Advanced Tokamak Studies in Full-Metal ASDEX Upgrade

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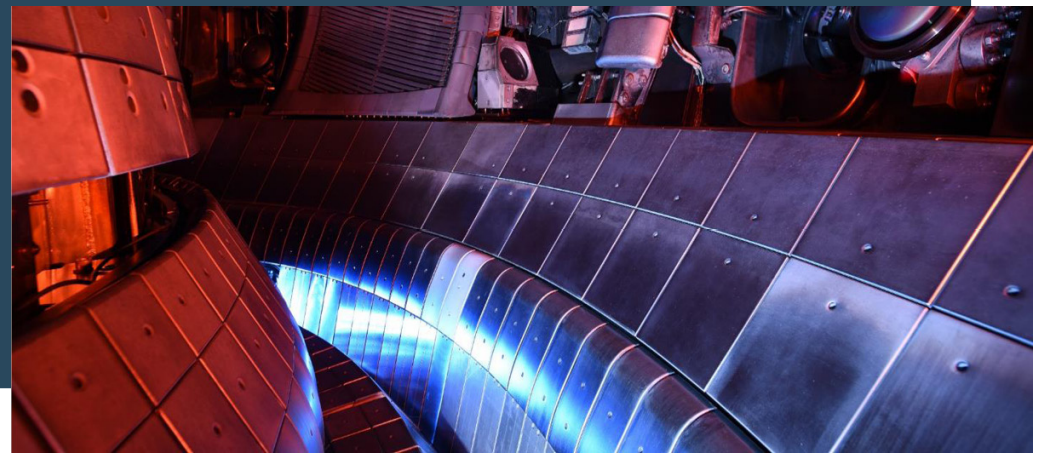

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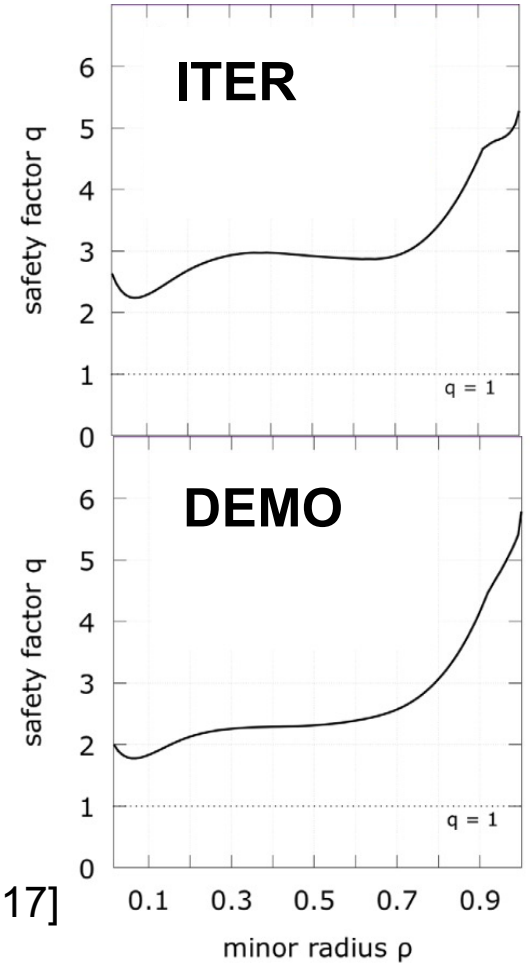
Motivation

- Envisaged steady-state EU-DEMO scenario
- Derived from 0-D considerations and 1.5-D ASTRA simulations
- Goalpost for scenario development at AUG
- Develop and verify models on such plasmas to allow extrapolation to future FPPs

	ITER		DEMO	
	ASTRA	0-D Ansatz	ASTRA	0-D Ansatz
P_{fus} (MW)	380	400	1940	2000
R (m)	6.2	6.2	8.09	7.85
a (m)	2.066	2.066	2.695	2.616
B (T)	4.5	4.5	5.77	5.6
I_p (MA)	9	9	14.85	14
H	1.3	1.4	1.2	1.2
β_N	3.07	3.5	3.4	3.5
q_{95}	4.82	4.5	4.81	4.5
f_{bs}	0.624	0.62	0.62	0.62
$f_{rad,core}$	0.525	0.3–0.7	0.717	0.72–0.78
Q	3.8	3.3	16.8	17.4
f_{LH}	1.39	1–2.4	1.17	1–1.25

[Zohm NF 2017]



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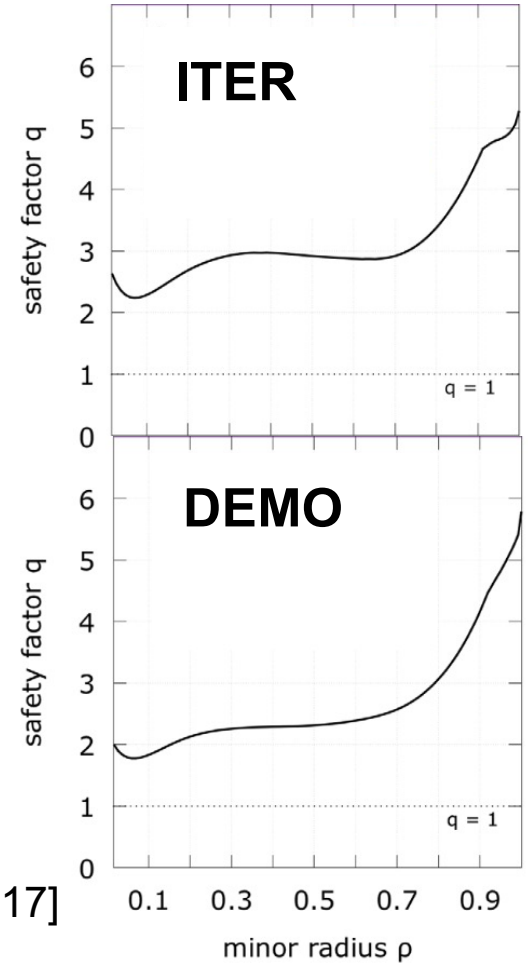

Outline

$q_{95} \approx 5$ hybrid scenario $q_{\min} > 1$

$q_{95} \approx 5$ flux pumping scenario $q_0 = 1$

$q_{95} \approx 4$ counter-ECCD scenario $q_{\min} \gg 1$

Summary

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Scenario Overview: high f_{NI} with off-axis CD

#32305

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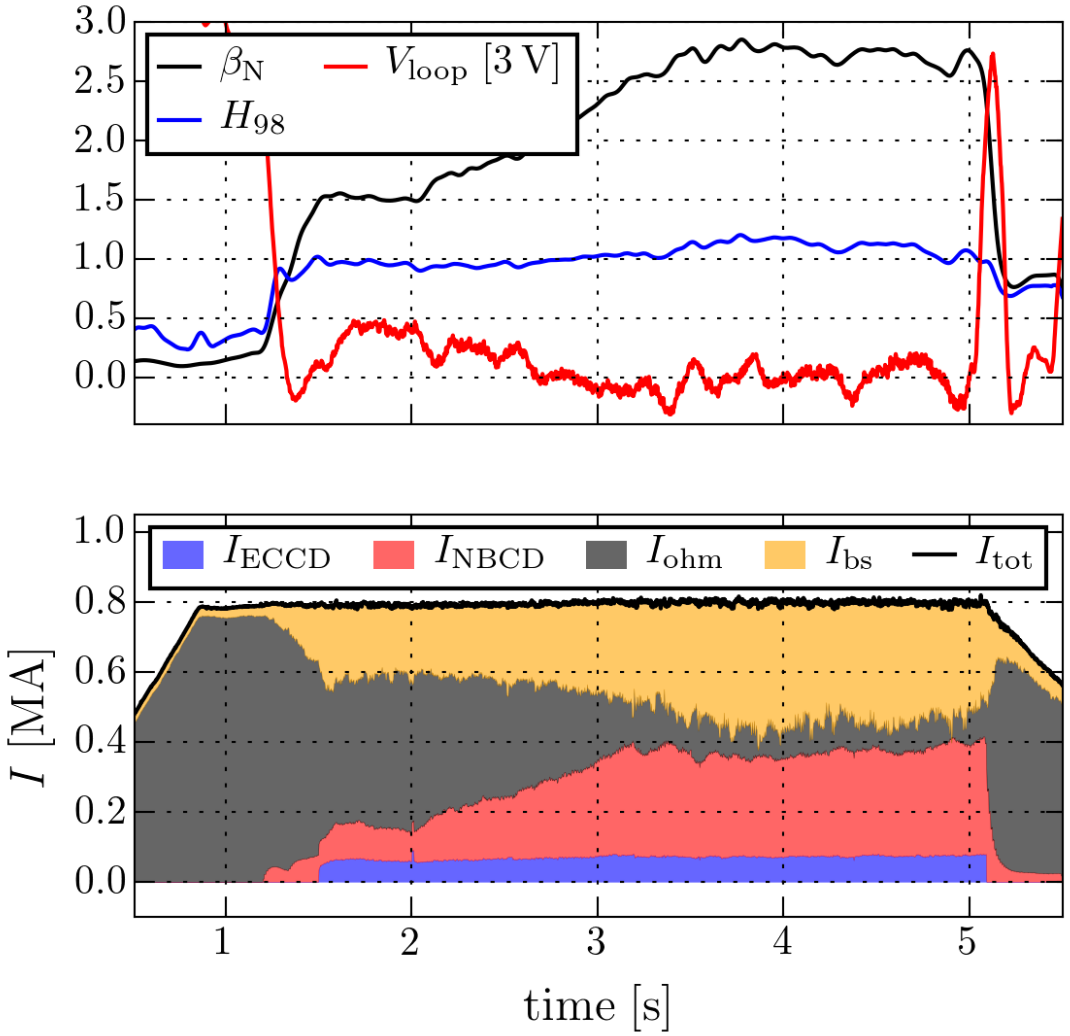

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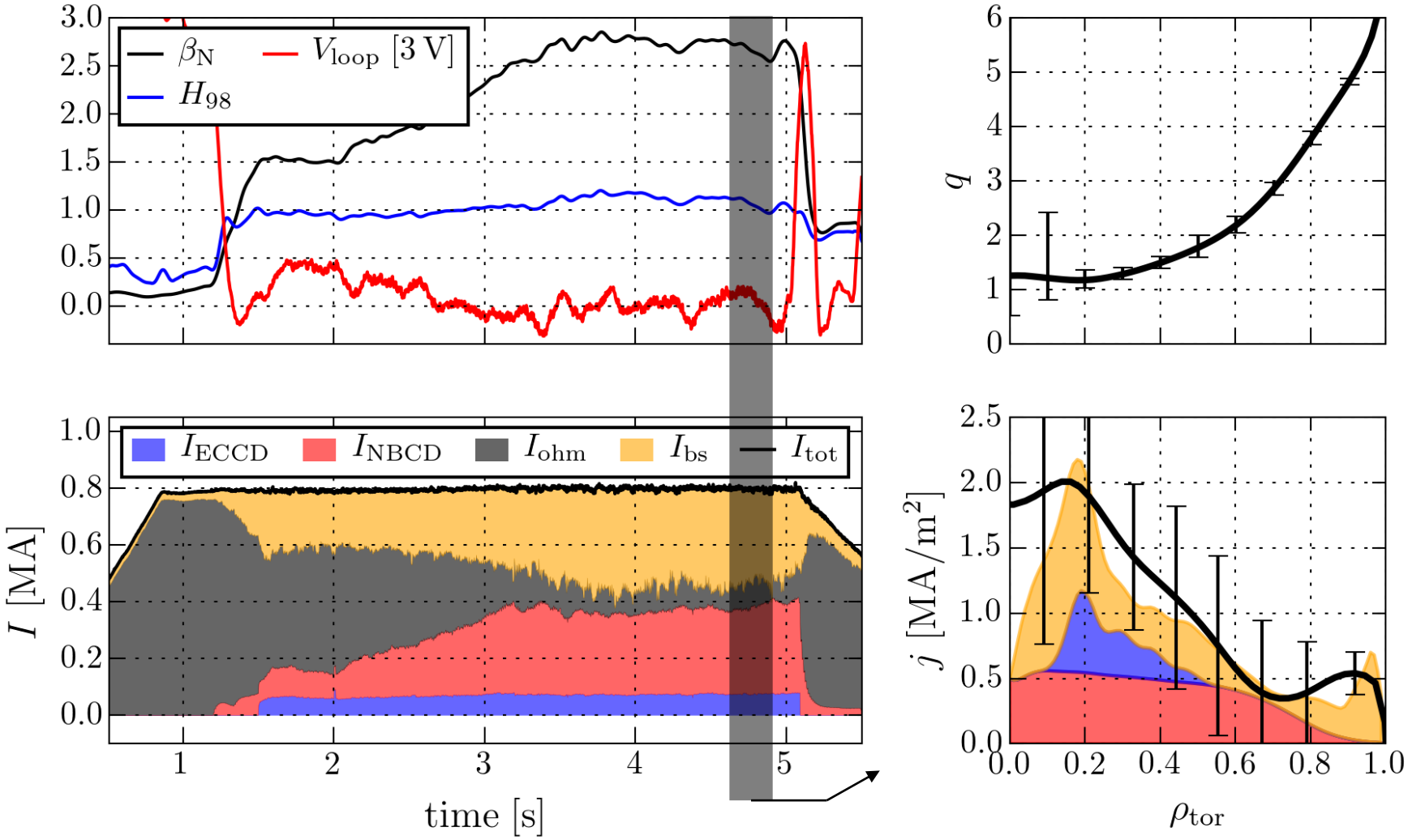

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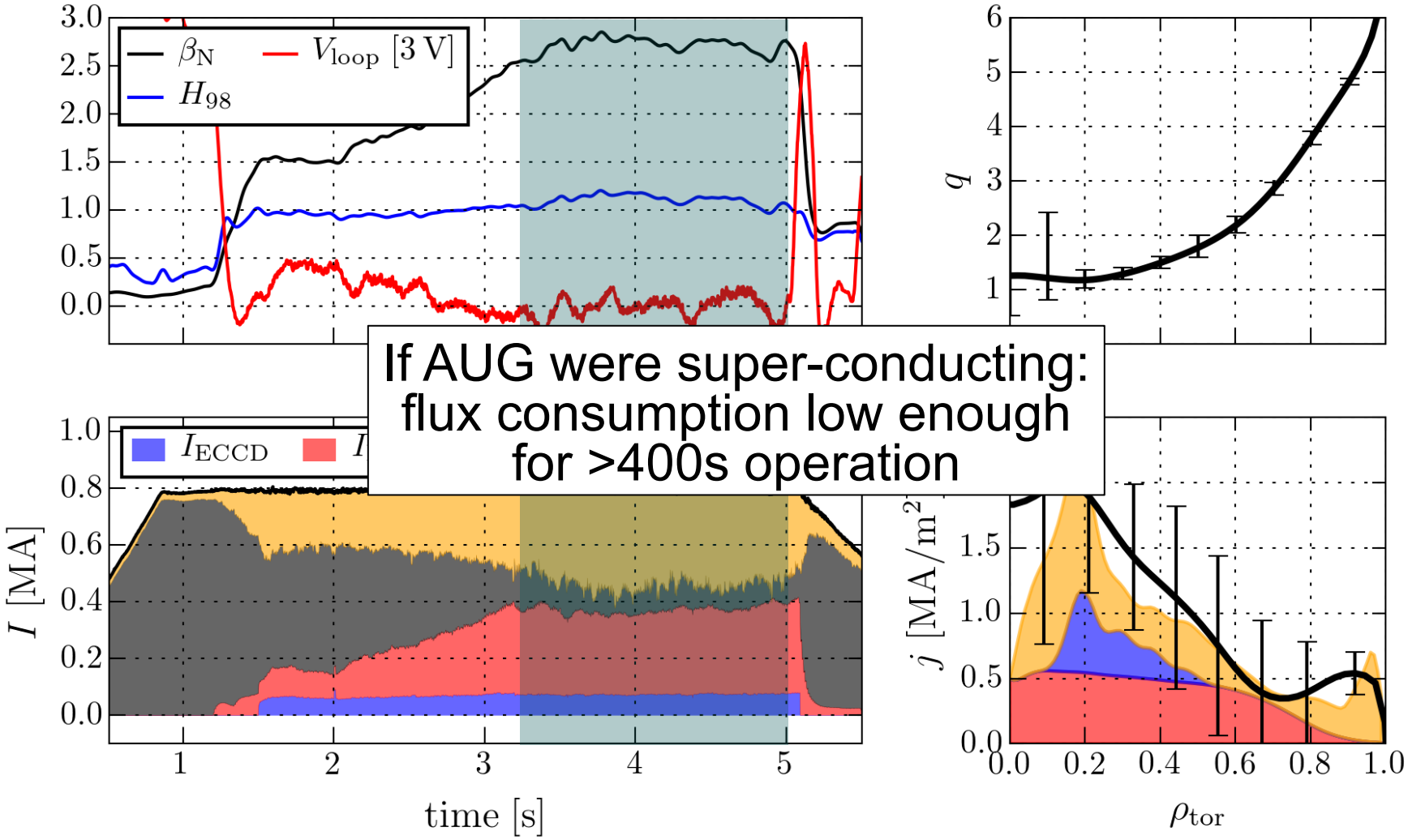
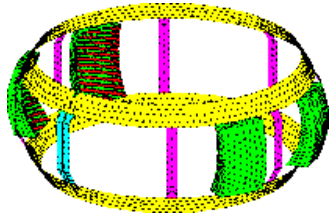


If AUG were super-conducting: flux consumption low enough for >400s operation

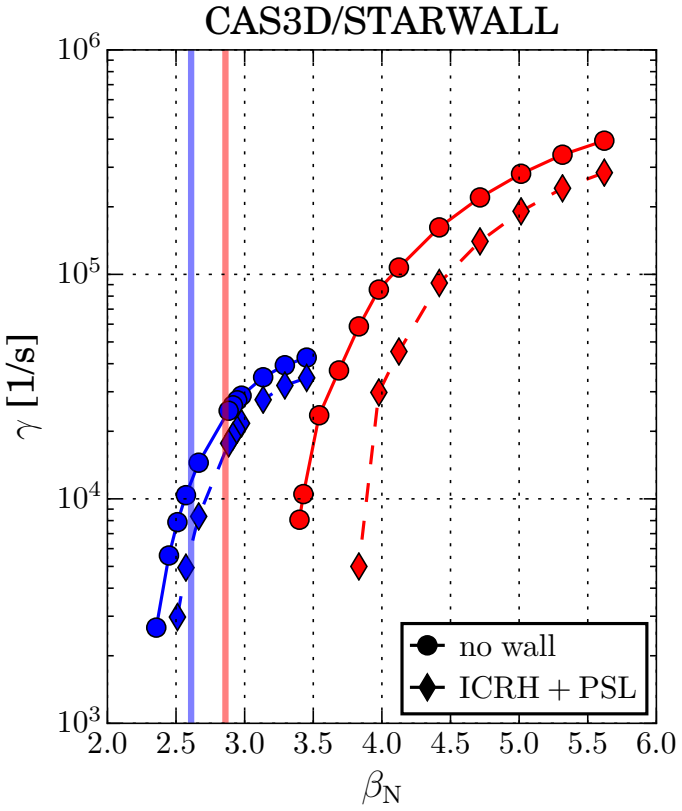
[Bock NF 2017]

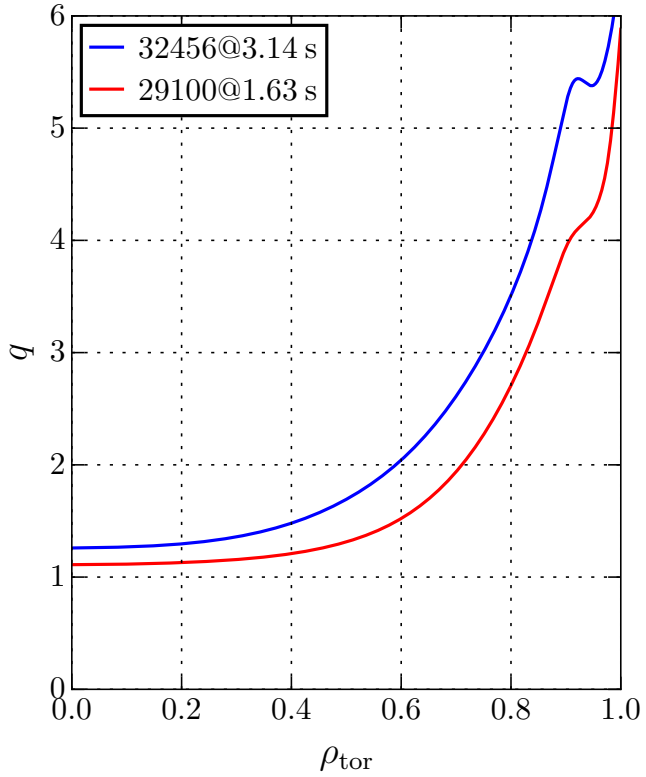
Understanding Ideal MHD Limits Quantitatively

- Stability limit can be **quantitatively understood**
- q-profile is key factor
- Presently installed AUG conductors offer little stability gain



- Not shown:
  - $n = 1$ EF correction gain: $\Delta\beta_N \approx 10\%$
    [Igochine EPS 2020/21]
  - Including plasma rotation/viscosity improves fidelity
    [Strumberger/Günter NF 2019]





[Igochine IAEA 2016]

Understanding Core Confinement with Transport Codes

- in-depth study with **gyro-kinetic code GENE**

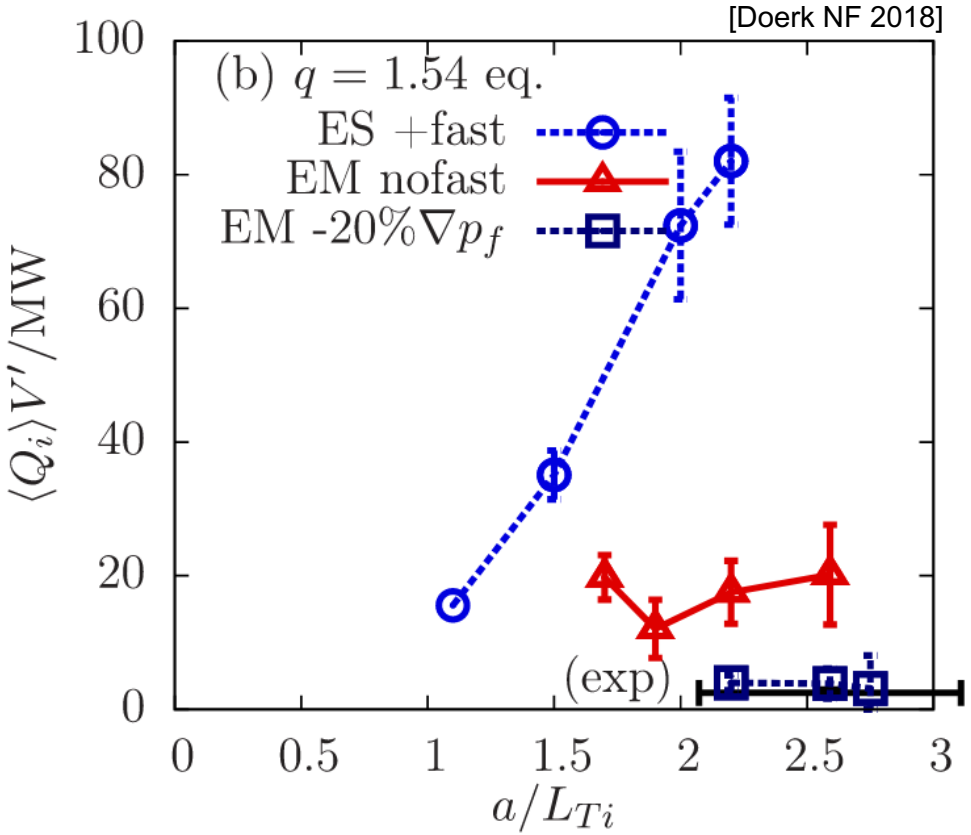
- identified 2 key physics ingredients to reproduce observed heat flux:

  1. **Electro-magnetic effects**
  2. **Fast ion interactions**

    - Non-linear energy transfer from turbulence to zonal flows

      [Di Siena NF 2019]

[Doerk NF 2018]



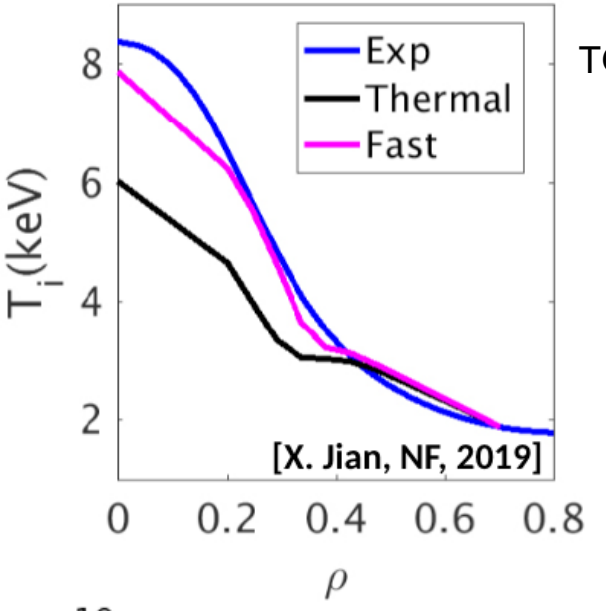
Reproduction of Observations Possible with TGLF

- Careful application of TGLF allows to reproduce observations, too

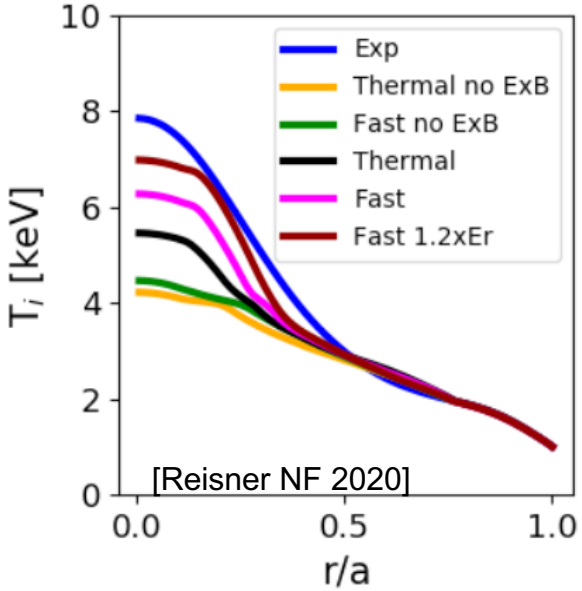
- Key aspects:
  - Updated saturation rules
  - Maintain fixed magnetic geometry incl. Shafranov shift
  - Include fast particles as diluting impurity species
  - Vary E_r within uncertainty
  - ➢ Result: T_i **reproduced**

➢ Contradiction:

TGLF: $E \times B$ effect ⚡ GENE: fast ion effect

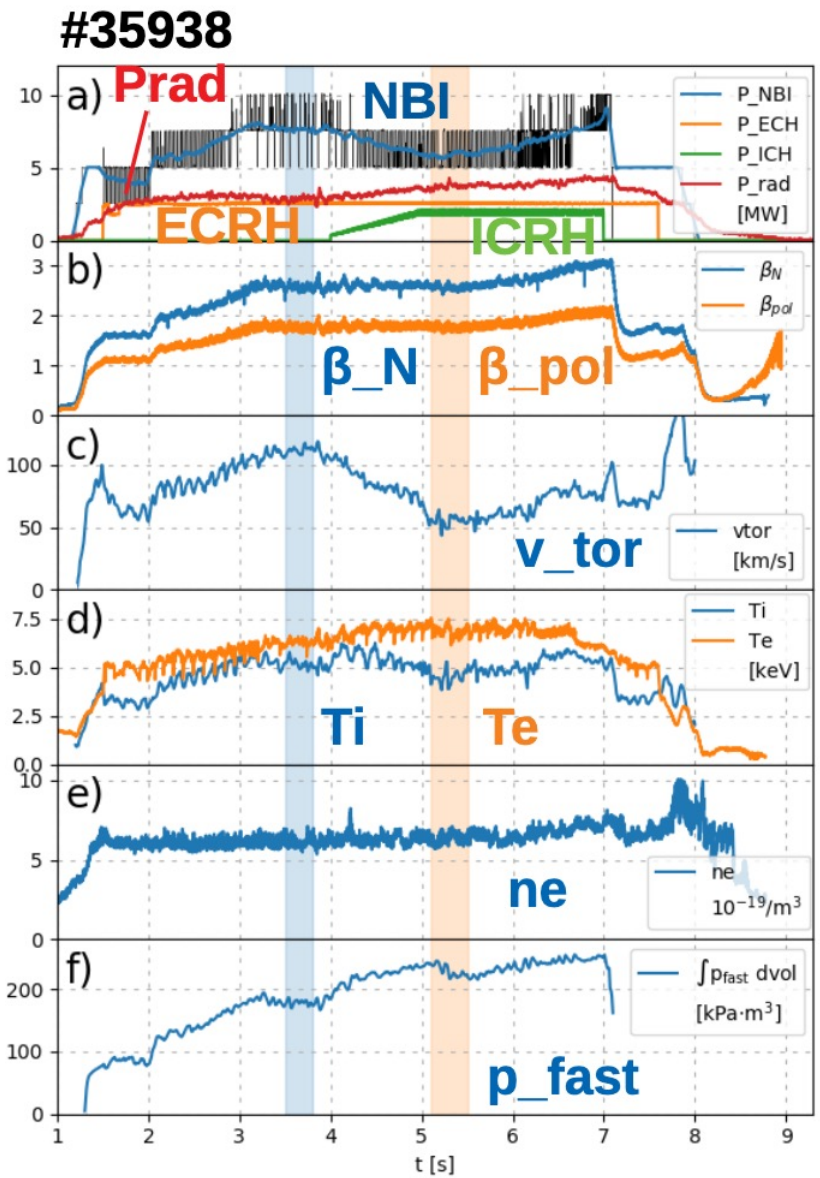


TGYRO/TGLF



ASTRA/TGLF

Experimental Discrimination of ExB and FI Effects



- Replacing NBI with ICRF heating
  - ➢ Reducing torque input and thus ExB shearing

[Reisner NF 2020]

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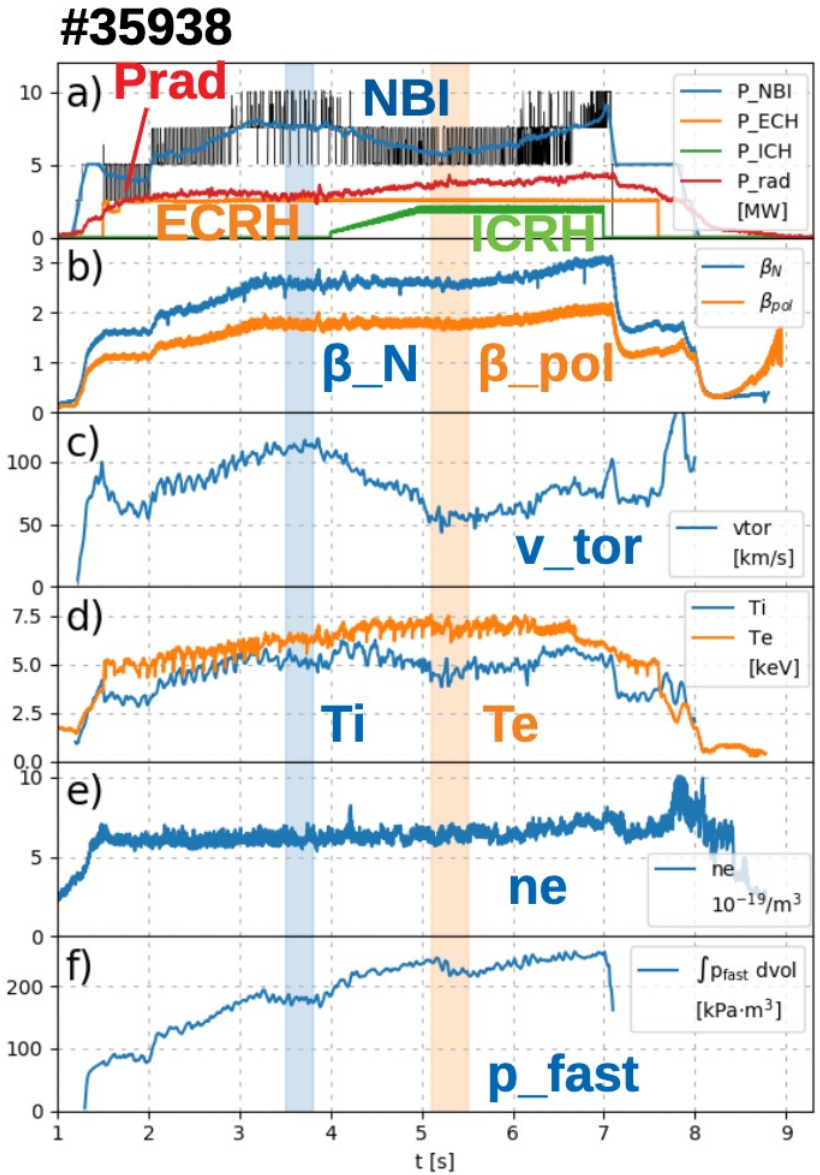

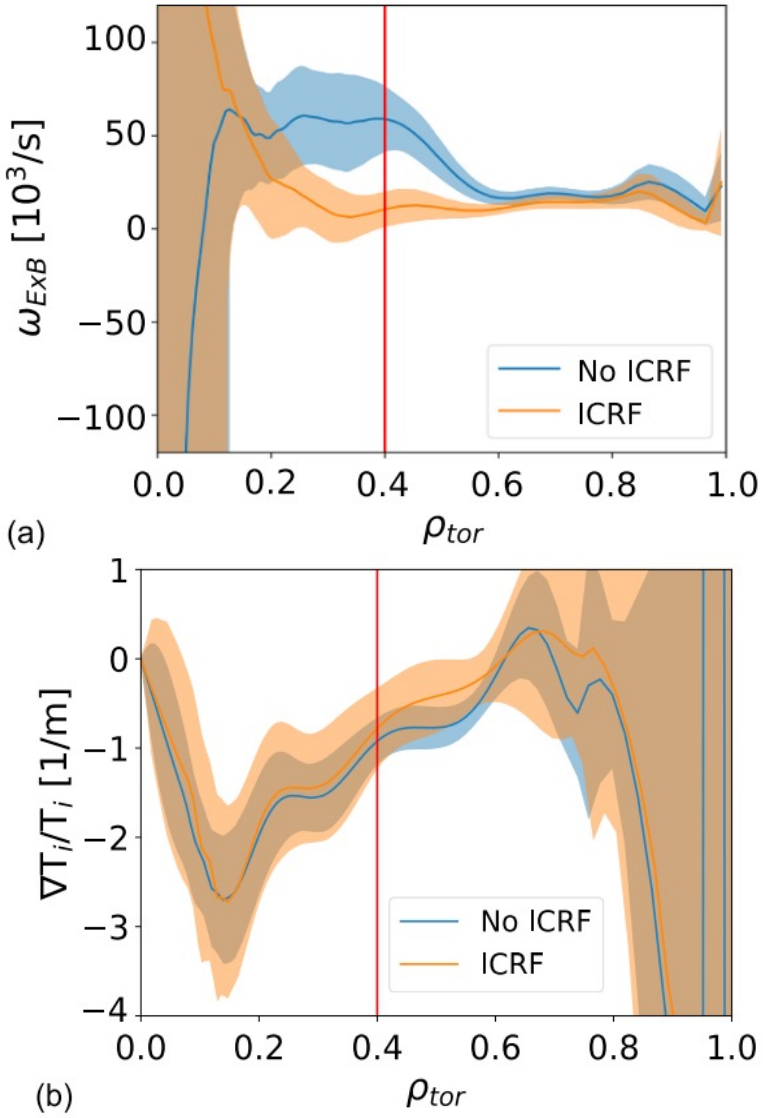

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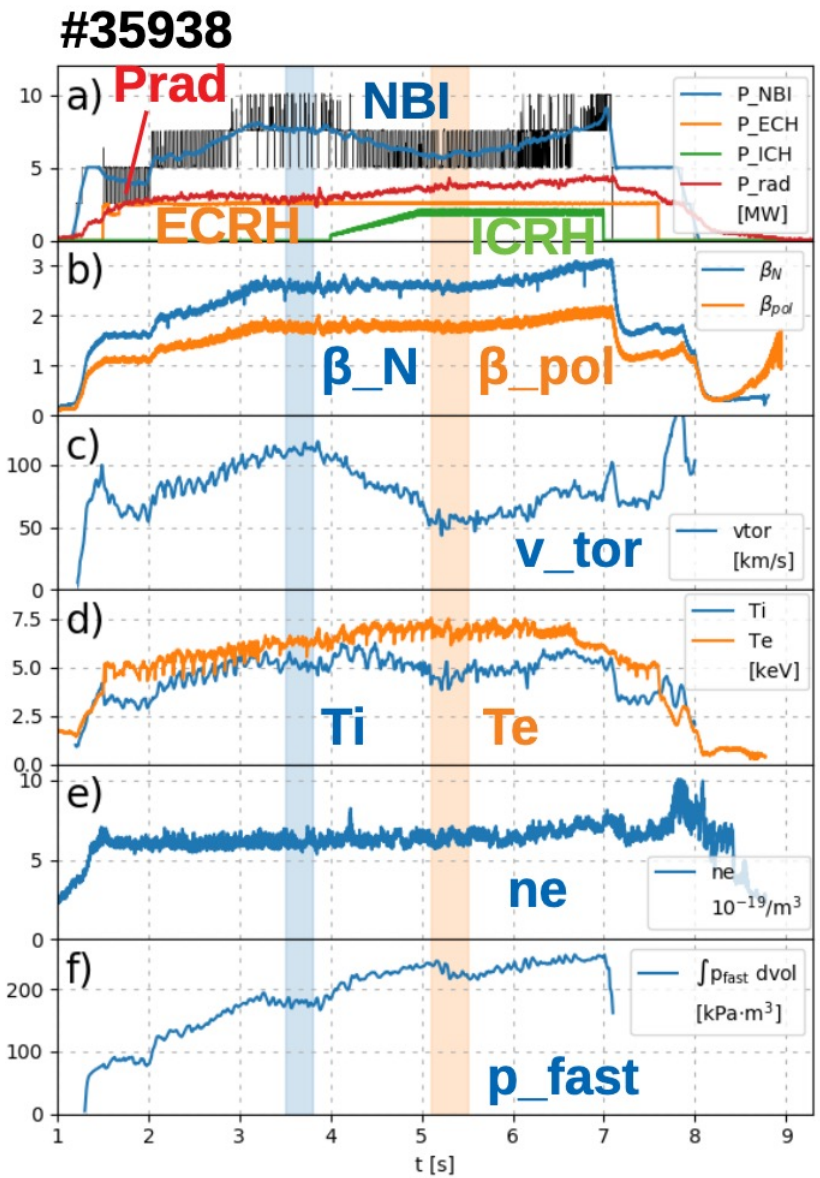

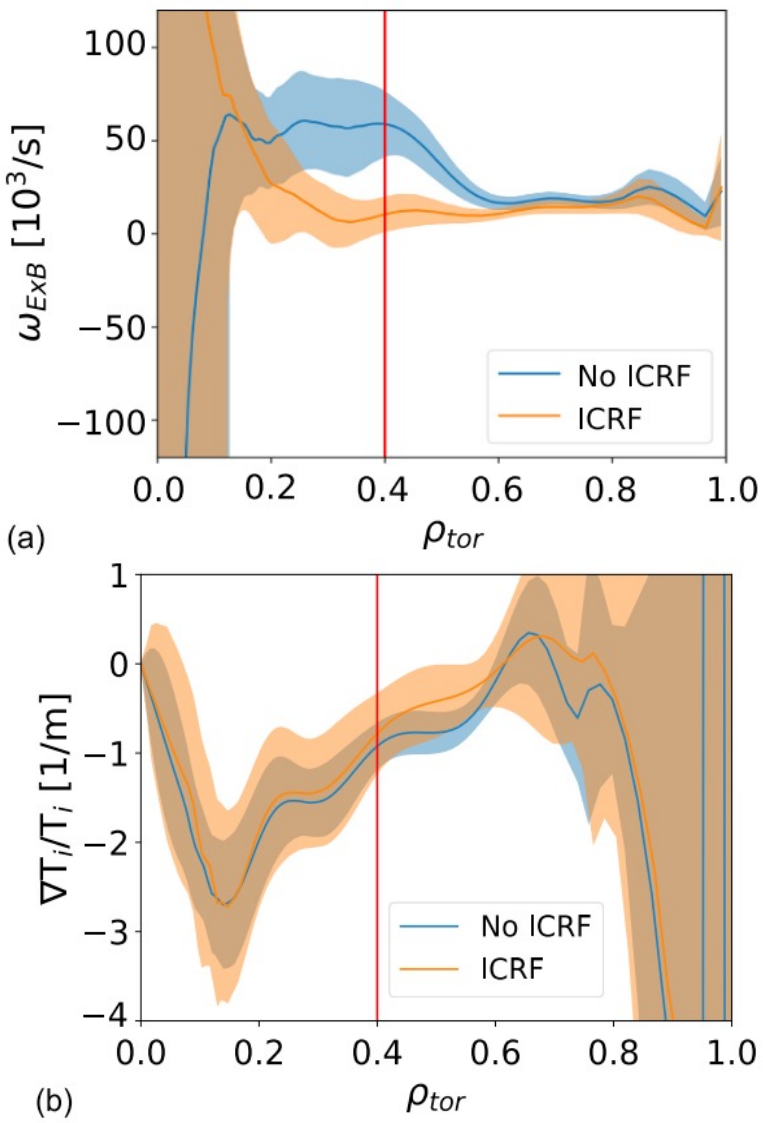

- Replacing NBI with ICRF heating
  - Reducing torque input and thus ExB shearing
  - Negligible impact on L_{ti}
- Under these conditions, TGLF right for the wrong reasons
- Special care when extrapolating to future devices crucial

[Reisner NF 2020]

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Summary

Anomalous Flux Redistribution ("Flux Pumping")

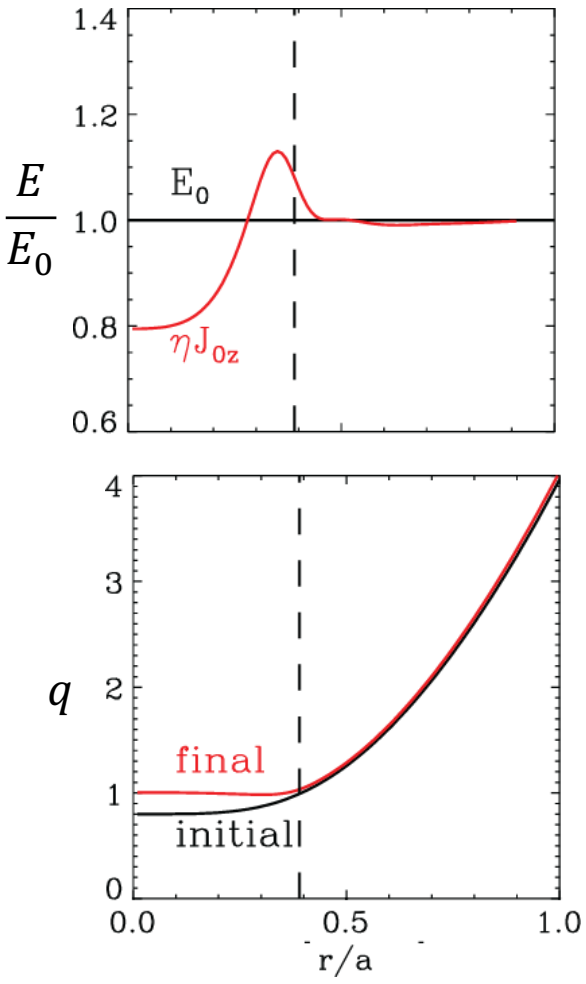
Flux Pumping

- Originally observed in DIII-D, attributed to 3,2-NTM [Petty PRL 2009]
- In AUG: thought to be caused by continuous 1,1 quasi-interchange mode
- Causes anomalous redistribution/broadening of j near plasma centre through **dynamo effect**

Benefits

- 1,1-mode **clamps central q-profile at ≈ 1**
  - ➢ minimal or no sawtooth crashes
- j-profile remains as peaked as possible while maintaining $q > 1$
  - ➢ maximises β-limit
- j-redistribution allows for highly efficient on-axis CD deposition

[Piovesan NF 2017]



Flux Pumping Scenario: q-Profile Clamped at Unity

#36663

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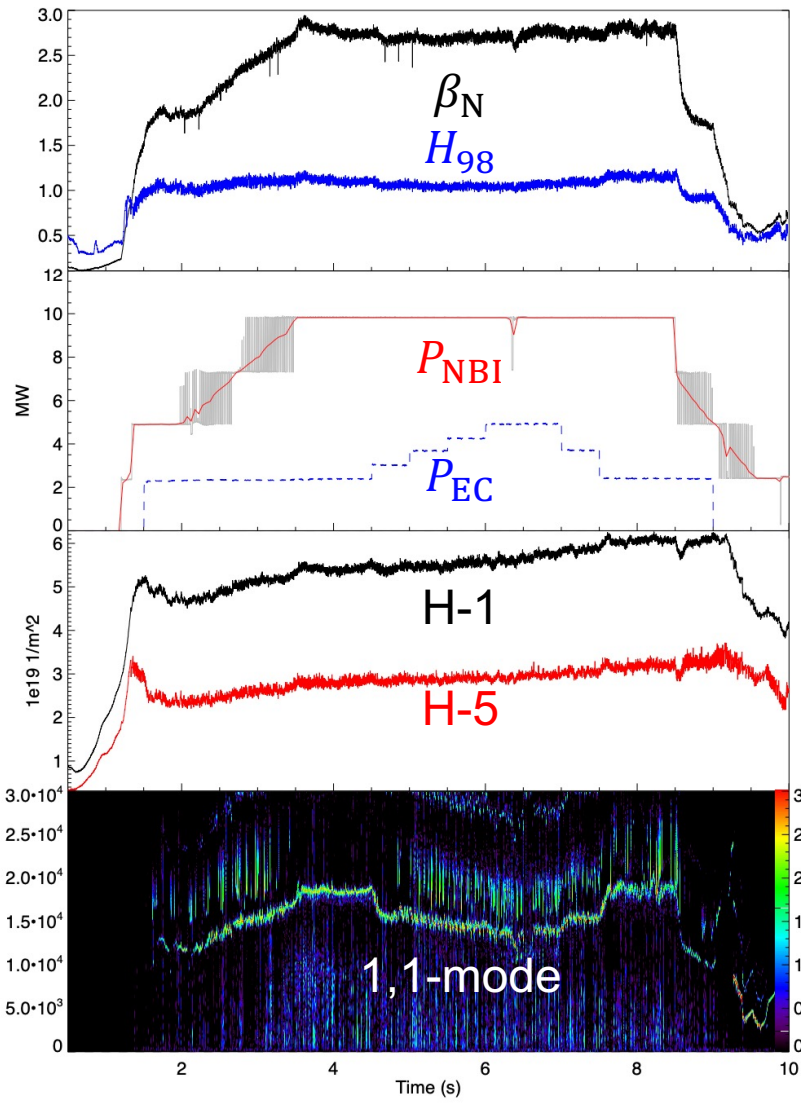
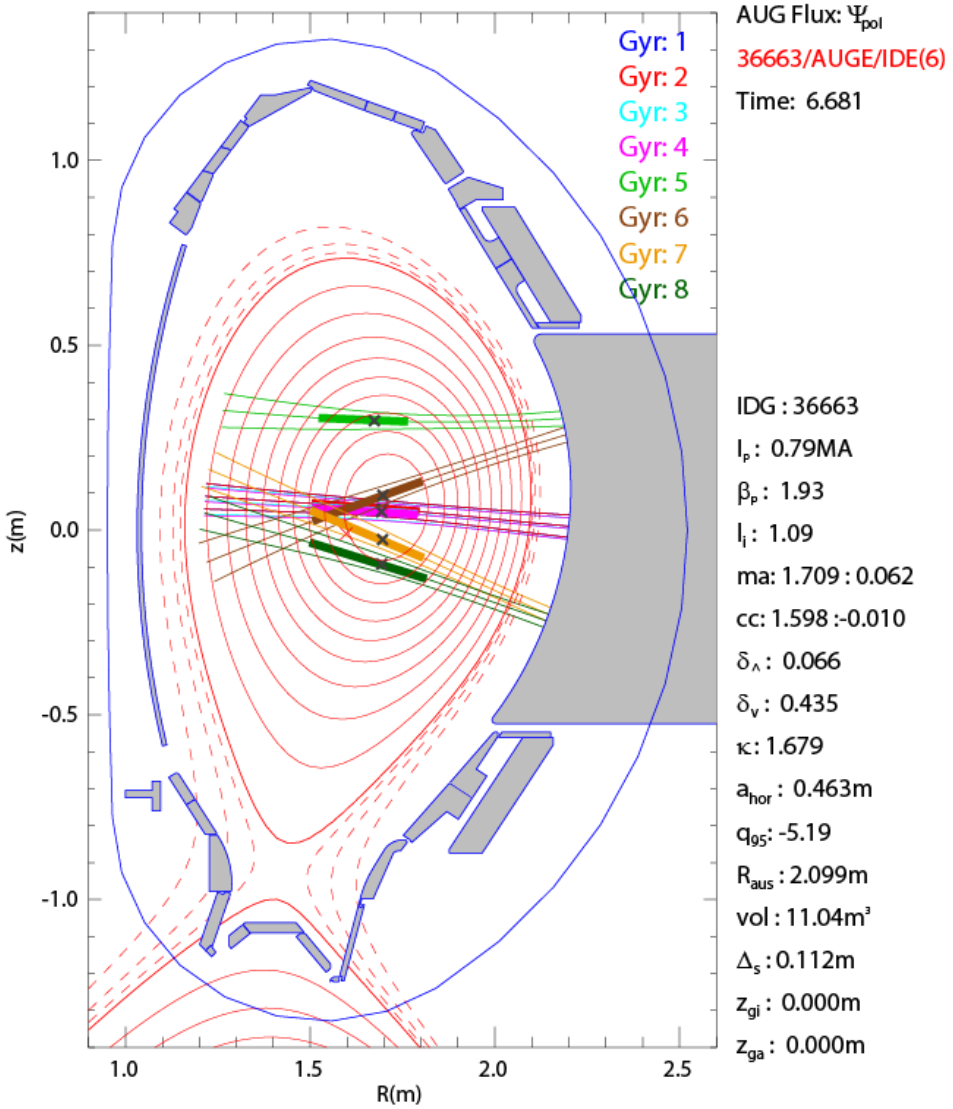
$B_T = 2.45$ T





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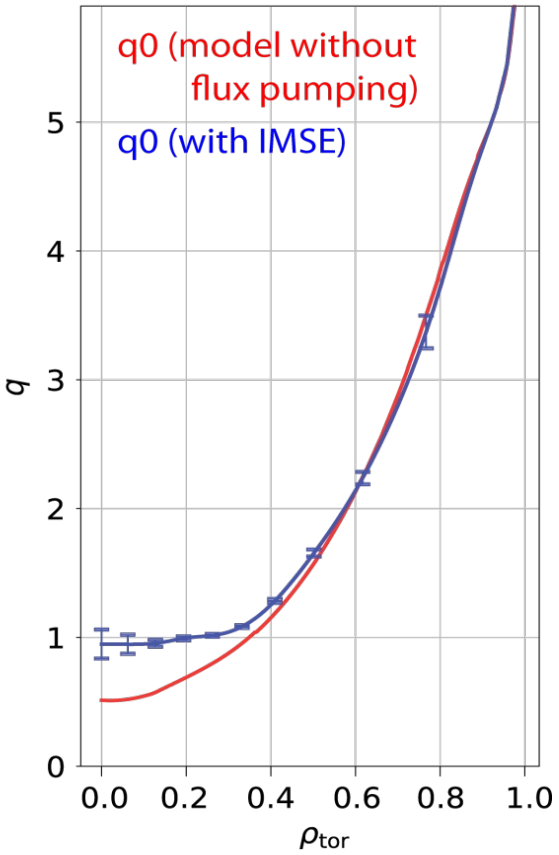
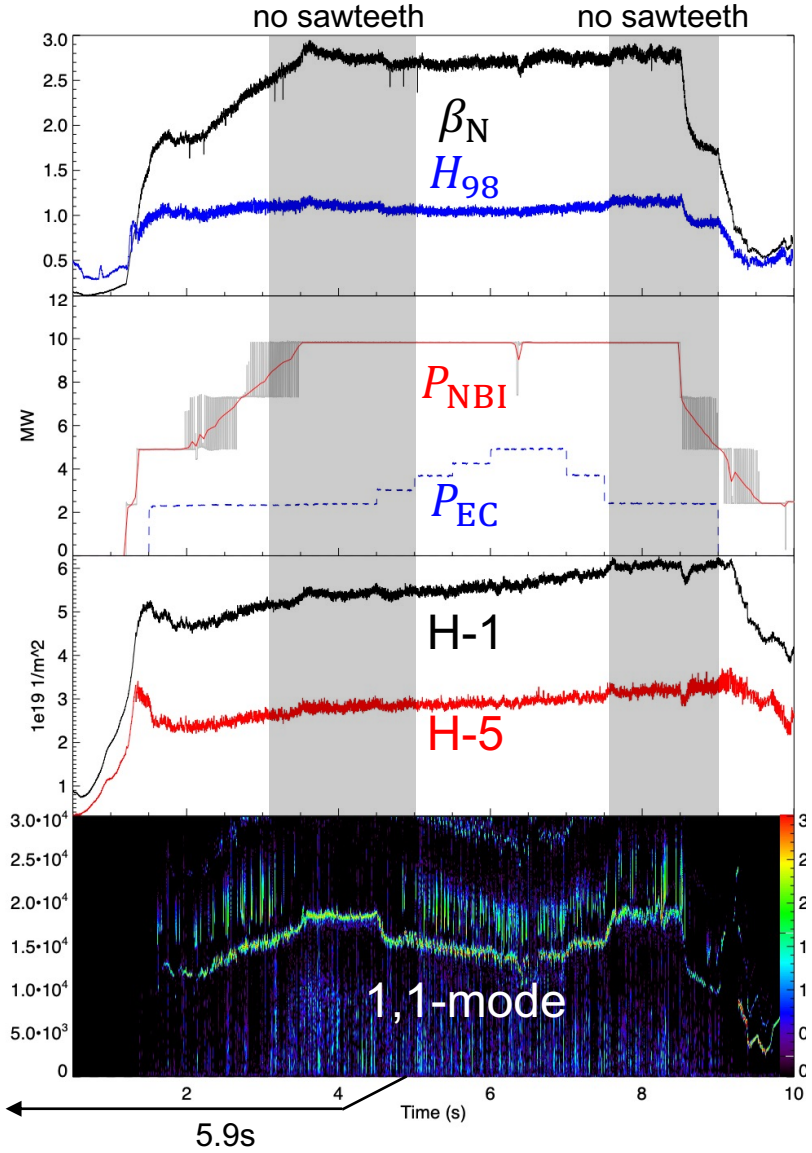
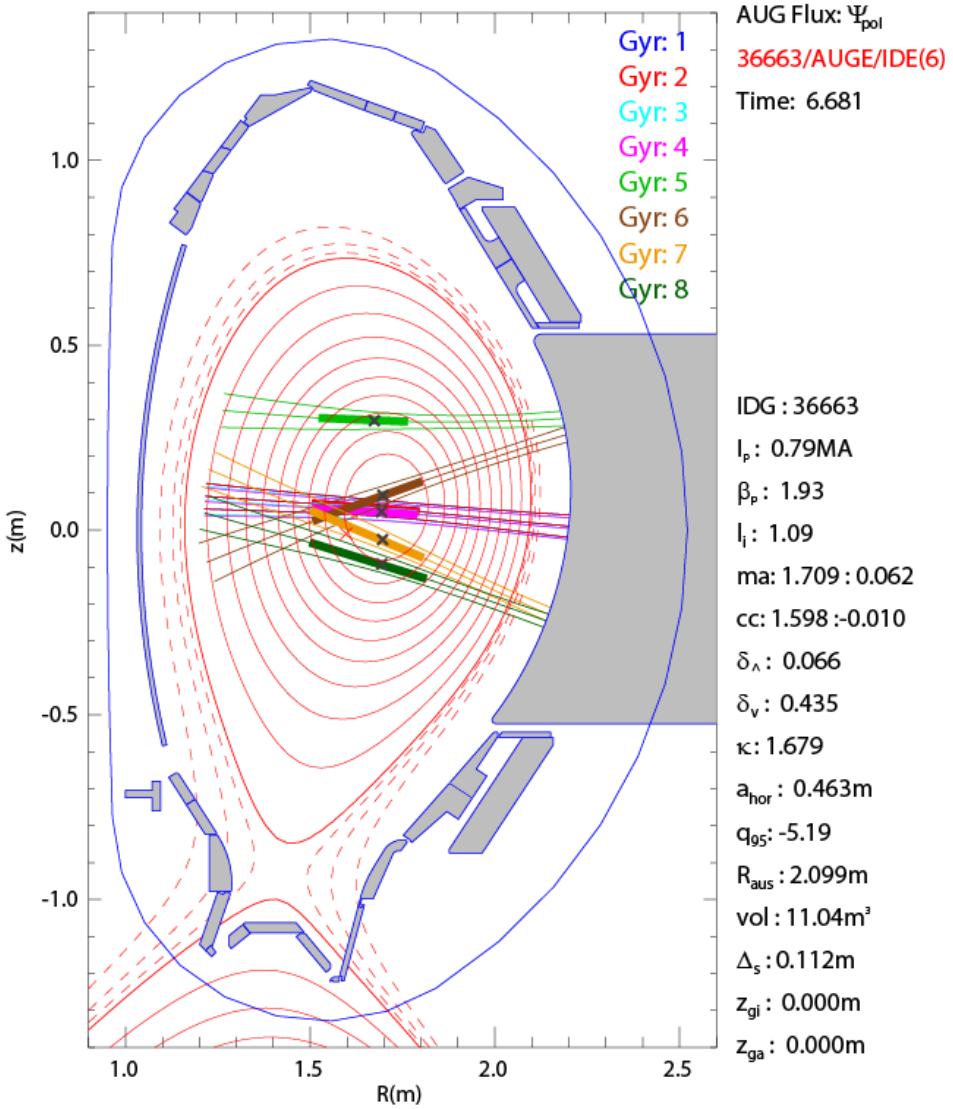
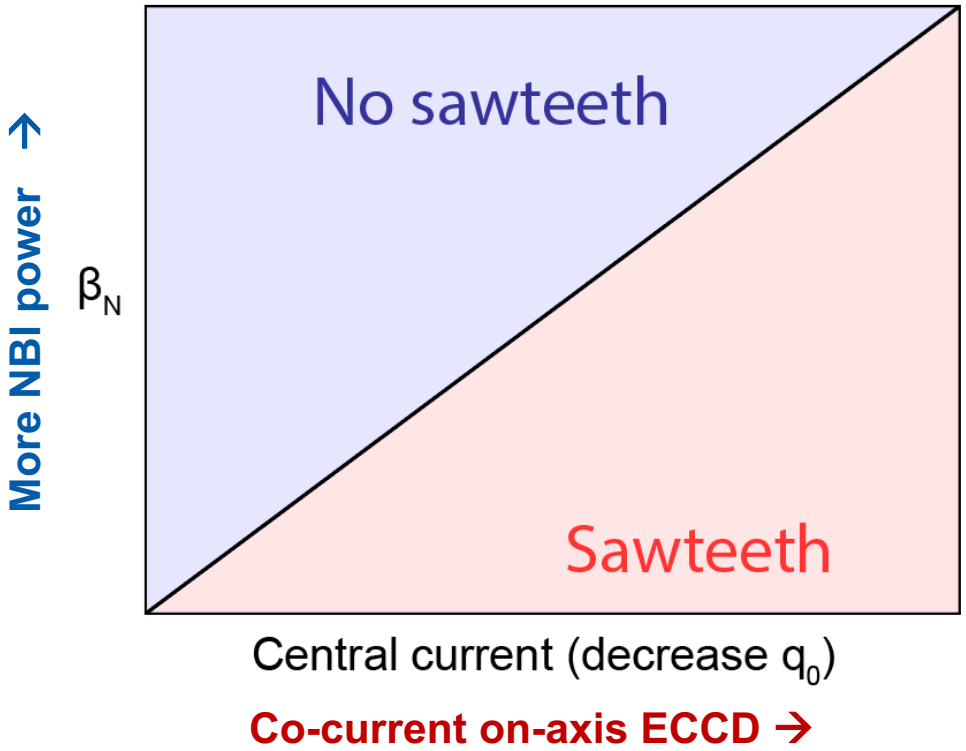






Observations in j-β diagram consistent



[Burckhart IAEA FEC 2020/2021]

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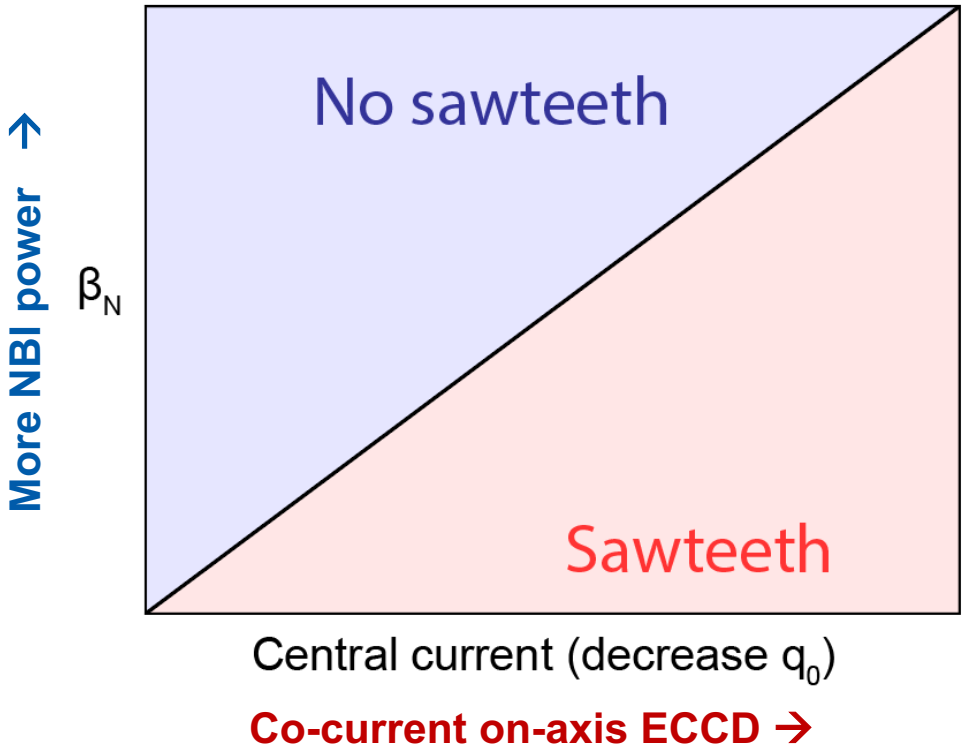

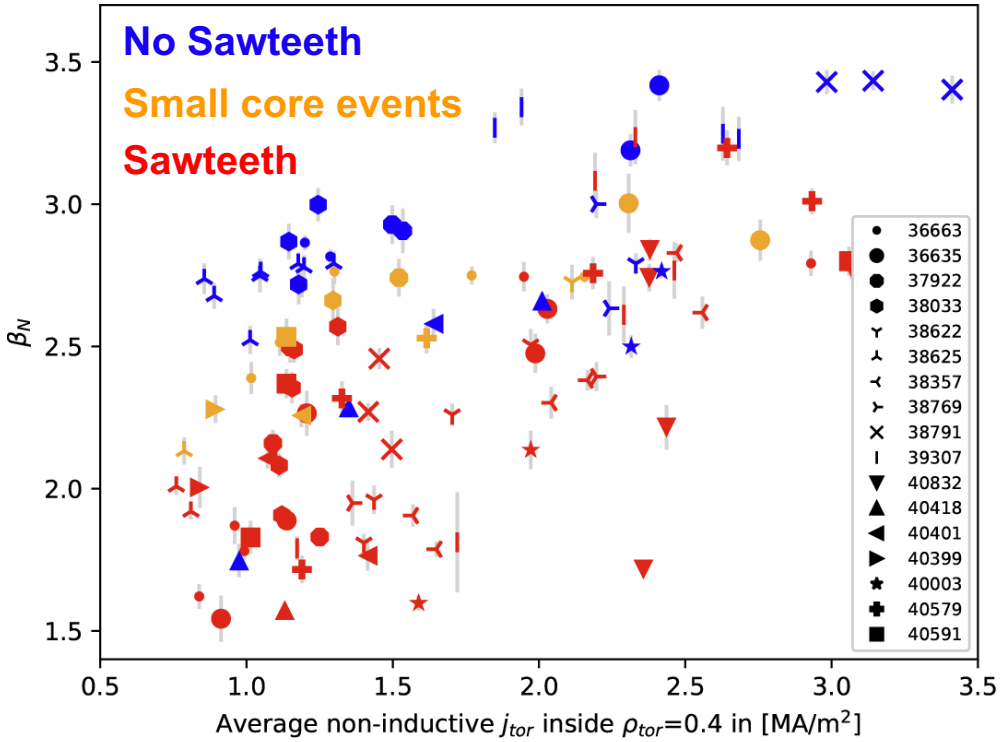

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High-β Non-Inductive Flux Pumping Scenario

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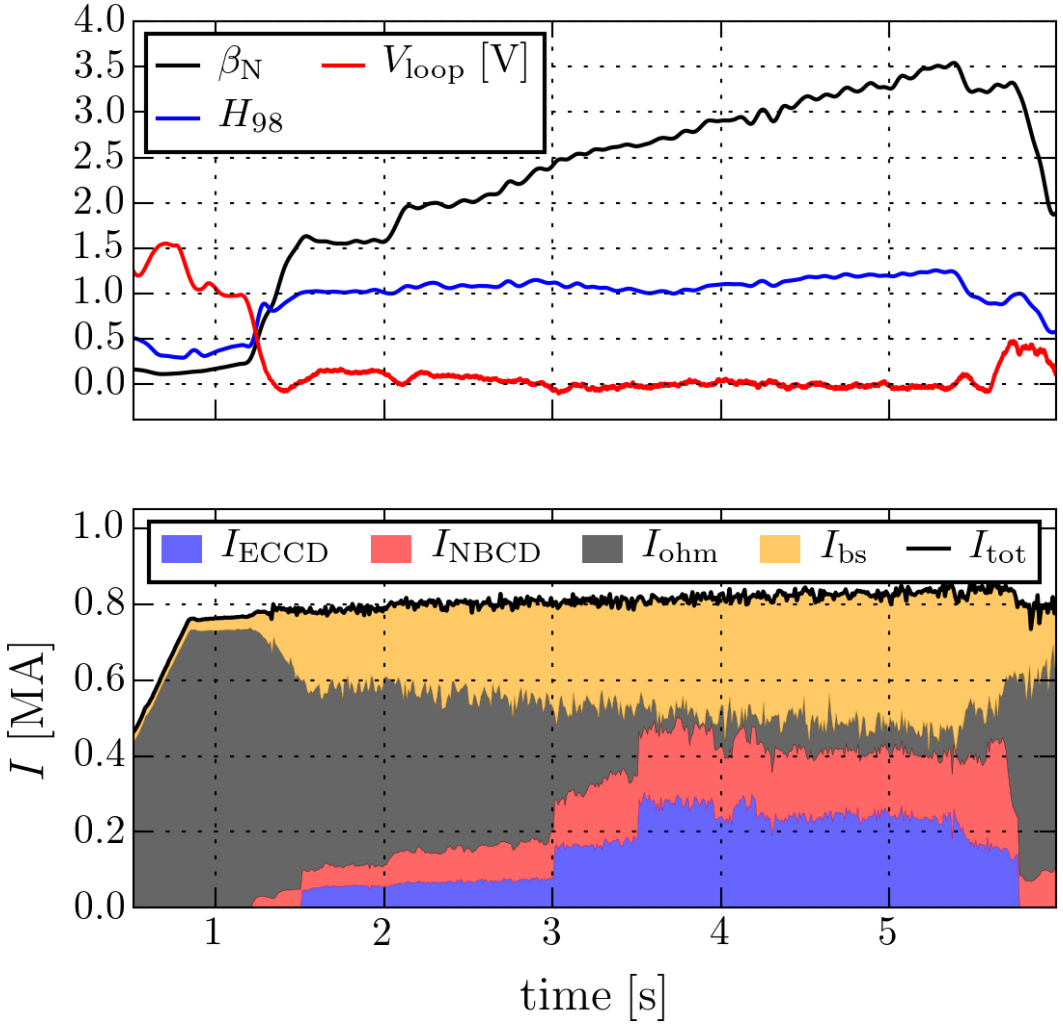

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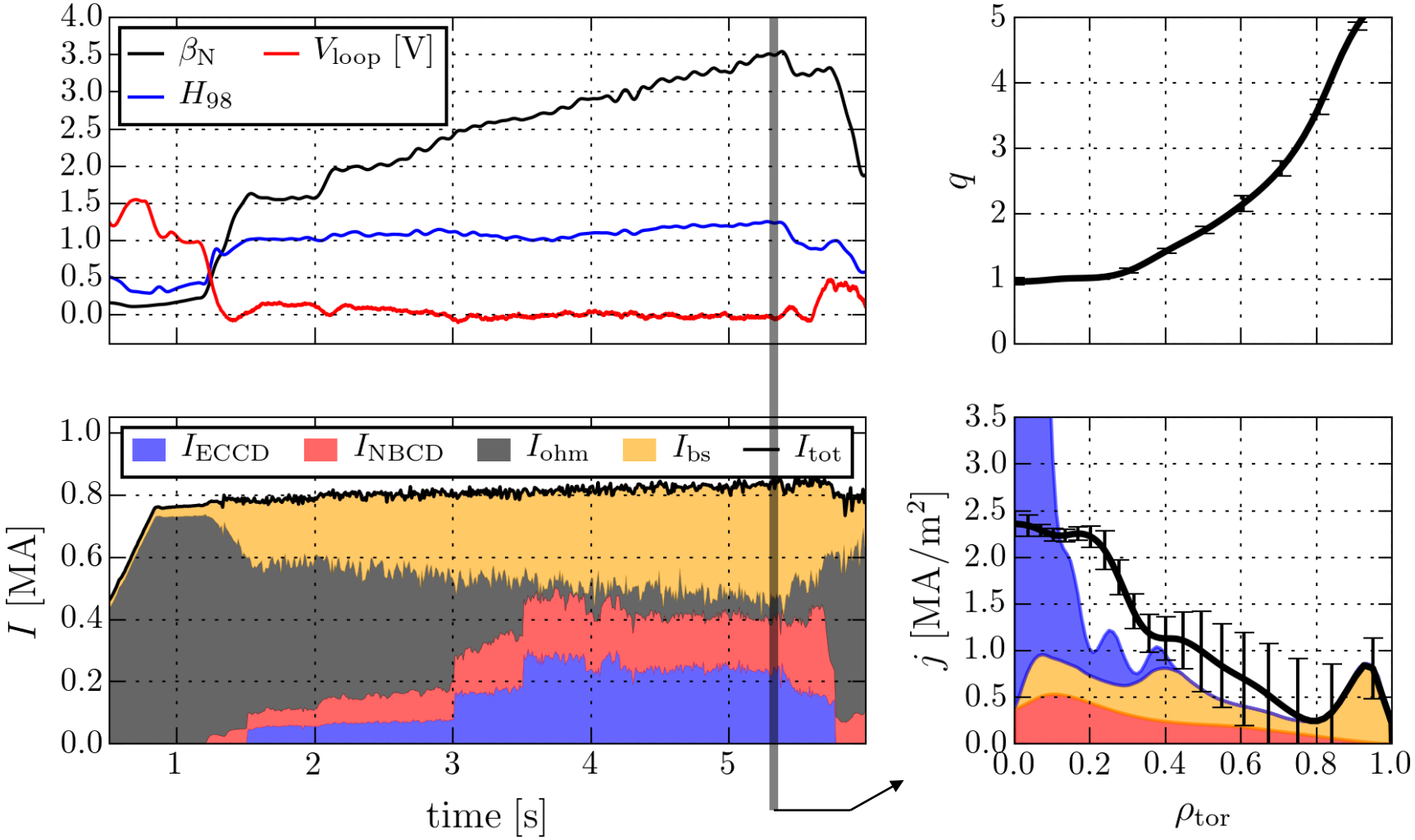

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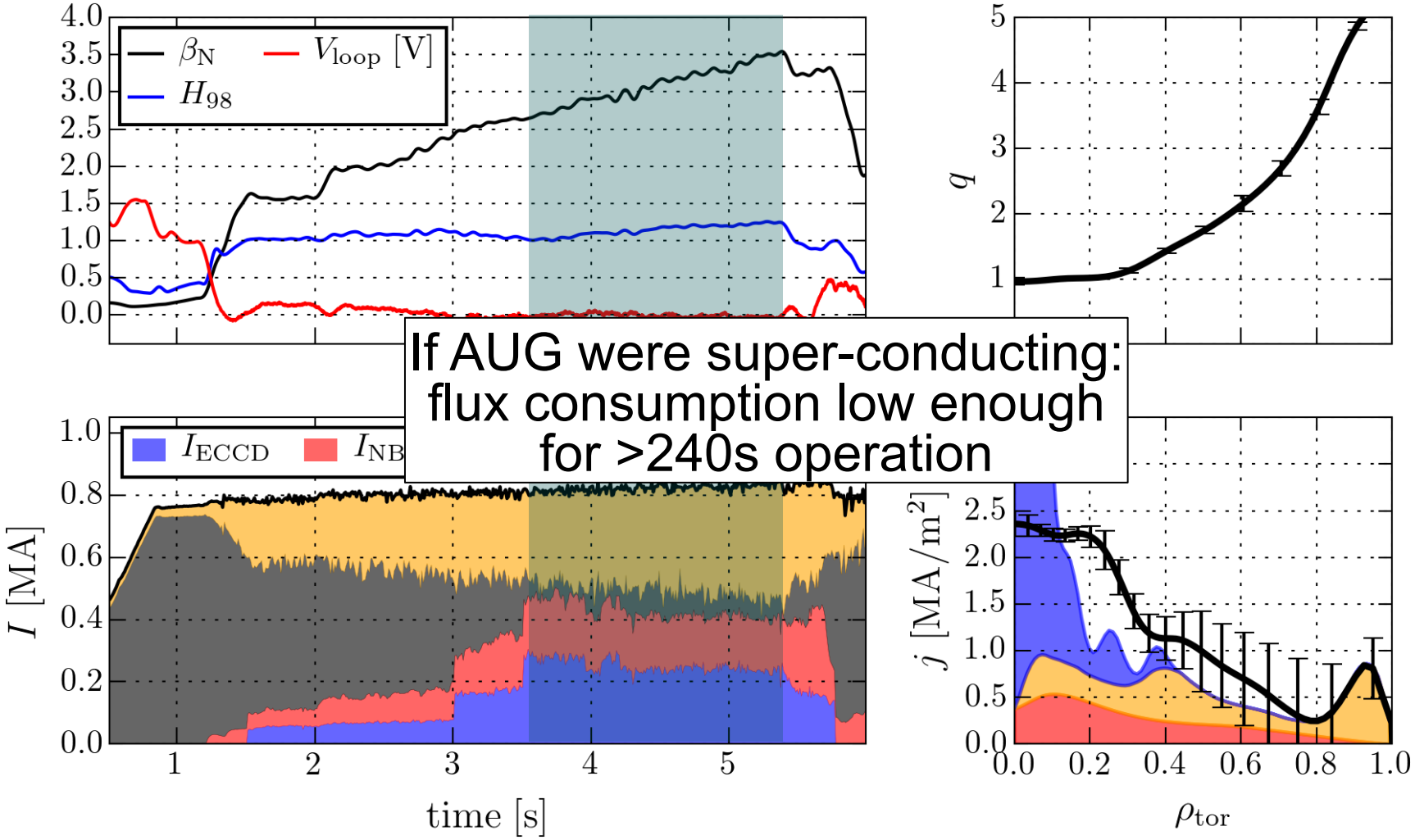
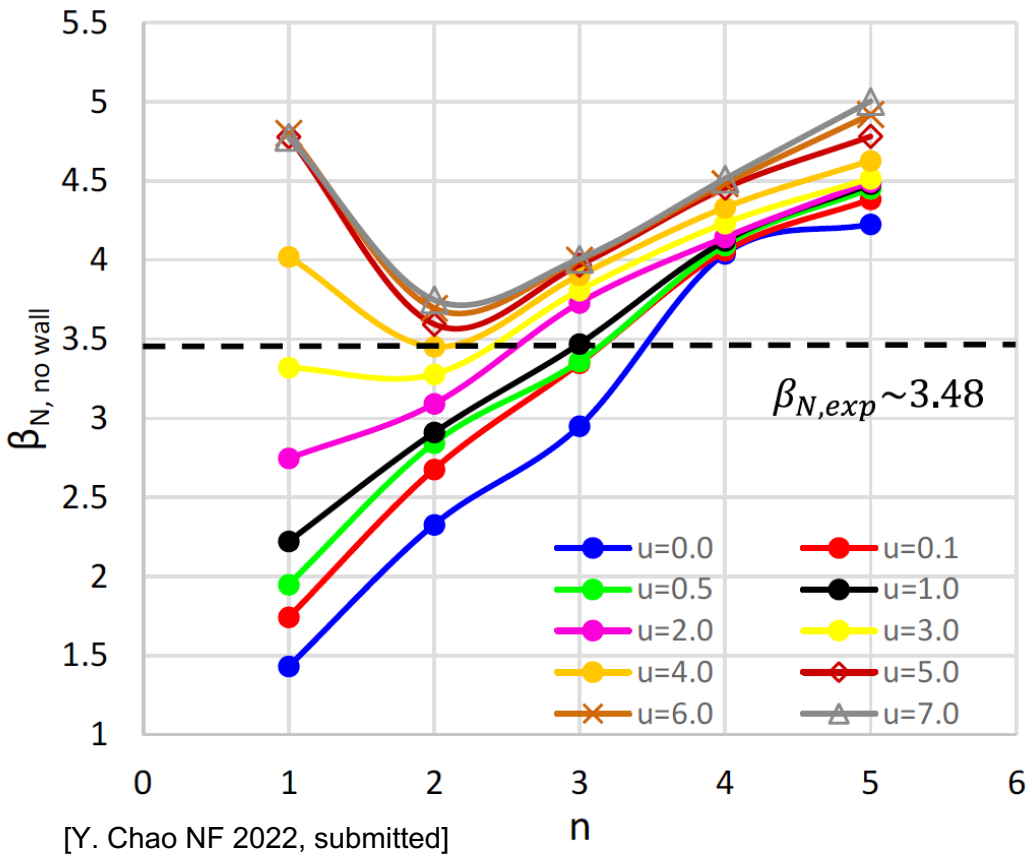


If AUG were super-conducting: flux consumption low enough for >240s operation

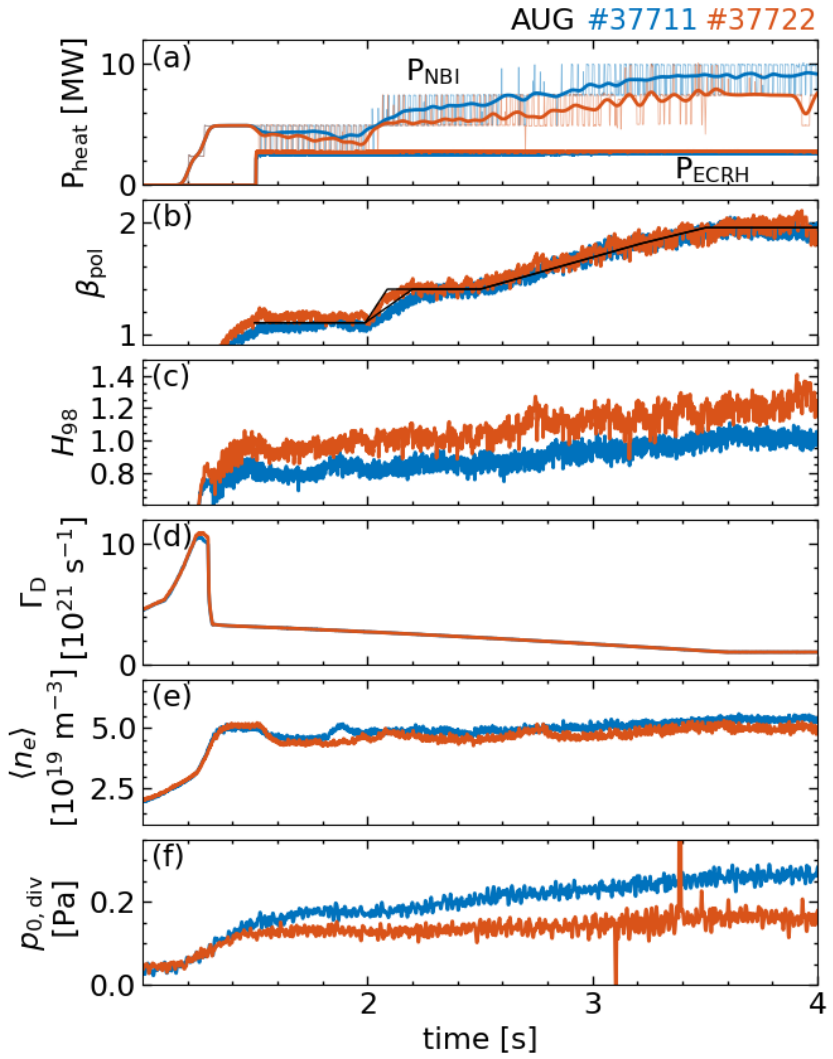
Observed Ideal MHD-Limit reproducible with CASTOR3D

- Pulse performance **limited by ideal 3,2-modes**
- Analysing ideal stability challenging due to centrally clamped *q*-profile around unity
- Varying the parallel viscosity $\mu_{\parallel}$ allows **matching the observations**



[Y. Chao NF 2022, submitted]

Confinement correlates inversely with divertor neutral pressure



Discharges close to boronization very sensitive to wall conditions

They can change $p_{0,div}$ even for the same gas puff

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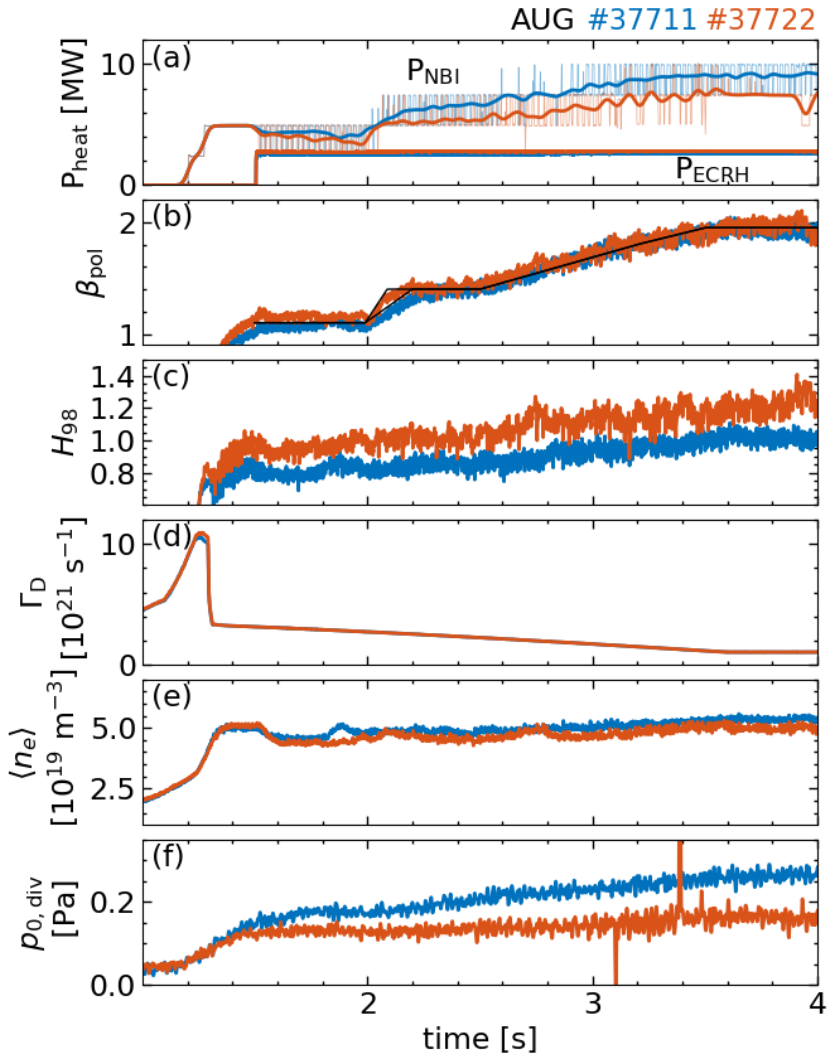

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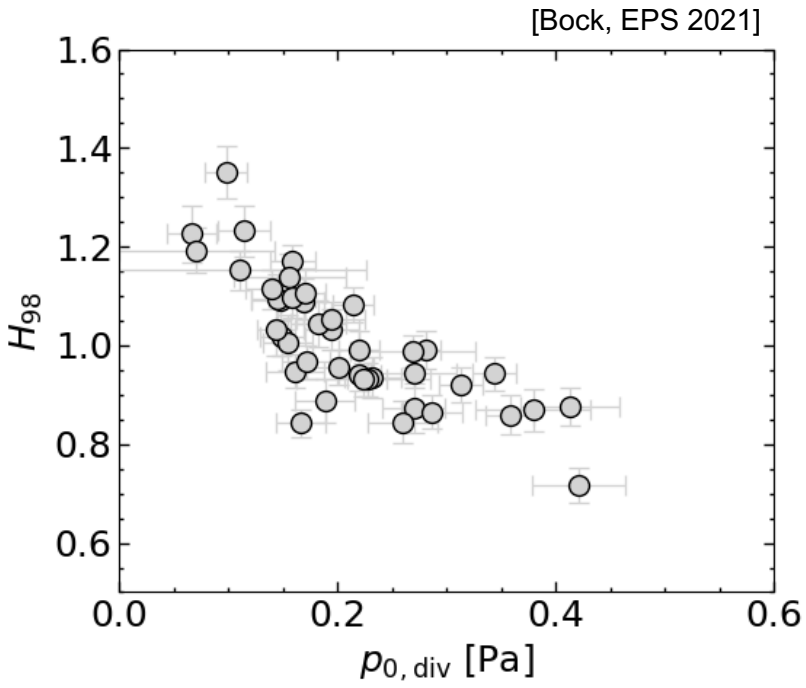
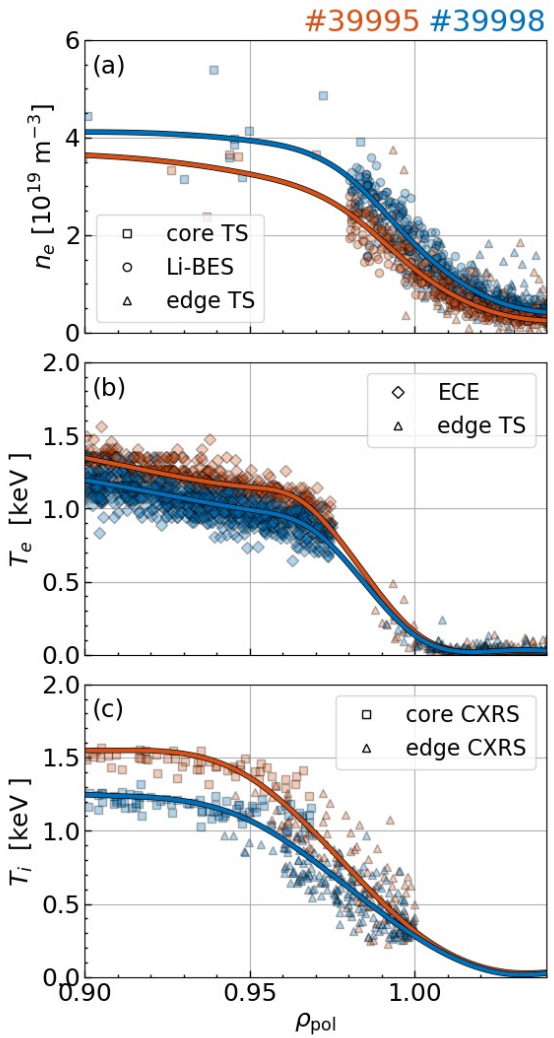


$p_{0,div} \sim n_{sep}/n_{ped}$

- Position of $\max(\nabla n_e)$ shifts outwards
- Confinement decreases

c.f. higher n_e operation at JET, AUG, C-Mod
[Dunne PPCF 2017, Frassinetti NF 2021]

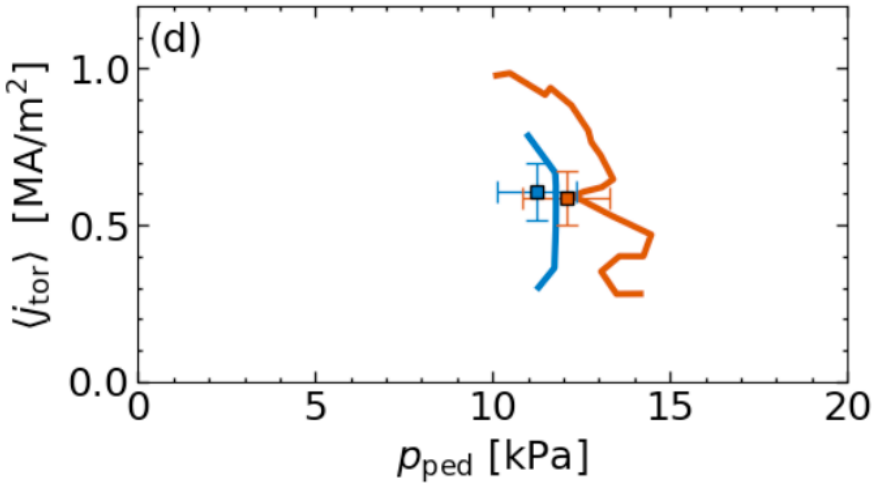
Confinement changes consistent with peeling-ballooning stability calculations



- Engineer discharges with intentionally varying divertor neutral pressure (high, low) and feedback-controlled NBI heating to maintain a target β

- Analyse linear MHD stability by scanning adjacent parameter space using MISHKA

[Silvagni NF 2022, to be submitted]



➢ **At lower $p_{0,div}$:**
stability boundary moves to higher p_{ped}

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$q_{95} \approx 4$ counter-ECCD scenario $q_{\min} \gg 1$ teaser

- Final parameter that strongly differs from target EU-DEMO scenario: q_{95}
  - ➢ Increase plasma current to 0.9/1.0 MA at 2.5 T
  - ➢ Considerable elevation of *q* achieved through **central counter-ECCD**
- Early plasma very sensitive to MHD activity, especially with reduced q_{95} and thus resonant surfaces closer to edge
  - ➢ Guide scenario design with **predictive modelling** and eventually RT *j* control
- **Main presentation tomorrow 15:45 by R. Schramm**

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- Covering broad range of parameters to develop and verify models for extrapolation to DEMO and beyond
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  - Anomalous Flux Diffusion
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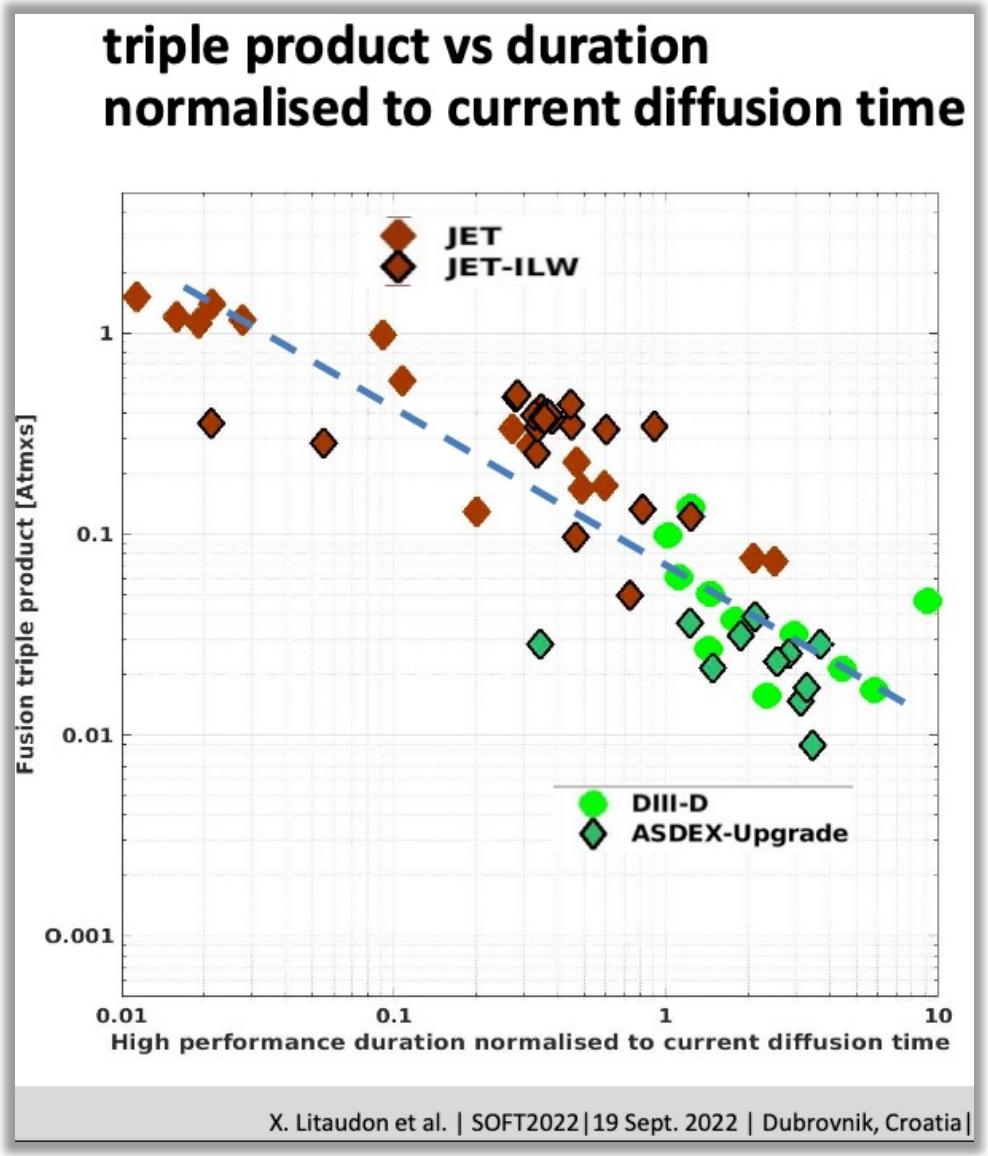


Summary

- AUG LPO research programme aimed at paving way to EU-DEMO steady state scenario
- Covering broad range of parameters to develop and verify models for extrapolation to DEMO and beyond
  - Core Transport (ExB ↔ FI)
  - Anomalous Flux Diffusion
  - Core/Edge MHD stability
- Successful operation in full W environment

Outlook

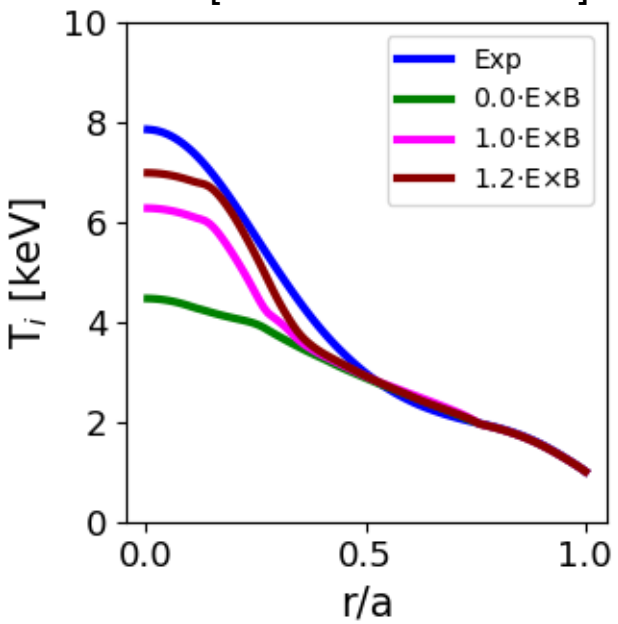
- Continuing exploring parameter space
- Exploit RT current profile control
  - Tomorrow 15:45 R. Schramm
- Explore higher shaping plasmas
- Investigate possible integration with power exhaust solutions

Backup Slides

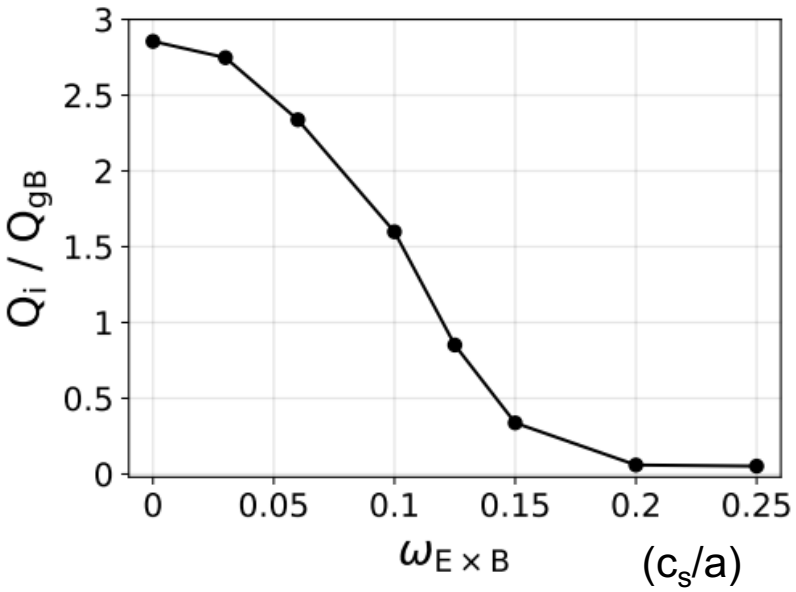
Introduction
Potential effects behind turbulence reduction

- In previous work, ASTRA/TGLF simulations find ExB-shear to play role in the reduction of transport.
- Contrary to that, GENE simulations do not find such a ExB-dependence.
- Instead: Coupling between ITG and fast ion driven modes. [A. Di Siena NF 2019][A. Di Siena JPP 2021]

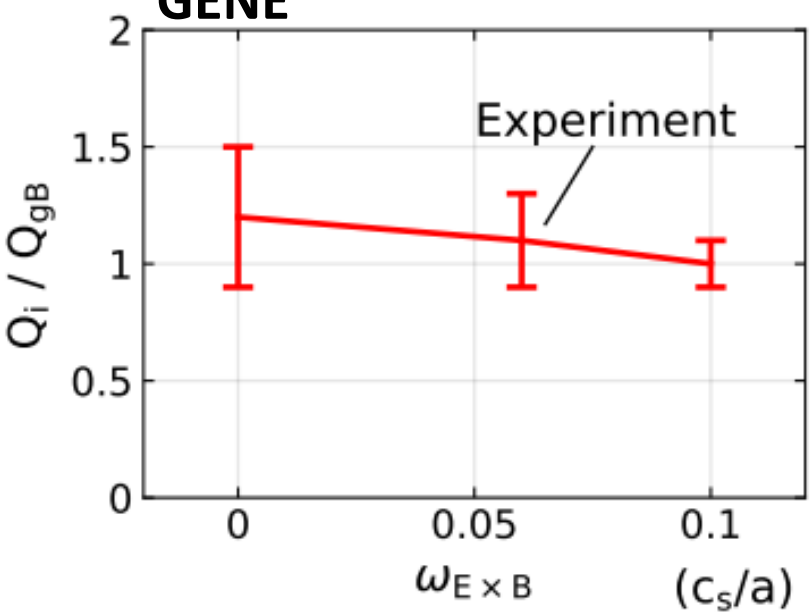
[M. Reisner NF 2020]



TGLF, spectral shift rule

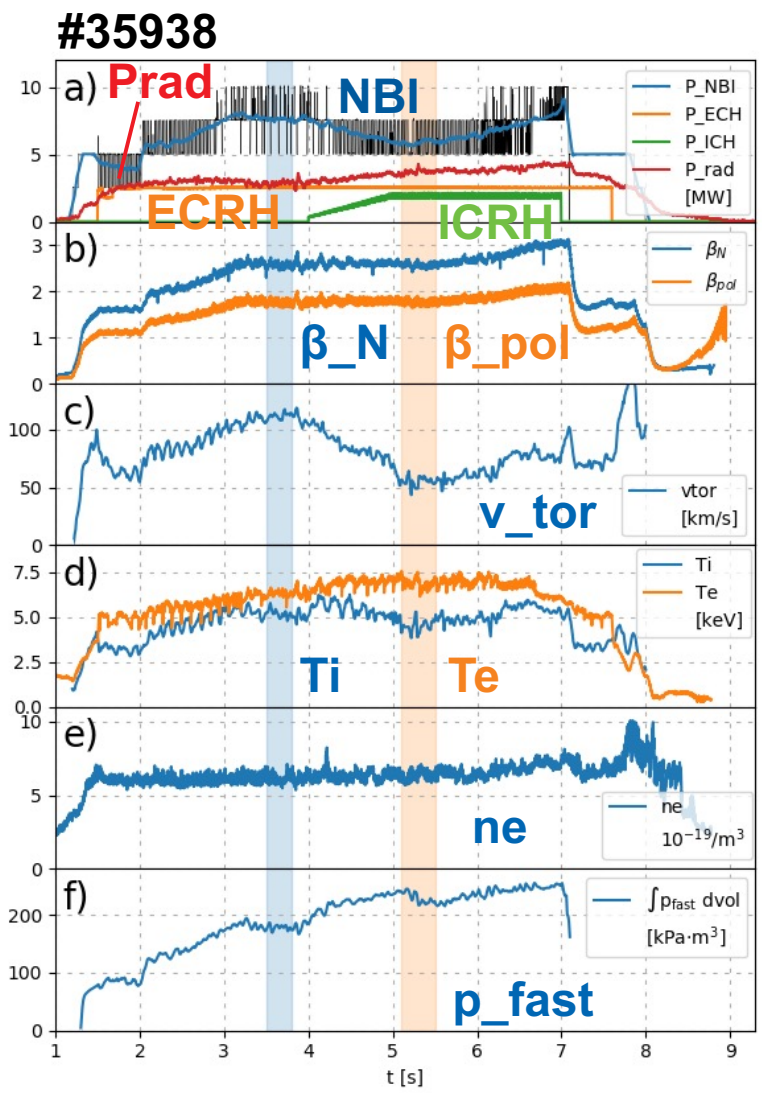


GENE



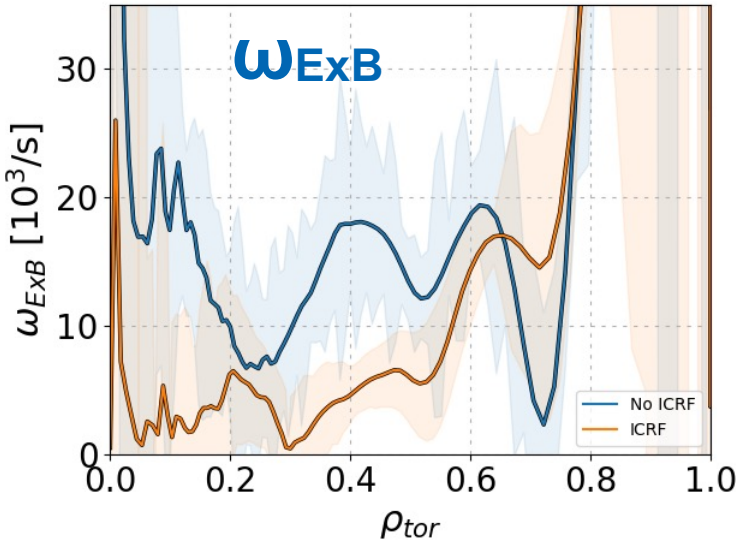
- Conduct dedicated experiments, to test importance of ExB-shear.

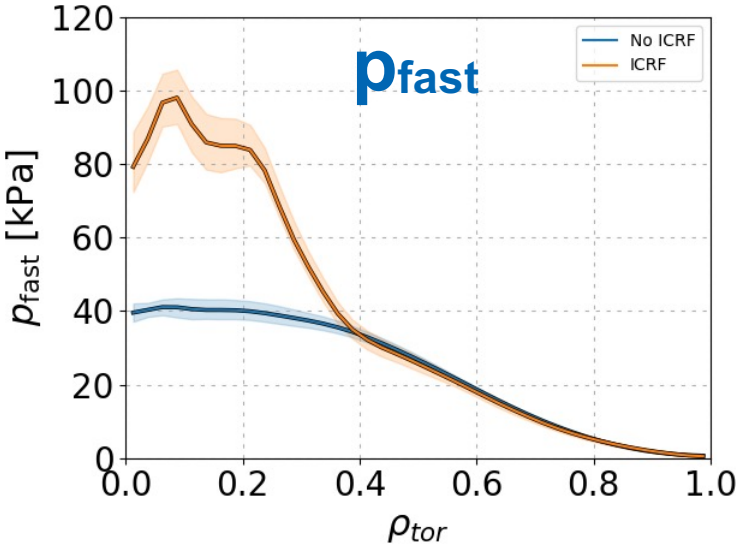
Experimental setup



- Experiment to test effect of ExB-shear
- Start with regular AT scenario, then replace some NBI with ICRF

  → reduced rotation → reduced ExB-shear → effect on R/LTi?





- Between time-intervals, Fast ion pressure increased.
- ICRF adds largly Hydrogen fast ions

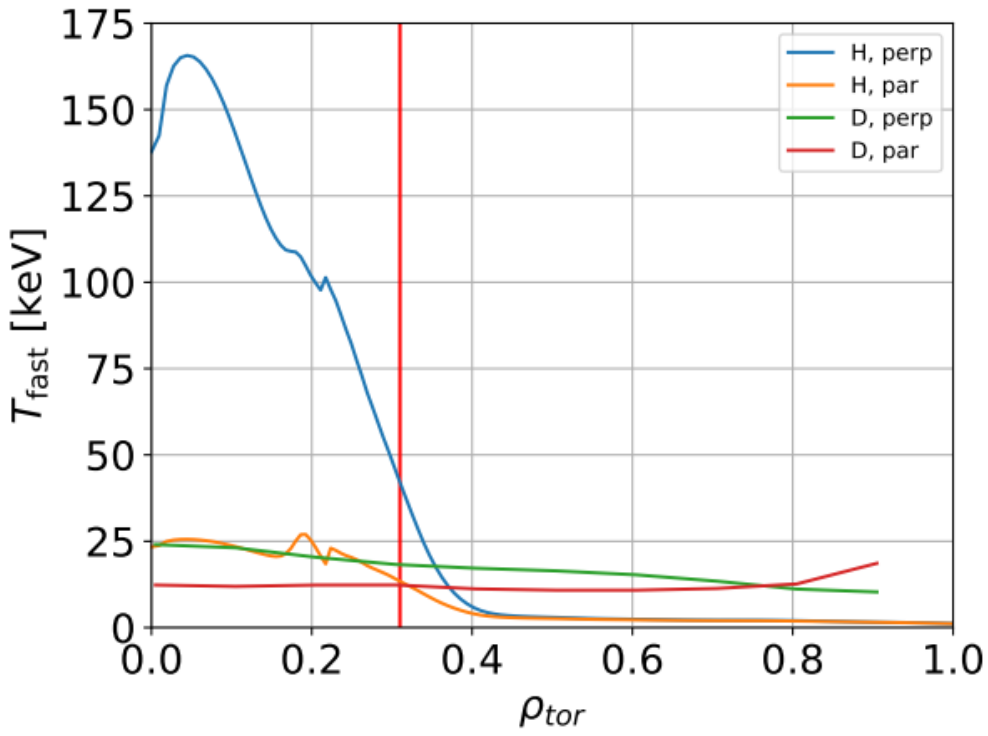
GENE simulations
ICRF case – realistic distribution necessary

- When using both FI species, simulations do not converge → fast ion driven modes become too strong
- Solution: Instead of Maxwellian, use more realistic bimaxwellian distribution → avoid resonances

$$F_{0,Maxwel} = \frac{n_0}{\pi^{3/2} v_{th}^3} exp\left(\frac{-mv_\parallel^2/2 - \mu B_0}{T_0}\right)$$

$$F_{0,Bimaxwel} = \frac{n_0}{\pi^{3/2} v_{th,\parallel} v_{th,\perp}^2} exp\left(-\frac{v_\parallel^2}{v_{th,\parallel}^2} - \frac{\mu B_0}{T_\perp}\right)$$

- D-FI temperatures calculated with TRANSP, coupling Nubeam with TORIC
- H-FI temperatures calculated with TORIC + SSFPQL



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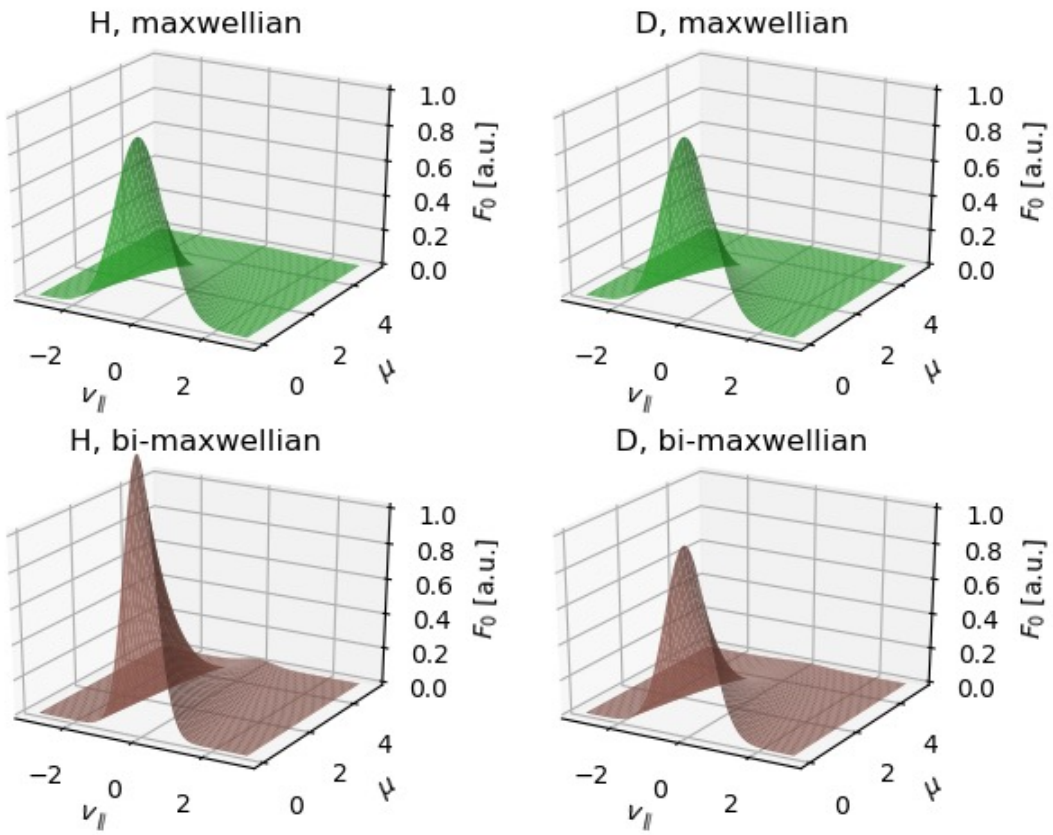
- Anisotropies have effect on FI modes and nonlinear Fluxes. Further studies ongoing.



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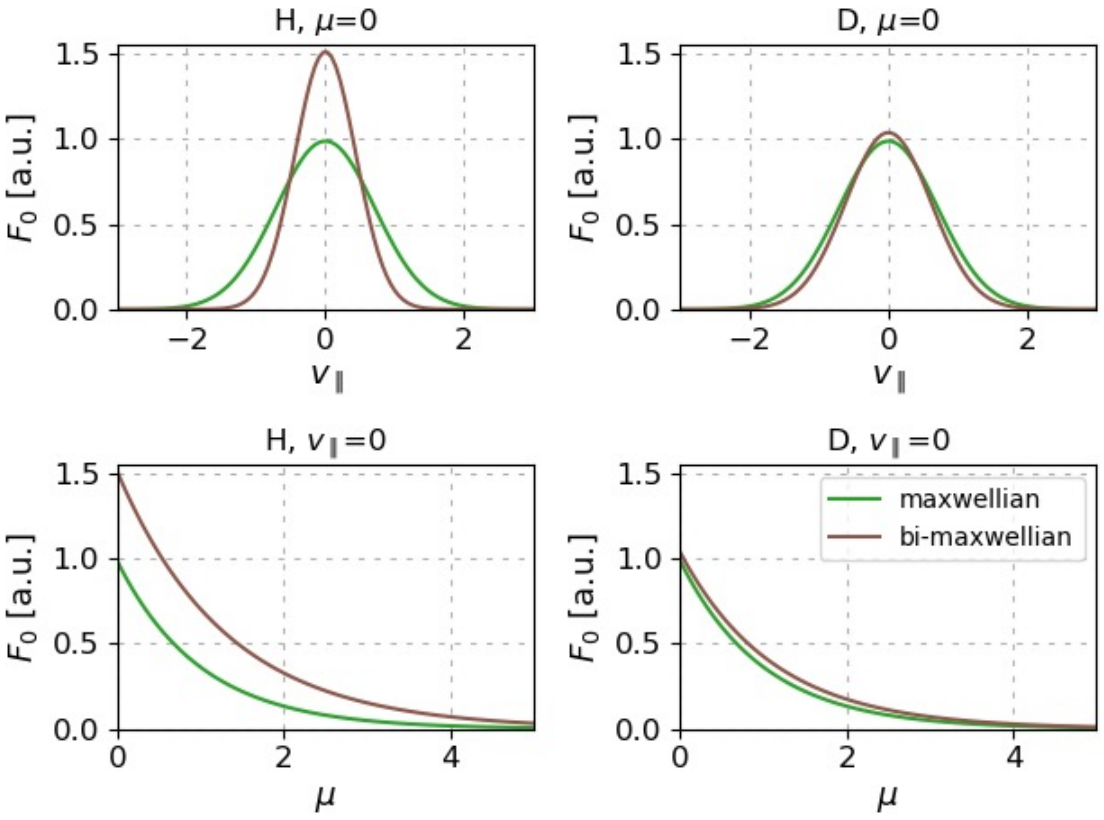
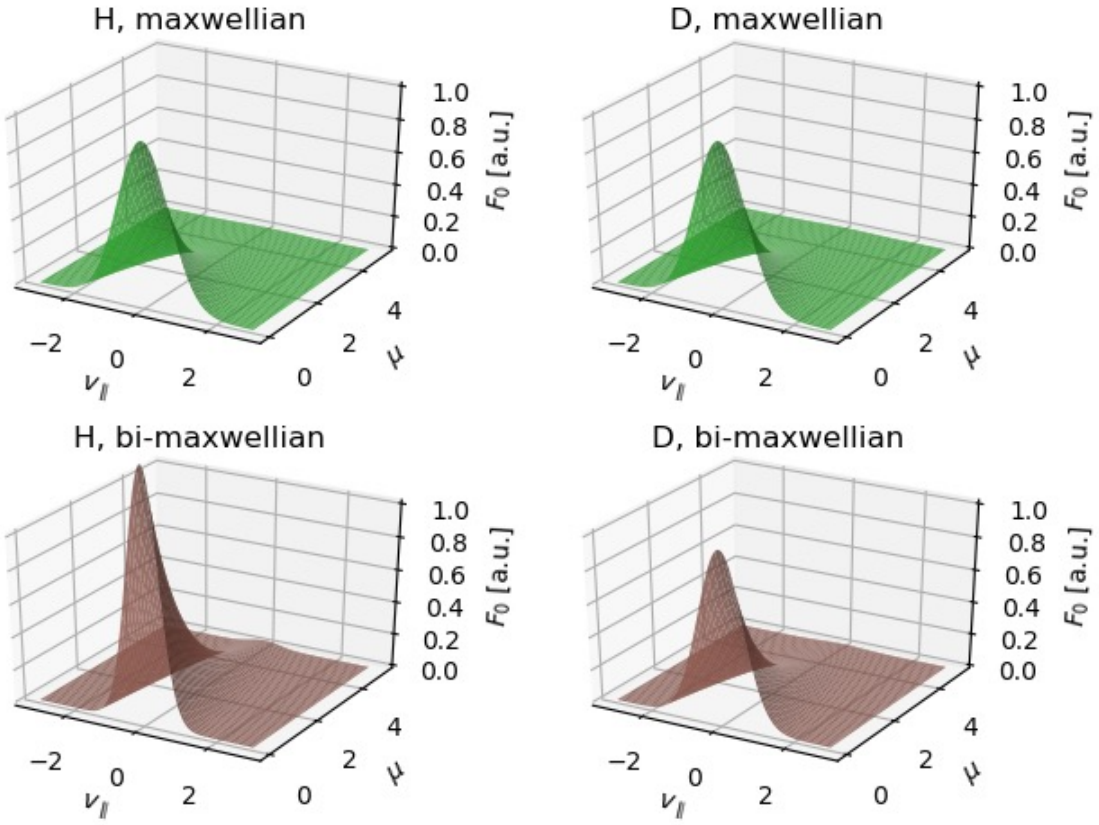
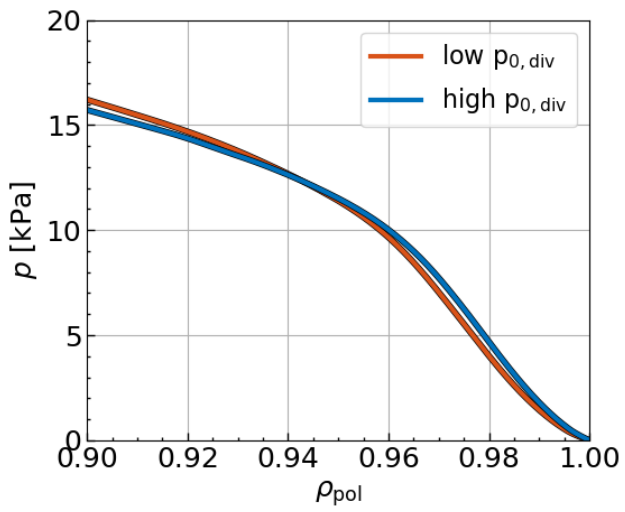




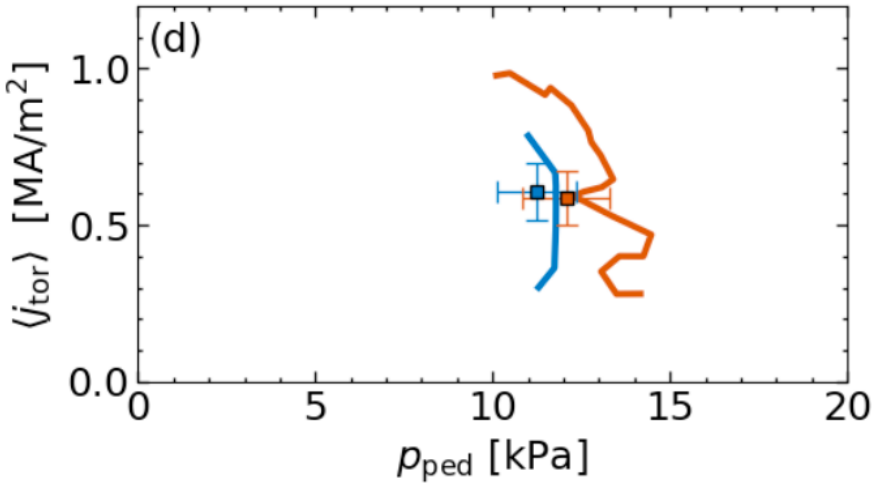
Confinement changes consistent with peeling-ballooning stability calculations

- Engineer discharges with intentionally varying divertor neutral pressure (high, low) and feedback-controlled NBI heating to maintain a target β



- Analyse linear MHD stability by scanning adjacent parameter space using MISHKA

[Silvagni NF 2022, to be submitted]



➢ **At lower $p_{0,\mathrm{div}}$:**
stability boundary moves to higher p_{ped}