NSTX PPPL Supported by U.S. DEPARTMENT OF ENERGY Office of Science

The Effects of Lithium Coatings on NSTX Performance

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for the NSTX Research Team

with special thanks to
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ISTW, October 23, 2009

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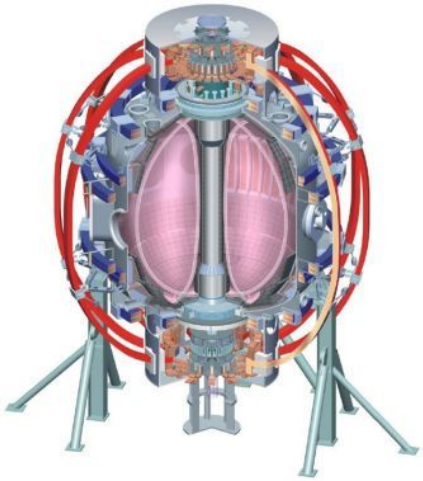

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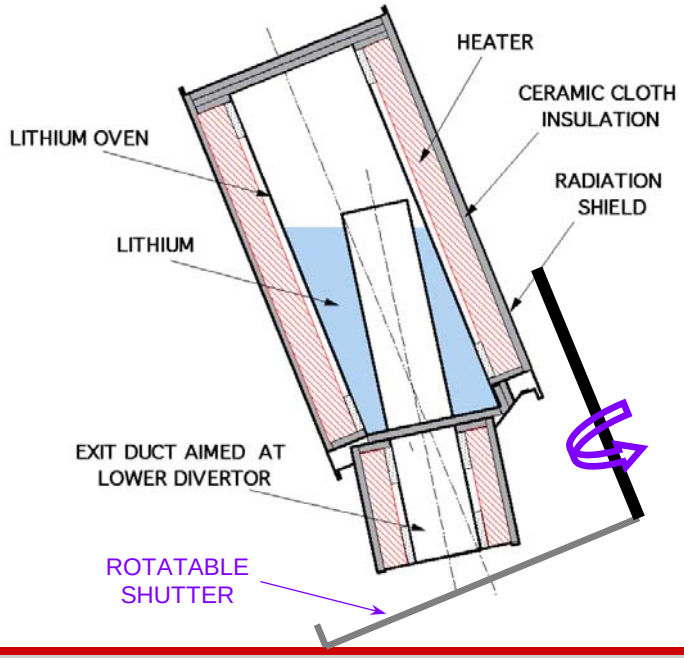
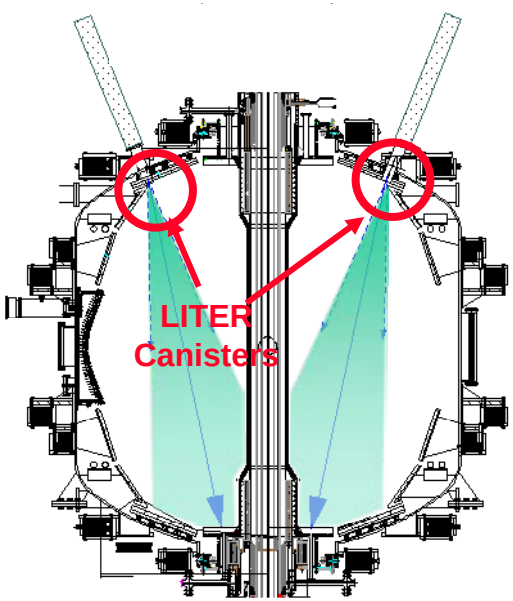
Dual LITERs Replenish Lithium Layer on Lower Divertor Between Tokamak Discharges

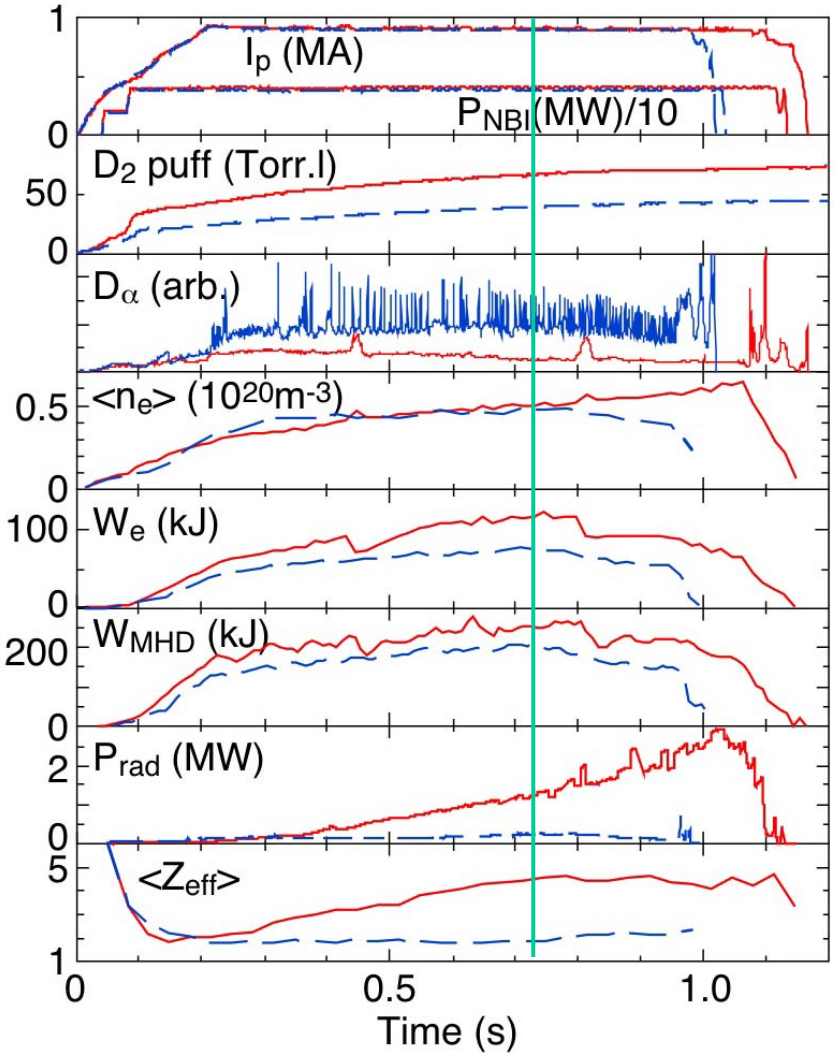
- Electrically-heated stainless-steel canisters with re-entrant exit ducts
- Mounted 150° apart on probes behind gaps between upper divertor plates
- Each evaporates 1 – 40 mg/min with lithium reservoir at 520 – 630°C
- Rotatable shutters interrupt lithium deposition during discharges & HeGDC
- Withdrawn behind airlocks for reloading and initial melting of lithium charge
- Reloaded LITERs 6 times during 2009 run (Mar - Aug): ~300g deposited

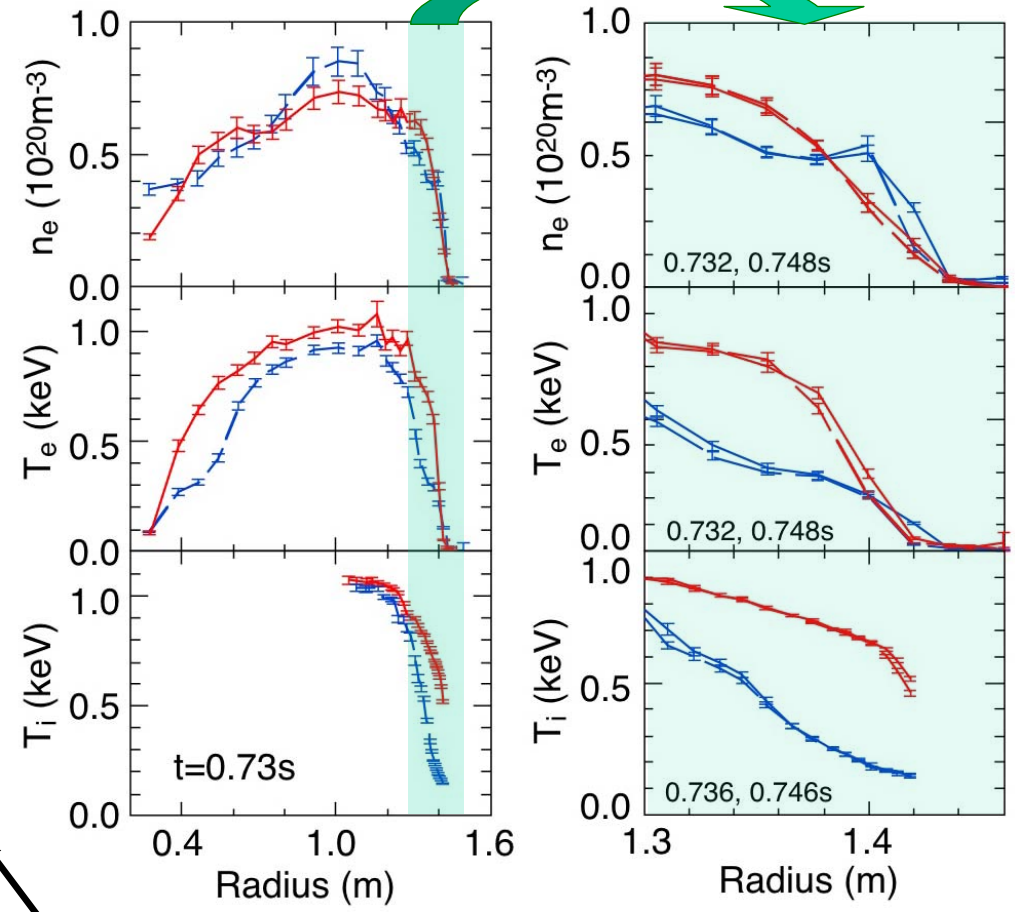




Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement

No lithium (129239); **260mg lithium** (129245)

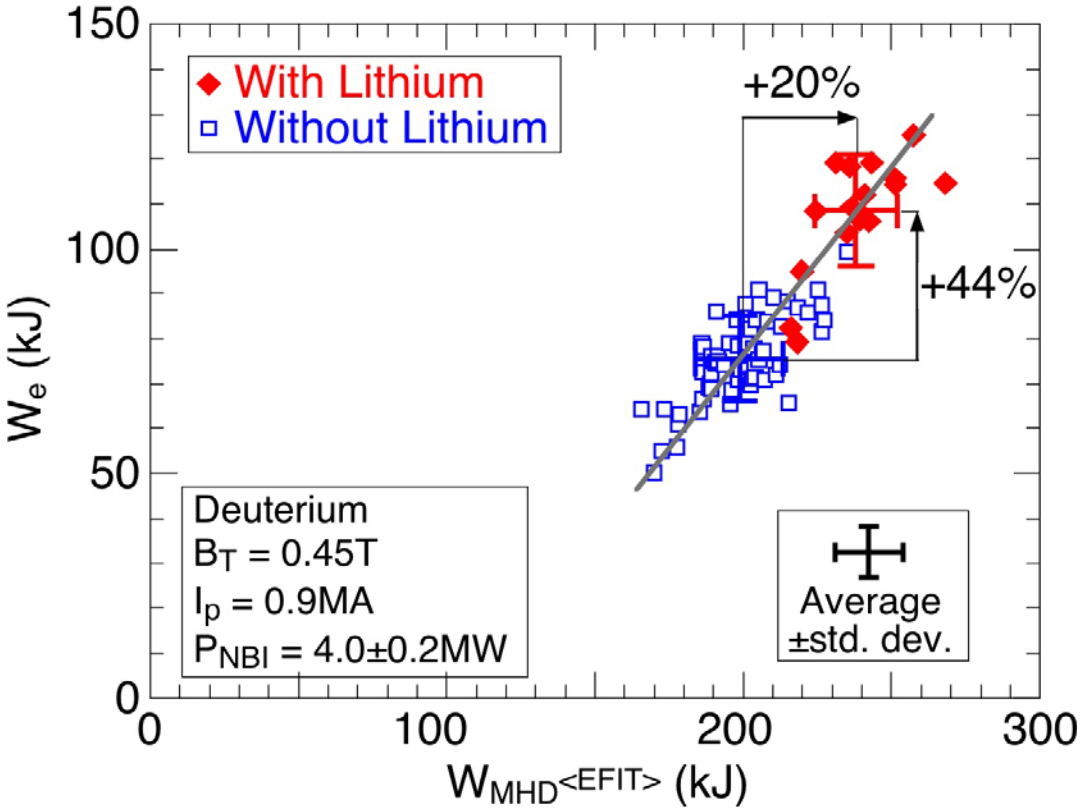




Without ELMs, impurity accumulation increases radiated power and Z_{eff}

Lithium Coating Improves Both Total and Electron Confinement

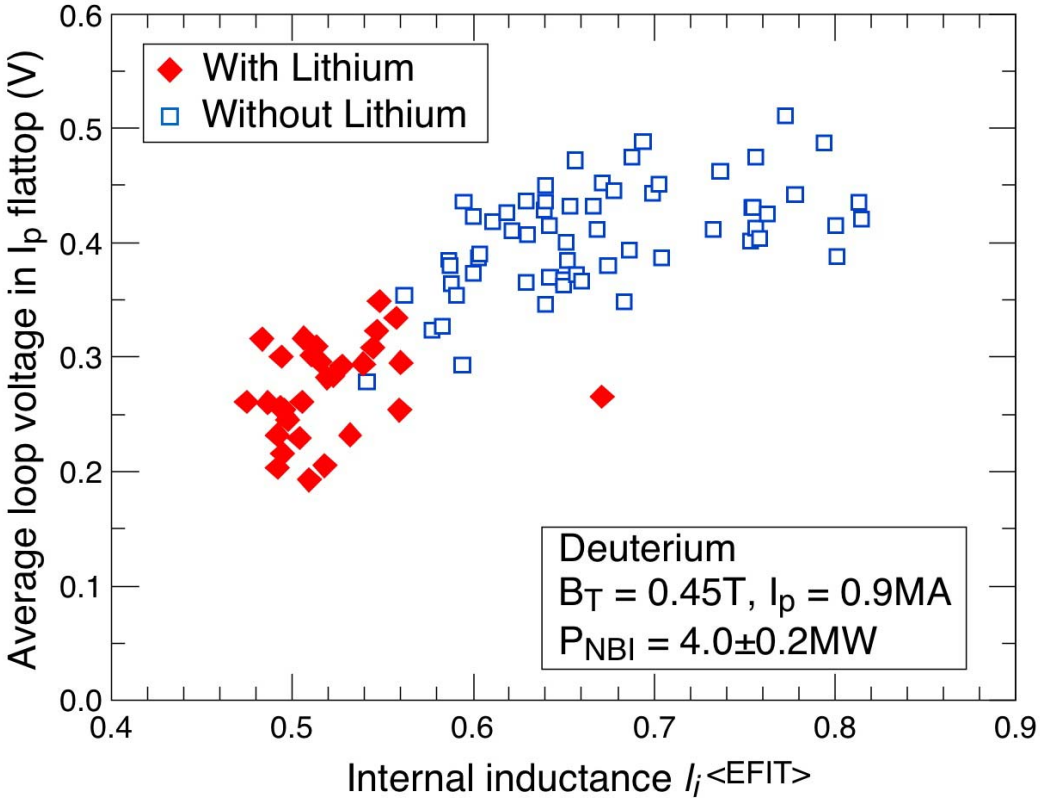
- W_e from integration of MPTS T_e, n_e profiles with EFIT flux surfaces
- W_{MHD} from EFIT with diamagnetic flux and kinetic profile constraints



- All plasmas in H-mode
- H-mode threshold is reduced by lithium coating by up factor 4

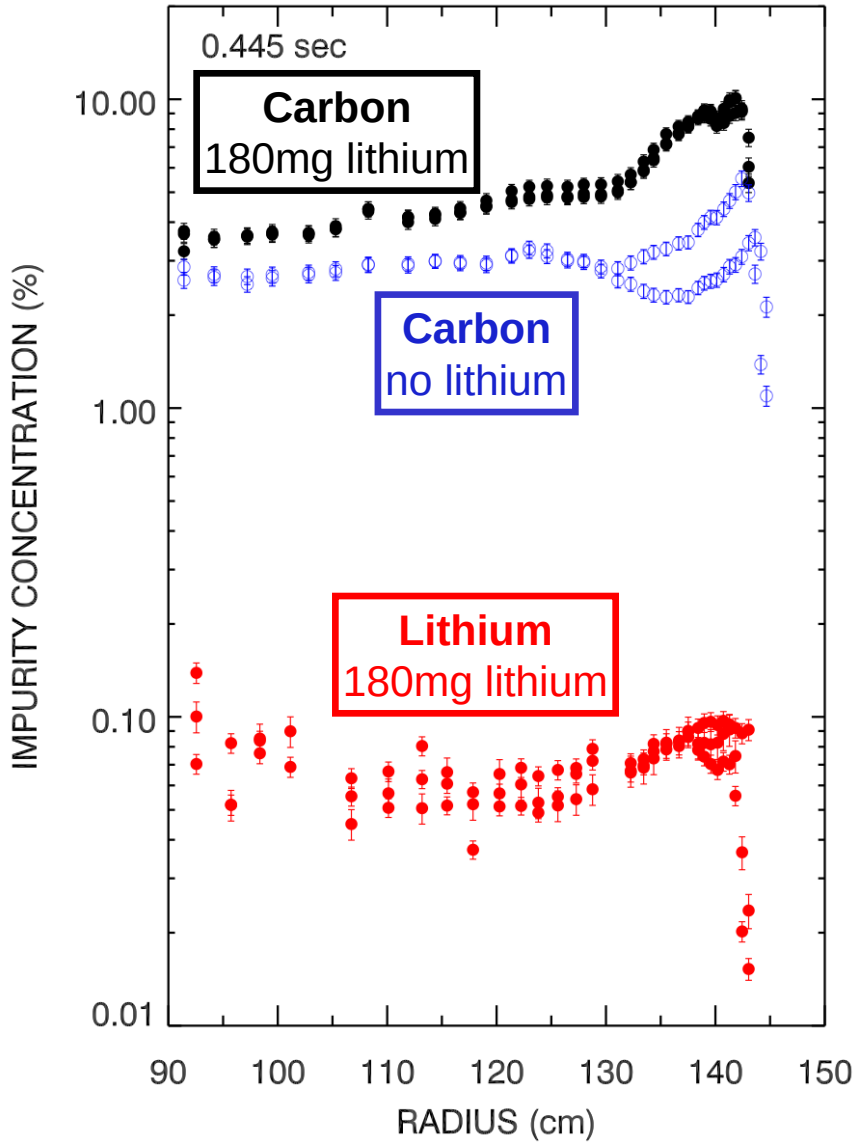
Broader T_e Profile with Lithium Coating Reduces Both Inductive and Resistive Flux Consumption

- Critical issue for development of low-aspect ratio tokamaks

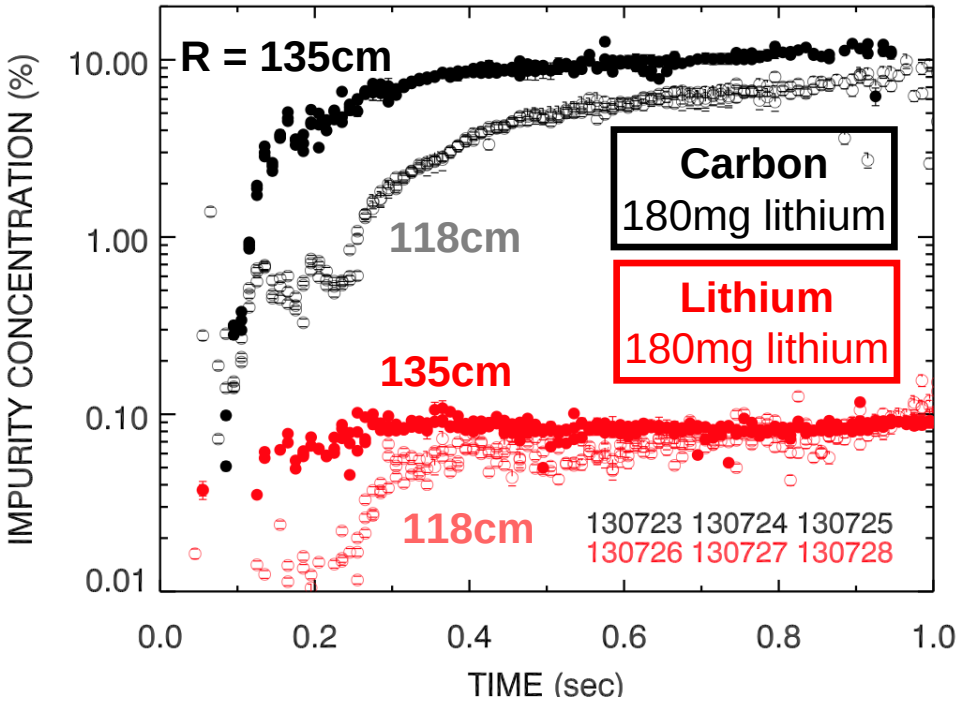


- Reduction occurs despite increase in $\langle Z_{eff} \rangle$ in ELM-free H-modes after lithium coating

Lithium Concentration in Plasmas Remains Low but Carbon Concentration Rises with Lithium Coating

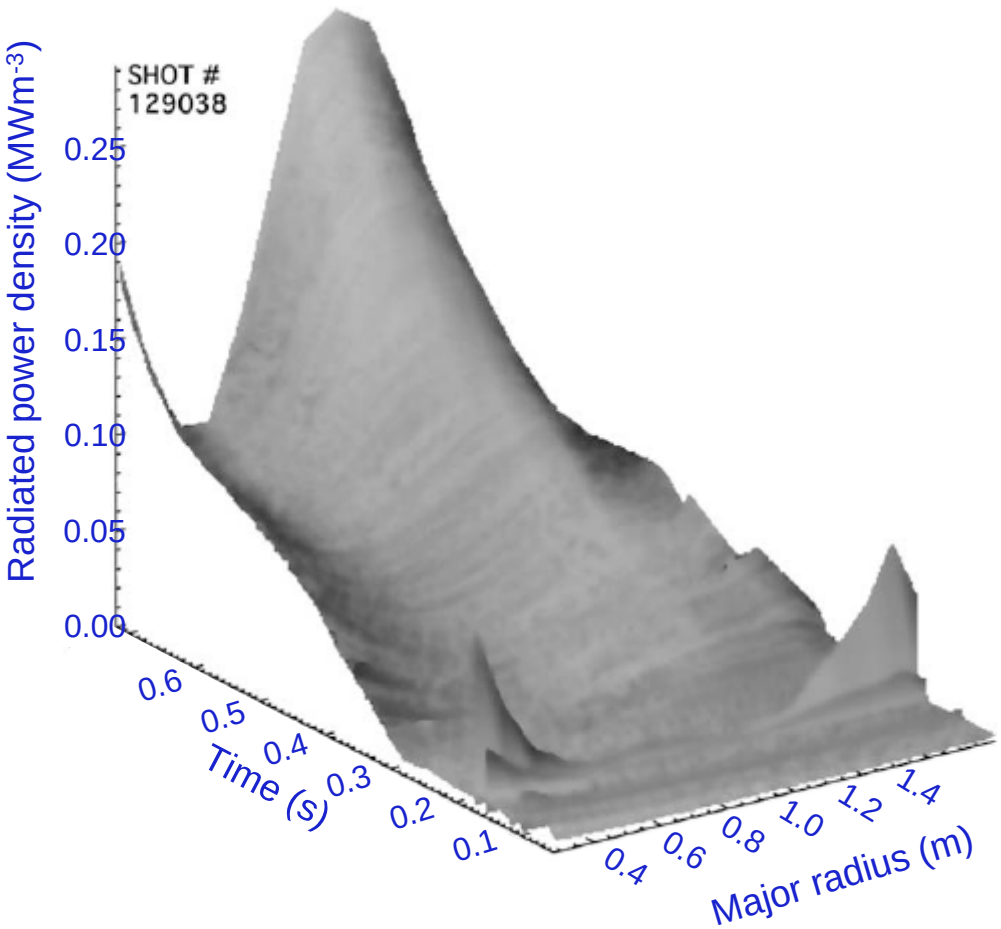


- Quantitative measurements of C^{6+}, Li^{3+} with charge-exchange recombination spectroscopy
- **$n_C/n_{Li} \sim 10^2$**
- Hollow profiles early for both C and Li fill in as time progresses



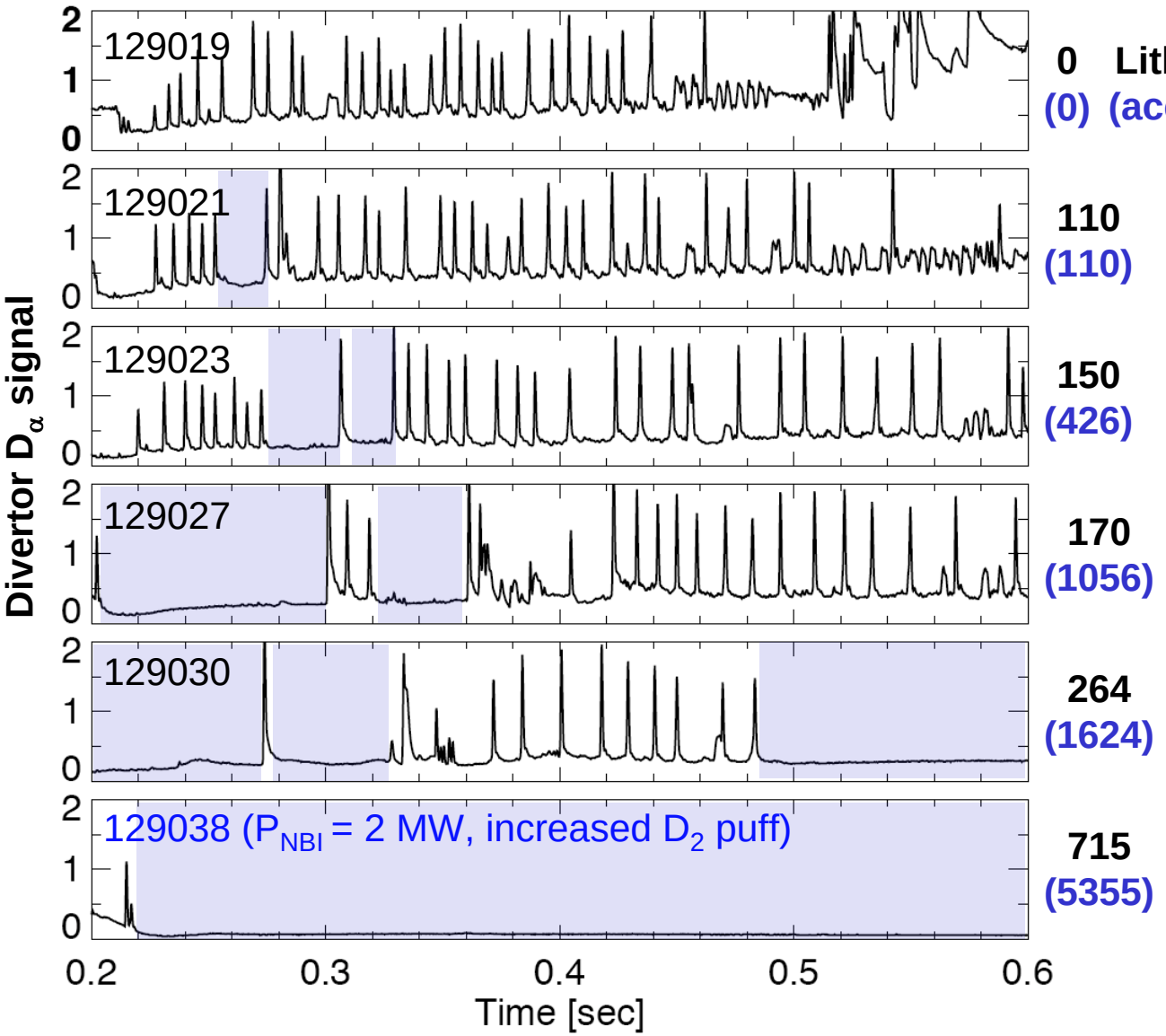
Metals Responsible for Most of the Increase in Radiation When ELMs Suppressed by Lithium

- Radiated power profile becomes centrally peaked in ELM-free discharges



- VUV and SXR spectra show iron lines (Fe X – XVIII) increasing during ELM-free periods
- Radiated power profile remains hollow when ELMs are present
  - Metals still present early but do not accumulate
- If increase in radiation is ascribed to iron-like metals:
  - $n_{\text{"Fe"}}/n_e \sim 0.1\%$
  - ΔZ_{eff}("Fe") ~ 0.3
- Dependence of radiation on I_p and midplane outer gap suggests sputtering by unconfined NB ions in early phases is source

Suppression of ELMs Occurs By Lengthening and Coalescence of ELM-free Periods

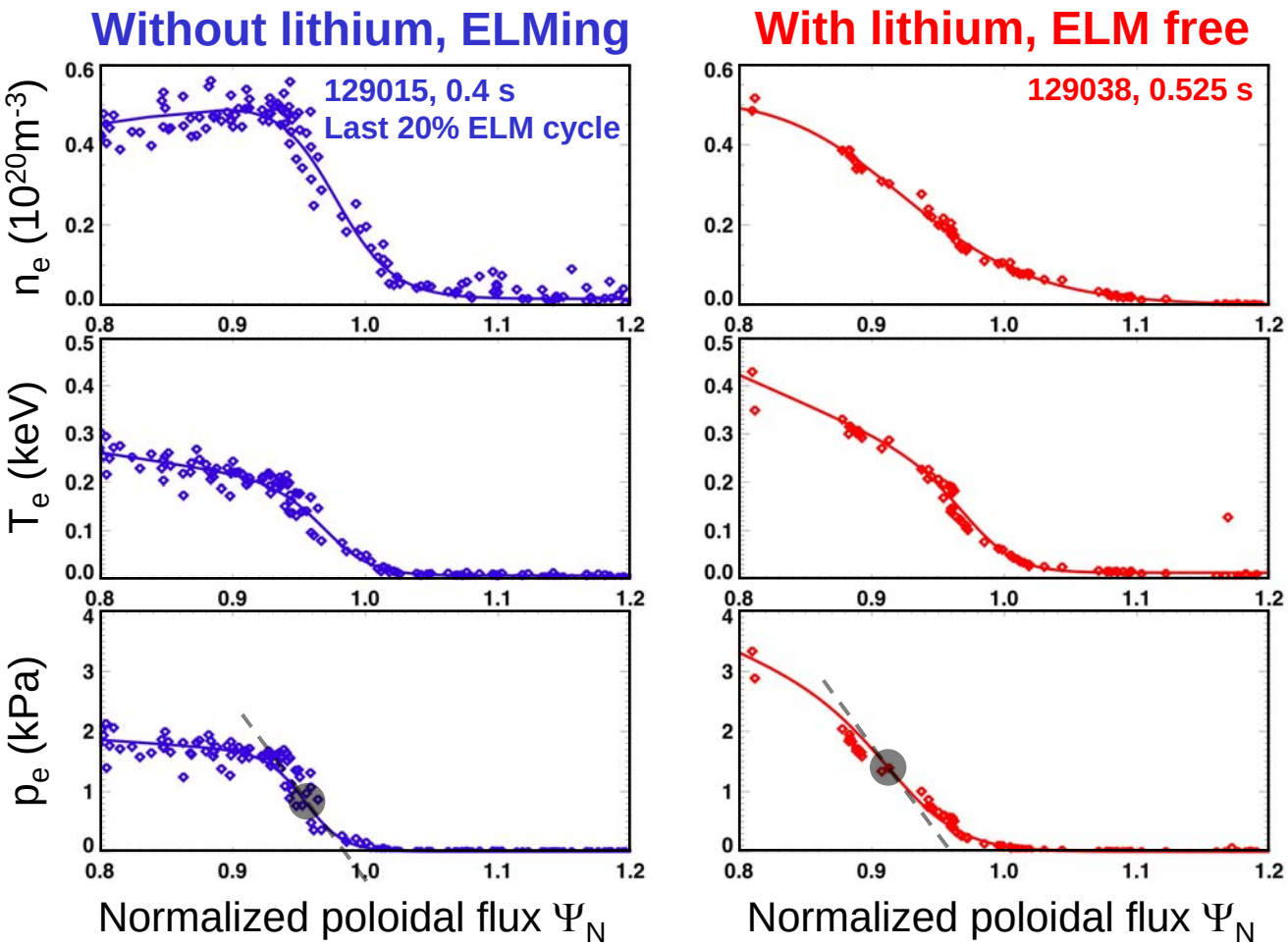


	Lithium deposited (mg)	(accumulated)
129019	0	(0)
129021	110	(110)
129023	150	(426)
129027	170	(1056)
129030	264	(1624)
129038	715	(5355)

- Shots with I_p = 0.8 MA, B_T = 0.5T, P_{NBI}= 4 MW
- All shots remain in H-mode
- ELM suppression was predicted through changes in location of current density gradient with respect to mode rational surfaces (Zakharov, 2006)

Lithium Affects ELMs Through Changes in Temperature and Pressure Profile at Edge

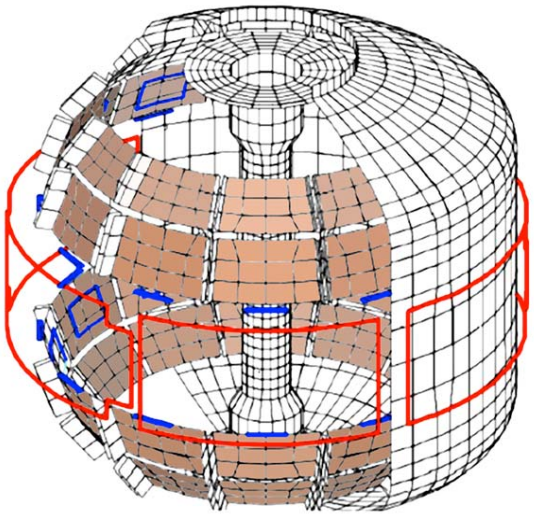
- Multiple timeslices mapped into composite profiles using EFIT equilibrium



- **Shift of max ∇pe to lower shear region with Li stabilizes kink/ballooning**

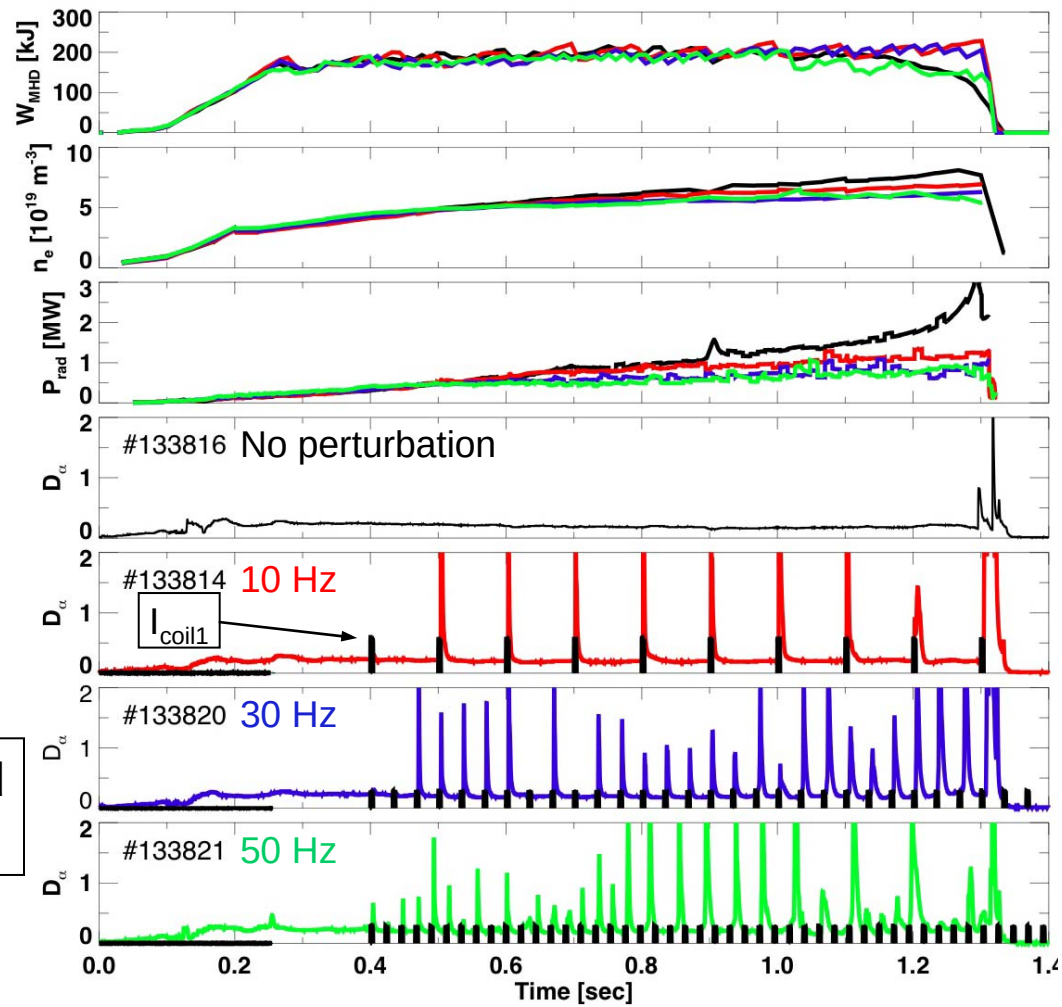
External Non-Axisymmetric Coils Can *Induce* Repetitive ELMs in Discharges with Lithium Coating

Generate n = 3 resonant radial field perturbations with 3 pairs of midplane coils



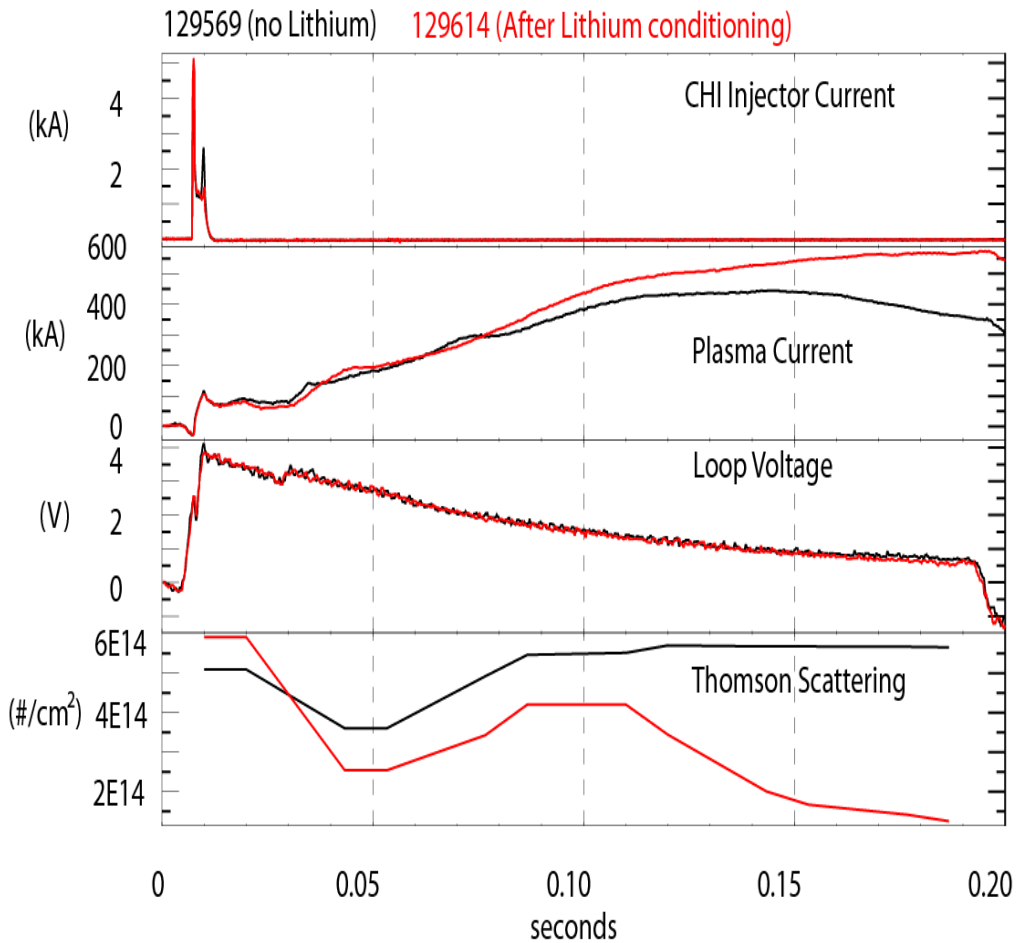
3 Switching Power Amplifiers applied trains of 3kA, 4ms square pulses

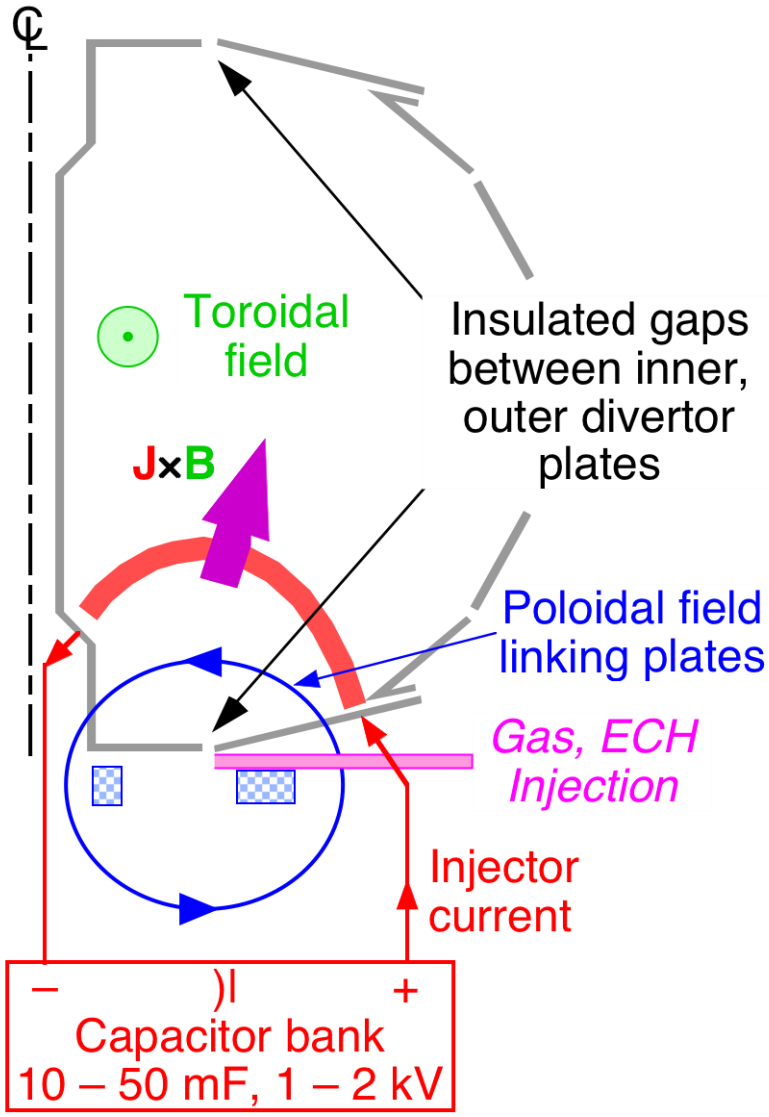
Double-null, κ=2.4, δ=0.8, 0.8MA, 0.45T, NBI 4 MW



- **Induced ELMs reduce n_e, P_{rad}, Z_{eff} with small effect on plasma energy**

CHI Discharges after Li Conditioning are More Reproducible and Reach Higher Currents

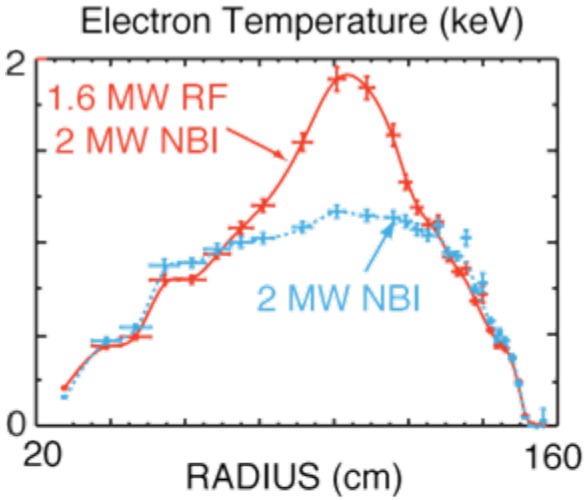


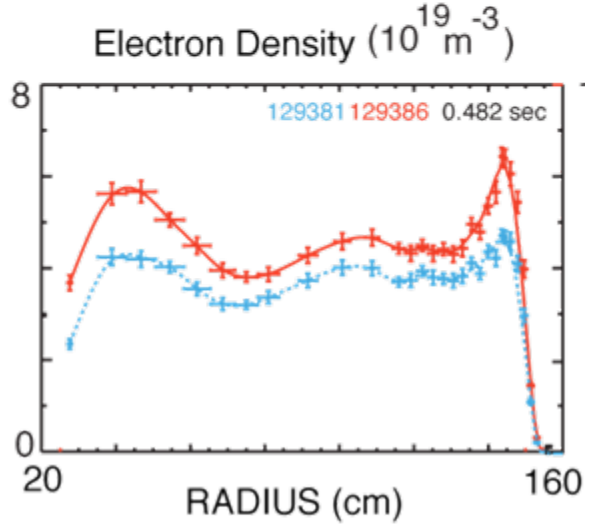


- **No use of cryopumping**
- **Improved performance after coupling to induction similar to that seen on HIT-II with Ti gettering**

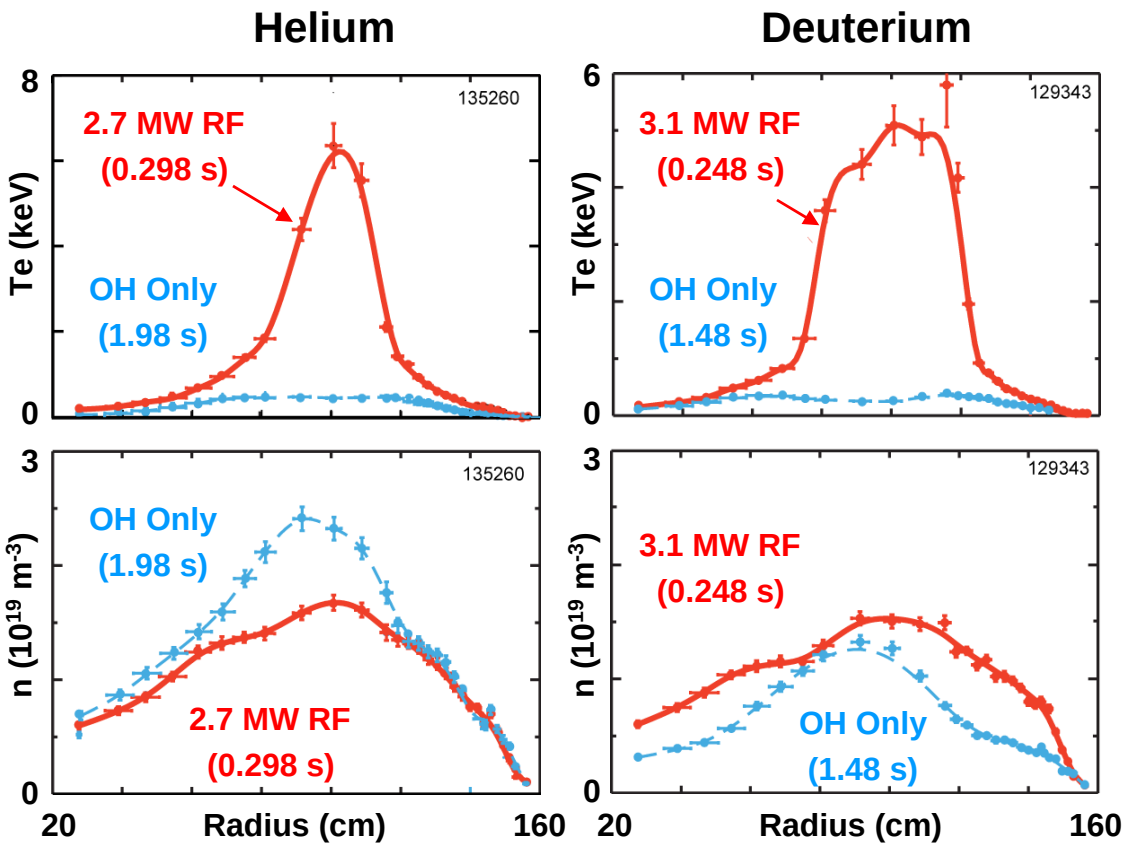
Li Coating Improves HHFW Heating Efficiency in Both NBI H-Modes and L-Modes at Low k_ϕ

Core Electron Heating D_2 NBI H-Mode





D_2 and He Plasmas Heated to NSTX Record Te(0) with ~ 3 MW of $k\phi$ = - 8 m^{-1} HHFW



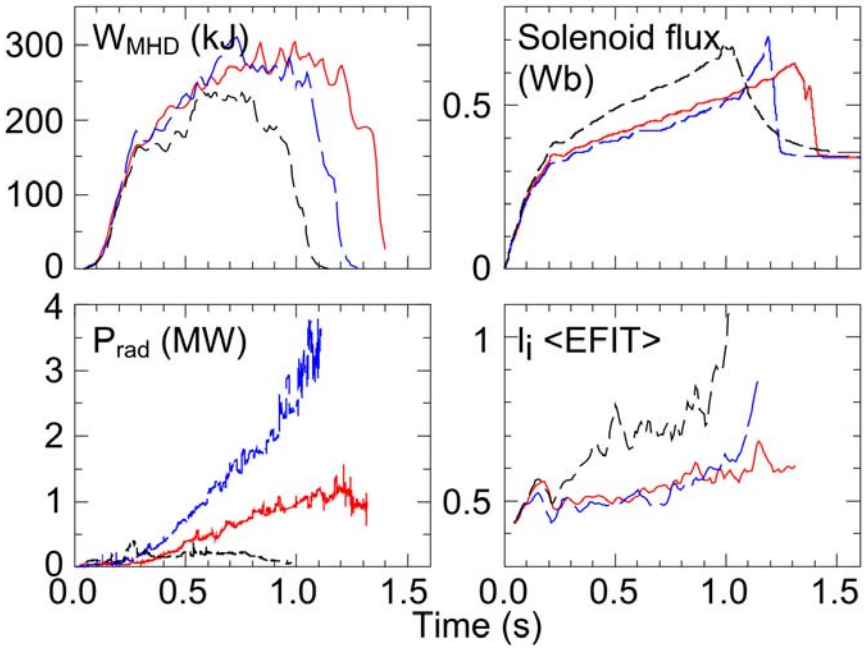
- Reflectometer measures reduced SOL density in front of antenna with lithium

Injecting Lithium Powder Produced Benefits Similar to LITER

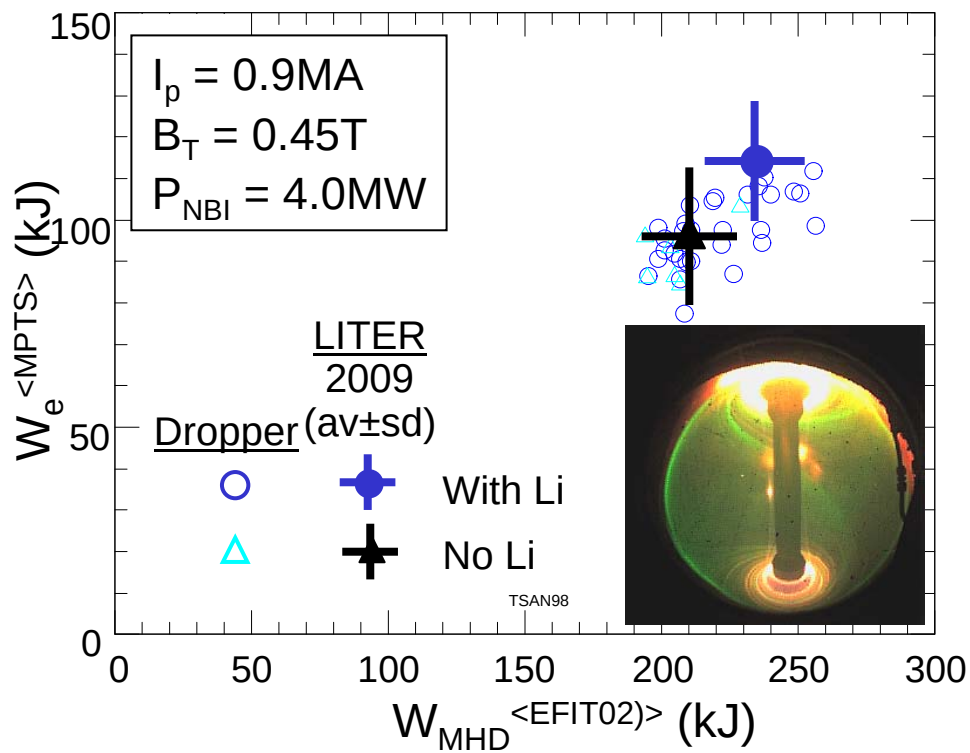
- Evident effect in initial 2008 experiment: ~10 mg introduced
  - Confinement increase, reduced flux consumption, reduced radiation
- In 2009, 50 – 170 mg/s injected – improvements seen but less dramatic
  - "Surgical" Li injection onto CS, dual droppers employed

2008

No lithium; LITER; Li Powder

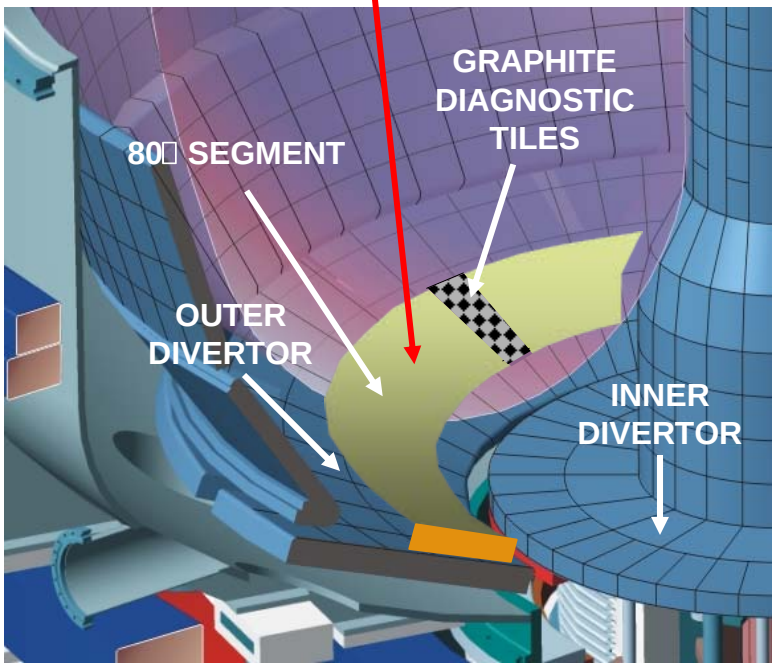


2009



In 2010, NSTX Will Begin Investigating Liquid Lithium on Plasma Facing Components

Liquid Lithium Divertor (LLD)



- Replace rows of graphite tiles in outer lower divertor with 4 segmented plates
- Semi-porous (~50%) plasma-sprayed molybdenum surface (~150µm) on copper plate with temperature control
  - Capability to heat to >400C (Li melting point 180°C)
  - Active heat removal to counteract plasma heating
- Initially supply lithium with LITERs and possibly lithium powder dropper

- Evaluate capability of liquid lithium to sustain deuterium pumping in high-power tokamak environment
  - Laboratory measurements in PISCES and experience in CDX-U show that liquid has much higher capacity for deuterium retention than solid

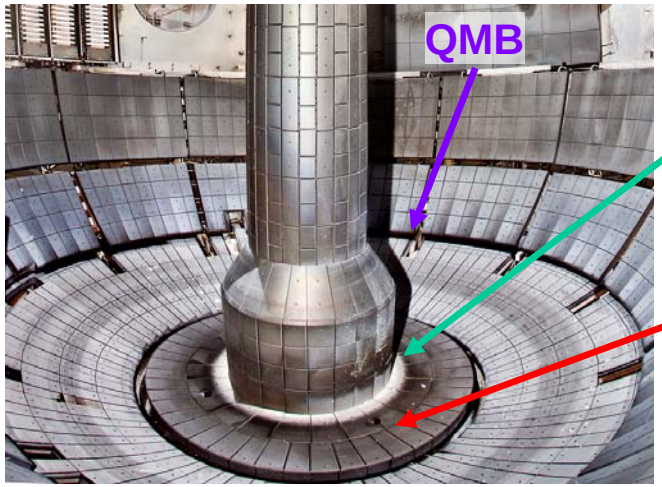
Lithium Coating of Carbon PFCs Has Shown Benefits for Divertor Plasma Operation in NSTX

- Reduces hydrogenic recycling
- Reduces H-mode threshold power by up to a factor 4
- Improves confinement
  - Electron confinement increased up to 40%
  - Broader T_e reduces both inductive and resistive flux consumption
- Lithium, in conjunction with active error field correction and mode control, has enabled longer pulse lengths within flux limit
- Suppresses ELMs in H-mode plasmas
  - ELM suppression increases carbon and high-Z metallic impurities
  - Lithium concentration remains very low
  - Metals responsible for secular rise in central radiation: *source not identified*
  - ELMs triggered by external coils reduced deleterious effects of impurities
- Coaxial Helicity Injection initiation successfully coupled to inductive ramp-up following lithium coating with saving of inductive flux
- Reduction of edge density improves HHFW coupling to core plasma by suppressing generation of parasitic surface waves

Extra Slides

Lithium Coating is Significantly Affected by Plasma Interaction in Divertor Strike Point Region

- Routine lithium deposition has obviated need for HeGDC between shots
  - Contributed to significantly higher shot rate in 2008–9
- Effects of lithium coating decay after several (3 – 10) discharges
- Formation of lithium compounds (Li_2O, LiOH, Li_2CO_3) after vacuum vessel is opened reveals areas of lithium deposition

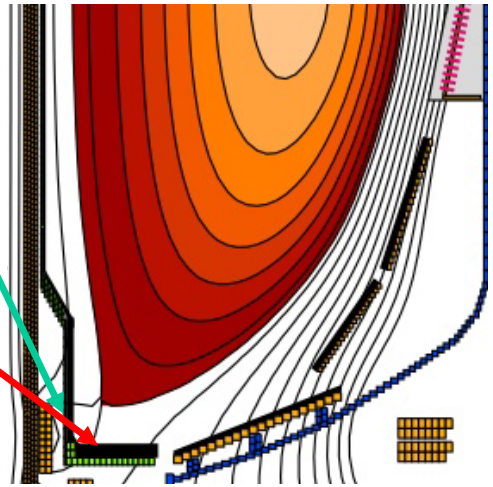


Lithium accumulated in private flux region

Lithium depleted at strike points

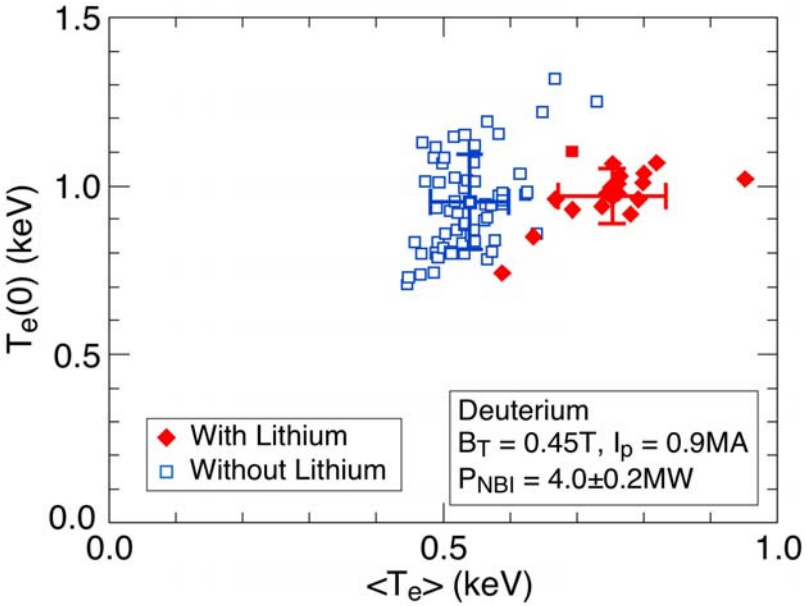
- In other areas lithium "shadows" are sharp

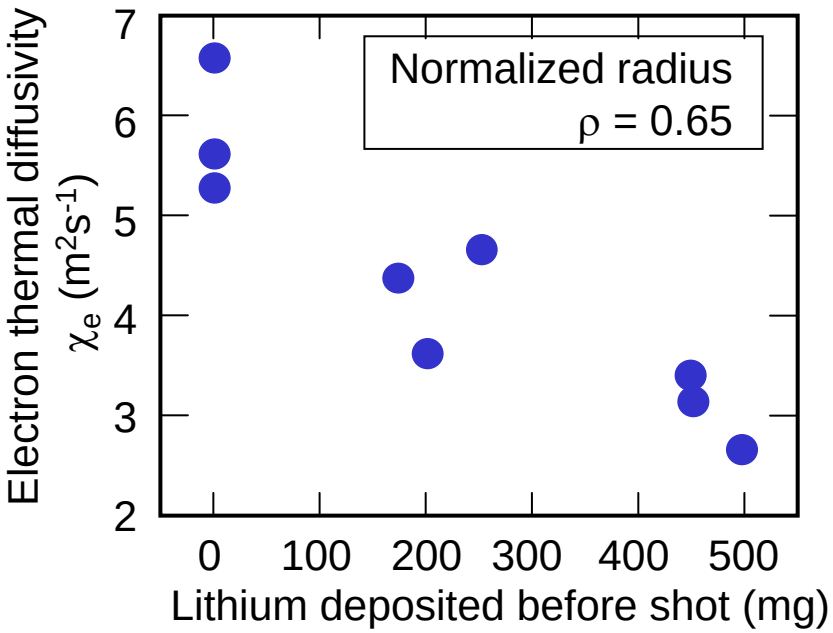
Typical LSN equilibrium



- Surfaces cleaned with water and light abrasion after oxidation in moist air for a few days (in NJ summer conditions)

Improvement in Electron Confinement Arises from Broadening of Temperature Profile

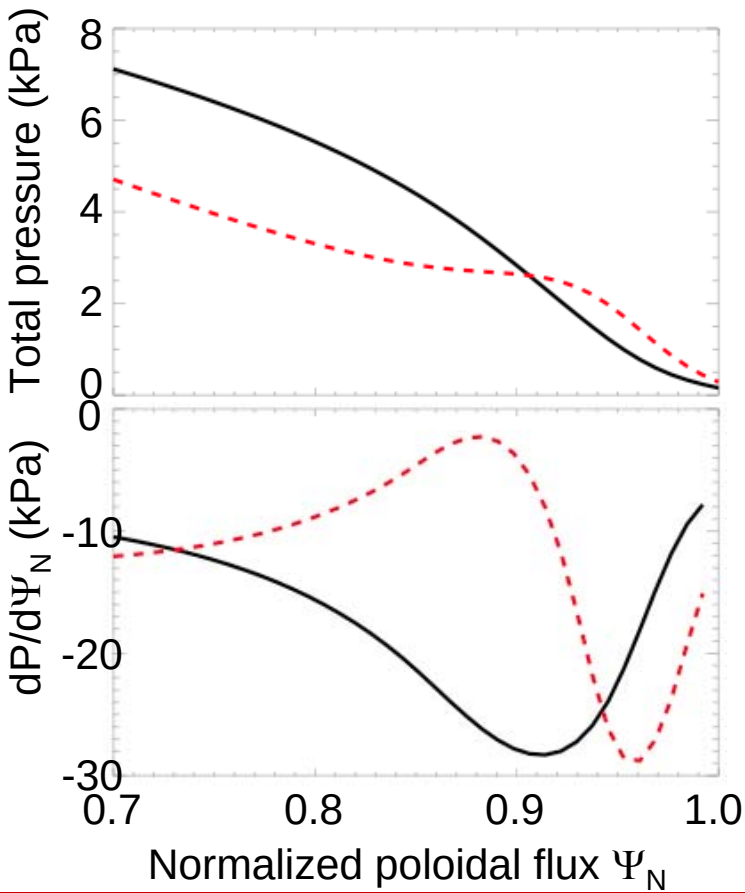


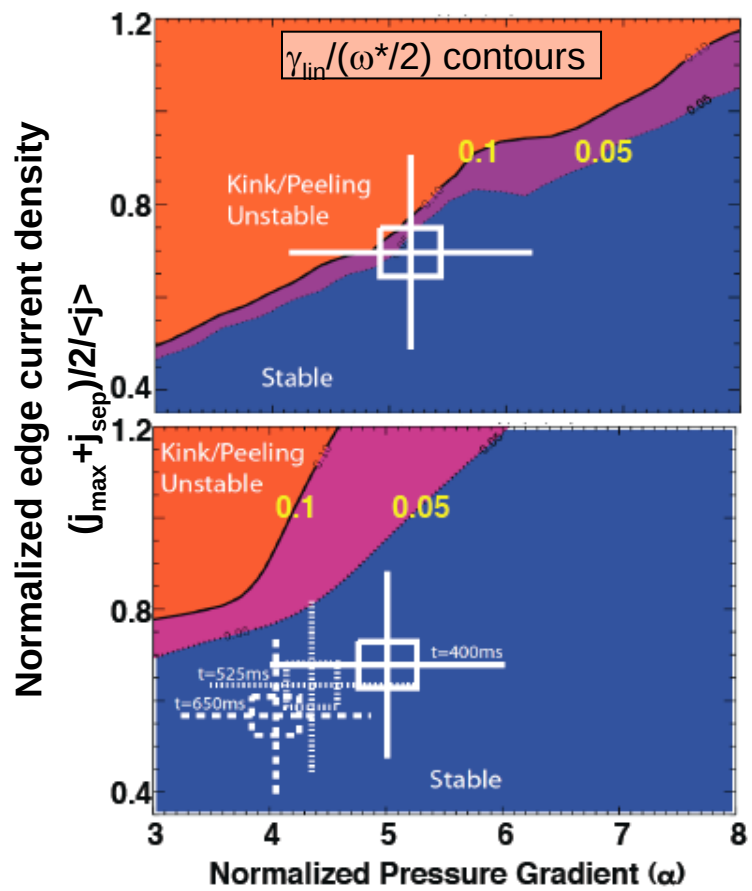


- TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium
- Fast-ion contribution to total energy increased
- Thermal ion confinement remains close to neoclassical level both with and without lithium

Shift of Maximum in ∇p_e to Region of Lower Shear with Lithium Stabilizes Kink/Ballooning

- Analysis with PEST and ELITE codes
- Change in recycling affects edge current
- Precursor activity with n = 1 – 5 observed before ELM onset





Without lithium (end of ELM cycle)

With lithium