ELM Pacing with 3D Magnetic Perturbations in NSTX

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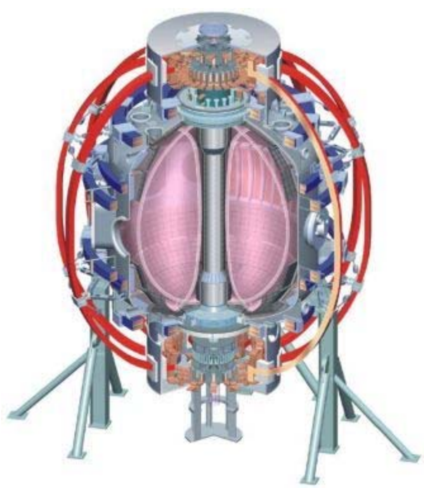

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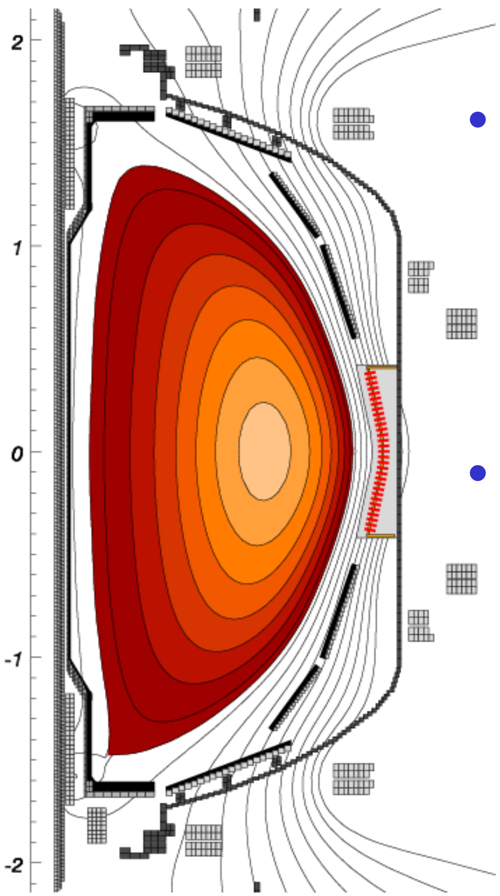
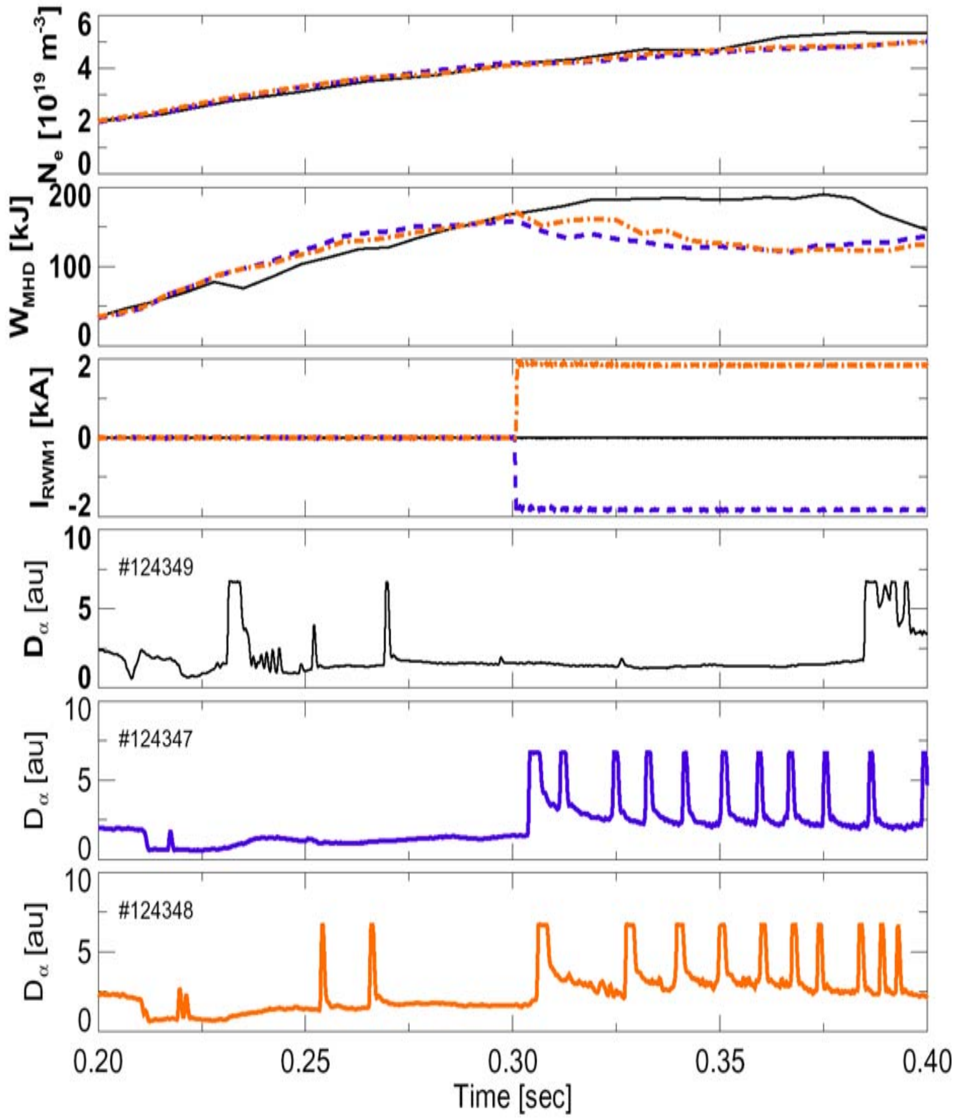
Application of 3D field can destabilize ELMs in NSTX

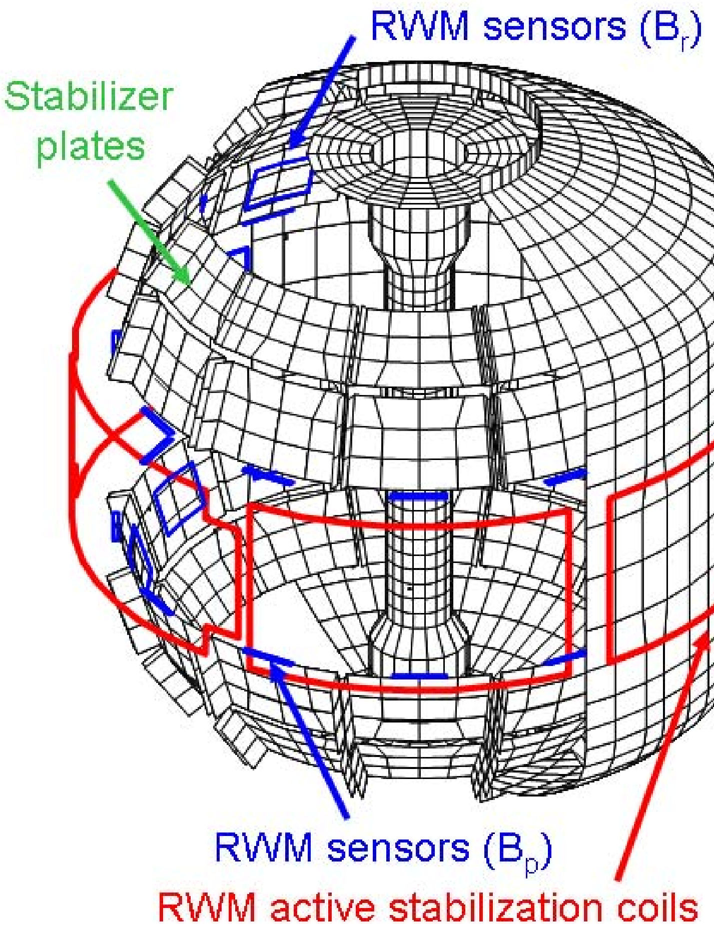


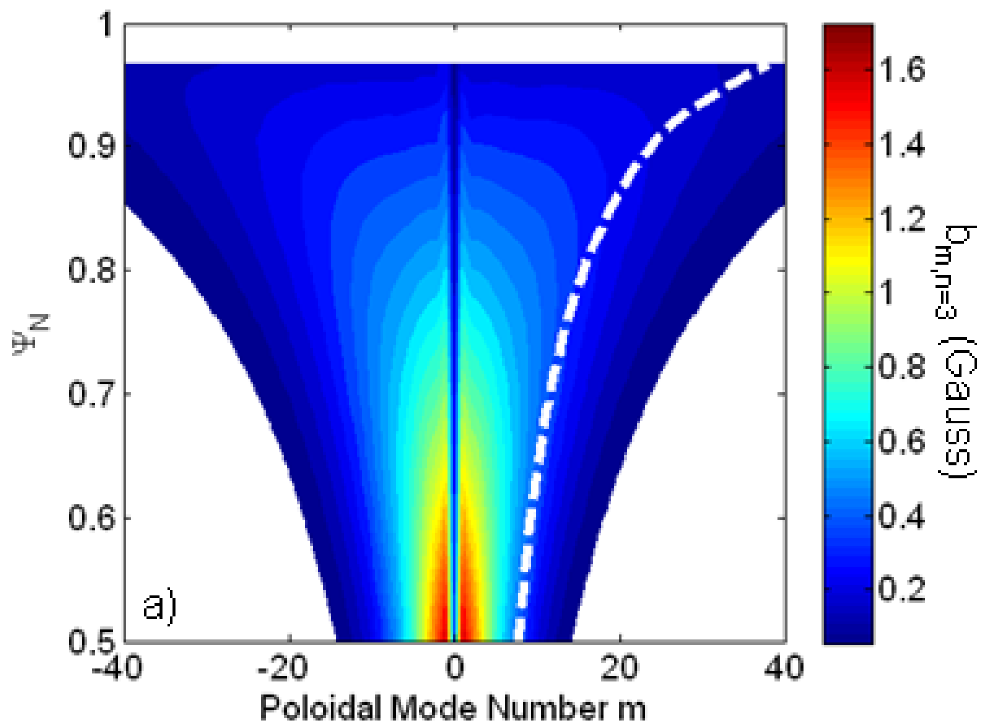
- NSTX: the National Spherical Torus Experiment
- Parameters of these expts:
  - R/a=85/65 cm
  - B_t=0.45 T, I_p=0.8-1.0 MA, P_{NBI} ≤ 6MW



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

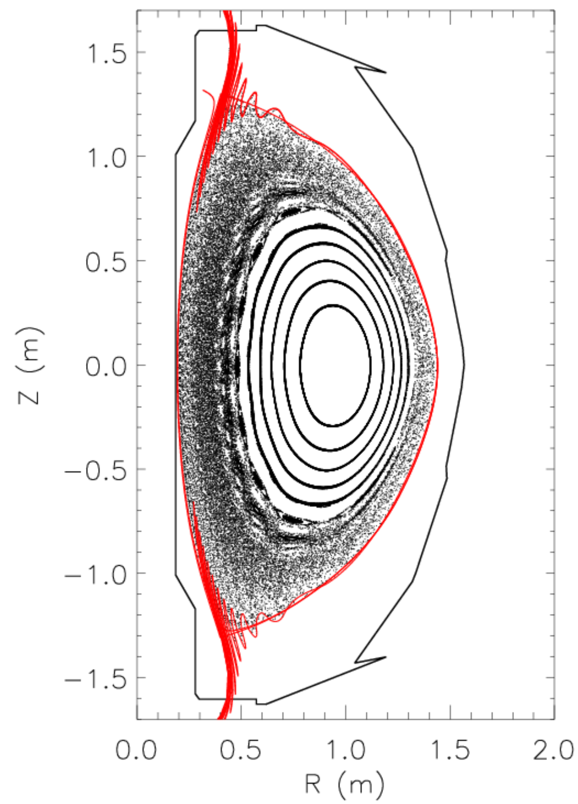




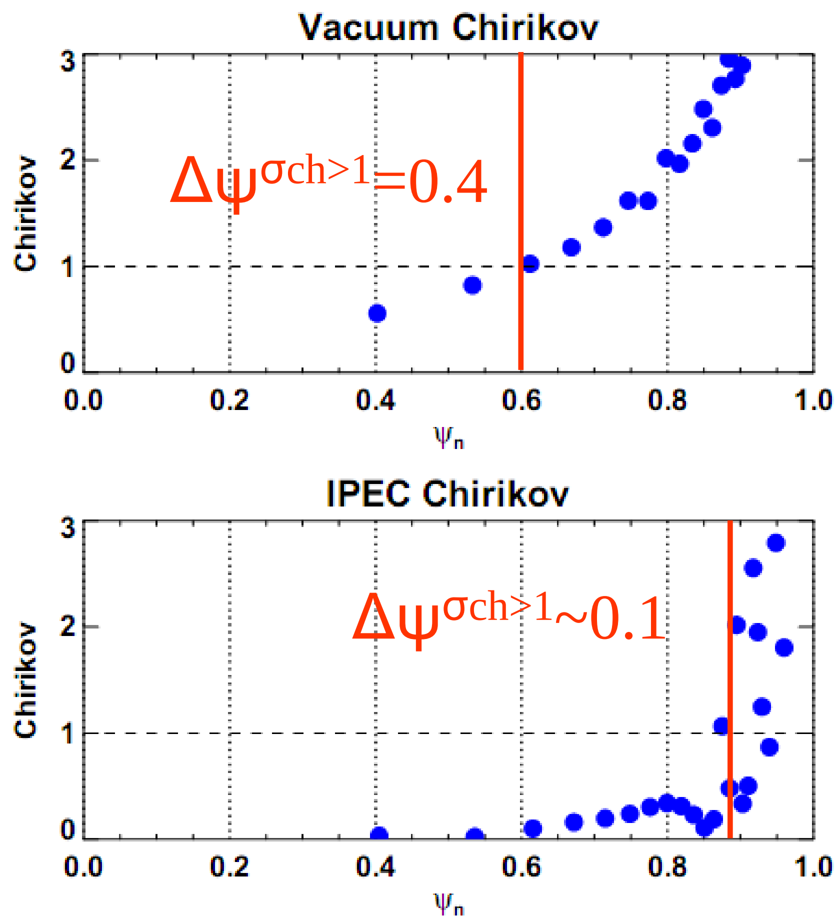
Vacuum Field

Resonant components are sufficient for edge stochasticity

- 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

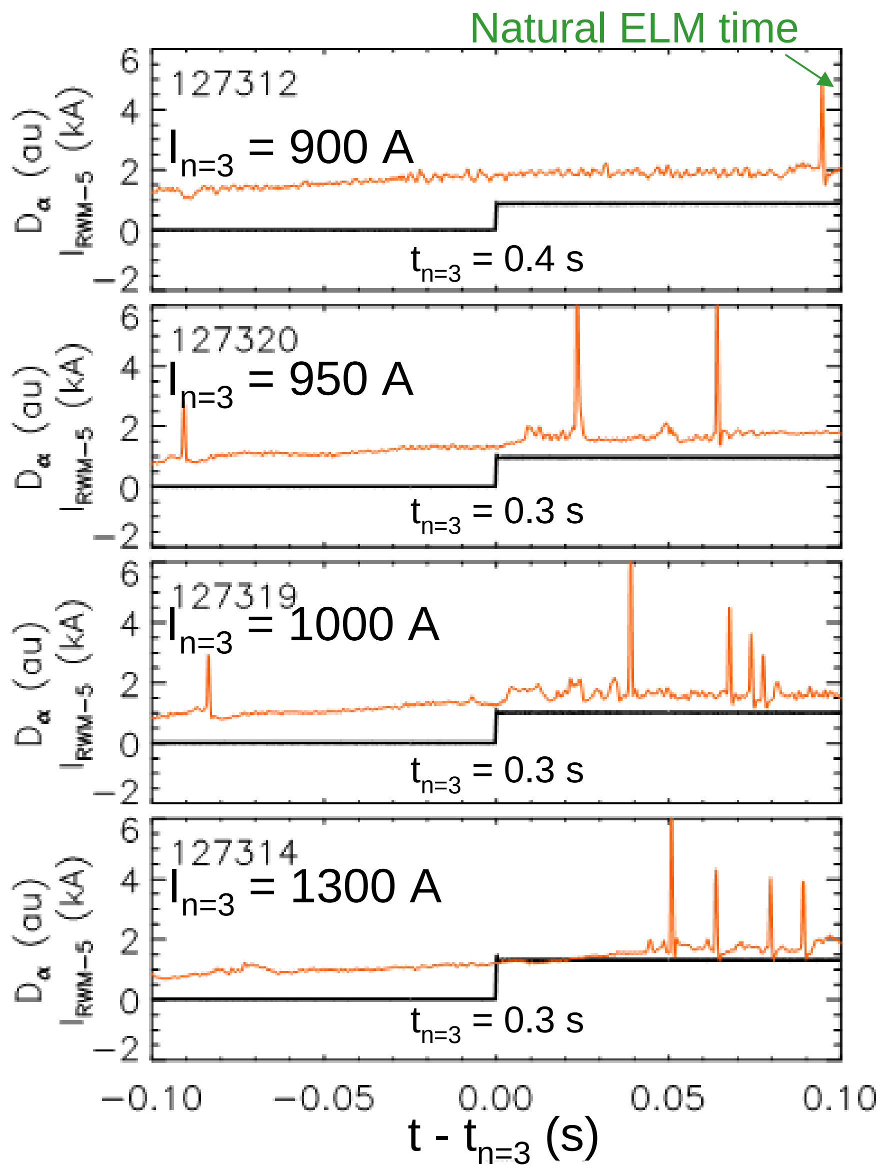


Vacuum fields



Midplane coil current scan shows threshold for destabilization without lithium coatings

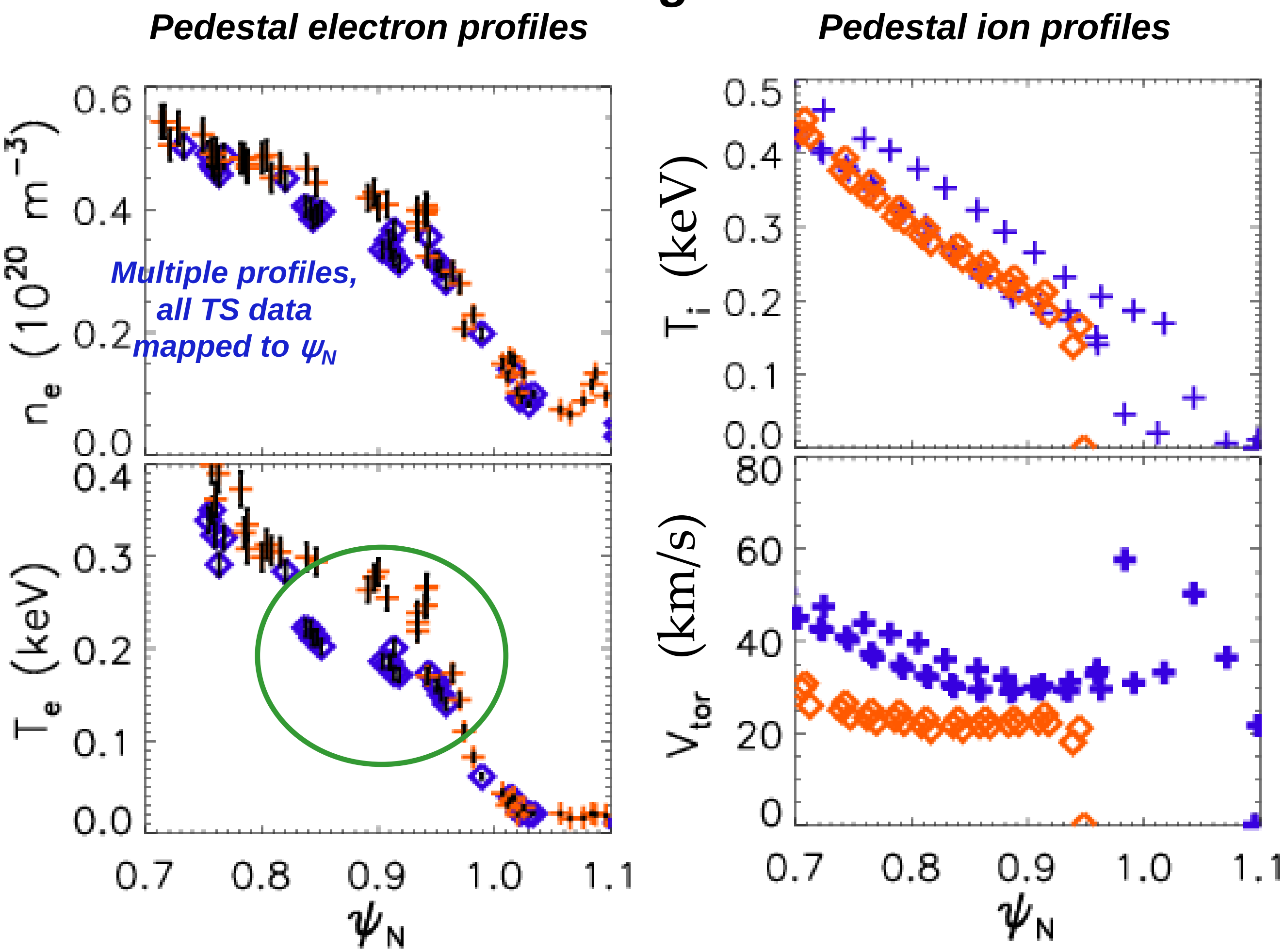
- Threshold coil current for ELM-triggering is ~950 A ->$\Delta B/B = 6\times10^{-3}$
  - No triggering at 900 A (natural ELMs start at ~0.5s in control discharge)
  - Intermittent ELMs at 950 and 1000 A
- ELM frequency appears to increase with n=3 field magnitude
  - ELMs become more regular
  - Tendency clouded by tendency of plasma to lock high currents- too much braking



T_e^{ped} increases when n=3 field is applied without lithium coatings

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

No lithium coatings in these shots



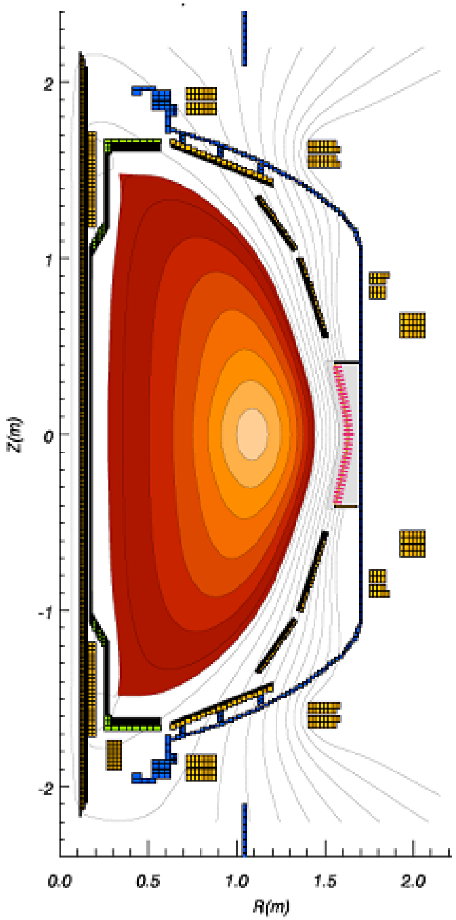
- Core n_e, T_e, T_i profiles unaffected, rotation decreases

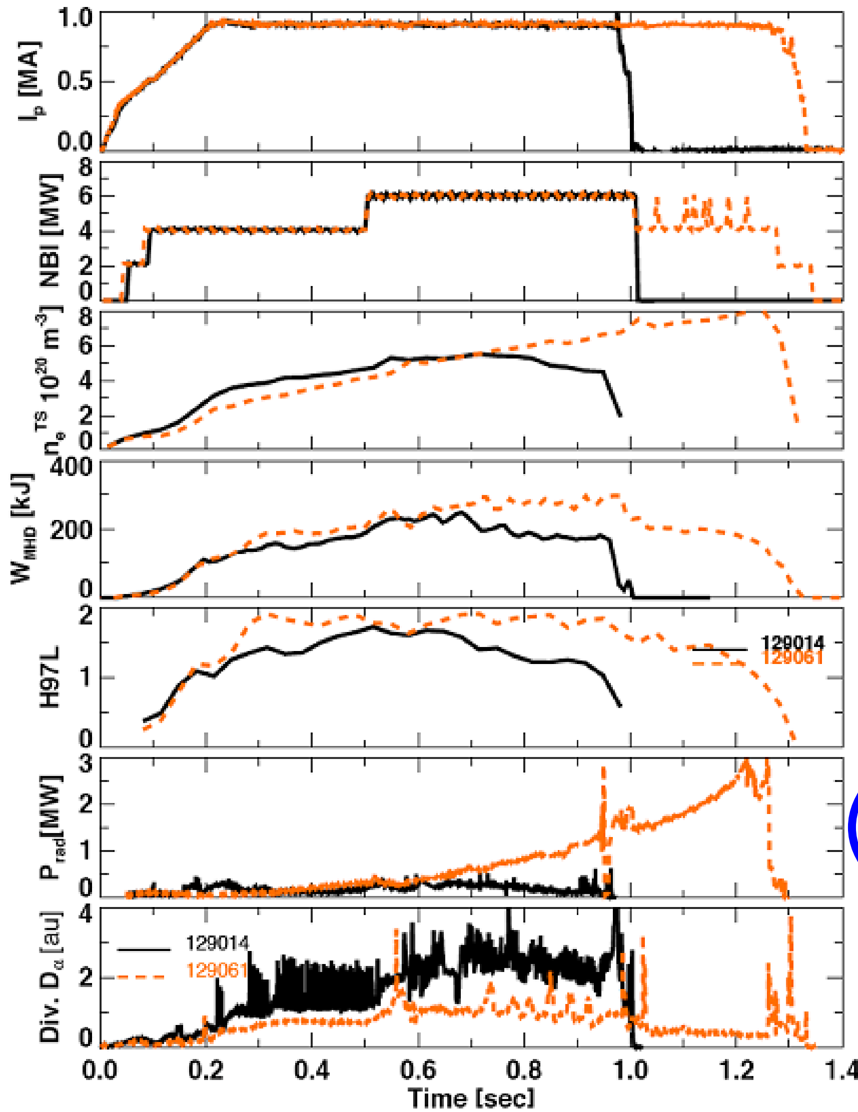
  No density pumpout is observed

  Te, pressure gradient increases after n=3 field is applied
  - Tanh fitting gives ~30% increase in peak pressure gradient
  - PEST shows edge unstable after n=3 application

Lithium wall conditioning improves pulse length, increases τ_E, suppresses ELMs, but shows impurity accumulation

Standard high
κ~2.3, δ~0.8 shape





- Pre-Li, Post-Li
- Longer pulse
- Lower n_e early, higher late
- Higher stored energy
- Higher H-factor
- Higher radiated power
- ELM-free, lower recycling

Kugel PSI08

Magnetic ELM triggering has been applied to Lithium enhanced ELM-free H-modes

Typical behavior with Li wall conditioning

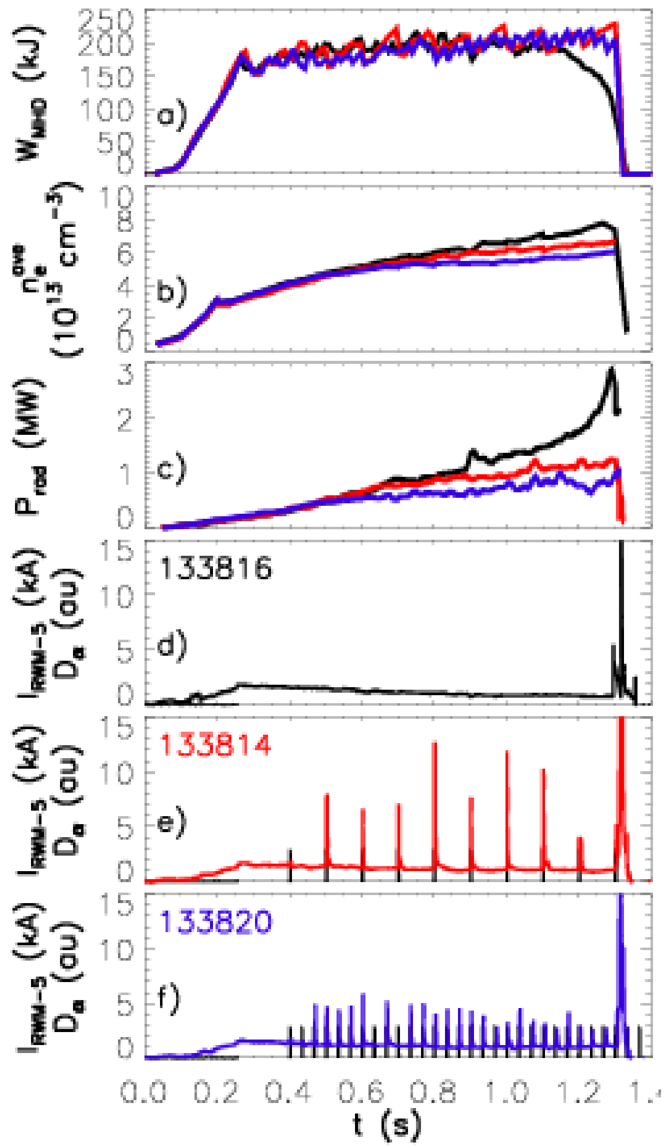
- ELMs suppressed
- P_{rad} ramps to ~2 MW; P_{NBI} = 3 MW

Square wave of n=3 fields applied to LITER discharge

- 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



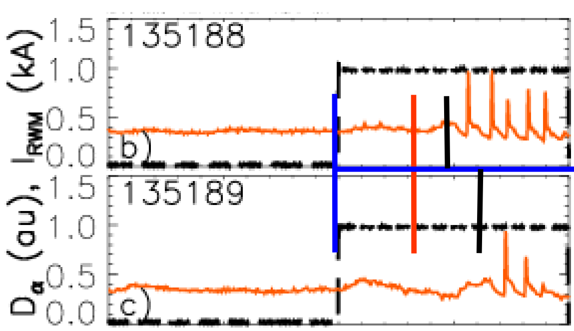
Pedestal response to perturbation with lithium coatings

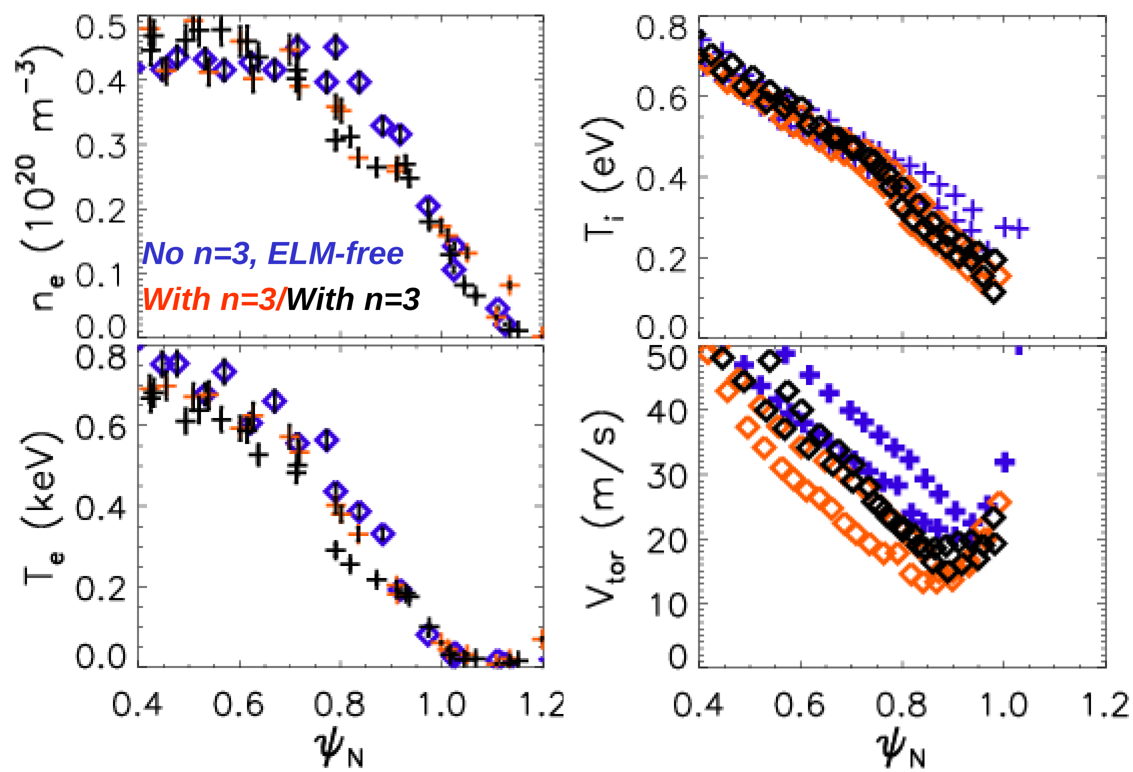
Data combined from several shots, all before ELMs start

Color code: Just before, 30 ms after, ~50/65 ms after n=3 turned on

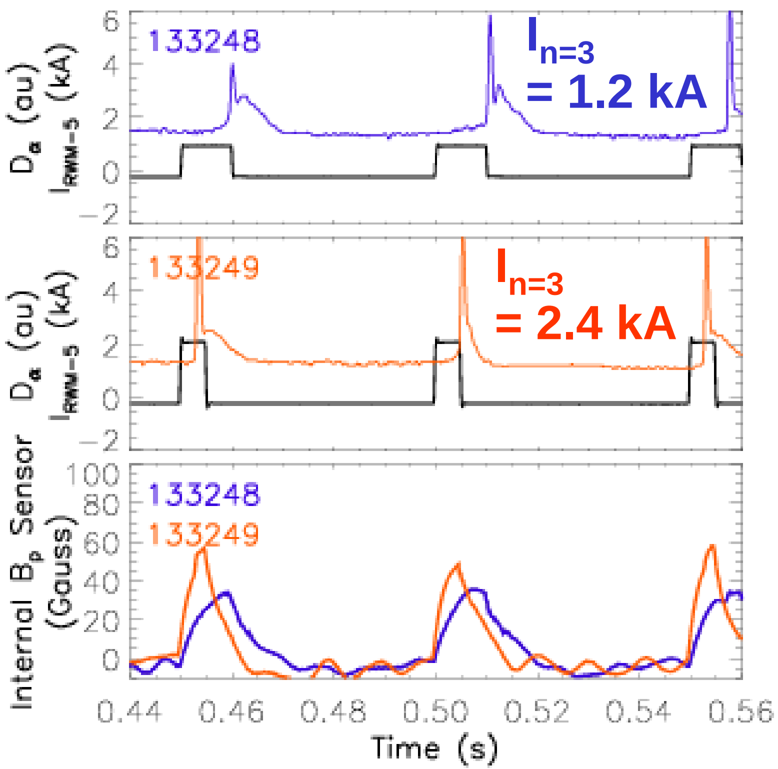
Edge ion temperature, toroidal rotation drop after n=3 field is applied

Te, ne show flattening from ψ_N ~0.8-0.9, similar gradient outside 0.9



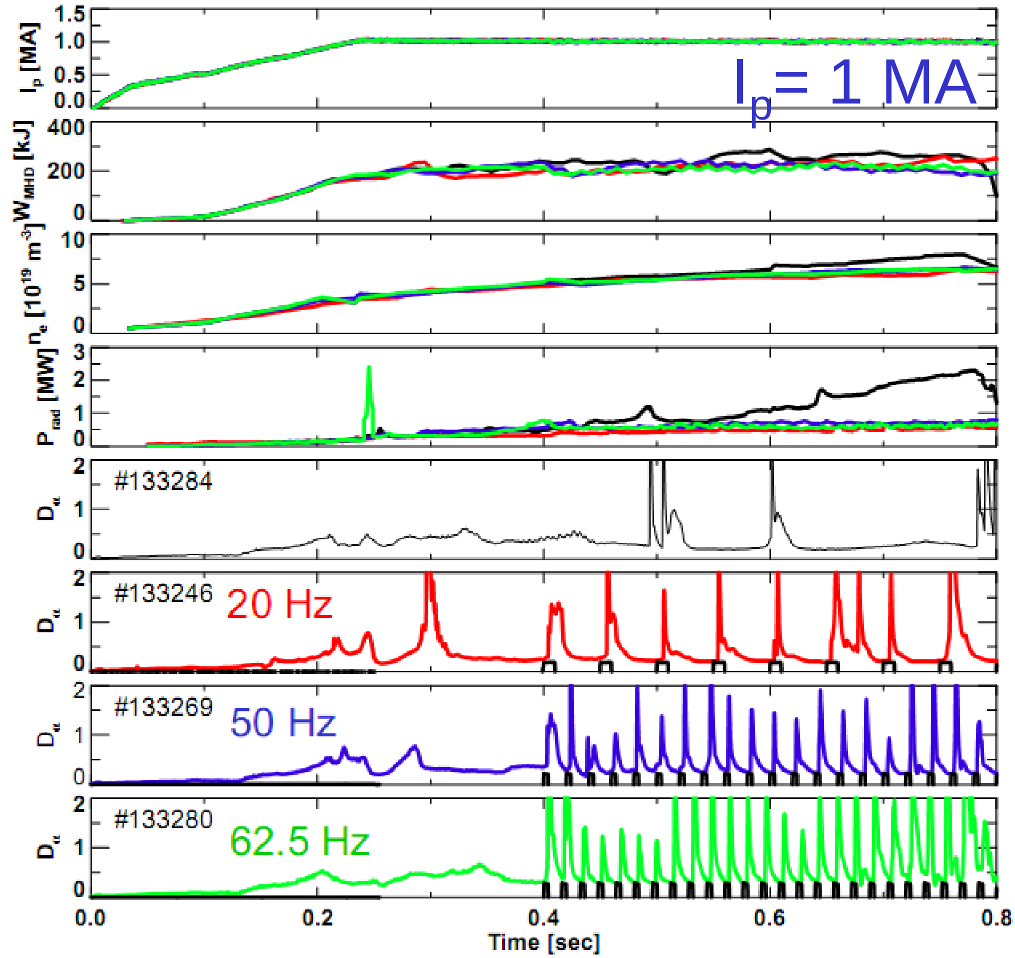


Optimizing ELM pacing for impurity control (1): Increasing the n=3 perturbation strength triggers ELMs faster



- With 1.2 kA pulses of in perturbation coils, ELMs are triggered in ~8 ms
- At 2.4 kA, ELM onset is reduced to ~3 ms
- Limited by field penetration time through vessel (estimated to be ~4 ms)
  - Internal coils may trigger much faster
- Provides a means for improving triggering efficiency for fixed pulse duration

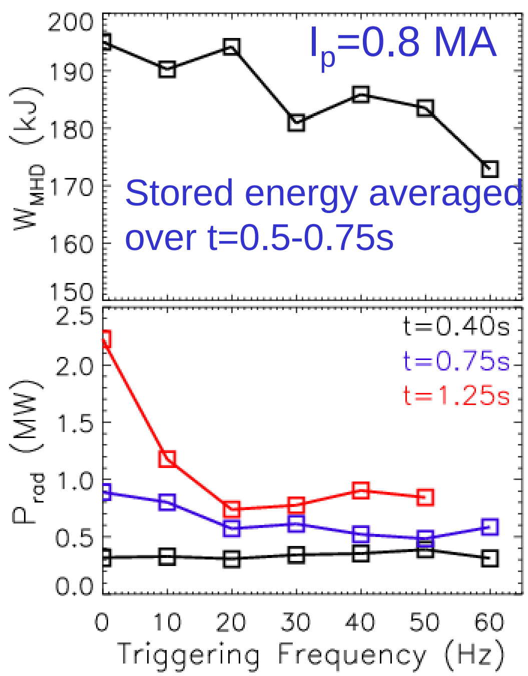
Maximizing the n=3 pulse amplitude allows high frequency triggering with very high reliability

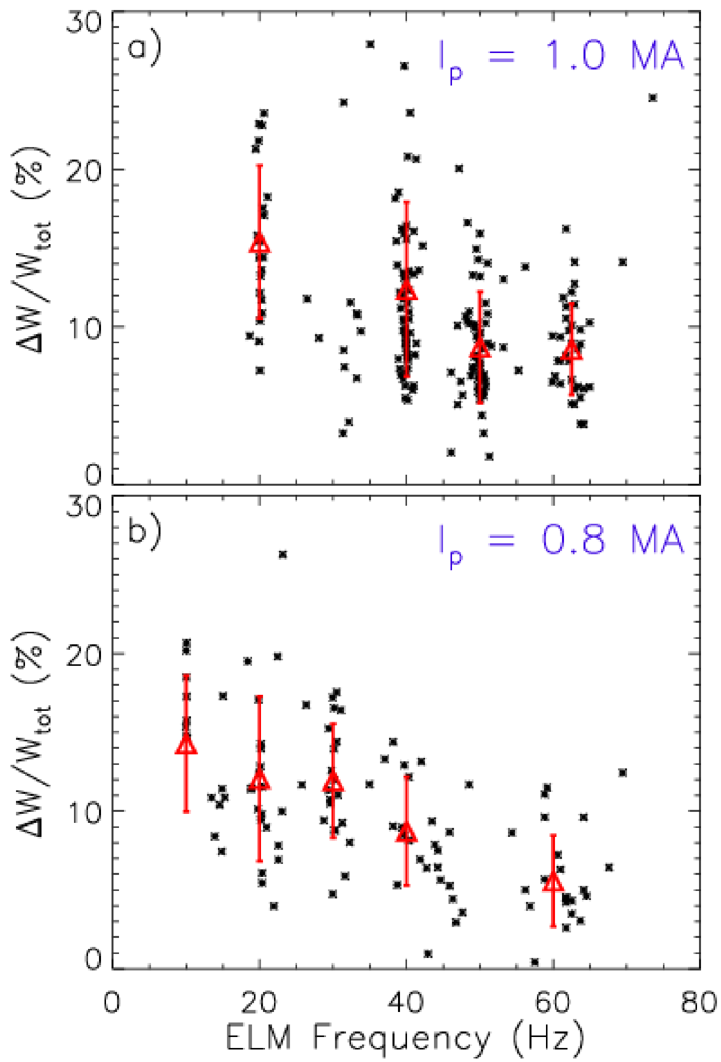


- ELM frequencies up to 62.5 Hz have been achieved while maintaining 100% triggering efficiency
  - Allows average ELM size to be reduced
  - Internal coils should allow faster triggering, higher frequency
- Time-average magnetic braking of rotation is strong at high frequencies

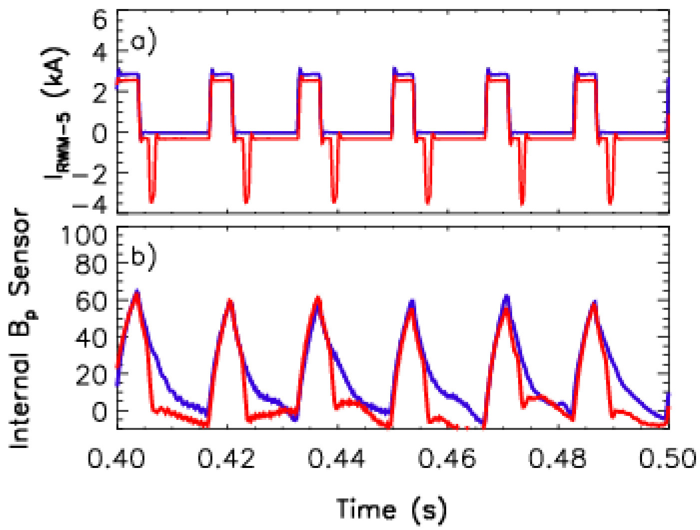
Lower triggering frequency may be optimal for impurity control, higher frequency reduces ELM size

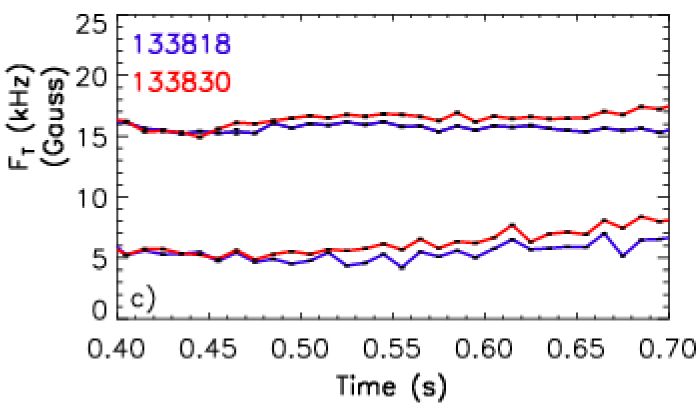
- Low frequency (20 kHz) triggering gives impurity control with minimal degradation of W_{MHD}
- Average ELM size can be reduced to ~5% by increasing triggering frequency to 60 Hz
  - Weak reduction with frequency (< 1/f)
  - Apparent I_p dependence on ELM size





Optimizing ELM pacing for impurity control (2):
Fast negative-going pulses can reduce the time-averaged magnetic field





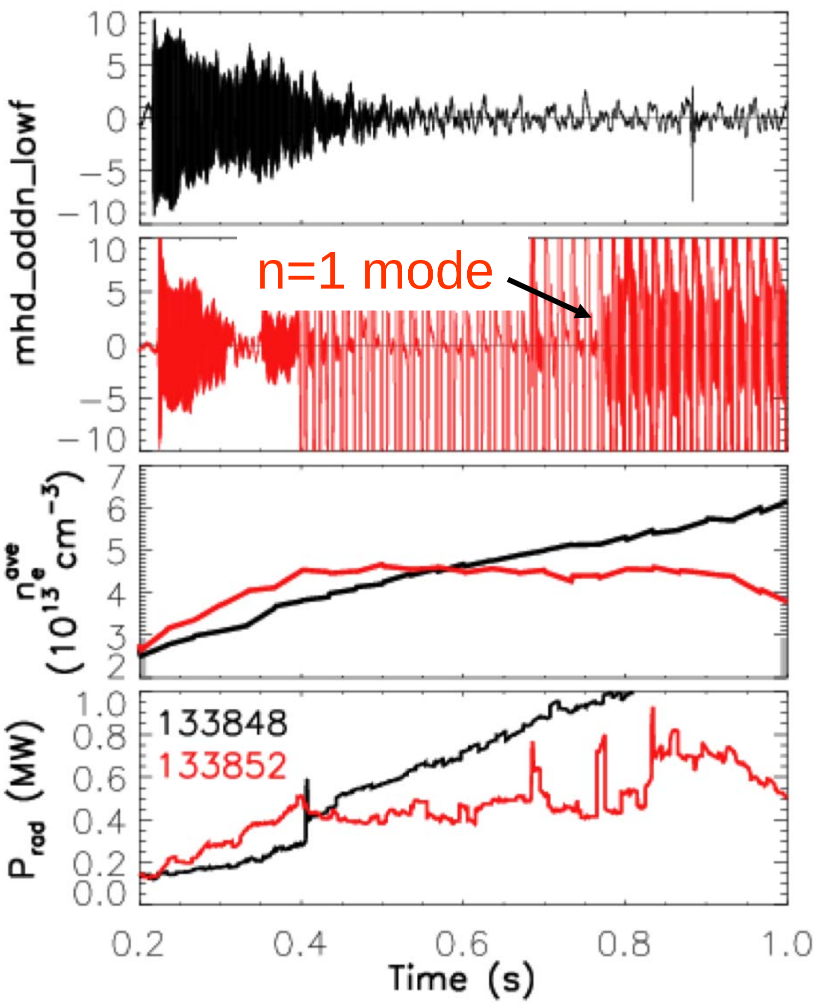
Each triggering pulse is followed by a shorter pulse of the opposite sign

- Cancels eddy currents
- Optimized to rapidly bring internal field to ~zero

Results in reduced time-averaged perturbation

-> less magnetic braking

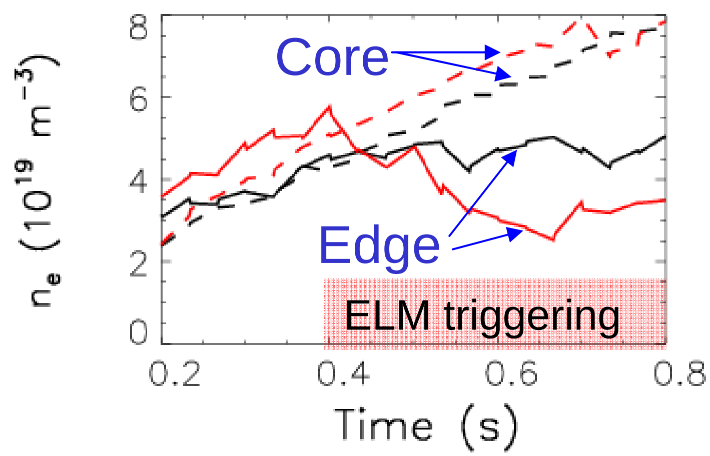
Combining high-frequency ELM pacing with improved fueling produces quasi-stationary global parameters, profiles still evolving



- 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

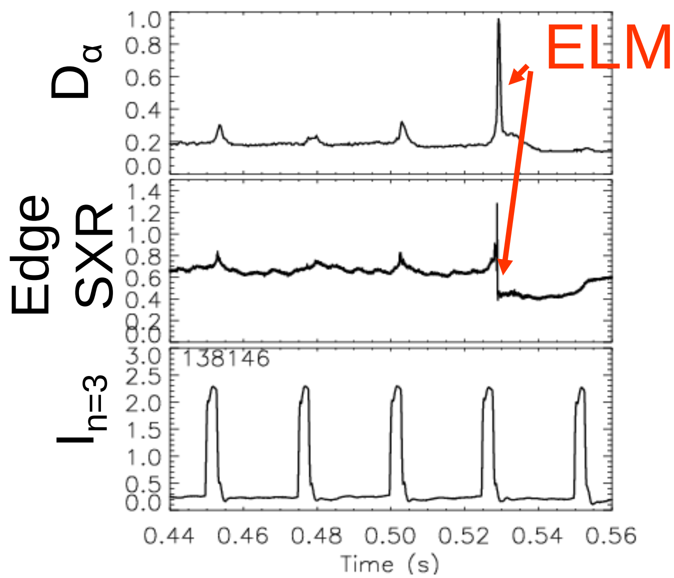
Applying n=3 pulses arrested the line-averaged density and total radiated power for 0.3 s

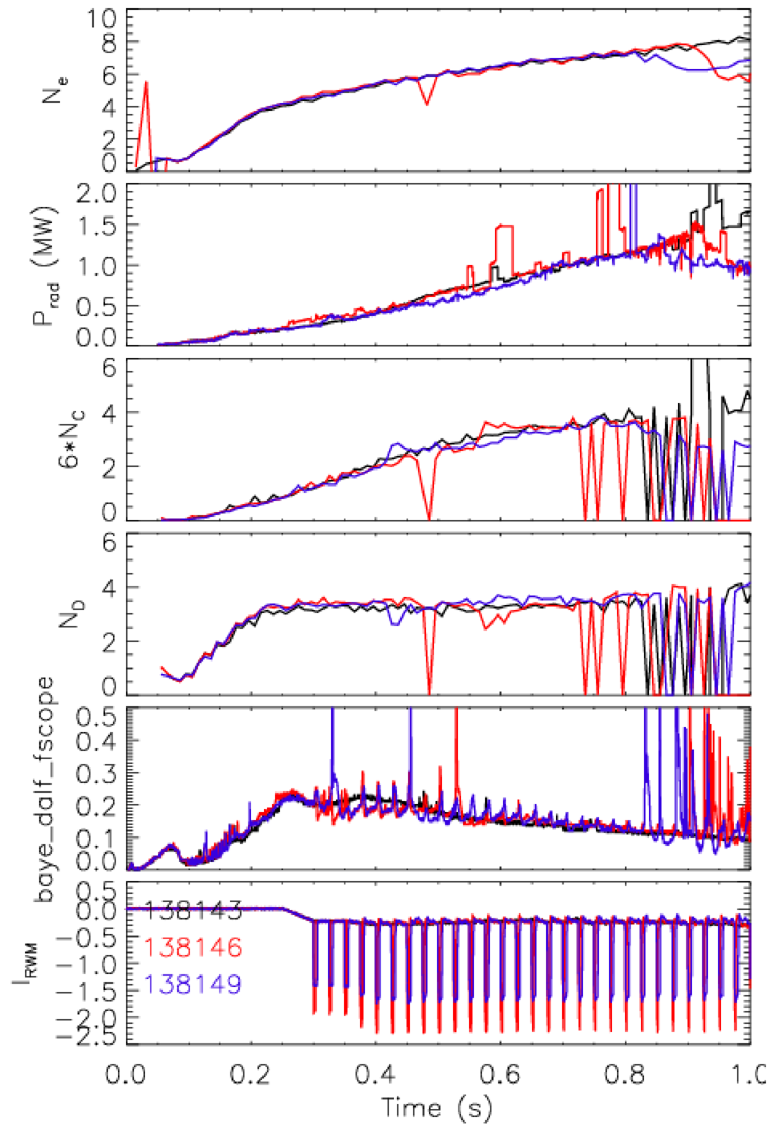
Profiles not stationary: core increasing, edge decreasing



3D field pulses below threshold for ELM-triggering ineffective for impurity screening

- Response to n=3 field observed in divertor D_{α} even when pulse is too brief or low amplitude to trigger ELM
- 3D field optimized for sub-threshold pulses
  - Maximize n=3 amplitude, duration while avoiding large ELMs
- Without ELMs, particle expulsion insufficient for impurity control
  - No dramatic impact on P_{rad} or carbon inventory evolution





Summary

- Application of n=3 fields can destabilize ELMs
  - Without lithium, n=3 reduces rotation, increases pedestal electron pressure in discharge *without* lithium coatings
    - Stability calculations show pedestal is near limits, more research needed to explore transition from stable to unstable
  - Initial data with lithium shows flattening of n_e, T_e, decrease of v_{tor}, T_i

- 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
    - Global parameters have been fully arrested, but not profiles
  - High frequency gives smaller ELMs