Plasma Response to Lithium-Coated Plasma-Facing Components in NSTX

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for the NSTX Research Team

36th EPS Conference on Plasma Physics
July 2, 2009

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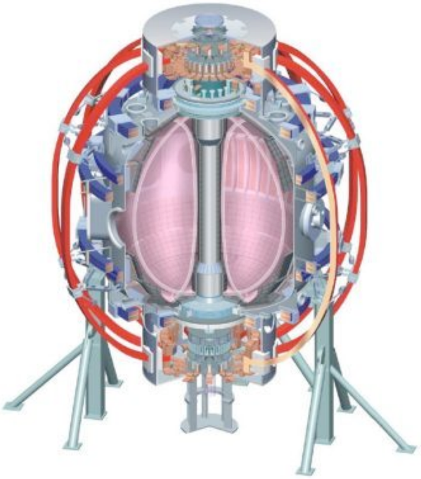

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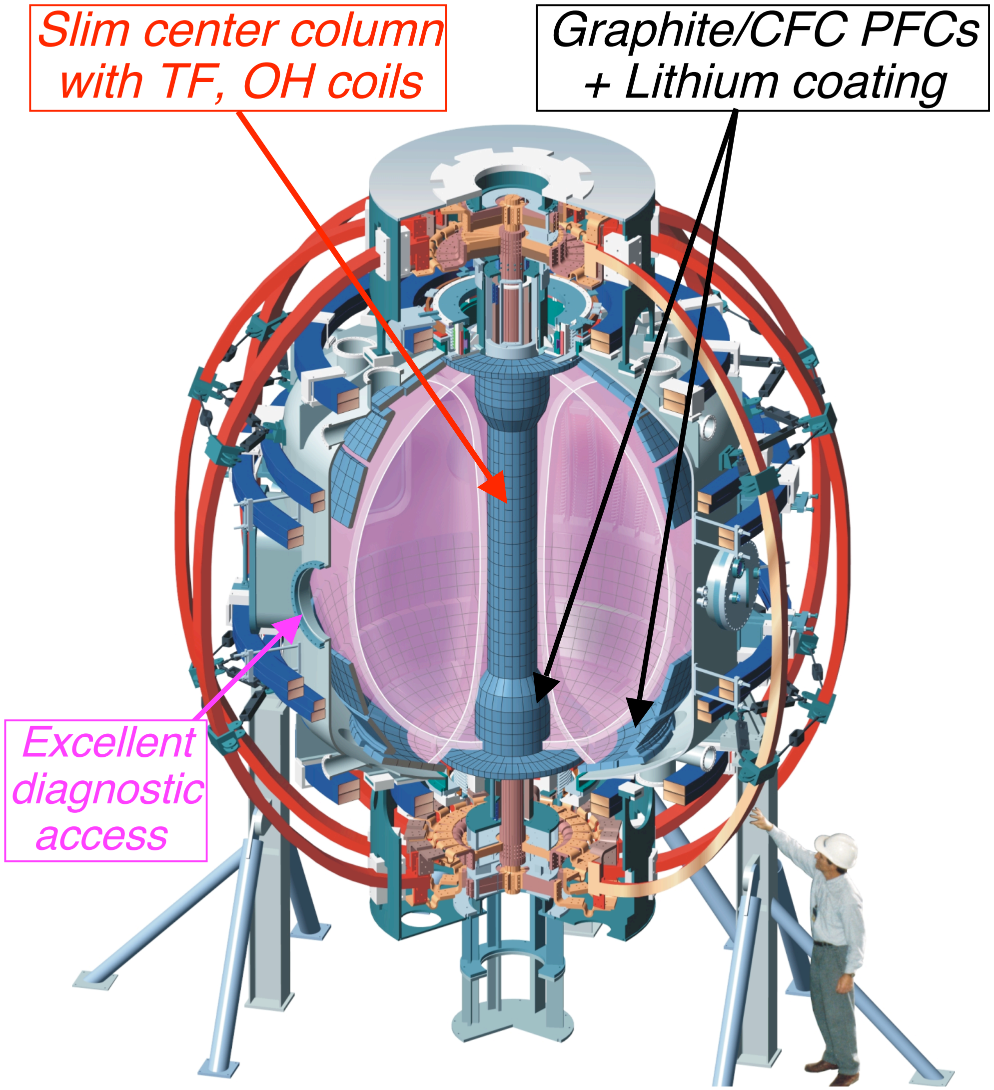
NSTX Designed to Study High-Temperature Toroidal Plasmas at Low Aspect-Ratio



Slim center column with TF, OH coils

Graphite/CFC PFCs + Lithium coating

Excellent diagnostic access

Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Toroidal Field B_{T0}	0.4 – 0.55 T
Plasma Current I_p	1.5MA
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 5 keV
Central density	$\le 1.2\times10^{20}\,\mathrm{m}^{-3}$

NSTX is Exploring and Developing Lithium-Coated Plasma Facing Components (PFCs)

2005: Injected lithium pellets into He discharges prior to D NBI shot

2006: LIThium EvaporatoR (**LITER**) deposited lithium on room-temperature center column and lower divertor

2007: Larger evaporator re-aimed to increase deposition rate on lower divertor

2008: Dual LITERs to eliminate shadowed regions on lower divertor

– Also used "lithium powder dropper" to introduce lithium through SOL

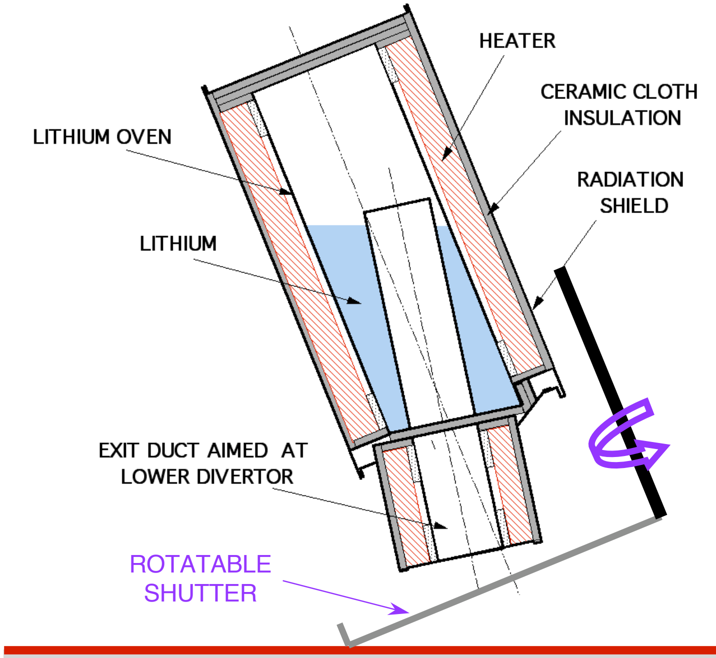
2009: Routine use of dual LITERs

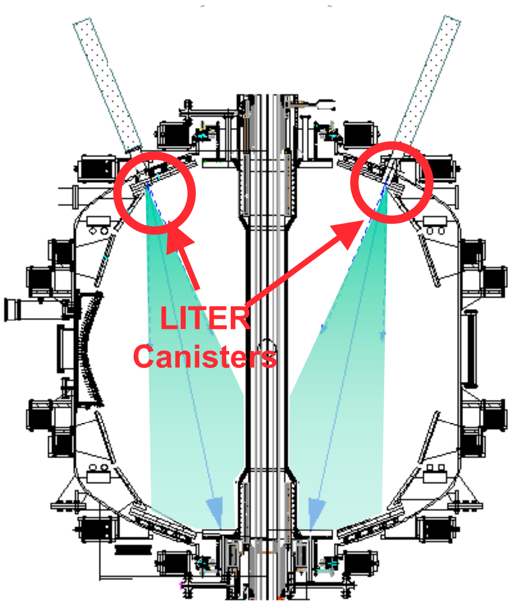
  - 80% of discharges now have lithium applied beforehand

- Complements and builds on experience with lithium coating of limiters in tokamaks TFTR (early 1990s), CDX-U (liquid), T-11, FTU, HT-7
  - Now also experimenting with lithium in stellarator TJ-II and RFP RFX

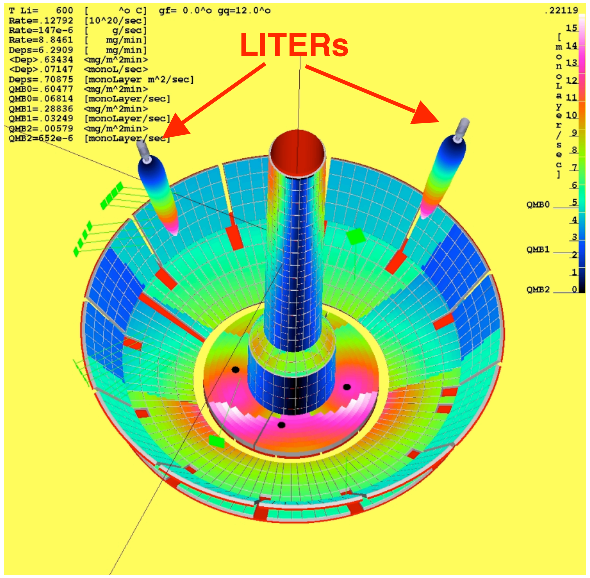
Dual LITERs Replenish Lithium Layer on Lower Divertor Between Tokamak Discharges

- Electrically-heated stainless-steel canisters with re-entrant exit ducts
- Mounted 150° apart on probes behind gaps between upper divertor plates
- Each evaporates 1 – 30 mg/min with lithium reservoir at 520 – 630°C
- Plumes of lithium vapor are roughly Gaussian in angular distribution
- Rotatable shutters interrupt lithium deposition during discharges & HeGDC
- Withdrawn behind airlocks for reloading and initial melting of lithium charge





Modeled deposition pattern



```
T Li=   600  [     ^o C]  gf= 0.0^o gq=12.0^o
Rate=.12792  [10^20/sec]
Rate=147e-6  [    g/sec]
Rate=8.8461  [   mg/min]
Deps=6.2909  [   mg/min]
<Dep>.63434  <mg/m^2min>
<Dep>.07147  <monoL/sec>
Deps=.70875  [monoLayer m^2/sec]
QMB0=.60477  <mg/m^2min>
QMB0=.06814  [monoLayer/sec]
QMB1=.28836  <mg/m^2min>
QMB1=.03249  [monoLayer/sec]
QMB2=.00579  <mg/m^2min>
QMB2=652e-6  [monoLayer/sec]
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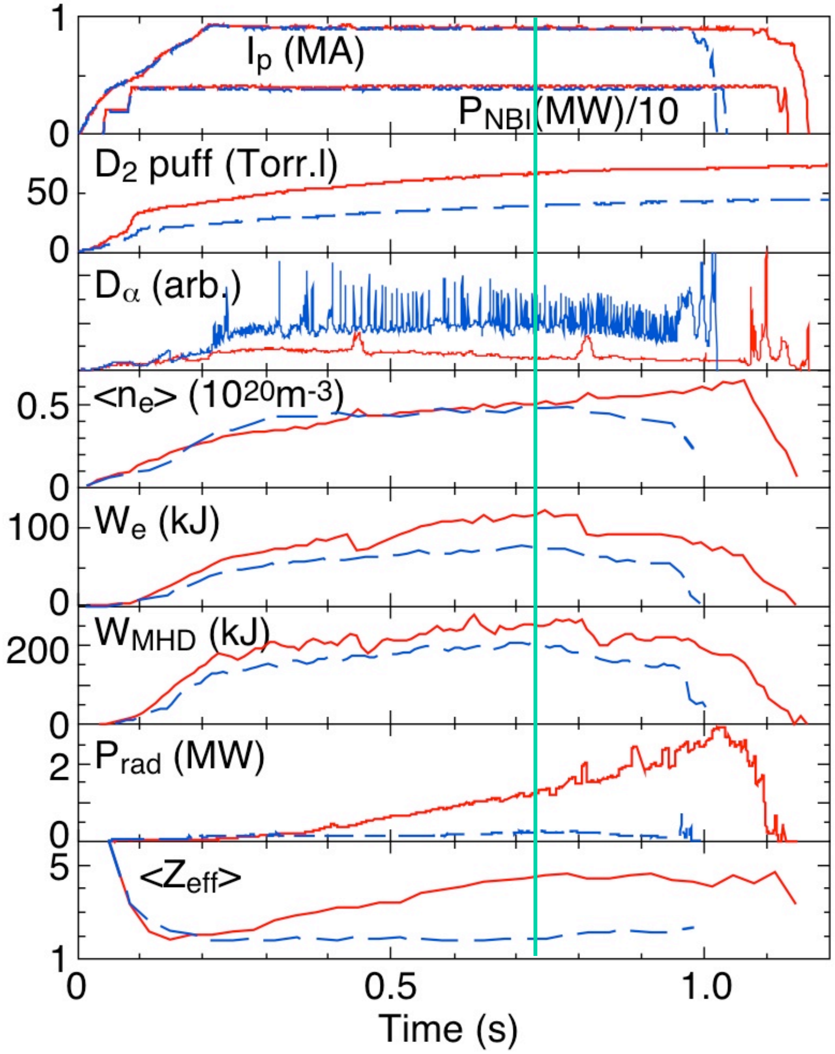
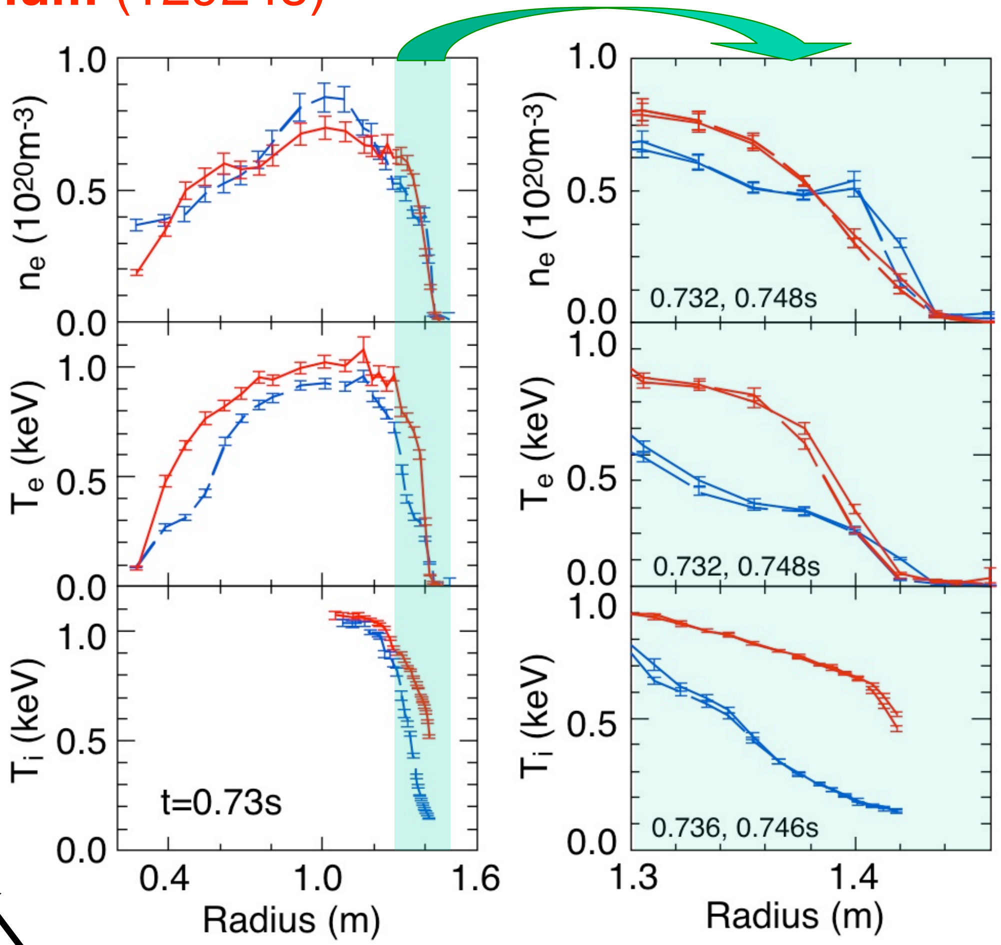
H. Kugel, L. Zakharov

Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement

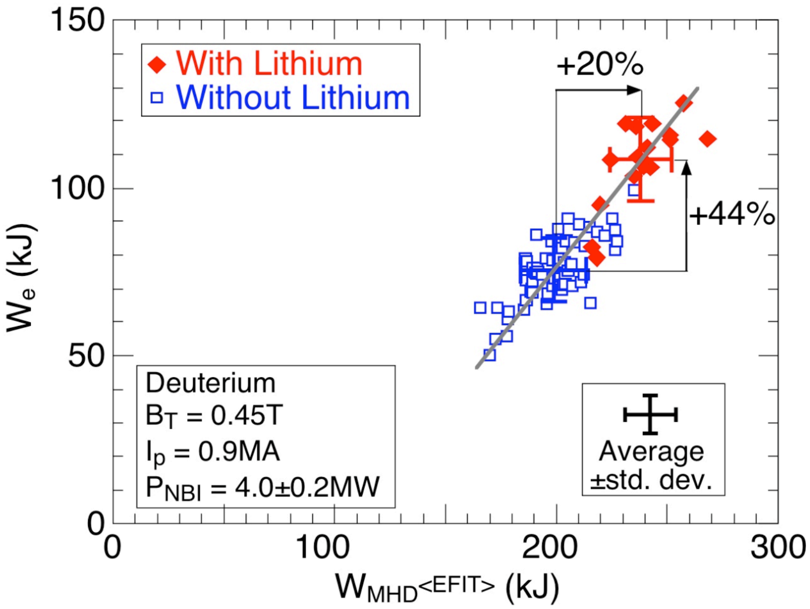
No lithium (129239); **260mg lithium** (129245)

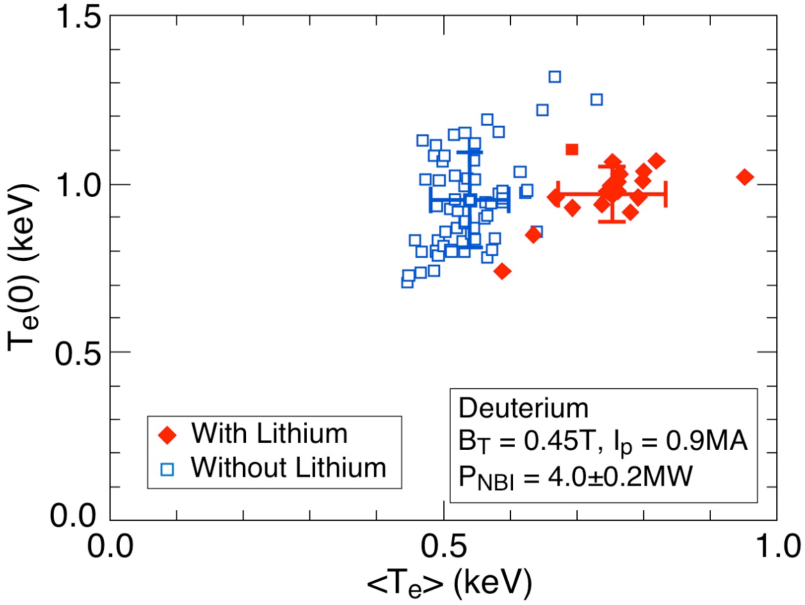




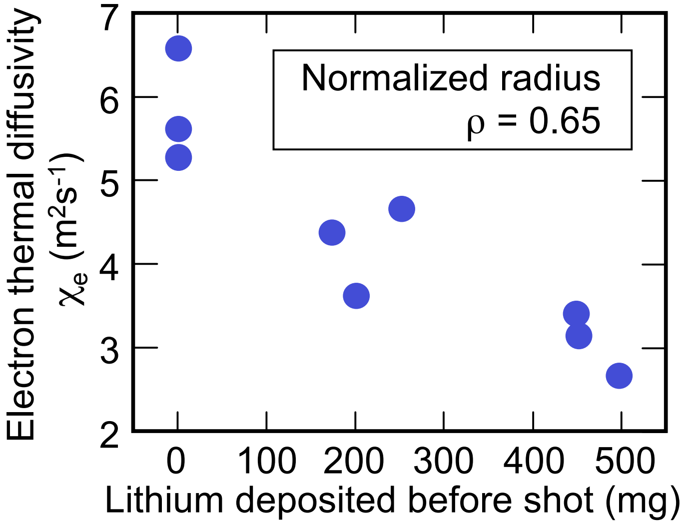
Without ELMs, impurity accumulation increases radiated power and Z_{eff}

Improvement in Confinement Arises from Broadening of Temperature Profiles



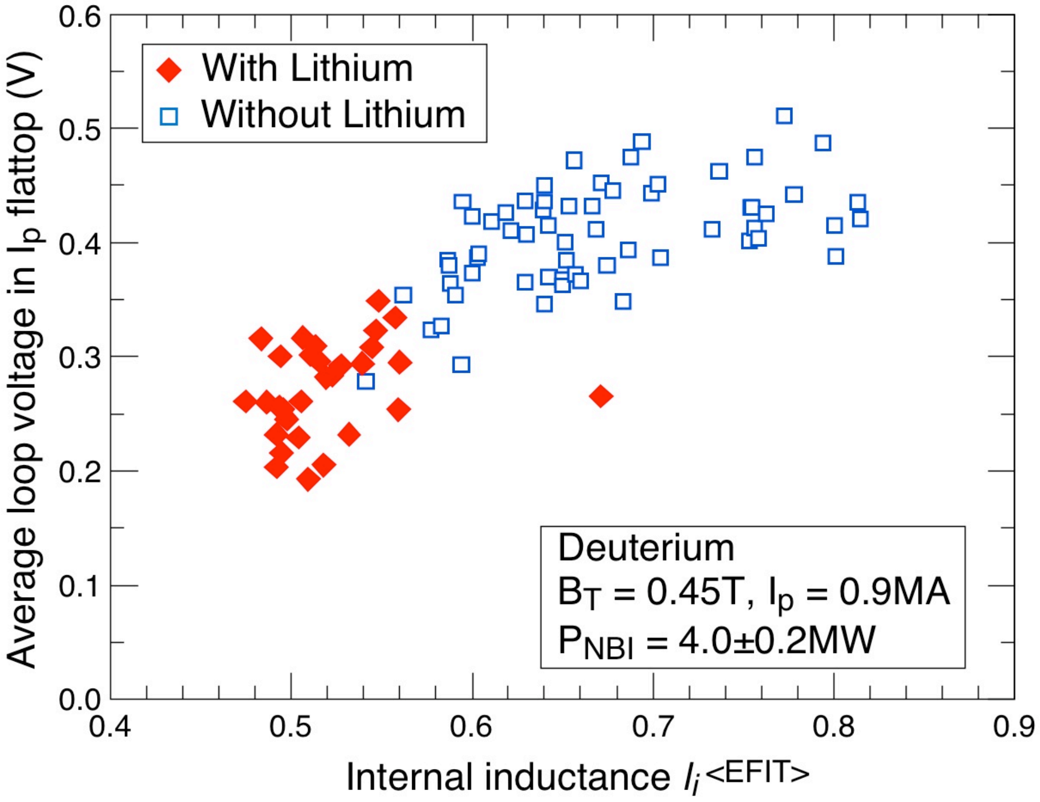


- All plasmas in H-mode
- TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium
- Ion confinement close to neoclassical level both with and without lithium



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

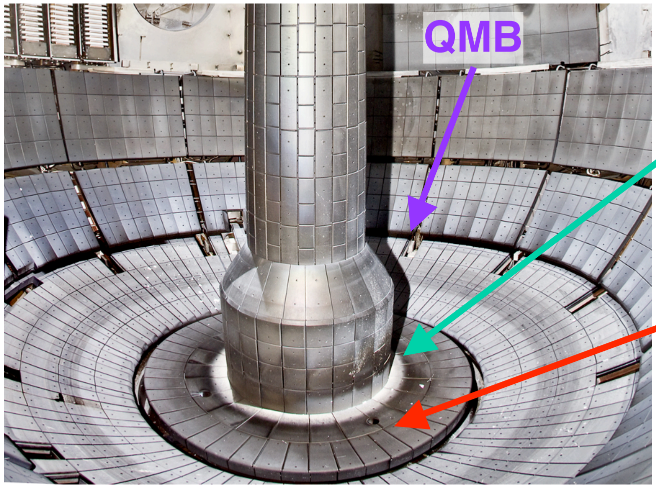
- Critical issue for development of low-aspect ratio tokamaks



- Reduction occurs despite increase in $<Z_{eff}>$ in ELM-free H-modes after lithium coating

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

- Lithium applied between discharges typically 20 – 600 mg
  - More than needed to react all injected D_2, typically 5 – 15 mg
- Lithium deposition has obviated need for HeGDC between discharges
- Quartz-crystal micro-balance (QMB) data implies maximum lithium thickness deposited is 5 – 160 nm on strike point of inner divertor plate
- 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

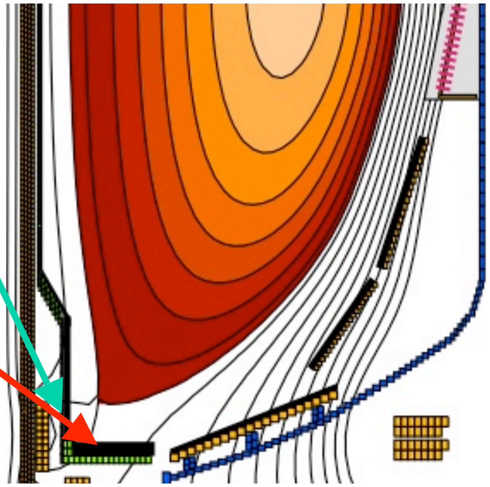


Lithium accumulated in private flux region

Lithium depleted at strike points

- In other areas lithium “shadows” are sharp

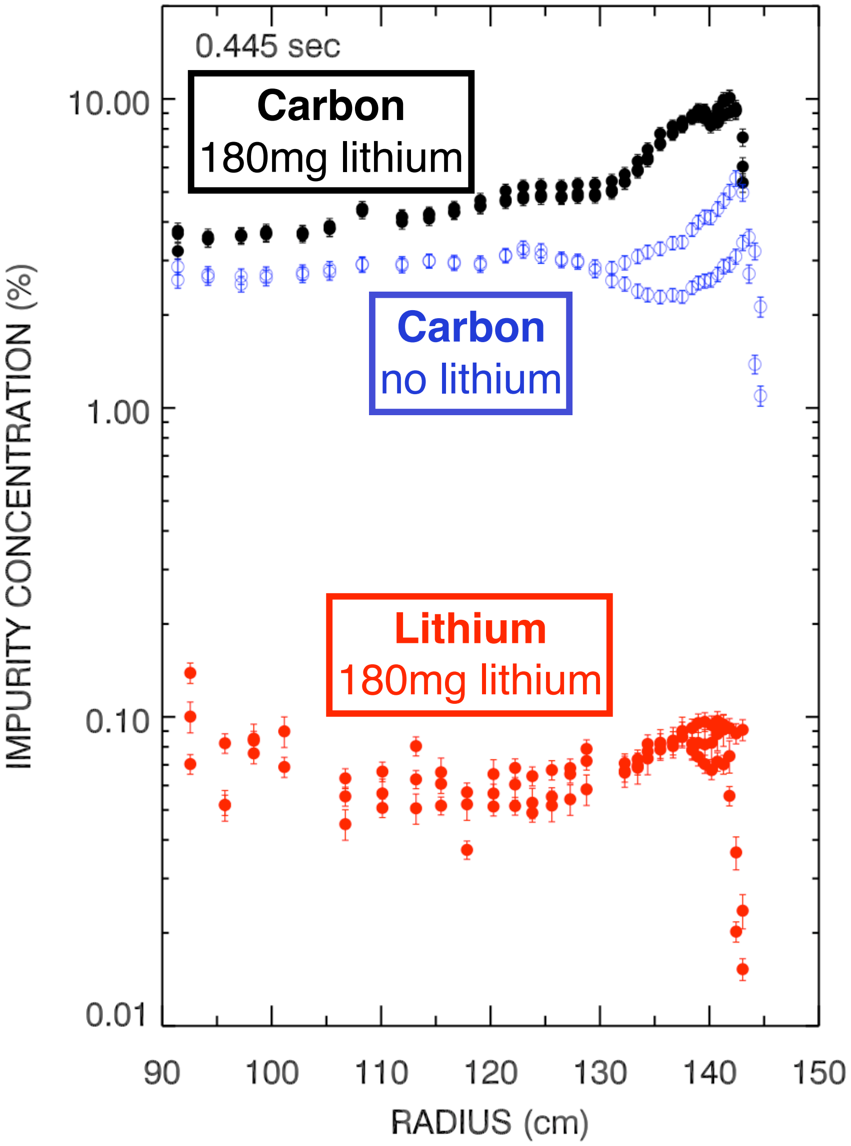
Typical LSN equilibrium



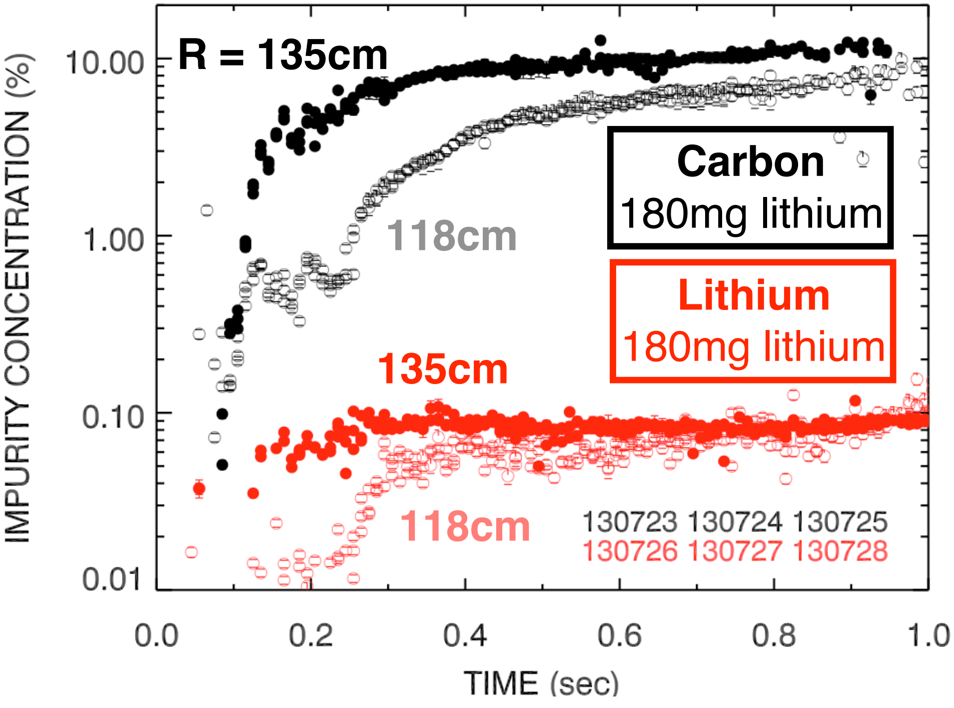
- PFC surfaces cleaned with water and lightly sanded after oxidation complete

H. Kugel, C. Skinner, H. Schneider

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

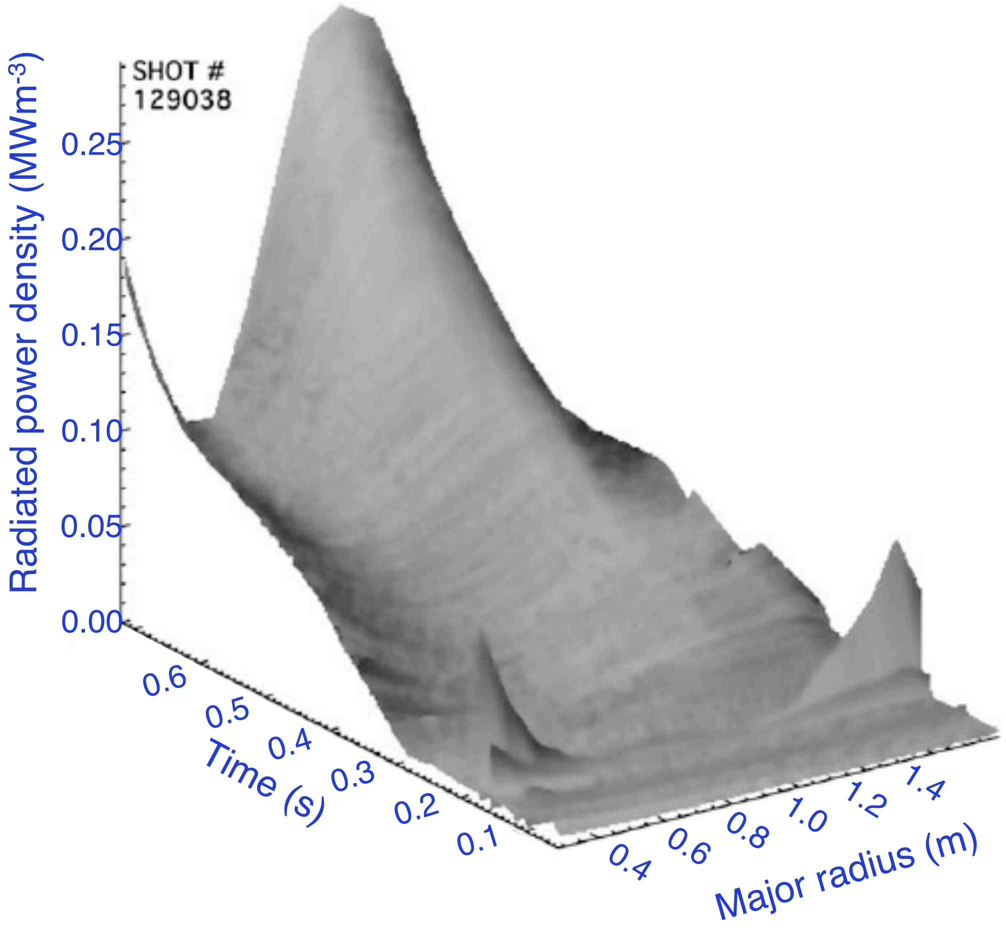


- Quantitative measurements of C^{6+}, Li^{3+} with charge-exchange recombination spectroscopy
- **n_C/n_{Li} = 30 – 100**
- Hollow profiles early for both C and Li fill in as time progresses



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

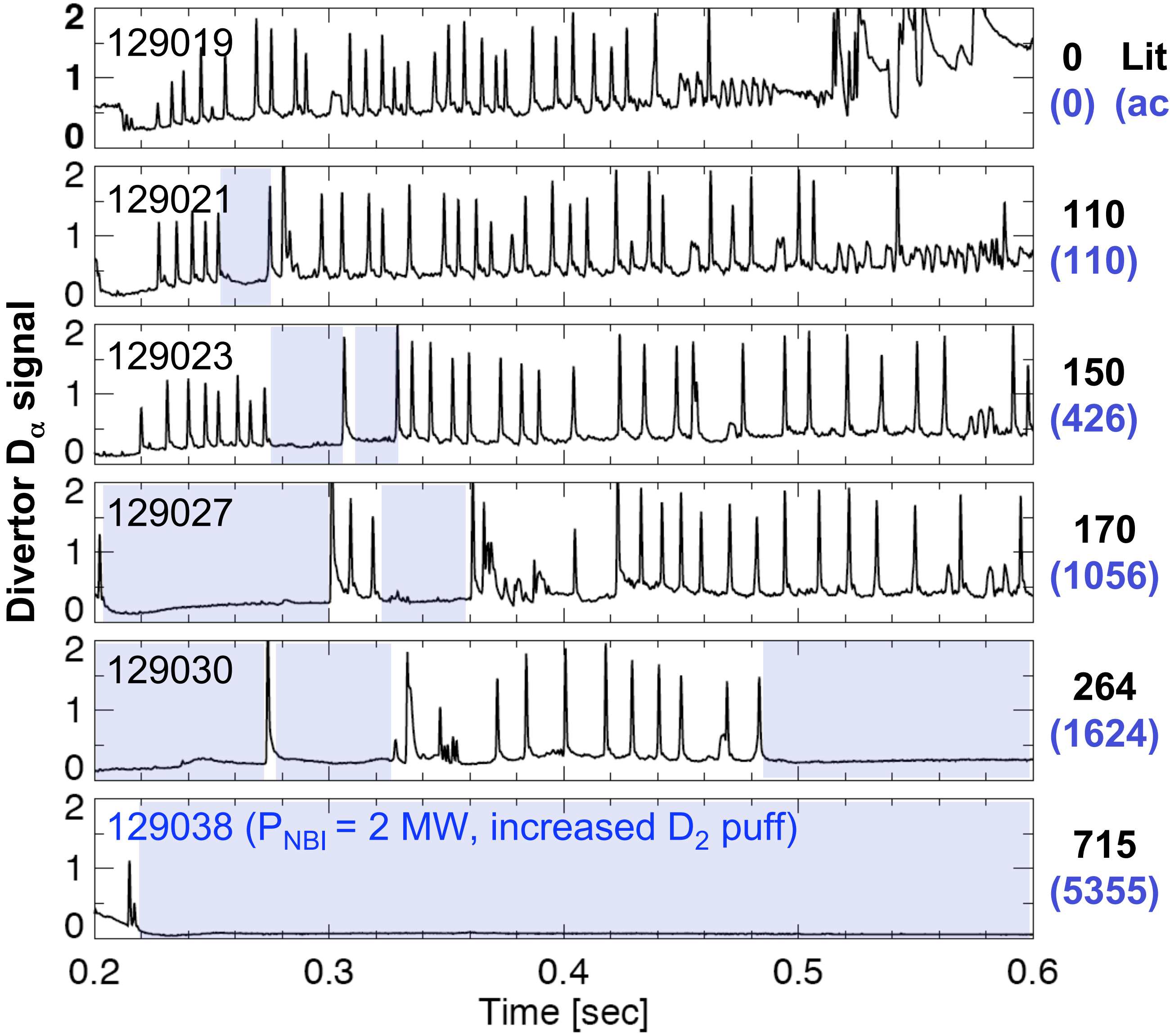
- Radiated power profile becomes centrally peaked in ELM-free discharges



- 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

S. Paul, S. Gerhardt, J. Kallman, P. Beiersdorfer, J. Lepson

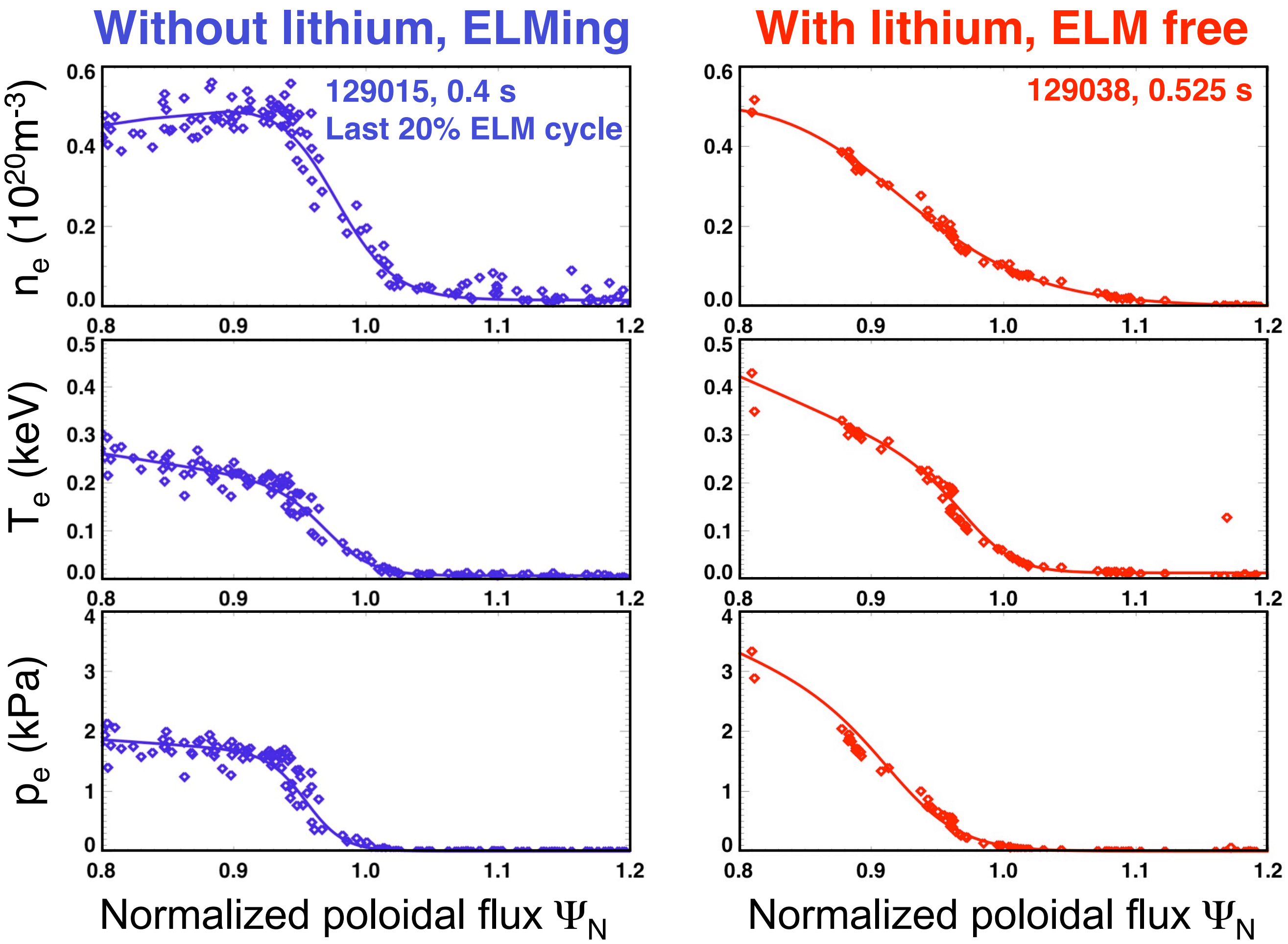
Suppression of ELMs Occurs By Lengthening and Coalescence of ELM-free Periods



- 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
- H-mode threshold power reduced by up to factor 4 by lithium

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

- Multiple timeslices mapped into composite profiles using EFIT equilibrium

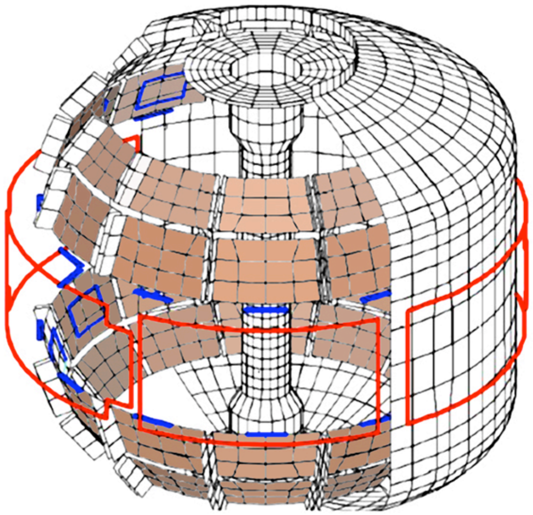


- Analysis shows improved stability to peeling-ballooning modes with lithium

R. Maingi (P2.175 this conference), T. Osborne

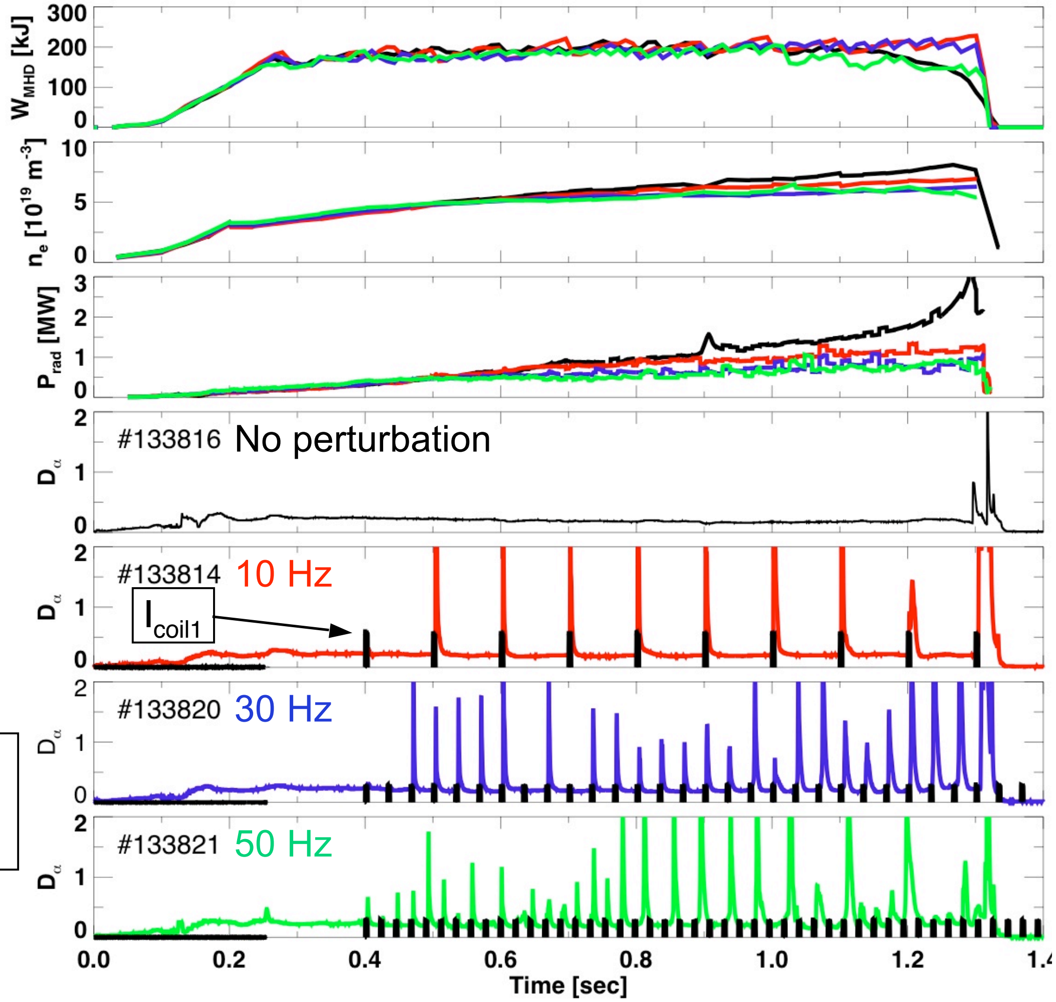
External Non-Axisymmetric Coils Can *Induce* Repetitive ELMs in Discharges with Lithium Coating

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



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

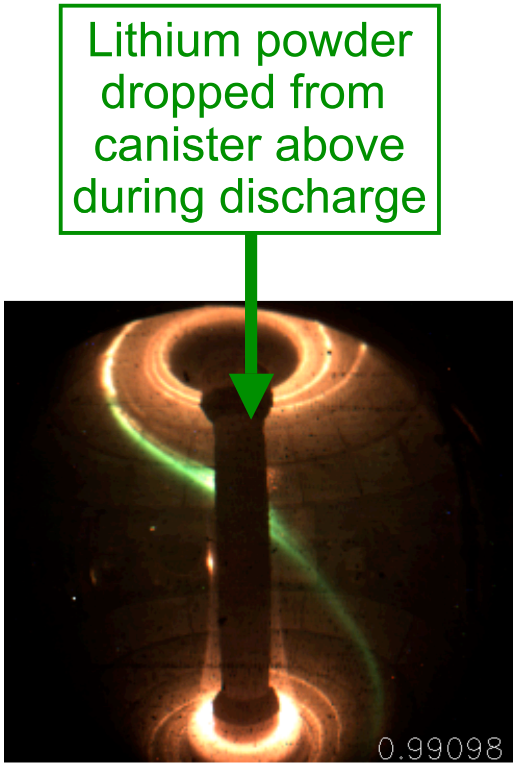
Double-null, κ=2.4, δ=0.8, 0.8MA, 0.45T, NBI 4 MW

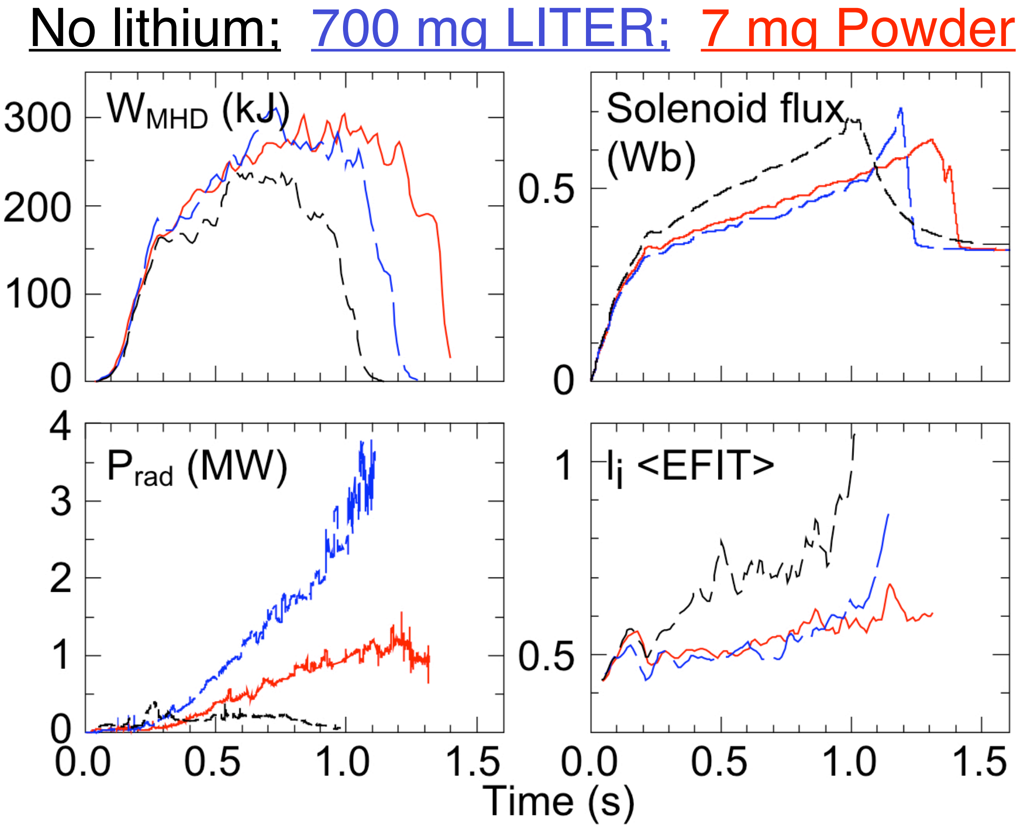


- **Induced ELMs reduce n_e, P_{rad}, Z_{eff} with small effect on plasma energy**

Lithium Coating by Dropping a Stream of Lithium Powder into SOL Produced Similar Benefits to LITER

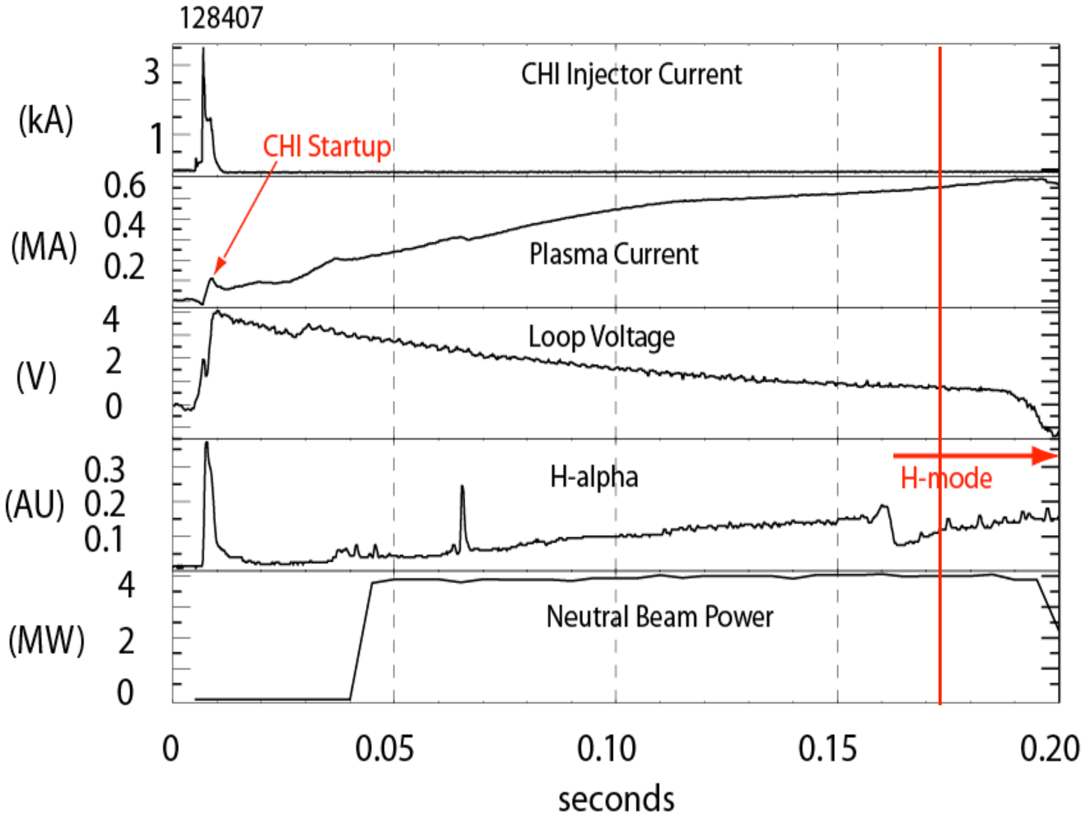
- Lithium powder (~40μm) stabilized against rapid oxidation in air by surface coating of Li_2CO_3 (<0.1%)
- Introduced by oscillating a piezo-electric diaphragm with a hole in the center on which the powder is piled
- Typical flow rates 5 – 40 mg/s: ***well tolerated by plasma, even in startup***

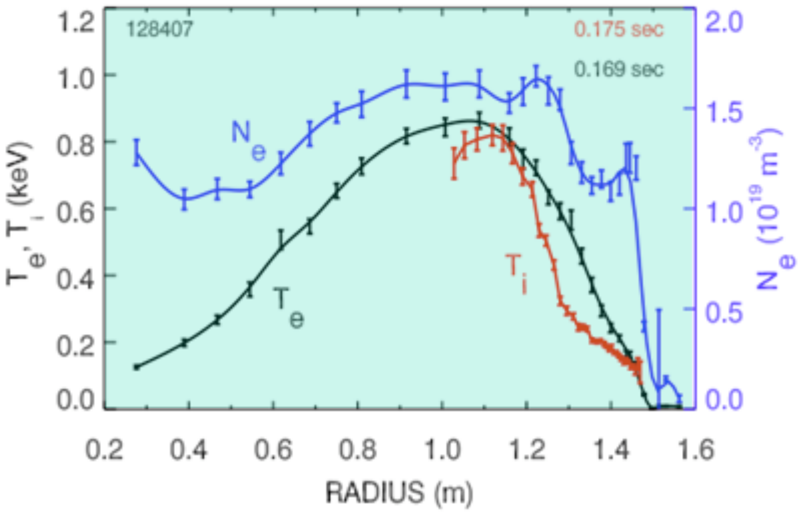

Lithium powder dropped from canister above during discharge



D. Mansfield

With Lithium, CHI Initiated Discharges Successfully Coupled to Inductive Ramp-up with NBI Heating



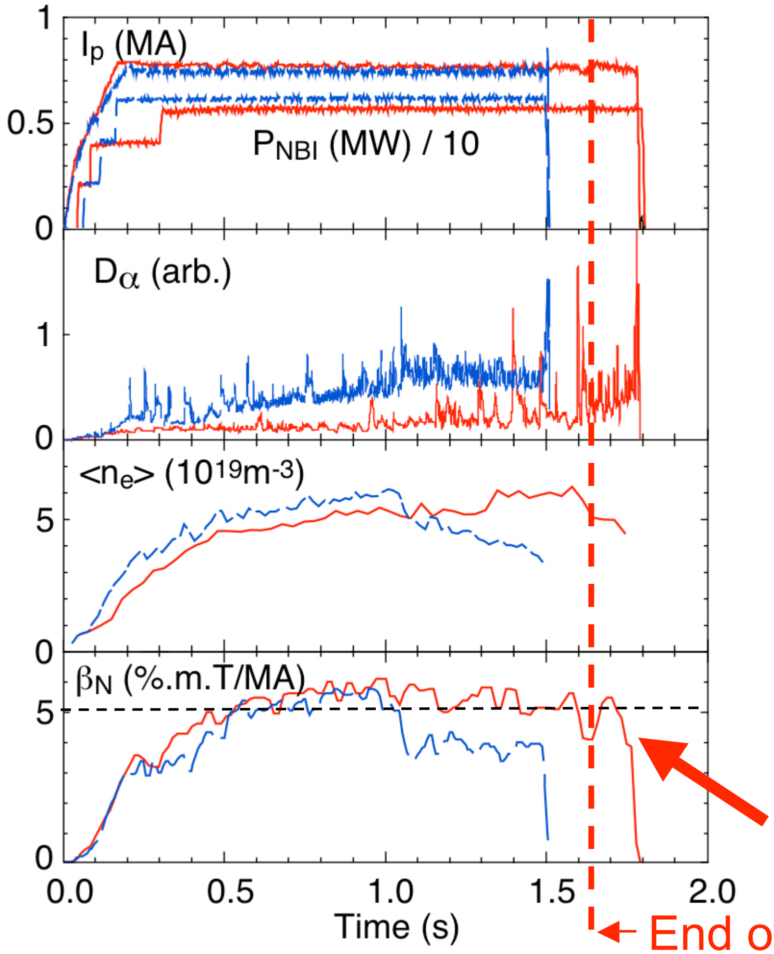


- Broad density profile during H-mode phase

- CHI generates initial current of ~100kA on closed flux surfaces
- Discharge is under full equilibrium control after CHI initiation
- Discharge transitioned to H-mode at usual time

Lithium Coating with n=3 Error Field Correction and n=1 RWM Feedback Extends High-β_N Discharges

116313 – no mode control or lithium
129125 – with mode control & lithium



$\beta_N \geq 5$ sustained for 3-4 τ_{CR}

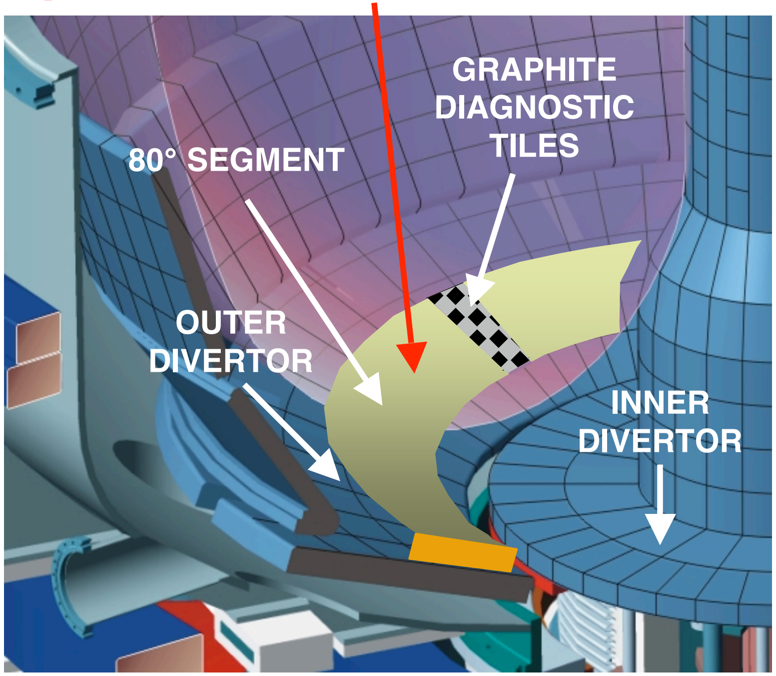
End of TF flattop

- Lithium helps control recycling, density
- Flux consumption reduced
  - Lower density increases NBI-driven current
  - High elongation increases bootstrap current
  - Central solenoid supplied only 0.6 Wb flux
- EFC/RWM control sustains rotation, β
  - Onset of n=1 rotating modes avoided
- NSTX record pulse-length = 1.8s
  - Reached limit imposed by TF coil heating

J. Menard, S. Gerhardt, S. Sabbagh, D. Gates

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

Liquid Lithium Divertor Modules



- Replace rows of graphite tiles in outer lower divertor with segmented plates
- Molybdenum surface on copper substrate with temperature control
  - – Heated above Li melting point 180°C
  - – Active heat removal to counteract plasma heating
- Initially supply lithium with LITERs and lithium powder dropper

- Evaluate capability of liquid lithium to sustain deuterium pumping
- 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 Many 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
- 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
  - ELMs triggered by external coils reduced deleterious effects of impurities
- Coaxial Helicity Injection initiation successfully coupled to inductive ramp-up following lithium coating
- Lithium, in conjunction with active error field correction and mode control, has enabled longer pulse lengths

Contributors

J. Ahn, J. Allain, M. Bell, R. Bell, J. Berkery, J. Breslau, J. Canik, D. Darrow, L. Delgado-Aparicio, T. Evans, E. Fredrickson, D. Gates, S. Gerhardt, N. Gorelenkov, T. Hahm, W. Heidbrink, J. Hosea, T. Jarboe, M. Jaworski, R. Kaita, J. Kallman, S. Kaye, C. Kessel, J. Kim, E. Kolemen, S. Kubota, H. Kugel, R. La Haye, B. LeBlanc, K. Lee, F. Levinton, R. Maingi, R. Majeski, J. Manickam, D. Mansfield, R. Maqueda, S. Medley, J. Menard, D. Mueller, B. Nelson, R. Nygren, M. Ono, T. Osborne, J. Park, S. Paul, M. Podesta, R. Raman, P. Ross, P. Ryan, S. Sabbagh, C. Skinner, P. Snyder, A. Sontag, V. Soukhanovskii, D. Stotler, B. Stratton, G. Taylor, K. Tritz, W. Wampler, J. Wilgen, H. Yuh, S. Zweben