ITER

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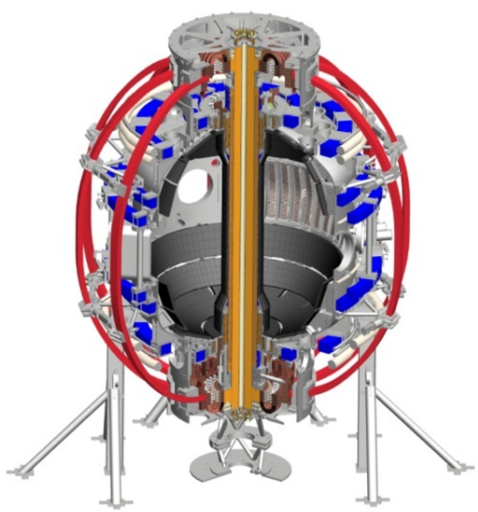

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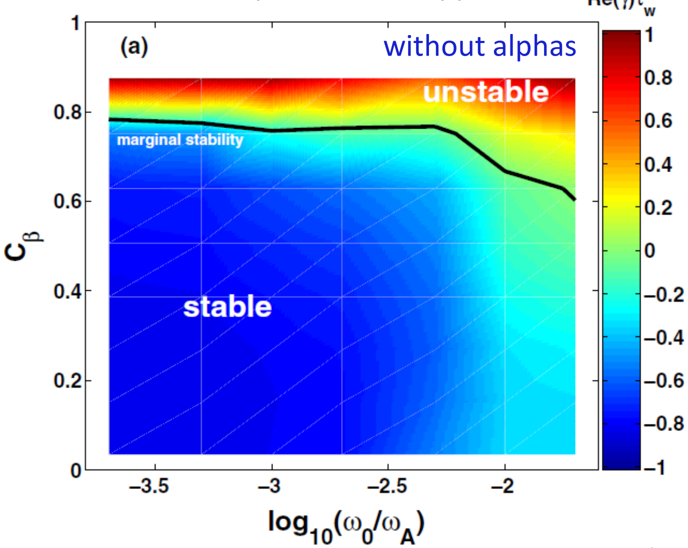
Long-Wavelength MHD Stability at High Pressure Required for ITER and Other Next-Step Devices

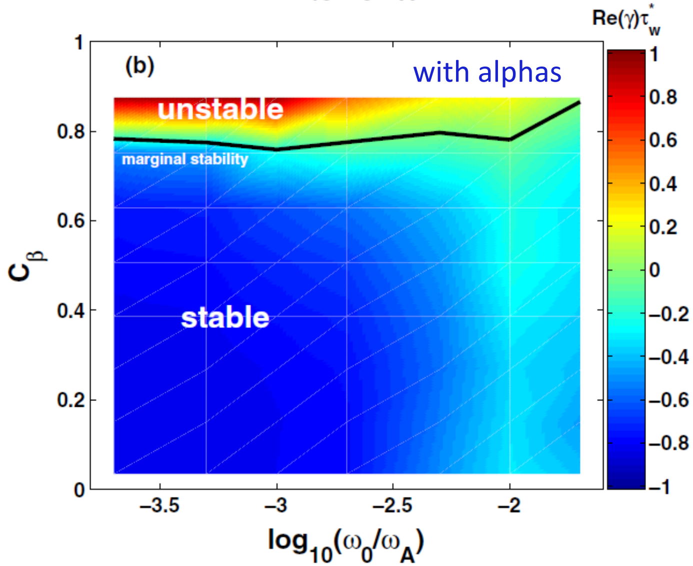
- Motivation
  - The resistive wall mode (RWM) is a primary cause of plasma disruption at high β
  - Understanding passive stabilization physics determining RWM stability is critical to extrapolate stability requirements for future devices

- Very brief history
  - Early theory: RWM can be stabilized by sufficient plasma rotation
  - Critical ω_ϕ for passive stability assessed (Ω_{crit})
  - Low levels of Ω_{crit} (< 0.5% Alfven at q =2) suggested
  - RWMs found to be unstable at relatively high ω_ϕ, and stability depends on profile, not simple scalar value – no simple, low Ω_{crit}!
  - Stability model including kinetic effects evaluated (NSTX) - can explain greater complexity of RWM marginal stability
  - Present effort: comparison of stability model in codes and experiments

MARS-K ITER Results

MARS-K perturbative approach





[Y. Liu, Nucl. Fusion **50** 095008 (2010)]

- Alphas are only slightly stabilizing
- Self-consistent approach much more unstable
  - How can $\gamma\tau_w$ be 50?

$$(\gamma + in\Omega)\boldsymbol{\xi} = \boldsymbol{v} + (\boldsymbol{\xi}\cdot\nabla\Omega)R\hat{\phi},$$

$$\rho(\gamma + in\Omega)\boldsymbol{v} = -\nabla\cdot\boldsymbol{p} + \boldsymbol{j}\times\boldsymbol{B} + \boldsymbol{J}\times\boldsymbol{Q} - \rho[2\Omega\hat{\boldsymbol{Z}}\times\boldsymbol{v} + (\boldsymbol{v}\cdot\nabla\Omega)R\hat{\phi}],$$

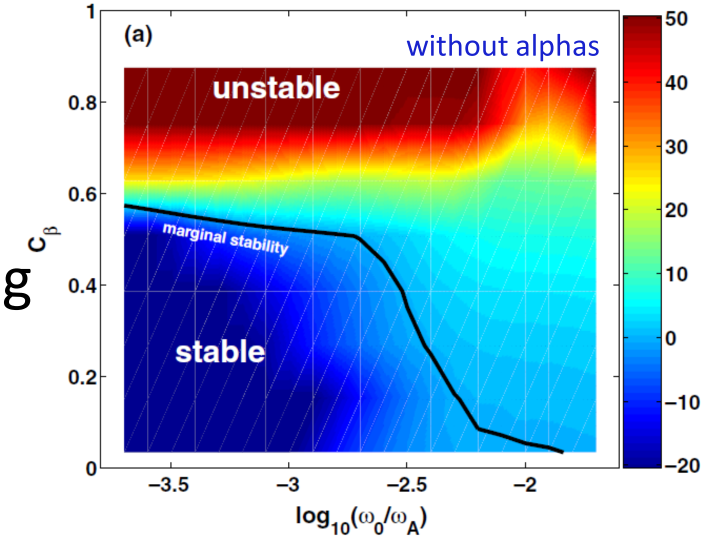
$$(\gamma + in\Omega)\boldsymbol{Q} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}) + (\boldsymbol{Q}\cdot\nabla\Omega)R\hat{\phi}$$

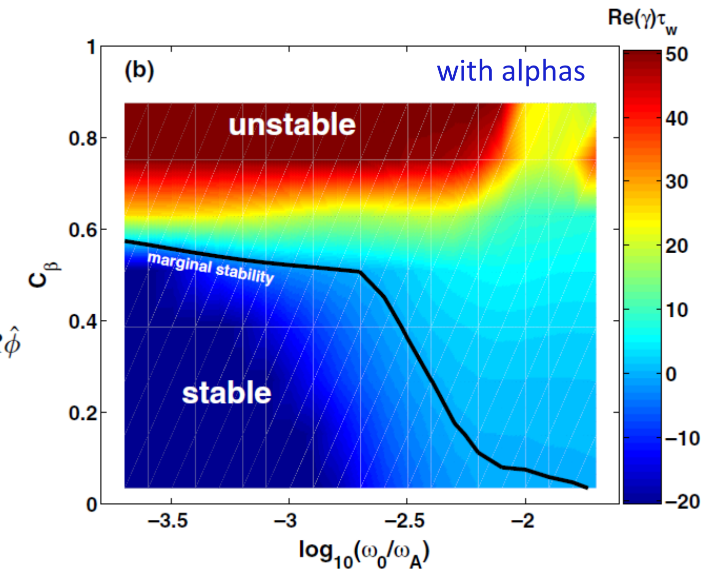
$$(\gamma + in\Omega)p = -\boldsymbol{v}\cdot\nabla P,$$

$$\boldsymbol{j} = \nabla\times\boldsymbol{Q},$$

$$\boldsymbol{p} = p\boldsymbol{I} + p_\parallel\hat{\boldsymbol{b}}\hat{\boldsymbol{b}} + p_\perp(\boldsymbol{I} - \hat{\boldsymbol{b}}\hat{\boldsymbol{b}}),$$

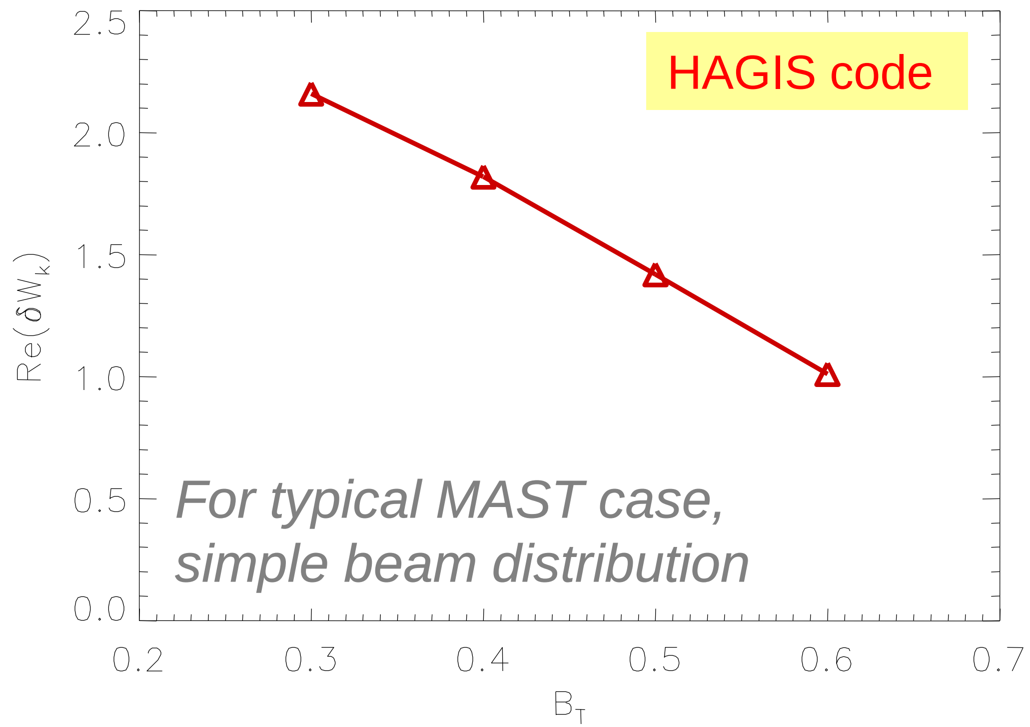
MARS-K self-consistent approach





Finite Orbit Width Kinetic damping of RWMs

- Orbit widths can be very important for fast ions
- Use guiding-centre following code to capture this physics

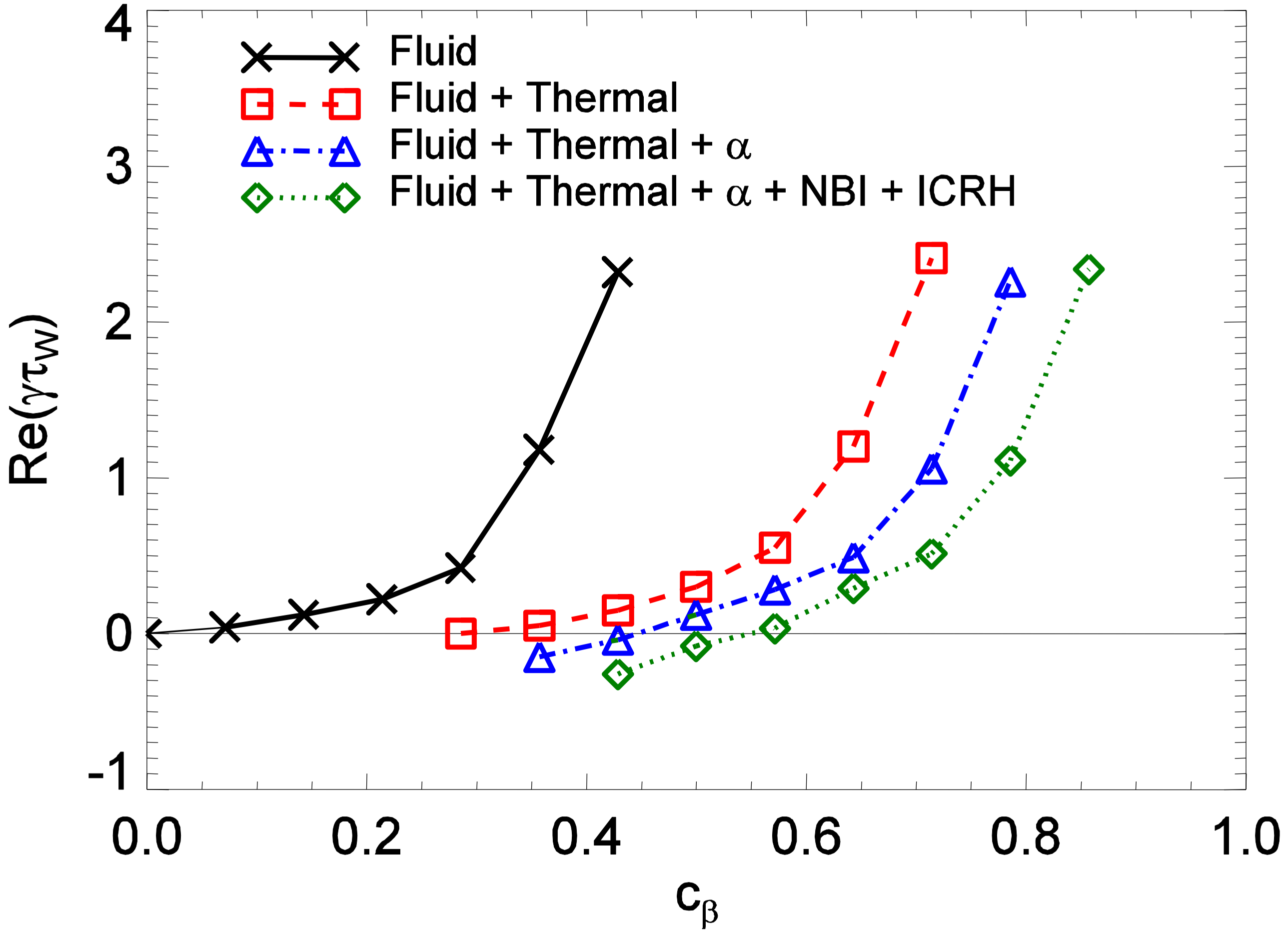


- RWM passively stable in ITER Advanced Scenario due to kinetic damping
- Only capture these effects by including orbit widths
- Sensitive to rotation, so should not be relied upon!

ITER RWM stability

- Including damping from fast ions allows RWM to be passively stabilised above target pressure

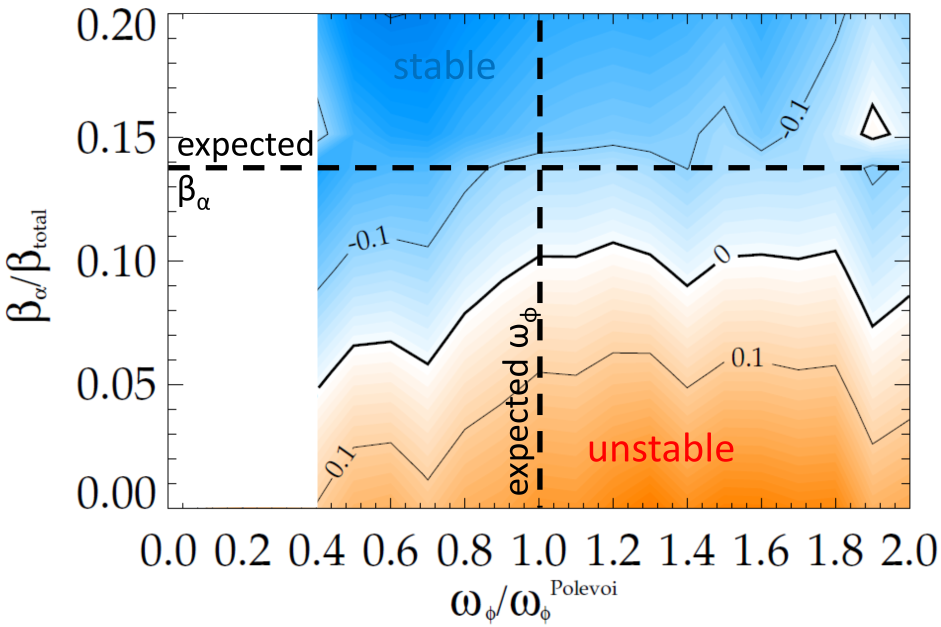
HAGIS code



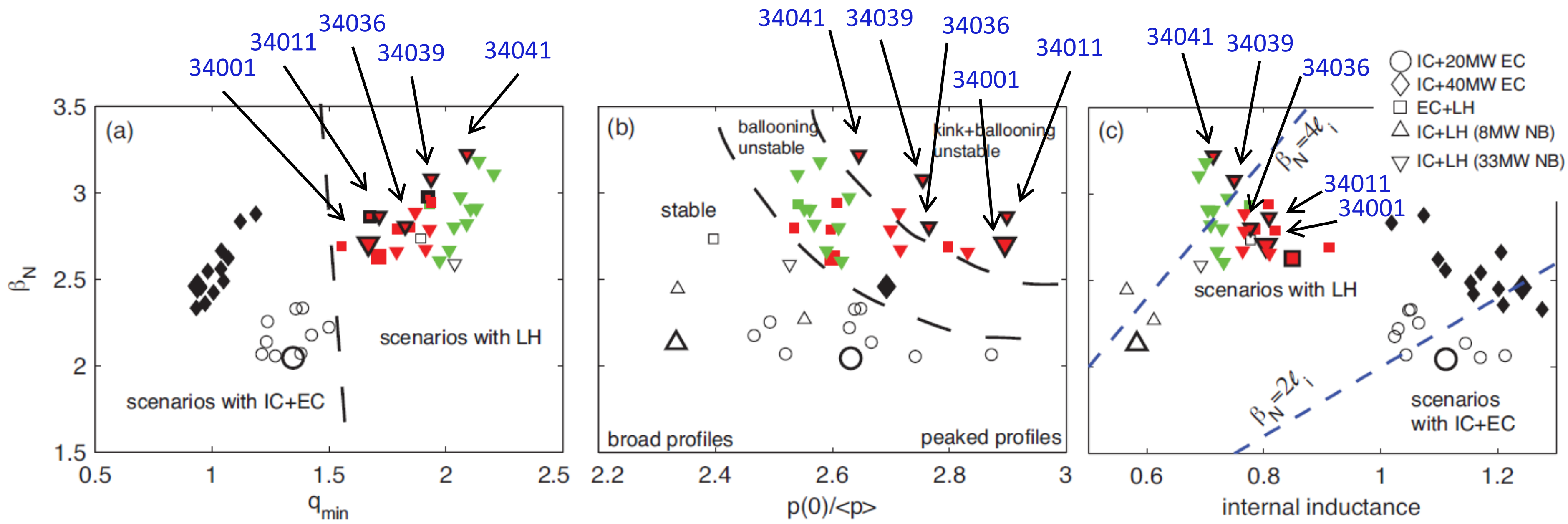
MIKS results: ITER requires alpha particles for RWM stability across all rotation values

- ITER requires alpha particles for stabilization across all rotation values.
  - Quantitatively different, but generally consistent with previously analyzed case (in: [J.W. Berkery et al., Phys. Plasmas 17, 082504 (2010)])
- Correction to ω_D makes calculation more stable, but doesn't affect the general conclusions

$\gamma\tau_w$ contours vs. β_α and ω_ϕ



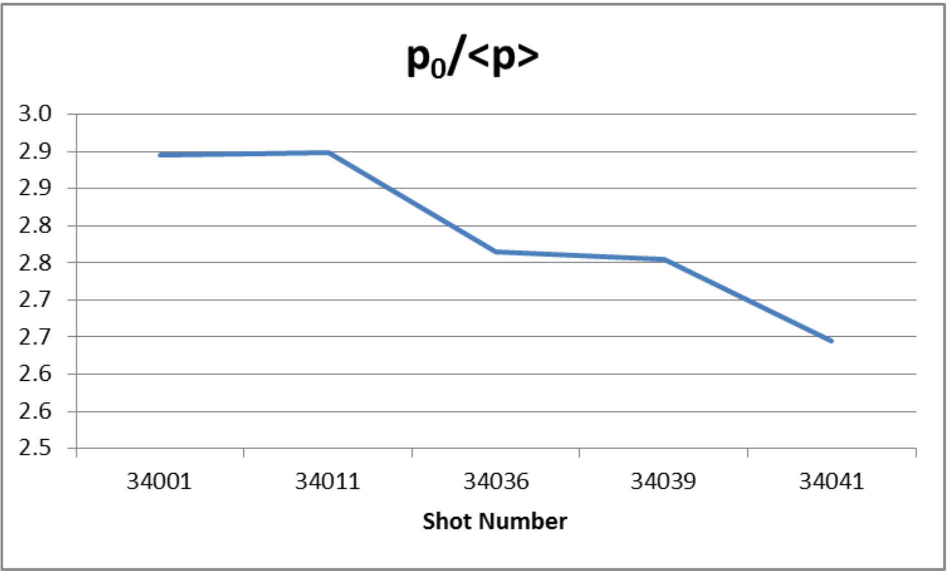
Kinetic RWM stability analysis started with MISK for a greater set of ITER advanced scenario equilibria

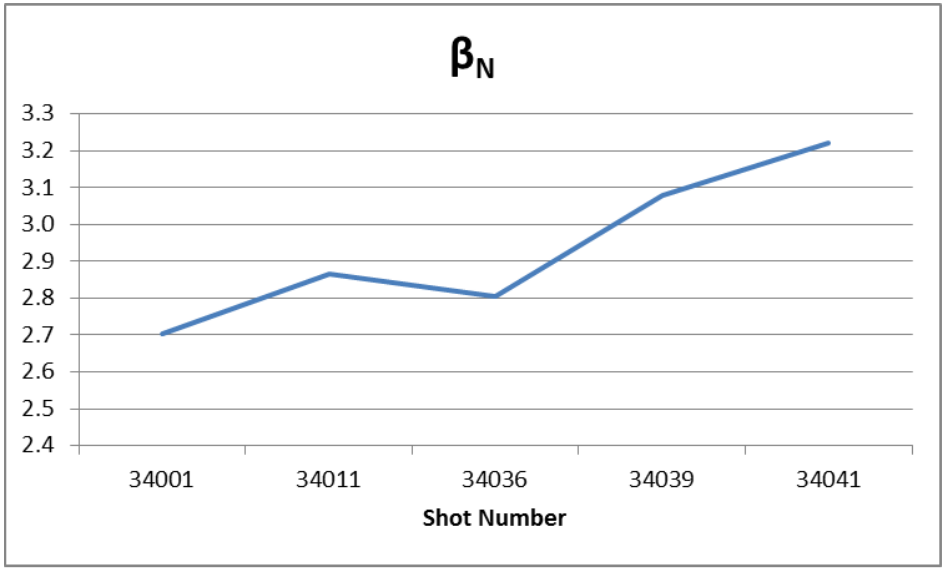


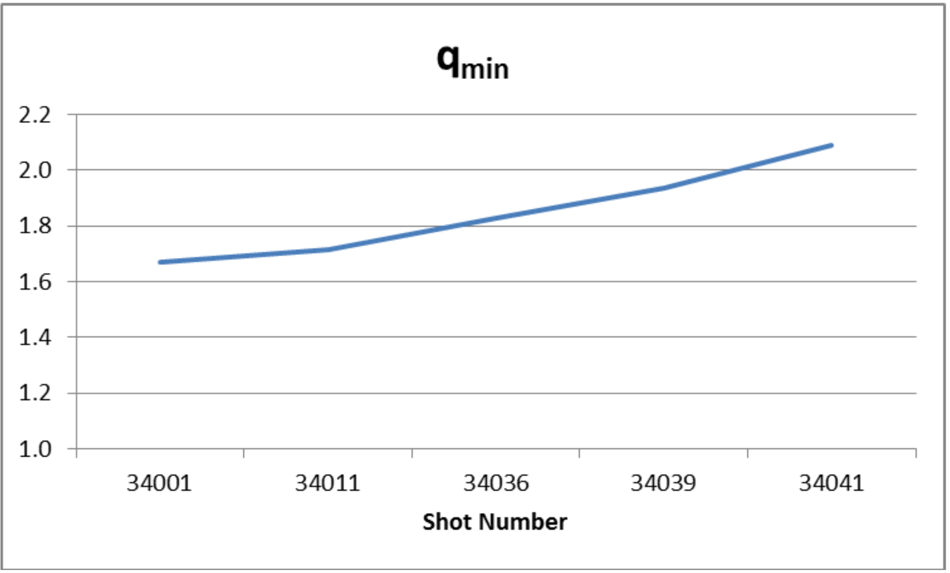
[F. Poli *et al.*, submitted to Nucl. Fusion (2012)]

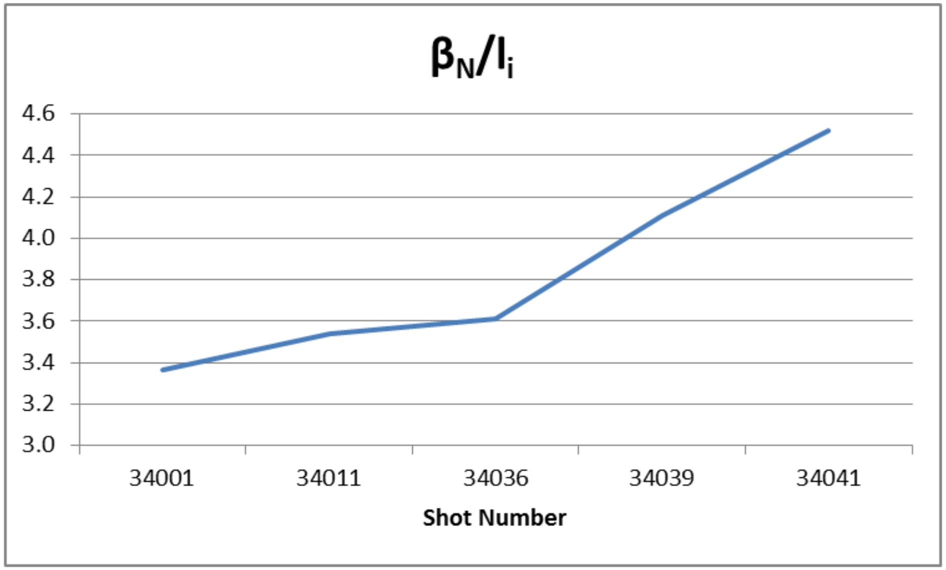
- Five discharges selected
  - Full discharge evolutions – created by combination of TSC and TRANSP codes
  - Range of β_N = 2.65 – 3.25; ideal n=1 no-wall unstable
  - Have internal transport barriers
- Include EPs from: 33MW N-NBI (D), 20 MW IC, 40 MW LH

Various parameters vs. shot number

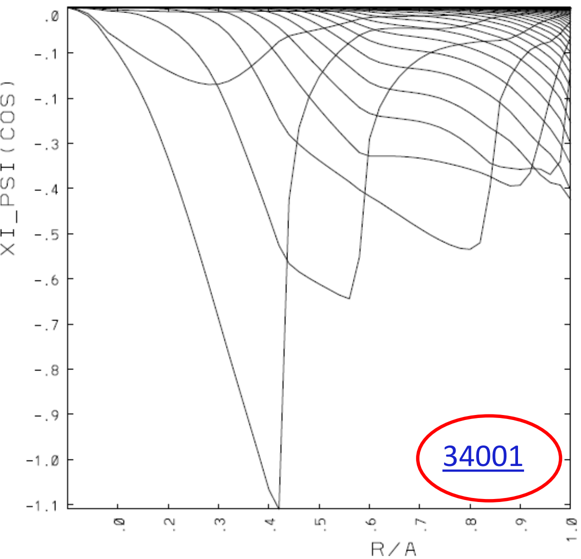


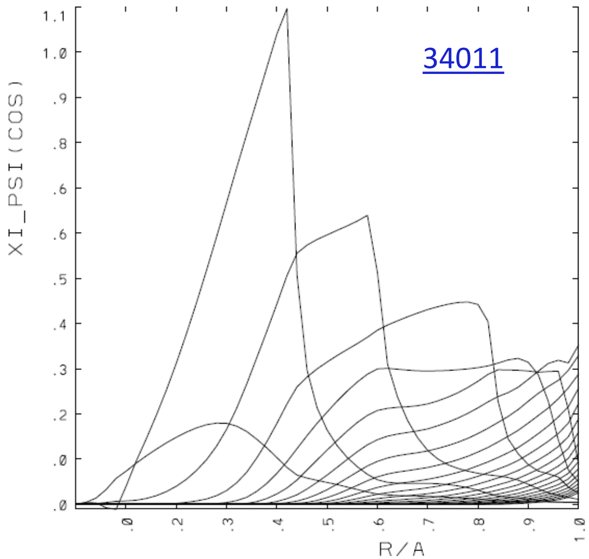


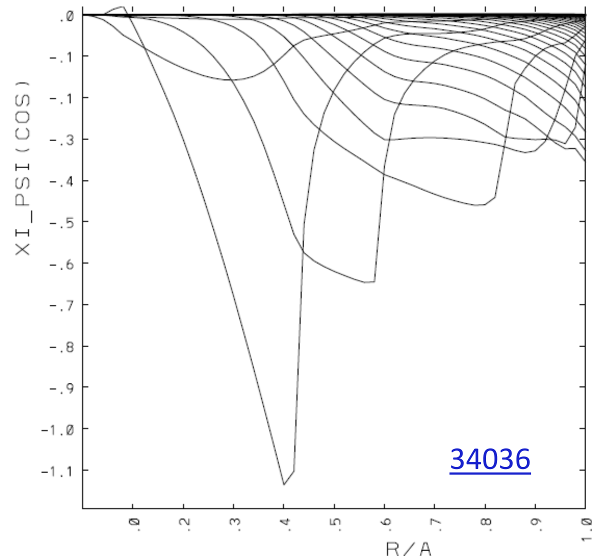


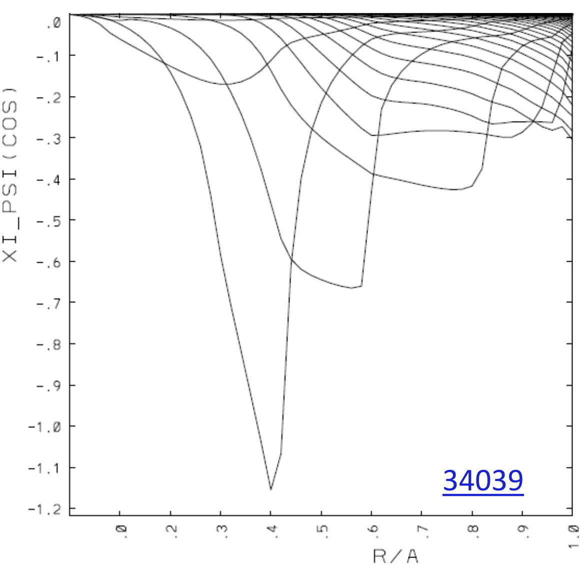


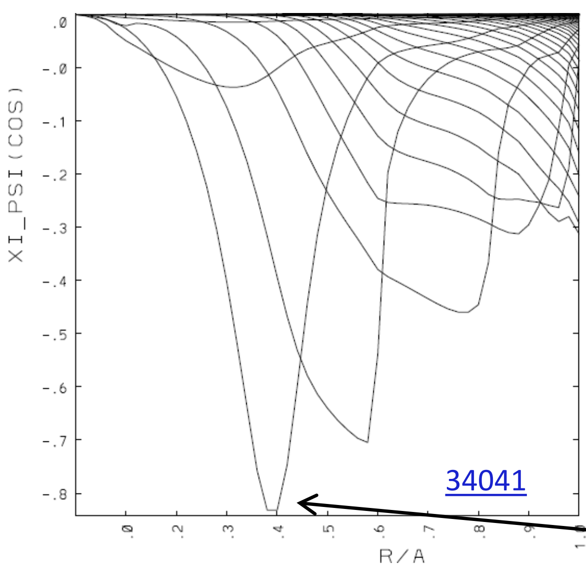
The eigenfunctions (from PEST) all are “infernal”-like modes

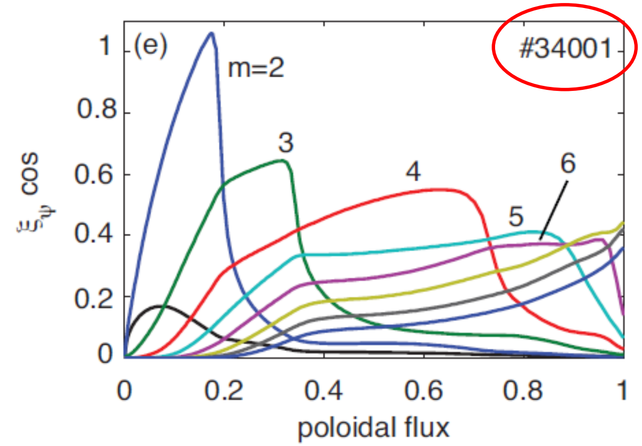








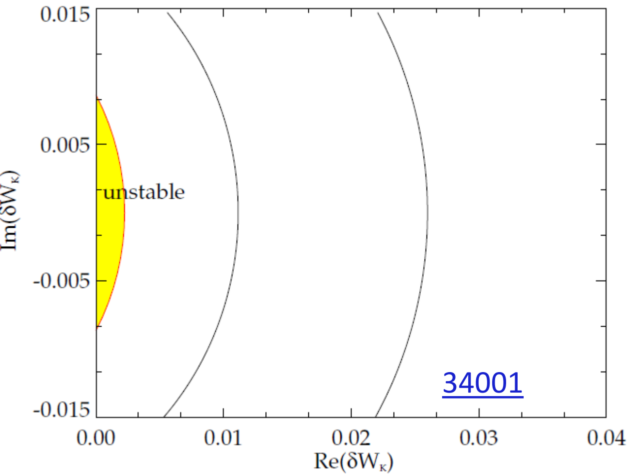


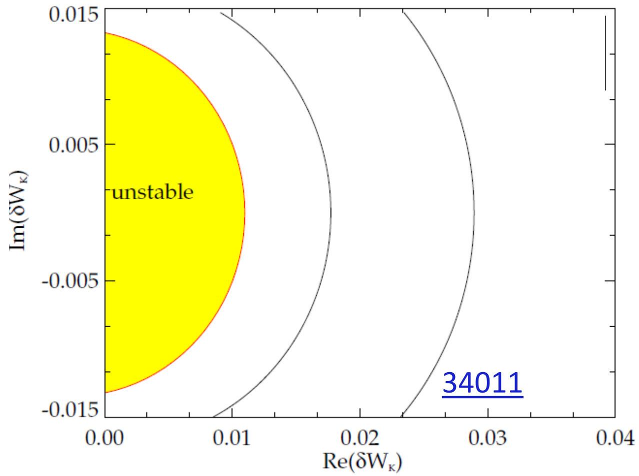


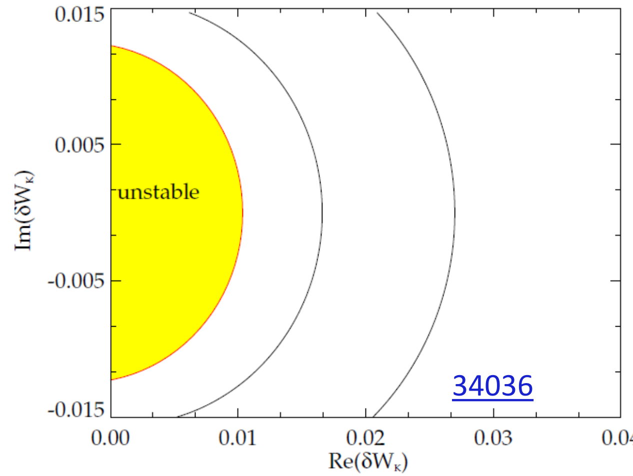
[F. Poli *et al.*, submitted to Nucl. Fusion (2012)]

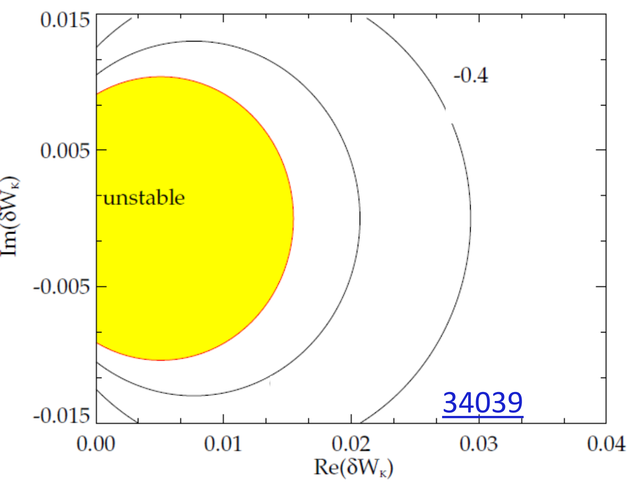
Note scales are different: this one has the smallest peak

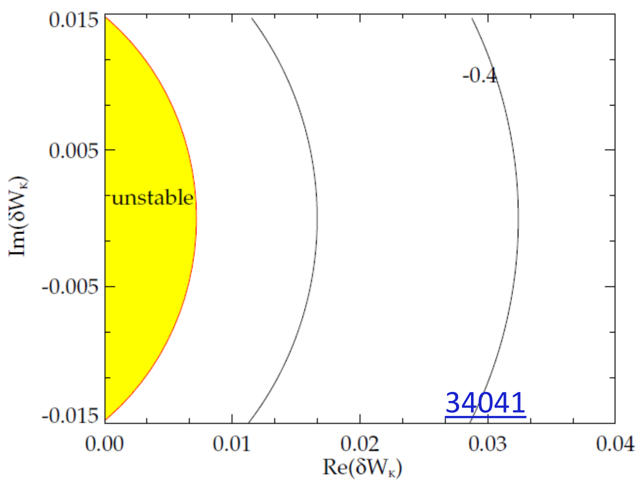
PEST Fluid δW results

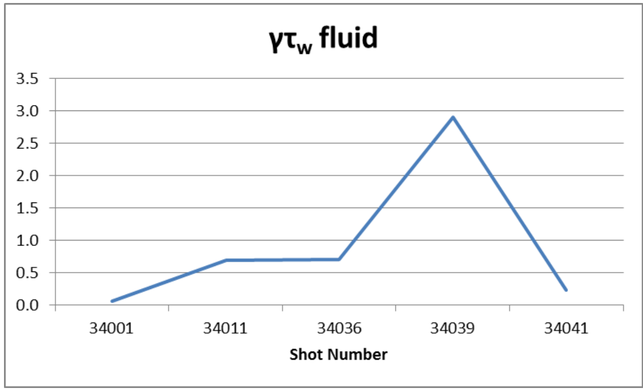




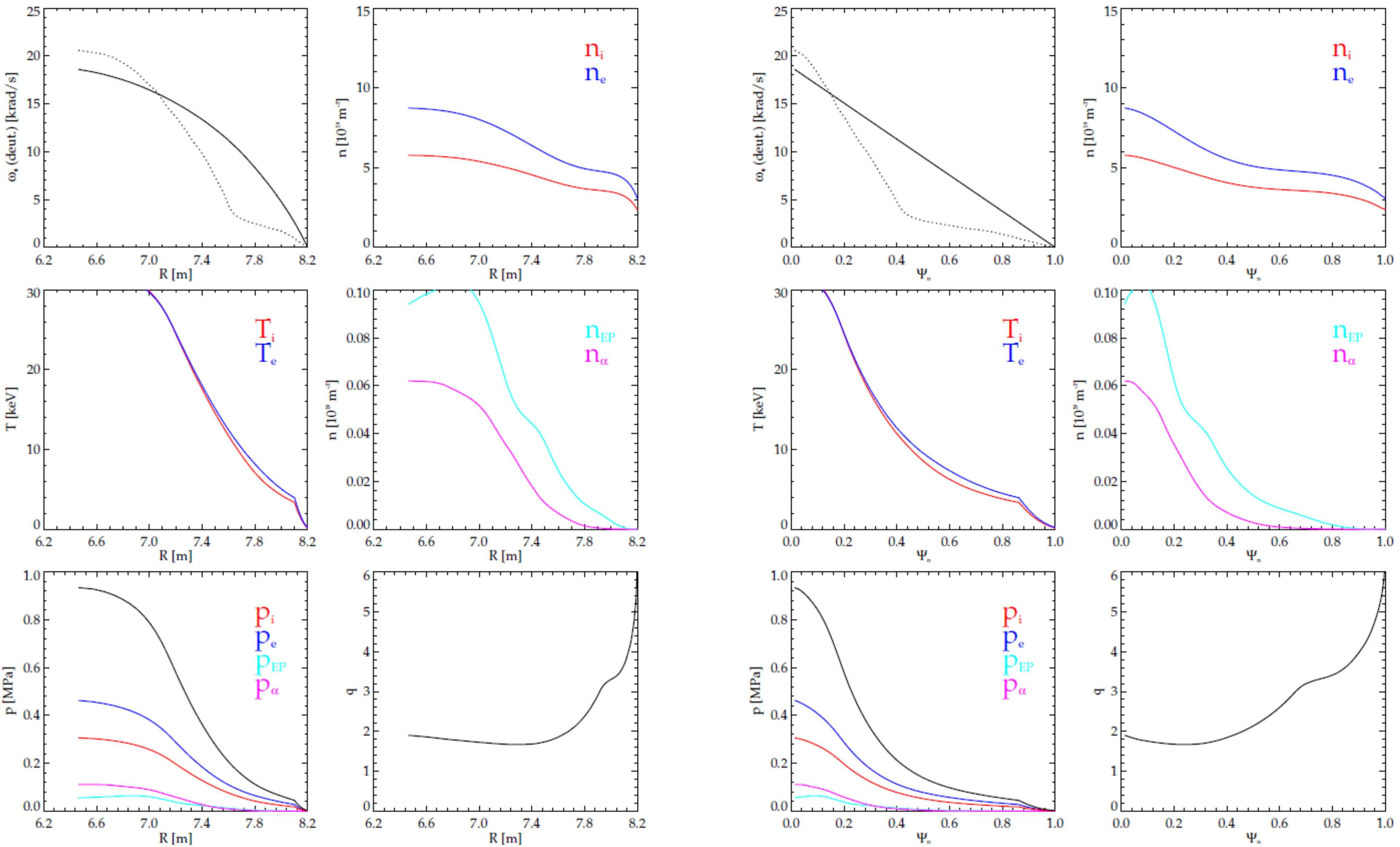








Profiles, 34001 @ 2500s



Notes on MISK δW_K results with deuterium and tritium

$$\delta W_K = \sum_j \sum_{l=-\infty}^{\infty} 2\sqrt{2}\pi^2 \int\int\int \left[|\langle H/\hat{\varepsilon}\rangle|^2 \frac{(\omega - n\omega_E)\frac{\partial f_j}{\partial \varepsilon} - \frac{n}{Z_j e}\frac{\partial f_j}{\partial \Psi}}{\underbrace{n\langle\omega_D^j\rangle + l\omega_b^j - i\nu_{\rm eff}^j}_{\text{go like } m^{-1/2}} + n\omega_E - \omega} \right] \frac{\hat{\tau}}{m_j^{\frac{3}{2}} B} |\chi| \hat{\varepsilon}^{\frac{5}{2}} d\hat{\varepsilon} d\chi d\boldsymbol{\Psi},$$

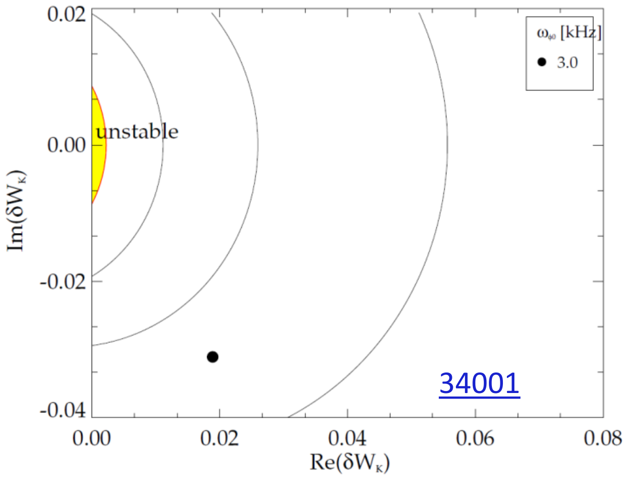
Splitting to 50% deuterium and 50% tritium makes very little difference (vs. 100% deuterium). Need to recheck the effect on Alfven layers.

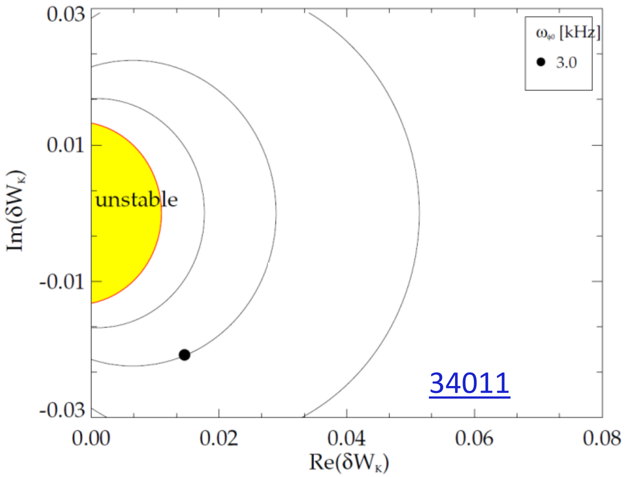
When including alpha particles, I had to pay close attention to the 50% deuterium and 50% tritium mix, because it matters for the alpha's slowing-down distribution:

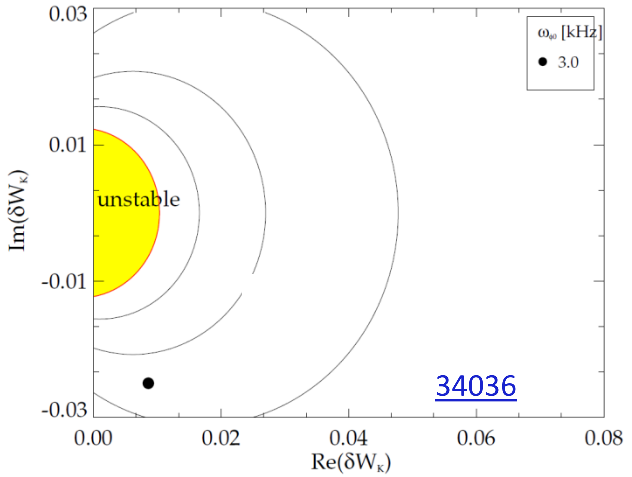
$$f_j^\alpha(\varepsilon, \Psi) = n_j A_\alpha \left(\frac{m_j}{\varepsilon_\alpha}\right)^{\frac{3}{2}} \frac{1}{\hat{\varepsilon}^{\frac{3}{2}} + \hat{\varepsilon}_c^{\frac{3}{2}}} \qquad \varepsilon_c = \left(\frac{3\sqrt{\pi}}{4}\right)^{\frac{2}{3}} \left(\frac{m_j}{m_e}\right) \left(\frac{m_e}{n_e}\sum_i \left(\frac{n_i Z_i^2}{m_i}\right)\right)^{\frac{2}{3}} T_e$$

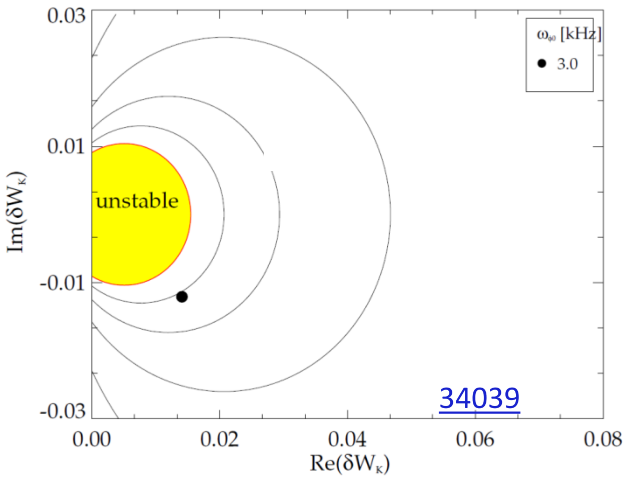
Note: I assumed alpha particles were isotropic (as usual). Nikolai has said that alphas can be beam-like in ITER, especially near the edge. I should ask him about that.

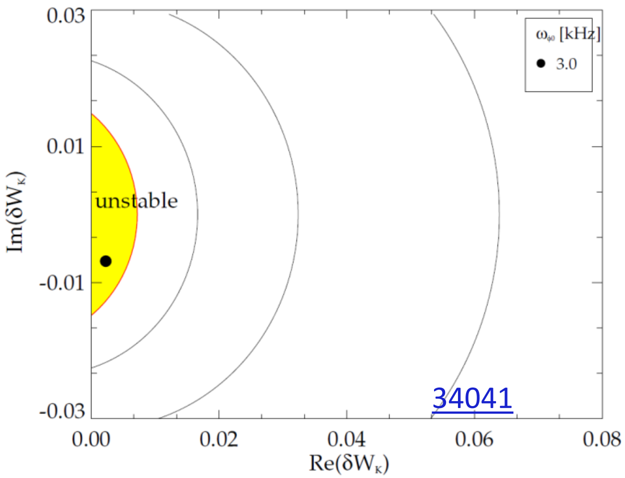
MISK Kinetic δW_K results, thermal particles only





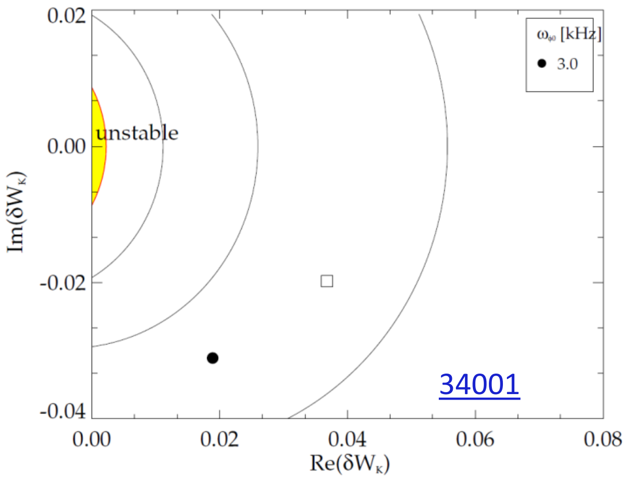


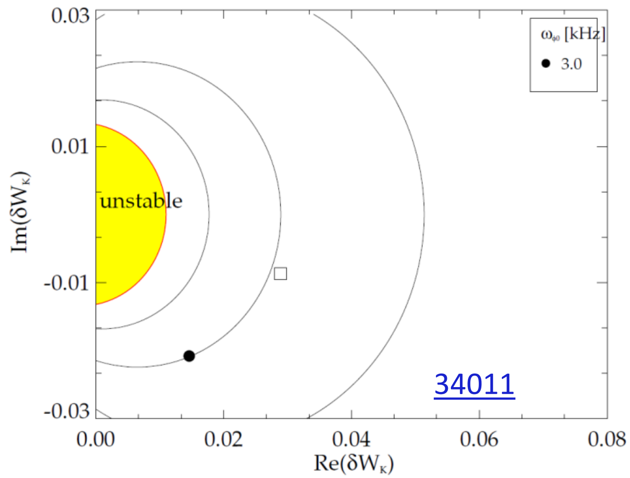


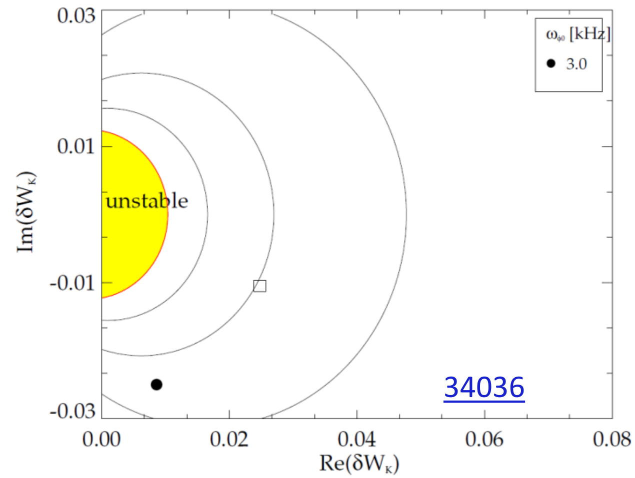


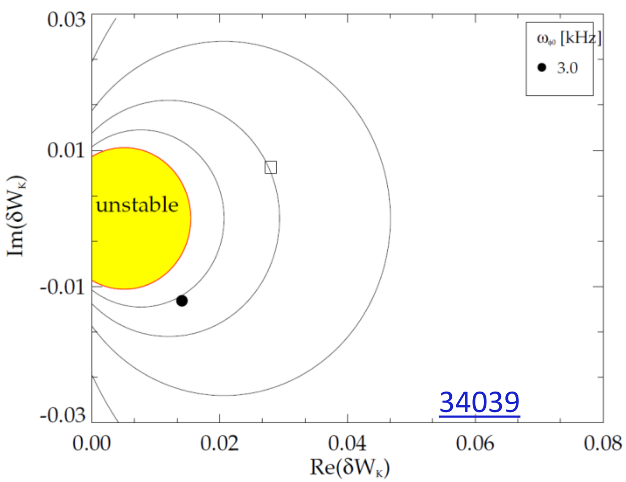
Kinetic effects basically continually decrease with shot number. What is causing this? Have to look in detail.

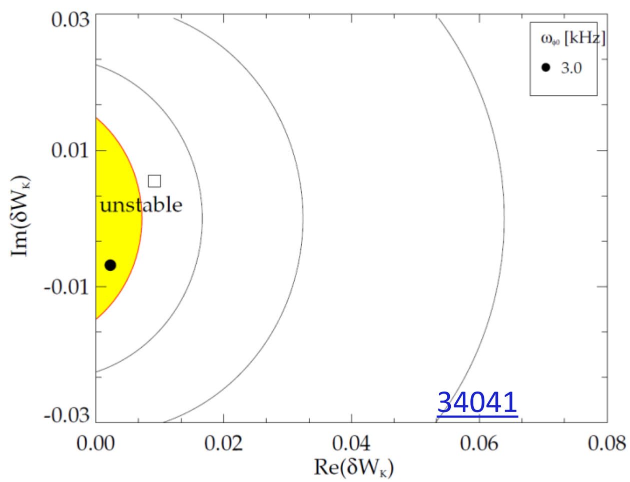
Results with alpha particles included







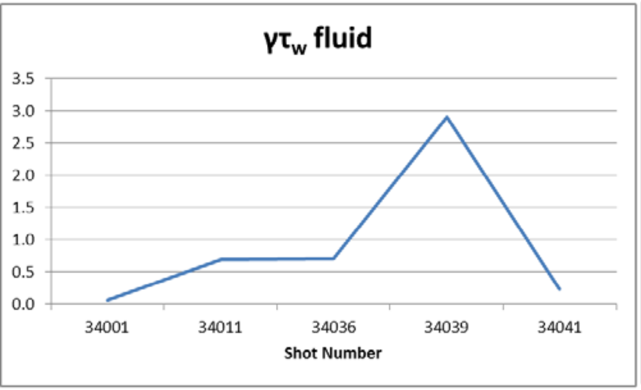


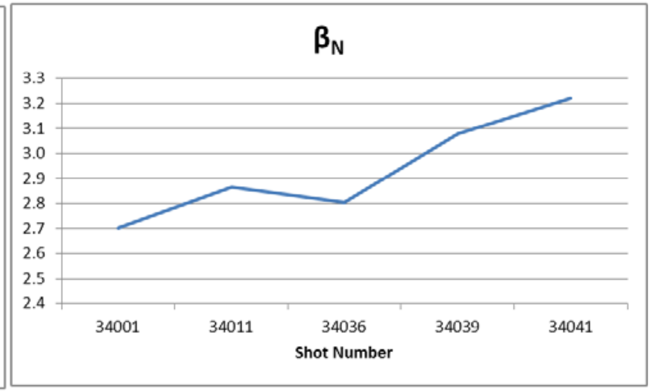


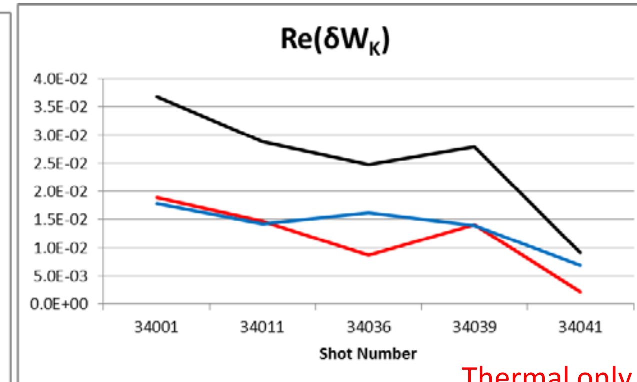
Alpha particles provide a roughly constant increment to δW_K, as expected.

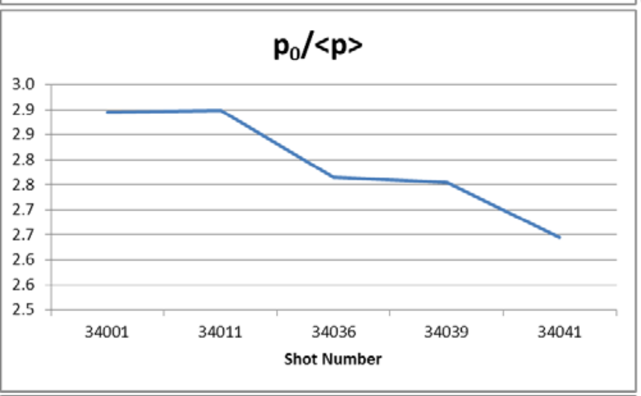
Interestingly, the imaginary increment is roughly the same as the real increment, which is unexpected.

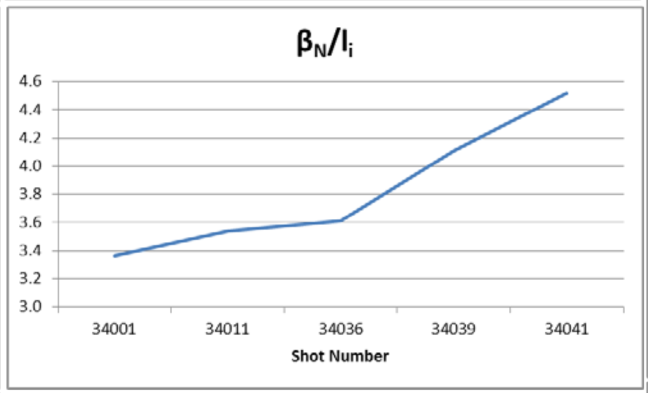
Various parameters vs. shot number







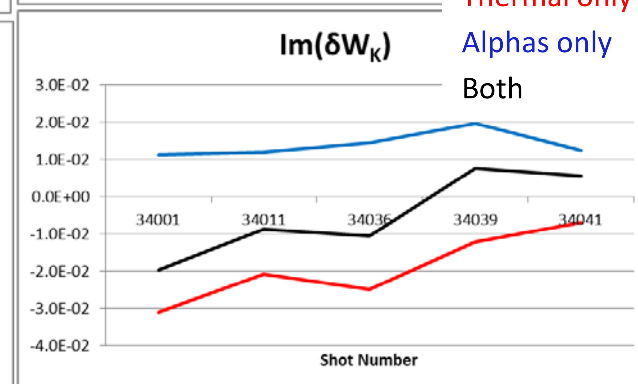


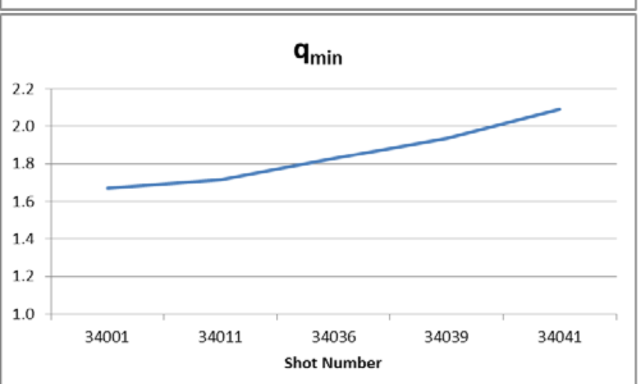


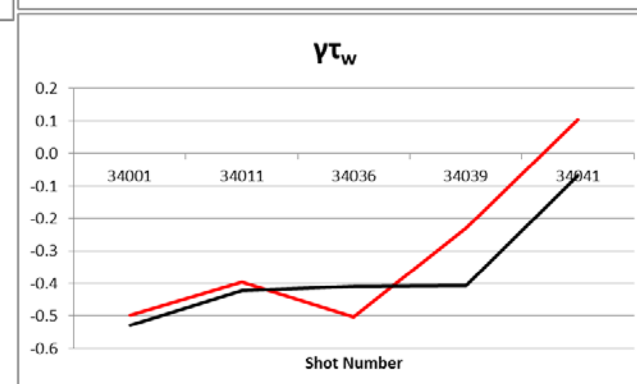
Thermal only

Alphas only

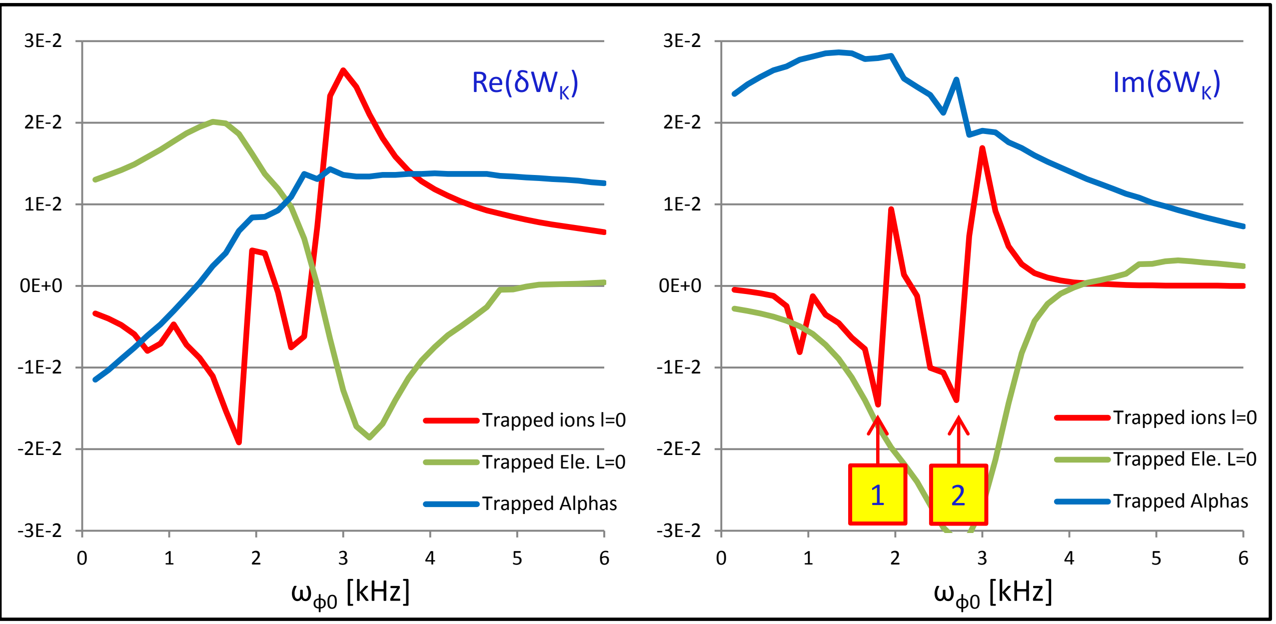
Both

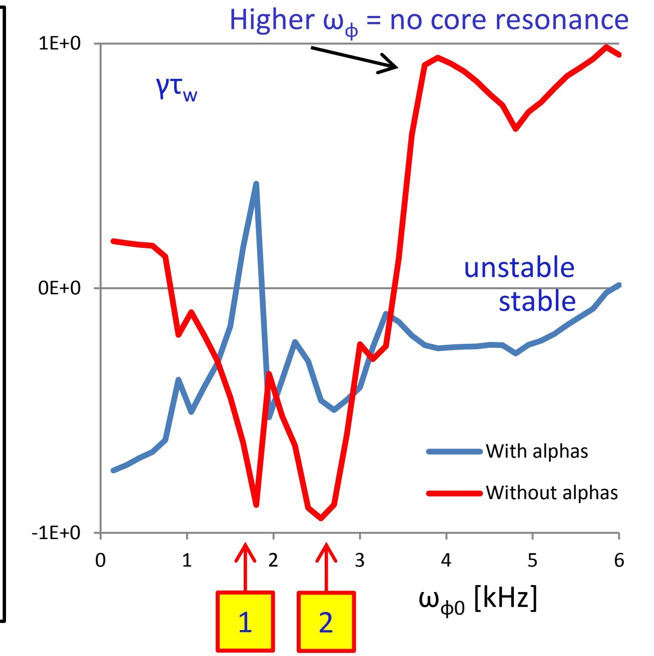


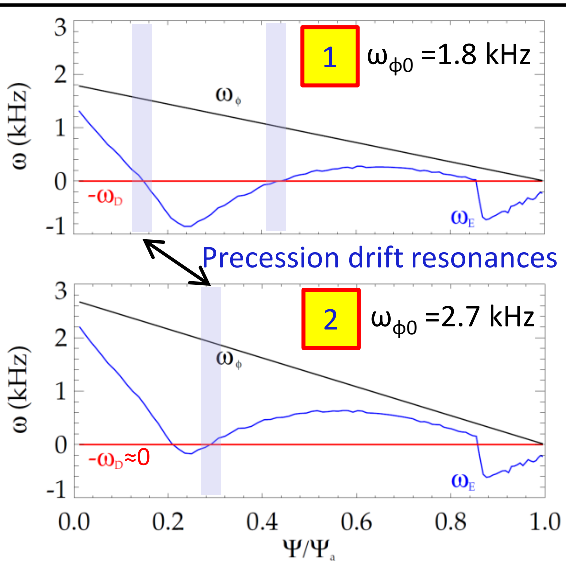


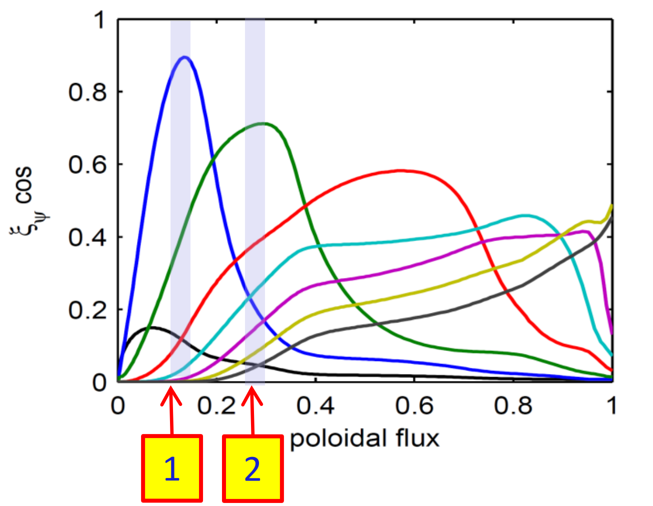


Initial analysis: Stable region appears at low rotation with no alpha particles – may be due to "infernal" eigenfunction





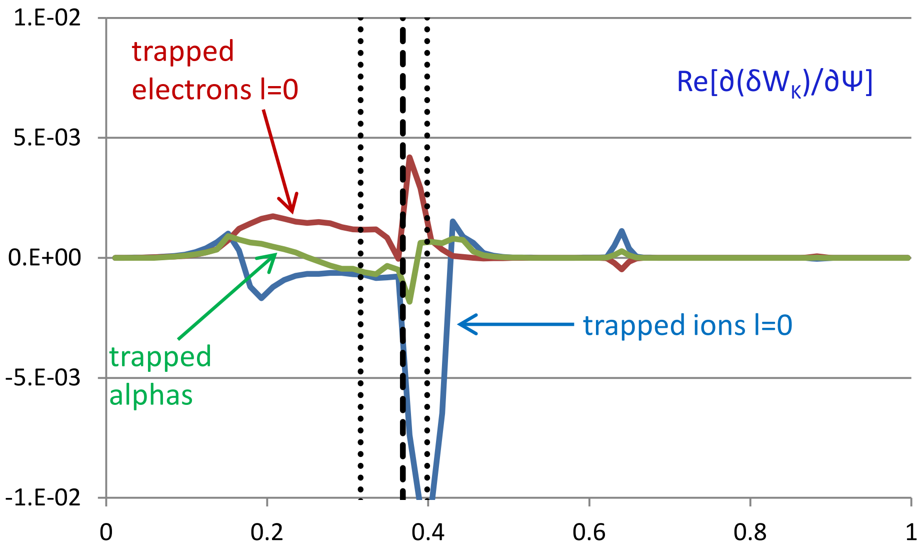


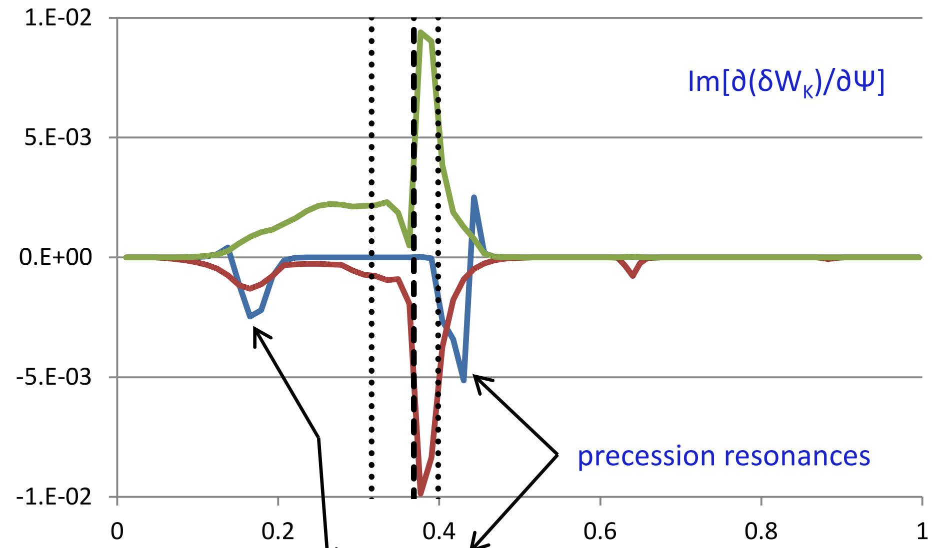


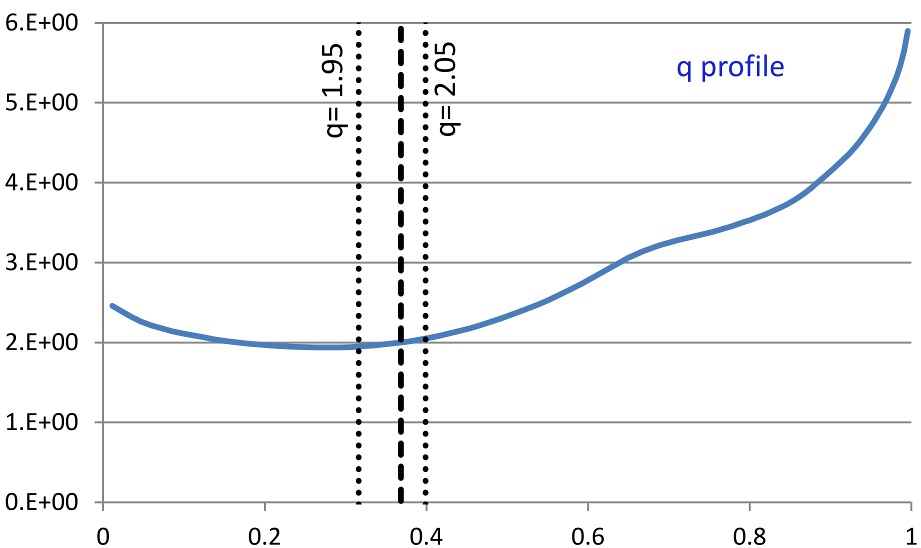
[F. Poli *et al.*, submitted to Nucl. Fusion (2012)]

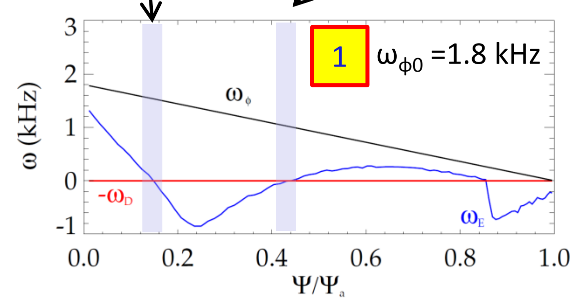
- Stable regions found with no alphas
  - Low ω_ϕ
  - Unstable region at higher ω_ϕ

When resonances are close to the rational surface, MISK might not properly include them



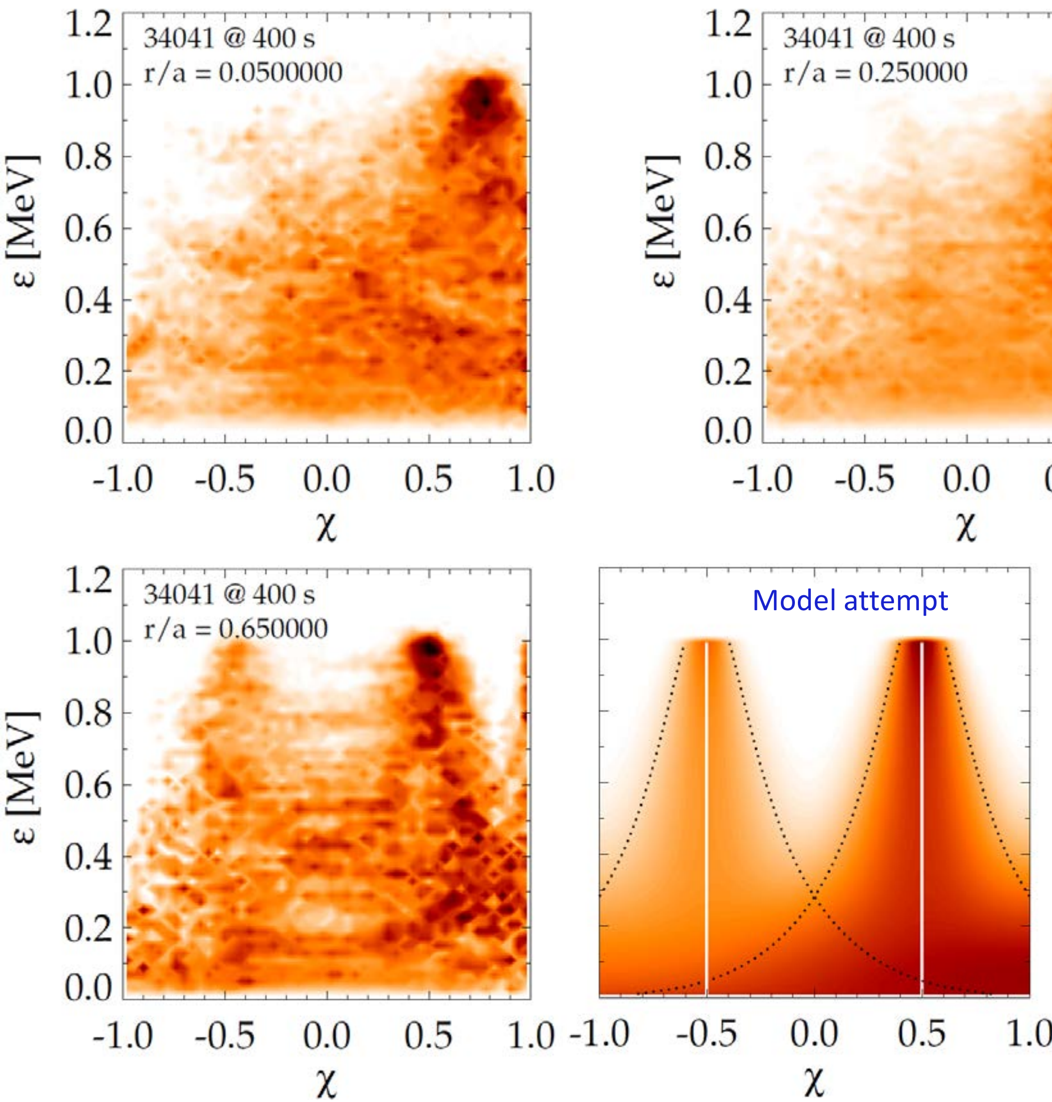






- Resonance near the q=2 surface
  - MISK Alfven layer scheme might cut off important effects (between 1 and 2)
  - How can we deal with this?

Energetic particle distribution function 34041 @ 400s

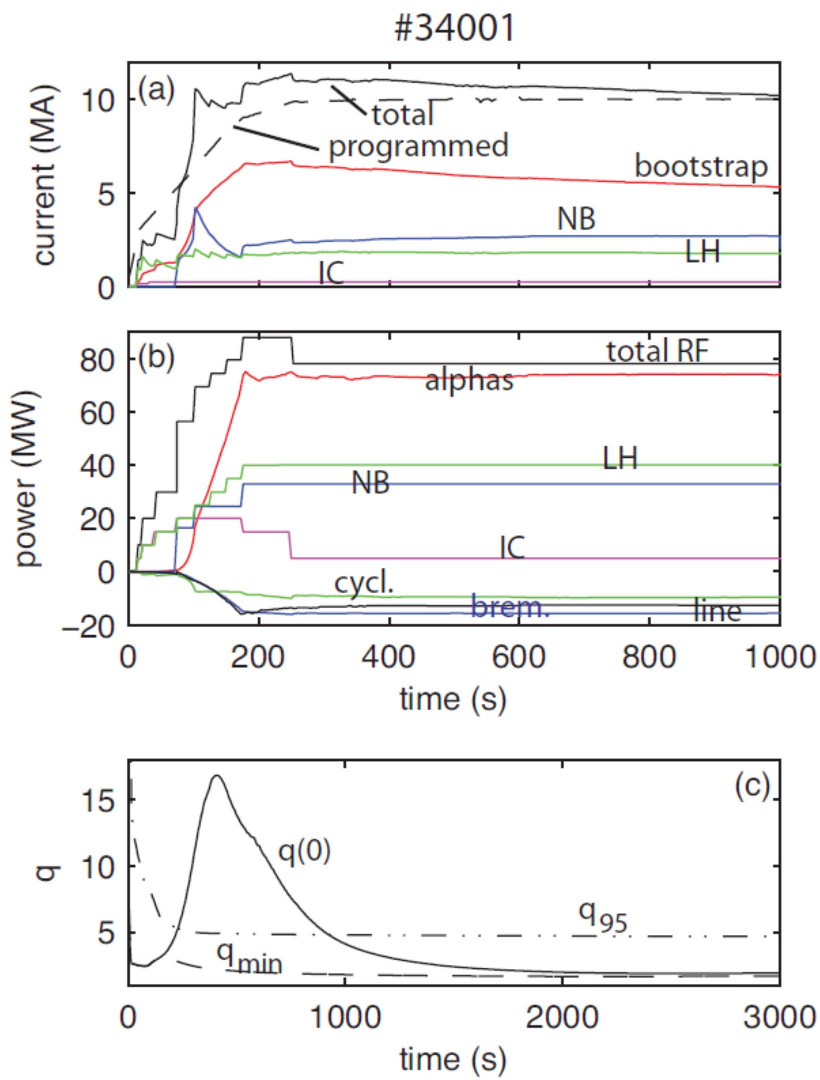


- EPDF from TRANSP is complex
  - Multiple heating sources
  - Can attempt to model it with Gaussian distributions

XXX

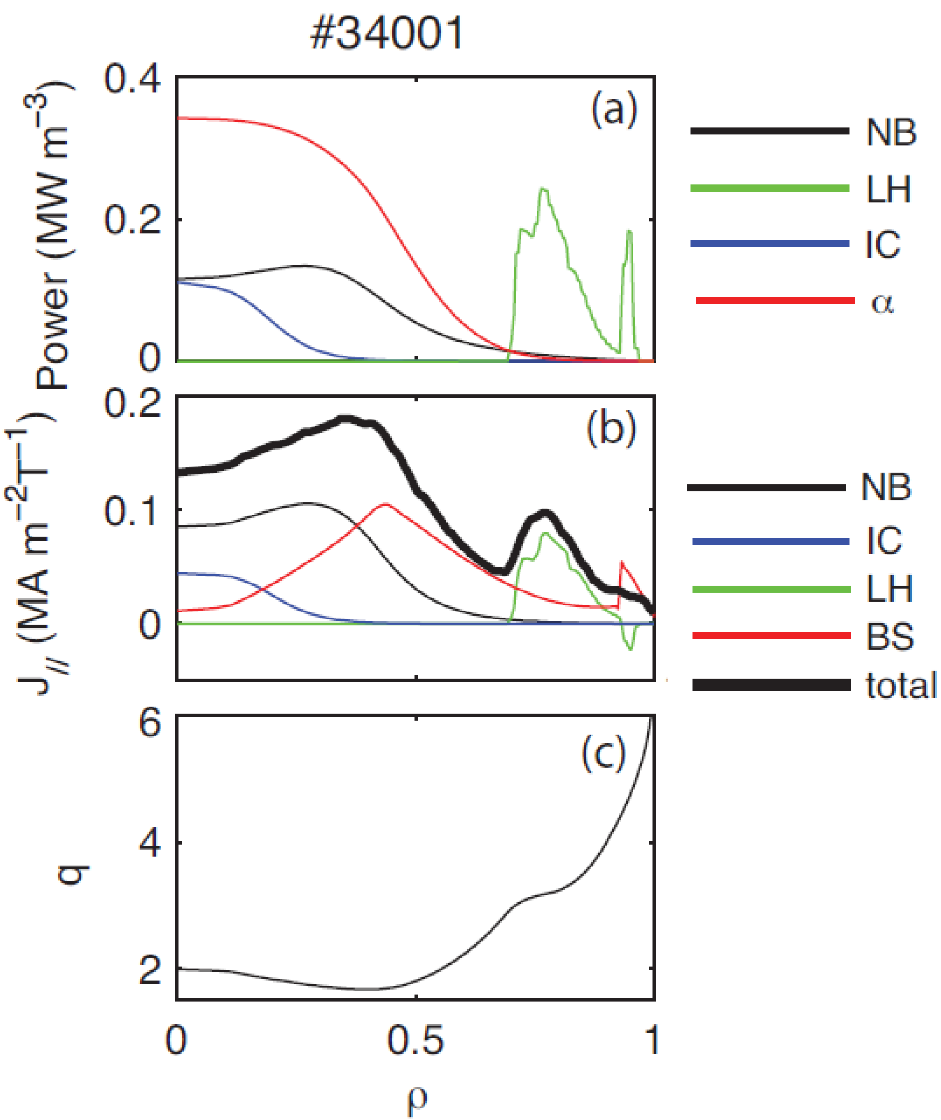
Some figures from Francesca's paper

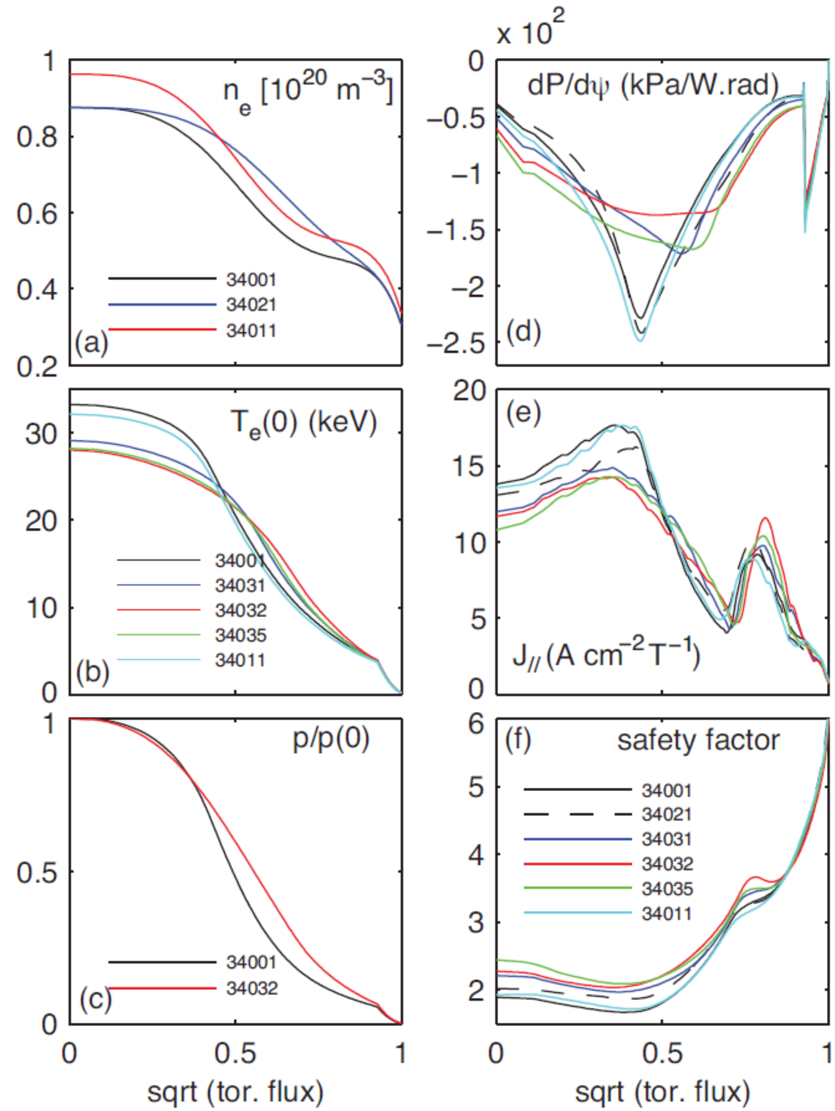
SHOT#	31001	32001	33001	34001	35001
NB (MW)	33	33	33	33	8
IC (MW)	20	20	/	20	20
EC (MW)	20	40	20	/	/
LH (MW)	/	/	20	40	40
$\mathbf{I_p}$ **(MA)**	7.0	9.0	8.85	10.0	7.25
I_{NI} (MA)	7.04	9.09	8.90	10.20	7.5
I_{BS} (MA)	3.4	3.8	4.8	5.2	4.9
I_{NB} (MA)	2.6	3.1	2.4	2.8	0.56
I_{EC} (MA)	0.74	1.66	0.73	/	/
I_{IC} (MA)	0.25	0.40	/	0.25	0.25
I_{LH} (MA)	/	/	0.83	1.8	1.75
f_{BS}	0.48	0.41	0.54	0.51	0.65
P_α	28	52	64	76	33
Q	2.4	3.3	4.3	4.9	2.4
P_{rad}	22	31	35	38	27
n/n_G	1.00	0.86	0.95	0.85	1.0
$\mathbf{n(0)[10^{19}m^{-3}]}$	7.0	7.5	8.5	8.7	7.2
$T(0)$ (keV)	19	32	25	32	18
$\mathbf{n(0)/\langle n\rangle}$	1.44	1.4	1.44	1.5	1.3
$p(0)/\langle p\rangle$	2.63	2.56	2.6	2.90	2.33
ρ_{ITB}	0.55	0.55	0.65	0.45	0.65
$l_i(1)$	1.07	1.22	0.85	0.80	0.58
$l_i(3)$	0.87	1.00	0.69	0.66	0.48
H_{98}	1.55	1.58	1.63	1.63	1.55
$q(0)$	1.61	1.67	3.3	1.88	6.05
q_{min}	1.35	0.96	1.71	1.67	4.5
q_{95}	7.0	5.4	5.2	4.7	6.78
β_N	2.0	2.4	2.6	2.7	2.13
Ballooning	S	S	U	U	S
$n=1$, no wall	S	U	S	U	S
$n=1$, wall	S	U	S	S	S



33 MW NB	34011
20 MW IC	
40 MW LH	
I_{NI} (MA)	9.9
I_{NB} (MA)	2.3
I_{BS} (MA)	5.5
P_α	87
Q	5.5
$p(0)/\langle p\rangle$	2.5
$\mathbf{n(0)/\langle n\rangle}$	1.4
$\mathbf{n(0)[10^{19}m^{-3}}$	9.6
$T_e(0)$ (keV)	32
ρ_{ITB}	0.45
β_N	2.86
$q(0)$	1.95
q_{min}	1.72
H_{98}	1.64
n/n_G	0.93
ballooning	U
n=1, no-wall	U
n=1 wall	S

Some figures from Francesca's paper





Some figures from Francesca's paper

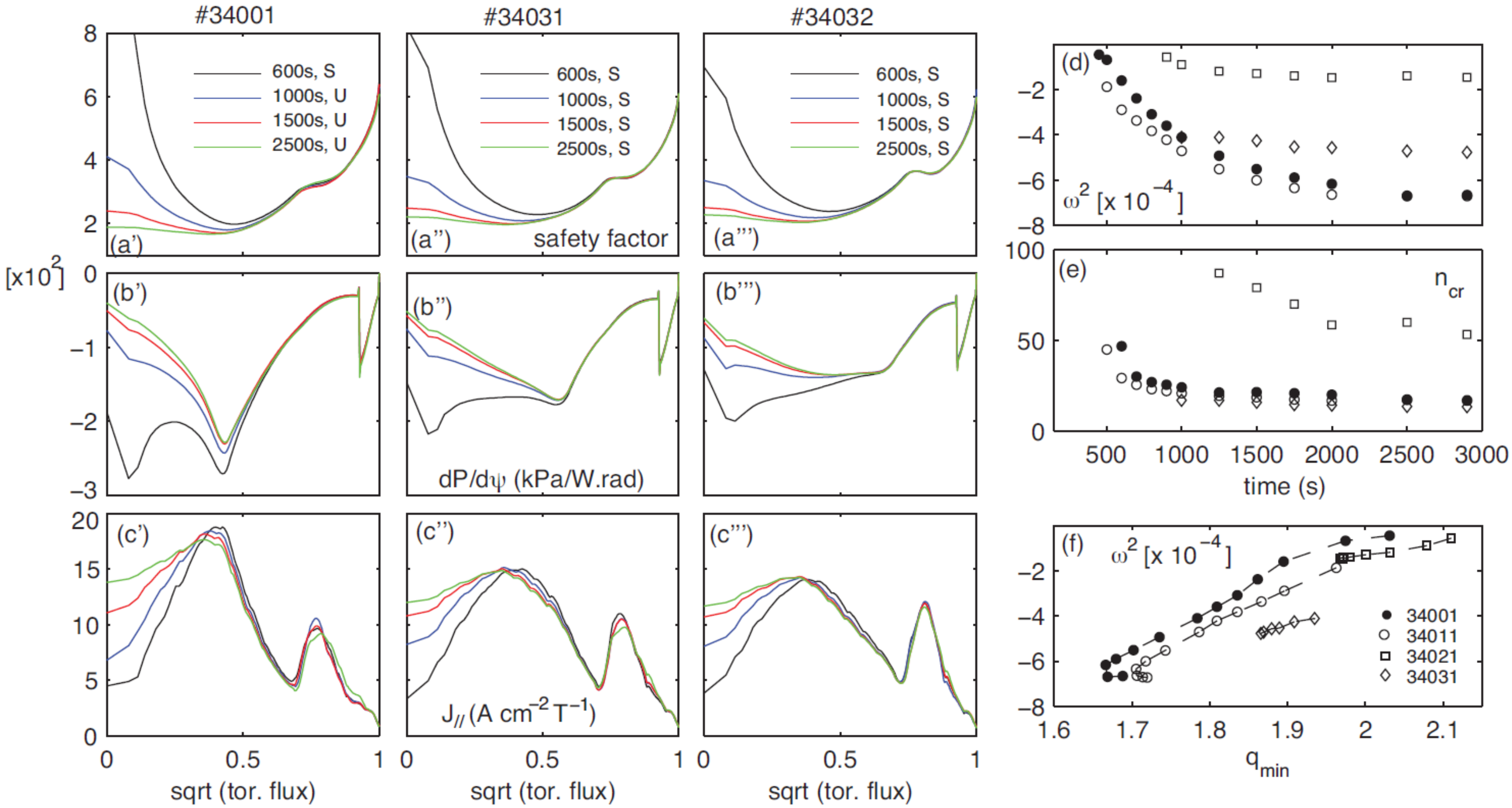


FIG. 16: (Colour online) Scenario with IC, LH and 33 MW NB. (a) Safety factor profile, (b) pressure derivative, (c) parallel current density profiles, calculated at four time slices during the flat-top phase. For each time it is noted whether the plasma is stable (S) or unstable (U) to $n = 1$ kinks. (d)-(e) Solutions of the ballooning equation calculated for the reference scenario (•), for broader density profile (◇), for ITB at $r/a = 0.60$ (□) and for central density 10% larger (○). (c) dependence of the eigenvalues ω^2 on $q_{\min}$.

PEST Fluid δW results

34001 @ 2500s
Marginal b = 1.20
Marginal eigenvalue = -0.1883e-5
δWinf = -0.2246451e-2
δW_b = 0.3334449e-1 (b = 0.35)
β_N = 2.7038
$p_0/\langle p\rangle$ = 2.8950
q_{min} = 1.66856
l_i = 0.8036

34011 @ 2500s
Marginal b = 0.561
Marginal eigenvalue = -0.2105e-5
δWinf = -0.1098658e-1
δW_b = 0.1593027e-1 (b = 0.35)
β_N = 2.8645
$p_0/\langle p\rangle$ = 2.8984
q_{min} = 1.71432
l_i = 0.8088

34036 @ 2500s
Marginal b = 0.555
Marginal eigenvalue = -0.9399e-5
δWinf = -0.1035962e-1
δW_b = 0.1456835e-1 (b = 0.35)
β_N = 2.8045
$p_0/\langle p\rangle$ = 2.7648
q_{min} = 1.82644
l_i = 0.7772

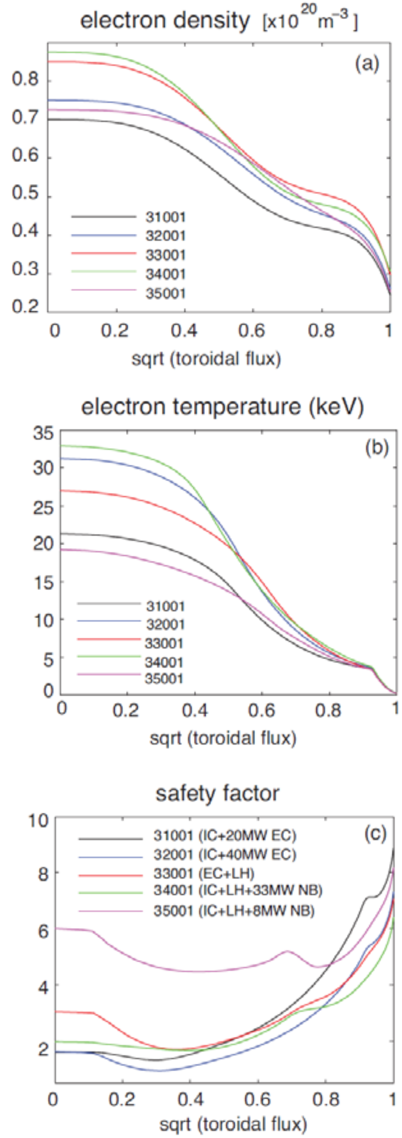
34039 @ 2500s
Marginal b = 0.414
Marginal eigenvalue = -0.3469e-5
δWinf = -0.15478102e-1
δW_b = 0.53414071e-2 (b = 0.35)
β_N = 3.0790
$p_0/\langle p\rangle$ = 2.7543
q_{min} = 1.93668
l_i = 0.7493

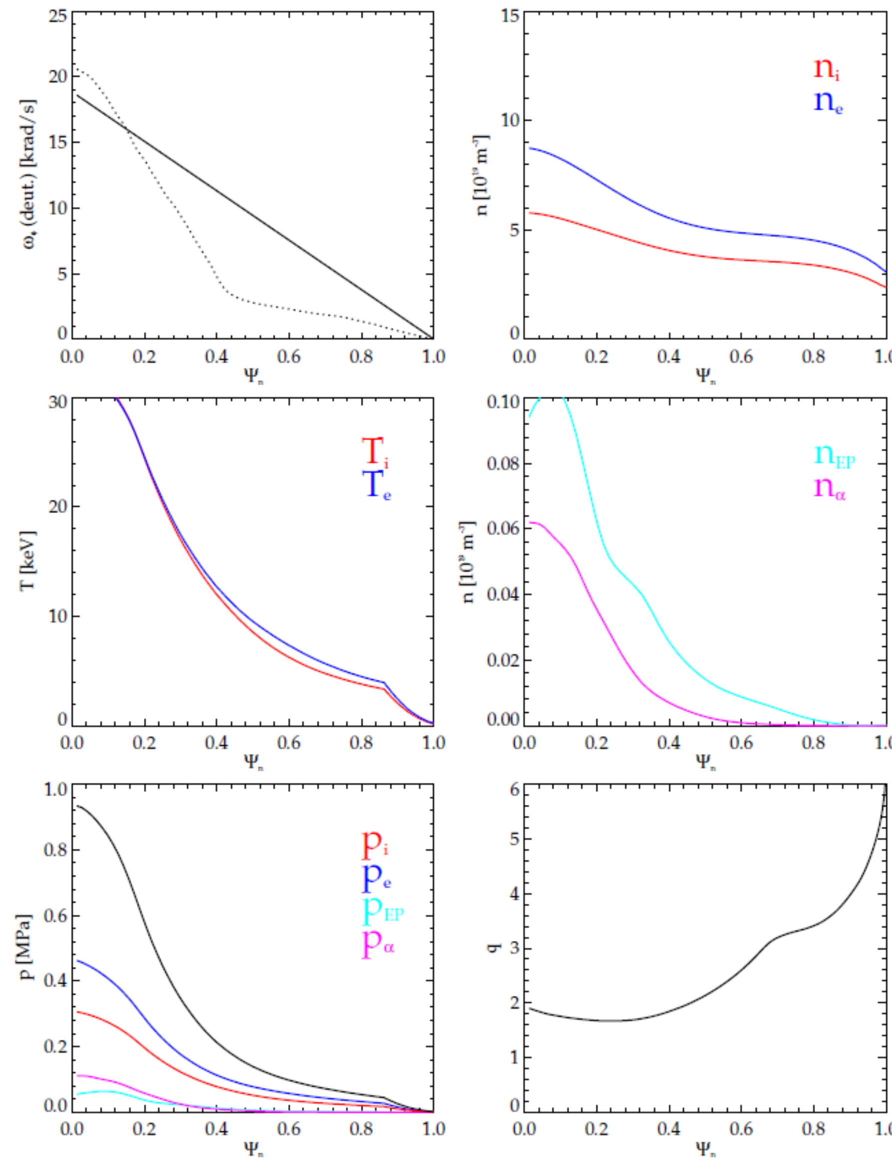
34041 @ 2500s
Marginal b = 0.789
Marginal eigenvalue = -0.6606e-6
δWinf = -0.72005936e-2
δW_b = 0.30589234e-1 (b = 0.35)
β_N = 3.2207
$p_0/\langle p\rangle$ = 2.6452
q_{min} = 2.09046
l_i = 0.7130

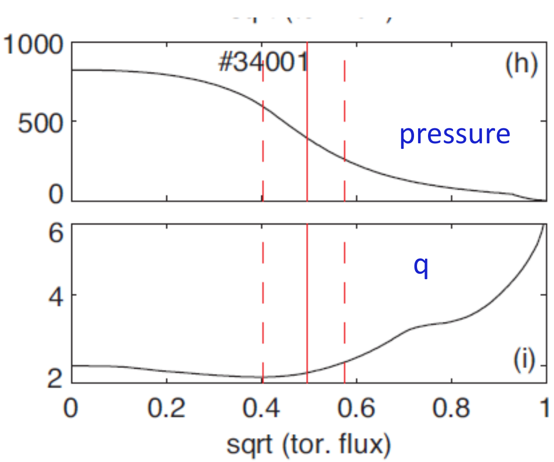
Results with the real wall are very similar to a conformal wall at b = 0.35, so we have used the conformal wall.

Profiles, 34001 @ 2500s

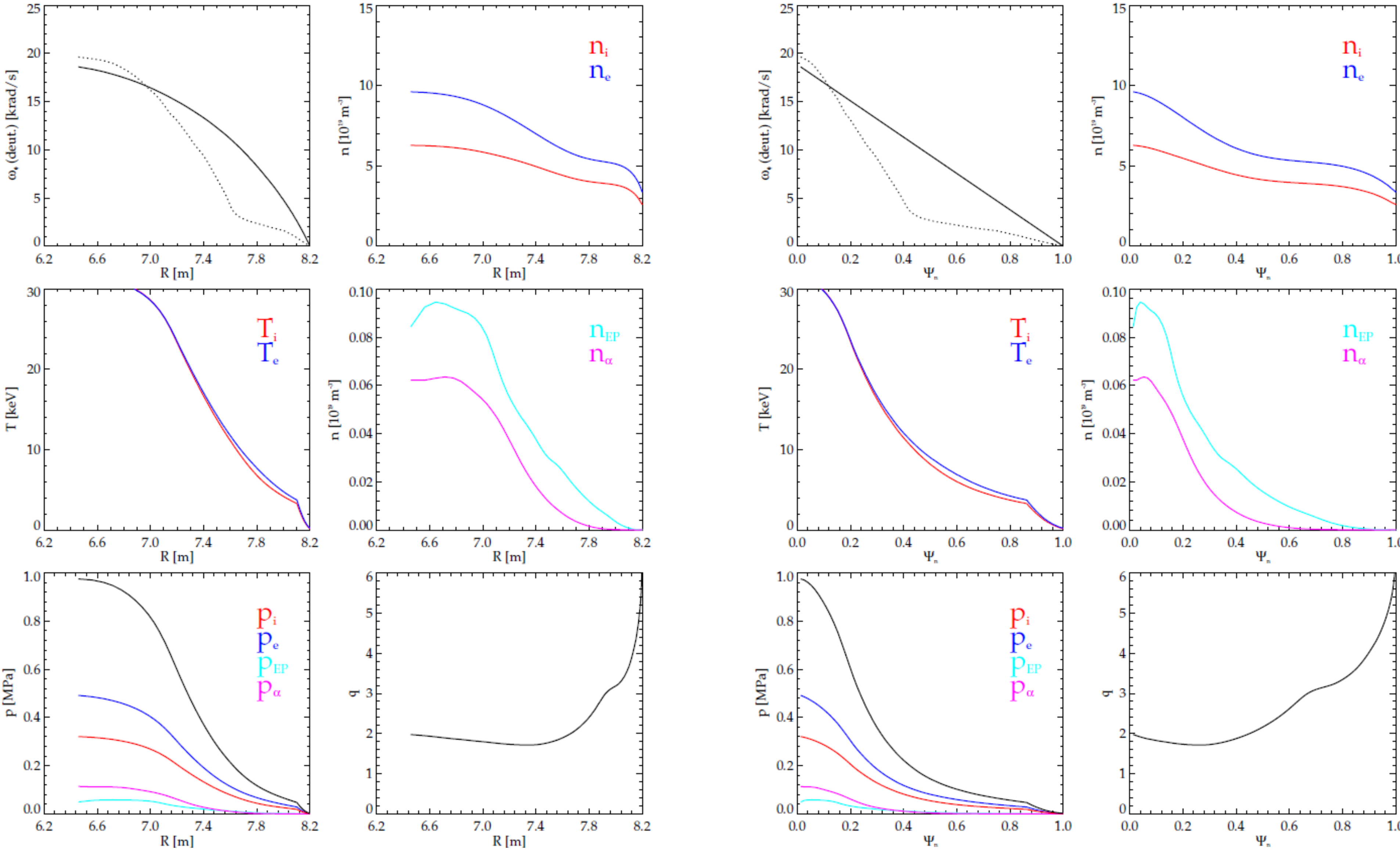
Compare to figures from
[F. Poli *et al.*, submitted to Nucl. Fusion (2012)]
(green profile is same shot, but at t = 2000s) →



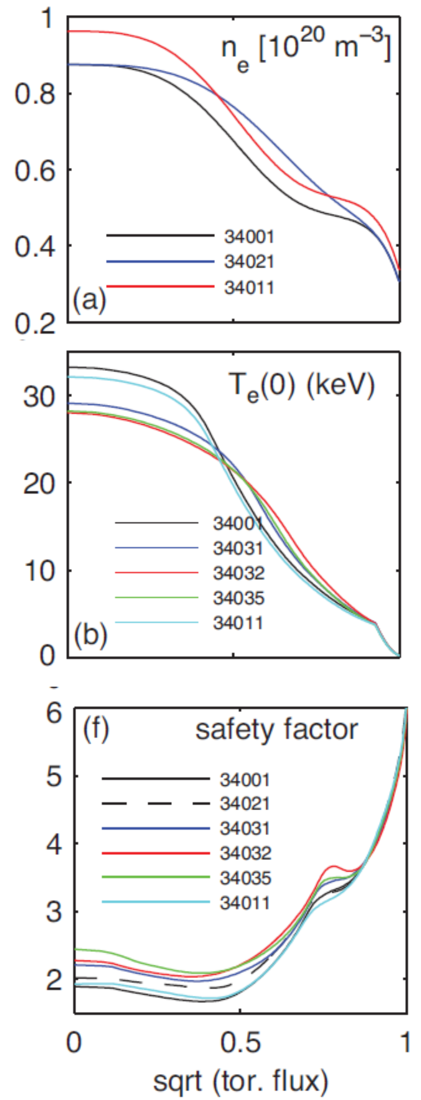


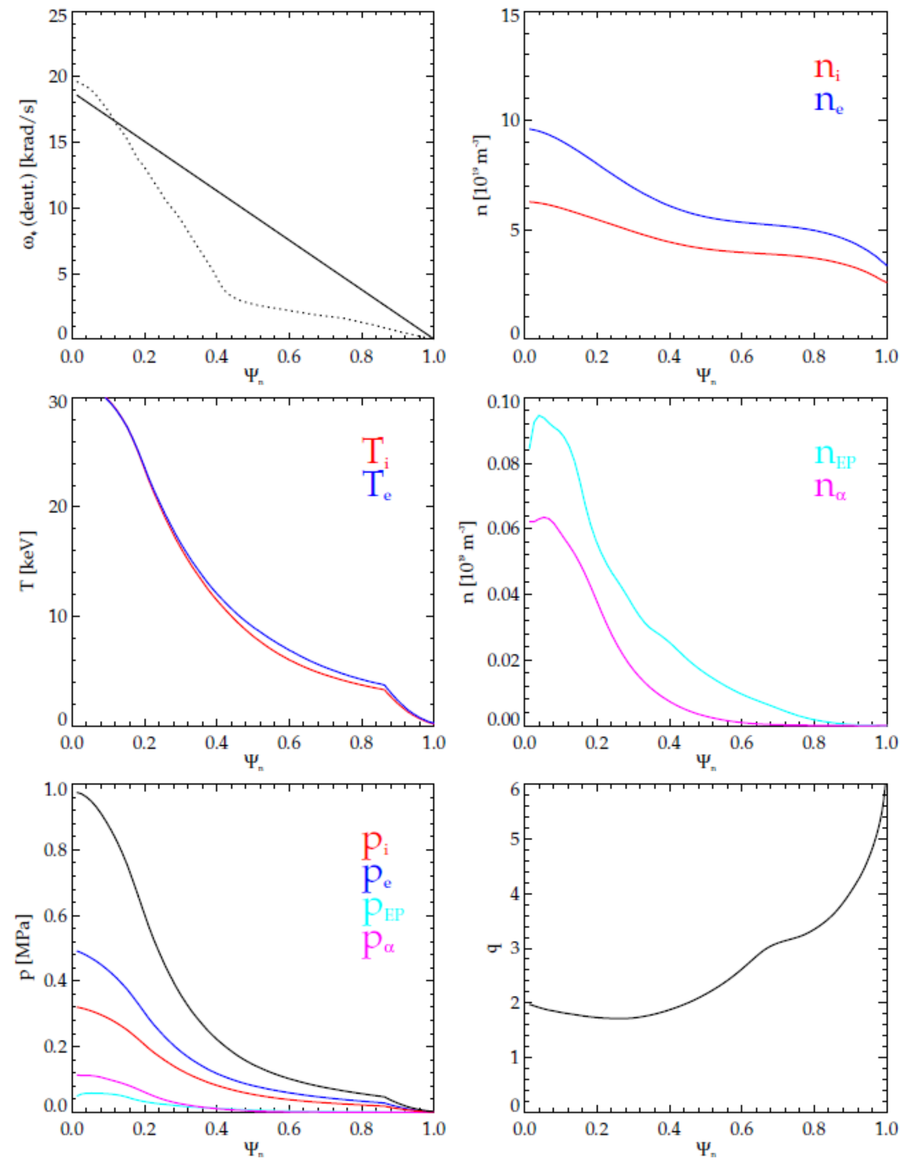


Profiles, 34011 @ 2500s

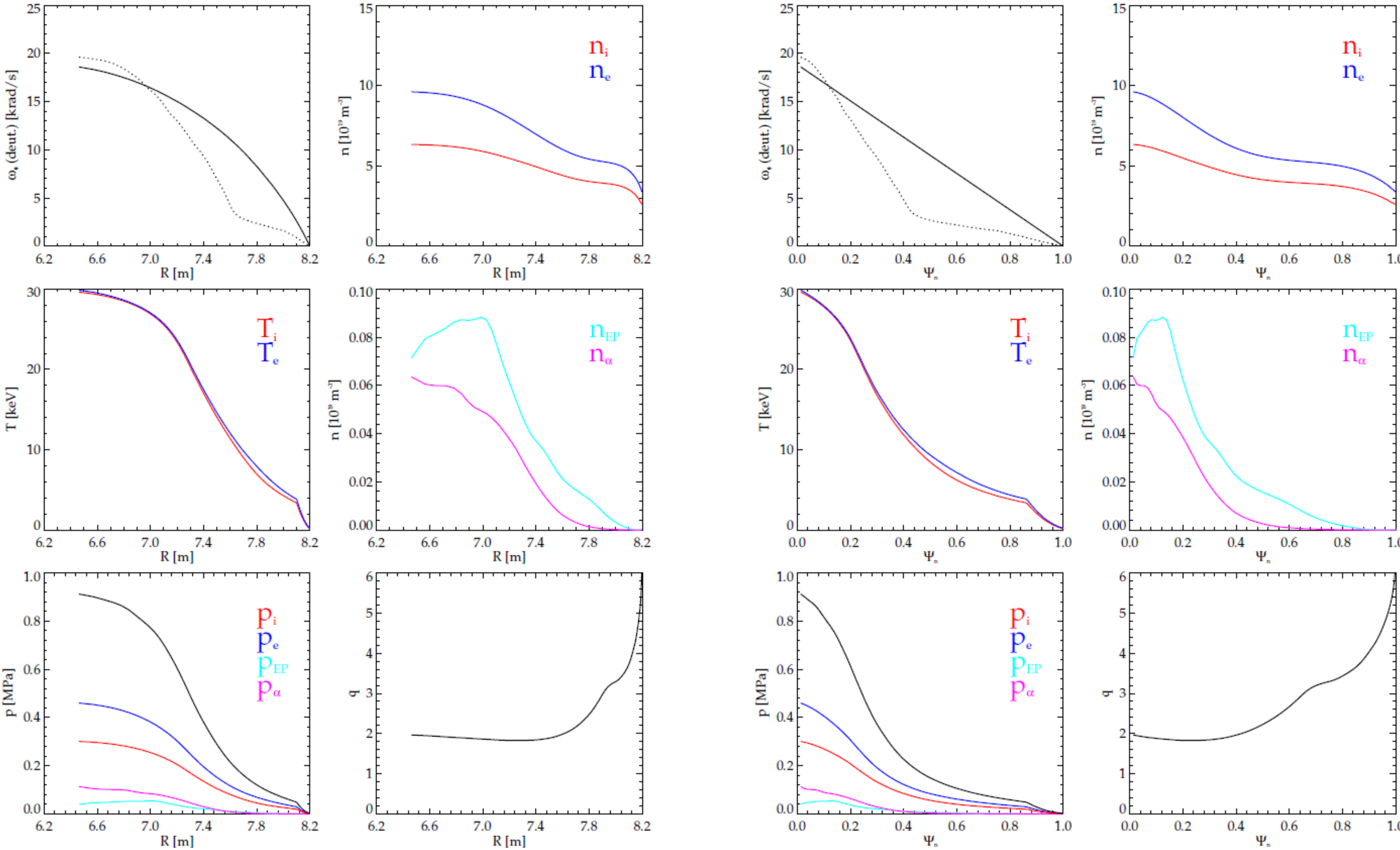


Profiles, 34011 @ 2500s

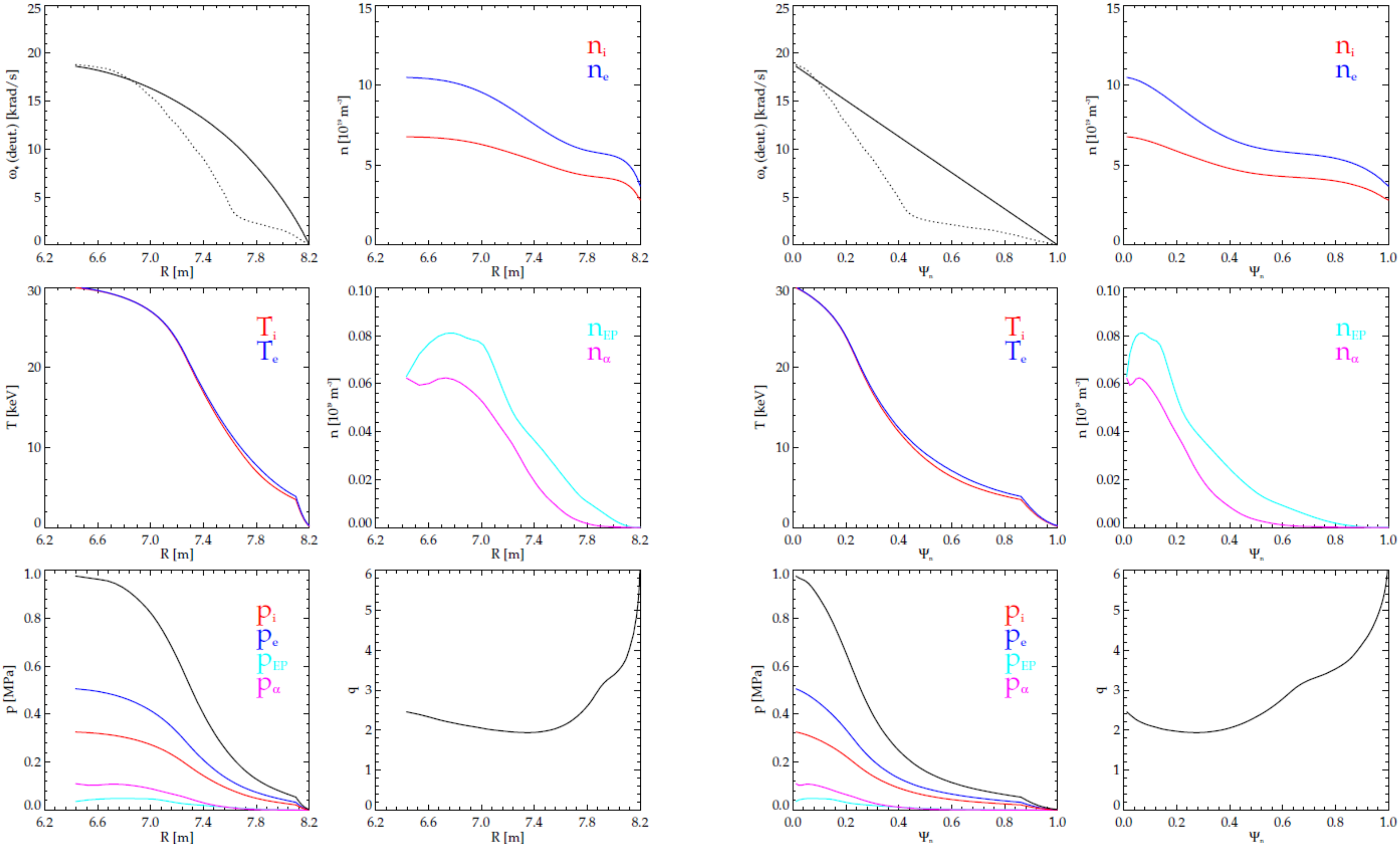




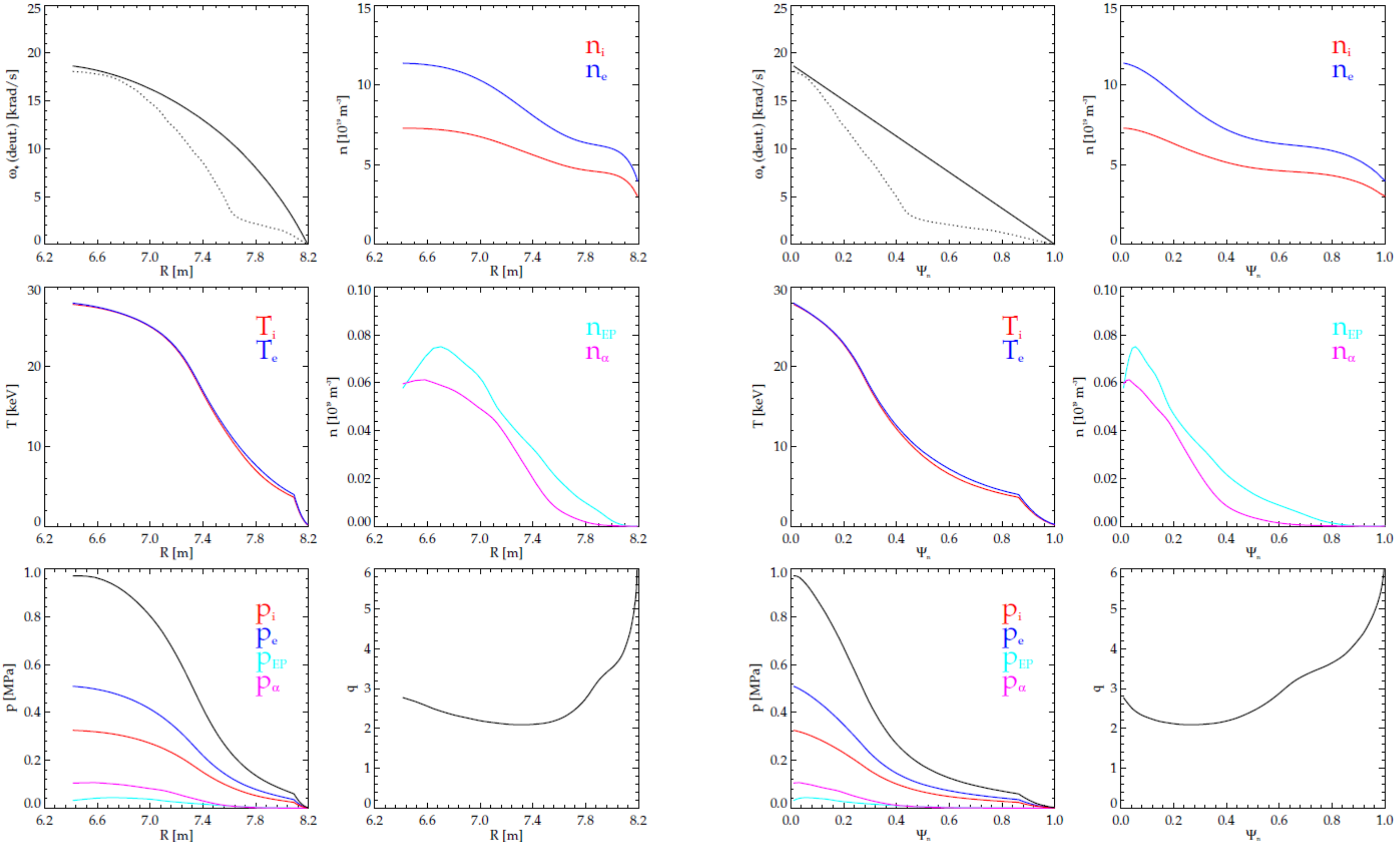
Profiles, 34036 @ 2500s



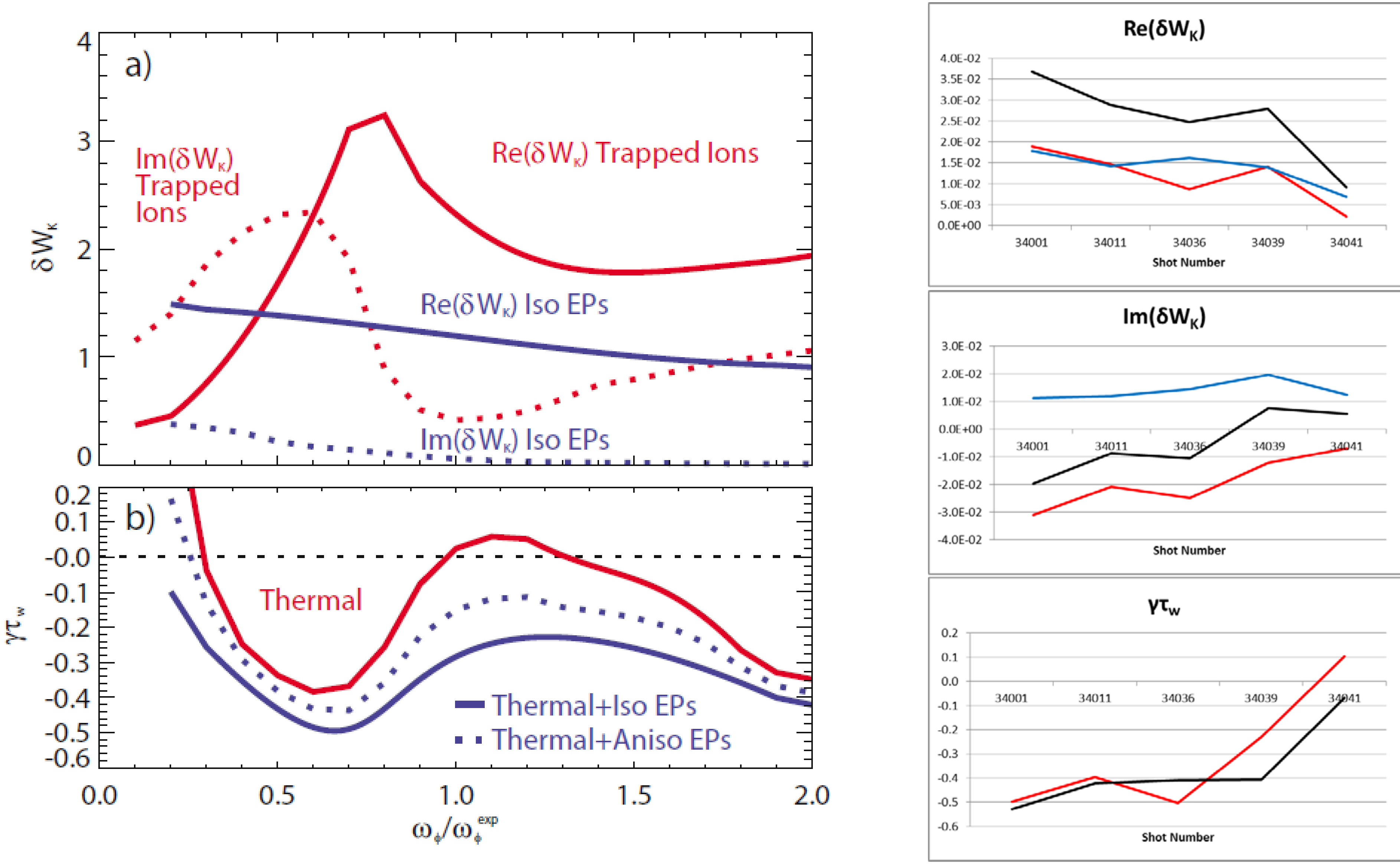
Profiles, 34039 @ 2500s



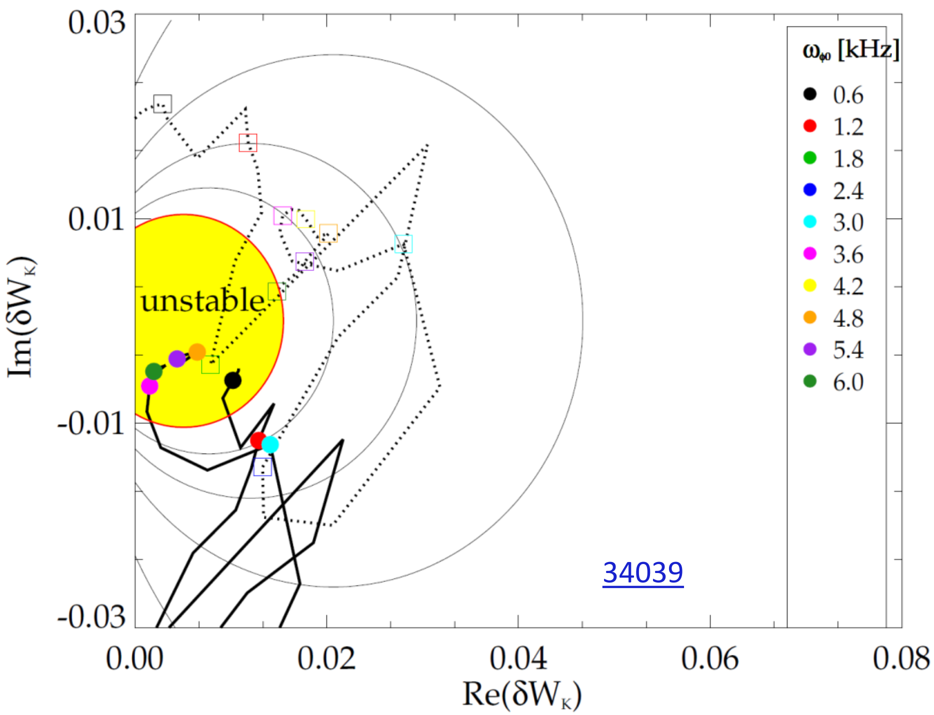
Profiles, 34041 @ 2500s

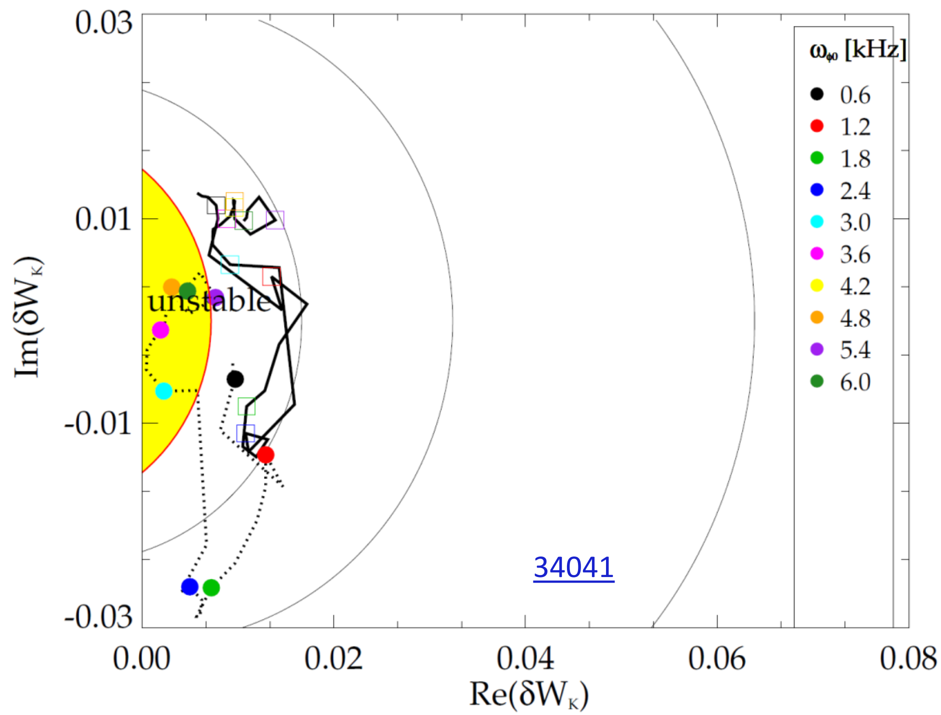


Various parameters vs. shot number

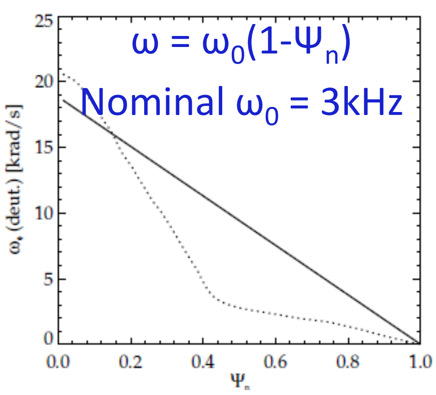


Results with scaled rotation profiles





Still working on this



Energetic particle distribution function 34039 @ 400s