Summary of some ECH/ECCD work presented at EC16

R. Prater

April 15, 2010

Tokamak Requirements for Steady State

- **Accessing the steady-state regime**
  - Plasma startup
  - Heating to burn
  - H mode access
  - Formation of the required current profile

- **Sustaining the steady-state regime**
  - Fully non-inductive operation
  - Stable operating point

  } Requires flexible current drive location and magnitude

- **Control of the operating point**
  - Impurity accumulation
  - Instability control

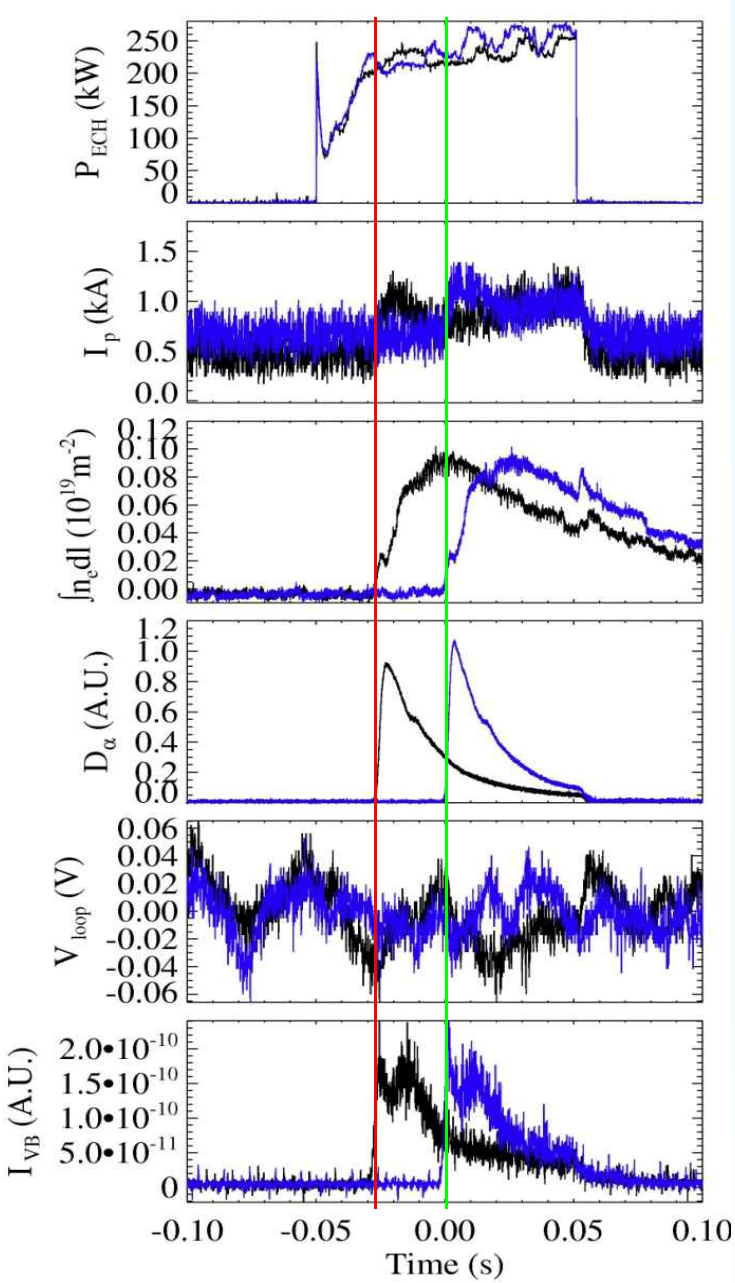
Preionization and startup

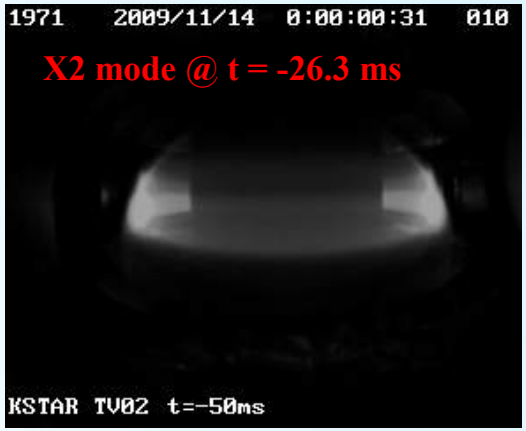
- **Preionization and startup are very robust for fundamental**
  - Only issue is power requirement for burnthrough, which depends on vacuum conditions
- **Second harmonic is an issue for superconducting tokamaks**
  - EAST and KSTAR need second harmonic breakdown to make use of available EC power
  - ITER needs it for half-field operation
  - clear statement of power requirement elusive
- **Active research program**

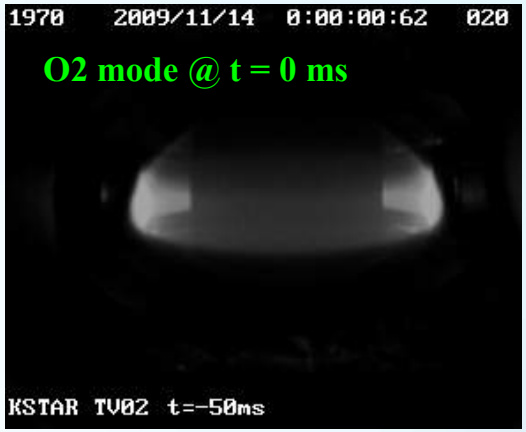
Scanned parameters for 110 GHz ECH

- Pre-ionization (without ohmic discharge)
  - Pre-fill gas pressure
  - Toroidal injection angle
  - Injection mode
  - Vertical magnetic field
- Plasma startup (with ohmic discharge)
  - Pre-fill gas pressure
  - B_z at the EC resonance
  - Additional gas puff in pre-ionization phase
- EC heating effect
  - With/without EC beam

Pre-ionization – EC wave mode



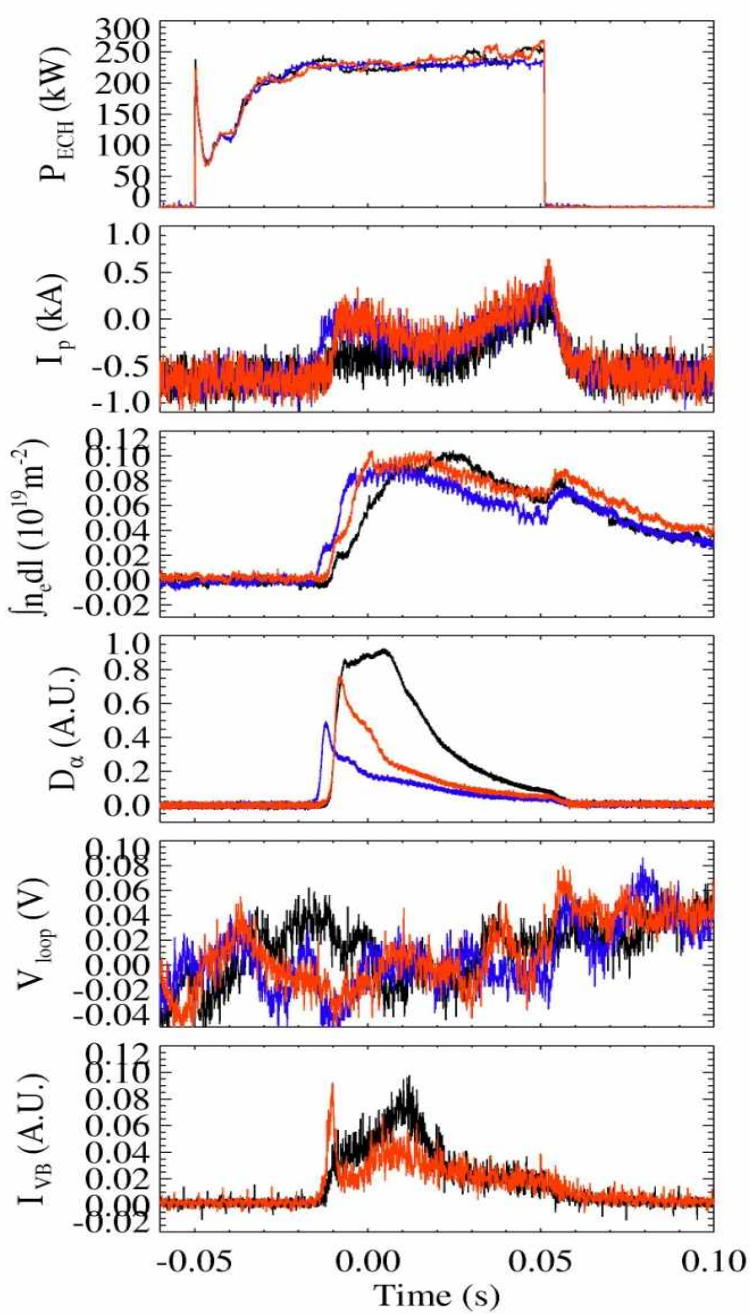




ECH power [kW]	250 kW
ECH injection angle (tor.) [deg.]	0.0 deg. (X2 perp.)
ECH injection mode	**X2 (#1971, black)** **O2 (#1970, blue)**
Pre-ionization time [ms]	22.45 (X2 mode) 50 (O2 mode)
ECH on-time [ms]	-30
TF current [kA]	13.3
Resonance position	R=1.6
Resonance field [T]	1.5
ECH beam target position [m]	R=1.6, Z=0
Gas pressure [10^{-5} mbar]	2.9

- X2 mode is best condition for pre-ionization.
- O2 mode pre-ionization was ignited very late.
- X3-mode injection (#2116) in B_T = 1.3 T and pre-ionization in the pure TF field was attempted but failed.

Pre-ionization – Toroidal injection angle



0°: #1949
-10° (counter): #1948
-20° (counter): #1950

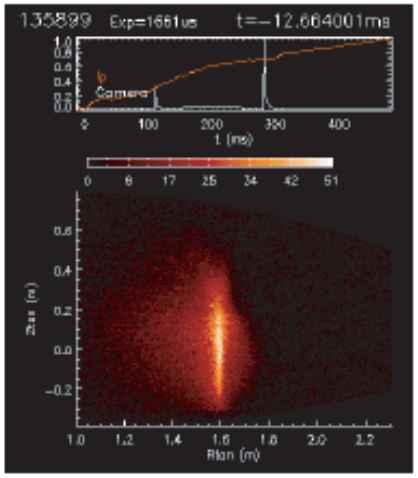
ECH power [kW]	250 kW
Pre-ionization time [ms]	36.98 (#1949) 34.17 (#1948) 37.06 (#1950)
ECH on-time [ms]	- 50
Resonance position	R = 1.8
Resonance field [T]	2
ECH beam target position [m]	R = 1.8, Z = 0
Gas pressure [10^{-5} mbar]	D2 gas, 1.25

- The **counter oblique EC beam launch** was most favorable for the pre-ionization and burn-through during KSTAR first plasma campaign.

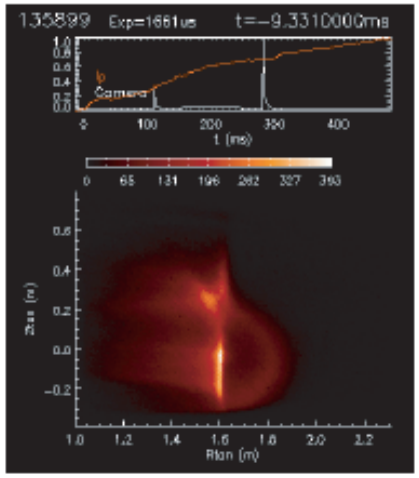
- Breakdown delay time was minimized at the toroidal injection angle of -10 degree. But the line integrated electron density at the perpendicular injection was more increased than at the toroidal injection angle of -10 degree.

- In the case of the injection angles of -20°, ECH pre-ionization was also observed.

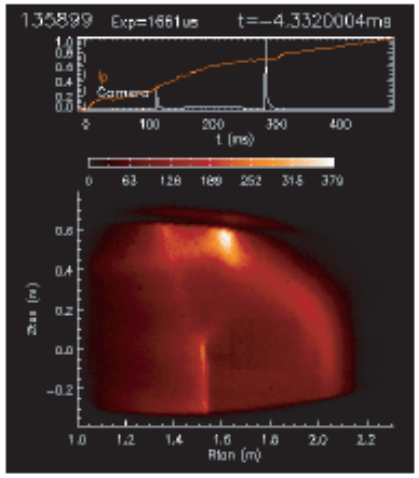
ECH startup seen by fast camera in C^{III} light



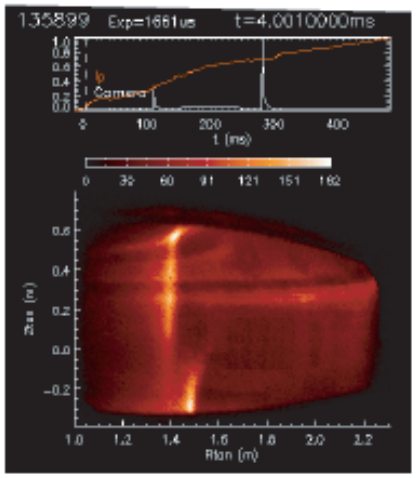
t= -12.7 ms, I p =1.8 kA, V_L= 0V
(Breakdown near X2 resonance)



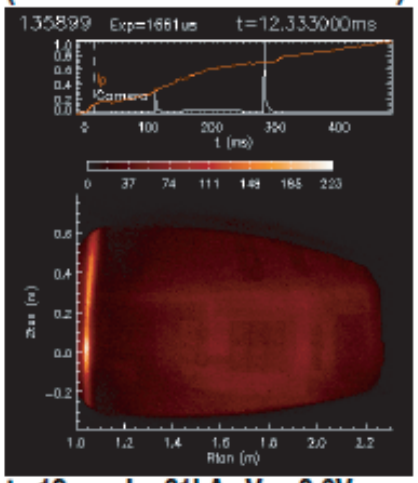
t= -9,3 ms, I p =1.9 kA, V_L= 0V
(CIII Light expands)



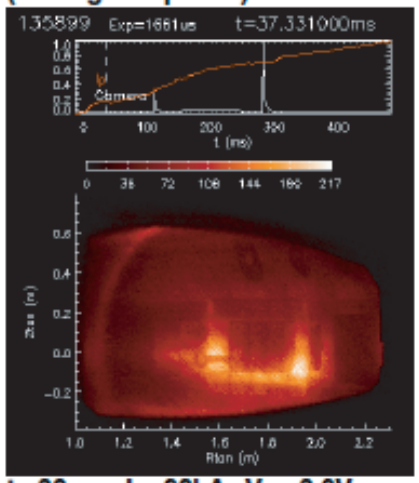
t= -4.3 ms, I p =5.6 kA, V_L= 0.6V
(Further expansion with V_L)



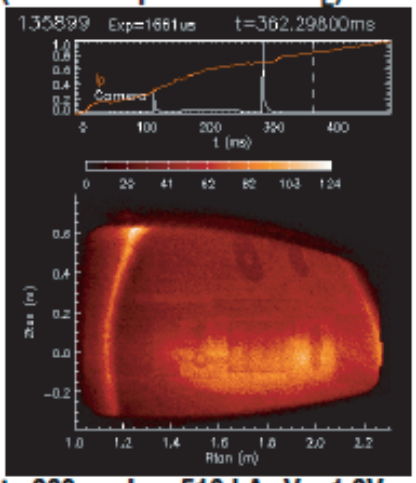
t= +4.0ms, I p =25kA, V_L=2.6V
(Closed flux, starts inward)



t= 12 ms, I p 61kA, V_L= 3.0V
(Limits on Inner Wall)



t= 39 ms, I p 98kA, V_L= 3.0V
(Limits on Outer Wall)



t= 360ms, I p =510 kA, V_L=1.3V
(Diverted)

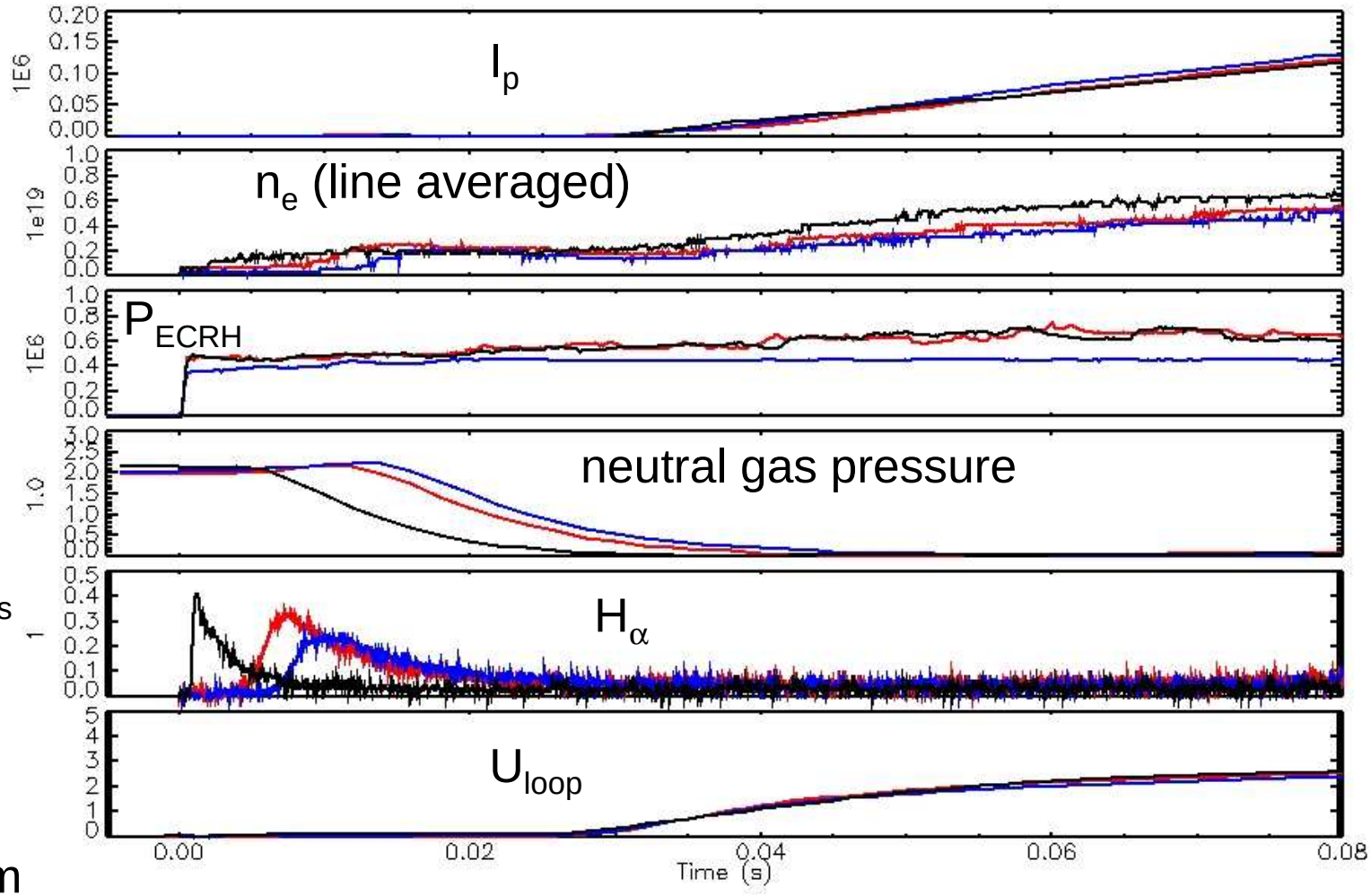
R_{IW}(midplane) = 1.02 m
R_{X2} = 1.64 m
R_{OW}(midplane)=2.36m
B_ϕ=1.9T, V_L=3V, $B_{V,pgm}$=-30G
$C^{III}_{ionization}$ = 48 eV
$C^{III}_{burnthrough}$ ≈ 16-24 eV

Plasma breakdown studies with O1 and X2

X2 140GHz

X2 105GHz

O1 105 GHz



$f/B_t \propto R_{dep}/R_{axis}$ as planned for ITER

dedicated start-up system not necessary

(*A.C.C. Sips et al*, NF 2009)

Plasma heating by ECH to desired operating point and access to H-mode

- **Not much experimental work on physics of ECH and ECCD reported—sign of success**
  - agreement or disagreement with full wave code still not resolved

- **Very significant effects of ECH on transport**
  - eg, 'density pumpout'
    - not a universal phenomenon
    - needs systematic multi-machine study
    - complicates statements about confinement, H-mode power threshold, etc

Project objectives

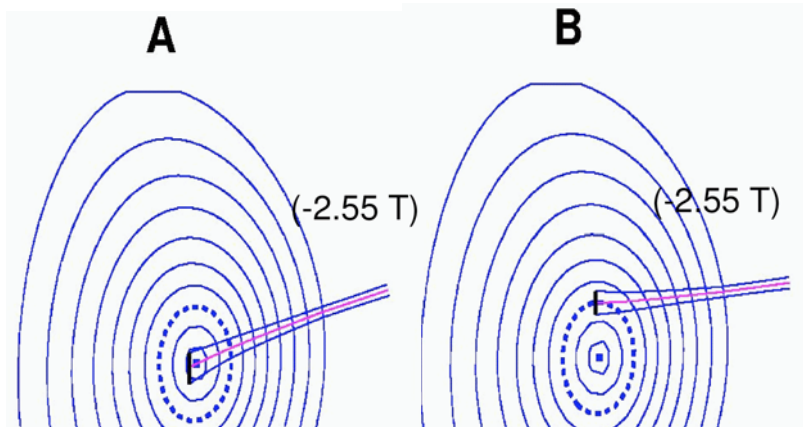
- To define the physics requirements of an ECRH system
  - → with respect to the main JET **scenarios**
  - → with respect to the main **functions**
  - → taking into account **priorities** of the JET programme

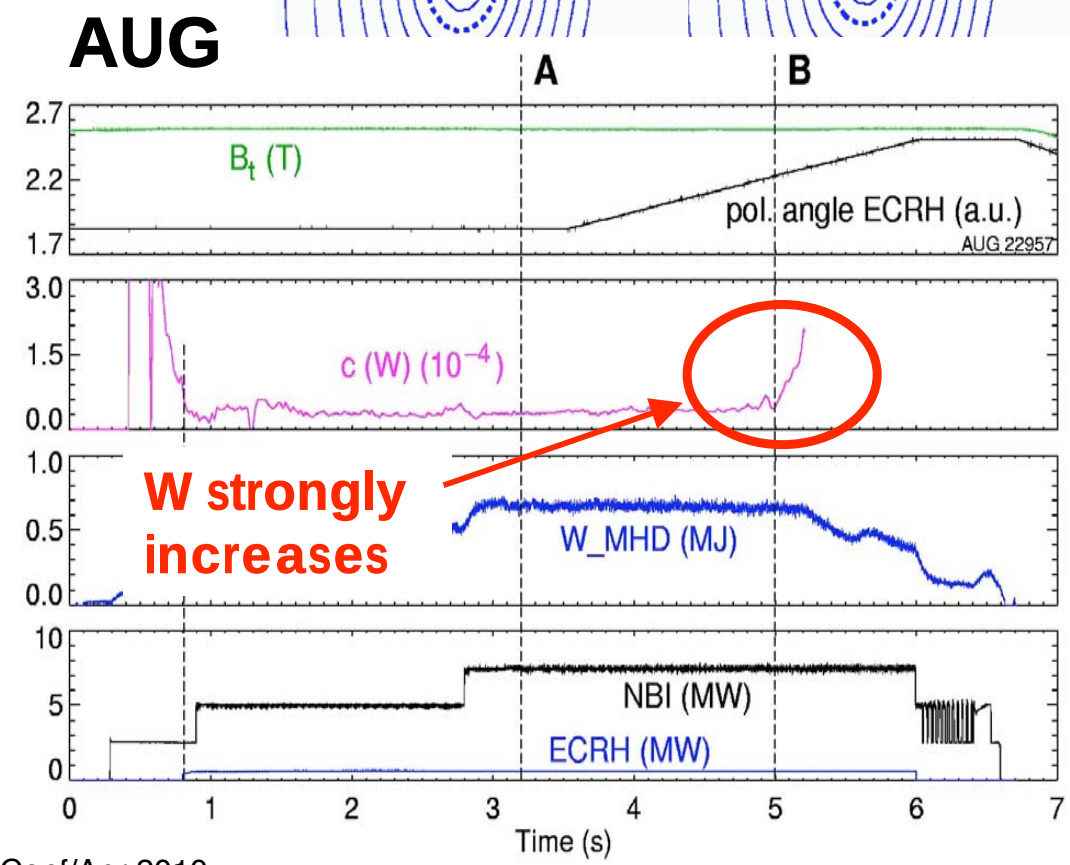
- To assess the feasibility of an ECRH system
  - → with respect to **time**
  - → with respect to resources (**cost** and **manpower)**
  - → with respect to the present JET layout (**ports**, **buildings**)
  - → with respect to **risks**
  - → in coherence with the future JET **programme**

- Main boundary conditions
  - → **time:** system ready by ~2014/2015
  - → **power:** ~ 10 MW in the plasma
  - → **strategy:** strong synergy with **ITER** ECCD system development; partnership with Russian Federation

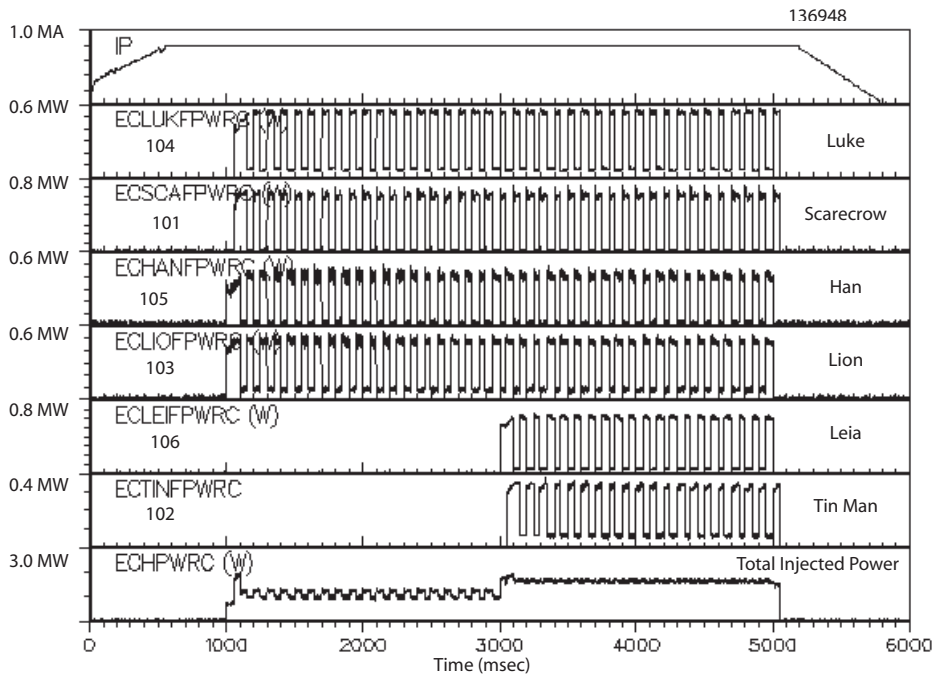
Intense Central Heating Counteracts the Effects of Metallic Impurity Accumulation

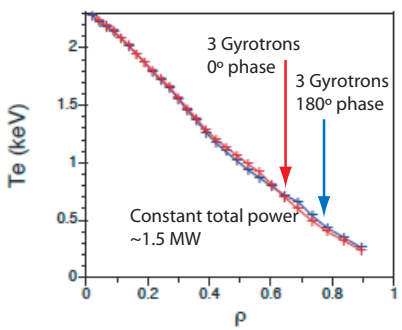
- **Power plants are likely to have a metallic first wall**
  - Neoclassical impurity transport yields very peaked impurity density ($n_Z \propto n_e^Z$)
  - High Z impurities can radiate intensely in power plant conditions
- **Cental EC heating mitigates the effects of W accumulation**
  - Physics mechanism still unclear:
    - Support power balance against radiation?
    - Enhanced particle flux?
  - Same spatial dependence seen for radial shift of heating

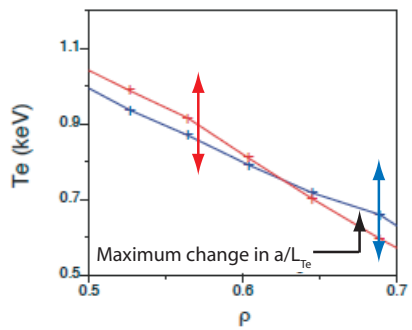




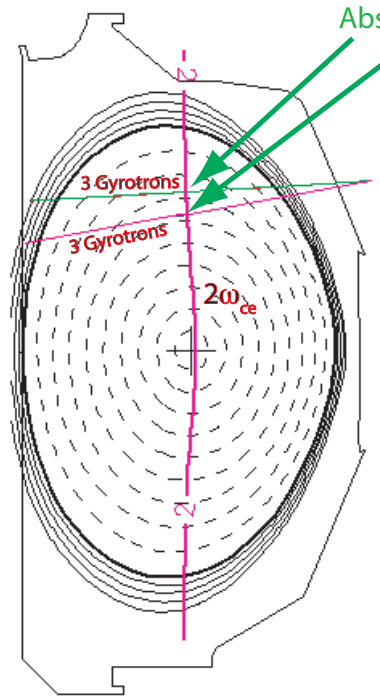
Turbulent transport experiment with modulated gyrotrons



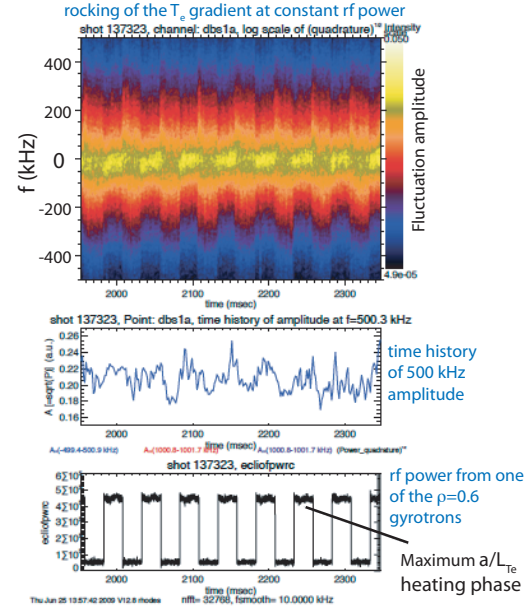




- ECH heating at ρ=0.6 and 0.7
- Total injected power constant
- Injection 180° out of phase at two locations
- Rock the T_e gradient periodically
- Use time correlation analysis



Doppler backscatter spectrum during periodic rocking of the T_e gradient at constant rf power



Fluctuation amplitude increases and frequency decreases during the period of steeper gradients

New modes of operation

Central X2 heating at densities above 7E19 m^{-3} requires

- 140 GHz and 2.45 T < B_t < 2.65 T
- I_p <= 1 MA to stay below cutoff-density
- q_{95} > 4.5 for lowest δ
- limitations are more severe if δ is increased

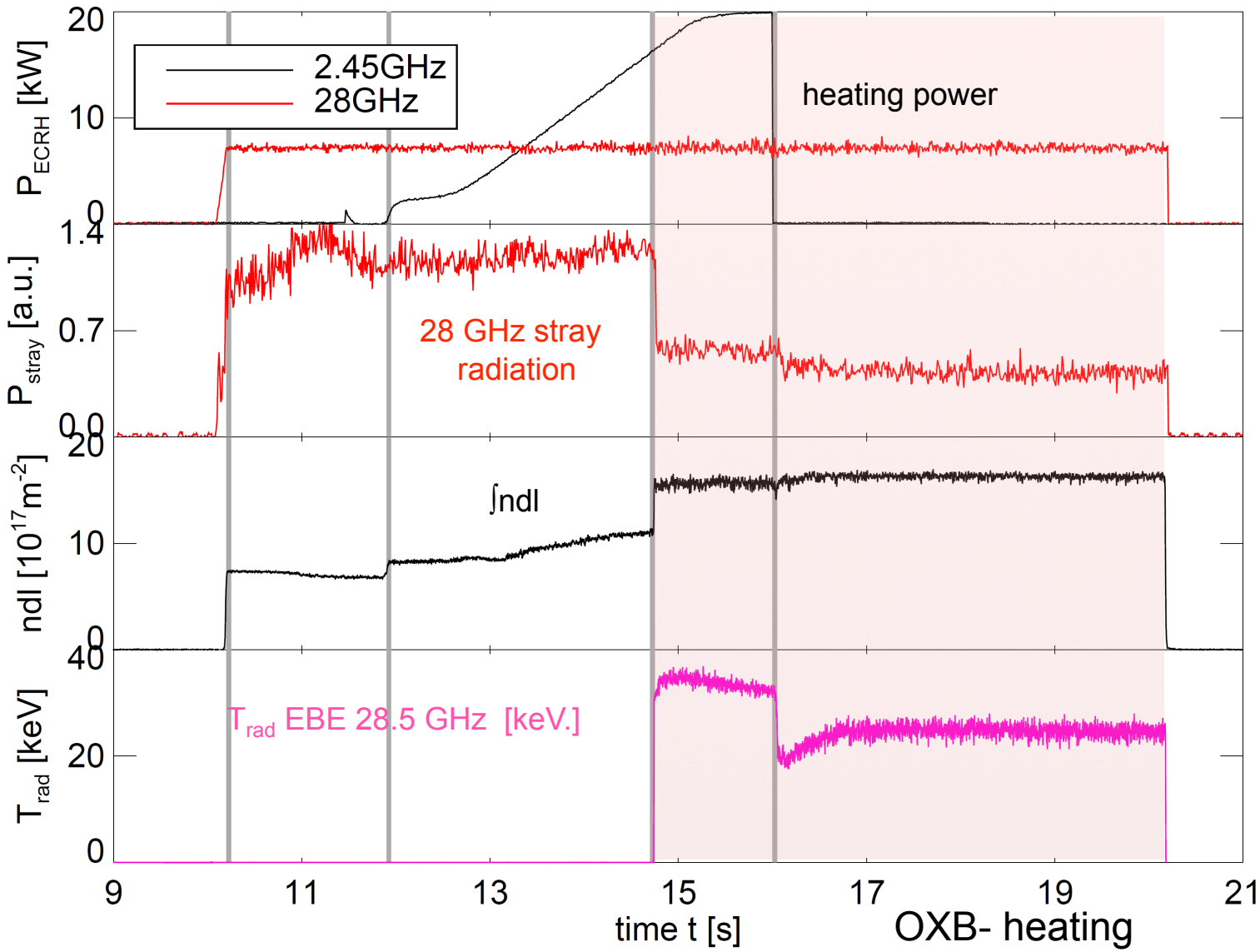
X3 heating allows to lower B_t

O2 heating allows to access higher densities / higher I_p

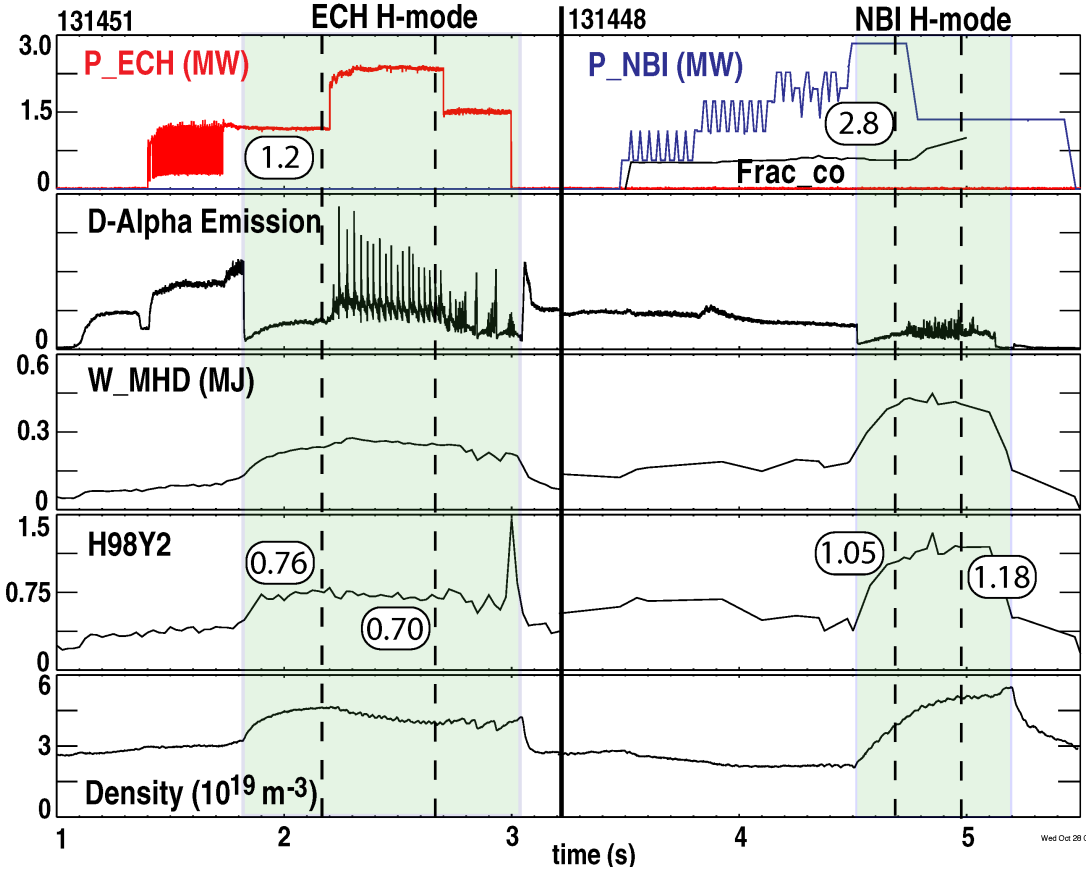
For both: see Poster by *H. Höhnle*

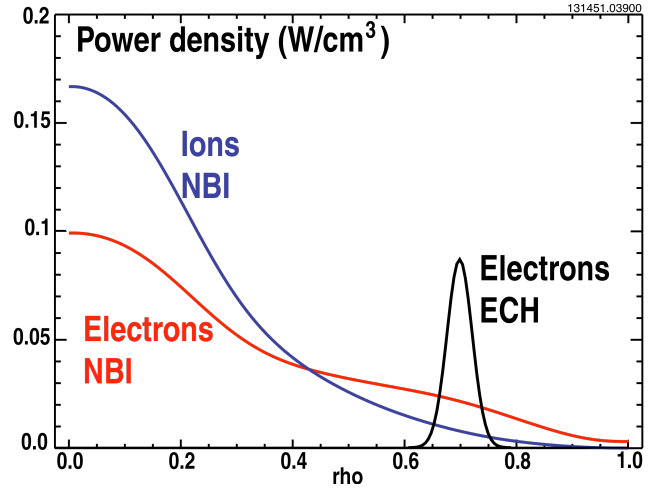
Need to find ways to handle non-absorbed power

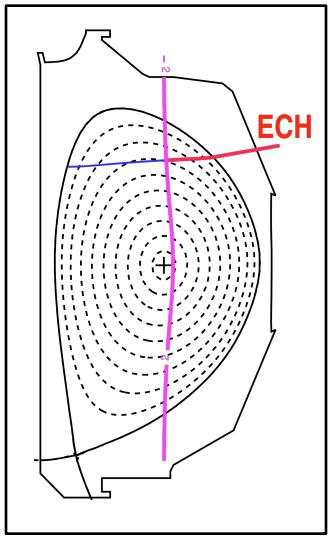
OXB-Transition at 0.48 T



P_{L-H} for ECH in Deuterium is significantly smaller than that in NBI H-mode



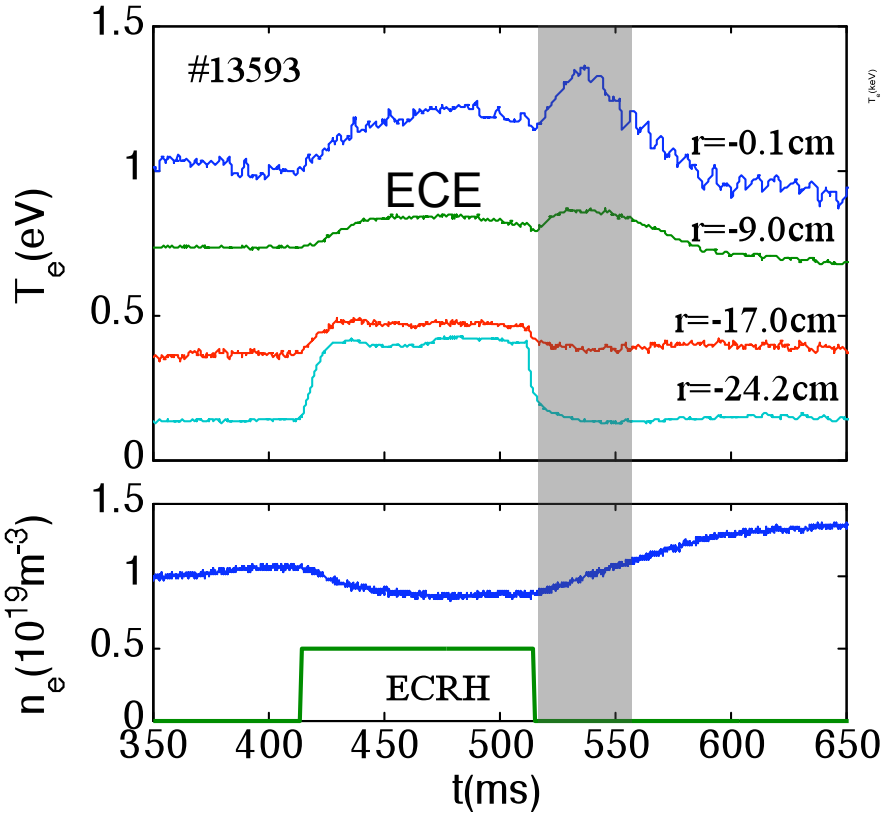


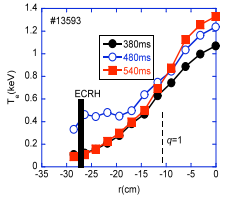


- Large Type 1 ELMs in ECH phase, quite different than in NBI phase
- ECH heating profile far out-board of NBI in this experiment
- Difference in P_{L-H} is MUCH smaller in H and He

ITB triggered by far off-axis ECRH switch-off

HL-2A





Bt=1.44T, Ip=165kA, P_{EC}=740kW in X2 mode

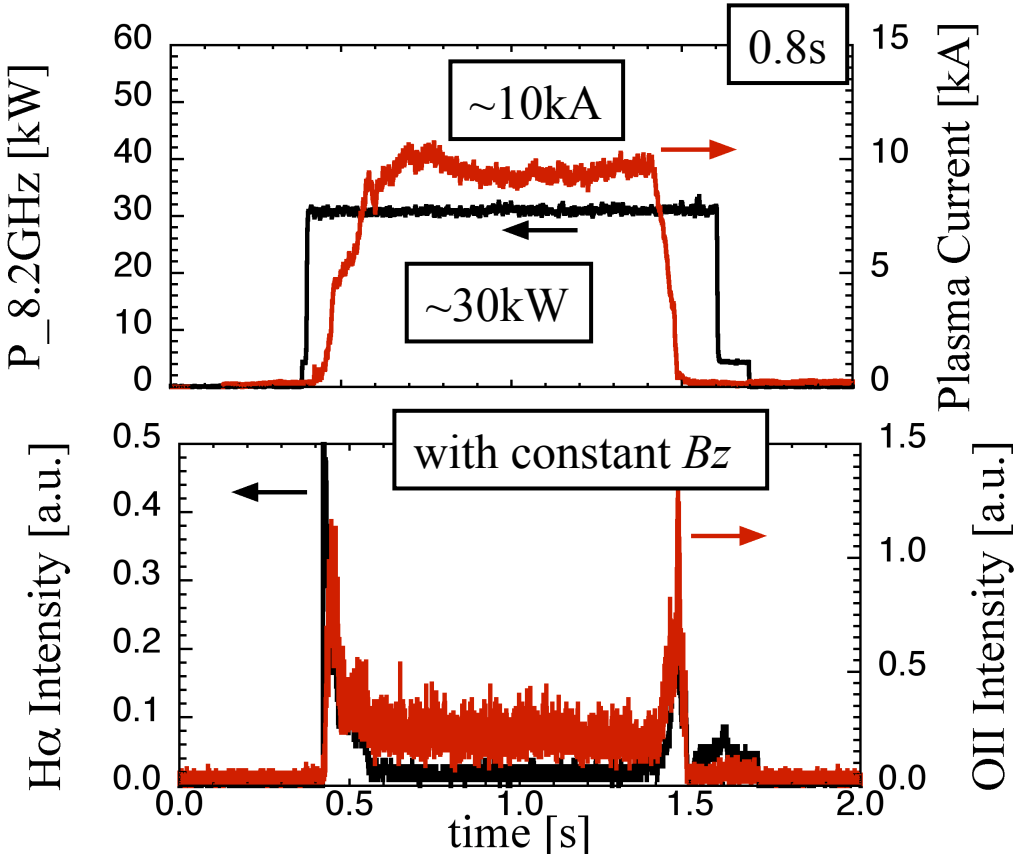
Sustainment of the steady-state regime

- **Fully noninductive operation for tokamaks**
  - steady-state for tokamaks requires high CD efficiency as well as high bootstrap fraction
  - no 'new physics' on the horizon

- **Controlling instabilities**
  - sawteeth
  - disruptions
  - tearing modes

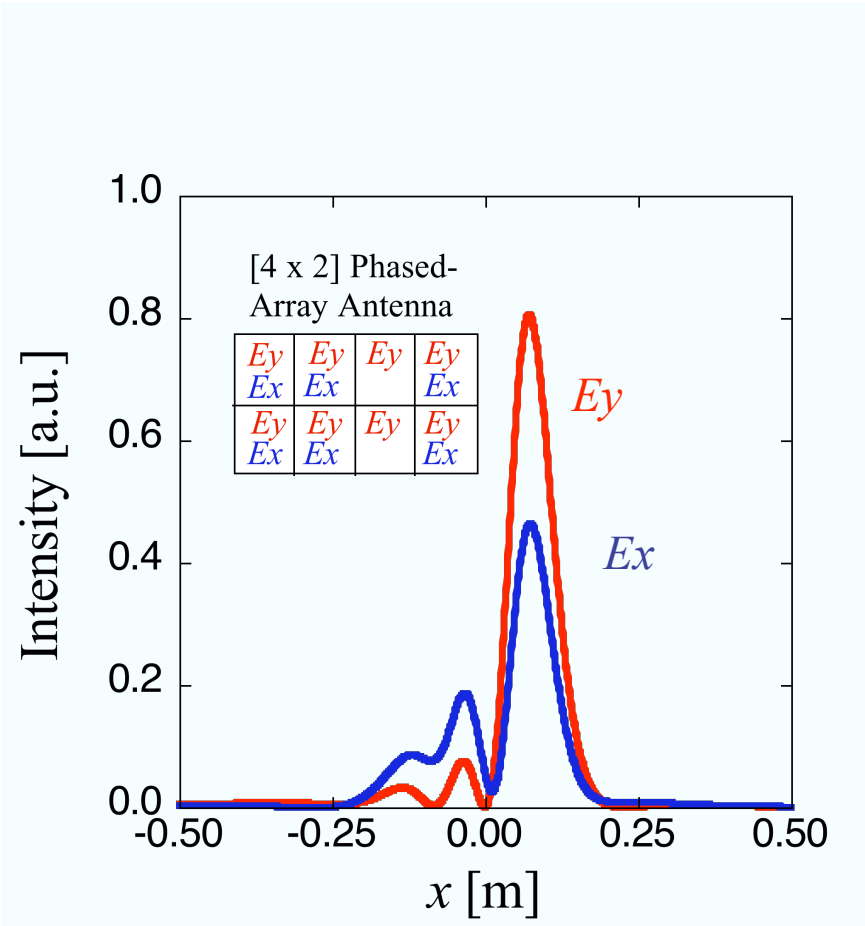
Non-inductive Current Sustainment (FY2009)

QUEST Advanced Fusion Research Center

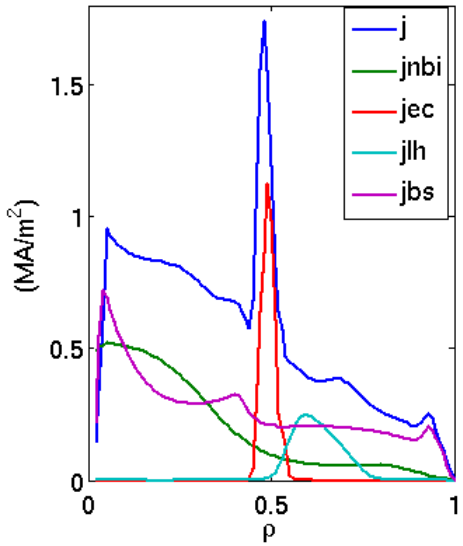


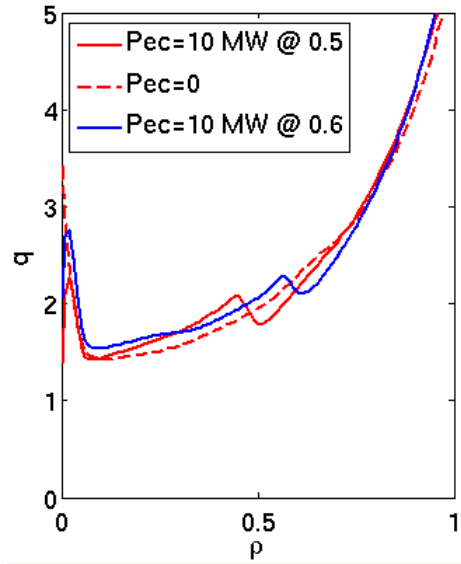
The 10kA plasma current was sustained for 0.8 second, but terminated with increment of the Hα and OII intensity.

One broken klystron could not be operated. It should be repaired.



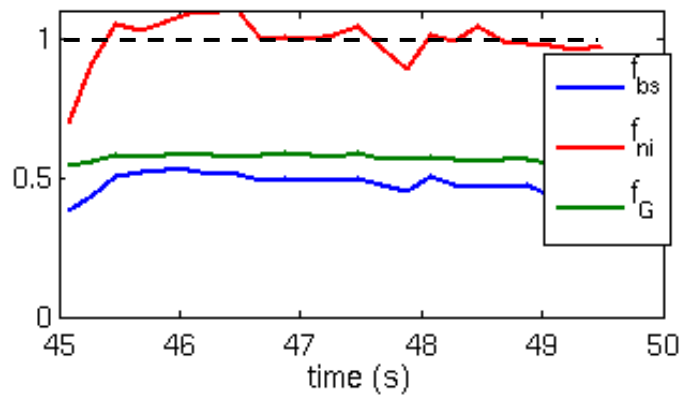
Effect of 10 MW ECCD at ρ = 0.5 or ρ = 0.6

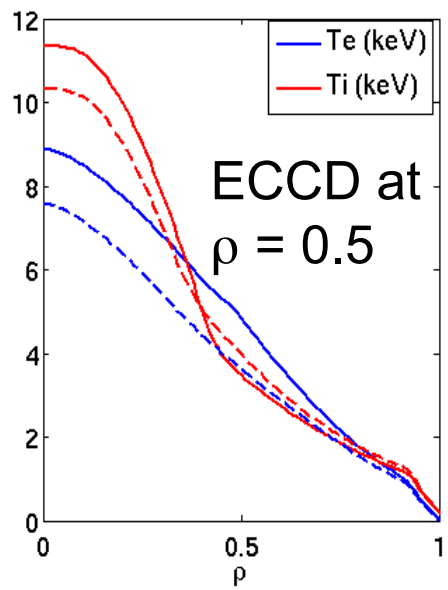


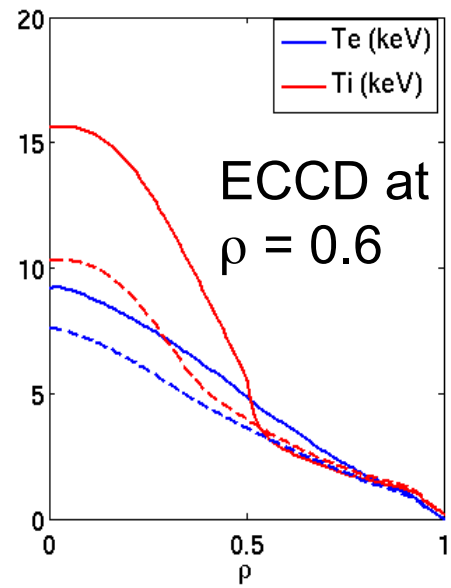


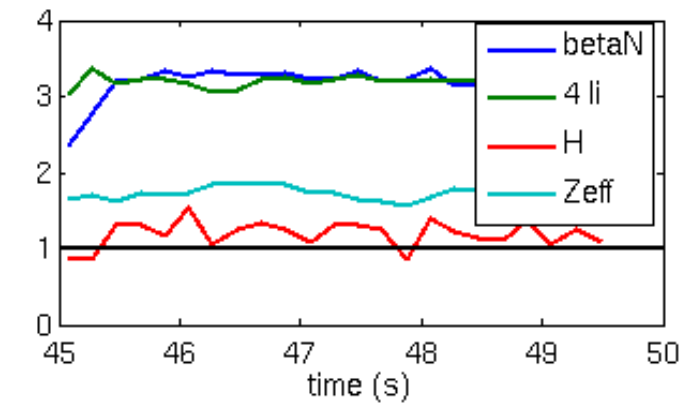
ECCD at ρ = 0.6

→ $V_{loop} \approx 0$



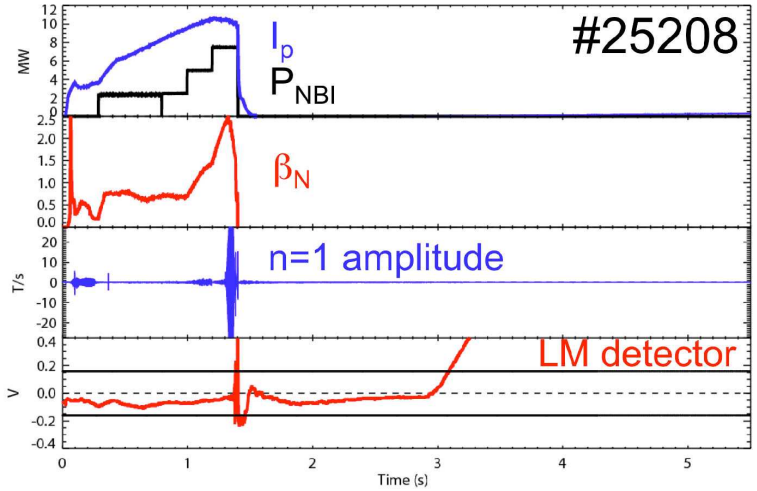


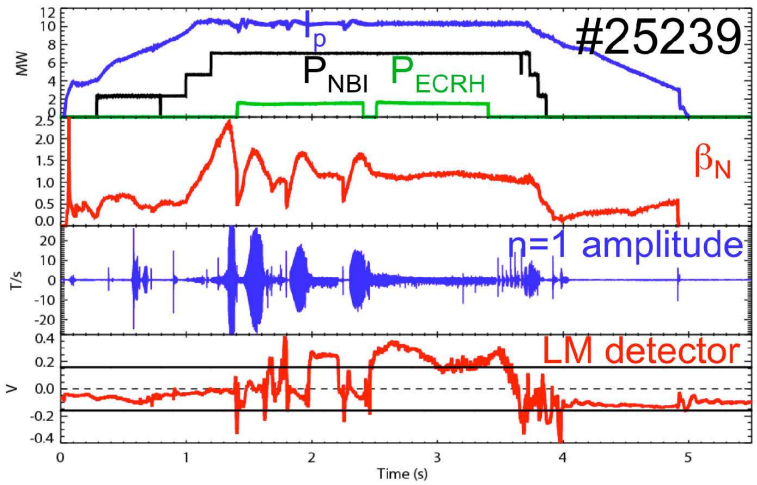




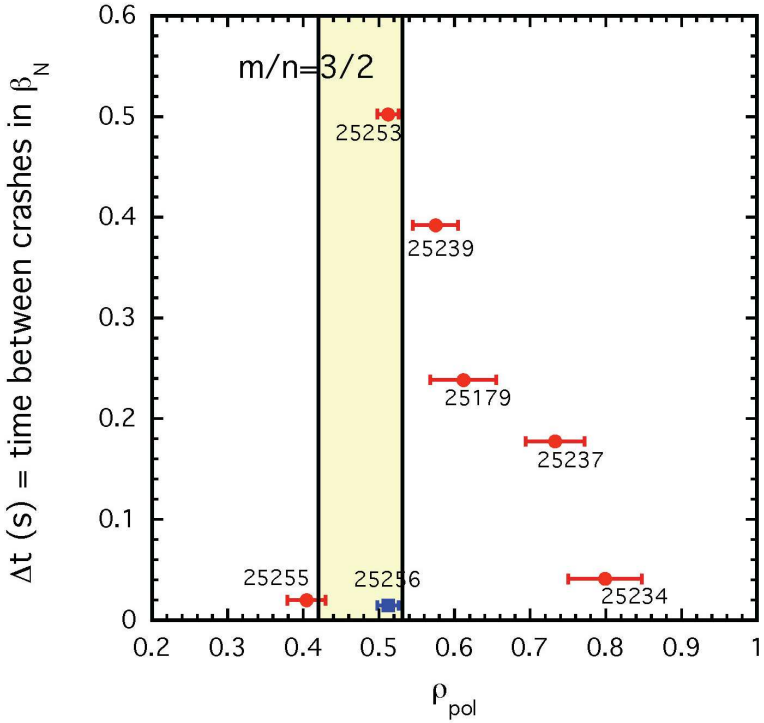
J. Garcia

Mitigation of high-β disruptions





High β disruptions are mitigated most efficiently when heating close to the q=1.5 surface

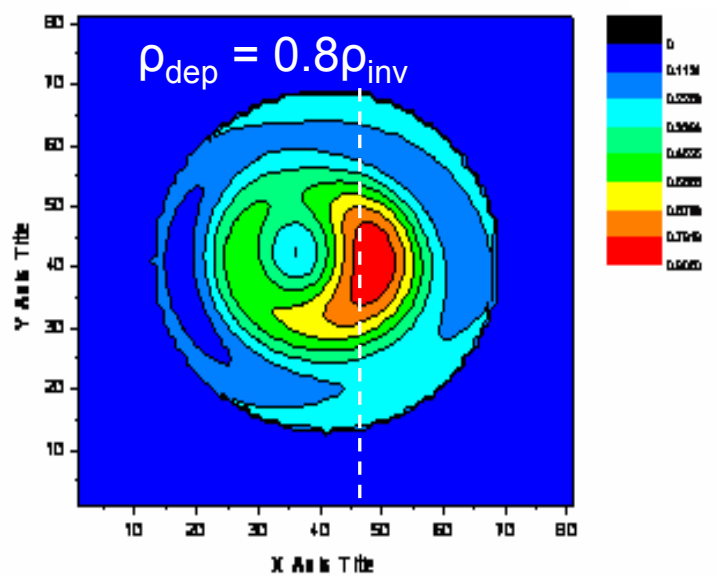


B. Esposito et al., submitted to PRL

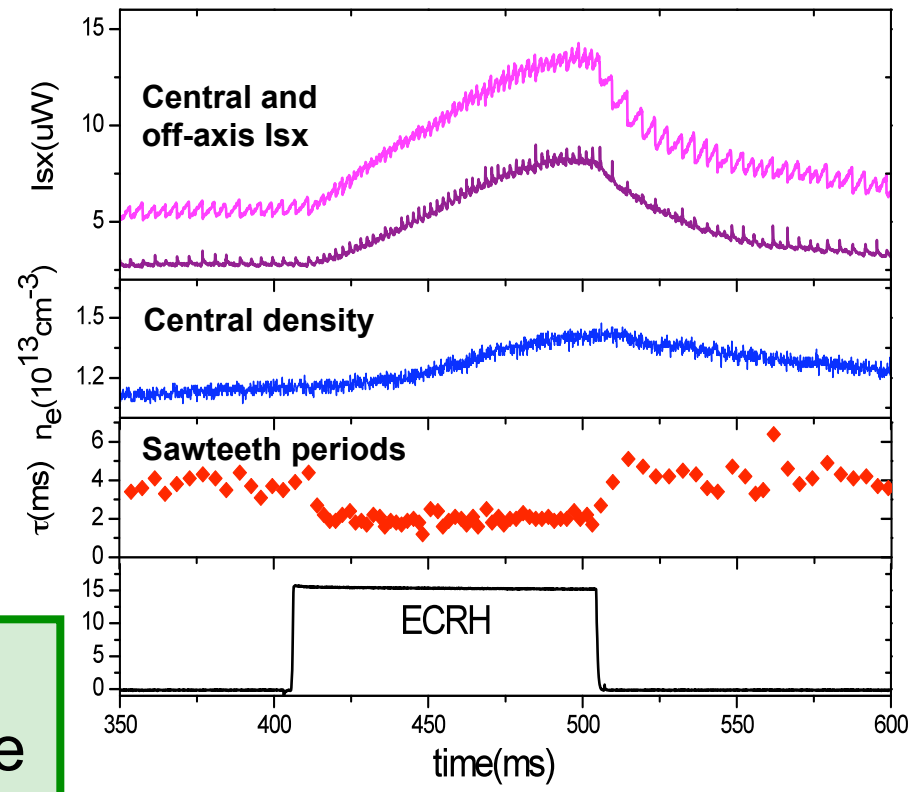
Sawtooth Control with ECRH on HL-2A

HL-2A

Heating just inside the q=1 surface



Destabilization of sawtooth

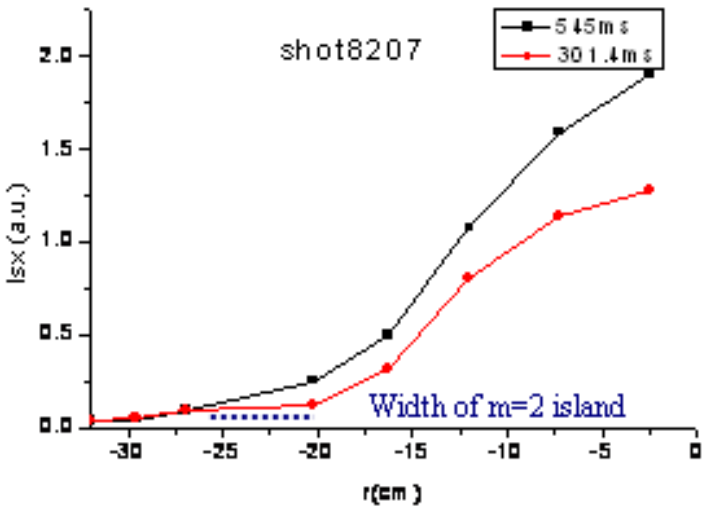


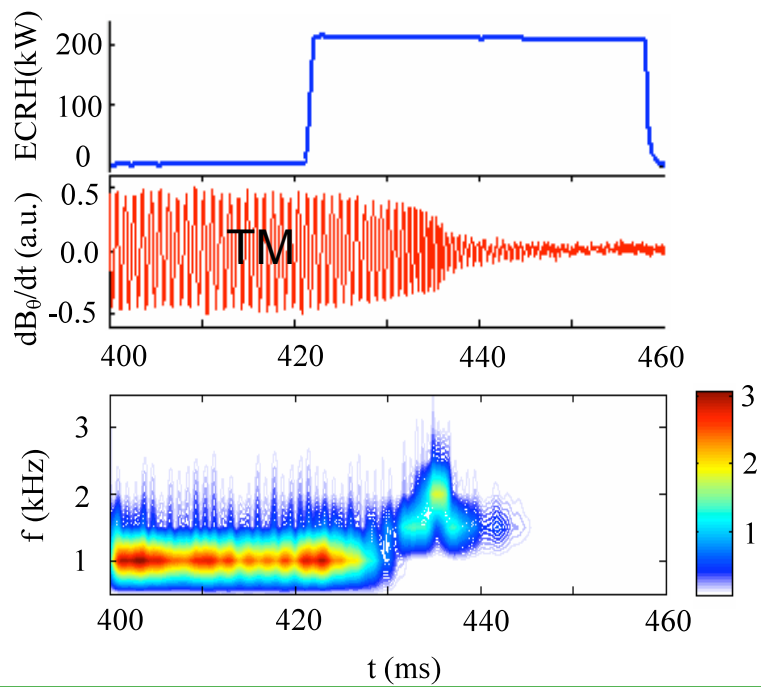
- Off-axis heating just inside q=1 surface can destabilize the sawtooth
- Heating just near or outside q=1 surface can stabilize the sawtooth.

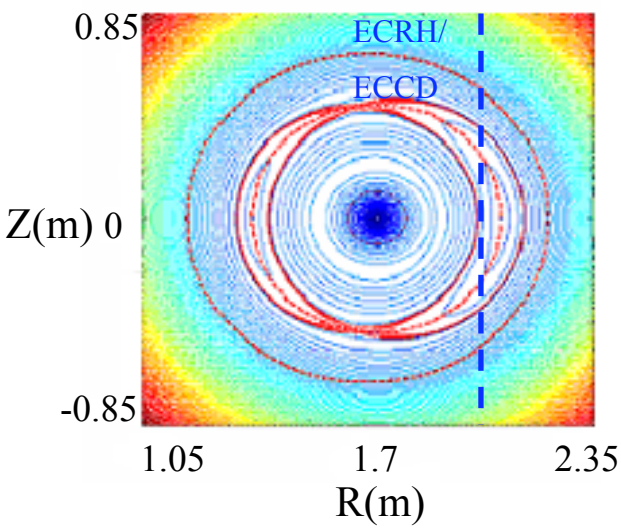
Bt=1.28T, r_{EC}=10cm, ρ_{dep}=0.8ρ_{inv}=12cm, 4ms->2ms, Ip=148kA, P_{EC}=530kW

Stabilization of Tearing mode with ECRH

HL-2A







- Off-axis heating near q=2 surface can stabilize the m=2 tearing mode
- With tearing mode stabilization, the plasma density as well as stored energy keep increase.

■ Further study will focus on NTM stabilization with ECCD/ECRH.

METHODOLOGY

ON-AXIS ECH - 1 – 3 gyrotrons 140 GHz, power 0.2 - 1.2 MW,

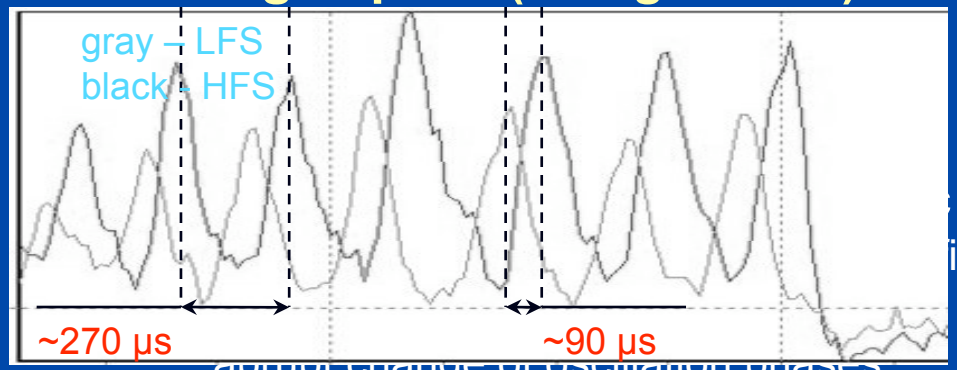
In addition OFF-AXIS ECH - 1 – 2 gyrotrons 129 GHz, up to 0.8 MW.

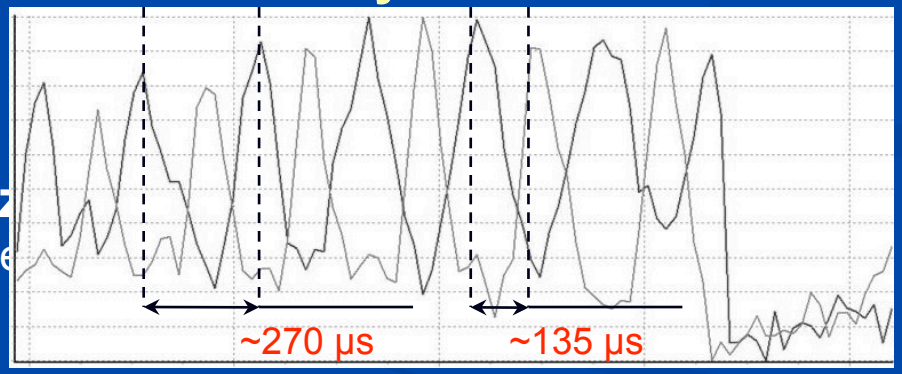
All launches – across the magnetic field. This method allows to get discharges both with single driving modes (m/n=1/1) and with family of modes (m/n=1/1, 3/2, 2/1, 3/1) by small change of current penetration to plasma center. At represented examples: B_t=25 kGs, I_p=250 kA, $\tilde{n}_e \sim 1.7 \cdot 10^{13} cm^{-3}$, $q_l \sim$ 3.1, column displacement Δ= -1cm, digitization – 15 μs

DIAGNOSTICS

ECE - 24 channels, 2nd resonance X-mode, IF band – 300 or 600 MHz

high space (*along radius*) resolution for every channel !!!





High space resolution (total angle of the antenna pattern ≤1^0, the inclination angle for compensation of the relativistic frequency shift ~1^0, the space resolution – no worse 1 cm), **disturbance motion is nonuniform**

Low resolution (angle of the antenna pattern ~2-3^0, zero angle of the inclination, the resolution – 2-2.5 cm), ECE signals are similar to the chord SXR signals, **disturbance motion looks like uniform**. Effect is hidden by averaging at real and energy space

CONCLUSION

1. Mode excitation occurs into all area inside corresponding rational zone
2. Mode m/n=1/1 is master mode. Current oscillations on its eigen frequencies fill total plasma volume
3. Measured and calculated by **kinetic model** eigen frequencies of modes m/n=1/1, 3/2, 2/1 and 3/1 coincide with accuracy no worse ± 10%
4. Key parameter for volume resonances of all modes is evidently central ion temperature
5. Only even upper eigen harmonics and odd subharmonics excite. Deviation of eigen frequencies is not exceed 5% for basic harmonics and 20% for the upper
6. Positions of resonance rational zones do not change during current plateau stage though strong sharpening of electron temperature profile under ECH (inside q=3/2 $k_{\text{profile sharpening}} \sim 1.5$)
7. Relations of measured eigen frequencies and radii of rational zones can be represent into 5% accuracy as relation of simple numbers

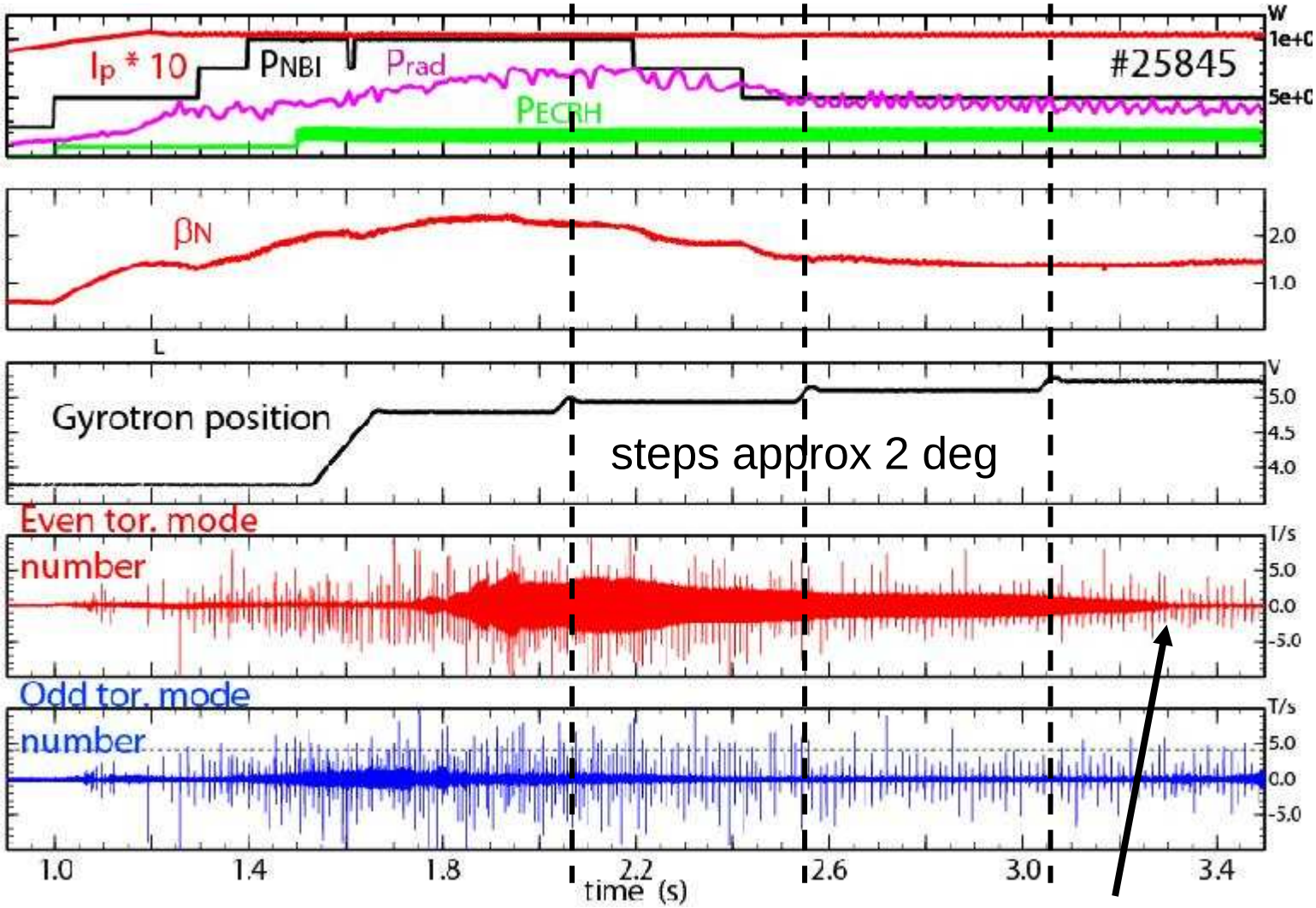
$$\mathbf{f^1_{1/1} : f^1_{3/2} : f^1_{2/1} : f^1_{3/1} = 3/2} \qquad \mathbf{r^1_{3/1} : r^1_{2/1} : r^1_{3/2} : r^1_{1/1} = 3/2}$$

$$f^4_{m/n} : f^2_{m/n} : f^1_{m/n} = 2/1 \qquad r^4_{m/n} : r^2_{m/n} : r^1_{m/n} = 1/2$$

Positions of rational zones do not depend on amplitudes of oscillations

Where they are when global oscillations are absent?

FF NTM-stabilisation using steerable mirror

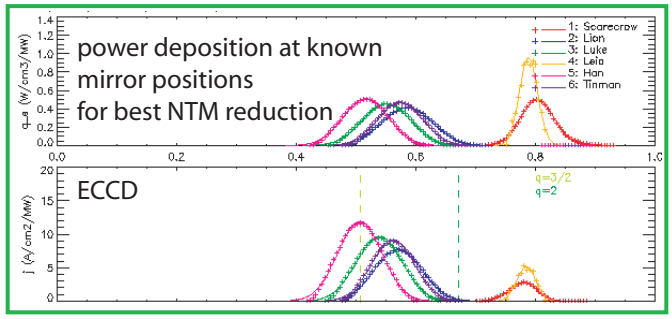


(3,2) NTM stabilized

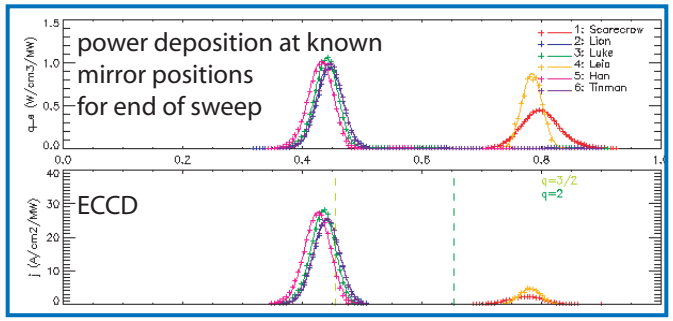
Reduction of the m/n=3/2 NTM with ECCD poloidal scan

The new electric motor drives for quasi-poloidal scanning of the ECH rf beams have been demonstrated to permit the reduction of the amplitude of the m/n=3/2 NTM in the first proof of principle experiment of this new capability at DIII-D.

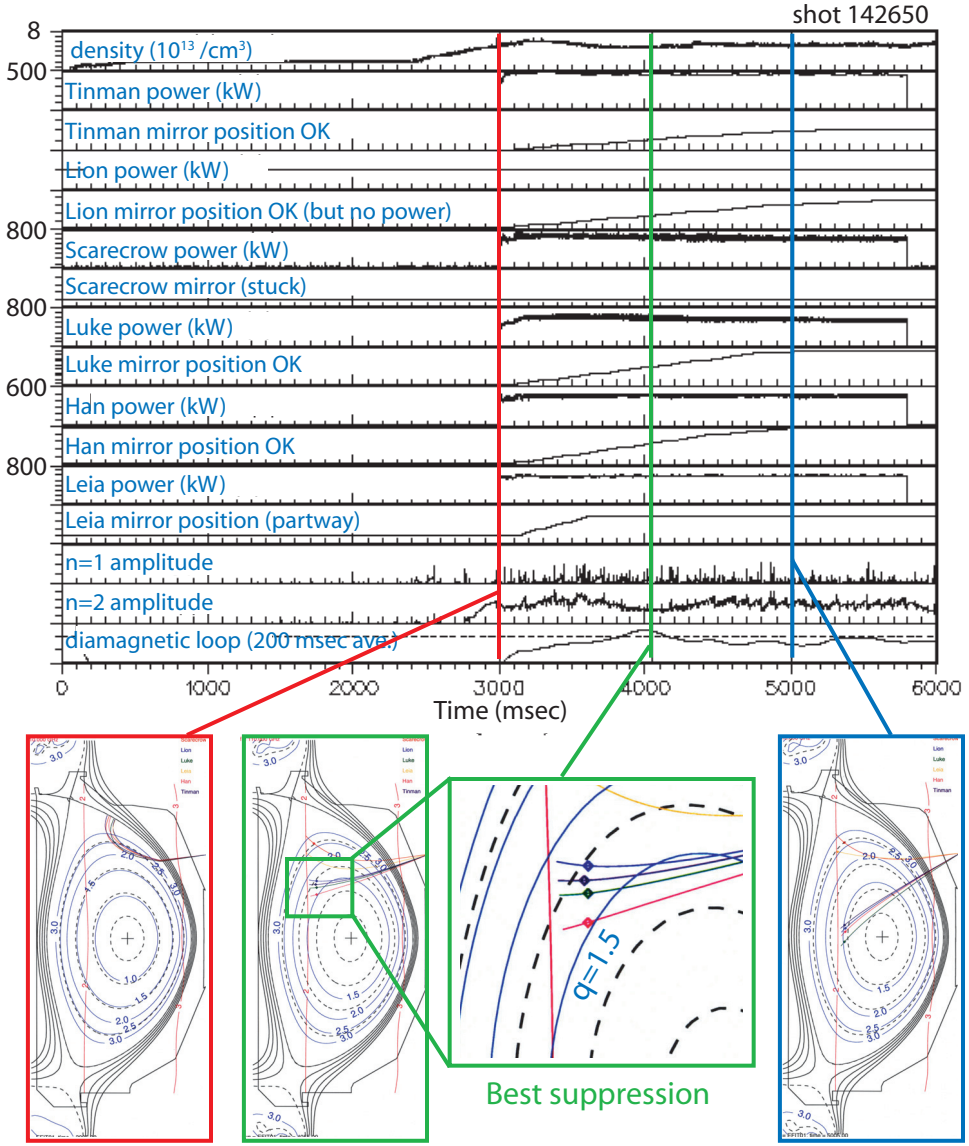
- Poloidal scan ~12°/sec, full 40° scan in 3.4 sec
- PCS control with a step function move command
- For this scan, Lion mirror scanned, but was not powered
- The Leia mirror moved about 20% of the command and stopped
- The Scarecrow mirror did not move due to a mechanical problem
- Three mirrors moved correctly and their gyrotrons injected ~1.5 MW ECCD
- Mechanical and control issues need to be addressed
- PCS feedback algorithms will be developed
- Mirror positions will be added to MDS



4050 msec
during NTM reduction
Deposition was broad
because of the different
sweep speeds for the
four moving mirrors



5000 msec
at the end of the
scan motion



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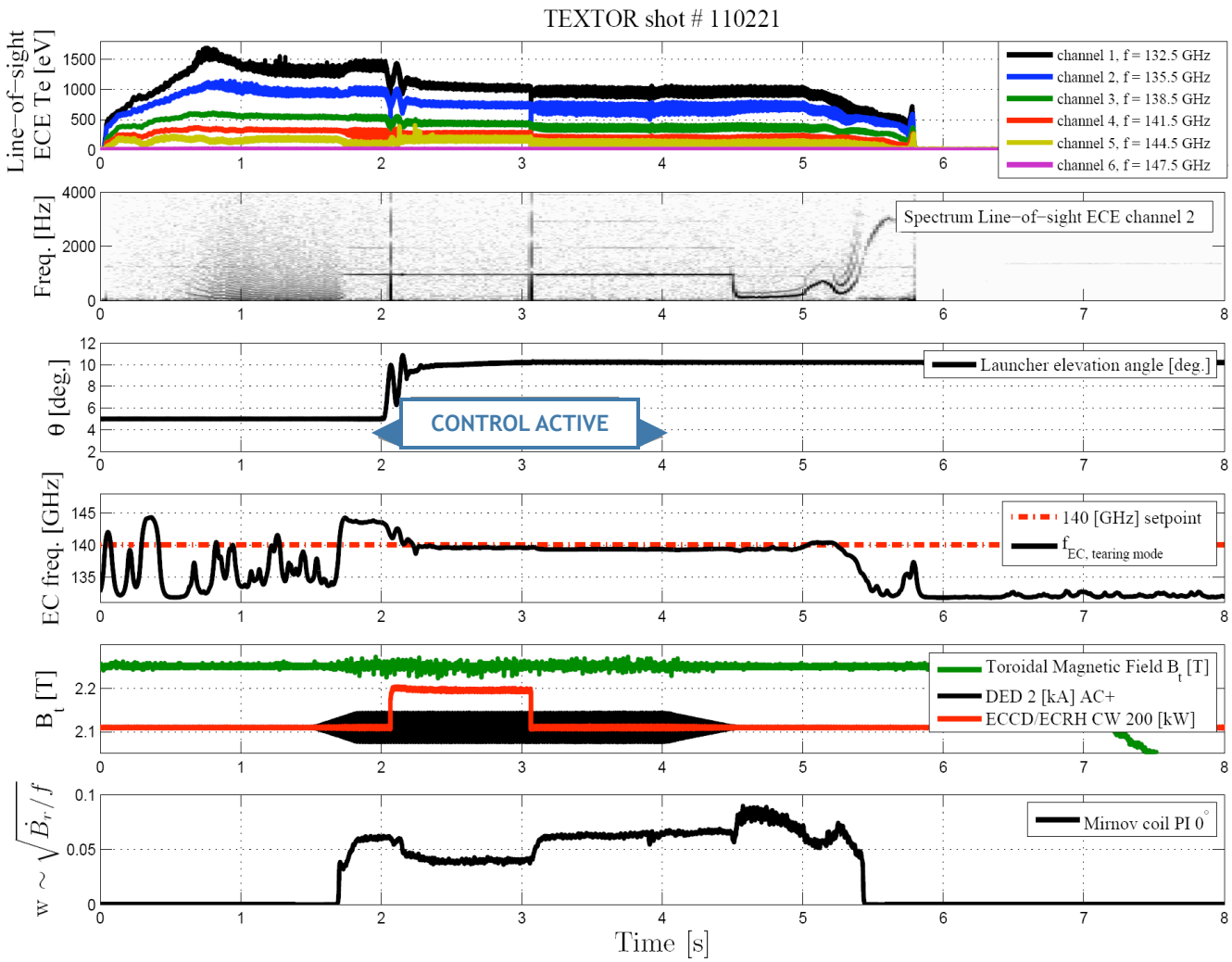
Experimental Results (1)

- 2/1 tearing mode **search-and-suppress**



- $\theta_{initial} = 5^\circ$
- $B_t = 2.25$ T
- $I_p = 300$ kA

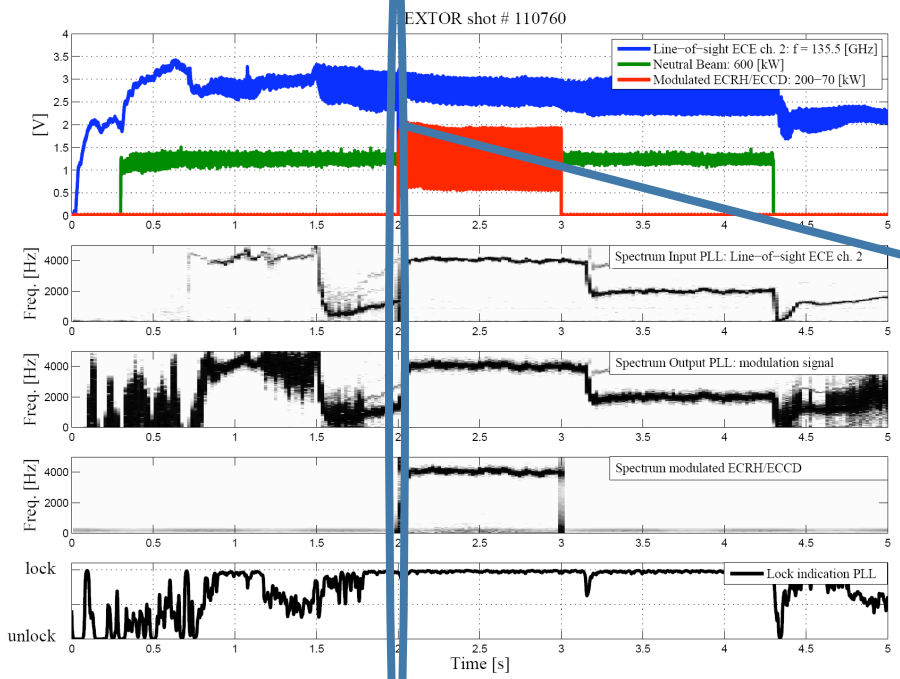
- Continuous ECRH/ECCD 200 kW, 1 sec.
- DED triggered

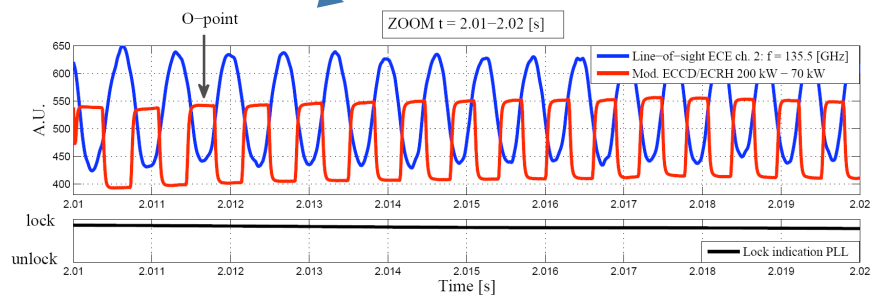
  m/n = 2/1 mode

- Controller active from t = 2-4 sec.
- Automatic trigger gyrotron

Experimental Results (5)

- Synchronous ECRH/ECCD modulation on O-point





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