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How far is magnetic fusion from being a component of nuclear energy[1]

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Contents

1 Fusion-4-fission and all together

The concept of fission-fusion (FF) has roots in the mid 70s (i.e., Bethe(1979), Golovin(1975), Orlov(1978), Rose (1980))

Many conceptual designs have been developed.

Was never tested (fusion is not ready, fission expansion was suppressed)

Now there are new hopes on re-emerging of nuclear energy and on new look on FF.

Chinese fusion program is an example of real intention to implement FF as the next step in developing a non-fossil energy source based on nuclear power

Energy from 1 kg of tritium

There is an evident conflict between clean fusion and economy

Fusion for clean energy

$$^2D + {}^3T = {}^4He_{3.5MeV} + n_{14.1MeV}, \quad n_{14.1MeV} => 14.1MeV \tag{1.1}$$

Energy in 1 kG of T

$$E^T_{kg} = 566 \cdot 10^{12} \text{ [J]} = 0.1572 \cdot 10^9 \text{ [kW} \cdot \text{hour].} \tag{1.2}$$

Monetary value of electricity

$$C^{el}_{kg} = \frac{6.29}{3} \frac{C^{cost\ of}_{electricity}}{0.04} \frac{C^{DT\rightarrow}_{electricity}}{0.33} \cdot 10^6 \text{ [\$]} \simeq \$2M, \tag{1.3}$$

and the cost of tritium (≃2003)

$$C^T_{kg} \simeq \$30M. \tag{1.4}$$

Consumption of 1 kg of T per m^2 is necessary and sufficient to destroy the First Wall, i.e., the first 15-20 cm of extremely complicated material structure. It should be first designed, using 1 kg of T /m^2 to withstand corresponding neutron fluence 15 MYa/m^2 and then replaced at a very limited cost $<$ \$2M/m^2 (neglecting all other expenses)

FF idea for energy production

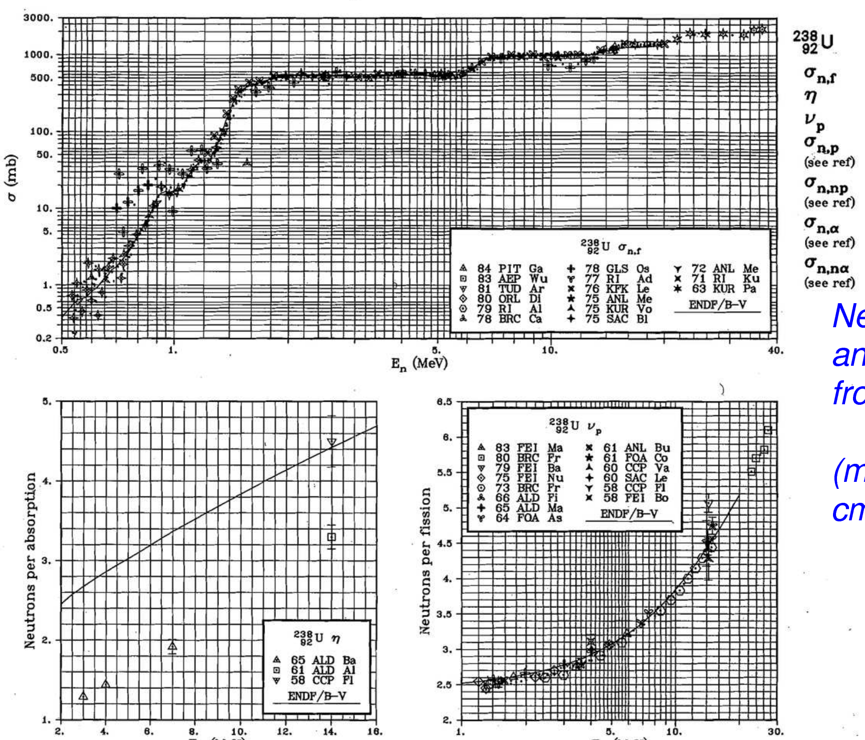
Fission suggests potentially much better utilization of fusion neutrons

$$
\begin{aligned}
{}^{238}_{92}U + n_{14.1MeV} &=> 193\ MeV + 3.5 n_{2MeV}, \\
{}^{natural}_{92}U + n_{14.1MeV} &=> 200\ MeV + 5 n_{2MeV}
\end{aligned}
\qquad (1.5)
$$

if fusion can meet some requirements (some simplified, some enhanced).

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

Neutron multiplication



Neutron Cross-sections and neutron production from 14 Mev *neutrons*

(mean free path $\simeq$ 20 *cm)*

2 Options for fission-fusion (FF)

(Taken from Kuteev, Khripunov, 2008*):*

Pu from FF:

$$\left|\begin{array}{l} n_{14MeV} \\ {}^{238}U \\ {}^{235}U\ (0.007) \\ C, H_2O, Be \end{array}\right| => \left\{\begin{array}{r} -{}^{238}U \\ -{}^{235}U\ (0.007) \\ +{}^{239}Pu \\ +17.6\ Mev/n \end{array}\right. \qquad (2.1)$$

wasting tritium

Pu from FF:

$$\left|\begin{array}{l} n_{14MeV} \\ {}^{238}U \\ {}^{235}U\ (0.007) \\ C, H_2O, Be \end{array}\right| => \left\{\begin{array}{r} -{}^{238}U \\ -{}^{235}U\ (0.007) \\ +4{}^{239}Pu \\ +T \\ 200\ Mev \end{array}\right. \qquad (2.2)$$

1 kg T => 320 kg Pu

For P_{DT}= 100 MW => 320 kg Pu/(2 months) +1136 MW of heat

1 $m^2|_{FW\ life\ time}$ => 320 kg Pu

T from industry instead of breeding

Energy from FF:

$$\left|\begin{array}{l} n_{14MeV} \\ {}^{238}U \\ {}^{235}U\ (0.007) \\ Na, Pb \end{array}\right| => \left\{\begin{array}{r} -{}^{238}U \\ -{}^{235}U\ (0.007) \\ \pm{}^{239}Pu \\ +T \\ 1000\ Mev \end{array}\right. \qquad (2.3)$$

Nuclear reactor in the blanket

Toroidal geometry of magnetic fusion devices creates a lot of problems.

Options for fission-fusion (FF)

New ideas of utilizing fusion neutrons for the control of near-critical fission reactors with effective neutron multiplication constant k_{eff} *close to 1:*

$$1 - k_{eff} \ll 1. \qquad (2.4)$$

Controlled fission:

$$|n_{14MeV}| => \left|\begin{array}{l} -{}^{238}U \\ -{}^{235}U\ (0.007) \\ \pm{}^{239}Pu \\ Na, Pb \\ (active\ zone) \end{array}\right| => \left\{\begin{array}{r} -{}^{238}U \\ -{}^{235}U\ (0.007) \\ +\dfrac{\nu-2}{-\rho}\nu^{239}Pu \\ +200\dfrac{\nu}{-\rho}\ Mev \end{array}\right. \qquad (2.5)$$

Here, ν *is the number of neutrons per fission (*$\nu \simeq 2.9$*),* ρ *is the negative reactivity of the active zone*

$$\rho = \frac{k_{eff} - 1}{k_{eff}} \qquad (2.6)$$

(Kuteev, Khripunov, 2008).

Options for fission-fusion (FF)

Table 2-3 Preliminary Fusion Neutron Product Evaluation Data

	Fusion Applications		Hydrogen Fuels	Transmutation of Nuclear Waste	Electricity, Central Station	Process Heat	Detection, Remote Sensing	Radioisotopes	Desalination, Fresh Water	Radiotherapy	Activation Analyses	Radiography	Tritium Production	Fusion-Fission Breeder
Attribute	Weight	Assumptions	Use HTE + electricity generation	Transmutation and power generation, no fuel recycle	Central station power plant	Heat only, no cogeneration	Land mines, remote surveying		Desalinate with electrodialysis + fusion-generated electricity	Neutron and proton	Neutron and proton	Neutron and proton	For other fusion plants + defense programs	Breeder + transmutation fuel recycle
Necessity	3		**3**	2	2	1	2	2	2	1	2	1	1	-2
Uniqueness	3		**4**	**4**	2	1	3	2	0	3	**4**	3	**4**	3
Market Potential	3		**4**	**4**	3	1	3	2	3	2	2	1	2	2
Resources	3		**4**	1	3	2	0	1	**4**	0	0	0	3	3
Environment	3		**5**	4	4	4	0	0	2	0	0	0	0	1
Competitive	2		-2	0	-2	-1	**1**	-2	-2	-2	**1**	-2	2	-1
Helps GNP	1		**4**	2	3	3	1	1	1	1	0	1	1	2
Investment	2		-4	-2	-4	-3	**-1**	**-1**	-2	**-1**	-2	**-1**	-2	-3
Technical Maturity	2		-4	-2	-3	-2	**-1**	**-1**	-3	**-1**	-2	**-1**	-3	-4
Time to Market	2		-4	-2	-3	-2	-2	**-1**	-3	**-1**	**-1**	**-1**	-2	-4
Prestige	1		**4**	3	3	2	1	1	2	1	1	1	-1	1
Public Support	3		**4**	2	3	2	1	3	1	3	0	2	-1	-1
Weighted Sum	± 140		52	44	33	22	23	22	19	19	17	13	17	-3

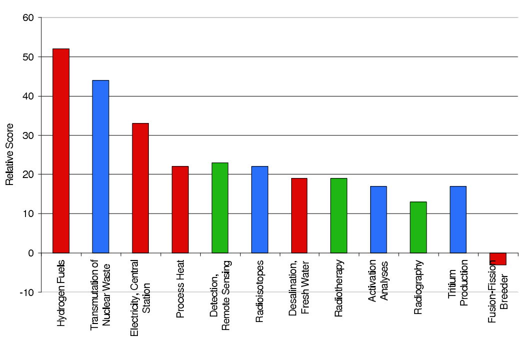


Figure 2-2. Ranked Weighted Values Of Fusion Products

8

Many possible applications of fusion neutrons with "marketability" analysis are given in

THE ARIES FUSION NEUTRON-SOURCE STUDY
D. Steiner, E. Cheng, R. Miller, D. Petti, M. Tillack, L. Waganer and the ARIES Team
UCSD-ENG-0083 (2000)

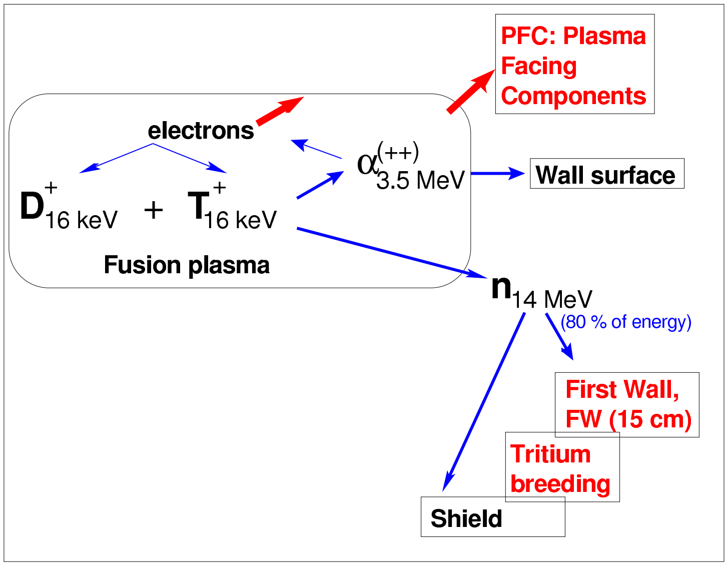
In contrast to Kuteev, FF breeders are highly downgraded.

3 Should fusion neglect FF opportunities?

1. *An order of magnitude lower fusion power, i.e.,* 0.1 GW *instead of* 3 GW*.*
2. *Life time of the first wall comparable with the life time of the machine with potential change in notion of the first wall vs inability to design the first wall for clean fusion reactor (requires consumption of* 1 kg *of T per* m^2 *of the first wall).*
3. *New opportunities for order of magnitude lower tritium breeding.*
4. *Energy production may not be required (in the case of Pu fuel factory for fast reactors). Energy can be a byproduct or a burden.*
5. *Utilizing fusion for burning the radioactive waste (now at high demand).*
6. *Merging efforts with nuclear energy for solving the energy problem.*

Main stream of fusion

“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:

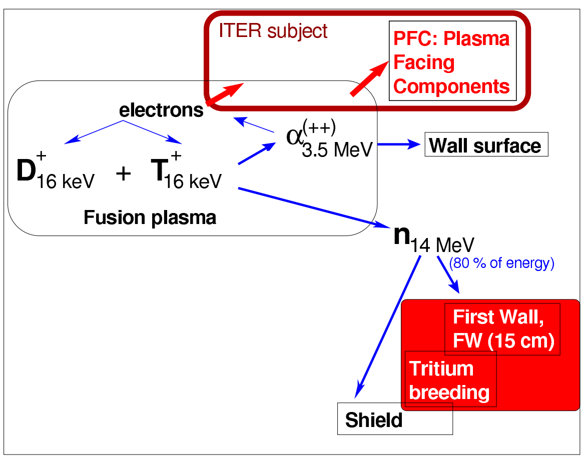
$$p = p_D + p_T + p_e + p_\alpha + p_I,$$

$$p_e > p_D + p_T$$

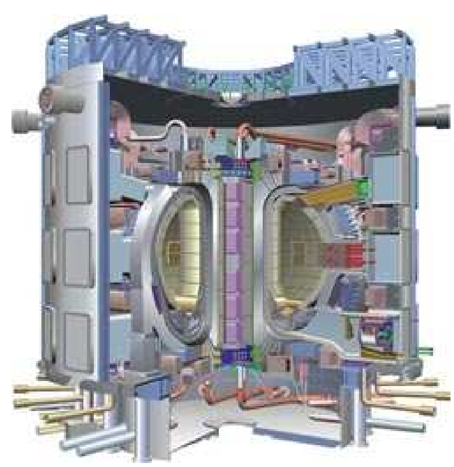
The plasma is in the “hot-electron” regime, the worst one.

ITER targets the alpha-heating regime

All current plasma physics issues are passed unresolved to the ITER “burning plasma”



$\Longrightarrow$



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

Main stream is full of problems

LiWF is consistent with common sense in all reactor issues

Issue	LiWF	BBBL70 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"
Cold He ash	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 for $\frac{\tau_E^*}{\tau_E} P_\alpha$	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	eliminates the Z^2 thermo-force, clean plasma by core fueling	invites all "junk" from the walls to the plasma core
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: $\beta_{DT} < 0.5\beta$

Currently adopted BBBL70 concept has little in common with controlled fusion and its power reactors

LiWF vs BBBL70 in plasma issues

LiWF has a robust plasma physics and technology basis. It contributes to present understanding of fusion in unique way

Issue	LiWF	BBBL70 concept of "fusion"
Physics:		
Confinement	diffusive, RTM≡ $\chi_= \chi_e = D = \chi_i^{neo}$	turbulent thermo-conduction
Anomalous electrons	plays 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 inavoidable
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
Operational DT regime	identical to DD plasma	needs fusion 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

3 step RDF program of LiWF suggests a way for bootstraping its funding

With no tangible returns the BBBL70 is irrational and compromizes credibility of fusion

Main stream of fusion

The main stream:

T-3 → PLT → [JET, TFTR, JT-60] → ITER → [DEMO ?] → NOWHERE

- JET, TFTR, JT-60: *failed in Q=1*
- ITER: failed in fluence 10 MWa/m^2
- DEMO ?: always 35 years away

The real question is not if "Should fusion neglect FF opportunities ?"

but

Can fusion meet highly reduced requirements of FF for the burning plasma, leaving for others resolving nuclear issues of FF

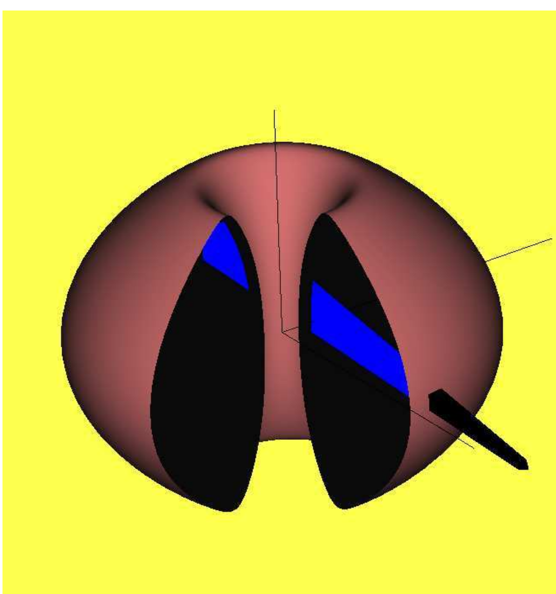
The part of the answer is that it is unthinkable to merge the present uncontrolled plasma with radioactivity of FF

In order to generate a laser beam it was necessary to make a transition to a new physics. It is not possible to do this by "improving" the flashlight.

Similarly, for both FF and "clean" fusion it is necessary to make a transition to a new concept of magnetic fusion.

LiWall Fusion (LiWF) approach

LiWF is a) core fueling (NBI) and b) pumping PFC (Li)



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

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

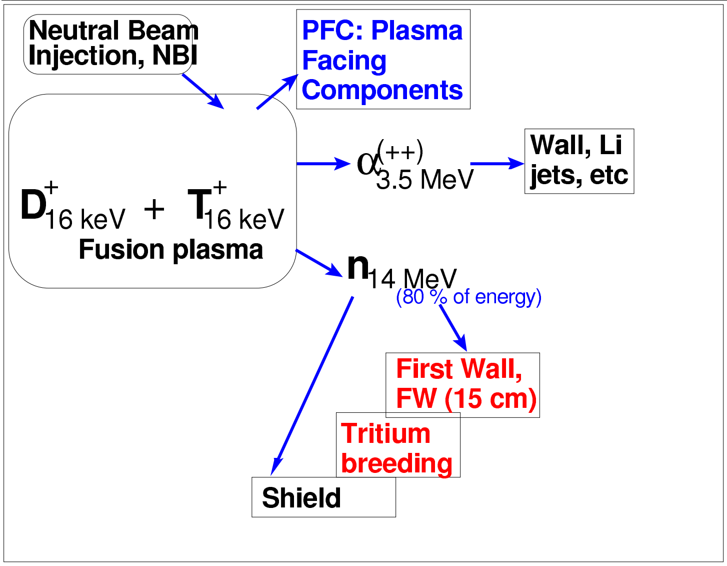
the temperature profile becomes flat automatically

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

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

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

$$P_{NBI} = \frac{3}{2}\frac{\langle p\rangle V_{pl}}{\tau_E},$$
$$\frac{dN_{NBI}}{dt} = \Gamma^{ions}_{core\rightarrow\ edge}$$

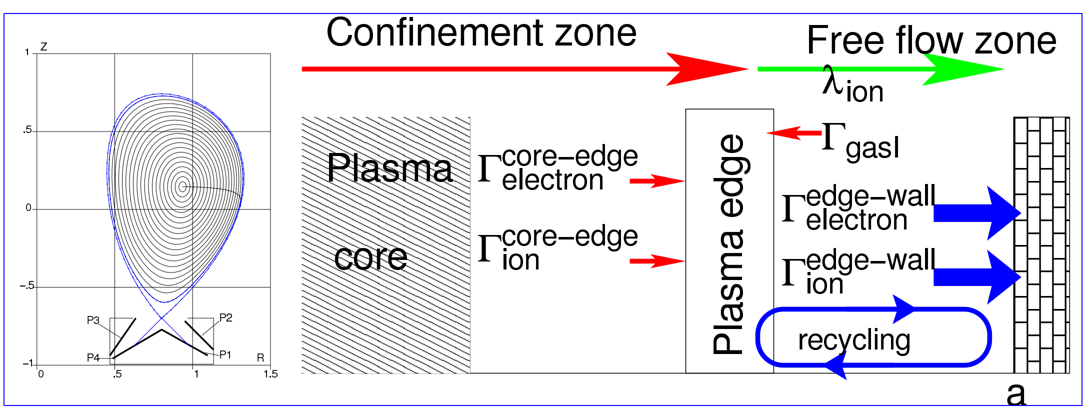
Super-Critical Ignition (SCI) confinement is necessary to make NBI work this way

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

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

Plasma edge

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

$$\lambda_{\|,D,m} = 121\frac{T^2_{keV}}{n_{20}} \qquad (3.1)$$

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.

Energy flux to the wall

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

$$\frac{5}{2}\Gamma_e^{edge-wall}T_e^{edge} = \int_V P_e dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} n T_e dV,$$
$$\frac{2}{5}\Gamma_i^{edge-wall}T_i^{edge} = \int_V P_i dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} n T_i dV. \quad (3.2)$$

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

$$\Gamma_i^{edge-wall} = \frac{\Gamma_i^{NBI} + \Gamma_i^{gasI}}{1-R_i}, \qquad \Gamma_e^{edge-wall} = \frac{\Gamma_e^{NBI} + \Gamma_e^{gasI}}{1-R_e} \quad (3.3)$$

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

$$T_e^{edge} = \frac{2}{5}\cdot\frac{1-R_e}{\Gamma_e^{NBI}+\Gamma^{gasI}}\left(\int_V P_e dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} n T_e dV\right),$$
$$T_i^{edge} = \frac{2}{5}\cdot\frac{1-R_i}{\Gamma_i^{NBI}+\Gamma^{gasI}}\left(\int_V P_i dV - \frac{\partial}{\partial t}\int_V \frac{3}{2} n T_i dV\right) \quad (3.4)$$

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

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

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

Plasma edge determines the core

1. New regimes is high T^{edge}, which is a boundary condition for confinement zone (core)

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

$R_{e,i}$, Γ^{gasI} *are much more important than the "brute" force parameters, like* P^{NBI}.

2. Both recycling $R_{e,i}$ and external particle sources Γ^{gasI} should be eliminated as much as possible, leading to a LiWall Fusion (LiWF) regime:

$$R_{e,i} \le 0.5, \quad \Gamma^{gasI} \le \Gamma^{NBI}$$

3. Resulted edge plasma density is low (δ_i is approximately the ion banana width).

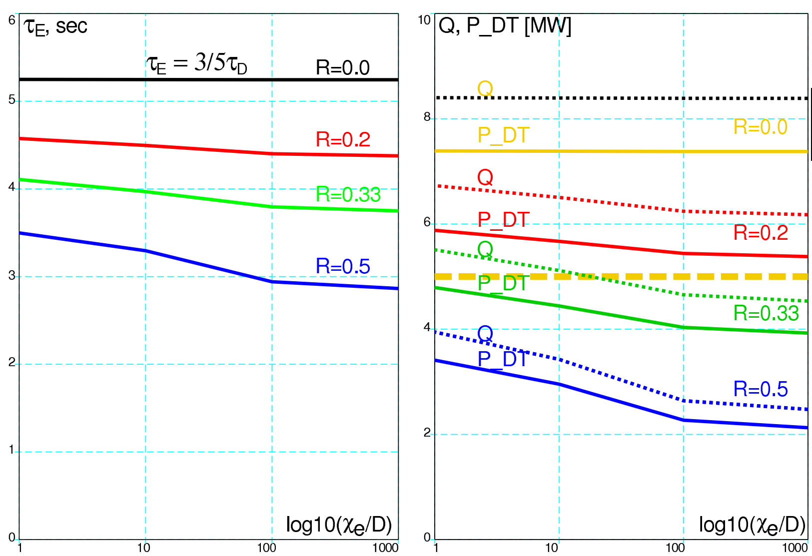
$$n^{edge} \simeq \frac{\langle n^{core}\rangle}{1-R_{e,i}} \cdot \left(1+\frac{\Gamma^{gasI}}{\Gamma^{NBI}}\right) \cdot \frac{\delta_i}{a}$$

4. ELMs are stabilized in the LiWF regime by a resonant term in the energy principle.

QHM regime and RMP experiments on DIII-D and ELM stabilization by Li on NSTX confirmed our basic understanding of plasma edge

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:

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

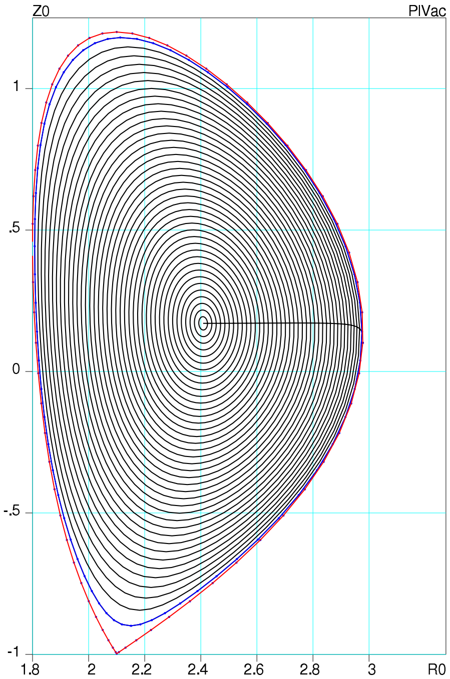
ST1:

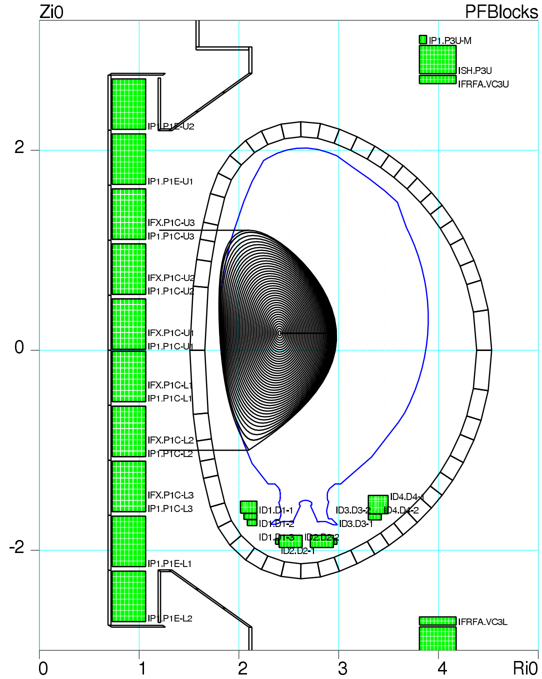
$$\begin{aligned} R_{max} &= 1.65\ m, \\ R_0/a &= 5/3, \\ R_0 &= 1.05\ m, \\ a &= 0.63\ m, \\ B &= 1.5\ T, \\ I_{pl} &= 4\ MA, \\ \beta &\simeq 0.2, \\ P_{NBI} &= 1\ MW \end{aligned}$$

There is a little sense to continue studies of the same 40 year old plasma with $R \simeq 1 > 0.5$ and edge dominated fueling $\Gamma^{gasI} > \Gamma^{NBI}$

The priorities should be focused on plasma boundary

4 From EAST to the EAST1 (FF)

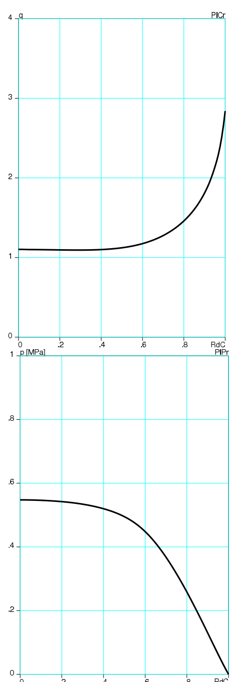


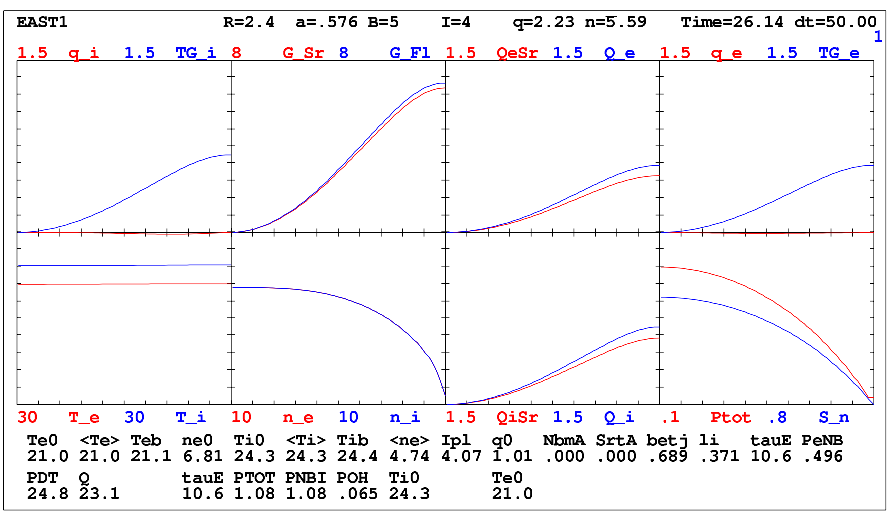


EAST1 plasma in comparison with JET

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

From EAST to the EAST1 (FF)

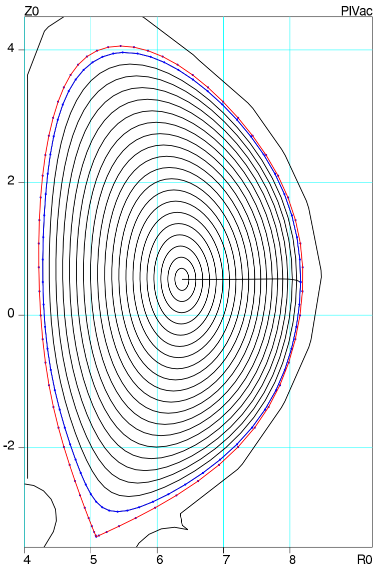




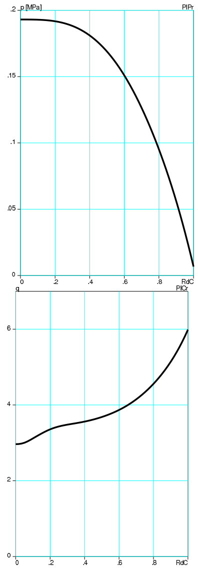
Ipl	=	*4 MA*	T_e	=	*21 keV*
B	=	*5 T*	T_i	=	*24 keV*
P_{DT}	=	*30 MW*	$n_{0,20}$	=	*0.6*
τ_E	=	*10 sec*	β	=	*3.3%*
P_{NBI}	=	*1 MW*	*Q*	=	*23*

5 Making ITER useful for fusion

ITER is too big for LiWF.



ITER geometry



p-, q-profiles

Can be safely ignited in LiWF regime at initial stage of operation

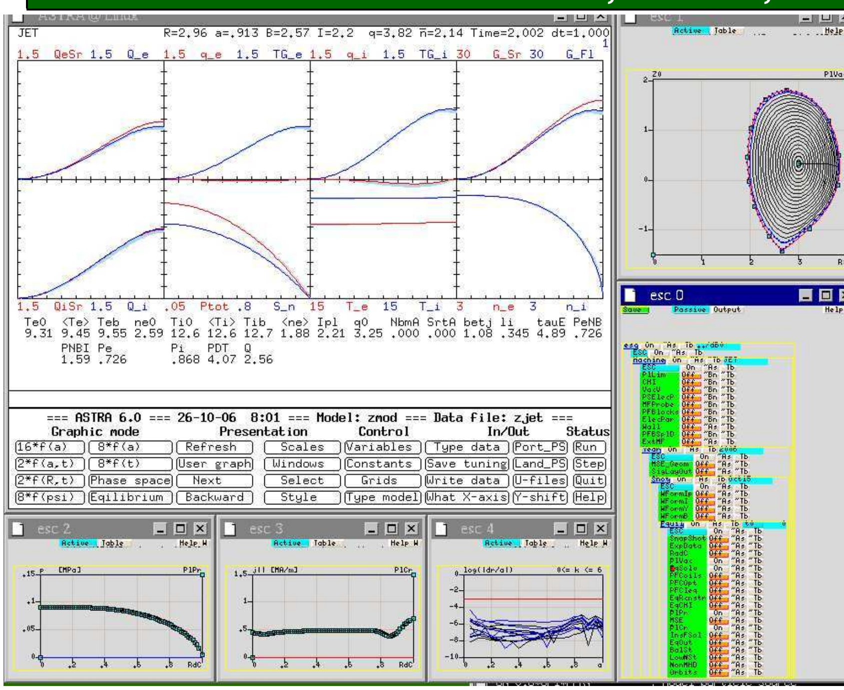
$$\begin{aligned} I_{pl} &= 8\ MA \\ B_{tor} &= 5.6\ T \\ \beta &= 1\ \% \\ p &= 0.125\ MPa \\ \tau_E &= 40\ sec \\ P_{DT} &= 100\ MW \\ p\tau_E &= 5 \gg 1 \\ T_i \simeq T_e &\simeq 20\ keV \end{aligned} \qquad (5.1)$$

10-20 g of Li can be evaporated at existing ITER target plates

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

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:

$$\begin{aligned} T_i &= 12.6\ \text{[keV]}, \\ T_e &= 9.45\ \text{[keV]}, \\ n_e(0) &= 0.3 \cdot 10^{20}, \\ \tau_E &= 4.9\ \text{[sec]}, \\ P_{NBI} &= 1.6\ \text{[MW]}, \\ P_{DT} &= 4\ \text{[MW]}, \\ Q &= 2.56\ \text{[MW]} \end{aligned}$$

For 50 keV NBI, 3+2 MWs are available

Can be experimentally tested on JET with intense Be conditioning.

In LiWF regime JET may be capable of Q≃20.

6 Crucial role of NSTX

ITER can be safely ignited in LiWF regime at initial stage of operation

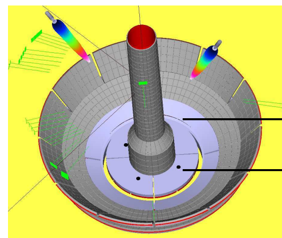
I_{pl}	$8\,MA$,
B_{tor}	$5.6\,T$,
n_{He}	$< 10^{18}\,m^{-3}$,
t	$30\,sec$, $(50\%D - 50\%T)$,
P^{NBI}	$3\|_{R=0}\,MW$,
$T_i \simeq T_e$	$\simeq 20keV$,
$\tau_E\|_{R=0}$	$40\,sec$,
p	$0.2\,MPa$,
β	$1\,\%$,
$p\tau_E$	$8\ (\gg 1$, *necessary for ign.*),
M_{Li}	$< 10\,g$,
P^{eq}_{DT}	$100\,MW$,
Q^{eq}_{DT}	30,
M^{eq}_{T}	$\simeq 0.015\,g$ *(30% burned up)*

NSTX is in a unique position to develop a NEW (LiWF) plasma regime for ITER.

1. ***The ITER LiWF regime can be designed using H- or D- plasma.***
2. ***Even a couple of ignitions can make ITER visible to society.***
3. ***P=100 MW is a characteristic fusion power for fission-fusion.***

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

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



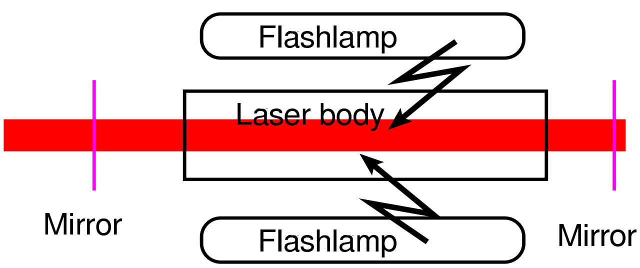
Outer leg LLD

Inner leg LLD

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

7 Summary

The analogy between making fusion work and making laser work is deeper than it seems to be.



In the case of laser the power is supplied to the laser body from the flashlamps (or electric current).

Well aligned mirrors are necessary for laser beam generation. They are the crucial part of the laser "know-how".

It is not possible to expect a success if all attention is paid to building a strong body and enhancing the flashlamp power, while ignoring necessity of mirrors.

Also, installation of one, right-hand side mirror (even with two more as spares, just in case) will not lead to the laser light generation.

This looks like what PPPL is doing now on NSTX, "finally" attempting the new confinement regimes, 10 years since their prediction in 1999.

Otherwise, without rush into radioactivity, it is possible to prove that magnetic fusion is suitable for FF, starting from obtaining the LiWF regime on NSTX, which is special among others, and supporting scientifically the EAST program in China.