FEST seminar

January 7, 2014

Tearing Mode Analysis and Modeling of Advanced Tokamak Discharges

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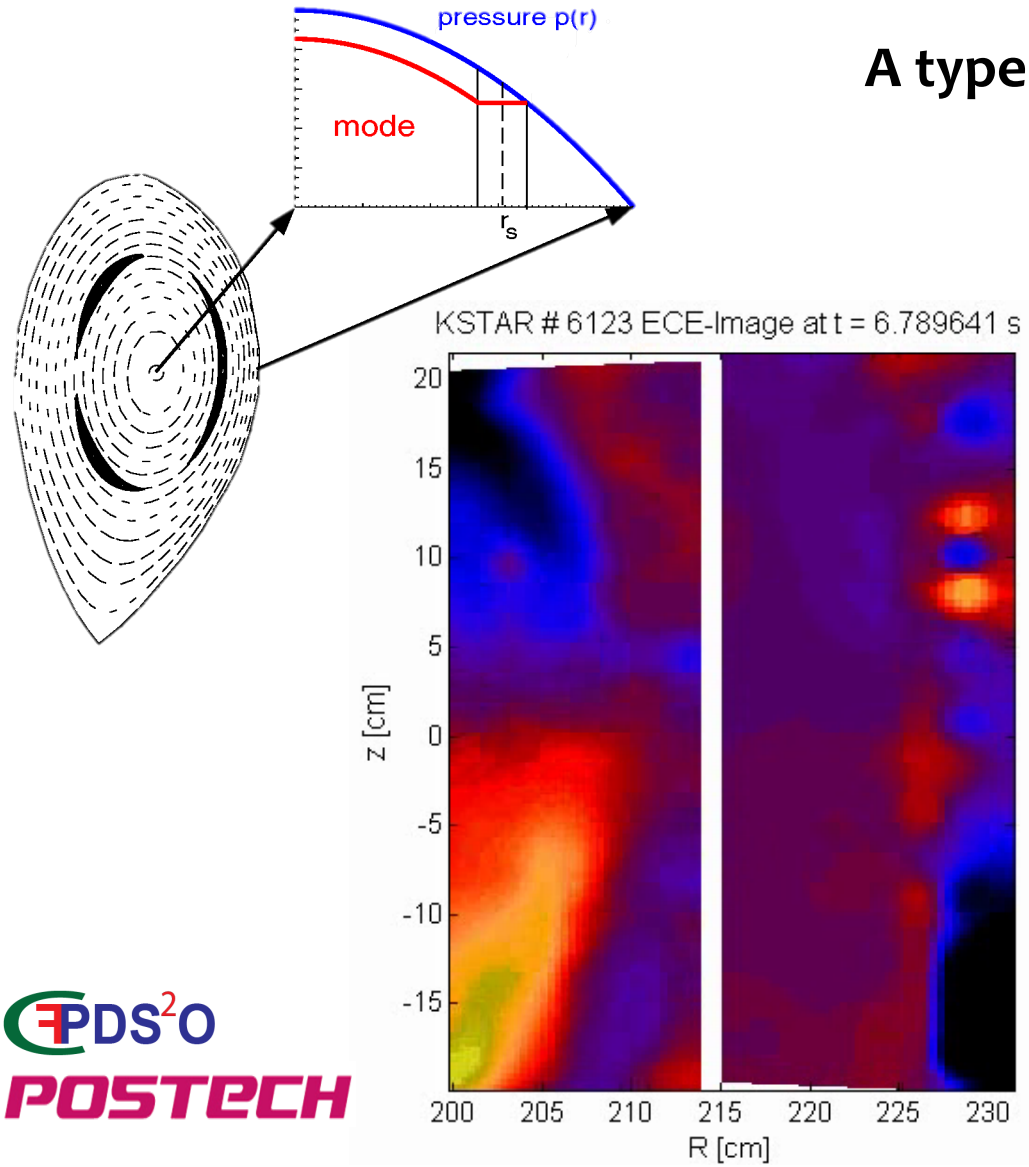
FUSMA Fusion and Plasma Application Lab.

KSTAR NFRI

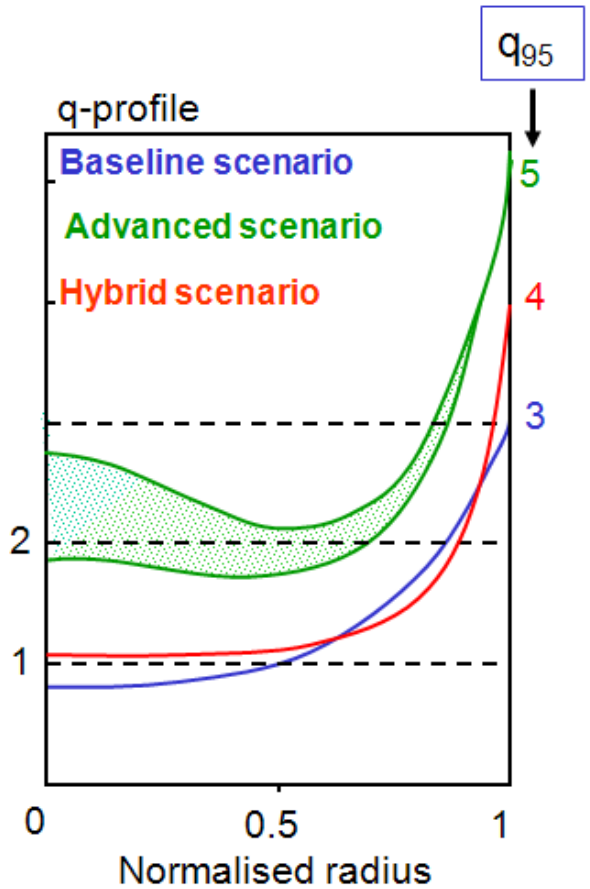
Tearing Mode / Neoclassical Tearing Mode

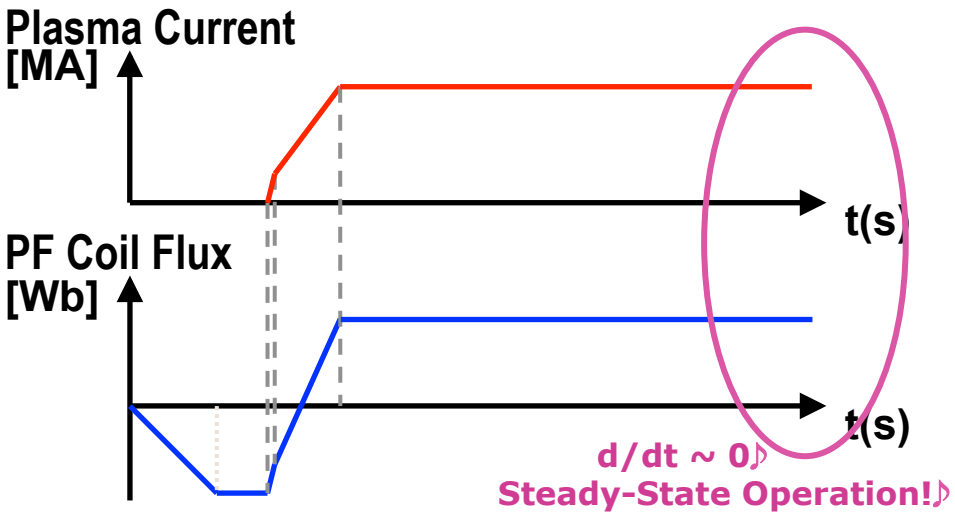


A type of resistive MHD instability

- Destabilize magnetic island that can significantly degrade confinement and even disruption.
- Its avoidance or control is major concern to achieve high fusion performance.
- Triggered by a perturbation of the bootstrap current due to the local flattening of the pressure profile over seed magnetic islands produced by MHD events, such as sawteeth
- Applying ECH/CD parallel to plasma current localized to the island makes the linear stability increase and replace the missing bootstrap current inside island.

Why important?





- the current profile can be broadened and the central value of q is raised by a relatively benign m/n=3/2 NTM
- more dangerous under high bootstrap current condition

Modified Rutherford Equation (MRE)

Estimate for island growth or decay

classical tearing index

stabilization
by small island effect

$$\frac{\tau_R}{r_s}\frac{dw}{dt} = \Delta'_0 r_s + \varepsilon^{1/2}\frac{rL_q}{L_{pe}}\beta_{\theta e}\left[\frac{1}{w} - \frac{w_{marg}^2}{3w^3}\right]$$

normalized growth rate

destabilization
by bootstrap current effect

$$\varepsilon = r_s / R$$

$$L_q = q/(dq/dr) \qquad L_{pe} = -p_e/(dp_e/dr) \qquad \beta_{\theta e} = 2\mu_0 p_e / B_\theta^2$$

$$w_{marg} \approx 2\varepsilon^{1/2}\rho_{\theta i}, \text{ where } \rho_{\theta i} = (2m_i k_b T_i / e^2 B_\theta^2)^{1/2}$$

Modified Rutherford Equation with EC effect

stability enhanced by ECCD

stabilization
by ECCD effect

$$\frac{\tau_R}{r_s}\frac{dw}{dt} = \Delta'_0 r_s + \delta\Delta' r_s + a_2 \frac{j_{bs}}{j_{\parallel}}\frac{L_q}{w}\left[1 - \frac{w_{marg}^2}{3w^2} - K_1\frac{j_{ec}}{j_{bs}} - \alpha_H F_H \frac{w}{w_{dep}}\frac{P_{ec}\eta_H}{I_{ec}}\right]$$

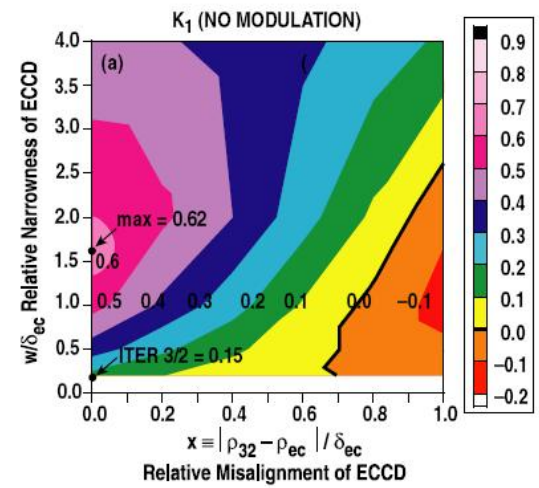
destabilization
by bootstrap current effect

stabilization
by ECH effect

$$\delta\Delta' r_s \approx -\frac{5\pi^{3/2}}{32} a_2 \frac{L_q}{\delta_{ec}} F(e) \frac{j_{ec}}{j_\phi}\tau,$$

where $F(e) = 1 - 2.43e + 1.40e^2 - 0.23e^3$

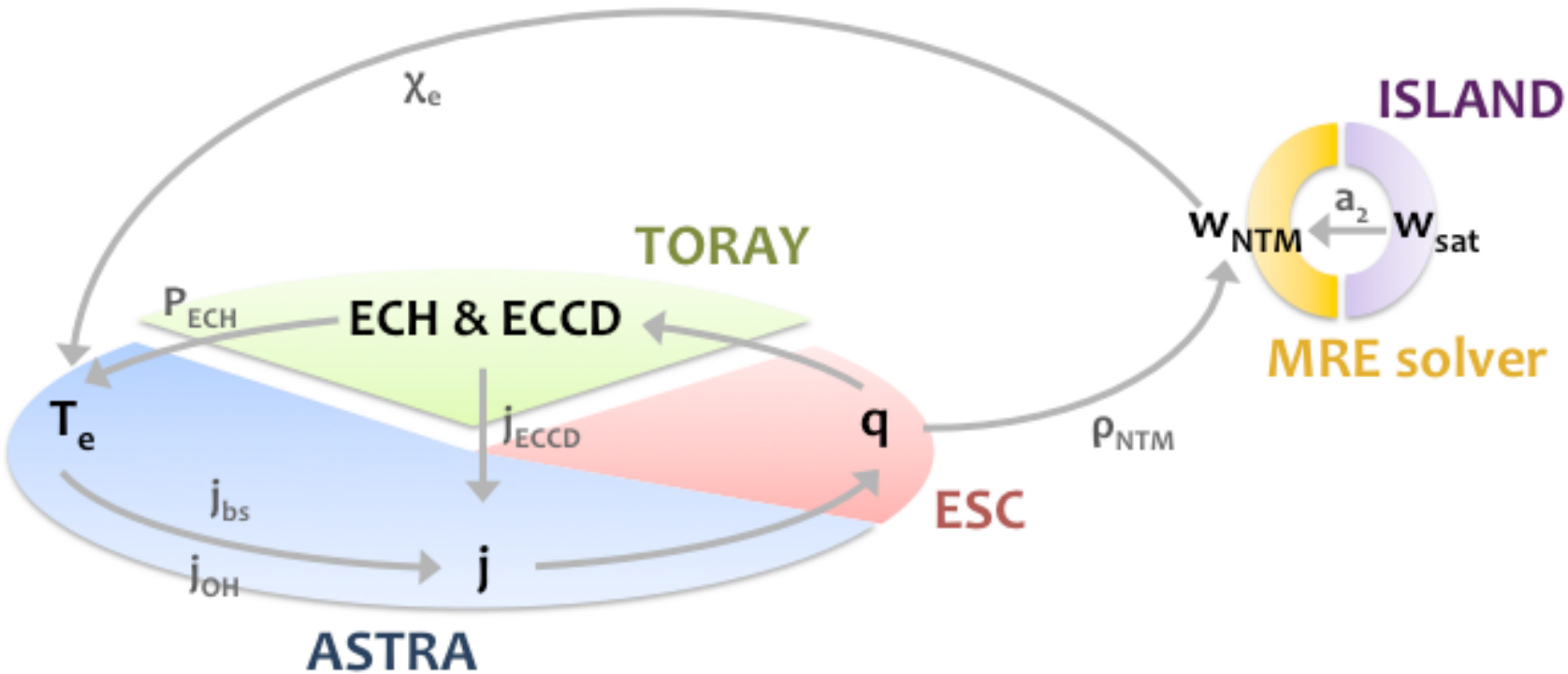
a_2 fitted by inferred size of saturated island from ISLAND or estimated by experiments



** D. De Lazzari, et al., Nuclear Fusion **49** 075002 (2009)

* R. J. La Haye, et al., Nuclear Fusion **46** 451 (2006)

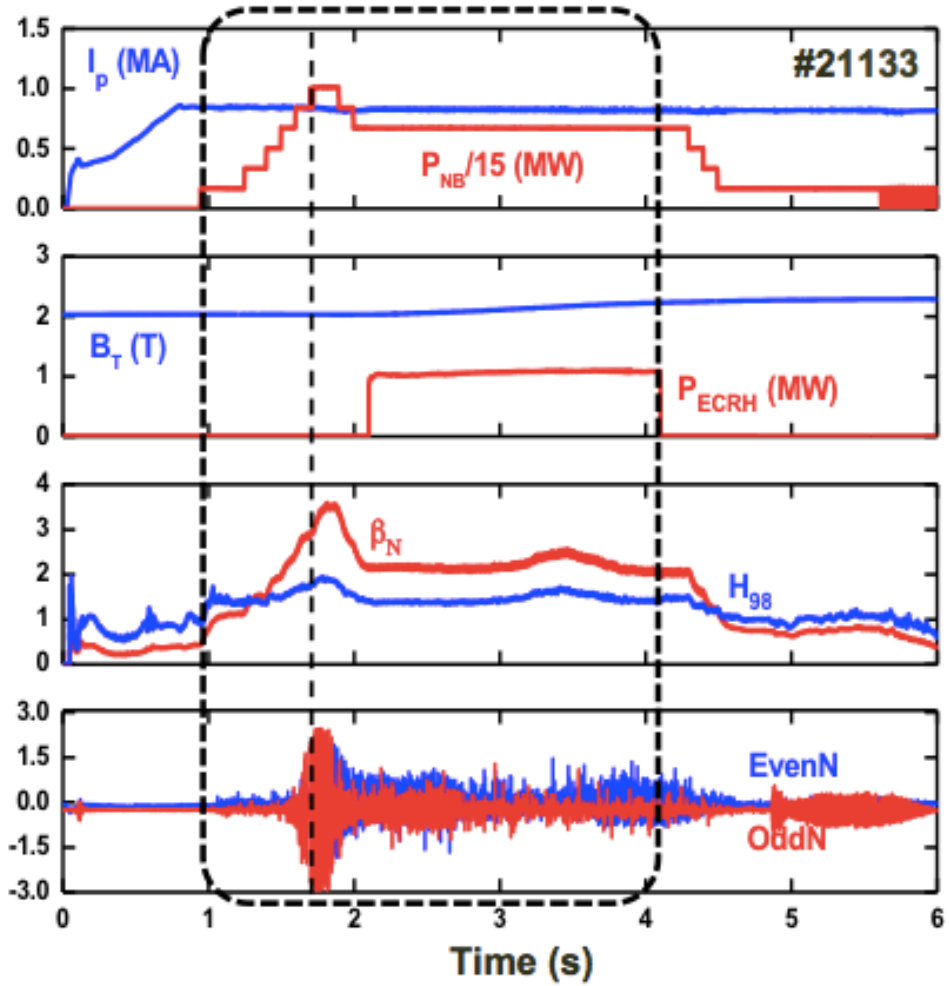
The integrated system for self-consistent simulations

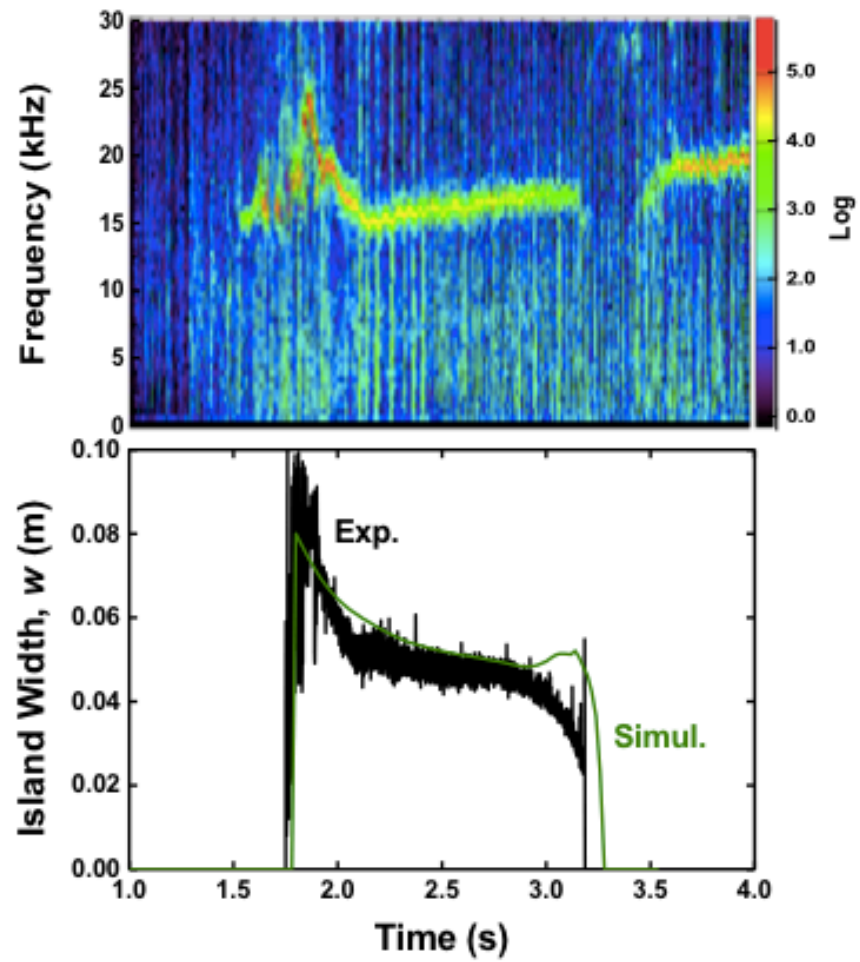


- Plasma equilibrium, current diffusion, heat transport, ECH/CD, and island growth calculated in a self-consistent way.

Validation of NTM model against experiments in AUG

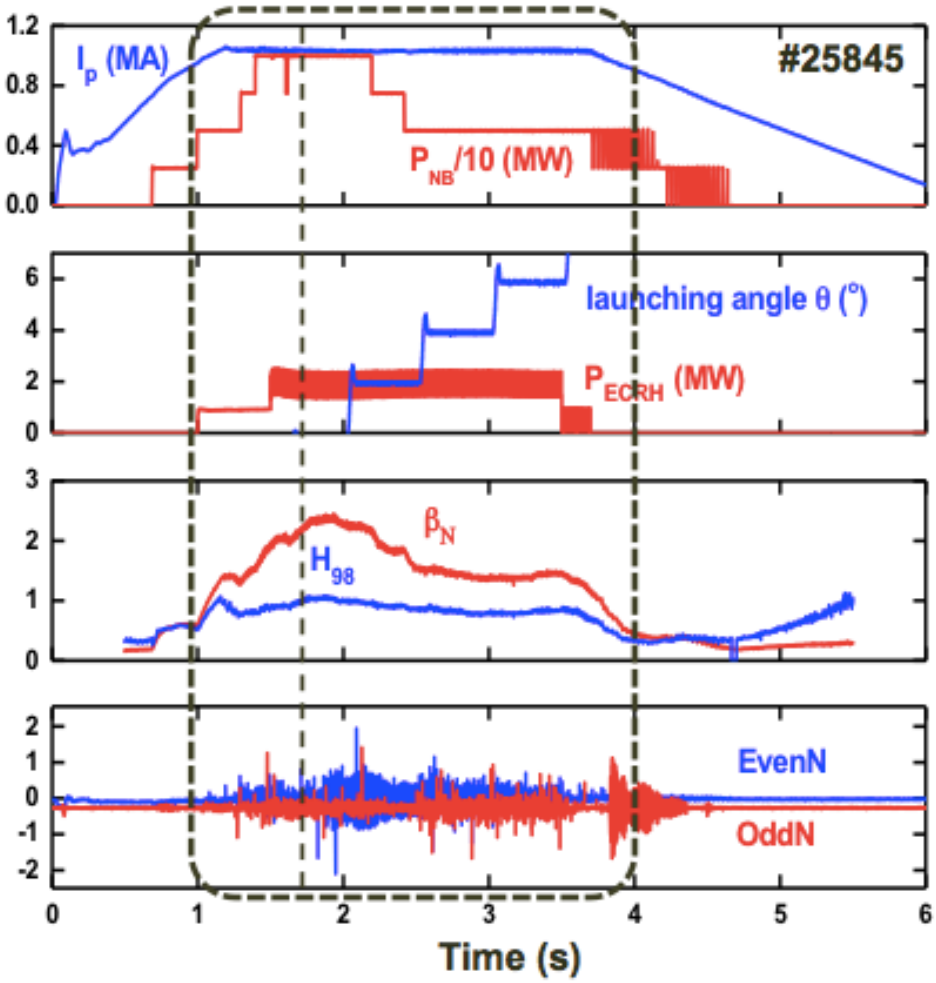
(3,2) NTM stabilization experiment by B_T scan

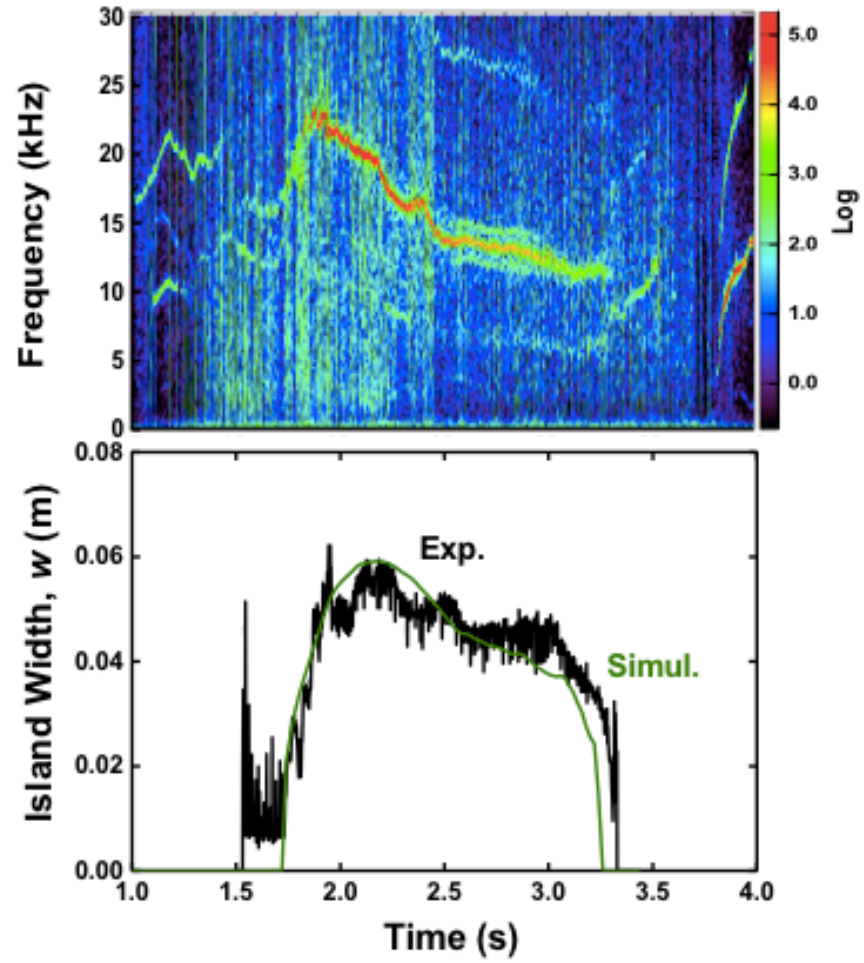




Validation of NTM model against experiments in AUG

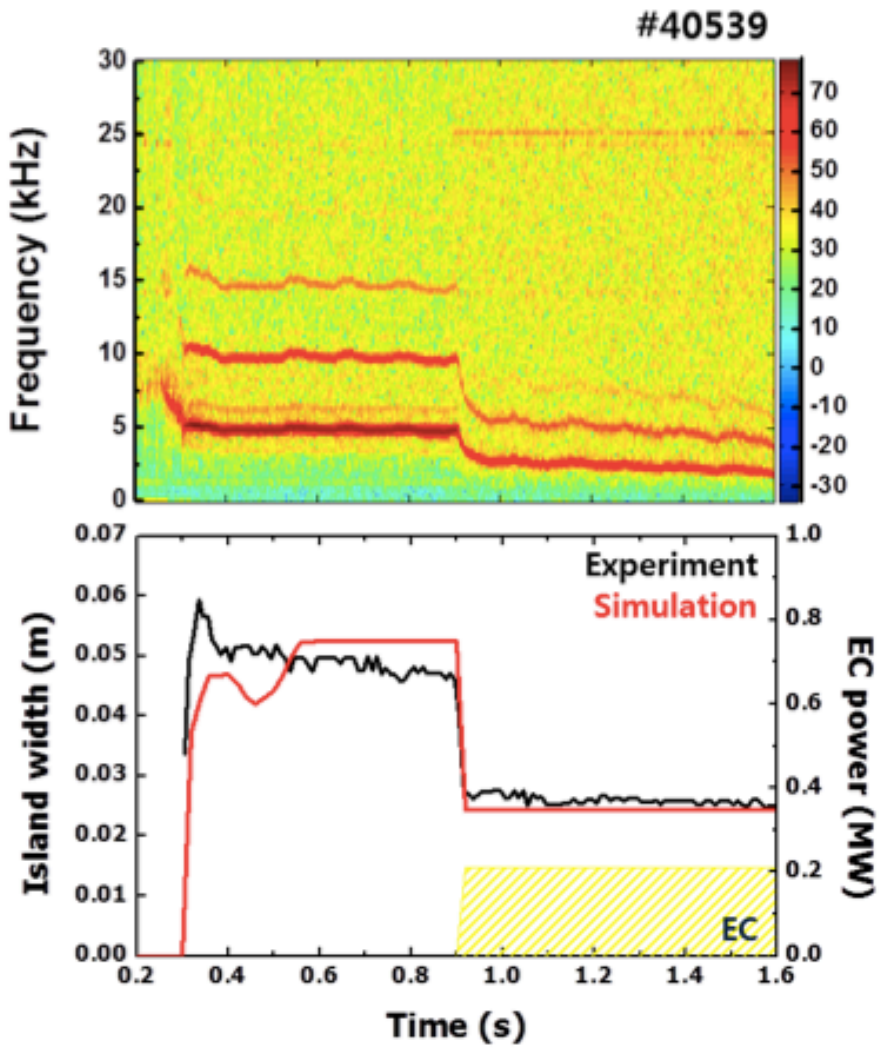
Feed-forward (3,2) NTM stabilisation experiment



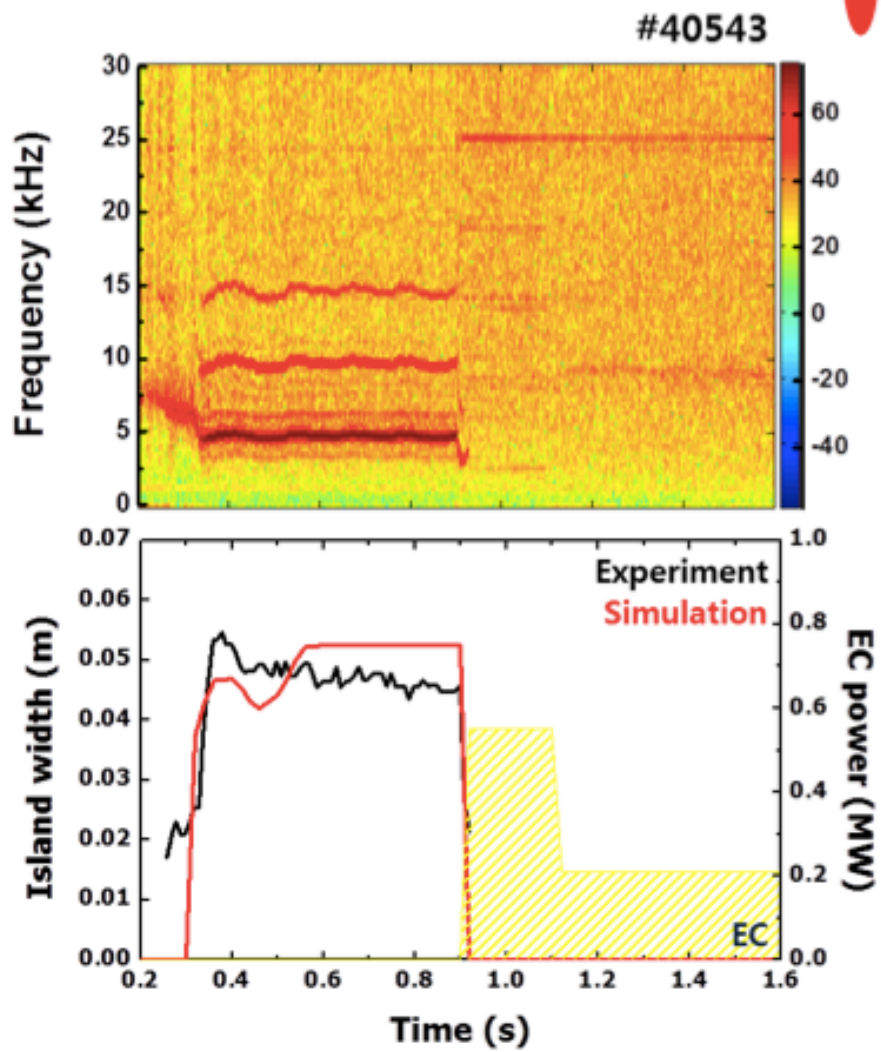


Validation of NTM model against experiments in TCV

Partial stabilization



Full stabilization



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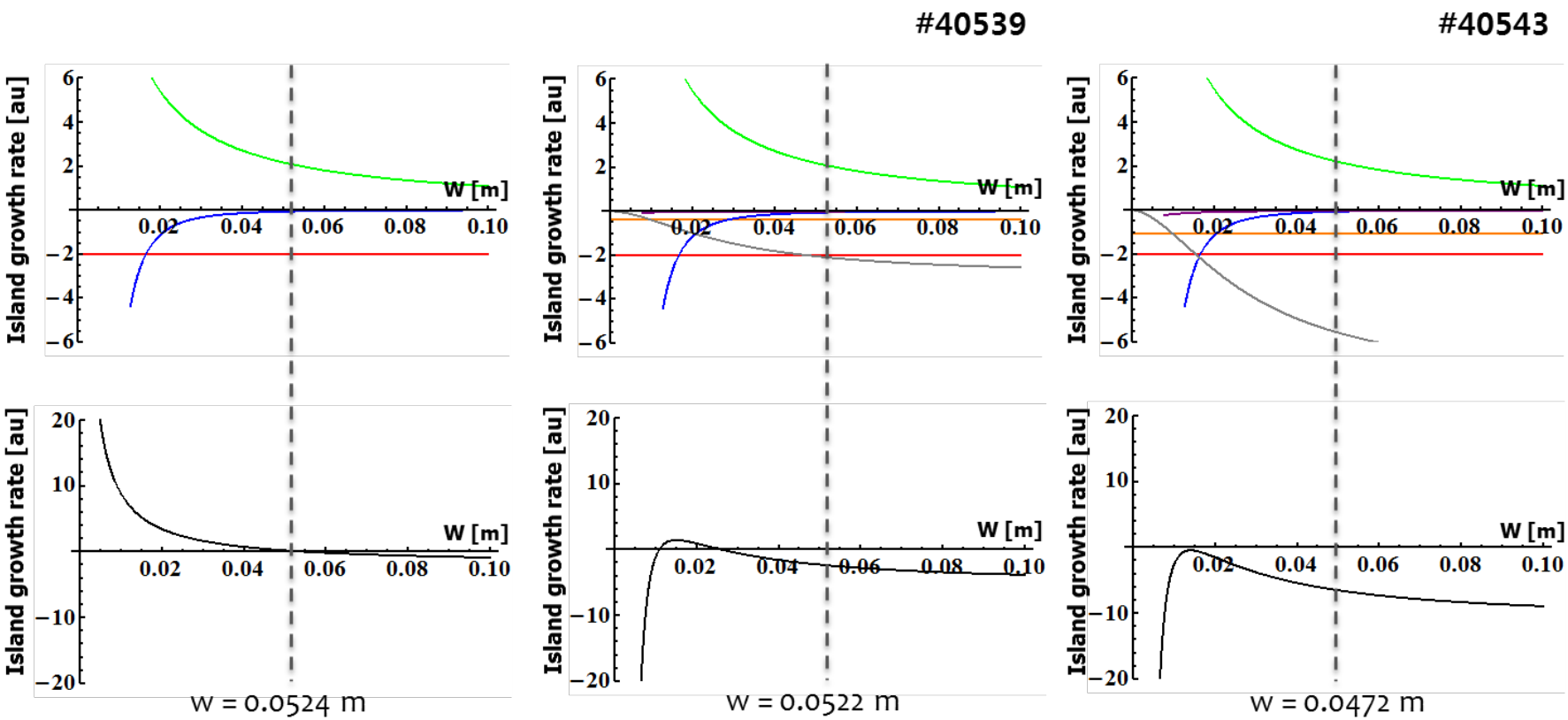
Validation of NTM model against experiments in TCV

$$\frac{\tau_R}{r_s}\frac{dw}{dt} = \Delta'_0 r_s + \delta\Delta' r_s + a_2 \frac{j_{bs}}{j_{\parallel}}\frac{L_q}{w}\left[1 - \frac{w_{marg}^2}{3w^2} - K_1\frac{j_{ec}}{j_{bs}} - \alpha_H F_H \frac{w}{w_{dep}}\frac{P_{ec}\eta_H}{I_{ec}}\right]$$

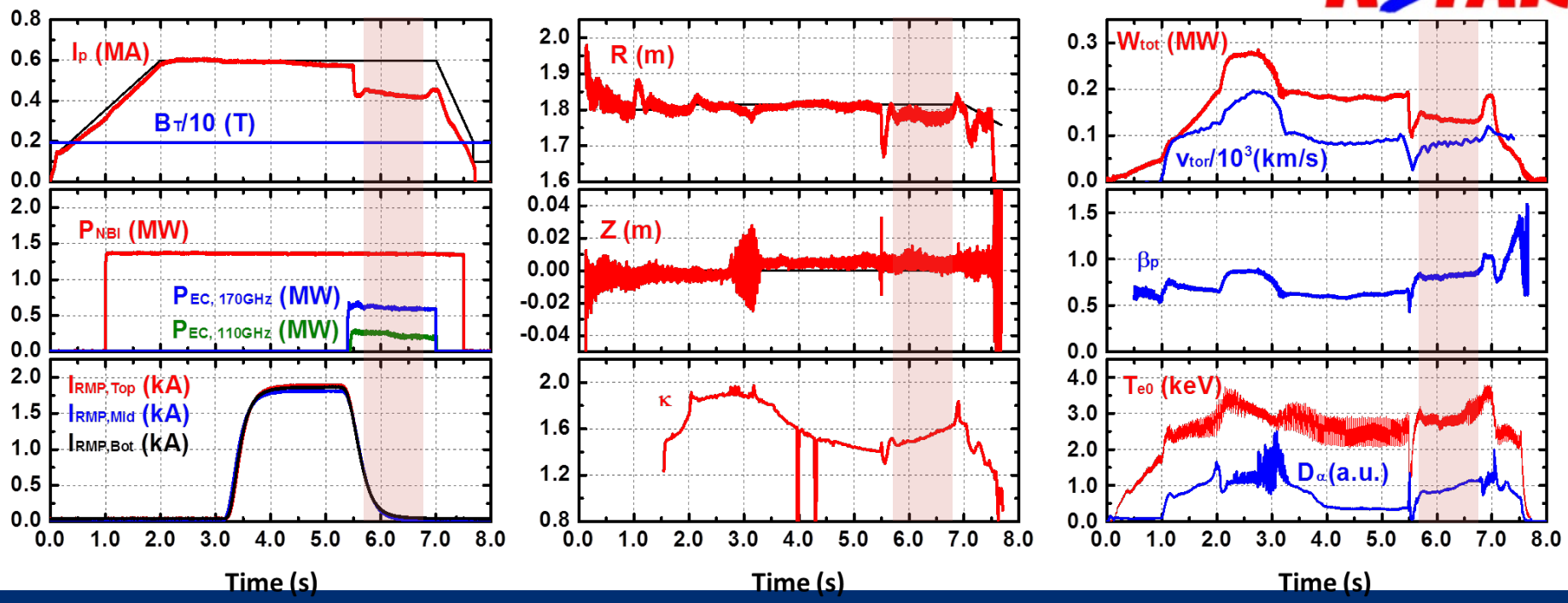
At 0.6 s (Saturated island)

At 0.9001 s (after EC injection)



Overview of Stabilisation experiment in KSTAR (#6272)

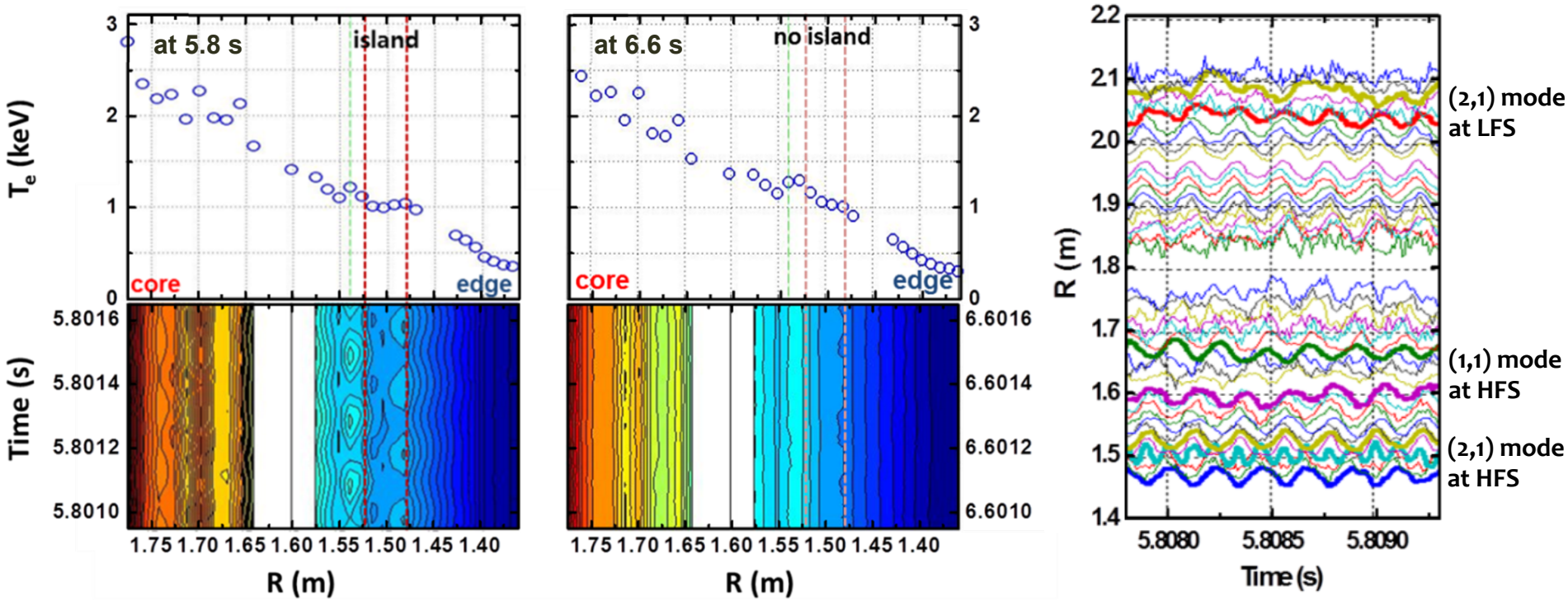
- During 2011 campaign of KSTAR,
  it was observed in L-mode plasmas with non-axisymmetric MP by external coils.
- At 5.4 s around ramping down of the MP coil currents,
  the off-axis ECH/CD were injected to the estimated island position.
- Immediately after the ECH/CD injection,
  the plasma moved radially inward and collided with the wall around 5.5 s
  which results in unexpected reduction of the plasma current to ~0.4 MA.
- The TM was occurred around 5.6 s.



Identification of island width and location

The local flattening and phase inversion of ECE signals

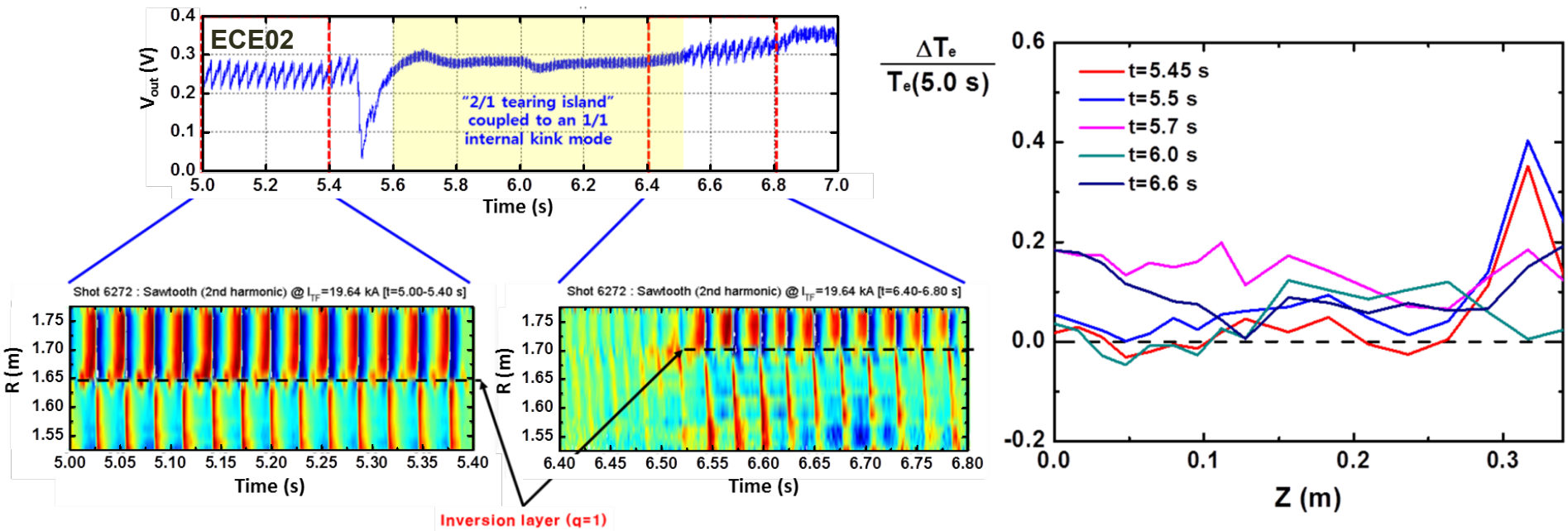
- A consequence of the mode activity appears around R = 1.5 m (HFS) and 2.05 m (LFS) during the TM phase (5.8 s), that disappear clearly after the mode is stabilised (6.6 s).
- Another phase inversion observed in temperature oscillations around R = 1.65 m is estimated to be (1,1) mode inferred from the inversion radius of the sawtooth.



Identification of island width and location

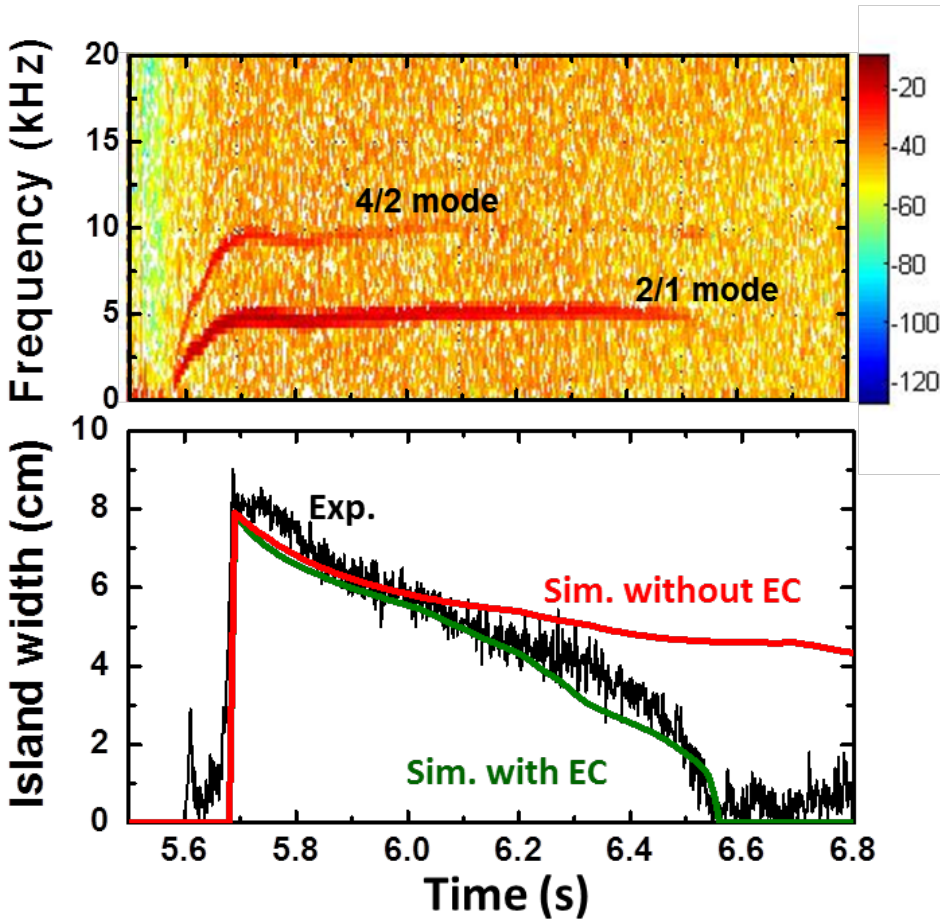
Evaluation of ECH/CD alignment to island position by XCS data

- Temporal and local increase of the T_e is observed around Z = 0.3-0.35 m which corresponds with the location of island O-point, R ~ 1.5 m.
- The hump correlated with the ECH deposition is observed to relax when the TM is supposed to take place yields that the island locates around the ECH deposition. The hump rises again after full suppression of the mode (6.6 s).



Simulation of the island evolution with ECH/CD

- The simulation starts at 4.0 s with initial plasma condition taken from the experiment at 5.0 s to adjust the proper q-profile.



- A seed island is forced to appear at 5.65 s with 8 cm similar to experimental island width*.

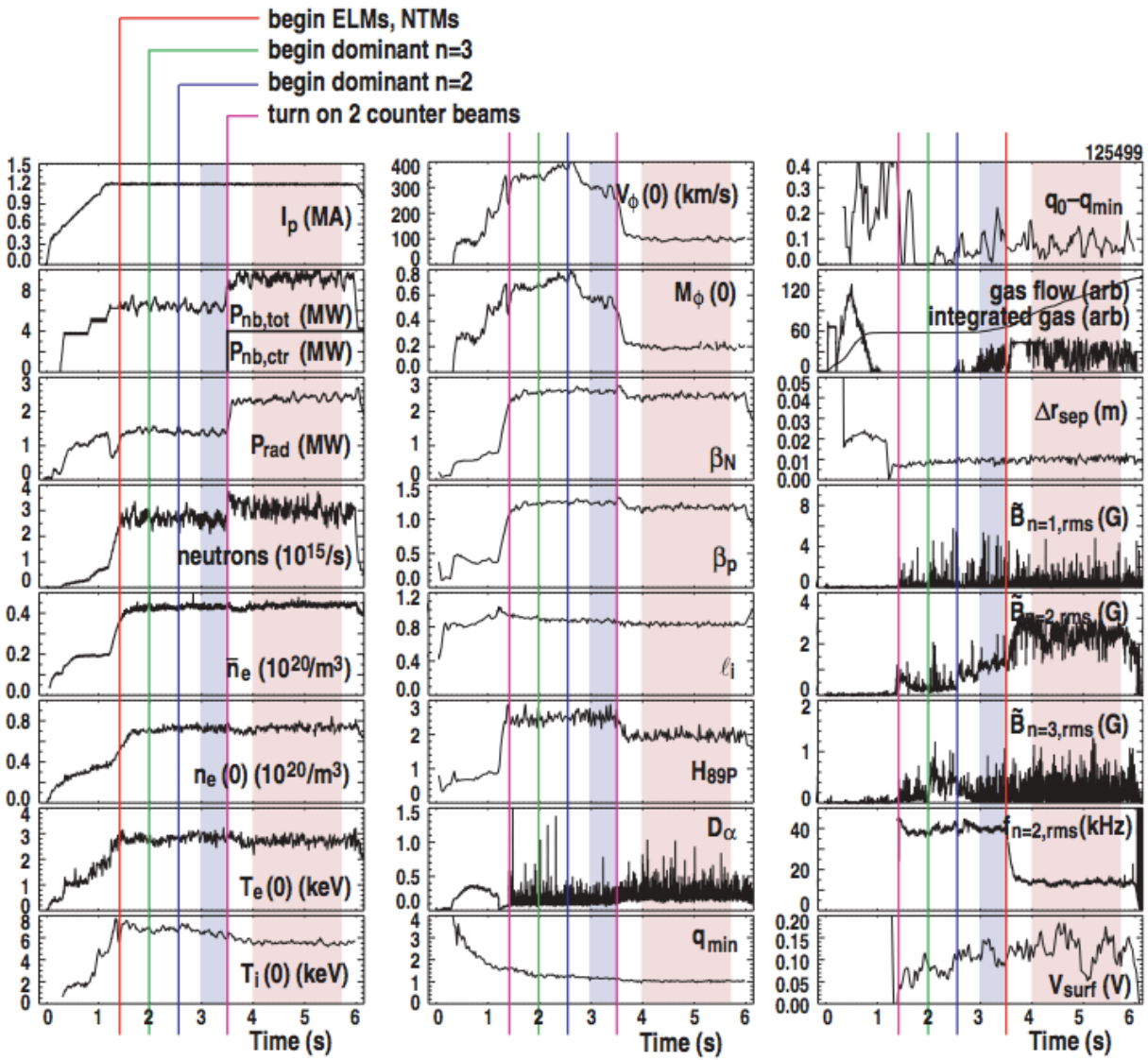
$$w = \left(\frac{16 r R_0 \left| \tilde{B}_r \right|}{3 s B_{\phi 0}} \right)^{1/2}, \text{ where } \left| \tilde{B}_r \right| \approx \frac{1}{2} \left(\frac{b}{r} \right)^{m+1} \left| \tilde{B}_\theta \right|_{wall}$$

- By including the EC effect in MRE, the simulation is in good agreement with the experiment while not if turning off the EC effect.

- If there is no EC to the island position, the mode may exist with the saturated size ~5 cm until the end of ramp down phase.

* *R. J. La Haye, et al., Phys. Plasmas* **7** *3349 (2000)*

Overview of Hybrid discharges in DIII-D



Hybrid scenario at low rotation

- to determine and evaluate changes in the current and q profiles with mixture of co- and counter- NBI
- to study changes in the MHD behavior as the rotation is reduced
- 3 counter- NBI power scan with β_N=2.6
  - q_{95}=4.0 or 4.5
  - <ne>=3.3 or 4.3 x10^{19}m^{-3}
- m/n=3/2 mode occurs and dominants

* *P. A. Politzer, et al., Nucl. Fusion* ***48*** *075001 (2008)*

Database of Hybrid discharges in DIII-D

Varying input torque under otherwise constant conditions

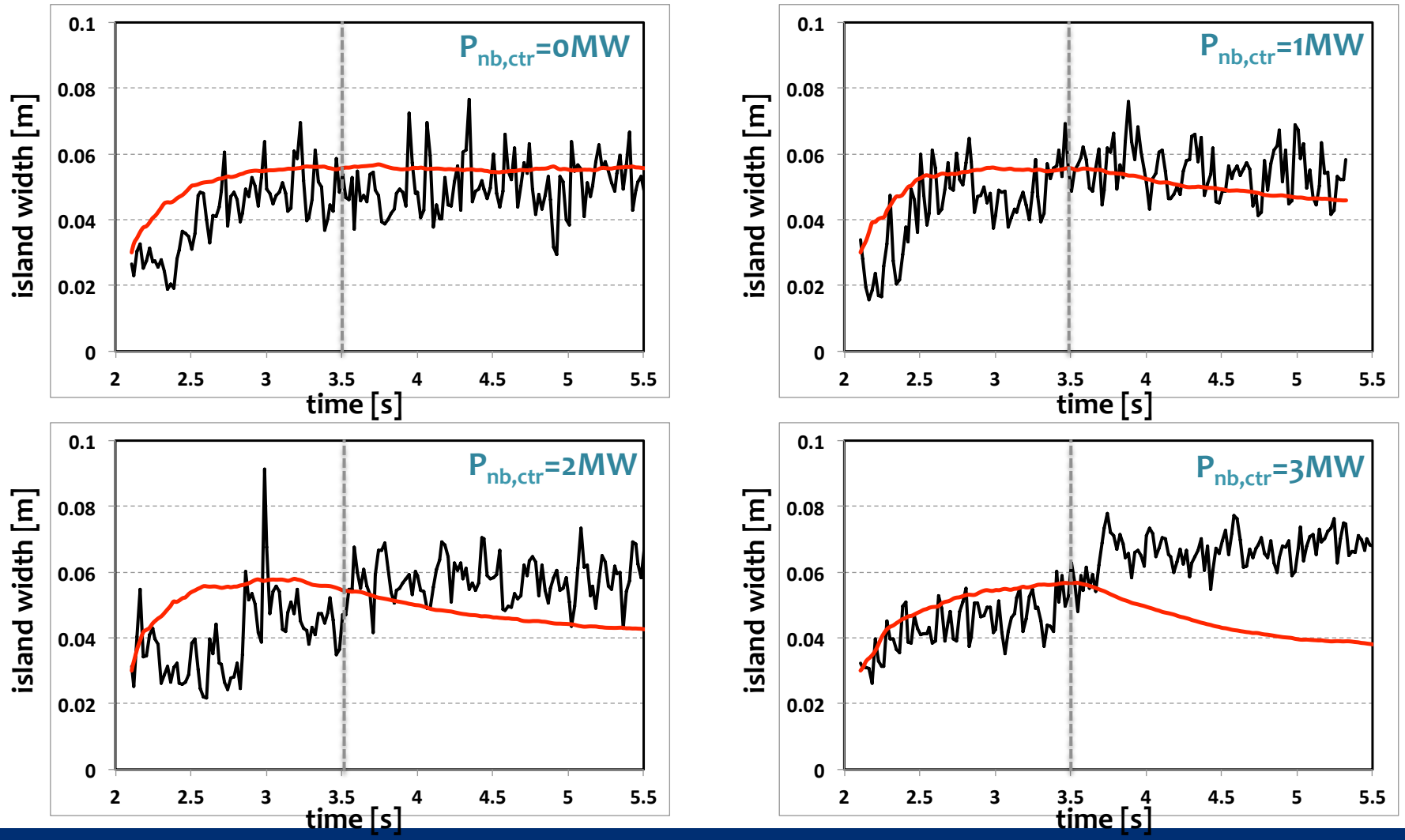
	$\langle ne \rangle = 3.3 \times 10^{19} m^{-3}$	$\langle ne \rangle = 4.3 \times 10^{19} m^{-3}$
$q_{95}=4.0$ ♪	#125469 ($P_{nb,ctr}$ =0MW) #125471 ($P_{nb,ctr}$ =1MW)♪ #125474 ($P_{nb,ctr}$ =2MW) #125475 ($P_{nb,ctr}$ =3MW)♪ #125476 ($P_{nb,ctr}$ =4MW)♪	
$q_{95}=4.5$ ♪	#125481 ($P_{nb,ctr}$ =0MW) #125482 ($P_{nb,ctr}$ =1MW)♪ #125483 ($P_{nb,ctr}$ =2MW) #125492 ($P_{nb,ctr}$ =4MW)♪ #125494 ($P_{nb,ctr}$ =3MW)♪	#125495 ($P_{nb,ctr}$ =0MW) #125496 ($P_{nb,ctr}$ =1MW)♪ #125497 ($P_{nb,ctr}$ =2MW) #125498 ($P_{nb,ctr}$ =3MW)♪ #125499 ($P_{nb,ctr}$ =4MW)♪

Calculations of the island evolution

exp. condition: q_{95}=4.0 with <ne>=3.3x10^{19}m^{-3}

calculated width from exp.

calculated width from MRE



Calculations of the island evolution

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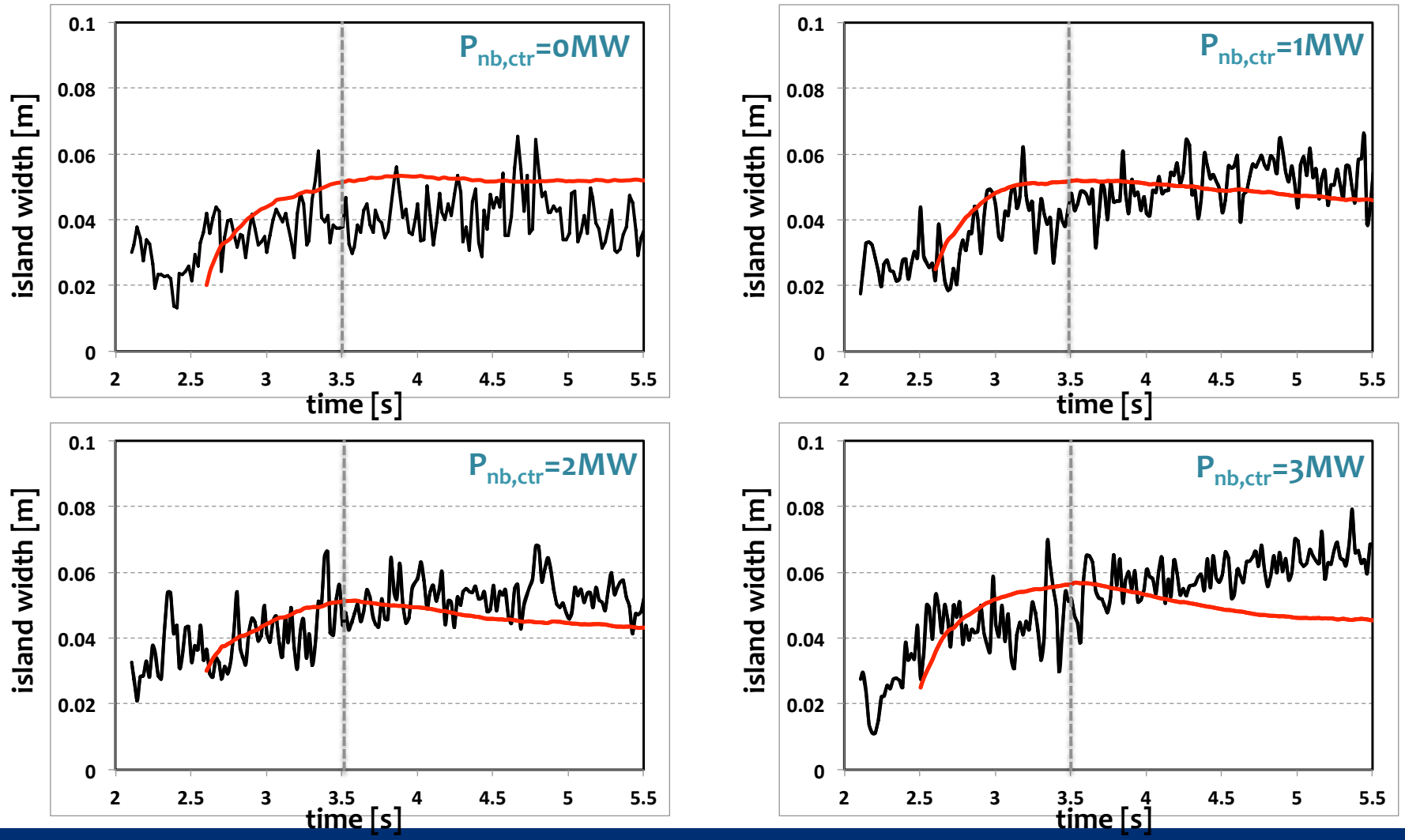
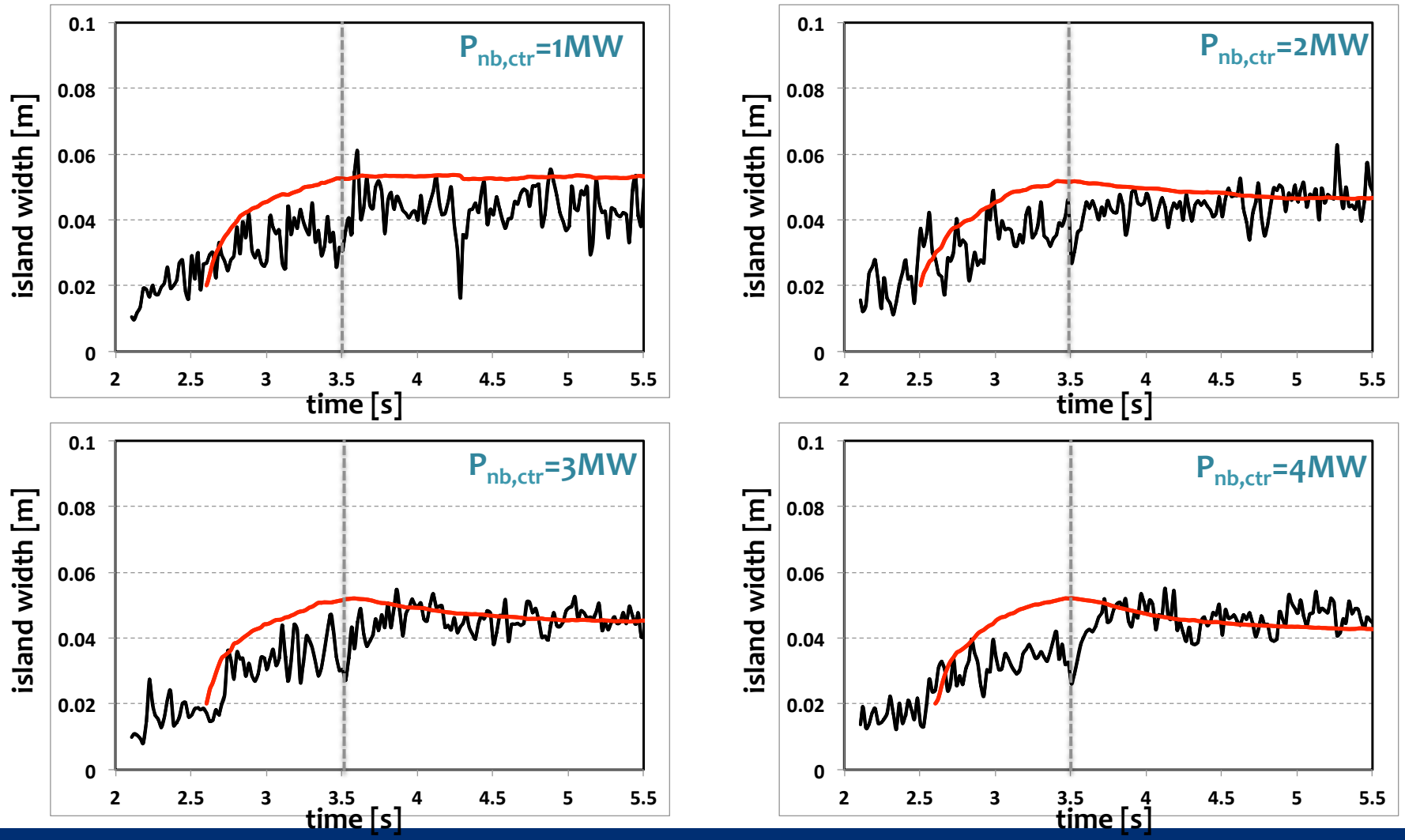


Calculations of the island evolution

exp. condition: q_{95}=4.5 with <ne>=4.3x10^{19}m^{-3}

calculated width from exp.

calculated width from MRE

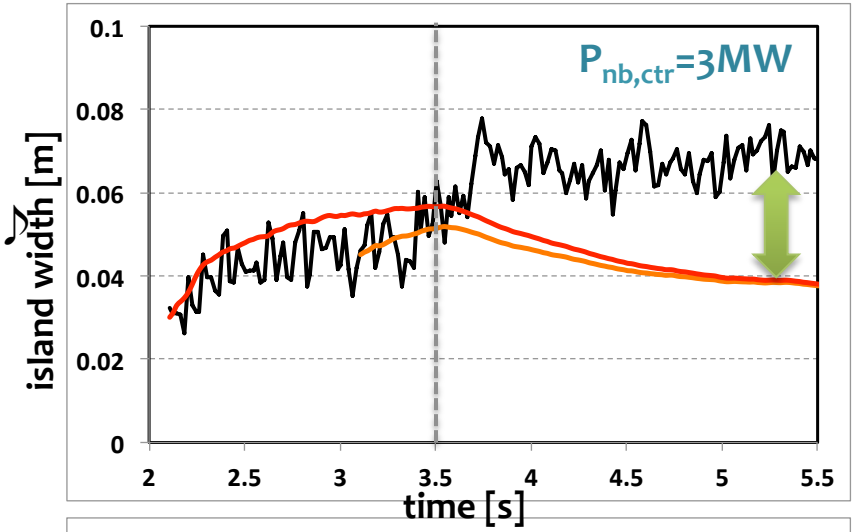


Difference between the island width at low rotation

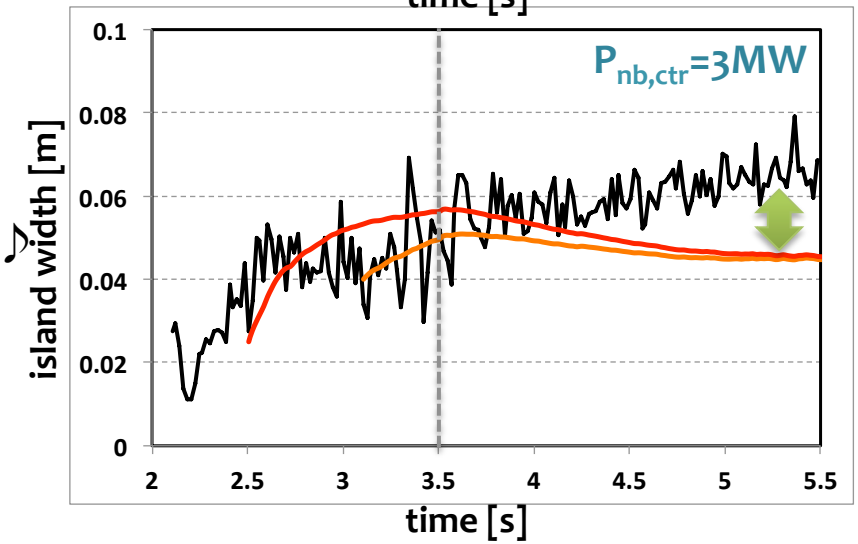
<ne>=3.3x10^{19}m^{-3}

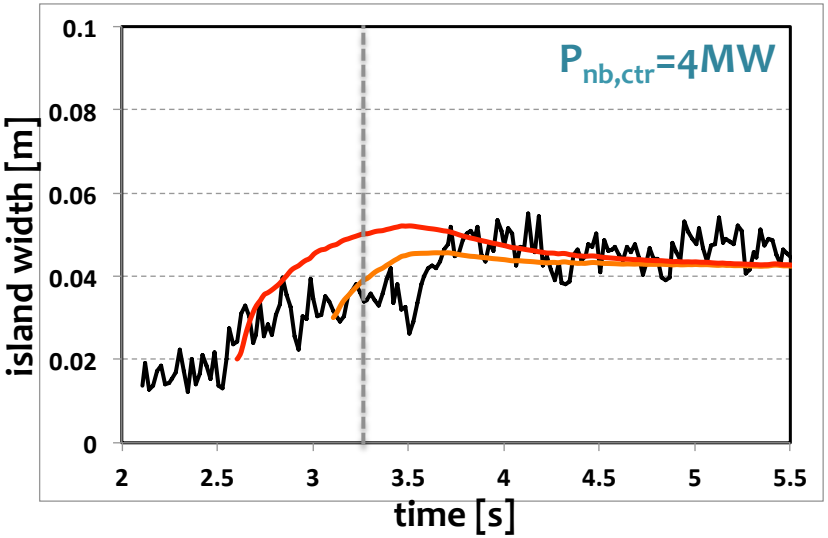
<ne>=4.3x10^{19}m^{-3}

q_{95}=4.0



q_{95}=4.5



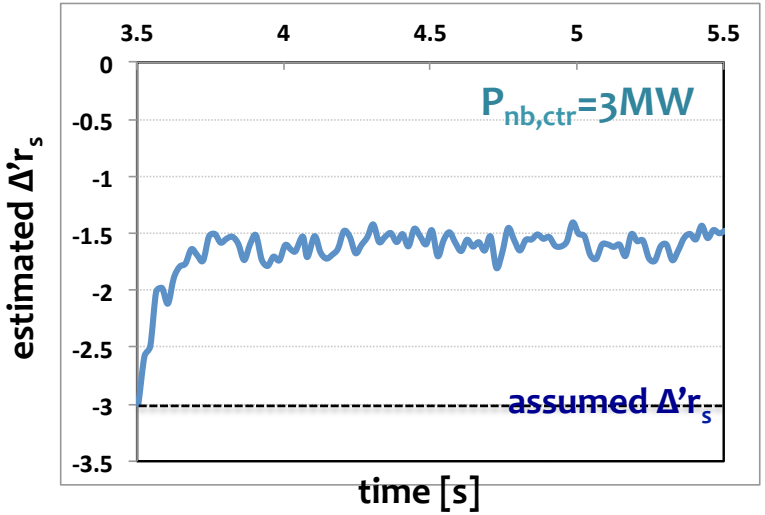


Estimation of $\Delta' r_s$ with saturated island at low rotation

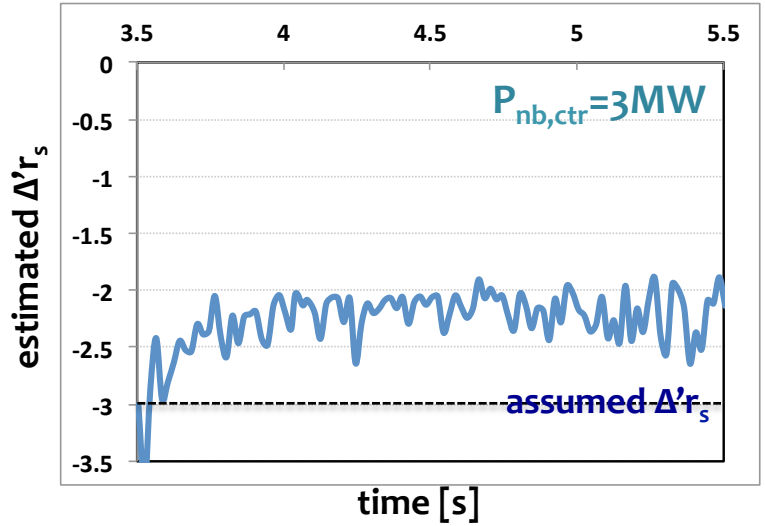
<ne>=3.3x10^{19}m^{-3}

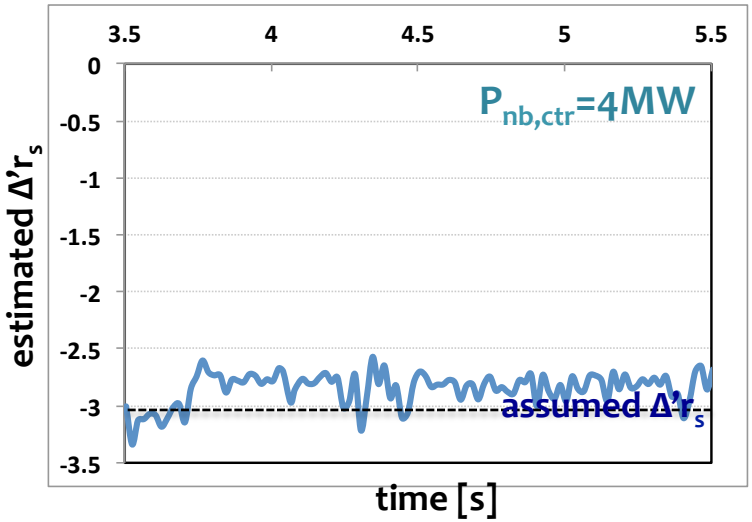
<ne>=4.3x10^{19}m^{-3}

q_{95}=4.0 ♪



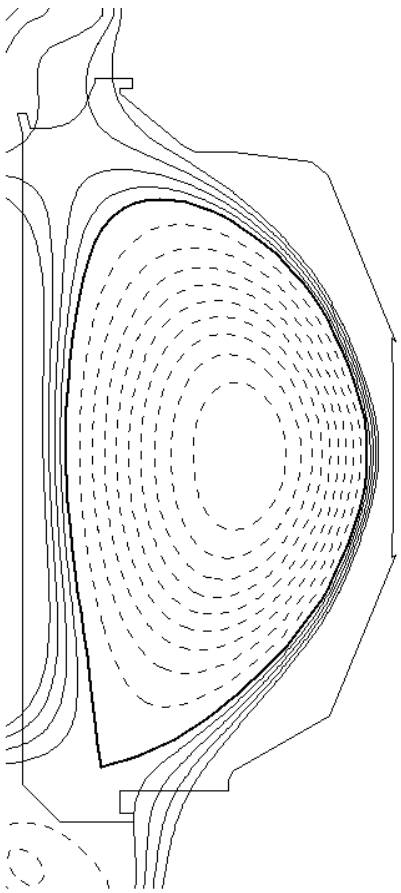
q_{95}=4.5 ♪

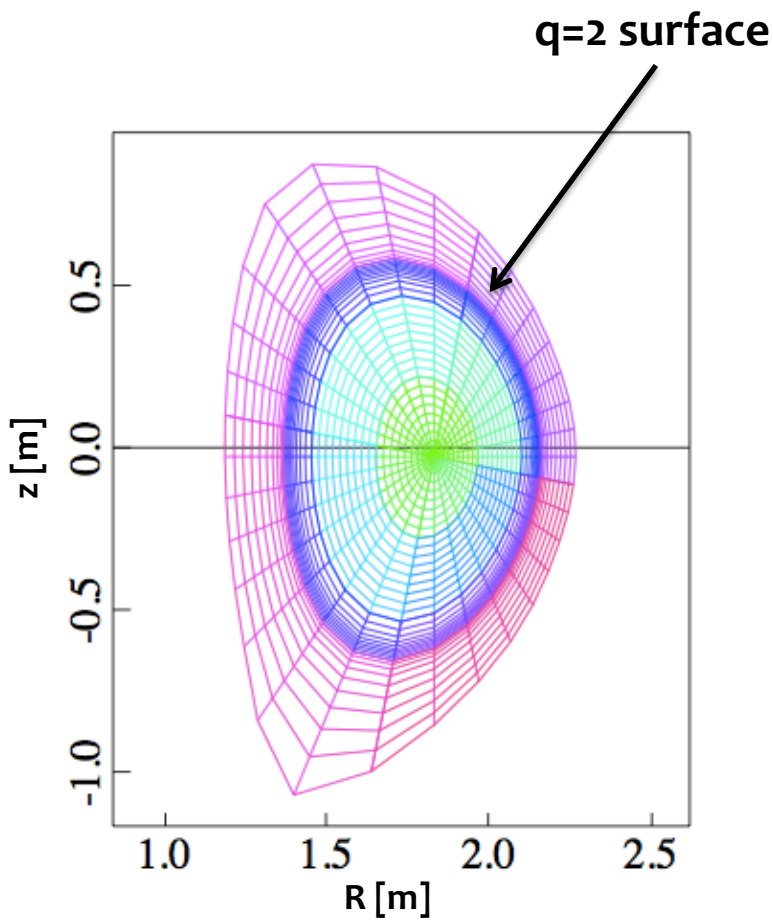




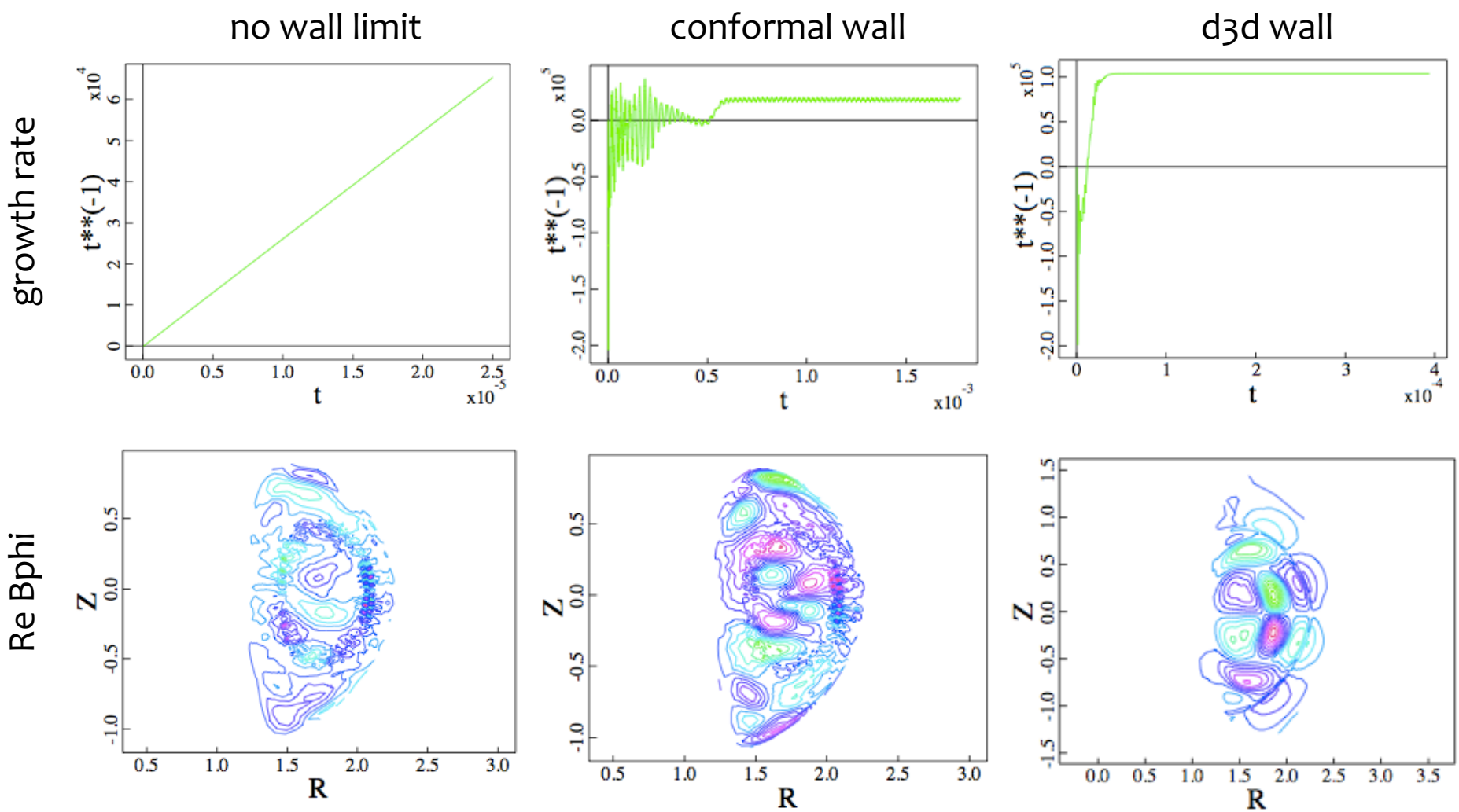
Preliminary results from NIMROD

Finite element mesh using DIII-D equilibrium (#153698)





Preliminary results from NIMROD



TM/NTM analysis for DIII-D high β steady-state discharges

Investigation of Δ'r for TM/NTM analysis

- **In previous simulations, Δ'r was assumed as –m**
  - Δ'r represents the free energy available to the mode from the current gradient
  - In general, it is difficult to determine an accurate Δ'r because the radial derivative of the current profile, dJ/dr, is required
- **Cross validation and verification among codes against experiments**
  - Δ'r can be calculated using codes such as ISLAND and PEST-III
  - From experimental data?

Simulation of TM/NTM behavior using nonlinear MHD codes

- **Magnetic Reconnection study and implementation for TM/NTM analysis**
  - Onset related magnetic reconnection
  - Evolution and saturation of island
  - Simulation with rotation, nonlinear, two fluid effects, and etc.

Contribution to IPS