NSTX PPPL PRINCETON PLASMA PHYSICS LABORATORY *Supported by* U.S. DEPARTMENT OF ENERGY Office of Science

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

- *College W&M*
- *Colorado Sch Mines*
- *Columbia U*
- *CompX*
- *General Atomics*
- *INL*
- *Johns Hopkins U*
- *LANL*
- *LLNL*
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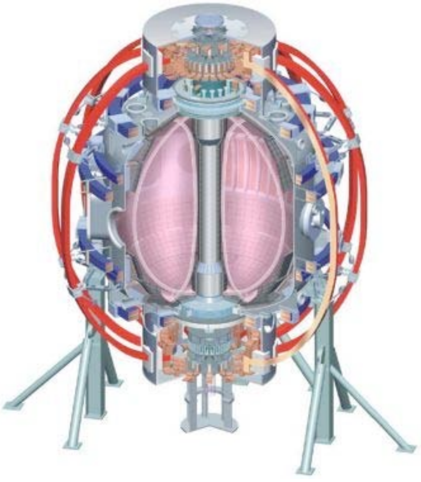
- *U Washington*
- *U Wisconsin*

Michael Bell
for the NSTX Research Team

PPPL Colloquium, January 13, 2010



- *Culham Sci Ctr*
- *U St. Andrews*
- *York U*
- *Chubu U*
- *Fukui U*
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- *Kyoto U*
- *Kyushu U*
- *Kyushu Tokai U*
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- *KAIST*
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- *ASIPP*
- *ENEA, Frascati*
- *CEA, Cadarache*
- *IPP, Jülich*
- *IPP, Garching*
- *ASCR, Czech Rep*
- *U Quebec*

NSTX has a Continuing Research Program into Effects of Lithium-Coated PFCs in *Divertor* Plasmas

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

– First use of “lithium powder dropper” to introduce lithium through SOL

2009: Routine use of dual LITERs

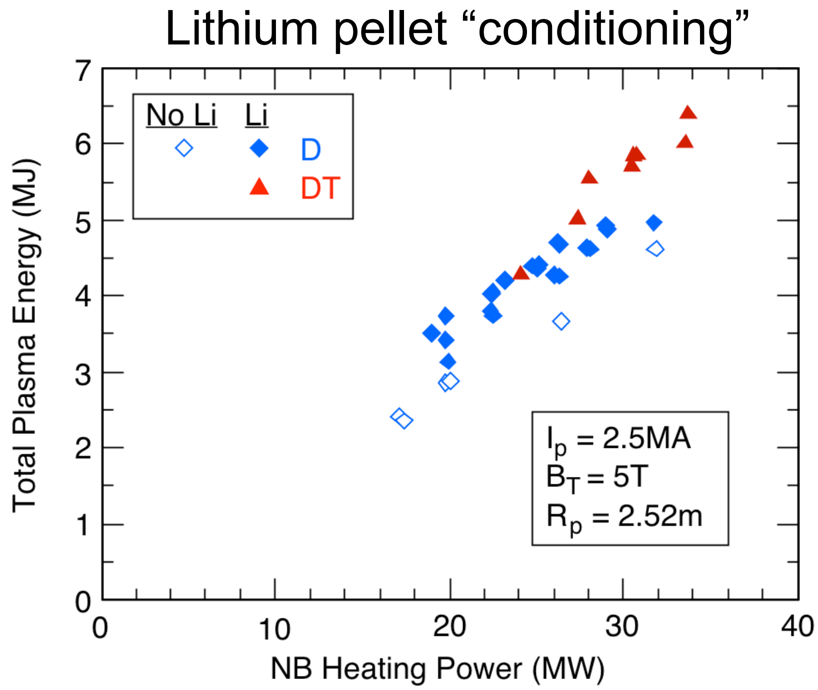
  - At end of run, 80% of discharges had lithium applied beforehand

– Also conducted experiment using dual lithium powder droppers

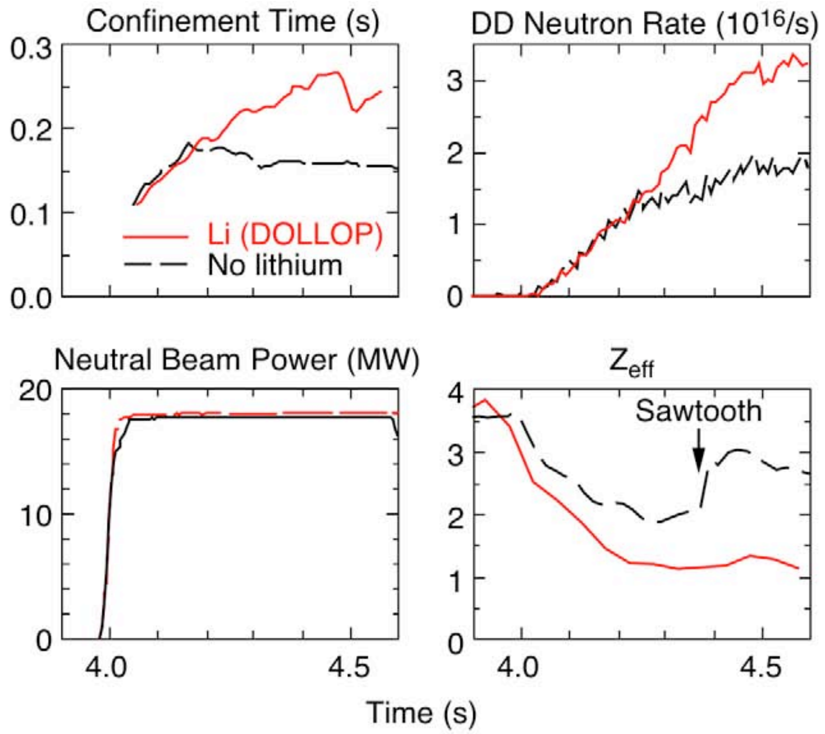
2010: *Liquid lithium coating on section of lower outer divertor plate*

Lithium Coating of Graphite Limiter in TFTR Produced Dramatic Changes in “Supershot” Confinement

- Used lithium pellets to deposit lithium (10s mg) on graphite limiter
  - Employed a “painting” technique to distribute the lithium
- Developed a laser-spark “splasher” of molten lithium (“DOLLOP”)
- Predeposited lithium had a beneficial effect but lithium introduced into a discharge immediately before NBI heating was most effective
- Both ion and electron confinement were improved



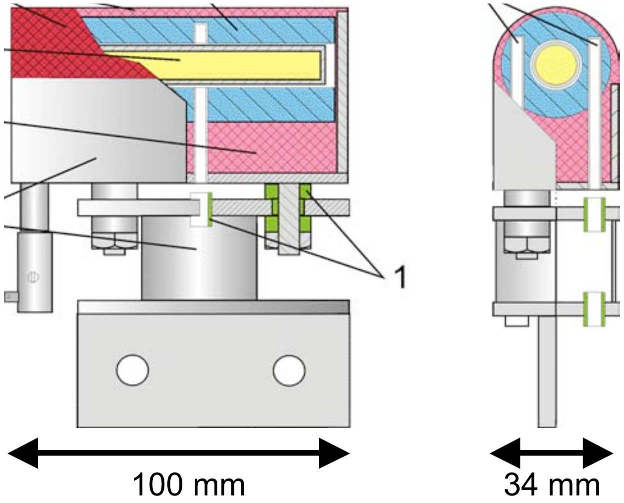
Lithium pellet “conditioning”



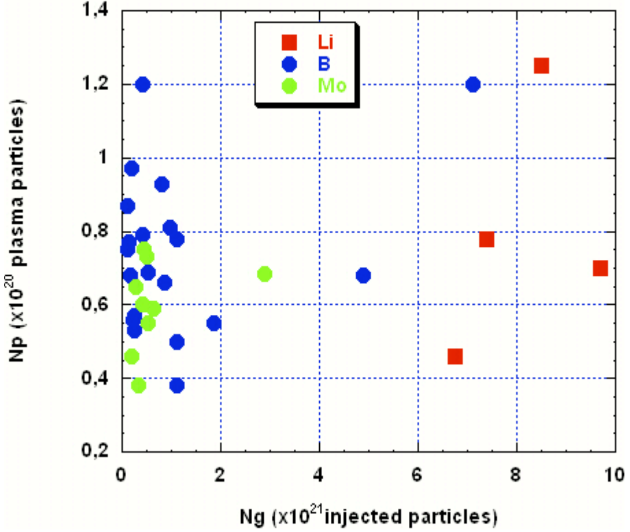
Several Other Toroidal Confinement Devices Have Benefited in Different Ways from Lithium Coating

- **T-11, FTU**: Liquid-lithium "Capillary Porous System" limiters
  - FTU units have withstood 5 MWm^{-2}; T-11 aiming for 20 MWm^{-2}
  - Reduced impurities: $Z_{eff} \approx 1.2$ (T-11), 1.2 – 2 (FTU)
- **CDX-U**: full toroidal liquid-lithium limiter reduced recycling, oxygen impurities and improved confinement in ohmically heated plasmas
- Stellarator **TJ-II** (higher n, τ_E) and in RFP **RFX**
- **HT-7** embarking on a lithium program
- **LTX** is beginning operation to investigate lithium-coated walls

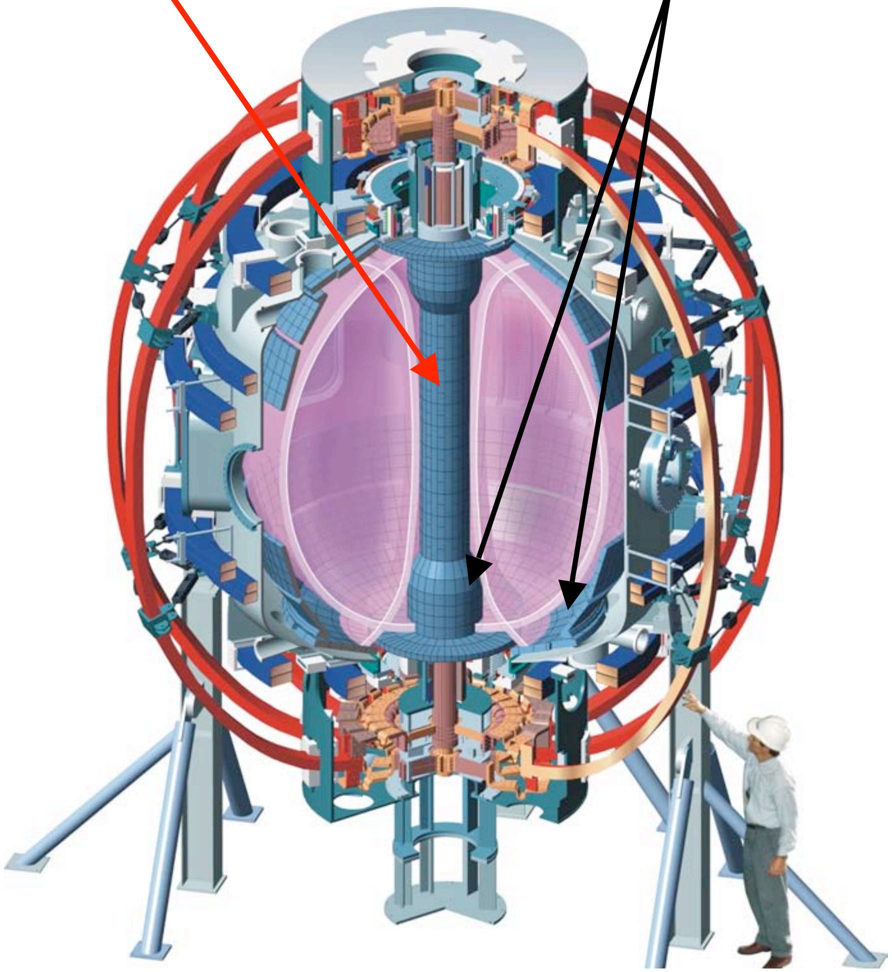
FTU CPS unit (1 of 3)



Strong D pumping in FTU



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



Slim center column with TF, OH coils

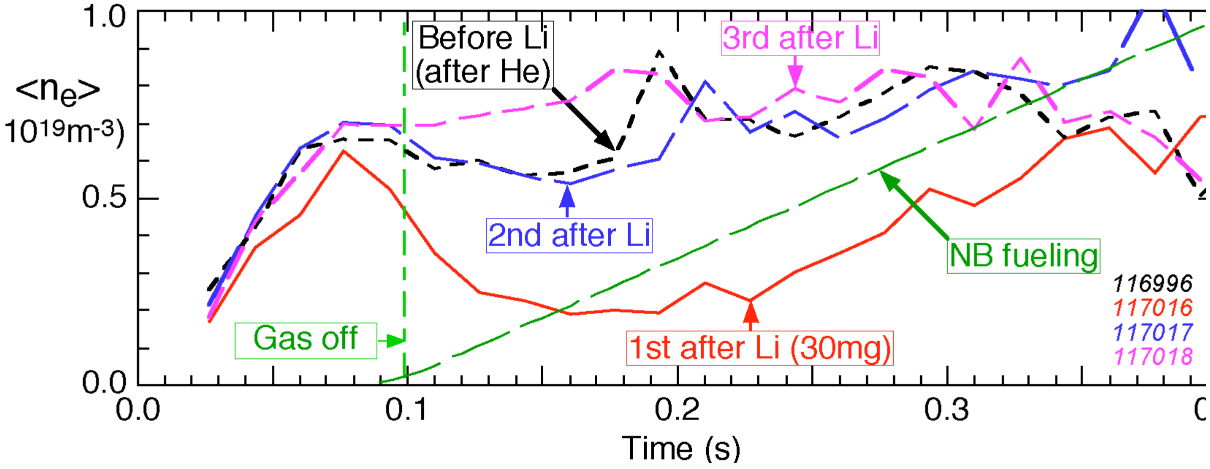
Graphite/CFC PFCs with lithium coating

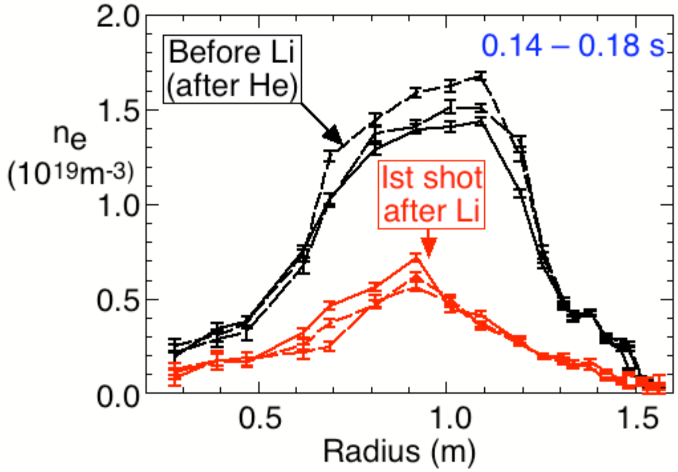
Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.2 – 0.8
Major radius	0.85 m
Toroidal Field B_{T0}	0.4 – 0.55 T
Plasma Current I_p	0.7 – 1.5 MA
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 5 keV
Central density	$\leq 1.2\times10^{20}\,\mathrm{m}^{-3}$
Toroidal beta β_T	10 – 40 %

Lithium from Pellets Produced a Dramatic Density Reduction in L-mode but Benefit Short-Lived

- Lithium pellets (total ~30mg) injected into preceding 10 ohmically-heated He discharges

Center-stack limiter discharges; 0.9MA, 0.45T, 4MW NBI; gas fueling: ~3.5mg D_2 per shot

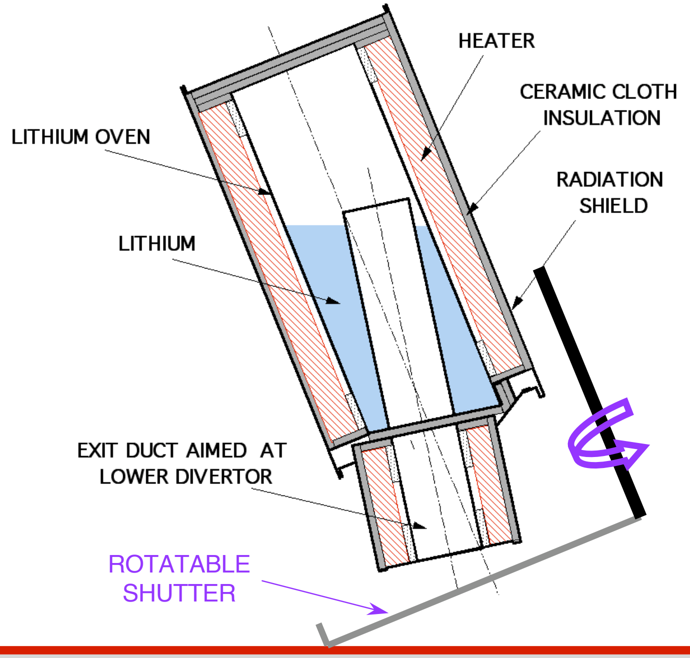


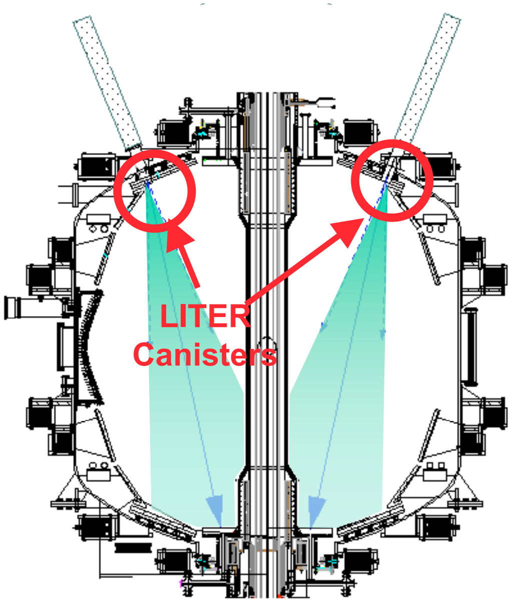


- Density after gas puff reduced by factor >2 after lithium coating
  - Rate of density rise matched NB fueling after initial rapid pumpout
- Effect had dissipated on second similar shot

Dual LITERs Replenish Lithium Layer on Lower Divertor Between Tokamak Discharges

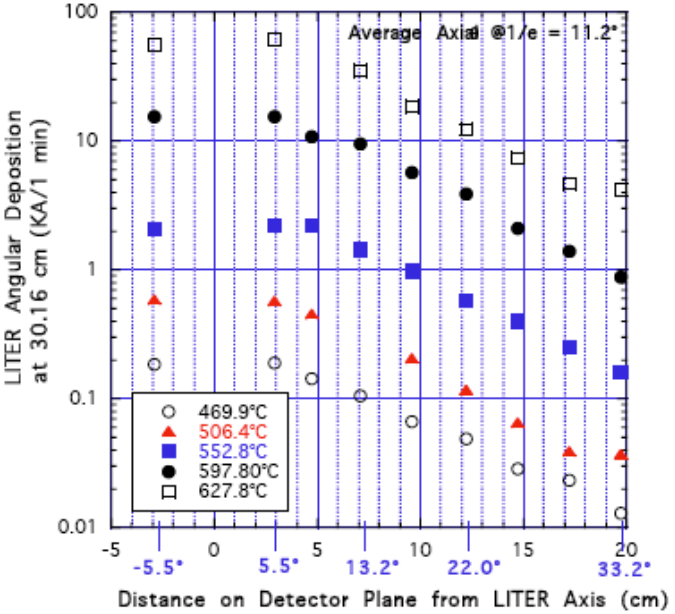
- Electrically-heated stainless-steel canisters with re-entrant exit ducts
- Mounted 150° apart on probes behind gaps between upper divertor plates
- Each evaporates 1 – 40 mg/min with lithium reservoir at 520 – 630°C
- Rotatable shutters interrupt lithium deposition during discharges & HeGDC
- Withdrawn behind airlocks for reloading and initial melting of lithium charge
- Reloaded LITERs 6 times during 2009 run (Mar - Aug): ***~250g on PFCs***



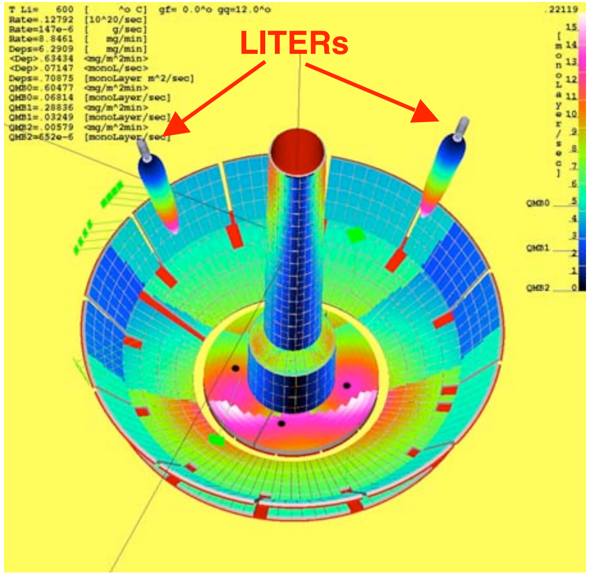


Dual LITERs Deposit Lithium on Lower PFCs Including Divertor Plates

- Measured deposition pattern in laboratory tests with scannable quartz-crystal micro-balance (QMB)
  - Plumes of lithium vapor are roughly Gaussian in angular distribution
  - Good agreement with model based on molecular flow through exit duct
- Lithium applied between discharges typically 20 – 600 mg
  - More than needed to react all injected D_2, typically 5 – 15 mg
- In-situ QMB data implies deposited lithium thickness is 5 – 160 nm on inner divertor plate near strike point of standard NSTX plasmas



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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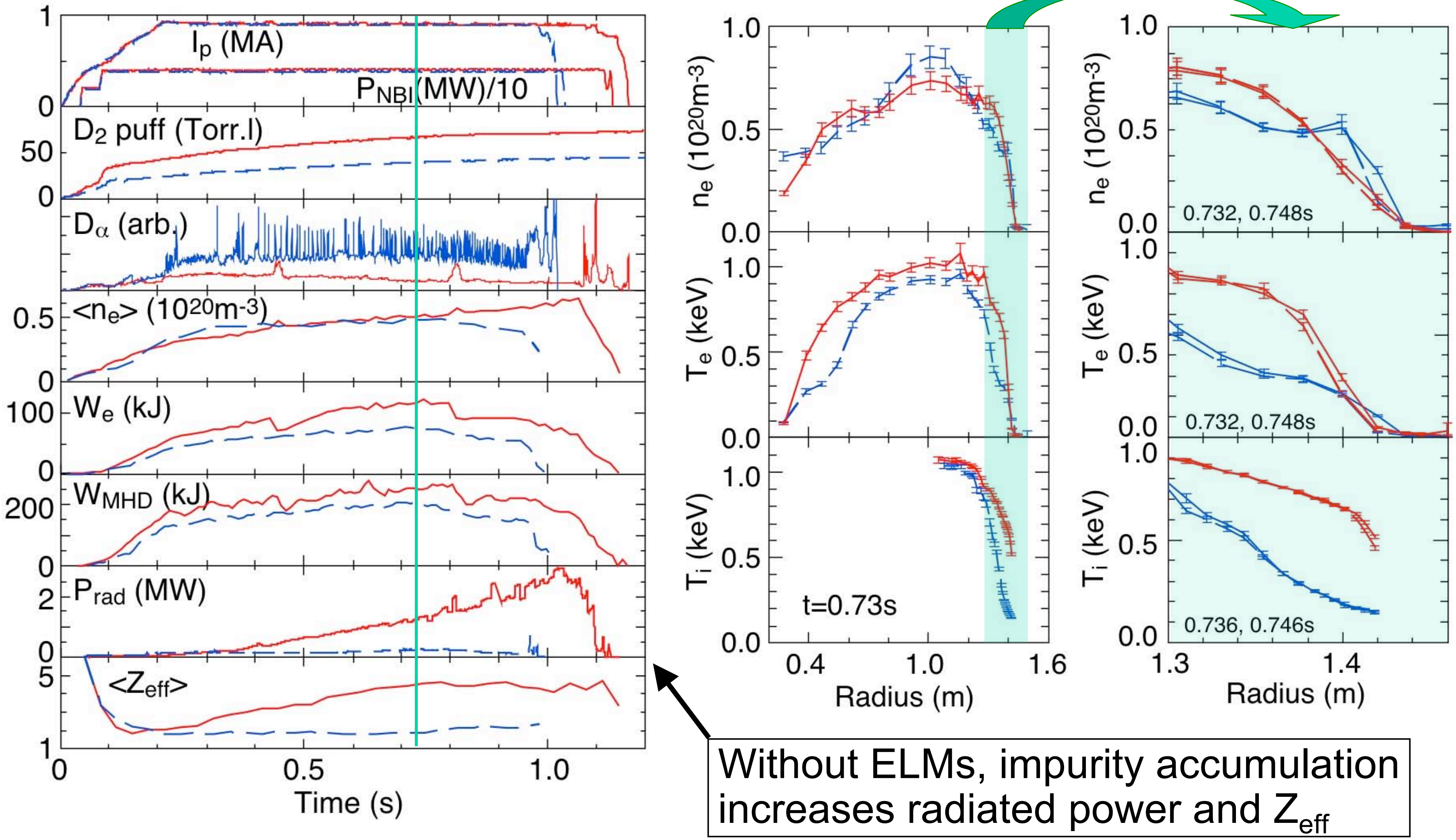
Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement

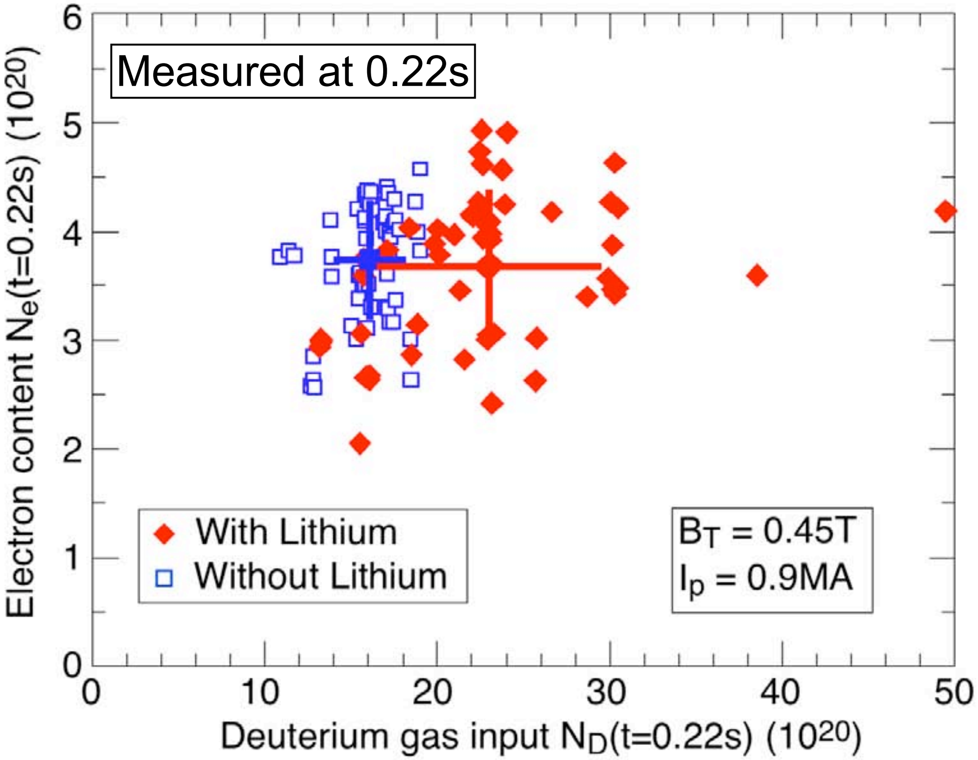
No lithium (129239); **260mg lithium** (129245)



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

Lithium Reduces Deuterium Recycling but Need to Increase Fueling to Avoid Early Locked Modes

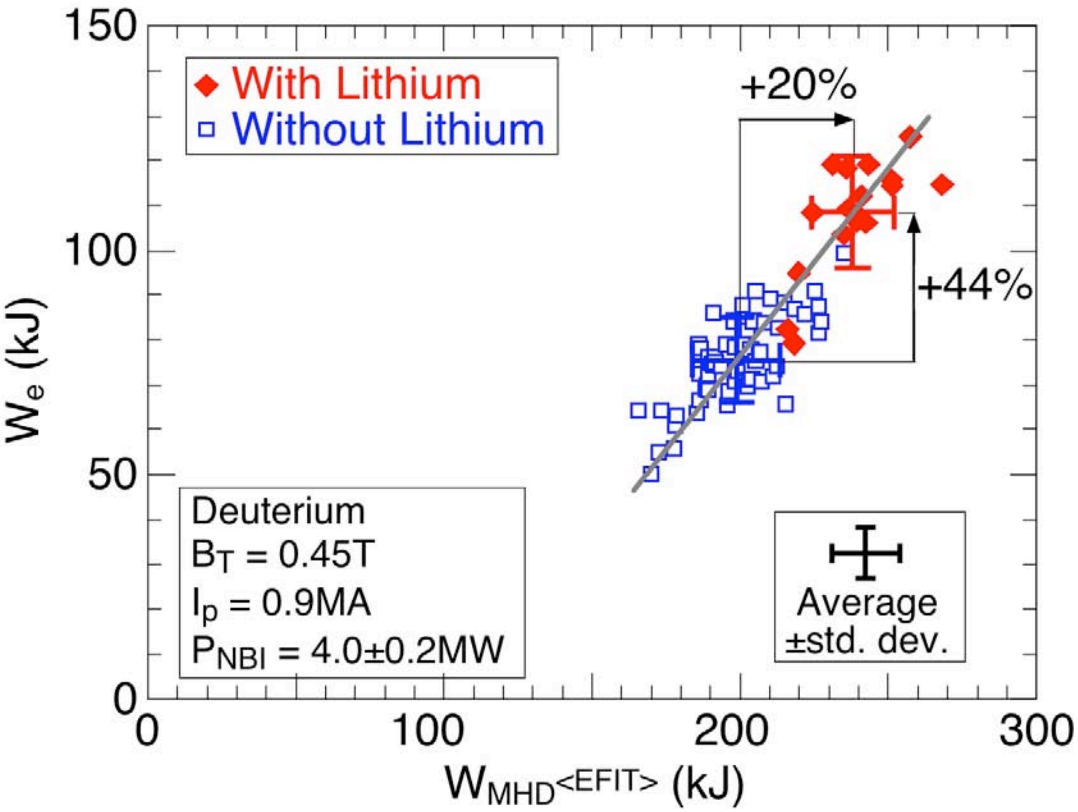
- Lower density achievable early in discharges both with and without lithium but likelihood of deleterious locked modes increases
  - – Extensive HeGDC, He ohmic- or HHFW-heated plasmas also effective



- Tangentially viewing camera for edge D_α emission shows greatly reduced neutral D density across outboard midplane with lithium

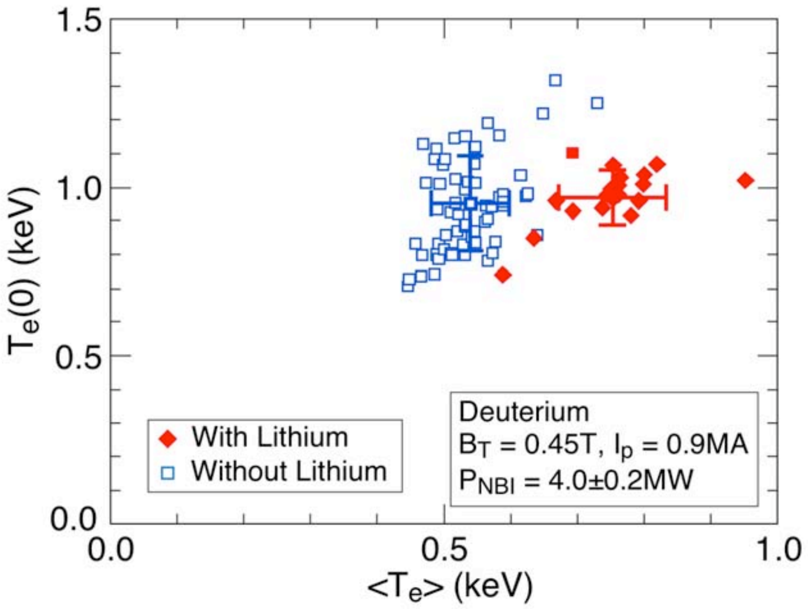
Lithium Coating Improves Both Total and Electron Confinement in H-mode Plasmas

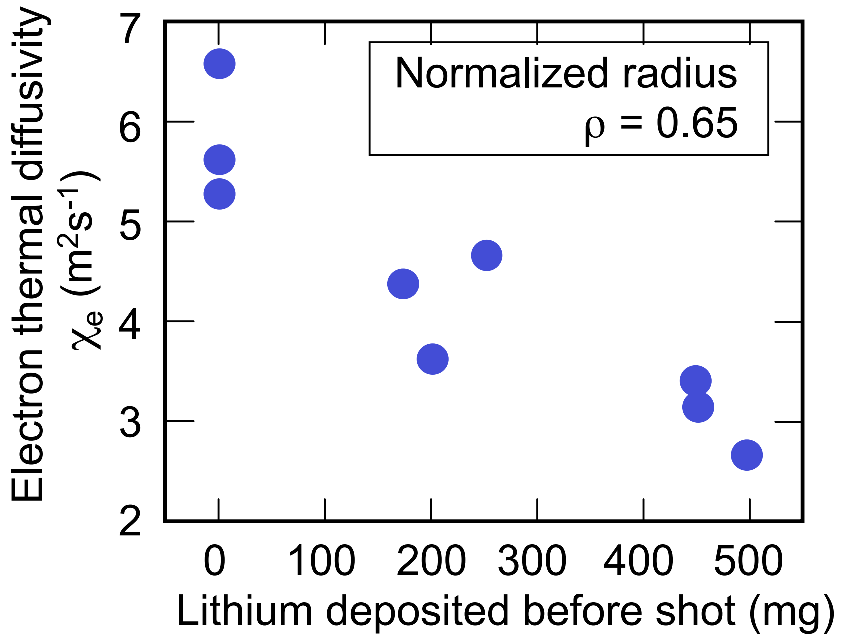
- W_e from integration of MPTS T_e, n_e profiles with EFIT flux surfaces
- W_{MHD} from EFIT with diamagnetic flux and kinetic profile constraints



- Plasmas both with and without lithium in H-mode
- H-mode threshold is reduced by lithium coating by up to factor 4

Improvement in Electron Confinement Arises from Broadening of Temperature Profile





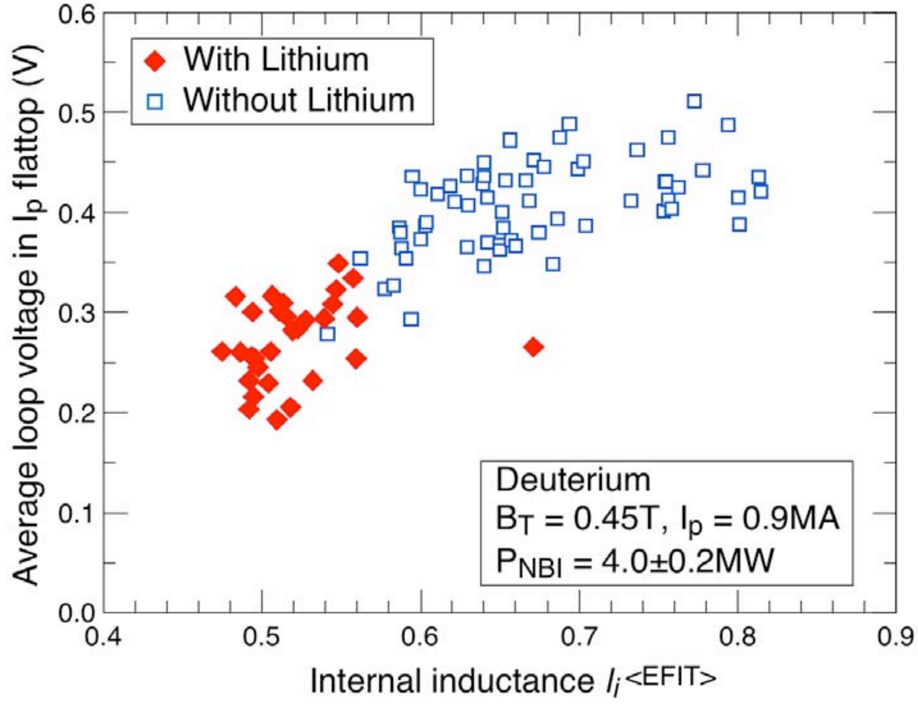
- TRANSP analysis confirms electron thermal transport in outer region progressively reduced by lithium
- Fast-ion contribution to total energy increased
- Thermal ion confinement remains close to neoclassical level both with and without lithium

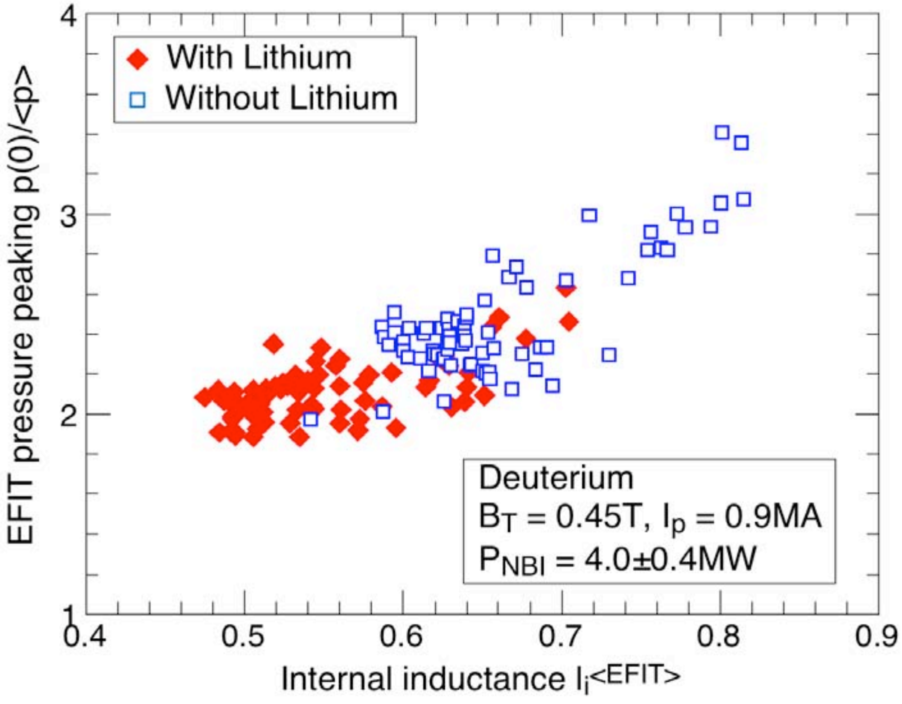
We Do Not Yet Have an Explanation for the Improved Confinement Produced by Lithium in NSTX

- In TFTR, improvement was in the “supershot” regime
  - Anomalous (ion) transport associated with ITG turbulence: $T_{i,max}(0) \propto T_i(a)$
  - Lithium reduced recycling below what was achievable with “conditioned” carbon PFCs allowing higher edge temperature *and*
  - Larger E/B shearing with peaked p(r) stabilized modes for $\omega_{EXB} > \gamma_{ITG}$
  - Electron temperature profile also broadened with lithium coating
- Also note theoretical predictions of enhanced ion neoclassical transport driven by cold ions from edge [A.A. Ware PFB **2** (1990) 1435]
- In NSTX, transport appears to be reduced in electron channel
  - Ion transport already appears to be neoclassical: high E/B shearing at lower B
  - Suppression of ETG modes has been associated with reduced χ_e in reversed-shear plasmas *but*
  - We do not have measurements confirming ETG suppressed by lithium
  - T_e profile is tending towards predictions of flat T_e with fully absorbing wall

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

- Critical issue for development of low-aspect ratio tokamaks
  - Little space for conventional central solenoid providing inductive current drive

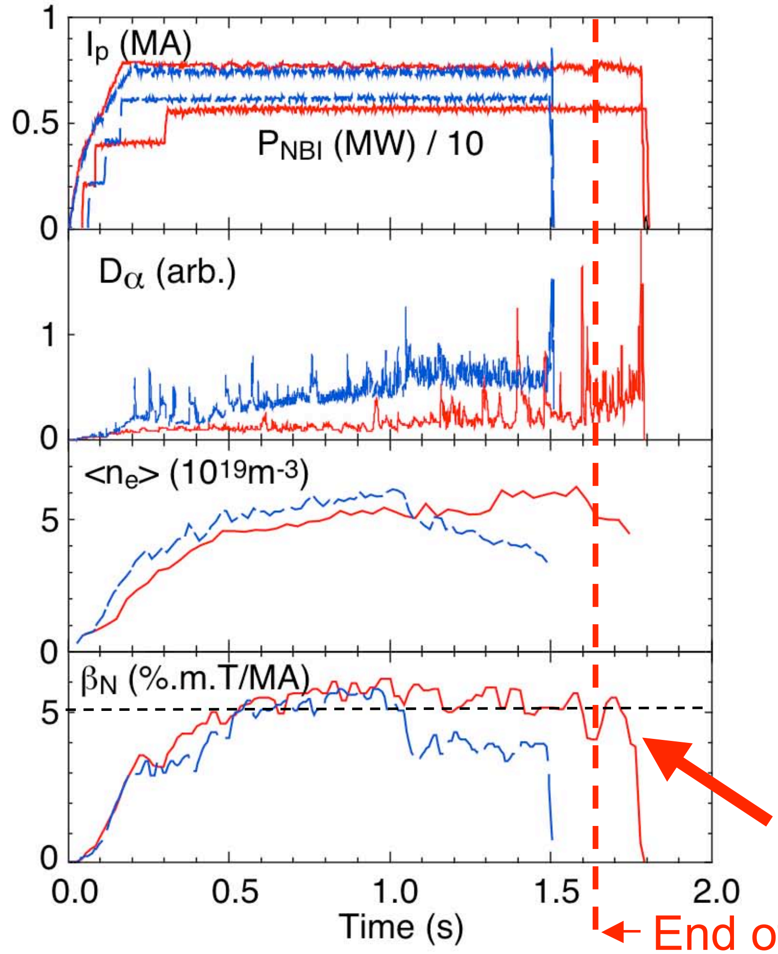




- Reduction occurs despite increase in $\langle Z_{eff} \rangle$ in ELM-free H-modes after lithium coating

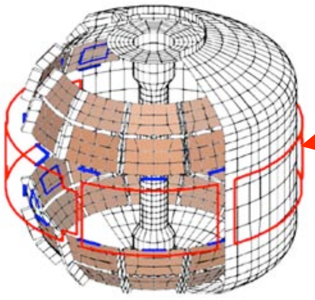
Lithium Coating with n=3 Error Field Correction and n=1 RWM Feedback Extends High-β_N Discharges

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



← End of TF flattop

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



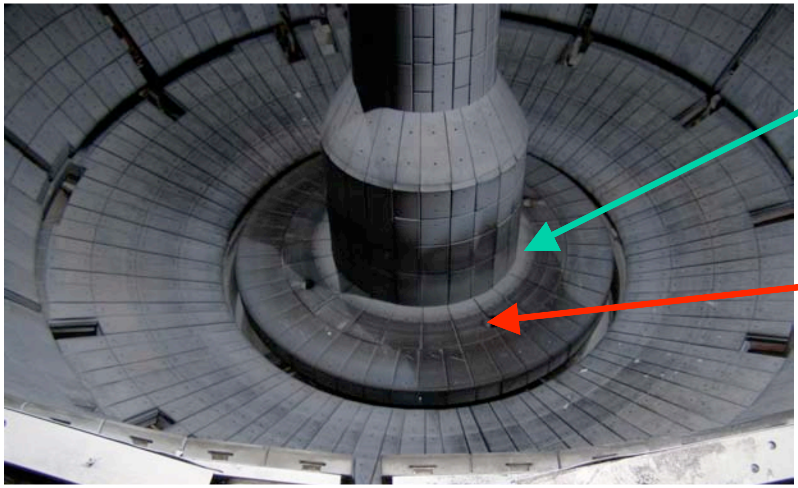
EFC/RWM coils
n=1, 3 perturbations

- 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

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

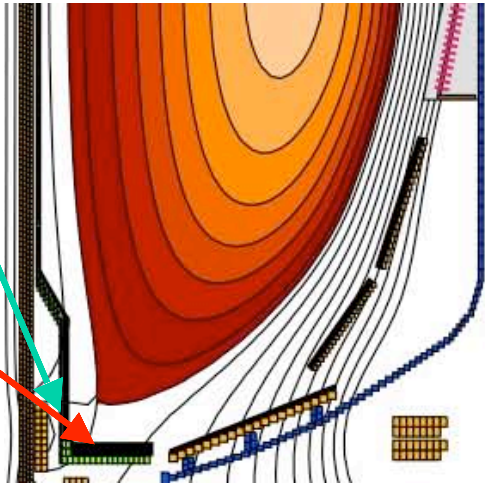


Lithium accumulated in private flux region

Lithium depleted at strike points

- In other areas lithium "shadows" are sharp

Typical LSN equilibrium



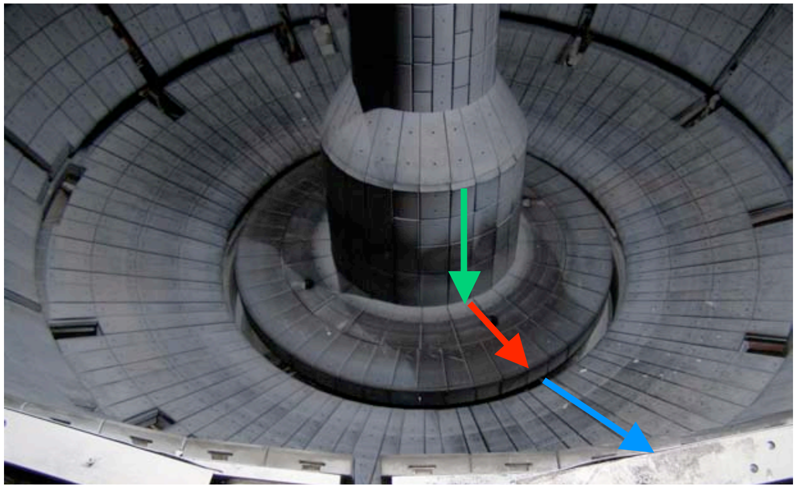
- Surfaces cleaned with water and light abrasion after oxidation in moist air for a few days (in NJ summer conditions)
  - Wiped down exposed surfaces with dilute acetic acid before closing vessel

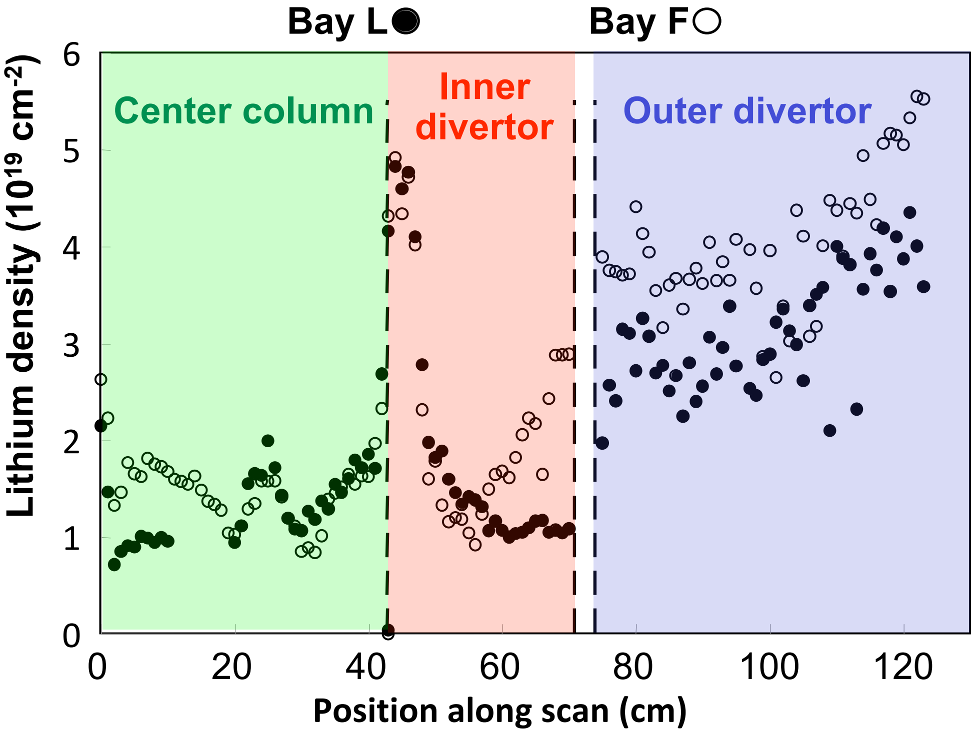
H. Kugel, C. Skinner

Analysis of Carbon Tile Surfaces Confirms Migration of Lithium Under Plasma Fluxes

- Analysis performed on surface of carbon tiles as removed from vessel
- Used ion-beam nuclear-reaction analysis for lithium and deuterium areal density in surface layer

Scan across lower divertor

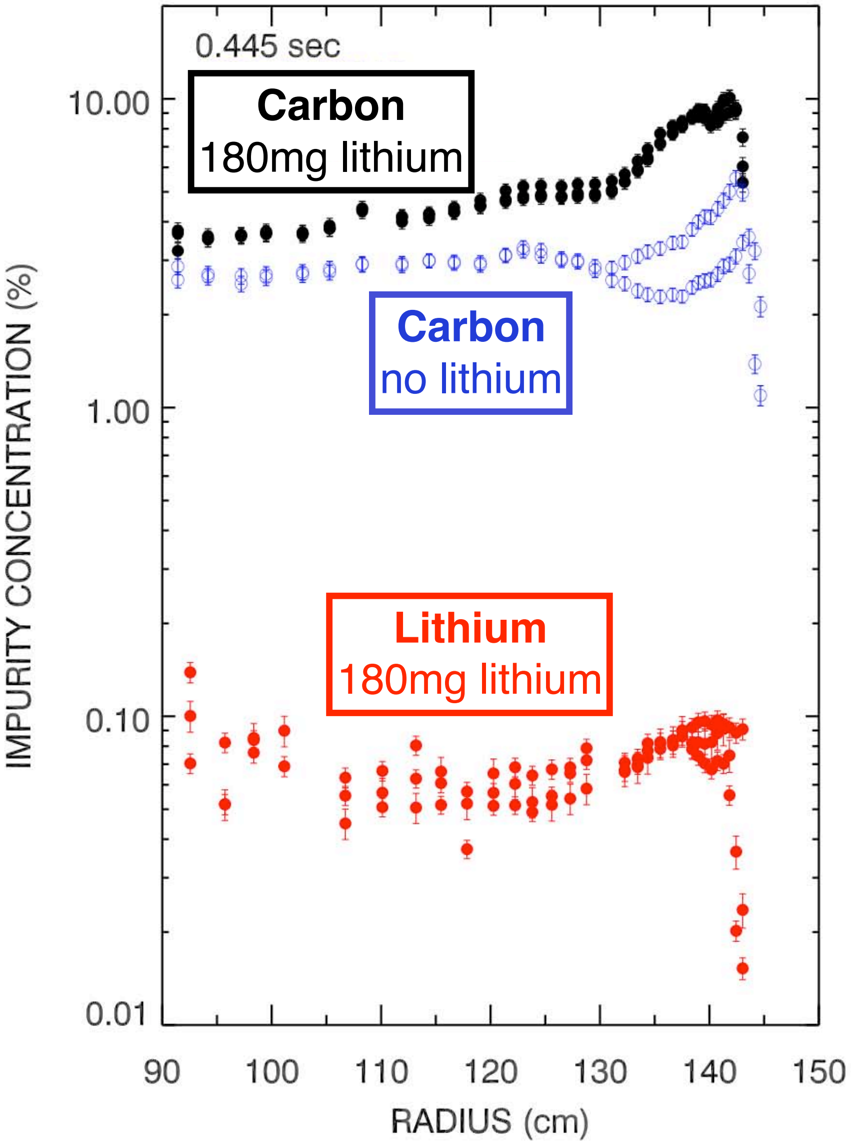




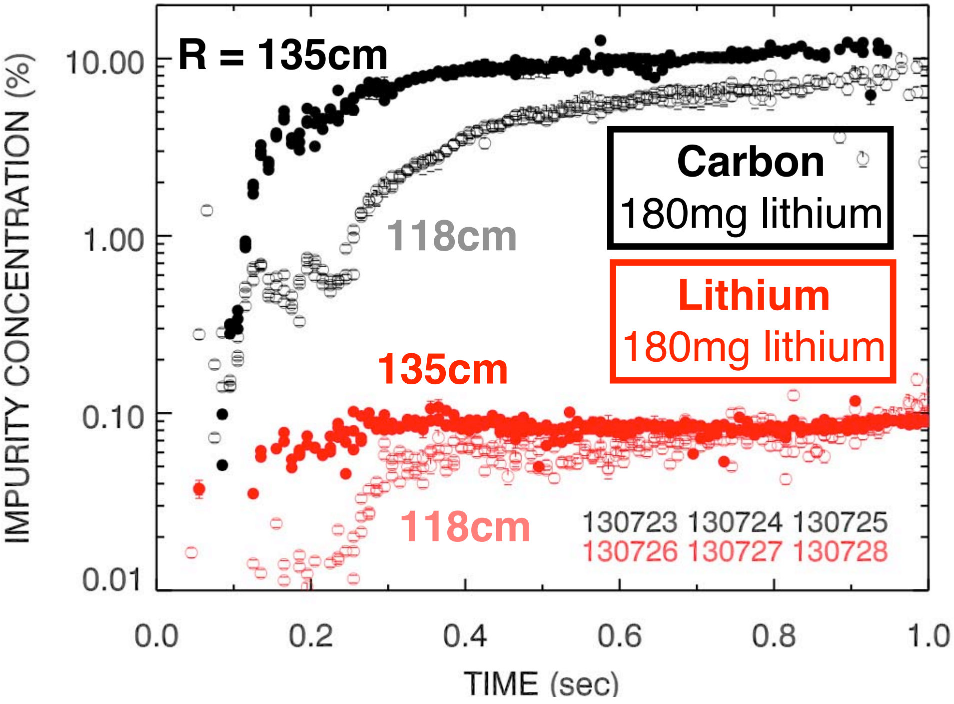
- Peak lithium density remaining on inner divertor ~0.6 mg·cm^{-2}
- Total deposition there estimated at ~8 mg·cm^{-2}

W. Wampler (SNL), C. Skinner, H. Kugel

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

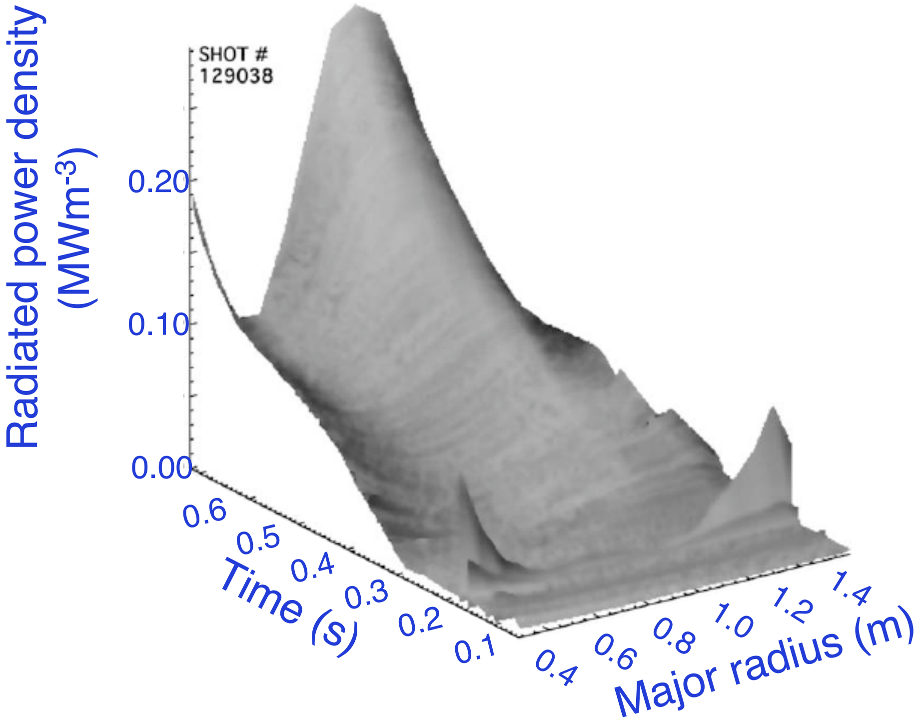


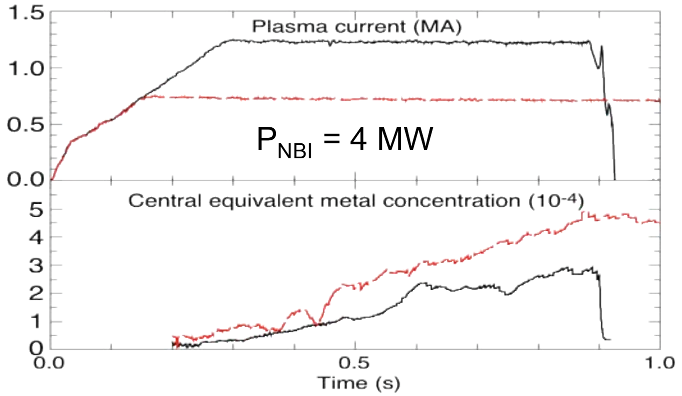
- Quantitative measurements of C^{6+}, Li^{3+} with charge-exchange recombination spectroscopy
- **n_C/n_{Li} = 30 – 100**
- Hollow profiles early for both C and Li fill in as time progresses



R. E. Bell

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

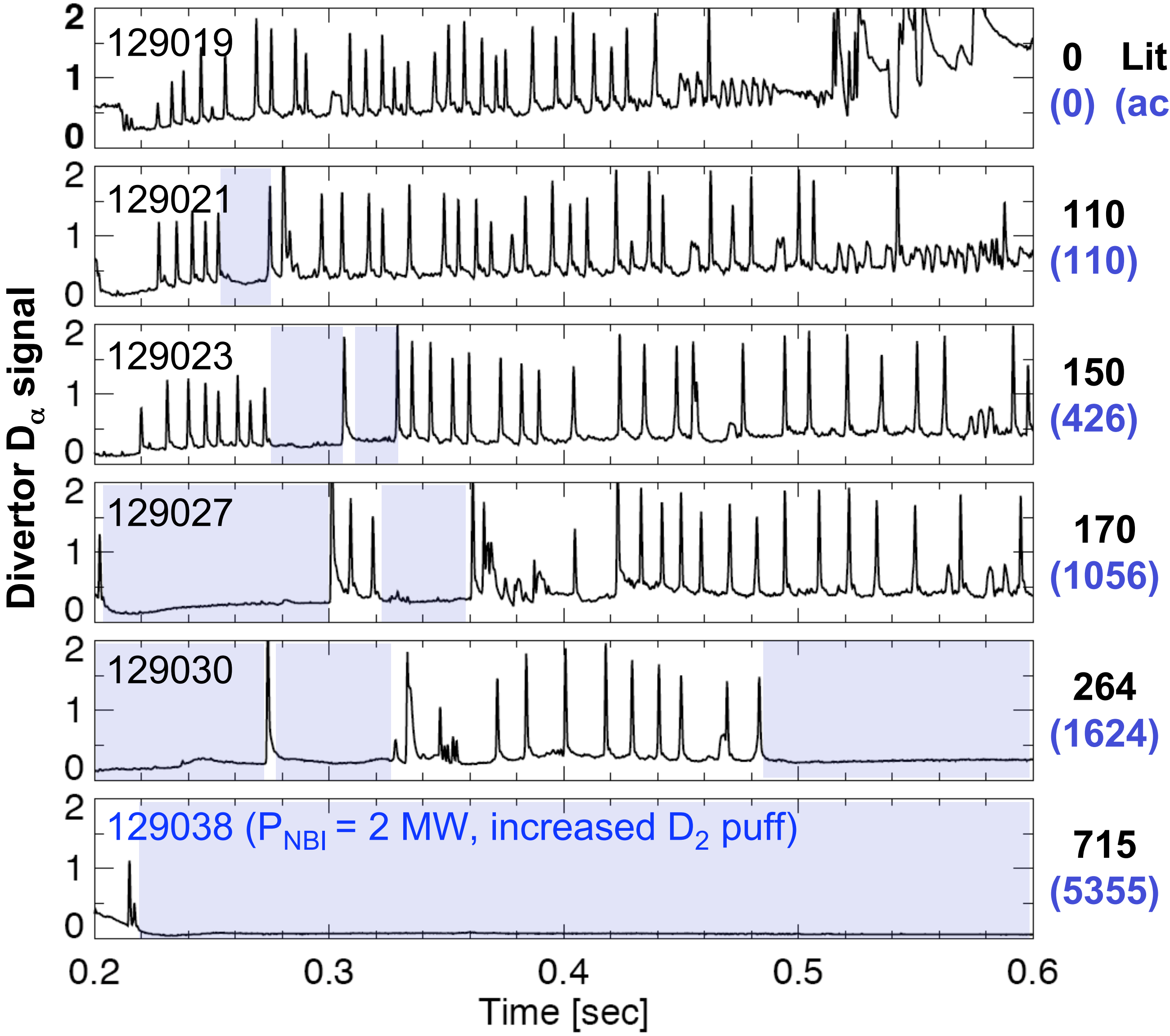




- Radiated power centrally peaked in ELM-free discharges
- VUV and SXR spectra show iron lines (Fe X – XVIII) increasing during ELM-free periods
- Radiated power profile remains hollow when ELMs are present
  - Metals still present early but do not accumulate
- If increase in radiation is ascribed to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

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

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

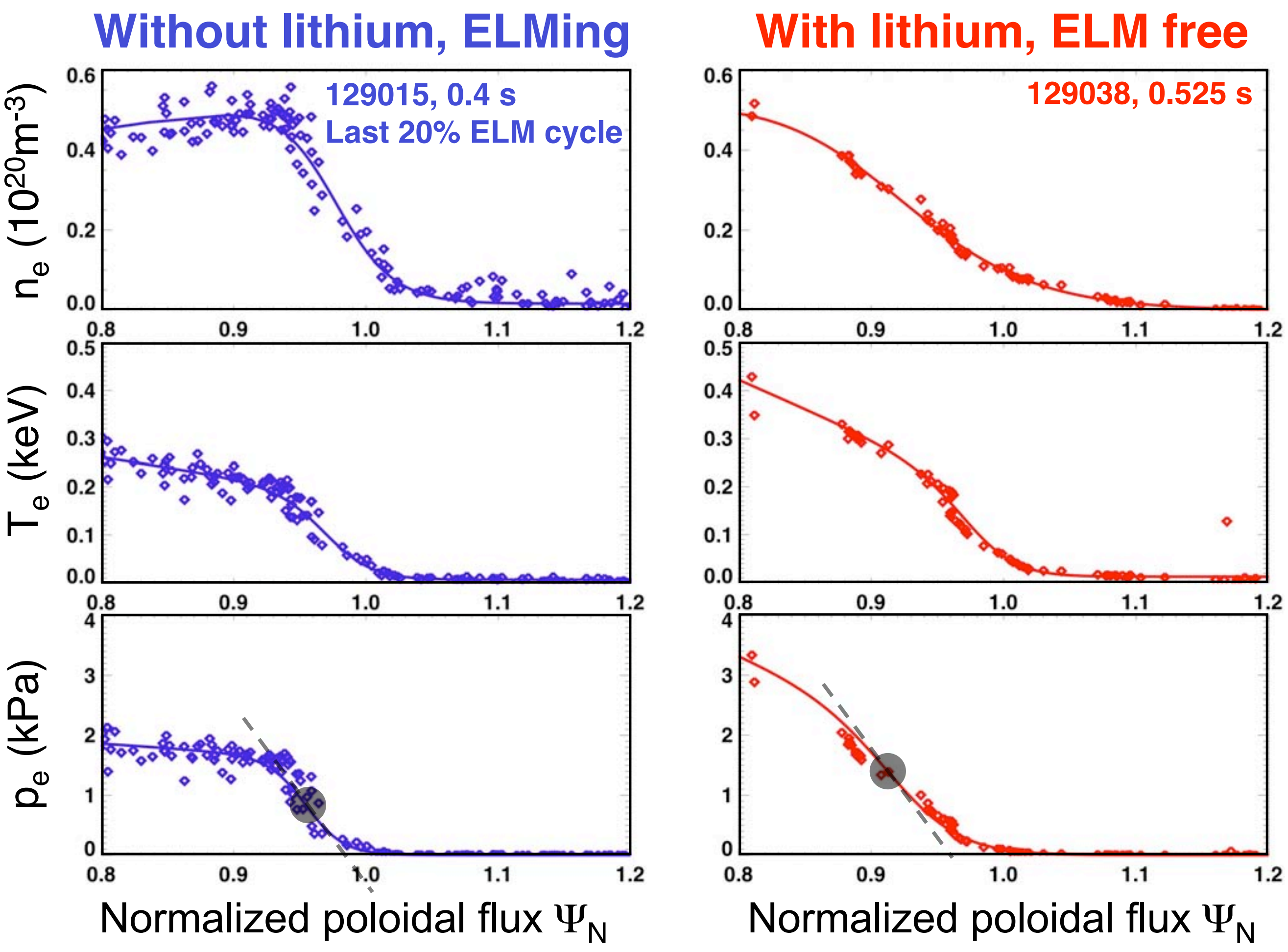


- Shots with I_p = 0.8 MA, B_T = 0.5T, P_{NBI}= 4 MW
- All shots remain in H-mode
- ELM suppression was predicted through changes in location of current density gradient with respect to mode rational surfaces (Zakharov, 2006)

D. Mansfield, R. Maingi

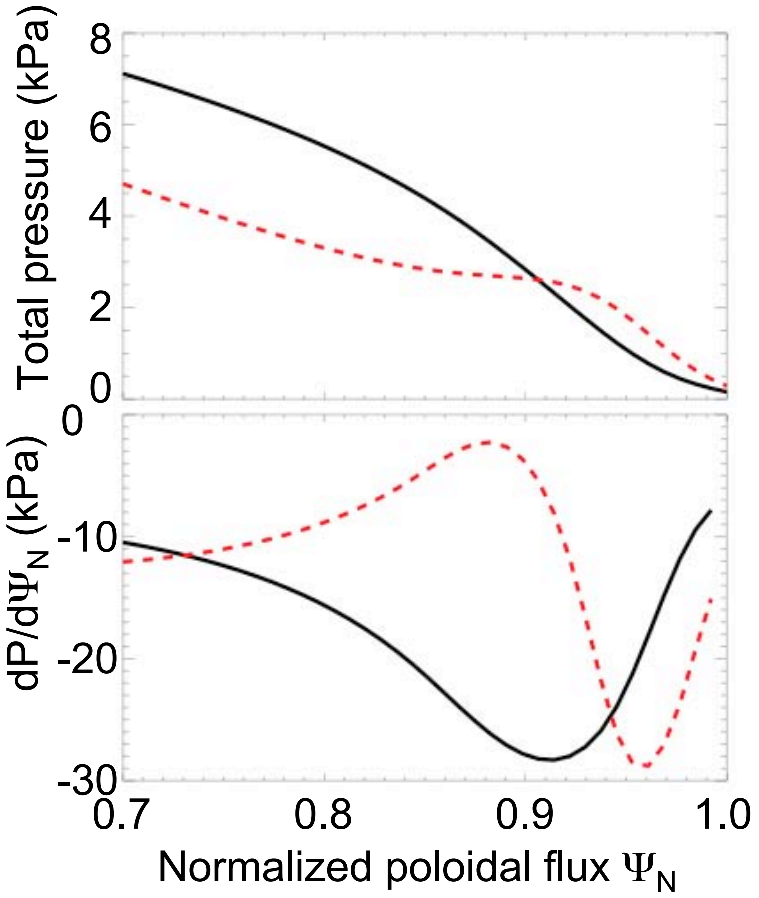
Lithium Affects ELMs Through Changes in Temperature and Pressure Profile at Edge

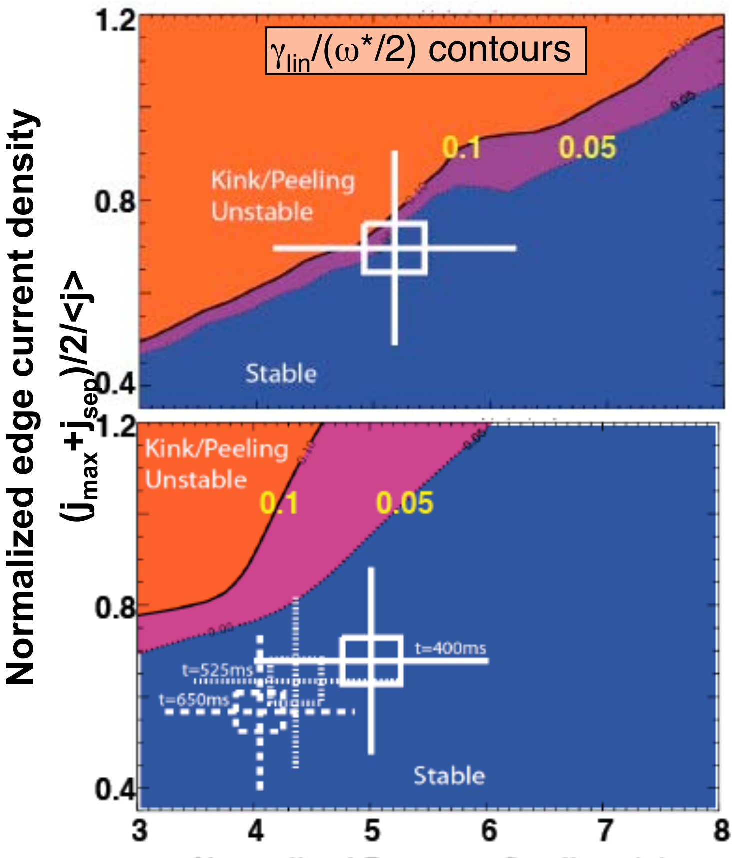
- Multiple timeslices mapped into composite profiles using EFIT equilibrium



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





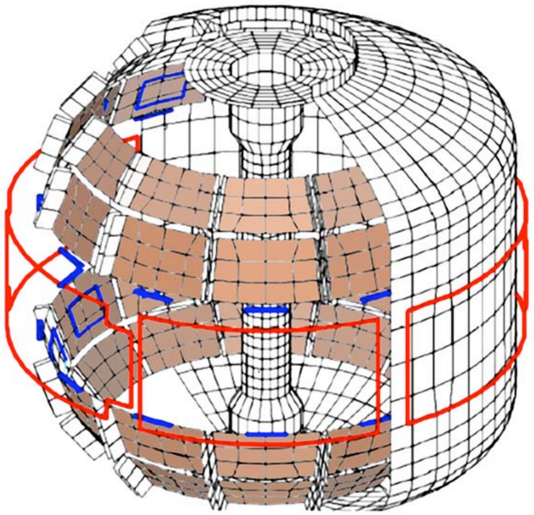
Without lithium (end of ELM cycle)

With lithium

R. Maingi, T. Osborne [PRL 103 (2009) 075001]

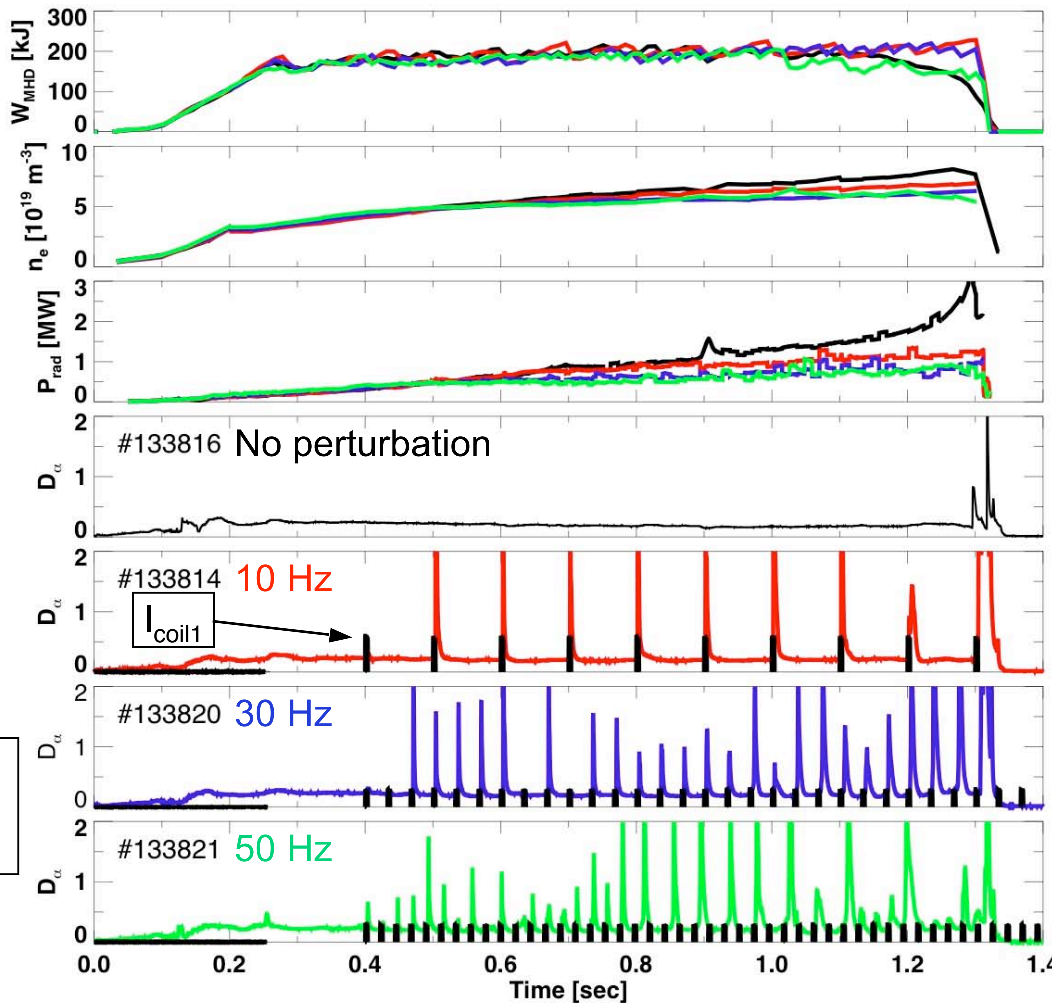
External Non-Axisymmetric Coils Can *Induce* Repetitive ELMs in Discharges with Lithium Coating

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

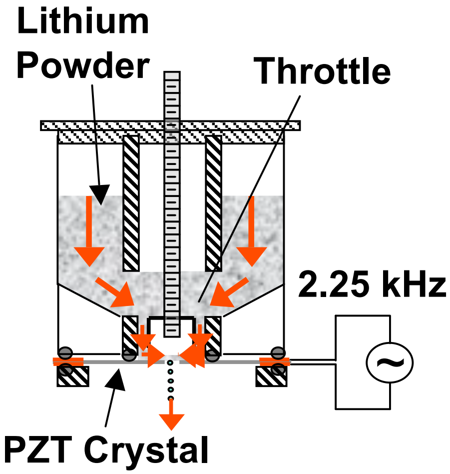


- **Induced ELMs reduce n_e, P_{rad}, Z_{eff} with small effect on plasma energy**

J. Canik, R. Maingi

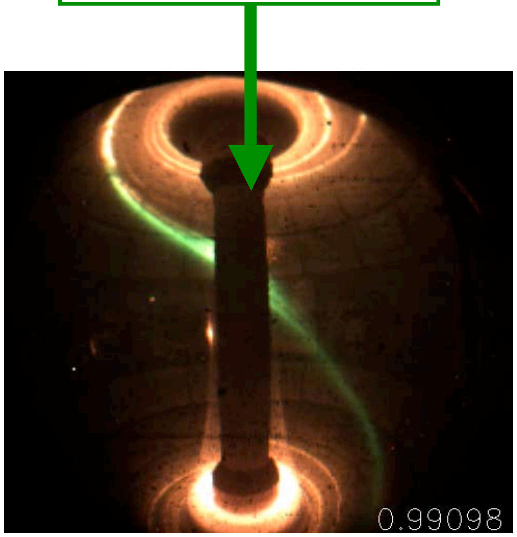
Also Investigated Lithium Coating by Dropping a Stream of Lithium Powder into SOL

- 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 – 80 mg/s: ***well tolerated by plasma, even in startup***



- Can modulate flow at up to 10Hz

Lithium powder dropped from canister above during discharge



Lithium powder flowing at t=0

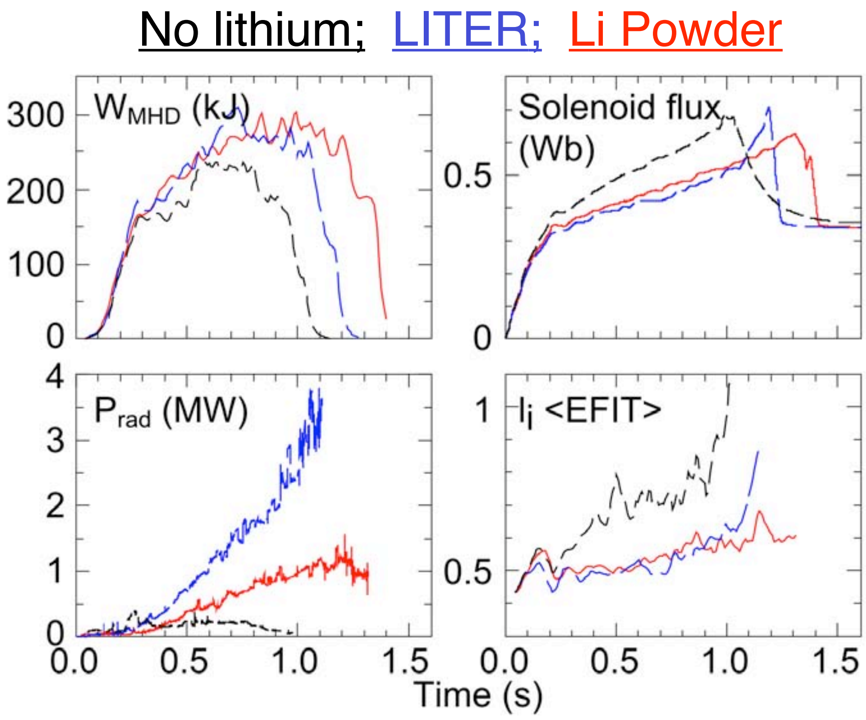
Movie in file Miro_135060_0-255msx2.mpg

D. Mansfield

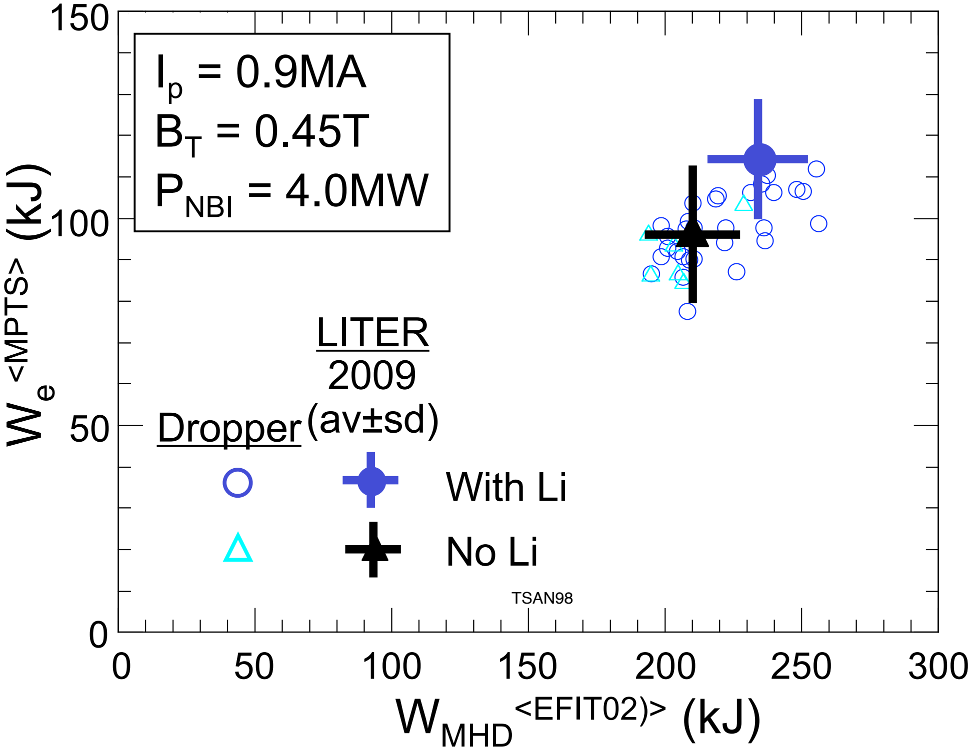
Injecting Lithium Powder Produced Benefits Similar to LITER

- Evident effect in initial 2008 experiment: ~10 mg introduced
  - Confinement improvement, reduced flux consumption
  - Less increase in radiated power
- In 2009, 50 – 100 mg powder injected, but improvement less reliable

2008

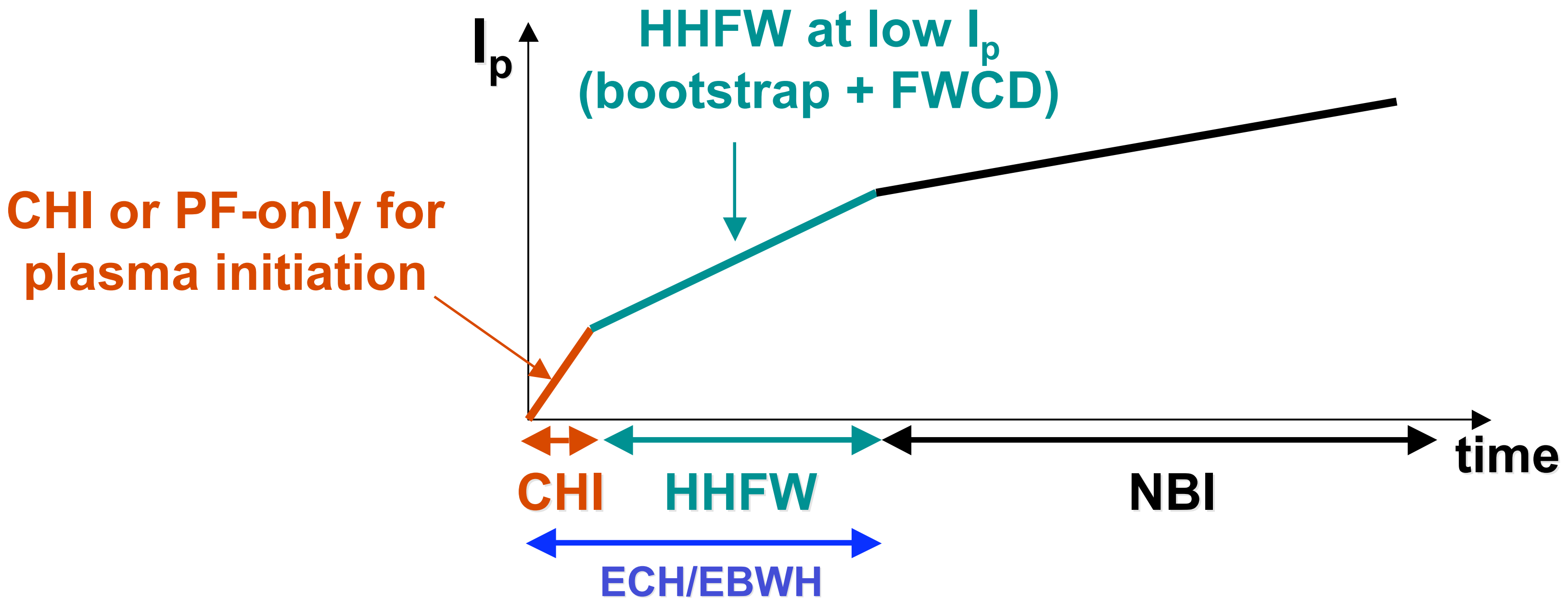


2009



D. Mansfield, L. Roquemore

Initiating, Ramping-up and Sustaining Plasma Current without Reliance on Central Solenoid Critical for the ST



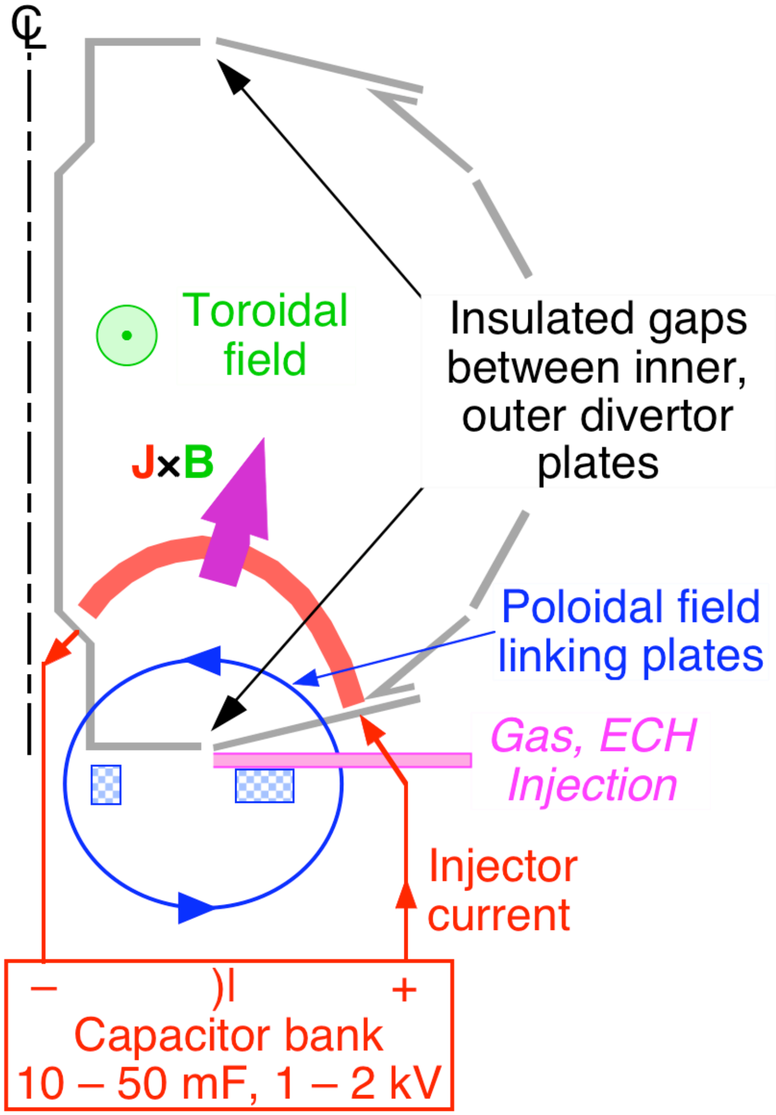
CHI: Co-Axial Helicity Injection

HHFW: 30 MHz (10 – 20th D harmonic), $k_{||} = 7 – 3.5\ m^{-1}$, 6 MW

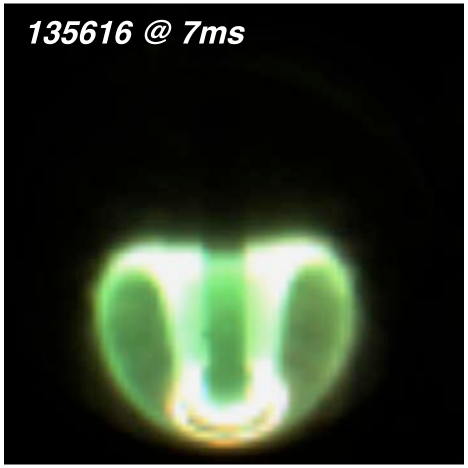
NBI: effective with enough initial current to confine ions

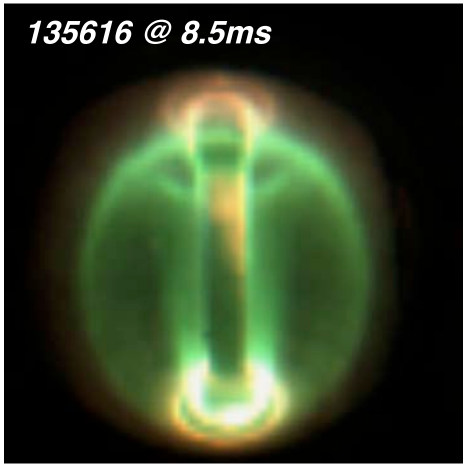
ECH/EBW: 28/15.3 GHz, 200 kW system (possible upgrade)

NSTX Developing Coaxial Helicity Injection (CHI) for Non-Inductive Initiation of Toroidal Plasma Current

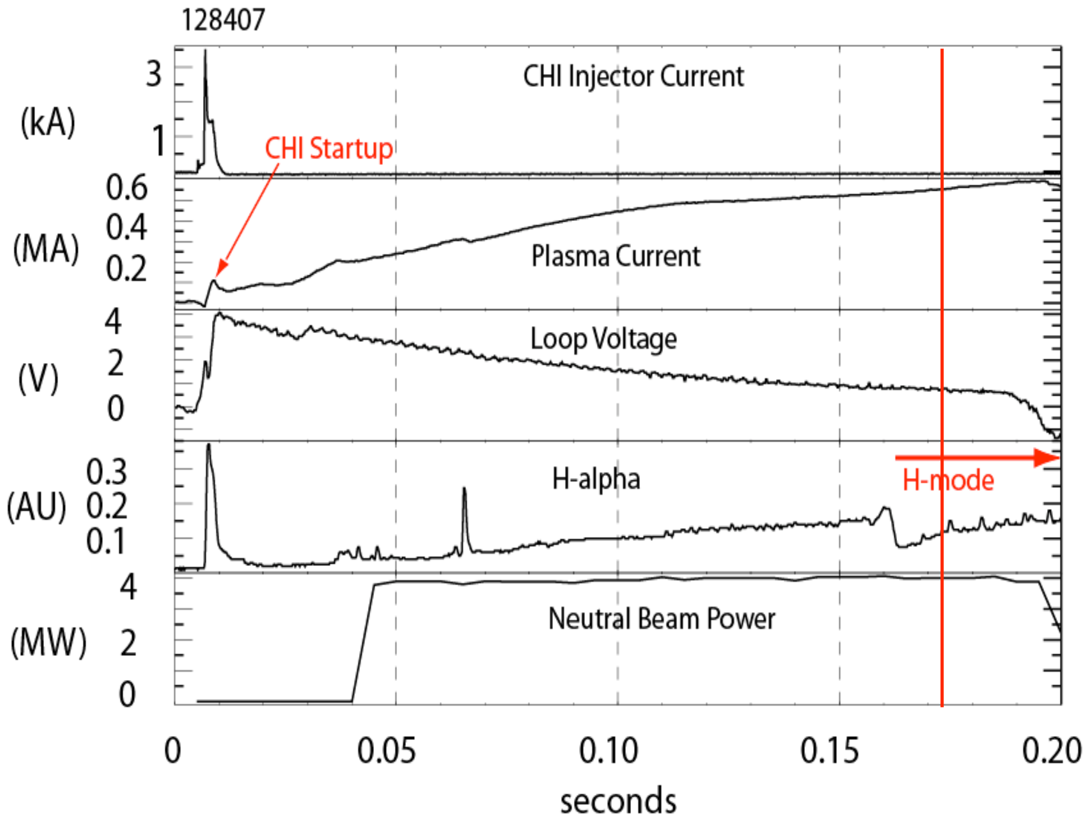


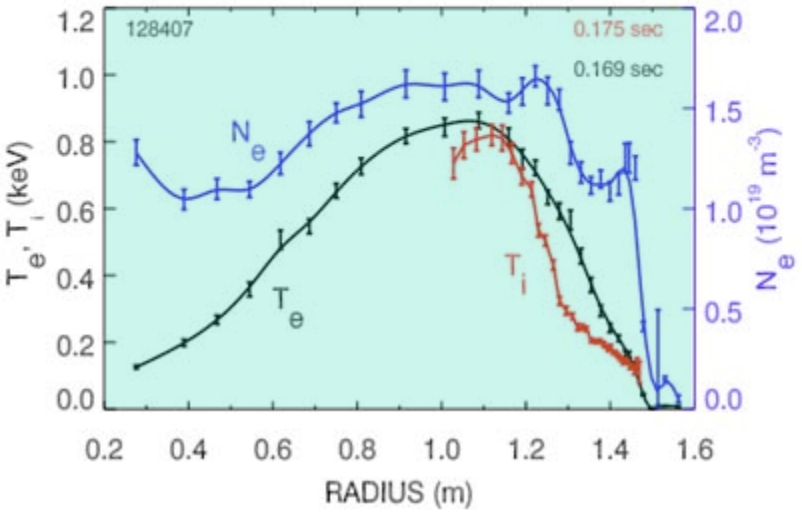
- Toroidal plasma currents up to 300kA generated in NSTX
  - Up to 180kA on closed flux surfaces
- Multiplication factor I_p/I_{inj} up to 70
- CHI involves discharge from electrodes: *surface conditions are important*





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



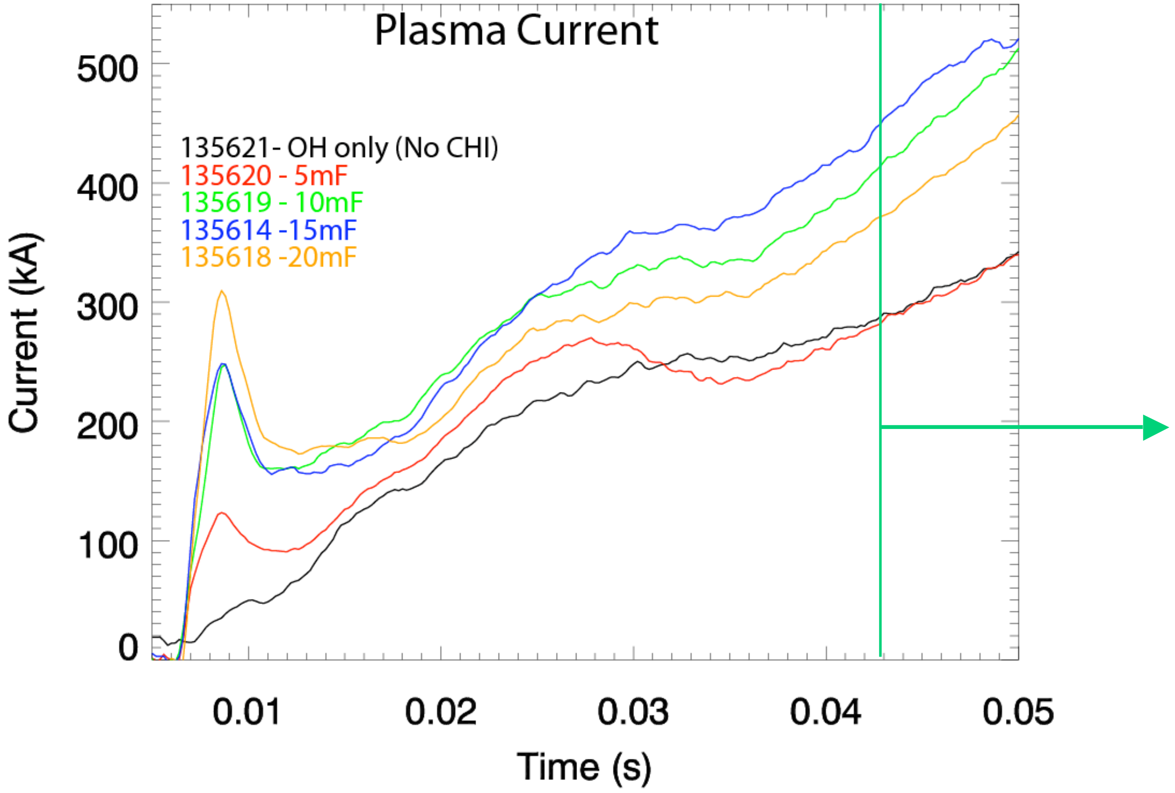


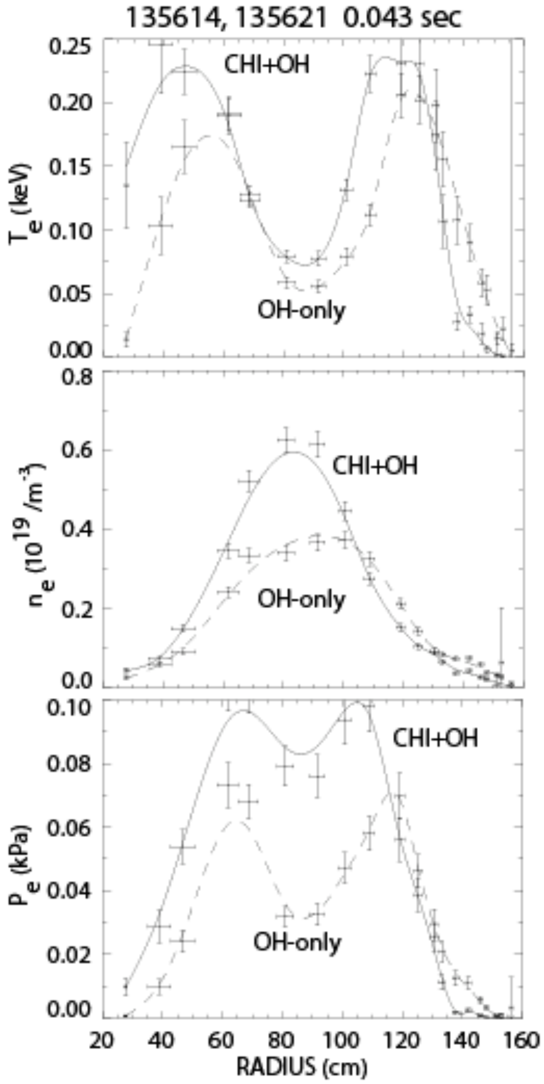
- Broad density profile during H-mode phase

- 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

R. Raman, B. Nelson, D. Mueller

With Electrode Conditioning and Lithium Applied, CHI Increases Plasma Current for Fixed Induction

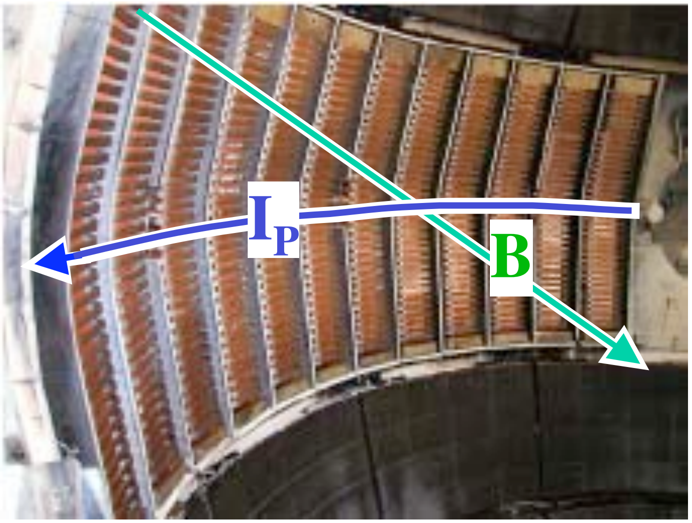


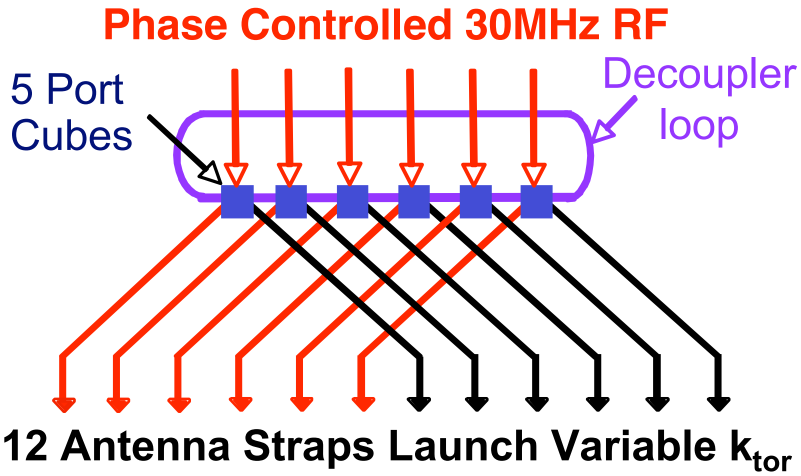


- All discharges used 0.11Vs of solenoid flux
- CHI initiation with 15mF @ 1.75kV (23kJ) produces 200kA more plasma current than induction alone
  - – absorber arc reduced current in 20mF case
- T_e and n_e, both are higher in CHI-started discharge

R. Raman, B. Nelson, D. Mueller

NSTX 12-Element Antenna Array Produces Highly Directional Fast-Wave Spectrum at 30MHz



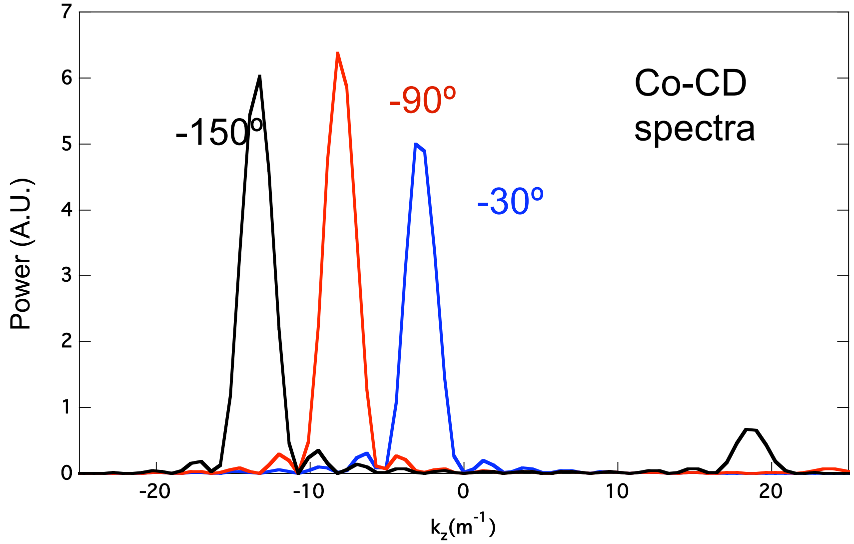


Phase Controlled 30MHz RF

5 Port Cubes

Decoupler loop

12 Antenna Straps Launch Variable k_{tor}



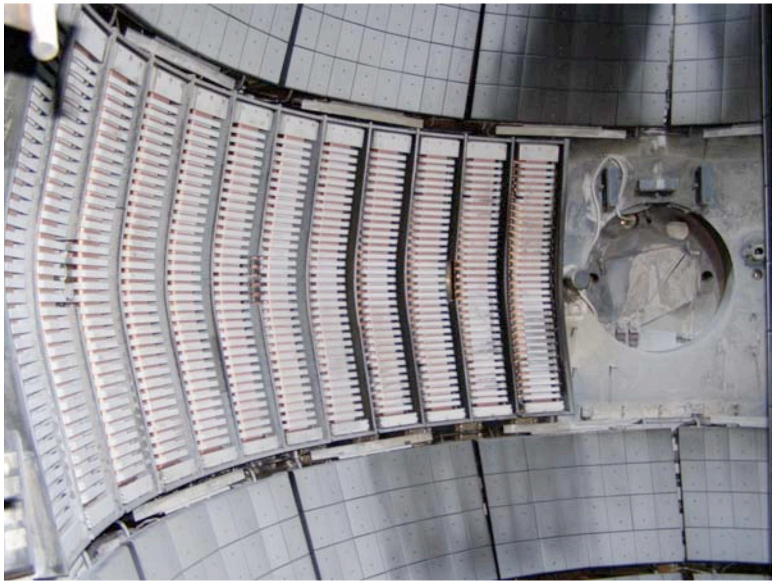
- Pair of straps for each source 180° out of phase
- Phase between adjacent loops adjustable in real-time 0 — ±180°
- Full 12-element array operation for $\Delta\phi$ = ±30° (±30°) ±150°
- Large field line pitch affects wave spectrum in plasma core

- Need directed waves with $k_{||} = 3.5 – 7 m^{-1}$ for HHFW-CD current drive

Heavy Lithium Coating On HHFW Antenna May Have Affected Coupled Power Limit

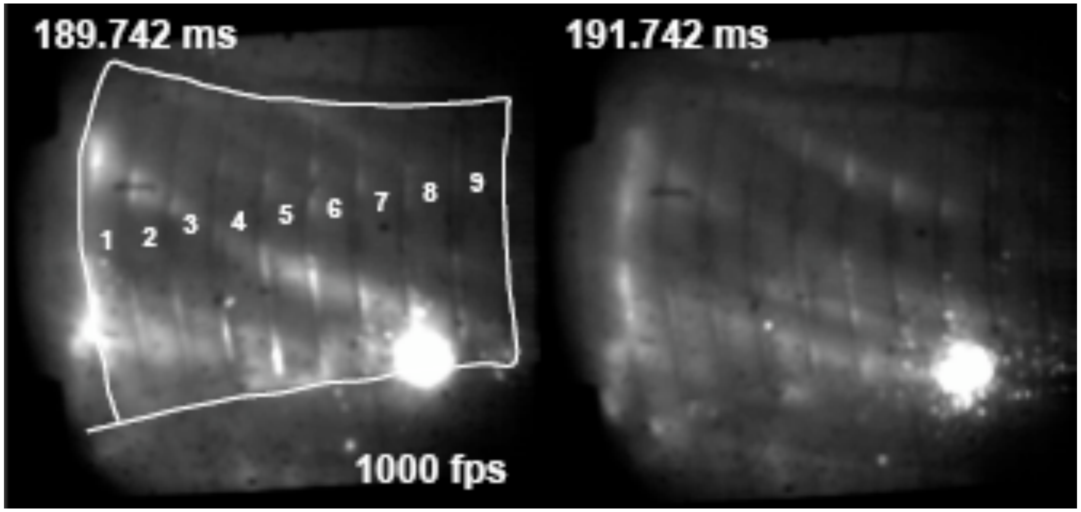
- Change to symmetric end feed for 2009
- ~300 g of lithium already evaporated before antenna was first used
- Antenna rapidly conditioned to previous voltage level (~25kV)
  - Lithium coating did not adversely affect RF feedthroughs or antenna internals
- In plasma operation saw ejection of material from front surface at P_{RF}>3MW

End of 2009 run



Visible camera images on shot 135242

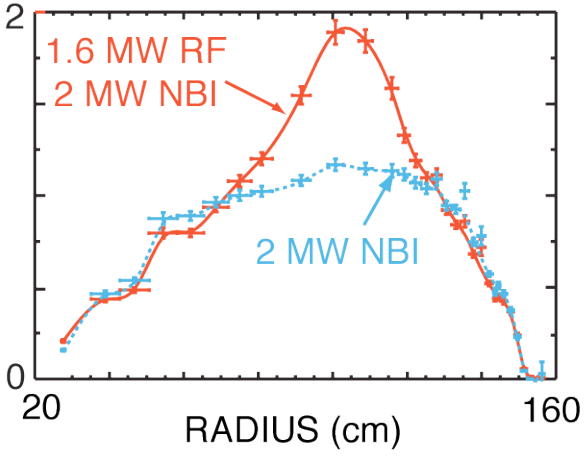
Source feeding Strap 7 tripped at 188.1ms



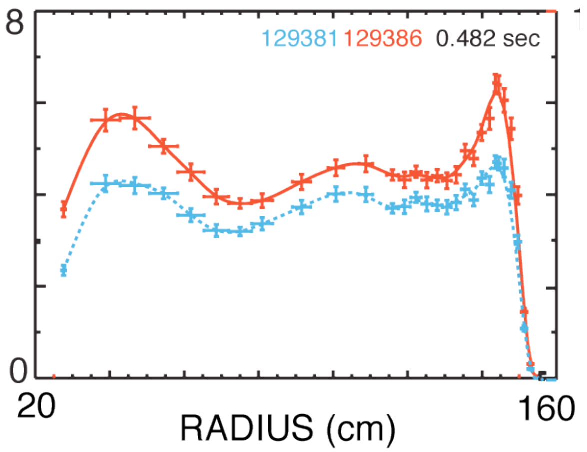
Lithium Coating Improves HHFW Heating Efficiency in NBI H-Modes and at Low $k_{||}$ for Current Drive

Core Electron Heating in Deuterium NBI H-Mode

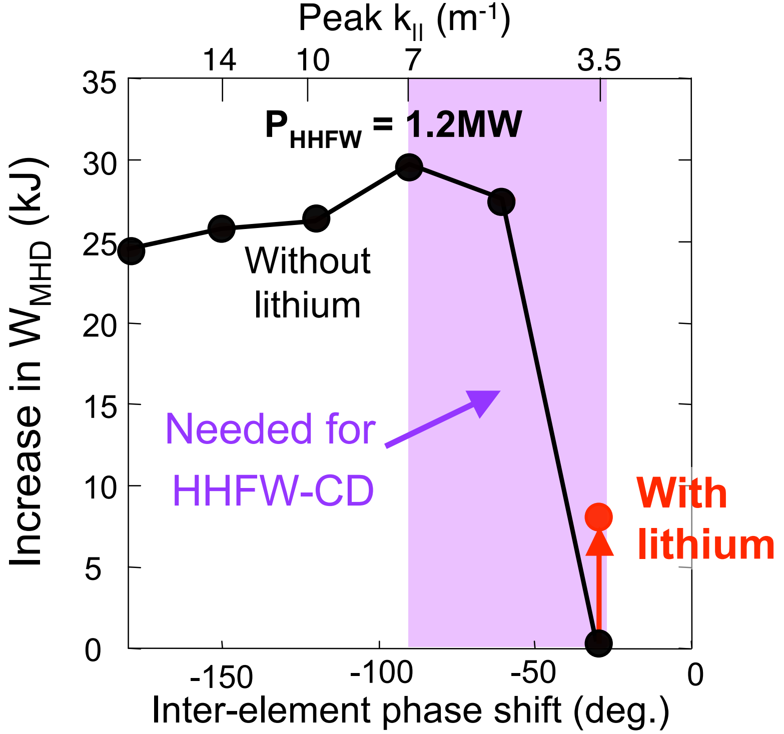
Electron Temperature (keV)



Electron Density (10^{19} m^{-3})



First indications of heating at low $k_{||}$ in D



- Reflectometer measures reduced SOL density in front of antenna with lithium
  - Results consistent with suppression of parasitic surface waves in SOL
    - $n_{e,SOL} < n_{e,crit} \propto B\, k_{||}^2 / \omega$

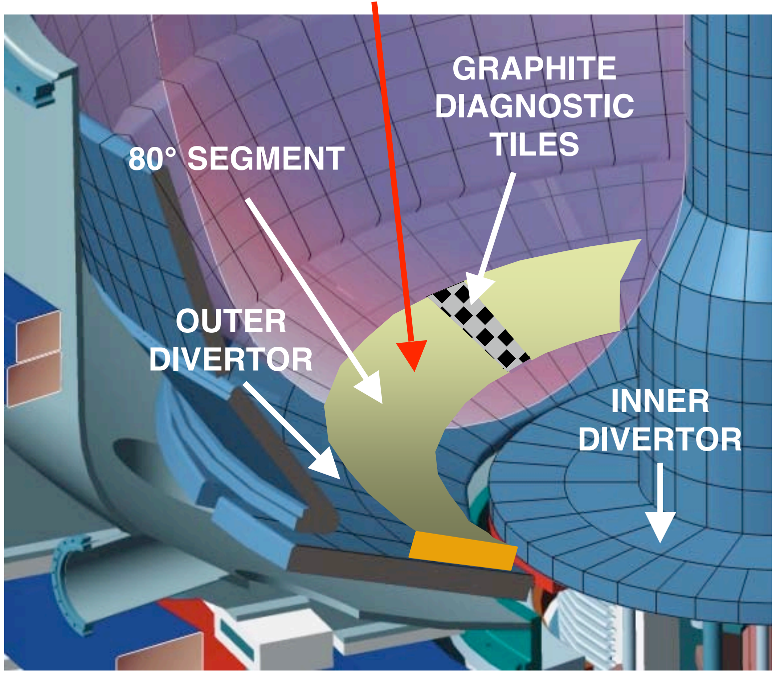
G. Taylor, P. Ryan, J. Hosea, B. LeBlanc

Solid Lithium Coating on 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 through changes in edge profiles
  - 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

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

Liquid Lithium Divertor (LLD)



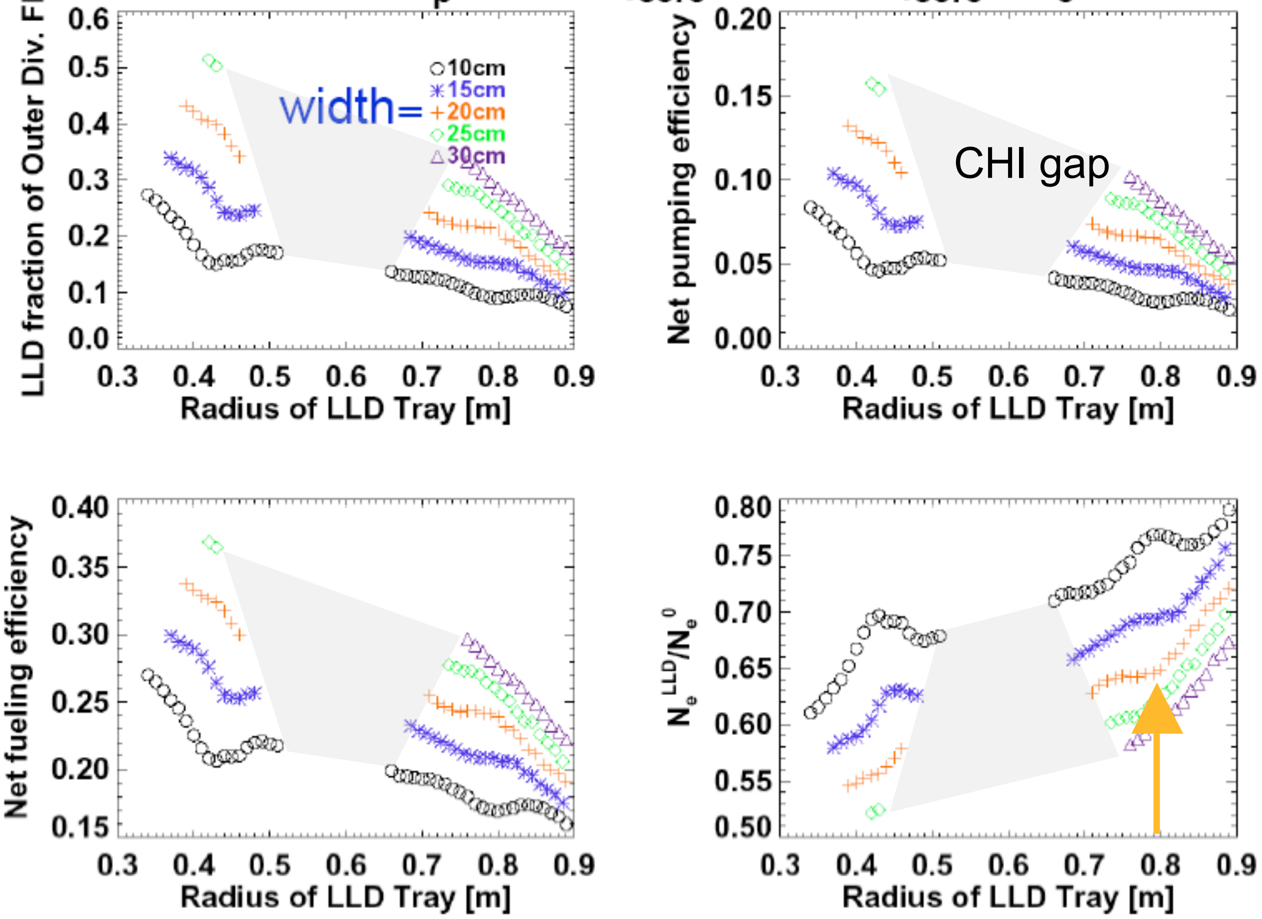
- Replace rows of graphite tiles in outer lower divertor with 4 segmented plates
- Plasma-facing surface coated with semi-porous (~50%) plasma-sprayed molybdenum (~150μm)
  - Surface can be heated to >400°C (Li melting point 180°C)
  - Active heat removal to counteract plasma heating
- Initially supply 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

Modeling of Particle Balance Shows LLD Should Pump Significantly Even for High-δ Plasmas

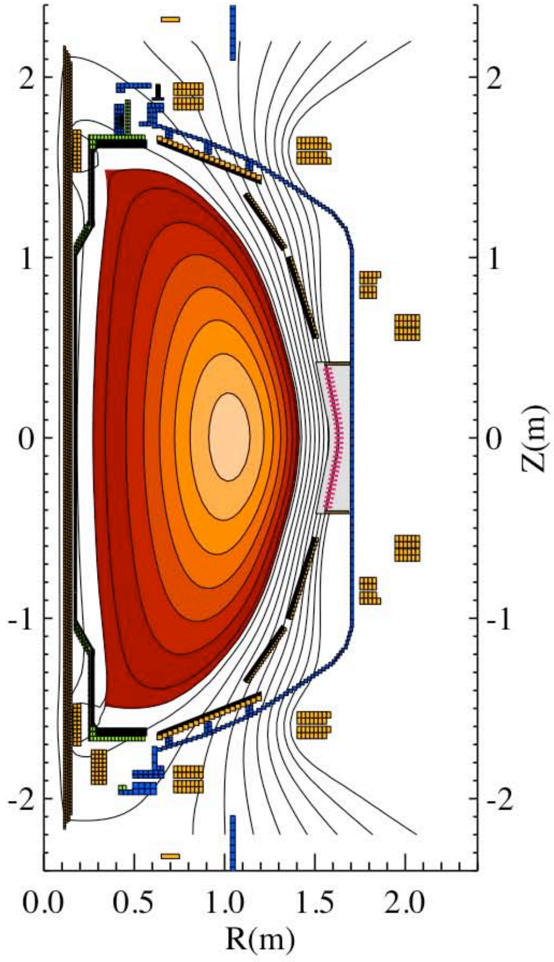
- Estimate LLD effects with divertor 2-point model
- Assume 85% D sticking coefficient on Li

R_p=0.98, η_{core}^{init}~0.1, $\eta_{core} \sim n_e^{-2}$



Modeled for shot with

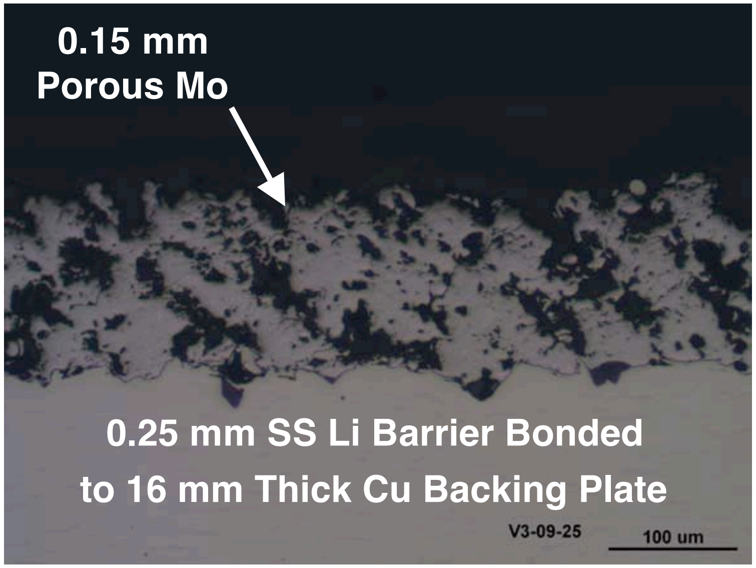
κ = 2.5, $\delta_{x,low}$ = 0.7



The LLD Plates and Their Control System Are Now Installed

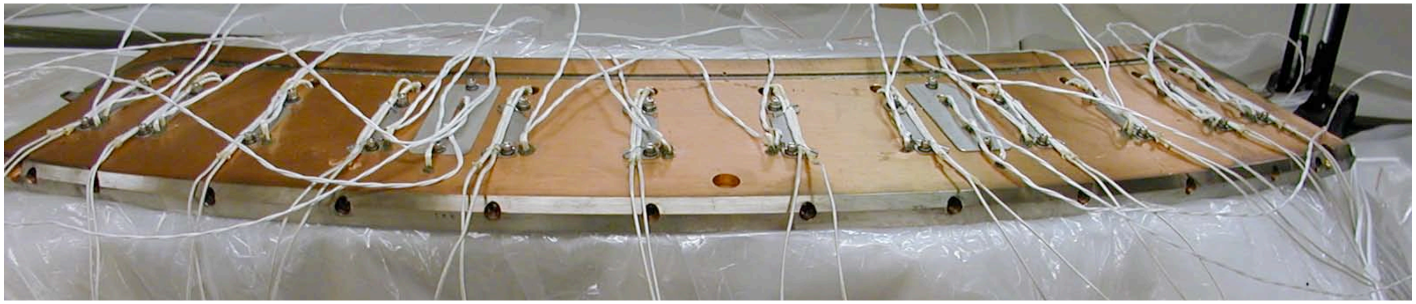
- Great effort by collaborators, technicians, electricians and engineers!

Micrograph of porous Mo layer



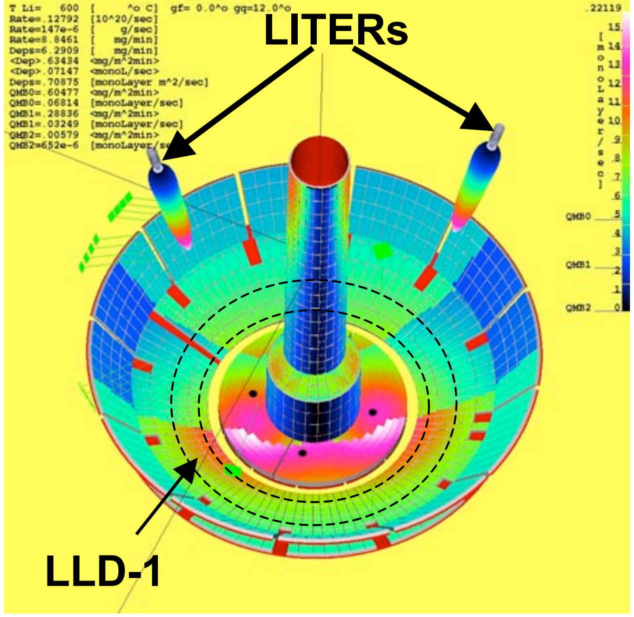
January 11, 2010

Back side of plate with heaters and thermocouples installed



H. Kugel, R. Nygren (SNL), S. O'Dell (PPI), E. Starkman

Plan to Fill LLD-1 with Lithium from Dual LITERs, Possibly Supplemented by Lithium Droppers



```
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>
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QMB2=652e-6  [monoLayer/se
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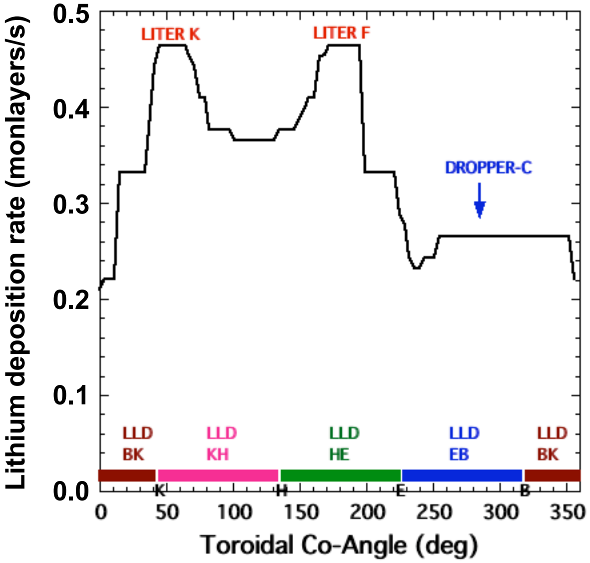

LLD loading at 60mg/min total rate

- Rely on liquid wetting the porous Mo surface to spread the lithium
- Only 7% of lithium evaporated by LITERs reaches LLD-1 plates
- Estimate ~40g lithium required to fill porous volume in Mo coating
  - ~600g evaporation to fill ⇒ 22 days at maximum rate & ~7 loadings
- Wettable area in porous Mo estimated at ~8 times plate area
  - 1.1g lithium on LLD would coat wettable area to 250nm penetration depth of incident D^+ ⇒ 15g evaporated ~ 1 day at normal evaporation rate

L. Zakharov, H. Kugel

LLD Operation will be Monitored with Several Diagnostic Systems

- Visible Cameras
  - 2 high-speed views from above
- Plate surface temperature
  - Fast IR Camera
  - Slow IR Cameras
  - Thermocouple arrays in plates for calibrating surface emissivity
  - Also developing 2-color IR capability to avoid emissivity issue
- Lyman-α photodiode array (for recycling rate)
- Divertor region extractable sample probe
- 3 Quartz Deposition Monitors
- Langmuir probes in diagnostic tiles between plates
  - Including high-density array of 99 probes

Initial Experiments will be Designed to Characterize LLD Operation and Limitations

- Questions to be addressed
  - Can previous operational scenarios with evaporated lithium coating be reproduced in the presence of the LLD when it is unheated?
  - What is the response of the unheated LLD to standard plasmas?
  - How much liquid lithium is needed on the LLD to produce effects?
  - At what rate is liquid lithium consumed by standard plasmas?
  - How sensitive are the effects of the LLD to the strike point location?
  - Does the LLD provide additional and more long lasting pumping than solid lithium on the PFCs?
  - What is needed to maintain or rejuvenate pumping by the LLD?
  - What is the response of the LLD to increasing power fluxes?
- Designing experiments to address these questions is challenging, *but*
- **The LLD represents an opportunity to enhance the capabilities of NSTX, and possibly influence the development of fusion**

Many thanks to the NSTX Team!