NSTX

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Optimization of Density and Radiated Power Evolution Control using Magnetic ELM Pace-making in NSTX

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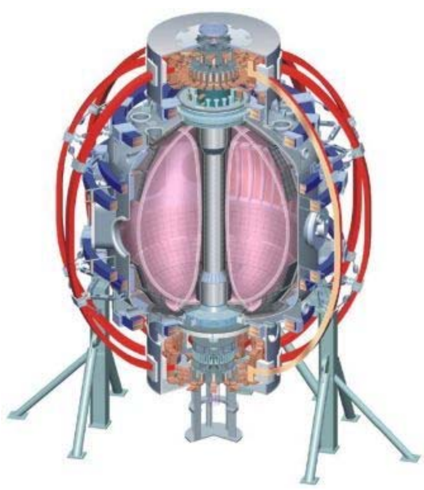

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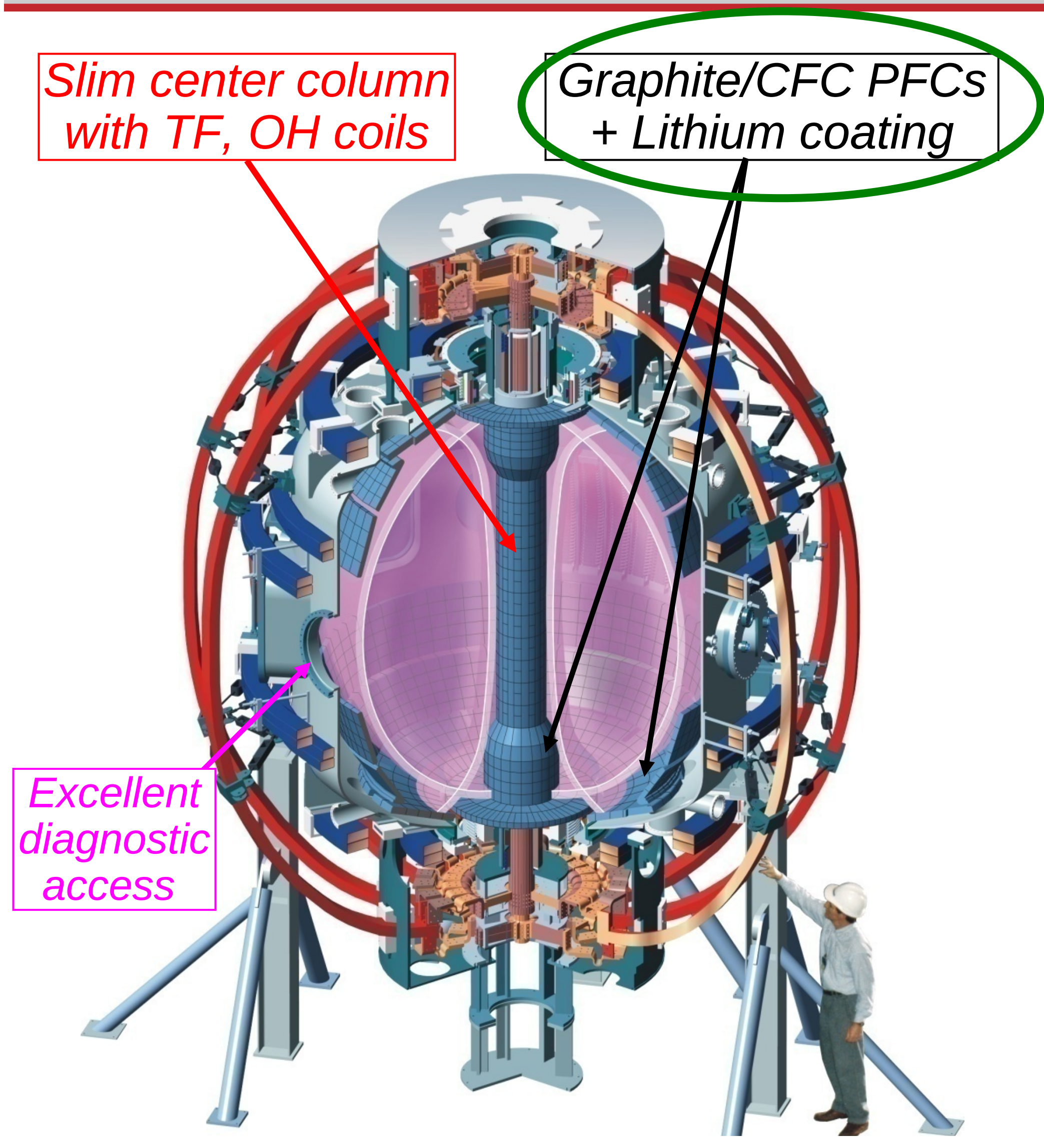
Outline

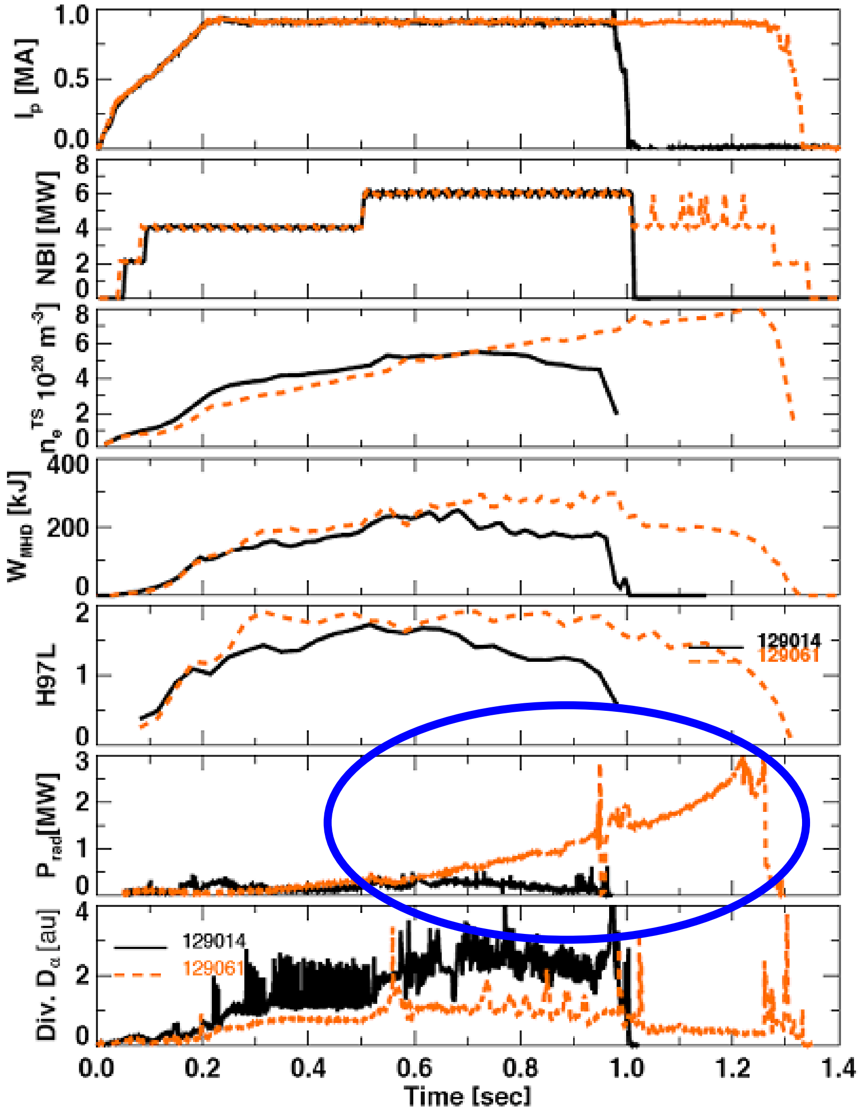
- Introduction to NSTX
  - PFC conditioning techniques
  - 3D magnetic perturbation coil set
- ELM destabilization with 3D fields
  - Threshold perturbation to cause ELMs
  - Changes to plasma profiles
- Perturbations are used for ELM-pacing with Li conditioning
  - ELM suppressed with Li-coated PFCs
  - 3D fields trigger ELMs at will, reduce impurity accumulation
  - Reduces ELM size-potential ELM control technique in future devices

NSTX Facility Capabilities



R, a_{max}	0.85, 0.67 m
Aspect ratio A	1.27 – 1.6
Elongation κ	1.6 – 3.0
Triangularity δ	0.3 – 0.8
Toroidal Field B_{T0}	0.3 – 0.55 T
Plasma Current I_p	≤ 1.5 MA
Auxiliary heating:	
NBI (100kV)	≤ 7.4 MW
Central temperature	1 – 6 keV
Central density	$\leq 1.2\times10^{20} m^{-3}$

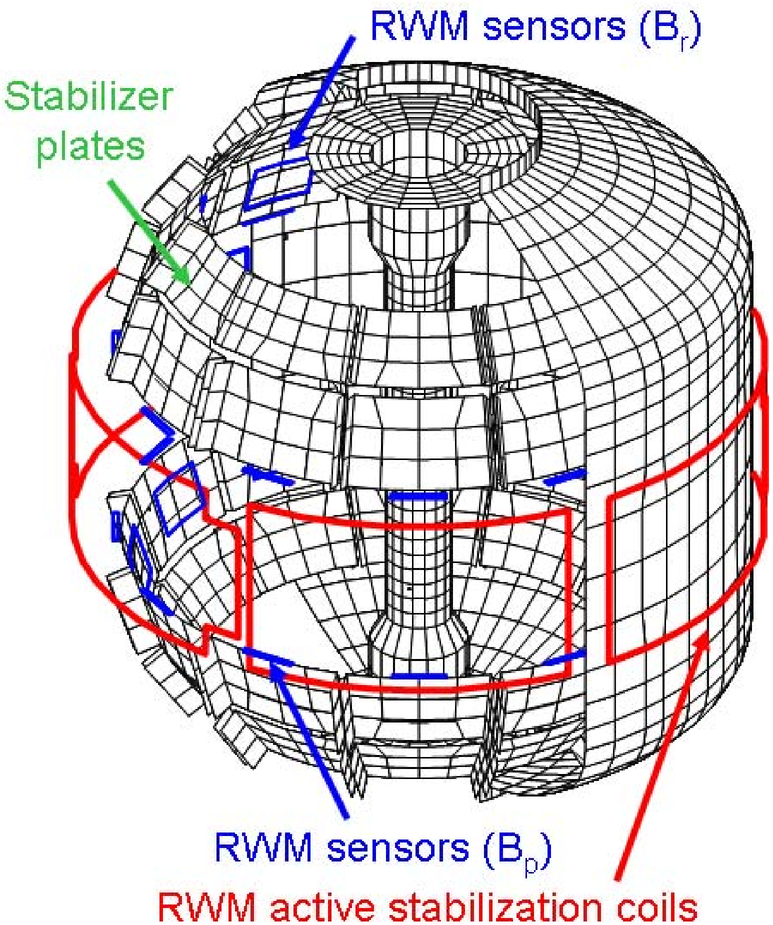
Two PFC conditioning techniques are studied: boronization and lithium coatings

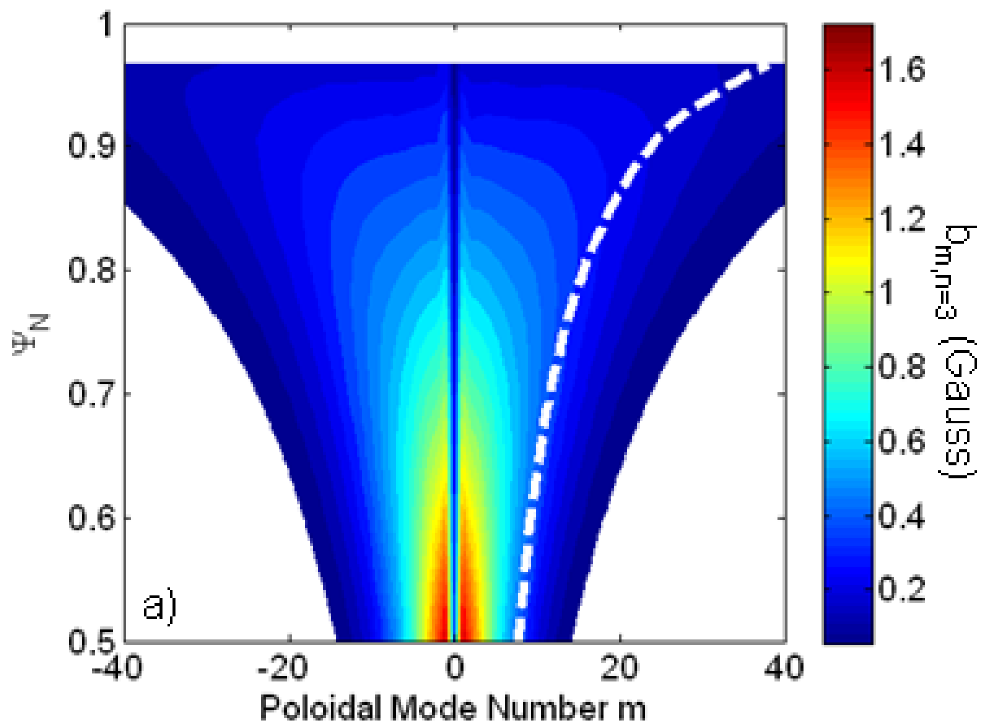


- Similar discharges compared with boronized/lithium coated PFCs
  - Lithium evaporated onto PFCs between discharges
- Plasma with lithium coated PFCs has higher energy confinement
- Boronization: ELMy
- Lithium: ELM-free
  - Suffers from impurity accumulation

External midplane coils are used to apply perturbation with strong resonant *and* non-resonant components

- n=3 configuration is used in all experiments presented here

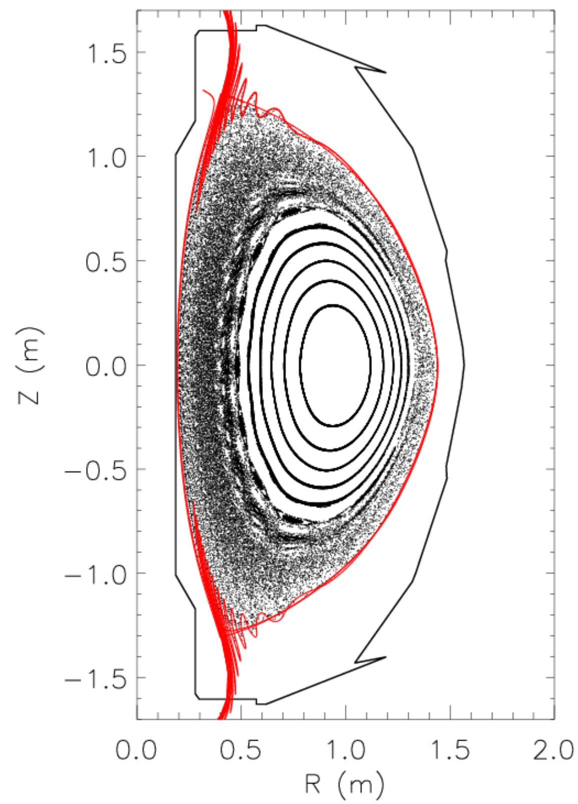




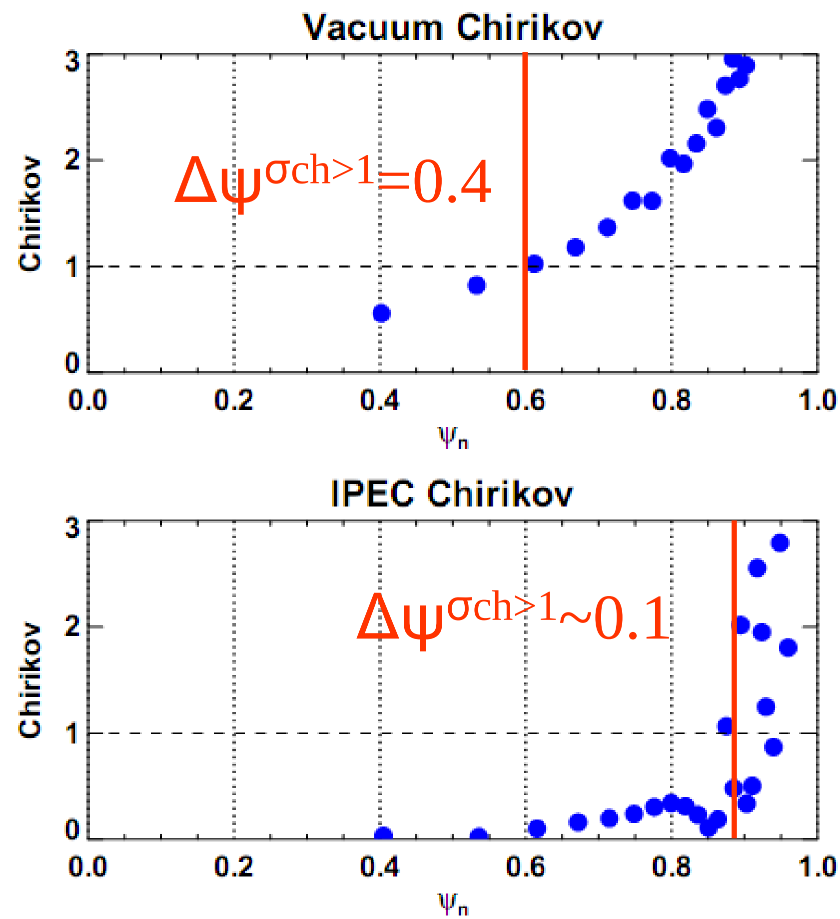
Vacuum Field

Resonant component amplitudes are sufficient for creating a stochastic edge

- Vacuum and IPEC calculations give different regions of strong resonance
  - Vacuum case: $\sigma^{ch} > 1$ implies overlapping islands, stochasticity
  - IPEC: ideal plasma response -> σ^{ch} is a measure of resonant fields, no islands are allowed

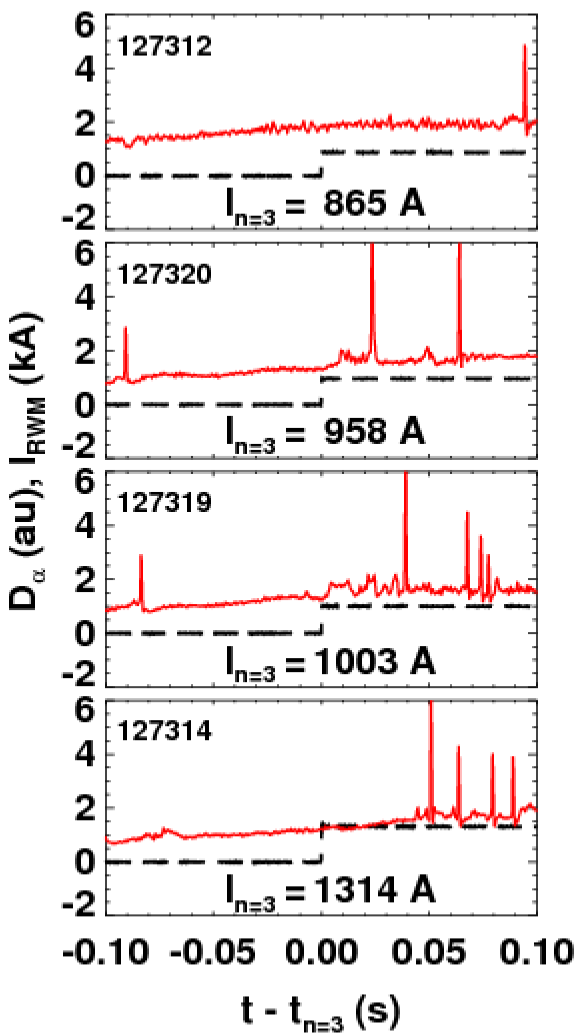


Vacuum fields



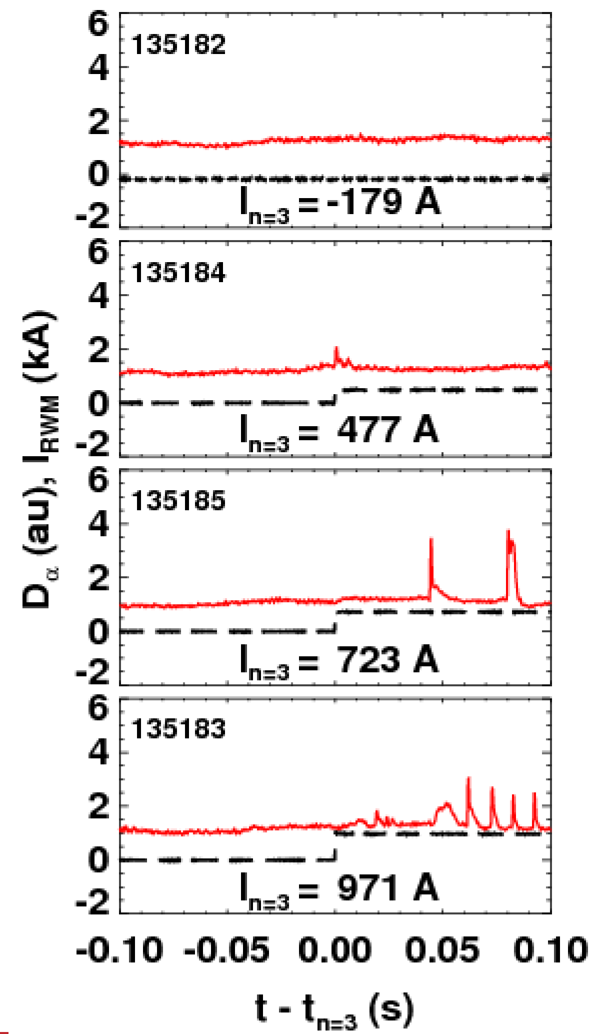
ELMs are destabilized above a threshold perturbation in both boronized and lithiumized plasmas

Boronized PFCs



- n=3 field applied during ELM-free/small ELM phase of discharge
- Above a threshold n=3 field ELMs destabilized for boroninzed or lithium-coated PFCs
- ELM frequency increases with n=3 field magnitude
  - High fields also brake plasma strongly, degrade global stability

Li-coated PFCs

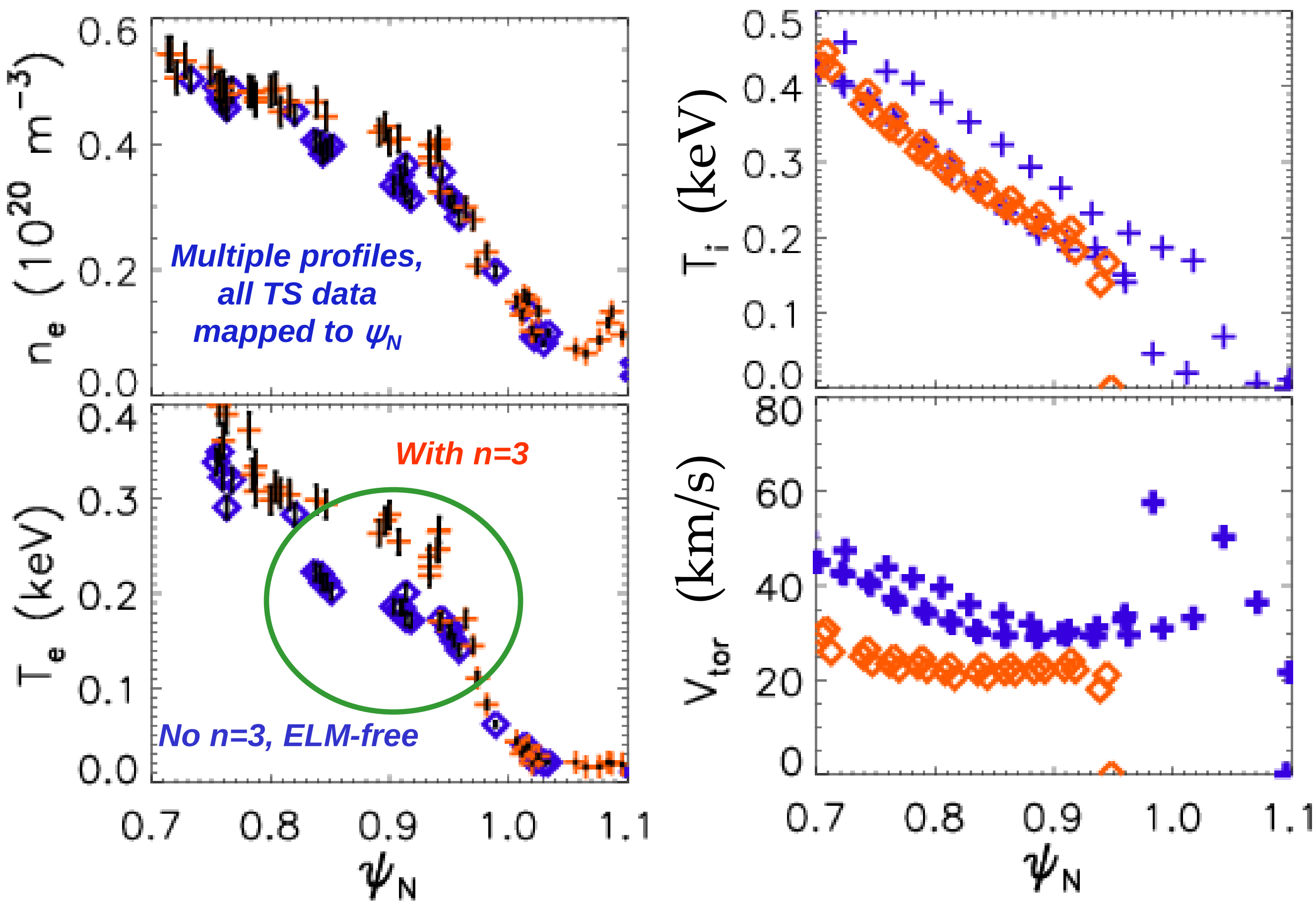


With boronized PFCs, T_e^{ped} increases when n=3 field is applied

- Blue profiles: no n=3 applied
- Red profiles: 20 ms after n=3 applied (before ELMs)

No lithium coatings in these shots

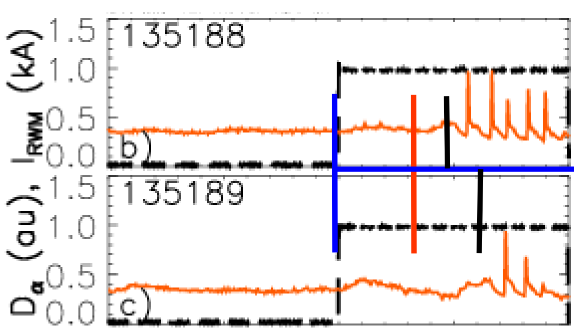
Pedestal electron profiles ***Pedestal ion profiles***

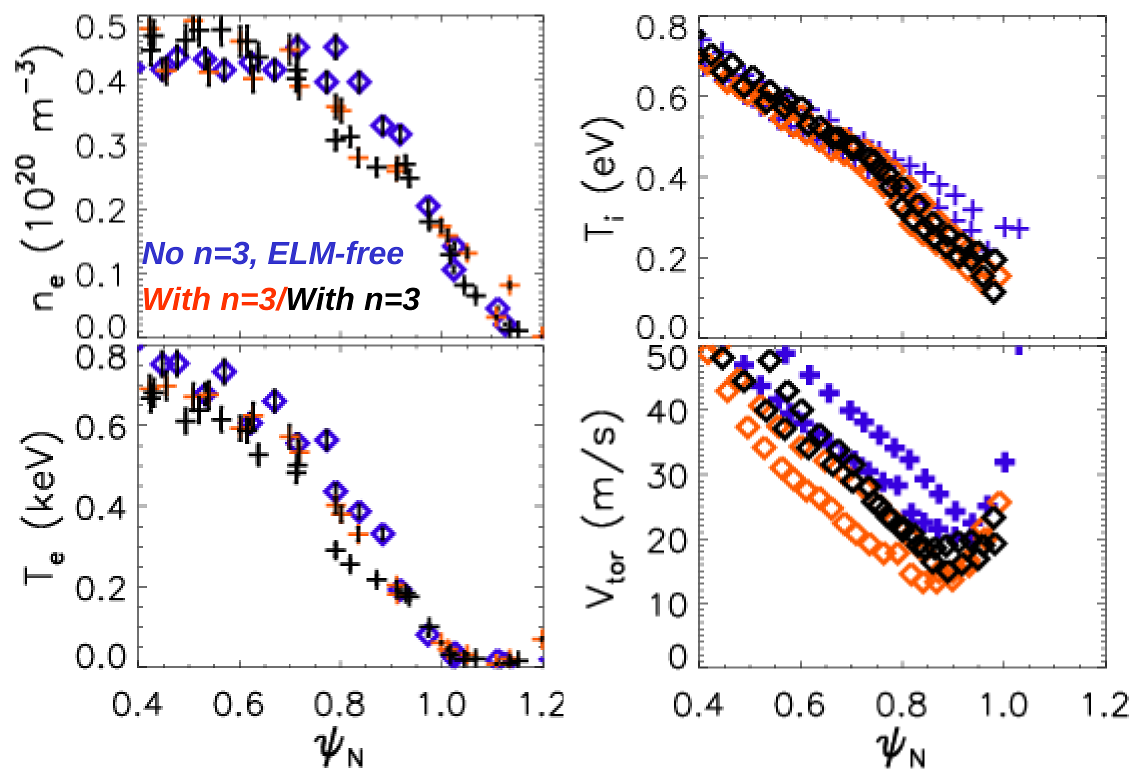


- No density pumpout is observed
- T_e, pressure gradient increases after n=3 field is applied
  - ~30% increase in peak pressure gradient from tanh fits
  - PEST shows edge unstable after n=3 application

Flattening of n_e/T_e inside pedestal in response to perturbation observed with lithium coatings

- Data combined from several shots, all before ELMs start
  - Color code: Just before n=3, 30 ms after, ~50/65 ms after
- T_e, n_e show flattening from ψ_N ~0.8-0.9, similar gradient outside 0.9
- Toroidal rotation reduced after n=3 field is applied, with a local minimum near ψ_N=0.9
- Island formation inside pedestal?





Magnetic ELM triggering has been applied to lithiumized ELM-free H-modes to control impurity accumulation

Typical behavior with Li wall conditioning

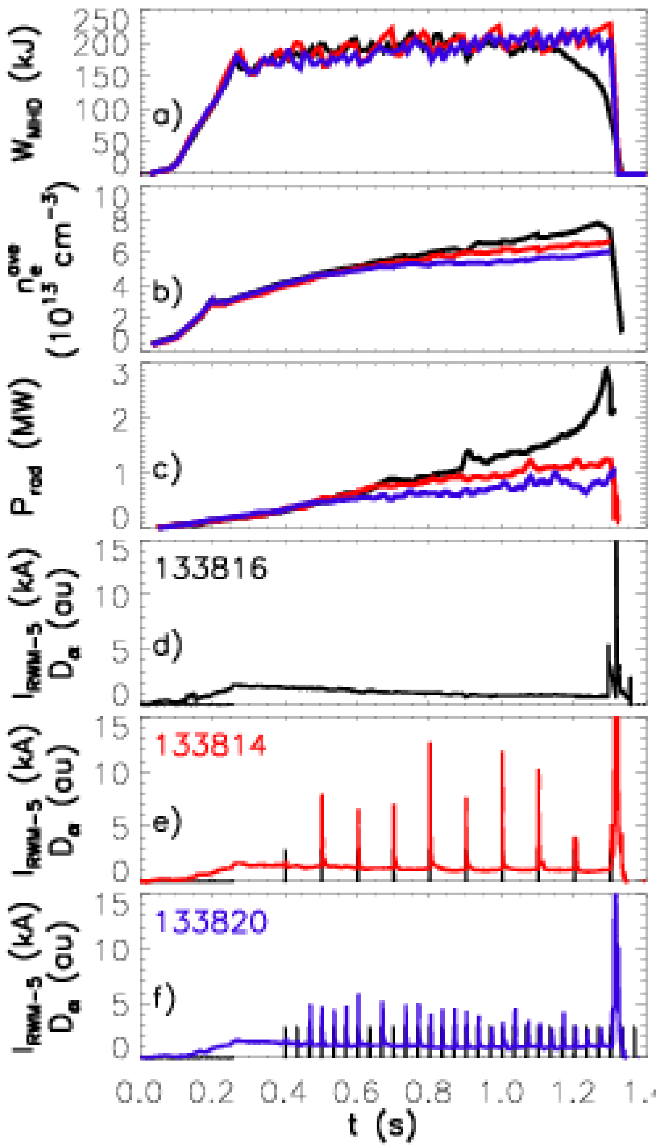
- ELMs suppressed
- P_{rad} ramps to ~2 MW; P_{NBI} = 3 MW

Square wave of n=3 fields applied to LITER discharge

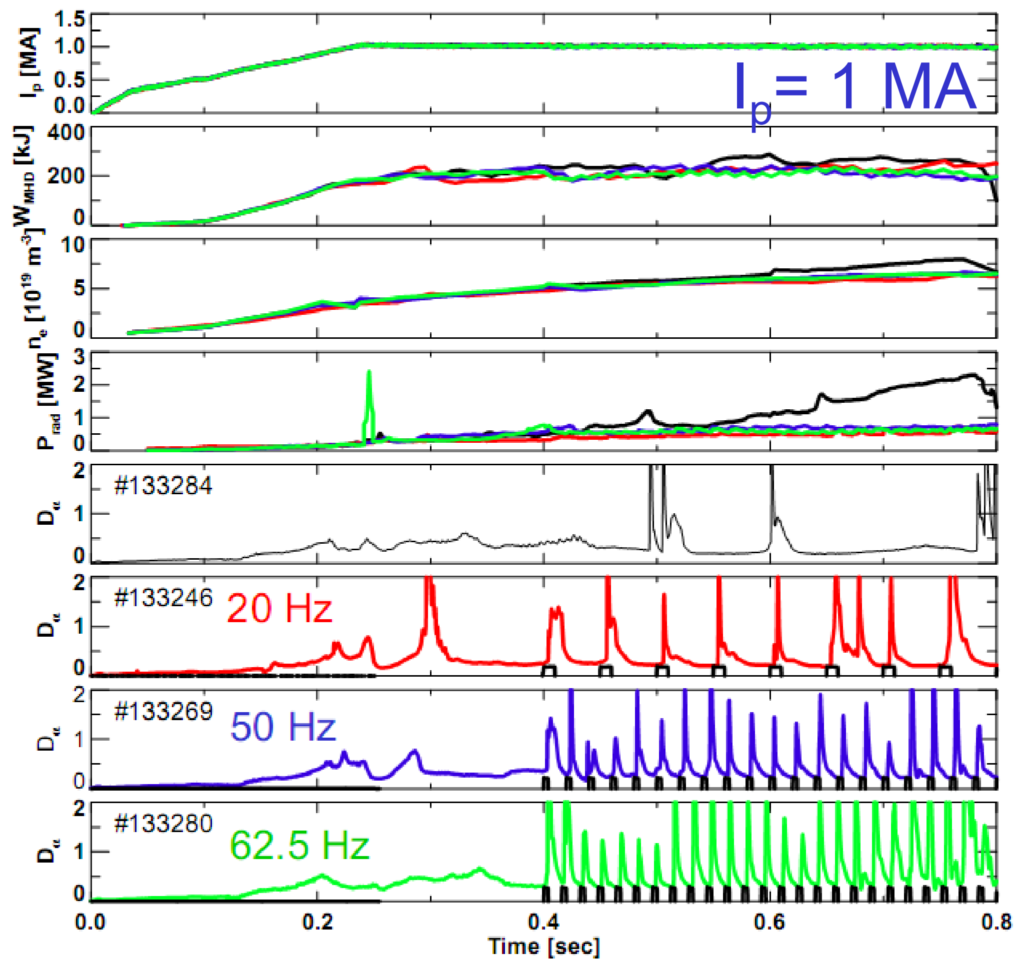
- Fast pulses used rather than DC fields to reduce rotation braking
- 4 ms pulses, f=10/30 Hz, amp. 2.2 kA

ELMs can be triggered at will

- Full control over ELM timing and frequency
- Used here for discharge control, reducing n_e and P_{rad} ramp rate



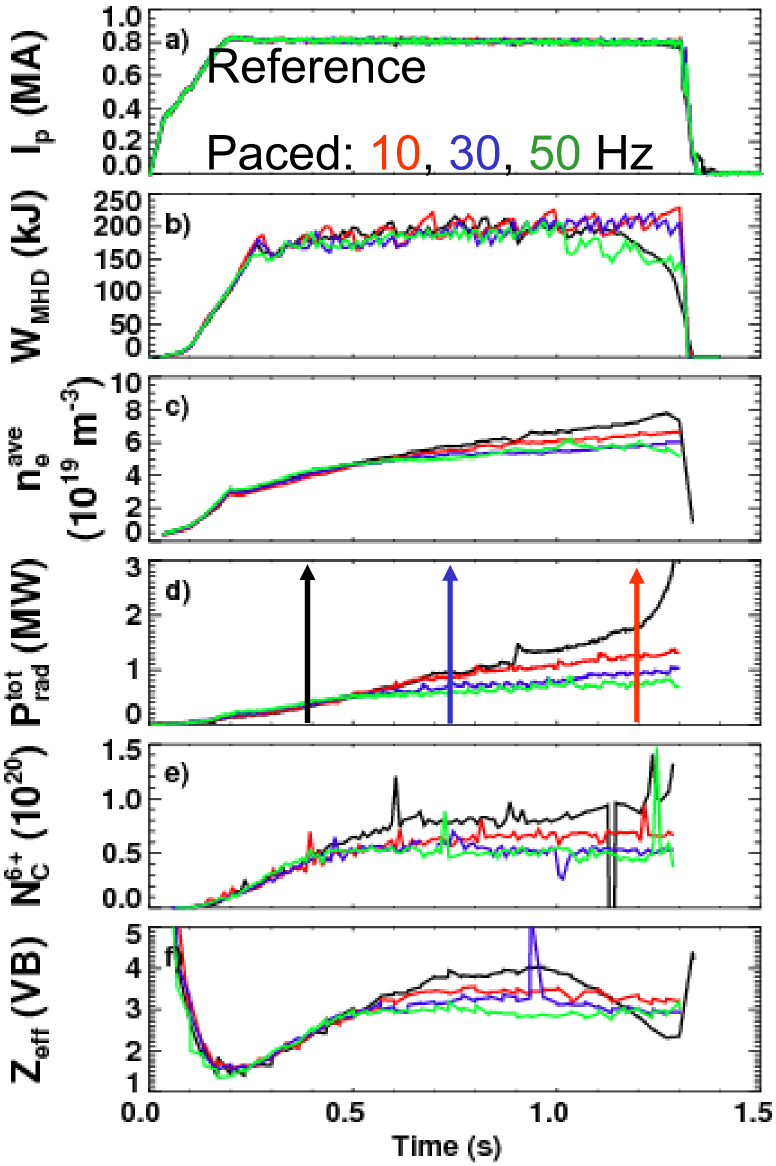
n=3 pulse waveform has been optimized to give reliable high frequency triggering with reduced rotation braking



- Maximizing pulse amplitude allows rapid triggering
  → Shorter pulses
- Opposite-sign trailing pulses added after each triggering pulse
  - Counteracts vessel eddy currents, reduces field inside vessel more quickly

  → Reduced plasma braking
- ELM frequencies up to 62.5 Hz have been achieved
  - Avoids intermittent very large ELMs seen with unreliable triggering
  - Frequency partially limited by vessel penetration time

Pacing frequency varied to optimize for impact on impurities, ELM size



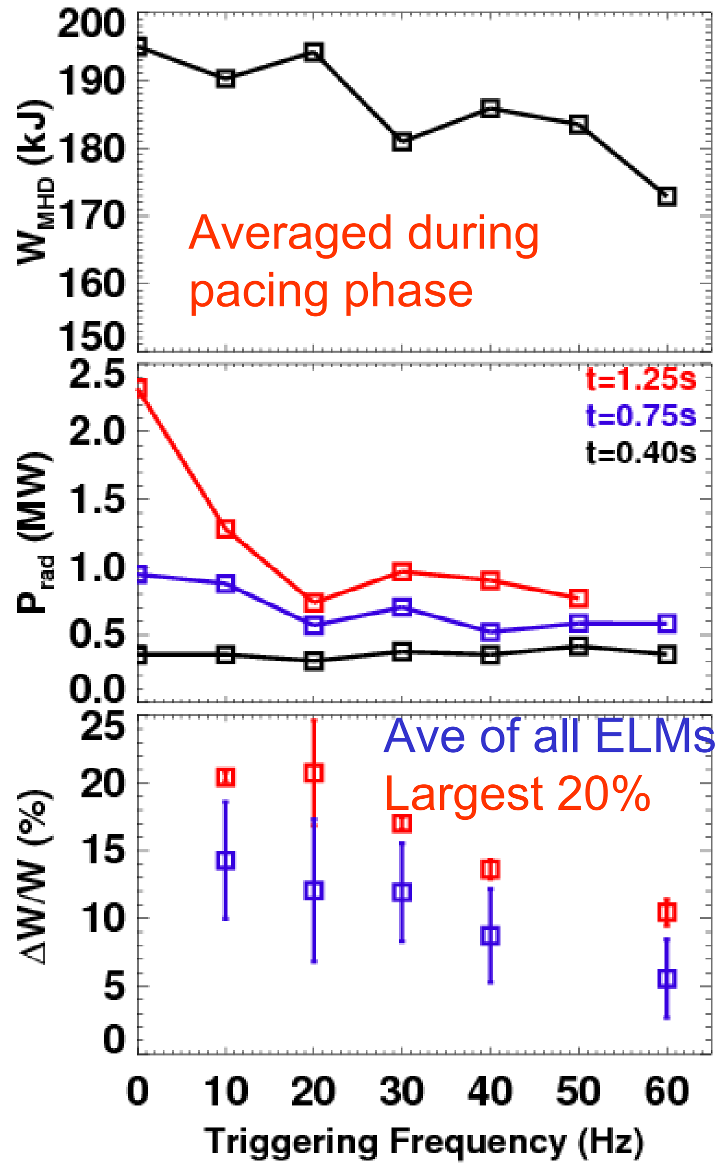
- Pacing has a positive impact on density/impurity evolution at all frequencies
  - n_e is reduced, rise is slowed
  - High-Z impurities: radiated power reduced, held below ~25% of P_{NBI}
  - Low-Z: total carbon content and Z_{eff} reduced, time evolution controlled

- Impact on impurities considered at three times in discharge
  - t=0.4 s: beginning of pacing
  - t=0.75 s: during pacing
  - t=1.25 s: near end of discharge

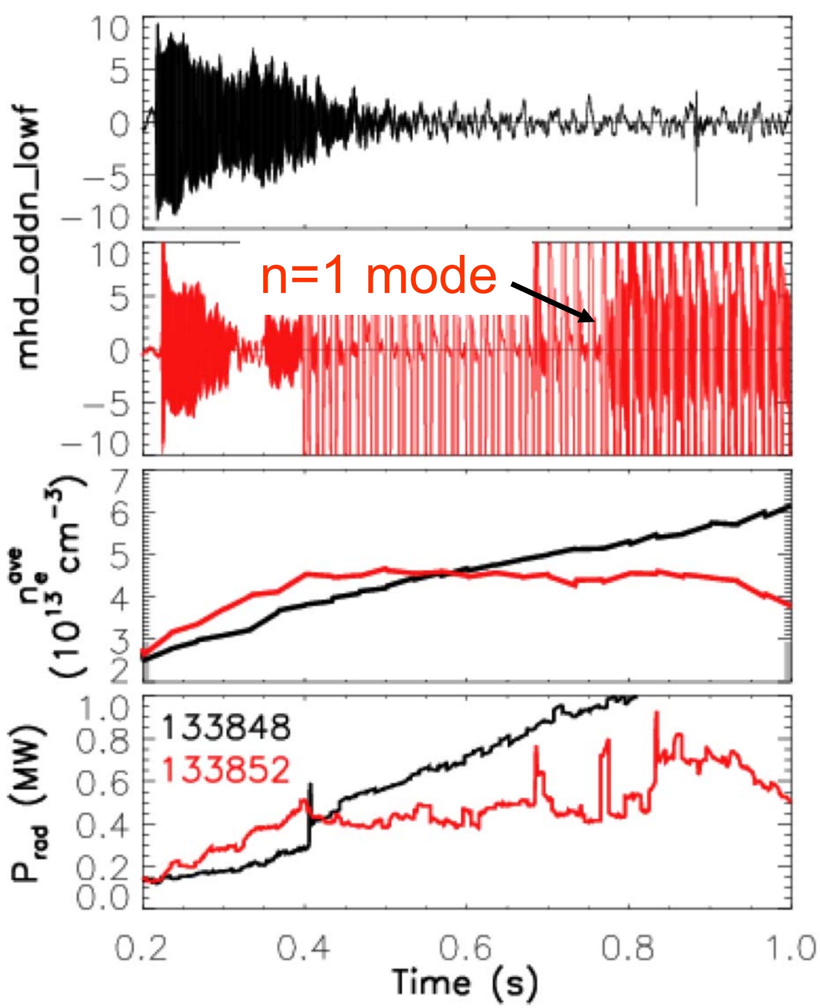
Pacing frequency varied to optimize for impact on impurities, ELM size

- Low frequency pacing may be ideal for impurity control while minimal impact on energy confinement
  - Stored energy reduced with high frequency (10% reduction at 60 Hz)
  - P_{rad} <1 MW for pacing >20 Hz

- ELM size is reduced at higher frequency pacing
  - Average ELM size reduced from ΔW/W~15% at 10 Hz to ~5% at 60 Hz
  - Mean size of largest 20% of ELMs reduced from ~20% to ~10%

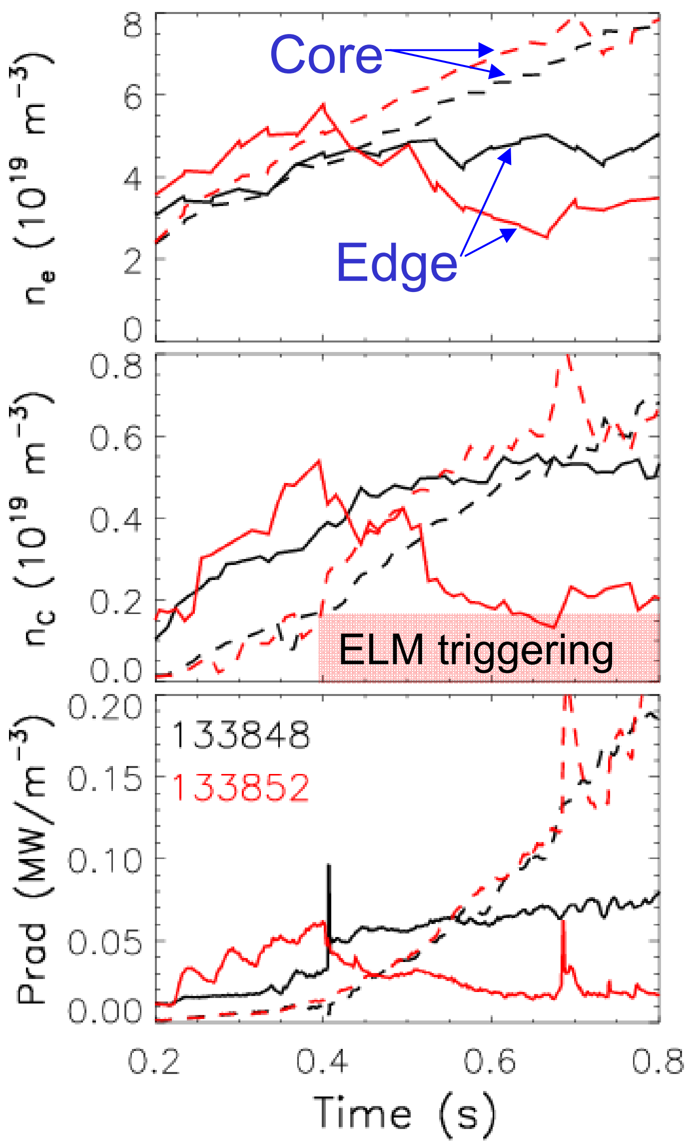


Combining ELM pacing with optimized fueling successful in producing quasi-stationary global parameters



- Fueling from a slow valve on the center stack was reduced, replaced with a puff with faster response
  - Allows fuelling to be turned off quickly following startup
- Applying n=3 pulses arrested the line-averaged density and total radiated power for 0.3 s
- Discharge performance was limited by n=1 rotating MHD

Although global parameters are stationary, profiles are still evolving



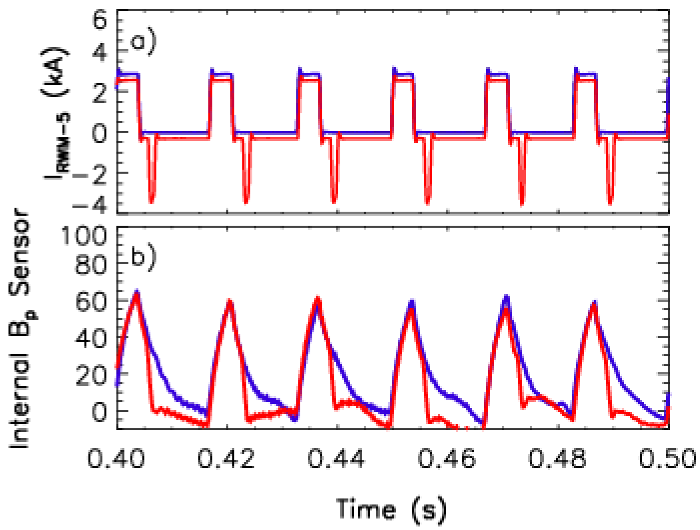
- Similar profile evolution observed in electron, carbon, and radiation densities
  - Edge density decreases in time during ELM pacing
  - Core value increases in time, rate is similar to case without pacing
- Core impurity control is needed
  - RF heating to mitigate central accumulation is planned

Summary

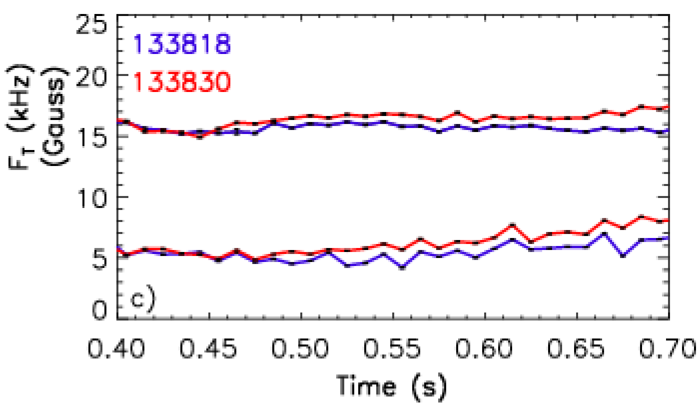
- Application of n=3 fields can destabilize ELMs
  - Without lithium, n=3 reduces rotation, increases pedestal electron pressure
    - Stability calculations show pedestal is near limits, more research needed to explore transition from stable to unstable
  - With lithium, pedestal shows flattening of n_e, T_e

- ELM triggering has been used for magnetic ELM pace-making in Li-enhanced ELM-free H-modes
  - Li coatings suppress ELMs, improve confinement, but problems with impurity accumulation
  - ELMs are controllably introduced with n=3 fields, reducing density and radiated power
  - Optimization of triggering waveform allows high frequency pacing
    - High amplitude, short duration pulses with negative-going trailing pulses give reliable triggering with reduced rotation braking
    - Global parameters have been fully arrested, but not profiles
    - ELM size is reduced at high frequency

Fast negative-going pulses can reduce the time-averaged magnetic field



- Each triggering pulse is followed by a shorter pulse of the opposite sign
  - Cancels eddy currents
  - Optimized to rapidly bring internal field to ~zero



- Results in reduced time-averaged perturbation
  - -> less magnetic braking