Fusion-Fission Research Facility (FFRF) as a practical step toward FFH[1]

Leonid E. Zakharov[1], *Jiangang Li*[2], *Yican Wu*[2]

[1] *Princeton Plasma Physics Laboratory, MS-27 P.O. Box 451, Princeton NJ 08543-0451*

[2] *Institute of Plasma Physics Chinese Academy of Sciences, P.O.Box 1126, Hefei, Anhui 230031, China*

Presented by Leonid E. Zakharov

DOE Workshop on Fusion-Fission Research

October 1, 2009, Hilton Hotel, Gaithersburg, MD

[1] This work is supported by US DoE contract No. DE–AC020–76–CHO–3073.

Contents

What is FFRF

FFRF is a fusion facility with capabilities for FFH research,

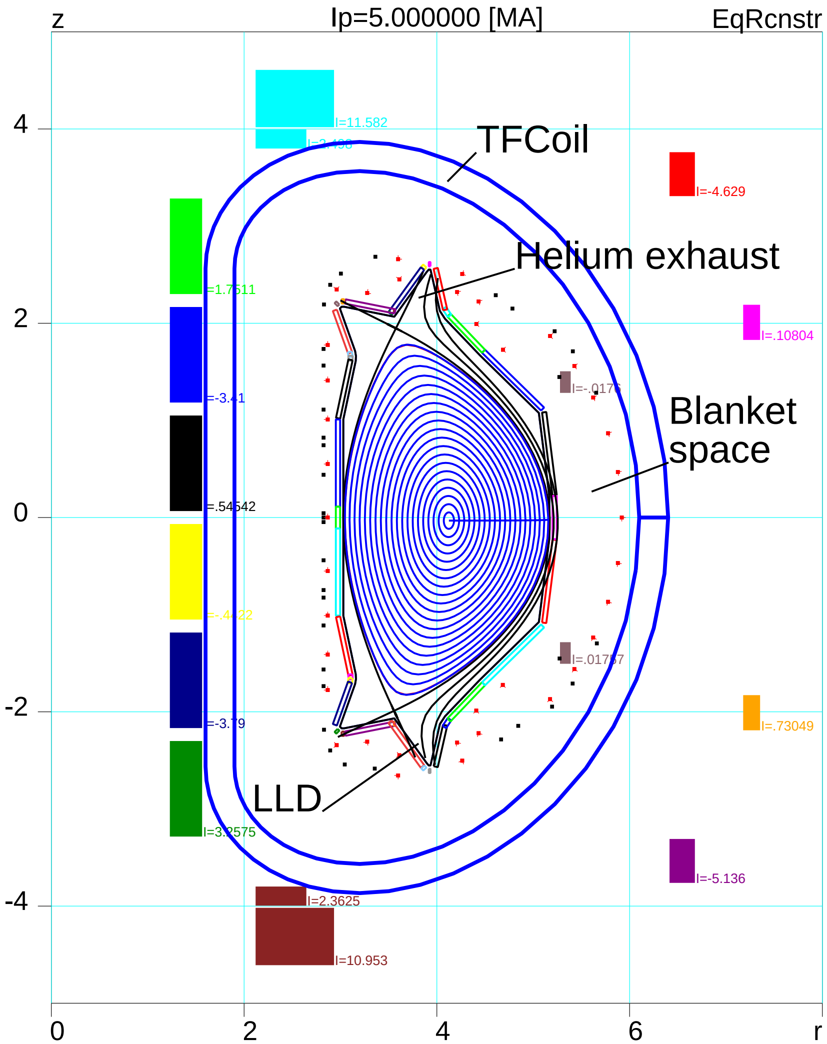
Presently, FFRF is a project of ASIPP (Institute of Plasma physics of Chinese Academy of Sciences, Hefei), which is a plasma physics institution for developing applications of fusion for nuclear energy.

There is a great interest from Chinese side in collaborative efforts with the US for designing, building and launching the facility in 12-15 years.

On the other hand, participation in this project (making it Joint one)

1. *is in strategic interests of the US,*
2. *is consistent with the US fusion program,*
3. *is an opportunity for initiating domestic FFH research and utilizing the US scientific and technological potential for operating a first multi-functional fusion-fission facility.*

1 Parameters of FFRF



Parameter	FFRF
$d_{blanket,m}$	1
a_m, R_m $V^{pl}_{m^3}, S^{pl}_{m^2}$ n_{20} E^{NBI}_{keV} $\frac{T_i+T_e}{2}\Big\vert_{keV}$ $B_{t,T}$ $I_{pl,MA}$	1.0, 4.0 150, 235 0.4 120 24 4 5.16
P^{DT}_{MW}	50
$W_{th,MJ}$ $\tau^{ind}_{E,sec}, \tau^{LHCD}_{E,sec}$ $P^{NBI}_{MW}, P^{LHCD}_{MW}$	42 21.4-8.5, 2 2-5, 20
$Q^{DT}_{ind}, Q^{DT}_{LHCD}$	25-10, 2

Active core power 80-4000 MW. Only thermal neutron regimes have been analyzed so far. He cooling is possible.

With cooperation of the US, China (and, possibly, RF), the machine can be launched before ITER will get its 15 MA of plasma current

2 Mission

The mission of FFRF is to advance fusion to the level of a stationary neutron source and to create a technical, scientific, and technology basis for utilization of high-energy fusion neutrons for needs of nuclear energy and technology.

FFRF is a research, rather than application device.

For its justification, FFRF does not need to compete with, e.g.,fast breeder reactors

FFRF has both fusion and FFH missions

Fusion Mission of FFRF

FFRF relies on the LiWall Fusion (LiWF) plasma regime. The fusion mission of FFRF is complementary to ITER. The milestones are

1. ***DD phase, as a preparation for DT operation:***

   (a) Achieving the ignition level of plasma performance

   $\langle p\rangle\,\tau_E \geq 1$ ***(ignition condition in the α-heated plasma)***

   with the inductive current drive.

   (b) Obtaining long lasting (hours), or stationary, externally controlled, stable plasma regime with non-inductive Lower Hybrid Current Drive (LHCD).

   (c) Achieving low density He pumping consistent with the stationary LiWF rgime.

2. ***DT phase:***

   (a) Demonstrating short lasting $(\simeq 1$min) ignitions in DT plasma

   (b) Obtaining long lasting (hours), or stationary regime of a fusion neutron source with

   $$P_{DT} \geq 50\text{MW},\ Q_{DT} \geq 2$$

Fusion-Fission mission

1. *Integrating toroidal plasma with a full size* **(1 m)** *blanket with a fission core(s)*
2. *Remote handling of blanket modules situated inside the toroidal magnetic field.*
3. *Controlled blanket operation with different content of fissile/(nuclear waste) materials at nuclear power in the range* **80-4000 MW** *and* $k_{eff} \leq$ **0.95**.
4. *Simultaneous operation of different kind of blankets in toroidal sectors of FFRF.*
5. *Tritium breeding with the use of both fusion and fission neutrons.*
6. *Determination of practical limits on the* **He cooled** *version of blanket.*
7. *Utilization of both fusion and fission neutrons for component testing (CTF) for purposes of non-Fission Fusion development.*

Utilization of a fast fission neutron spectrum regime would be a significant enhancement in the mission of FFRF

3 Non-Fission Fusion and its 5 “Bigs”

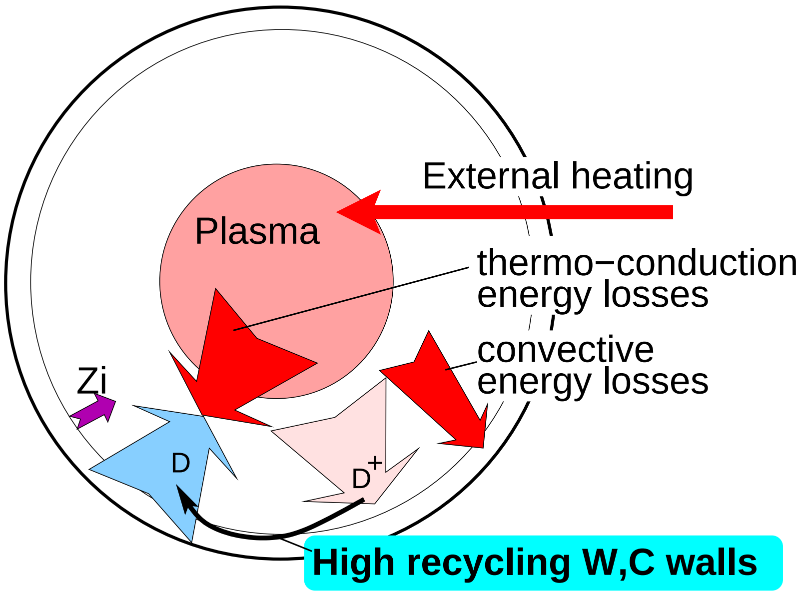
“Pure fusion” is referred below as “non-Fission Fusion” or nFF.

From fusion community the question would be

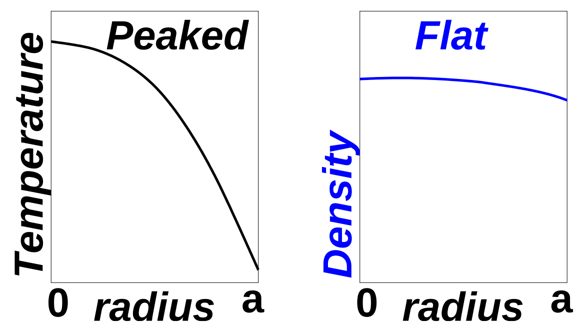
In linear size FFRF is 2/3 of ITER. Why would fusion development need FFRF ?

Fighting cooling with heating

Plasma particles recycled from the walls cool down the plasma edge



The edge temperature is low



As a "gift" from plasma physics MSF gets ITG/ETG turbulent transport.

Bad core and edge stability (saw-teeth, ballooning modes, ELMs)

Most of the plasma volume does not produce fusion

Low plasma temperature ⟶ temperature gradient in the core ⟶ thermo-conduction losses, unfortunately always turbulent.

More heating power ⟶ enhanced turbulence level and losses

And this is a Big problem, leading in turn to many related problems (i.e., the bad use, 1/4-1/3, of the plasma volume for fusion)

5 Bigs

The mainstream fusion relies on 5 Bigs:

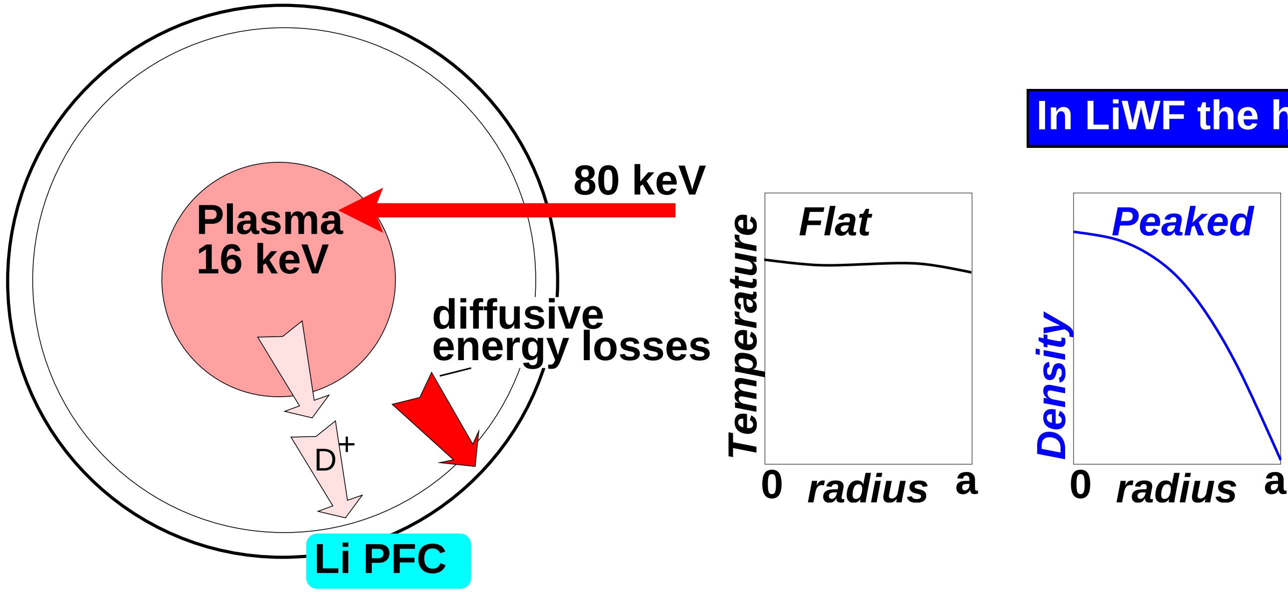
1. ***bigger size,***
2. ***stronger magnetic field,***
3. ***larger plasma current (and crazier plasma shapes),***
4. ***higher heating power, and***
5. ***never sufficient funding.***

In contrast to this approach, it is much more efficient to prevent plasma cooling rather than to compensate unlimited recycling by extensive heating power

4 LiWF plasma regime

With appropriate technology development, Li can be used as a "black hole" for absorbing plasma particles

Then, everything becomes much simpler in magnetic fusion



No "gifts" from plasma physics (ITG/ETG, sawteeth, ELMs) are expected or accepted.

Stability is excellent. LiWF relies only on external control.

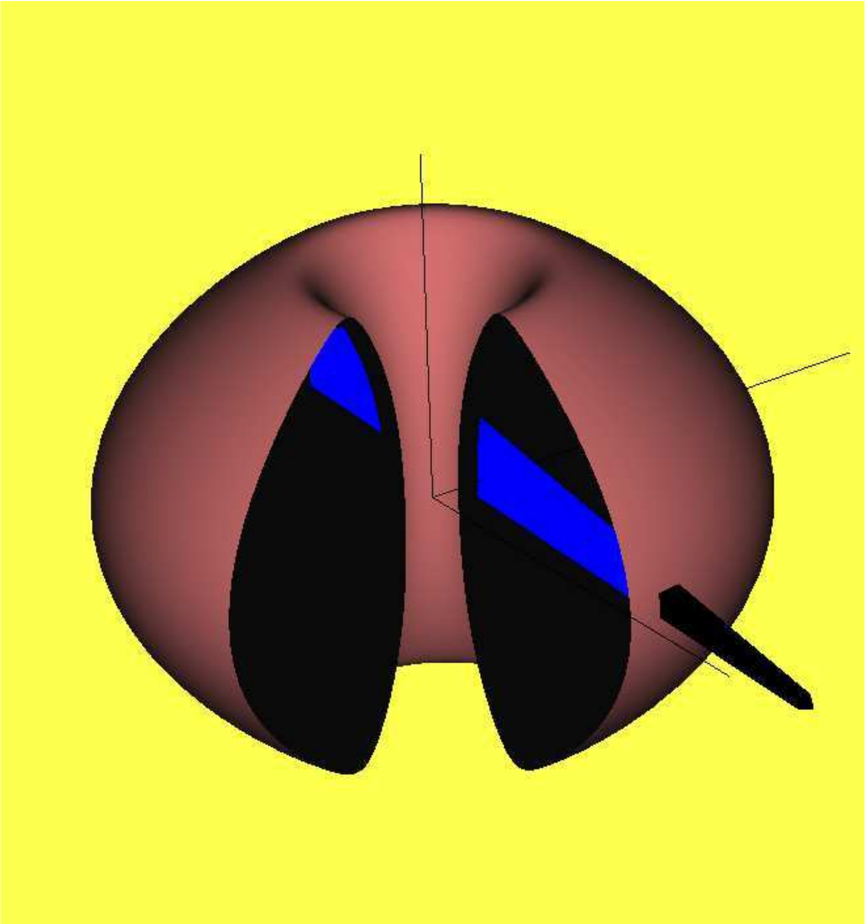
Now, plasma diffusion, rather than thermo-conduction, determines the energy losses.

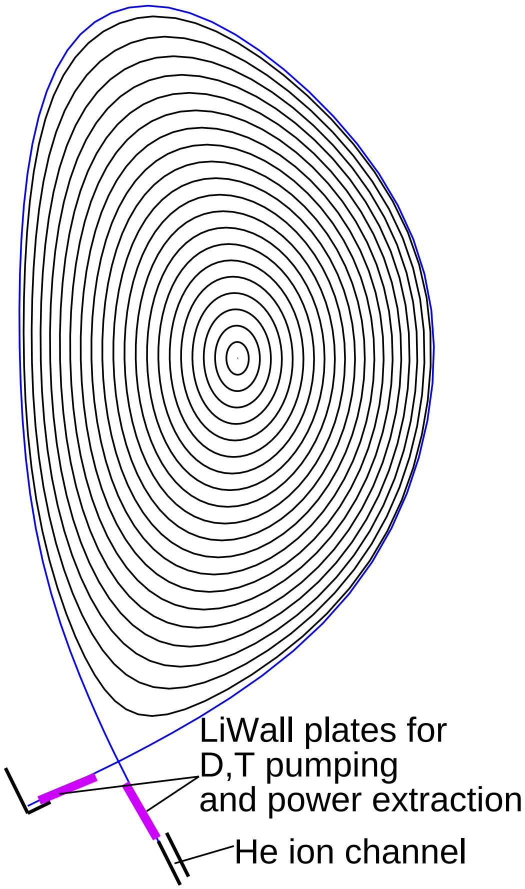
Independent of anomalous electrons, rate of losses is determined by ions, which are much better confined.

This new quality leads to many new good qualities, e.g., to the use of full plasma volume for fusion.

Implementation in tokamaks

What will happen if:* (a) Neutral Beam Injection (NBI) supplies particles into the plasma core, while (b) a layer of Lithium on the Plasma Facing Surface (PFC) absorbs all particles coming from the plasma *?
(Maxwellization is much faster than the particle diffusion.)





Plasma temperature will be uniform

Plasma physics is not involved into this answer.

The only processes, which are going on, are thermalization of the beam energy and plasma diffusion.

With pumping walls there are no cold particles in the system (other than Maxwellian) and the temperature is uniform automatically

$$\nabla T_i = 0, \quad \nabla T_e = 0 \qquad (4.1)$$

The resulting plasma is under full external control: its temperature is determined by the beam energy, the density is determined by the beam current and diffusion, fusion power density is determined by the beam deposition

The "know-how" of the LiWF regime

The simple formula

$$\frac{T_i^{edge} + T_e^{edge}}{2} \geq \frac{1 - R_{ei}}{1 + (\Gamma^{gasI}/\Gamma^{NBI})} \cdot \frac{\left\langle E^{NBI} + E^{aux} \right\rangle}{5}$$

$$\left(\text{where} \quad R_{ei} \equiv max\{R_e, R_i\}, \quad E^{aux} \equiv \frac{P^{aux}}{I^{NBI}}\right)$$

encodes the "know-how" of the LiWF regime.

***Trapped Electron Modes (TEM)** are frequently mentioned as a blame that LiWF replaces one turbulence by another.*

There is no TEM turbulence in the formula. LiWF regime is not sensitive to TEM.

Increase in NBI current can confront TEM without involvement of plasma physicists.

In order to obtain the LiWF regime the recycling and external gas sources should be eliminated

5 5+ Bests vs 5 Bigs

The LiWF relies on 5+ Bests:

1. ***the best possible (diffusion based) confinement regime***
2. ***the best possible core MHD stability (no saw-teeth)***
3. ***the best possible plasma edge stability (no ELMs)***
4. ***the best possible stationary plasma-wall interaction (no thermo-force)***
5. ***the comprehensive plasma control by NBI and edge conditions (not a hostage of plasma unknowns)***
   - ***(a) the best possible conditions for non-inductive current drive***
   - ***(b) the best possible power extraction approach (no reliance on α-heating)***
   - ***(c) the best possible use of plasma volume for fusion***
   - ***(d) the best possible helium ash exhaust regime***

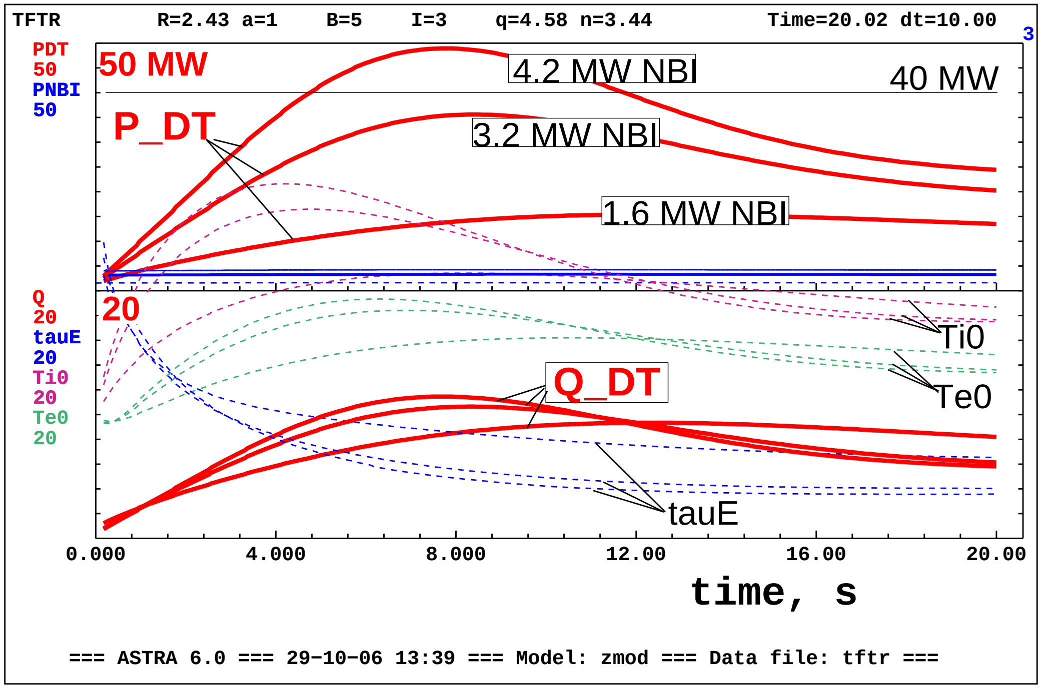
Implementation of LiWF can really be a "dream to be true" for controlled fusion.

The real question is "How good is the Best?"

FFRF will address this question.

TFTR - missed opportunity for fusion

ASTRA-ESC simulations of TFTR, B=5 T, I=3 MA, 80 keV NBI



Even with no α*-particle heating:*

$$P_{NBI} < 5 \ [\mathrm{MW}],$$
$$\tau_E = 4.9 - 6.5 \ [\mathrm{sec}],$$
$$P_{DT} = 10 - 48 \ [\mathrm{MW}],$$
$$Q_{DT} = 9 - 12$$

within TFTR stability limits, and with small PFC load (< 5 *MW)*

	PNBI	n	T	P DT	Q DT	tauE	nend	Ti0	Te0	gb %
(a)	1.65	0.3	10	15.4	9.34	6.54	0.42	18.7	14.8	1.64
(c)	3.30	0.3	10	35.5	10.6	4.04	0.55	17.6	13.6	1.96
(d)	4.16	0.3	10	48.9	11.6	3.58	0.59	17.5	13.4	1.96

The "brute force" approach (*$P_{NBI} = 40$ MW*) did not work on TFTR for getting* $Q_{DT} = 1$*. With* $P_{DT} = 10.5$ MW *only* $Q_{DT} = 0.25$ *was achieved.

In the LiWall regime, using less power, TFTR could easily challenge even the $Q = 10$ goal of ITER

Predicting tokamak regimes

So far, the theory of LiWF (originated in Dec. 1998) had no failure in understanding and predicting plasma performance

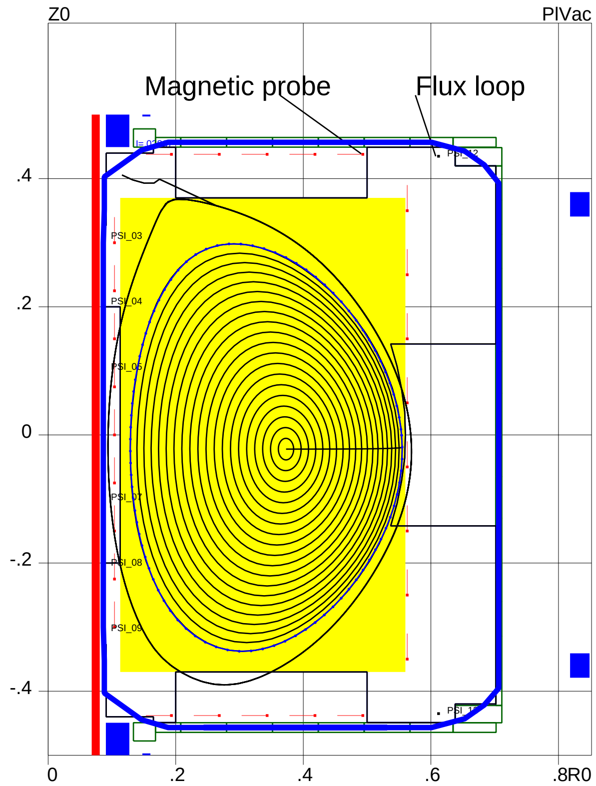
Tokamak experiments with Li conditioning have confirmed what was predicted, e.g.,

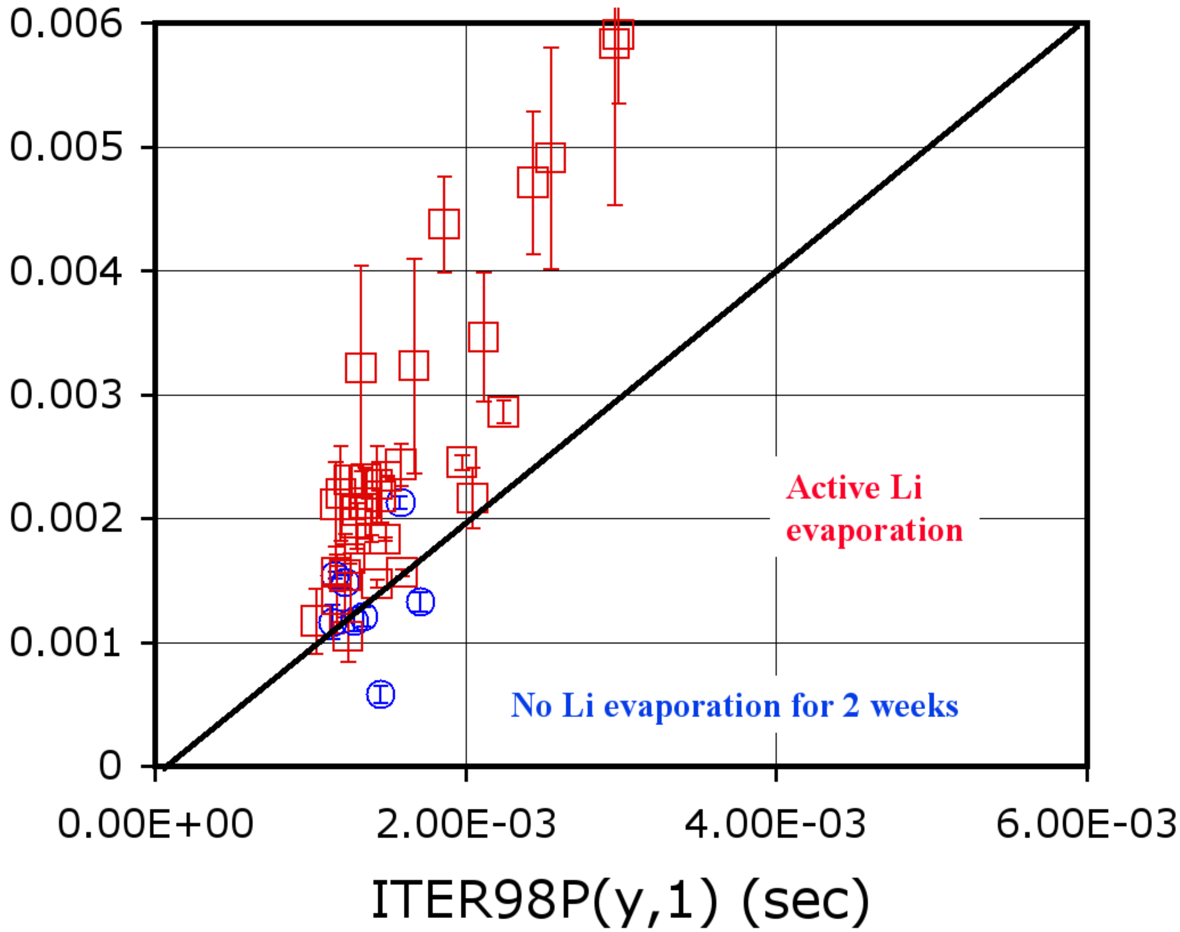
1. ***enhanced confinement (CDX-U, NSTX)***
2. ***enhanced global MHD stability (CDX-U)***
3. ***enhanced edge temperature pedestal (NSTX)***
4. ***stabilization of ELMs (NSTX)***
5. ***absence of Greenwald density limit (FTU)***

LiWF understanding of the plasma edge was found to be consistent with RMP experiments on DIII-D.

CDX-U with Li quadrupled confinement

Only with after appropriate calibration it was possible to extract the energy confinement time in CDX-U (pulse length 20 msec)





Transport model is consistent with CDX-U

CDX-U experiments with liquid lithium surface are consistent with the Reference Transport Model (RTM):

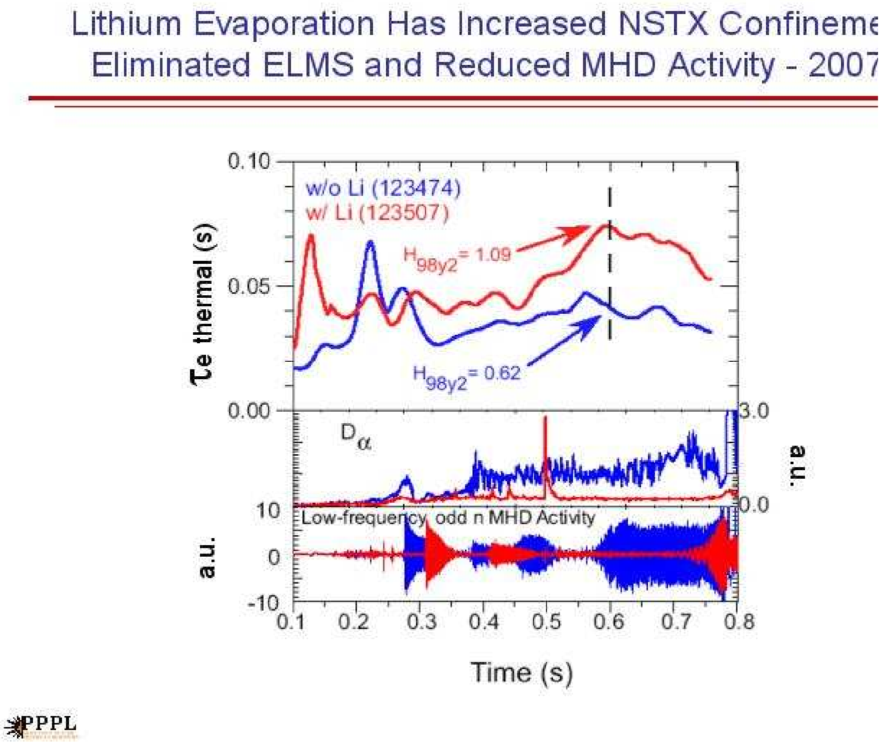
$$\begin{aligned} \Gamma^{core} &= \chi_i^{neo-classical} \nabla n, & & \\ q_i &= n\chi_i^{neo-classical} \nabla T_i, & \text{not important}, & \quad (5.1) \\ q_e &= n\chi_i^{neo-classical} \nabla T_e, & \text{not important} & \end{aligned}$$

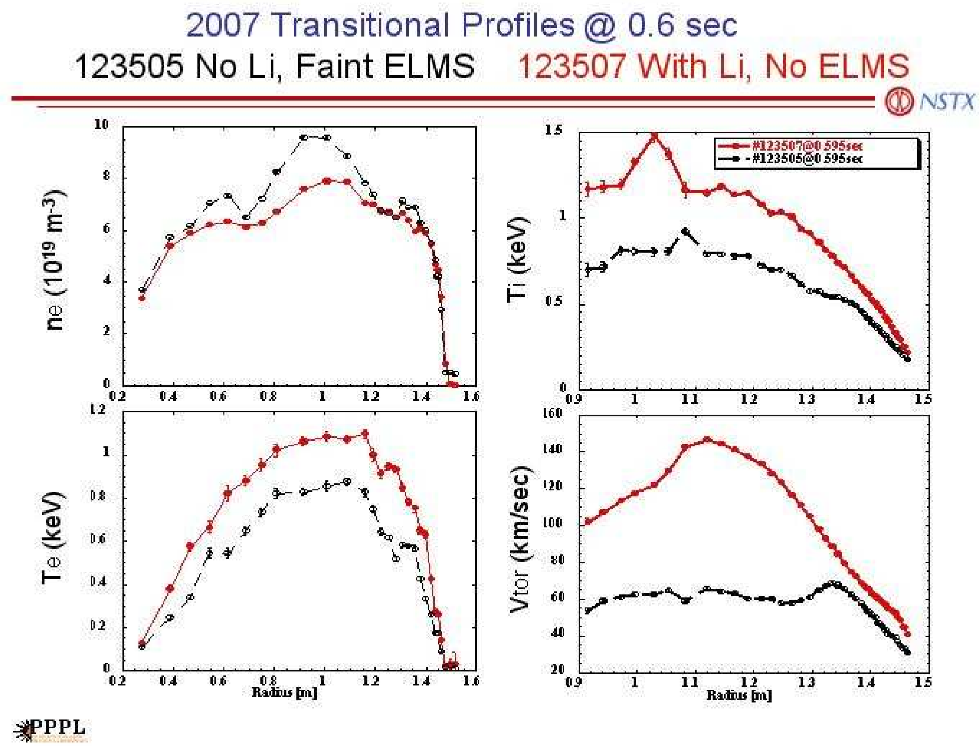
Parameter	CDX-U	RTM	RTM-0.8	glf23	Comment Table 1
$\dot{N}$, 10^{21} part/sec	1-2	.98	0.5	0.8-3	Gas puffing rate adjusted to match
β_j	0.160	0.151	0.150	0.145	measured β_j
l_i	0.66	0.769	0.702	0.877	internal inductance
V, Volt	0.5-0.6	0.77	0.53	0.85	Loop Voltage
τ_E, msec	3.5-4.5	2.7	3.8	2.3	
$n_e(0)$, $10^{19} part/m^3$		0.9	0.7	0.9	
$T_e(0)$, keV		0.308	0.366	0.329	
$T_i(0)$, keV		0.031	0.029	0.028	

RTM gives a solid basis for predictions, including FFRF

Li does improve confinement

NSTX had 4 campaigns with Li conditioning by evaporation





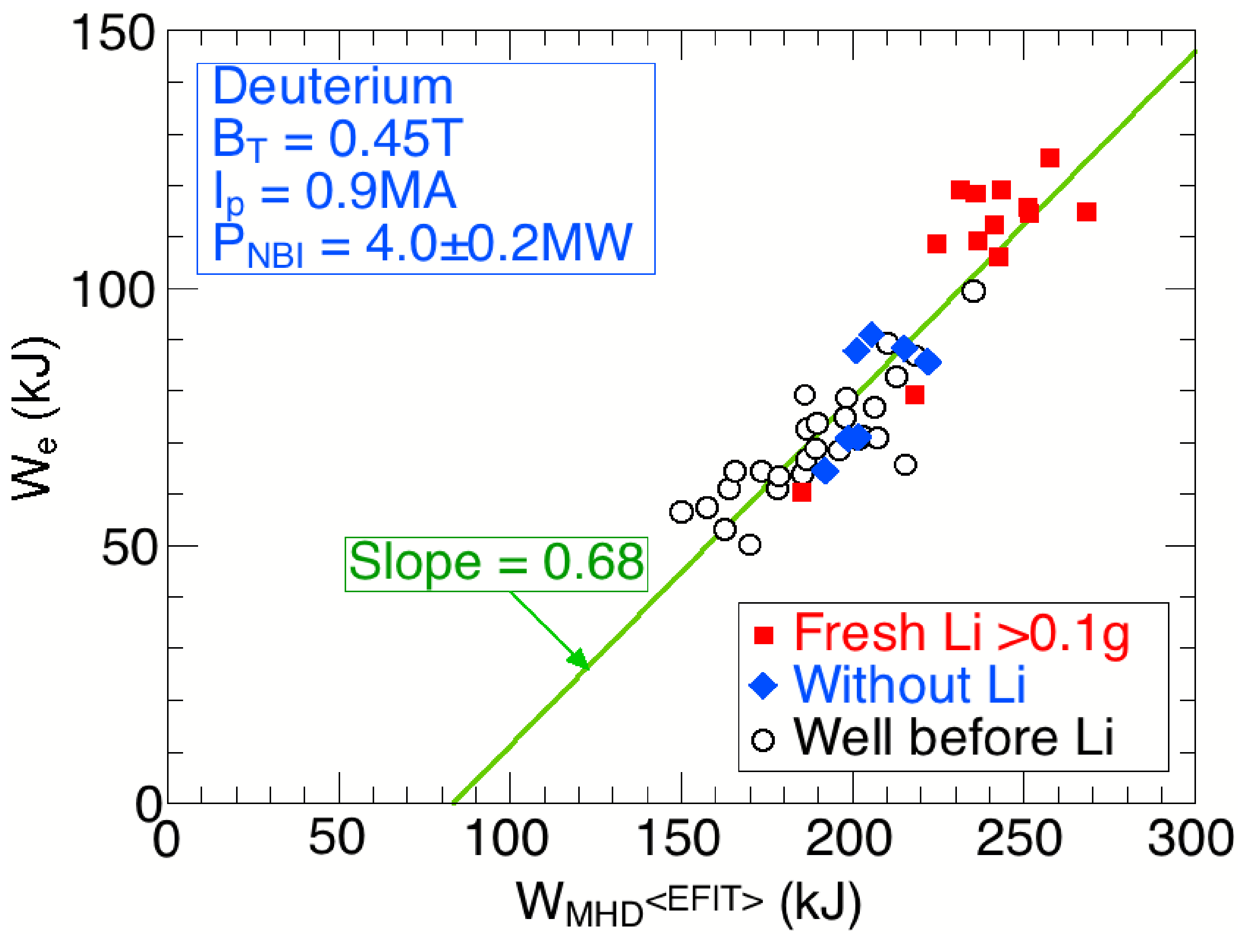
There are indications of improved confinement with Li conditioning on NSTX after evaporation.

NSTX is not yet in the LiWall regime. There is no effect on the density rise

Li improves performance (NSTX)

Stored Energy (W_{MHD}) Increases After Li Deposition Mostly Through Increase in Electron Stored Energy (W_e)

NSTX

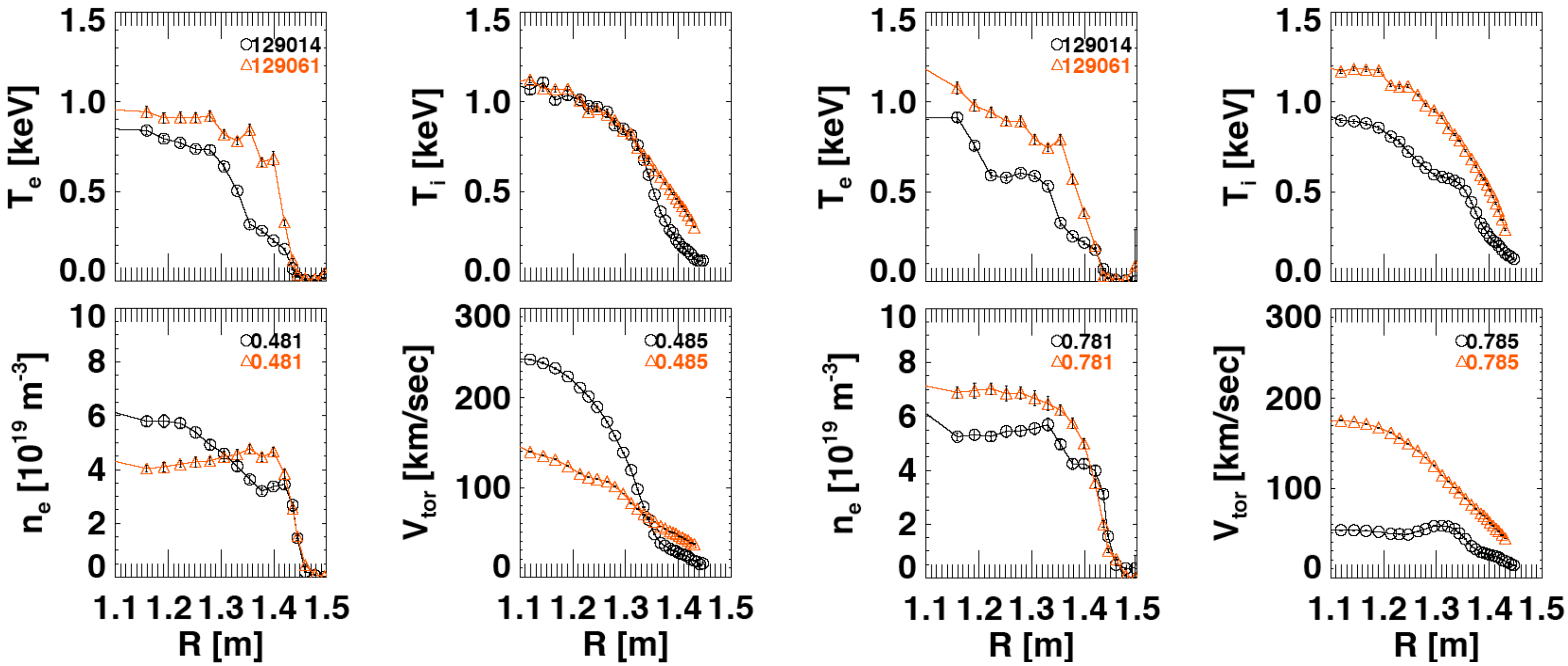


M. G. Bell

- **Data sampled at time of peak W_e**

Li improves performance (NSTX)

Lithium Edge Conditions Increased Pedestal Electron and Ion Temperature



Te, Ti, rotation velocity near plasma edge are increased with Li

R. Maingi, ORNL

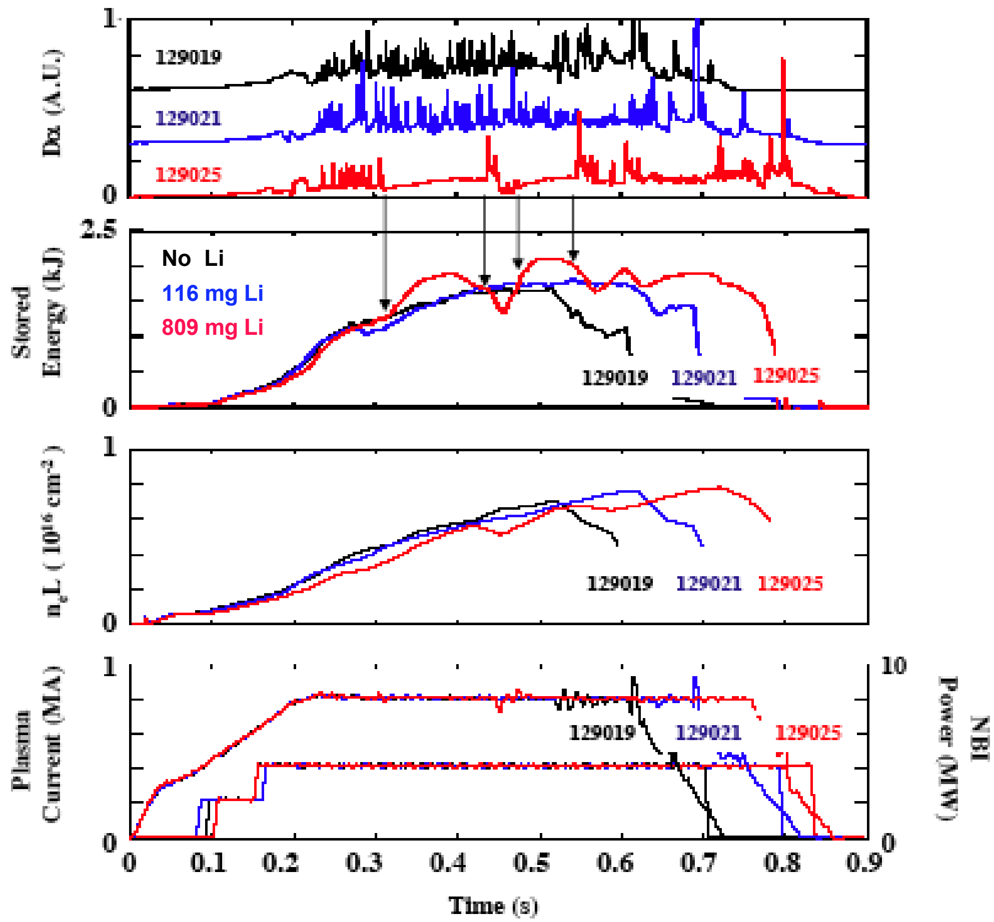
ELMs were stabilized as predicted 3 years earlier

Lithium Edge Conditions Affect Plasma Behavior

NSTX

As Li increases

- **ELMs decrease**
- **Stored energy increases**
- **Pulse lengthens**



The record pulse length 1.8 sec for NSTX has been achieved with Li

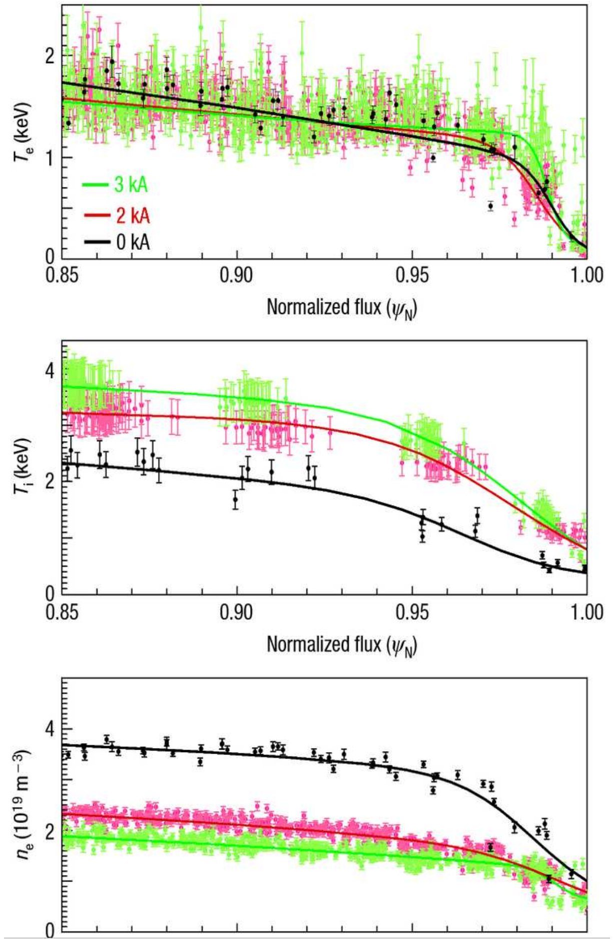
O-28, D. Mansfield

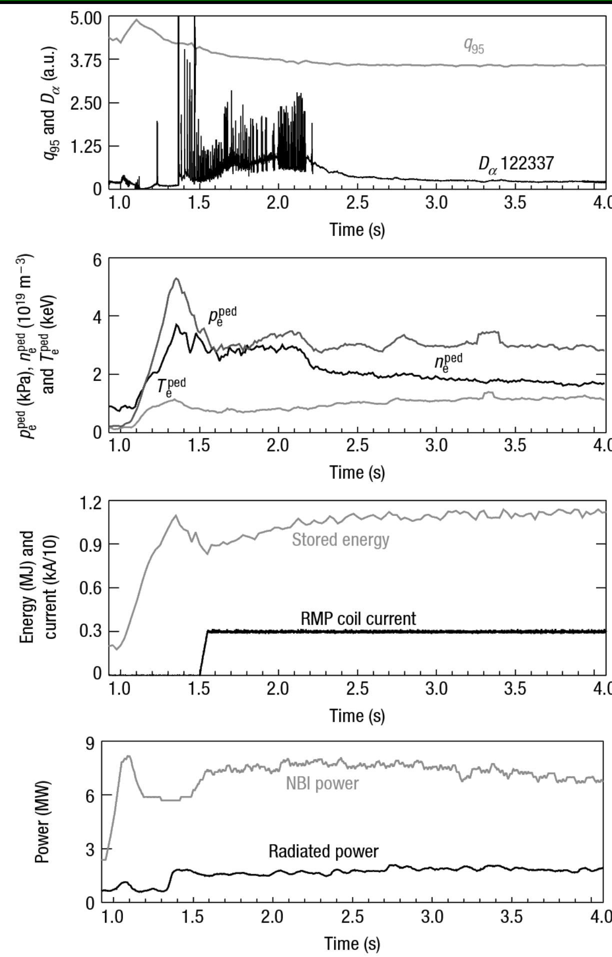
PPPL PRINCETON PLASMA PHYSICS LABORATORY

12

DIII-D made crucial input to LiWF

DIII-D experiments have confirmed that the pedestal value of T_{edge} is not affected by RMP. The gradients n' and $T'_{edge-core}$ are affected





No indications of screening RMP:

The gradients

$$n'(x),\ T'_e(x)$$

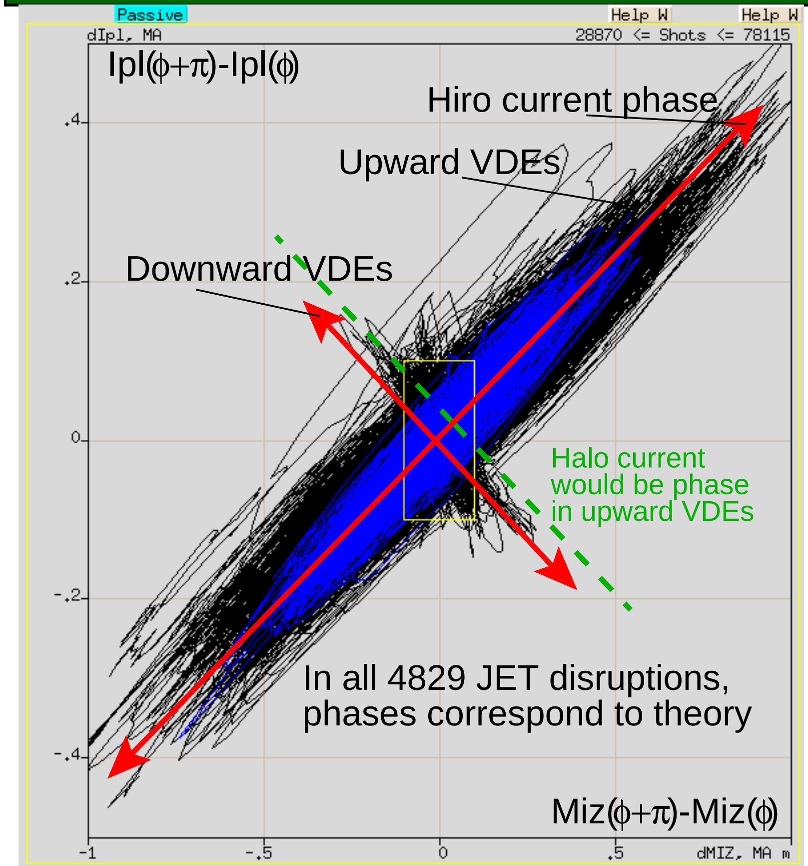
in the core are affected.

0 kA, 2 kA, 3 kA $I_{RMP-coil}$ *T.Evans at al., Nature physics 2, p.419, (2006)*

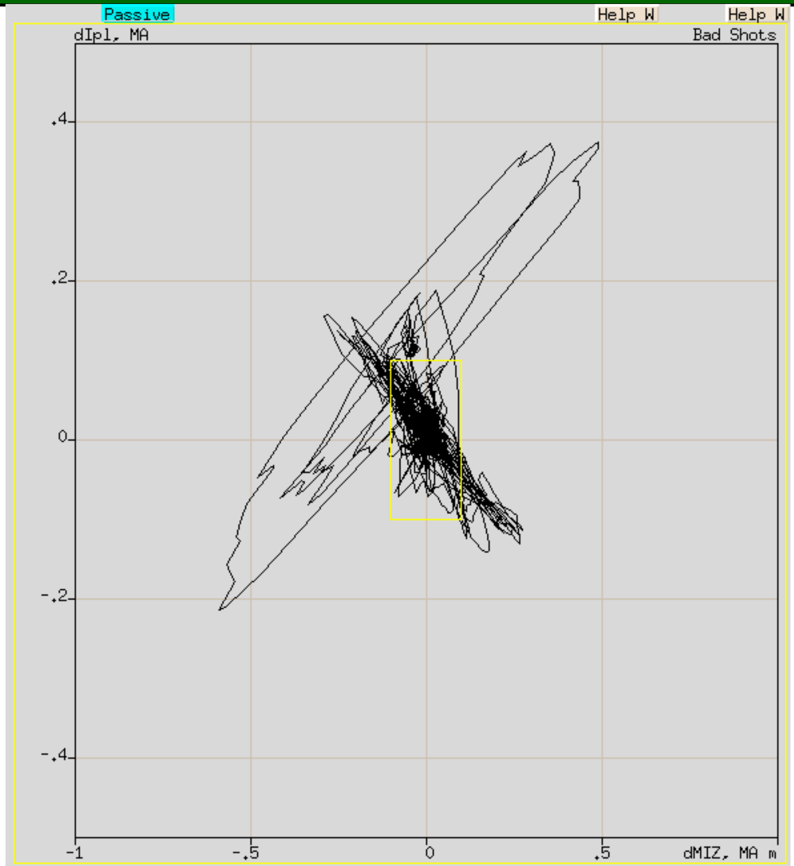
There is no confinement in the “edge transport barrier” zone

LiWF and disruptions

Triggered by ITER Organization progress in understanding disruptions was made



Black: $I_{pl,7}(t) - I_{pl,3}(t)$ vs $M_{IZ,7}(t) - I_{IZ,3}(t)$
Blue: $I_{pl,5}(t) - I_{pl,1}(t)$ vs $M_{IZ,5}(t) - I_{IZ,1}(t)$
(All 4829 disruption shots, 814 upward+20 downward VDEs)



Black: $I_{pl,7}(t) - I_{pl,3}(t)$ vs $M_{IZ,7}(t) - I_{IZ,3}(t)$
(20 downward disruption shots)

With no single exception JET disruption data are consistent now with theory. The 46 old puzzle has been resolved.

Regardless of solidarity of fusion nomenclature (whose entire "strategic thinking" is limited by 5 Bigs) in its contempt to LiWF and all obstacles

LiWF is already driving fusion research in the right direction

6 The design approach of FFRF

The design solutions of FFRF will use as much as possible the ITER design solutions (e.g., same superconductor, magnetic coil design, support structures, etc)

At the same time, regarding the plasma regime, instead of ITER reliance on "well established" plasma physics data (from messy plasma regimes),

the design of FFRF will be synchronized with development of new plasma regimes with much simpler and predictable plasma physics, which stratifies extrapolation from the previous level of experiments.

NSTX in PPPL is one of pillars

"…experiments…in the NSTX facility promise many exciting discoveries that should directly impact our ability to understand ***the new plasma regimes expected in ITER****."*

(Dr. Raymond L. Orbach, "Future of the Princeton Plasma Physics Laboratory (PPPL)", May 22, 2008)

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
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
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Think Tank, Inc.
UC Davis
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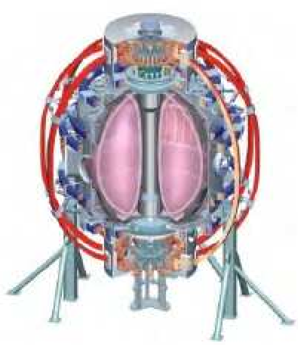
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

M.G. Bell
for the NSTX Research Team

36th EPS Conference on Plasma Physics
July 2, 2009



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TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

NSTX is crucial for fusion

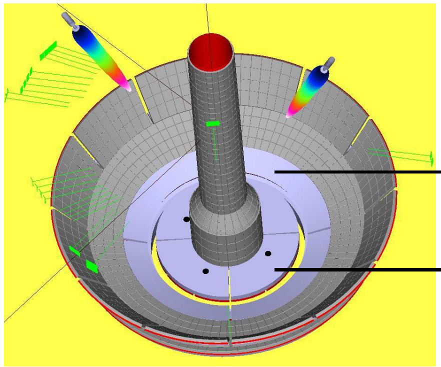
PPPL and NSTX team have everything to demonstrate the LiWF regime: people, experience with Li handling, NBI, and understanding of necessary steps.

The machine should be converted into ST0 device which would provide

$$R < 0.5, \quad \Gamma^{gasI} < \Gamma^{NBI} \qquad (6.1)$$

and then target the mailestone

Reproduce the CDX-U results in 3-4 fold confinement enhancement (tauE≃200 ms)



Outer leg LLD

Inner leg LLD

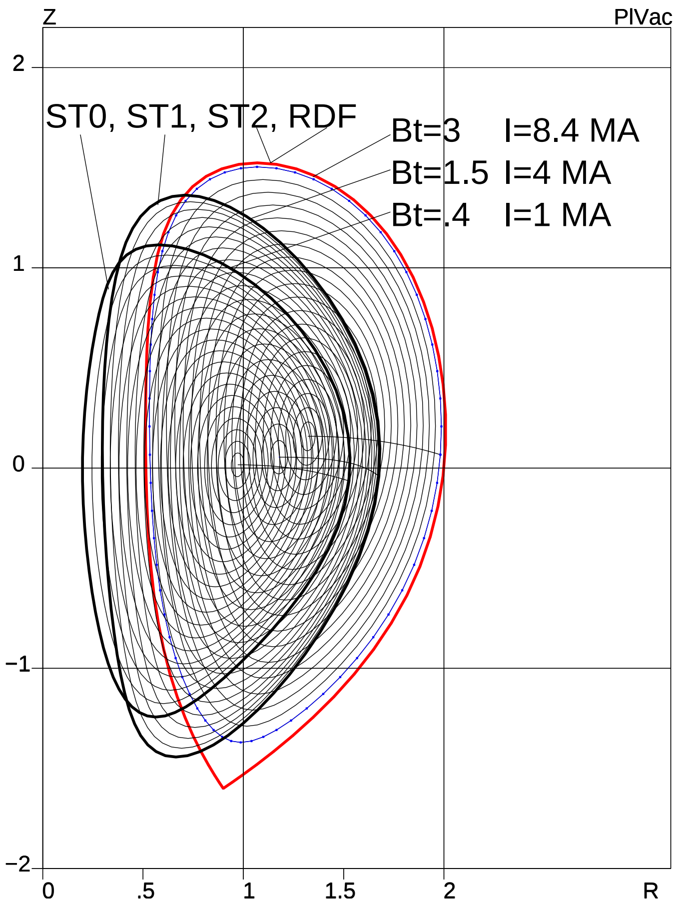
New plasma regimes require plasma contact with Li on the target plates.

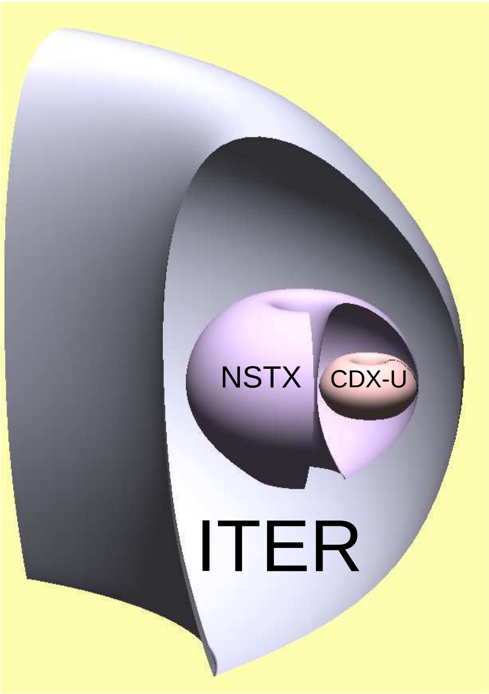
LLD on NSTX should include the entire surface of the low divertor.

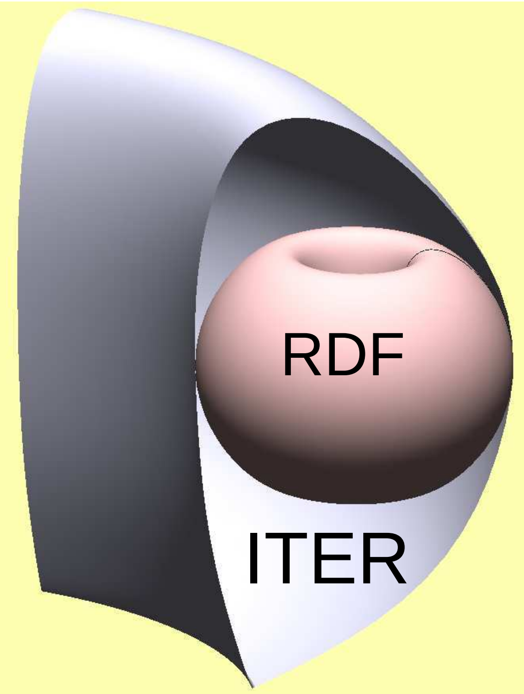
Instalaltion of full LLD would be a real step of NSTX toward new plasma regimes, crucial for both nFF and FFRF

ST0, ST1 are parts of 3 step program

Three new Spherical Tokamaks ST1 (DD),ST2 (DD),ST3 (DT) should implement the LiWF regime in a Reactor Development Facility (RDF)







RDF with P_{DT}=0.2-0.5 GW is 27 times smaller than ITER

Stationary EAST is another pillar

EAST Update

Full performance commissioning

Plasma

I_p=0.6MA B_T=2-3T

N_e=1-5x$10^{19}m^{-3}$, T_e=1-2keV

LHCD:0.8MW(2MW)

ICRF:0.2MW(4.5MW)

Internal structures Active cooled C PFC

Fast IV coils

Cry-pump >10^5 l/s

2 Active cooled C movable Limiters

20 diagnostics

Reliable safety and interlock system

(taken from Director of ASIPP Jiangang Li talk "EAST current status and its short-term and long-term plans", Hefei, Dec. 24, 2008)

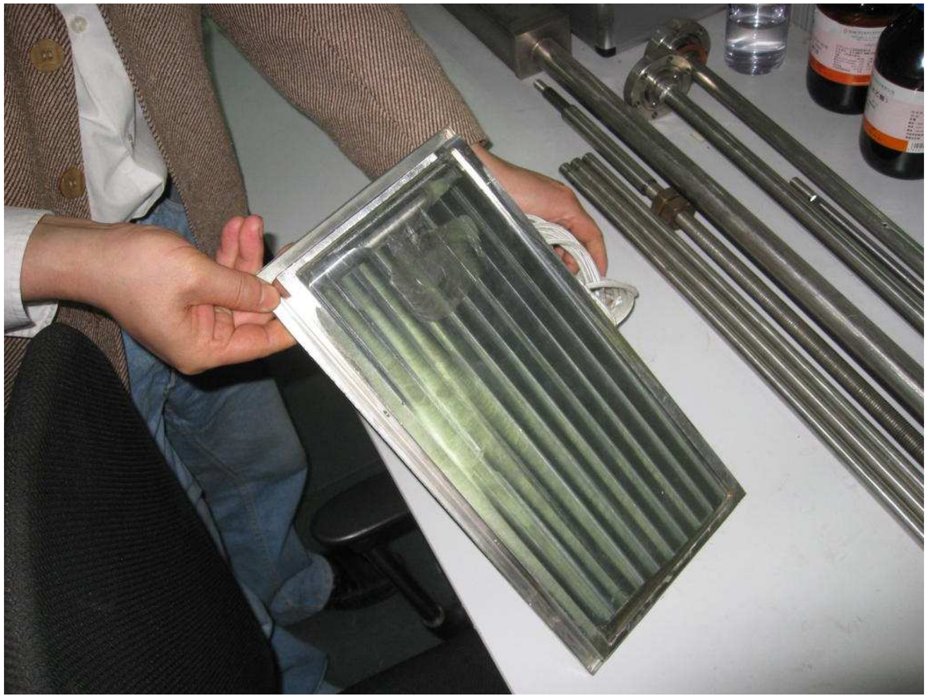
B=3.5-4 T, Ipl=1-1.5 MA, R=1.8, a=0.5, k=1.8

In April 2009, the currrent Ipl=0.25 MA for 63 sec has been demonstrated.

Lithium in ASIPP

On July 8, 2008, ASIPP Director Li decided to start the Li conditioning studies on HT-7 within a year

Li capsule for EAST conditioning

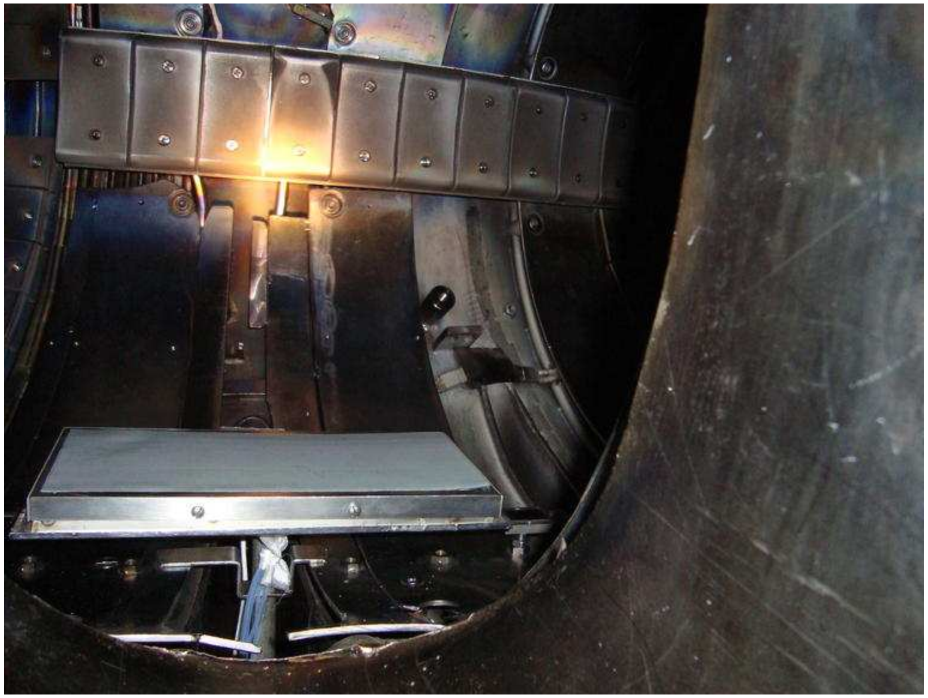


Tray for liquid Li on HT-7

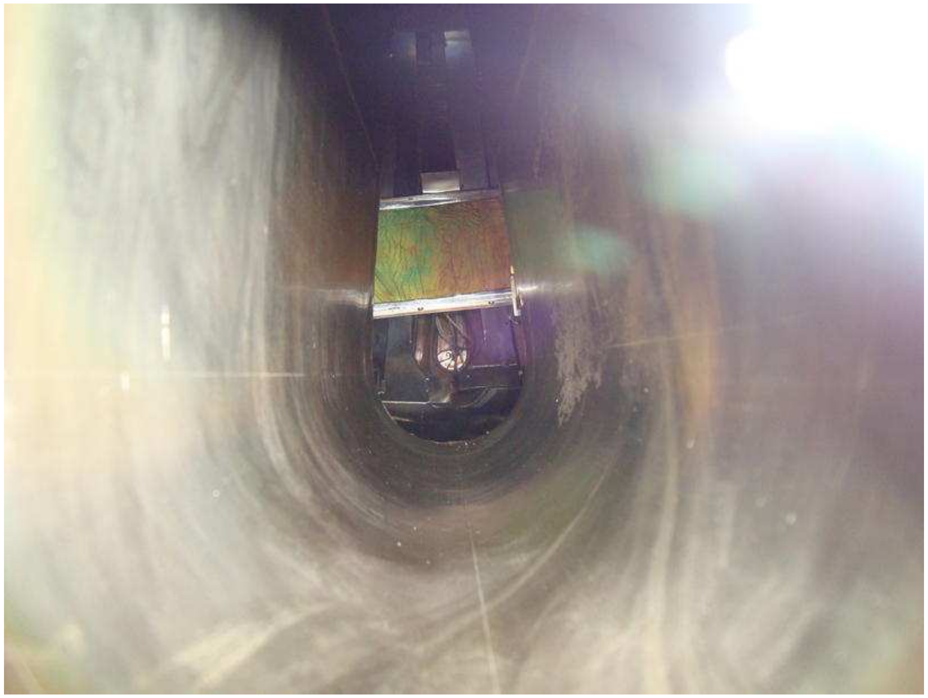
To my big surprise, 2 mg *of Li have been evaporated by e-beam inside EAST machine at the end of experimental campaign in April, 2009.*

Li on HT-7

Li tray is now installed inside HT-7 and is ready for plasma physics studies, scheduled for June 30, 2009



3 mm thick Li plate inside the tray on HT-7



Interference pattern from the oil on the surface of liquid Li

No single second deviation from the words of Director Li

7 Reference Timetable

Project	2010	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
FFRF	pre-CD	CD,TD				Go ahead			Assembly			DD, $p\tau_E = 1$				DT, Ignition					FFH
TFCoils	CD	TD				Manuf			Assembly			4-6 T									FFH
VVessel	CD			TD			Manuf			Assmbl		LLD		HeP		αP					FFH
PFC	CD			TD			Manuf			Assmbl		LLD		HeP		αP					FFH
Control	CD			TD			Manuf			Assmbl		LLD		HeP		αP					FFH
Blanket	CD										TD				Manuf			Assmbl			FFH
NSTX	LLD1	LLD2,τ_E=0.25			Upgrade		LiWF														
HT-7	Li tray	LLL		graduate implementation of Flowing LLL																	
EAST	0.5 MA	1 MA		NBI			Flowing LLL			HeP			Simulation of FFRF								
ST1				CD		TD		Manuf		Assmbl		LLD		LiWF		$p\tau_E = 1$					
NBI	CD long pulse 120 keV				TD stationary 120 keV						stationary 120 keV										
FLLL	Demo FLLL		FLLL for HT-7				FLLL for EAST				FLLL for FFRF										
HeP		CD		TD			HeP for EAST				HeP for FFRF										

In the case of a Joint US-China FFRF project, the Timetable is expected to be 50 % accurate.