Stability Studies of Plasmas with Significant Rotational Transform from Toroidal Currents in the W7-AS Stellarator

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A. Weller, E. Sallander*) for the W7-AS Team

MPI für Plasmaphysik, IPP-EURATOM-Assoc., Garching, Germany

*) *Royal Institute of Technology, SE-10044 Stockholm, Sweden*

- essential design element of Wendelstein: suppression of toroidal currents
- New stellarator concepts relying on rotational transform generated by toroidal currents will need to achieve sufficent stability against current driven instabilities.
- Experimental flexibility of W7-AS and good diagnostics may contribute to investigate this issue

Outline:

- Experimental Scenarios of Current Drive Experiments
- Characterization of Instabilities
- Stability Calculations
- Discussion

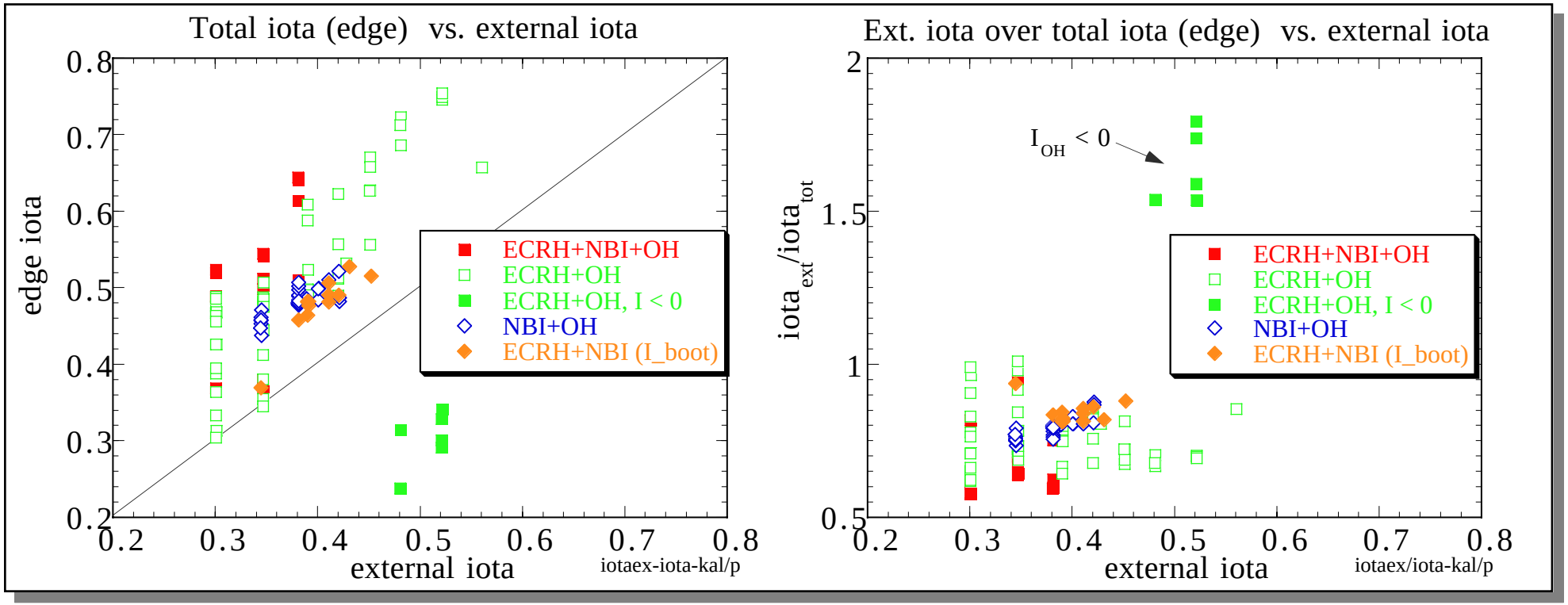
Experiments with Toroidal Current Drive

- Operational Regimes -

- OH-current drive experiments under **different heating** scenarios:
  - NBI target plasmas
  - ECRH target plasmas
  - ECRH+NBI target plasmas
- experiments w/o OH with **maximum bootstrap current** (ECRH+NBI)
- experiments with **negative OH current**

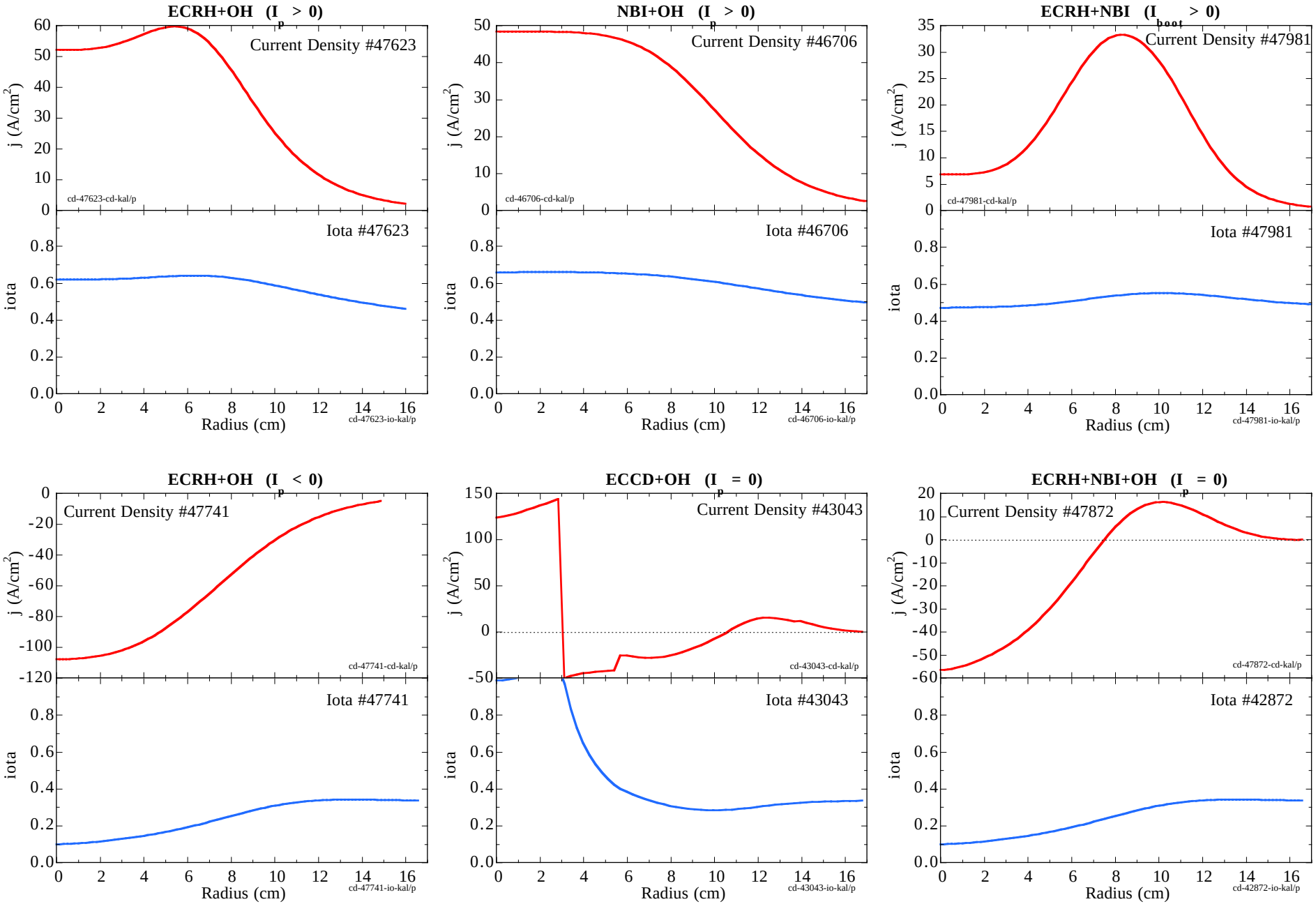
  ⇒ bootstrap current reduces current density in the gradient region !

⇒ variety of different current density profiles investigated



Oak99_exp_ov1.cd

W7-AS Current- and Iota- Profiles for different Heating Scenarios



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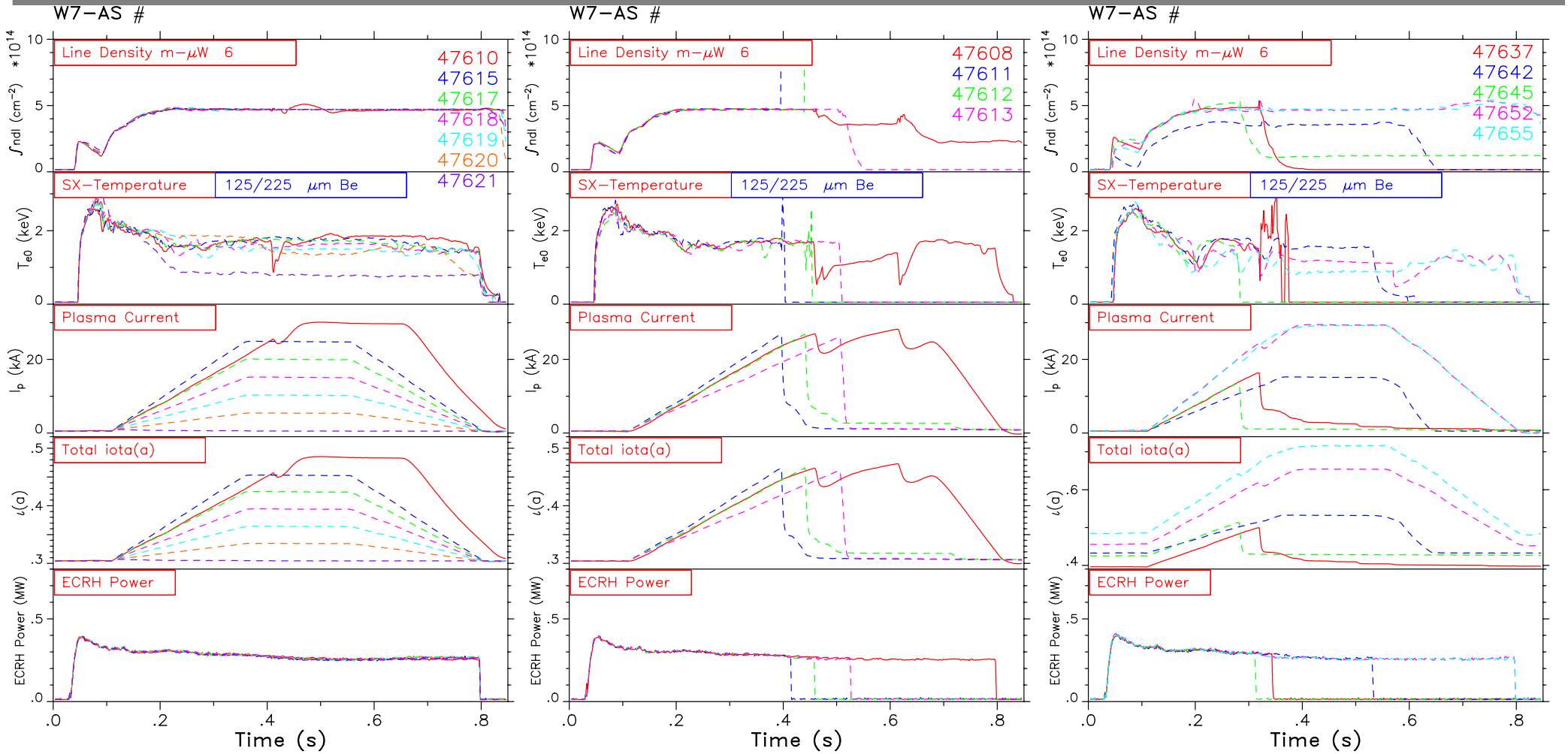
Experiments with Toroidal Current Drive

- Ohmic Current Drive Experiments in ECRH Discharges -



If low order rational surfaces are excluded in the outer plasma, stable plasmas with significant net current can be maintained

Iota = 1/2 disruptive events with (2,1) tearing mode precursors of large amplitudes $\tilde{B}/B \geq 10^{-3}$ appear if iota = 2 is reached with significant current

Current can be driven beyond iota = 1/2 with lower currents and increased external iota. Minor effects of (3,2) tearing modes

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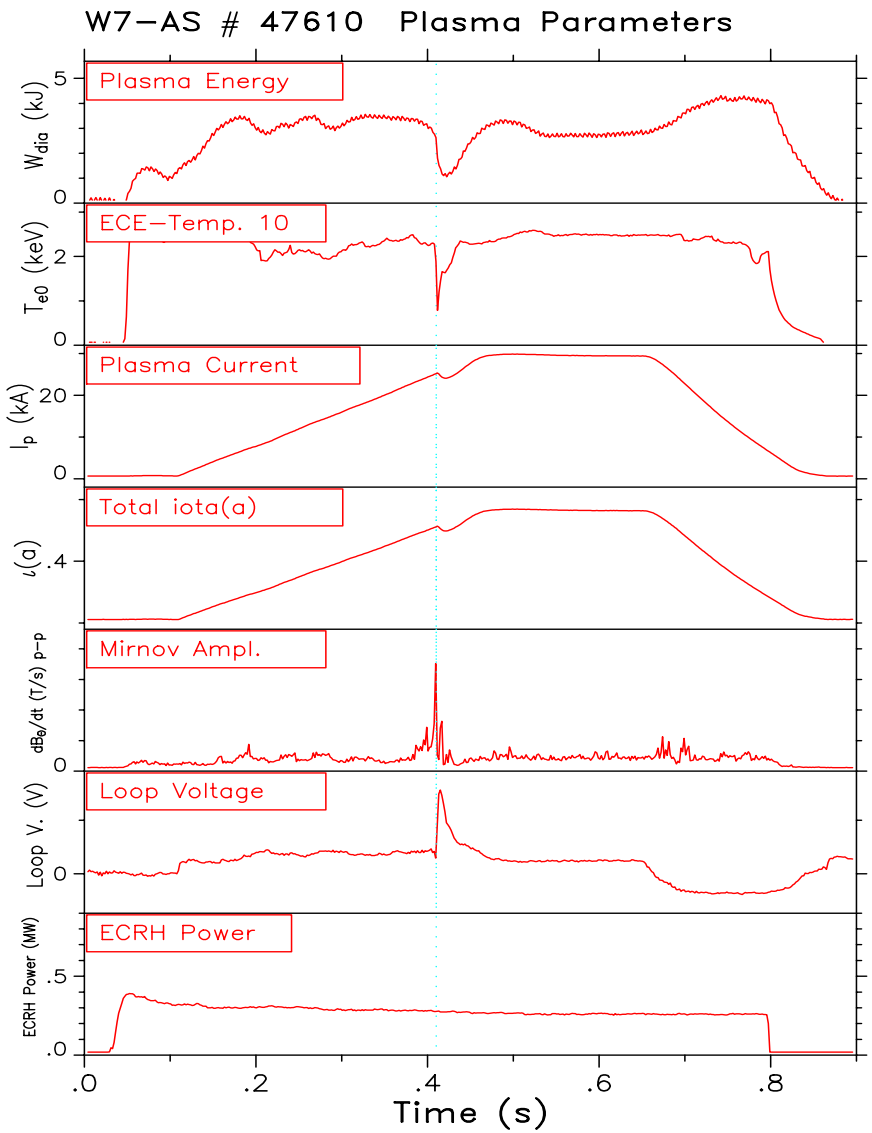
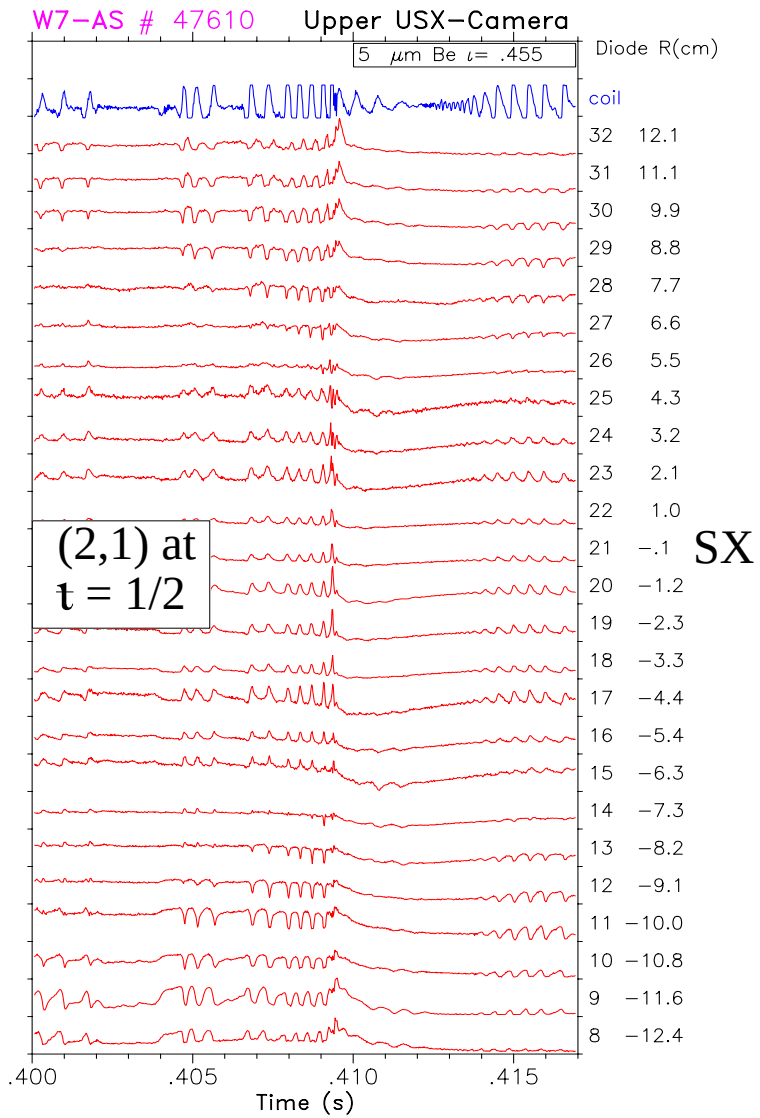
Tearing Modes and Soft Disruption during OH Current Drive

- experimental results -

400 kW ECRH Target with 25 kA OH-current ramp, B = 2.54 T, ι_{ext} = 0.301





- Partial collapse of plasma energy preceeded by high amplitude m = 2 modes

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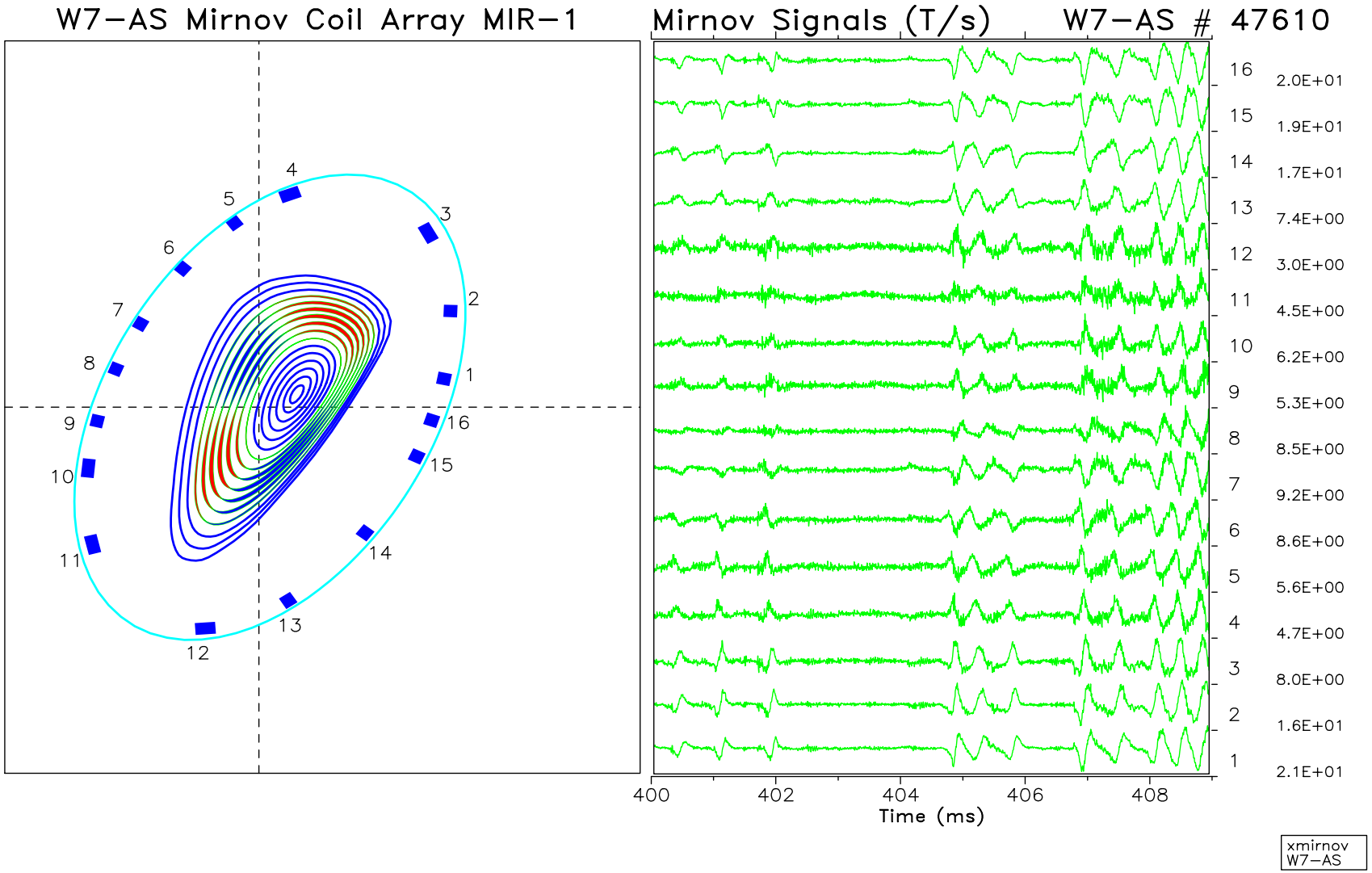
Tearing Mode Activity detected by Mirnov Coils

- m = 2 precursors before soft disruption -

400 kW ECRH Target with 30 kA OH-current ramp, B = 2.55 T, ι_{ext} = 0.301



$\Rightarrow$ high amplitudes of $\widetilde{B}_\theta/B \geq 4\cdot10^{-3}$ at plasma boundary !

Oak99_47610_mir1.cd

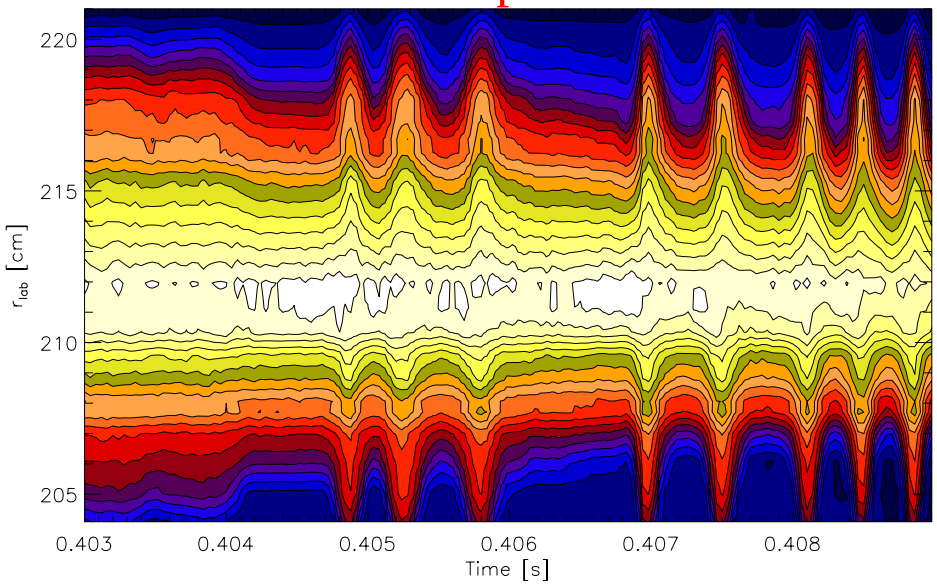
Tearing Mode Activity detected by ECE- and X-Ray Diagnostics

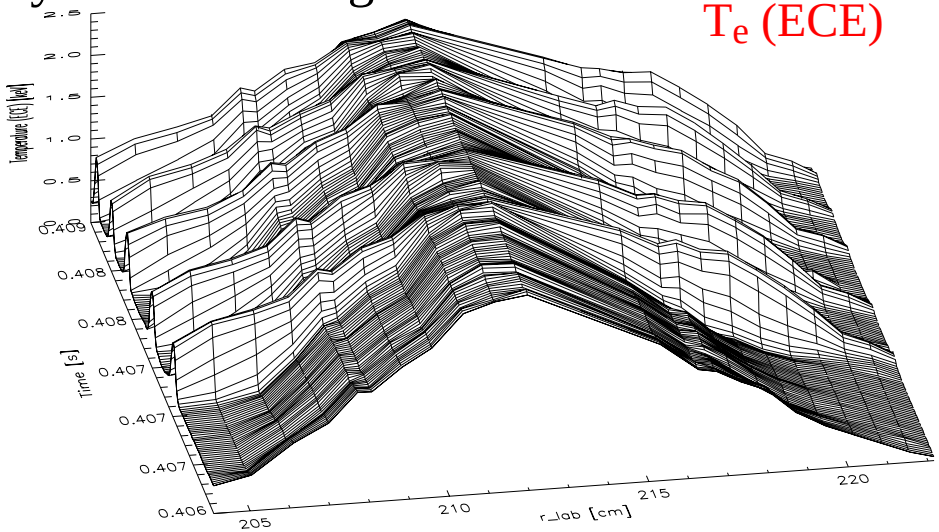
- rotating m = 2 tearing mode before partial collapse -

WENDELSTEIN 7-AS

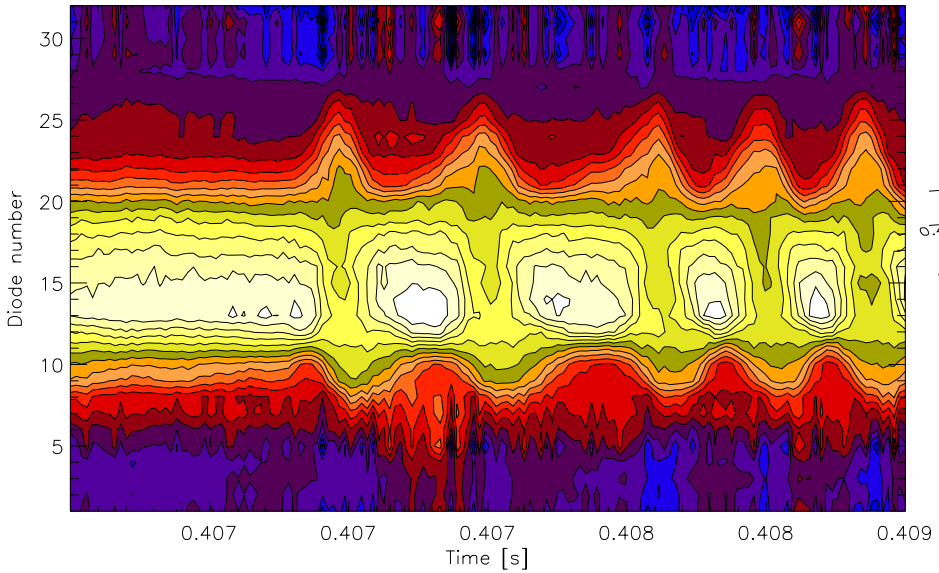
IPP

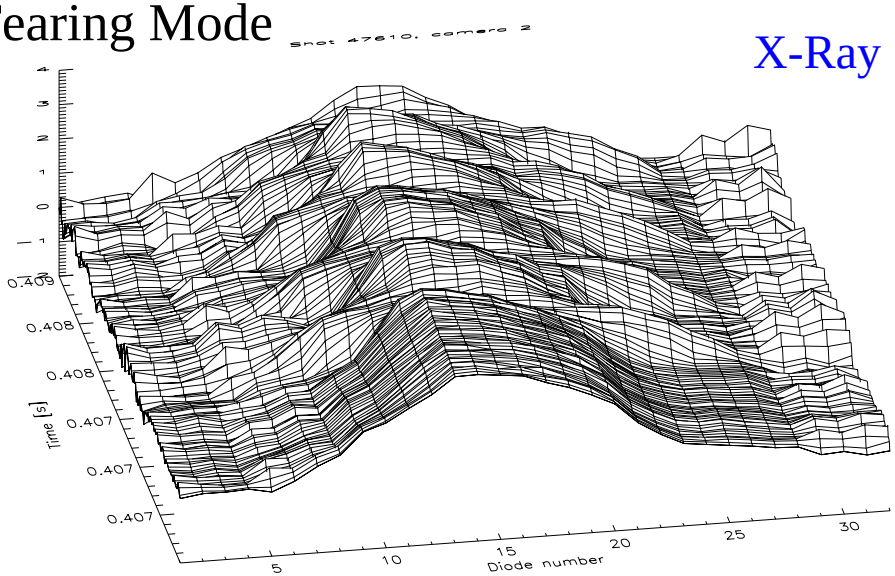
#47610 ECE-Temperature Modulation by m = 2 Tearing Mode





#47610 X-Ray Modulation by m = 2 Tearing Mode





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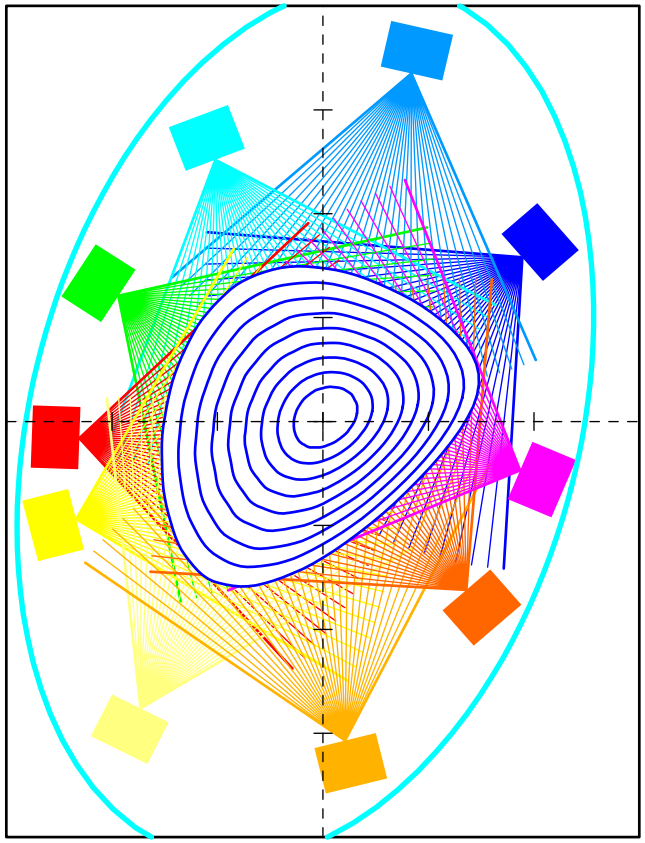
X-Ray Tomographic Reconstruction of Mode Structures

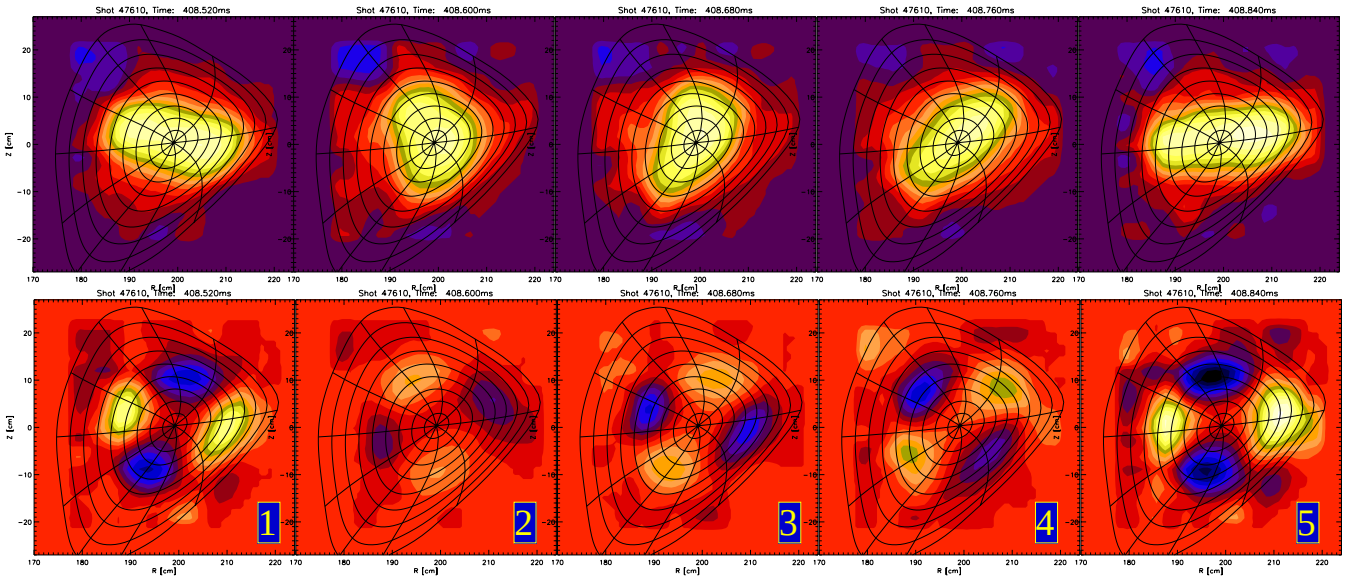
- rotating m = 2 tearing mode before partial collapse -

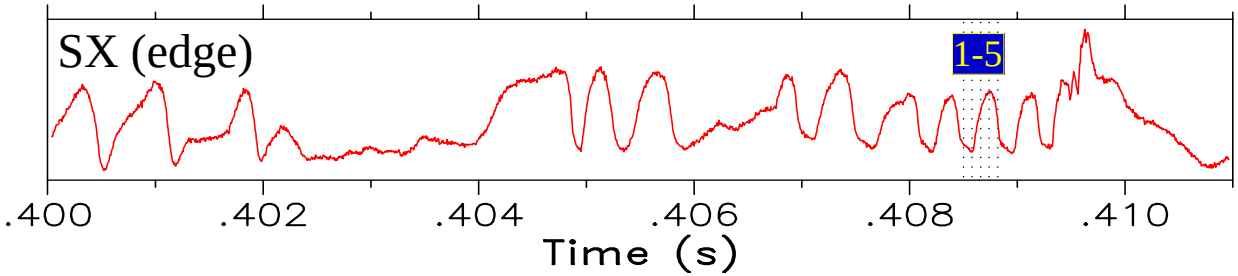
400 kW ECRH Target with 25 kA OH-current ramp, B = 2.54 T, ι_{ext} = 0.301

W7–AS MiniSoX System



X-ray Tomograms (lower row: SVD filtered)





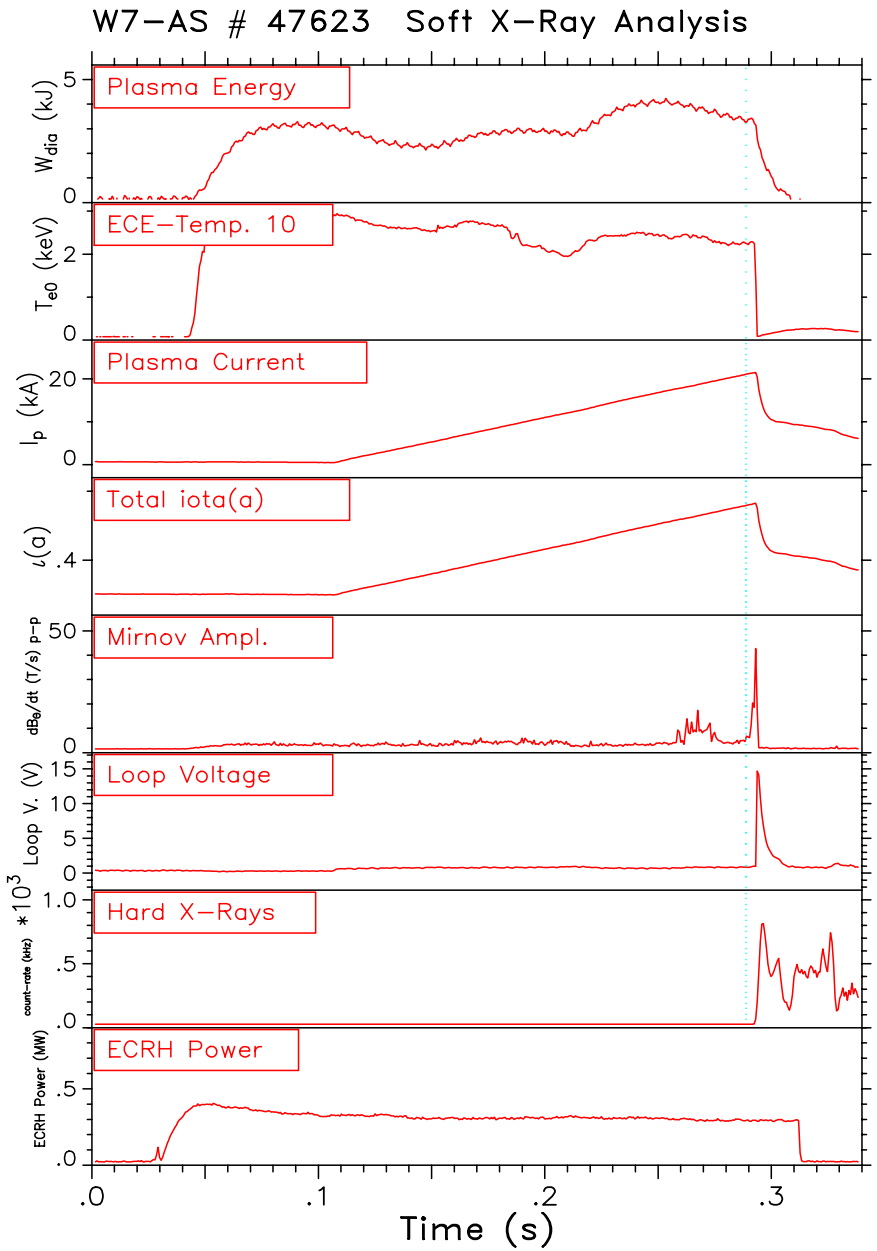
2-d reconstructions show modification of equilibrium profiles by large m = 2 islands

Oak99_47610_exp2.cd

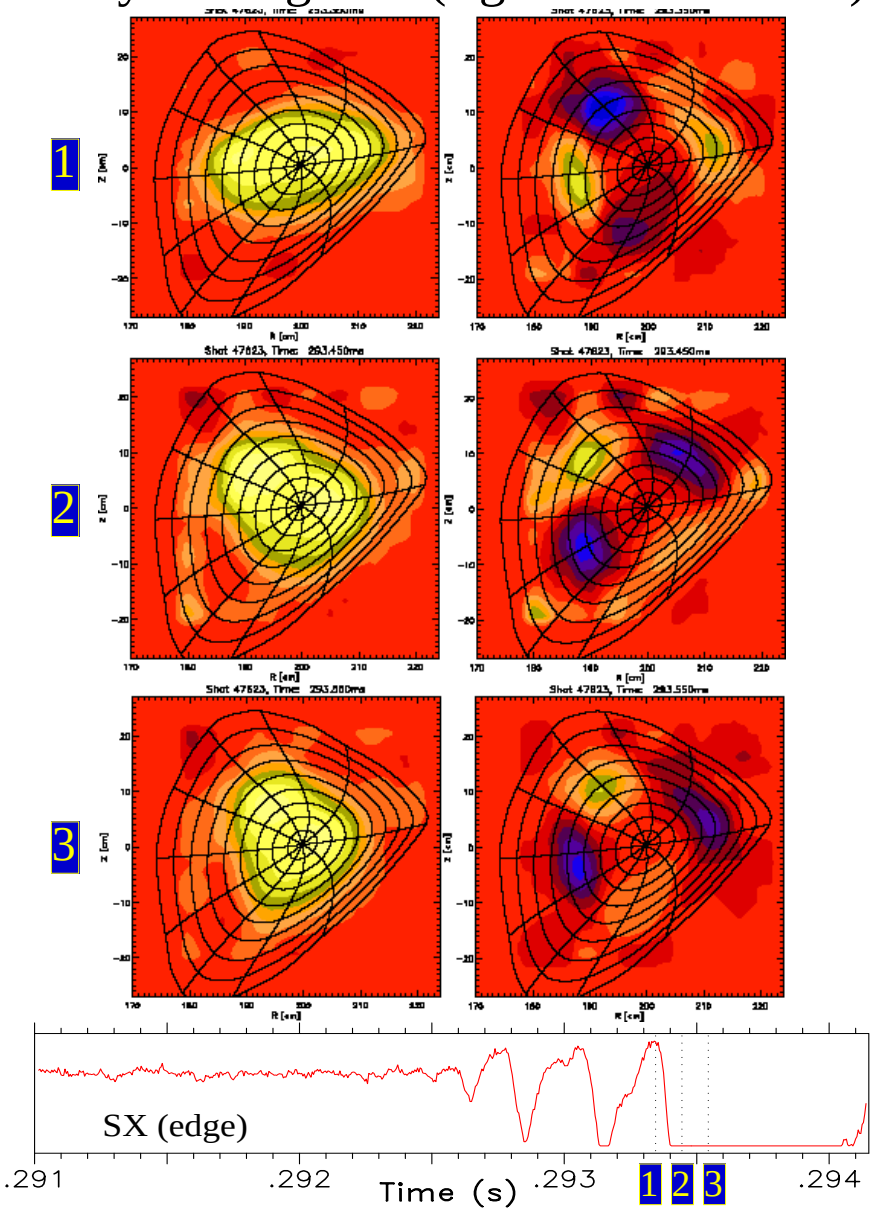
Tearing Modes and Soft Disruption during OH Current Drive

- experimental results -

400 kW ECRH Target with 21 kA OH-current ramp, B = 2.54 T, ι_{ext} = 0.347



X-ray Tomograms (right: SVD filtered)

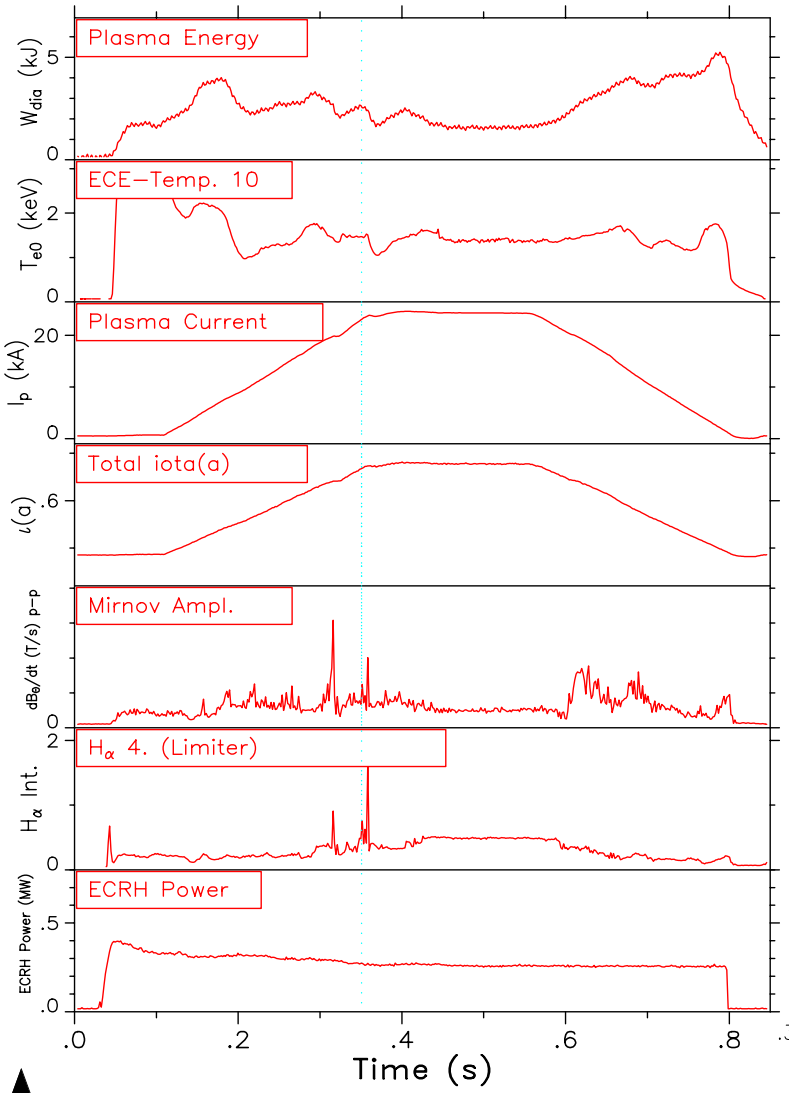


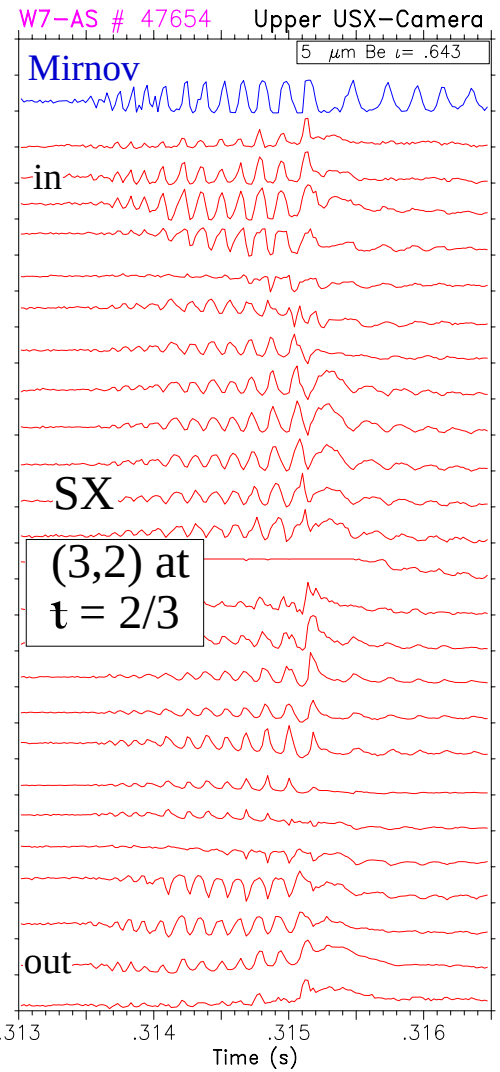
Oak99_47623_exp.cd

Tearing Modes and Soft Disruptions during OH Current Drive

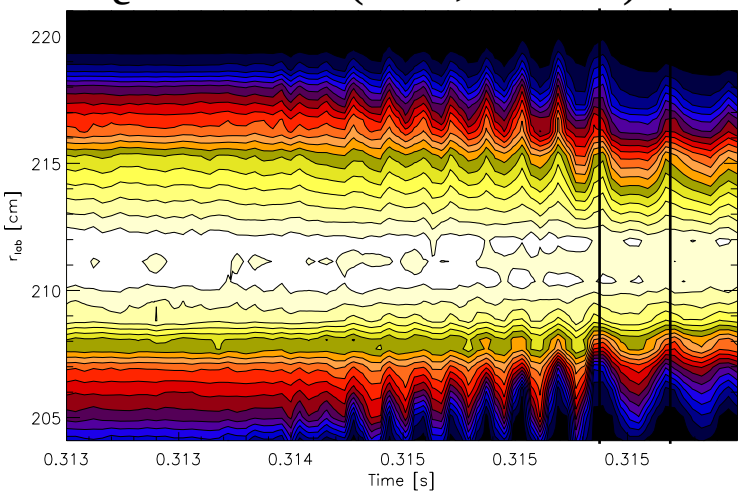
- experimental results (ECRH at high iota) -

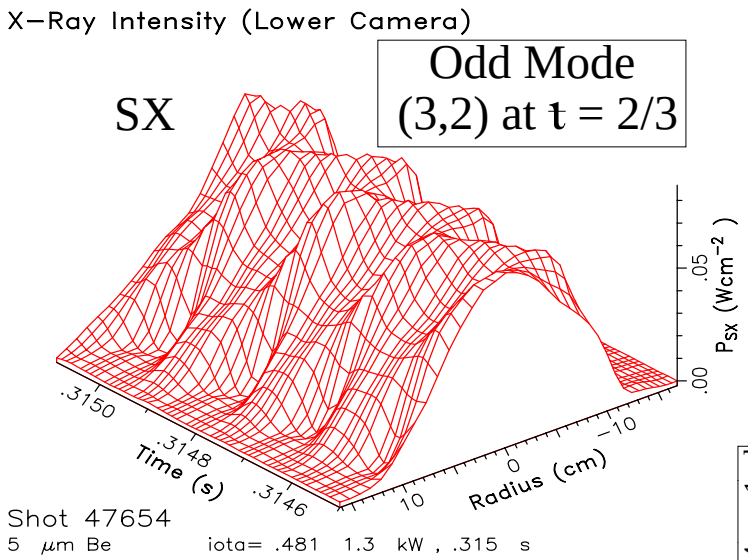
0.4 MW ECRH Target with 25 kA OH-current ramp, B = 2.55 T, ι_{ext} = 0.482





T_e -Contours (ECE, #47654)





- Similar but weaker activity at ι = 2/3, Δ´-code predicts stability for m=3,n=2 modes !

Oak99_47654_exp1.cd

Tearing Mode Stability Analysis of W7-AS Current Profiles

Tearing Mode Equation in cylinder geometry:

$$\frac{1}{r}\frac{\mathrm{d}}{\mathrm{d}r}r\frac{\mathrm{d}\Psi}{\mathrm{d}r}-\frac{m^2}{r^2}\Psi-\frac{\mathrm{d}j/\mathrm{d}r}{\frac{B_{0\theta}}{\mu_0}\left(1-\frac{nq}{m}\right)}\Psi=0 \qquad B_{0\theta}\approx\frac{r}{R_0}\frac{B_0}{q}$$

solved for perturbed helical flux $\Psi = \mathrm{i}\,rB_r/m$

Corresponding **energy functional equation**:

$$\delta W=-\frac{\pi R_0}{2\mu_0}\int_0^a r\,\mathrm{d}r\left[\left(\frac{\mathrm{d}\Psi}{\mathrm{d}r}\right)^2+\frac{A}{r^2}\Psi^2\right] \qquad A\equiv m^2+\frac{rR_0\cdot\mathrm{d}j/\mathrm{d}r}{\frac{B_0}{\mu_0}\left(\iota(r)-\frac{n}{m}\right)}$$

A: measure of free magnetic energy density, destabilising if < 0

Delta-Prime:

$$\Delta'=\left.\frac{\Psi'}{\Psi}\right|_{r_s-\varepsilon}^{r_s+\varepsilon} \qquad > 0 \;\Rightarrow\; \text{unstable !}$$

Saturated **Island Width** estimated from:

$$\Delta'=\left.\frac{\Psi'}{\Psi}\right|_{r_s-w/2}^{r_s+w/2}\rightarrow 0$$

Relation between w and Ψ used to renormalise Ψ and for calculation of perturbed magnetic fields:

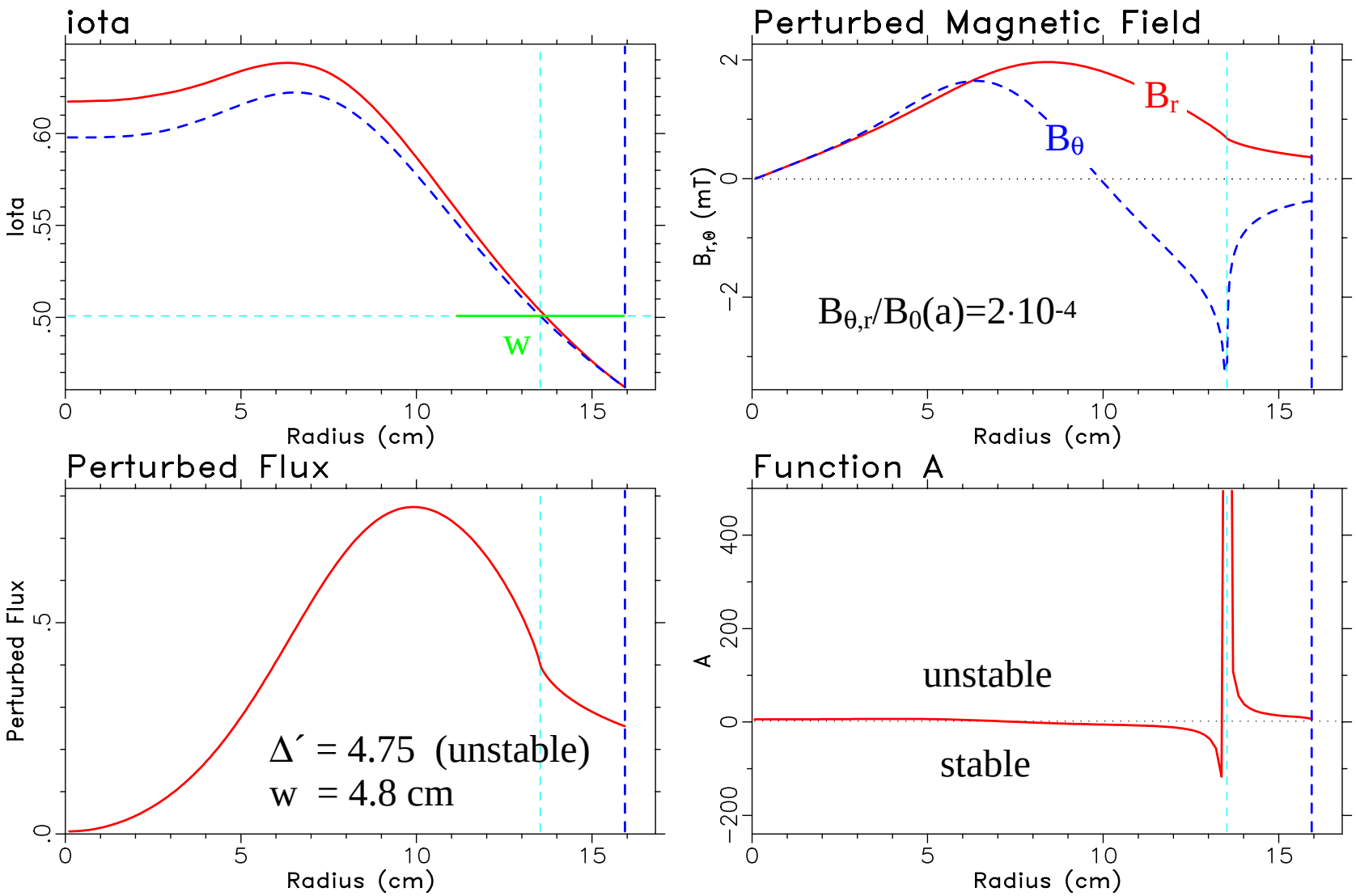
$$w=4\sqrt{\frac{R_0\,\Psi}{r_sB_0\,\iota'(r_s)}}$$

Oak99_dprime-intro.cd

Tearing Mode Stability Analysis of W7-AS Current Profiles

#47623 (m=2,n=1)

400 kW ECRHI Target with 21 kA OH-current ramp, B = 2.54 T, ι_{ext} = 0.376, soft disruption

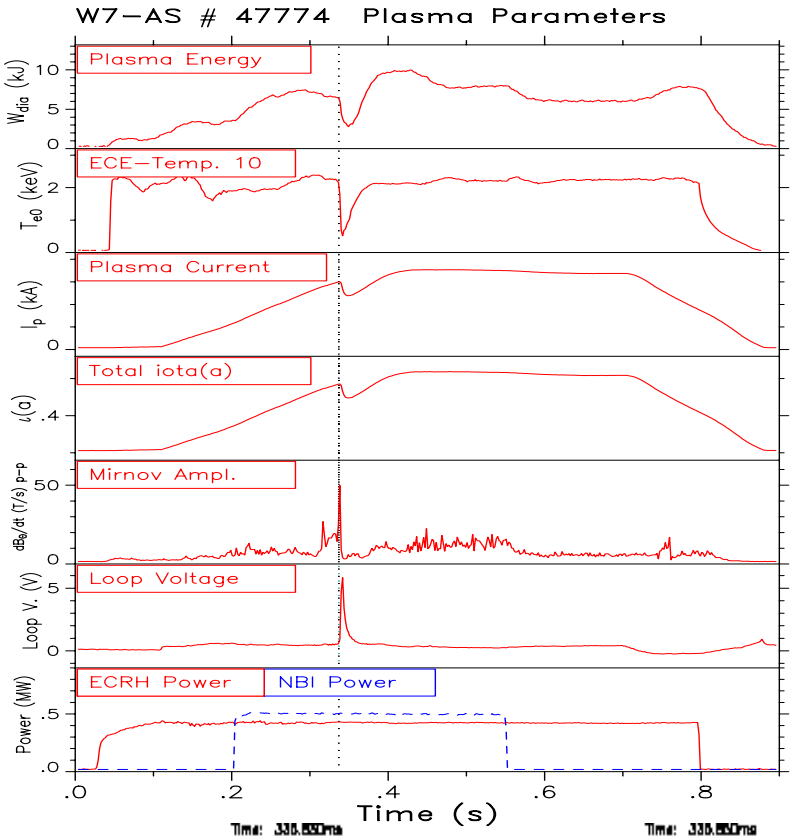


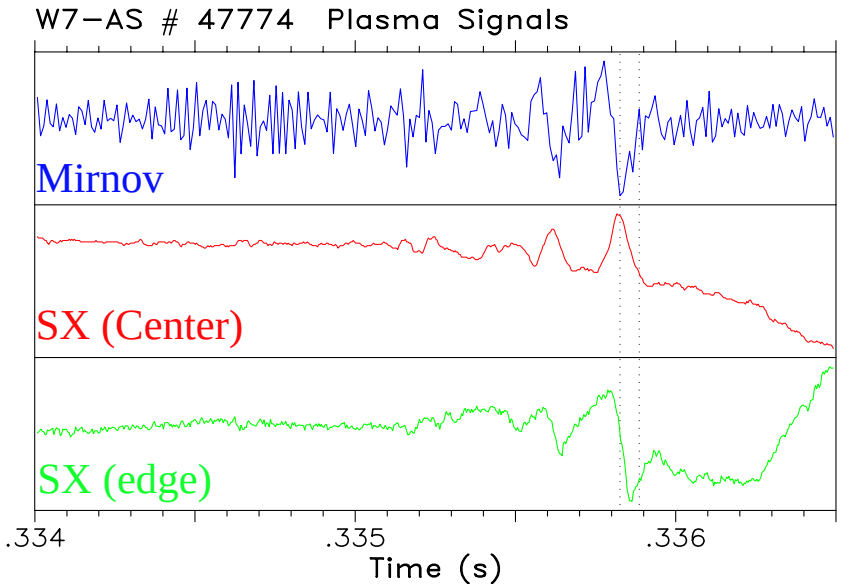
Oak99_47623_tear.cd

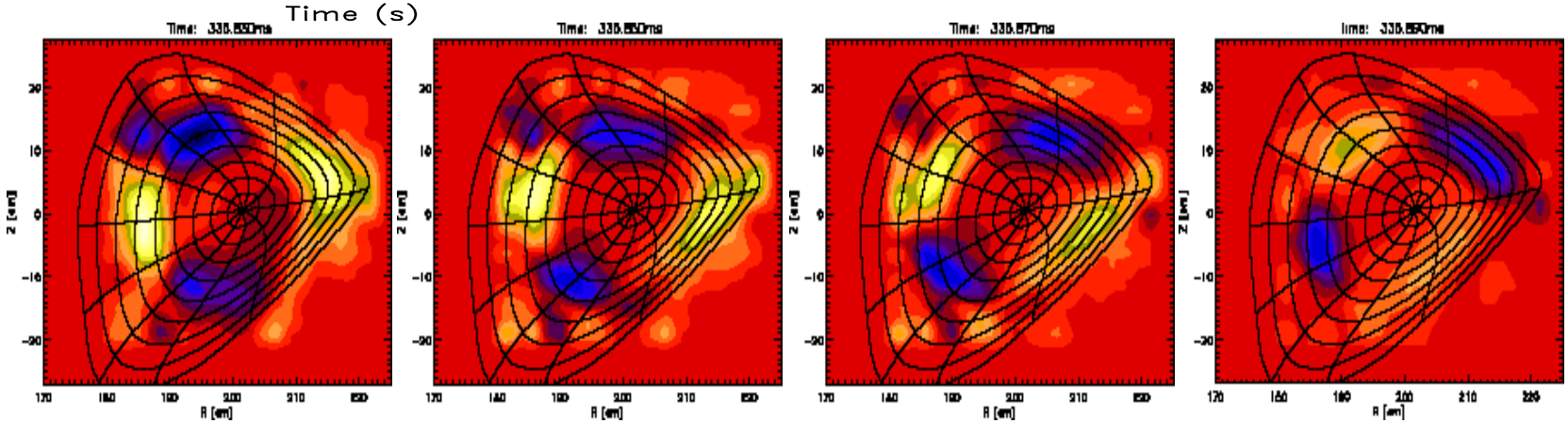
Tearing Modes and Soft Disruption during OH Current Drive

- experimental results -

400 kW ECRH +500 kW NBI Target with 35 kA OH-current ramp, B = 2.51 T, ι_{ext} = 0.301





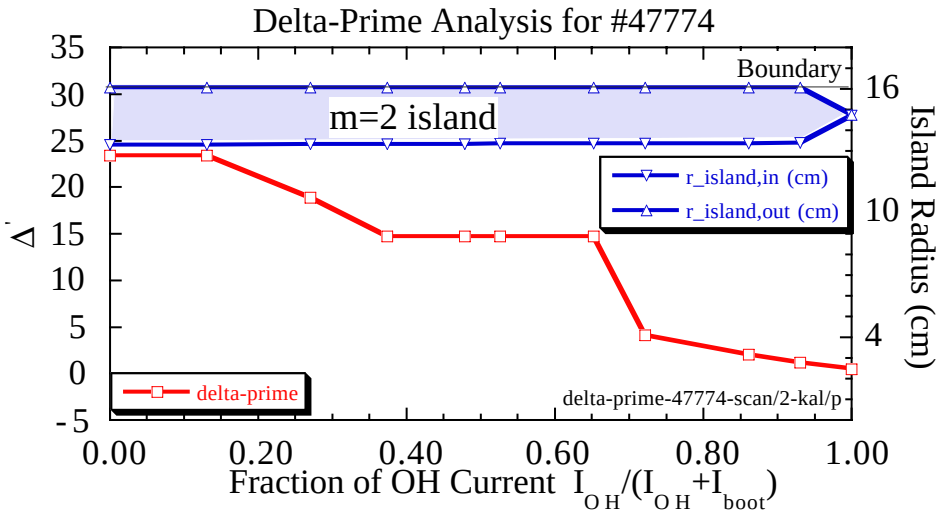


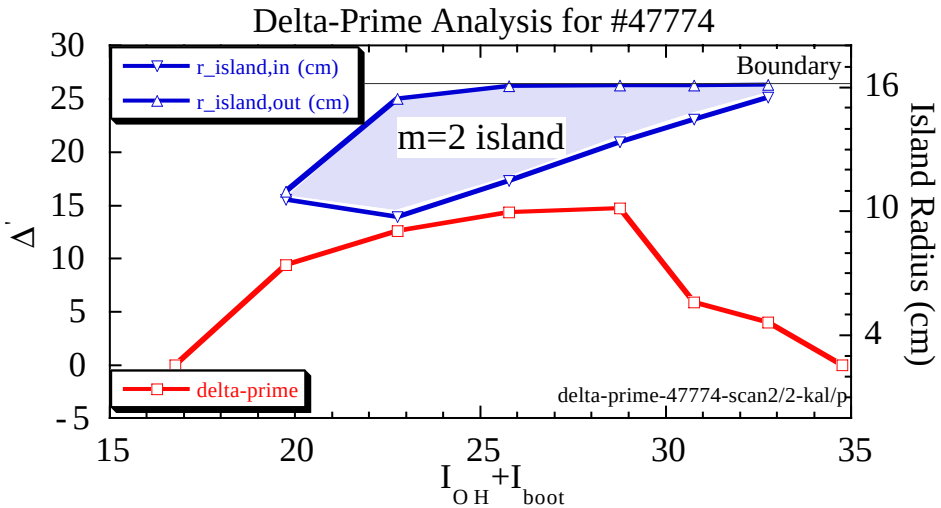
Oak99_47774_exp.cd

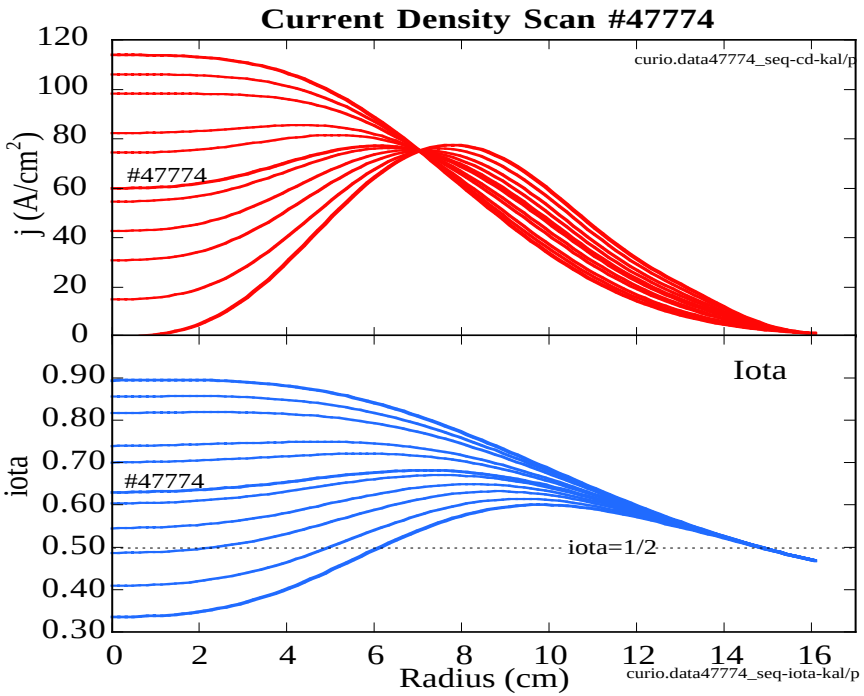
Δ´ Analysis of W7-AS Current Profiles

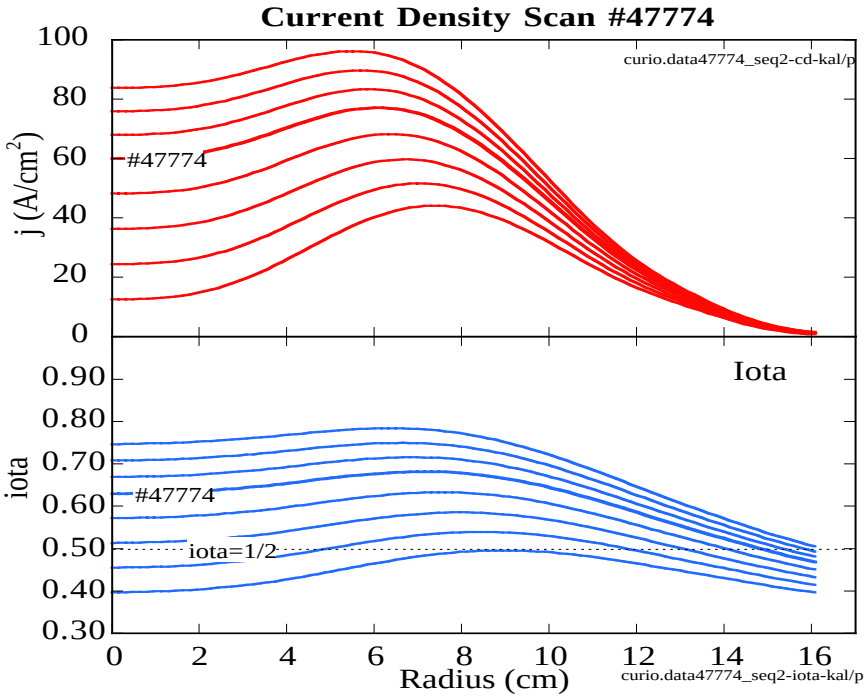
- m = 2 tearing modes predicted unstable before soft disruption -

400 kW ECRH +500 kW NBI Target with 35 kA OH-current ramp, B = 2.51 T, ι_{ext} = 0.301







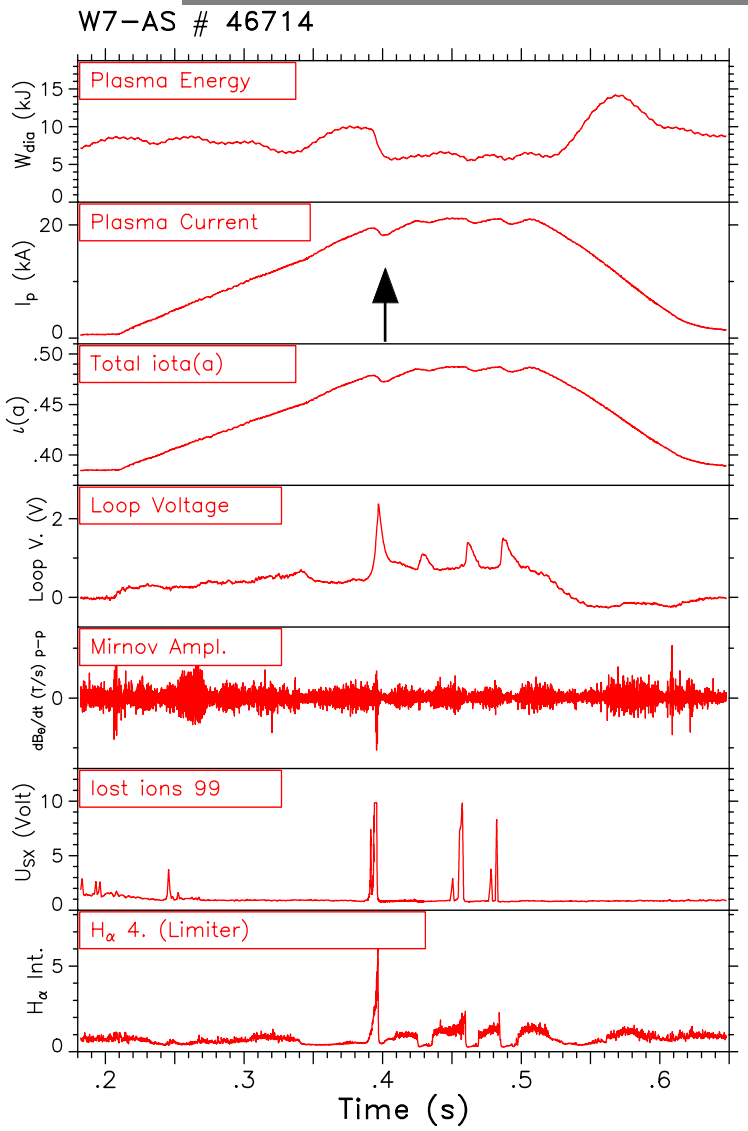


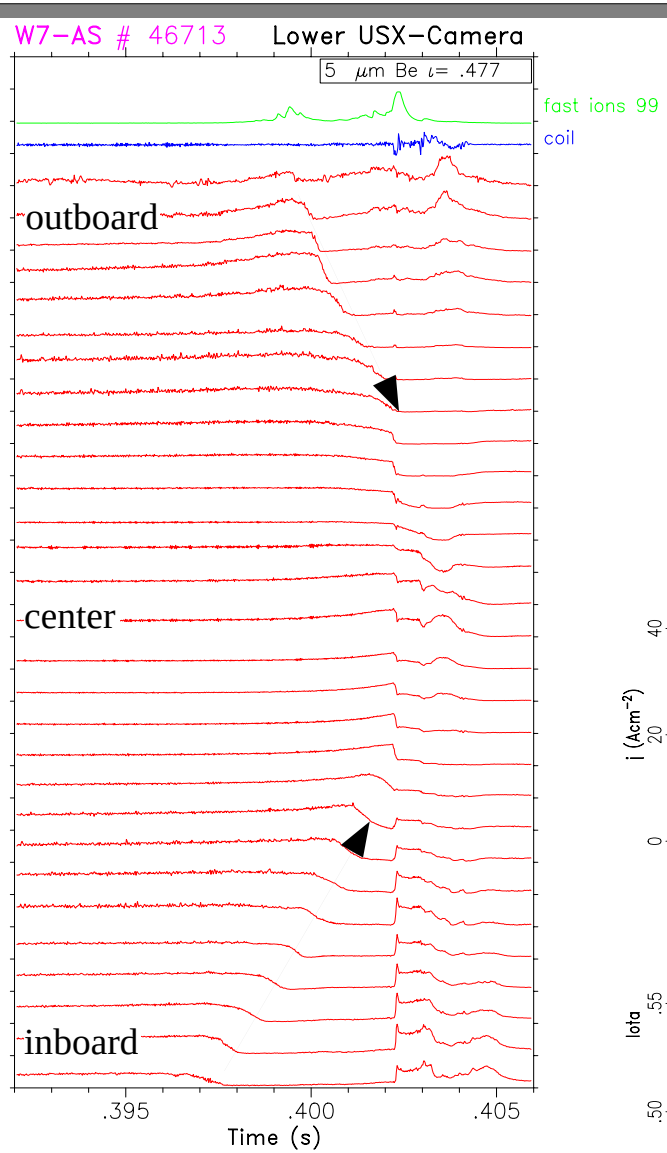
Oak99_47774_dp-scan.cd

Tearing Modes and Soft Disruptions during OH Current Drive

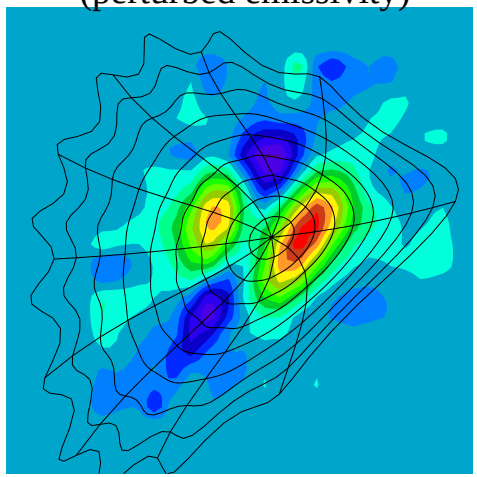
- experimental results (NBI) -

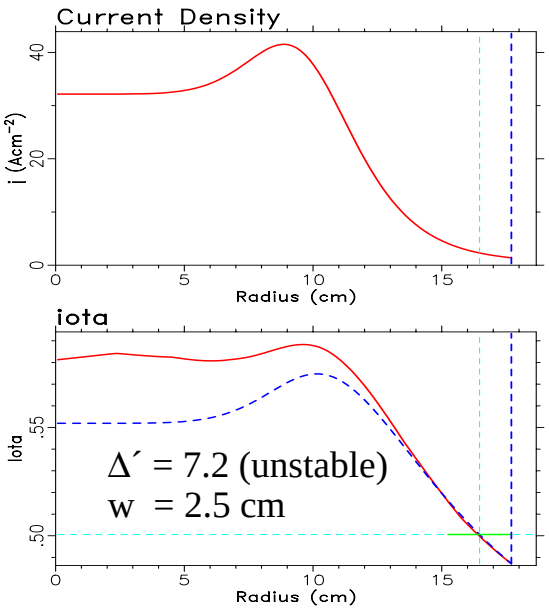
1 MW NBI Target with 21 kA OH-current ramp, B = 2.54 T, ι_{ext} = 0.382





SX-Tomography
(perturbed emissivity)



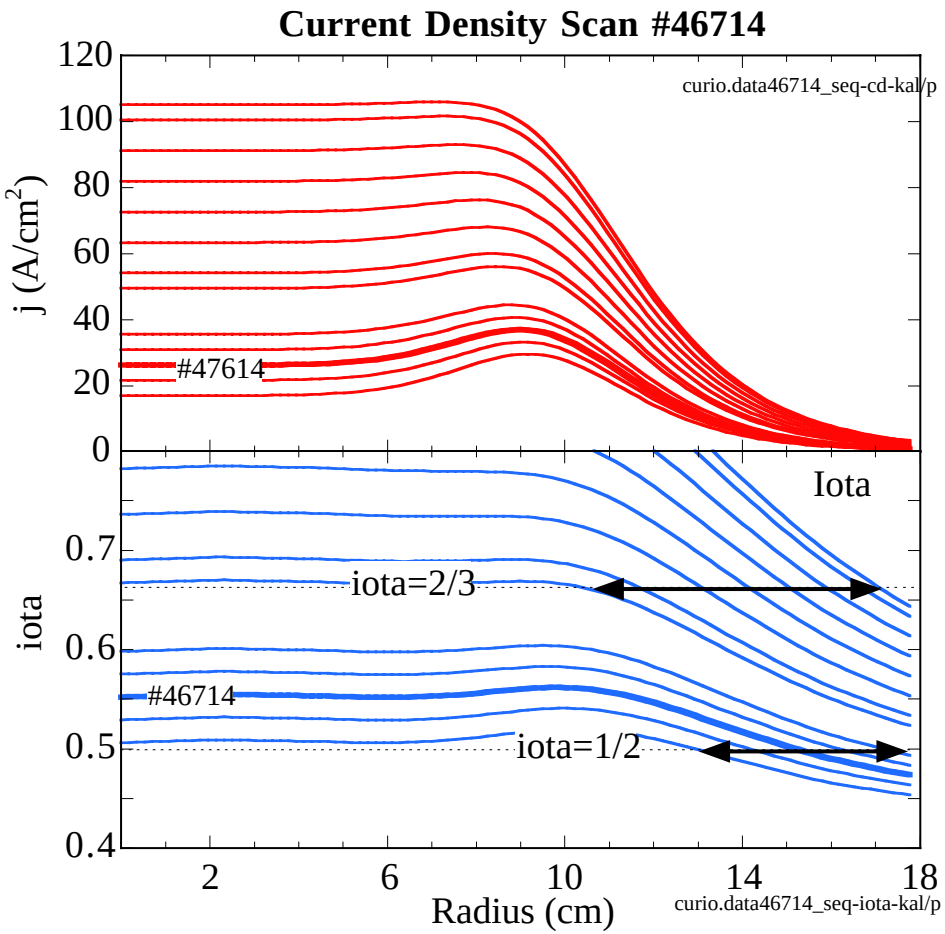


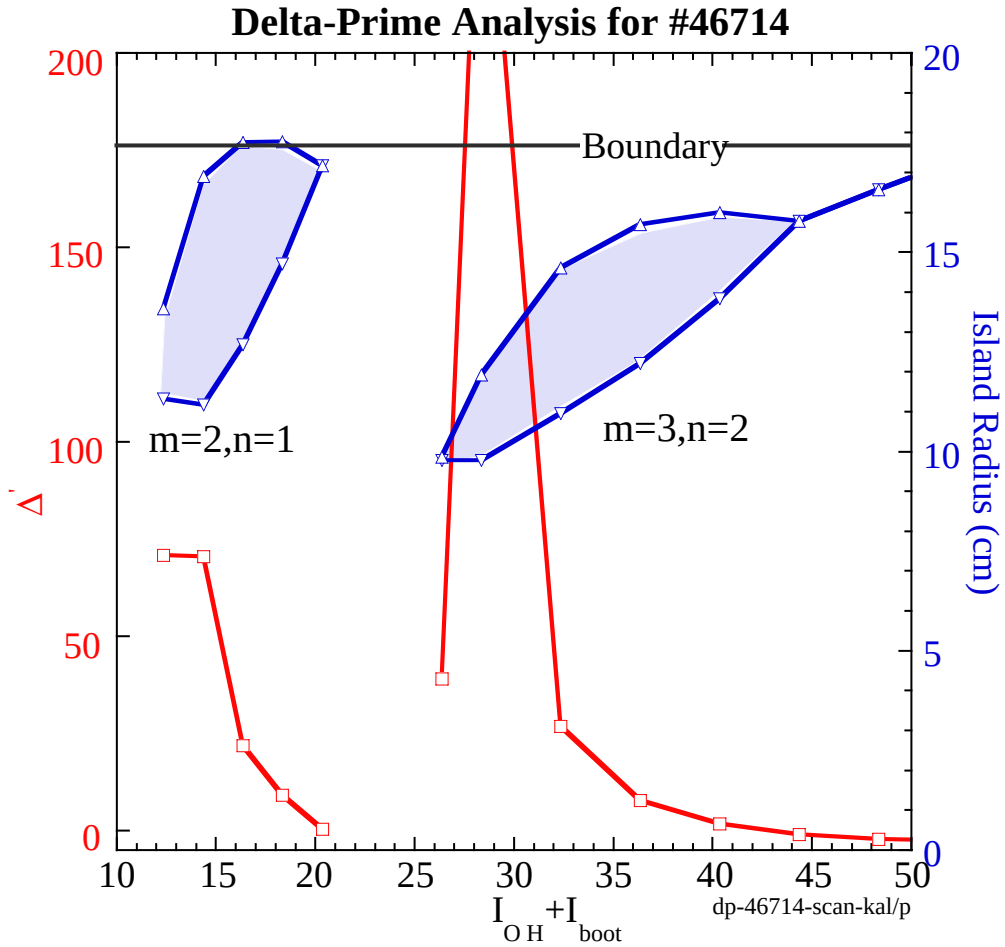
- Partial collapses of plasma energy preceeded by fast growing locked m = 2 mode

Oak99_46714_exp1.cd

Δ´ Analysis of W7-AS Current Profiles
- (m,n) = (2,1) and (3,1) tearing modes -

Calulated Current Scan based on NBI Shot 46714
(1 MW NBI with 21 kA I_{OH} ramp, B = 2.5 T, ι_{ext} = 0.38)





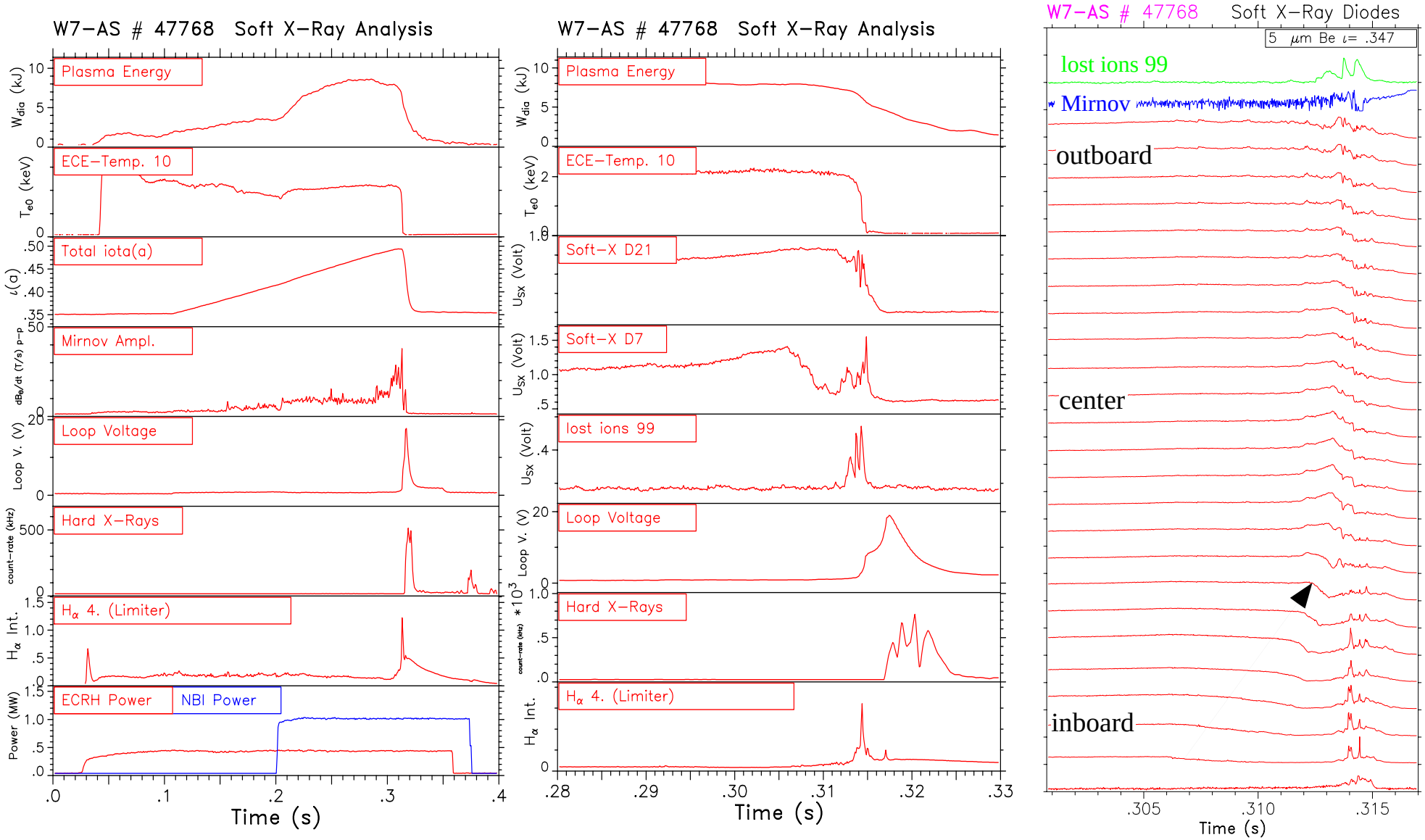
For relatively broad current density profiles
tearing modes can be driven unstable even for large values of ι_{ext}

Oak99_46714_dp-scan.cd

Tearing Modes and Disruptive Events during OH Current Drive

- experimental results (ECRH + NBI) -

1 MW NBI + 0.4 MW ECRH Target with 25 kA OH-current ramp, B = 2.54 T, ι_{ext} = 0.35



- Fast thermal collapse of plasma energy preceeded by fast growing locked m = 2 mode ?

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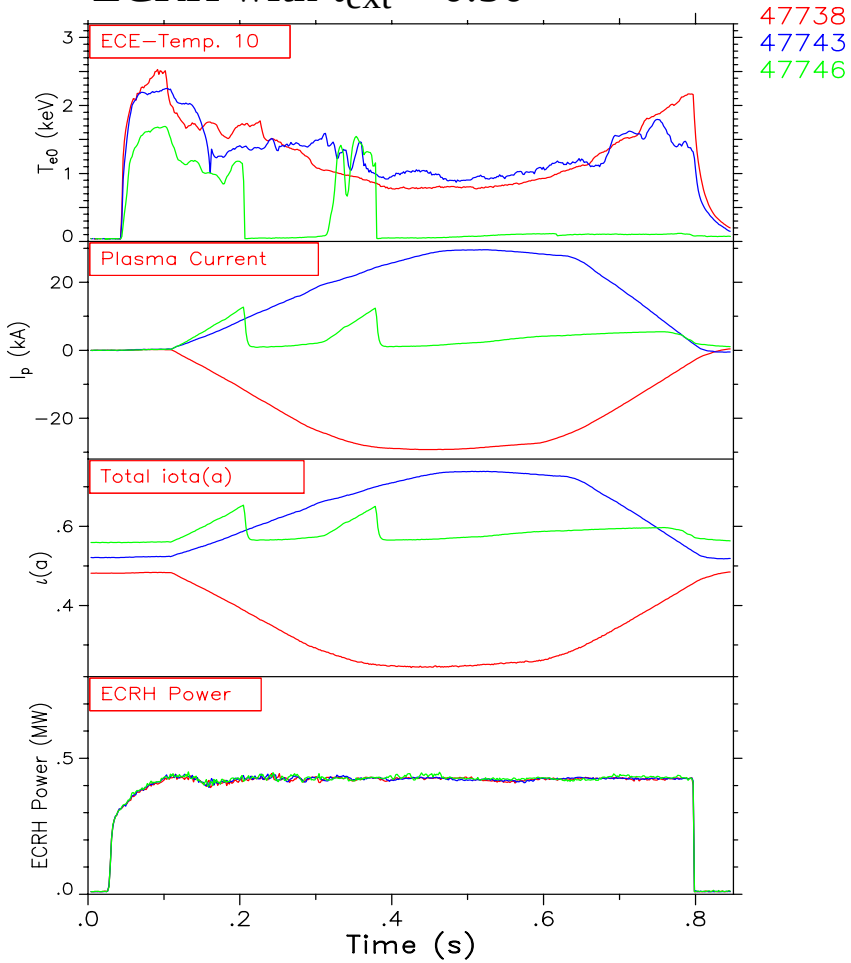
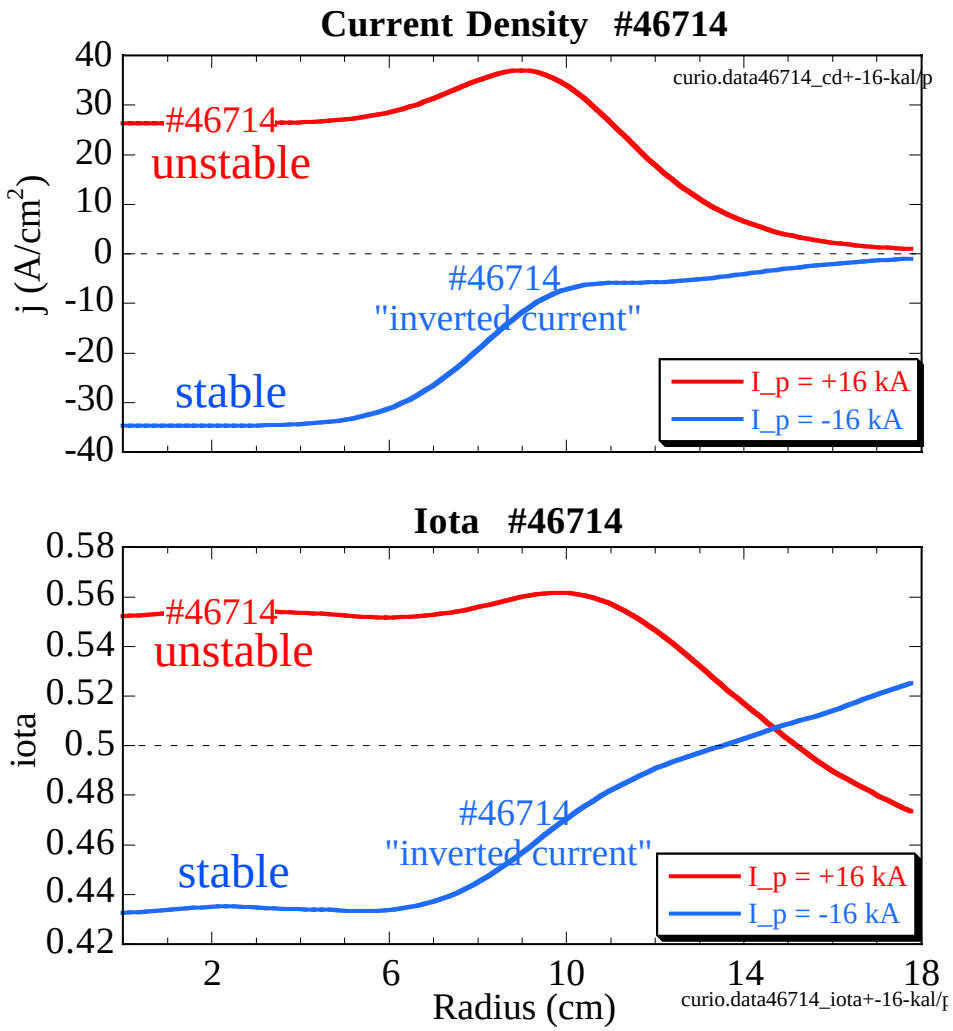
Experiments and Calculations with inverted Currents
- bootstrap current causes different profiles -

ECRH with $\iota_{ext} \approx 0.50$



- I_{boot} relatively small
- very little MHD effects in cases with $I_p < 0$
- few cases with collapse by ι=2/3 effects

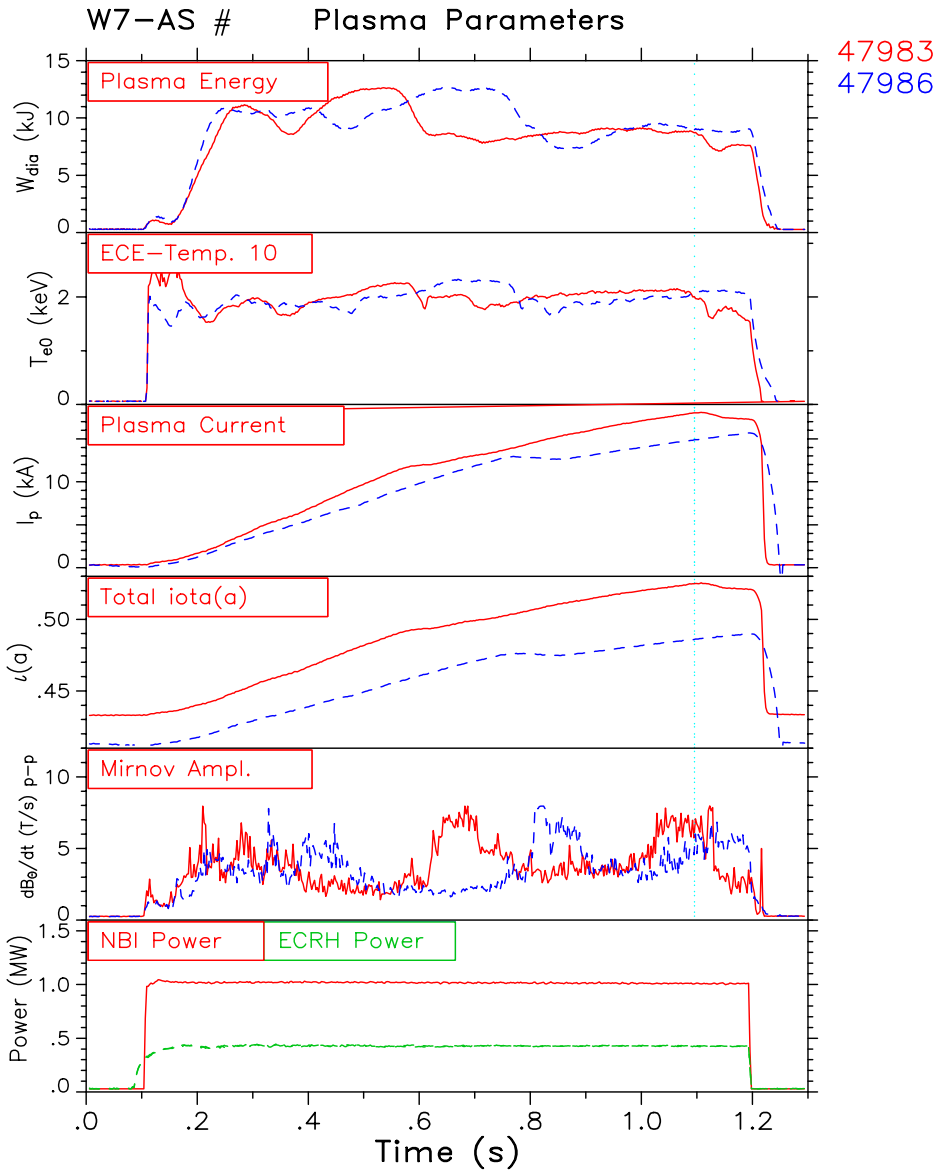
Calulated Current Density Profiles
based on NBI Shot 46714

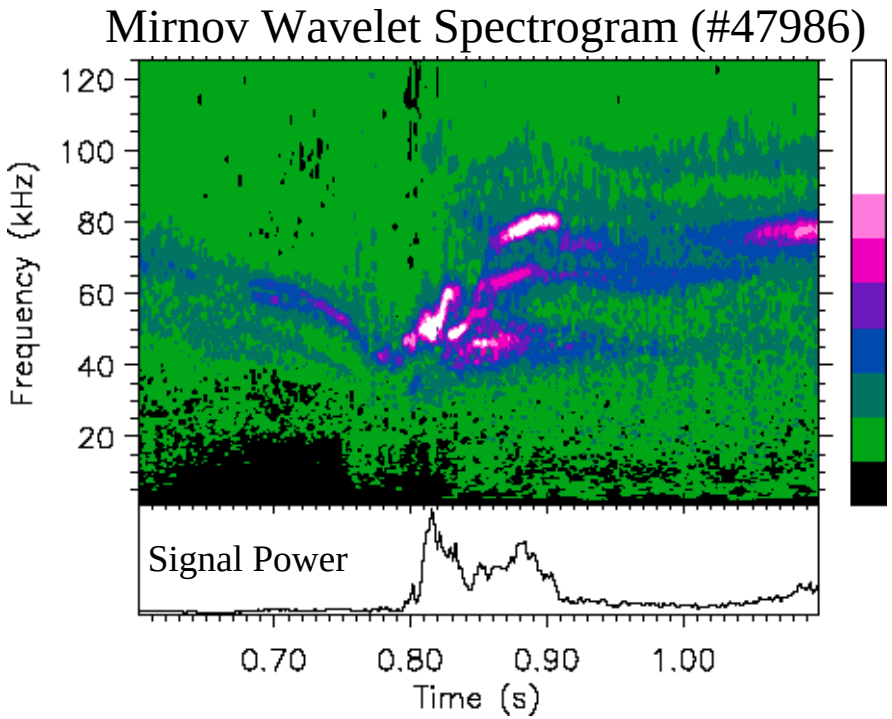


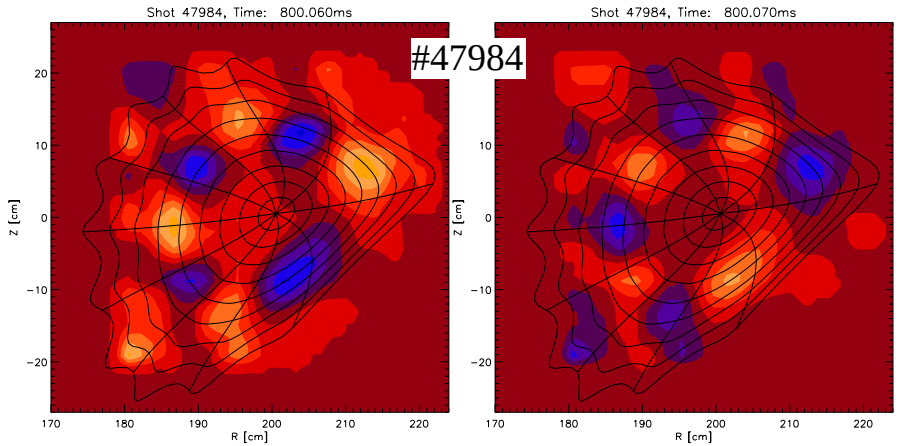
Oak99_47738_I<0.cd

Experiments with large Bootstrap and Okhawa Currents (I_{OH} = 0)

- no evidence of tearing modes (ECRH+NBI), but NBI driven GAE/TAE ? -







When ι(a) approaches rational values 1/2 or 2/3 high frequency modes appear in correlation with deterioration of confinement and reduced current rise rate

Oak99_47986/4_exp1.cd

Stability Studies of Plasmas with Significant Rotational Transform from Toroidal Currents in the W7-AS Stellarator

Conclusion:

- Tearing modes and disruptive events occur even at high ι_{ext} in W7-AS, in contrast with earlier OH results in W7-A w/o additional heating
- This behaviour seems to be related with wider current profiles in W7-AS due to bootstrap currents and additional heating
- In many cases only a partial thermal collapse occurs, and the OH driven current can be raised above critical values
- The plasma response on relatively large bootstrap currents at resonant surfaces does not prevent the current to increase beyond the critical values
- Initial results with a Δ´-code are roughly consistent with the experiment, results may suffer from uncertainities in the current density and iota profiles
- The assessment of the stability against current driven modes has to be performed by 3-d resistive MHD calculations, in particular in the case of compact stellarators with strong toroidal and poloidal curvature.