Does tokamak have a chance to avoid disruptions ?

Leonid E. Zakharov

LiWFusion, PO Box 2391, Princeton, NJ 08543, USA

Department of Physics, University of Helsinki, P.O. Box 43, Helsinki, FIN - 00014, Finland

Department of Plasma Physics, National Research Nuclear University MEPhI, Moscow, 115409, Moscow, RF

IAEA Technical Meeting on Plasma Disruptions and their Mitigation

20-23 July, 2020

* *Supported by the US Department of Energy under Grant DE-SC0019060*

Contents

1 Disruptions and tokamak fusion

- ***1958 - First tokamak with Shafranov's $q > 1$ by Yavlinski, the start***
- ***1962 - First disruption observation on TM-2 in Kurchatov with negative V-spike.*** ***Disruptions recognized as a potential obstacle to fusion power***
- ***1994 - lack of success for $Q_{DT} = 1$ on TFTR***
- ***1997 - lack of success for $Q_{DT} = 1$ on JET***
- ***Disruptions are widely recognized as the major problem for tokamak fusion***
-
- ***2020 - $Q_{DT} = 1$ is still out of horizon***
- ***2020 - Disruption avoidance still is not possible, only mitigation.***

62 years with no $Q_{DT} = 1$ (the minimal milestone toward fusion power)
and
58 years with no clue for disruption avoidance
indicate some fundamental flaw in the approach.

2 Both linked together

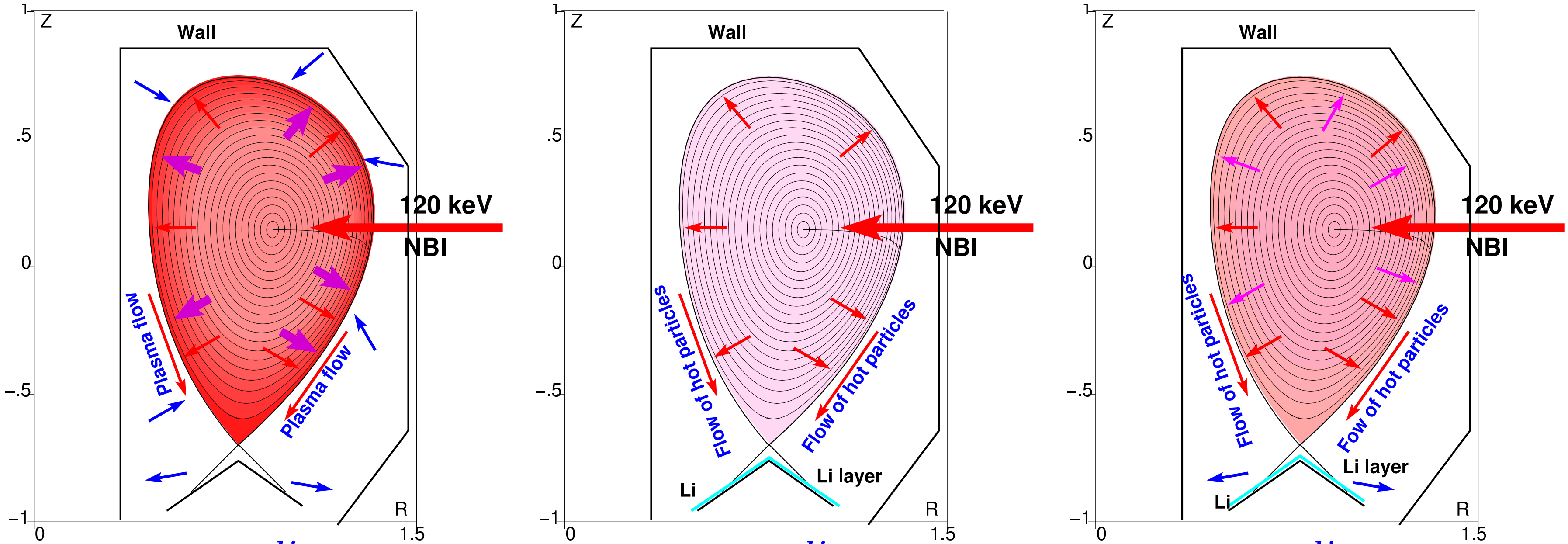
- ***The problem with $Q_{DT} = 1$ is in insufficient confinement.***
- ***The disruptions are unavoidable because the plasma is shaky in a very complicated environment.***

Both have roots at very deep level in the approach and are strongly linked to each other.

This level goes down to recycling on the wall and cooling plasma edge by cold atoms.

Recognized as a problem by Igor Tamm in 1951 in his fusion mini-reactor project, recycling stays $\simeq 1$ for 60+ years and probably will for more years to come.

3 Three tokamak regimes determined by recycling



High $R^{ecycling} \simeq 1$ ***Zero*** $R^{ecycling} = 0$ ***Low*** $R^{ecycling} \simeq 0.5$

cold edge, $T^{edge} \ll T^{core}$ ***hot edge,*** $T^{edge} = E_{NBI}/5$ $T^{edge} = E_{NBI}/10$

In Zero- and Low- recycling regime

1. only diffusion matters,

2. SoL is the particle flux instead of plasma flux

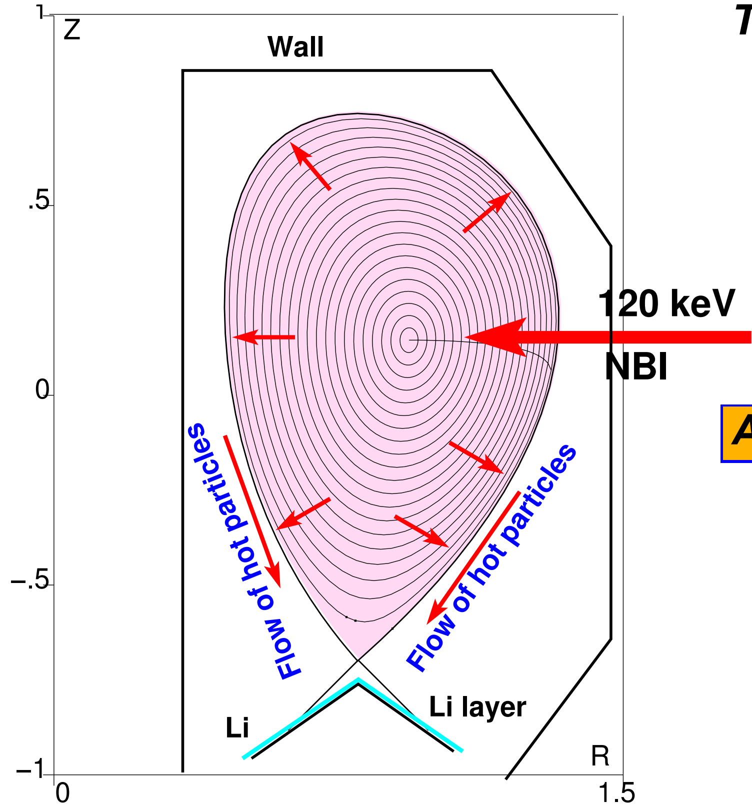
4 High recycling is the main reason of both problems

(a) cold edge, $T^{edge} \ll T^{core}$, (b) T^{core}_{plasma} is determined by power P of NBI, which struggles with plasma cooling by recycling.

- *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 . . .*

The physics is terribly complicated while plasma is unpredictable.

5 In contrast, the physics of Zero recycling regime



The most relaxed plasma:

- ***No stress on temperature profile***
- $T^{edge} = E_{NBI}/5$ ***is controlled externally***
- n^{core} ***is controlled externally by current*** I_{NBI} ***(given particle diffusion)***

All physics of confinement is reduced to general physics:

- ***Capture and thermalization of NBI atoms***
- ***Particle diffusion from the plasma core***
- ***Free flow of hot (15 - 20 keV) electrons and ions along open field lines***
- ***Impingement of energetic particles to liquid lithium***

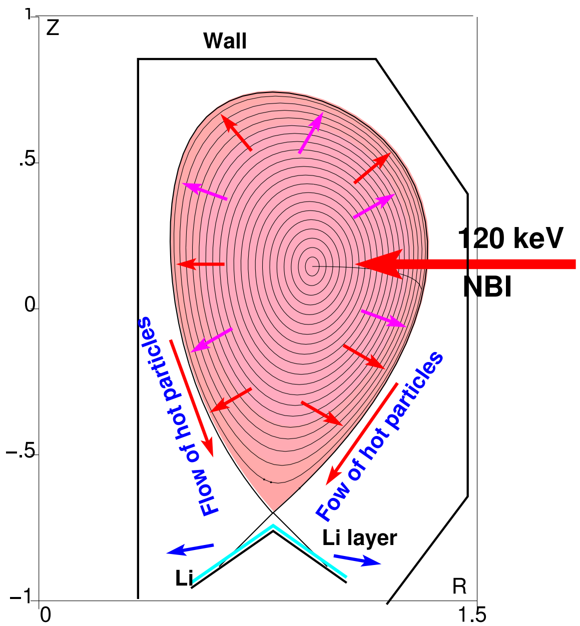
- ***There is no plasma physics of thermal conduction with its turbulence, draining program resources***
- ***No mess of plasma-surface interaction (PSI), conflicting with plasma performance and stability***

6 0.5 of recycling is much closer to 0 than to 1

High edge temperature by general physics through the global parameters.

$$\frac{T_i^{edge}+T_e^{edge}}{2}=\frac{1-R^{ecycling}}{1+\frac{\Gamma_{gas\ puff}}{\Gamma_{NBI}}}\cdot\frac{E_{NBI}}{5}\cdot\left(1+\frac{P_\alpha-P_{rad}}{P_{NBI}}\right). \tag{6.1}$$

$1-R^{ecycling}$ *matters, rather than* $R^{ecycling}$



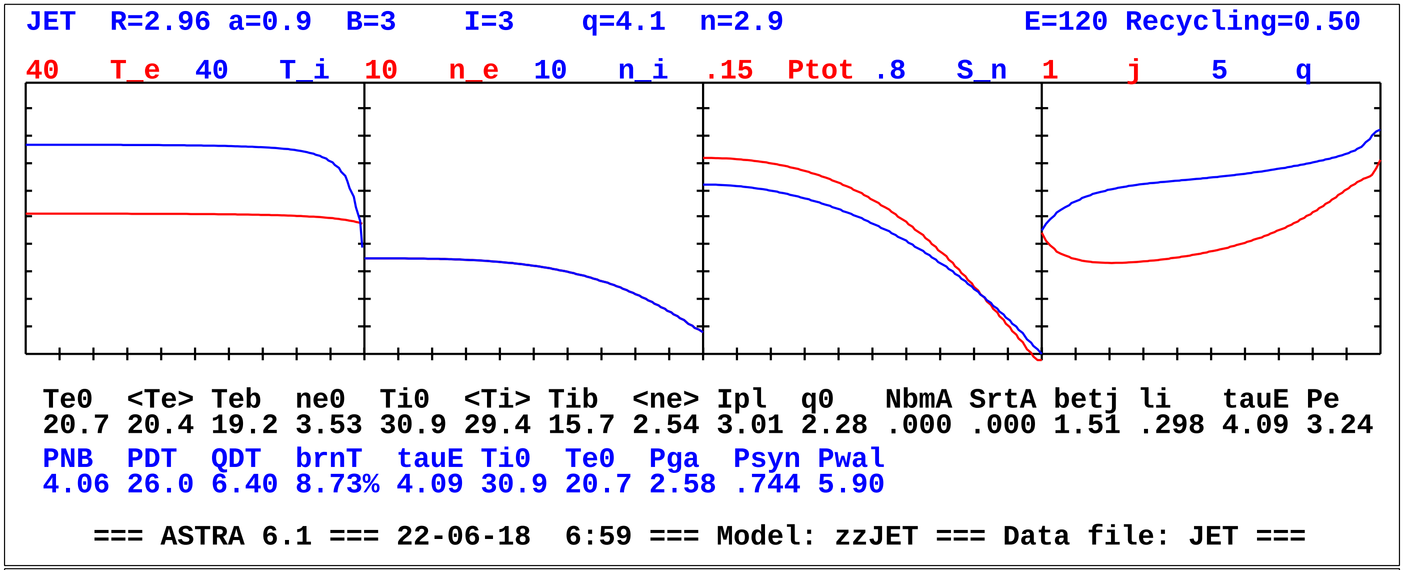
For $R^{ecycling}=0.5$*:*

- $T^{edge}=E_{NBI}/10$
- *negligible therm. condct.*
- n^{core} *is determined by* P_{NBI}
- *Collisionless SoL, MFP* $\lambda_m\simeq 75\cdot\frac{T_{keV}^2}{n_{20}}$
- *No PSI. Instead particle flow.*
- *Plasma physics plays minor role*

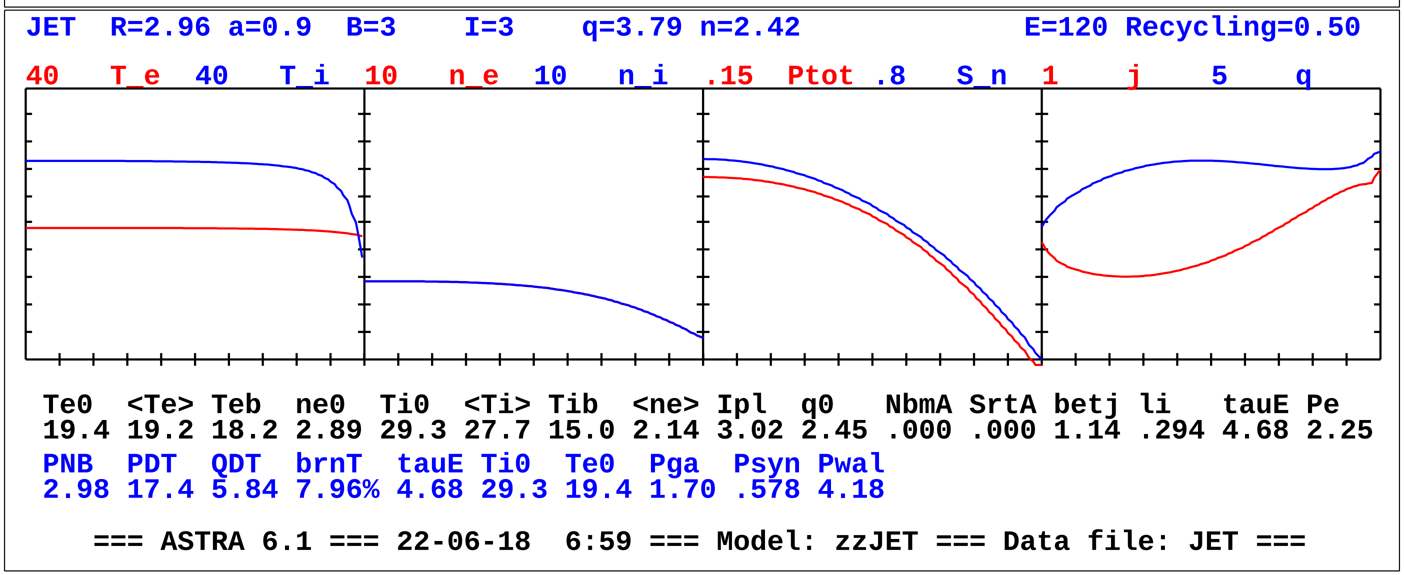
In low recycling there is no place for PSI with its 20 eV (!!!) at W

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

(P_{NBI}=4 MW)



(P_{NBI}=3 MW)



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

8 Core stability, no sawteeth, no ELMs

- $q(a) > 1$ - *no sawteeth automatically*
- ***high edge current density stabilizes the plasma boundary. The dominant term in MHD energy principle is resonant***

$$W \propto \int \frac{\bar{\jmath}' R}{B_{tor}\left(\frac{1}{q} - \frac{n}{m}\right)} \quad \rightarrow \quad -\frac{\bar{\jmath}^{edge} R}{B_{tor}\left(\frac{1}{q^{edge}} - \frac{n}{m}\right)} > 0 \qquad (8.1)$$

and stabilizing if plasma is limited by a separatrix.

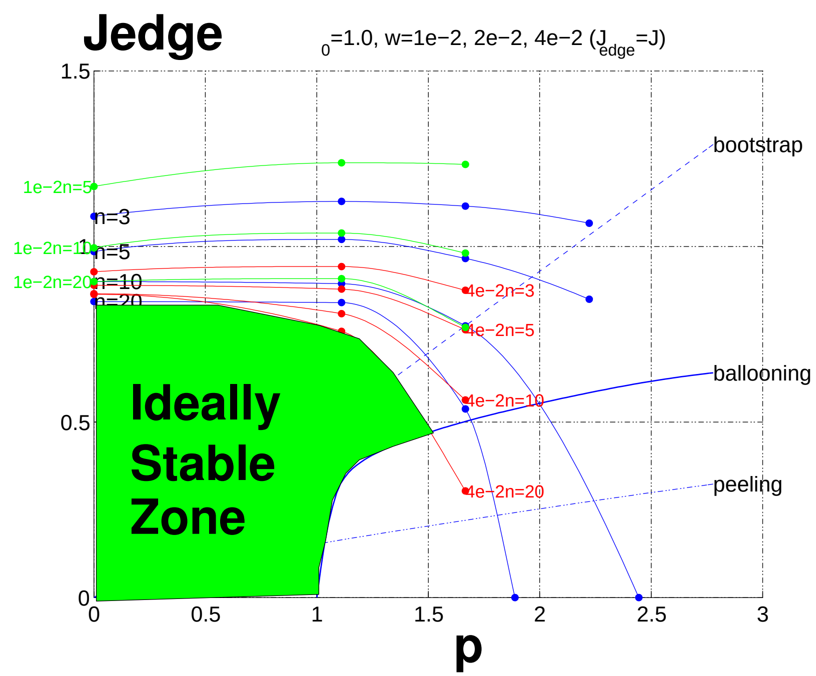
ELMs stabilization by Li was predicted in 2005, same year suggested to JET,
in 2007 easily reproduced on NSTX using Li evaporation

(in sharp contrast with ELMs "understanding" by rest of the community).

- ***There is no NTM triggering (by non-existing sawteeth)***
- $q(a) > 1$ ***corresponds to the second stability regime for ballooning modes (1978, Mercier, Haas, Zakharov)***

In all aspects of core/edge MHD stability the Low Recycling Regime is outstanding compared to the present complexity in core stability.

9 Free boundary stability. Summary



High edge temperature is consistent with free boundary stability diagram, no peeling modes

Keldysh Institute, KINX calculations, (Medvedev, 2003)

The low recycling regime eliminates as players the most dirty parts of tokamak physics:
(1) thermal conduction in the core, and
(2) PSI, which holds tokamak hostage of low performance and makes plasma disruptive.

These two advances would make tokamak plasma predictable and relying on general physics.

Only low recycling regime allows to realistically think about disruption avoidance in tokamaks (as well as about a burning plasma)

And technically 0.5 recycling is perfectly realistic