Google: [Leonid Zakharov] ⟶ http://w3.pppl.gov/~zakharov

The LiWall Fusion (LiWF) Concept (part I)

Leonid E. Zakharov

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

ASIPP Seminar, ASIPP

July 07, 2008, Hefei, Ahnui, China

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

Contents

Abstract

The presently adopted plasma physics concept of magnetic fusion has been originated from the idea of providing low plasma edge temperature as a condition for plasma-material interaction. During 30-years of its existence this concept has shown to be not only incapable of addressing practical reactor development needs, but also to be in conflict with fundamental aspects of stationary and stable plasma.

Meanwhile, a demonstration of exceptional pumping capabilities of lithium surfaces on T-11M (1998), discovery of the quiescent H-mode regime on DIII-D (2000), and a 4 fold enhancement of the energy confinement time in CDX-U tokamak with lithium (2005), contributed to a new vision of fusion relying on high edge plasma temperature. The new concept, called LiWalls, provides a scientific basis for developing magnetic fusion.

The talk outlines 3 basic steps toward the Reactor Development Facility (RDF) with DT fusion power of 0.3-0.5 GW and a plasma volume $\simeq 30$ ***m***^{3}***. Such an RDF can accomplish three reactor objectives of magnetic fusion, i.e.,***

1. ***high power density*** $\simeq 10$ ***MW/m***^{3} ***plasma regime,***
2. ***self-sufficient tritium cycle,***
3. ***neutron fluence*** $\simeq 10-15$ ***MW·year/m***^{2}***,***

all necessary for development of the DT power reactor. Within the same mission a better assessment of DD fuel for fusion reactors will also be possible.

The suggested program includes 3 spherical tokamaks. Two of them, ST1, ST2, are DD-machines, while the third one, ST3, represents the RDF itself with a DT plasma and neutron production.

All three devices rely on a NBI maintained plasma regime with absorbing wall boundary conditions provided by the Li based plasma facing components. The goal is to utilize the possibility of high edge temperature plasma with the super-critical ignition (SGI) regime, when the energy confinement significantly exceeds the level necessary for ignition by α***-particles. In this regard all three represent Ignited Spherical Tokamaks, suggested in 2002.***

Abstract

Specifically, the mission of ST1, with a size slightly larger than NSTX in PPPL but with a four times larger toroidal field, is to achieve the absorbing wall regime with confinement close to neo-classical. In particular, the milestone is $Q_{DT-equiv} \simeq 5$ corresponding to the conventional ignition criterion.

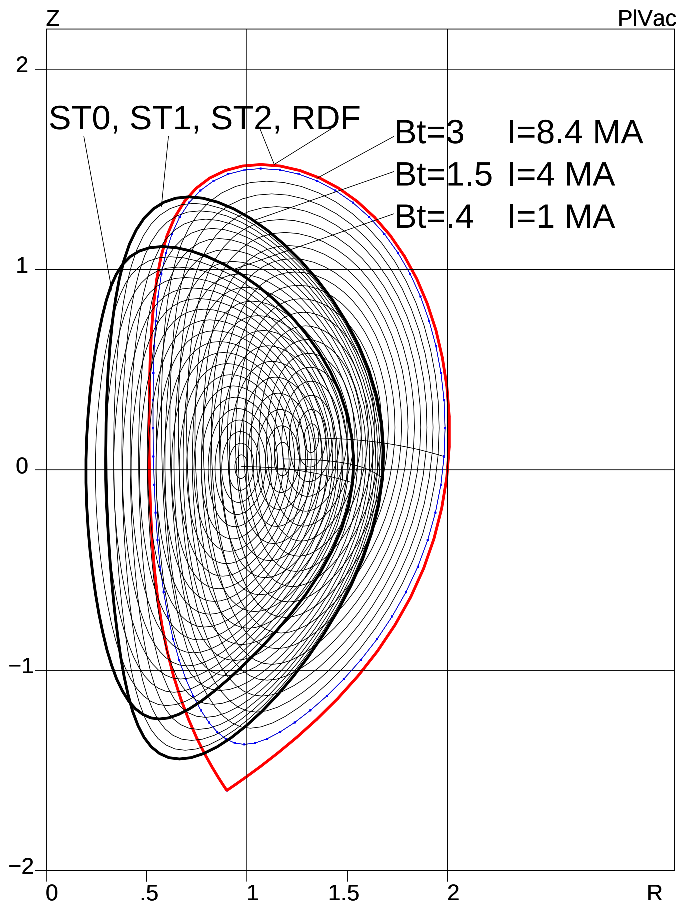
The mission of ST2, which is a full scale DD-prototype of the RDF, is the development of a stationary super-critical regime with $Q_{DT-equiv} \simeq 40-50$.

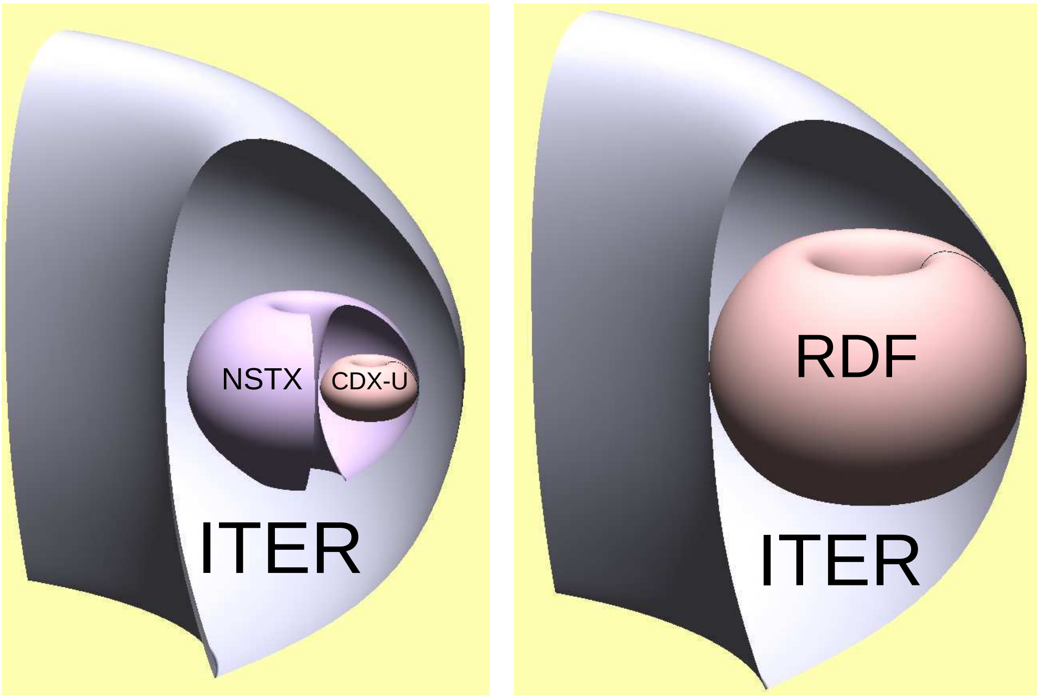
ST3 is a DT device with $Q_{DT} \simeq 40-50$ with sufficient neutron production to design the nuclear components of a power reactor. Still the mission of ST3 contains a significant plasma physics component of developing α-particle power and He ash extraction.

As a motivational step (ST0), the suggested program assumes a conversion of the existing NSTX device into a spherical tokamak with lithium plasma facing components. The demonstration of complete depletion of the plasma discharge by lithium surface pumping, first shown on T-11M, is considered as a well-defined milestone for readiness of the machine for the new plasma regime. The final mission of ST0 would be doubling or tripling the energy confinement time with respect to the current NSTX.

1 Three steps of RDF program

RDF program relies on conversion of NSTX into ST0 and on 3 new Spherical Tokamaks ST1 (DD),ST2 (DD),ST3 (DT RDF)





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

Tritium availability sets the strategy

The criterion of conceptual relevance to reactor R&D is very simple: ability of delivering

15 MWa/m^2

of neutron fluence,

or burn-up of

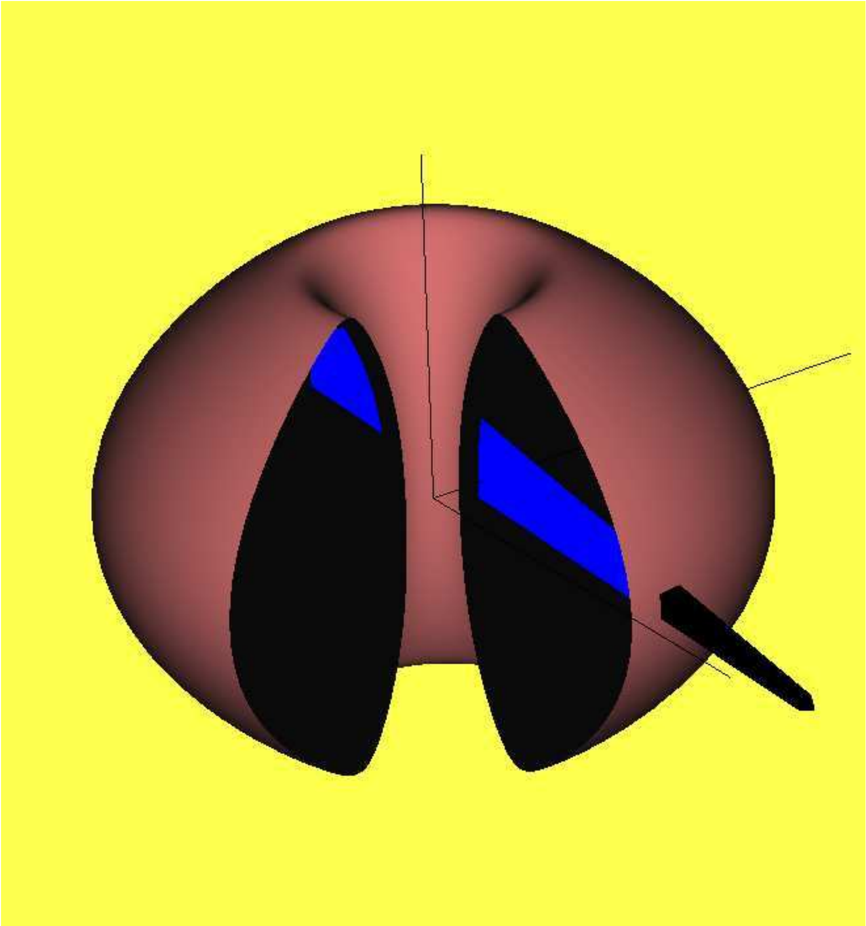
1 kg(T)/m^2(FW)

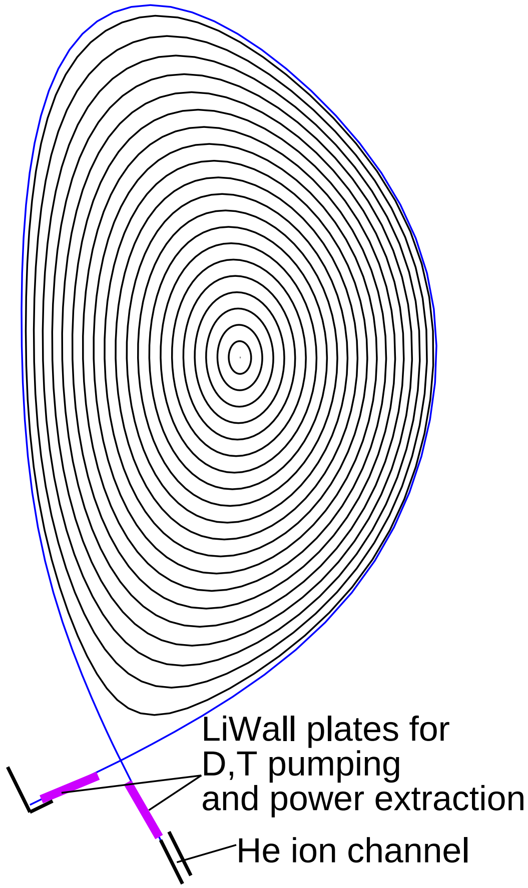
First, the Reactor Development Facility (RDF), then the power reactor

(ITER is capable of only 0.3-0.4 MWa/m^2 (burn-up of 10-15 kg of T, instead of 650 kg)

2 Basics of Lithium Wall Fusion

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 ?
(Assume that 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 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

$$\nabla T_i = 0, \quad \nabla T_e = 0 \qquad (2.1)$$

Ion/electron temperature gradient instabilities (ITG, ETG), which are the major cause of energy losses, will be eliminated automatically

Elimination of thermo-conduction

In fact, with pumping walls any thermo-conduction, even classical, will be eliminated

Independent of plasma heating method (NBI, RF, Ohmic, α-particles) the plasma temperature profile will adjust itself in order to eliminate the heat flux

$$q_i + q_e = 0 \qquad (2.2)$$

Energy from the plasma will be lost only due to particle diffusion

$$\frac{d}{dt}\int \frac{3}{2} n(T_i + T_2) dV + \oint \left(\frac{5}{2}\Gamma_i T_i + \frac{5}{2}\Gamma_e T_e\right) dS = \int P dV \qquad (2.3)$$

With central heating and pumping walls the temperature profile will be inverted

(particles acquire energy on way to the wall).

The best possible confinement regime

Unlike thermo-conduction, particle diffusion is limited

Particle fluxes of electron and ion are always equal to each other

$$\Gamma_i = \Gamma_e \tag{2.4}$$

As a result, the particle and energy confinement is determined ***by the best confined component.***

Even if electrons are not confined, still they cannot escape (together with their energy) without ions.

For the first time, the theory revealed the regime which is not sensitive to anomalous electrons

Transition from thermo-conduction (turbulent) to diffusion dominated plasma regime represents a fundamental shift in fusion and the LiWall Fusion (LiWF) concept

Since the beginning of fusion research in the early 50s, electrons were the major obstacle for controlled fusion (beam based fusion, inertial and magnetic fusion).

Electrons remain the major, unresolved problem for magnetic fusion these days as well.

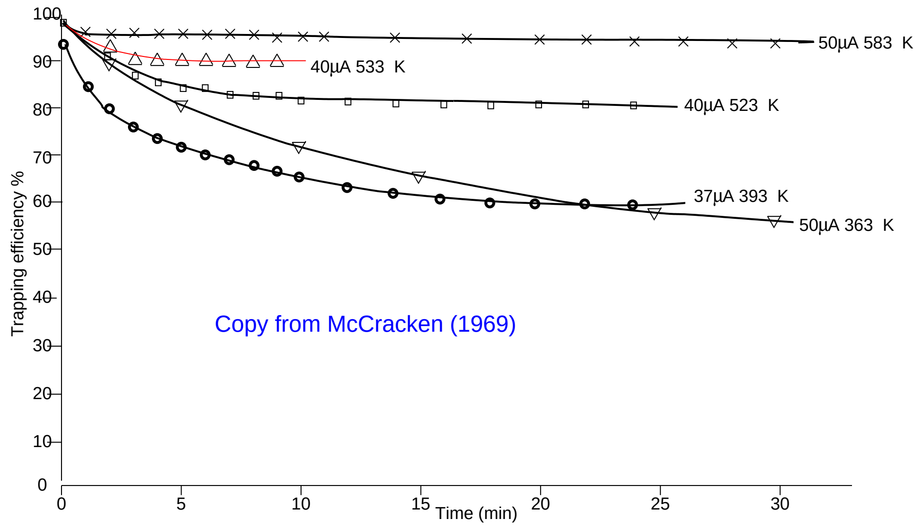
Because all present high performance experiments are made exclusively with NBI and in hot-ion regime

Our projections to the burning plasma using conventional concept have no scientific basis

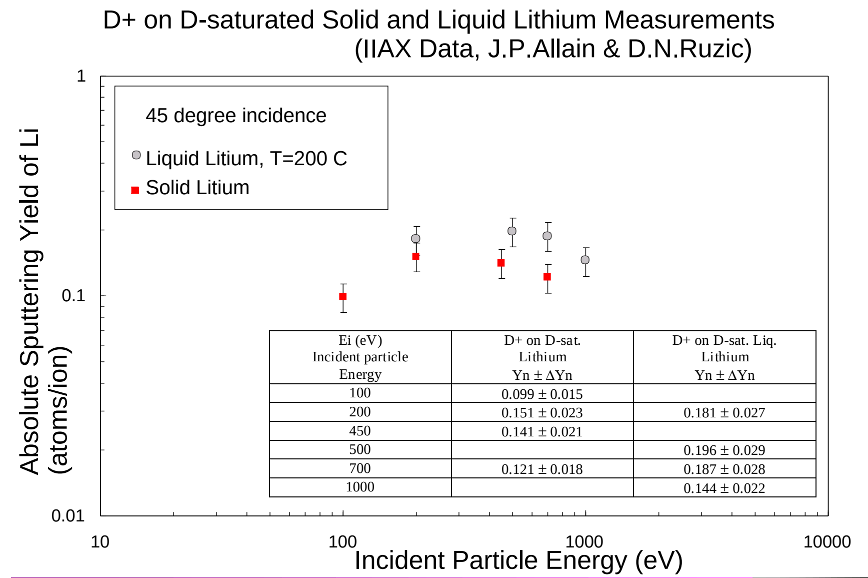
The development of new, LiWall regimes gives a chance for a science based strategy toward the reactor

4 Li is an outstanding pump for H,D,T

Lithium can retain $\simeq$10% of H,D,T atoms per Li atoms



McCracken retention curves



Ei (eV) Incident particle Energy	D+ on D-sat. Lithium $Yn \pm \Delta Yn$	D+ on D-sat. Liq. Lithium $Yn \pm \Delta Yn$
100	0.099 ± 0.015	
200	0.151 ± 0.023	0.181 ± 0.027
450	0.141 ± 0.021	
500		0.196 ± 0.029
700	0.121 ± 0.018	0.187 ± 0.028
1000		0.144 ± 0.022

ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN Plasma-material interaction Group

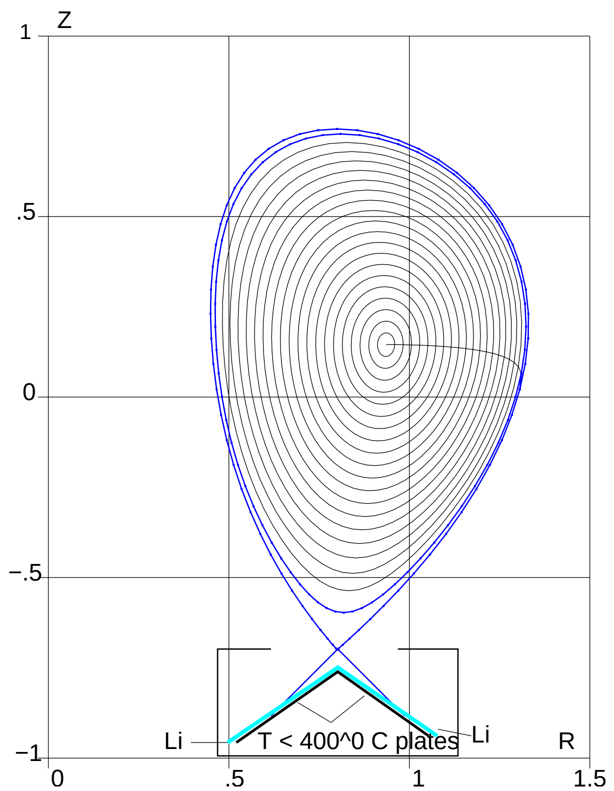
Because of evaporation, the surface temperature of Li should be limited (by $\simeq$ 400^o C)

Probably, the short lasting retention allows higher temperatures (R.Majeski)

More Li technology studies are necessary

V$\simeq$1 cm/sec is sufficient for pumping

PLD $\equiv$ actively cooled plates with flowing h$\simeq$ 0.1 mm Li layer



Gravity, Marangoni effect, residual $\mathbf{j} \times \mathbf{B}$ *forces,*

$$V_g = \frac{\rho g h^2}{2\nu} \sin\theta = 0.049 \sin\theta \; [m/s], \qquad (4.1)$$
$$V_M = \frac{d\sigma(T)}{dT} \frac{h \nabla T}{\nu} = 0.8 h \nabla T \; [m/s]$$

are sufficient for replenishing Li surface.

Lithium can accept 5-10 MW/m^2 *and keep* $T_{Li} < 400^o C$

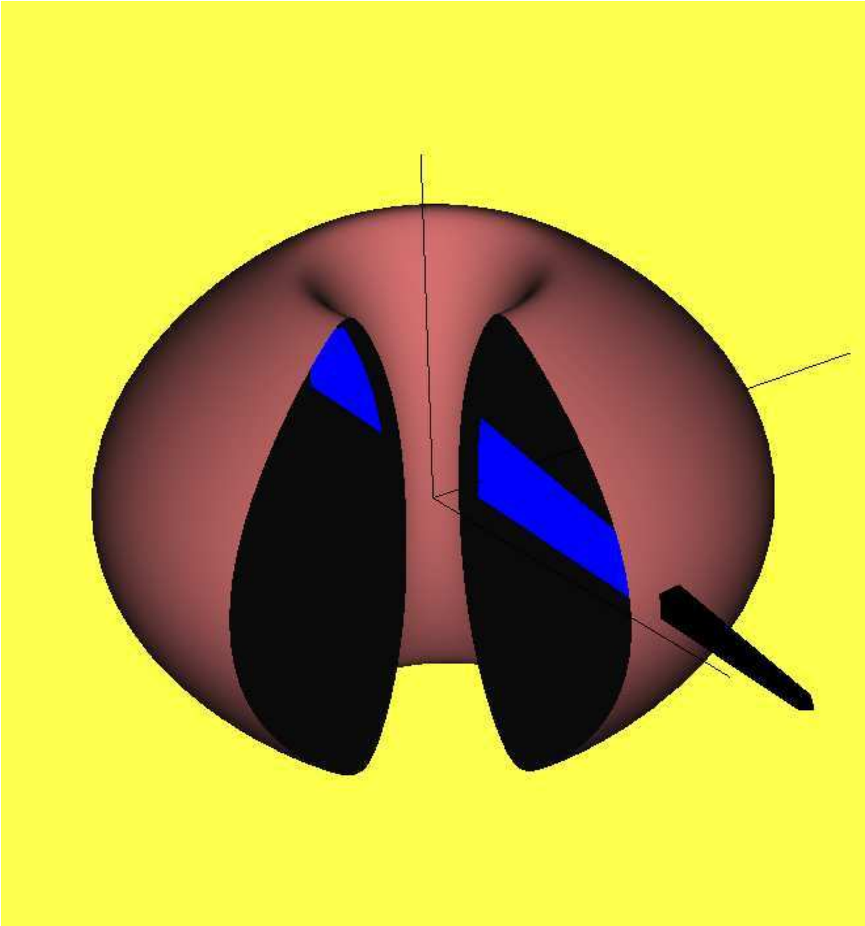
$$\chi_{Li} = 47.6,$$
$$\Delta T \, [^o C] = 100 \frac{q}{4.7} \cdot h \left[\frac{MW}{m^2} \cdot mm \right]. \qquad (4.2)$$

Power extraction is limited by the coolant temperature, rather than by the temperature of plasma facing surface.

No Li rivers, Li water-falls, evaporation, Li dust, pellets, LiLi trays, meshes, sponges, or thick ($\geq$ 1 mm) Li on the target plate

5 Fueling is not the issue

NBI is a ready-to-go fueling method for LiWF



The energy should be consistent with the plasma temperature

$$E_{NBI} = \left(\frac{3}{2} + 1\right)(T_i + T_e),$$

e.g., for

$$T_e \simeq T_i \simeq 16\ keV$$

$$E_{NBI} = 80\ keV$$

In absence of cold particles from the walls, after collisional relaxation

$$\nu_i = 68\frac{n_{20}}{T_{i,10}^{3/2}}, \quad \nu_e = 5800\frac{n_{20}}{T_{e,10}^{3/2}}$$

the temperature profile becomes flat automatically

$$T_i = const, \quad T_e = const, \quad T_e < T_i$$

The plasma is always in the “hot-ion” regime (as all existing machines)

6 Reference Transport Model

In Spherical Tokamaks ions are neoclassical (NSTX)

A simple Reference Transport Model (RTM) *is relevant for projections of LiWall regime*

$$\Gamma^{core} = \chi_i^{neo-classical} \nabla n,$$
$$q_i = n\chi_i^{neo-classical} \nabla T_i, \qquad \textit{not important}, \qquad (6.1)$$
$$q_e = n\chi_i^{neo-classical} \nabla T_e, \qquad \textit{not important}$$

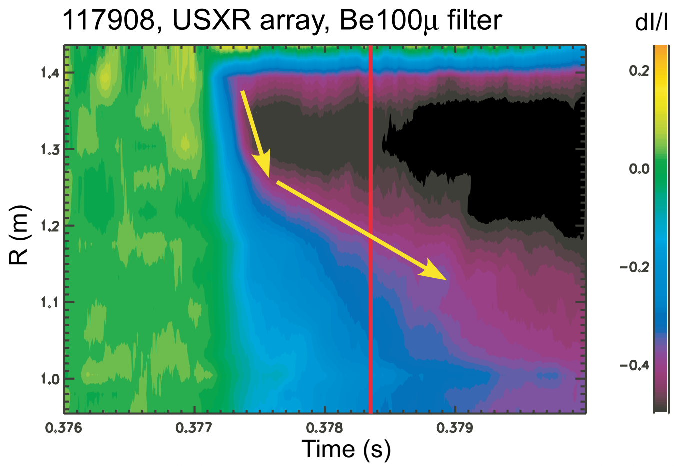
Electrons are anomalous, unpredictably anomalous, and determine energy losses

Ions are neoclassical in NSTX

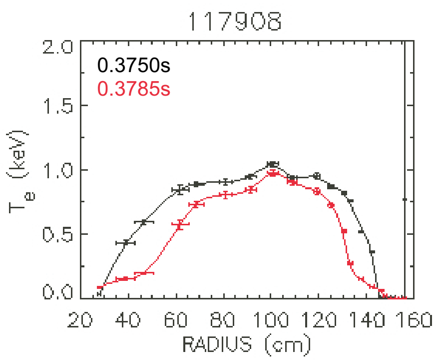
JOHNS HOPKINS UNIVERSITY

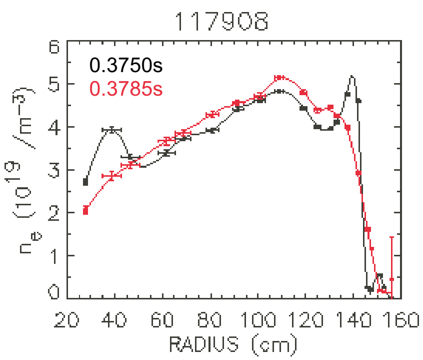
NSTX

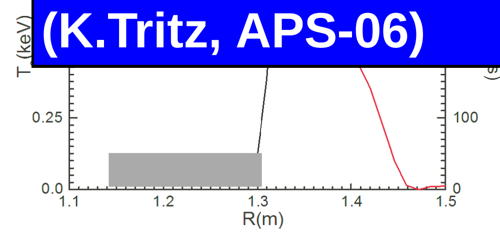
Perturbation Analysis Indicates Two Regions of $\chi_{e,pert}$



- T_e crash propagates from edge to core, n_e globally unperturbed
- Difference in propagation speed corresponds to differences in pertur







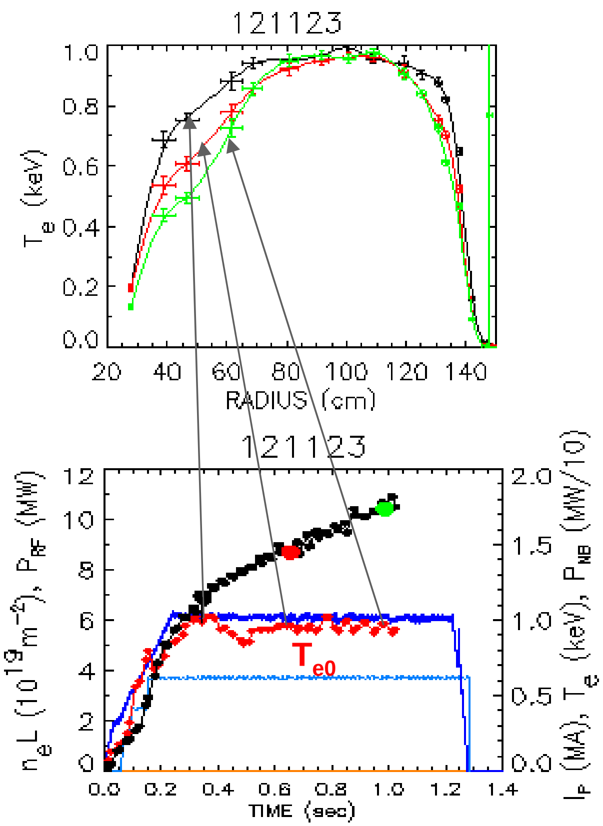
NSTX experiments:
Ions are neo-classical,
Electron are anomalous,
Density profile is not "stiff"
(K.Tritz, APS-06)

- Dependence of $\chi_{e,pert}$ on T_e gradient suggests critical gradient threshold

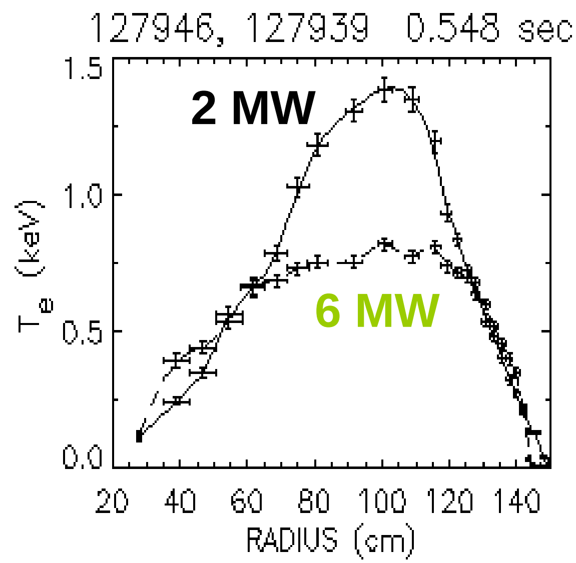
RTM reproduced the basic parameters of CDX-U discharges with Li tray.

Electrons are sensitive to everything

Effect persists throughout discharge, as well as at higher B_t, I_p



1.1 MA, 5.5 kG

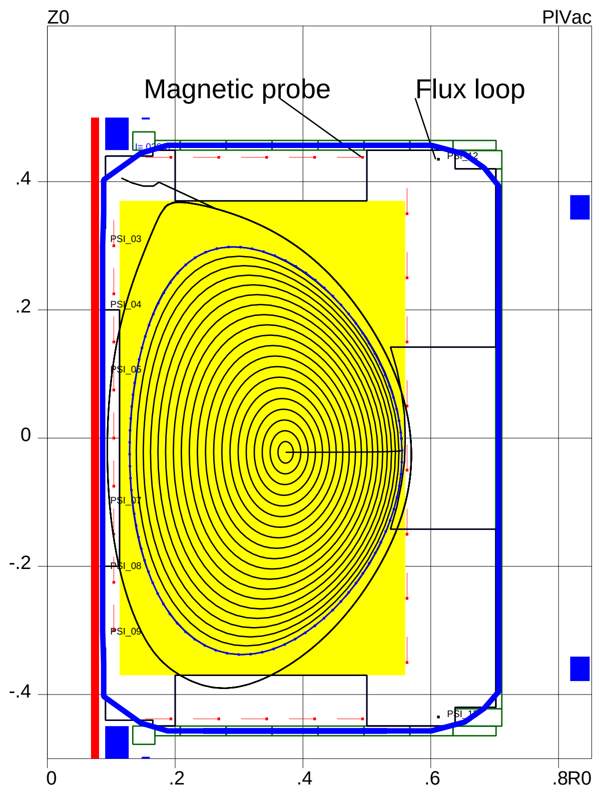


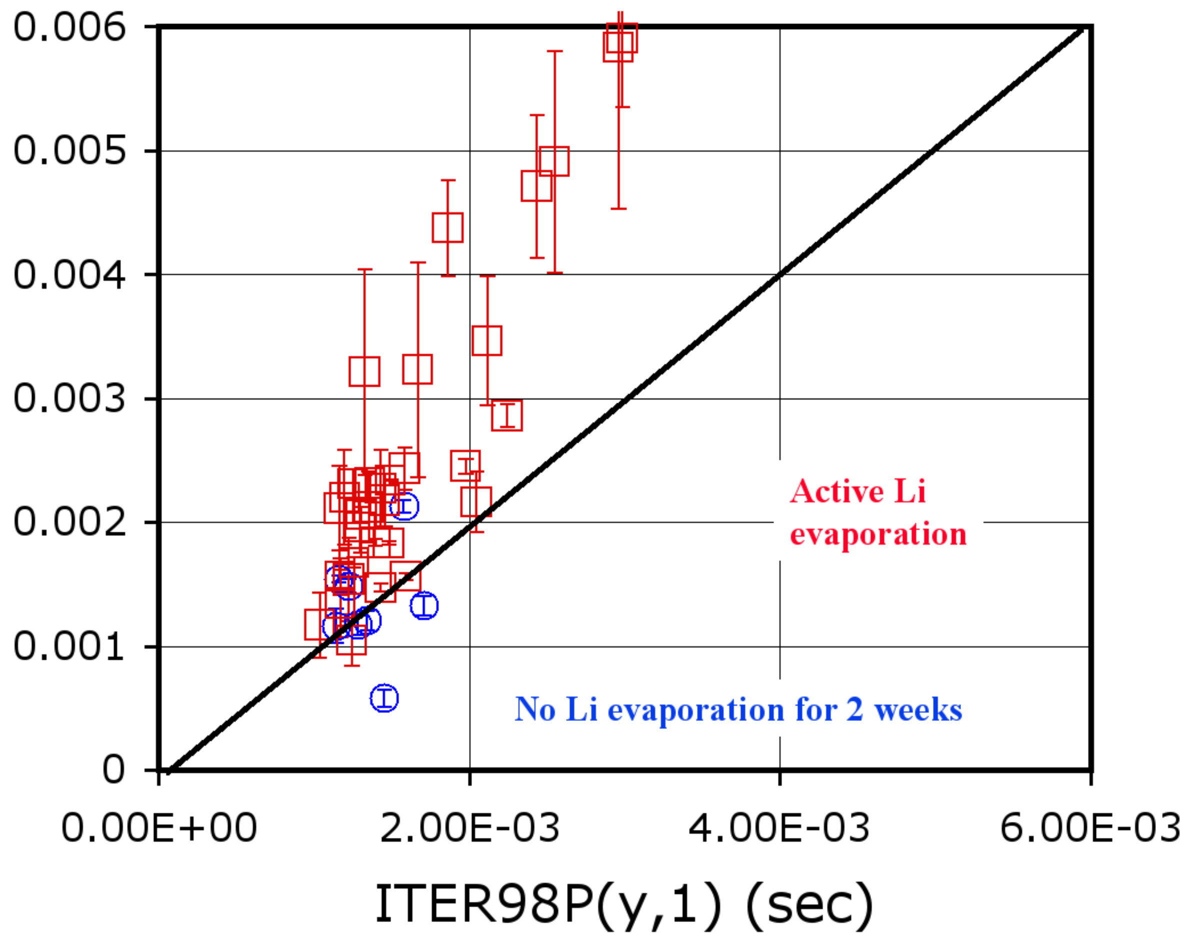
D. Stutman, L. Delgado, K. Tritz and M. Finkenthal

- Only slight rounding of T_e 'shoulders' with time
- Central T_e higher at 2 MW than at 6 MW, even at increased B_t and I_p

Li improves confinement (CDX-U)

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





RTM is consistent with CDX-U

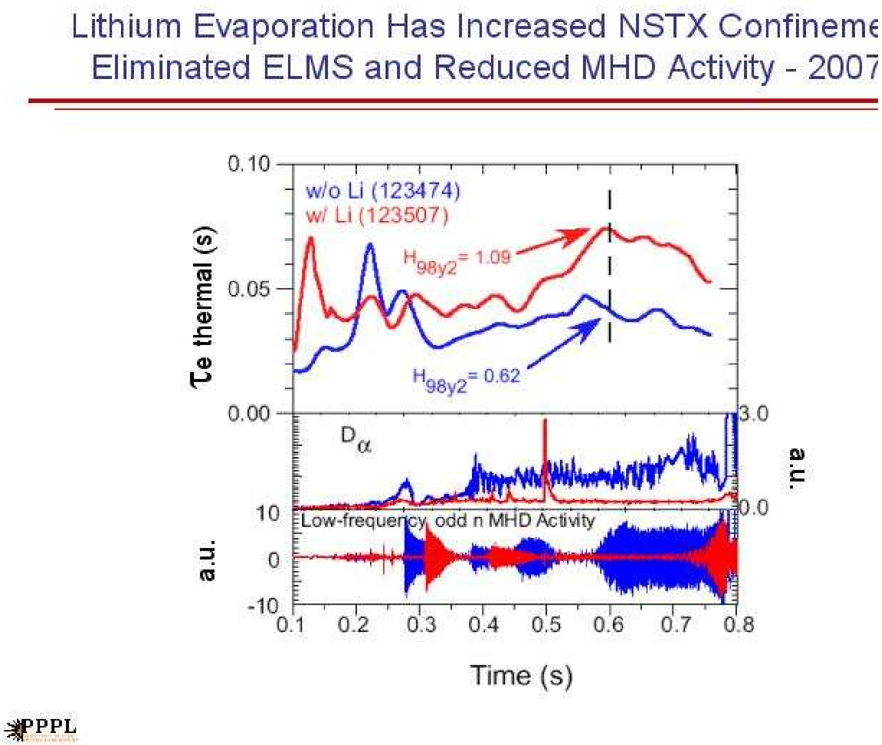
CDX-U experiments with liquid lithium surface are consistent with RTM

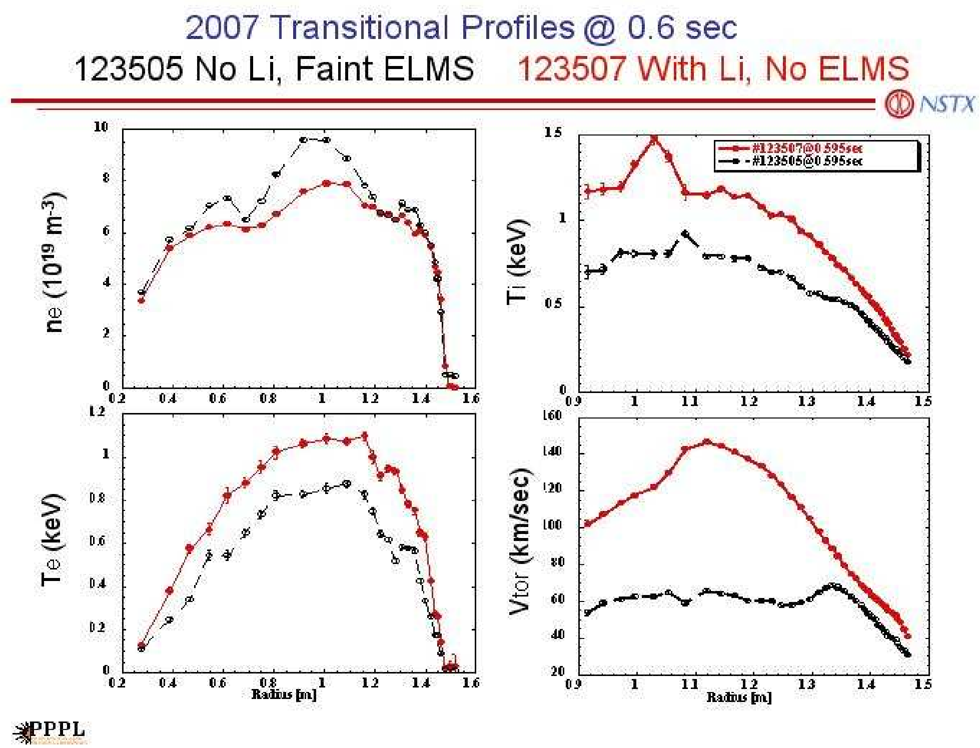
$$\Gamma_{i,e} = \chi_i^{neo-classics} \nabla n \qquad (6.2)$$

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 does not contradict CDX-U measurements and equilibrium reconstruction

NSTX had 3 campaigns with Li conditioning by evaporation





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

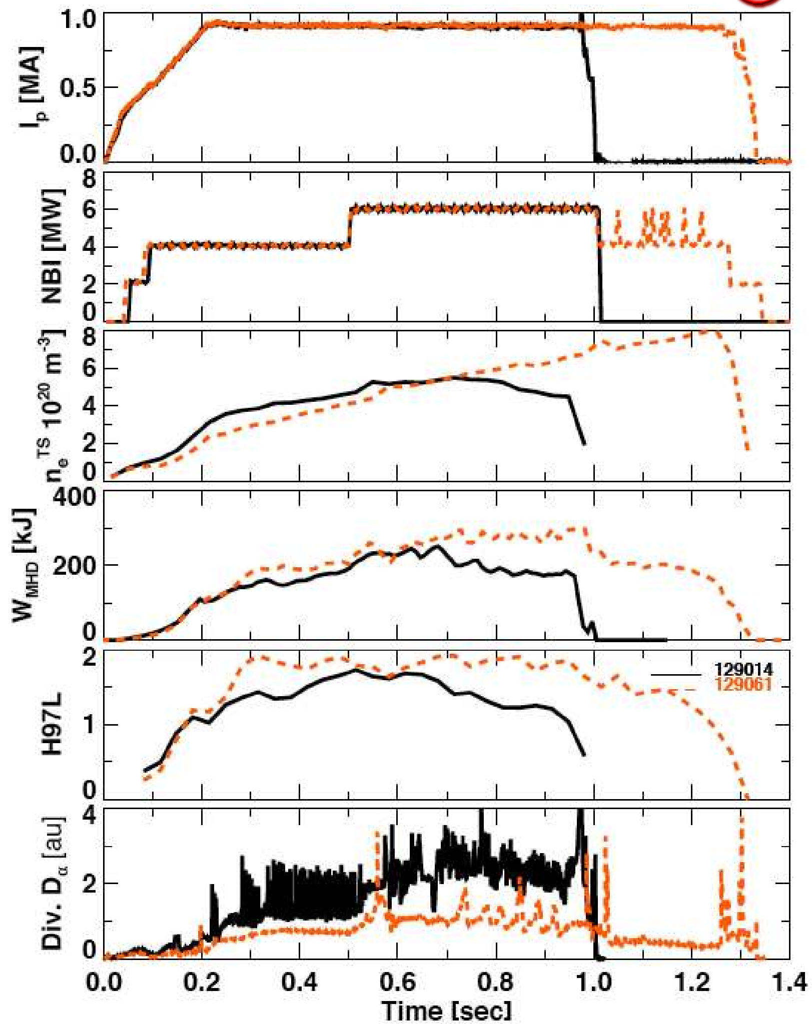
NSTX is not yet in the LiWall regime. There is no effect on the density rise

Li improves performance (NSTX)

Lithium Edge Conditions
Increase Confinement, Stored Energy, and Pulse Length

NSTX

- Comparison for pre-Li and post-Li reference shots with constant NBI, constant external gas, etc.
- Lithium (188 mg) reduced density in initial period up to 0.6s
  – pre-Li discharge was ELMy
  – ELMs were absent on Li shot
- In time, the lack of ELMs causes the density in the discharge with Li to overtake the shot without Li.

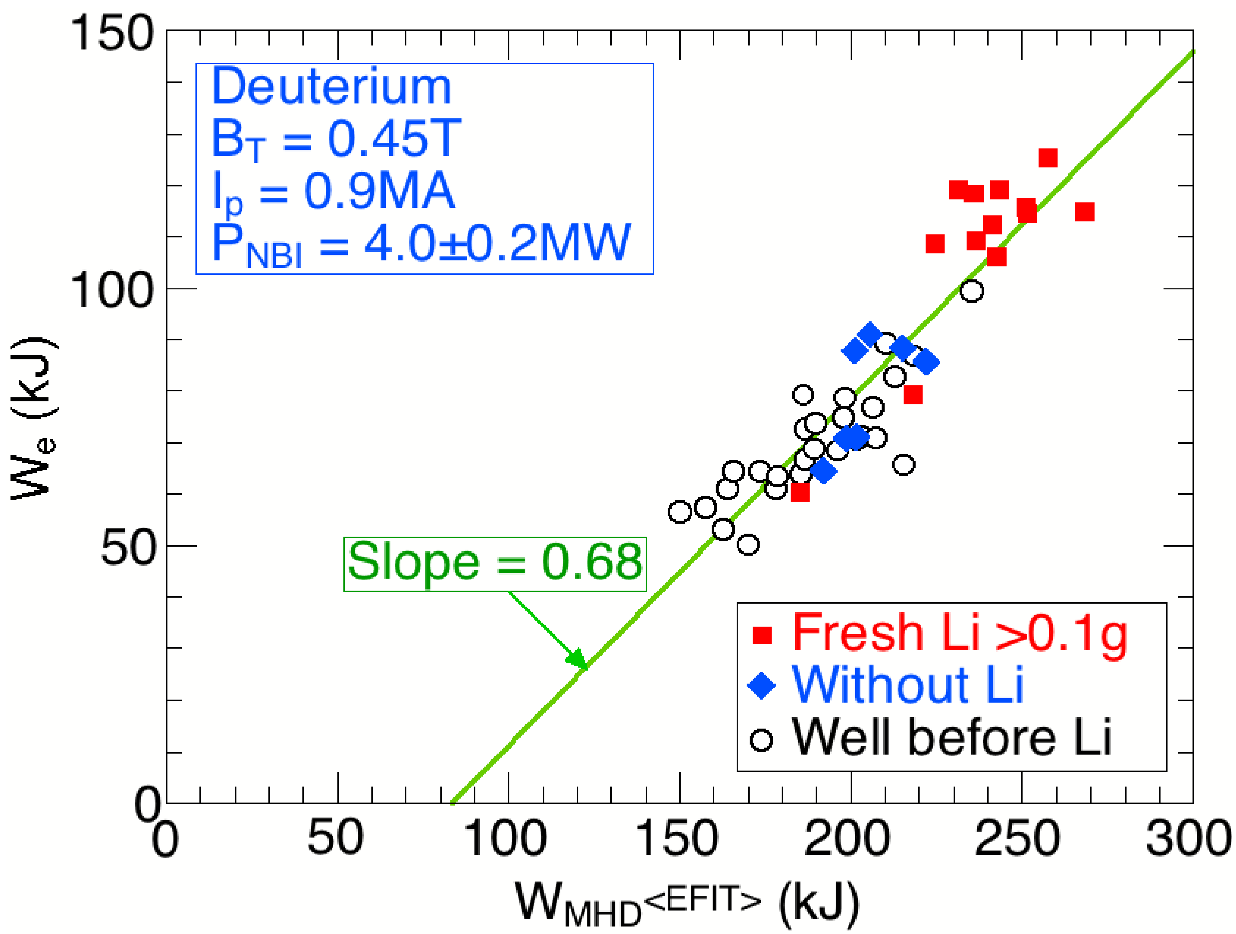


R. Maingi, ORNL 7

Li improves performance (NSTX)

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

NSTX



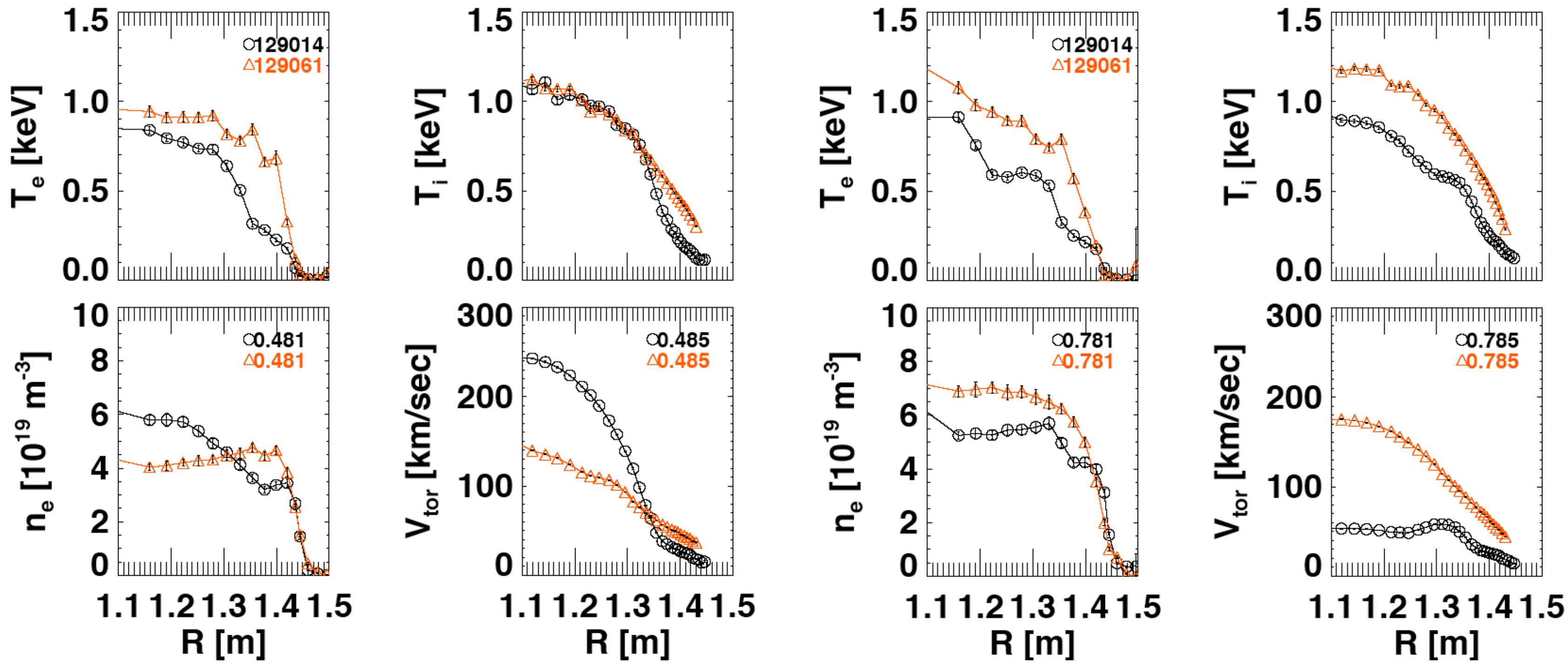
M. G. Bell

• Data sampled at time of peak W_e

Li improves performance (NSTX)

Lithium Edge Conditions Increased Pedestal Electron and Ion Temperature

NSTX



R. Maingi, ORNL

14

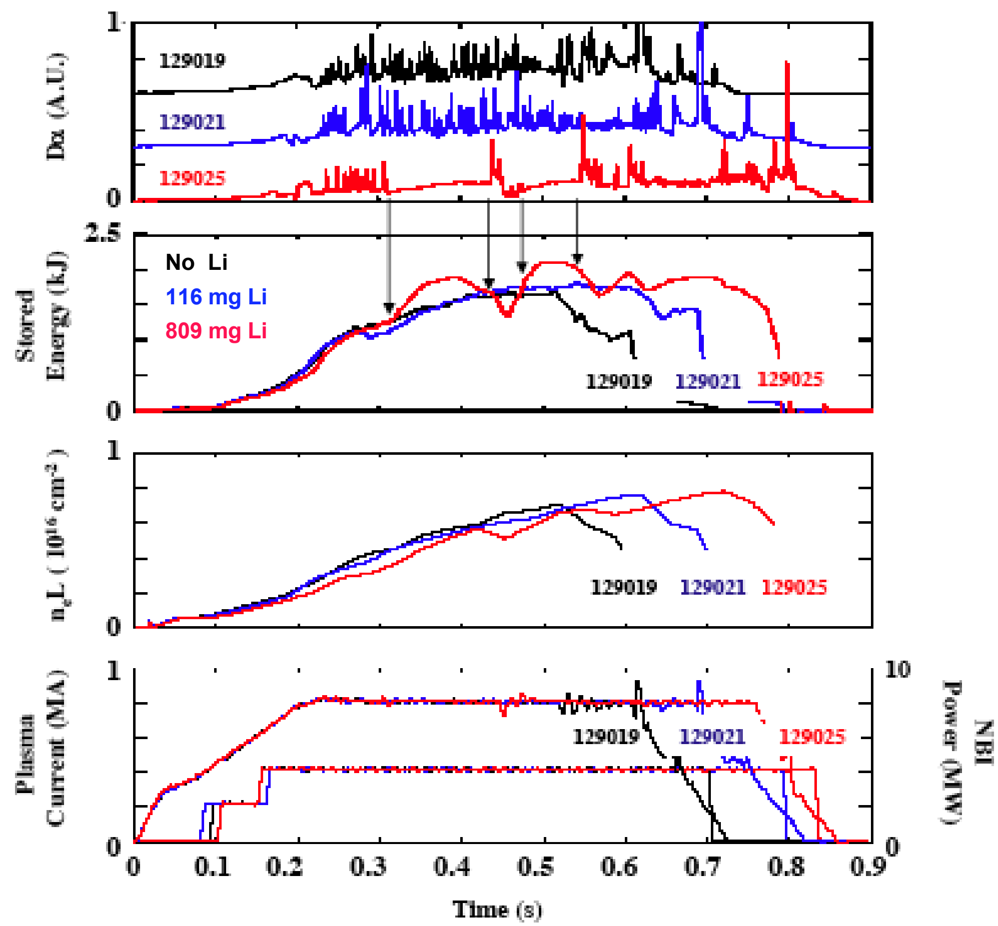
Li improves performance (NSTX)

Lithium Edge Conditions Affect Plasma Behavior

NSTX

As Li increases

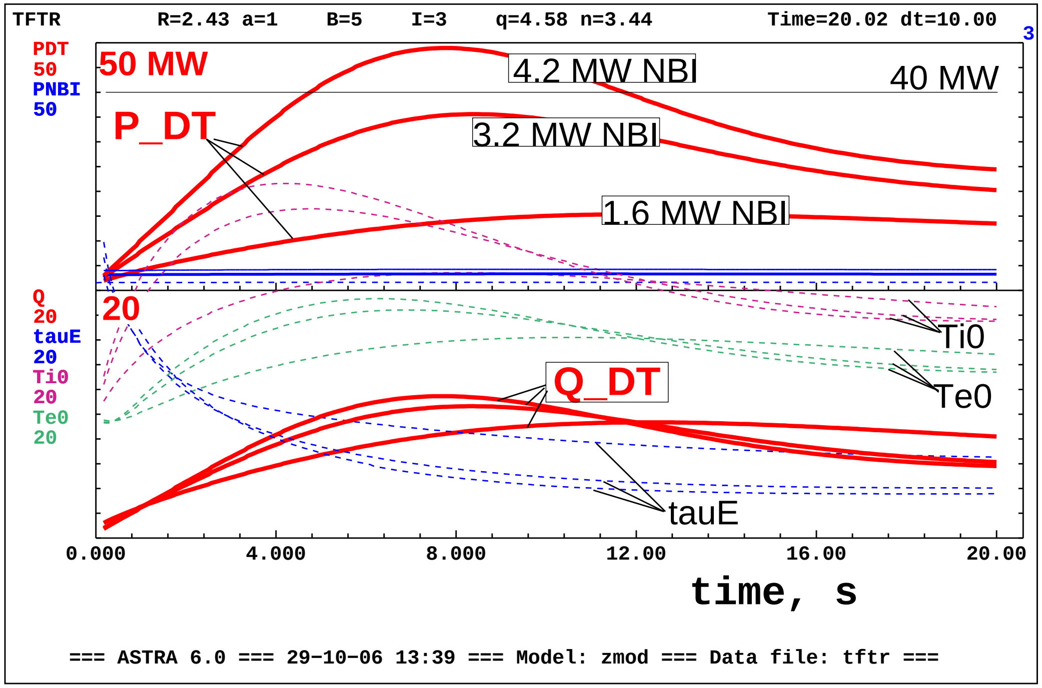
- ELMs decrease
- Stored energy increases
- Pulse lengthens



O-28, D. Mansfield

12

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



Even with no α-particle heating:

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

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

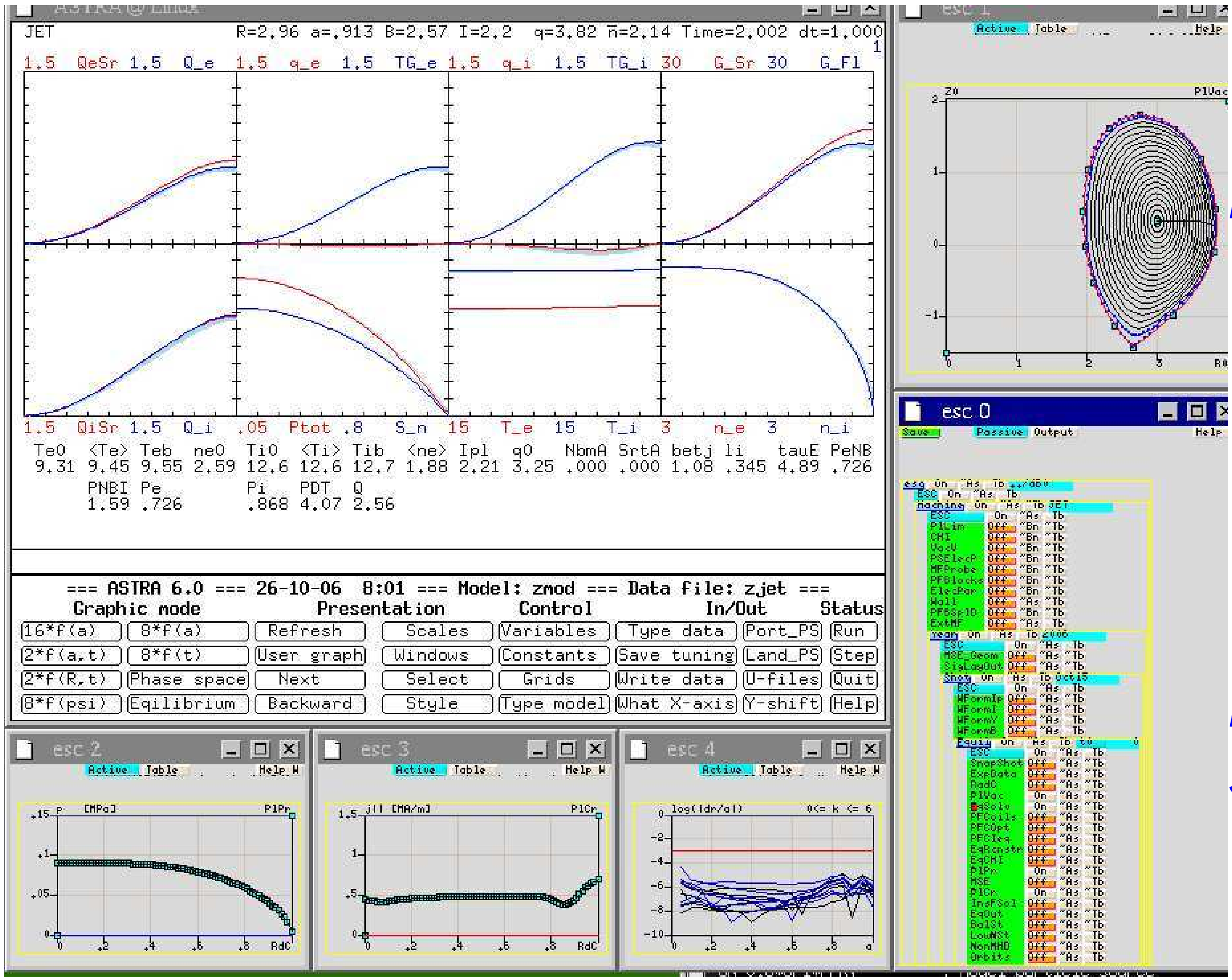
The "brute force" approach ($P_{NBI} = 40$ MW) did not work on TFTR for getting $Q_{DT} = 1$. With $P_{DT} = 10.5$ MW only $Q_{DT} = 0.25$ was achieved.

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

(Ignition criterion corresponds to $Q = 5$)

Simulation of LiW regime for JET

ASTRA-ESC simulations of JET, B=2.6 T, I=2.2 MA, 50 keV NBI



Hot-ion mode:

$$T_i = 12.6 \text{ [keV]},$$

$$T_e = 9.45 \text{ [keV]},$$

$$n_e(0) = 0.3 \cdot 10^{20},$$

$$\tau_E = 4.9 \text{ [sec]},$$

$$P_{NBI} = 1.6 \text{ [MW]}$$

For 50 keV NBI,

3+2 MWs are available

Can be experimentally tested on JET with intense Be conditioning

7 Alpha heating is a Bible of fusion

Ignition condition

$$f_{pk} \cdot \langle p_{\text{MPa}} \rangle \cdot \tau^*_{E,\text{sec}} = 1 \tag{7.1}$$

is a still distant target for magnetic fusion

Here, the τ^*_E *is confinement time required for ignition, while peaking factor* f_{pk}

$$f_{pk} \equiv \frac{\langle 16 p_D p_T \rangle}{\langle p \rangle^2} \simeq 1 \tag{7.2}$$

converts plasma pressure p*:*

$$p = p_D + p_T + p_e + p_\alpha + p_I \tag{7.3}$$

into the fusion producing pressure $p_D p_T$ *of D,T.*

The ignition criterion by itself is controversial:

1. ignition requires large τ^*_E *and reduced* p

2. power production (operational regime) requires high p *and reduced* τ^*_E

and sensitive to dilution: $p_\alpha, p_I, p_e > p_D + p_T$.

No needs in alpha heating for LiWF

RTM predicts the feasibility of the super-critical ignition regime with $\tau_E \gg \tau_E^*$

With LiWall regime the power reactors do not need plasma heating by α-particles

$$Q_{DT} \equiv \frac{P_{DT}}{P_{NBI}} = 5\frac{\tau_E}{\tau_E^*}, \quad \text{e.g., for} \quad \frac{\tau_E}{\tau_E^*} = 10, \quad Q_{DT} = 50. \qquad (7.4)$$

α-particles are free to go out of plasma (together with all huge problems associated with them)

NBI controls everything: temperature, density, density profile, fusion power

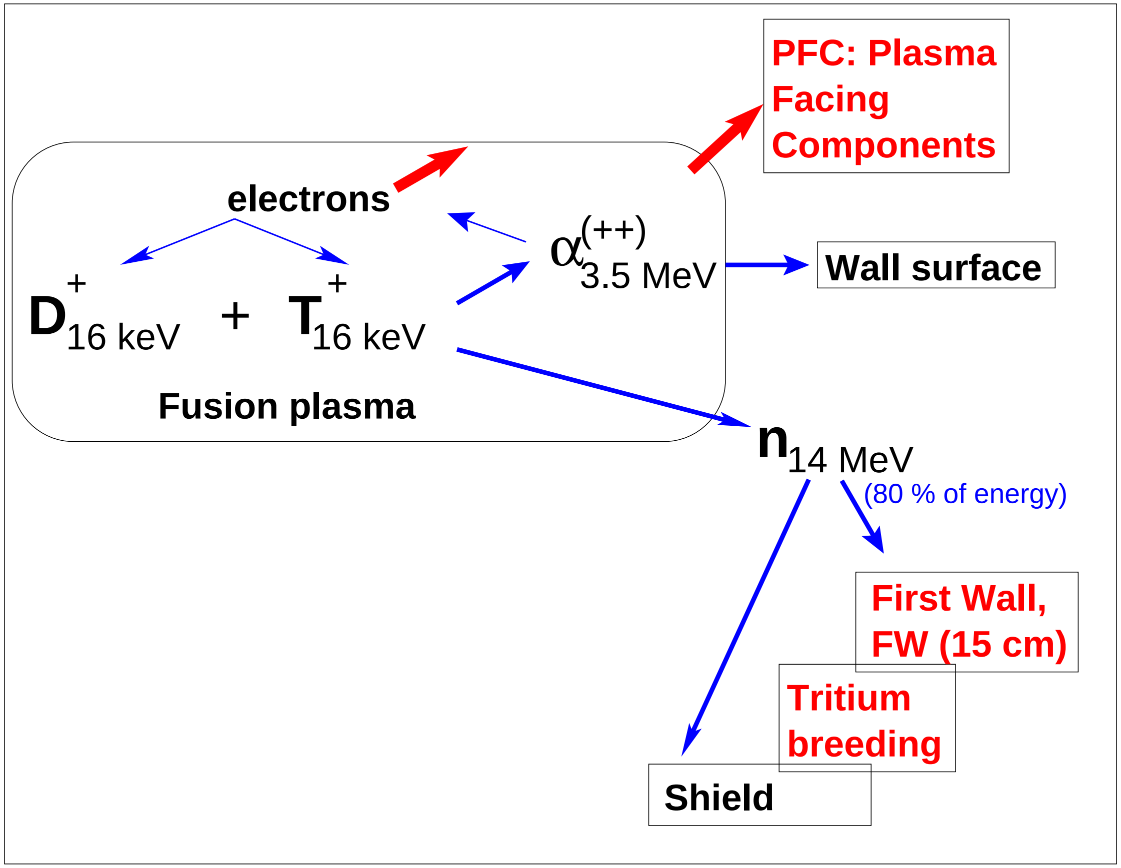
$$T_i \simeq T_e \simeq \frac{1}{5}E_{NBI}, \qquad \int n dV = \tau_E \cdot \frac{1}{e} I_{NBI} \qquad (7.5)$$

No dilution, no impurities, no surprises. Only P_{NBI} goes to the target plates.

For the first time, the LiWF introduces a regime of a “controlled thermonuclear fusion”

8 Two concepts: BBBL70 and LiWF

“The Bib$_b$le of the 70s” (BBBL70) relies on plasma heating by alpha-particles



Flow pattern of fusion energy (since the 50s)

Ignition criterion:

$$f_{pk} \cdot \langle p \rangle \cdot \tau_E^* = 1$$

[MPa • sec]

Peaking factor f_{pk}:

$$f_{pk} \equiv \frac{\langle 16 p_D p_T \rangle}{\langle p \rangle^2}$$

Plasma pressure p:

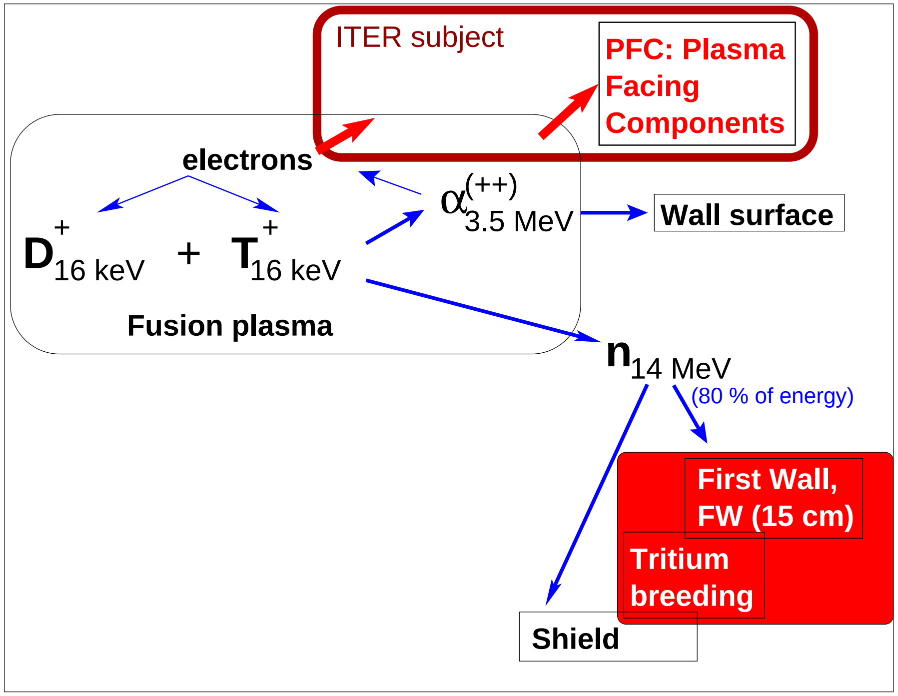
$$p = p_D + p_T + p_e + p_\alpha + p_I,$$

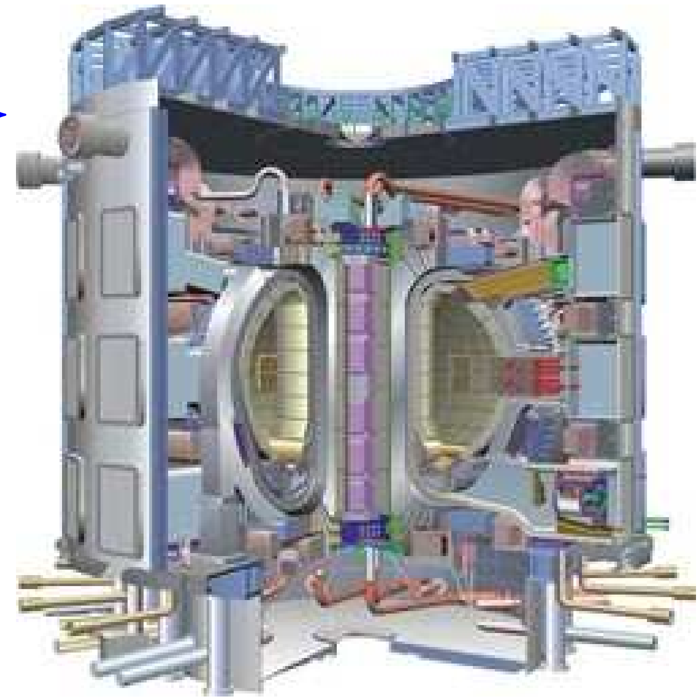
$$p_e > p_D + p_T$$

The plasma is in the “hot-electron” regime, the worst one.

ITER targets the alpha-heating regime

All current plasma physics issues are passed unre-solved to the ITER "burning plasma"

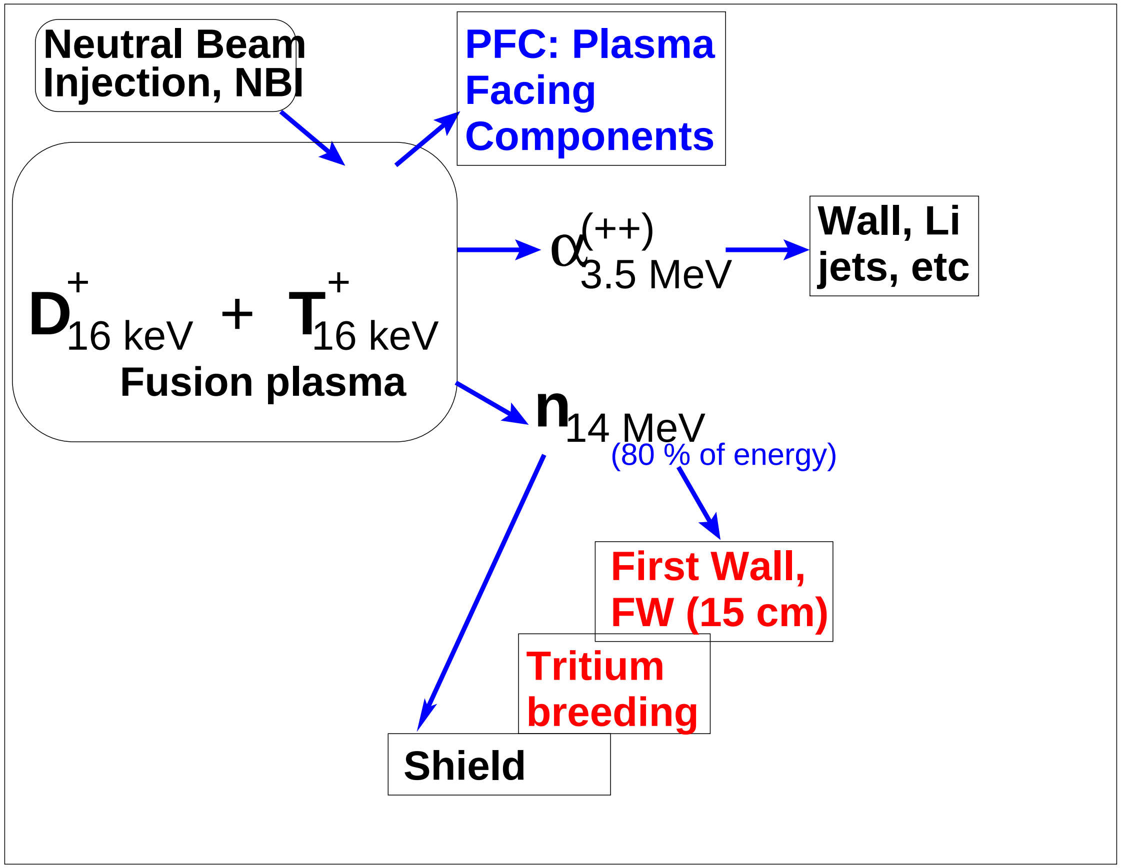




Being an implementation of the old concept, ITER only barely touches the reactor aspects of fusion

LiWF has a clean path to reactor

Reactor issues rather than plasma physics are the focus of LiWF



LiWall concept has a clean pattern of flow of fusion energy

α-particles are free to go out of plasma

NBI controls both the temperature and the density

$$P_{NBI} = \frac{3}{2}\frac{\langle p\rangle V_{pl}}{\tau_E},$$

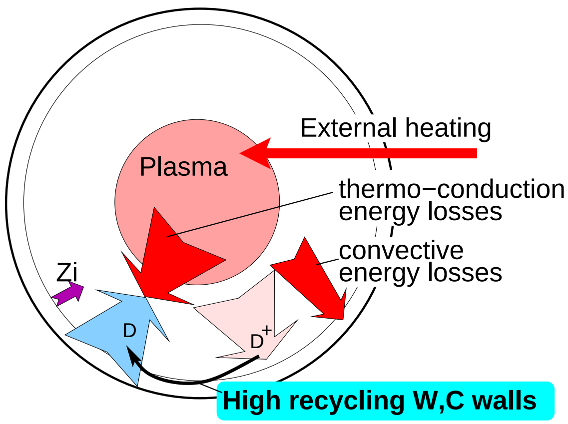
$$\frac{dN_{NBI}}{dt} = \Gamma^{ions}_{core \rightarrow\ edge}$$

Super-Critical Ignition (SCI) confinement is necessary to make NBI work this way

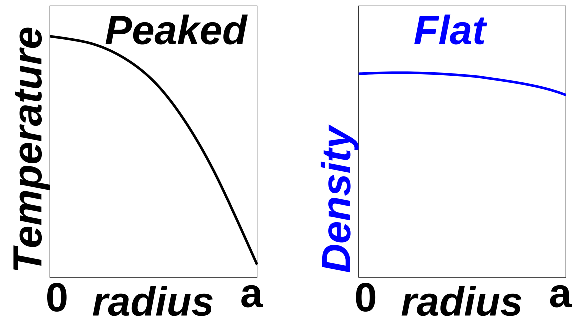
$$\tau_E >> \tau_E^*$$

LiWF conceptually resolves fundamental issues, intractable for BBBL70 for 40 years

Right plasma-wall contact is the key



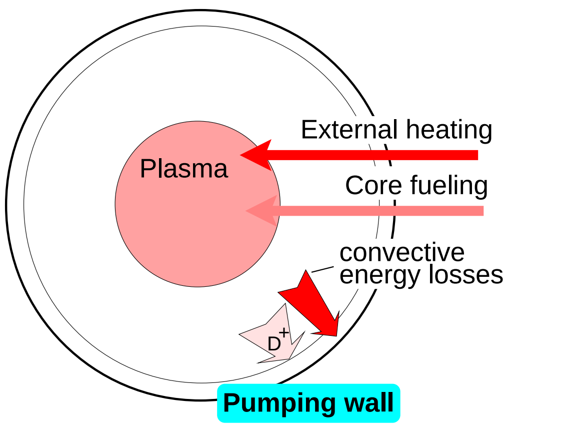
BBBL70 requires a low temperature plasma edge



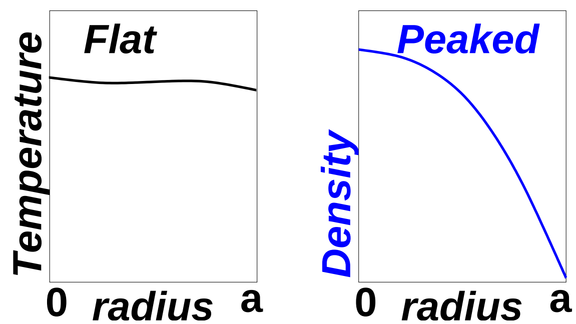
As a "gift" from plasma physics BBBL70 gets ITG/ETG turbulent transport.

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

Most of the plasma volume does not produce fusion



In LiWF the high edge T is OK



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

Stability is excellent. LiWF relies only on external control.

The entire plasma volume produces fusion

Plasma edge and wall surface, rather than the plasma core, have a profound impact on plasma regimes.

9 Summary

Instead of recognizing a failure, the presently adopted

BBBL70 uses the science for keeping alive a failed concept

In contrast

the LiWF relies on science for making its concept consistent with the strategy of DT fusion

The target LiWF plasma regime has been formulated.

There is no visible plasma physics of technology obstacles for fusion to make a decisive step toward power reactor development. It is the nature of the stagnation phase of the program which does not allow to even initiate the first steps in this direction.