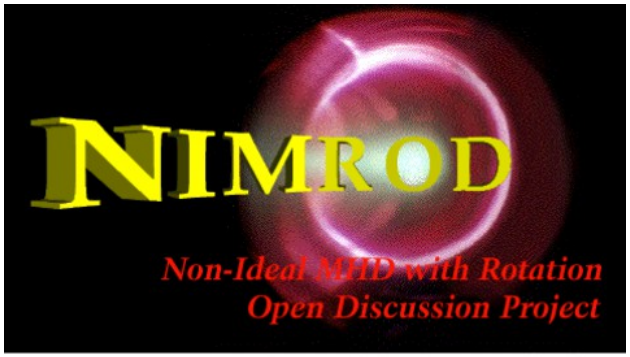

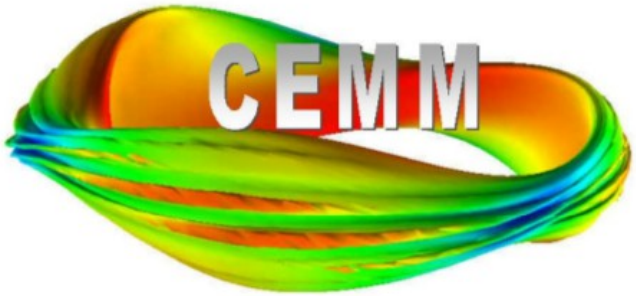

Update on EHO modeling

J. King & **S. Kruger** (Tech-X);
A. Garafalo, R. Groebner & P. Snyder (General Atomics)

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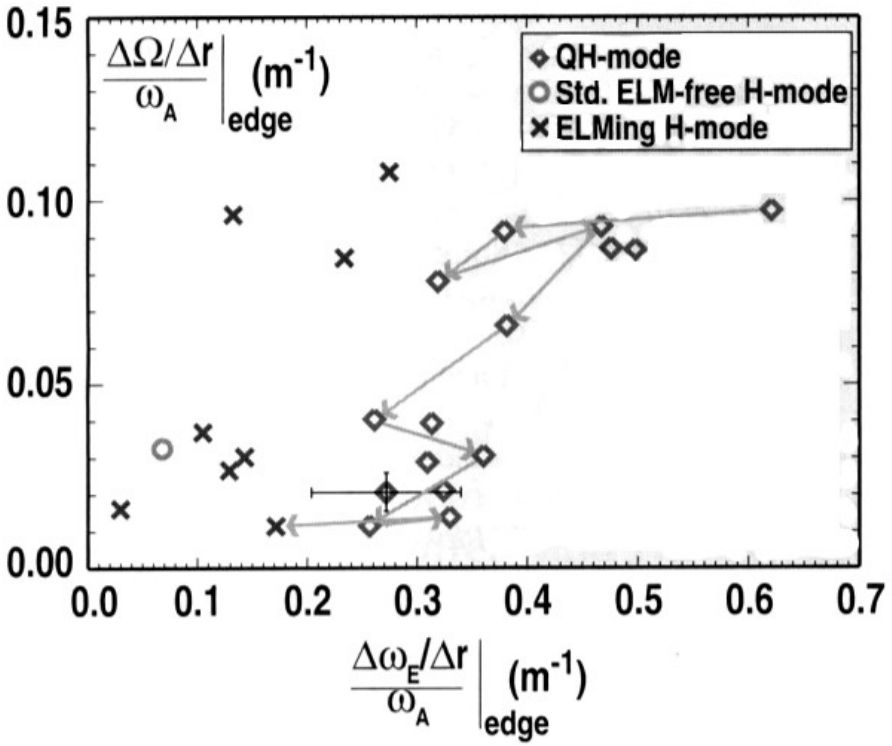
Fusion Energy Sciences

Tokamak operation with edge harmonic oscillations (EHO) provides access to a quiescent H-mode regime [Burrell 2012].

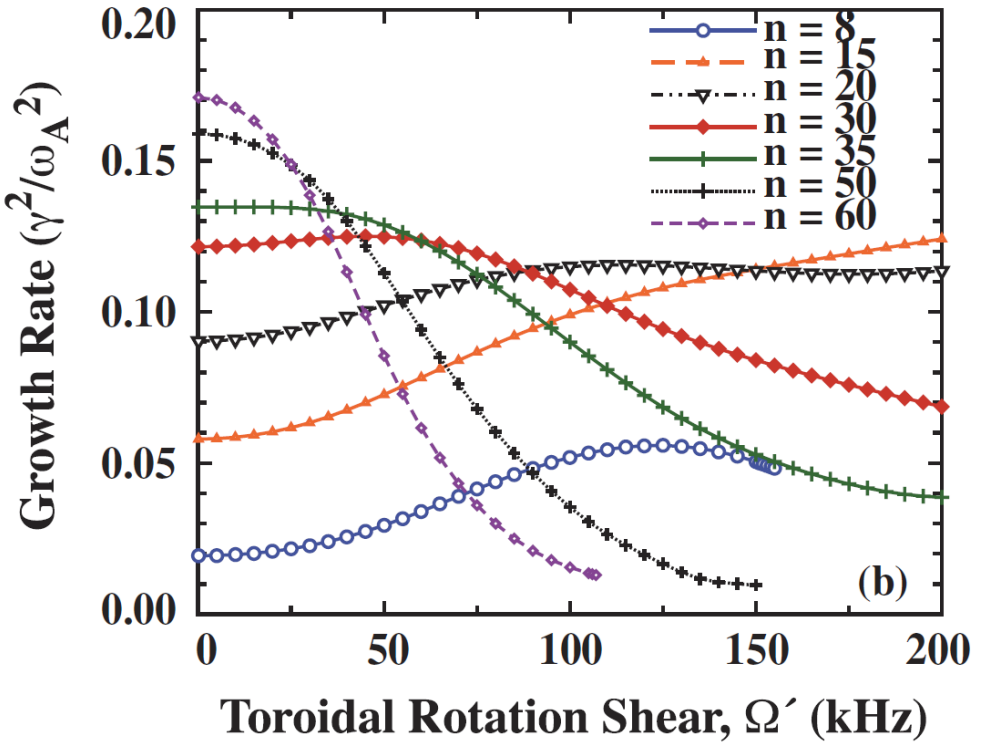
- EHO: a small toroidal mode number (n~1-5) perturbation localized to the magnetic separatrix [Burrell et al., PoP **19** 056117 (2012) and refs within].
- Particle transport enhanced leading to steady-state pedestal profiles.
- Access to EHO operation regime requires control of the flow profile.
- One of the aims of this work is to ascertain the role of the flow shear.
- In particular, experimental observations indicate that the ExB flow shear is a key component in the generation of EHO [Garofalo et al., NF **51** 083018 (2011)].



from Garofalo 2011

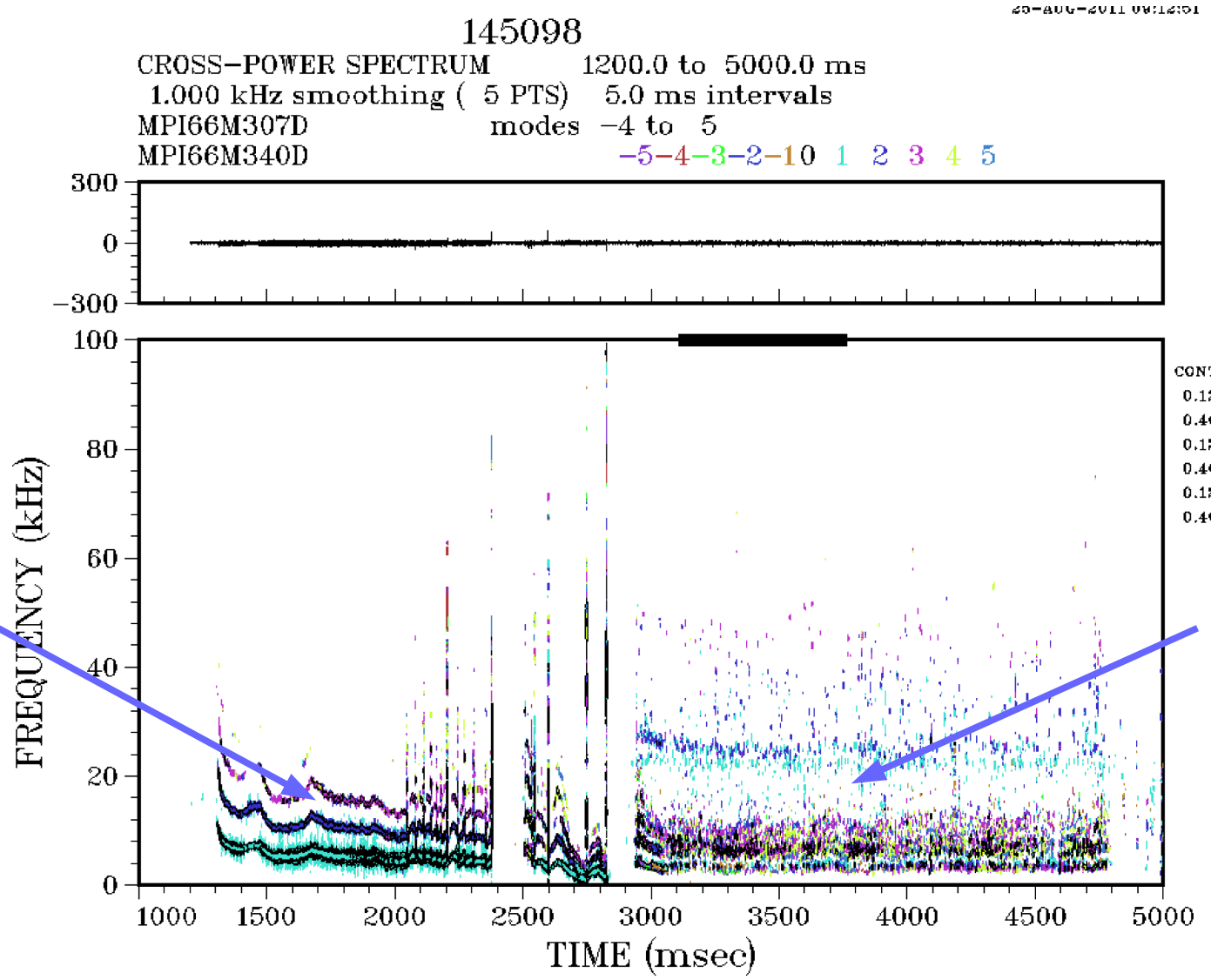
The physical mechanisms of EHO are not fully understood.

- Linear MHD calculations suggest EHO may be a saturated kink-peeling mode partially driven by flow-profile shear [Snyder et al., NF **47** 961 (2007)].
- Hypothesis: the saturated mode drives particle and thermal transport to maintain steady state pedestal profiles.
- Why NIMROD?
  - Low-n mode requires global computations
  - Can model realistic x-point geometry
  - Drift stabilization built into model
  - Nonlinear capabilities



ELITE results from Snyder 2007

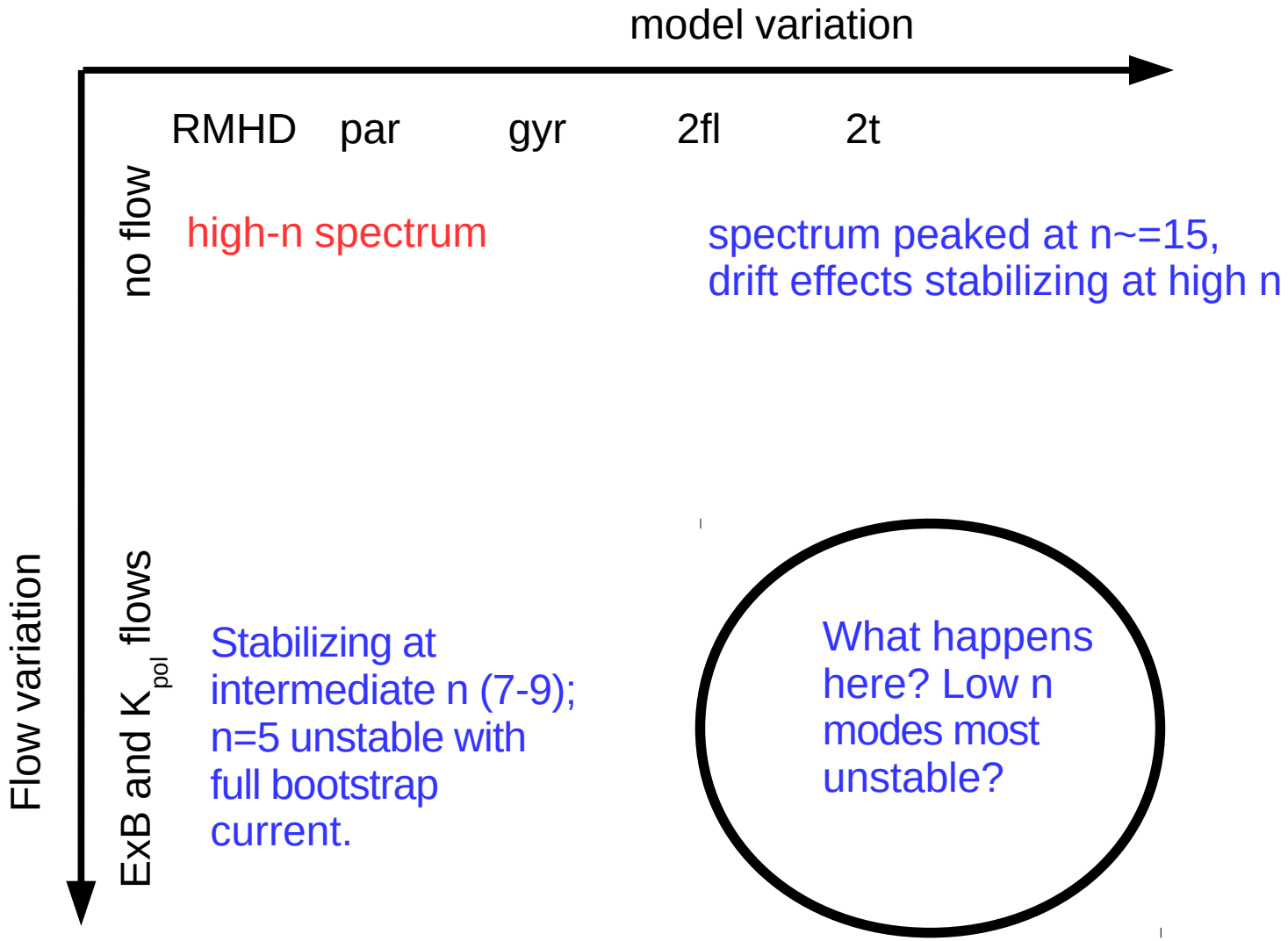
We analyze DIII-D shot 145098 at 4250 ms while the discharge is ELM free with broadband EHO.



Coherent EHO

Broadband EHO

Linear results as of APS-DPP indicate “full” modeling is important.



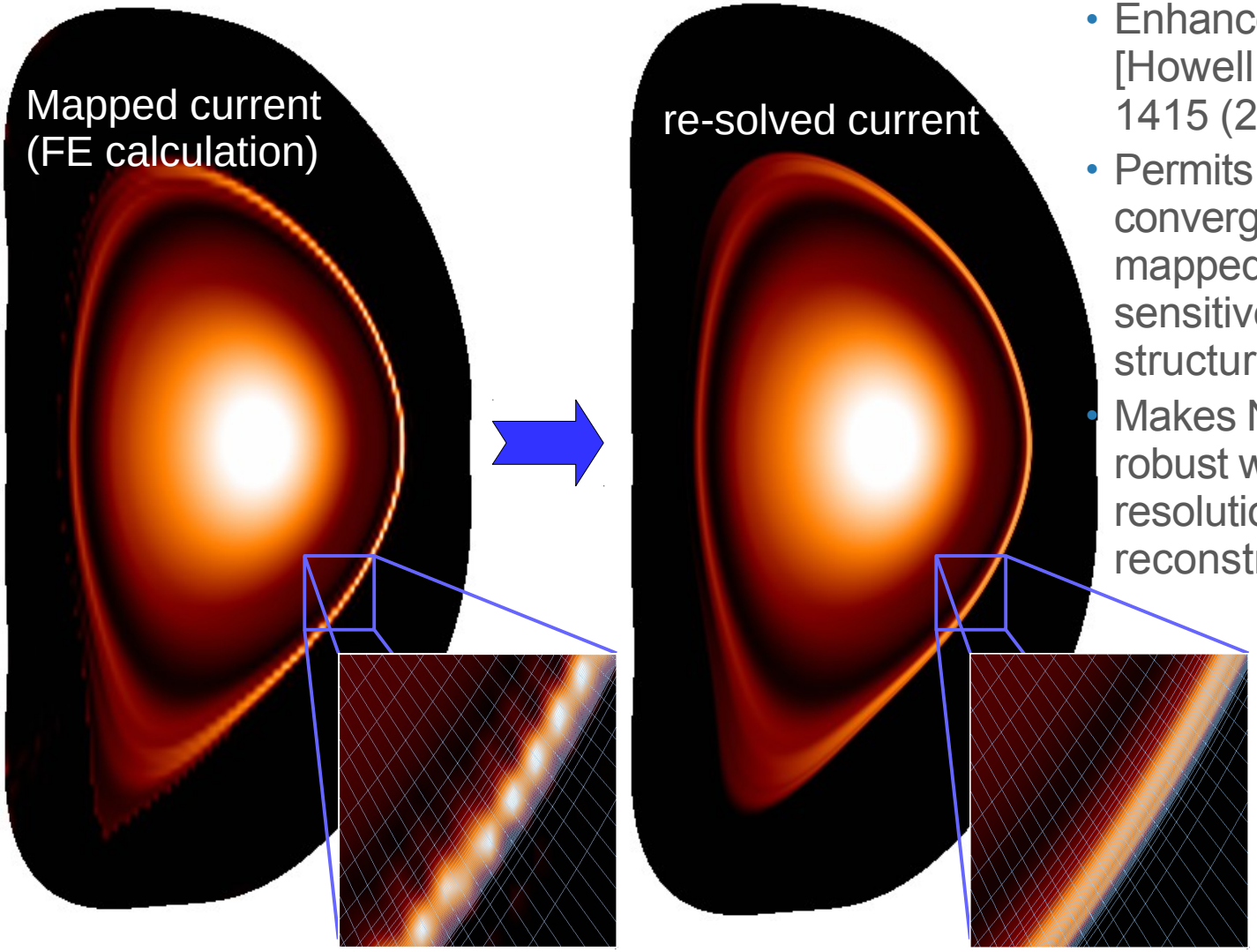
(shot 145098 with profiles “smoothed” to eliminate the edge current discontinuity)

Results required refinement of techniques to use experimental reconstructions.

- Original method: “Map” equilibrium onto NIMROD grid
- New method: Re-solve Grad-Shafranov equation on NIMROD grid
- This has resolved many issues: edge cases now converge to a result!
- However issues remained:
  - How to deal with an edge current discontinuity
  - Difficulty with two-fluid cases with flow

- Rest of talk reviews how we resolved those difficulties

Resolving equilibrium critical to enabling convergence in edge cases



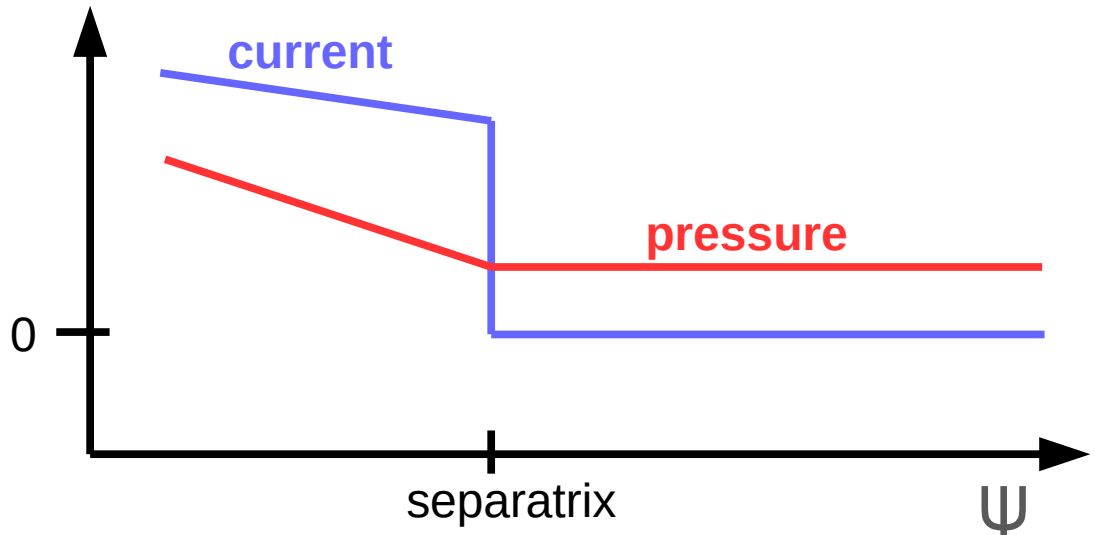
- Enhancement to NIMEQ [Howell et al., CPC **185** 1415 (2014)]
- Permits spatial convergence where mapped fields were sensitive to small-scale structures.
- Makes NIMROD more robust with (low resolution) experimental reconstructions.

Tokamak equilibrium reconstructions typically contain discontinuous current profiles across separatrix

- EFIT: No currents outside of separatrix

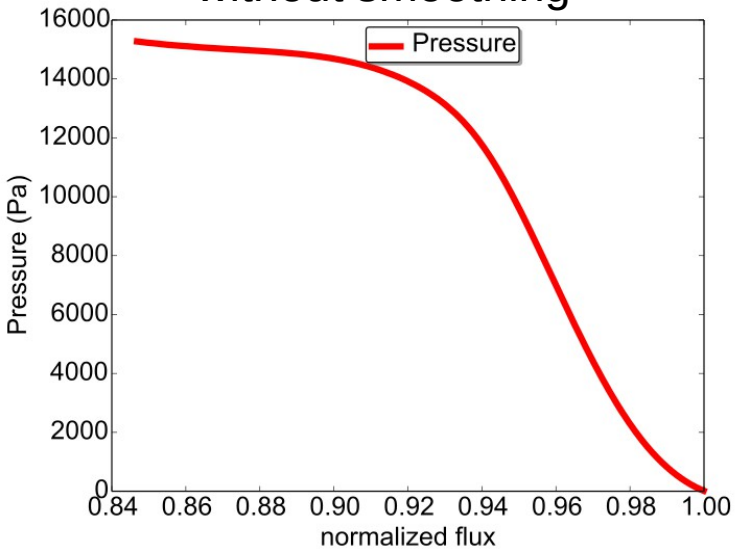
  => Pressure is constant outside the separatrix.

  => No variation in toroidal flux function
- Data, shown later, typically shows finite gradients on separatrix
- EHO mode particularly troublesom:
  - Large current drive at edge (lives on the peeling boundary).
  - Discontinuity is problematic for FGNIMEQ re-solves.
- Can smooth toe continuity of the derivatives, and a self consistent solution generated.
  - However, the method increases the pressure gradient.
  - Empirically, this leads to high-n modes.

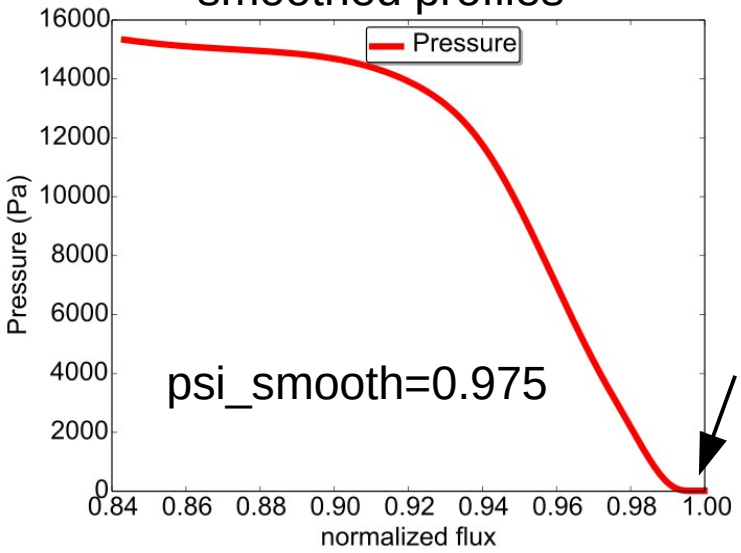


Smoothing example: current and pressure gradient are increased.

without smoothing

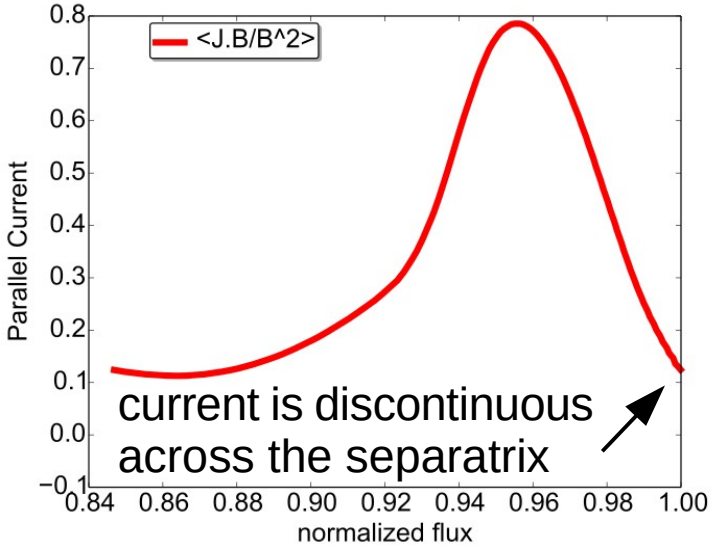


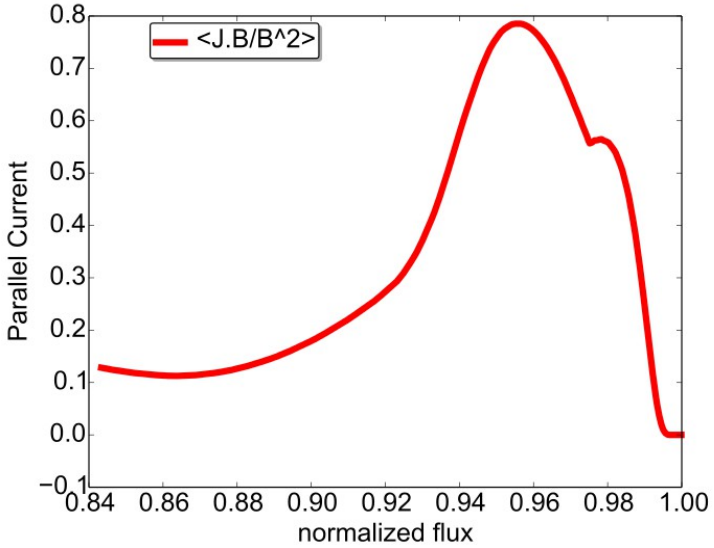
smoothed profiles



Smoothing often works for core modes

p'=0 at the separatrix



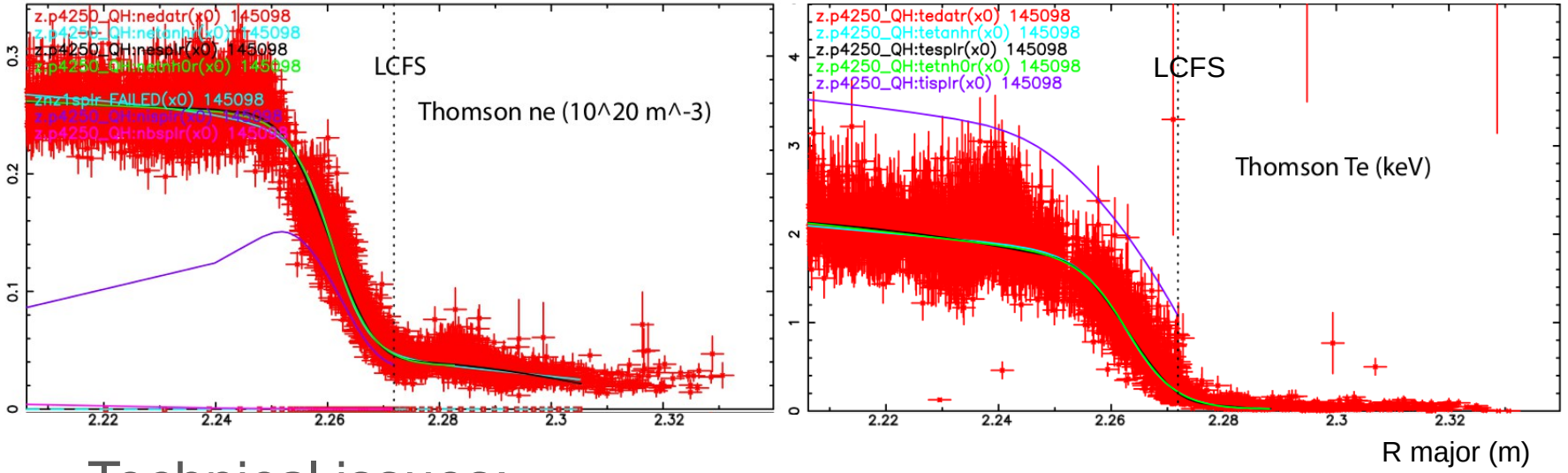


edge current profile is modified

Changes physics!

Data shows that scrape-off layer has currents

- Experimental reconstruction does not set profile gradienst to zero on the LCFS because they are NOT measured to be zero

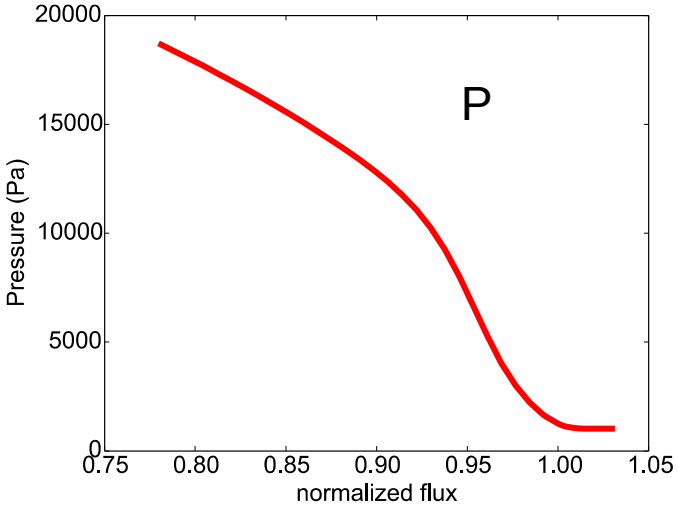


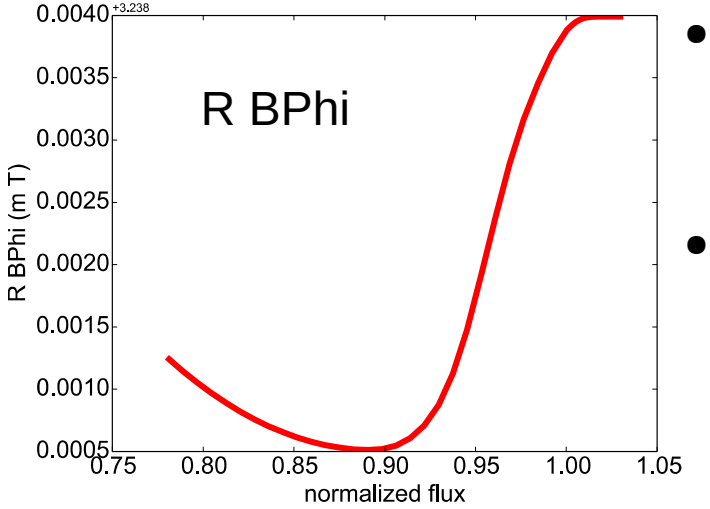
- Technical issues:
  - EFIT has discontinuity so we only use part of EFIT data
  - How do we include SOL currents?
  - Result should be as close to possible to known measurements.

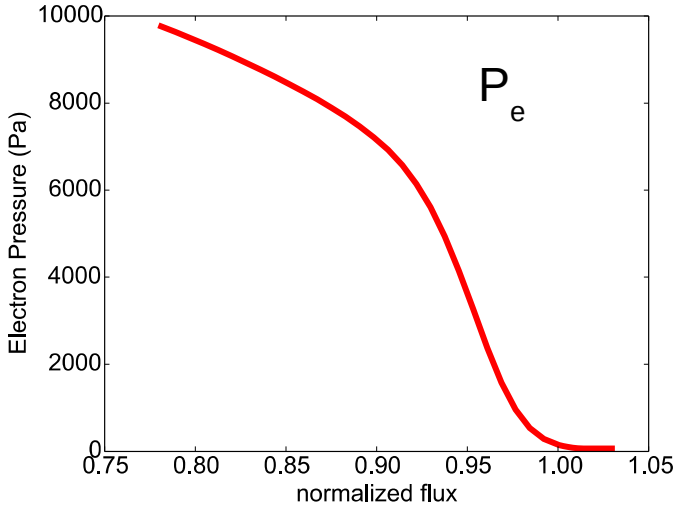
Extrapolation of currents to SOL

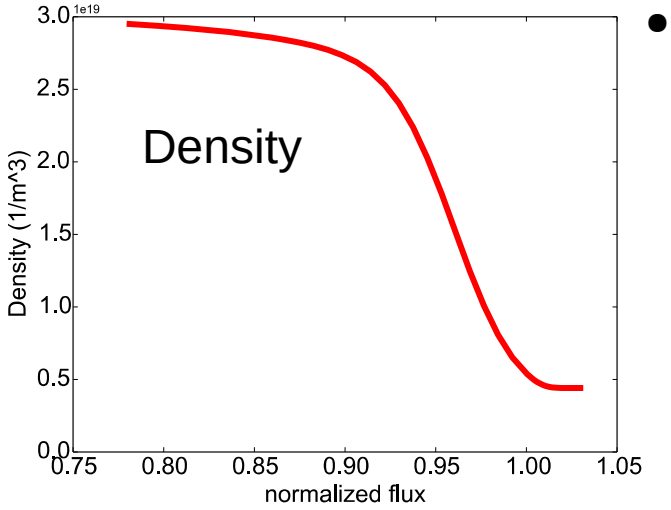
- Constraints on P, F profiles:
  - At separatrix function should be C1 continuous.
  - Width is an important experimental value: [Eich et al., NF 53 (2013) 093031].
- Possible additional constraints:
  - Make functions C2 continuous: Results in C1 smooth J and V profiles (~ to p' and F').
  - Use experimental values if possible

Examples of SOL extrapolation



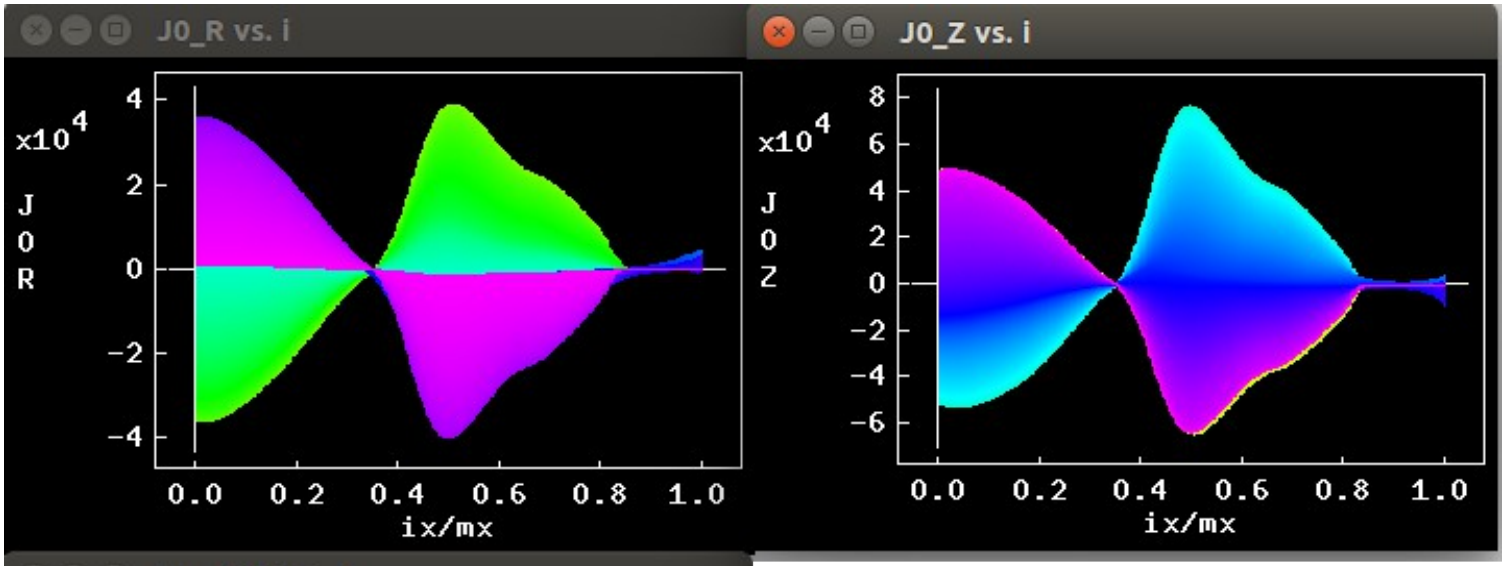


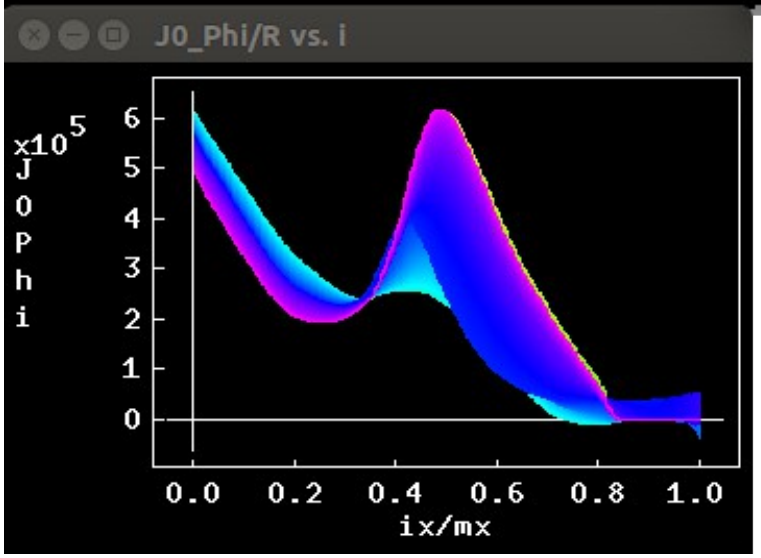




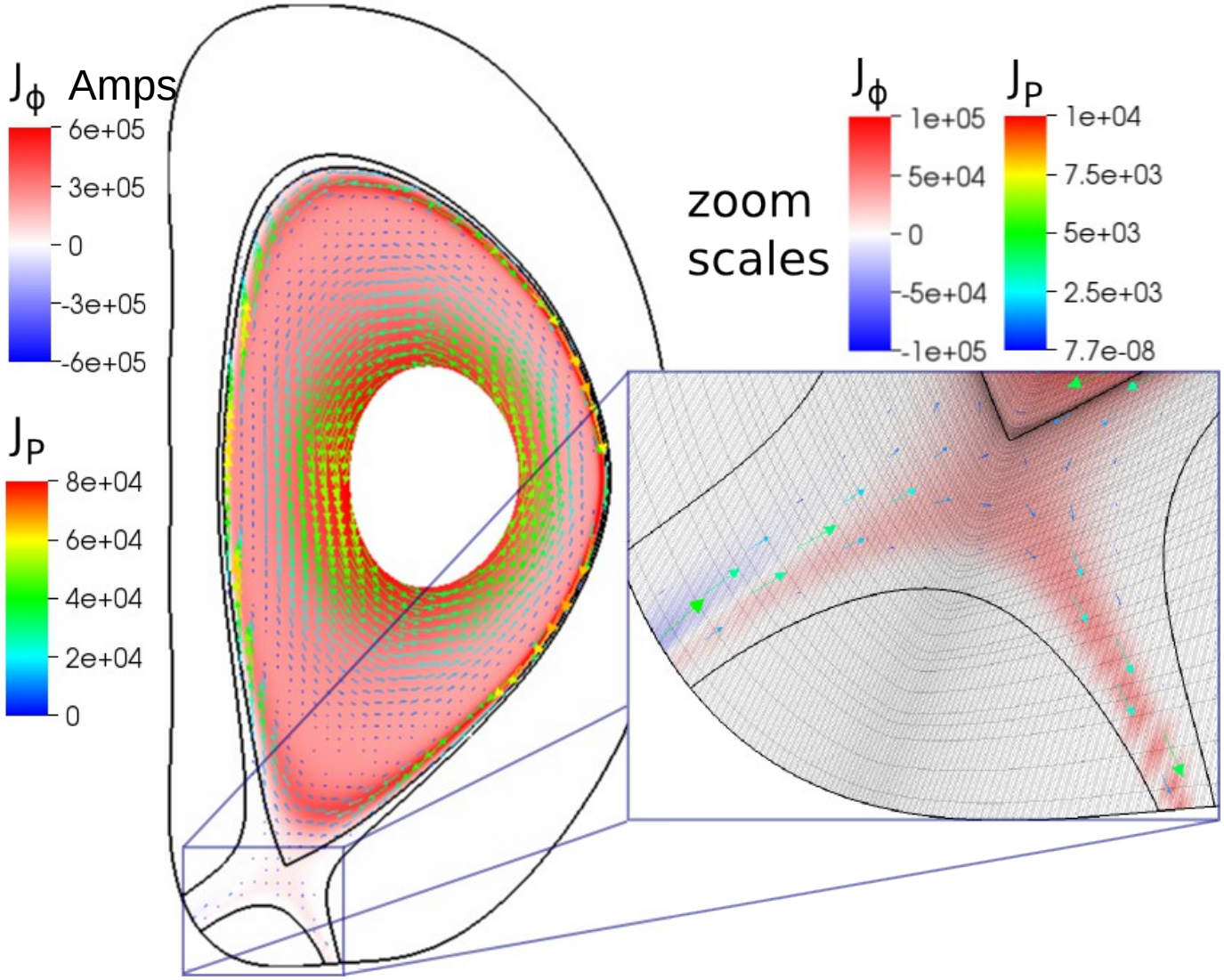
- Psi=1 defines separatrix
- Width is 3% o Psi inside separatrix
- Enforce C2 smoothness

C2 extrapolation of F and p leads to smooth current profiles.





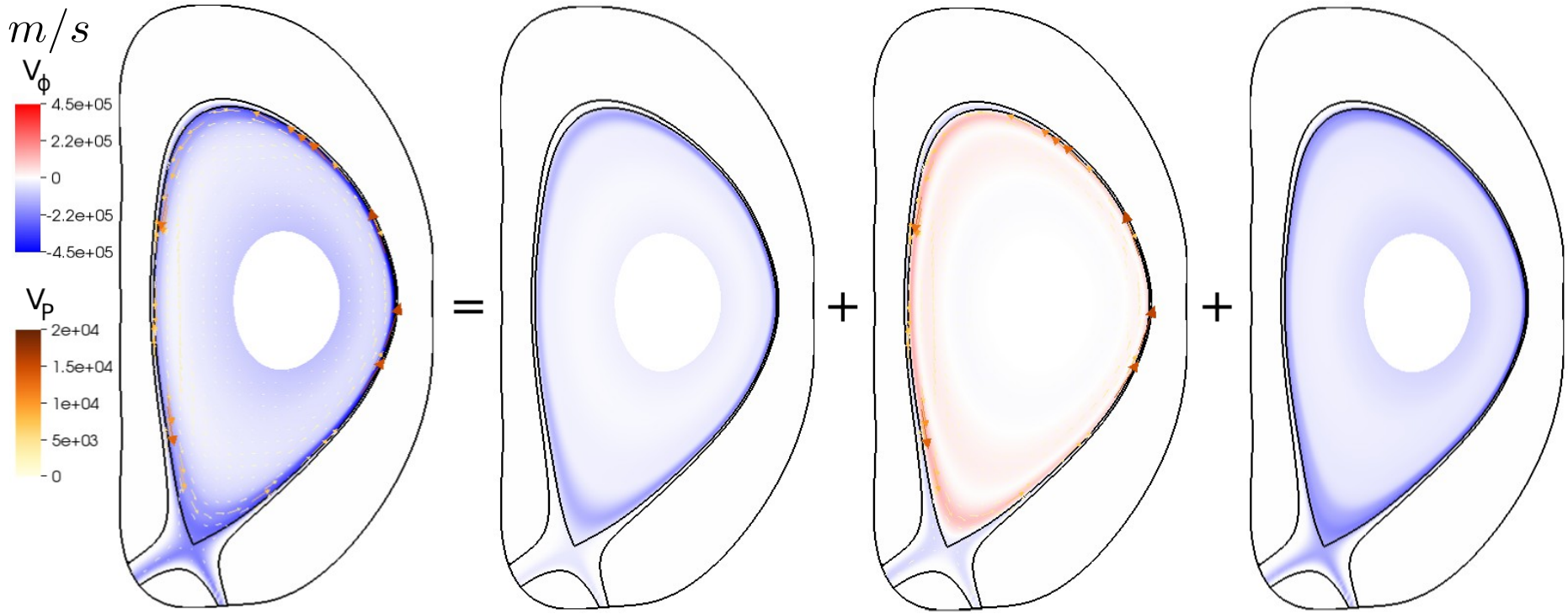
Currents (and flows) extend into the divertor private region including private flux region



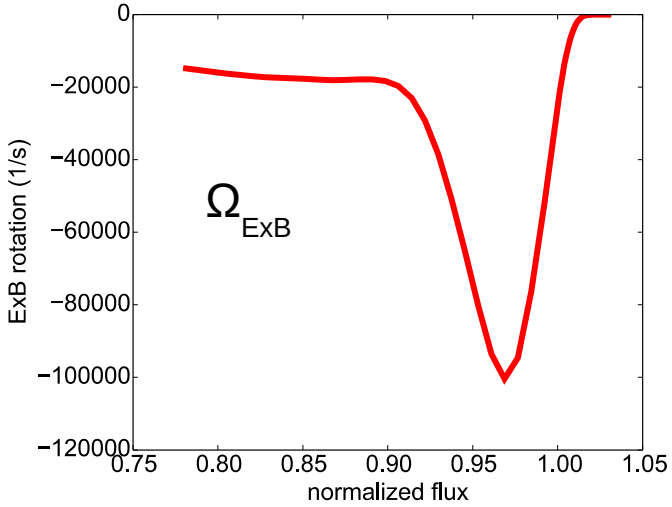
- Force balance is enforced through-out the domain.
- Divertor current limited to less than the ion saturation current [~10^5 A for this case].
- Should have minimal effects on dynamics

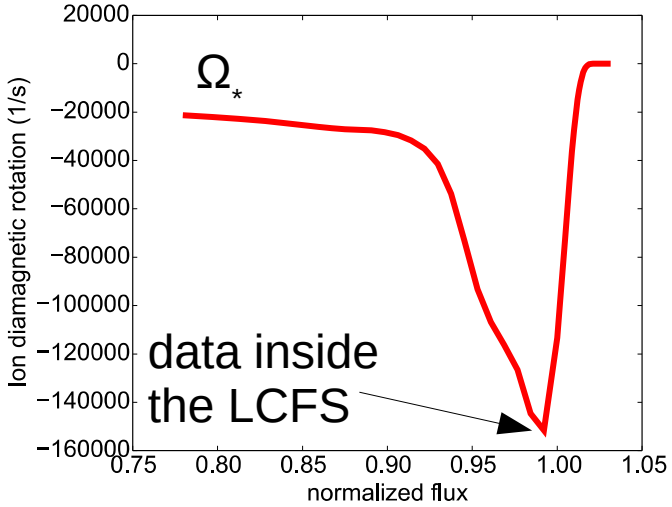
Flow effects are known to be crucial to EHO

$$\mathbf{v}_{EQ} = \Omega_{E\times B} R\hat{\phi} + K_p(\psi)\,\mathbf{B} + \Omega_{\nabla p} R\hat{\phi}$$

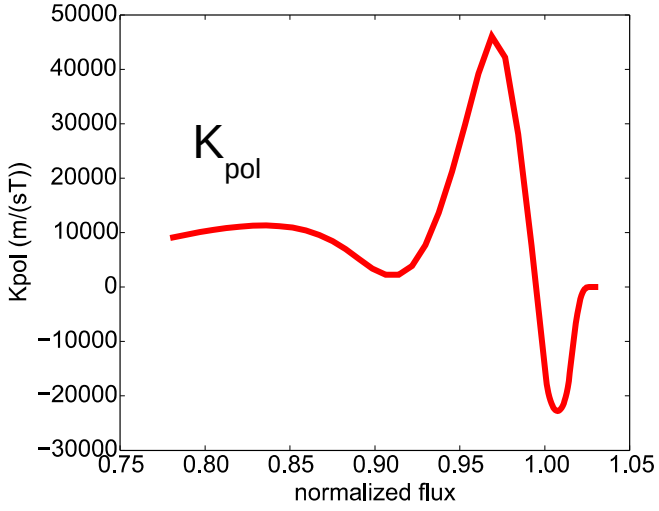


ExB and Kpol also need to be extrapolated because the data included only up to separatrix





For the experts: Using pfile data from "Osborne reconstructions"

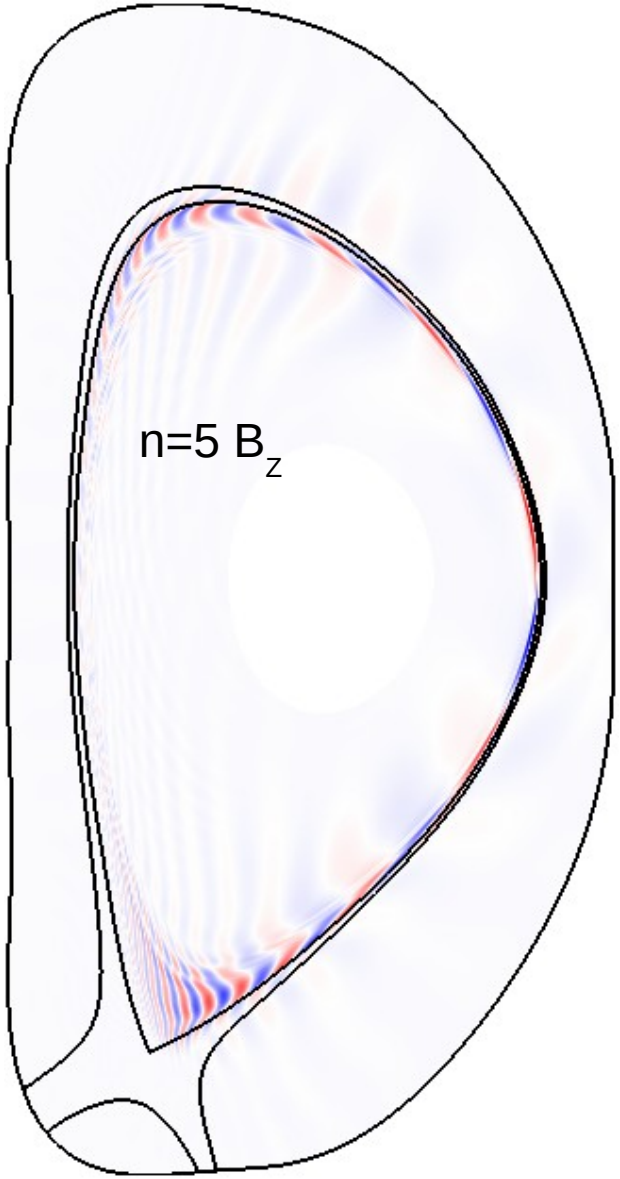


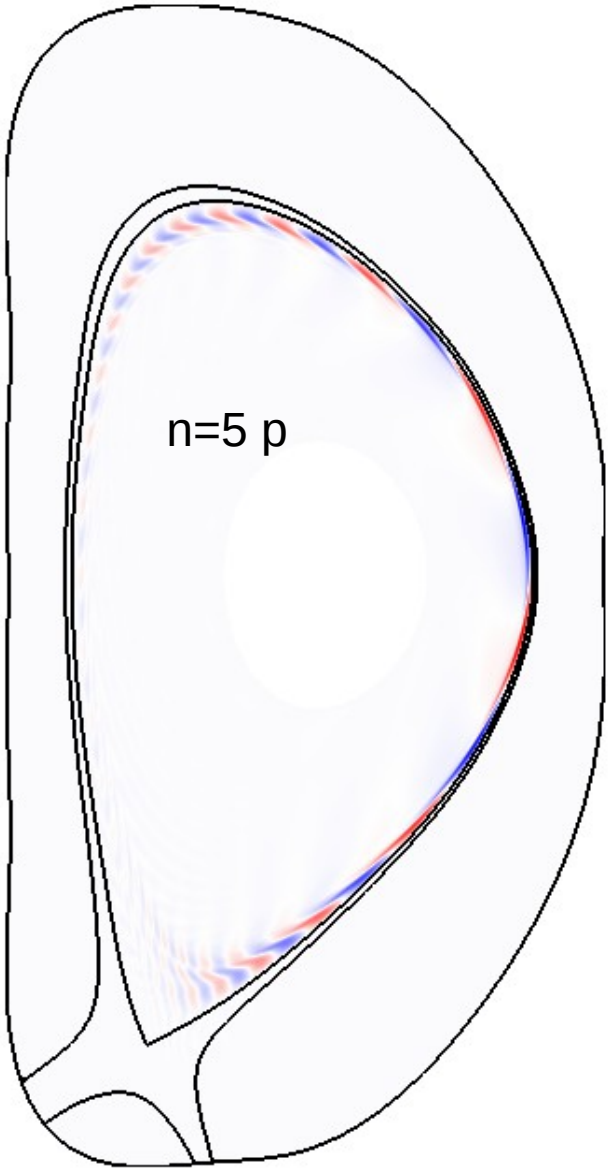
- Flows use a C1 fit with a specified zero value at the SOL-current-free interface (Ψ_{jfree}).
- Ψ_{jfree} =1.03

Recent modeling focus on full two-fluid model with flow cases

- Consistent ordering implies no terms should be dropped
- Can always 'work backwards' to decrease mode sophistication to investigate importance of effects (e.g. flow, FLR terms,...) if desired
- Using shot 145117 instead of 145098 (APS-DPP)

Significant progress on full two-fluid modeling with flow.





- Results are preliminary
- Temporal and spatial convergence studies underway
- Extrapolation does not have large effect on dynamics for linear studies
- Expect much better results for nonlinear simulations

JOREK results have motivated ITER interest in the EHO

- JOREK results included in recent paper by DIII-D collaborators (A. Garafalo)
- Results are of high visibility within the ITER organization
- Good news: EHO simulations have gained in visibilty

Recent JOREK results need more toroidal resolution

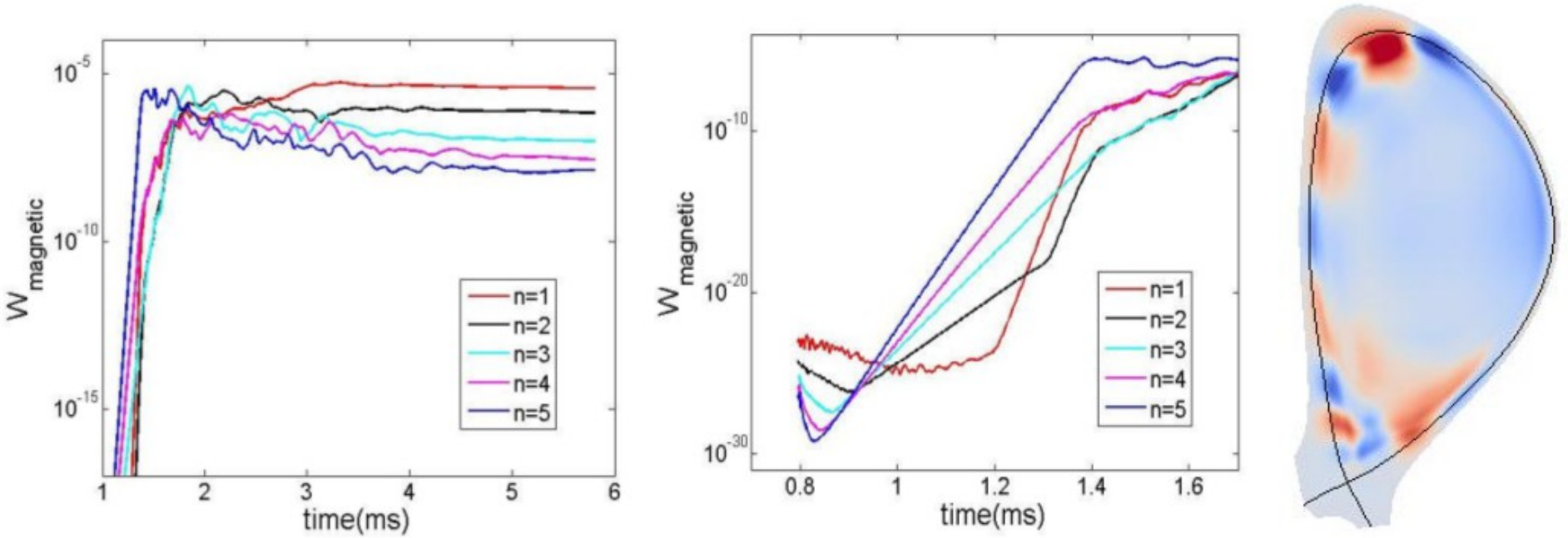


Figure 1 (a) *Evolution of the perturbed magnetic energy (n=1-5) as a function of time* ***(b)*** *Contour plot of poloidal flux perturbation of the saturated n=1-5 kink/peeling modes from MHD simulations.*

- Figure from F. Liu et al., EPS proceedings O5.135
- Only 6 modes in calculation with n=5 most unstable.
- Nonlinear coupling may be significant, but increased toroidal resolution is needed.
- When questioned, they said they have different answer when run with more toroidal resolution

Summary

- Modeling with a fitted SOL eliminates edge current/flow discontinuities
  - Slightly easier to converge for these high current, high T (low dissipative) edge cases
  - Impact on nonlinear cases expected to be more important
- EHO cases for full two-fluid modeling with flow are now working – results preliminary and convergence tests are needed