NSTX

Supported by U.S. DEPARTMENT OF ENERGY | Office of Science

Tools For Developing Advanced Spherical Tokamak Plasmas in NSTX

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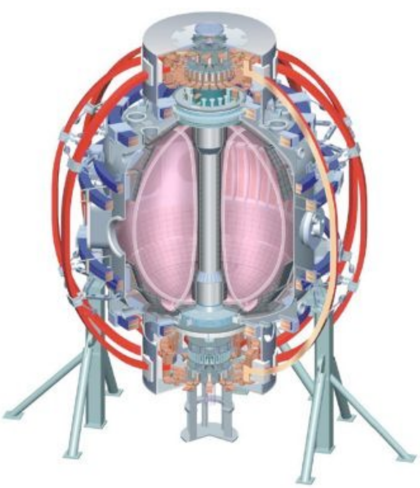
Innovative Confinement Concepts 2010
LSB Auditorium, PPPL
Feb. 19th, 2010



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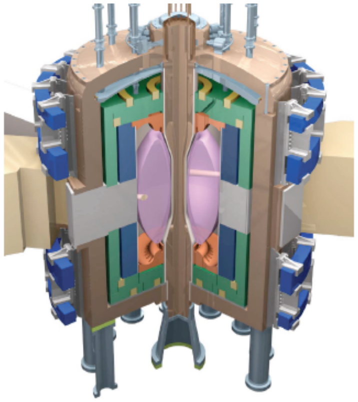
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

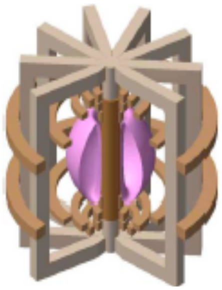
Scenario Development Research in NSTX Focused on Needs of Next-Step Devices

- Next-step STs are envisioned to provide important engineering and physics knowledge for fusion energy:
  - ST Fusion Nuclear Science Facility
    - Develop fusion nuclear science.
    - Test nuclear components for Demo
    - Sustain $W_{neutron} \sim 0.2\text{-}0.4 \rightarrow 1\text{-}2 MW/m^2$, $\tau_{pulse} = 10^3 \rightarrow 10^6 s$
  - ST Plasma Material Interface Facility
    - Develop long-pulse PMI solutions for FNSF / Demo.
    - High $P_{heat}/S \sim 1 MW/m^2$, high T_{wall}, $\tau_{pulse} \sim 10^3 s$
  - Both facilities make use of the compact ST geometry to fulfill their missions.
    - Both are steady state.
- NSTX scenario develop research:
  - Maximize the non-inductive current fraction in high-β plasmas.
  - Study the stability, transport, and overall performance, of plasmas with largely non-inductive current drive.
  - Develop an understanding of the control tools needed to achieve these configurations.

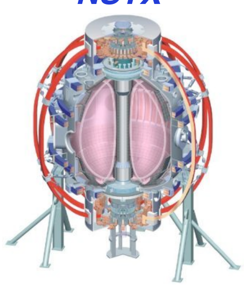
***FNSF** (ST-CTF)*



***PMIF** (NHTX)*

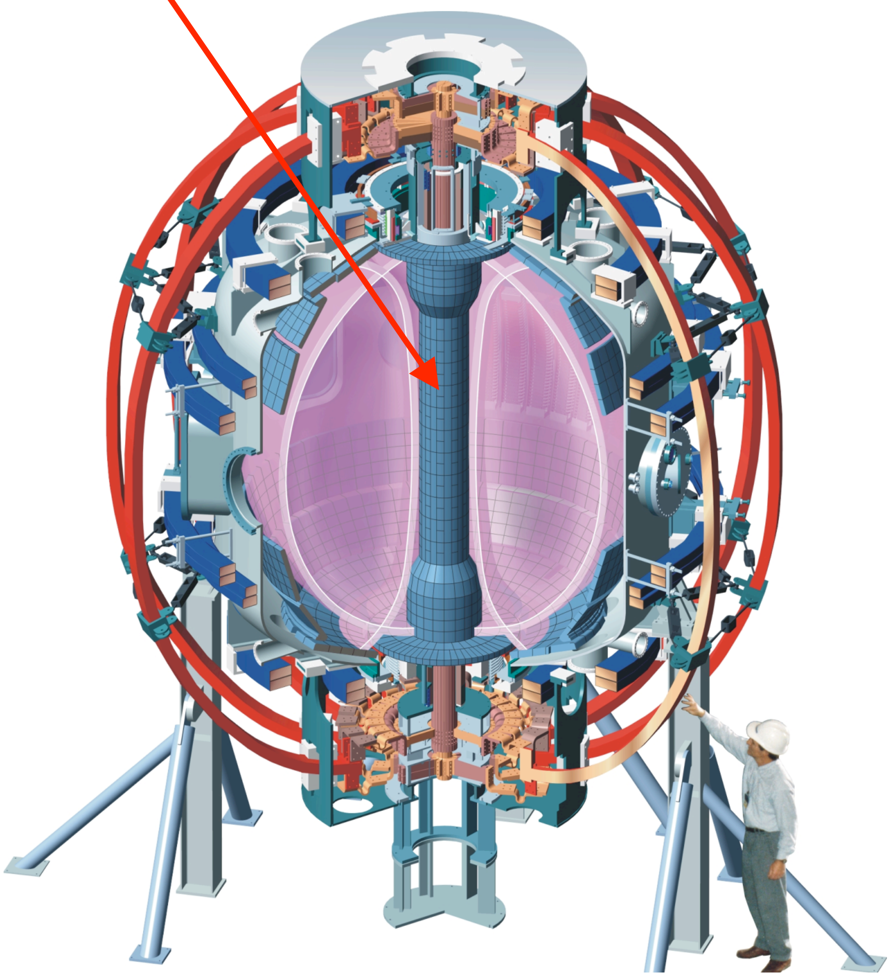


NSTX



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

Slim center column with TF, OH coils



Aspect ratio A	1.27 – 1.6
Elongation κ	1.8 – 3.0
Triangularity δ	0.3 – 0.85
Toroidal Field B_{T0}	0.35 – 0.55 T
Plasma Current I_p	$\leq$1.5 MA
Pulse Length	$\leq$ 2 sec
Auxiliary heating:	
NBI (100kV)	7 MW
RF (30MHz)	6 MW
Central temperature	1 – 5 keV
Central density	$\leq 1.2\times10^{20} m^{-3}$

Best NSTX Discharges Achieve CTF-level β_N, with Good Confinement and High Non-Inductive Fraction

133994

Optimized for largest non-inductive fraction

B_T=0.48 T

Pulse length limited by TF coil heating

135445

Optimized for longest pulse

B_T=0.375 T

Operations and Analysis Tools for Integrated Performance

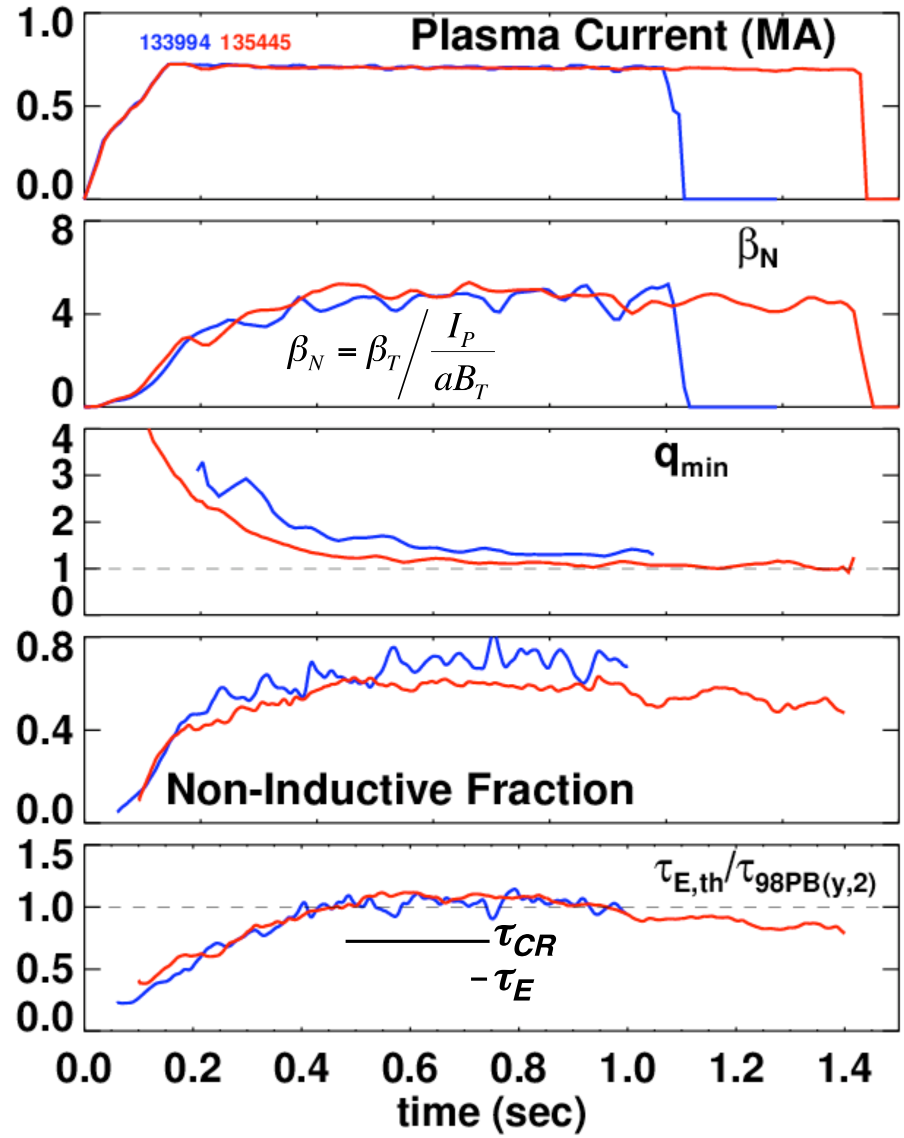
Plasma Shaping

n=1 Mode Control

Lithium Conditioning

Current Profile Analysis

Future Liquid Lithium Divertor

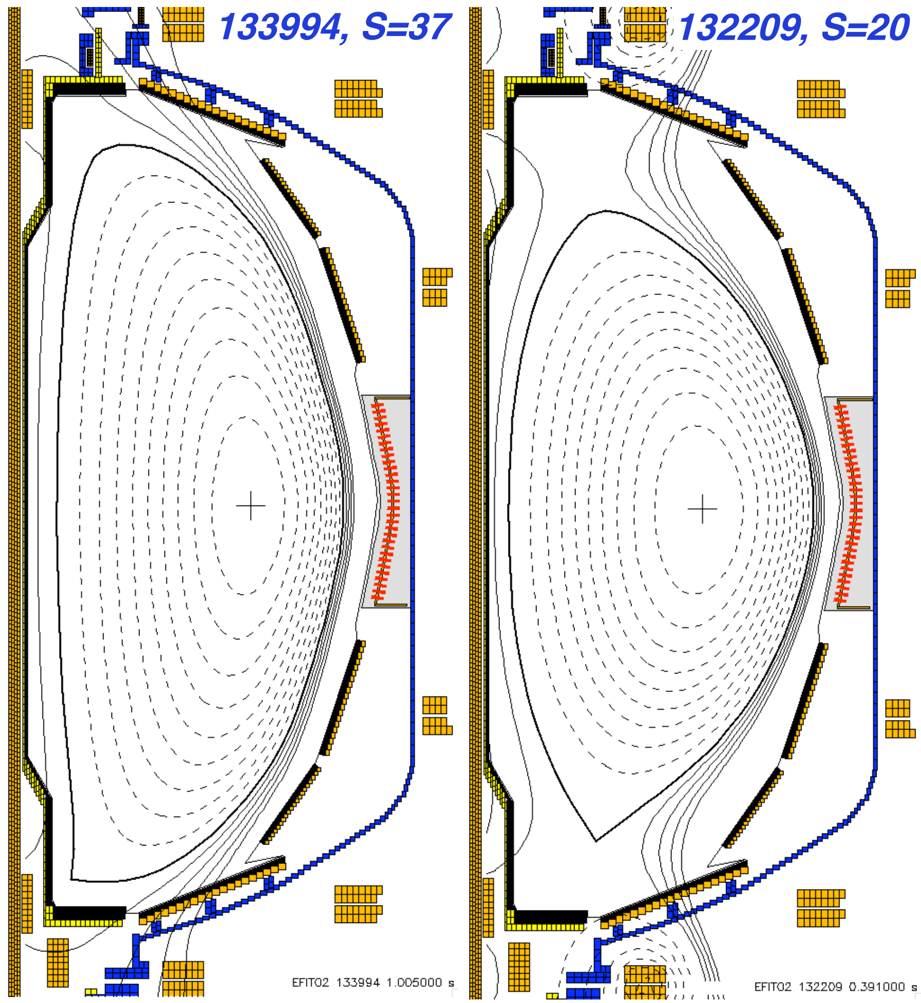


Shaping is Described by the "Shape Parameter" S

- Two important degrees of freedom in axisymmetric plasma boundary shaping.[1]
  - Elongation: Increasing elongation increases q, improving the *kink stability* & increasing *bootstrap currents*.
  - Triangularity: Increasing the triangularity causes fields lines to spend more time in the *high-field good-curvature* region.

- "Shape Parameter" S encapsulates both effects.

$$S = \frac{q_{95} I_P}{a B_T} \propto \varepsilon\left(1+\kappa^2\right) f\left(\kappa,\delta,\varepsilon,\ldots\right)$$

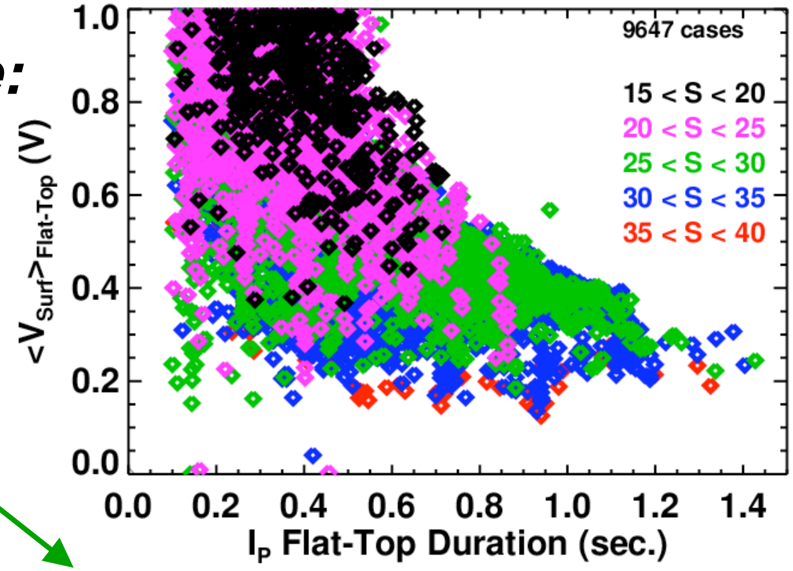


[1] E. Lazarus, et al, Phys. Plasmas B **3**, 2220 (1991)
[2] E.J. Strait, Phys. Plasmas **1** 1415 (1994)
[3] D. Gates, et al, Phys. Plasmas **10**, 1659 (2003)
[4] D. Gates, et al, Phys. Plasmas **10**, 1659 (2003)

Strong Plasma Shaping is Important For Sustained High-β

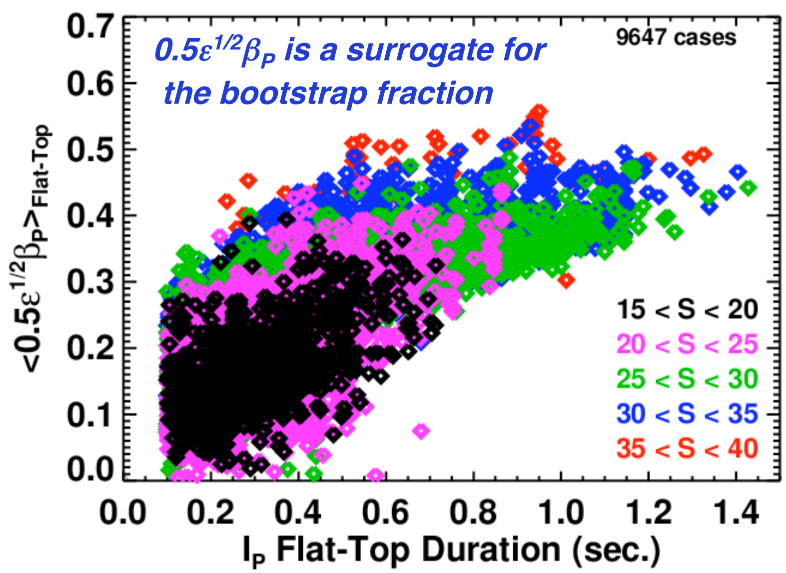
Large values of shaping help achieve:

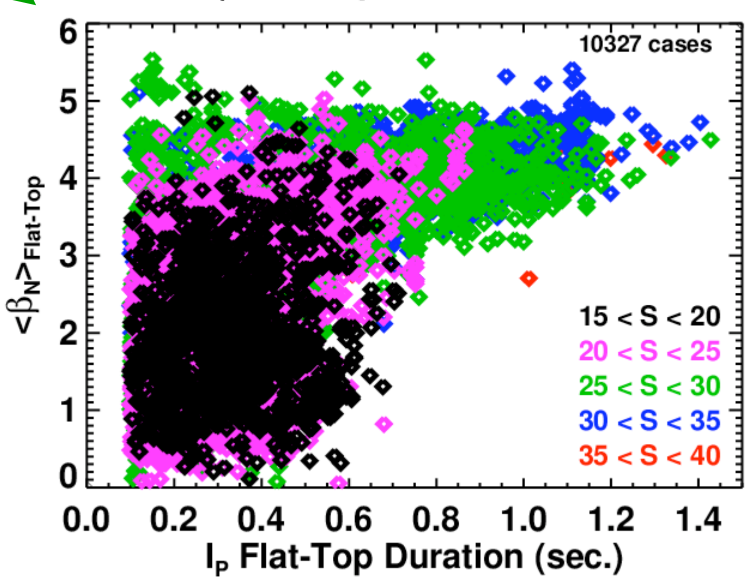
Low surface voltage



Long-pulse at high-β_N

High bootstrap fraction

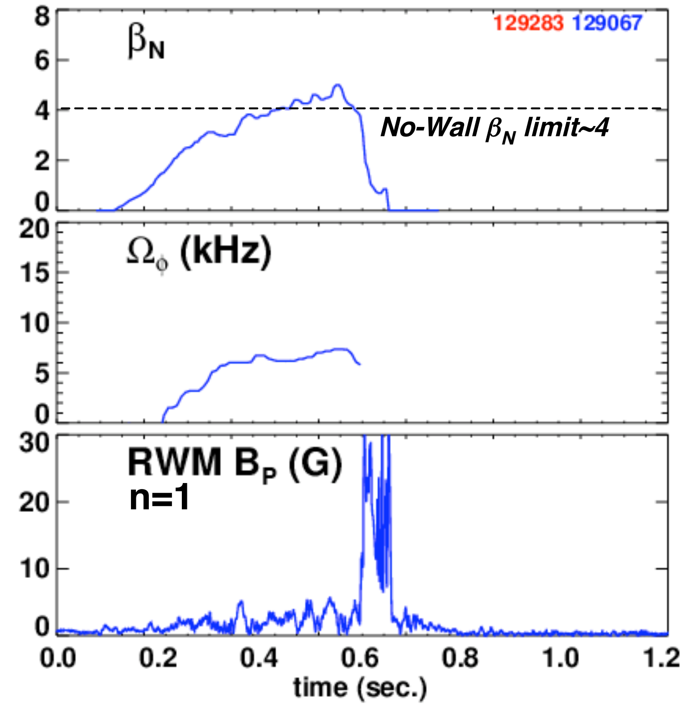




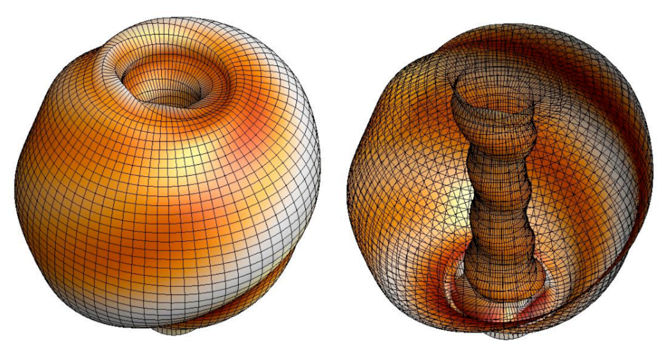
[1] D. Gates, et al, Phys. Plasmas ***10****, 1659 (2003), [2] D. Gates, et al, Phys. Plasmas* ***10****, 1659 (2003)*

Resistive Wall Modes (RWMs) And Error Field Amplification Can Inhibit High-β Operation

- The RWM[1] is a branch of the kink-ballooning instability that occurs in the presence of a resistive wall.
  - Slow growth rates: $\gamma \approx \tau_W$, 10-15 msec in NSTX.
- Onset of an unstable RWM cause:
  - Severe confinement degradation.
  - Disruption.
- RWMs can be stabilized by rotation + dissipation.
  - Exact physics depends on dissipation model, kinetic effects, and is an area of active research.[2]
- Even stable RWM can cause trouble.
  - Error fields can be amplified by the stable RWM.
  - Resulting plasma response has RWM structure.
  - Plasma-amplified 3-D field leads to rotation braking.
  - Reduced rotation leads to RWM destabilization.



Distorted Plasma Boundary with an RWM



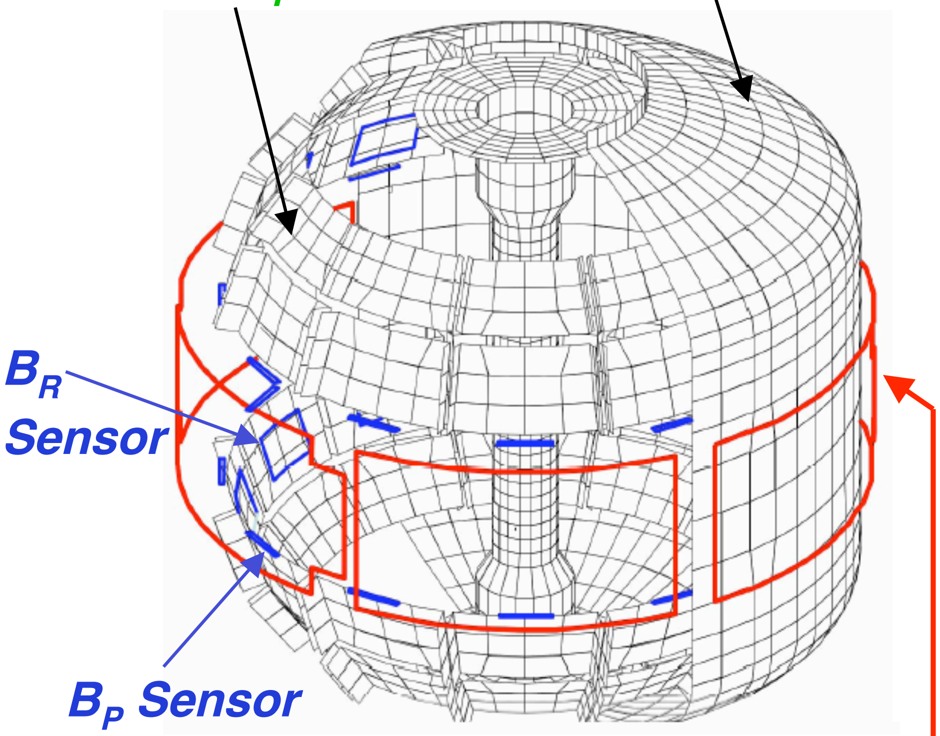
NSTX Solution for Advanced Scenario Experiments

Maintain rapid rotation using neutral beam injection.

Use active feedback to control *BOTH* the plasma amplified error field and the RWM.

*[1] S. Sabbagh, et al., Nuclear Fusion **46**, 635 (2006)*
*[2] J. W. Berkery, et al, Phys. Rev. Lett **104**, 035003 (2010)*

n=1 Mode Control Provided with Internal Sensors and External Midplane Coils



- Copper stabilizing plates to enable high-β operation.
- 6 ex-vessel midplane coils.
- 48 Internal sensors for non-axisymmetric fields.
  - 24 B_R for perturbations.
  - 24 B_P for perturbations.
- Use internal sensors to reconstruct an n=1 amplitude (B_1) and phase (θ_1) at each time.

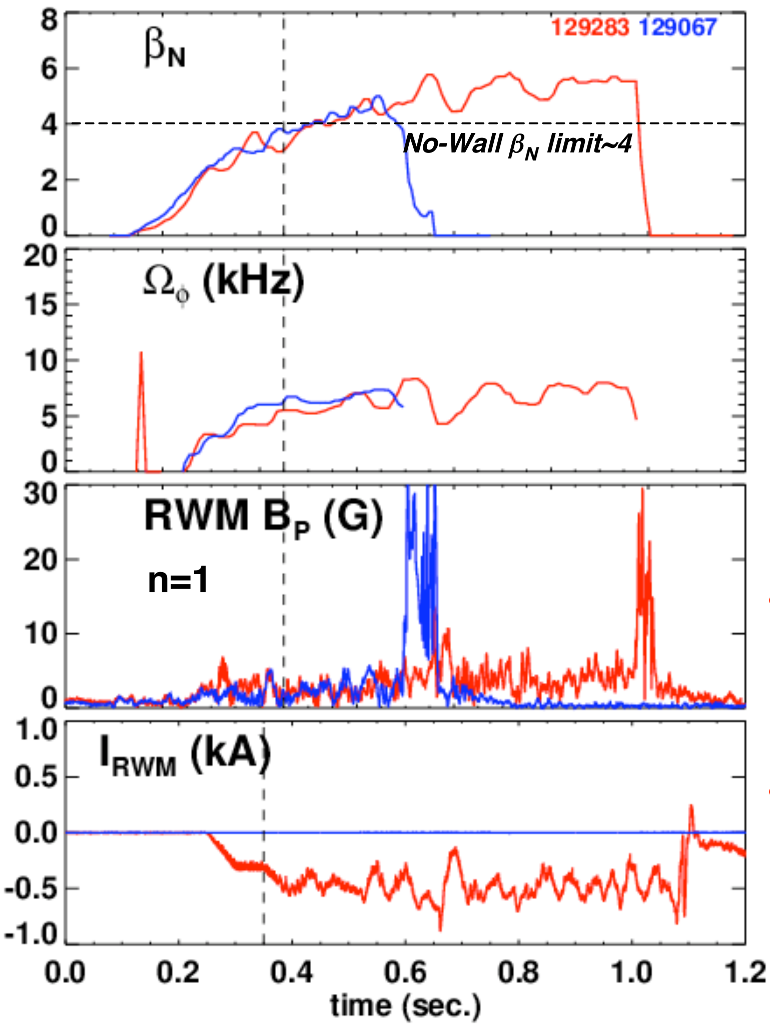
$$B_{RWM}(\phi) = B_1 \cos(\phi - \theta_1)$$

- Apply a phase shifted n=1 field.
  - Feedback Gain G
  - Feedback Phase δ

$$B_{F.B.}(\phi) = GB_1 \cos(\phi - \theta_1 - \delta)$$

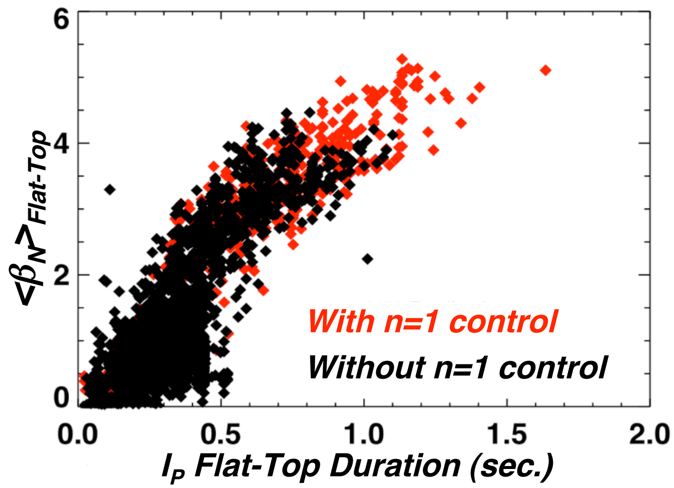
n=1 Mode Control Enables Reliable Access to Higher β

Comparison with & without n=1 control



[1] S. Sabbagh, et al, Phys. Rev. Lett **97**, 045004 (2006)
[2] S. Sabbagh et al, Nucl. Fusion **50**, 025020 (2010)

Long-Pulse High-β_N Facilitated by n=1 Control

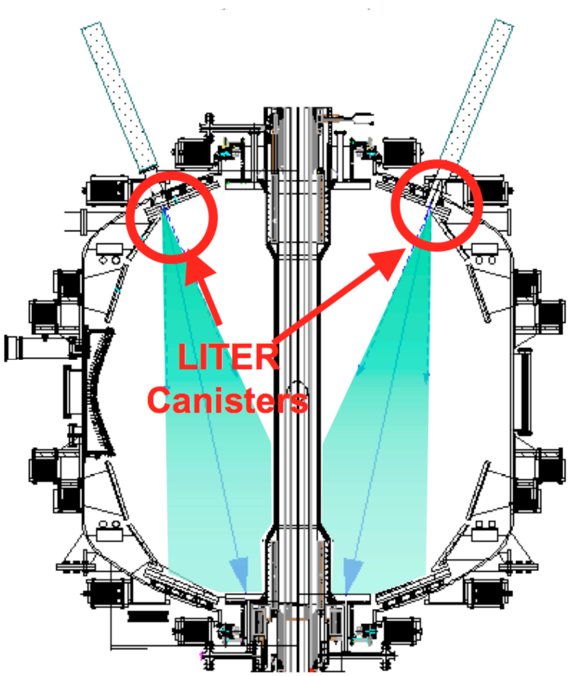


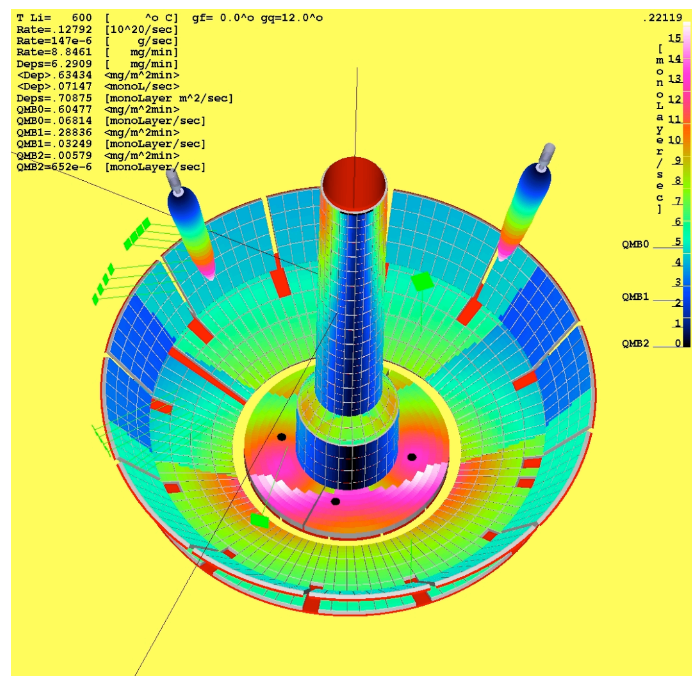
Why does n=1 control work?

- ***Slow Time-Scale:*** *Use n=1 feedback system to correct the plasma-amplified time varying error fields. This:*
  - *Helps to sustain rotation, which*
  - *Helps maintain good confinement and stability.*
- ***Fast Time-Scale:*** *Use n=1 feedback system to stabilize growing resistive wall modes.*[2]
  - *Phase locked RWM is observed with internal sensors*
  - *Feedback system responds.*
  - *RWM uncouples from the wall, spins-up as a global kink.*
  - *Rotating kink either decays away, or (rarely) converts to a tearing instability.*

Lithium Conditioning Provided by Dual Lithium Evaporators

- Two evaporators, separated by ~150º toroidal, deposit solid lithium on graphite PFCs
  - LITER=LIThium EvaporatoR
- Typically deposit 50-300 mg of lithium between discharges.
  - In-situ quartz micro-balance data implies deposited lithium thickness is 5 – 160 nm on inner divertor plate.
- Need 40-60% more gas with Li conditioning to match density evolution.
- Eliminated the need for both helium GDC between discharges and bi-weekly boronization.
  - Also increases shot-to-shot reproducibility and reliability.

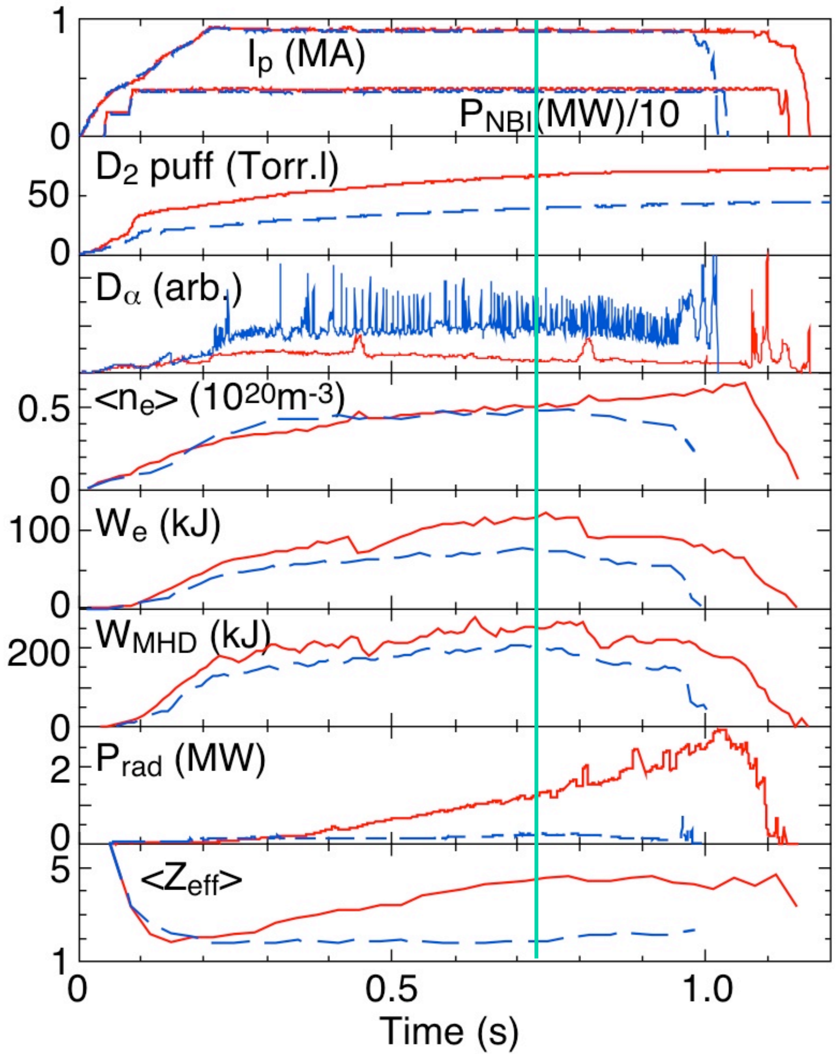




[1] H. Kugel Phys. Plasmas **15**, 056118 (2008)   [2] M. Bell et al, Plasma Phys Control Fusion **51**, 124054 (2009)

Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement

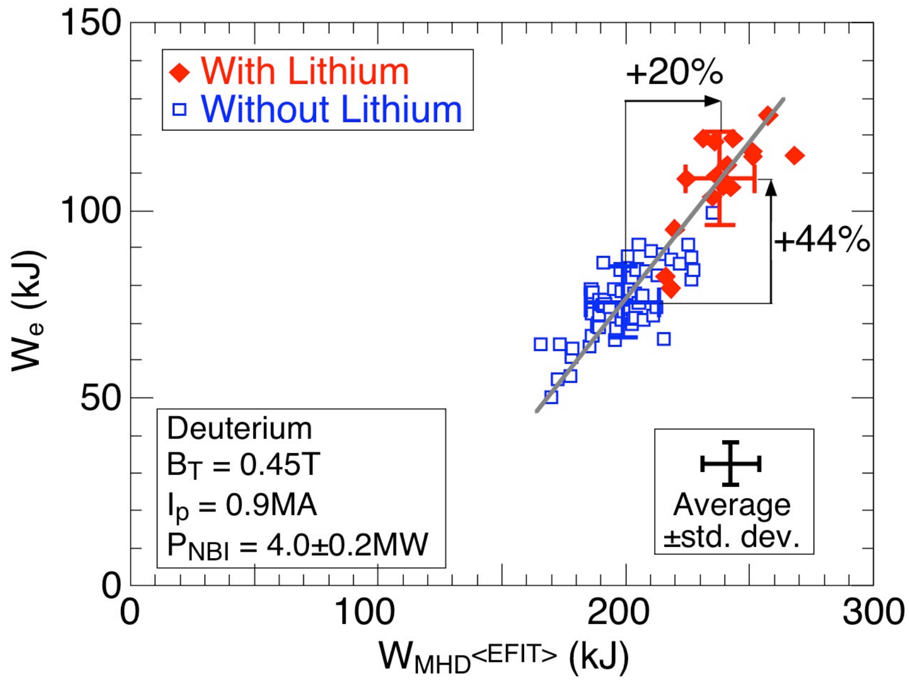
No lithium (129239); **260mg lithium** (129245)



- Same plasma current and heating power.
- 60% more D_2 injection to maintain the same density.
- ELMs are eliminated.
- Both the total and electron stored energy increase with Li conditioning.
- Both Z_{eff} and radiated power increase with Li conditioning.
  - Elimination of ELMs allows the plasma to accumulate both carbon and metallic impurities.

*[1] M. Bell et al, Plasma Phys Control Fusion **51**, 124054 (2009) [2] R. Maingi, et al, Phys. Rev. Lett. **103**, 075001 (2009)*

Confinement Improves, and Temperature Profiles Broaden, With Li Conditioning of the PFCs

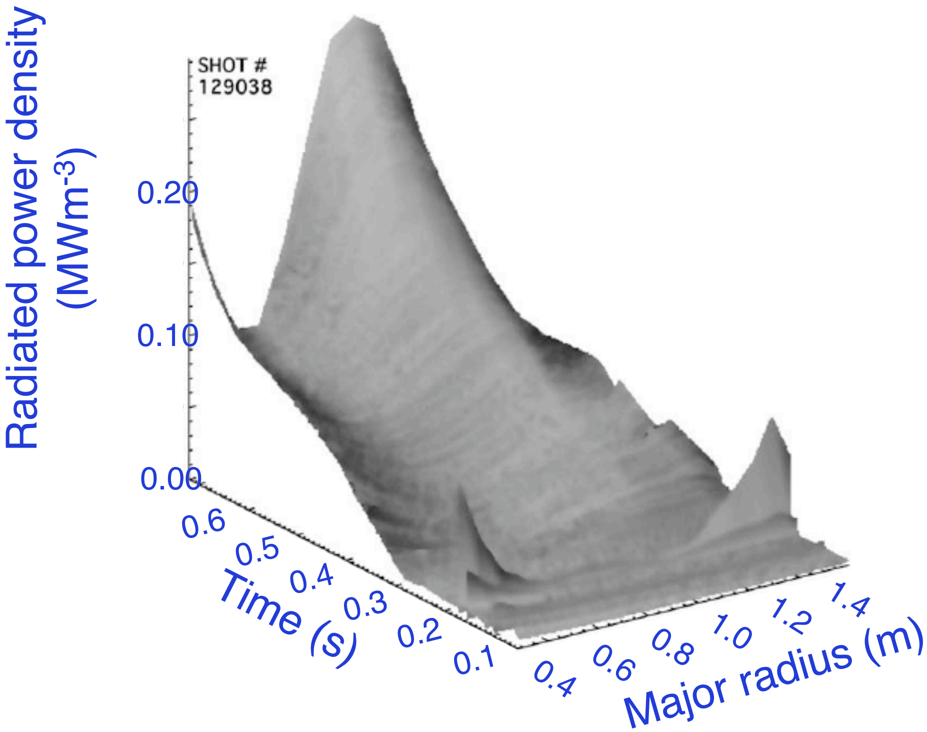


- Electron stored energy increase due to a broadening of the profiles.
- TRANSP analysis continually reduced transport in the outer part of the plasma as between shot lithium deposition is increased.
- Root cause of confinement improvement with lithium is not understood.
  - Ions remain approximately neoclassical.
  - Electron transport in NB-heated H-mode ST plasmas is not understood.

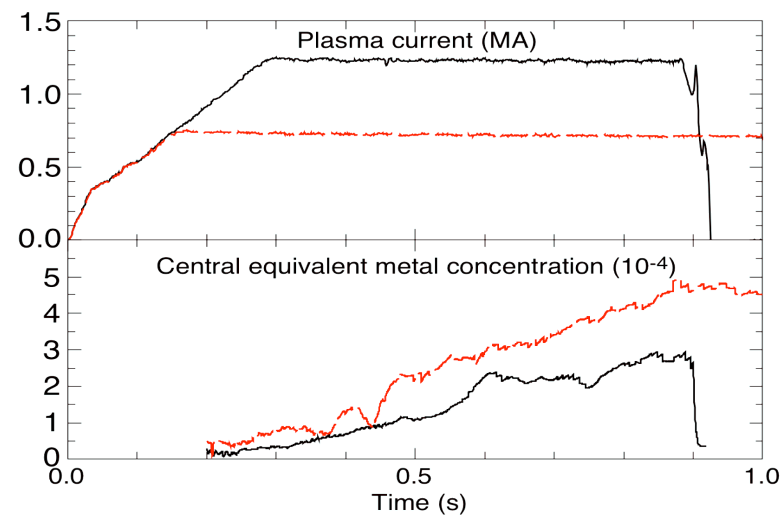
*[1] M. Bell et al, Plasma Phys Control Fusion **51**, 124054 (2009), [2] S. Ding, Plasma Phys. Control Fusion **52**, 015001 (2010)*

ELM-Free H-Mode Leads to Impurity Accumulation

- ELMs are eliminated with lithium conditioning.
  - Modifications to the edge profiles results in modifications to the peeling-ballooning stability boundary.[2]
- Core radiation grows to unacceptable levels.[1]
- Magnitude of apparent metals concentration depends on plasma current.
  - Consistent with sputtering from lost fast-ions being an important impurity source.



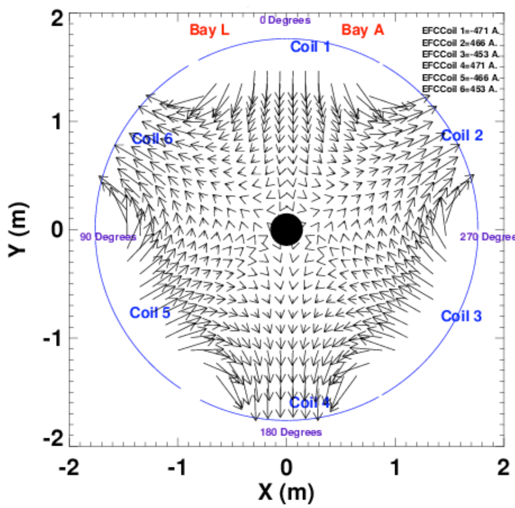
Apparent Metals Concentration Increases at Reduced Plasma Current



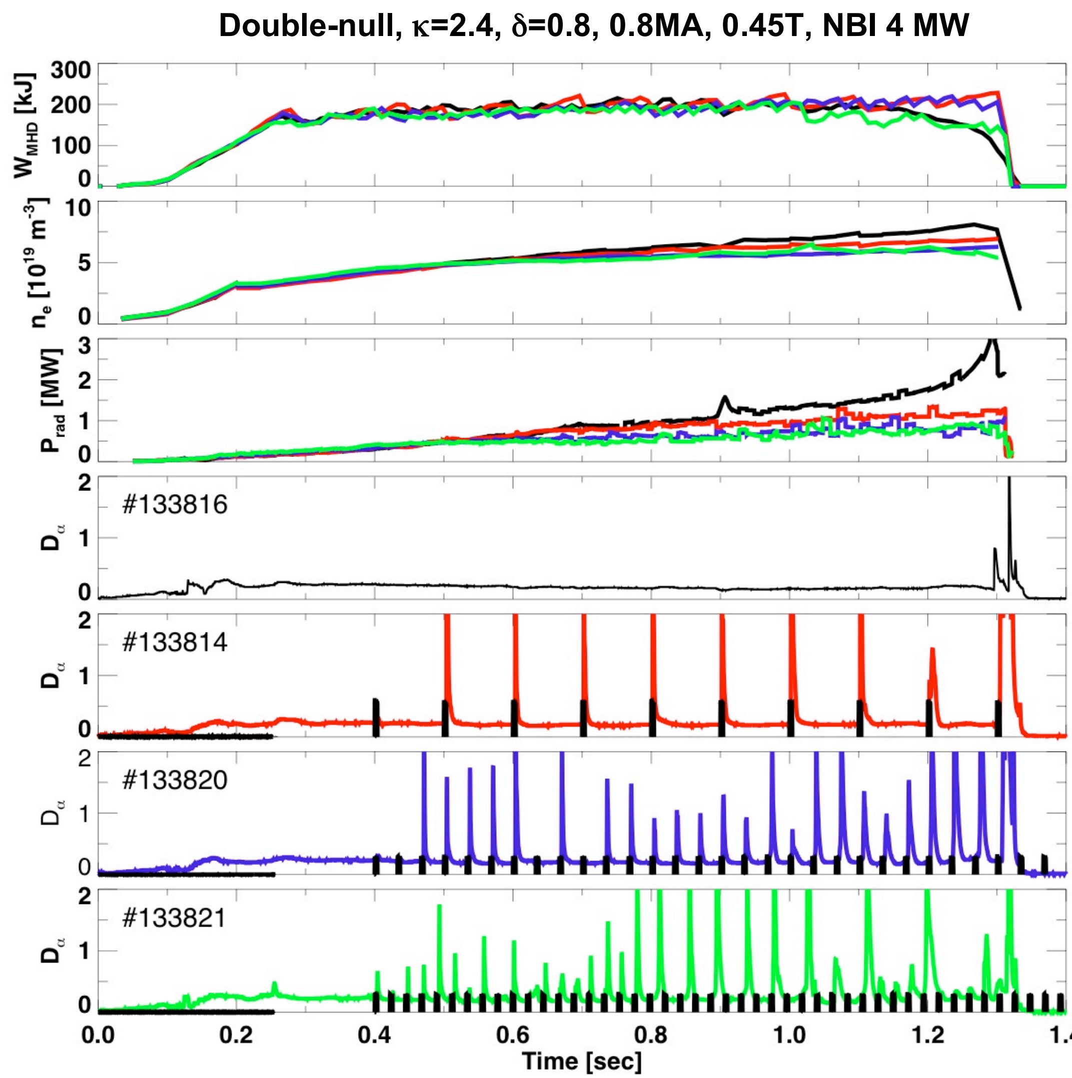
*[1] M. Bell et al, Plasma Phys Control Fusion **51**, 124054 (2009), [2] R. Maingi, et al, Phys. Rev. Lett. **103**, 075001 (2009),*

Radiated Power Rise Can Be Arrested With Triggered ELMs

- Use 3-D field (n=3) pulses to reintroduce ELMs and reduce radiated power.
  - Short duration (~3 msec)
  - Large amplitude (~2.5kA)
  - Eddy current effects are important on this timescale.



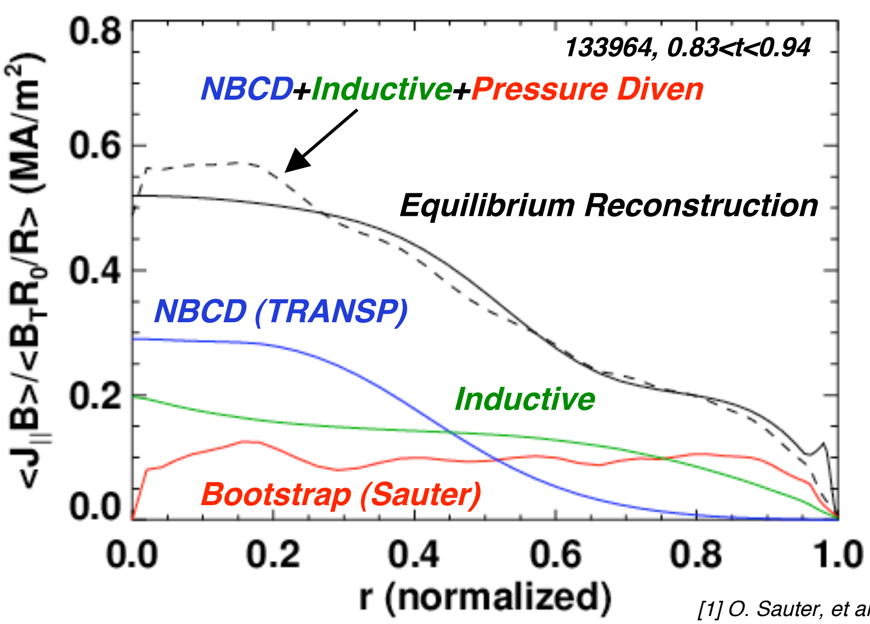
- Reliable ELM triggering from 10-70 Hz.
- Arrested the rise in radiated power and Z_{eff}.



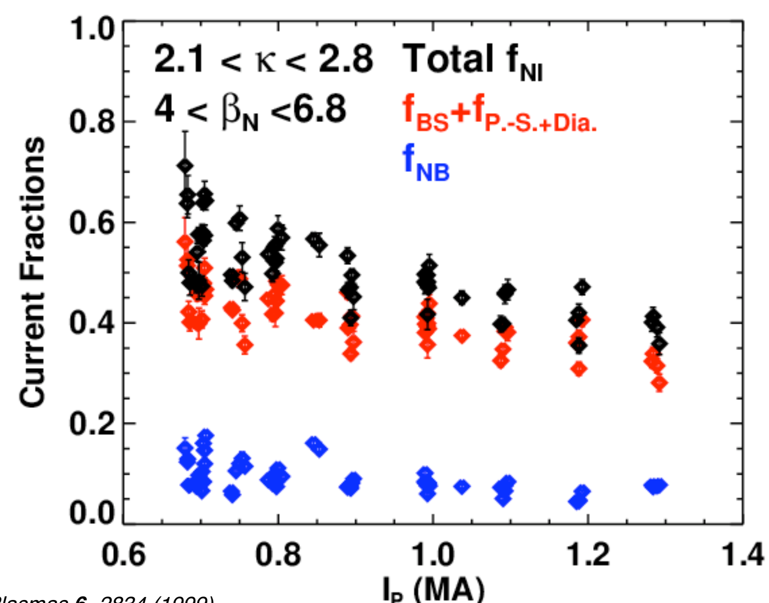
[1] M. Bell et al, Plasma Phys Control Fusion **51**, 124054 (2009), [2] R. Maingi, et al, Phys. Rev. Lett. **103**, 075001 (2009), [3] J.M. Canik Phys. Rev. Lett **104**, 045001 (2010)

Current Profile Analysis Shows That Present Configurations Are Limited to f_{NI}<70%

- ***Separate calculations of each current profile constituent in NSTX***
  - **Inductive Currents:** Electric field from time derivates of equilibria, and neoclassical resistivity[1]
  - **Bootstrap Currents:** Calculate using either the NCLASS model in TRANSP, or the Sauter model.[1]
  - **Neutral Beam Currents:** Calculate using the NUBEAM module in TRANSP.
- ***Process repeated for ~80 high-β discharges over a range of parameters.***



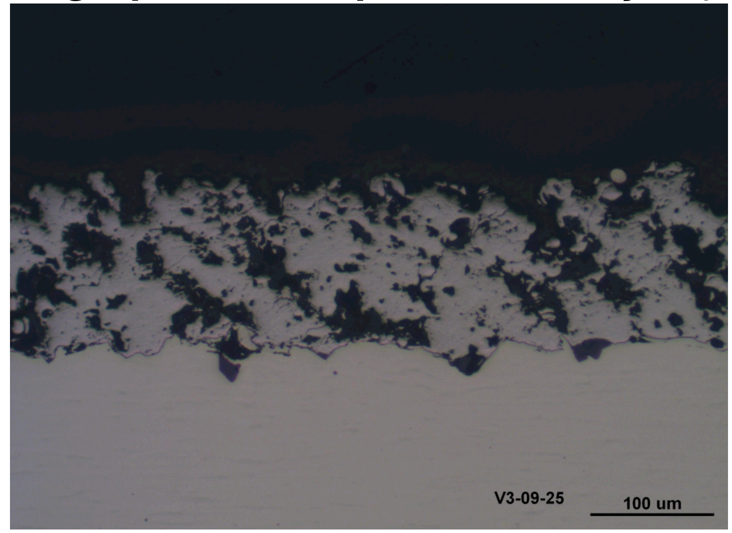
[1] O. Sauter, et al., Phys. Plasmas **6**, 2834 (1999)



Liquid Lithium Divertor Plates Have Been Installed in NSTX For Improved Pumping of Hydrogenic Species

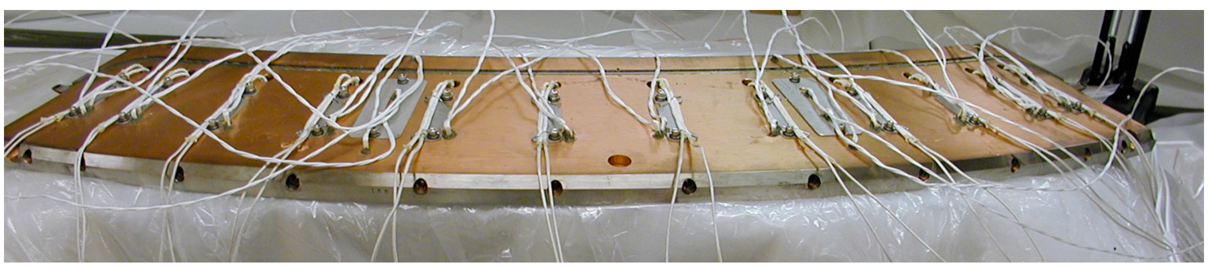
[1] H. Kugel et al., Fusion Engineering and Design **84**, 1125 (2009)

Micrograph of semi porous Mo layer (100 μm)

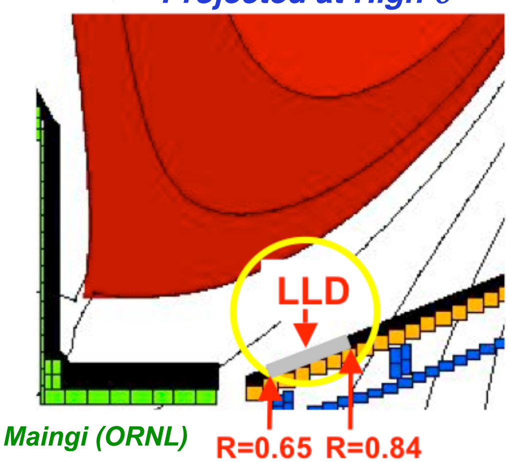


H. Kugel, R. Nygren (SNL), S. O'Dell (PPI), E. Starkman

Back side of plate with heaters and thermocouples installed



25-30% Density Reduction Projected at High-δ

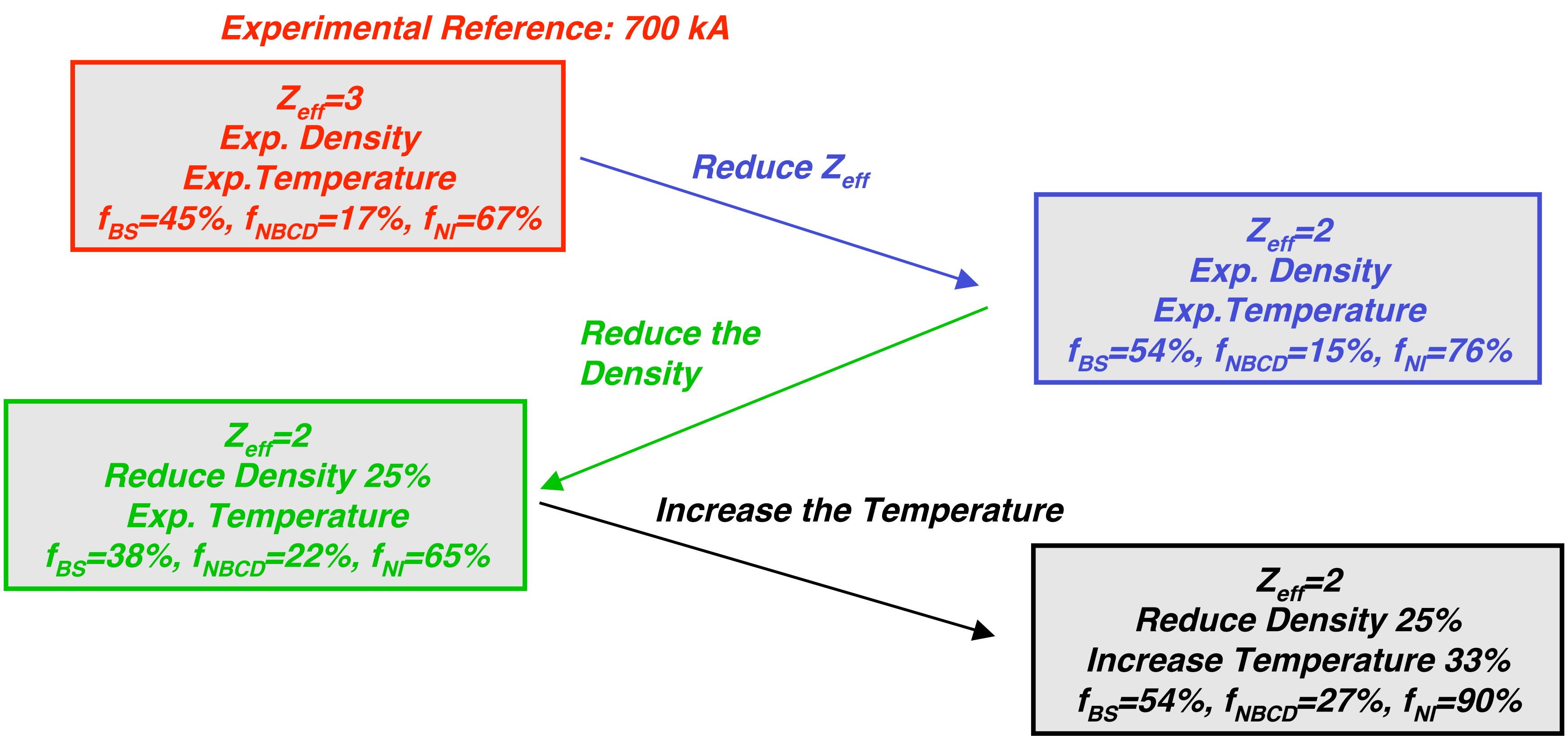


R. Maingi (ORNL)

LLD to be filled with lithium from the dual LITER evaporator system

Will LLD Pumping Increase the Non-Inductive Fraction? Depends on Impurity Accumulation and Confinement

- Fix plasma boundary and profile shapes from high-elongation, high-β_P discharge 133964 (65% Non-Inductive Current Drive).
- Scale profiles to test various scenarios.
  - For instance, scale down the density profile to simulate the effect of pumping.
- Use the TRANSP code to predict fully evolved current profile.



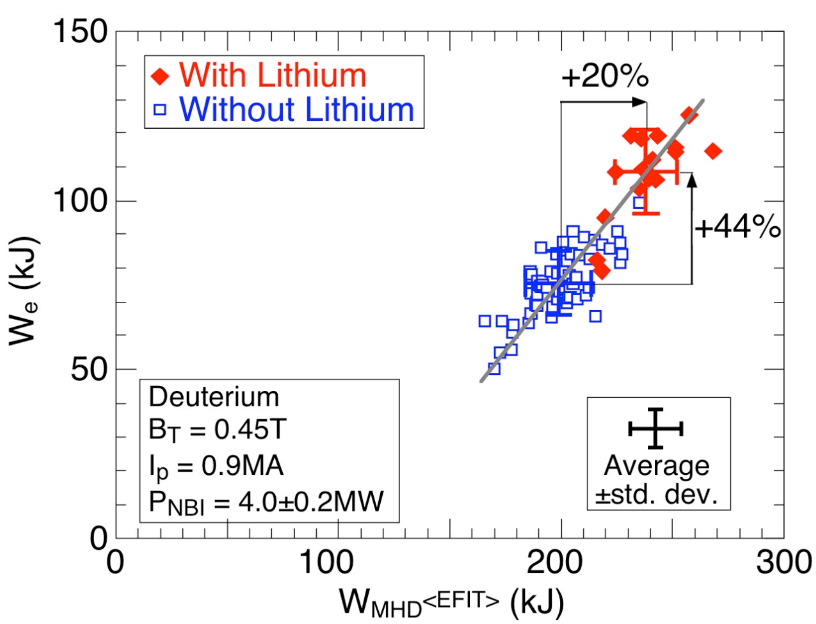
Summary

- NSTX discharges have achieved long-pulse stationary levels of bootstrap current and β_N appropriate for next-step devices
  - Up to 70% of the current has been driven non-inductively in long-pulse quiescent discharges.
  - Off-axis beam current drive assumed in FNSF/PSIF designs, and included in the NSTX-Upgrade proposal.
- A large number of analysis and operational tools facilitate this:
  - Plasma shaping
  - n=1 mode control
  - Lithium conditioning
  - Current profile analysis
  - Many others…

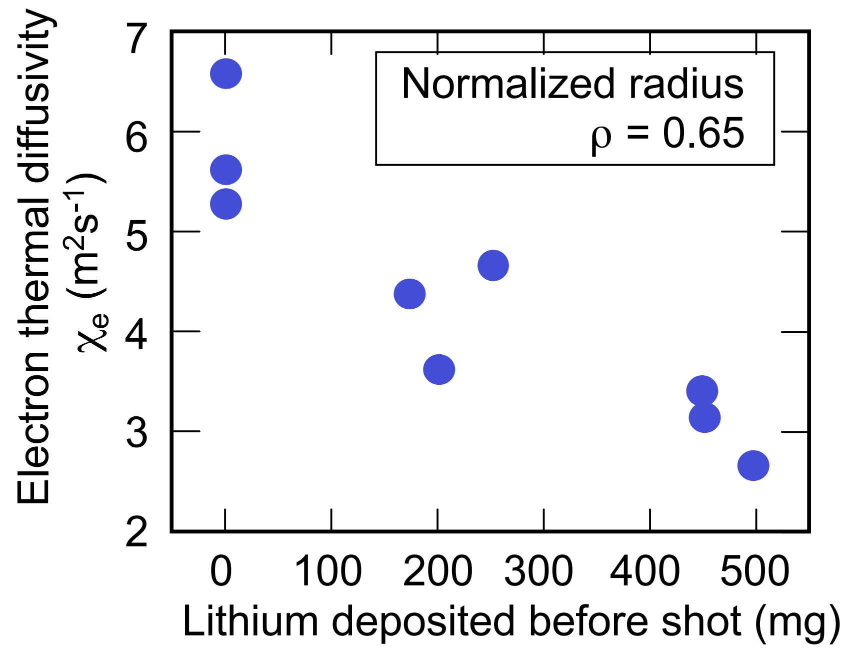
Backup

Confinement Improves, and Temperature Profiles Broaden, With Li Conditioning of the PFCs

Both Total and Electron Stored Energy Increase with Lithium Conditioning[1]



Increased Lithium Deposition Reduces Transport[2]



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  - **Inductive Currents:** Electric field from time derivates of equilibria, and neoclassical resistivity[1]

$$\langle J_{OH}\cdot B\rangle = \sigma_{Neo}\langle E\cdot B\rangle$$

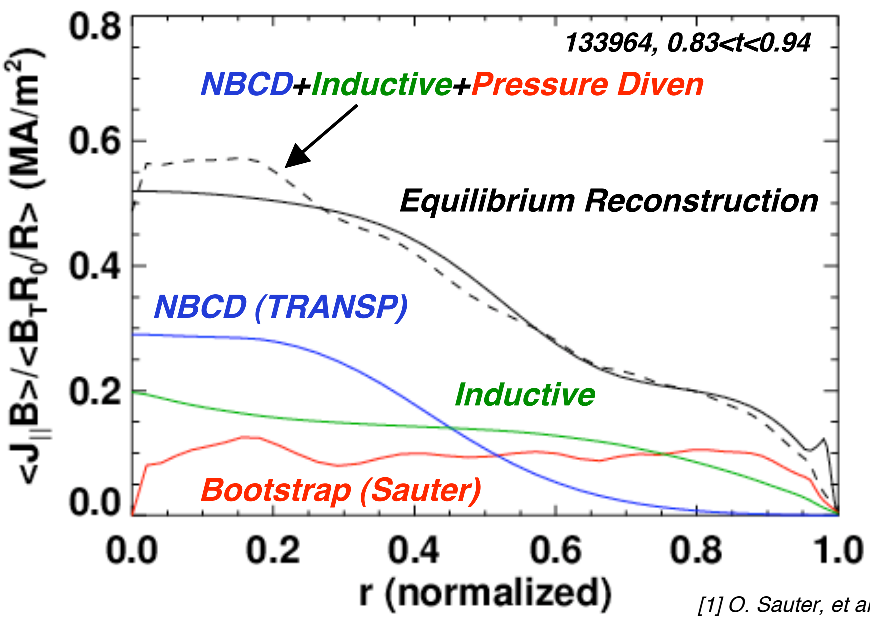
  - **Bootstrap Currents:** Calculate using either the NCLASS model in TRANSP, or the Sauter model.[1]

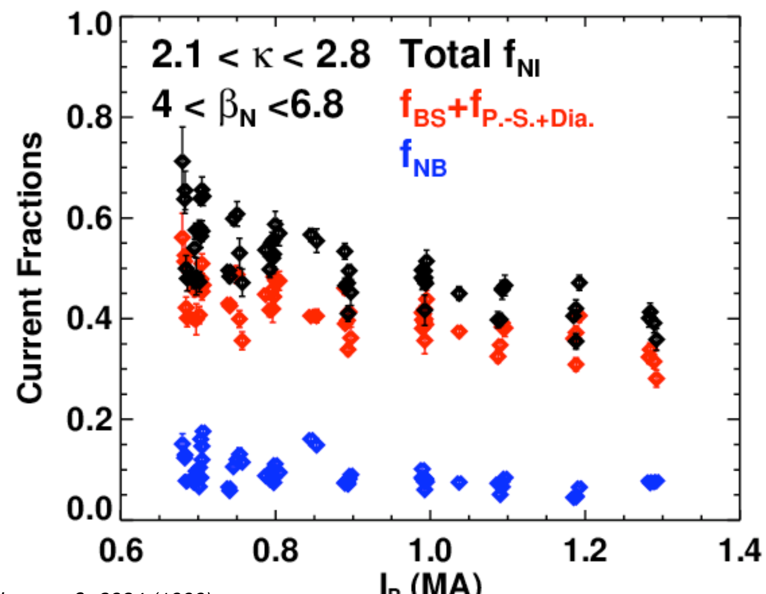
$$\langle J_{BS}\cdot B\rangle = (RB_\phi)p_e\left[L_{31}\frac{1}{p_e}\left(\frac{\partial p_e}{\partial\psi}+\frac{\partial p_i}{\partial\psi}\right)+L_{32}\frac{1}{T_e}\frac{\partial T_e}{\partial\psi}+L_{34}\alpha\frac{1-R_{pe}}{R_{pe}}\frac{1}{T_i}\frac{\partial T_i}{\partial\psi}\right]$$

  - **Neutral Beam Currents:** Calculate using the NUBEAM module in TRANSP.

$$J_{NB}=J_F\left[1-\frac{Z_F}{Z_{eff}}(1-G)\right],\quad J_F \textit{ is the current density of circulating ions}$$

- ***Process repeated for ~80 high-β discharges over a range of parameters.***





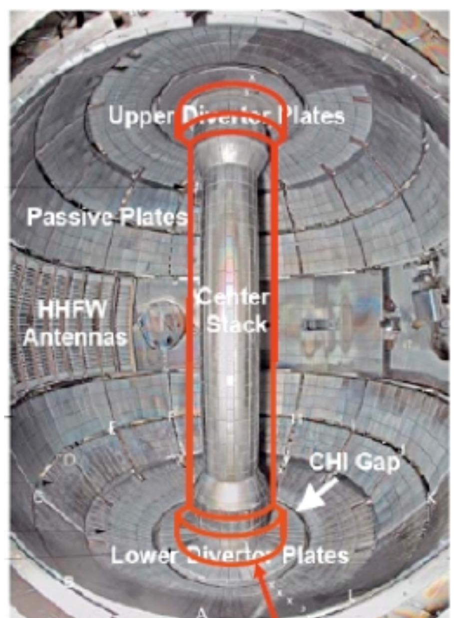
[1] O. Sauter, et al., Phys. Plasmas **6**, 2834 (1999)

NSTX Upgrade Would Be A Major Step Along ST Development Path

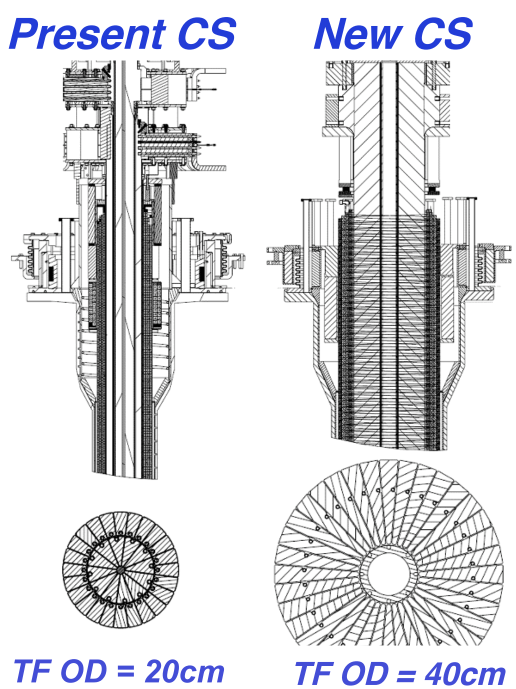
(next factor of 2 increase in current, field, and power density)

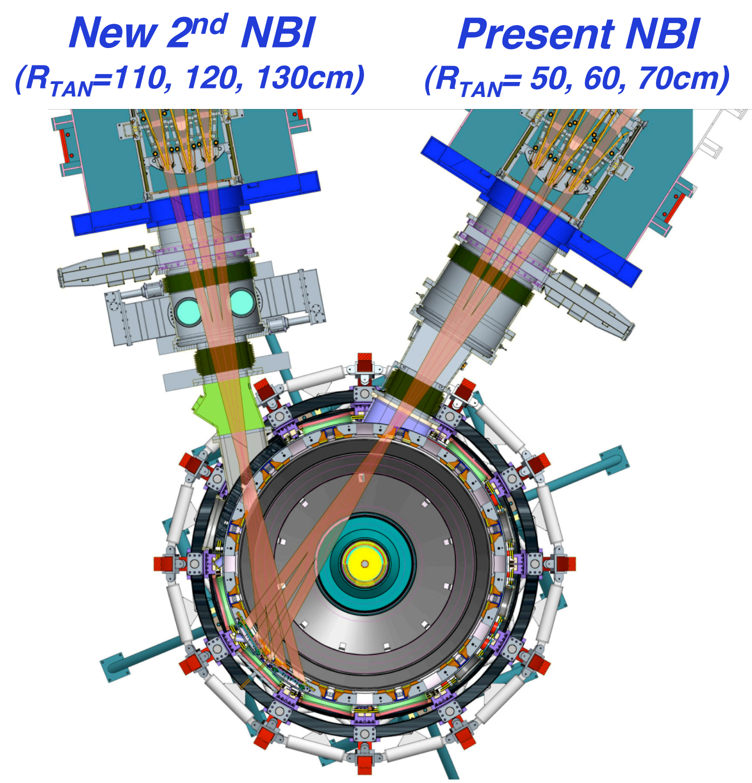
	NSTX	NSTX Upgrade	Plasma-Material Interface Facility	Fusion Nuclear Science Facility
Aspect Ratio = R_0 / a	≥ 1.3	≥ 1.5	≥ 1.7	≥ 1.5
Plasma Current (MA)	1	2	3.5	10
Toroidal Field (T)	0.5	1	2	2.5
P/R, P/S (MW/m,m^2)	10, 0.2*	20, 0.4*	40, 0.7	40-60, 0.8-1.2

** Includes 4MW of high-harmonic fast-wave (HHFW) heating power*



Outline of new center-stack (CS)

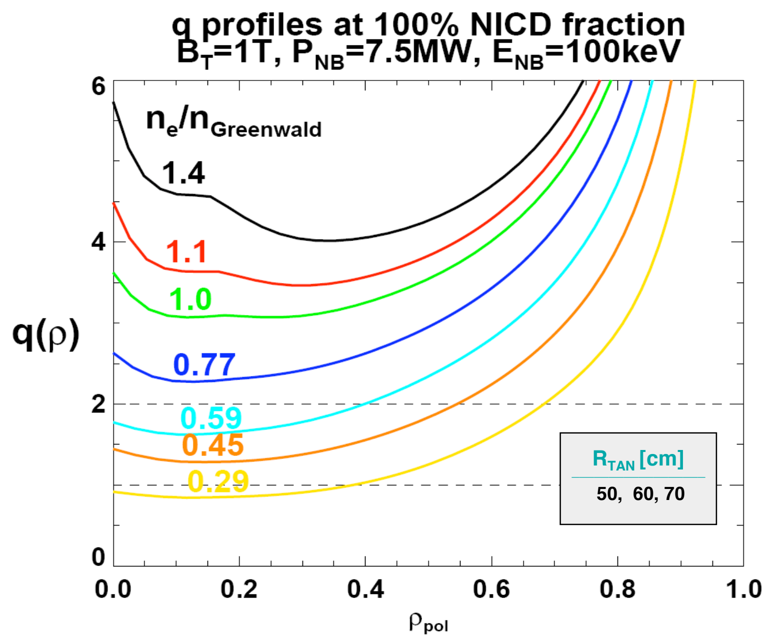




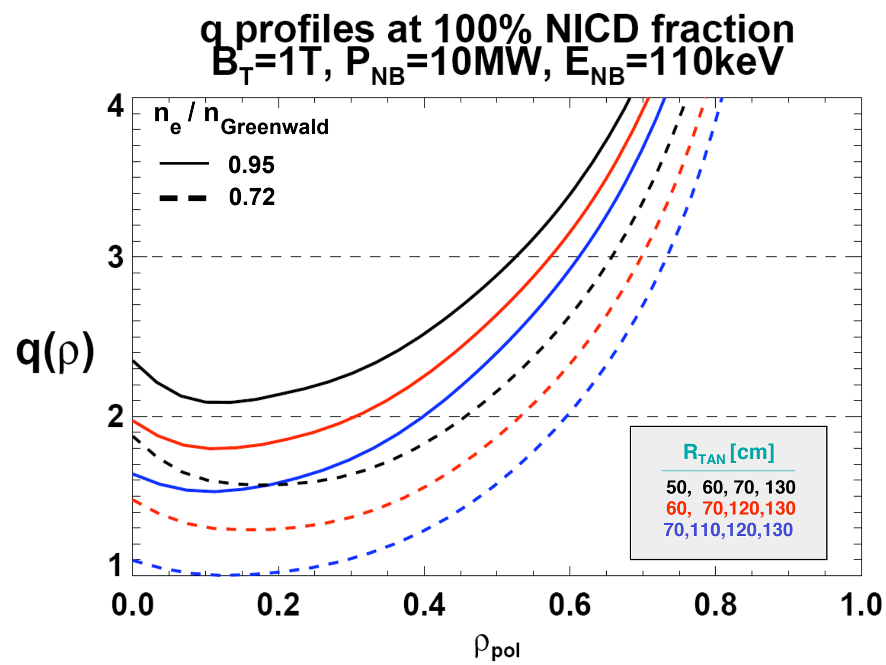
Higher Field B_T=1T from new CS + 2nd NBI Would Enable Access to Wide Range of 100% Non-Inductive Scenarios

- **New CS + present NBI-CD + fast wave:**
  - Study confinement scaling vs. I_P and B_T
    - Limited range of auxiliary power levels
  - 100% non-inductive for 1-1.5s (~1 τ_{CR})
    - NBI duration limited to 2s at 7.5MW
    - Vary q_{min} with density (CD efficiency $\propto T_e/n_e$)

- **Addition of 2nd NBI would enable:**
  - Study confinement scaling vs. I_P and B_T with:
    - Full range of auxiliary power available
    - Assured access to high-β at reduced ν*
  - 100% non-inductive for 3-4 τ_{CR} → relaxed J(r)
    - 10MW NBI available for 5s
    - Control q_{min} & q-shear w/ NBI source, n_e, & B_T
    - Study long-pulse NTM stability with q > 2
  - Study compatibility of high-β w/ PMI solutions



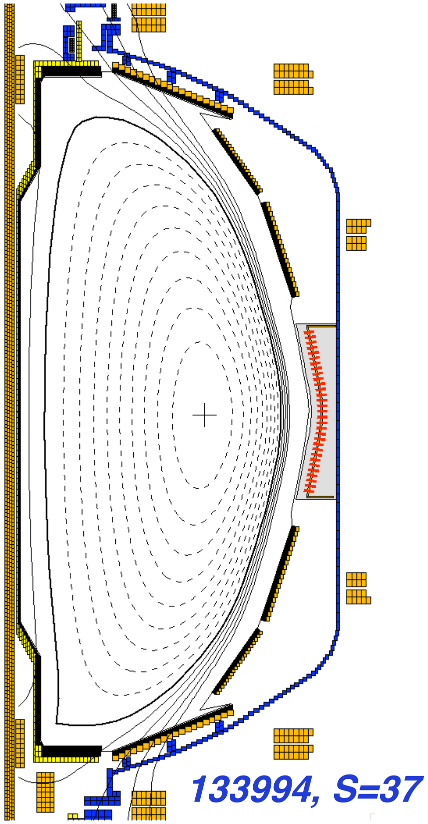
I_P = 0.8-1.2MA, H_{98y2} = 1.2-1.4, β_N = 4.5-5, β_T = 10-12%, 4MW RF



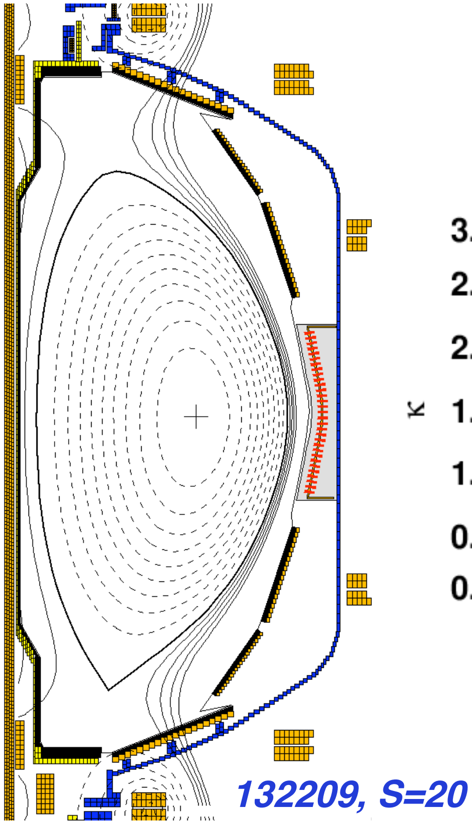
I_P = 0.95MA, H_{98y2} = 1.2, β_N = 5, β_T = 10%, 4MW RF

Shaping is Described by the "Shape Parameter" S

- Freedom in axisymmetric plasma boundary shaping[1]
  - Elongation: Increasing elongation increases q, improving the *kink stability* & increasing *bootstrap currents*.
  - Triangularity: Increasing the triangularity causes fields lines to spend more time in the *high-field good-curvature* region.
- "Shape Parameter" S encapsulates both effects.

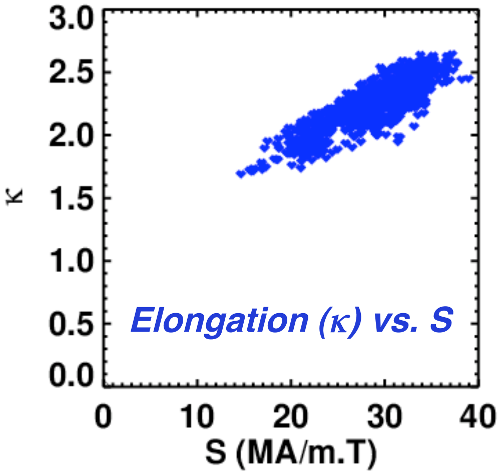


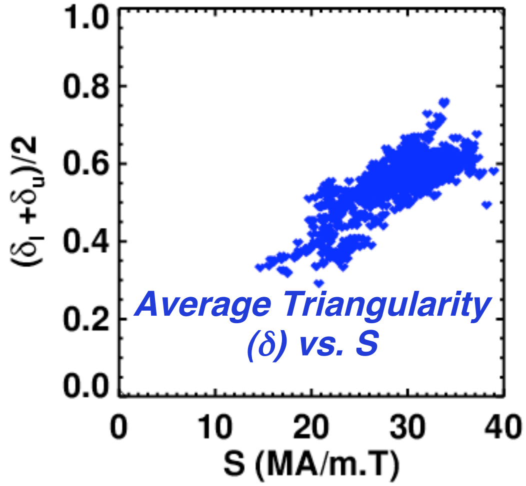
133994, S=37



132209, S=20

$$S = \frac{q_{95} I_P}{a B_T} \propto \varepsilon\left(1+\kappa^2\right) f(\kappa,\delta,\varepsilon)$$





[1] E. Lazarus, et al, Phys. Plasmas B **3**, 2220 (1991)

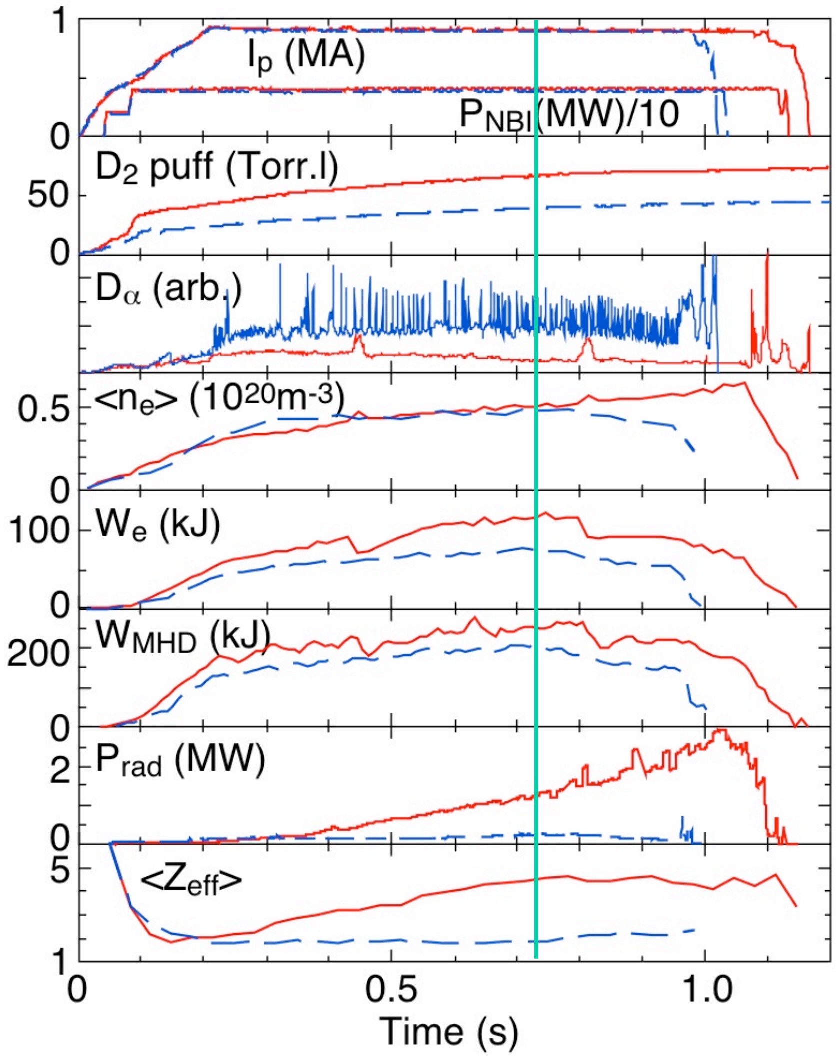
[2] E.J. Strait, Phys. Plasmsa **1** 1415 (1994)

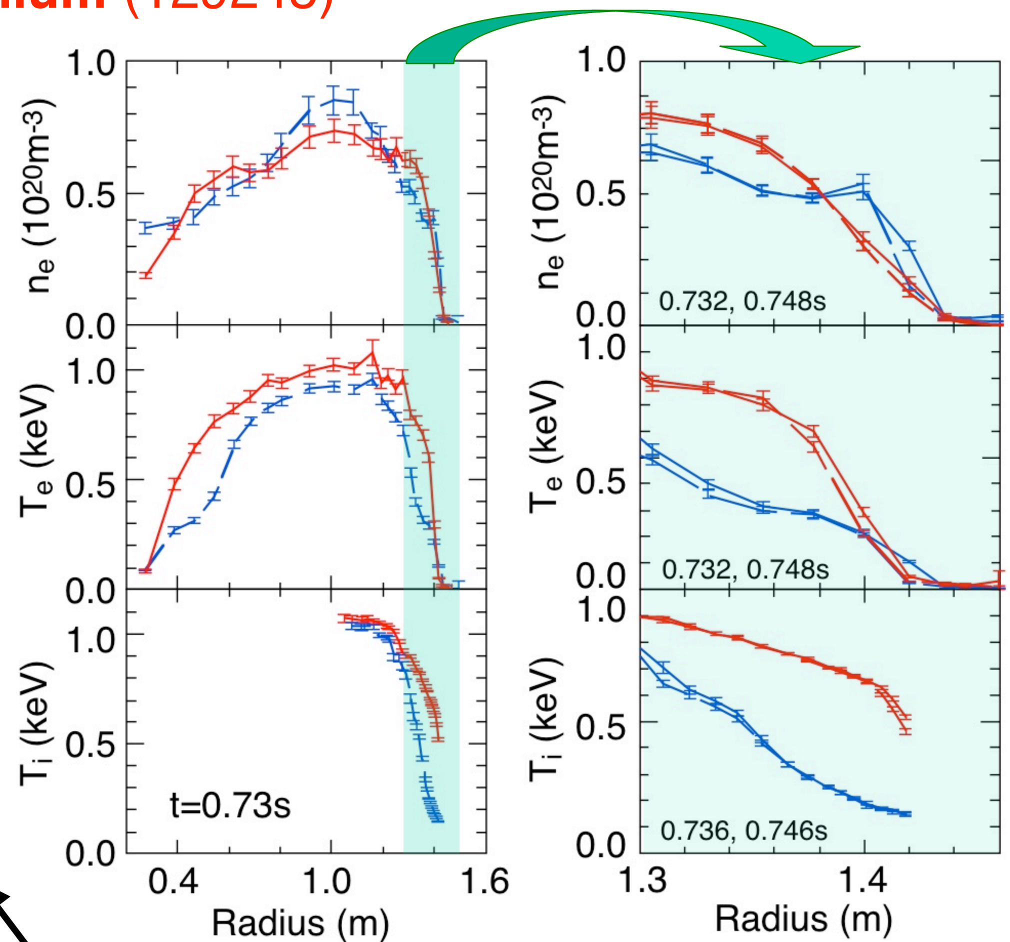
[3] D. Gates, et al, Phys. Plasmas **10**, 1659 (2003)

[4] D. Gates, et al, Phys. Plasmas **10**, 1659 (2003)

Lithium Coating Reduces Deuterium Recycling, Suppresses ELMs, Improves Confinement

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



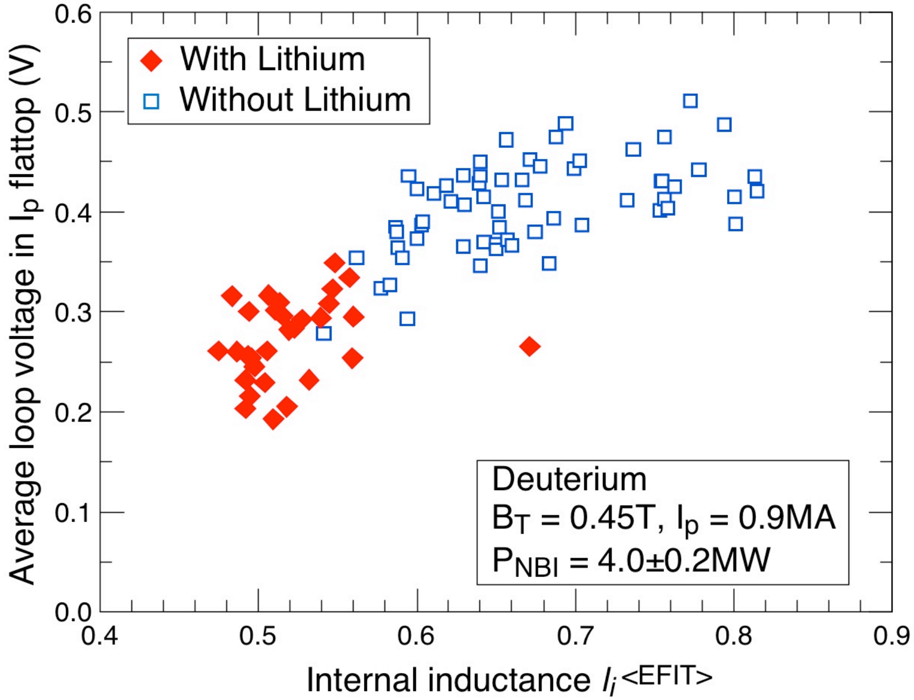


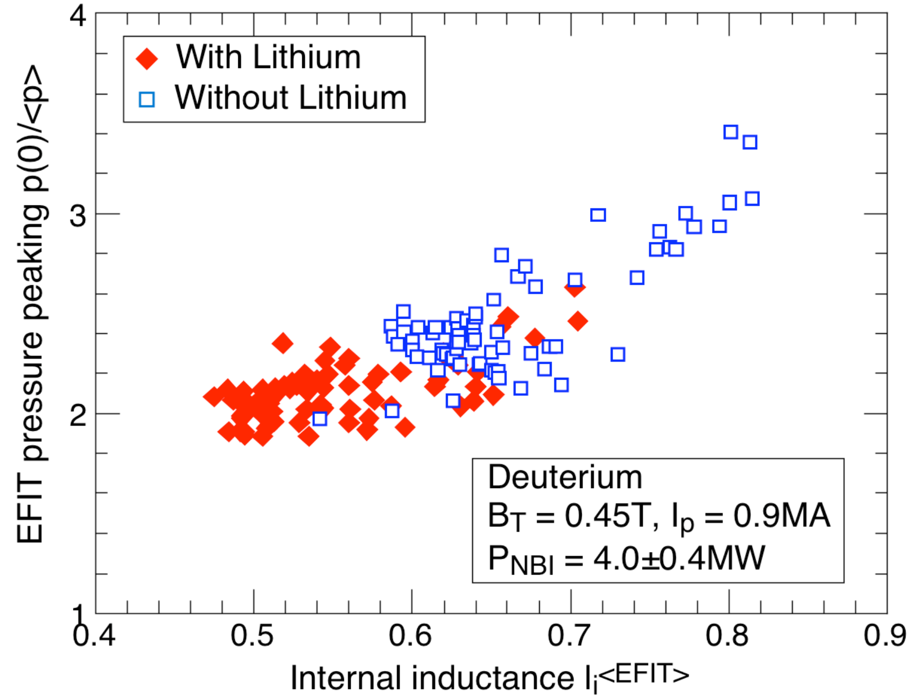
Without ELMs, impurity accumulation increases radiated power and Z_{eff}

[1] M. Bell et al, Plasma Phys Control Fusion ***51****, 124054 (2009) [2] R. Maingi, et al, Phys. Rev. Lett.* ***103****, 075001 (2009)*

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

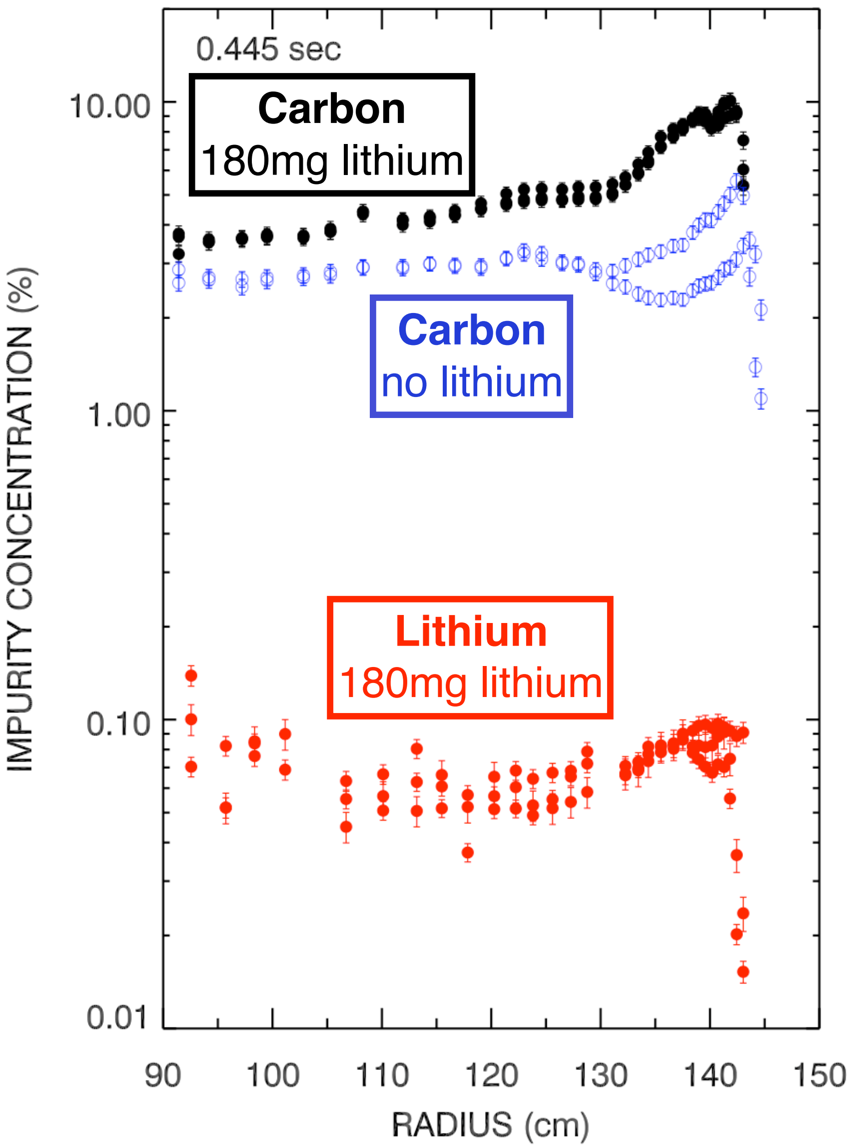
- Critical issue for development of low-aspect ratio tokamaks
  - Little space for conventional central solenoid providing inductive current drive



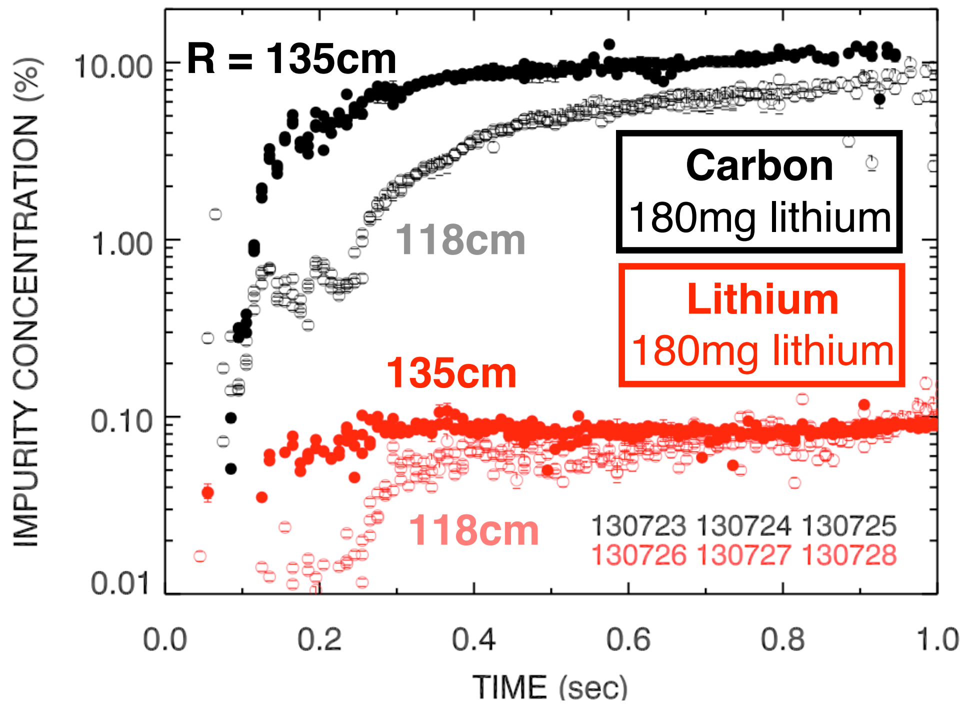


- Reduction occurs despite increase in $\langle Z_{eff} \rangle$ in ELM-free H-modes after lithium coating

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

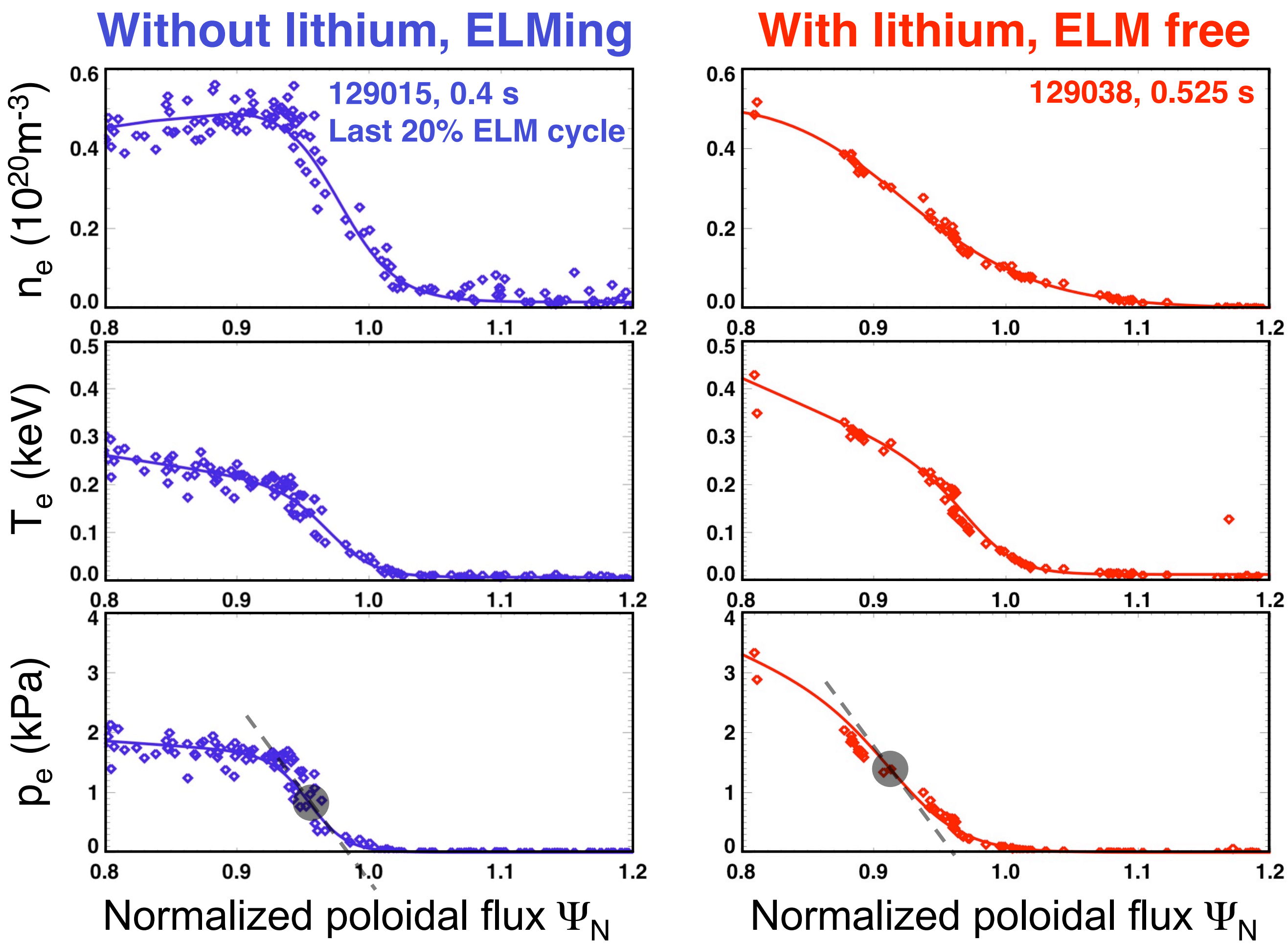


- Quantitative measurements of C^{6+}, Li^{3+} with charge-exchange recombination spectroscopy
- **n_C/n_{Li} = 30 – 100**
- Hollow profiles early for both C and Li fill in as time progresses



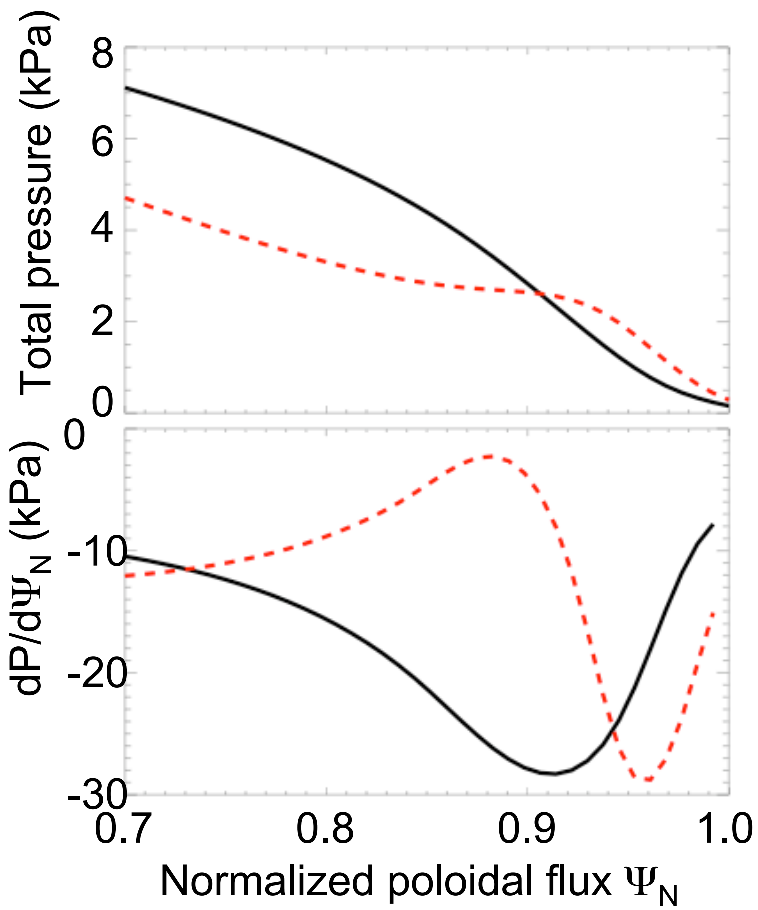
Lithium Affects ELMs Through Changes in Temperature and Pressure Profile at Edge

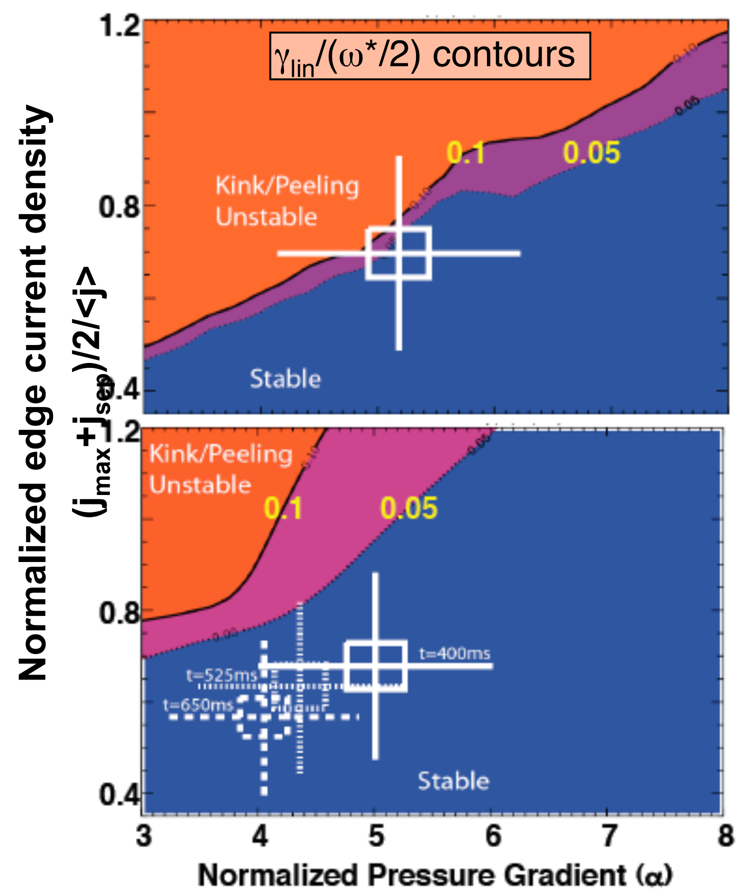
- Multiple timeslices mapped into composite profiles using EFIT equilibrium



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



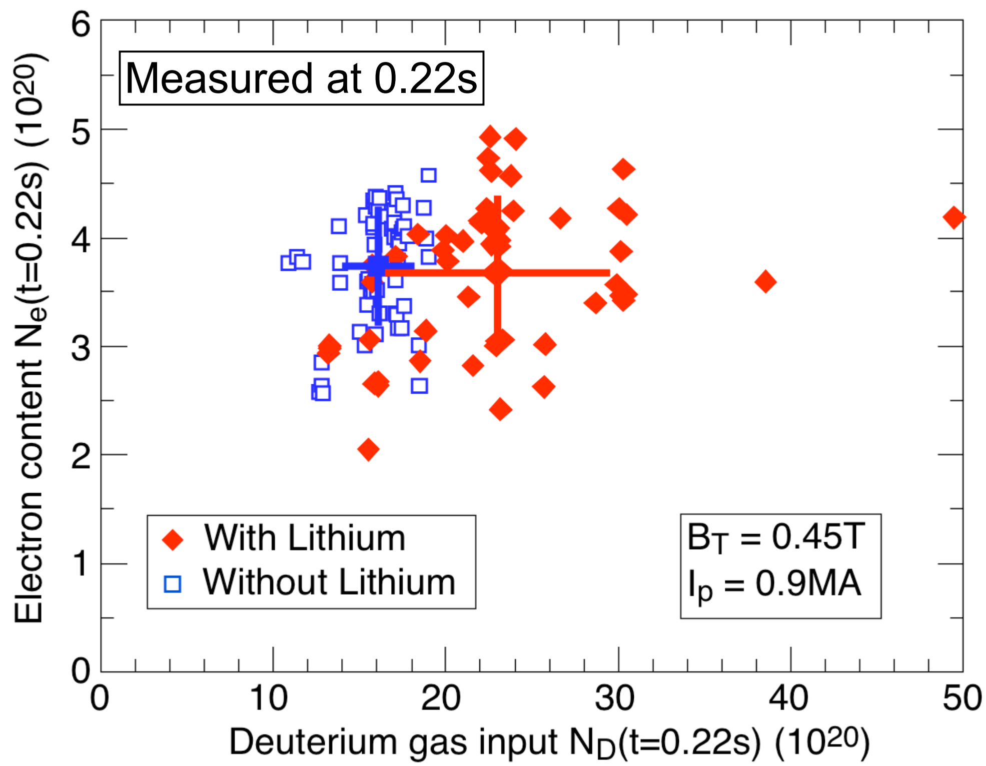


Without lithium (end of ELM cycle)

With lithium

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

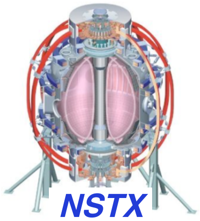
- Lower density achievable early in discharges both with and without lithium but likelihood of deleterious locked modes increases
  - Extensive HeGDC, He ohmic- or HHFW-heated plasmas also effective

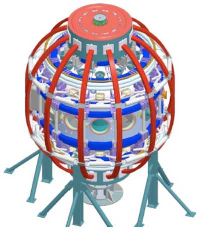


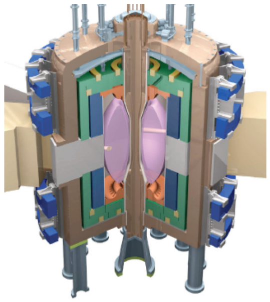
- Tangentially viewing camera for edge D_α emission shows greatly reduced neutral D density across outboard midplane with lithium

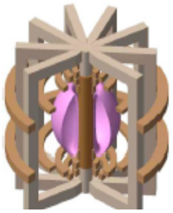
NSTX Upgrade will contribute strongly to toroidal plasma science and preparation for a fusion nuclear science (FNS) program

- NSTX:
  - Providing foundation for understanding ST physics, performance
- NSTX Upgrade:
  - Study high beta plasmas at reduced collisionality
    - Vital for understanding confinement, stability, start-up, sustainment
  - Assess full non-inductive current drive operation
    - Needed for steady-state operating scenarios in ITER and FNS facility
  - Prototype solutions for mitigating high heat, particle exhaust
    - Can access world-leading combination of P/R and P/S
    - Needed for testing integration of high-performance fusion core and edge
- NSTX Upgrade contributes strongly to possible next-step STs:
  - ST Fusion Nuclear Science Facility
    - Develop fusion nuclear science, test nuclear components for Demo
    - Sustain $W_{neutron}$ ~ 0.2-0.4 → 1-2MW/m^2, τ_{pulse} = 10^3 → 10^6s
  - ST Plasma Material Interface Facility
    - Develop long-pulse PMI solutions for FNSF / Demo (low-A and high-A)
    - Further advance start-up, confinement, sustainment for ST
    - High P_{heat}/S ~1MW/m^2, high T_{wall}, τ_{pulse} ~ 10^3s

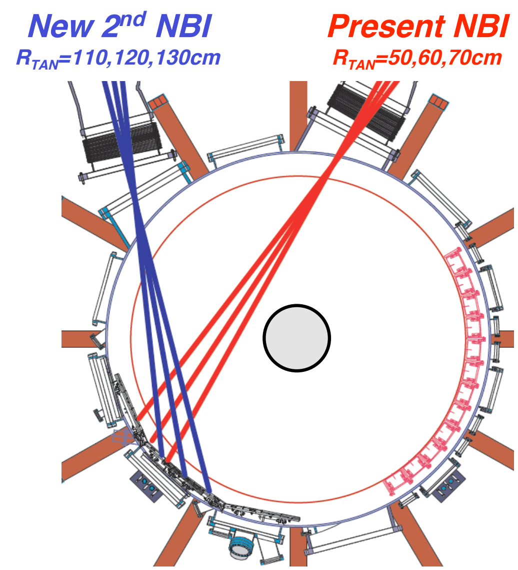

NSTX


NSTX-U


FNSF (ST-CTF)

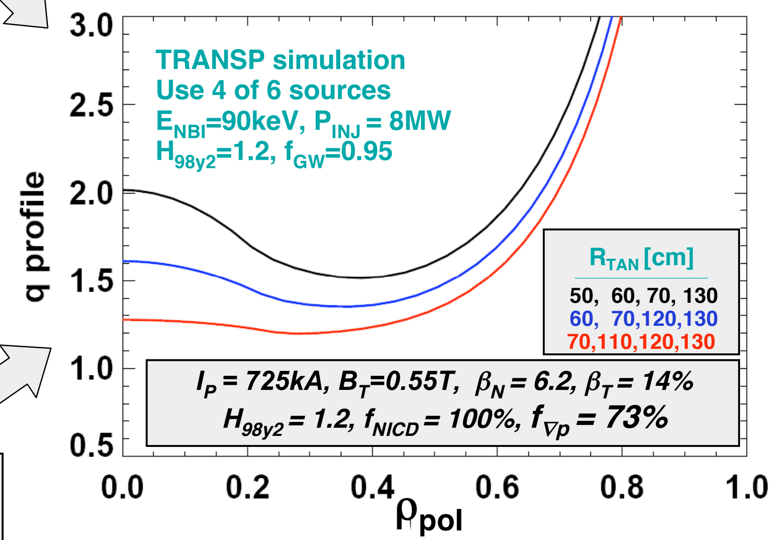

PMIF (NHTX)

Upgrade 2nd NBI injecting at larger $R_{tangency}$ will greatly expand performance and understanding of ST plasmas



- Improved NBI-CD and plasma performance
  - Higher CD efficiency from large R_{TAN}
  - Higher NBI current drive from higher P_{NBI}
  - Higher β_P, f_{BS} at present $H_{98y2} \leq 1.2$ from higher P_{HEAT}
  - Large R_{TAN} → off-axis CD for maintaining $q_{min} > 1$
  - Achieve 100% non-inductive fraction (presently < 70%)
  - Optimized $q(\rho)$ for integrated high τ_E, β, and f_{NI}

- Expanded research flexibility by varying:
  - *q*-shear for transport, MHD, fast-ion physics
  - Heating, torque, and rotation profiles
  - β, including higher β at higher I_P and B_T
  - Fast-ion $f(v_{||},v_{\perp})$ and *AE instabilities
    - 2nd NBI more tangential – like next-step STs
  - Peak divertor heat flux, SOL width



- q(r) profile variation and control very important for global stability, electron transport, Alfvénic instability behavior

Will LLD Pumping Increase the Non-Inductive Fraction? Depends on Impurity Accumulation and Confinement

- Fix plasma boundary and profile shapes from high-β_P discharge 133964.
- Modify the TRANSP input data to predict fully evolved current profiles.

Experimental Reference

Z_{eff}=3
Exp. Density
Exp.Temperature
f_{BS}=45%, f_{NBCD}=17%

Reduce Z_{eff}

Z_{eff}=2
Exp. Density
Exp.Temperature
f_{BS}=54%, f_{NBCD}=15%

Reduce the Density

Z_{eff}=2
Reduce Density 25%
Exp. Temperature
f_{BS}=38%, f_{NBCD}=22%

Increase the Temperature

Z_{eff}=2
Reduce Density 25%
Increase Temperature 33%
f_{BS}=54%, f_{NBCD}=27%