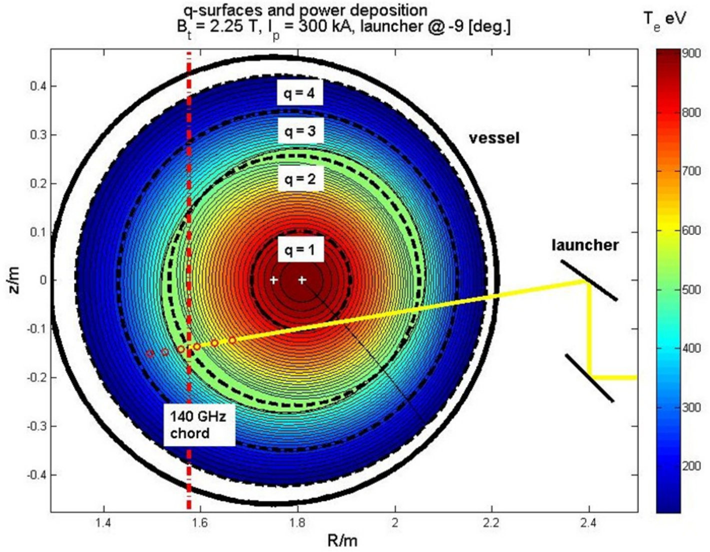
pressure

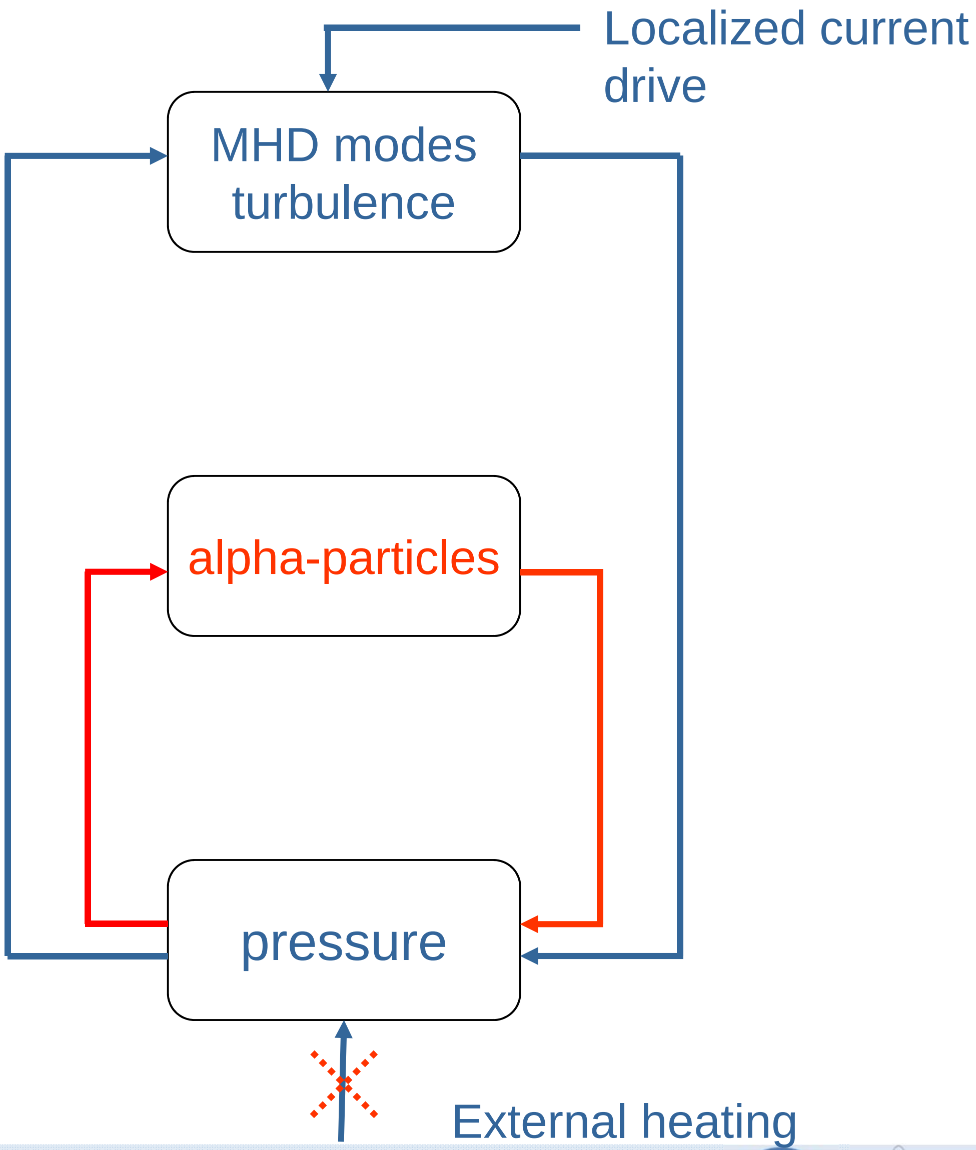
External heating

Control of MHD modes in present plasmas

Limited possibilities for control by external heating

Emphasis on localized heating & current drive for control





Localized current drive

MHD modes turbulence

alpha-particles

pressure

External heating

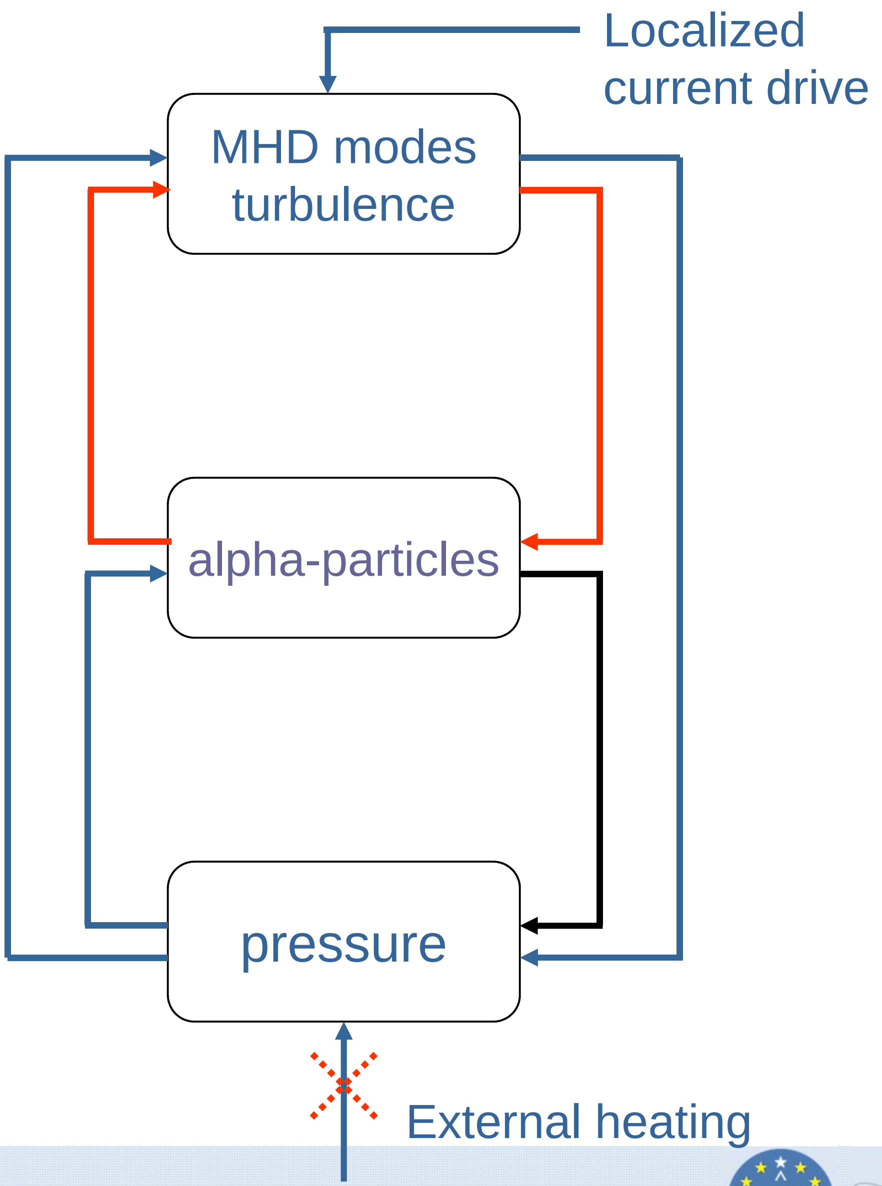
New physics in burning plasmas

Alpha particles directly interact with MHD modes and vice versa

⇒ We want to understand this

So we need knowledge on:
- MHD physics
- Physics of fast particles
- Advanced Control Processes

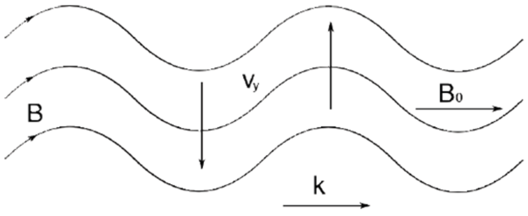
And tools:
- Diagnostics
- Electron Cyclotron Current Drive



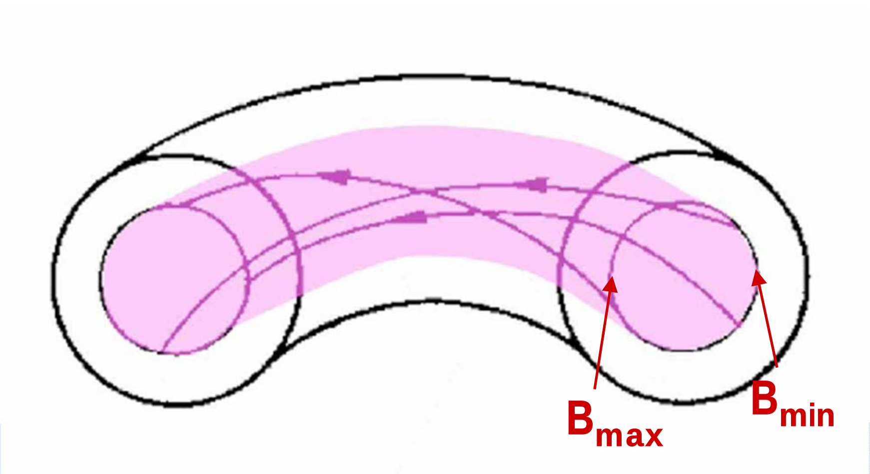
Alfven waves are transverse waves that travel along the magnetic field lines at v_A

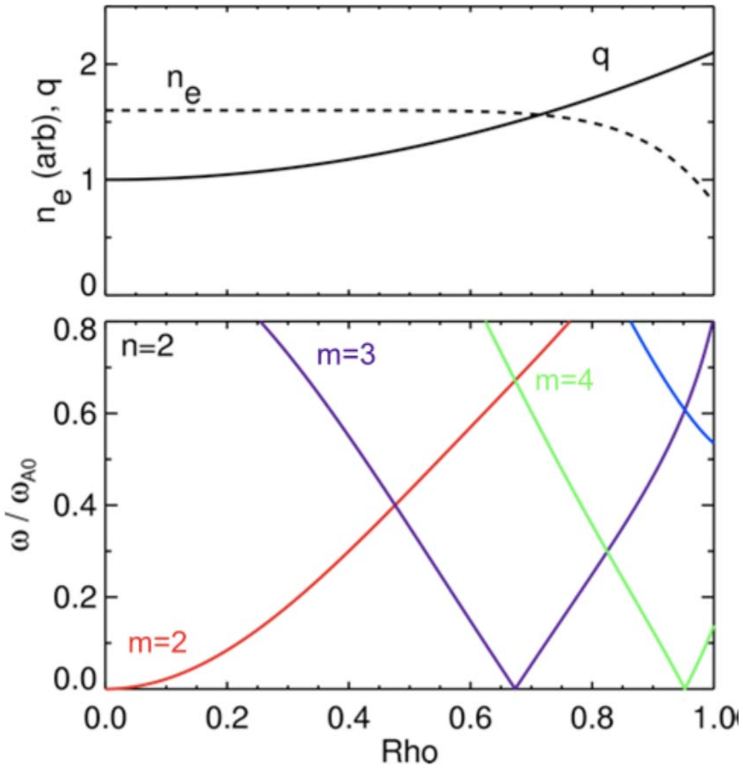
Alfvén speed: $v_A = B/(\mu_0 n_i m_i)^{1/2}$

$\omega = k_{\parallel} v_A$

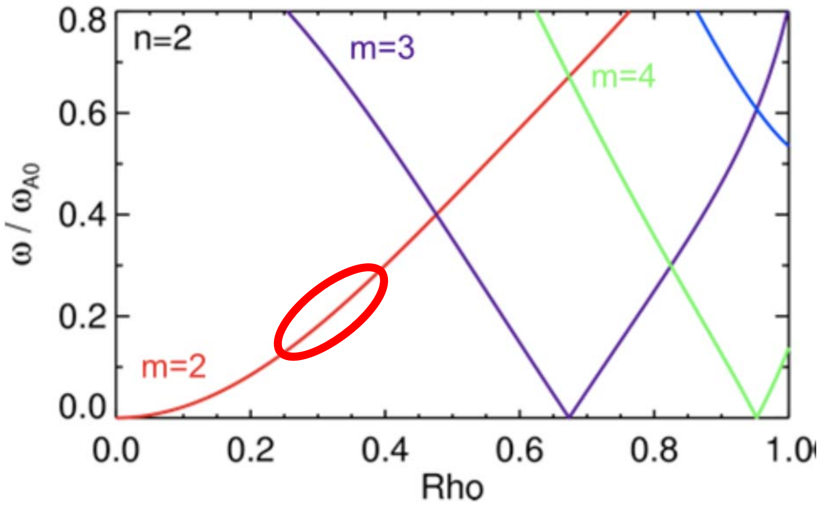


In a Tokamak: Periodicity ➔
with $k_{\parallel} \sim |n - m/q|$

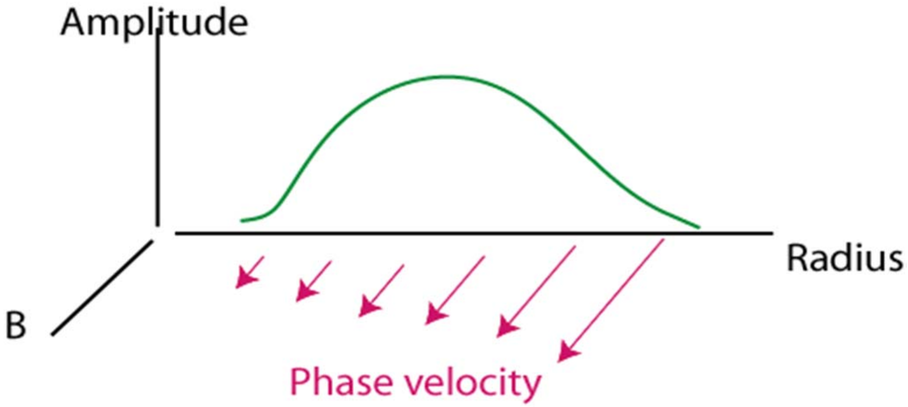




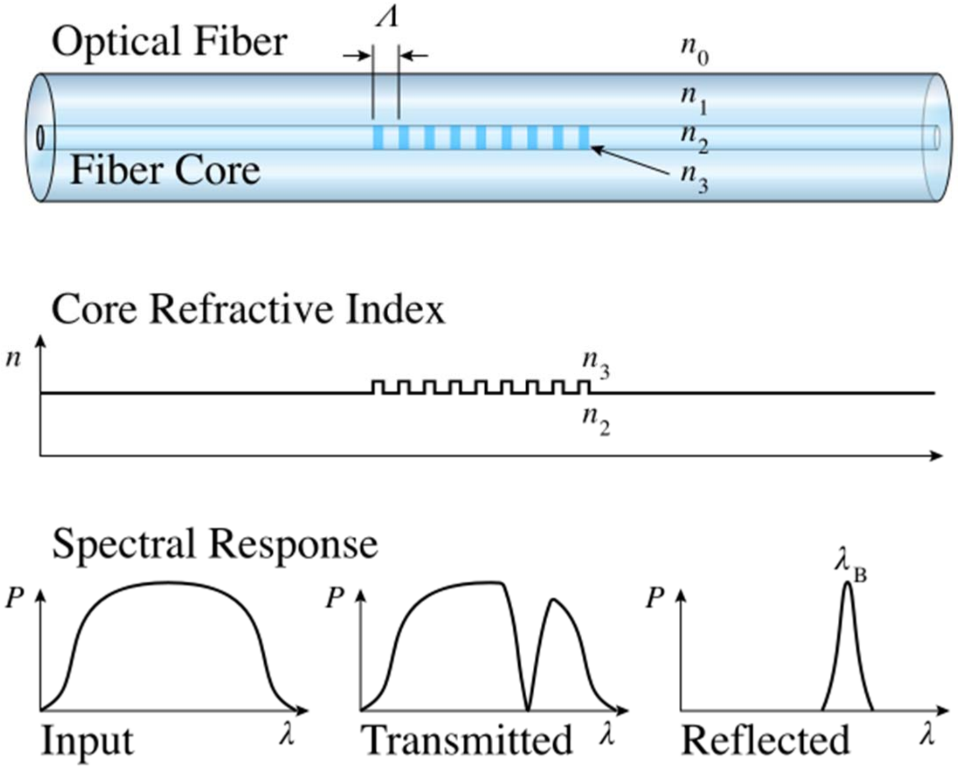
Alfven waves in the continuum are strongly damped



$$\boxed{\gamma \sim d\,(k_{||}\, v_A)\ /\ dr}$$



A propagation gap occurs at the Bragg frequency



- Destructive interference between counter propagating waves
- Bragg frequency: $f = v/2\Lambda$
- $\Delta f/f \sim \Delta N/N$

for shear Alfvén waves

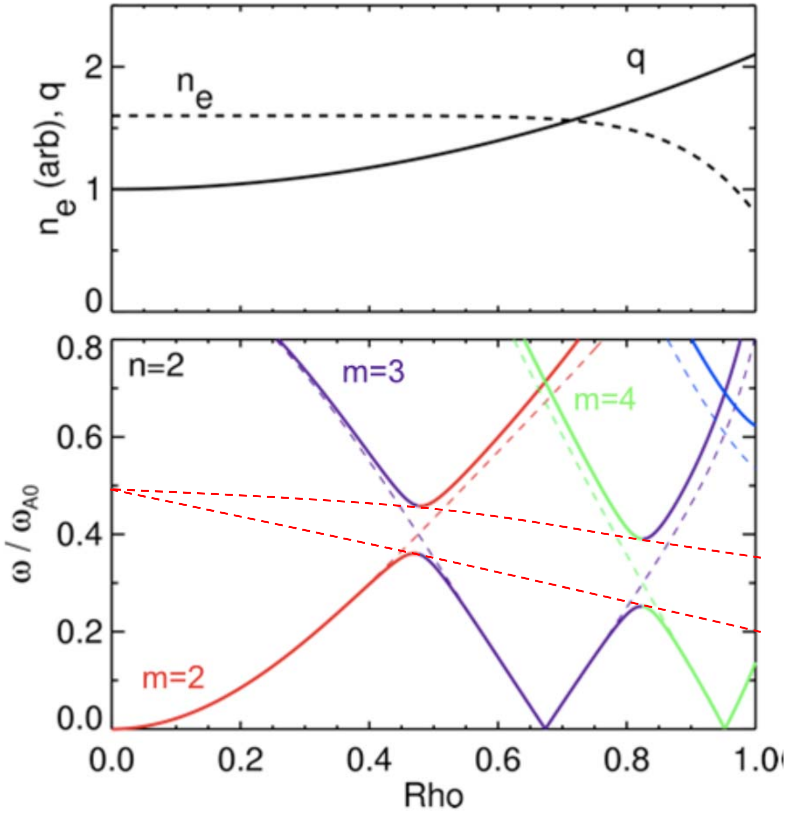
- $f = v_A/\ 2\Lambda$, where Λ is the distance between field maxima along the field line

$\Lambda = q\ (2\pi R)$

➔ $f_{gap} = v_A/4\pi qR$

➔ $\Delta f \sim \Delta B/B$ $(\Delta B \sim a/R)$

Frequency Gaps and the Alfvén Continuum depend on position

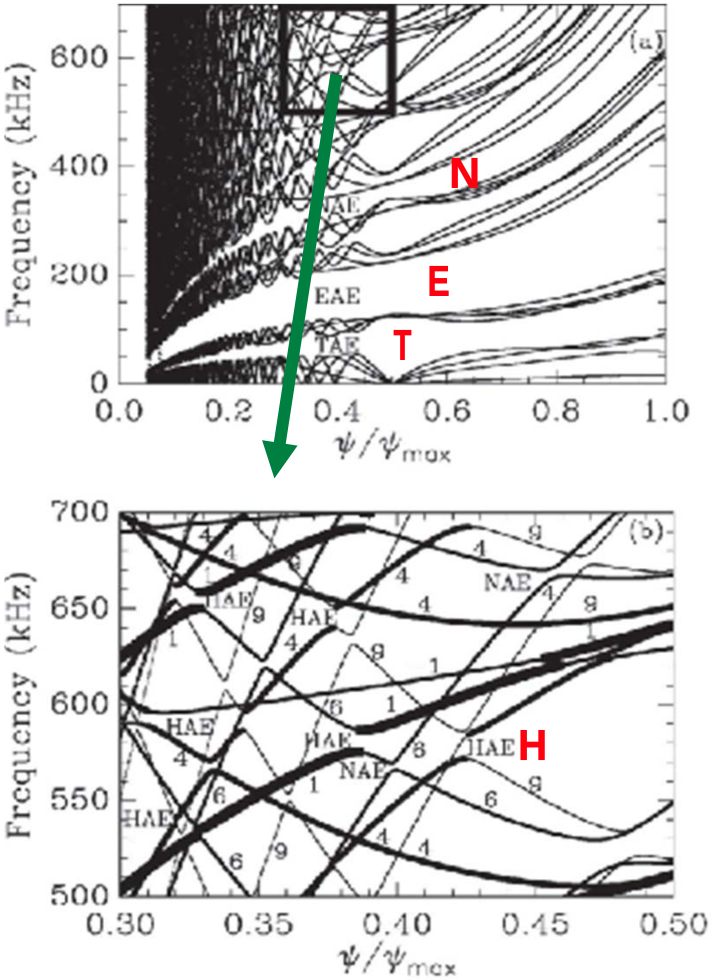


- **Counter-propagating waves cause frequency gap**
- **Coupling avoids frequency crossing (waves mix)**

All periodic variations introduce frequency gaps

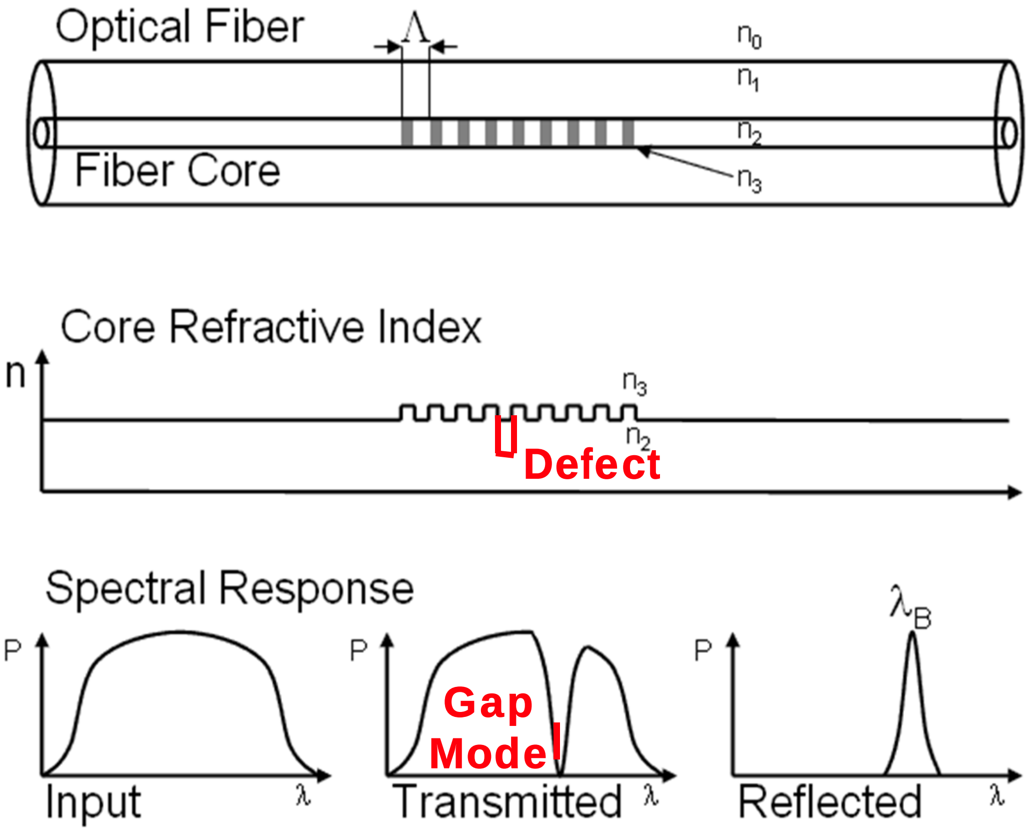
BAE	“beta”	compression
TAE	“toroidicity”	m & m+1
EAE	“ellipticity”	m & m+2
NAE	“noncircular”	m & m+3
MAE	“mirror”	n & n+1
HAE	“helicity”	both n’s & m’s

Shear Alfvén wave continuua in an actual stellarator



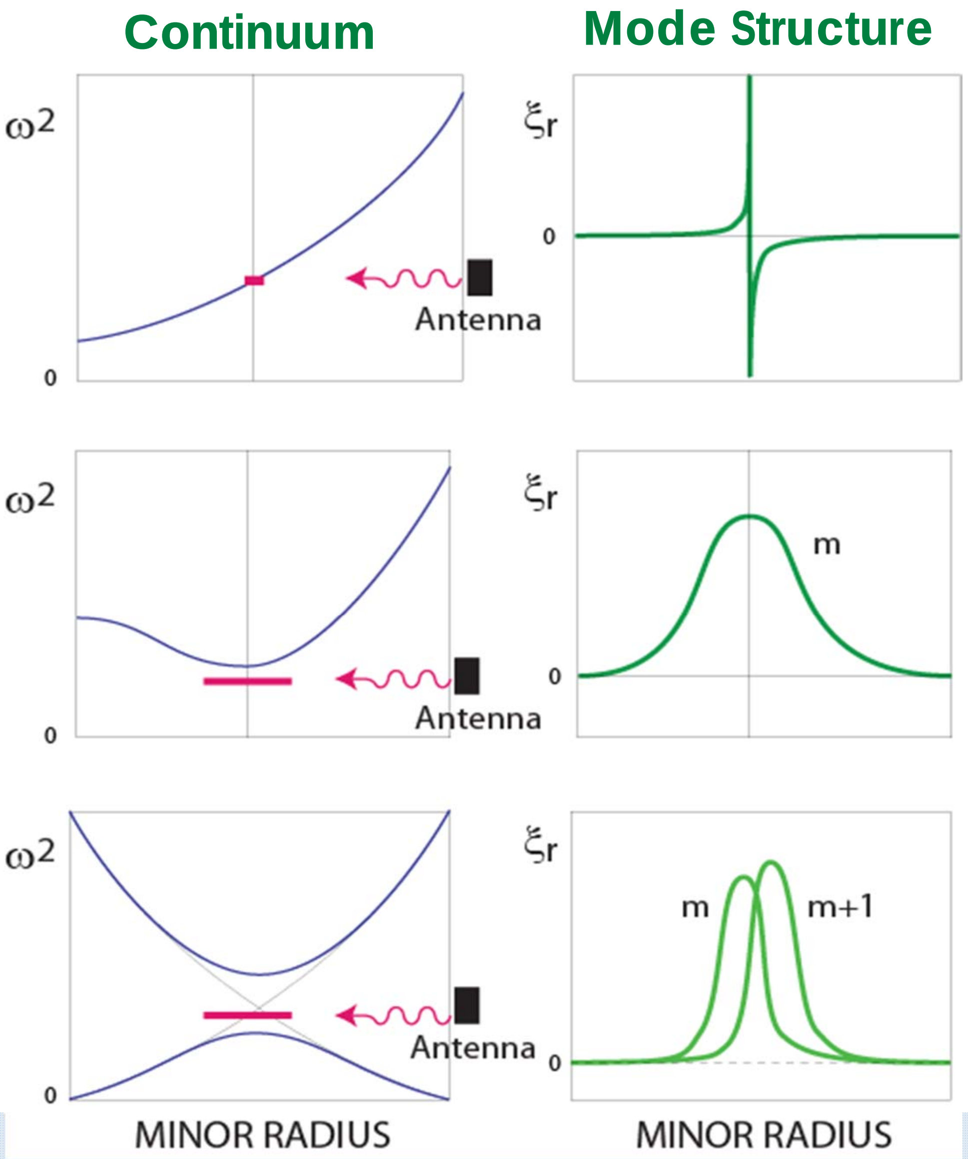
Spong, Phys. Plasmas 10 (2003) 3217

'Defects' cause modes in the gaps



Magnetic shear (dq/dr) creates extrema

Radially extended Alfvén eigenmodes are more easily excited



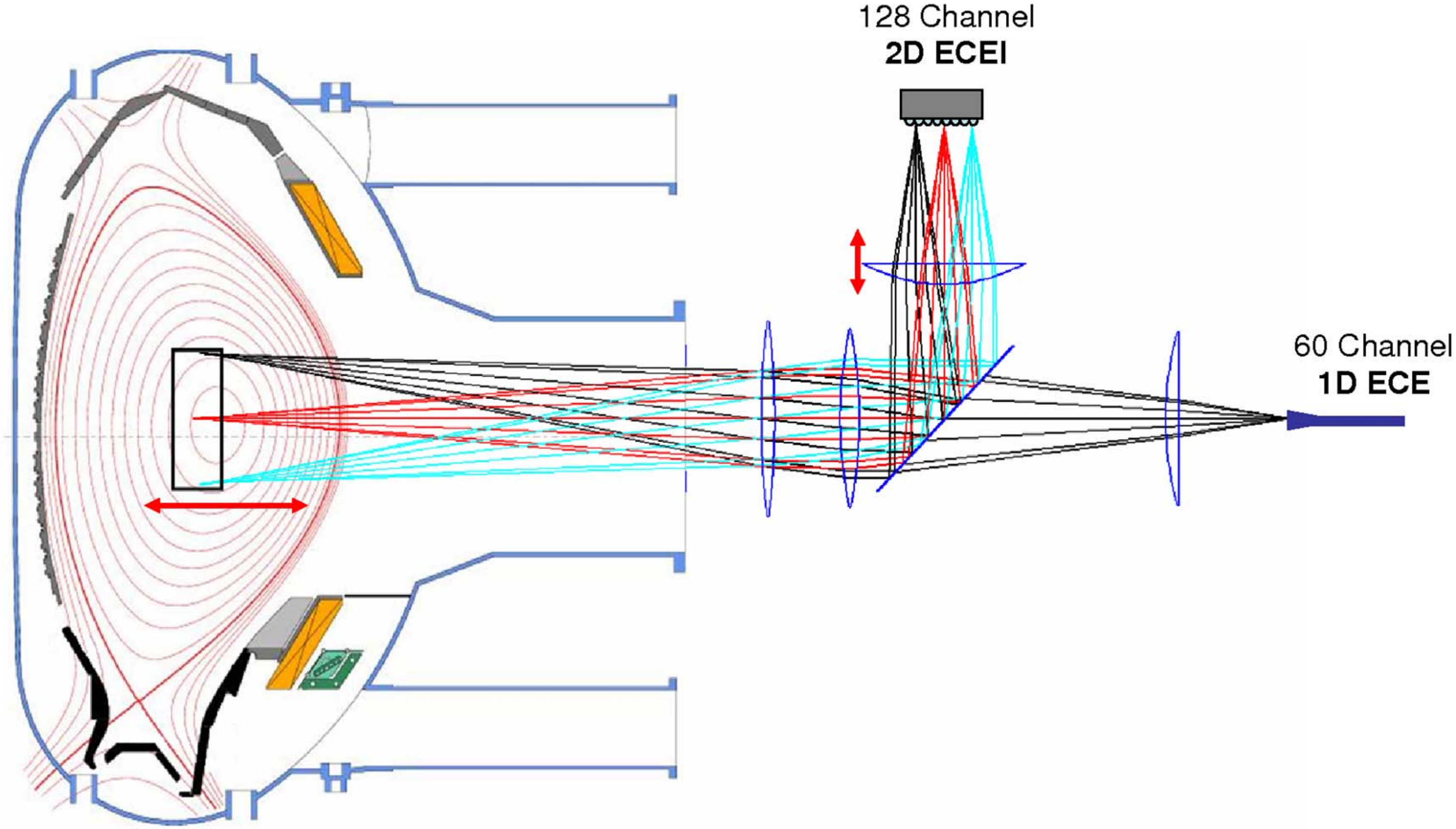
Where gap modes exist, the eigenfunction is regular & spatially extended

Reversal in q ➔ RSAE (or AC)

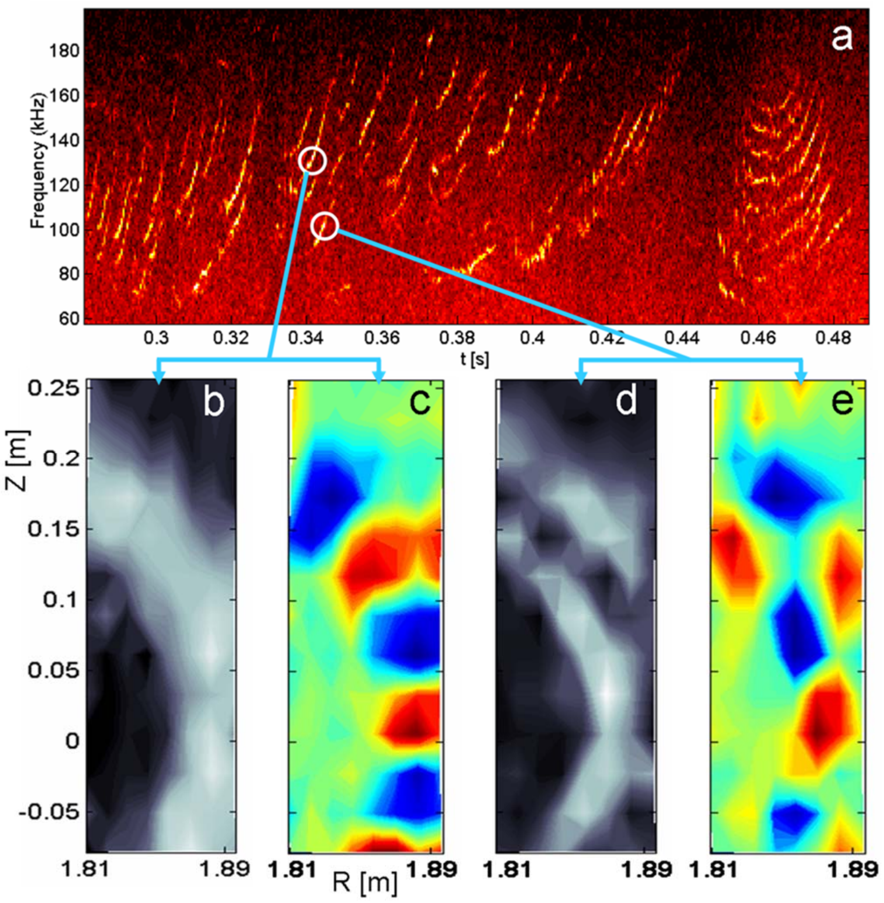
TAE

Pinches, Ph.D. Thesis

AUG diagnostics to measure them: ECEI



Mode structure of RSAEs

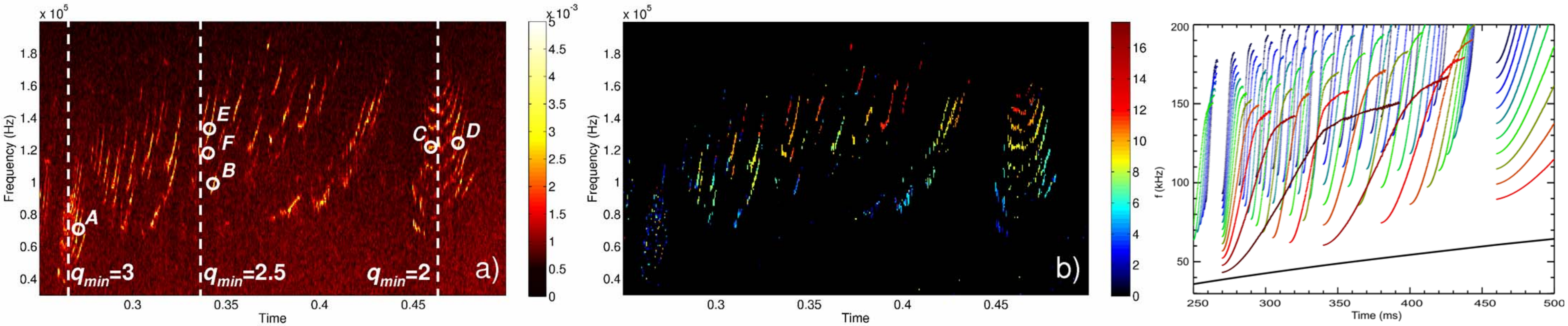


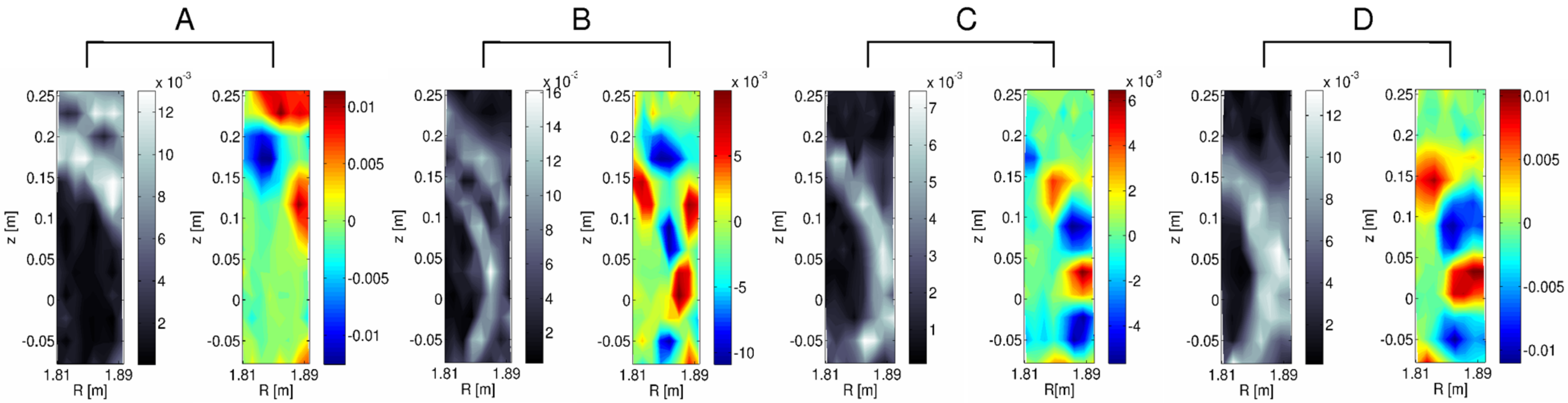
Many RSAEs observed, with different poloidal mode numbers and radial harmonics

Amplitude and mode structure for selected frequencies

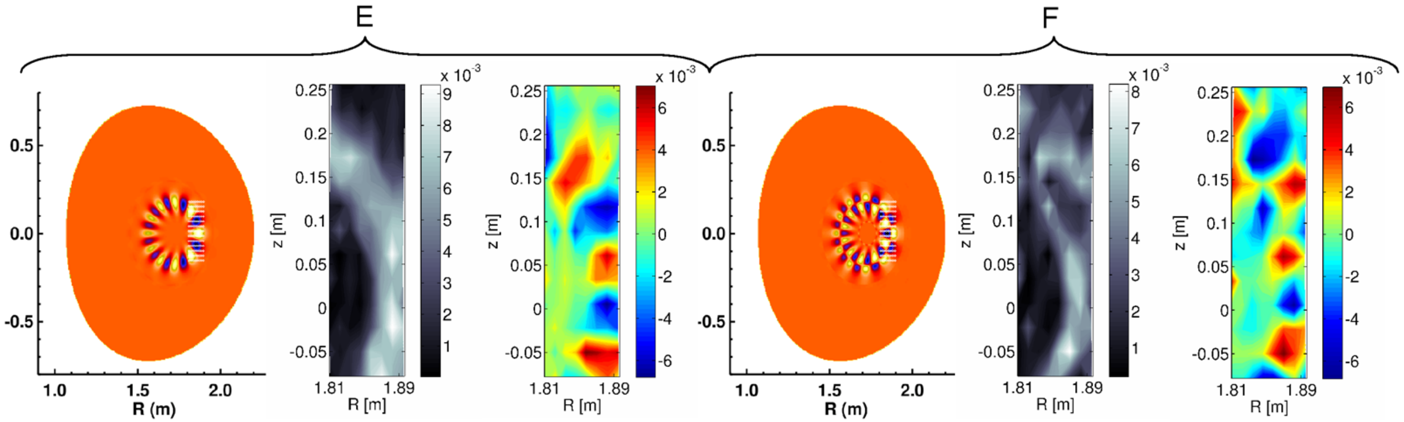
Relative amplitudes around 1%

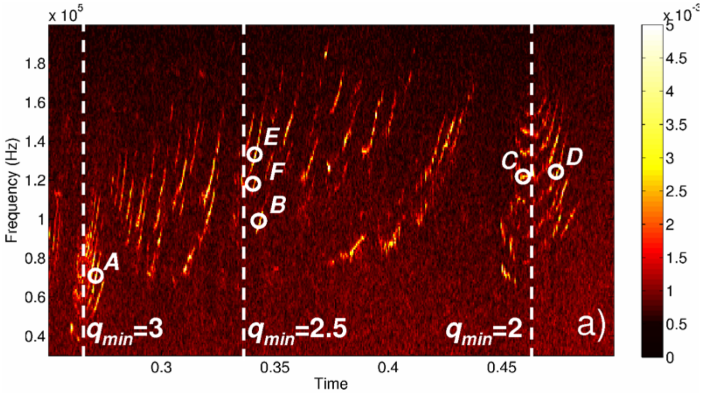
Clear imaging in this case possible due to both SVD and Fourier frequency selection


x 10^5
Frequency (Hz)
Time
x 10^-3
A
B
C
D
E
F
q_min=3
q_min=2.5
q_min=2
a)
b)
f (kHz)
Time (ms)
250
300
350
400
450
500
50
100
150
200

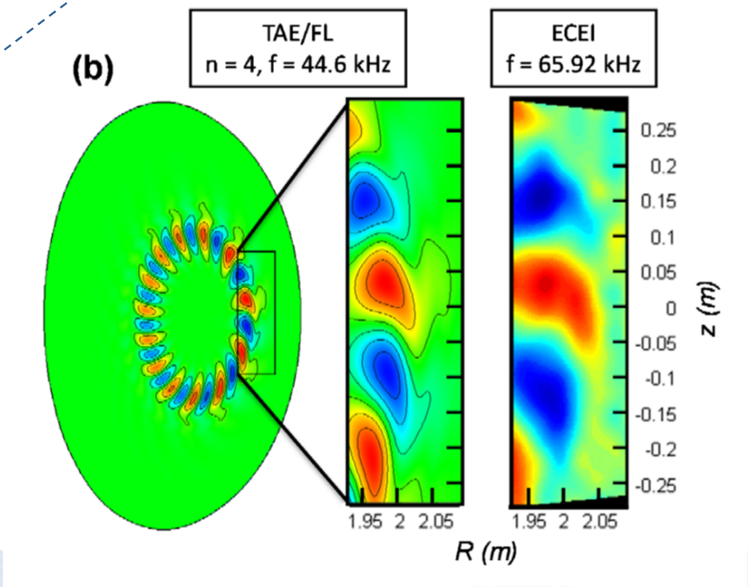

A
B
C
D
z [m]
R [m]
1.81
1.89
x 10^-3

Mode structure simulations



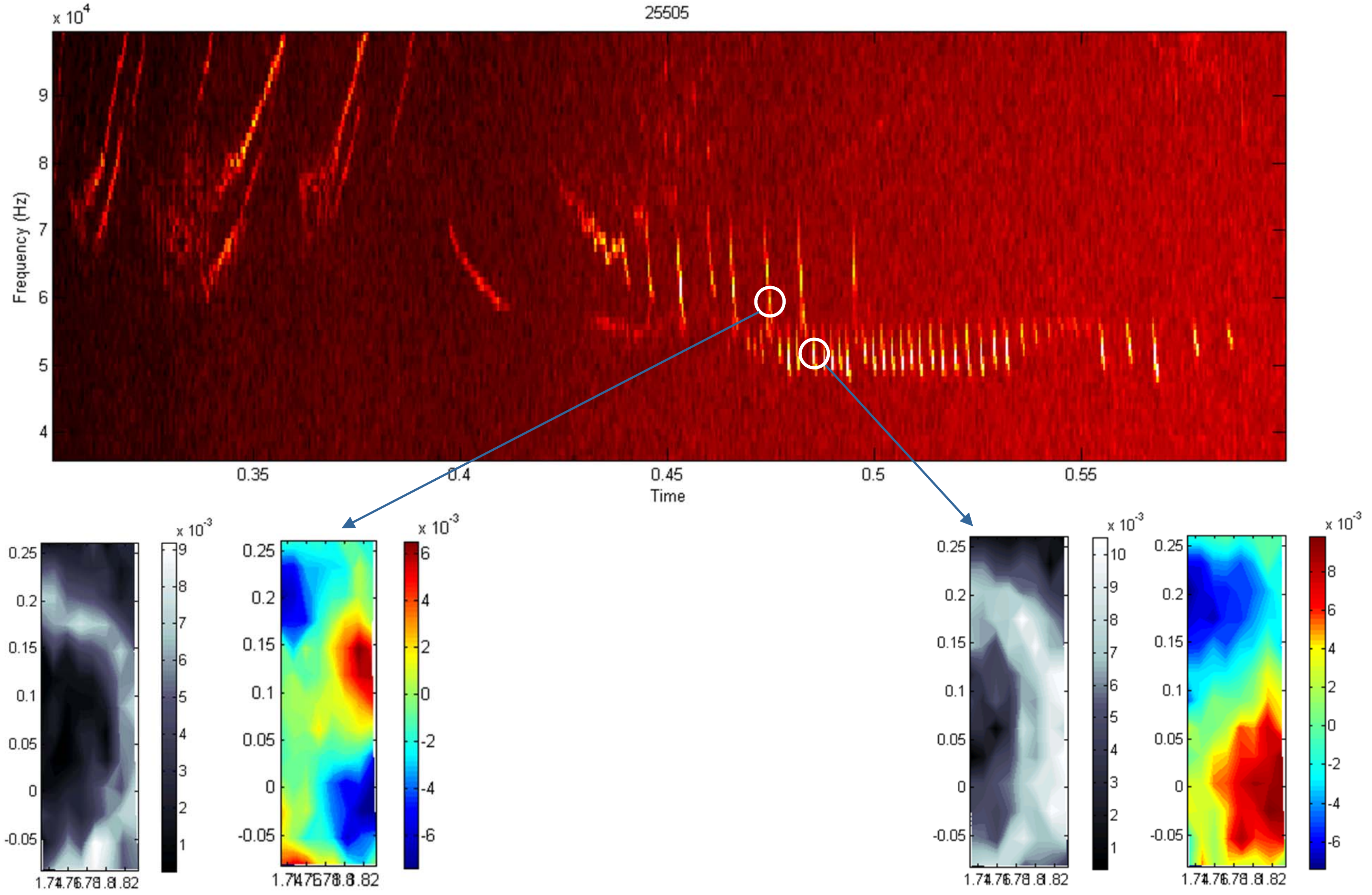


AUG



DIII-D

Energetic Particle Modes



To take home

- Understanding of fusion plasmas is continuously improving
  - This can lead to higher performance & better control algorithms.

- Many instabilities can be controlled in present devices
  - Much work to be done for burning plasmas because of the dominant alpha heating.
  - This involved a tight interaction of plasma physicists, control engineers and mathematicians.