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Effects of Applied Non-axisymmetric Fields on ELMs and Plasma Rotation Using New Midplane Coil Configurations in NSTX

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Modeling of Plasma Effects of Applied Resonant Magnetic Perturbations

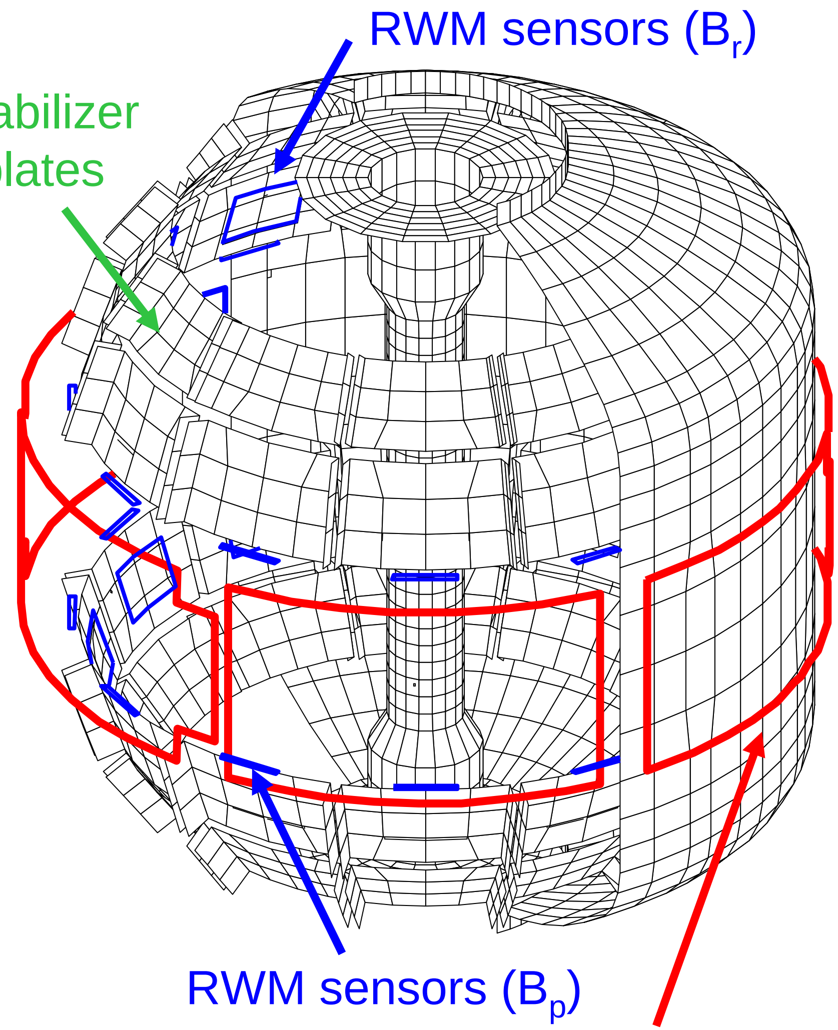
August 25th, 2008

General Atomics, San Diego, CA

Examine effects on ELMs, plasma rotation using new midplane coil configurations

- Motivation
  - Potential simplification of coils for ELM control/mitigation desired/required in tokamaks (e.g. ITER) – midplane coils enough?
  - Will even parity, non-resonant fields effect plasma rotation? – future V_ϕ profile control

- Applied fields from reconfigured coil circuitry
  - New field spectra add dominant even parity fields to past odd parity configurations



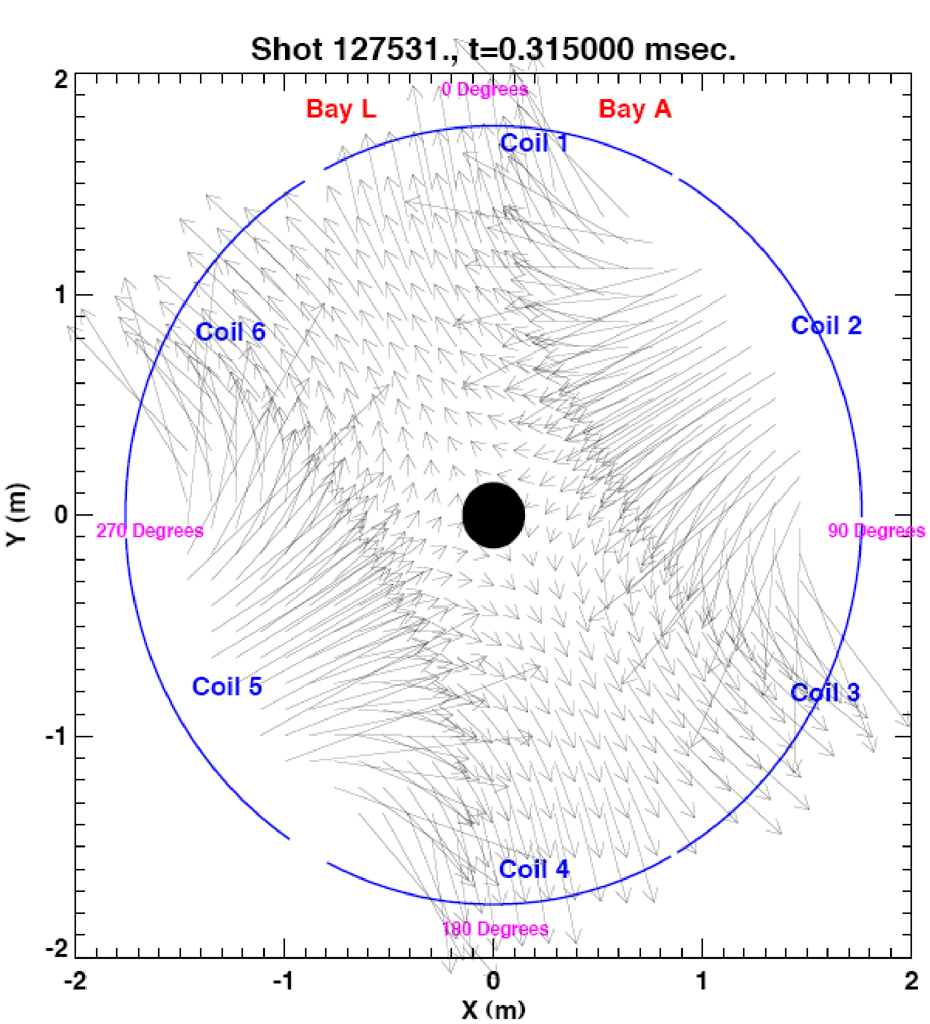
Exploratory approach to ELM control with midplane non-axisymmetric coils

- Follows past NSTX experiments by T. Evans, et al.
  - n = 3 fields: ELM suppression not reproducible, ELM triggering observed

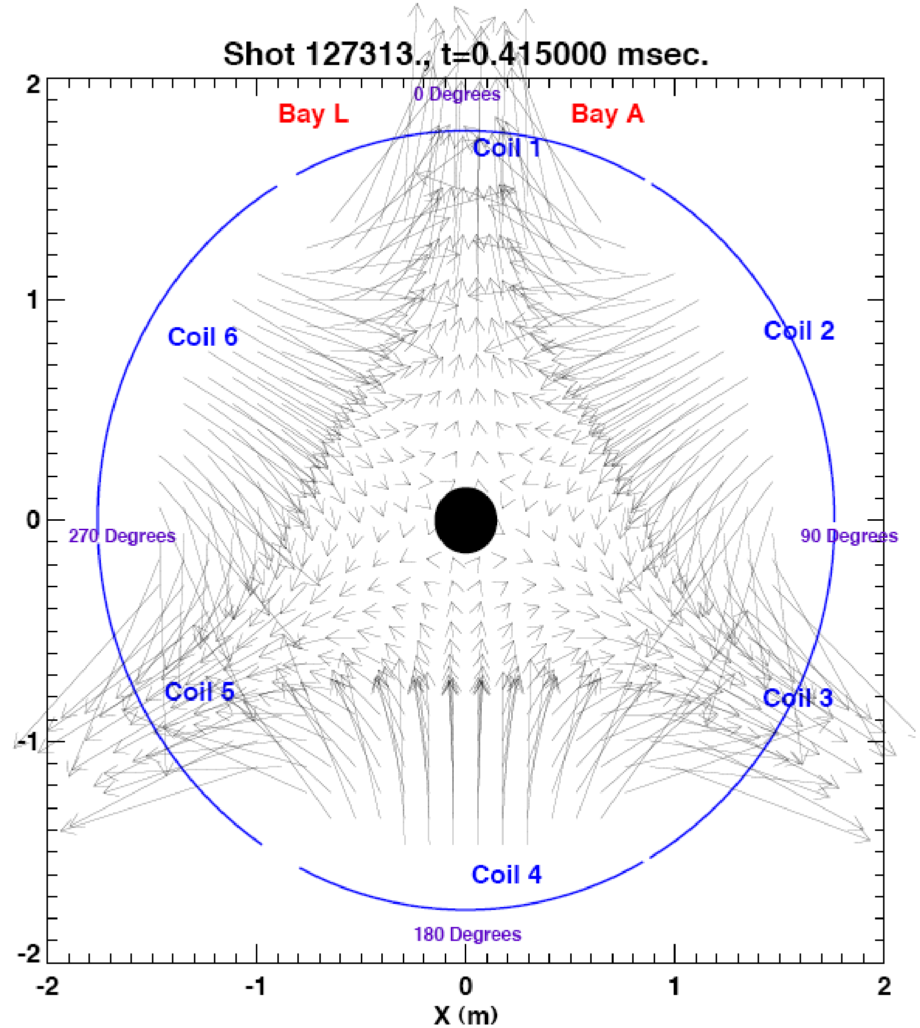
- Approach
  - Target development
    - Run with reduced q_{95} = 6 – 8 thought to be superior for mitigation
    - Variation of q_{95} in this range to insure mitigation not missed due to possible resonance effects
  - Application of DC fields
    - Past odd parity fields (n = 3) operating on lower q_{95} target
    - New even parity field (n = 2, with strong n = 4) capability for 2008
    - New combined odd/even parity (n = "2 + 3")
  - Application of AC fields
    - Using either/both odd and even parity fields
  - Repeat best cases in low recycling plasmas with lithium first wall preparation

New n = 2 configuration used to compare to past n = 3 results

n = 2 field configuration (planform view)



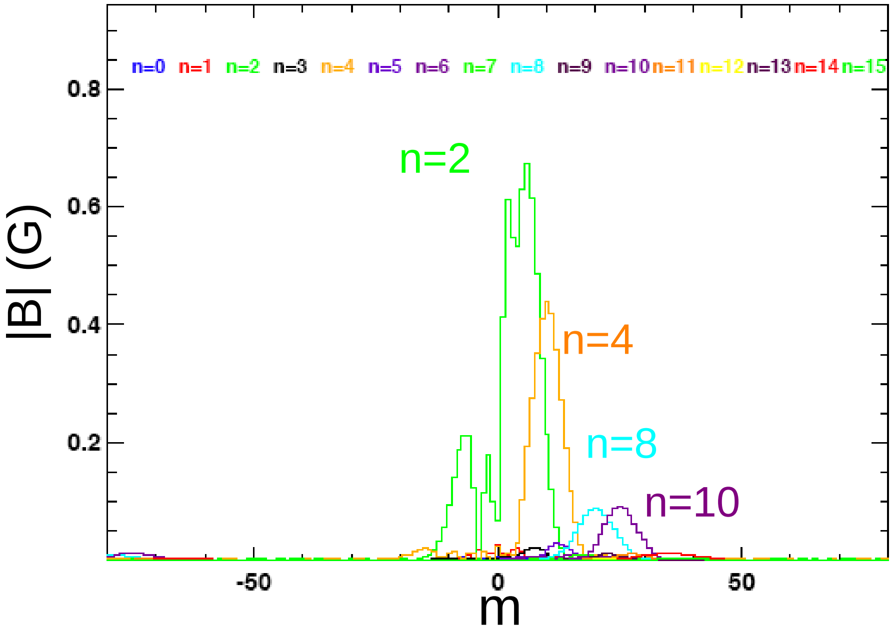
n = 3 field configuration (planform view)



Broader field spectrum in n = 2 vs. n = 3 configuration

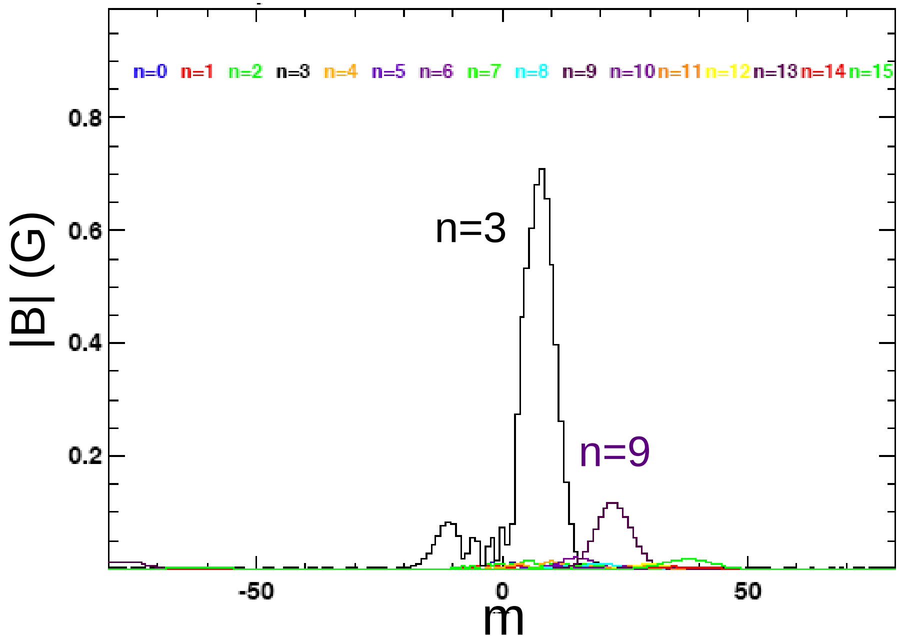
“n = 2 configuration”

Spectrum at r/a=0.8



“n = 3 configuration”

Spectrum at r/a=0.8

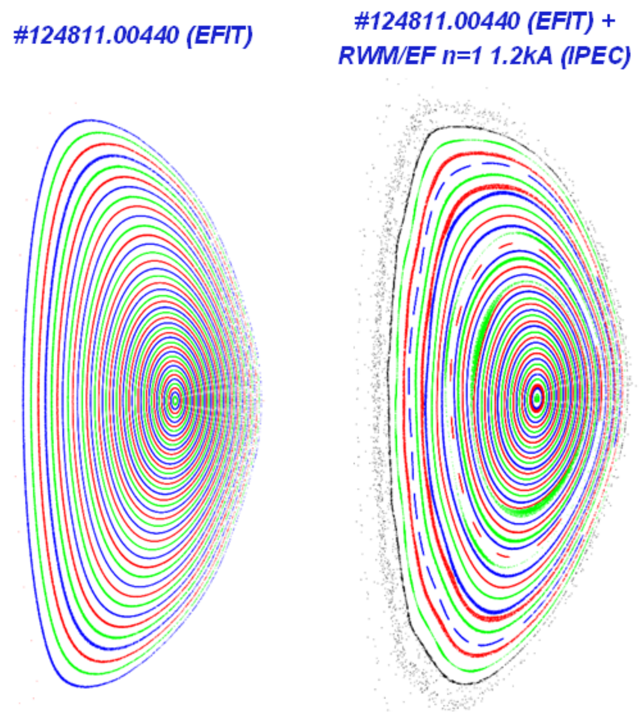


- Broader spectrum and greater radial penetration should lead to larger non-resonant damping by neoclassical toroidal viscosity (NTV)
- n = 2 configuration has very small n = 1 component – reduces resonant braking and n = 1 NTV due to resonant field amplification

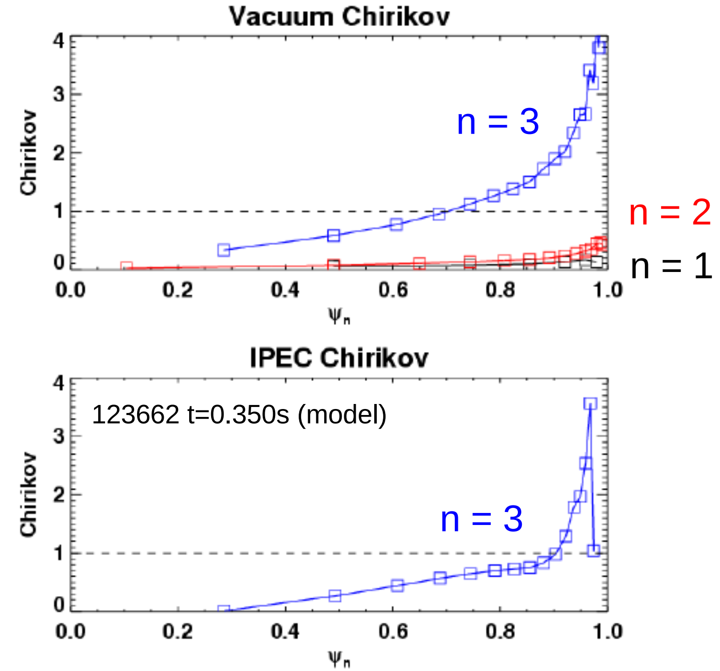
IPEC used to analyze Chirikov parameter

Ideal Perturbed Equilibrium Code (IPEC)

J.-K. Park, et al., Phys. Plasmas **14**, 052110 (2007).

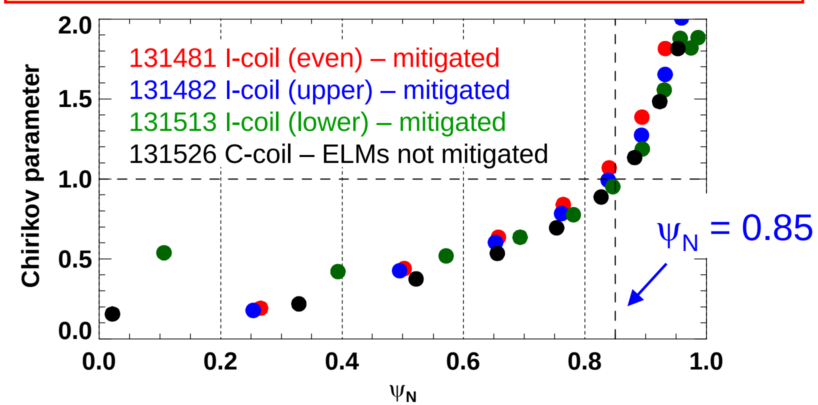


NSTX n = 3 field config., q_{95} = 5.5



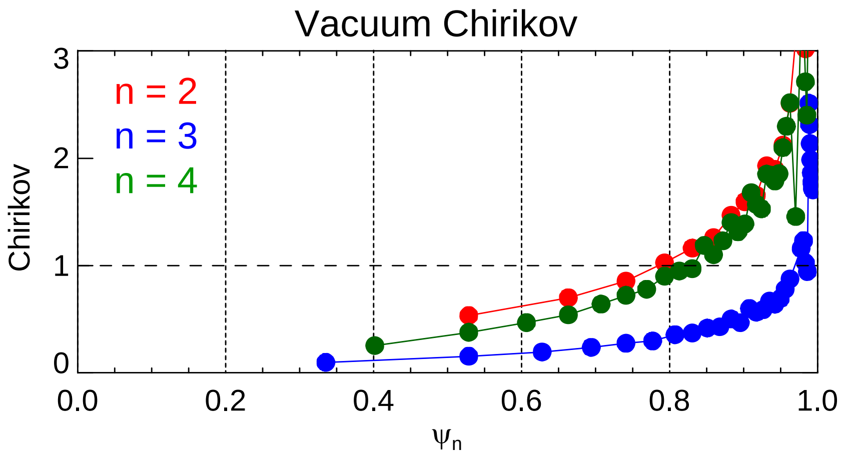
- Ideal MHD plasma response to applied field included in IPEC
  - IPEC Chirikov computed using field jump at rational surfaces

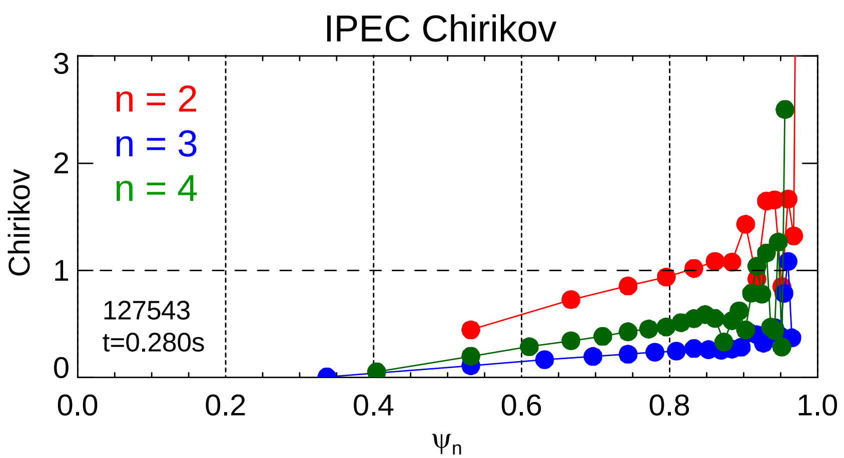
DIII-D: IPEC Chirikov for ELM mitigation



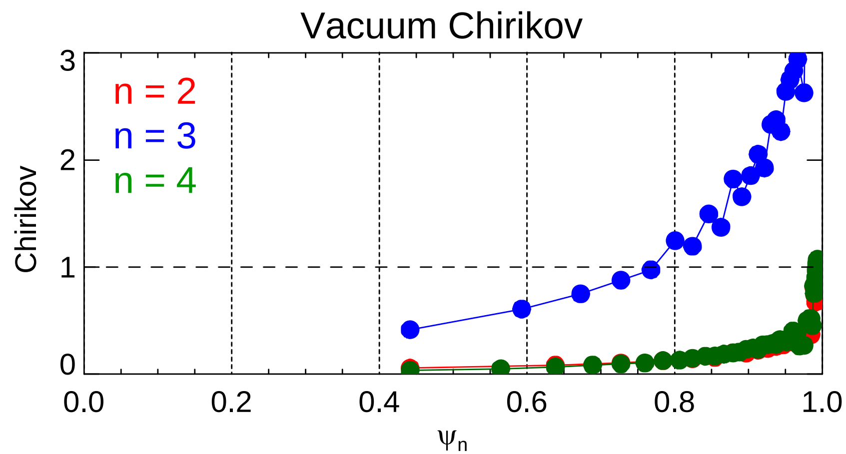
Vacuum and IPEC computed Chirikov parameter > 1 near edge for n = 2, n = 3 field configurations used in experiments

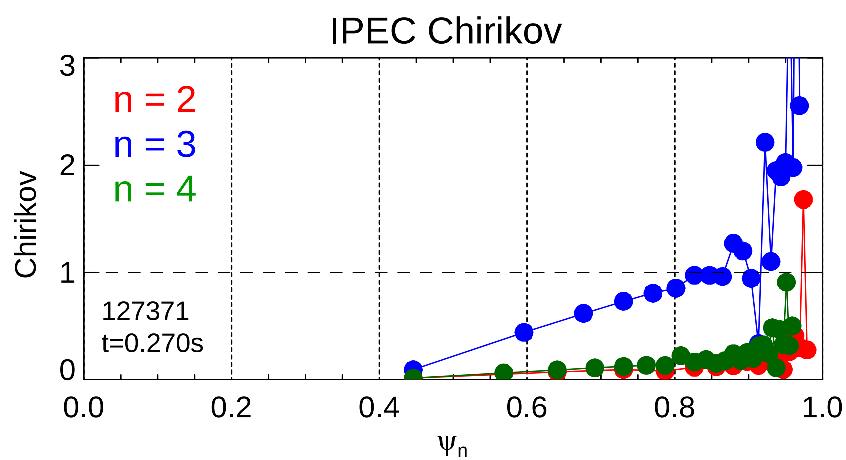
n = 2 field configuration, q_{95} = 7.4





n = 3 field configuration, q_{95} = 7.7



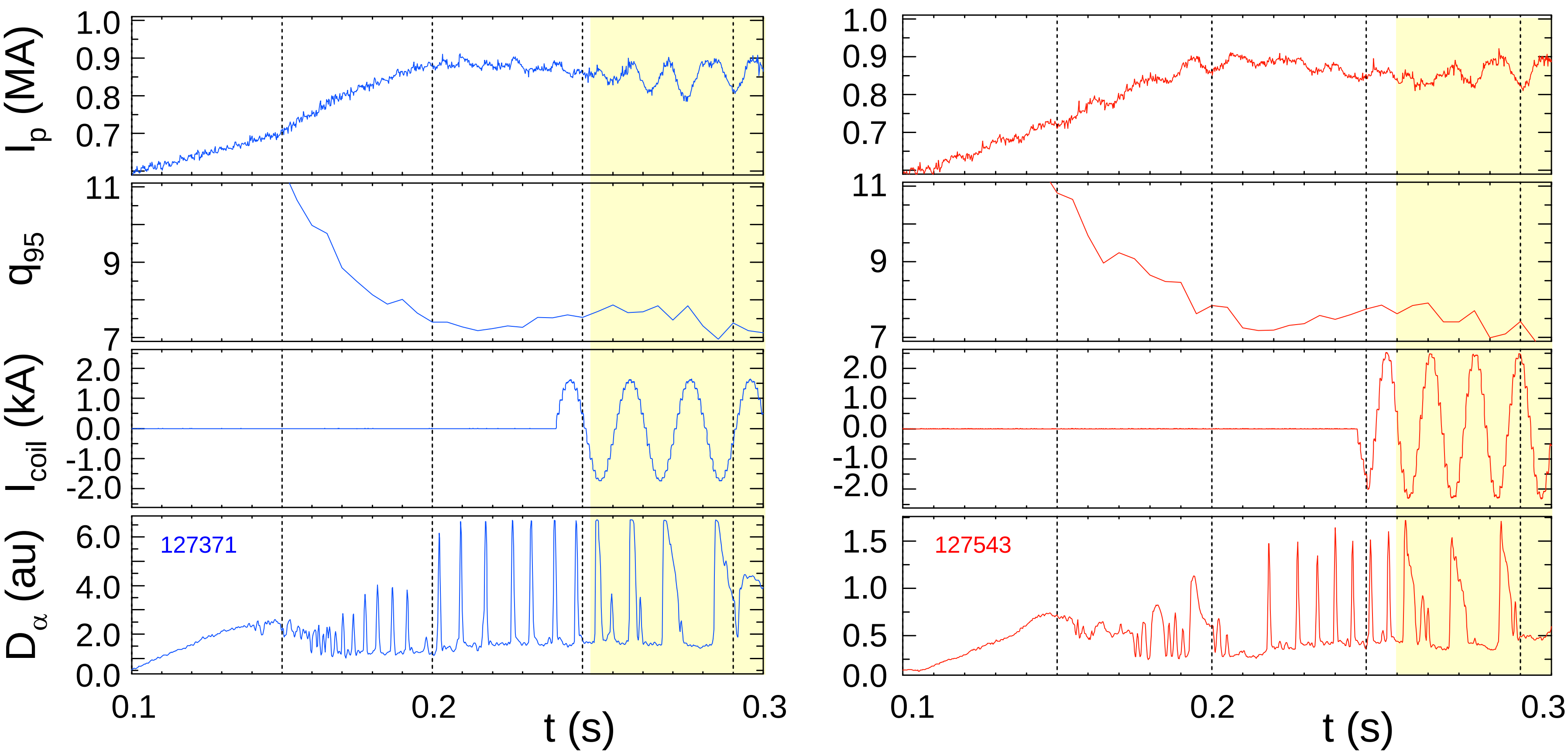


- IPEC shows n = 4 significantly reduced
- n = 3 Chirikov > 1 at ψ_N ~ 0.8

Reduced ELM frequency, increased D_α duration observed in AC applied field configurations

n = 3 AC field, 70 Hz, 3.8 kA peak-to-peak

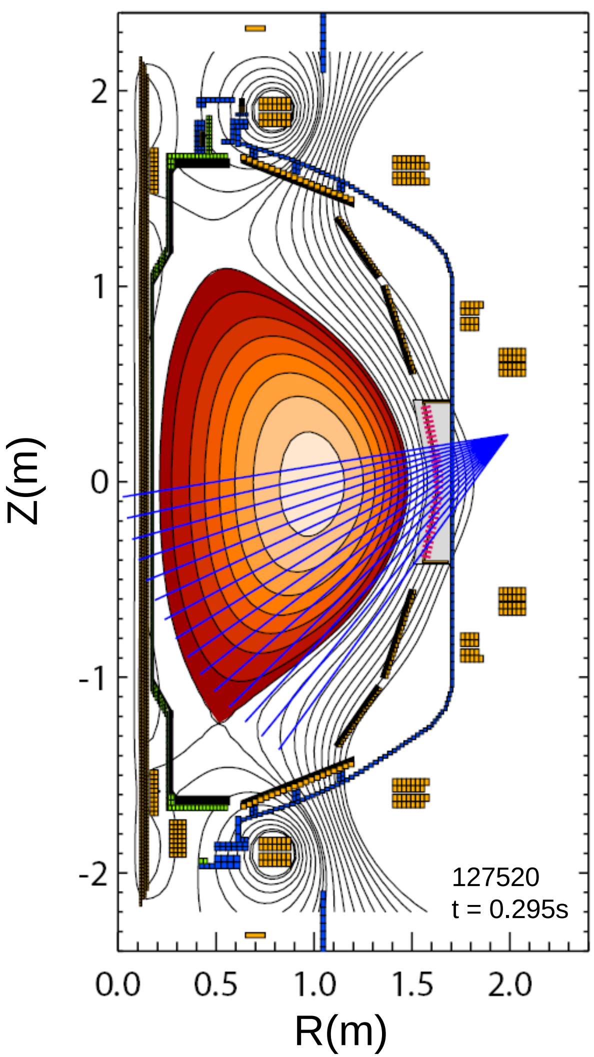
n = 2 AC field, 70 Hz, 5.5 kA peak-to-peak

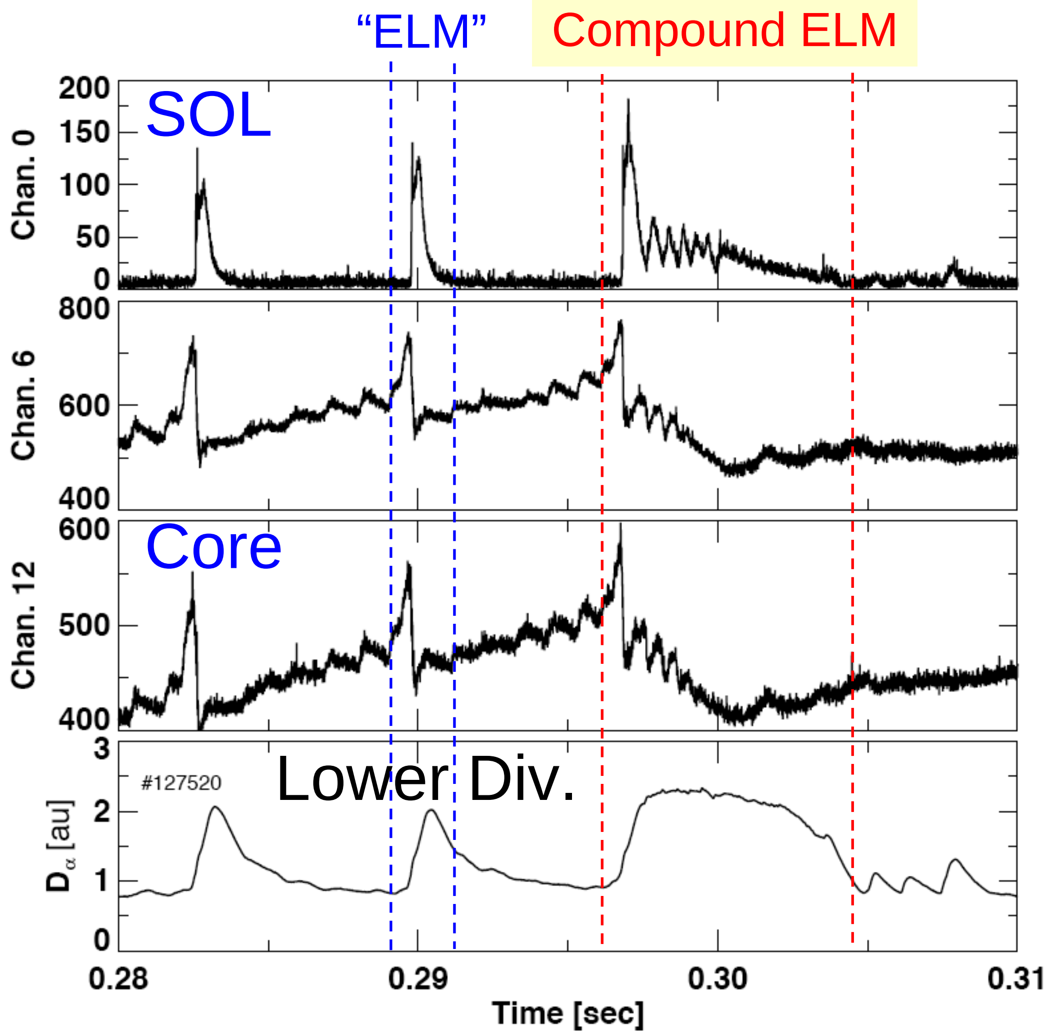


- ELMs broaden, roughly match frequency of applied field
- Broadening due to multiple ELMs/filaments "compounded" together
  - effectively decreases frequency

Compound ELMs distinguished from single ELM with USXR

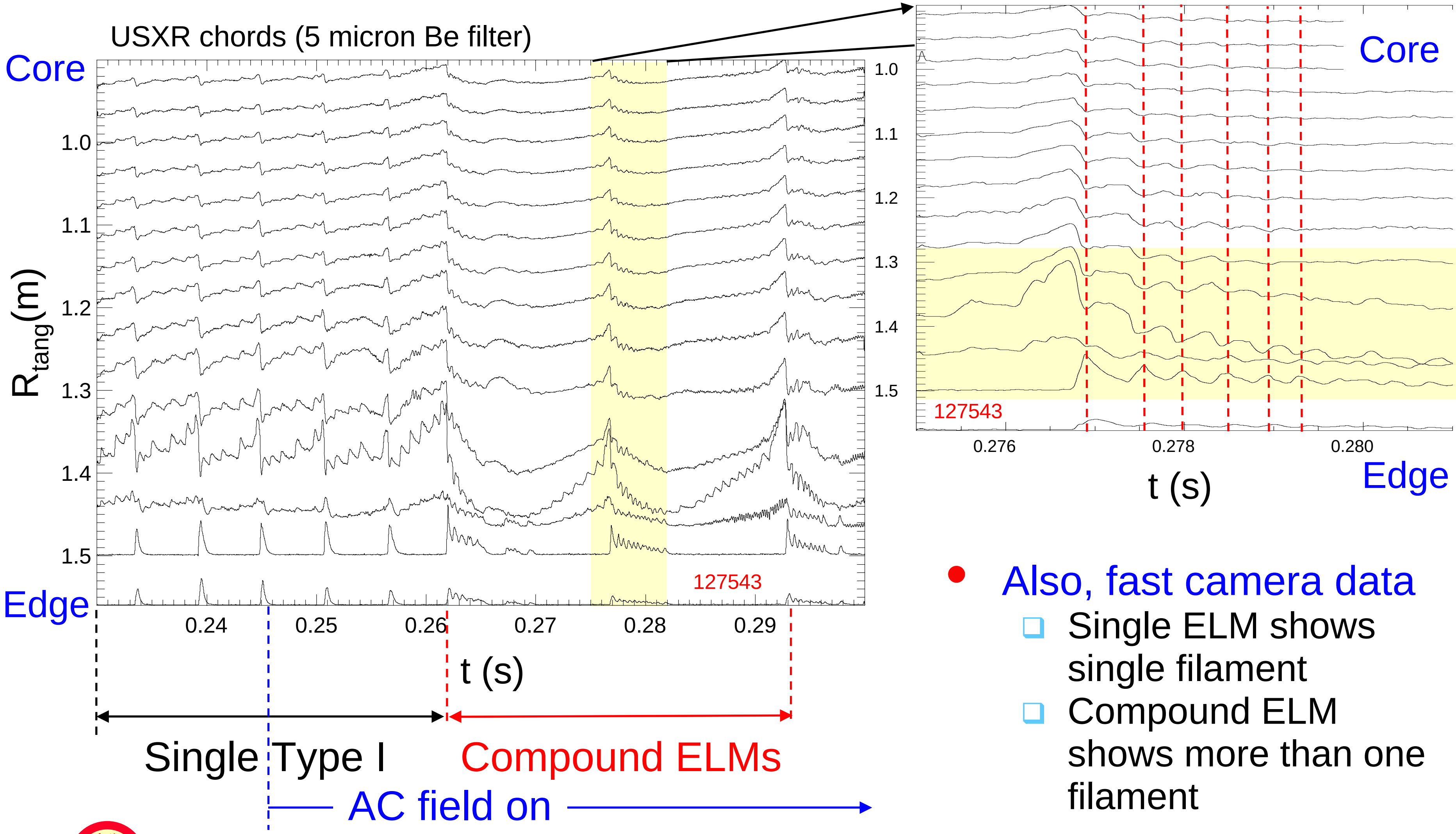
USXR chords (lower array)





- Apparent multiple ELM events follow initial USXR drop

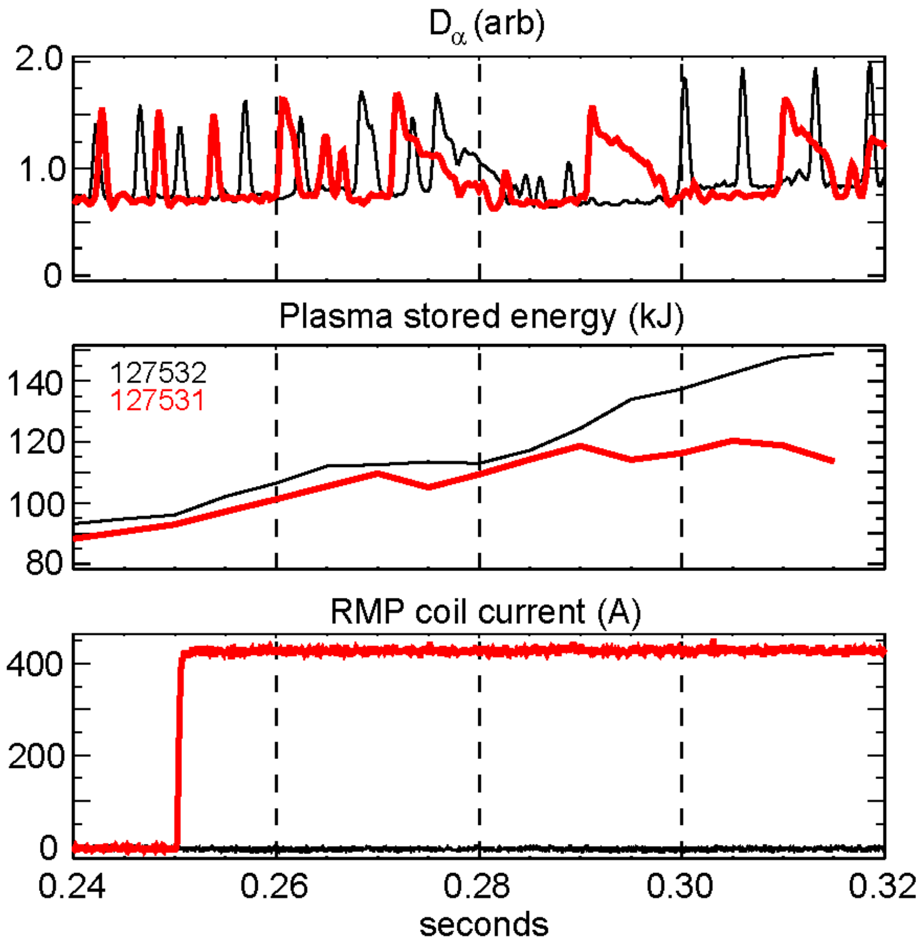
Soft X-ray detail supports compound ELM leading to multiple energy expulsions



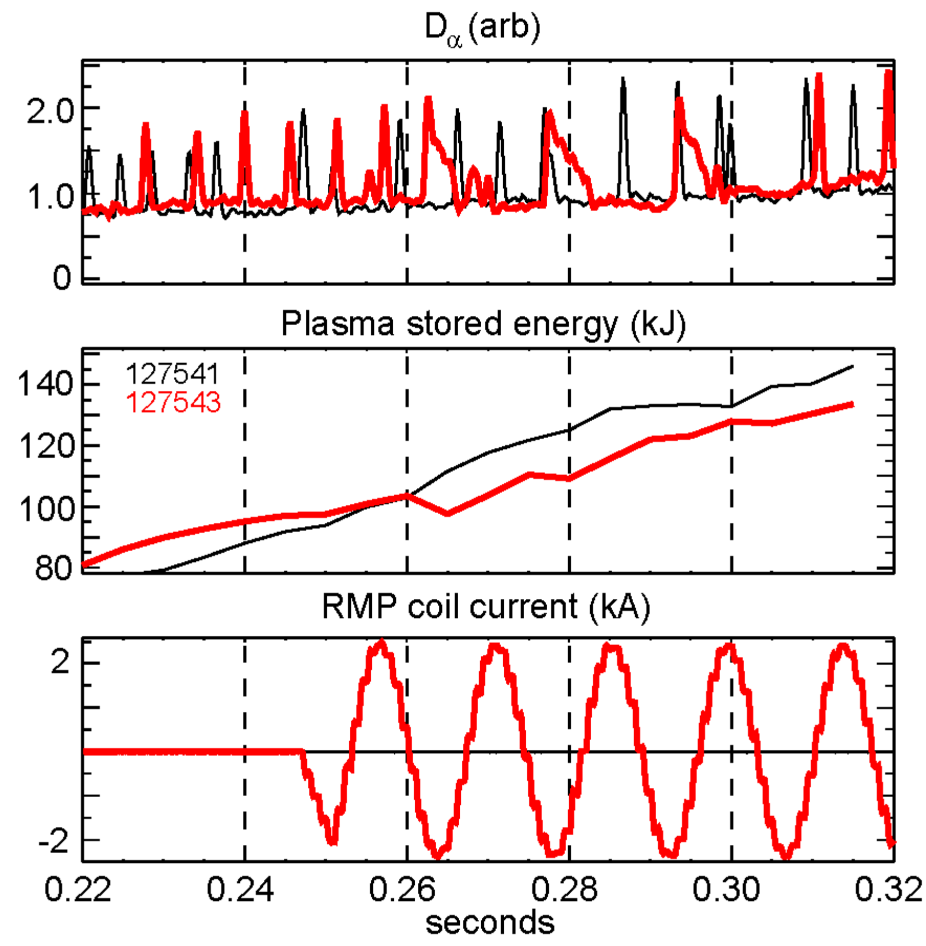
- Also, fast camera data
  - Single ELM shows single filament
  - Compound ELM shows more than one filament

ELMs modified with either DC or AC fields

n = 2 DC field vs. no field



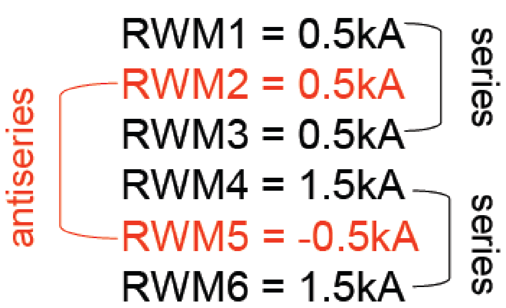
n = 2 AC field, 70 Hz vs. no field



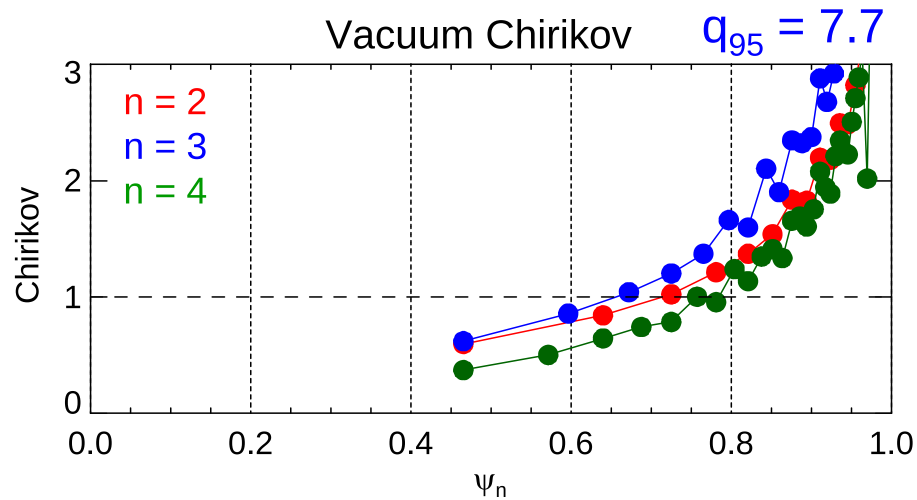
NSTX

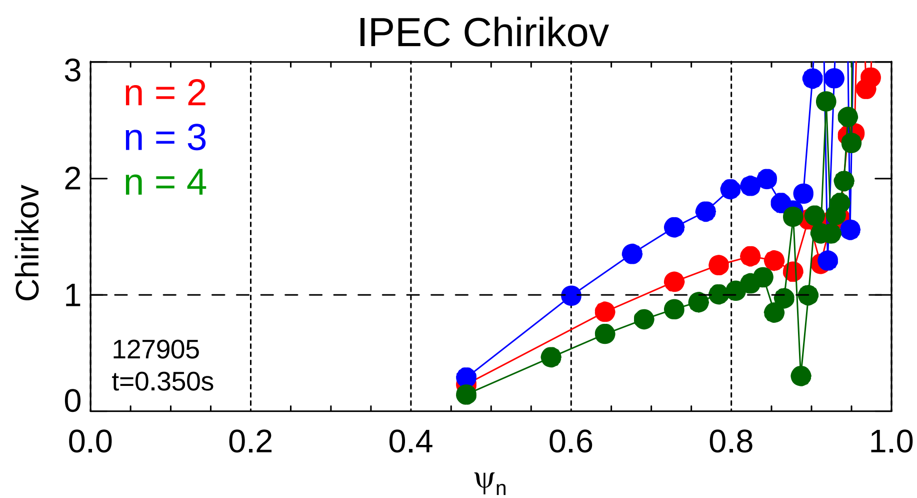
Mixed “2 + 3” field configuration tested for potential increase in edge ergodization

n=2+3 Mixing Configuration



J-K. Park



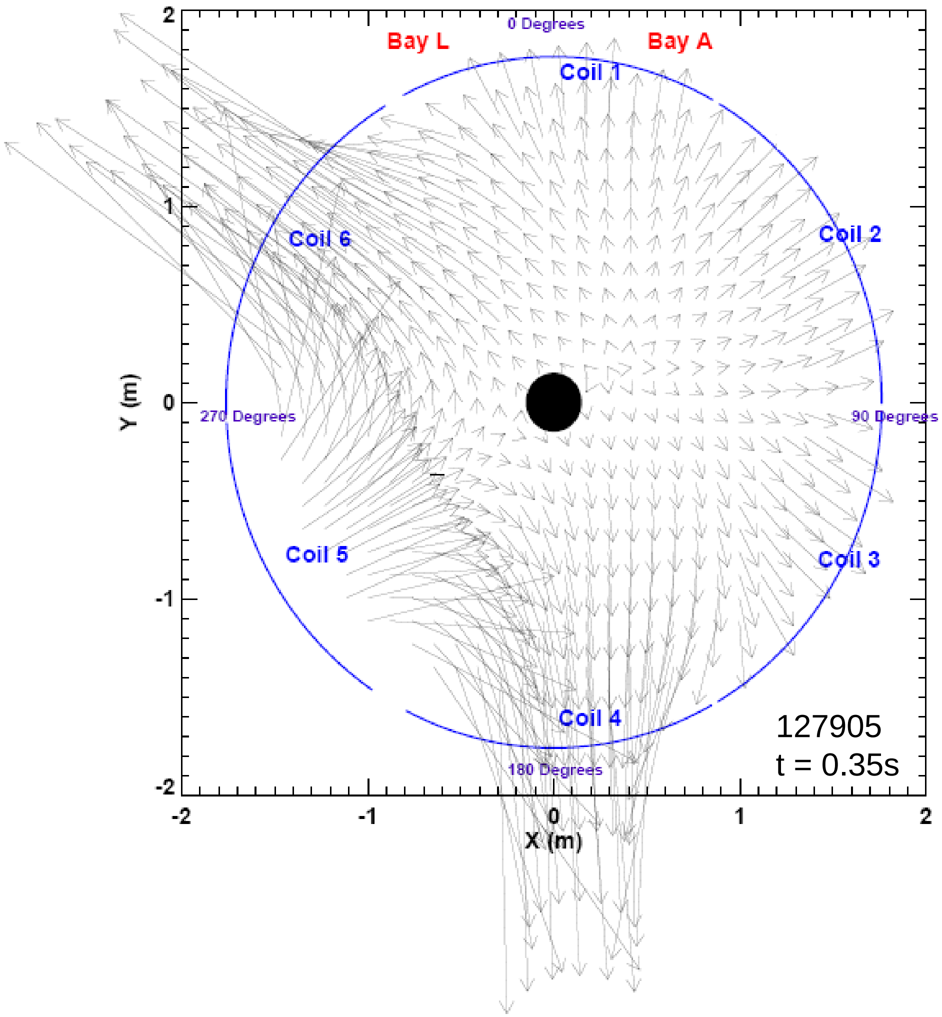


- Chirikov > 1 for n = 2, 3, 4 over significant portion of edge plasma
  - Vacuum and IPEC calculations
- Chirikov > 1 penetrates further to core than separate n = 2, 3 field configurations

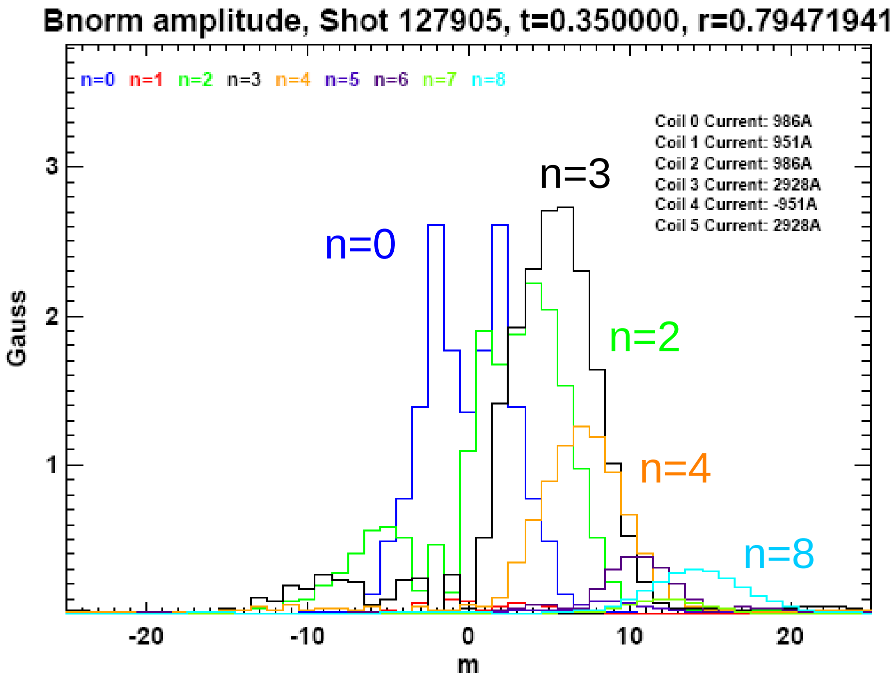
NSTX

New n = "2+3" configuration with broader field spectrum used

n = 2+3 configuration (planform view)



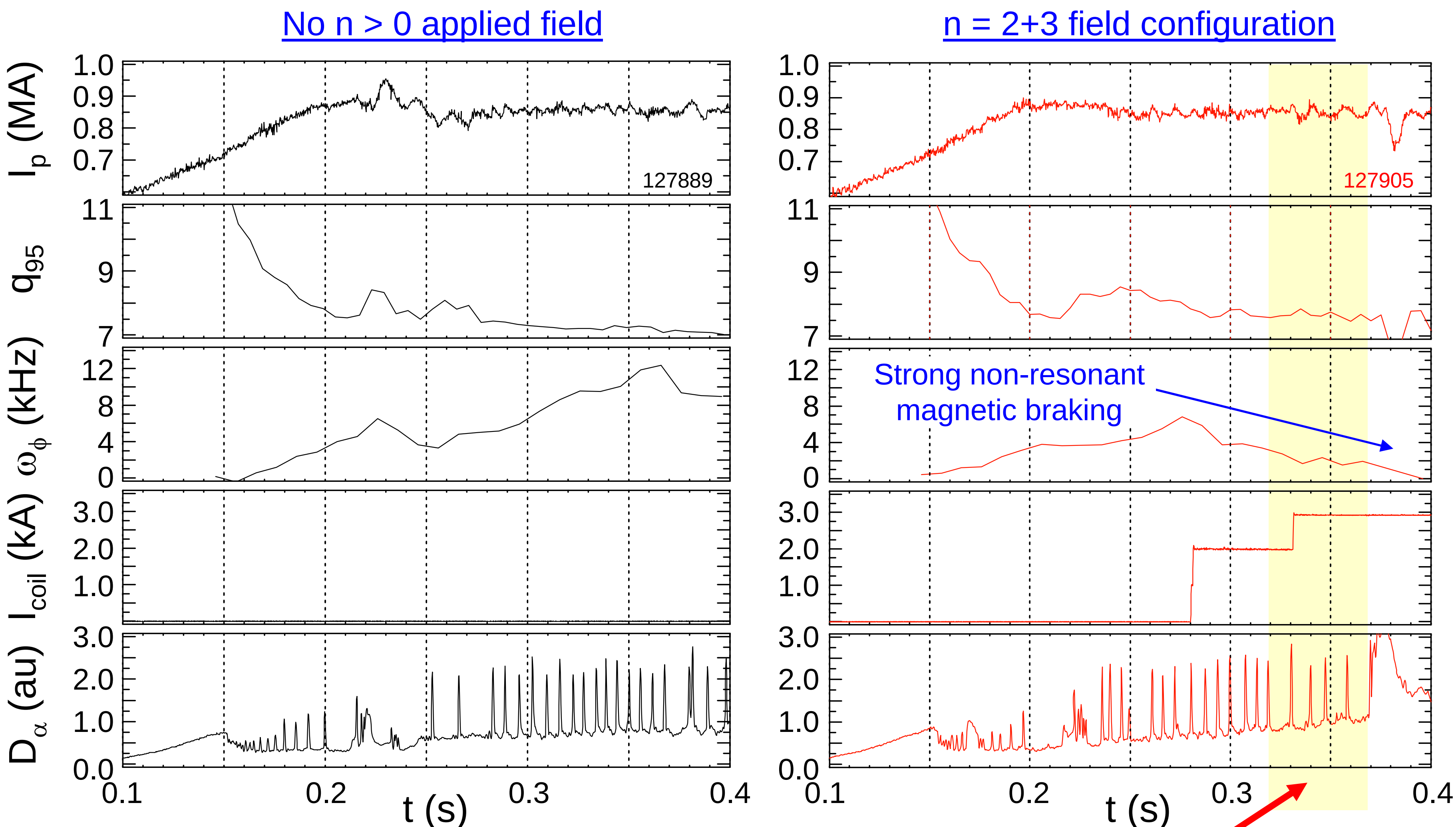
n = 2+3 configuration n, m spectrum



- Broadest n, m spectrum of all configurations attempted
- n = 2, 3 components strongest
  - Significant n = 0 component cancelled by vertical stability control

NSTX

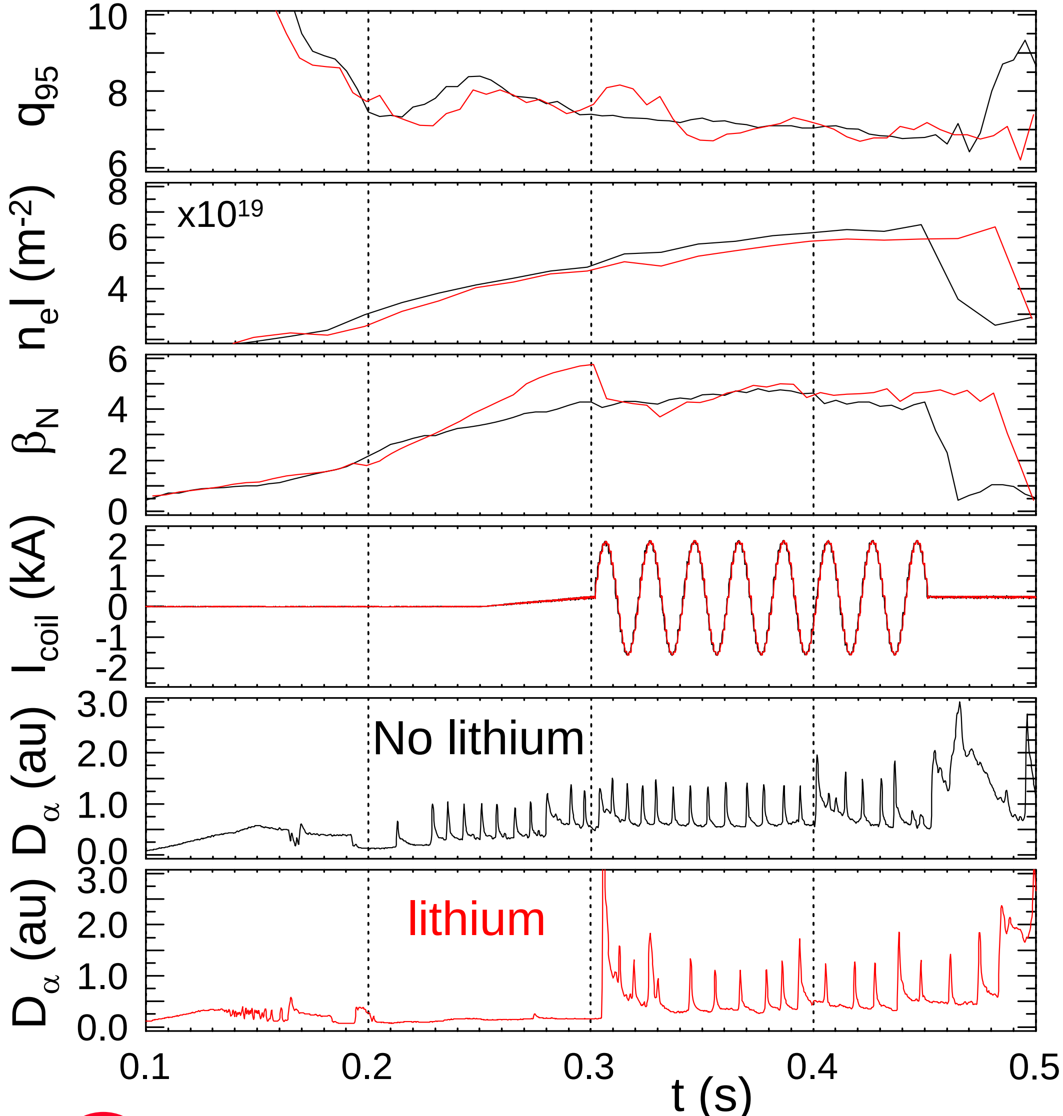
ELMs not mitigated with n = 2 + 3 field; frequency reduced



- Decrease in ELM frequency at maximum allowed field

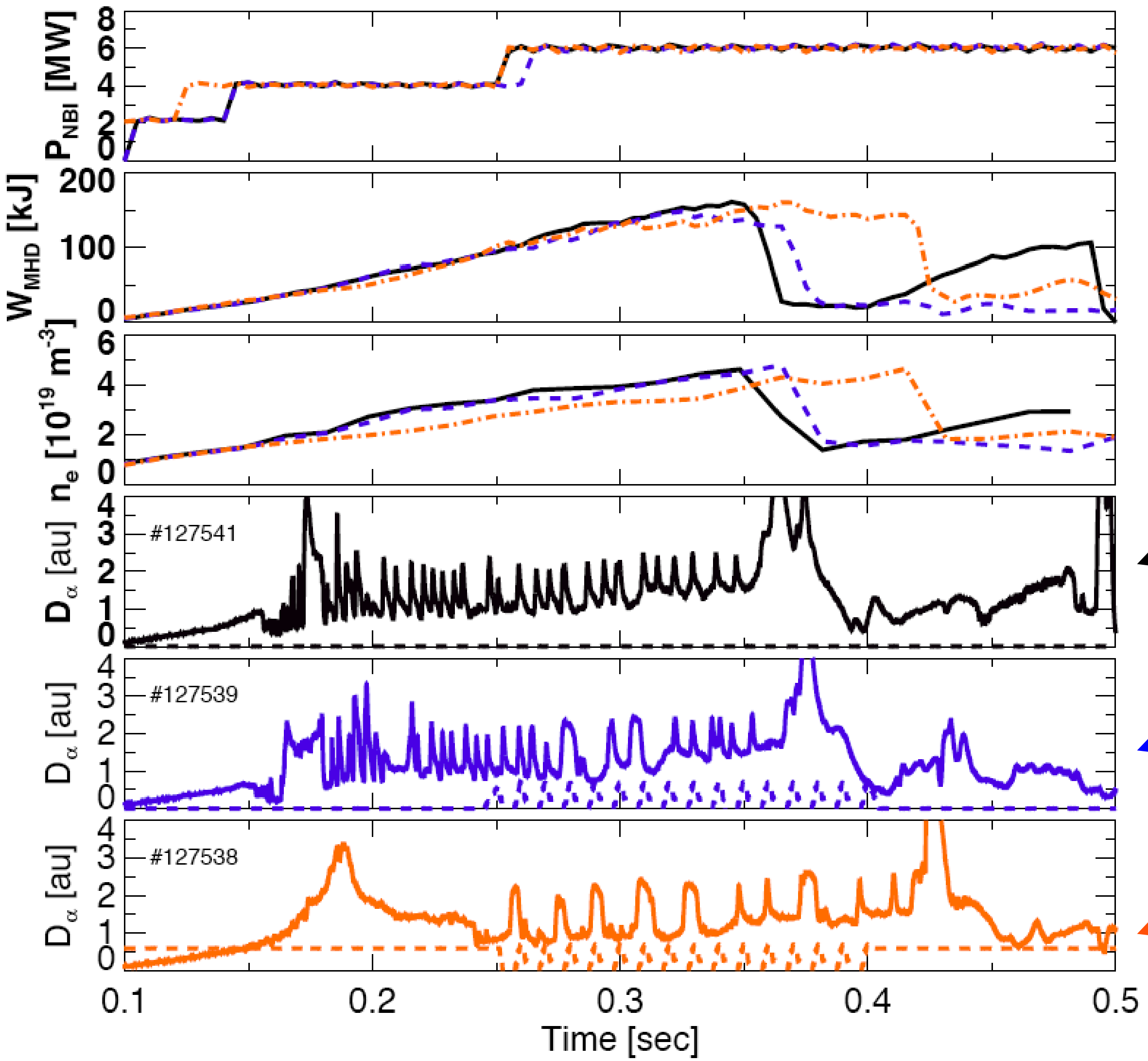
NSTX

Lithium input to reduce recycling led to ELM mitigation *without* applied field; field triggers ELMs



- As found in XP728 (Mansfield, et al.)
  - Reproduced with significantly smaller Li evaporation here
- Similar line-averaged n_e evolution
- Significant increase in β_N with lithium pre-ELM
- Non-axisymmetric field used to trigger ELMs for impurity control (see J. Canik, next talk)

L-H threshold time can be delayed by application of RMP during I_p ramp



- Useful tool for L-H transition physics experiments
- Control shot (no applied field)
- n=3 AC applied field
- n=3 AC with DC offset during I_p ramp
  - Delayed H-mode
  - Compound ELMs

NSTX

Even parity non-axisymmetric fields used to determine impact on plasma rotation

- Follows past experiments
  - n = 3 field configuration used on NSTX for a few years for (non-resonant) rotation control

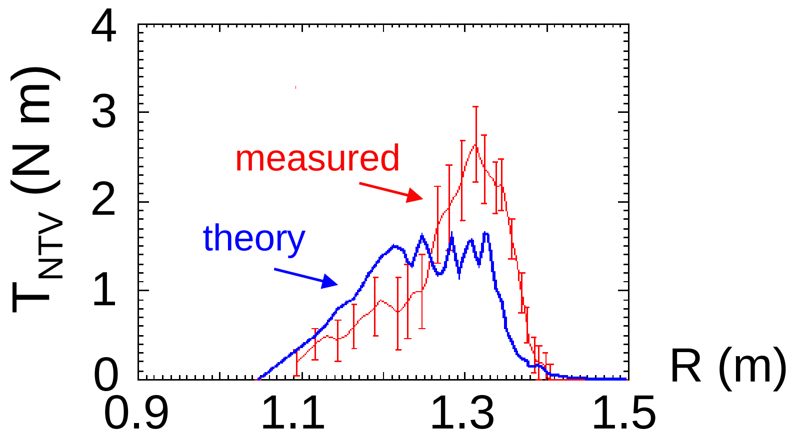
- General results
  - n = 2 applied field configuration shows expected global, non-resonant character of damping
    - Damping not due to resonant n = 1 component (as conjectured for n = 3 configuration) since n = 1 component is small
  - Increased rotation damping observed with lithium evaporation
    - Theoretical increase in non-resonant torque expected at increased T_i (lower ion collisionality)

Experimentally observed braking in quantitative agreement with NTV theory for n = 3 field configuration

- Quantitative agreement in NSTX between neoclassical toroidal viscosity (NTV) theory and non-resonant damping by odd parity fields
  - Revised calculation including Shaing erratum maintains O(1) agreement
    - Past factor used to invoke field shielding in core not used here

Measured $d(I\Omega_p)/dt$ profile vs. theoretical NTV torque (n = 3 field) in NSTX - revised)

W. Zhu, et al., *Phys. Rev. Lett.* **96,** 225002 (2006).



- Details of saturation of $1/\nu_i$ dependence important for ST-CTF and ITER
  - Additional physics may increase torque at lower collisionality
    - e.g. precession drift/bounce frequency resonances

Dominant NTV Force for NSTX collisionality…

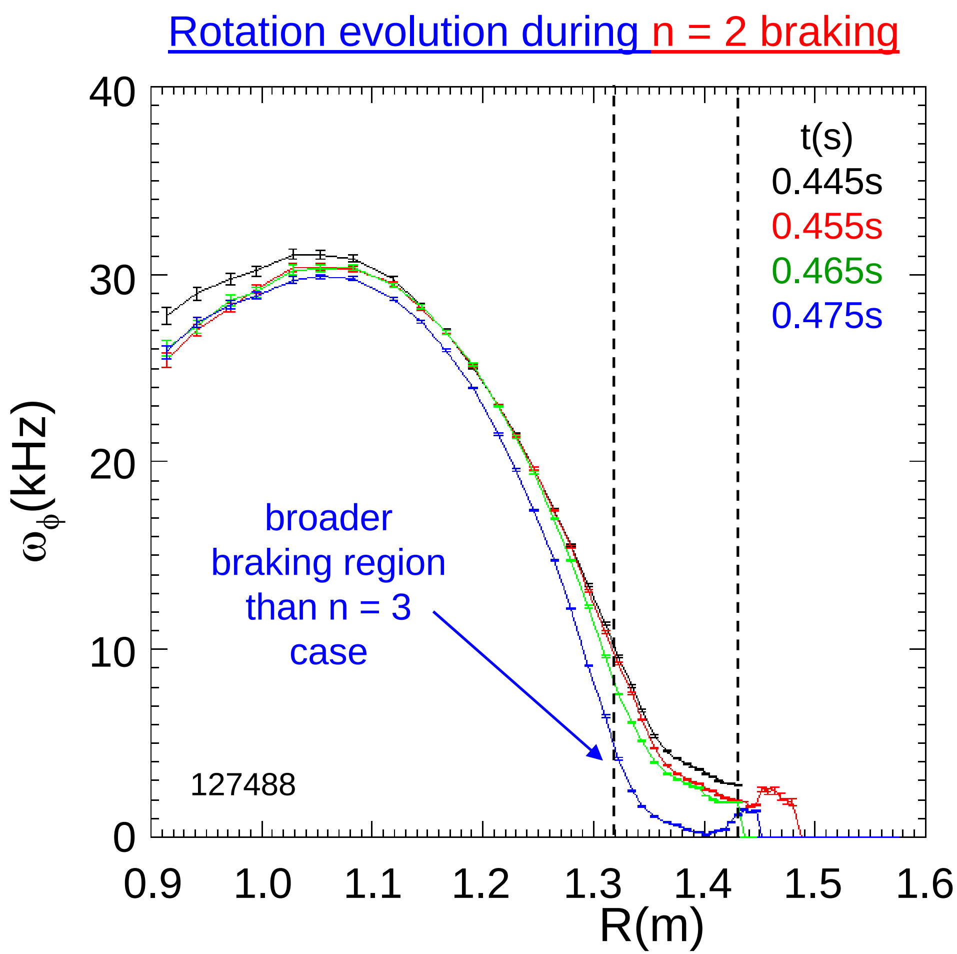
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\Omega_\phi - \Omega_{NC}) I_\lambda$$

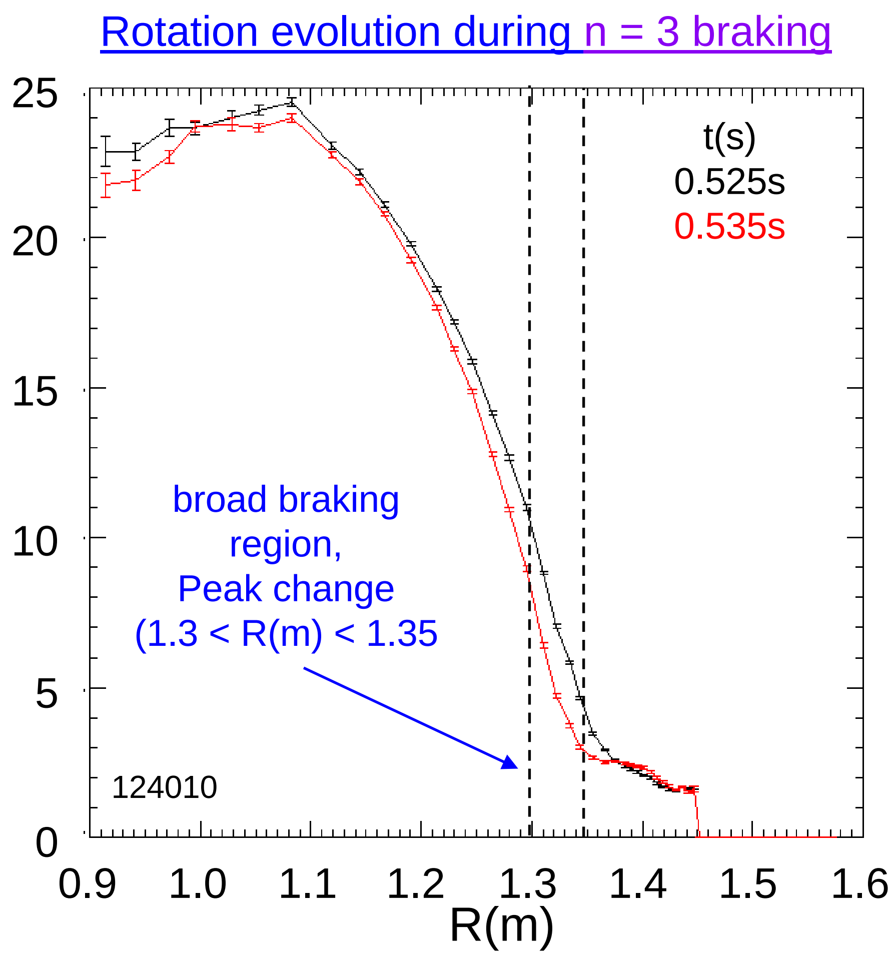
…expected to saturate at lower ν_i

$$\frac{1}{\nu_i} \Rightarrow \frac{\nu_i}{\left(\nu_i^2 + \omega_E^2\right)}$$

but - uncertainty in level of torque at which effect will saturate

Clear braking observed due to n = 2 field

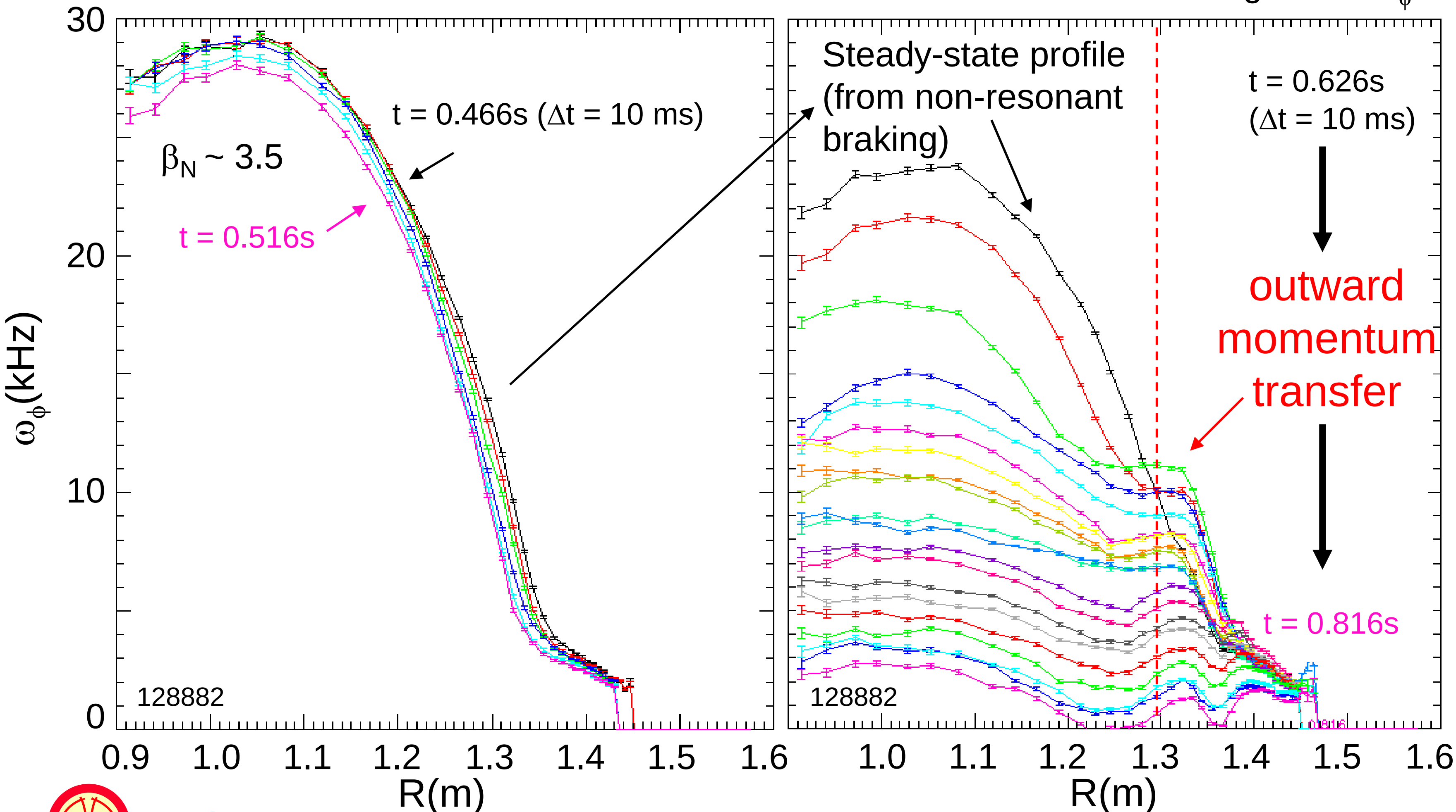




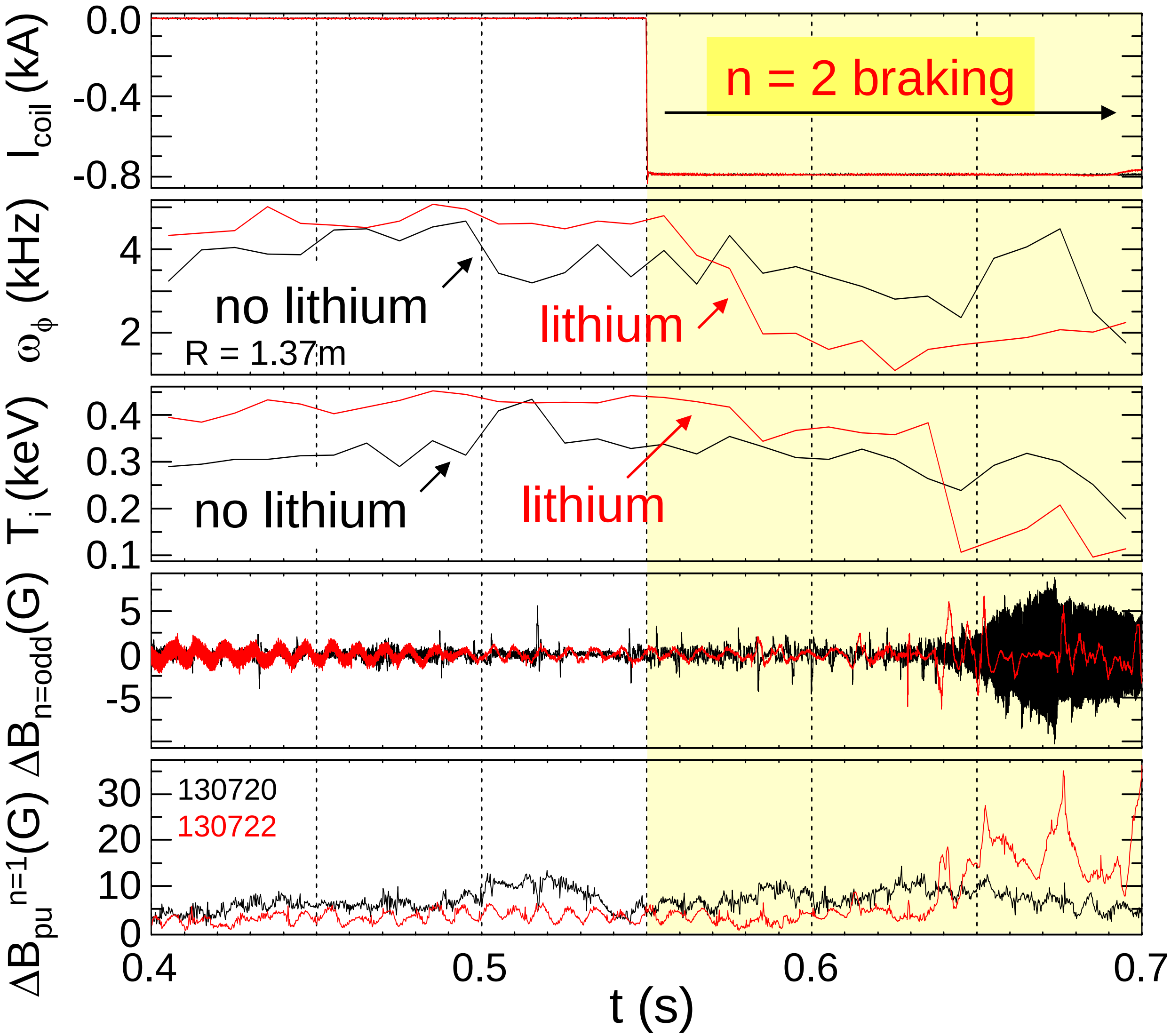
- n = 2 has broader braking profile than n = 3 field (field spectrum)

n = 2 non-resonant braking evolution distinct from resonant

- Non-resonant:
  - broad, self-similar reduction of profile
  - Reaches steady-state (t = 0.626s)
- Resonant:
  - Clear momentum transfer across rational surface
  - evolution toward rigid rotor core
  - Local surface locking at low ω_ϕ



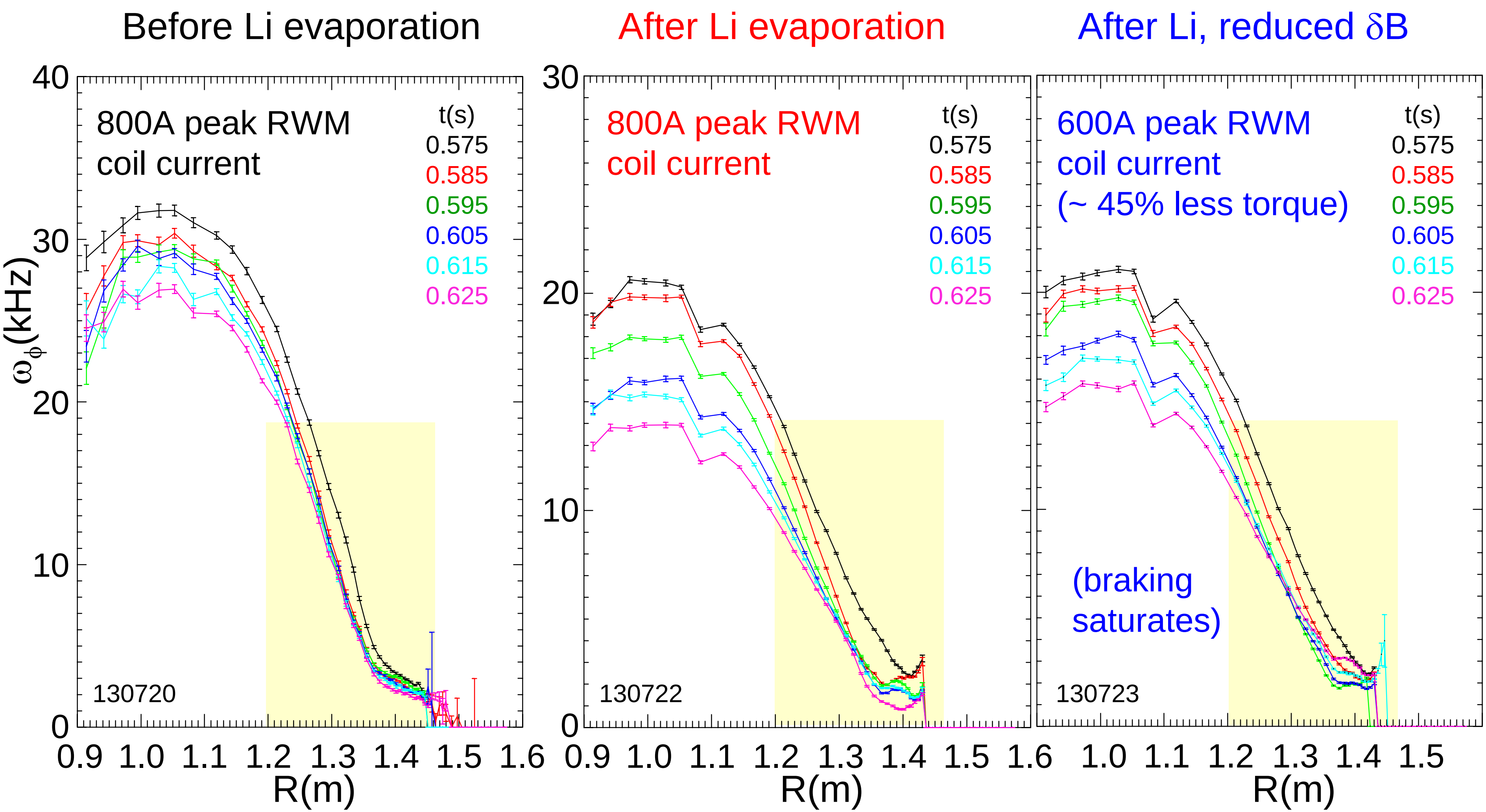
Stronger non-resonant braking with Li evaporation



- Examine ν_i dependence of NTV by injecting lithium
- Li produces higher T_i in region of high rotation damping
- Expect stronger NTV torque at higher T_i ($\sim T_i^{5/2}$)
  - At braking onset, Ti ratio$^{2.5}$ = $(0.45/0.34)^{2.5} \sim 2$
  - Consistent with measured $d\omega_\phi/dt$
- Rotating MHD eliminated with Li evaporation

NSTX

Non-resonant n = 2 braking evolution altered by Li evaporation



- Stronger V_ϕ damping by NTV at higher T_i ($\tau_{NTV} \sim T_i^{5/2}$)
- V_ϕ saturates in case with lithium at reduced applied δB

NSTX

New non-axisymmetric field spectra in NSTX used to influence ELMs and plasma rotation

- ELMs affected, not fully mitigated
  - ELMs frequency “lowered” (duration increased - compound ELMs created) by AC and DC fields
  - *n* = 2 + 3 configuration showed reduction in ELM frequency at maximum permitted coil current
  - Lithium wall conditioning attempted for pumping
    - ELMs fully mitigated with application of lithium alone, ELMs *triggered* by fields
- H-mode onset time altered by n = 2 DC field application
- Non-resonant V_ϕ braking observed with even parity fields
  - Significant braking at field levels used to produce Chirikov > 1
  - Global non-resonant braking supports NTV theory in $1/\nu_i$ regime
  - Lithium wall conditioning increases T_i, non-resonant braking strength
- Edge plasma rotation may play key role in ELM stability physics
  - Li increases edge V_ϕ → mitigation, field reduces V_ϕ → ELM less stable

Design proceeding for potential upgrade of non-axisymmetric control capabilities

- Non-axisymmetric control coil (NCC) – at least four applications
  - ELM control
    - Poloidal spectrum flexibility and greater *n* spectrum
    - Initial analysis by Evans shows favorable conditions for ELM control
  - RWM stabilization
    - *n* > 1 control, address poloidal deformation of mode
    - higher β_N – new design reaches β_N up to the ideal with-wall beta limit
  - Plasma rotation control
    - increased V_ϕ profile control, possible *n* > 1 propagation
  - Error field correction capability significantly enhanced
- Similarity to proposed ITER coil design (VAC02)
- In 5 Year Plan incremental budget

Proposed Internal Non-axisymmetric Control Coil (NCC) (initial designs - 12 coils toroidally)