The basics of the LiWall Fusion (LiWF) concept

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KSTAR Seminar, NFRI

April 24, 2009, Daejeon, Korea

[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 science of a stationary and stable plasma.

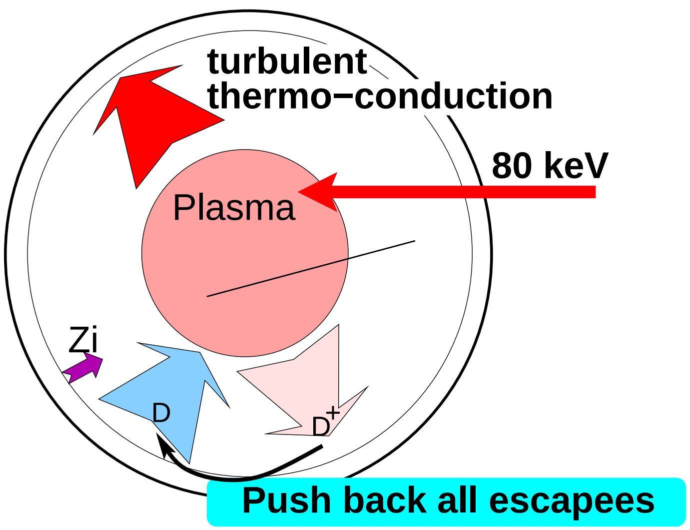
Meanwhile, the demonstration of exceptional pumping capabilities of lithium surfaces on T-11M (1998), discovery of the quiescent H-mode regime on DIII-D (2000), and a 4 fold enhancement of the energy confinement time in CDX-U tokamak with lithium (2005), contributed to a new vision of fusion relying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

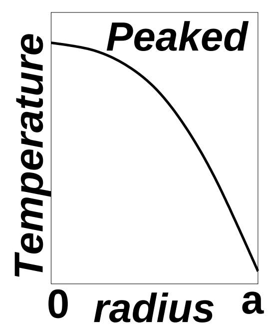
The talk gives an introduction to the LiWF concept for KSTAR people.

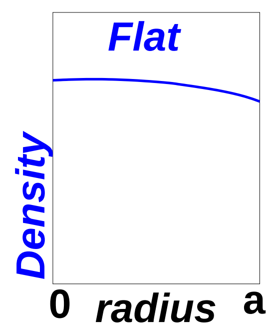
1 Two approaches to fusion plasma

Approach 1:

1. **mix the energetic (80 keV), the most capable particles with the cold stuff from walls,**
2. **charge-exchange and throw away those “capable” who do not “obey”,**
3. **return all escapees back to configuration,**
4. **and make all plasma particles equal and happy at 1 keV, reportable to DoE.**







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

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

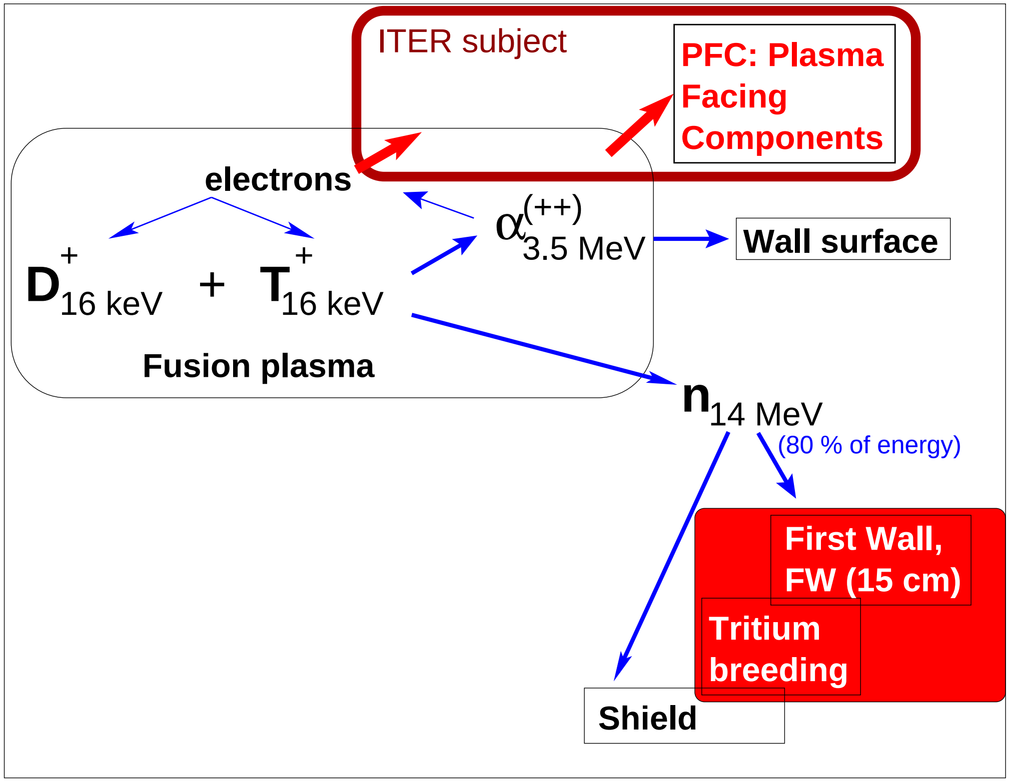
Most of the plasma volume does not produce fusion

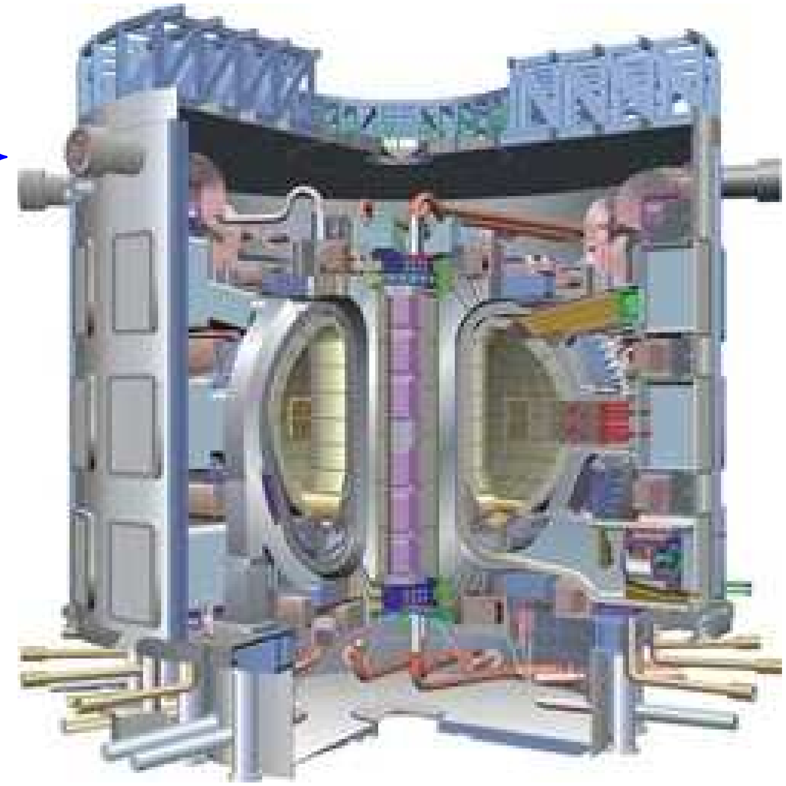
Plasma pays back by low performance: energy is lost due to turbulent thermo-conduction (unlimited).

Practicing “slavery” is in conflict with science and does not lead to progress

ITER targets the alpha-heating regime

All current plasma physics issues are passed unresolved to the ITER "burning plasma". Anomalous electrons lead to large size.

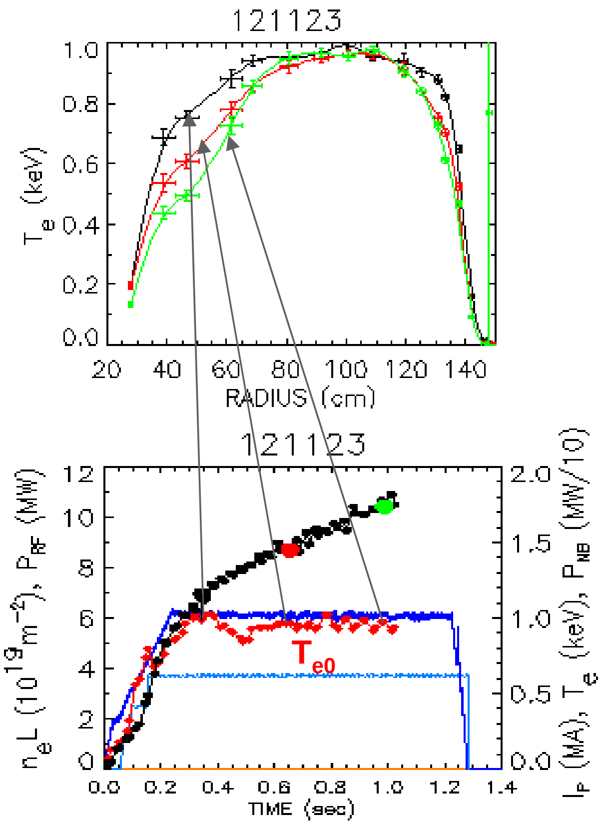




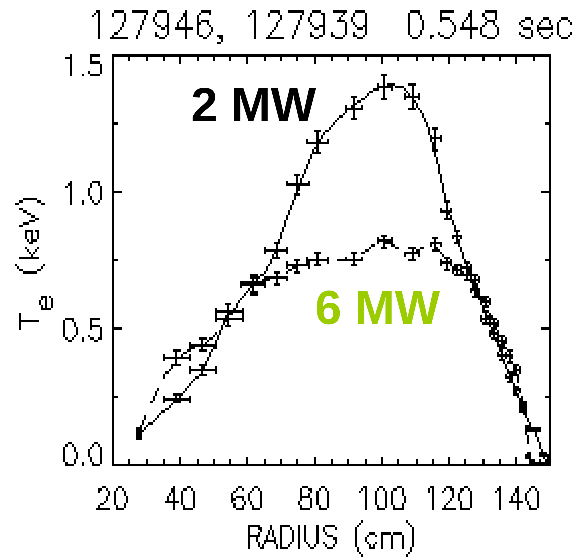
Being an implementation of the old concept, ITER only barely touches the reactor aspects of fusion

Electrons are and will be unpredictable

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

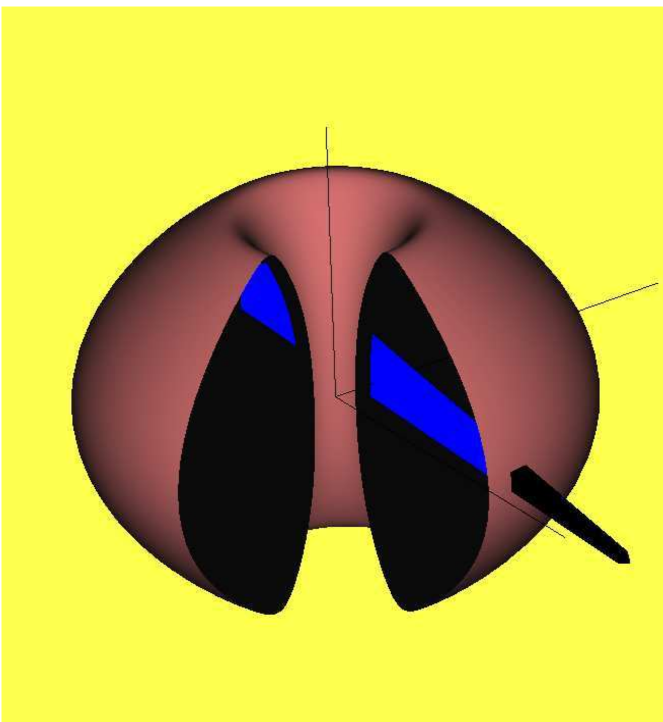
- Only slight rounding of T_e 'shoulders' with time
- Central T_e higher at 2 MW than at 6 MW, even at increased B_t and I_p

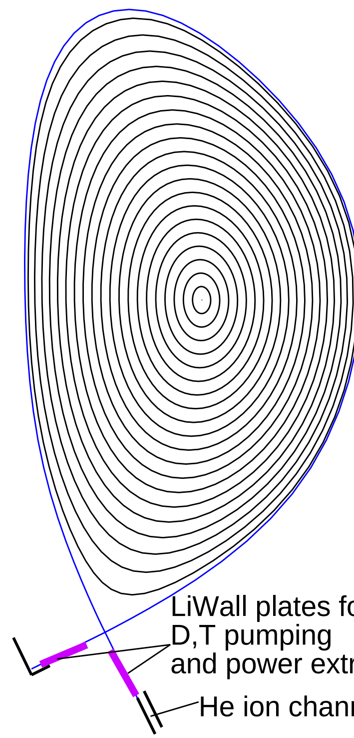
2 Two elements of LiWall Fusion

Approach 2: What will happen, if

1. **Neutral Beam Injection (NBI) supplies particles into the plasma core, while**
2. **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.)





LiWF relies on "Let my plasma go", rather than on "slavery"

The essence of the LiWF regime

The answer is simple:

Plasma temperature will be uniform

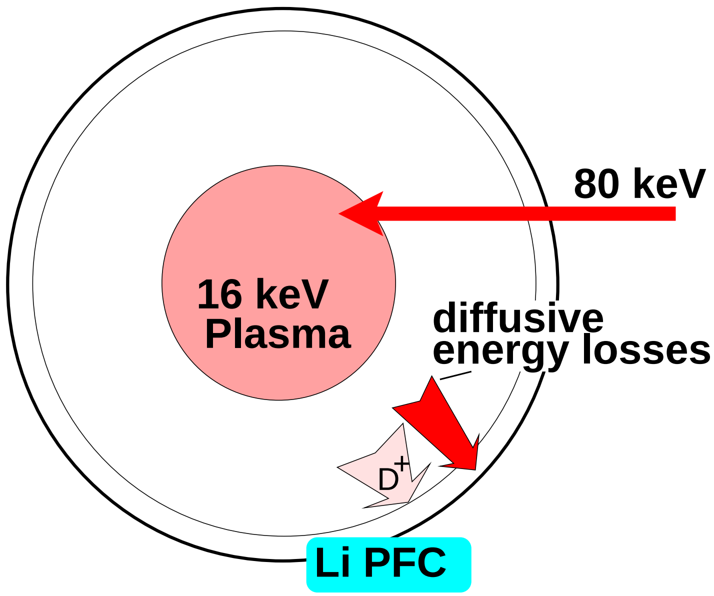
$$\frac{T_i + T_e}{2} \simeq \frac{E^{NBI}}{5}, \quad \nabla T_i = 0, \quad \nabla T_e = 0 \qquad (2.1)$$

Plasma physics is not involved into this answer.

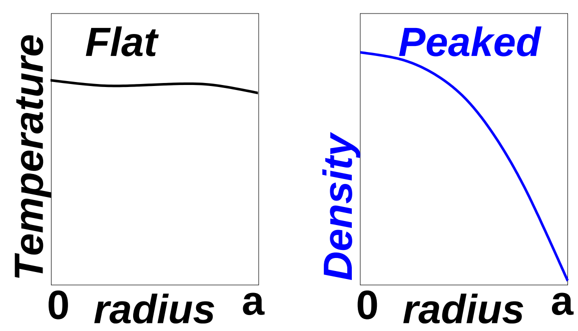
ITG, ETG, which are the major cause of energy losses, will be eliminated automatically, and there is no science fiction here.

Only particle diffusion matters

Independent of anomalous electrons, rate of losses is determined by neo-classical ions, the best confined plasma component.



In LiWF the high edge T is OK



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

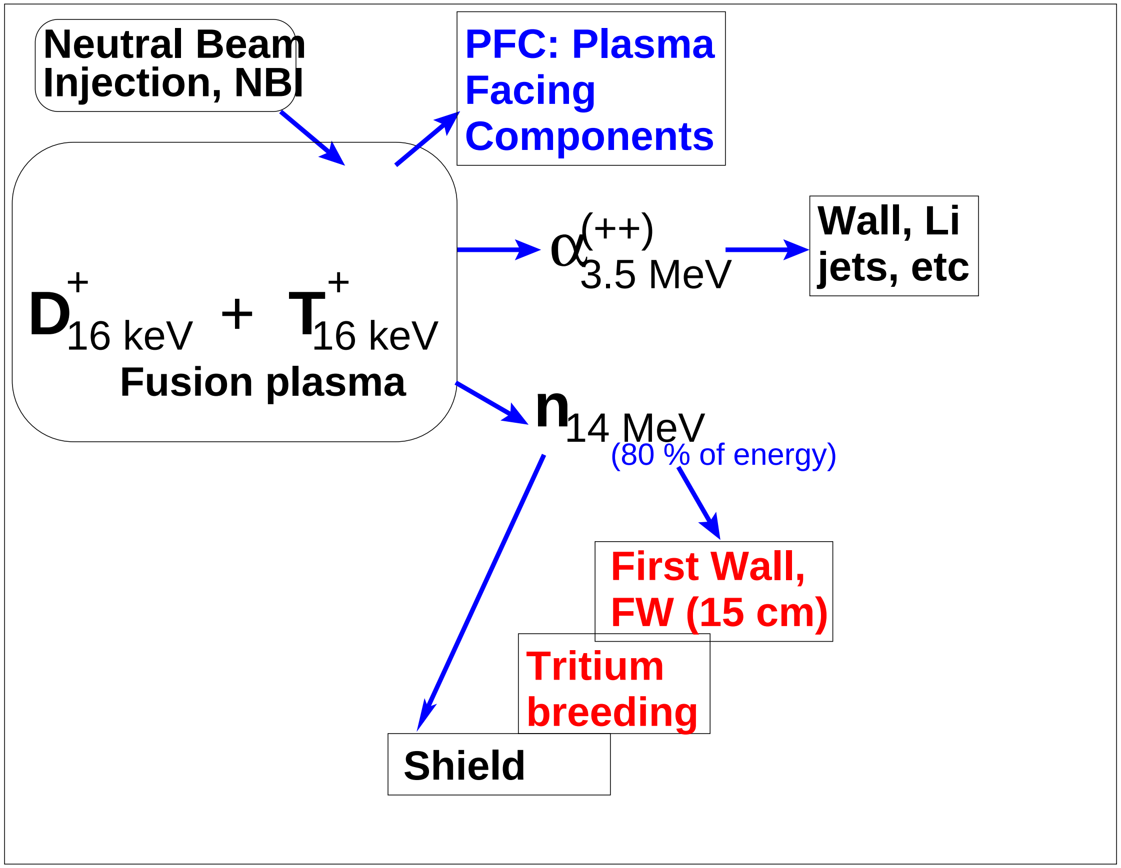
Stability is excellent. LiWF relies only on external control.

"Let my plasma go" is the best possible confinement regime. Also, the entire plasma volume will produce fusion.

Anomalous electron thermo-conduction, an unresolvable problem for fusion, plays no role in LiWF.

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 is very consistent with Fusion-Fission ideas

The target plasma regime can be develop without use of tritium

3 Physics of LiWF

LiWF introduces (a) core fueling and (b) the right plasma-wall interaction when plasma particles are absorbed by the wall.

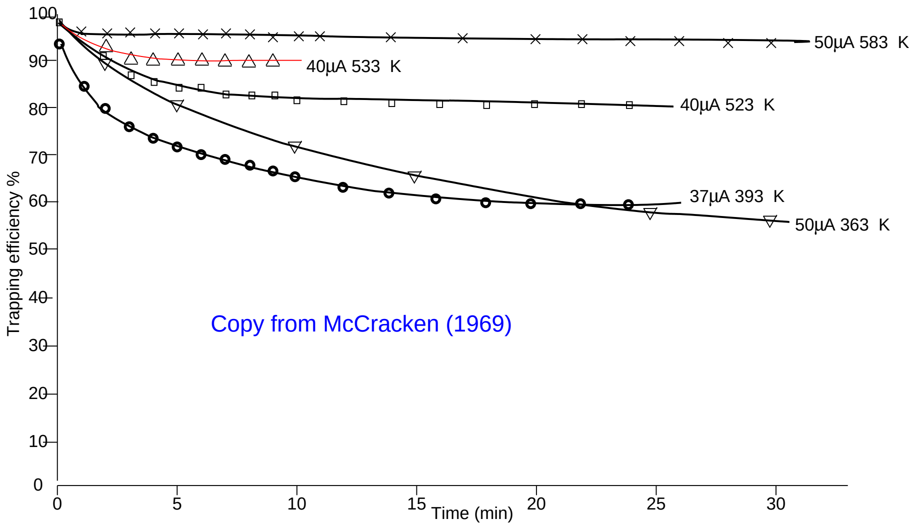
This combination multiplies by 0 the value for fusion (if ever existed) of ongoing ITG, ETG turbulence studies

(whether plasma physicists want to accept this or not).

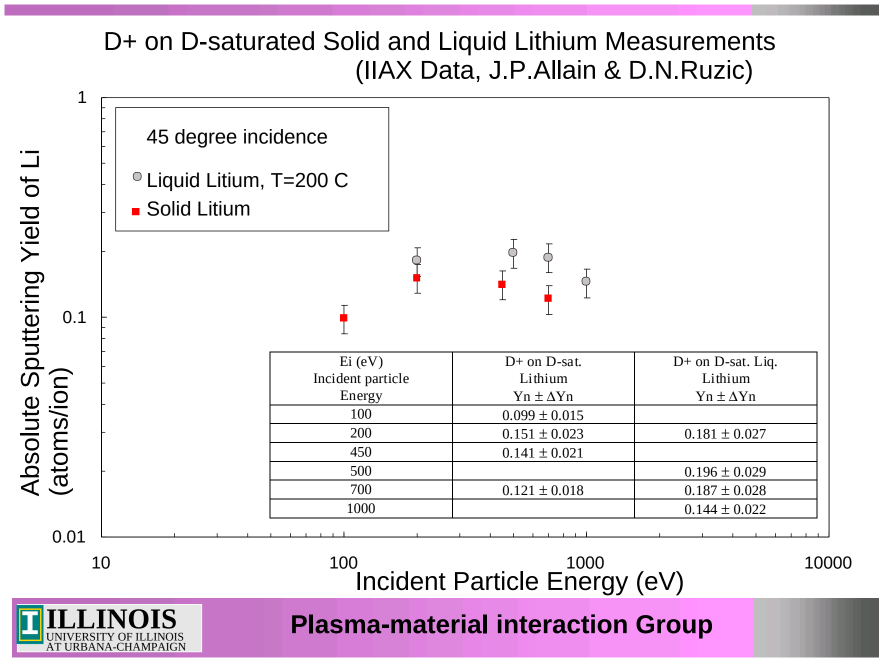
The right plasma contact with the wall, rather than the transport properties of the core, determines the plasma regime for controlled magnetic fusion.

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

Lithium can retain ≃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

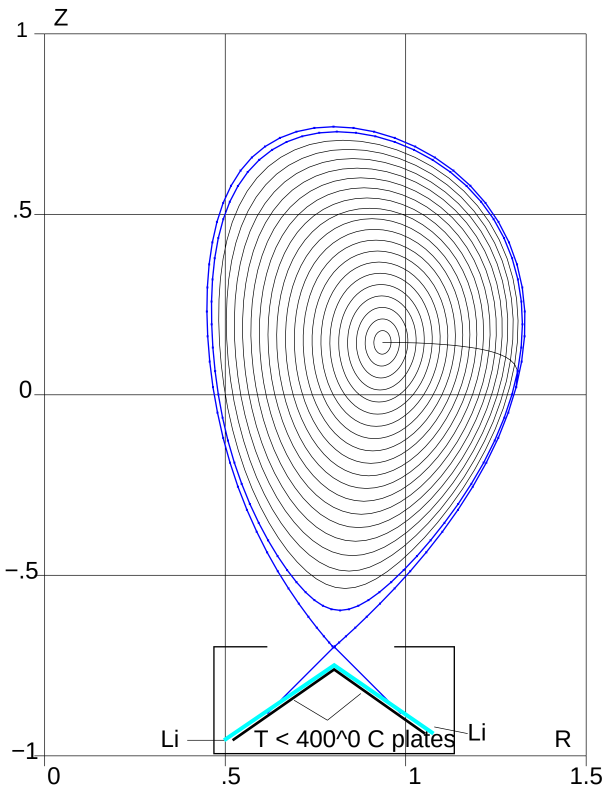
Because of evaporation, the surface temperature of Li should be limited (by ≃ 400^o C)

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

More Li technology studies are necessary

V≃1 cm/sec is sufficient for replenishment

Pumping Li Divertor ≡ flowing h≃ 0.1 mm Li along the actively cooled plate



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

$$V_g = \frac{\rho g h^2}{2\nu} \sin\theta = 0.049 \sin\theta \; [m/s],$$
$$V_M = \frac{d\sigma(T)}{dT}\frac{h\nabla T}{\nu} = 0.8 h\nabla T \; [m/s] \qquad (3.1)$$

are sufficient for replenishing Li surface.

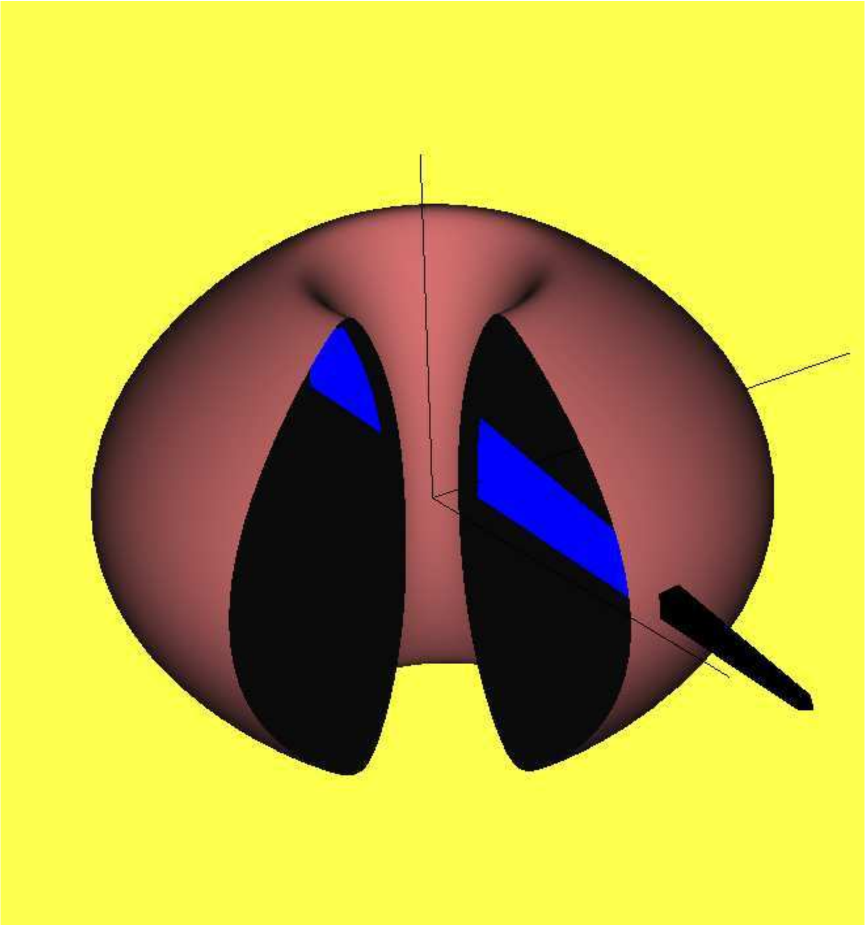
Lithium can accept 5-10 MW/m^2 *and keep* $T_{Li} < 400^o C$

$$\chi_{Li} = 47.6,$$
$$\Delta T\,[^oC] = 100\frac{q}{4.7} \cdot h \left[\frac{MW}{m^2} \cdot mm\right]. \qquad (3.2)$$

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 (≥ 1 mm) Li on the target plate

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

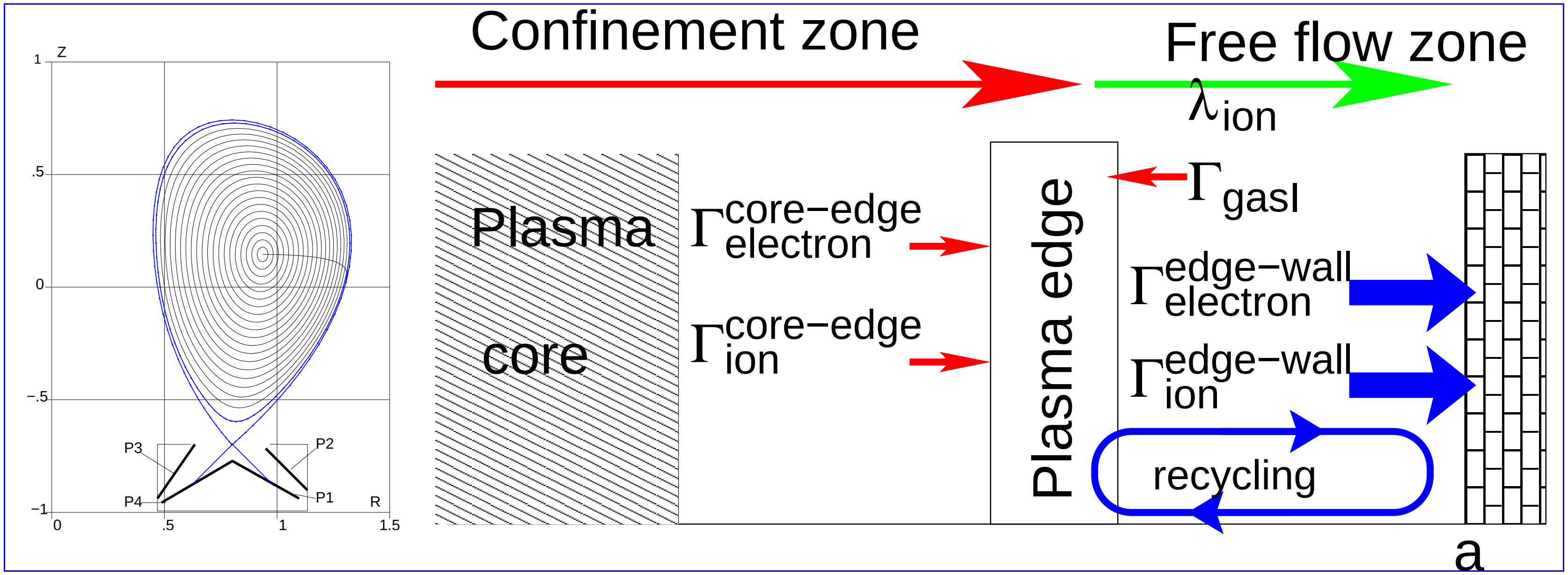
$$\nu_i = 68\frac{n_{20}}{T_{i,10}^{3/2}}, \quad \nu_e = 5800\frac{n_{20}}{T_{e,10}^{3/2}}$$

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)

Analysis comes from LiWF, which requires recycling $R \ll 1$



The plasma edge, understood as a transition zone from diffusive transport to a convective one, is located approximately at one mean free path

$$\lambda_{\|,D,m} = 121\frac{T_{keV}^2}{n_{20}} \qquad (3.3)$$

from the plasma facing surface. For $T_{edge} > 1$ keV the mean free path $\lambda_{\|,D,m}$ can be as large as $\simeq 1$ km or more.

Edge plasma temperature is determined by the particle fluxes self-consistently with power (Krasheninnikov)

Across the last mean free path, λ_D, in front of PFC surface the energy is carried out by moving particles

$$\frac{5}{2}\Gamma_e^{edge-wall}T_e^{edge} = \int_V P_e dV - \frac{\partial}{\partial t}\int_V \frac{3}{2}nT_e dV,$$
$$\frac{2}{5}\Gamma_i^{edge-wall}T_i^{edge} = \int_V P_i dV - \frac{\partial}{\partial t}\int_V \frac{3}{2}nT_i dV. \qquad (3.4)$$

In its turn the particle fluxes to PFC are related to the fluxes from the core by recycling coefficients $R_{i,e}$

$$\Gamma_i^{edge-wall} = \frac{\Gamma_i^{NBI} + \Gamma_i^{gasI}}{1-R_i}, \qquad \Gamma_e^{edge-wall} = \frac{\Gamma_e^{NBI} + \Gamma_e^{gasI}}{1-R_e} \qquad (3.5)$$

In the Lithium Wall Fusion (LiWF)

$$\Gamma_{e,i}^{edge-wall} \simeq \Gamma_{e,i}^{NBI}$$

T_{edge} is a boundary condition

T_{edge} is not sensitive to transport coefficients near the plasma edge

$$\begin{aligned} T_e^{edge} &= \frac{2}{5}\cdot\frac{1-R_e}{\Gamma_e^{NBI}+\Gamma^{gasI}}\left(\int_V P_e dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} n T_e dV\right), \\ T_i^{edge} &= \frac{2}{5}\cdot\frac{1-R_i}{\Gamma_i^{NBI}+\Gamma^{gasI}}\left(\int_V P_i dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} n T_i dV\right) \end{aligned} \qquad (3.6)$$

and serves as a **boundary condition** *for the confinement zone.*

In the LiWF regime this implies that

$$T_{edge} \simeq T_{core}$$

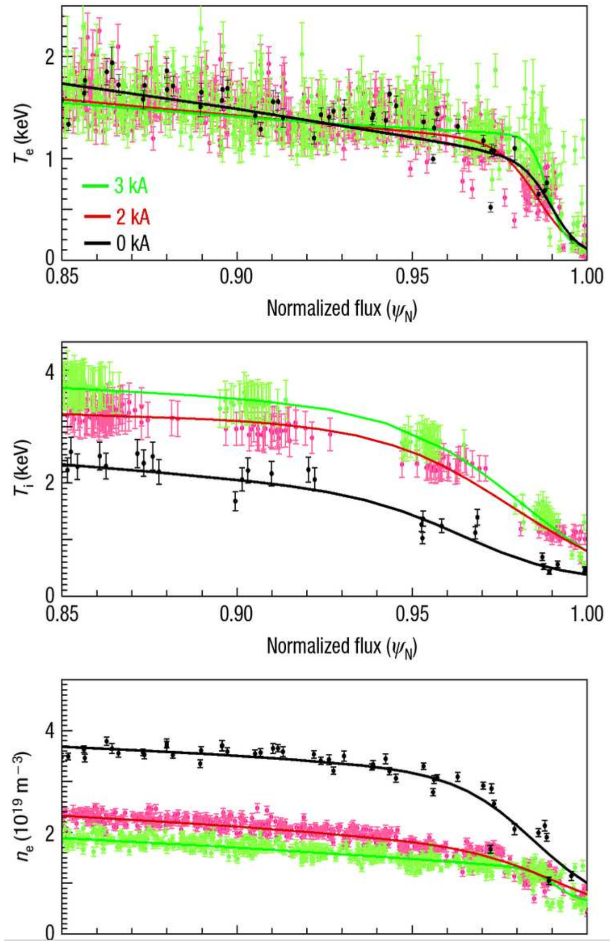
Widespread among plasma physicists and wrong boundary condition

$$T_{edge} = T_b = \mathrm{const}$$

leads to misconceptions, like "the edge transport barrier".

DIII-D made crucial input to LiWF

RMP experiments on DIII-D have confirmed the basic point of LiWF: the pedestal temperature is a boundary condition determined by boundary physics



0 kA, 2 kA, 3 kA $I_{RMP-coil}$

RMP experiments exposed an outstanding^2 fiasco of transport theory of toroidal plasma, which for 30 years considered the pedestal region as a so-called "edge transport barier".

In the talk "Magnetic Confinement: Establishing the Principles through Experiment" *APS-2008 (Session AR0: Celebration of Plasma Physics Plenary Presentations I, November 17, 2008)****,***

the invited speaker has presented the shear rotation stabilization of turbulence in the edge transport barrier as a great success of turbulence theory.

In fact, there is no electron confinement in the pedestal region. The confinement zone is only of inside the tip of the pedestal.

T.Evans at al., Nature physics 2, p.419, (2006)

LiWF puts toroidal confinement of the real plasma on a scientific basis

3.3 The “know-how” of the LiWF regime

The simple formula

$$\frac{T_i^{edge}+T_e^{edge}}{2} \simeq \frac{1-R_{e,i}}{1+(\Gamma^{gasI}/\Gamma^{NBI})} \cdot \frac{\left\langle E^{NBI} \right\rangle}{5}$$

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 this formula. LiWF regime is not sensitive to TEM.

They might be important only because $\tau_E = 3/5\tau_D$ can be affected.

Increase in NBI current will confront TEM e-e-e-e-e-e-e-easily without involvement of plasma physicists.

3.4 Confinement: Ions are neo-classical in NSTX

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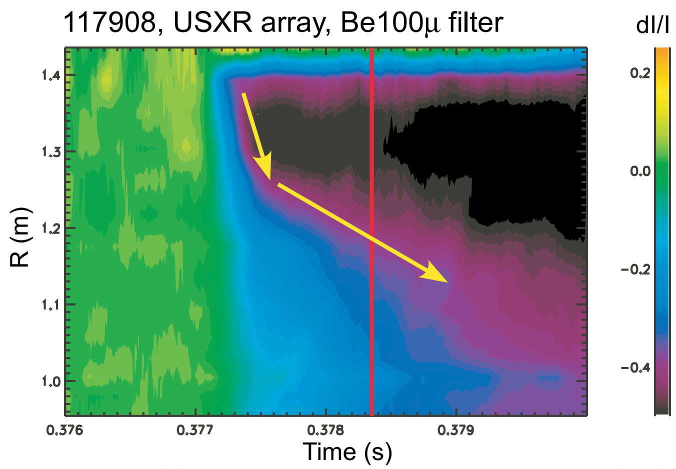
NSTX

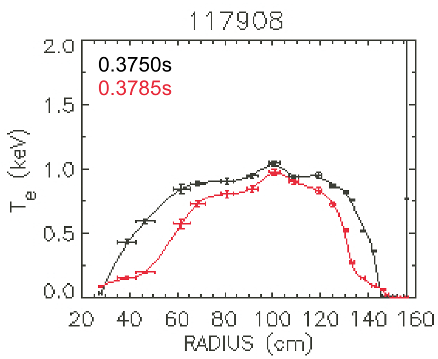
Perturbation Analysis Indicates Two Regions of $\chi_{e,pert}$

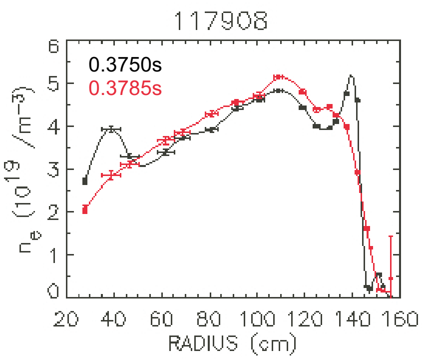


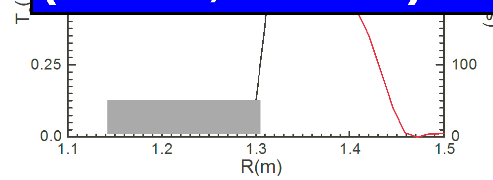
- T_e crash propagates from edge to core, n_e globally unperturbed

- 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)





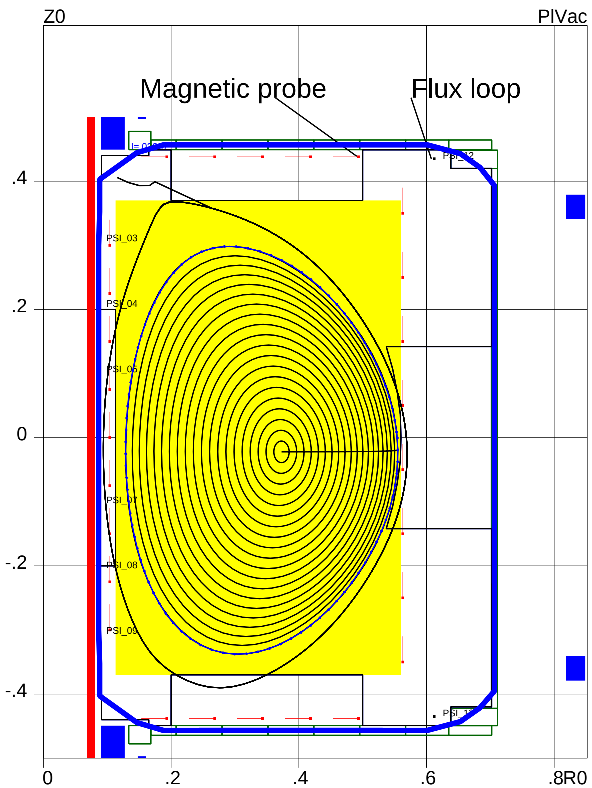


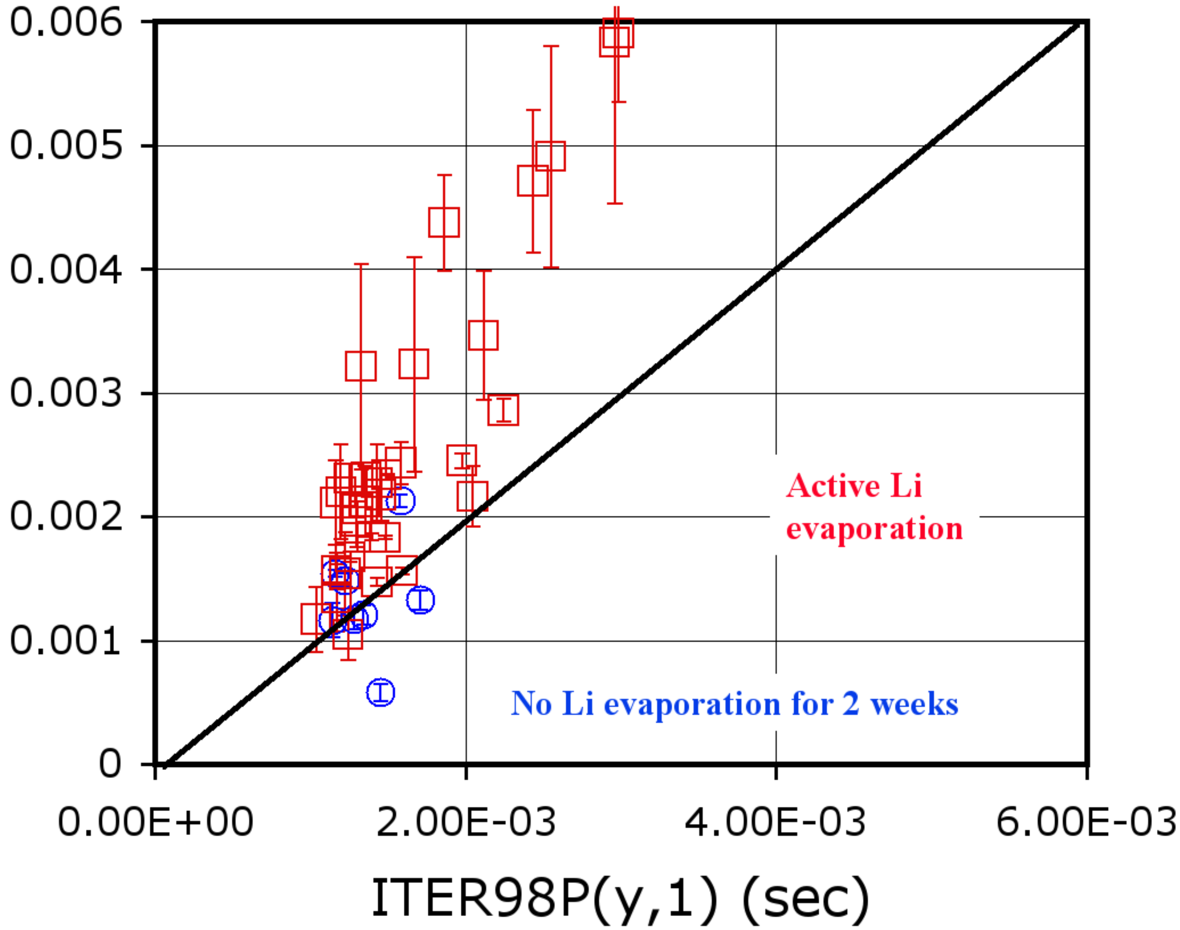
- Dependence of $\chi_{e,pert}$ on T_e gradient suggests critical gradient threshold

Reference Transport Model (RTM) $D = \chi_i = \chi_e = \chi_i^{neo}$ **uses this fact**

Four fold confinement improvement in CDX-U

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





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

$$\begin{aligned} \Gamma^{core} &= \chi_i^{neo-classical}\nabla n, \\ q_i &= n\chi_i^{neo-classical}\nabla T_i, \qquad \text{not important}, \\ q_e &= n\chi_i^{neo-classical}\nabla T_e, \qquad \text{not important} \end{aligned} \tag{3.7}$$

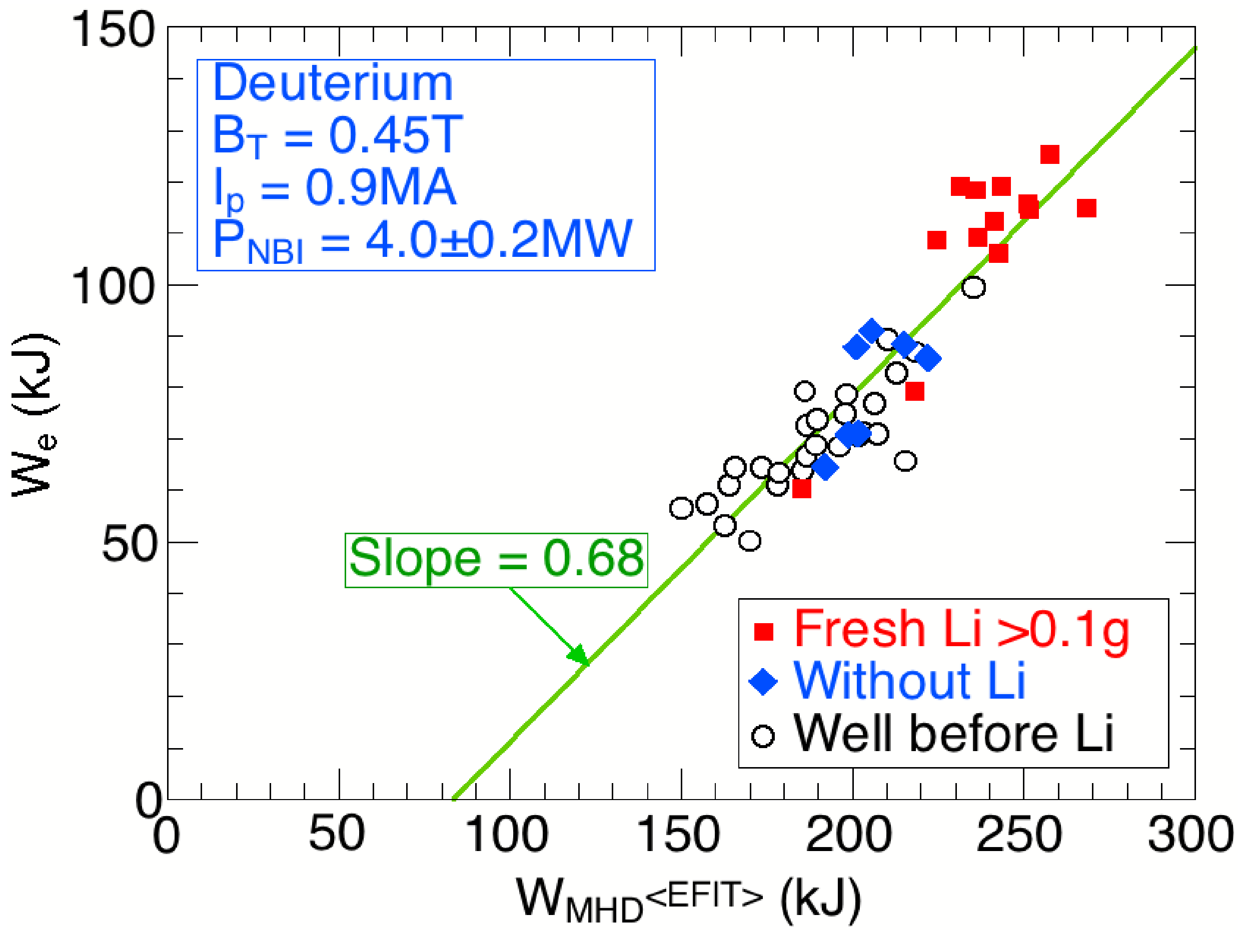
Parameter	CDX-U	RTM	RTM-0.8	glf23	Comment Table 1
$\dot{N}$, 10^{21} part/sec	1-2	.98	0.5	0.8-3	Gas puffing rate adjusted to match
β_j	0.160	0.151	0.150	0.145	measured β_j
l_i	0.66	0.769	0.702	0.877	internal inductance
V, Volt	0.5-0.6	0.77	0.53	0.85	Loop Voltage
τ_E, msec	3.5-4.5	2.7	3.8	2.3	
$n_e(0)$,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

Li improves performance (NSTX)

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

NSTX



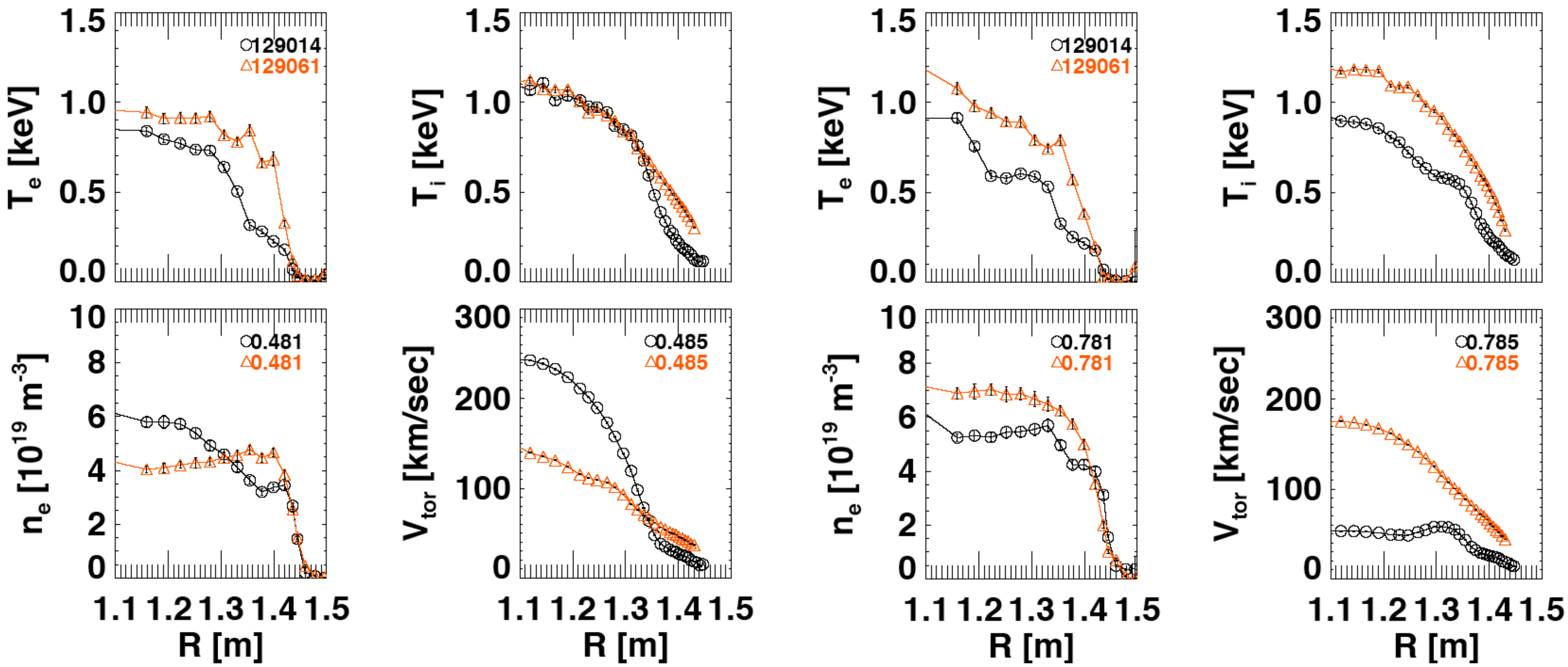
M. G. Bell

• Data sampled at time of peak W_e

Li improves performance (NSTX)

Lithium Edge Conditions Increased Pedestal Electron and Ion Temperature

NSTX



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

R. Maingi, ORNL

PPPL PRINCETON PLASMA PHYSICS LABORATORY

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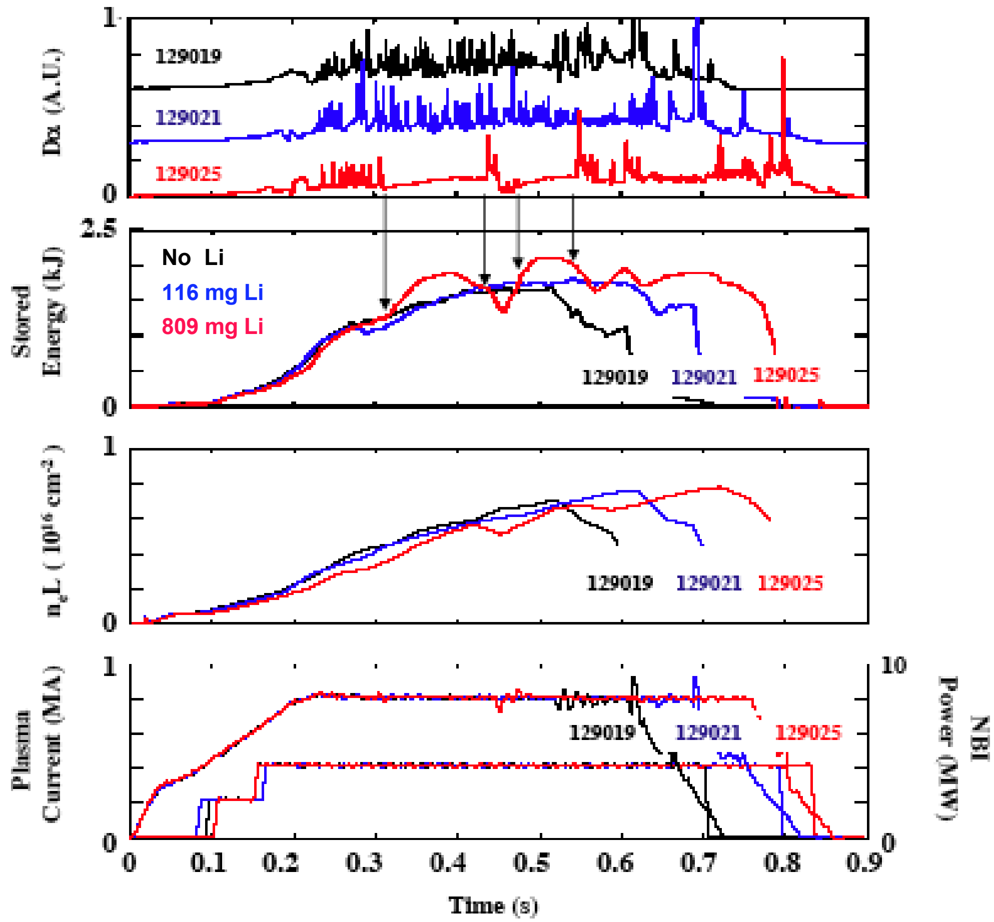
Li improves performance (NSTX)

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

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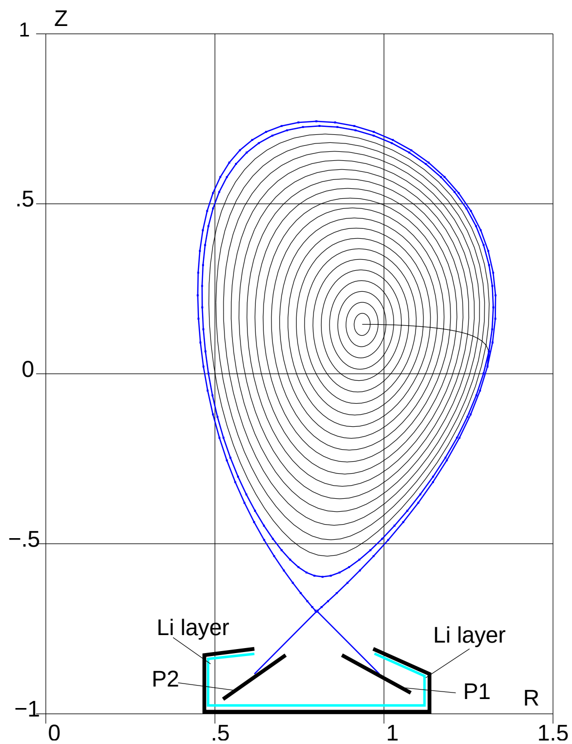
3.5 LiWF and stationary plasma

LiWF suggests the self-consistent approach to the stationary plasma



Three forces are acting on impurities on the way from PFC to the plasma:

1. ***A small electro-static force ZeE_{SOL}, directed back to the plate.***
2. ***Friction $R_V \propto Z^2$ with the ion flow, also directed back to the plate.***
3. ***Thermo-force $R_T \propto Z^2$, driving impurities into the plasma.***

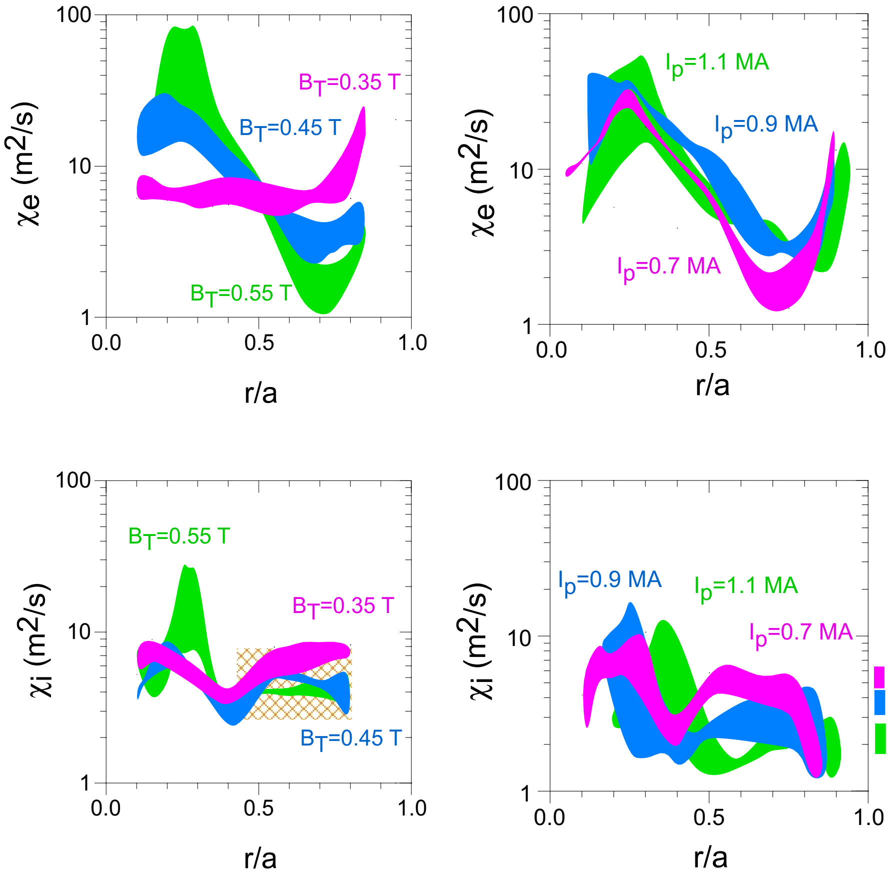
In addition, there is a direct plasma-wall interaction through the radial bursts of blobs.

At high T_{edge} and collision-less SOL the thermo-force is absent, leading to $Z_{eff} \simeq 1$

Interaction with side walls is not expected (blobs are absent)

3.6 Three potential problems for LiWF

1. Trapped electron modes due to density gradient. Their role is questionable.



LiWF regime relies on ion confinement (diffusion).

Ions remain neoclassical even in the presence of anomalous electrons (and turbulence).

Fig.3 and Fig.5 from "Scaling of Electron and Ion Transport in the High-Power Spherical Torus NSTX" by S. M. Kaye, R. E. Bell, D. Gates, B. P. LeBlanc, F. M. Levinton, J. E. Menard, D. Mueller, G. Rewoldt, S. A. Sabbagh, W. Wang, and H. Yuh. Phys.Rev. Lett. v.98, p. 175002 (2007)

2. Secondary electron emission is equivalent to a high electron recycling. Looks as a more serious problem.

3. Pumping out the low density helium ash should be learned

None is really troublesome.

4 LiWF never failed with its predictions

Despite existence of LiWF for more than 10 years, there is no single experiment implementing it. At the best, there are Li limiters (T-11M, CDX-U, FTU) with no core fueling or Li conditioning (TFTR, NSTX). But even with partial implementation:

1. *Confinement was e-e-e-e-e-e-easily enhanced in all machines with Li PFC (4 fold in CDX-U, 1.5 fold in NSTX)*
2. *Plasma density e-e-e-e-e-e-easily passed the Greenwald limit in FTU (from 0.7 to 1.8 with Li)*
3. *All MHD activity disappeared in CDX-U immediately after obtaining the liquid Li surface.*
4. *NSTX control system e-e-e-e-e-e-easily enhanced the discharge length to a record 1.8 sec (shot #129125)*
5. ***ELM stabilization, understood and predicted in 2005, have been confirmed on NSTX***
6. *Perfect fit with CHI discharge initiation was confirmed on NTSX.*
7. *and so and so on.*

Confirmations of other predictions are expected in near future.

Two things were unexpected: (a) the easiness in obtaining predicted effects in experiments, and (b) the excellent coupling of HHFW with plasma.

Diffusion based confinement

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

LiWF vs Main Stream Fusion (MSF)

LiWF is compatible with existing fusion technology

Issue	LiWF	MSF concept of "fusion"
The target	RDF as a useful tool	Political "burning" plasma
Operational point:	$P_{NBI} = E/\tau_E$	ignition criterion $f_{pk} p \tau_E = 1$
Hot-α, 3.5 MeV	"let them go as they want"	"confine them"
He ash, mixed with plasma	residual, flashed out by core fueling	"politely expect it to disappear"
$P_\alpha = 1/5 P_{DT}$	goes to walls, Li jets	dumped to SOL
Power extraction from SOL	conventional technology	no idea except to radiate 90 % of P_α by impurities
Plasma heating	"hot-ion" mode: NBI $\rightarrow i \rightarrow e$	to heat first useless electrons, then ions: $\alpha \rightarrow e \rightarrow i$
Use of plasma volume	100 %	25-30 %
Tritium control	pumping by Li	tritium in all channels and in dust
Tritium burn-up	$>$10%	fundamentally limited to 2-3 %
Plasma contamination	no Z^2 thermo-force, core fueling	junk from walls goes to the plasma
He pumping	Li jets, as ionized gas, $p_{in} < p_{out}$	gas dynamic, $p_{in} > p_{out}$
Fusion producing β_{DT}	$\beta_{DT} > 0.5\beta$	diluted: $\beta_{DT} < 0.5\beta$
Fusion power control	Existing NBI technology	no idea

Currently adopted MSF concept has little in common with controlled fusion and its power reactors

LiWF and plasma physics issues

LiWF relies existing plasma physics

Physics issues	LiWF	MSF concept of "fusion"
Confinement	diffusive, RTM$\equiv \chi_{=}\chi_e = D = \chi_i^{neo}$	turbulent thermo-conduction
Anomalous electrons	play no role	is in unbreakable 40 year old marriage with anomalous electrons
Transport database	easyly scalable by RTM (Reference Transp. Model)	beliefs on applicability of scalings to "hot e"-mode
Sawteeth, IREs	absent	unpredictable and uncontrollable
ELMs, $n_{Greenwald}$-limit	absent	intrinsic for low T_{edge}
p'_{edge} control	by RMP through n_{edge}	through T_{edge} and reduced performance
Fueling	existing NBI technology	no clean idea yet
Fusion power control	existing NBI technology	no clean idea yet
Current drive	efficient at low n_e, high T_e	inefficient
Stationary plasma	straightforward external control, no thermo-force driving impurities	unresolvable issue
Operational DT regime	identical to DD plasma	needs DT power for its development
Time scale for RDF:	$\Delta t \simeq 15$ years	$\Delta t \simeq \infty$
Cost:	$\simeq$ $2-2.5 B for RDF program	$\simeq$ $20 B with no RDF strategy

The LiWF so far never failed in predictions (not interpretations!!!) of relevant tokamak experiments

5 Which strategy to follow ?

Fusion strategy starts from realizing that the energy from 1 kg of tritium is finite

Fusion for clean energy

$$^2D + {}^3T = {}^4He_{3.5MeV} + n_{14.1MeV} \qquad (5.1)$$

Energy in 1 kG of T

$$E^T_{kg} = 566 \cdot 10^{12} \textit{[J]} = 0.1572 \cdot 10^9 \textit{[kW} \cdot \textit{hour]}. \qquad (5.2)$$

Monetary value of electricity

$$C^{el}_{T,kg} = \frac{6.29}{3} \frac{C^{cost\ of}_{electricity}}{0.04} \frac{C^{DT\rightarrow}_{electricity}}{0.33} \cdot 10^6 \textit{[\$]} \simeq \$2M, \qquad (5.3)$$

and the cost of tritium (≃2003, CANDU reactors)

$$C^T_{kg} \simeq \$30M. \qquad (5.4)$$

Clean fusion has ahead a huge problem of breeding tritium in unprecedented amounts (56 kg/(GW$_{DT}$·year).

5.1 Strategic meaning of 1 kg of Tritium

A bigger problem is related to destruction of the First Wall (FW) by 14 MeV neutrons.

Neutron fluence ***15 MW·a/m^2*** *can be considered as a* ***reference*** *level for destruction of the First Wall, which is the first* ***15-20 cm*** *of extremely complicated material structure.*

15 MW·a/m^2 translates into consumption of 1 kg/m^2 T

The First Wall should be first designed, using 1 kg of T per each m^2, to withstand corresponding neutron fluence 15 MYa/m^2 and then replaced at a very limited cost $< \$2$M/m^2 (neglecting all other expenses)

Would it be possible when the FW is inside a toroidal device ?

Toroidal topology of tokamaks and stellarators is their big disadvantage

1 kg/m^2 determines fusion 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

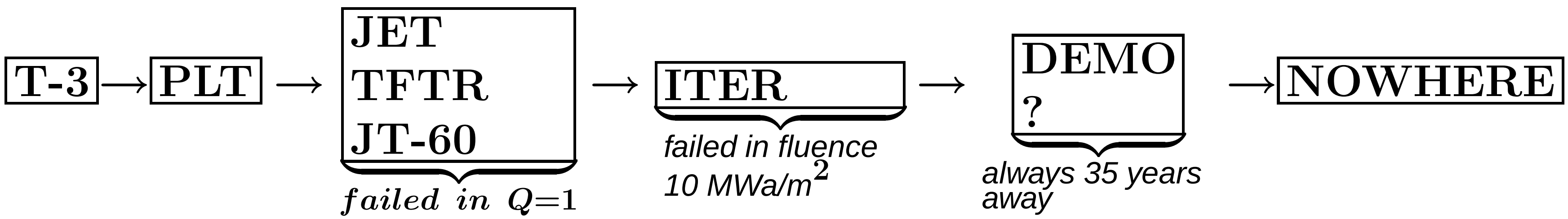
1 kg(T)/m^2 (FW)

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

Large fusion machines are not consistent with the strategy. The primary target should be a compact powerful neutron source

Fusion Main Stream to nowhere

The "main stream fusion" does not follow this strategy



The situation is worse. MSF is incapable to follow the science based strategy.

Only LiWF approach is potentially suitable for developing first a compact Reactor Development Facility,e and then, a fusion power reactor

5.2 Fusion-for-fission and all together

Fission suggests potentially much better utilization of fusion neutrons in uranium-like blanket

$$ {}^{natural}_{92}U + n_{14.1MeV} => 200\ MeV + 5n_{fast}, \tag{5.5} $$

1 ***kg T*** $\longrightarrow$ ***fission of*** $k_{\textit{eff}} \cdot 80$ ***kg U, Pu, MA***

*This allows to drop fusion power P_{DT} from $\simeq 3$ **GW** to $\simeq 100$ **MW** or even < 10 **MW** depending on applications.*

*The minimal requirements for fusion device are: (a) stationary plasma, and (b) sufficient space for blanket (at least **50 cm** thick, including reflectors and shield).*

Potentially this, FF, approach can mitigate or even eliminate huge problems for fusion of tritium breeding in unprecedented amounts, First Wall destruction, and extraction of high temperature heat from a toroidal device.

6 Three missions - three machines

1. ***First step toward RTF (PPPL):** conversion of **NSTX** into **ST0** device for developing the **LiWF** regime and then go toward the **DD ST1, Ri=0.42 m, Re=1.65 m**, based on **LiWF** regime, targeting*

$$p\tau_E = 1, \quad Q_{DT}^{equiv} > 5, \quad P_{DT}^{equiv} > 15 - 20\, MW \qquad (6.1)$$

2. ***First Fission-Fusion Hybrid (China):** from LiWF R&D on **HT-7** to **EAST** (ASIPP, Hefei) and then toward a STATIONARY DT tokamak with fission blanket **"EAST1"***

3. ***The reference 100 MW DT power for FFH:** the **ITER-100** regime at the early hydrogen phase of the project, **B=5.6 T, Ipl=8 MA,** $Q_{DT}^{equiv} > 20$**,** $P_{DT}^{equiv} \simeq 100$ **MW**.*

$$Q_{DT}^{equiv} > 20, \quad P_{DT}^{equiv} \simeq 100\, MW \qquad (6.2)$$

NSTX is unique and crucial for fusion

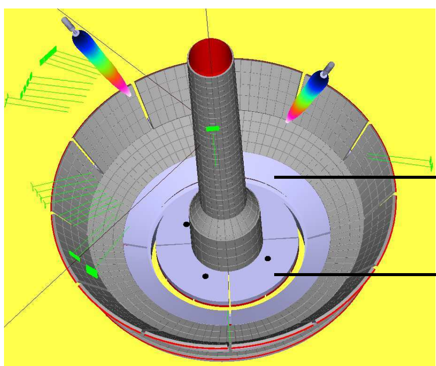
PPPL and NSTX team have everything to demonstrate the LiWF regime: people, experience with Li handling, NBI, and understanding of necessary steps.

The machine should be converted into ST0 device which would provide

$$R < 0.5, \quad \Gamma^{gasI} < \Gamma^{NBI} \qquad (6.3)$$

and then target the mailestone

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



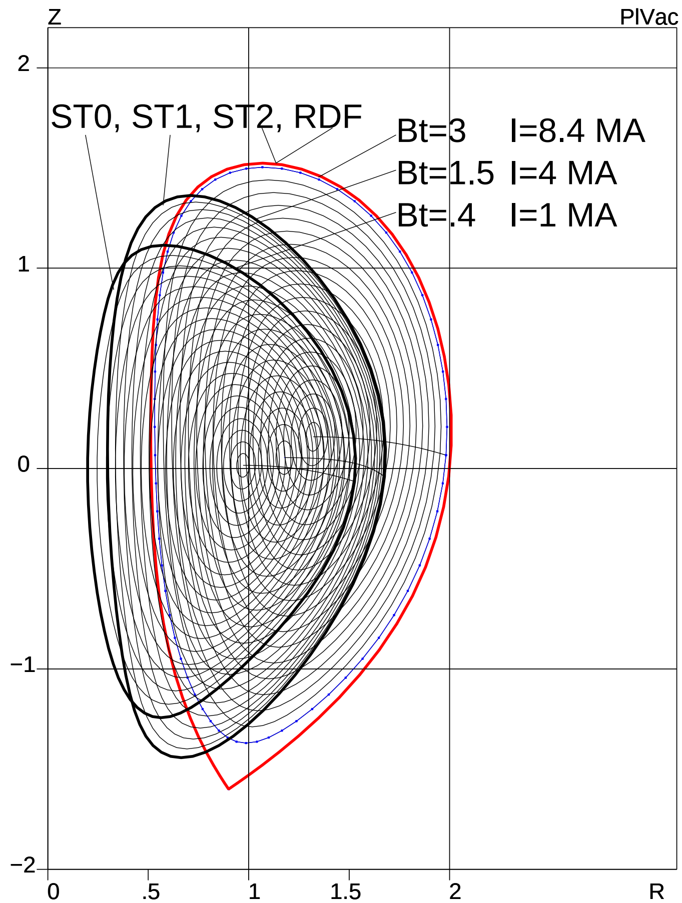
New plasma regimes require plasma contact with Li on the target plates.

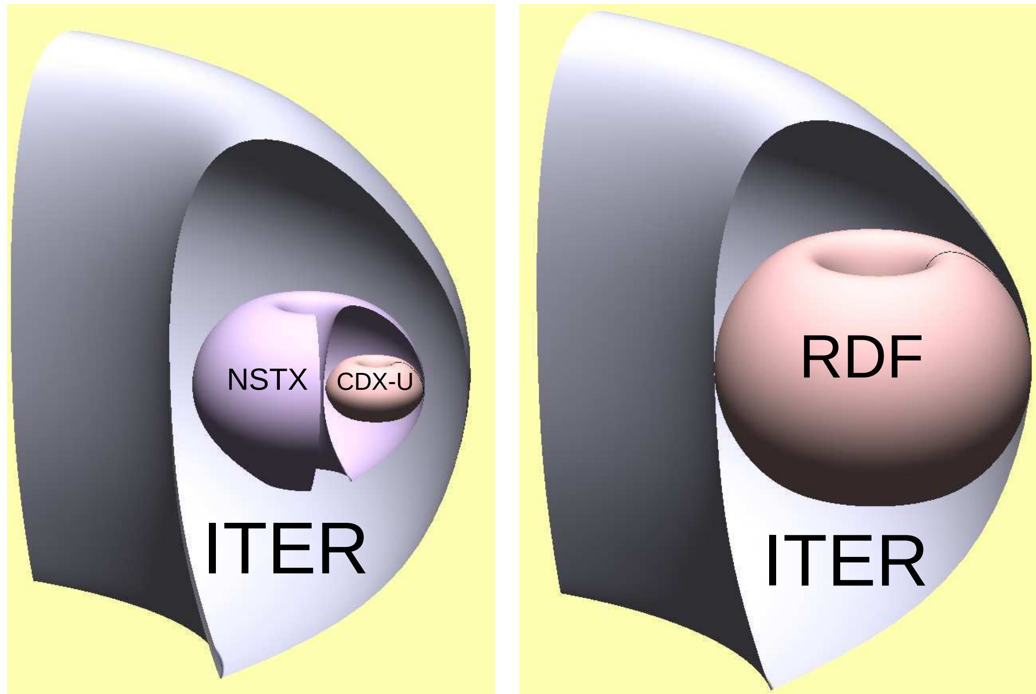
LLD on NSTX should include the entire surface of the low divertor.

Instalaltion of full LLD would be a real step of NSTX toward relevance to ITER and consistency with Orbach's letter on future of PPPL

6.1 St0, ST1 are parts of a 3 step program for RDF

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

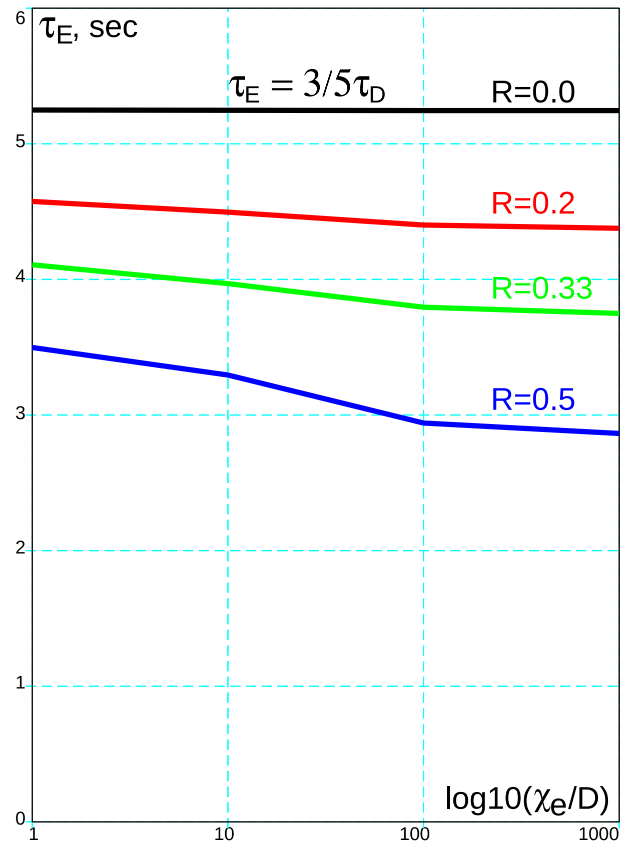


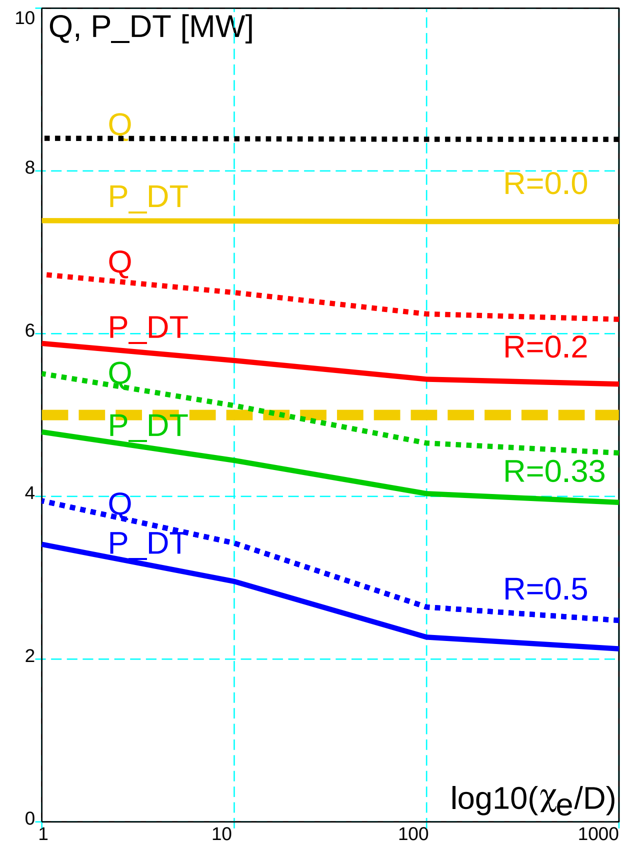


RDF with P_{DT}=0.2-0.5 GW is 27 times smaller than ITER

Breaking with anomalous electrons

LiWF boundary automatically leads to a diffusion controlled confinement regime, where nothing depends on anomalous electron heat conduction.





Reference Transport Model:

$D = \chi_i = \chi_i^{neo}$, $\chi_e = f \cdot \chi_i^{neo}$, $1 \le f \le 10^3$

ST1:

$$
\begin{aligned}
R_{max} &= 1.65 \text{ m},\\
R_0/a &= 5/3,\\
R_0 &= 1.05 \text{ m},\\
a &= 0.63 \text{ m},\\
B &= 1.5 \text{ T},\\
I_{pl} &= 4 \text{ MA},\\
\beta &\simeq 0.2,\\
P_{NBI} &= \text{1-3 MW}\\
P_{DT}^{equiv} &= \text{10-20 MW}\\
Q_{DT}^{equiv} &= \text{5-8}
\end{aligned}
$$

Instead of "NSTX upgrade", PPPL should target ST1 as a facility with a real value for fusion

6.2 From EAST to First FFH

EAST Update

Full performance commissioning

Plasma

Ip=0.6MA B_T=2-3T

Ne=1-5x$10^{19}$$m^{-3}$, Te=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

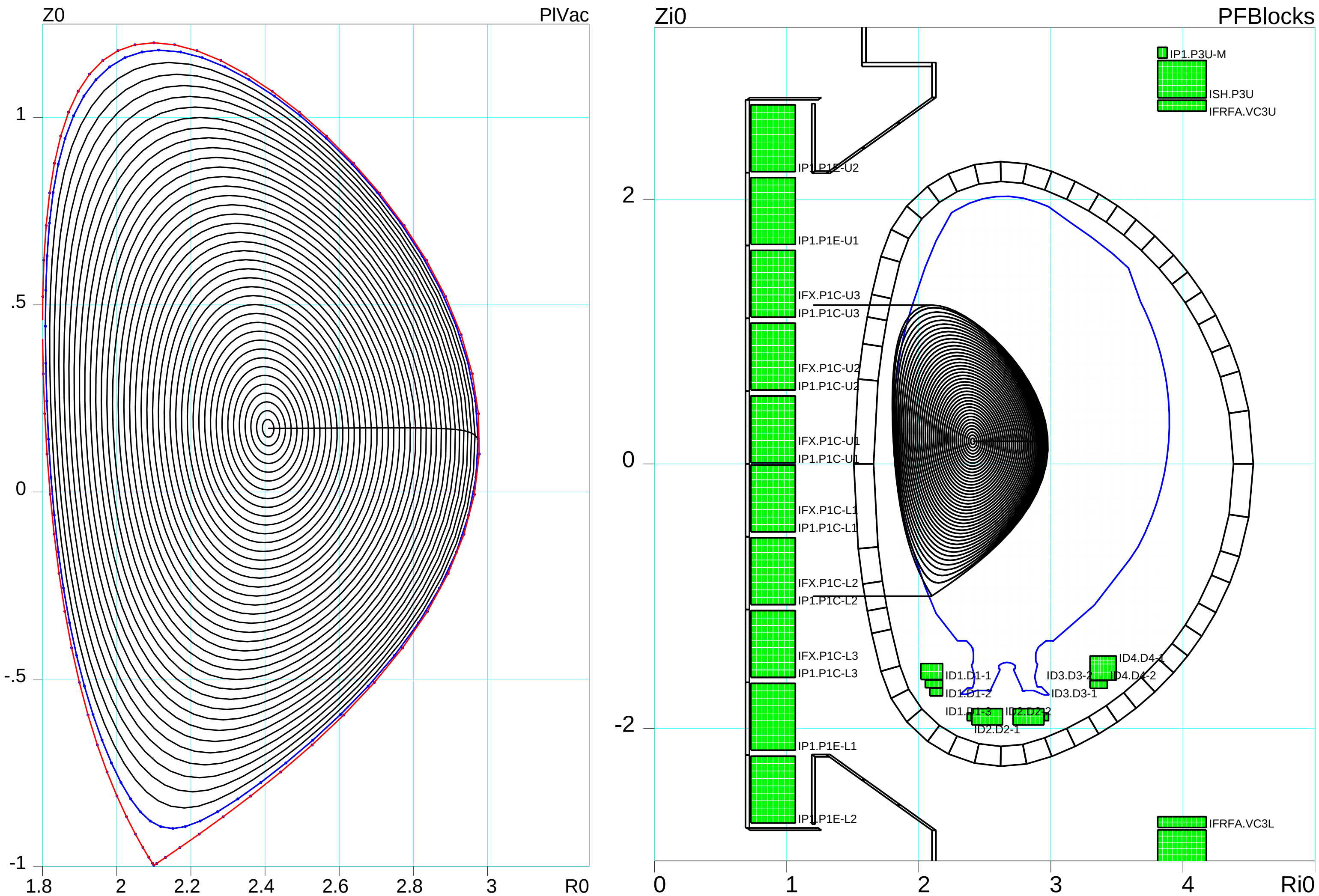
20 diagnostics

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

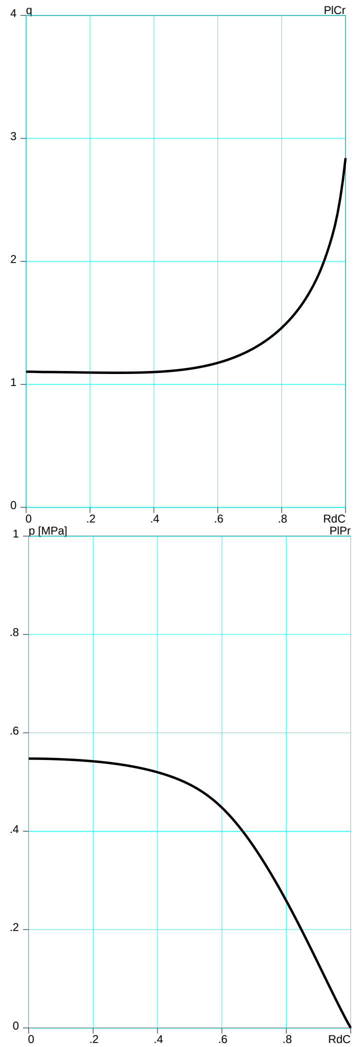
EAST1 - an option of the first DT FFH

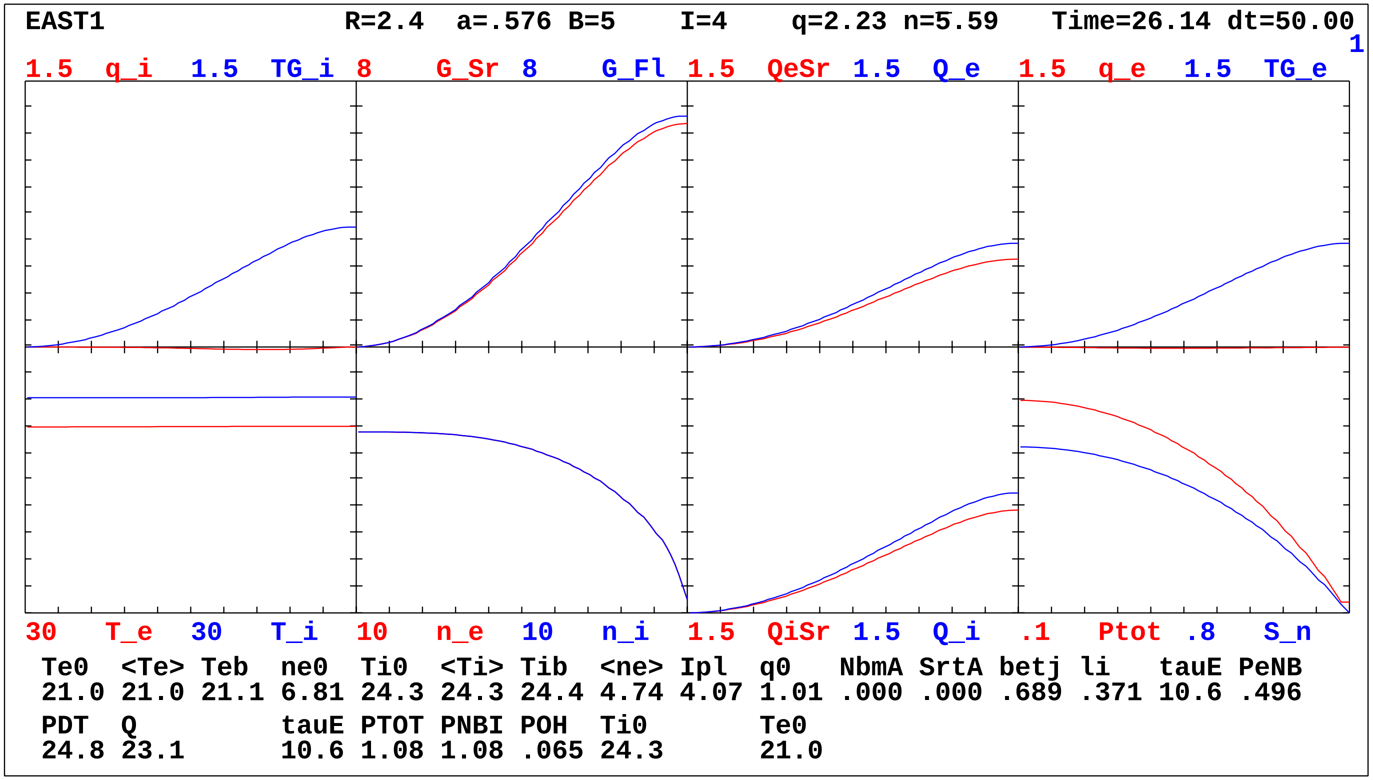


EAST1 plasma in comparison with JET

Ipl=4 MA, B=5 T, 30 MW fusion power, stationary plasma as a step to FFH

30 MW DT power on EAST1



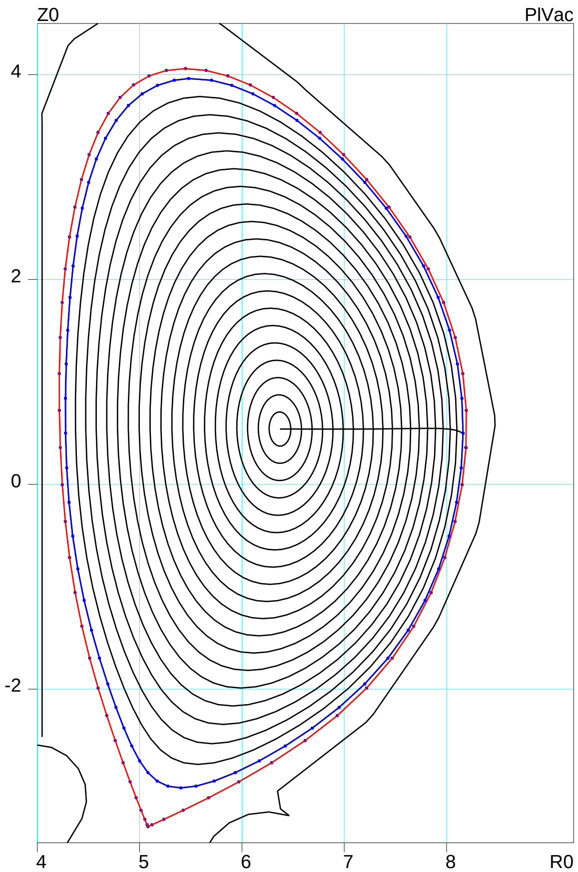


Ipl	$=$	4 MA	T_e	$=$	21 keV
B	$=$	5 T	T_i	$=$	24 keV
P_{DT}		30 MW	$n_{0,20}$	$=$	0.6
τ_E	$=$	10 sec	β	$=$	3.3%
P_{NBI}	$=$	1 MW	Q	$=$	23

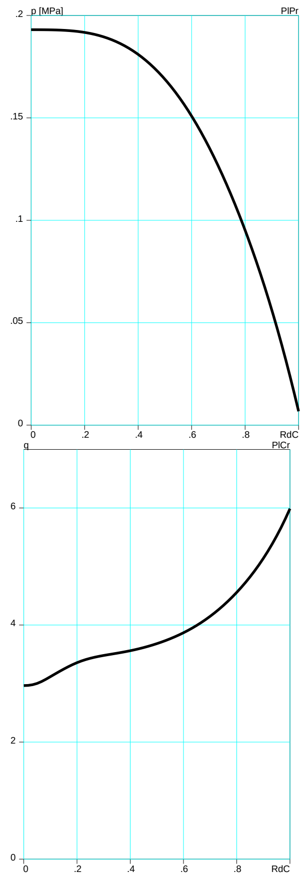
High temperature, $\simeq$20 keV, low density n_e $\simeq 0.6\cdot 10^{20}$ are perfect for the current drive

6.3 Making ITER visible to society

ITER is too big for LiWF.



ITER Plasma cross-section



p-, q-profiles

Can be safely "ignited" in LiWF regime at initial (H) stage of operation

$$
\begin{aligned}
I_{pl} &= 8\ MA\\
B_{tor} &= 5.6\ T\\
\beta &= 1\ \%\\
p &= 0.125\ MPa\\
\tau_E &= 40\ sec\\
P_{NBI} &= 3.3\ MW\\
P_{DT} &= 100\ MW\\
p\tau_E &= 5 \gg 1\\
T_i \simeq T_e &\simeq 20\ keV
\end{aligned}
\qquad (6.4)
$$

The existing ITER target plates can be coated with th necessary 10-20 g using Li evaporators or droppers

Even a few ignitions with PDT=100 MW can make ITER visible to society and can launch domestic programs for the fission-fusion energy source

7 Summary

1. It is necessary to realize that the present concept of magnetic fusion (originated in the 60-70s) has been exhausted at the end of the 80s.

   Switching the program to a new concept is necessary. The emphasis should be shifted from heating the core to prevention of cooling the plasma edge.

2. The Li conditioning is an established and a relatively easy method for significant improvement of the plasma-wall interaction (removes O, H_2O, reduces recycling) and plasma performance.

   The effect of Li conditioning is limited and it is still not the answer

3. The LiWF fusion concept, i.e, (a) core fueling by NBI + (b) Li pumping target surfaces + (c) elimination of edge particle sources, does require additional technology development of flowing Li layers. In return,

The LiWF suggests the best possible (diffusion based) confinement regime, the best possible stability regime, exceptional consistency with stationary plasma requirements and with power extraction.

Based on our best present understanding of plasma physics and technology, the LiWF gives the scientific basis for development of both RDF for a power reactor and the neutron sources for the fission-fusion hybrids.