Advances in Understanding Quiescent H-Mode Plasmas in DIII–D

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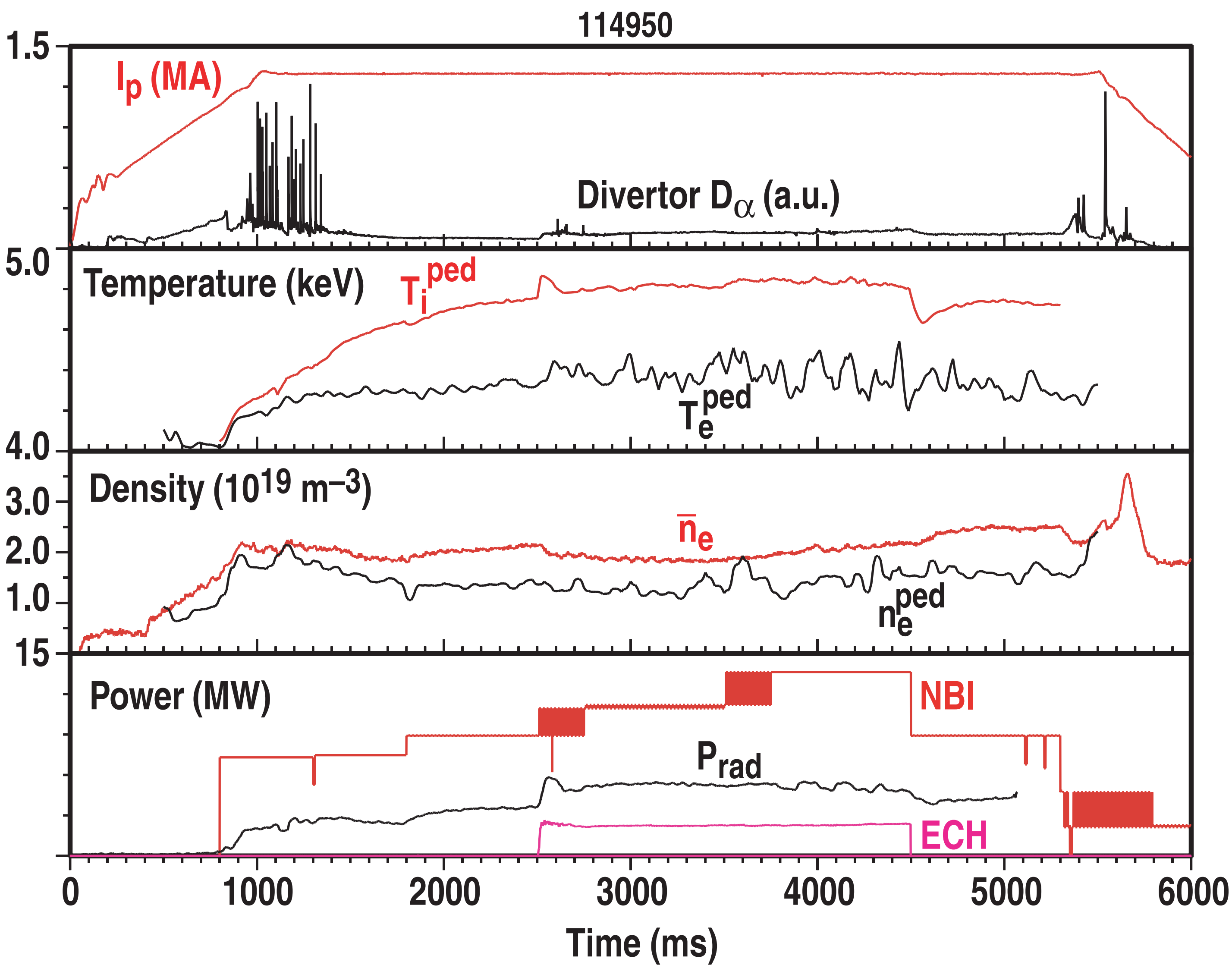
QUIESCENT H–MODES ARE THE IDEAL H–MODE PLASMAS

- Quiescent H–modes (QH–mode) exhibit the H–mode confinement improvement $H_{ITER\text{-}89P} \cong 2$
  - Constant density and radiated power
  - Long duration (>4 s or 30 τ_E, 2τ_R) limited only by hardware constraints
- QH–modes remain free of edge localized modes (ELMs) at all input powers from 3 MW up to those needed to reach the core beta limit (~15 MW)
- No ELMs means no pulsed divertor heat loads
  - Quite important for next-step devices such as ITER
- Quiescent edge is compatible with core transport barriers
- In order to utilize the advantages of QH–mode in future devices, the goals of our research are to
  - Improve our physics understanding of the QH–mode
  - Broaden the QH–mode operating space using scans suggested by MHD stability theory

QUIESCENT H–MODE RUNS ELM–FREE FOR LONG PULSES WITH CONSTANT DENSITY AND RADIATED POWER

- Duration limited by neutral beam pulse length



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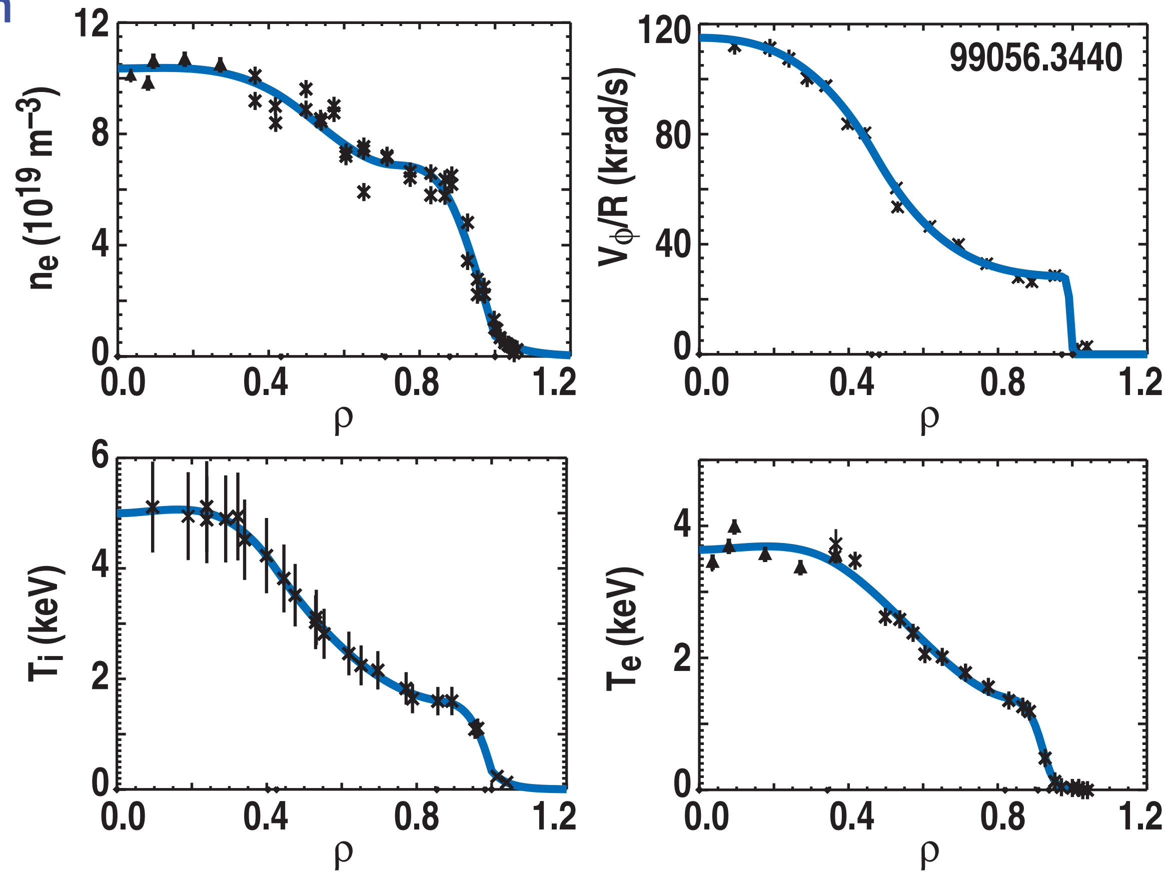
QUIESCENT H–MODE HAS BEEN SEEN OVER A RANGE OF PARAMETERS

- Requires neutral beam injection counter to I_p direction plus divertor cryopumping
- QH–mode seen to date for
  - $3.1 \leq q_{95} \leq 5.8$
  - $1.0 \leq I_p\ (\mathrm{MA}) \leq 2.0$
  - $1.8 \leq B_T\ (\mathrm{T}) \leq 2.1$
  - $1.0 \leq n_e^{ped}\ (10^{19}\ \mathrm{m}^{-3}) \leq 6.5$
- Low field example at $B_T = 0.95$ T, $I_p = 0.67$ MA and $n_e^{ped} = 1.1 \times 10^{19}\ \mathrm{m}^{-3}$

High Density QH–Mode

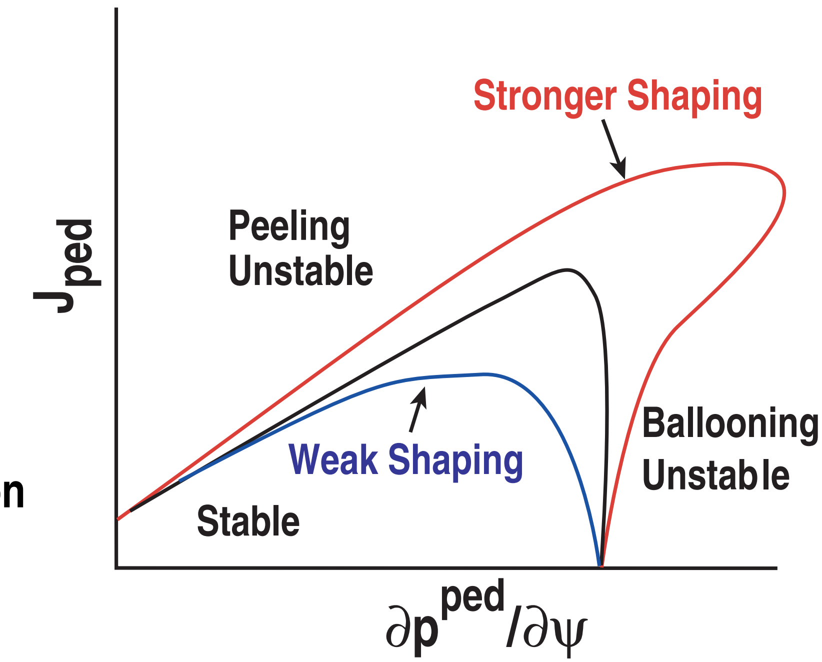


KEY QUESTIONS FOR QUIESCENT H–MODE

- **Why do the ELMs go away? What is the stabilization mechanism?**
  - Peeling/ballooning mode theory explains some of the observations
  - Edge rotation or radial electric field effects play a role
- **What is the role of edge electromagnetic oscillations such as the edge harmonic oscillation (EHO)?**
  - Enhanced particle transport relative to that in ELMing phase
- **Does QH–mode extrapolate well to future devices?**
  - Obtained pedestal β and ν^* values bracketing the ITER design values
  - QH–mode seen over a range of ρ^* in DIII-D, ASDEX-U, JET, and JT-60U

EDGE PEELING-BALLONING THEORY PROVIDES A GOOD WORKING HYPOTHESIS FOR ELM STABILITY IN QH–MODE

- Diagram shows simplified overview of theory
- Stable region expands markedly with plasma shaping
  - — Weak shaping is circular cross section
  - — Stronger shaping is modest triangularity, elongated, single null divertor
  - — High triangularity double null divertor (not shown) has even broader stable region
- First question is: Where does QH–mode lie in this operating space?



P.B. Snyder et al. Phys. Plasmas 9, 2037 (2002)

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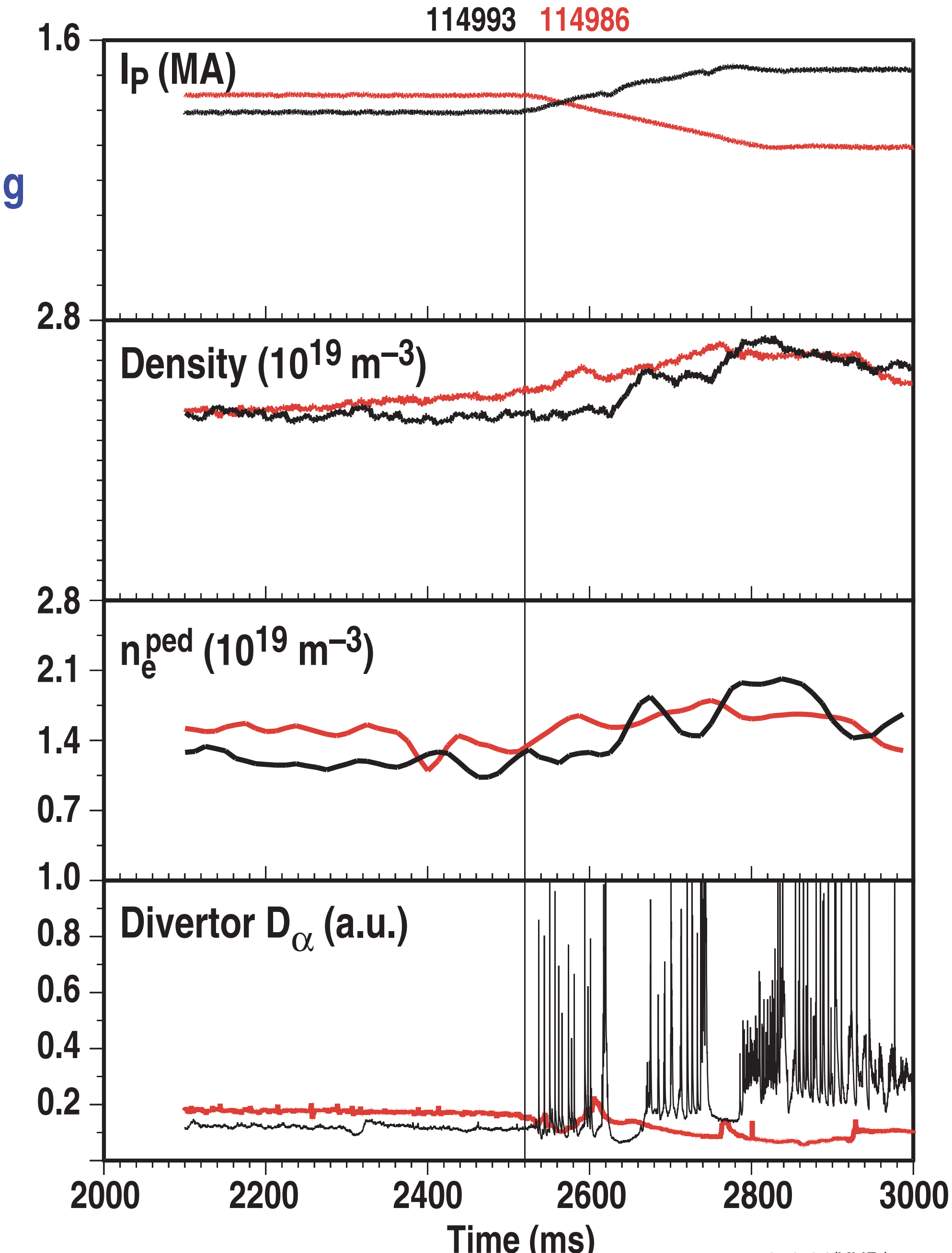
DIII–D QH–MODE OPERATES NEAR EDGE CURRENT LIMIT TO PEELING MODES

- Increasing plasma current (1 MA/s) in QH–mode plasmas causes return of ELMs in about 20 ms, while decreasing current at same rate allows plasma to stay in QH–mode
  - Ramp rates as low as 0.15 MA/s cause return of ELMs
- This behavior indicates the QH–mode edge is close to the J_{edge} limit in the peeling -ballooning mode diagram
- Being close to this limit is also consistent with control room observation that QH–mode is easier to get at lower plasma currents



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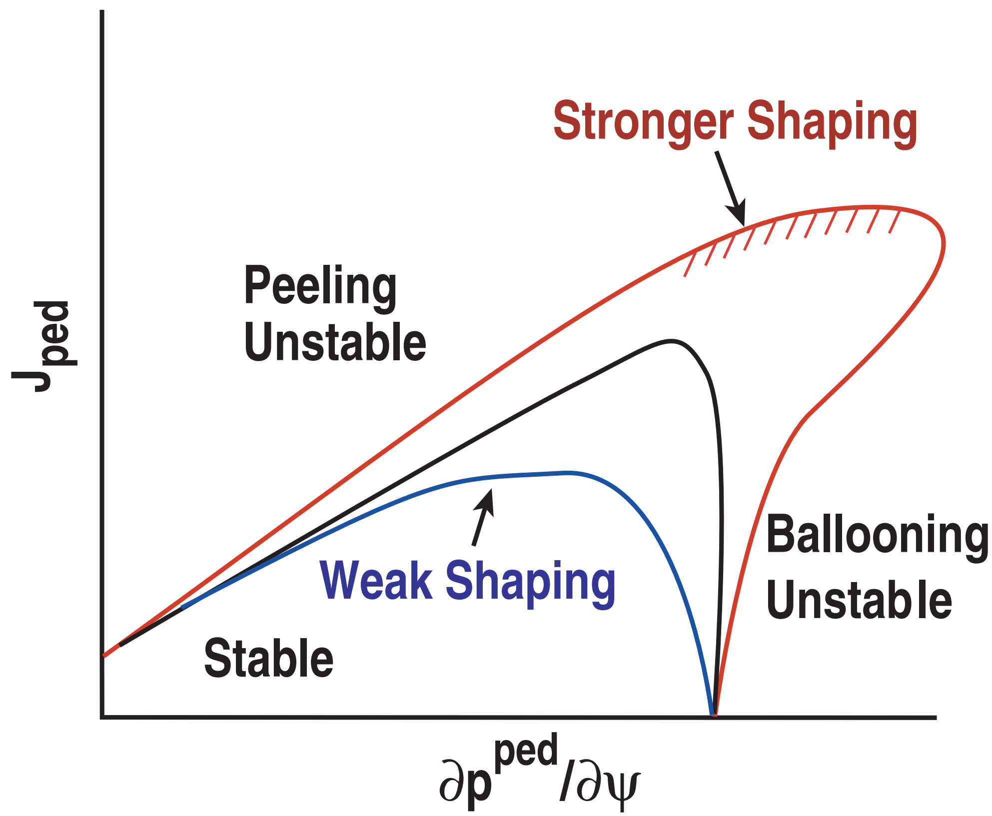

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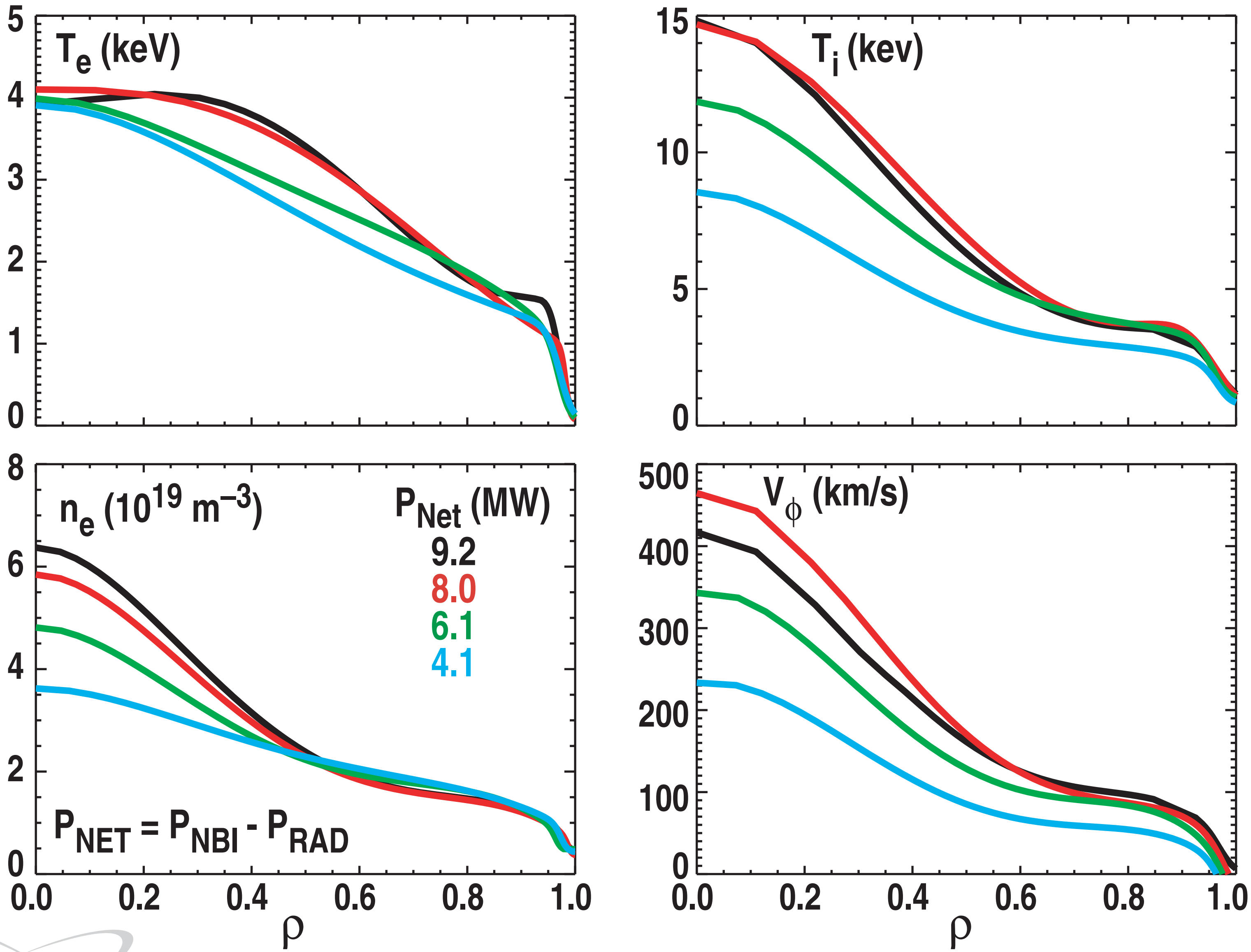
INPUT BEAM POWER IS CHANGED TO CHANGE PLASMA GRADIENTS

- Core density, ion temperature and rotation gradients steepen with increasing input power



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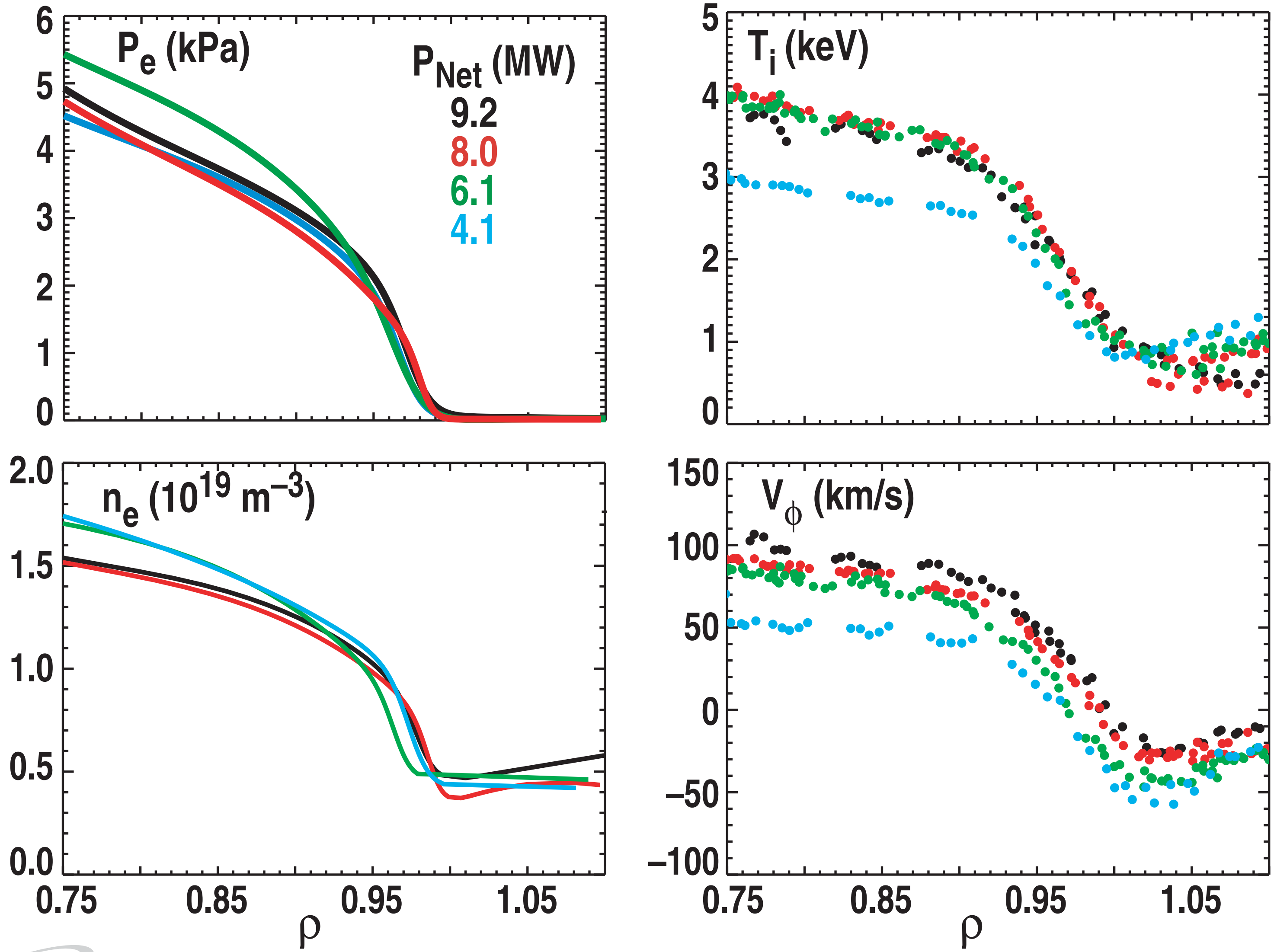
INPUT BEAM POWER IS CHANGED IN ATTEMPT TO CHANGE EDGE GRADIENTS

- Edge gradients saturate as power increases
- Process limiting edge gradients allows QH–mode operation at powers up to core beta limit



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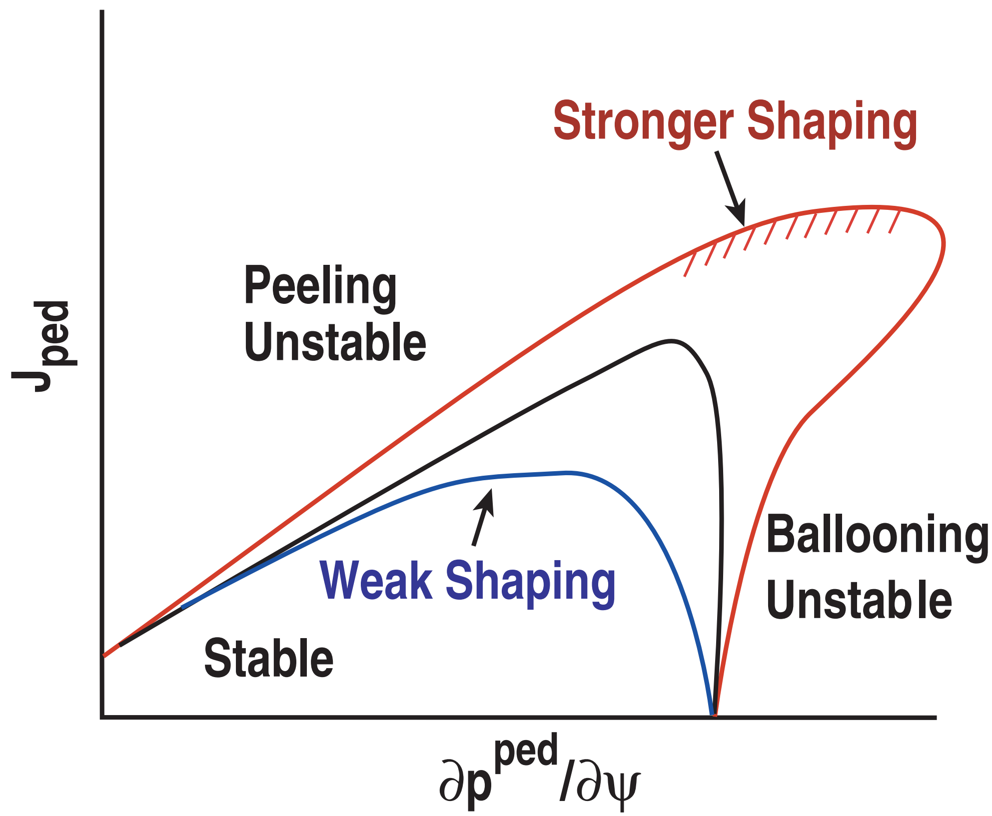

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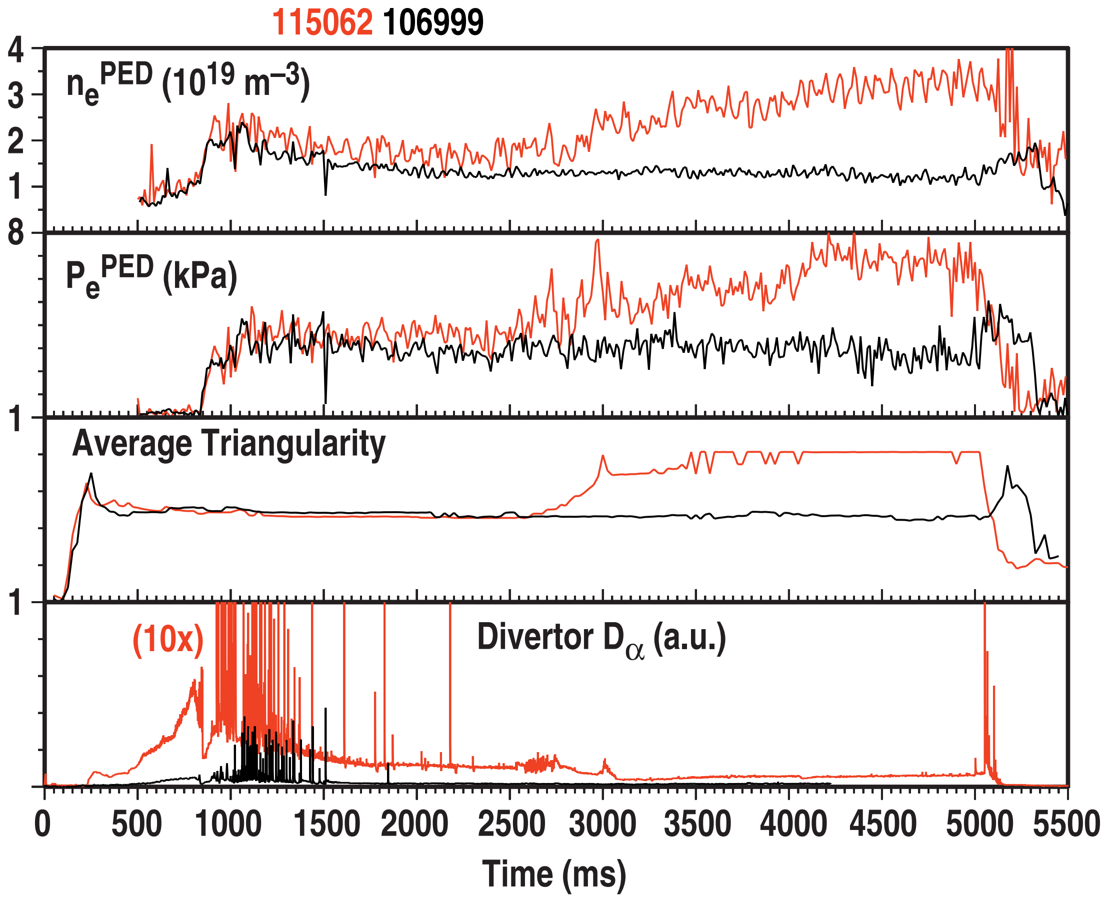
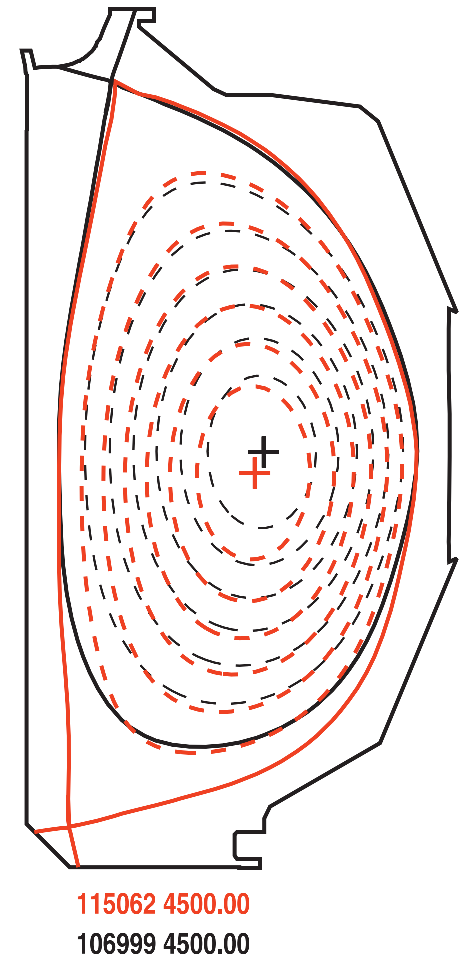
HIGHER TRIANGULARITY GREATLY EXPANDS QH–MODE PARAMETER SPACE

- More than doubled the pedestal density and pressure with higher triangularity
- n_e^{PED}/n_G rises from 0.1 to 0.25





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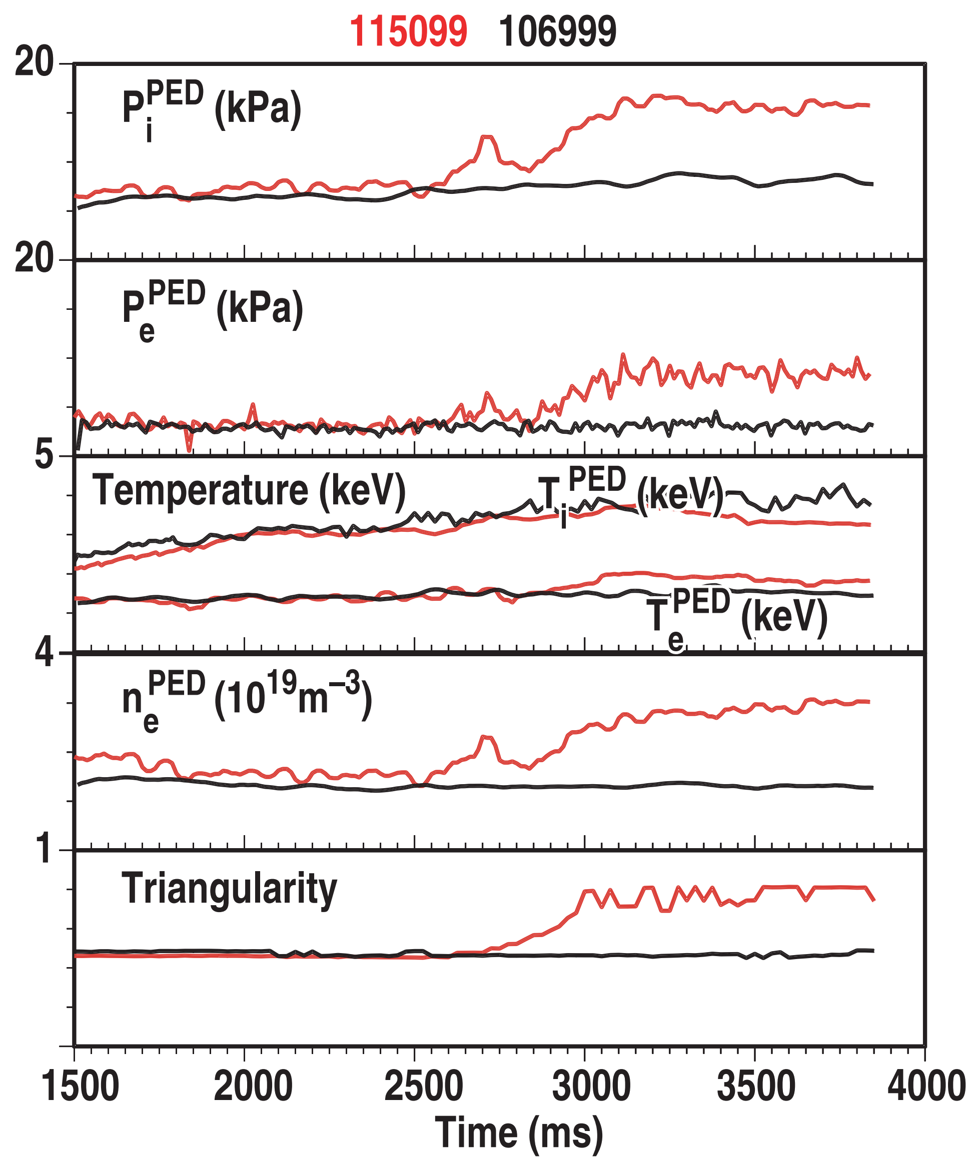
INCREASING TRIANGULARITY IN DOUBLE NULL PLASMA PRODUCES RISE IN ELECTRON AND ION PEDESTAL PRESSURE

- Ion pedestal pressure doubles and electron pedestal pressure more than doubles
- Ion pressure is dominant contribution to pedestal pressure
- Increased triangularity is the key to quiescent operation at higher pedestal pressure and density
  - — ELMs return at this density in lower triangularity shots



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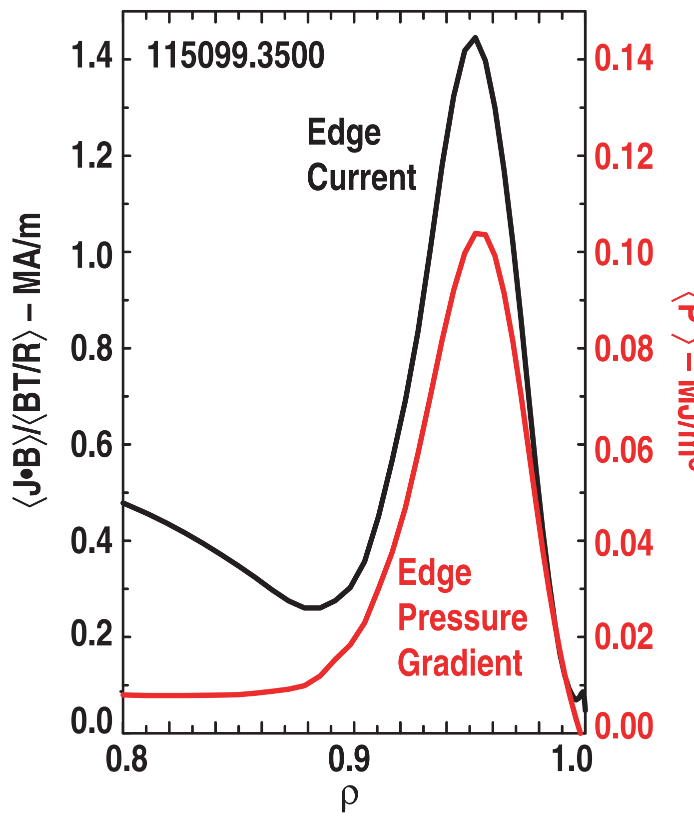
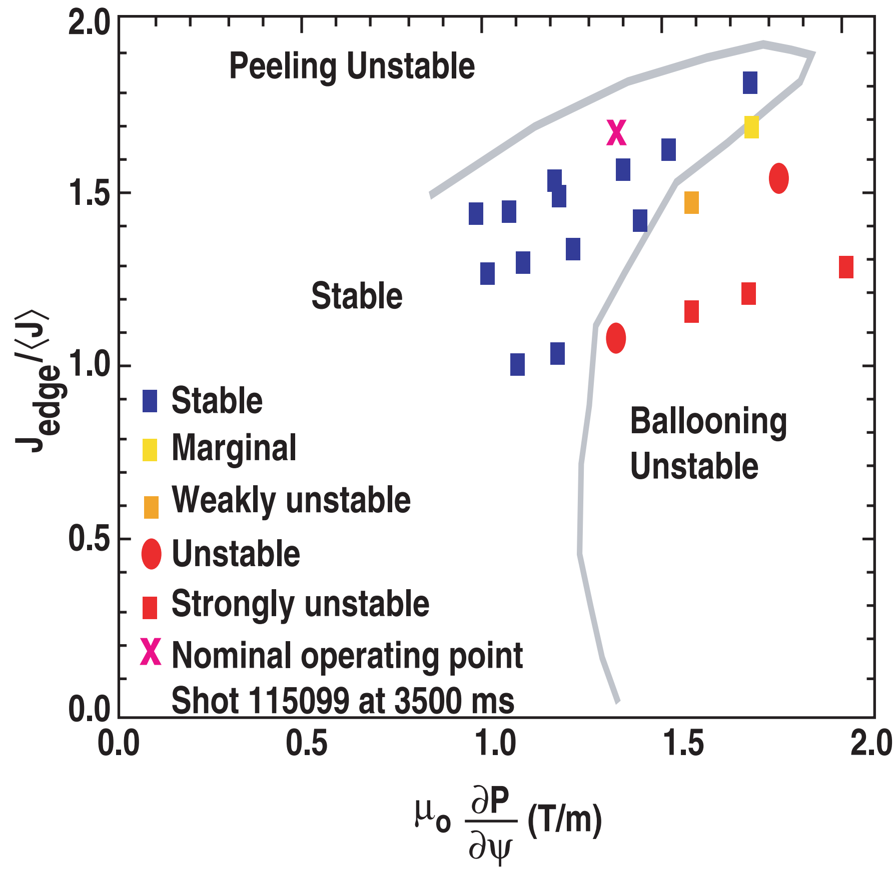
ELITE STABILITY MODELING: QH–MODE IS MARGINALLY STABLE TO CURRENT DRIVEN PEELING/BALLOONING MODES

Edge Current (from NCLASS) and Pressure Profiles in CORSICA equilibrium



ELITE Stability Diagram for the experimental case, x, and perturbed equilibria



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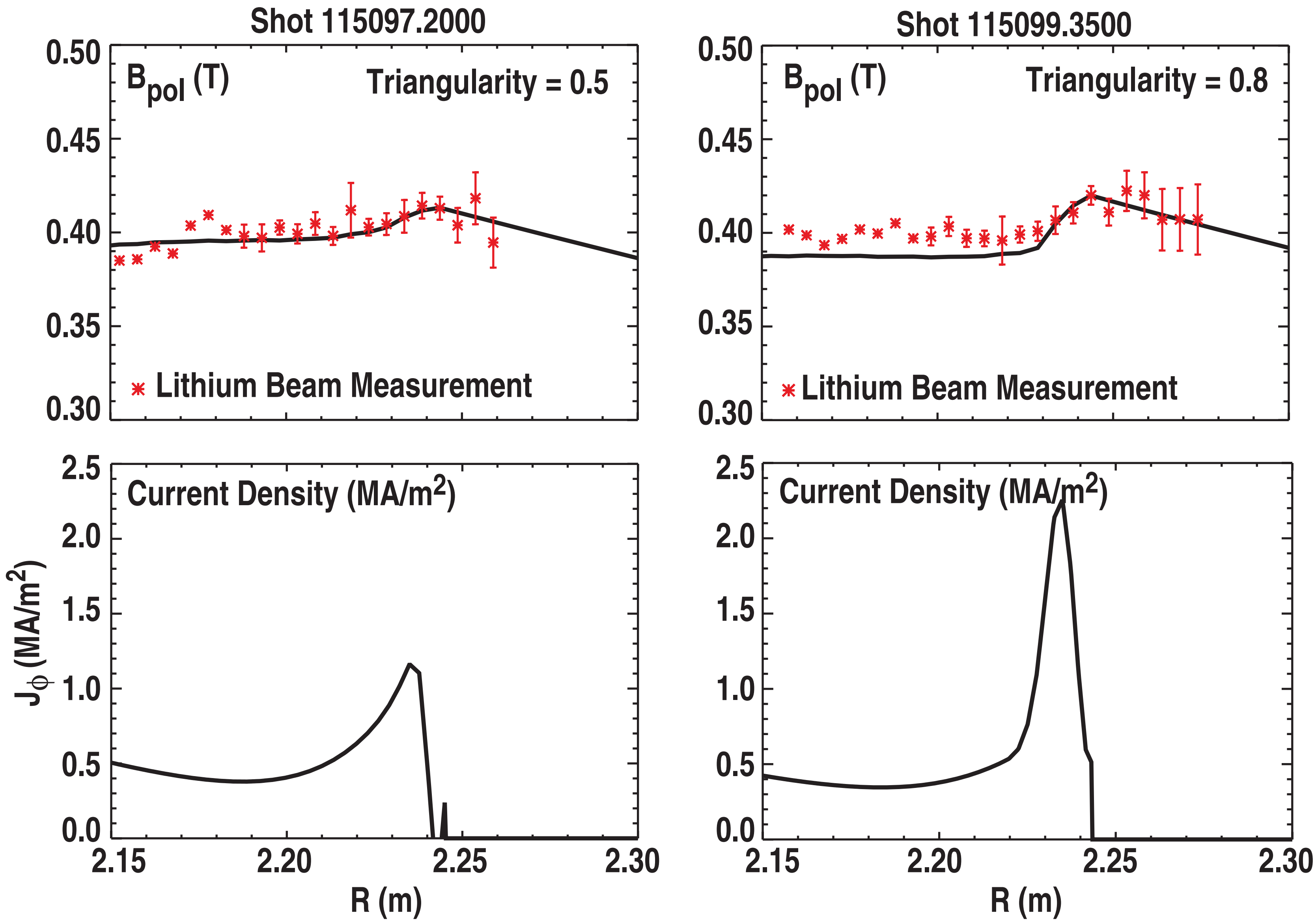
EDGE POLOIDAL FIELD FROM CALCULATED CURRENT COMPARES WELL WITH LITHIUM BEAM MEASUREMENT



D. Thomas JI-2.006 Wednesday afternoon

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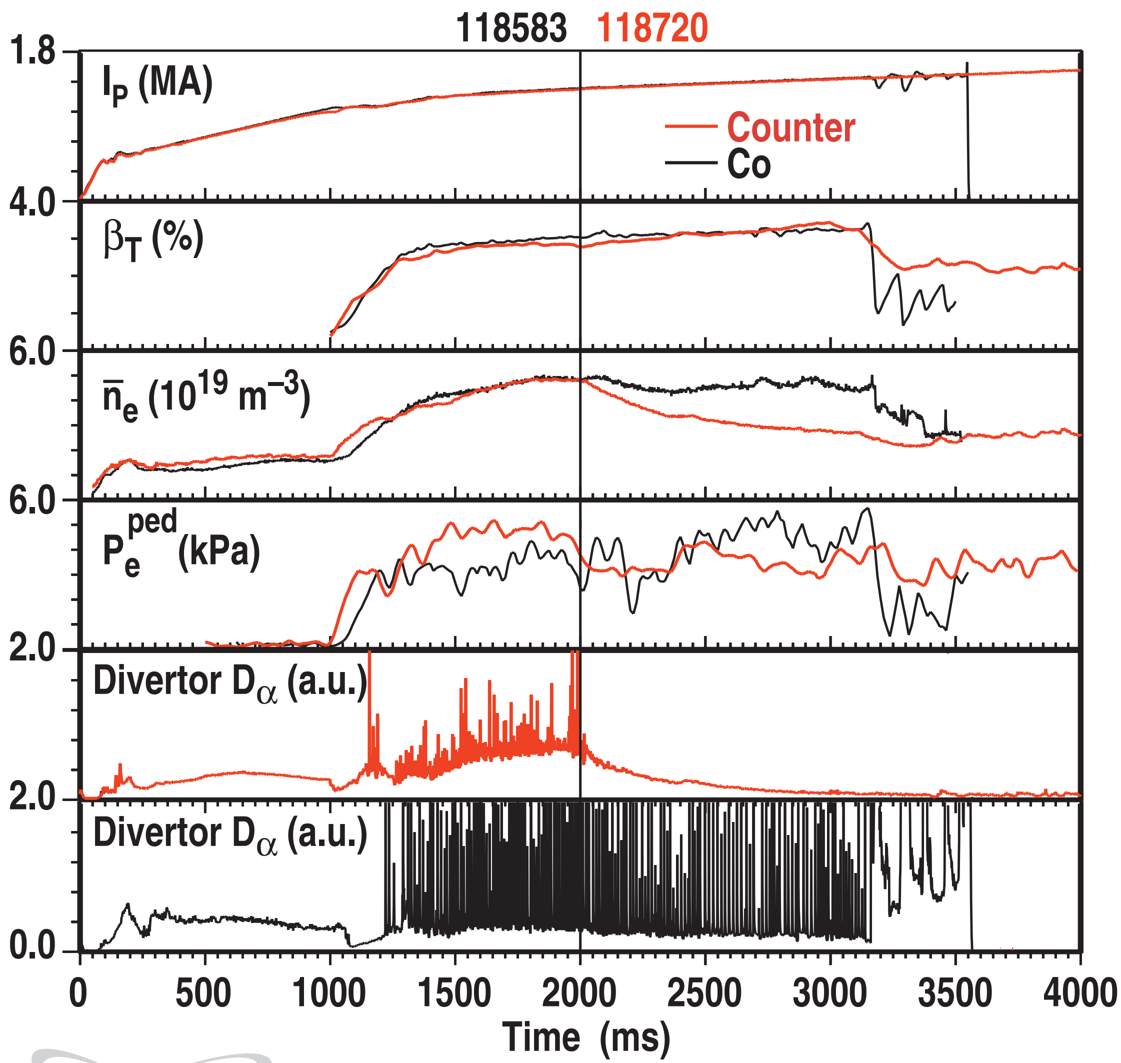
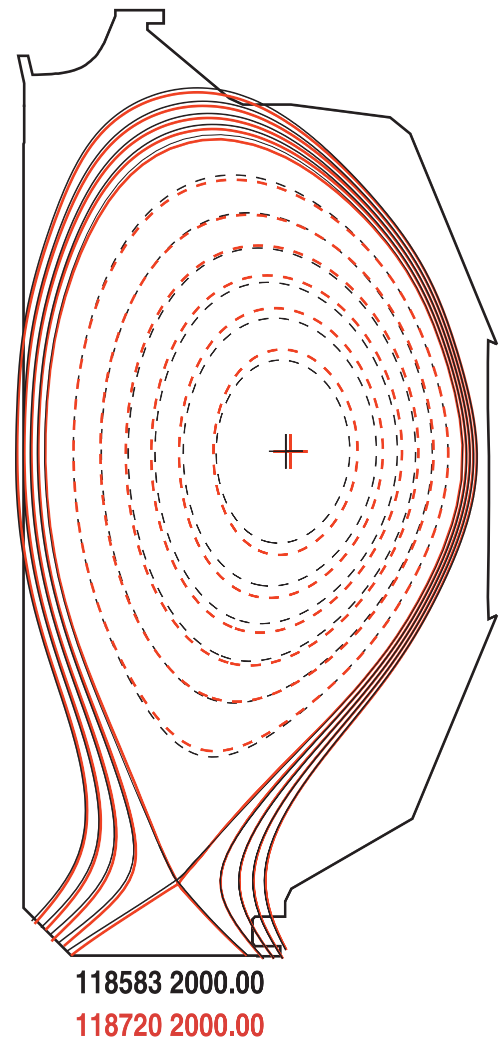
MATCHED PAIR OF CO AND COUNTER INJECTED DISCHARGES SELECTED FOR ELMING (CO) VERSUS QUIESCENT (COUNTER)

- Shots selected for identical shapes and pedestal parameters at time quiescent phase starts in counter injected shot





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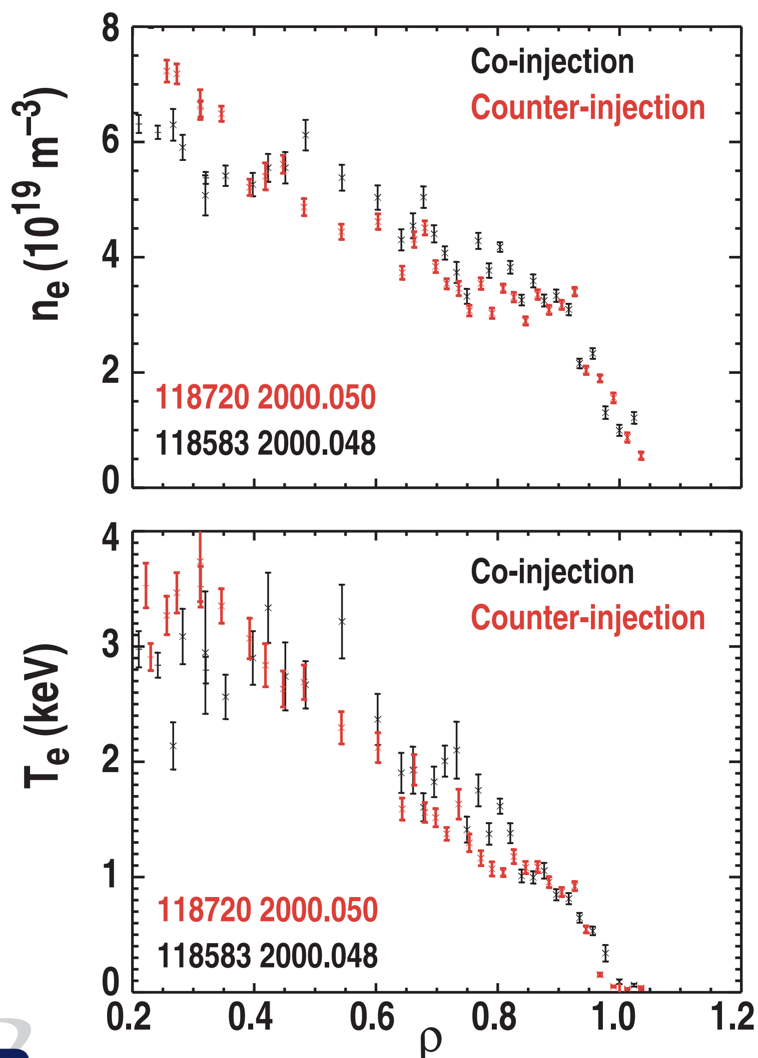
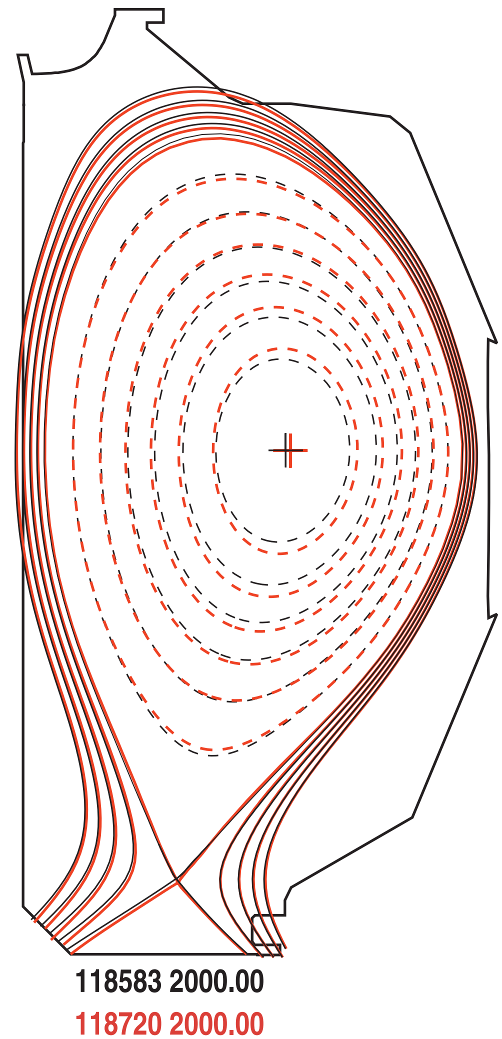
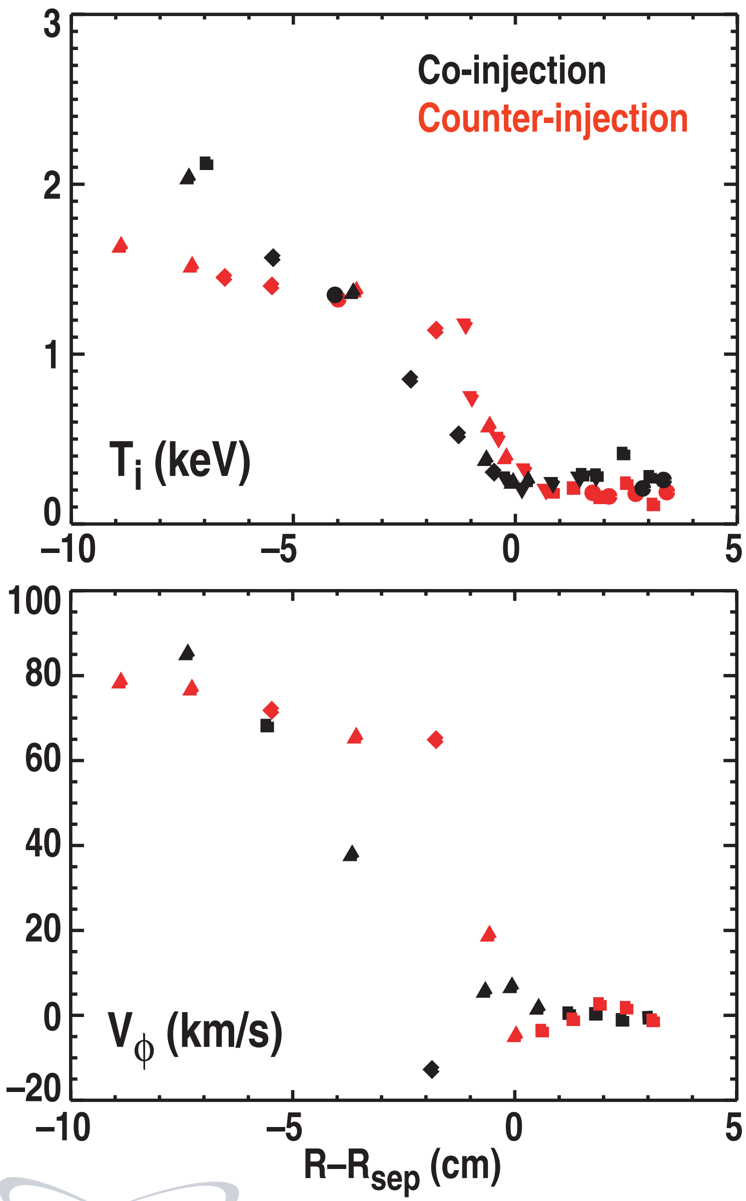
MATCHED PAIR OF CO AND COUNTER INJECTED DISCHARGES SELECTED FOR ELMING (CO) VERSUS QUIESCENT (COUNTER)

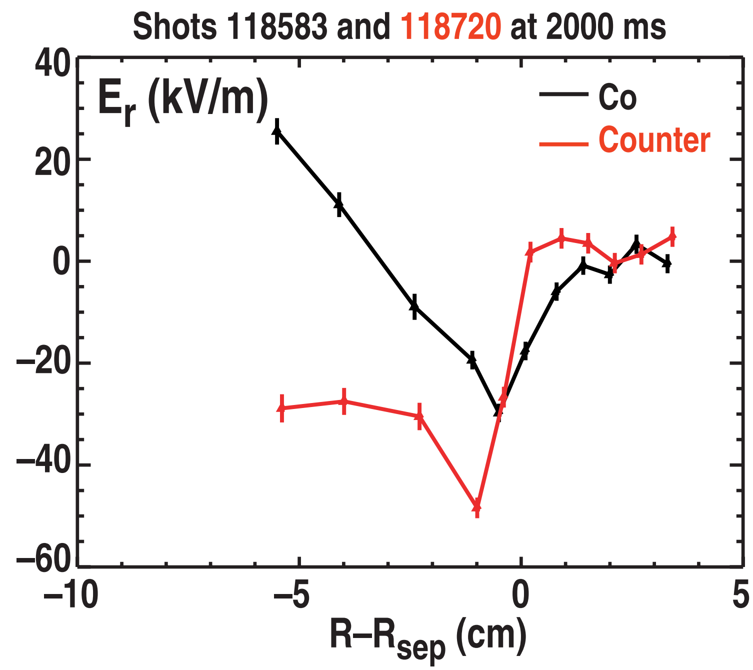
- Both have I_P = 1.36 MA, B_T = 1.9 T, β_T = 3.0%
- Outer flux surface shapes are identical





EDGE V_ϕ and E_r ARE QUITE DIFFERENT IN MATCHED PAIR OF ELMING (CO) AND QUIESCENT (COUNTER) DISCHARGES





- E_r and V_ϕ affect ELM stability
- V_ϕ effects recently added to ELITE (P. Snyder JI-2.005 Wednesday afternoon)

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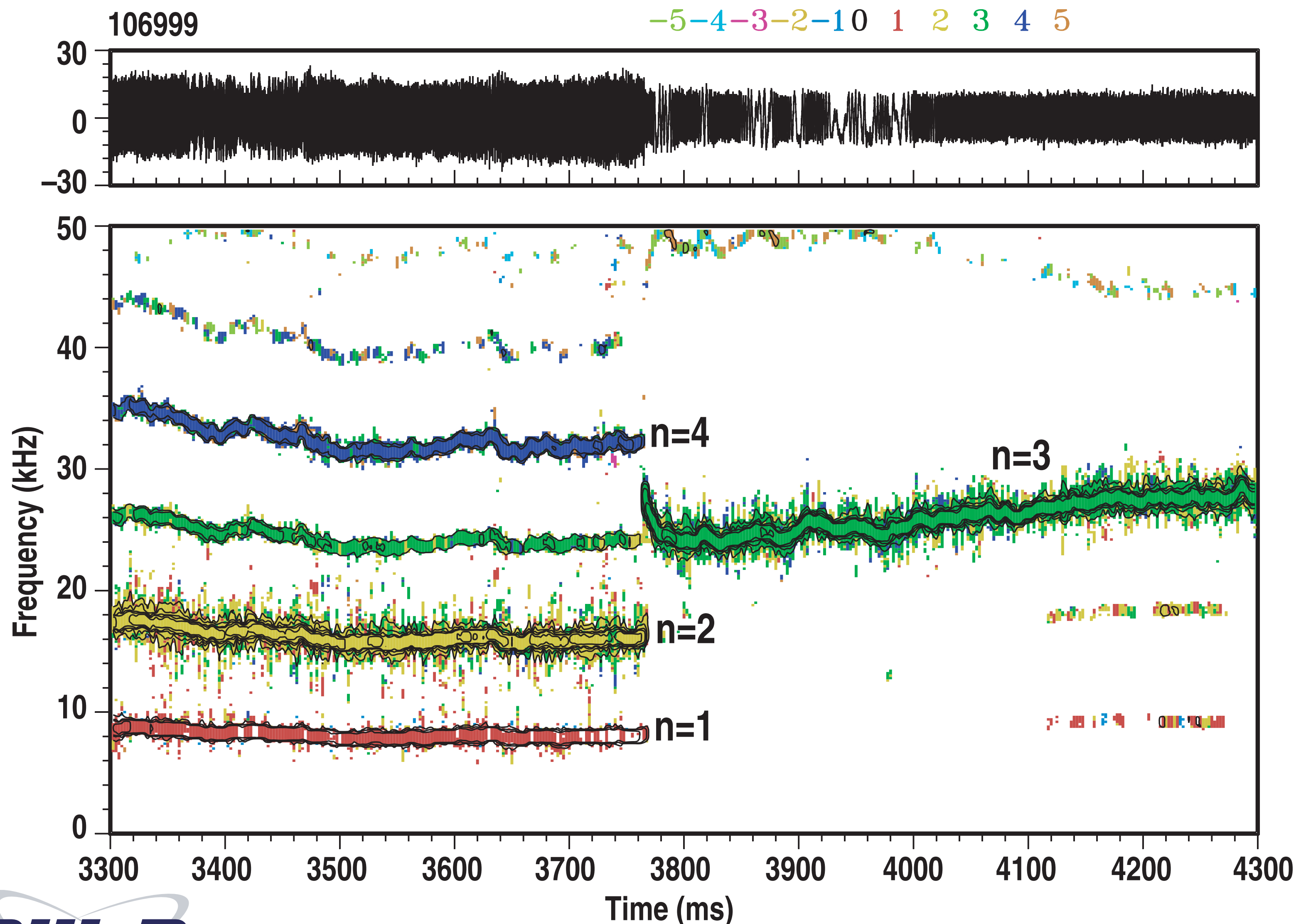
EHO CAN SPONTANEOUSLY CHANGE TOROIDAL MODE NUMBER

- Edge harmonic oscillations directly measured in B_{pol}, n_e and T_e



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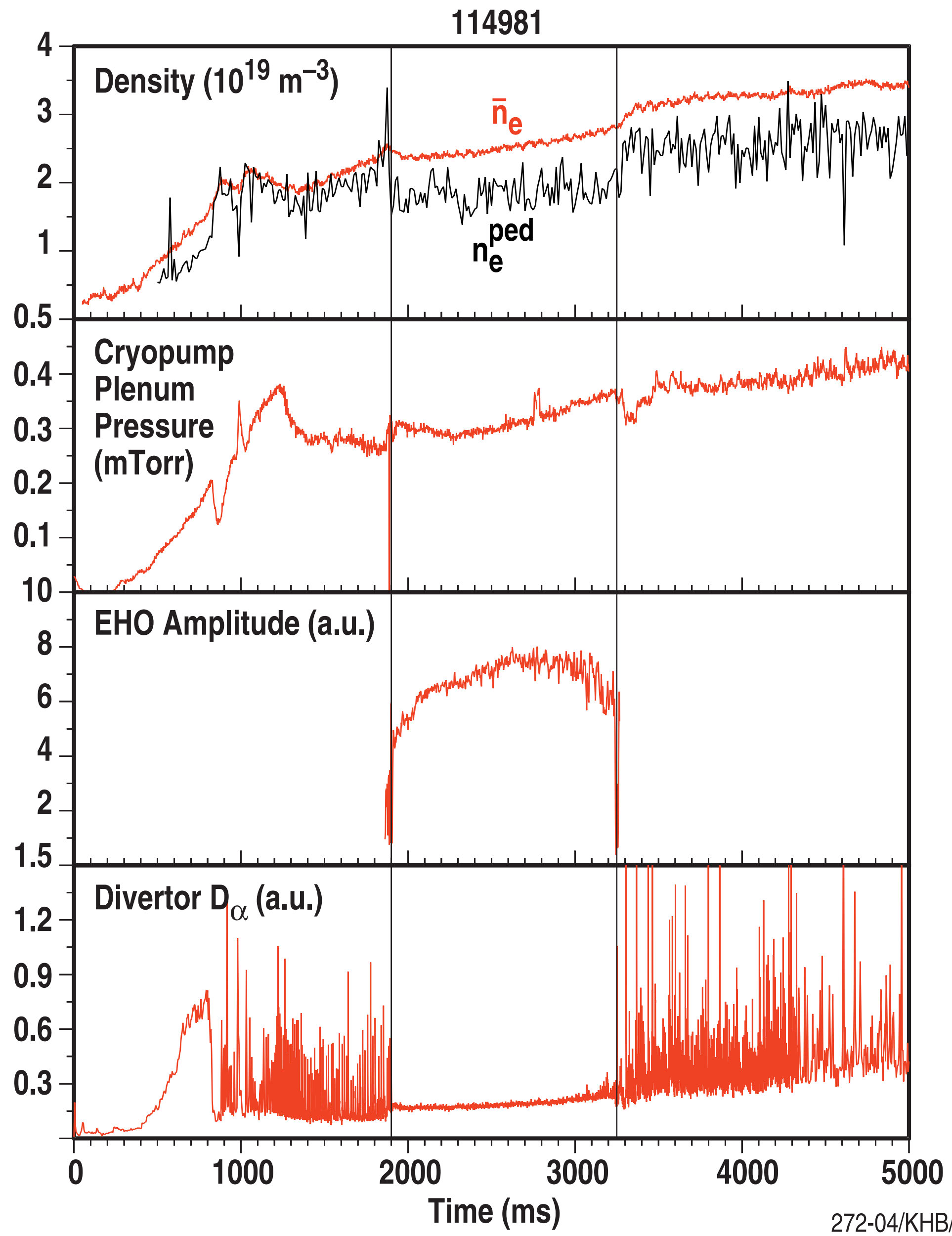
EHO TRANSPORTS PARTICLES MORE RAPIDLY THAN ELMS

- Density drops when EHO turns on and rises when it ceases
  — Particle input constant

- Pressure in pumping plenum rises when EHO turns on, consistent with particle exhaust from plasma



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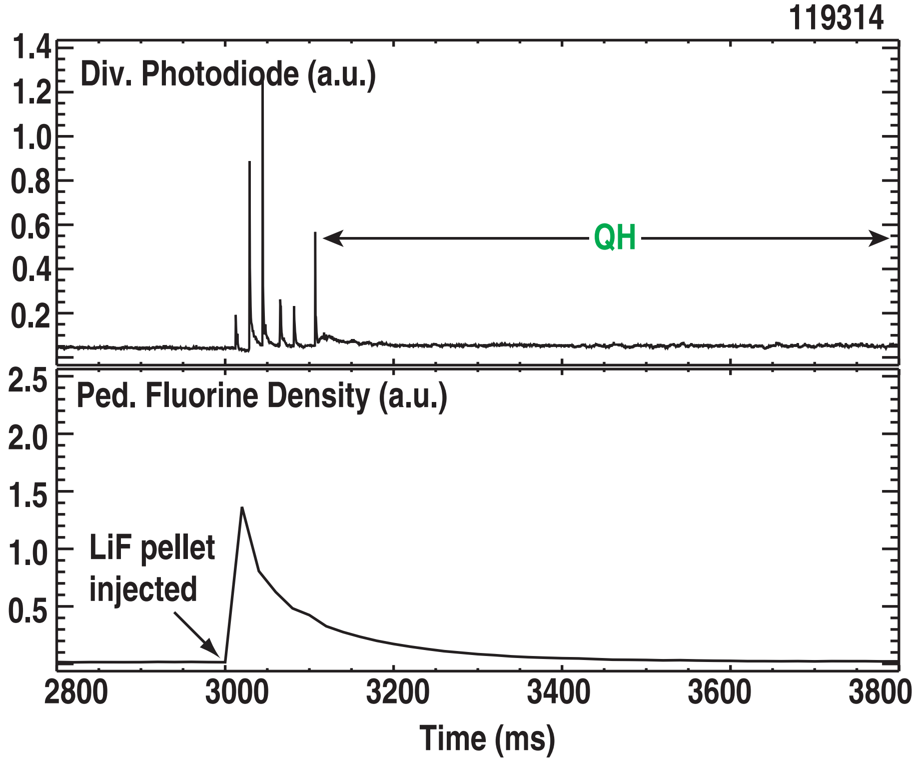
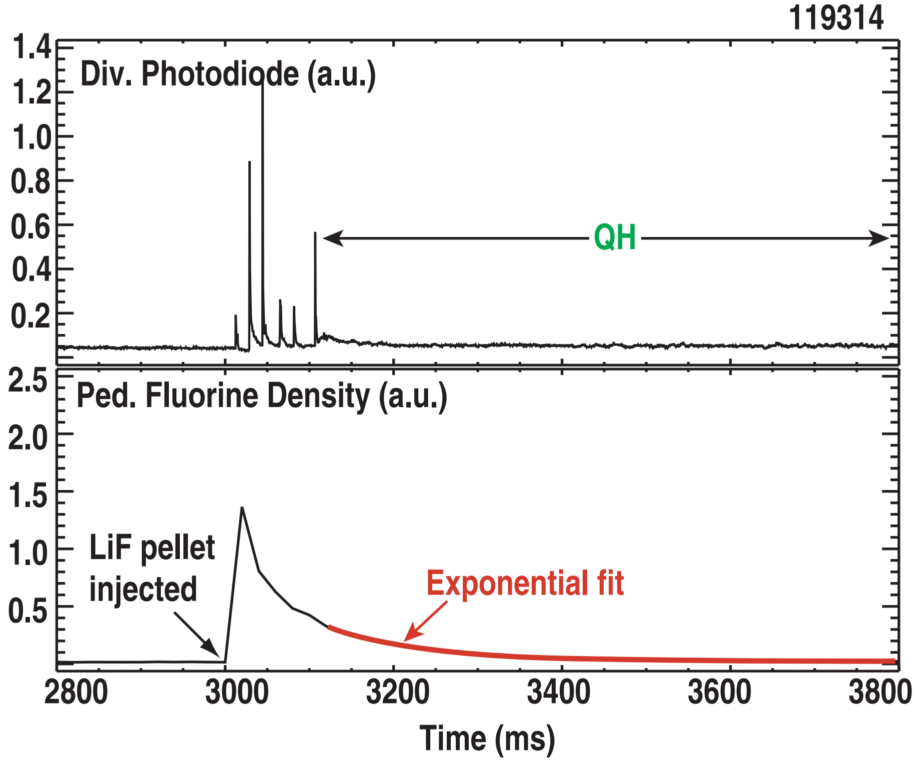
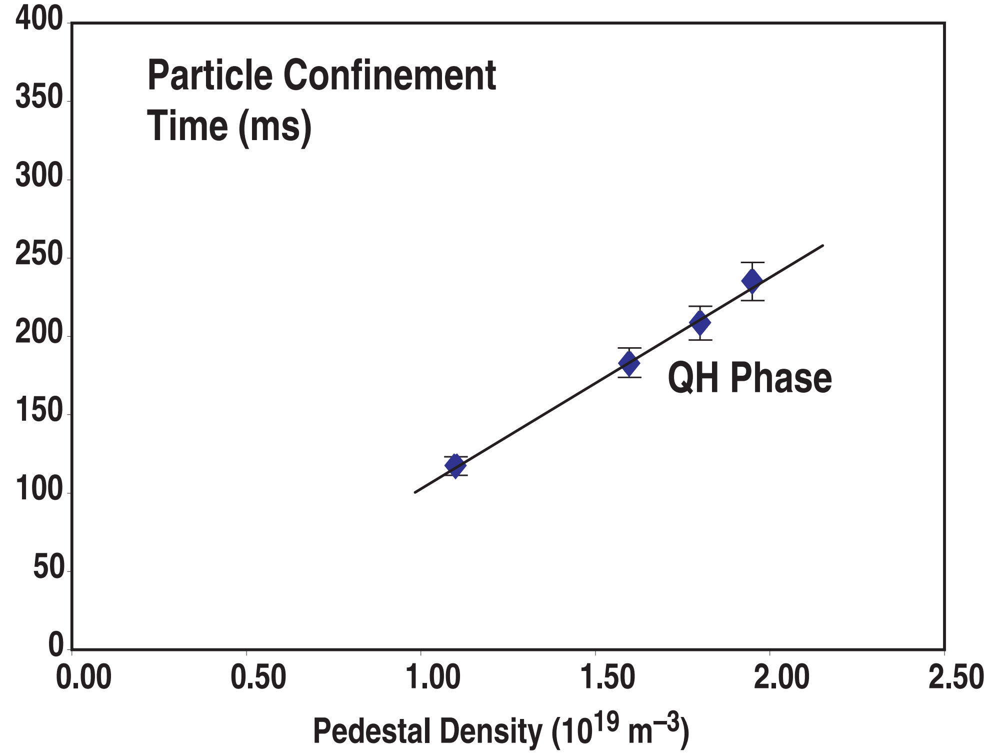
IMPURITIES AT THE PLASMA EDGE ARE EXHAUSTED FASTER IN THE QH–MODE PHASE THAN IN THE ELMING PHASE



IMPURITIES AT THE PLASMA EDGE ARE EXHAUSTED FASTER IN THE QH–MODE PHASE THAN IN THE ELMING PHASE

- The impurity particle confinement time at the plasma edge increases with the pedestal density





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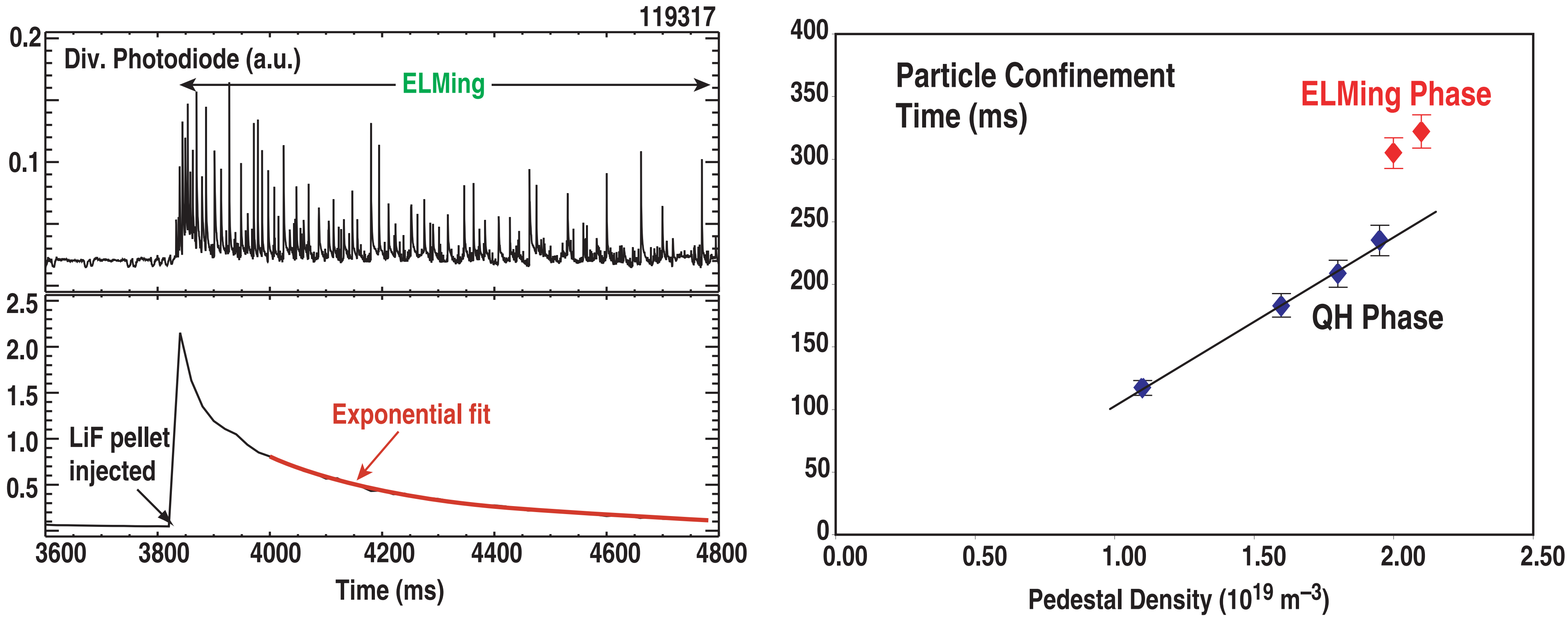
IMPURITIES AT THE PLASMA EDGE ARE EXHAUSTED FASTER IN THE QH–MODE PHASE THAN IN THE ELMING PHASE

- The impurity particle confinement time at the plasma edge increases with the pedestal density
- EHO exhausts impurities faster than ELMs



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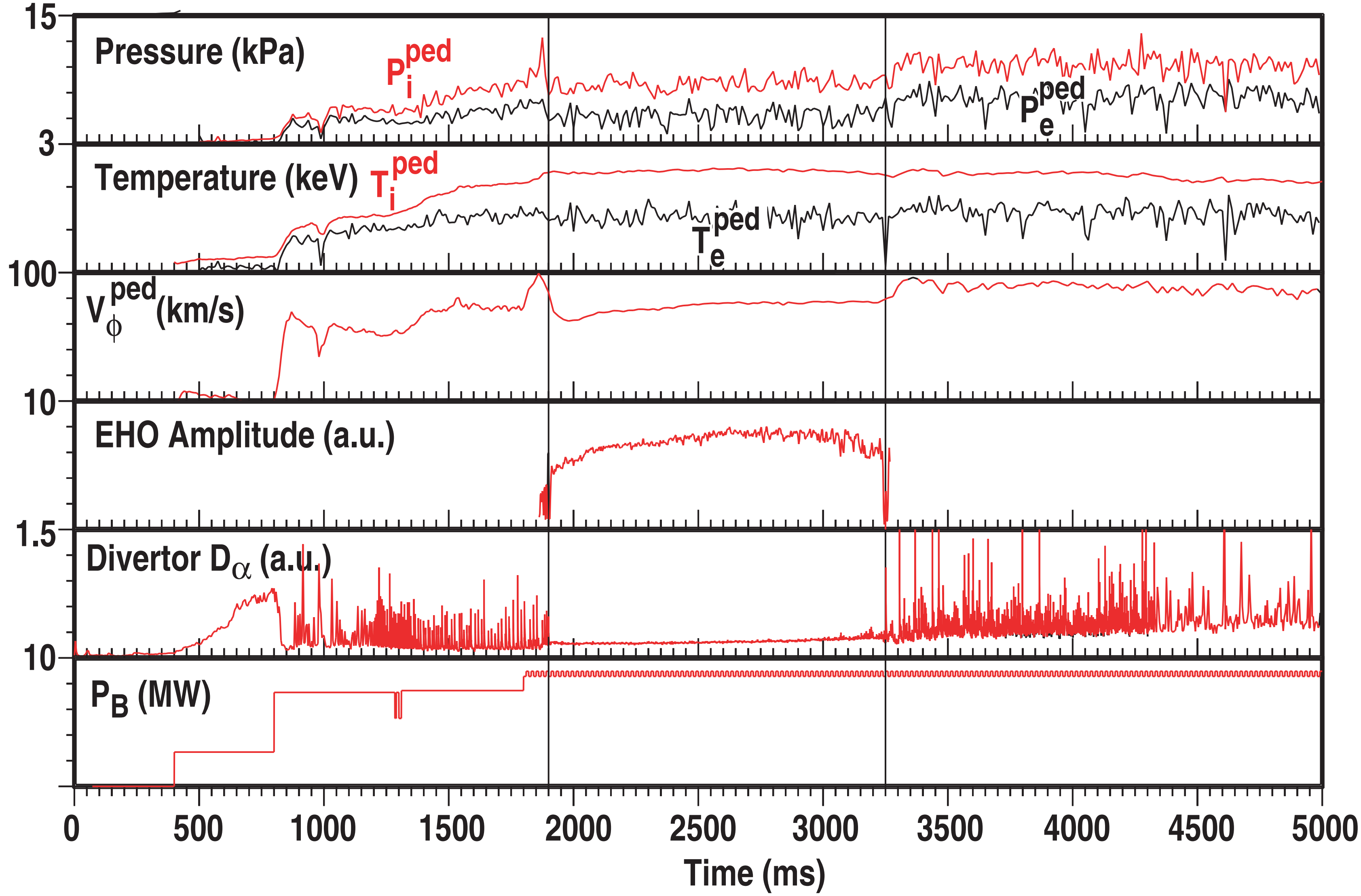
EDGE PRESSURE AND ROTATION CHANGE WHEN EHO TURNS ON AND OFF; PEDESTAL T_e AND T_i DON'T CHANGE



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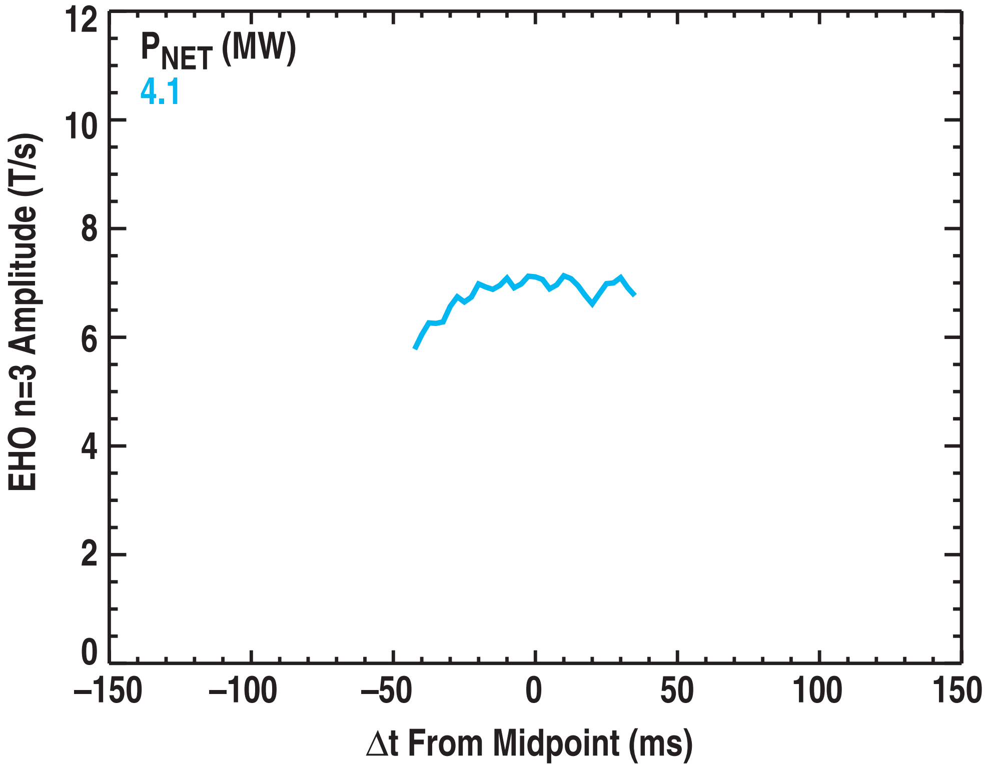
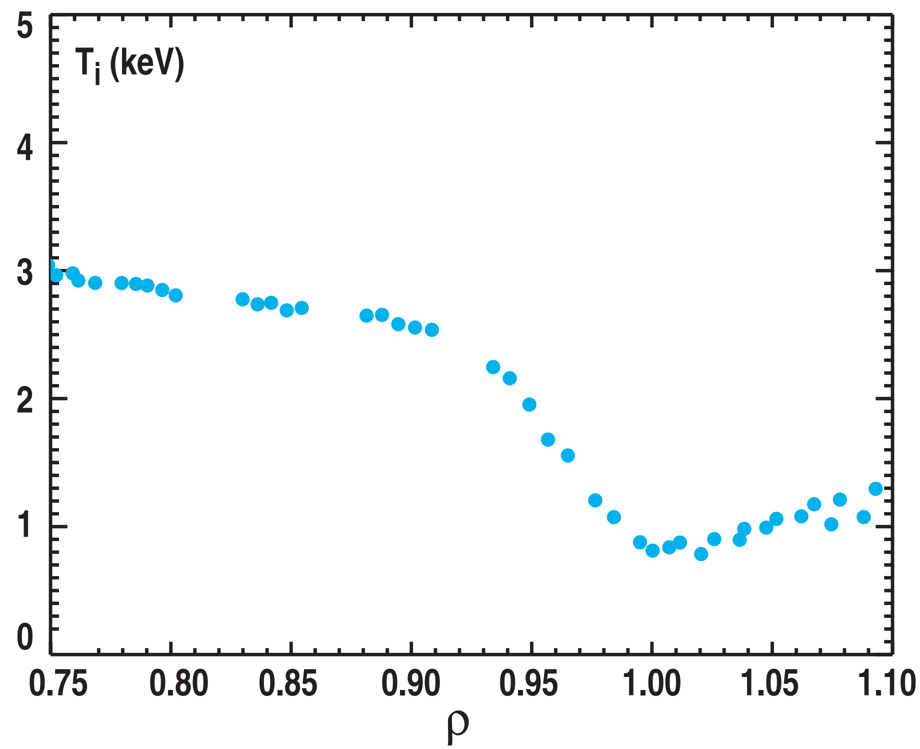
EHO AMPLITUDE DOES NOT CORRELATE WITH SATURATION OF EDGE PROFILES AS POWER INPUT INCREASES





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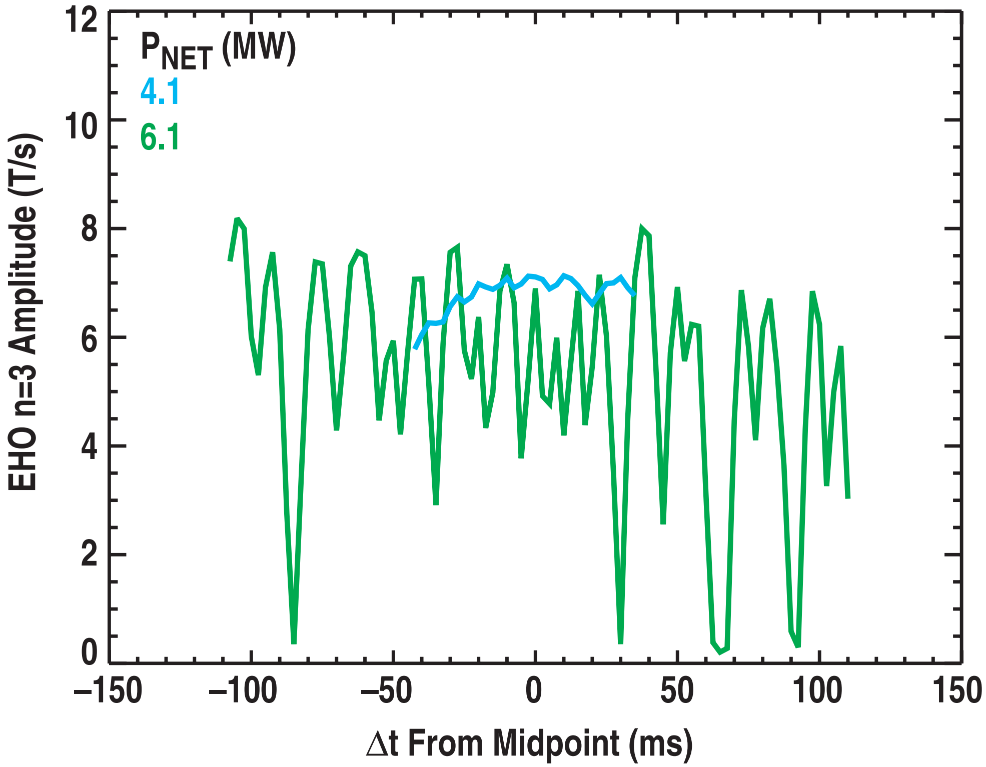

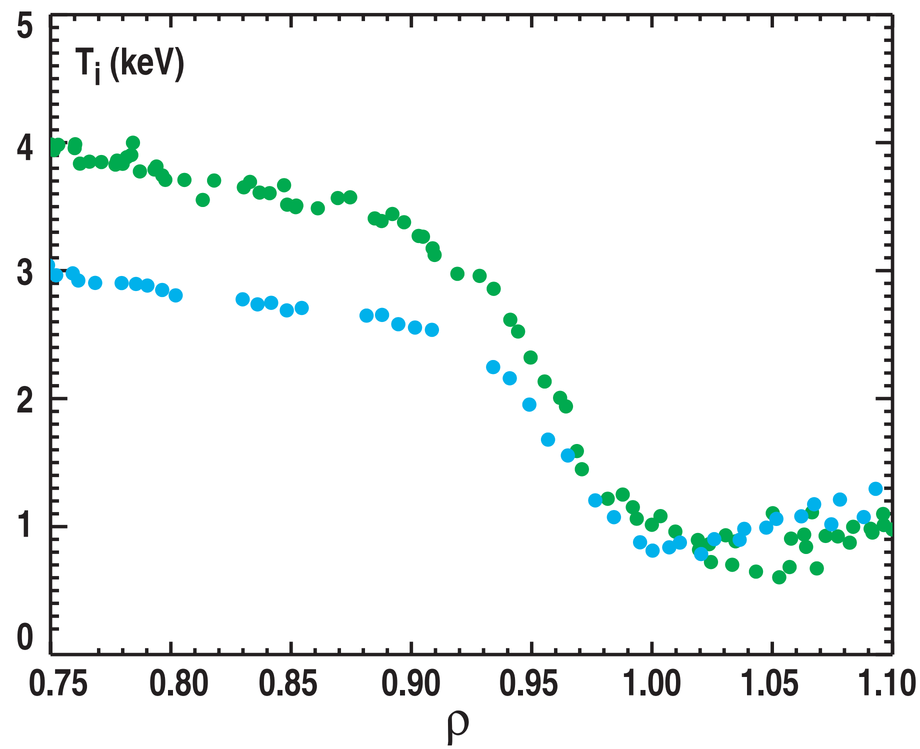

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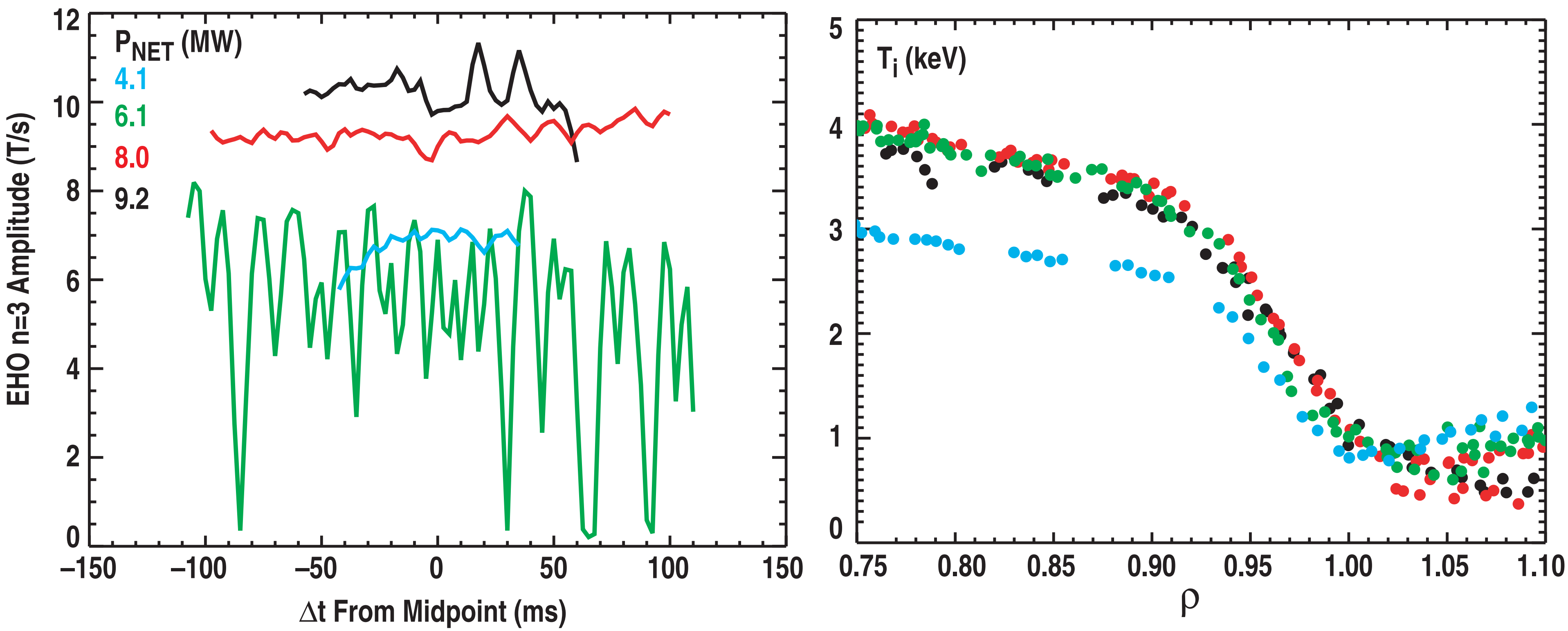

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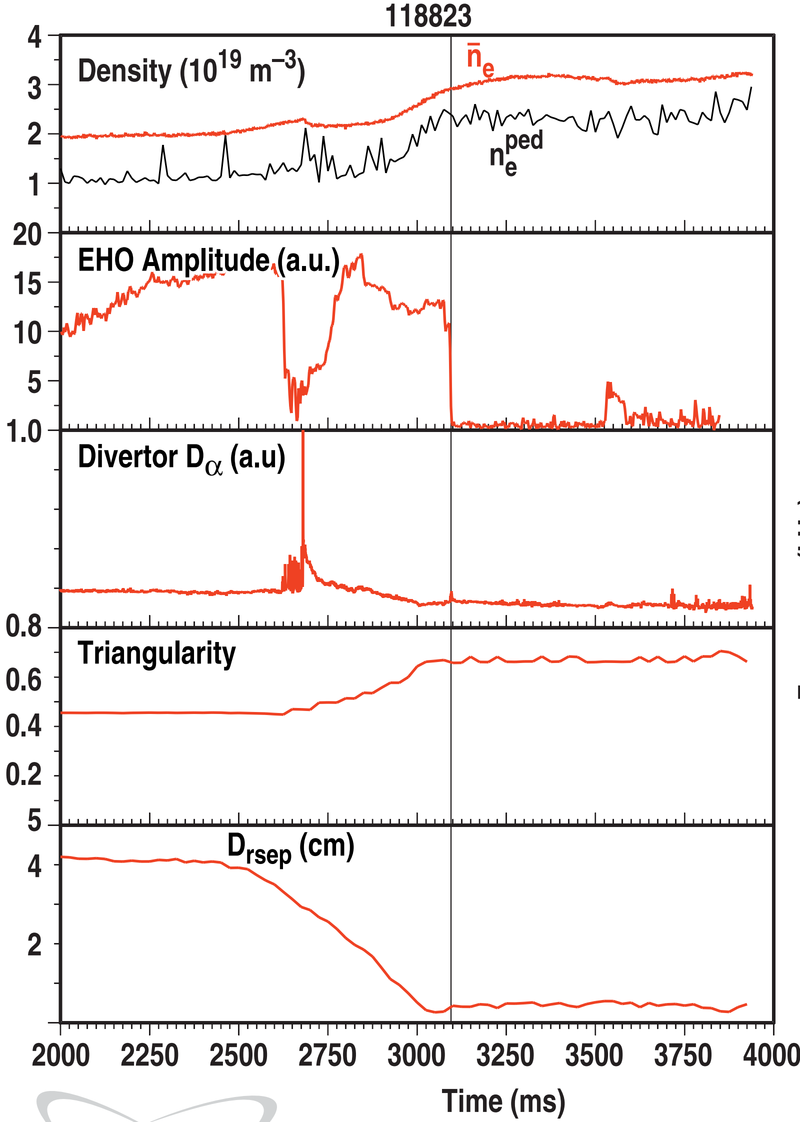
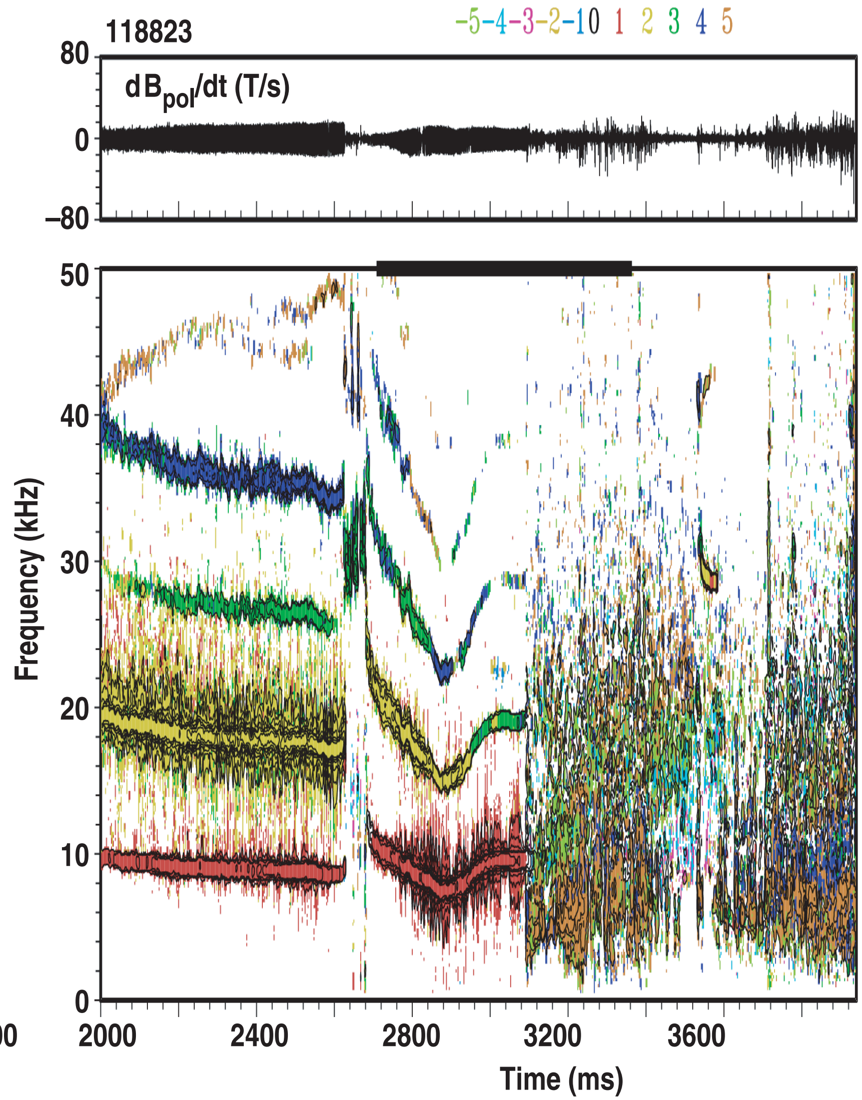
BROADBAND EDGE ELECTROMAGNETIC ACTIVITY EXHAUSTS PARTICLES

- Constant density QH–mode operation is possible without ELMs or EHO





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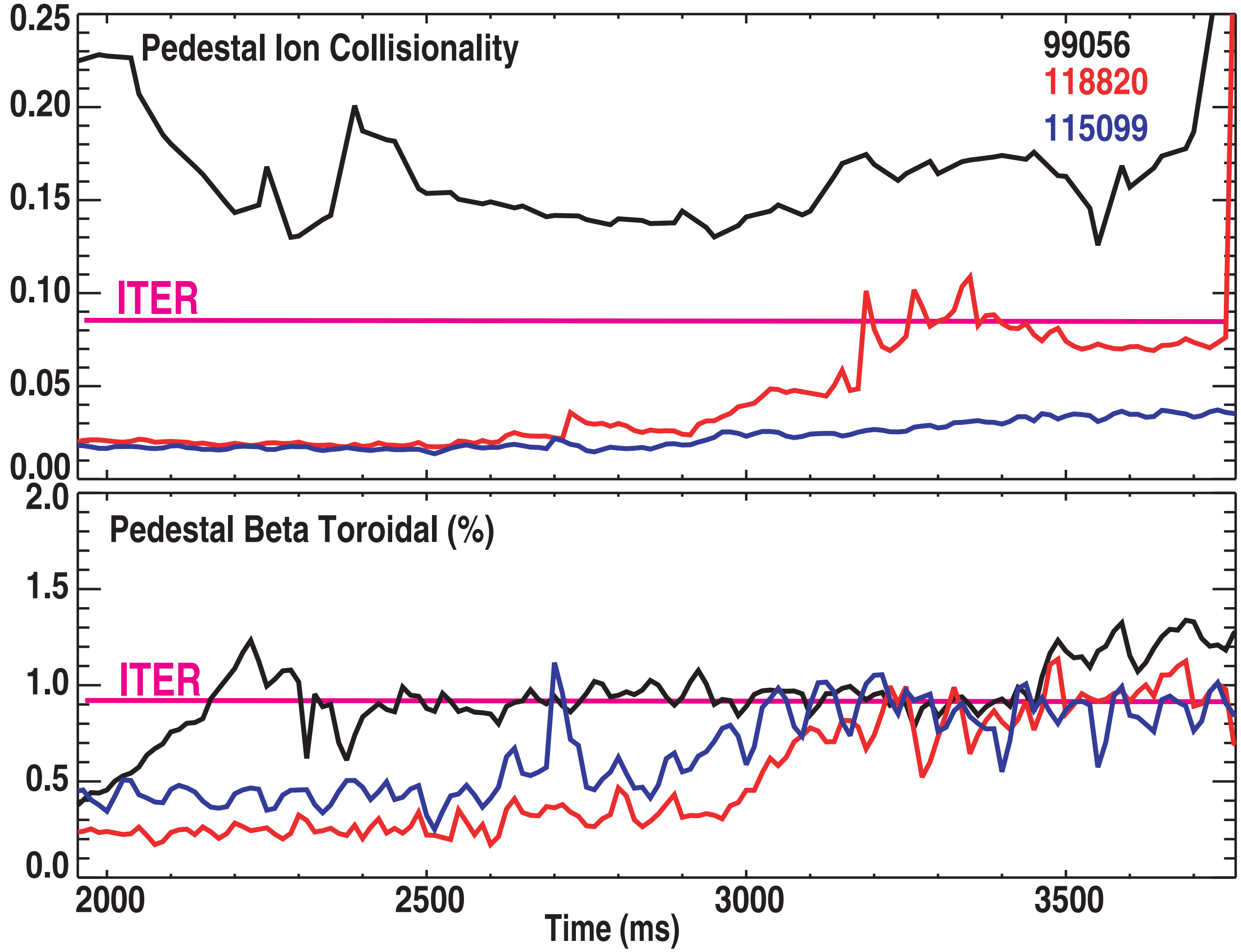
PEDESTAL β_T AND ION COLLISIONALITY COMPARABLE TO ITER REFERENCE DESIGN ACHIEVED IN DIII–D QH-MODES



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CONCLUSIONS

- Peeling-ballooning mode theory allows explanation of
  - QH–mode current limits
  - Substantial improvement in edge pressure with triangularity
- Edge electron and ion pressures saturate as power flow through the separatrix increases in QH–mode
  - Allows QH operation up to powers needed to reach beta limit
  - Mechanism at present is unknown (related to EHO??)
- Comparison of co- and counter-injected discharges at same electron parameters indicates that edge E_r or toroidal rotation plays a role in ELM stabilization
- Edge harmonic oscillation facilitates particle transport (electron, main ion and impurity) across the plasma edge
  - EHO-induced particle transport is faster than transport averaged over ELMs
  - Other electromagnetic modes can have similar effect on particle transport
  - EHO decreases pedestal density and rotation; no effect on T_e^{ped} and T_i^{ped}
- QH–mode extrapolates well to next step machines
  - DIII–D has operated at pedestal β and ν_* values bracketing the ITER values
  - QH–mode has been seen over a range of ρ^*: $3.5\times10^{-3} \leq \rho^* \leq 1.5\times10^{-2}$ (DIII–D, ASDEX, JT-60U, JET)

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