RF power experiments in WEST to prepare for next-step fusion device operation

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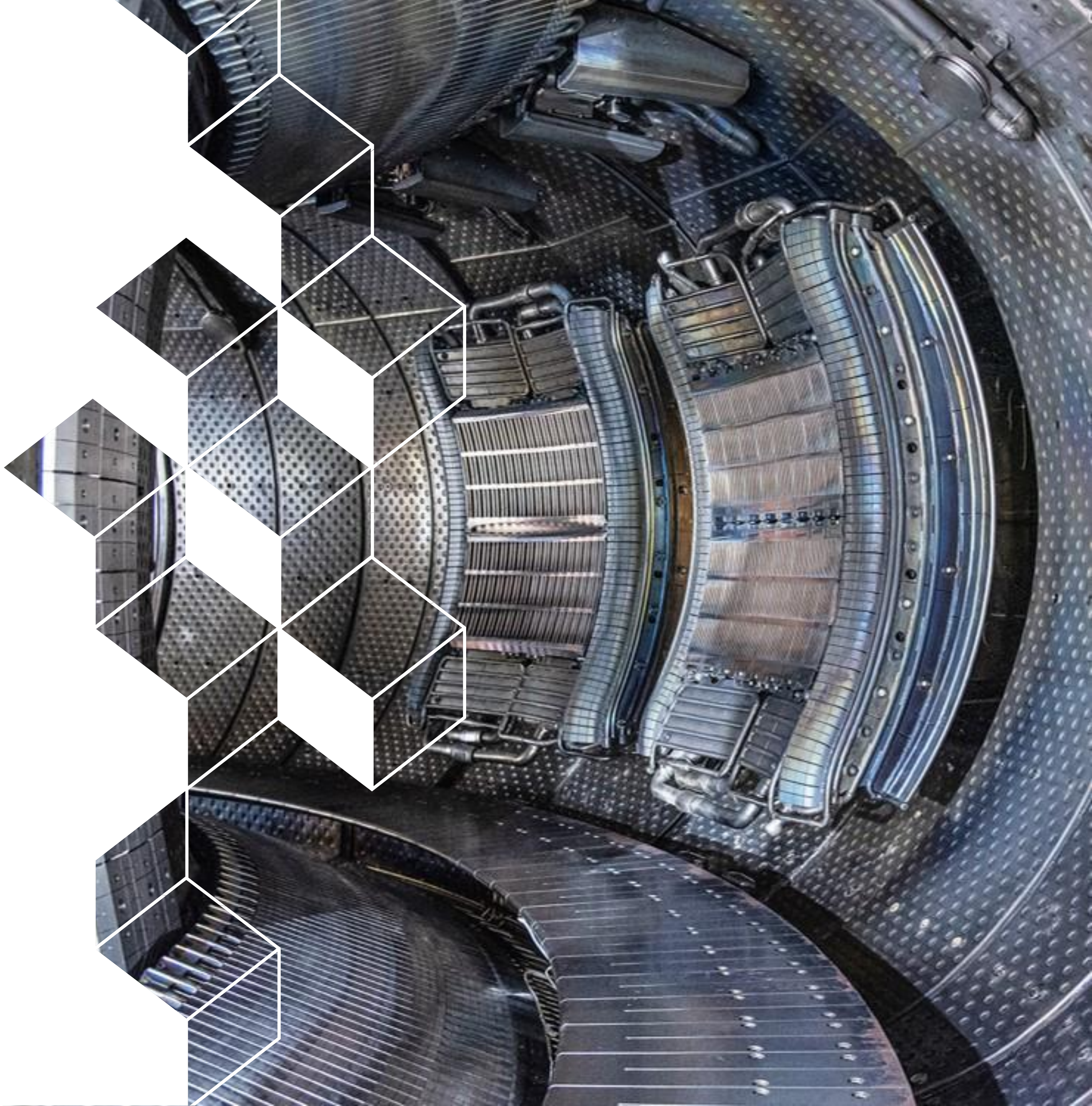
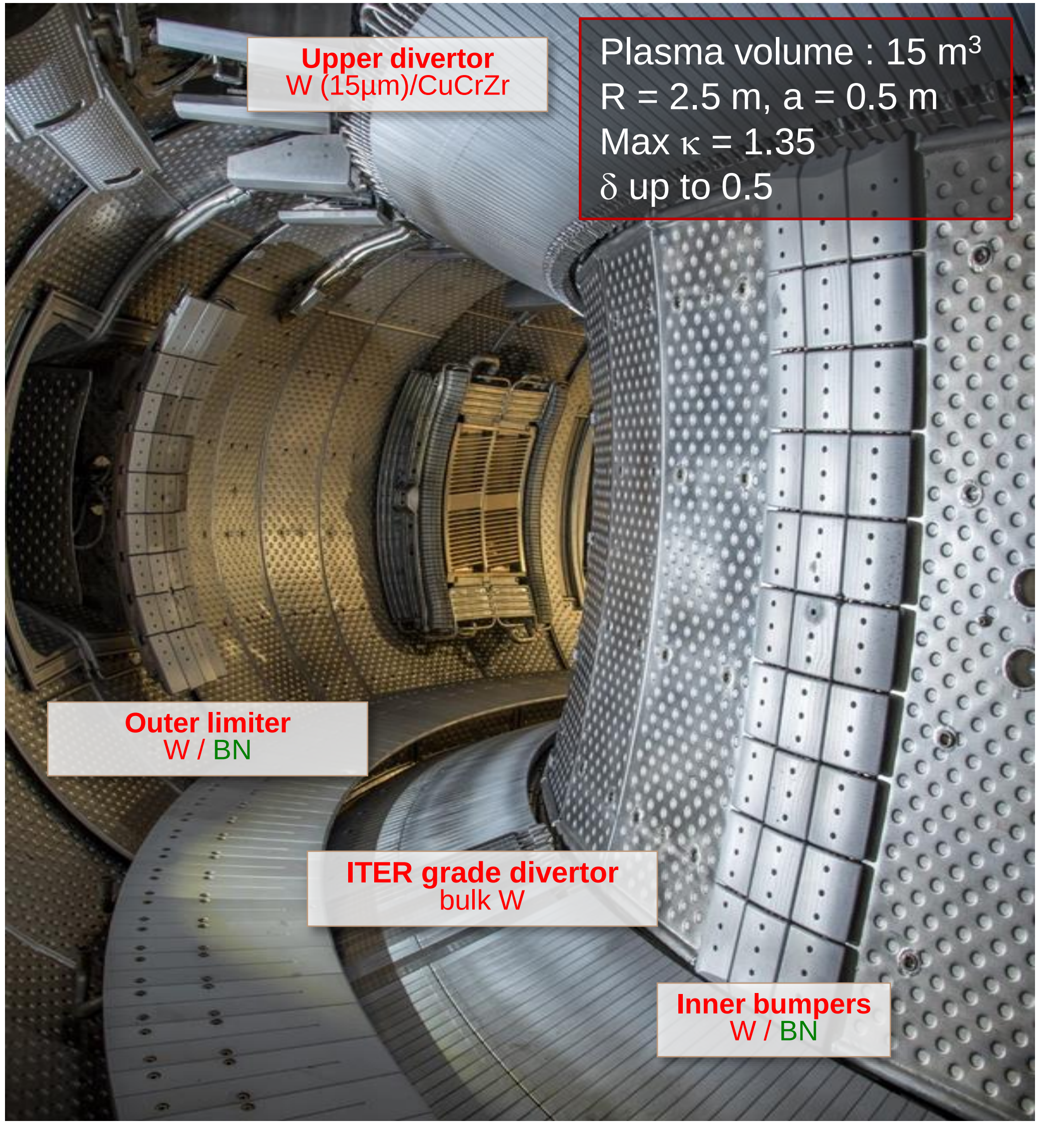


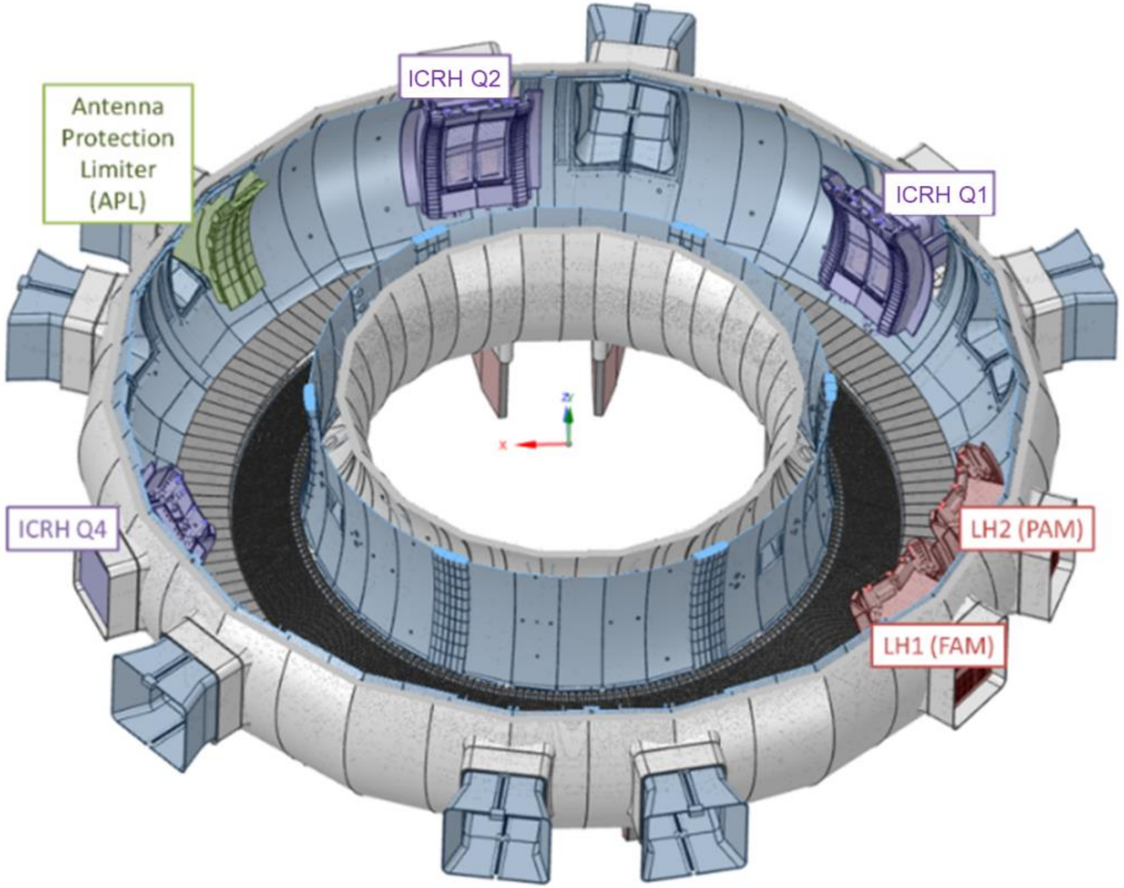
WEST: a testbed for tungsten-related aspects of next-step device preparation

- **Tungsten environment**
  - Actively cooled ITER-grade tungsten divertor
  - Inner / outer bumpers
    - W coated until mid-2020,
    - BN at mid-plane until spring 2024,
    - Bulk W from autumn 2024
- **Long Pulse capability**
  - Superconducting magnets, nominal field B_0~3.7T
  - Lower/Upper X-point, Double-Null configurations
  - Bespoke radiofrequency (RF) systems

[Bucalossi, NF 2024]



WEST auxiliary power is exclusively supplied by radiofrequency sources



- **WEST RF systems**
  - **LHCD:** non-inductive current drive
    - FAM launcher (4MW, $n_{//}$~2)
    - PAM launcher (3MW, $n_{//}$~1.7)
    - Frequency: 3.7 GHz
  - **ICRF:** bulk heating, energetic ion generation
    - 3 load-resilient (internal) conjugate-T antennas
    - 9MW/30s – 3MW/1000s
    - Usually D(H) minority scheme
    - Frequency: 48-63 MHz
  - **ECRH/CD:** bulk heating, non-inductive current drive
    - 1MW → 3MW, started operation in 2025 (1MW)
    - Frequency: 105 GHz

→ No torque injection (low rotation)

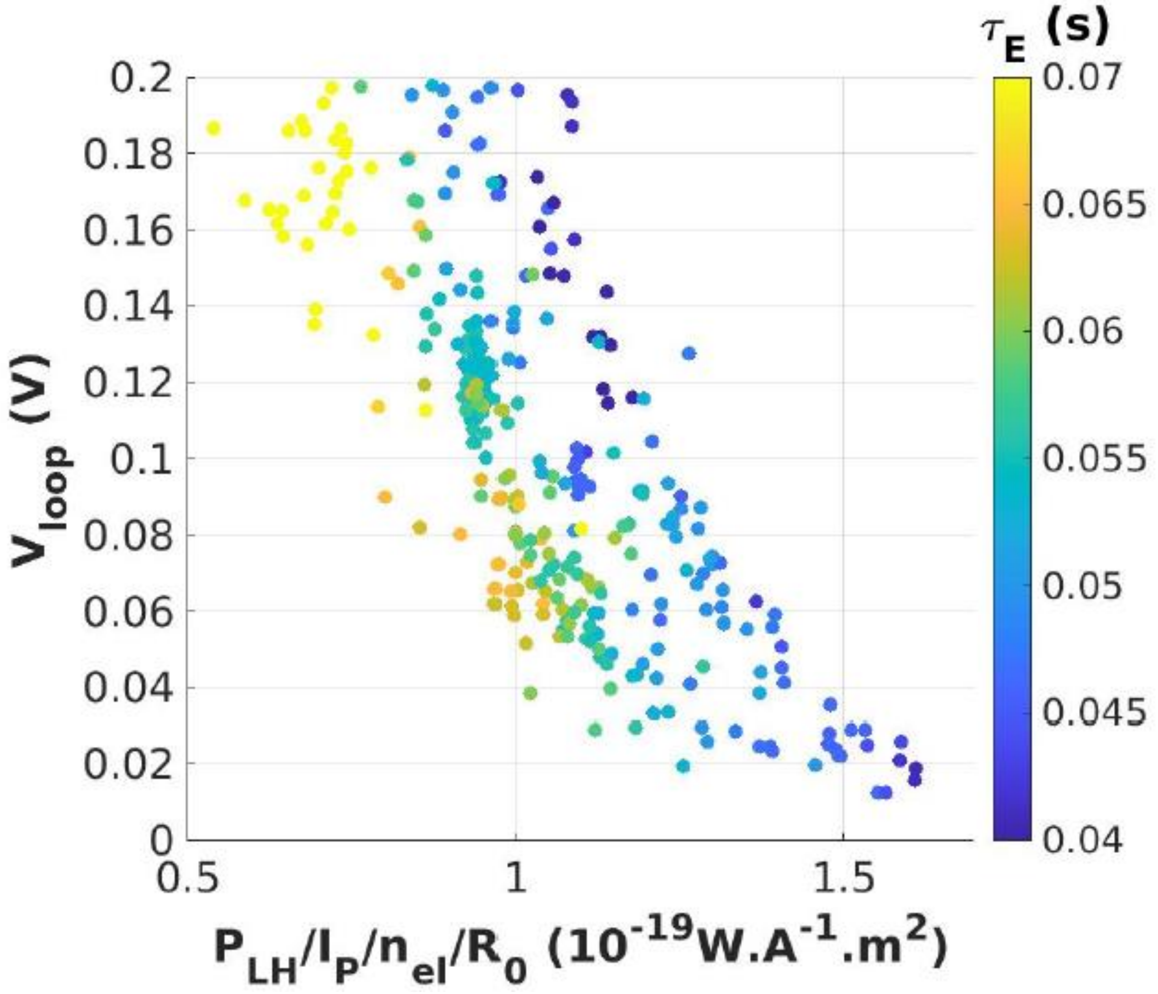
→ Electron heating dominant

Outline

1. **Long pulse scenarios based on LH power**
2. **Enhancing long pulse performance with RF power**

1. Long pulse scenarios based on LH power

LHCD physics determines key parameters for non-inductive current maximization



- Loop voltage drop when LH power is applied

$$-\frac{\Delta V}{V_\Omega} = f_{bs} + \eta_{LH} \frac{P_{LH}}{\bar{n}_e R I_p}$$

- LHCD efficiency (fit)

$$\eta_{LH} = 2.37 \times 10^{19} D^{0.3} Z_{eff}^{-0.12} \tau_E^{0.4}$$

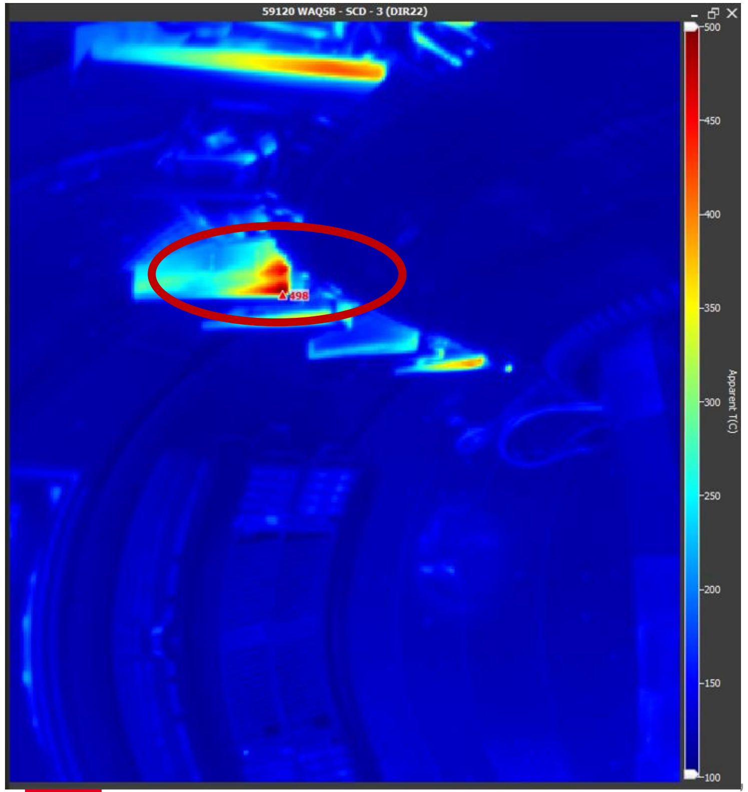
[Goniche, AIP proc. 2005]
[Fonghetti, NF 2025]

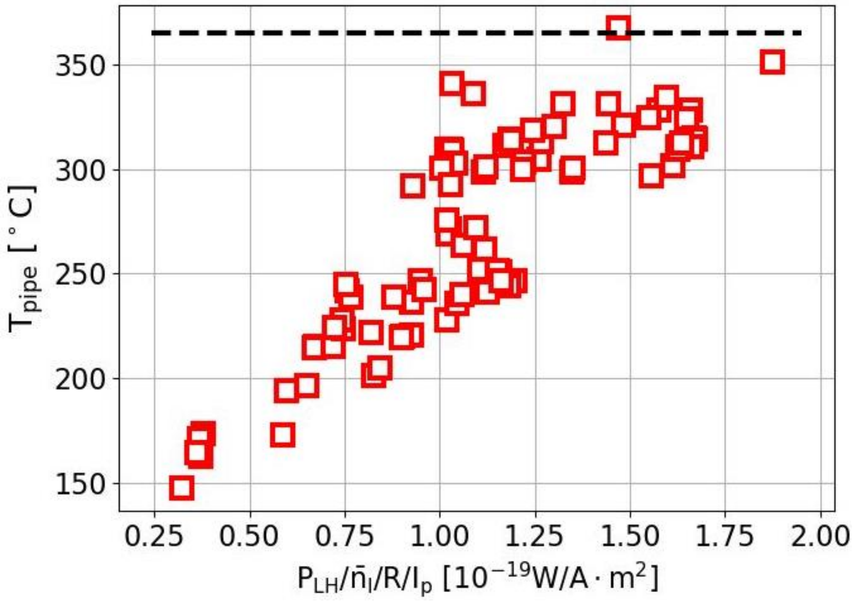
- Fraction of current driven by LH waves

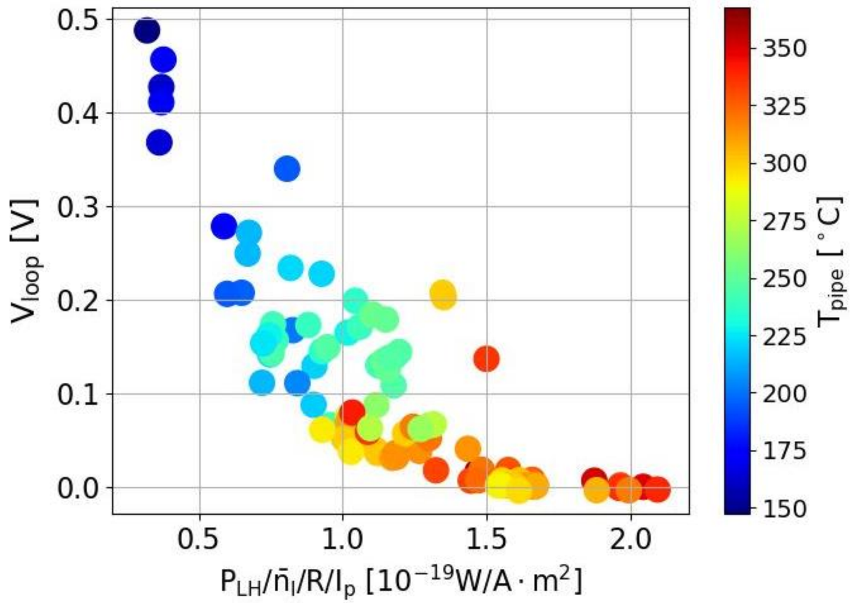
$$\frac{I_{LH}}{I_P} \propto \frac{P_{LH}}{\bar{n}_e R I_p} \tau_E^{0.4}$$

Overheating of in-vessel components restricts operational domain in the presence of LH-driven electrons

- Electron ripple protections installed in upper part of vacuum chamber with adapted cooling pipes, surveyed in real-time by IR first wall protection monitoring system
- WEST Operating Instructions: maximum apparent IR temperatures on upper pipes set to 365°C
- Found to follow known electron ripple loss dependences: $T_{pipe\ [°C]}=134+678\ P_{LH[MW]}^{1.07}\ I_{p[MA]}^{0.58}\ n_{l3[10^{19}m^{-2}]}^{-2.24}$

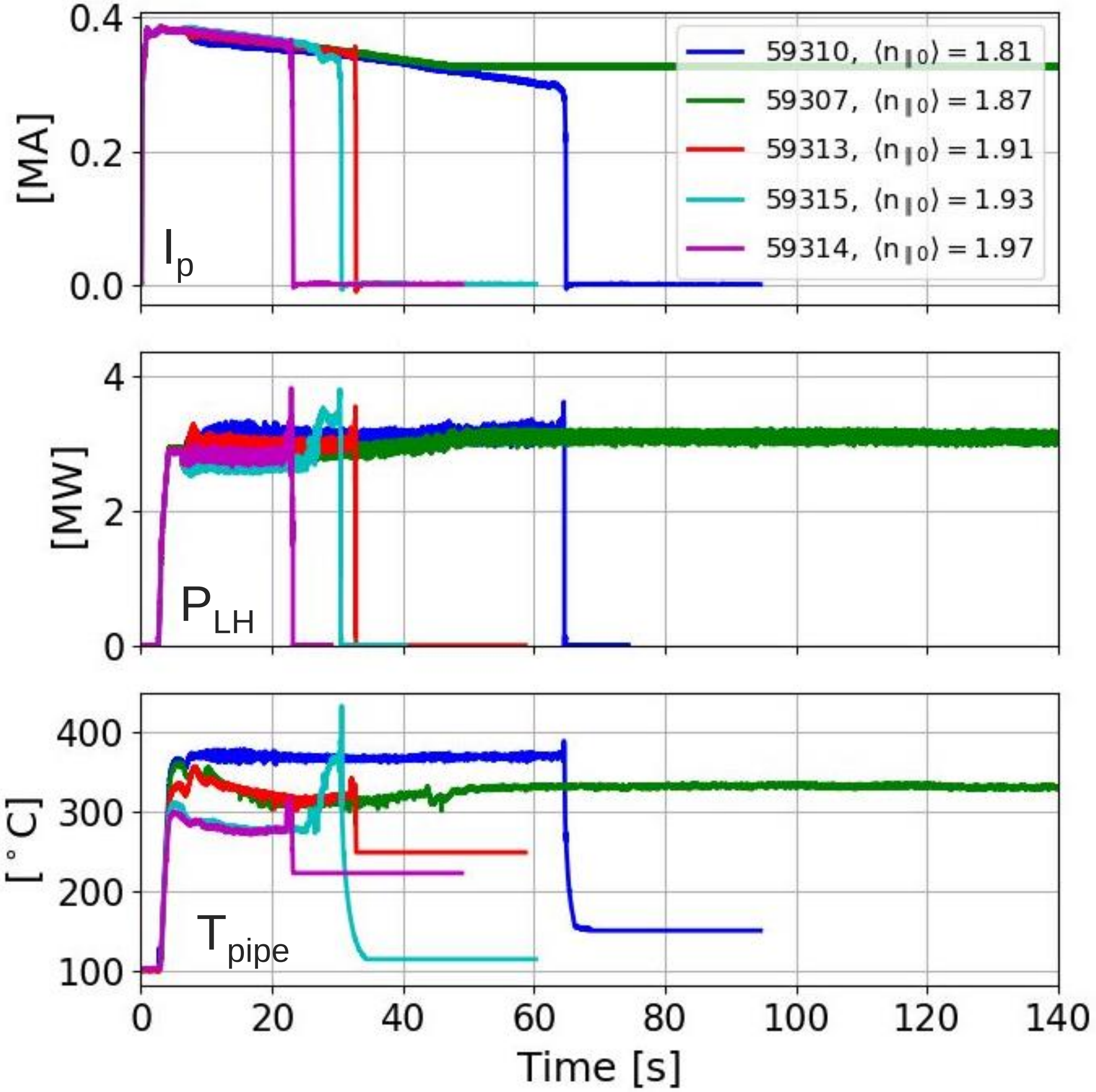






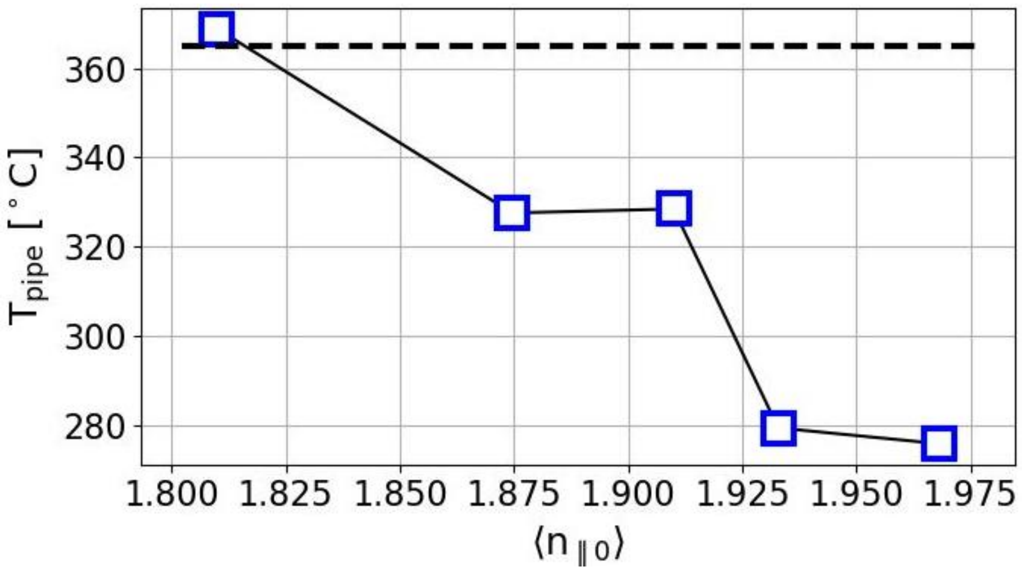
→ Strong constraints on non-inductive scenario development

Main LHCD actuator: toroidal phasing, plays a major role in Ip controlled discharges

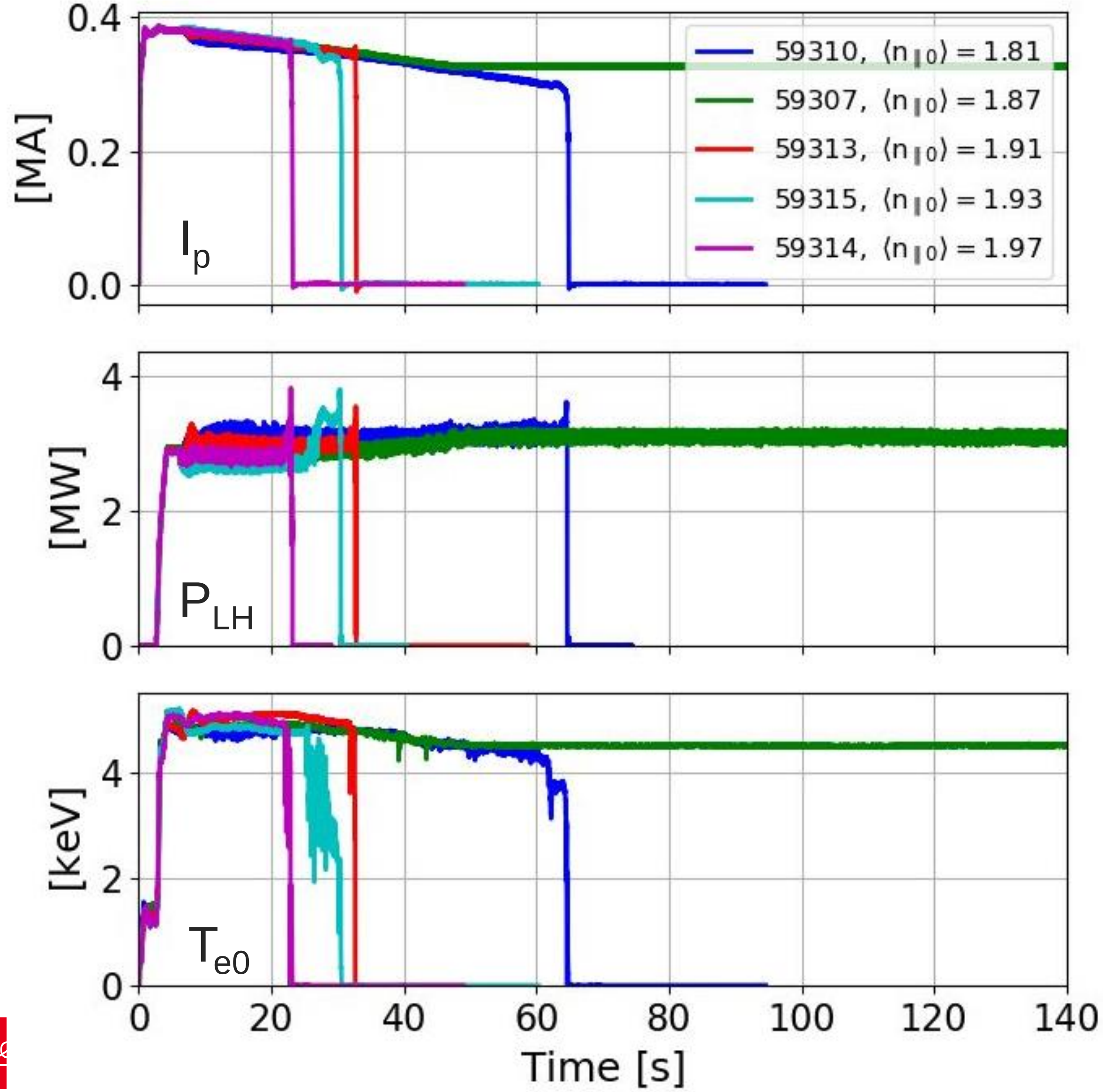


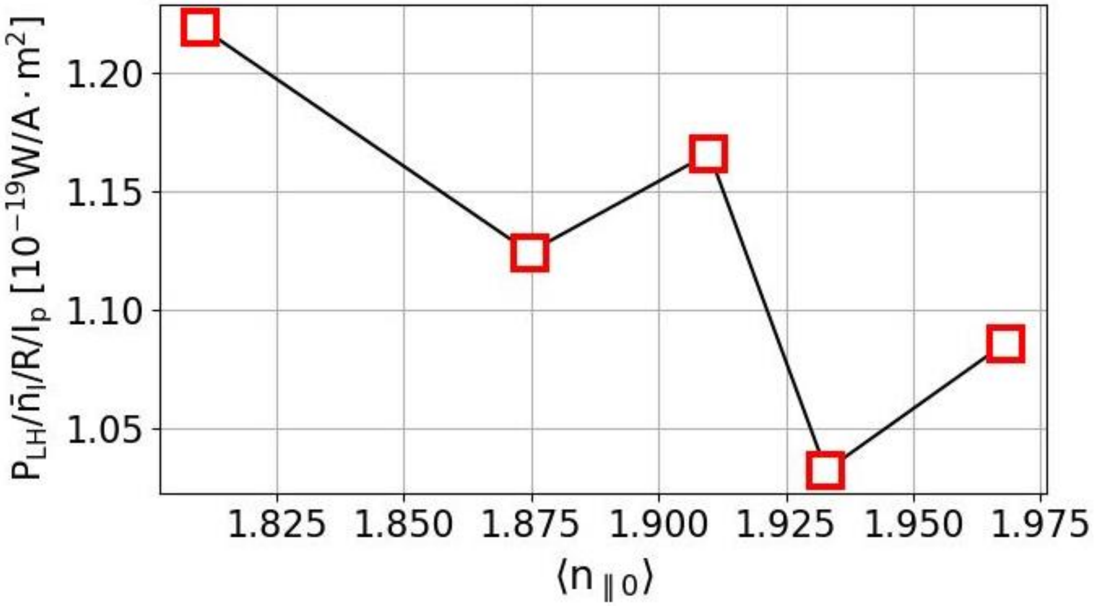
Peak $n_{//0}$		LH1		
		2.0	1.9	1.8
LH2	1.9	MHD	MHD	Untested
	1.8	MHD	Good	Pipe T°

- Disruption-inducing MHD instabilities triggered at low V_{loop} depending on toroidal phasing
- Clear effect on pipe temperature, consistent with LH-driven electron physics



Toroidal spectrum variations point towards complex non-linear discharge evolution



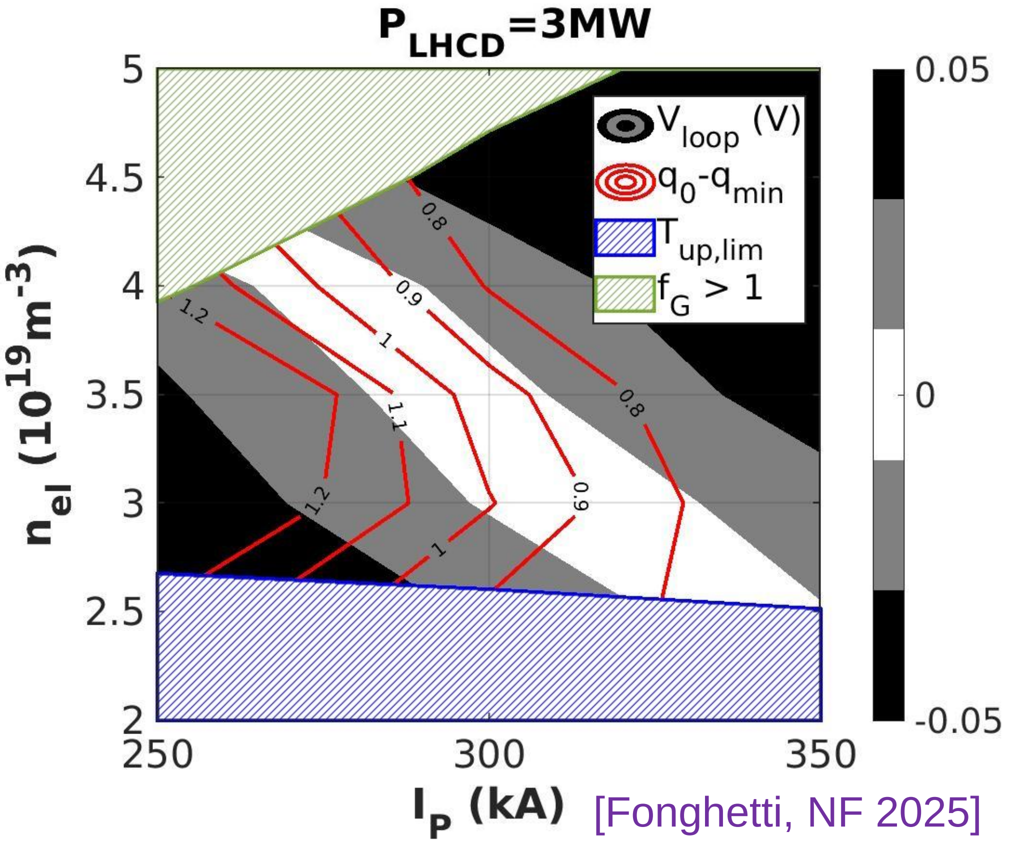


- Power required to sustain plasma current decreases with <$n_{//0}$>
- In apparent contradiction with current drive physics, which predicts LH efficiency proportional to $1/n_{//}^2$
- Strong influence of T_e profile, which results from
  - LH power/current source
  - Heat (and particle) transport

Pulse development requires description of heat source, transport, must include operational aspects

- High Fidelity Pulse Simulator (HFPS) based on JINTRAC/JETTO employed EUROfusion
  - Simplified model used for LHCD deposition profile [Dumont, PoP 2000], with experimental scaling law for current drive efficiency: $\eta_{LH} \alpha \tau_E^{0.4}$ [Goniche, AIP proc. 2005]
  - TGLF-sat2 model for turbulent transport [Staebler, PPCF 2020; Angioni, NF 2022]

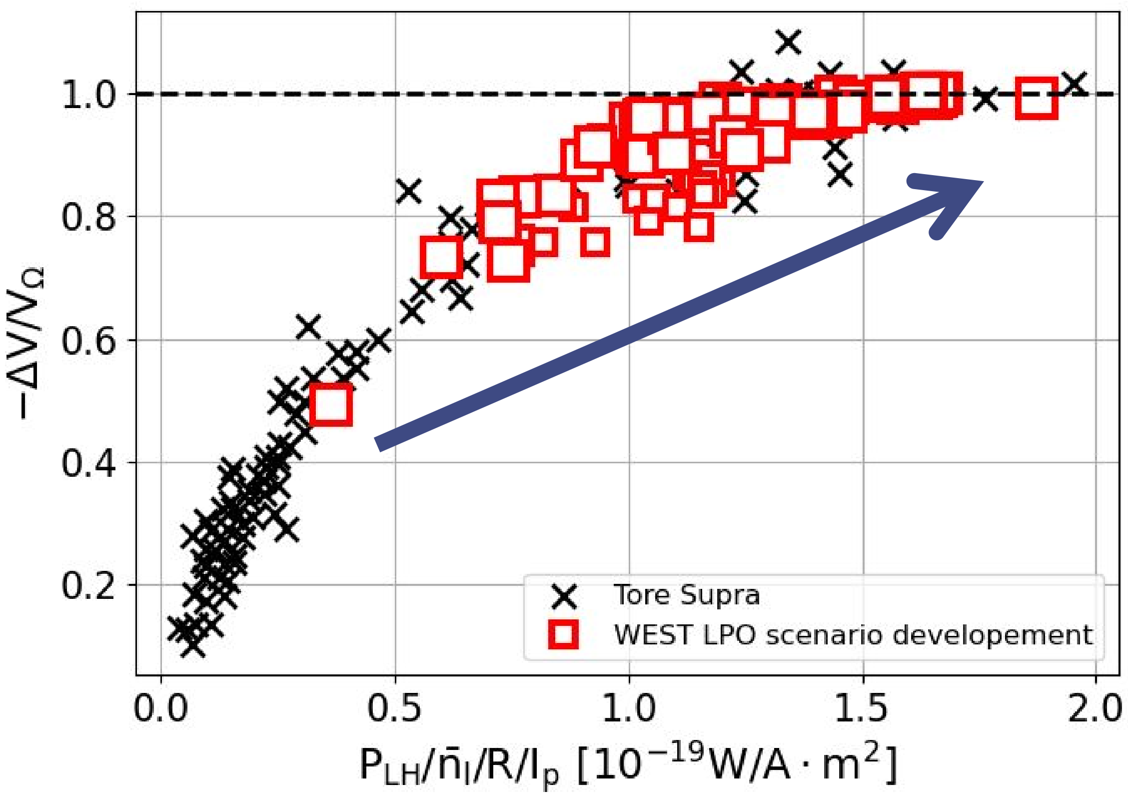
- Elements included, with strong impact on available parameter space:
  - Greenwald density limit
  - Upper cooling pipe temperature interlock
  - Occurrence of q-profile reversal minimized at lower P_{LH} and/or larger I_p

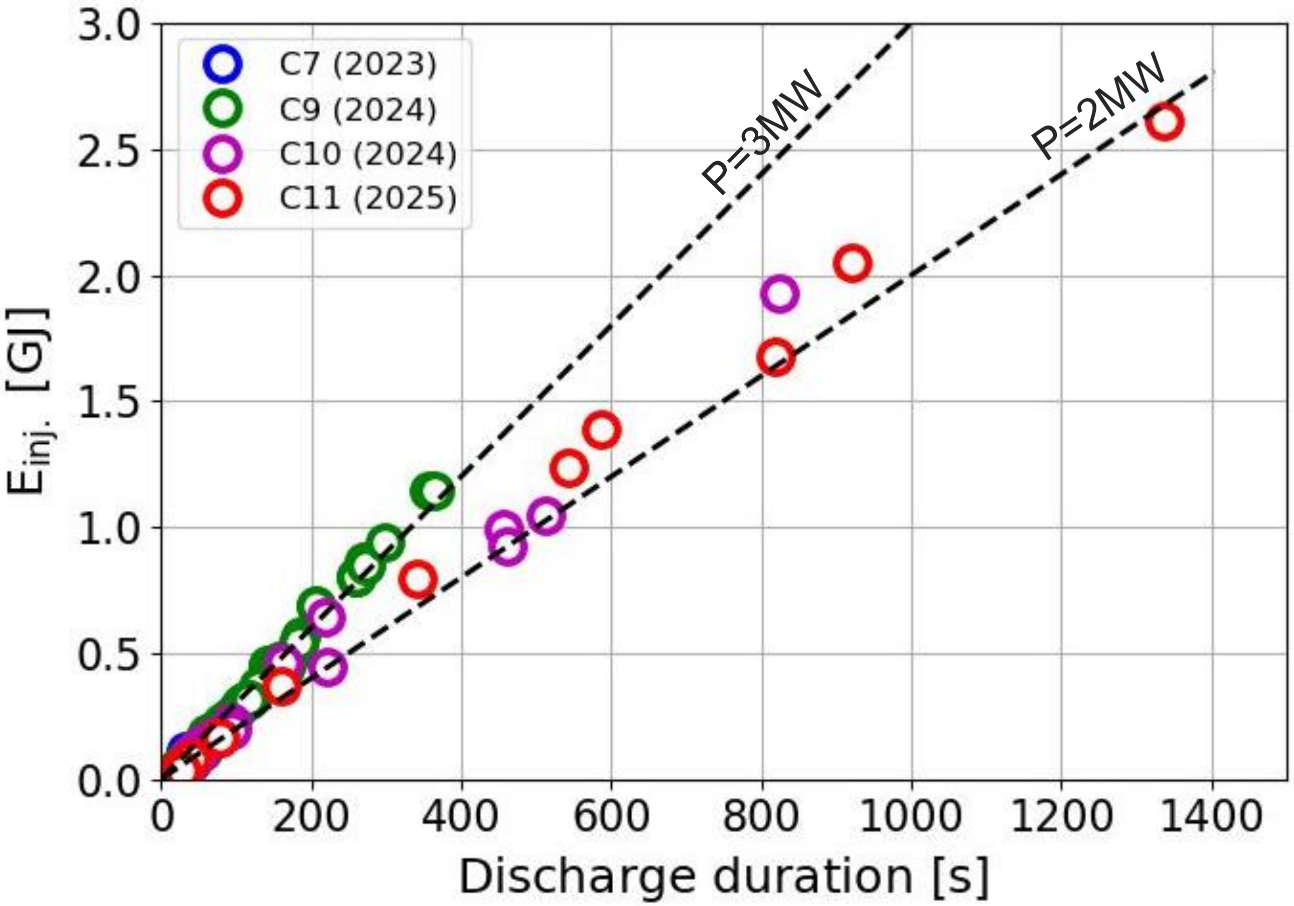


[Fonghetti, NF 2025]

A continuous progress in long pulse development, based on LH power since 2023

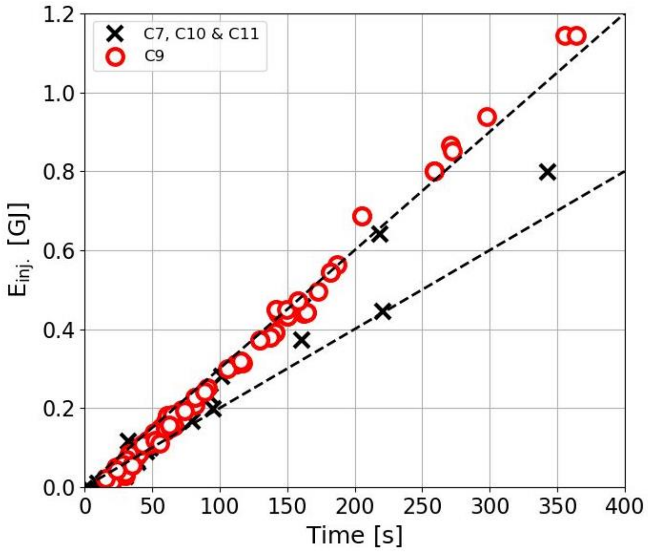
LHCD efficiency - C7 to C10

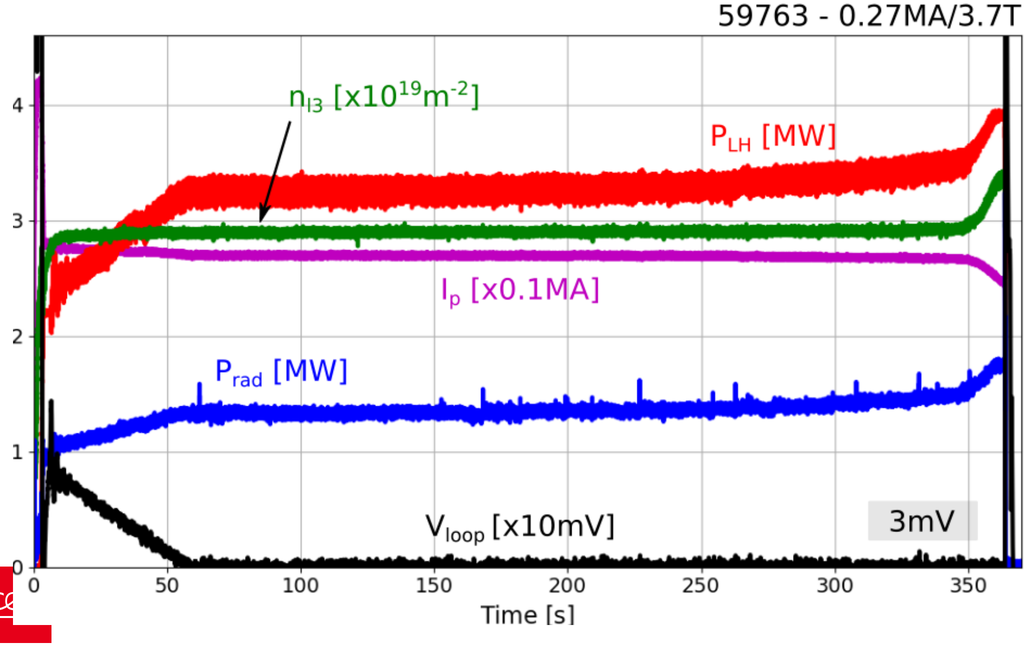




- Tore Supra LHCD efficiencies recovered, consistently with LUKE predicting no significant influence of W impurities on LHCD [Peysson, IAEA 2020]

Duration records achieved during C9 (2024)

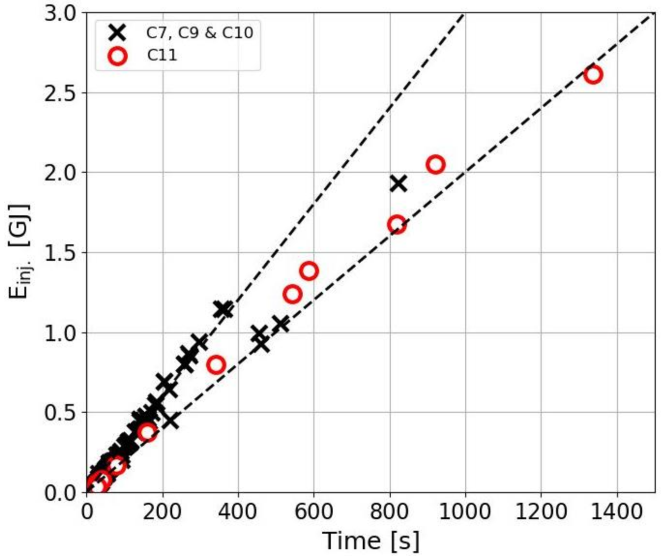


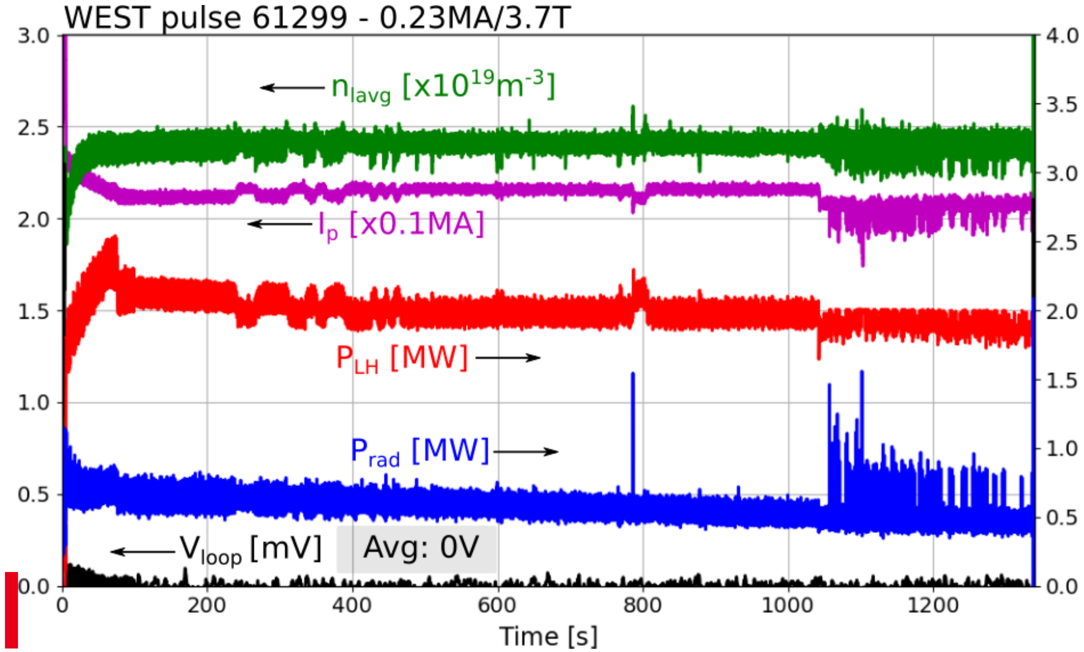


- **WEST pulse 59763**
  - **Duration: 364s**
  - **Energy injected/extracted: 1.15GJ**
    (Energy record of WEST **and** Tore Supra at the time)
  - Double feedback-control (V_{loop}, V_{G0}), (I_p, P_{LH})
  - Plasma current 0.27MA
  - LH power ~3-3.5MW
  - Loop voltage: 3mV → could in principle last >1100s
  - $H_{98,y2}$~1, β_p~2, β_N~0.8
  - No particular issue related to tungsten accumulation
  - Increase of density at ~300s, caused by outgassing of remote elements in vacuum vessel
    → I_p could not be maintained despite increase of LH power by feedback control system

[Dumont, APS 2024]

Duration records during C11 (2025)

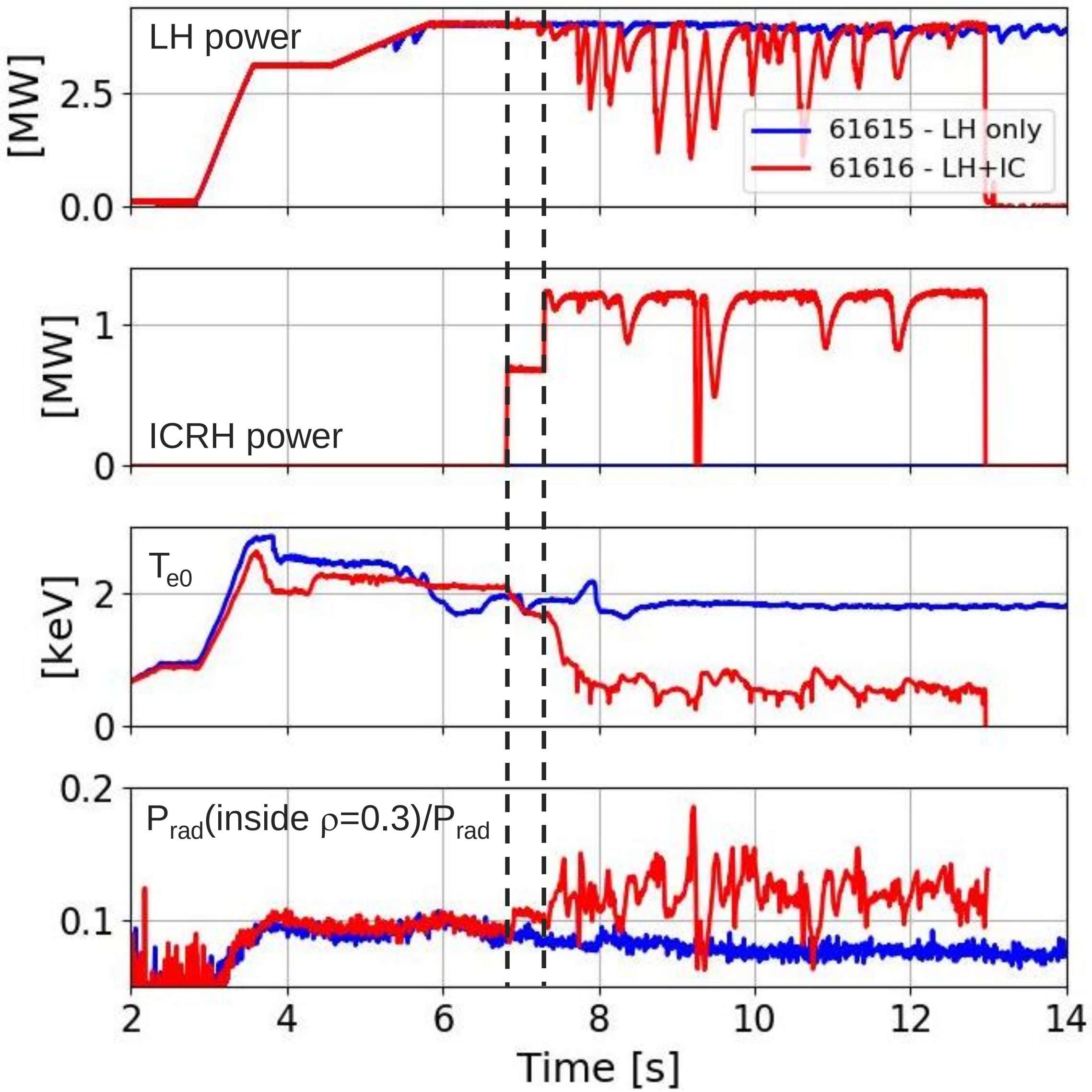




- **WEST pulse 61299**
  - **Duration: 1337s**
  - **Energy injected/extracted: 2.61GJ**
    (Current duration/energy record of WEST **and** Tore Supra)
  - Double feedback-control (V_{loop}, V_{G0}), (I_p, P_{LH})
  - Plasma current 0.23MA
  - LH power ~2MW. LH FAM coupler only (other long-duration pulses with both couplers)
  - Loop voltage: 0mV → fully non-inductive
  - $H_{98,y2}$~0.9, β_p~1.6, β_N~0.6
  - Mild MHD activity present during whole duration, degrading confinement
  - Quite resilient to external perturbations
  - Performed in H_2 and D_2 gases → isotopic effect under study

2. Enhancing long pulse performance with RF power

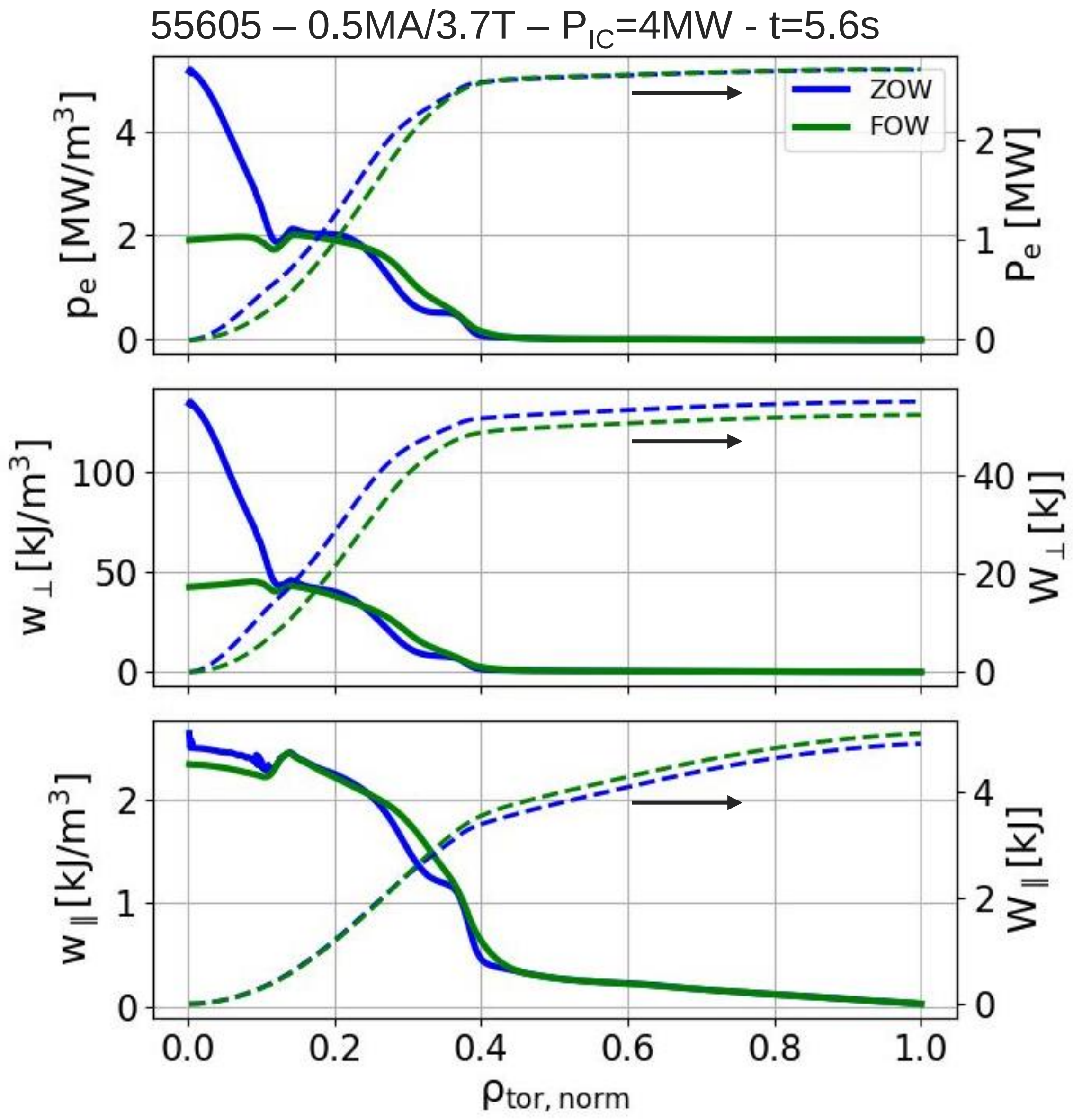
Adding ICRH power in LH-dominated long pulses often induces radiative collapses



- The application of ICRF power on LH-dominated plasmas
  - Makes LH coupling more difficult
  - Often triggers sudden drops of T_{e0}
- Similar to radiative collapses sometimes observed in ICRH pulses. Chain of events:
  - Increase of power radiated in the plasma core, not compensated by electron heating from ICRH → drop of T_{e0} [Maget, PPCF 2023]
  - Outward displacement of LH driven current as a result [Ostuni, NF 2022]
  - Current profiles becomes hollower and eventually triggers MHD instabilities
- ICRF-driven energetic ions expected to impact W accumulation
  - Poloidal asymmetry + induced rotation → W peaking
  - Core electron heating → balance radiated power

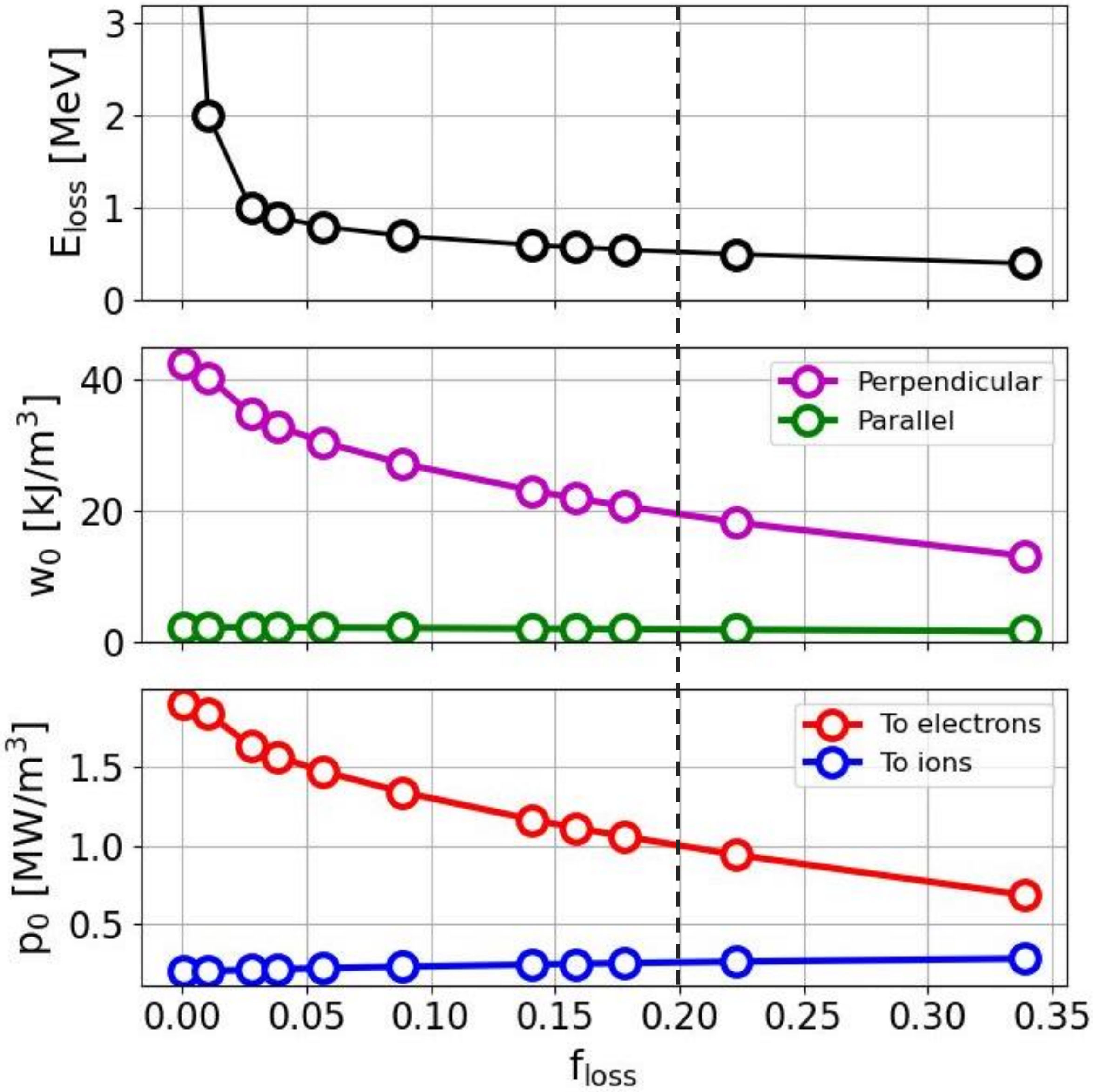
→ RF simulations required

Energetic ion calculations in medium size devices must retain finite orbit width effects

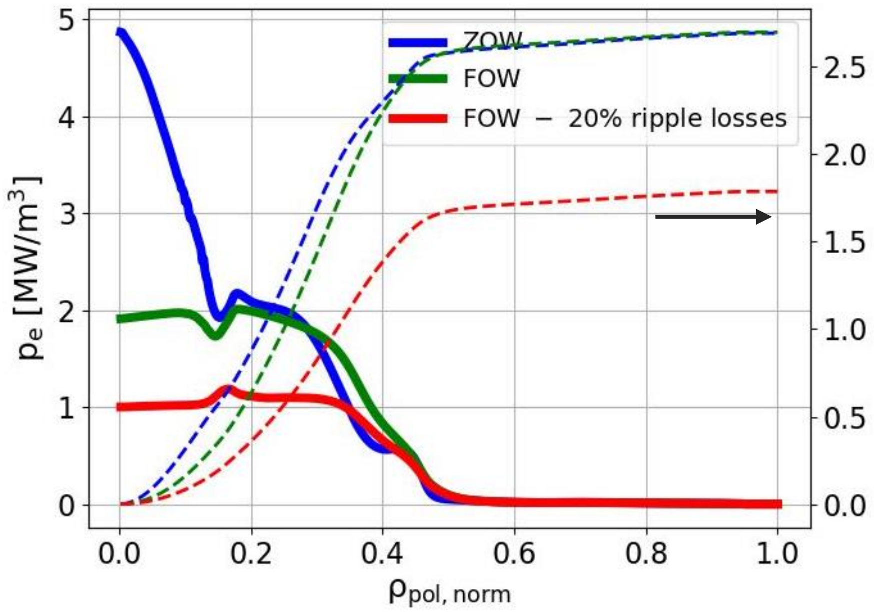


- Numerical study of ICRH-only pulse 55605, which collapses at t~5.6s [Maget, PPCF 2023]
- Zero-orbit width (ZOW) calculations with EVE/AQL [Dumont, NF 2013] yield central power source on electrons very peaked, and significantly larger than radiated power → should prevent radiative collapse
- A surrogate model is designed to enlarge the ICRH power source profile based on averaged potato/banana widths
- Finite orbit width (FOW) compared to ZOW solution
  - Total energetic ion energy content only slightly changed
  - Core perpendicular energy significantly reduced → electron heating reduced
  - Also: anisotropy profile less peaked → weaker ICRH drive for tungsten peaking
- Still predicts power source on electrons approximately 4 times larger than central radiation (~0.5MW/m^3)

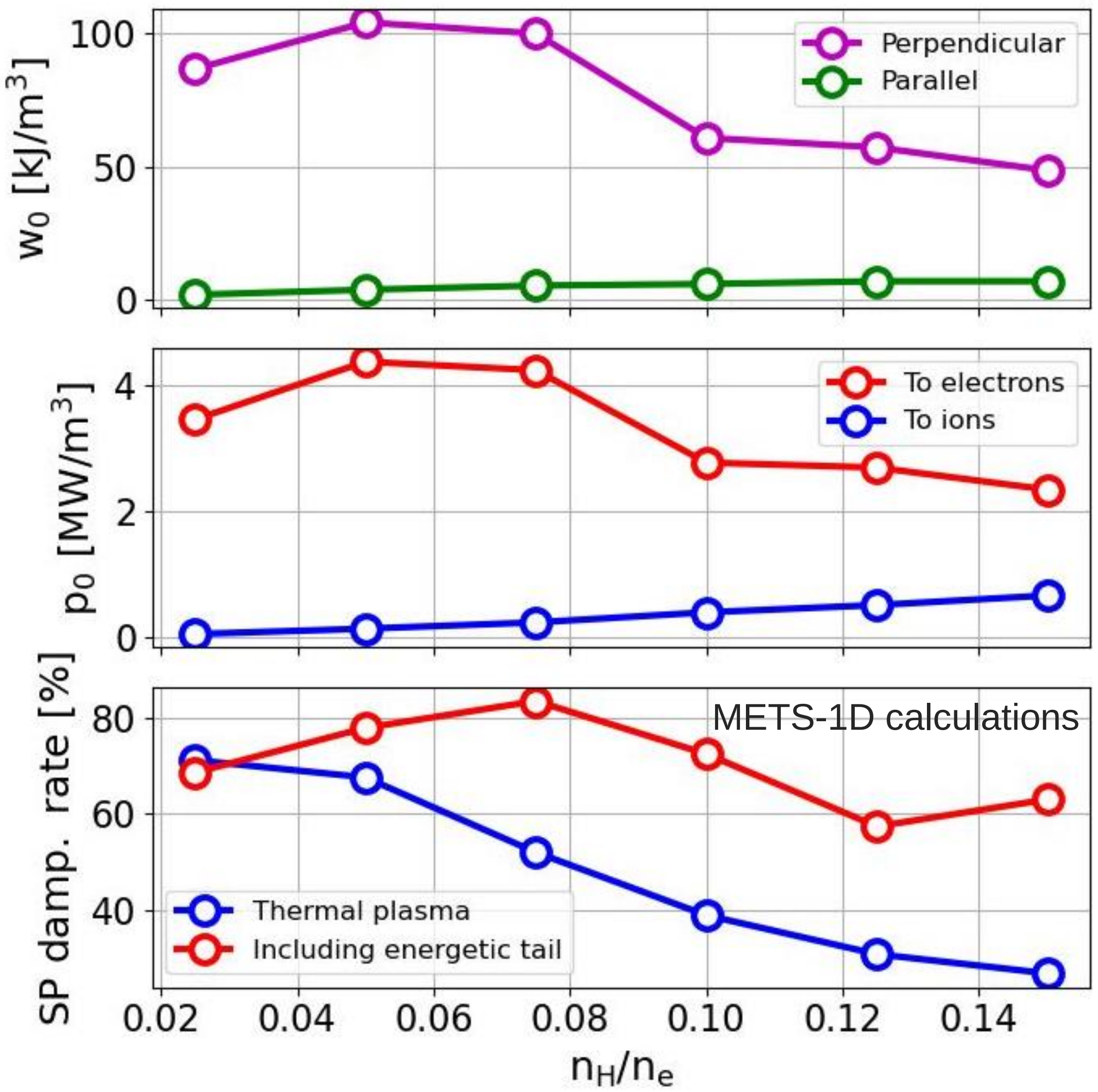
Ripple losses of ICRF-driven ions



- Ripple losses estimated to be about 20% of the coupled ICRH power at collapse time in this discharge
  - Power loss fraction increases ~linearly with ICRH power (as in Tore Supra) [Moiraf, NF 2023]
  - Ripple losses modelled by truncating H distribution function over a given energy in EVE/AQL [also: Ph. Huynh, in preparation]
- Loss of fast H impacts power deposited on electrons
  - Losing 20% of the ICRH power induces a reduction by 50% of the power from minorities to electrons → compatible with estimated electron heating deficit (incl. ICRF-induced rotation)

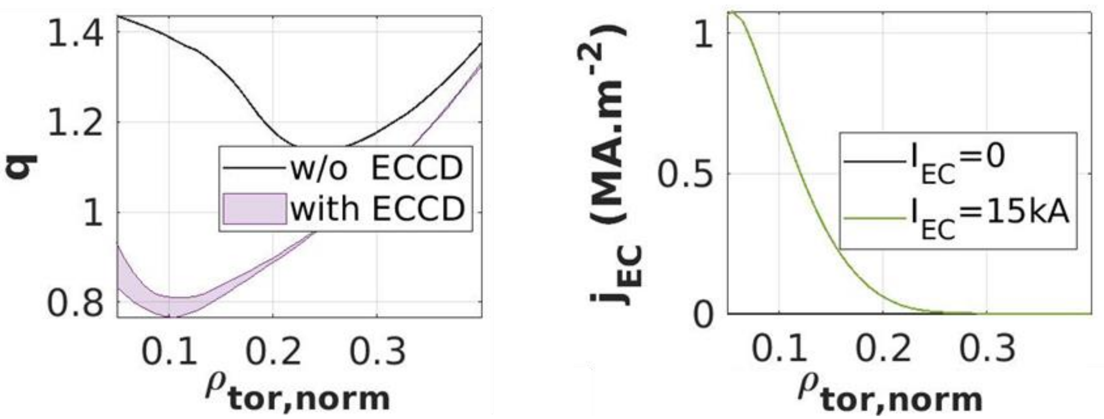


Improving ICRF operation in WEST non-inductive discharges

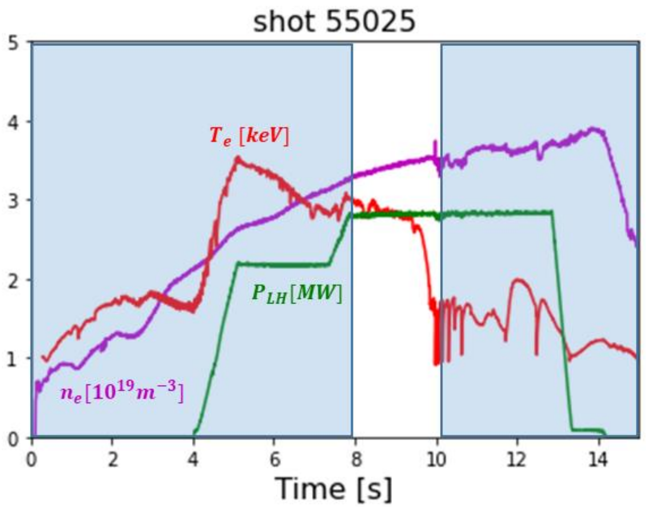


- Energetic ions must supply central power to electrons but very energetic tails result in large ripple losses
- Increasing current/density has been shown to be efficient, but difficult to reconcile with non-inductive scenario requirements
- Increasing minority concentration induces global weakening of energetic ion tail
  - Decrease of central electron heating, but only limited (critical energy E_c~20keV for these conditions in WEST)
  - Must still ensure good single-pass damping rate → should not exceed ~15%
  - → optimization experiments ongoing
    [S. Mazzi, E. Lerche et al., ICRF optimization]
- Future Toroidal Wave Array (TWA) antenna expected to provide more flexibility (spectrum, poloidal phasing…)
  [J. Hillairet, this conference] [L. Kassem Hijazi, this conference]

EC power to enlarge parameter space, help increase performance in non-inductive regimes



HFPS simulation of central ECCD to control q-profile reversal [Fonghetti, NF 2025]



Radiative collapse in a LHCD-only pulse, caused by combination of W radiation and off-axis LH power deposition [Ostuni, NF 2022]

- EC power available in next WEST: 1MW in 2025 → 3MW
- Applications to long-duration pulses
  - Central ECCD to control q-profile reversal [Fonghetti, NF 2025], improve overall CD efficiency → possibility to control current profile, operate at larger densities
  - Central ECRH against radiative collapses observed as density increased [Ostuni, NF 2022] or ICRF power applied [Maget, PPCF 2023]
    - Counterbalances central radiation in unstable range of electron temperatures (T_e~1.5-3keV)
    - Opens the possibility to use ICRF power, beneficial for MHD stability when V_{loop}~0 [Dumont, PPCF 2014]
    - “Anchors” LH deposition profile to plasma core [e.g., in EAST: Du, NF 2018; Li, NF 2023]
- H-mode access
- MHD control
- …

Summary and prospects

- **LHCD power: the workhorse of non-inductive operation in WEST**
  - High sensitivity of I_p-controlled discharges to injected power spectrum
  - Complex interplay between heat/particle transport / RF source requires advanced integrated modelling
  - Pulses at ~280kA/3MW LHCD display good confinement, with outgassing issues (conditioning over time) – **Up to 364s/1.15GJ**
  - Pulses at ~230kA/2MW LHCD
    - Good confinement when both FAM/PAM LH couplers used simultaneously – **Up to 824s/1.93GJ**
    - Degraded confinement with FAM launcher only (mild MHD throughout pulses) – **Up to 1337s/2.91GJ**
  - Topic not addressed in this presentation: superthermal electron transport studies [J. Cazabonne, this conference]
- **ICRH usage requires careful optimization when used in conjunction with LH power**
  - Simultaneous coupling challenging (as was the case in Tore Supra, even more so in W environments)
  - Must prevent too energetic ion tails from developing at low densities/currents, whilst ensuring adequate core electron heating
  - TWA expected an improvement over current conjugate-T antennas [J. Hillairet, this conference] [L. Kassem Hijazi, this conference]
  - Topics not addressed in this presentation:
    - RF sheath effects and code validation [R. Diab, this conference] [L. Colas, this conference]
    - Argon pumpout experiments [C. Perks, this conference]
    - Ongoing ITER-relevant experiments: ICWC and IC-assisted breakdown [E. Lerche, J. Hillairet]
- **EC power to enlarge parameter space, help increase performance in non-inductive regimes**
  - Central ECCD to control q-profile reversal, central ECRH against radiative collapses
  - H-mode access