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Predict-first integrated modeling of WEST long pulse operation with combined ECRH/ECCD and LHCD

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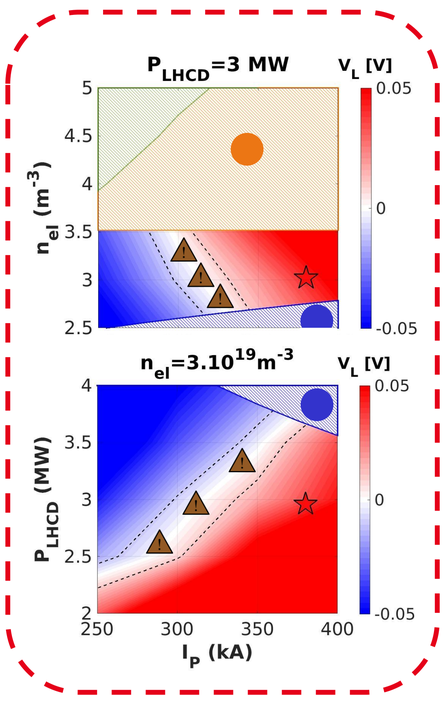
The WEST long pulse operational domain is highly constrained

- **WEST** can operate **20+ min long pulses** in a full-W environment ► Large non-inductive current provided by Lower–Hybrid Current Drive (**LHCD**) *[Bucalossi, NF, 2026]*
- These long pulses were designed based on **predict-first integrated modeling** (Fig.) *[Fonghetti, NF, 2025]* ► **non-inductive operational domain** (Fig.) **constrained by**:

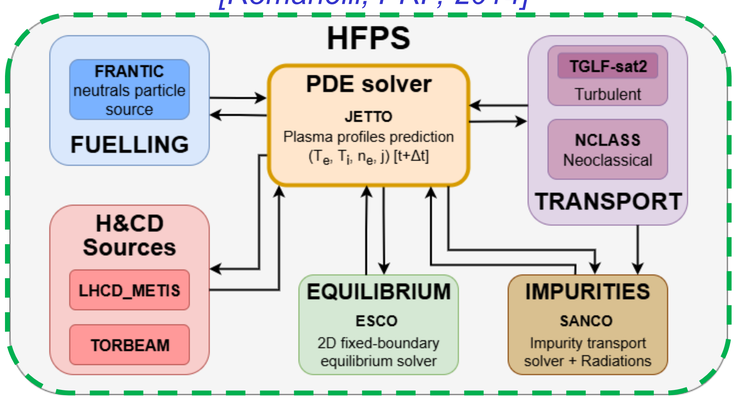
- **Radiative collapses** at high density ► core radiation exceeds heating
- Core q-profile reversal at low V_{loop} ► **tearing mode instabilities** ► disruption
- LHCD-induced **suprathermal electron losses** ► overheating and safety limits

A New **3 MW/1000 s** Electron Cyclotron Resonance Heating **(ECRH)** is being installed *[Delpech, FED, 2025]*

How can ECRH and integrated modelling help investigate routes towards higher performance long pulses?



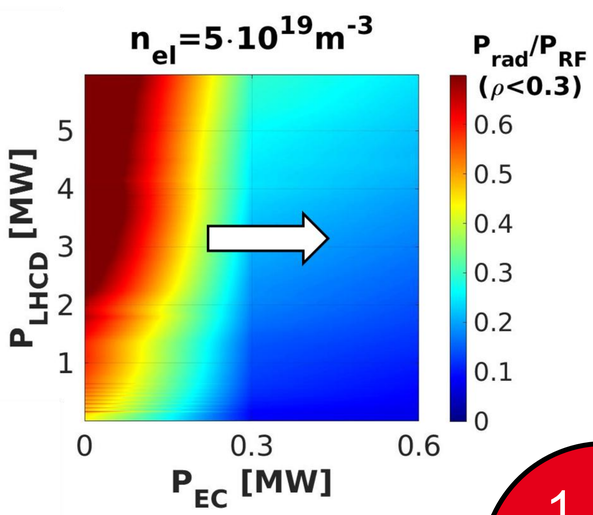
[Romanelli, PRP, 2014]



- Target n_{el} ► feedback-controlled **neutral gas puffing**
- **Sawtooth** crashes from Kadomtsev reconnection *[Kadomtsev, JPP, 1975]*
- P_{rad} **fixed** from initial reconstruction profile, rescaled to maintain f_{rad}**=50%, N content adjusted with** Z_{eff}
- Multi-machine scaling for **LHCD efficiency** validated on WEST discharges *[Fonghetti, NF, 2025]*

Improve core power balance ► radiative collapses

- Core W radiations dominate over LHCD heating at high density with LHCD-only *[Morales, NF, 2025; Ostuni, NF, 2022]*
- Injecting **on-axis ECRH** helps **burning-through W**
- **Enables high-density operation ►** n & T_i ↑↑

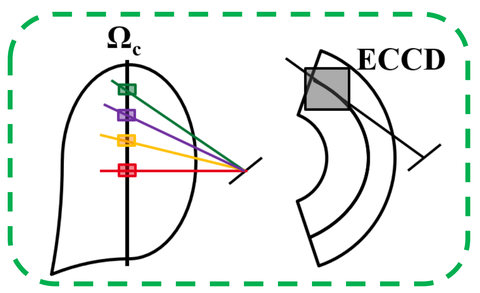


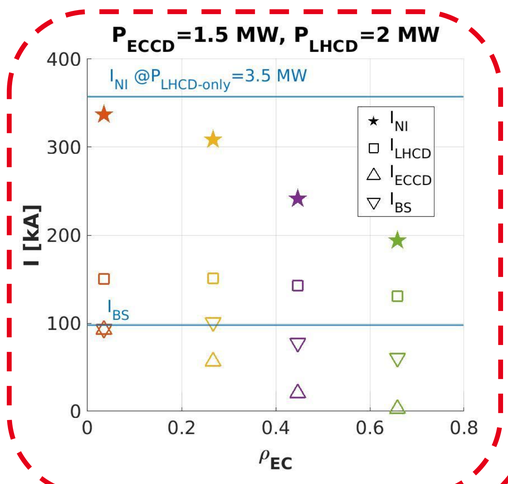
Maintain large non-inductive current

4 EC configurations ► toroidal angle optimized for CD, poloidal angle scanned (Fig) ► compared to LHCD-only at P_{TOT}=3.5 MW

Similar non-inductive current than LHCD-only configuration with **on-axis ECCD** (Fig.):

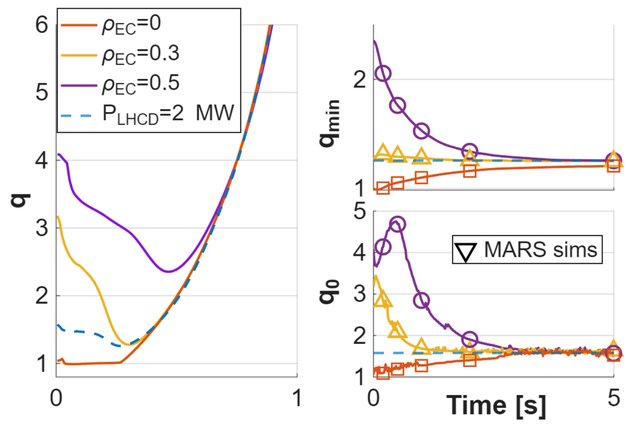
- $I_{ECCD} \propto T_e(\rho_{EC})$ ► Te larger on-axis
- $I_{BS} \propto \nabla_r p$ ► larger with on-axis ECCD





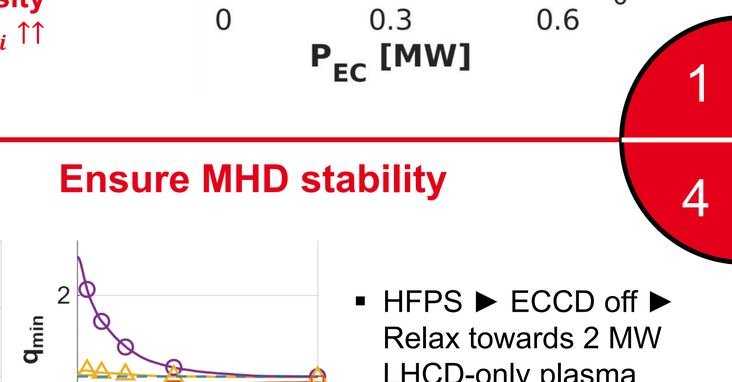
1 2 4 3

Ensure MHD stability



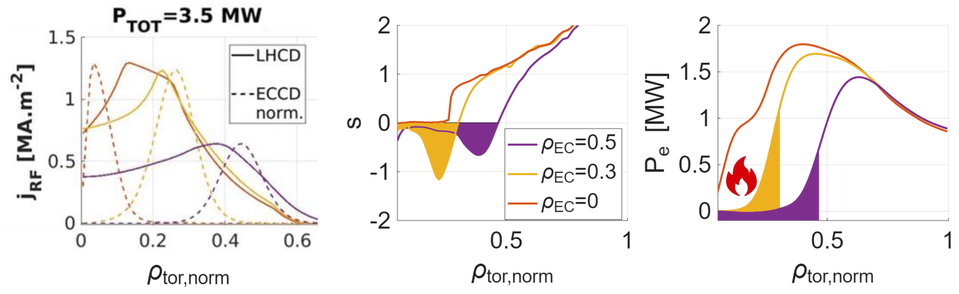
- HFPS ► ECCD off ► Relax towards 2 MW LHCD-only plasma conditions *[Bondeson, PF, 1992]*
- MARS linear resistive MHD modeling along the relaxation

- Stability conditions identified ► away from q reversal
- Trajectory up to the stable configuration must be stable

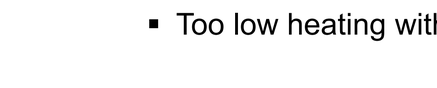


From P_{LHCD} = 2 MW up to P_{TOT} = 3.5 MW, adding ECCD, the only stable configuration all along is the on-axis ECCD

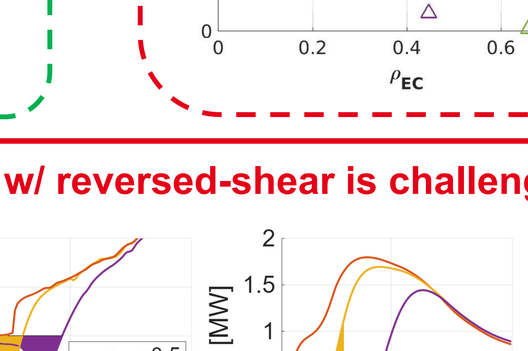
Improving confinement w/ reversed-shear is challenging



- ECCD steers LHCD *[Choi, APS, 2024]* ► q-profile tailoring ► Reversed-shear (s<0) ► stabilize turbulence
- Too low heating within s<0 region ► Add on-axis ECRH on top ?



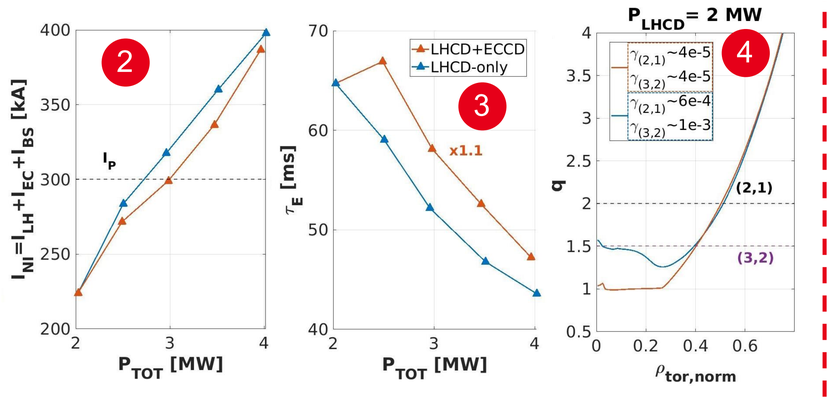
Off-axis ECCD + on-axis ECRH ► No improvement



Core increased bootstrap current ► q-profile reorganisation ► lost reduced turbulence ► **path to improved regime requires ECCD optimization**

On-axis ECCD

1. Core heat source ► potential **high-density operation**
2. **Similar non-inductive current ►** I_{BS} ↑, $\eta_{EC} \propto T_e$
3. **10% higher** τ_E even though limited by Sawtooth
4. From likely unstable q-reversed configuration to stable monotonous q-profile down to 1



Perspectives

- **Commission & exploit ECRH/ECCD.** Optimize LHCD/ECCD power sharing and **quantify** operational gains toward **higher performance long pulses**.
- **Improve model fidelity & robustness.** Couple core & edge, upgrade RF modeling, build reduced models for LH–EC synergy
- **Make predict-first the default.** Towards ITER-like machines, **standardize predict-first** so models get **validated**