Fusion with and without plasma physics*

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Abstract

- ***The first tokamak was built in 1958 in Kurchatov Institute (Moscow) (61 year ago)***
- ***In 1994 TFTR and in 1997 JET with DT plasma tried unsuccessfully to get fusion efficiency factor Q***$_{DT} = 1$***, while getting instead 0.25 and 0.6.***
- ***23 year later in 2020, JET is scheduled to perform the DT experiments even without a chance to approach the previous result 0.6.***
- ***What would be the credibility of the "Big JET", called ITER, after the planned experimental prove of inability of the fusion program to make any progress for more than two decades,***

The talk explains the root reason of the failure of magnetic fusion with Q=1. High recycling in all existing tokamaks creates a very complicated physics of plasma-wall interactions, which is turn results in insufficient confinement determined by turbulent energy losses from the plasma core. As JET will show, this approach has no hopes for fusion.

In contrast, the low recycling regime, which seems to be feasible due to flowing liquid lithium technology (24/7-FLiLi) can suppress recycling and associated plasma cooling, thus, automatically leading to "the best confinement regime" determined by particle diffusion.

Without two messiest parts of tokamak plasma physics (turbulent thermal conduction and complicated plasma edge) the implementation of new regime on JET (if extended till 2024) can demonstrate the real fusion:

fusion power P$_{DT}$ ***= 22-26 MW,***
fusion efficiency Q$_{DT}$ ***= 5.7-6.4,***
tritium burn up 7.8-8.7 %
NBI power P$_{NBI}$ ***= 4 MW, E***$_{NBI}$ ***= 120 keV***

Outline

I. **Recycling sets up the plasma confinement**

II. **Fusion, rich with plasma physics (PPF)**

III. **Fusion, driven by the general physics (LiWF)**

IV. **R*ecycling* = 0.5, “impossible” but DOABLE**

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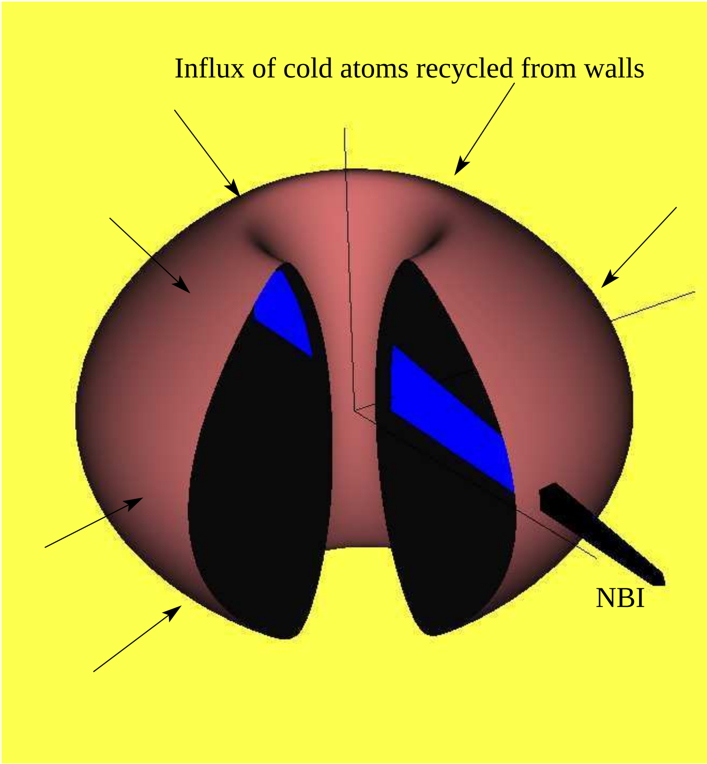
I. Recycling sets up the plasma confinement

It was a big mistake of the entire program to relate the plasma energy confinement solely with the core thermal conduction transport.



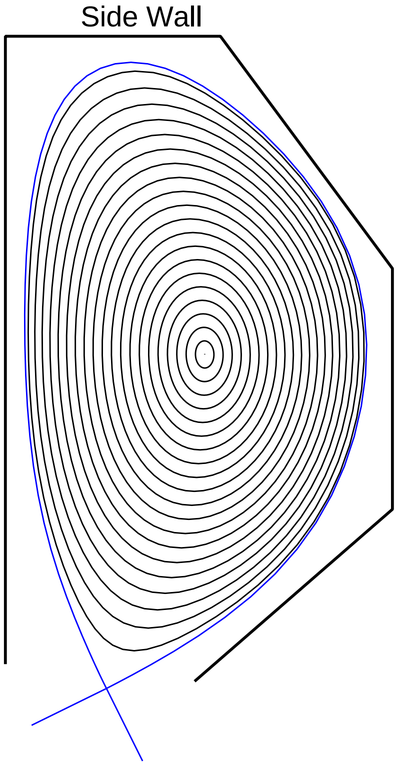
NBI - Neural Beam Injection:

Supplies a flux of energetic atoms (H,D,T)

17 - 130 keV used on tokamaks routinelo

The original idea of fusion:

insulate plasma from the wall

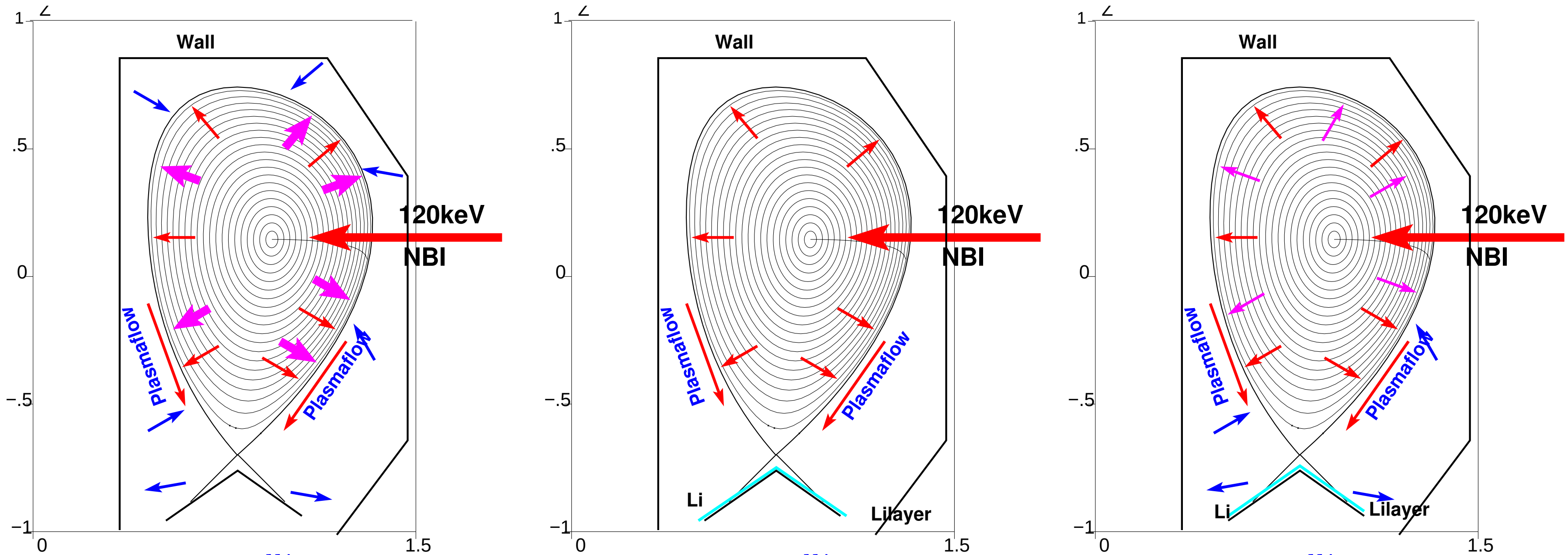


In primitive description, the tokamak concept can be expressed as

1. ***toroidal plasma is confined by poloidal magnetic field***
2. ***plasma global stability is provided by strong toroidal magnetic field***
3. ***plasma is heated by high energy Neutral Beam Injection (NBI)***
4. ***plasma boundary is cooled by interaction with cold atoms recycled from the wall***

Recycling of plasma on the wall is a deviation from original idea

1.1 Three tokamak regimes determined by recycling



High $R^{recyclling} \simeq 1$

- *cold edge,* $T^{edge} \ll T^{core}$
- *large thermal conduction*
- T_{plasma} *is determined by* P_{NBI}

Complicated plasma physics of core energy losses and PSI

Zero $R^{recyclling} = 0$

- $T^{edge} = E_{NBI}/5$
- *only diffusion matters*
- n^{core} *is determined by* P_{NBI}

No such plasma physics (except diffusion) in the game !!!

Low $R^{recyclling} \simeq 0.5$

- $T^{edge} = E_{NBI}/10$
- *negligible therm. condct.*
- n^{core} *is determined by* P_{NBI}

Plasma physics plays minor role

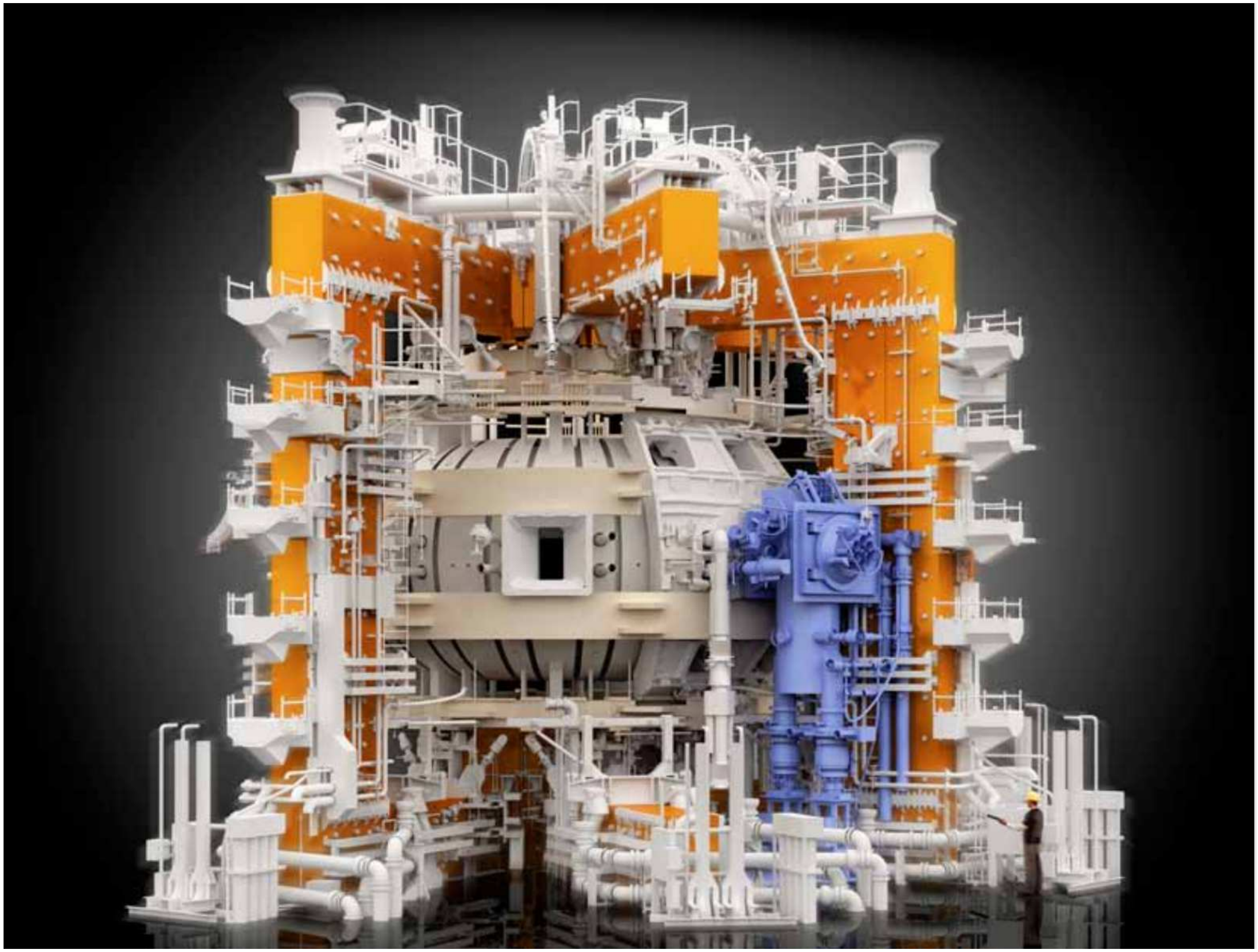
Plasma remains hot if is not cooled down

II. Fusion, rich with plasma physics (PPF)

(PPF - Plasma Physics Fusion)

The first tokamak was built
in 1958
in Kurchatov Institute (Moscow)
(61 year ago)

The best tokamak: Joint European Torus (JET)

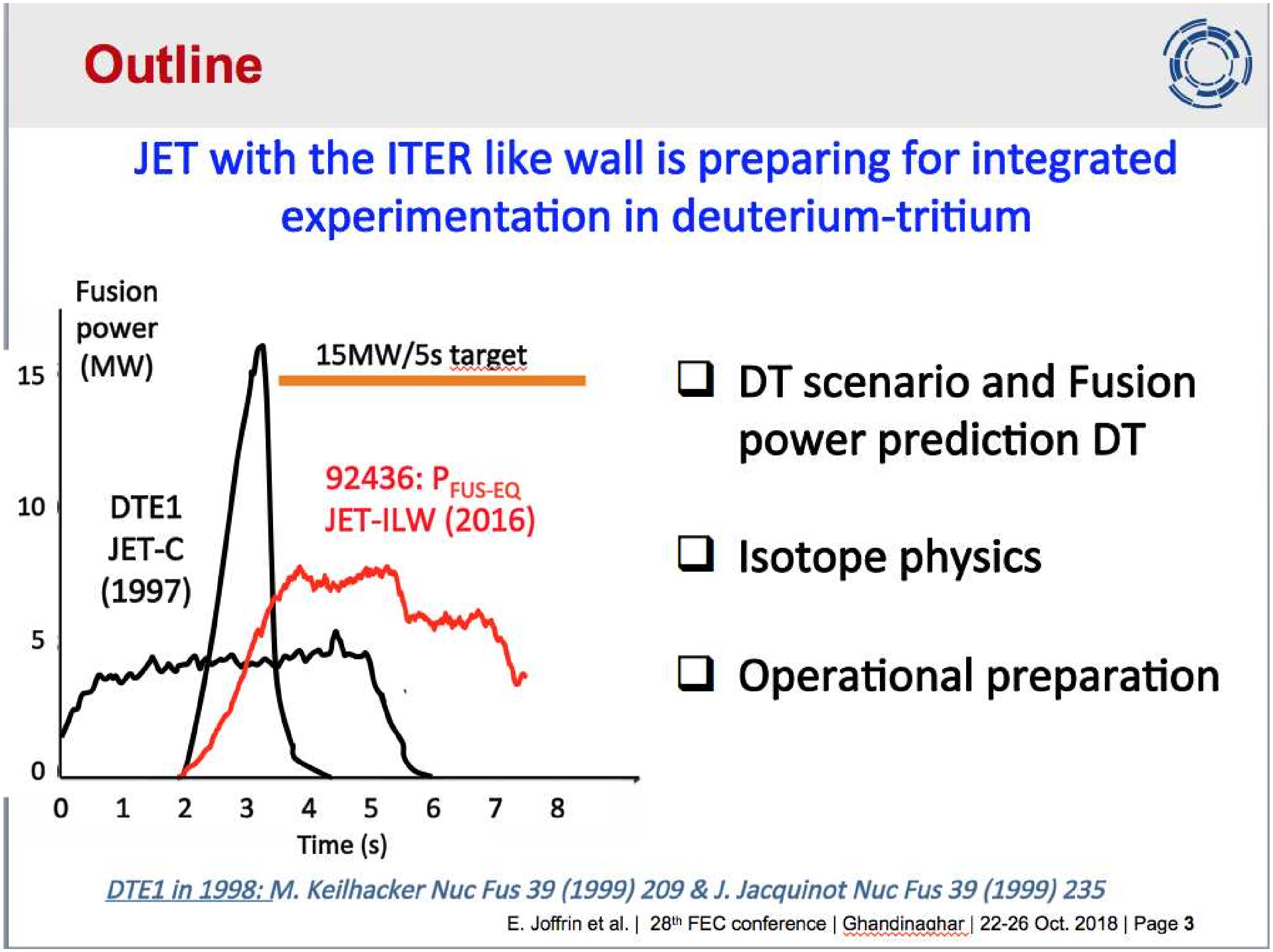


Picture from "EFDA. Fusion Electricity. A roadmap to the realisation of fusion energy by F. Romanelli, 2012"

JET is planning DT experiment in 2020 and probably in 2024

In 1997 in DT plasma JET has achieved P_{DT} = 16 MW

Plans for 2020, 2024: P_{DT} = 15 MW for 5 sec. No way to even repeat Q_{DT}=0.6



Tokamak and fusion efficiency factor Q_{DT}

The measure of progress: Fusion Efficiency Factor $$Q_{DT} \equiv \frac{P_{DT}}{P_{\text{external heating}}} \qquad (1.1)$$

1	Q_{DT}=1	$P_{DT} = P_{NBI,external}$	- The minimal milestone for fusion energy, explainable to society
2	Q_{DT}=5	$P_\alpha = P_{NBI,external}$	- Heating by α particles is equal to applied heating
3	Q_{electr}=1	$P_{electr} > P_{consumed}$	- the definition and objectives of fusion DEMO
3	$Q_{\$\$}$=1	$\$\$_{electr} > \$\$_{consumed}$	- electricity produced covers all expenses

- In 1997 (39 years after 1958) $Q_{DT} =$ 0.6 for a fraction of sec
- In 2020 (23 years after 1997) $Q_{DT} \simeq$ 0.3-0.4 (?????)
- What is the credibility of “Big JET” ? .

The present approach to fusion has a fundamental problem even at the plasma physics stage of development:
After 62 years of tokamaks
even the minimal milestone $Q_{DT} = 1$ cannot be met.

All the problems of magnetic fusion in demonstrating fusion gain factor $Q_{DT} = 1$ (minimal fusion milestone) are related to cold plasma edge.

- *Cold edge* $\Rightarrow$ *peaked core plasma temperature* T^{core}
- *Peaked* T^{core} $\Rightarrow$ *turbulence* $\Rightarrow$ *bad confinement*
- *Bad confinement* $\Rightarrow$ *excessive heating* $\Rightarrow$ *more turbulence*
- *Bad confinement* $\Rightarrow$ *large, costly, and inefficient devices*
- *Large size plasma* $\Rightarrow$ *nearly impossible core fueling by tritium* (T_{burnup} $\simeq$0.1 %)
- *Large size plasma* $\Rightarrow$ *potentialy catastrophic disruptions*
- *peaked plasma* T^{core} $\Rightarrow$ *bad use of plasma volume for burning*
- *High power, high-z PSI, radiation* $\Rightarrow$ *unpredictable plasma, disruptions*
- *Peaked* T^{core} $\Rightarrow$ *bad core stability, low* β
- *Bad confinement* $\Rightarrow$ *a pile of unsolvable technological problems, including the power extraction problem.*
- *. . . The list has no end . . .*

Auxiliary heating struggles with plasma cooling by recycling.
With DT, JET will experimentally prove the absence of progress in fusion since 1997

III. Fusion, driven by the general physics (LiWF)

3 Physics of the low recycling regime

Low recycling plasma edge corresponds to the most relaxed plasma:

- ***NBI fuels the plasma core and then let particles go on their own***
- ***The stress on the plasma temperature profile is eliminated by suppressed recycling***
- ***The edge temperature is free to go to the high value.***

3.1 High edge temperature is natural for plasma

At the last mean free path energy is transported to target plates by free flow of particles. Accordingly

$$\frac{5}{2}\left(T_i^{edge}+T_e^{edge}\right)=\frac{1-R^{ecycling}}{\Gamma_{NBI}+\Gamma_{gas\ puff}}\int P_{NBI+\alpha-synchr}d^3\vec{r}. \quad (3.1)$$

or

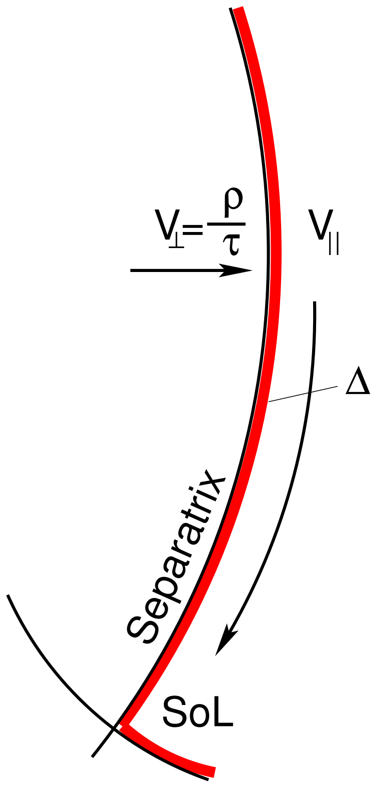
$$\frac{T_i^{edge}+T_e^{edge}}{2}=\frac{1-R^{ecycling}}{1+\frac{\Gamma_{gas\ puff}}{\Gamma_{NBI}}}\cdot\frac{E_{NBI}}{5}\cdot\frac{P_{NBI}+P_{\alpha}-P_{rad}}{P_{NBI}}. \quad (3.2)$$

Edge plasma temperature is determined exclusively by global parameters
It cannot be perturbed by core transport properties.

- ***This fundamental property determines simplicity, predictability and reliability of low recycling regime.***
- ***Its physics is the general physics of 19-20 centuries. No needs in expensive verification of it.***
- ***The most messy parts of plasma physics (turbulent core thermal conduction and complicated plasma edge) are not present in low recycling regime***

3.2 Edge density

***Edge plasma density:* through the separatrix both particles and energy are transported by their unidirectional fluxes.**



In banana regime the unidirectional velocity $V_\perp$ from the core to the edge can be assessed as

$$V_{\perp,m/s} \simeq \frac{\rho_i}{\tau_{ii}} \cdot \underbrace{\sqrt{0.68 \frac{a^2}{R^2} \frac{B_{tor}^2}{B_{pol}^2} \left(\frac{R}{a}\right)^{3/2}}}_{orbit\ factor} = 15.7 \frac{n_{20}^{edge}}{B_{pol,T} T_{keV}} \cdot \left(\frac{a}{R}\right)^{1/4} \cdot \frac{\ln \Lambda}{19.5} \tag{3.3}$$

There is no "isotope" effect in $V_\perp$

The convective heat flux determines n^{edge} in terms of heating power, temperature independent

$$\int P_{MW/m^3} d^3\vec{r} = \frac{5}{2}(T_e + T_i)_{keV}^{edge} \cdot 1.6 \cdot 10^4 \cdot n_{20}^{edge} \cdot V_\perp \cdot S_{m^2}^{side}. \tag{3.4}$$

The level of edge density can be reduced, e.g., by RMP, which affect $V_\perp$.

There is a critical power P^{L-H}

$$P^{L-H} \equiv \frac{5}{2}(T^{edge}_{e,keV} + T^{edge}_{d,keV}) \cdot 1.6 \cdot 10^4 \cdot n^{edge}_{20} \cdot V_\perp \cdot S^{side}_{m^2}$$
$$\propto n^{edge^2}/B \qquad (3.5)$$

which is independent on the edge temperature.

> ***At given*** n^{edge} ***plasma can transport not more than*** P^{L-H} ***of heating power - power trapping effect.***

The power trapping effect may explain the L-H transition.

The effect is consistent with the basic observations:

- ***For*** $P^{heating} > P^{L-H}$ ***the excess of heat is trapped in the core leading to rise of both core and edge temperatures***
- ***The following rise of edge density makes the new level of*** P^{L-H} ***equal*** $P^{heating}$
- ***Edge temperature rises ahead of the edge density rise***
- ***In JET, the observed enhanced NBI L→H power in H vs D is due to higher*** n^{edge} ***in L-mode in H than in D, rather than due to the "isotope" effect.***

3.3 Core transport model for low recycling regime

***Reference Transport Model (RTM):* specified by transport coefficients**

$$D = \chi_i^{neo}, \quad \chi_i = f\chi_i^{neo}, \quad \chi_e = 100\chi_i^{neo}. \tag{3.6}$$

(Pseudo-ions with mass $2.5m_p$ were used in DT simulations.)

At high edge tempergture, thermal conductivity plays minor, if any, role. In most of simulations $f = 1$ and enhanced up to 100 to illustrate the effect of anomaly in ion thermal conduction.

Forelectrons this factor was taken 100 in order to avoid discussion of this pain in the neck for conventional plasma.

Only diffusion coefficient D is important in "the best possible confinement" or LiWF regime.

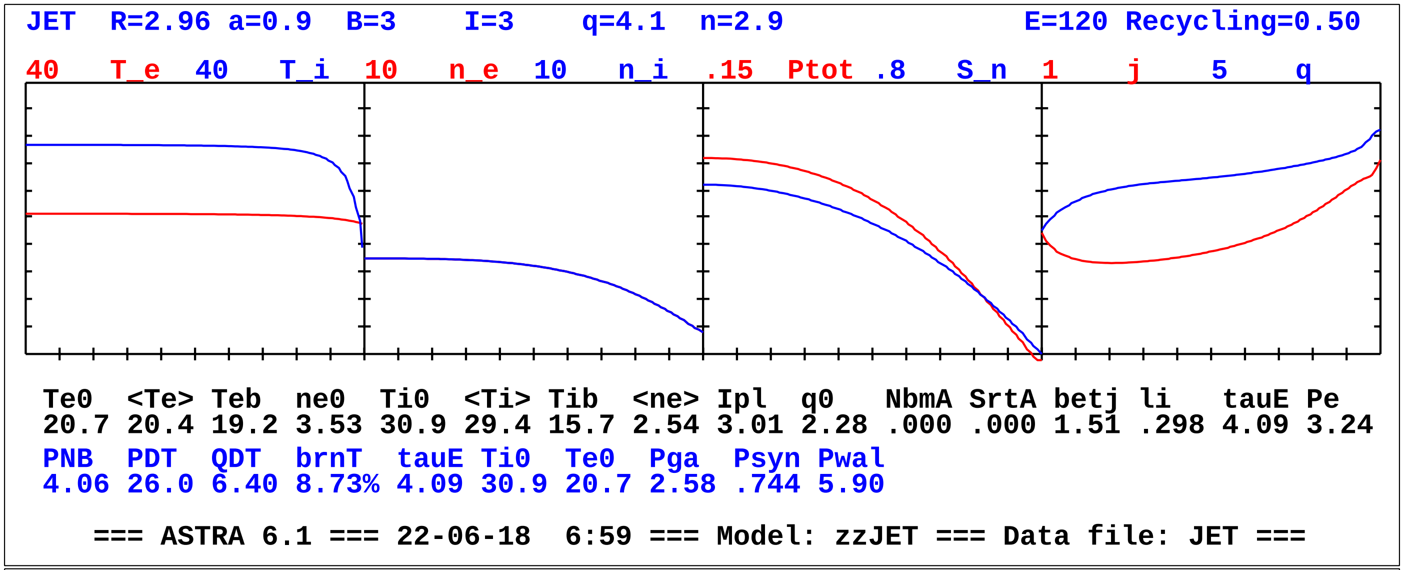
The ASTRA (Pereverzev, Yushmanov) code solves three diffusion equations for core n_e, T_i, T_e (helium accumulation neglected) and one - for diffusion of magnetic flux, including bootstrap current.

In 2005, RTM was used successfully (with $D = 0.8\chi_i^{neo}$) for simulating CDX-U four-fold enhancement of τ_E by liquid lithium.

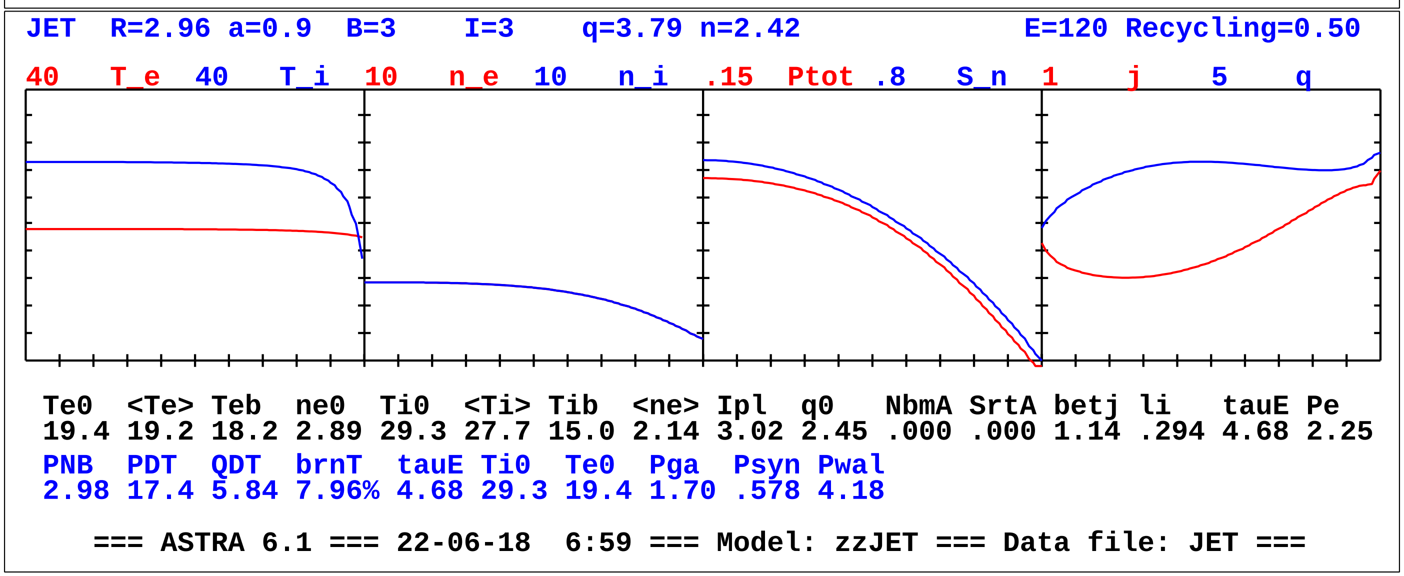
All assumptions of the RTM are conservative.

3.4 Projected JET DT performance with $Q_{DT} > 5$

(P_{NBI}=4 MW)



(P_{NBI}=3 MW)



$T_{i,e}^{edge}$ = 15.5, 19.2; Q_{DT} = 5.84, 6.4; P_{DT} = 17.4, 26.0 MW; T_{burnup} = 7.96, 8.73 %

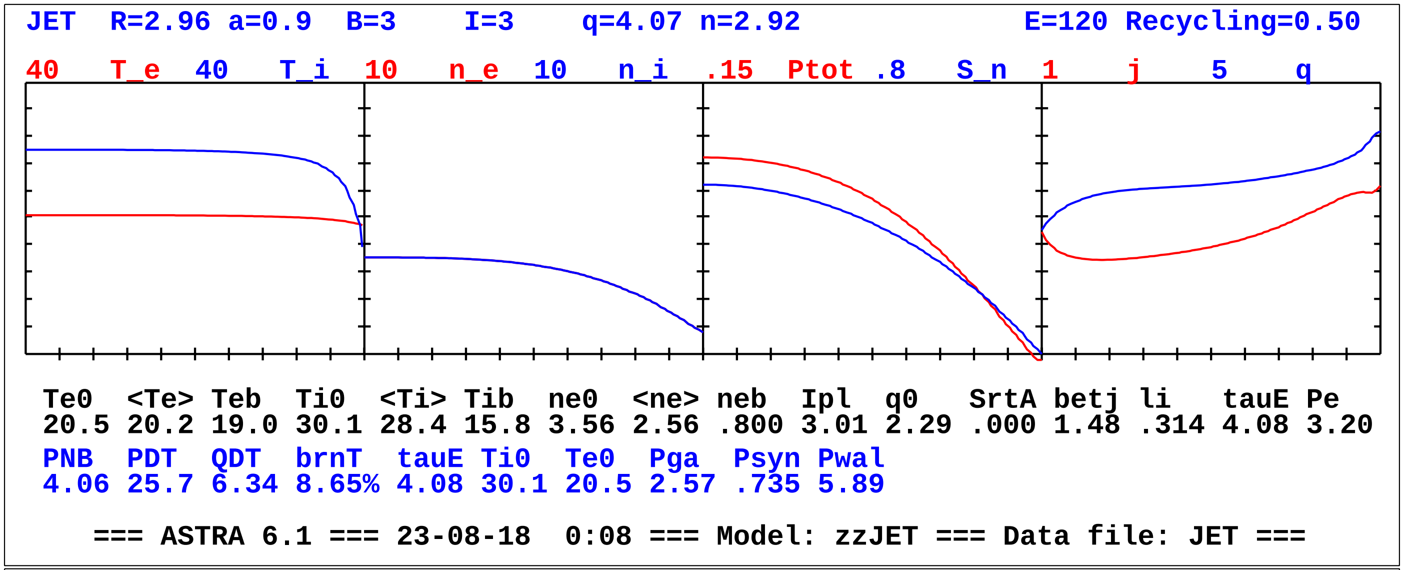
Burning plasma performance in JET DT by ASTRA code

JET Fusion performance, B=3 T, I_{pl}=3 MA						Recycling 0.50 Table 1	
#	P_{NBI} MW	E_{NBI} keV	P_{DT} MW	Q_{DT}	$f_{T-burnup}$	NBI deposition profile	Heating by α-particles
1	4.06	120	26.0	6.4	8.73 %	parabolic	50 %
2	2.98	120	17.4	5.84	7.96 %	parabolic	50 %
3	3.99	120	23.0	5.76	7.85 %	hollow	50 %
4	3.06	120	15.5	5.08	6.93 %	hollow	50 %
5	4.03	100	21.2	5.25	5.97 %	parabolic	50 %
6	3.01	100	15.6	5.19	5.90 %	parabolic	50 %
7	4.01	100	19.0	4.73	5.38 %	hollow	50 %
8	3.00	100	13.6	4.53	5.15 %	hollow	50 %
9	3.52	120	25.5	7.25	9.89 %	parabolic	75 % (85 % expected)

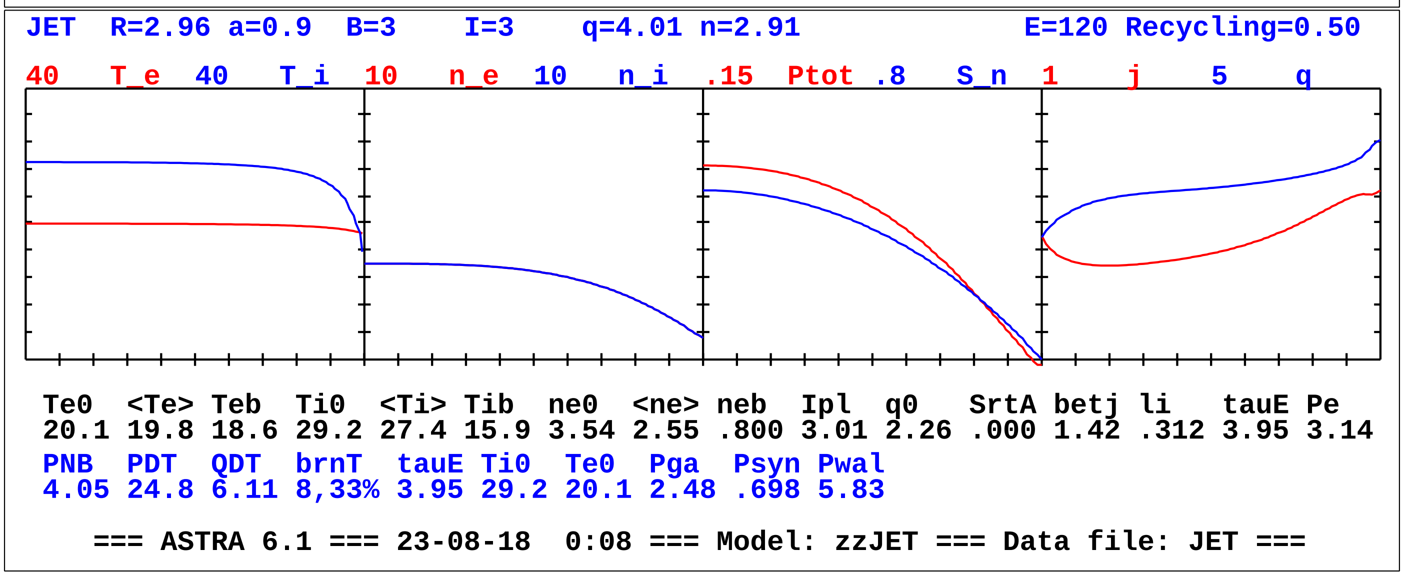
- $Q_{DT} > 5$ is almost in all cases with $P_{NBI} = 3\text{-}4$ MW.
- Only 50 % of α-particle energy was assumed for heating.
- Tritium burnup 5-9 % exceeds any expectations:
  1. core fueling
  2. the best possible confinement
  3. entire plasma cross-section makes fusion energy

Effect of enhanced ion thermal conduction

$$\chi_i = 2\chi_i^{neo}$$



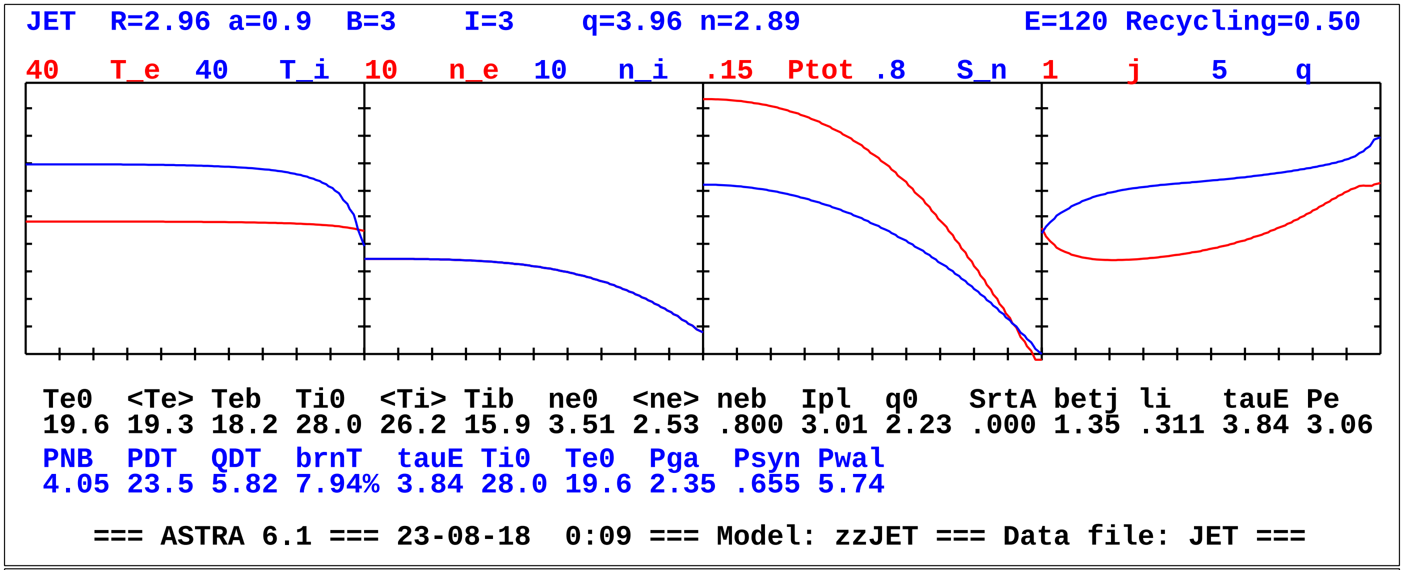
$$\chi_i = 3\chi_i^{neo}$$



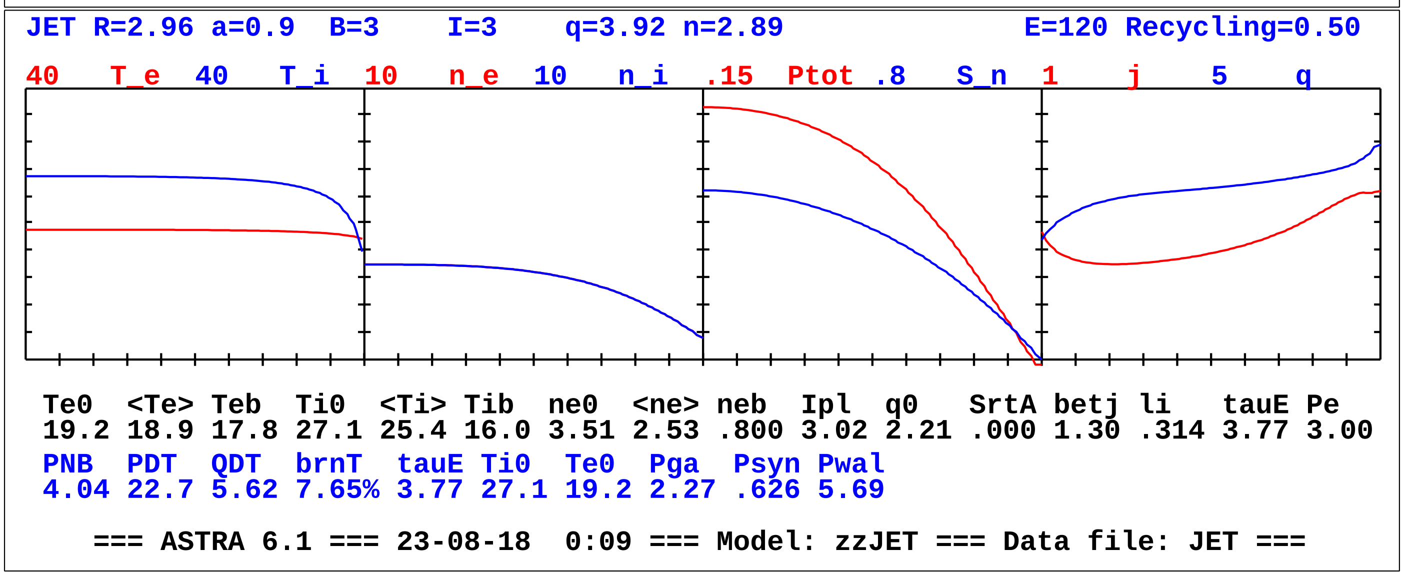
Low recycling regime is insensitive to thermal conductions

Effect of enhanced ion thermal conduction

$$\chi_i = 4\chi_i^{neo}$$

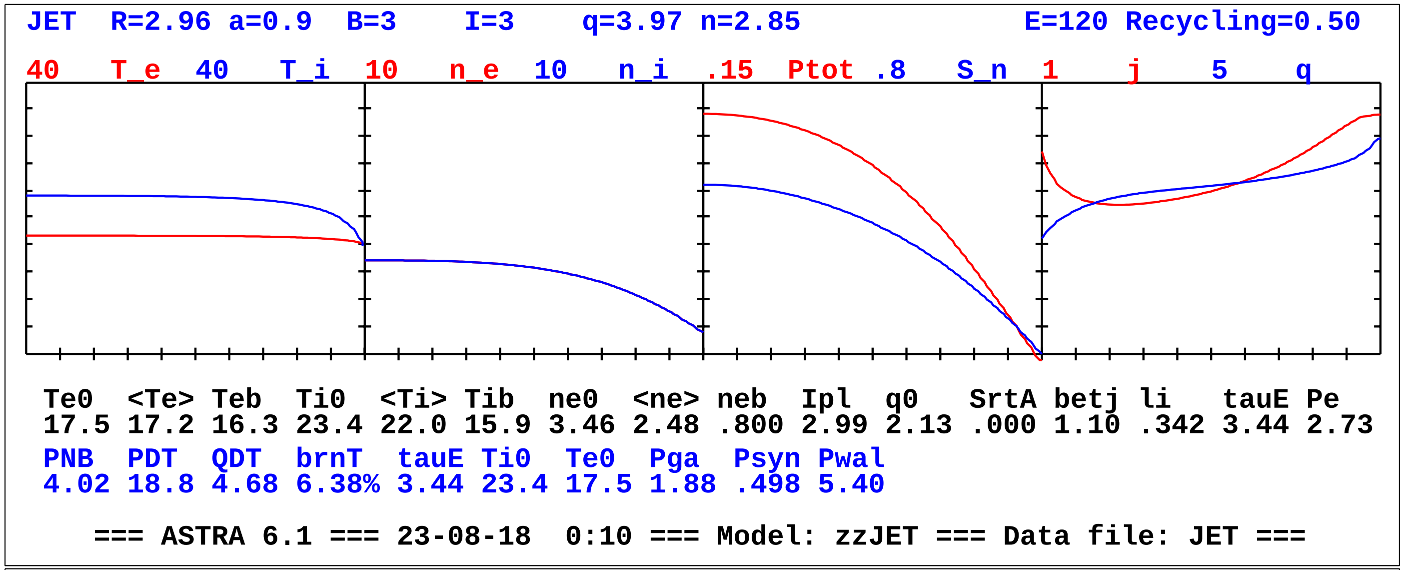


$$\chi_i = 5\chi_i^{neo}$$

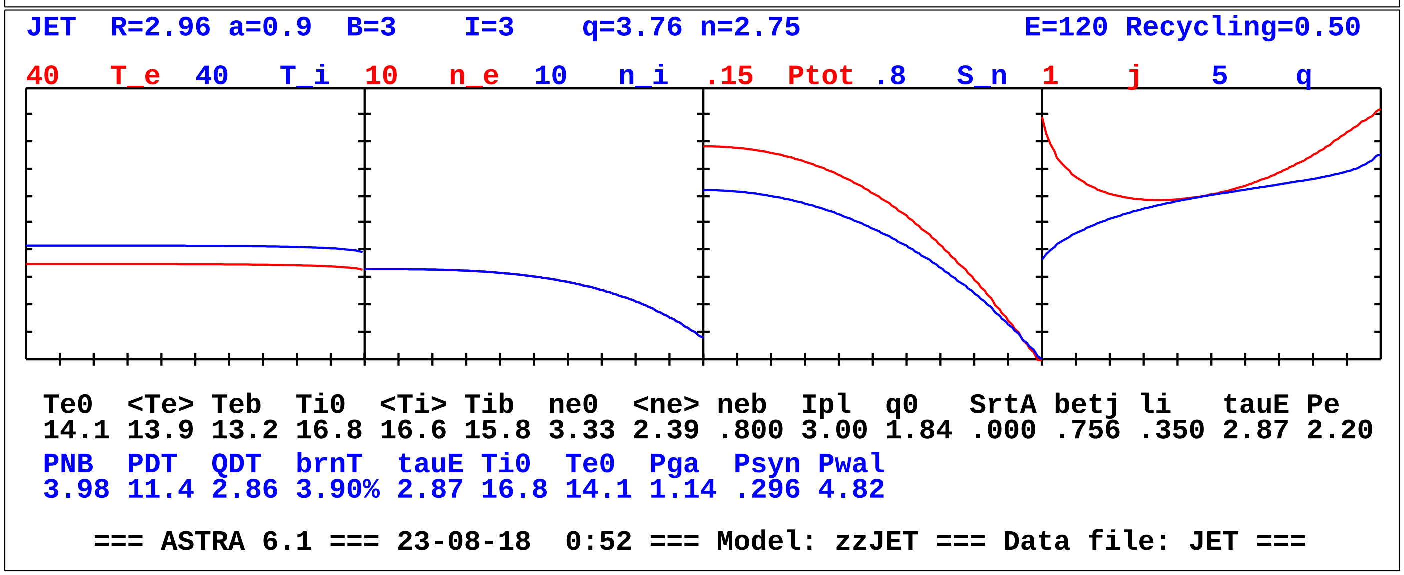


Effect of enhanced ion thermal conduction

$$\chi_i = 10\chi_i^{neo}$$



$$\chi_i = 100\chi_i^{neo}$$



High recycling plasma would not survive at so high thermal conduction

Effect of enhanced ion thermal conduction

Enhanced ion thermal conductivity χ_d						Recycling 0.50 Table 2	
#	P_{NBI} MW	E_{NBI} keV	P_{DT} MW	Q_{DT}	$f_{T-burnup}$	$f = \chi_i/\chi_i^{neo}$	Heating by α-particles
1	4.06	120	26.0	6.4	8.73 %	1	50 %
1a	4.06	120	25.7	6.34	8.65 %	2	50 %
1b	4.05	120	24.8	6.11	8.33 %	3	50 %
1c	4.05	120	23.5	5.82	7.94 %	4	50 %
1d	4.04	120	22.7	5.62	7.65 %	5	50 %
1e	4.02	120	18.8	4.68	6.38 %	10	50 %
1f	3.89	120	11.4	2.86	3.90 %	100	50 %

The effect of core thermal conduction is minuscule !

This is the essence
of the best possible confinement regime

The most challenging part of tokamak plasma physics research

- the core energy transport studies -

in fact, does not contribute to fusion development.

Effect of enhanced recycling

JET Fusion performance						Recycling 0.75 Table 3	
#	P_{NBI} MW	E_{NBI} keV	P_{DT} MW	Q_{DT}	$f_{T-burnup}$	NBI deposition profile	Heating by α-particles
10	5.03	120	14.6	2.91	3.97 %	parabolic	50 %
11	3.98	120	11.9	2.99	4.07 %	parabolic	50 %
12	2.97	120	8.7	2.93	3.99 %	parabolic	50 %
13	4.97	120	17.2	3.46	4.72 %	parabolic	75 %
14	4.00	120	14.7	3.68	5.02 %	parabolic	75 %
15	3.02	120	10.4	3.45	4.70 %	parabolic	75 %
16	5.00	120	15.1	3.03	4.14 %	hollow	75 %
17	4.02	120	12.3	3.07	4.18 %	hollow	75 %
18	3.01	120	9.1	3.03	4.13 %	hollow	75 %

Enhanced recycling does deteriorate plasma performance.
Still, even in this case the predicted DT JET performance highly exceeds expectations based on existing high recycling regimes.

At 0.75 recycling the RTM model becomes not reliable.

80 keV NBI fits JET shine-through constrains

JET Fusion performance. T/D in the plasma 50% / 50%							Recycling 0.50 Table 4
#	P_{NBI} MW	E_{NBI} keV	P_{DT} MW	Q_{DT}	$f_{T-burnup}$	Volume averaged density $\langle n_e \rangle$	Central density n_0
19	4.01	80	17.1	4.26	3.87 %	2.83	3.89
20	4.49	80	17.6	3.93	3.57 %	2.90	3.88
21	5.00	80	18.2	3.64	3.31 %	2.97	3.89
22	5.49	80	19.1	3.47	3.16 %	3.05	3.95
23	5.74	80	19.9	3.47	3.16 %	3.12	4.04

Depleted tritium plasma: T/D in the plasma 25% / 75%							Recycling 0.50 Table 5
#	P_{NBI} MW	E_{NBI} keV	P_{DT} MW	Q_{DT}	$f_{T-burnup}$	Volume averaged density $\langle n_e \rangle$	Central density n_0
24	3.99	80	9.87	2.47	2.25 %	2.74	3.74
25	4.51	80	10.9	2.41	2.19 %	2.87	3.89
26	5.00	80	12.0	2.40	2.18 %	3.00	3.98
27	5.49	80	12.9	2.34	2.13 %	3.10	4.08
28	5.99	80	13.7	2.28	2.07 %	3.19	4.18
29	6.50	80	14.3	2.20	2.00 %	3.27	4.22
30	7.00	80	15.0	2.15	1.95 %	3.35	4.31

Still good performance $Q_{DT} > 3$ or $Q_{DT} > 2$ with suppressed shine-through losses

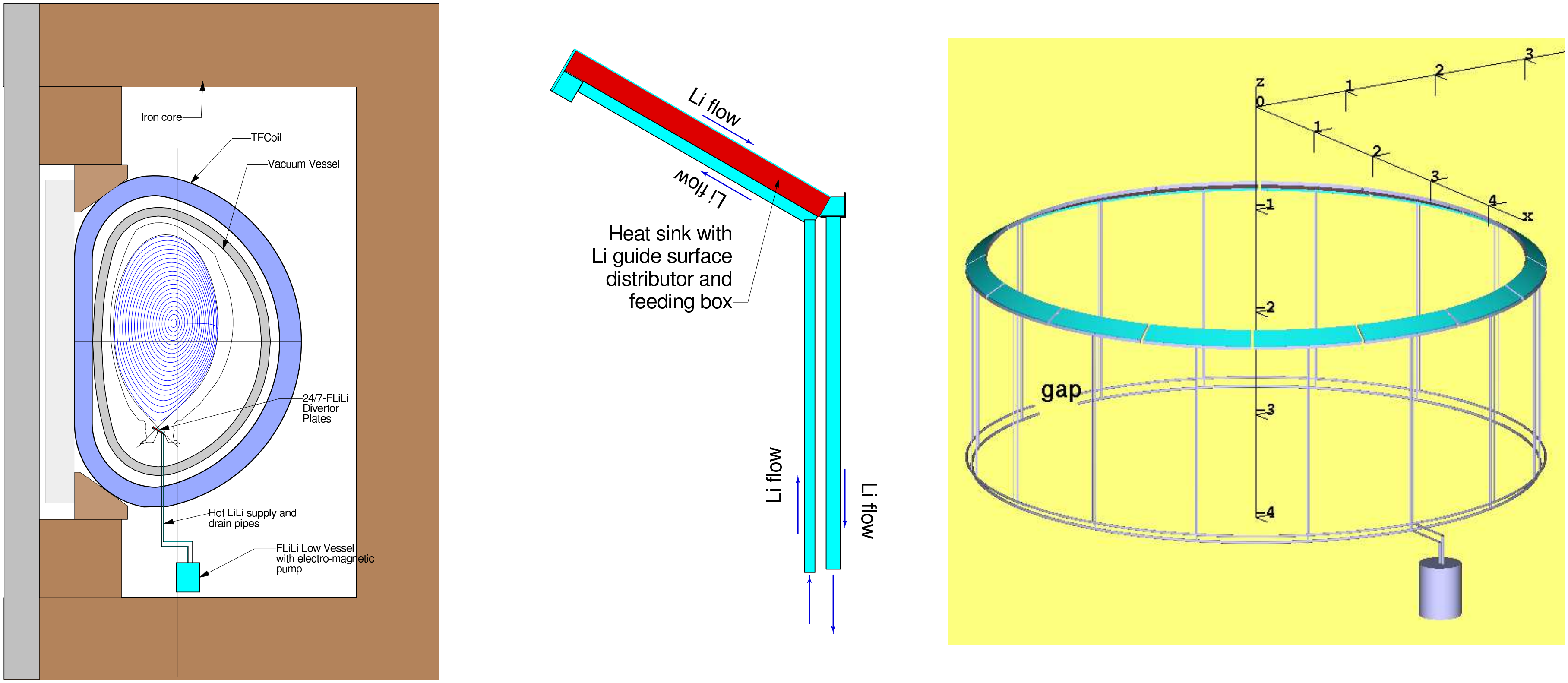
3.5 Key properties of the low recycling regime

The most essential features:

- ***Externally controlled plasma by NBI: plasma temperature set up by E_{NBI}, plasma density by I_{NBI} and by beam deposition***
- ***Predictable plasma what is critical for disruption avoidance***
- ***The best possible confinement, the most relaxed plasma***
- ***Absence of sawteeth, NTM triggering, and ELMs***
- ***Consistency with outstanding performance of burning plasma: full plasma volume produces fusion***
- ***Innovative approach to power extraction problem by reducing heat flow to the plates***
- ***Enhanced burnup of tritium***
- ***Potential Real Time Tritium Recycling (not discussed here)***
- ***Potential, JET-size 100-150 MW DT DEMO device with $Q_{electric} > 1$ (not discussed here)***

4 Implementation: 24/7-FLiLi divertor

Reference, simplified sketch of 24/7-FLiLi (Continuously Flowing Liquid Lithium)

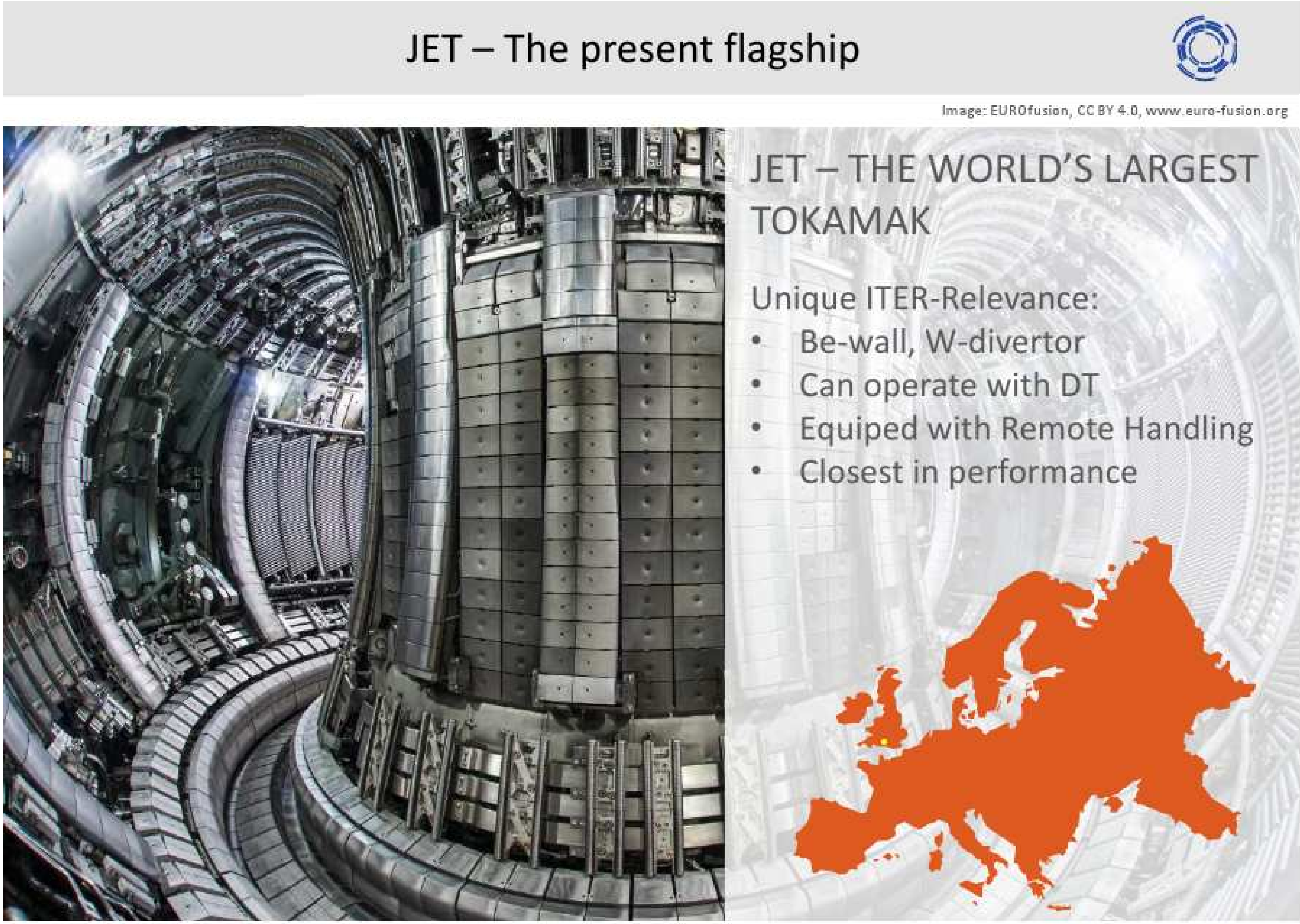


(a) ***(c)*** ***(b)***

Figure 2. (a) Relative position of the 24/7-FLiLi target plate inside the JET vessel and "lithium plumbing" inside the iron core. (b) 3-D view on entire 24/7-FLiLi system with a single lower vessel, controlling the flow, and horizontal drain/supply ring pipes.

Some complications are due to needs in 200^{o}C for all tubes with LiLi.
Thermal regime of divertor plate is a challenge to keep 200^o $<$T$_{LiLi}$ $<$400^o

Plasma/wall interaction is very complicated



24/7-FLiLi plates to replace inner lower row of JET divertor plates

Flow parameters:

Critical number of 24/7-FLiLi technology: 1 g/s flow rate

Necessary flow rate R_{LiLi} of Liquid Lithium with $\simeq$10 atomic % retention of D,H,T

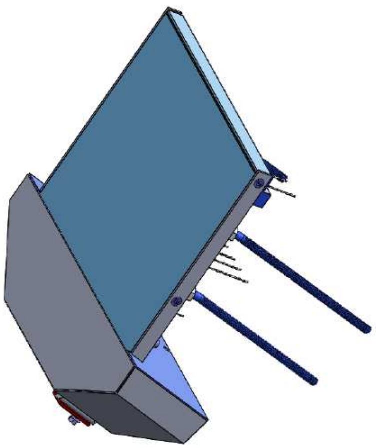
$$\Gamma = 10^{22}/s \quad \rightarrow \quad R_{LiLi} = 1 \text{ g/s} \tag{4.1}$$

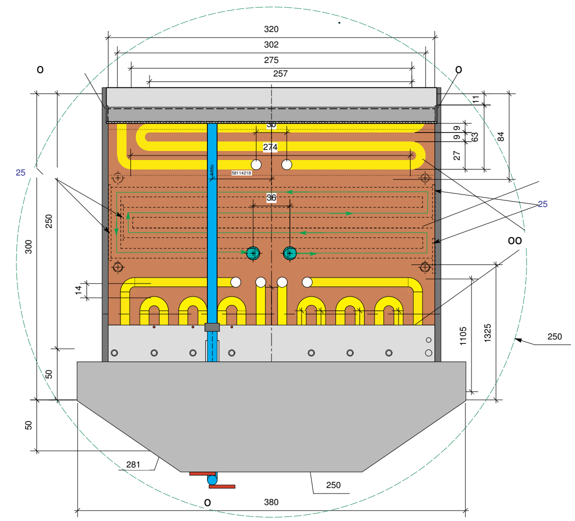
- Gravity driven LiLi along the SS foils on copper heat sink
- Wetting SS by Li is critical
- 0.1 mm thick
- $<$ 1 cm/s velocity (creeping rather than flow)
- $T_{Li} < 400^o C$ to limit evaporation
- No interaction with $\vec{B}$ of tokamak
- Relatively straightforward to implement safely

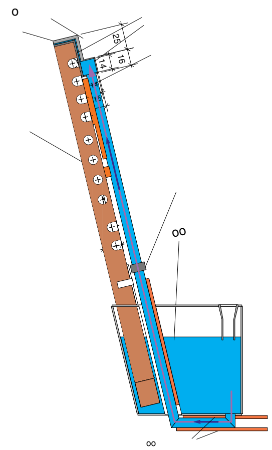
Liquid Lithium should flow continuously 24/7 with no interruptions

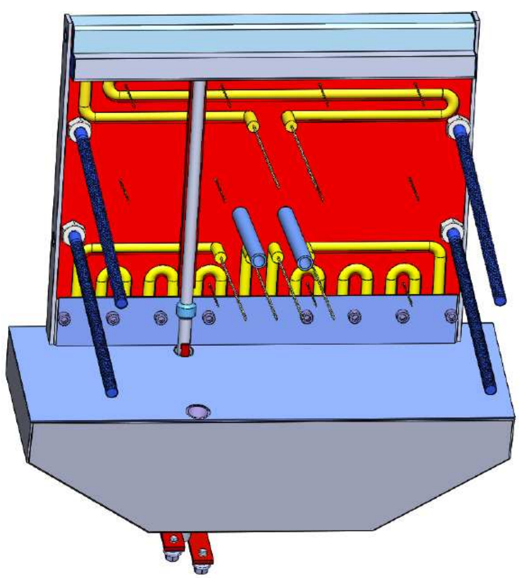
4.1 24/7-FLiLi limiter with JxB pump for EAST (China)

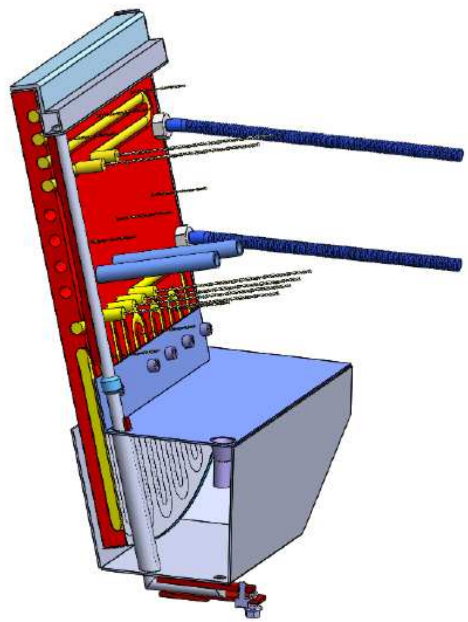
Modular device for EAST H-port, delivered in 2014, operated in 2014 exp. campaign

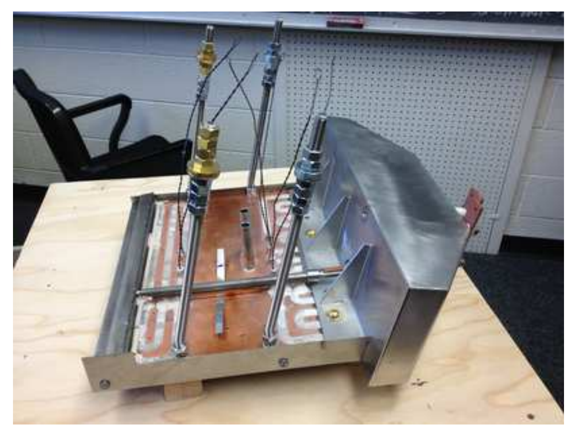












4.2 Amazing property of 24/7-FLiLi

In tokamaks 24/7-FLiLi can serve two functions simultaneously:

1. ***during the discharge,***

   24/7-FLiLi pumps out plasma particles, making the best possible confinement regime

2. ***between discharges,***

   24/7-FLiLi acts as a garbage collector and cleans the vacuum chamber from wall out-gasing,

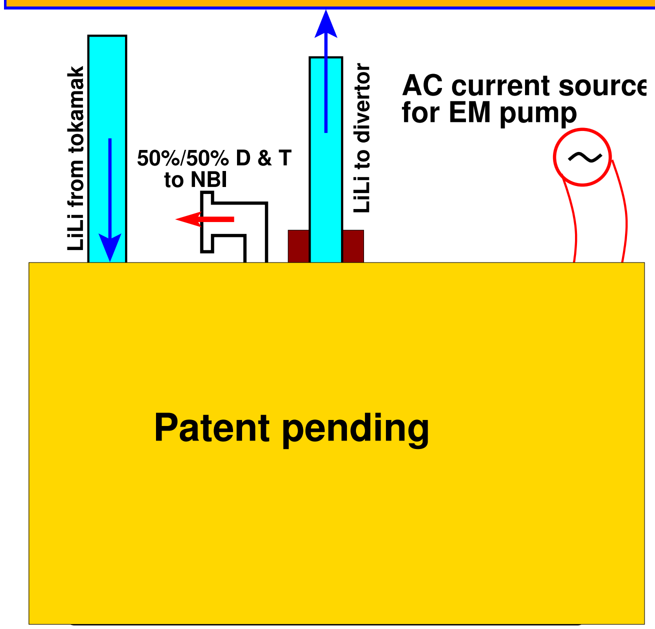
   thus, making the best possible vacuum conditions.

These concept represents a big step in Li applications

For JET, 24/7-FLiLi would be a gift rather than a burden

4.3 Future: Real Time Tritium Recycling (RTTR)

In burning plasma only 1 % of injected tritium is burned up.
99 % exhausted from the plasma should be recycled.



Single low vessel with EM driven FLiLi can be designed to:
(a) supply LiLi to the chamber,
(b) collect LiLi with D,T from the plasma exhaust,
(c) release 50%-50% mixture of absorbed D and T for the use in NBI,

24/7-FLiLi makes possible the Real Time Tritium Recycling of tritium injected to the burning plasma,

the objectives which never been formulated in the fusion program.

24/7-FLiLi vs ITER tritium plant

Complexity of processing, still never challenged RTTR

FUSION FOR ENERGY

Generic Site Tritium Plant Building Layout (ITER FDR 2001)

- Dimensions

Length:	80 m
Width:	25 m
Height:	35 m

- Outdated design:
- New regulations:
  - Escape routes not clear and too long.
  - Airlocks not included consistently.
  - HVAC to be changed.
- Increase of width and length.
- Stairways: 2 → 3
- Elevator: 0 → 1

G. Piazza, Seminario Industrial 13 June 2012 9

IV. $R^{ecycling} = 0.5$, “impossible” but DOABLE

Lithium is excellent in all aspects:
minimal Z_{eff}, liquid at modest temperatures
outstanding hydrogen pumping and retention, including absorption of tritium.
24/7-FLiLi resolves the issues related to high chemical activity of liquid Li.
In fact, it utilizes it.

Flowing Li is the only technology for making the recycling of 0.5 possible.

The goal is to limit the influx of D,T atoms from the wall and divertor by $\simeq 2 \cdot 10^{20}$/s

The design challenges are related to

1. ***Special thermal regime of divertor plate with $T > 200^o C$ of Li surface***
2. ***Narrow range of working temperatures $200^o C < T < 400^o C$***
3. ***Finite sputtering (although modest)***
4. ***Elimination of leading edges***
5. ***Pumping of Helium ash (in future)***

There is no simplistic solutions for achieving the goal,
but also there is no fundamental stoppers

5.1 Low recycling on LTX

In 2016 LTX (PPPL) demonstrated transient implementation of the original idea of magnetic fusion of plasma insulation from the wall

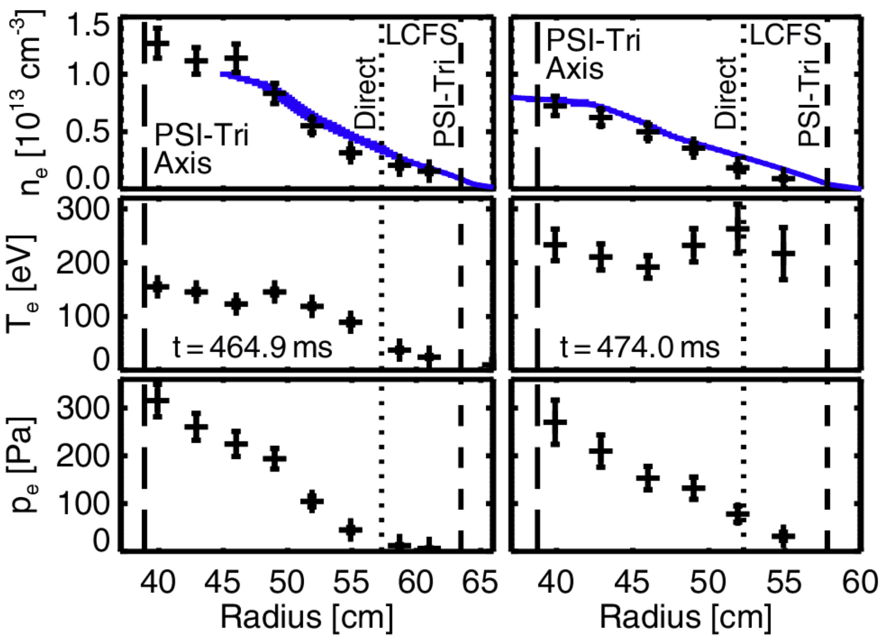


FIG. 4. Thomson scattering (TS) n_e, T_e, and p_e profiles during

D. P. Boyle et al. "Observation of Flat Electron Temperature Profiles in the Lithium Tokamak Experiment". Phys. Rev. Letters 119 015001 (2017)

No NBI present.

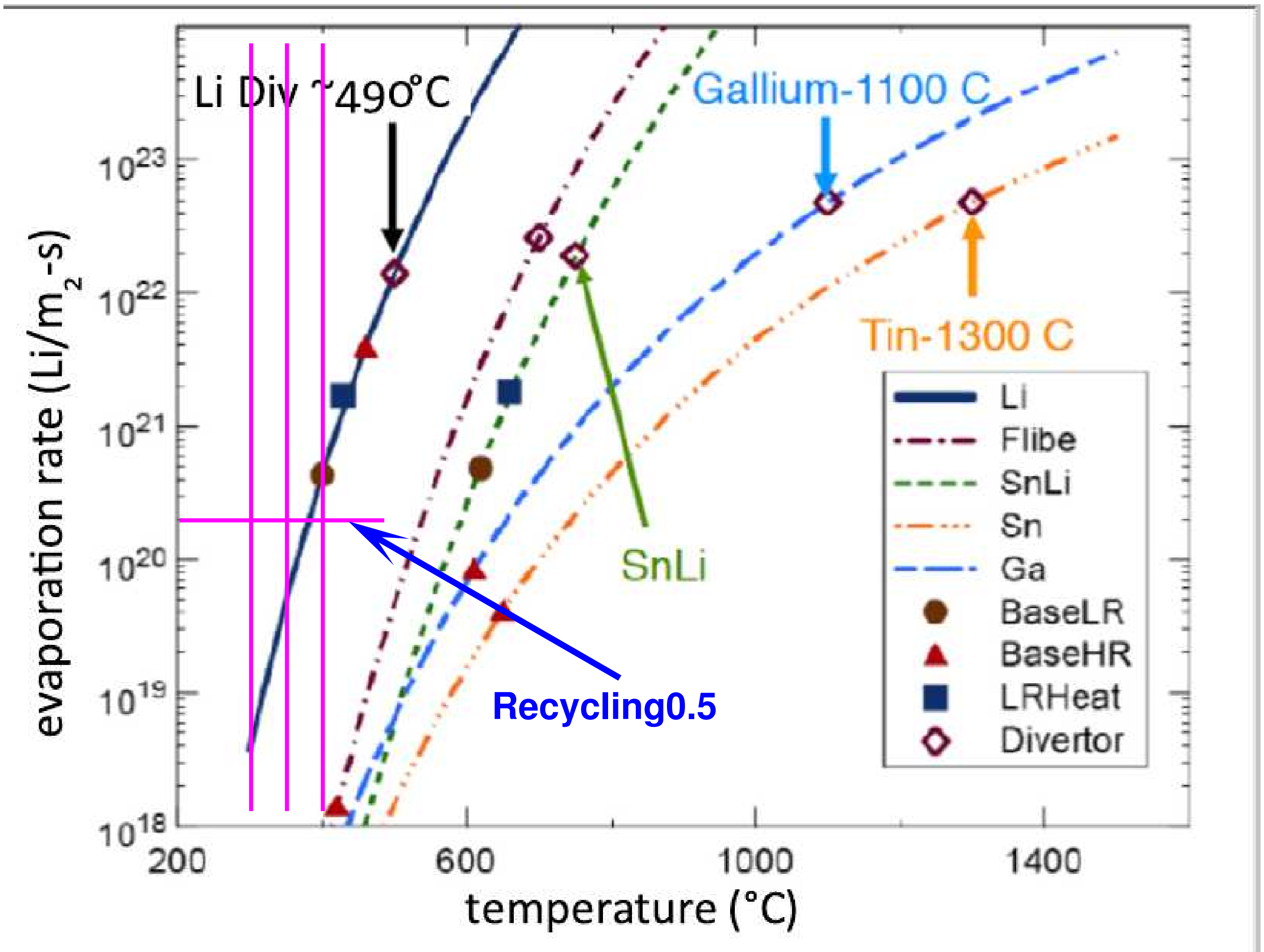
Shutoff of gas puff under Li pumping results in:

- **flat temperature,**
- **enhanced temperature,**
- **reduced density**

In the transitional phase on LTX the recycling was essentially absent

TFTR indicated 0.85 recycling and CDX-U 0.5-0.75.

5.2 Evaporation should be kept inder control



The Allain Research Group,

Radiation Surface Science and Engineering Lab, CPMI

Deuterium Sputtering on Lithium-Coated Tungsten

Samuel Bennett, Muhammad Abdelghany

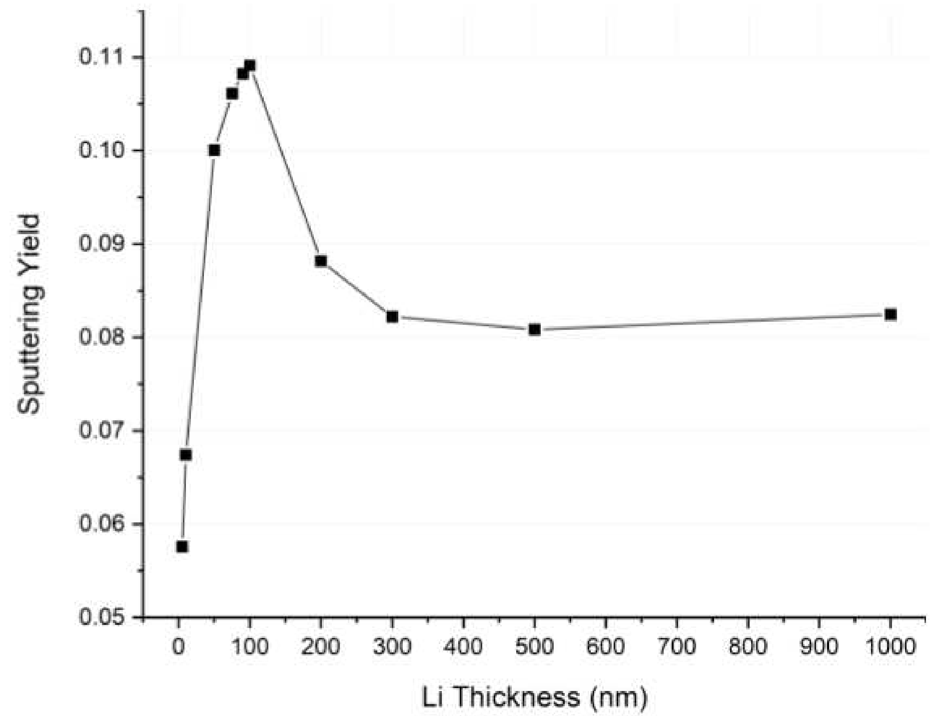
March 5, 2019

Sputtering yield of 20 keV D on Li at 80° incidence

***Modest and acceptable** (one the frequent false objections to Li in tokamaks)*

Sputtering Yield

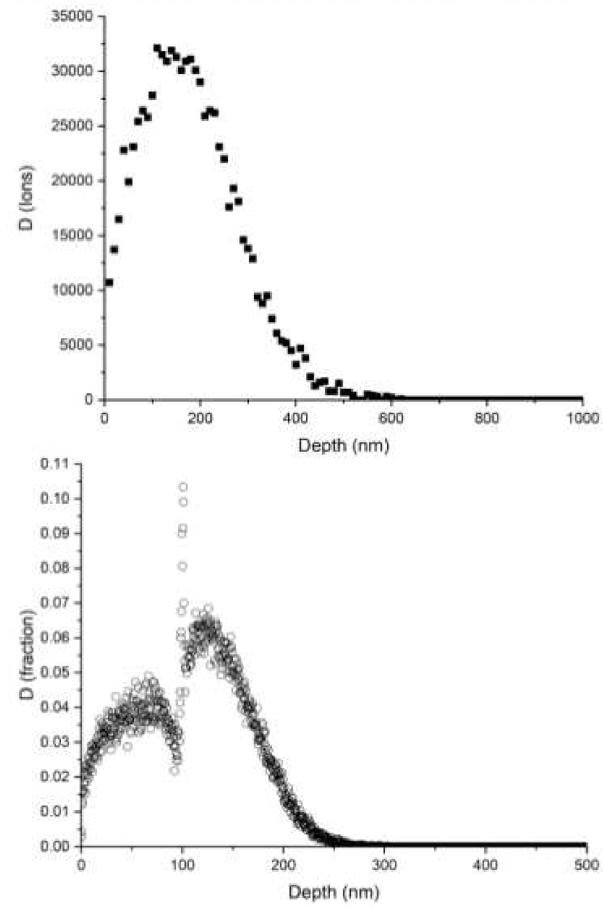
- Sputtering yield of pure lithium is 0.08
- Yield increases as layer gets thinner, likely due to reflection at W-Li interface
- Sputtering yield of pure tungsten is 0.096



Deposition range $\simeq$ 4000 monolayers

Deuterium Range

- Top: SRIM range of deuterium in lithium
  - Range peaks around 175 nm
  - Deuterium range coincides with increased sputtering yield
- Bottom: DYNAMIX simulation of 100-nm lithium layer on tungsten
  - Li-W interface exhibits trapping of implanted deuterium



CPMI http://cpmi.uiuc.edu
Center for Plasma-Material Interactions

3

The Allain Research Group
Radiation Surface Science and Engineering Lab
http://rssel.engineering.illinois.edu
RSSEL

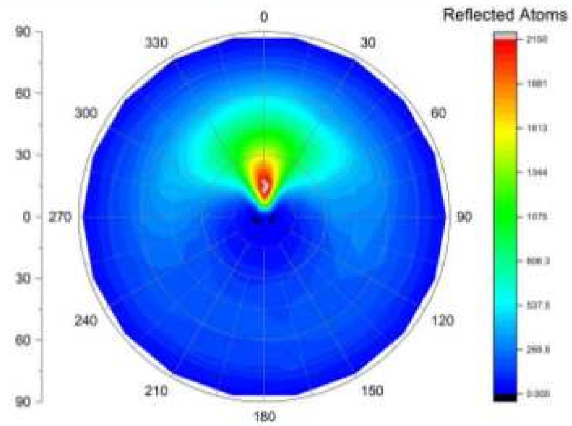
LiWF

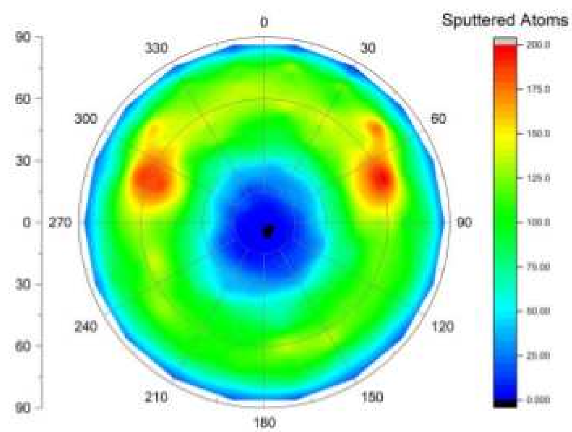
Reflection of D and spattering pattern of Li

Very important data for a divertor design (need additional energy deposition analysis)

Reflection and Sputtering

- Top: angular distribution of reflected atoms, 0° is parallel to incident radiation
  - 53% of incident atoms are reflected
  - BCA tends to underestimate reflection of grazing-incidence irradiation
- Bottom: angular distribution of sputtered lithium atoms
  - Sputtered atoms show characteristic cosinusoidal dependence on polar angle with an added forward bias.





Comments

- Erosion rate is very low, fluence on the order of 10^{19}-10^{20} cm^{-2} would likely be required to erode 1 micron of lithium
- While BCA consistently underestimates reflection rate at grazing incidence, this may be possible to remedy by simulating a higher “effective incidence angle”
- Behavior of implanted deuterium, particularly at the interface, may differ from DYNAMIX simulations and would be better served by MD

6 Making low recycling ready for DT on JET in 2024

The plasma physics of low recycling regime is relatively simple and reliable

Many technology problems related to Li are already resolved

Near future issues to be resolved by a special Working Group, which has to be formed:

1. ***Stability analysis of low recycling plasma at different I_{pl}, B_{tor}, NBI deposition, etc***
2. ***Check of applicability of the current drive***
3. ***Analysis of charge exchange effect on recycling***
4. ***Design of 24/7-FLiLi divertor for 0.5 recycling with potential use of multiple Li films***
5. ***Design of the thermal regime of the copper heat sink***
6. ***Development of fabrication technology of void less attaching SS foil to the copper surface and of entire heat sink***
7. ***Design of the manifold for Li flow for 200^oC and the lower vessel***
8. ***Design of feed through of Li supply/drain tubes to the vacuum vessel of JET***
9. ***Design of the safety system compatible with liquid Li***

Essentially all technology developments can be performed separately of tokamak

With the required only 3-5 MW of NBI heating for JET this represents the most cost effective approach to demonstration of fusion

7 Summary

While suggesting
the best confined, relaxed, predictable and controllable plasma,
the "Fusion without plasma physics" (LiWF)
does need a lot of plasma physics research in:

- ***general MHD and α-particle driven instabilities and oscillations,***
- ***analysis of the collisionless SoL,***
- ***analysis of details of plasma density profile at the very edge,***
- ***helium confinement and transport,***
- ***assessment of Li level, if any, in the plasma,***
- ***assessment of energy losses by synchrotron radiation,***
- ***etc,***

These topics are different from the present dominance of (a) turbulent thermal conduction and (b) a high recycling plasma-wall interaction.

The low recycling concept moves technologists and engineers to the leadership position in developing fusion with a mission of creating the 0.5-recycling divertor for JET and tokamaks.