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The next step in magnetic fusion, driving the fusion science R&D and driven by it[1]

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presented by Leonid E. Zakharov

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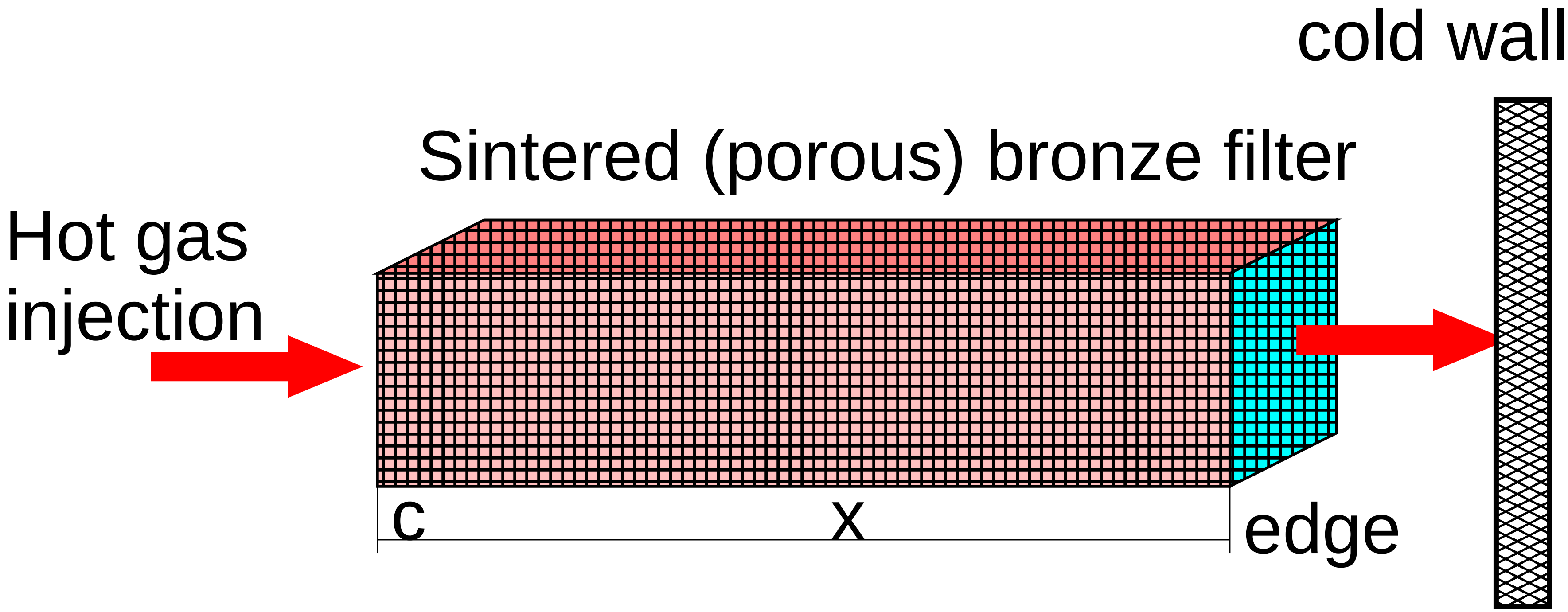
1 Confinement: simple example of heat transfer



1. ***Hot gas is injected into the porous metal filter from left;***
2. ***Heat is transferred to the right by thermal conduction and with gas diffusion;***
3. ***Side surfaces are assumed to be thermally insulated.***

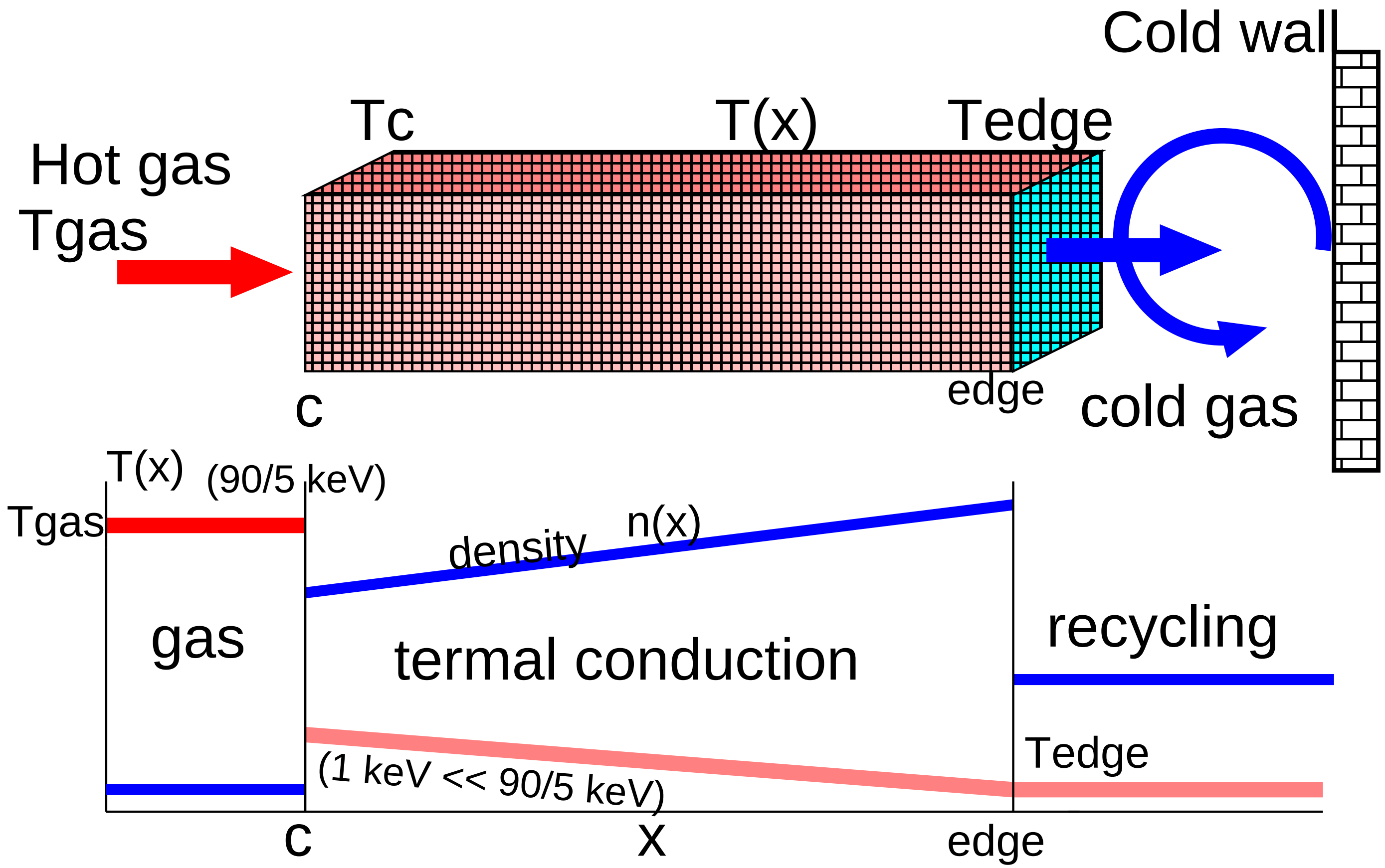
$$q^{heat} = \frac{5}{2} T^{gas} \Gamma^{hot\ gas} = -\chi \frac{dT(x)}{dx} - \frac{5}{2} T(x) D \frac{dn(x)}{dx} = \frac{5}{2} T^{edge} \Gamma^{edge \to wall}, \qquad (1.1)$$

($\Gamma^{hot\ gas}, -D\frac{dn(x)}{dx}, \Gamma^{edge\to wall}$ ***are the particle fluxes).***

The process depends on boundary conditions on the right surface.

(a) Regime controlled by thermal conduction

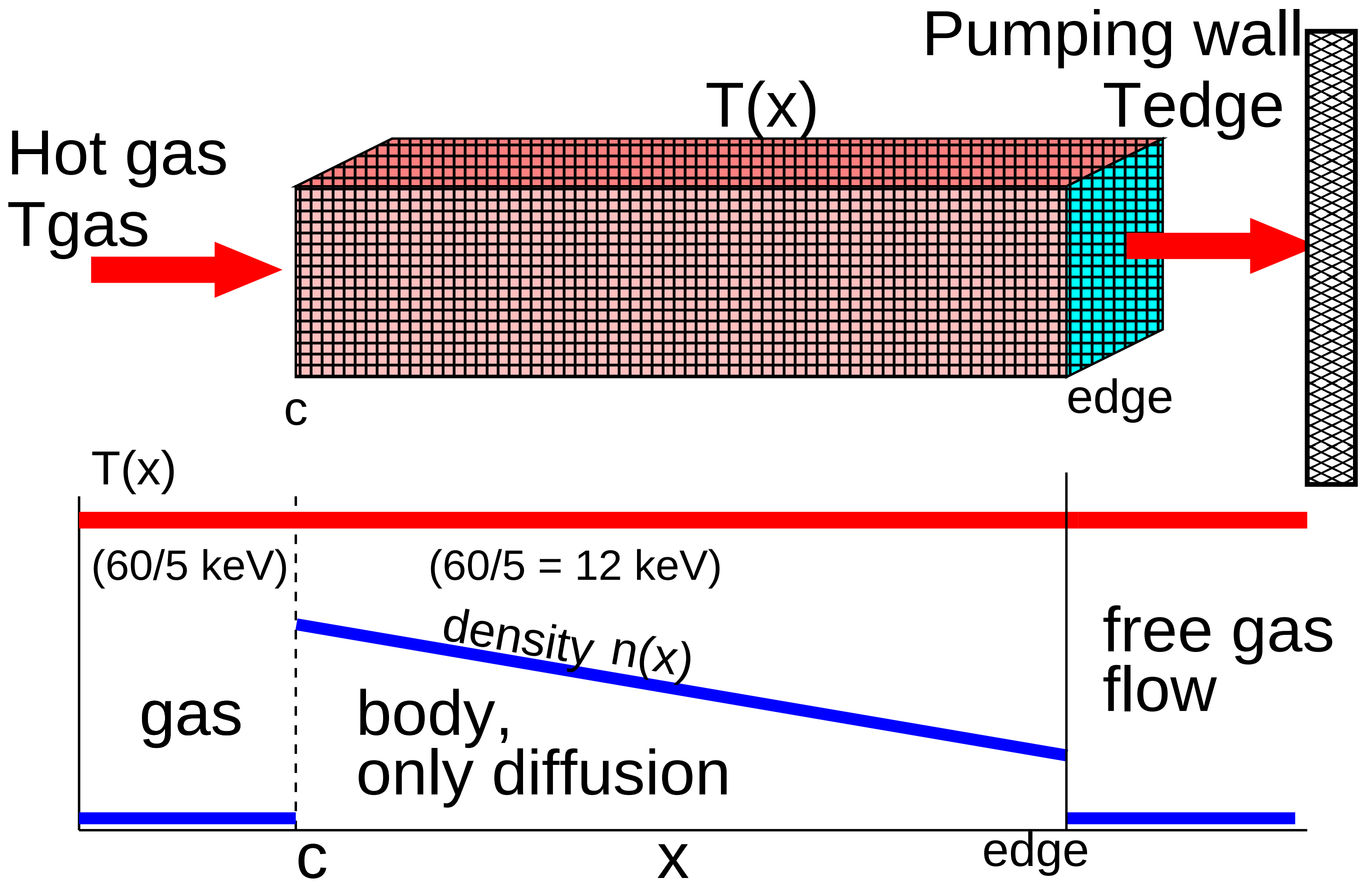
Low right edge temperature due to high recycling



$$T^{edge} = \frac{2}{5} \cdot \frac{q^{heat}}{\Gamma^{edge \to wall}}, \qquad \nabla T(x) = \frac{q^{heat}}{\chi}, \qquad T(x) \ll T_{gas} \qquad (1.2)$$

(b) Pumping walls. Diffusion controlled heat transfer

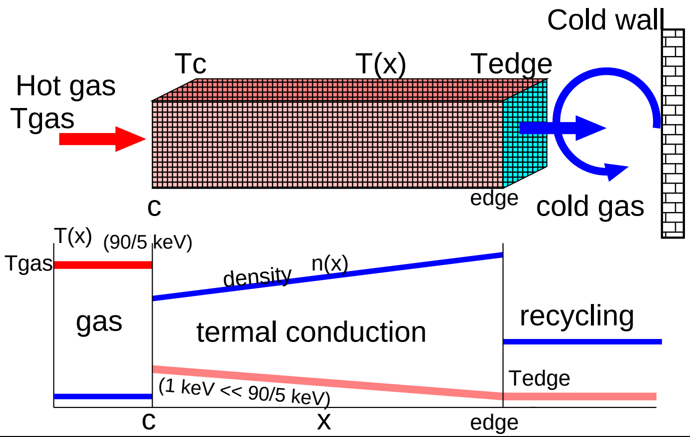
Pumping walls prevent edge cooling

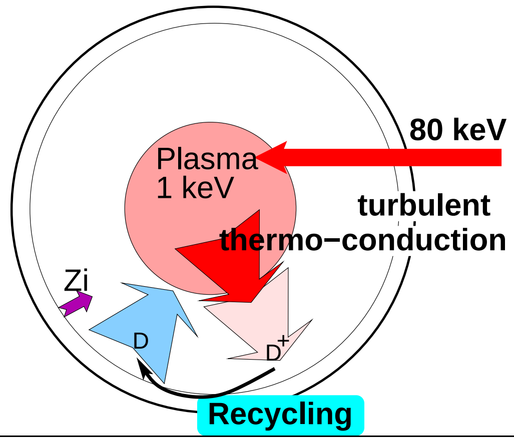


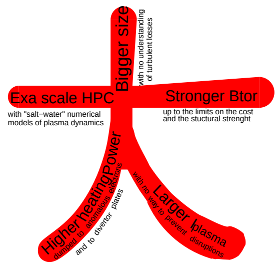
Everything is very simple: $$T(x) = T_{gas} \quad (1.3)$$

No dependence on thermal conduction χ. Wall is invisible.

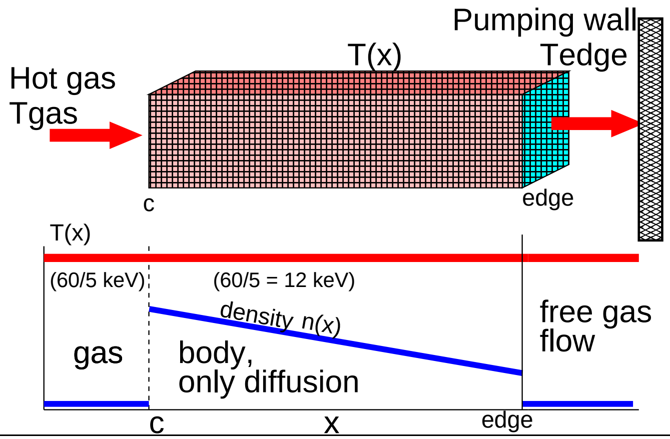
Heat transfer in porous metal and in plasma

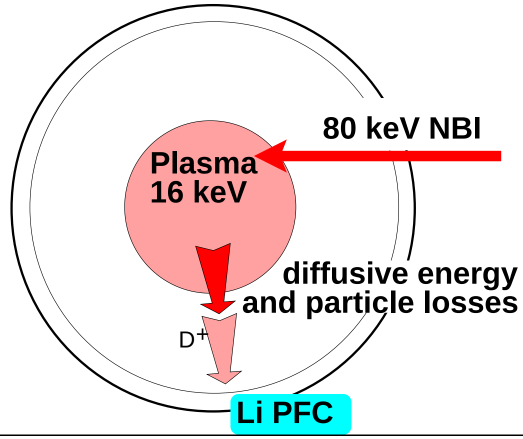






Fusion of 5 "Bigs"





LiWF

(Lithium Wall Fusion)

high metal χ_e	*high* χ_e *in toroidal plasmas*
modest gas χ_g	*modest ion* χ_i
modest diffusion D_g	*modest plasma diffusion* D_i
"fueling" by gas injection	*NBI* ***fueling*** *of the plasma core*
heating by gas injection	*NBI* ***heating*** *of the plasma core*

2 Fusion energy from magnetic fusion

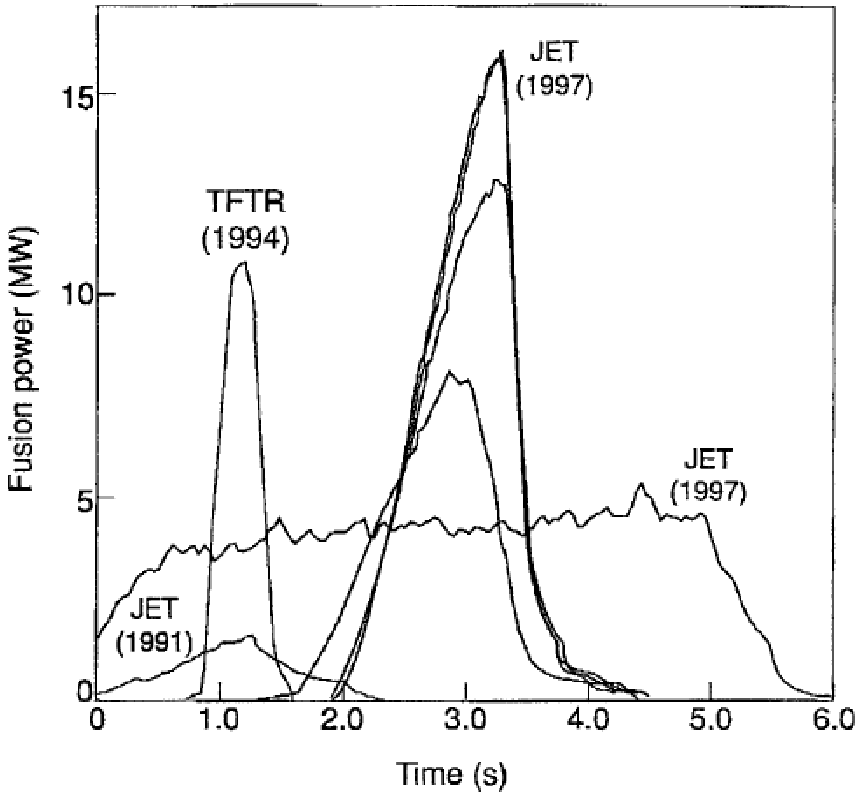


FIG 1 Fusion power development in JET and the Tokamak Fusion Test Reactor

Top magnetic fusion achievements:

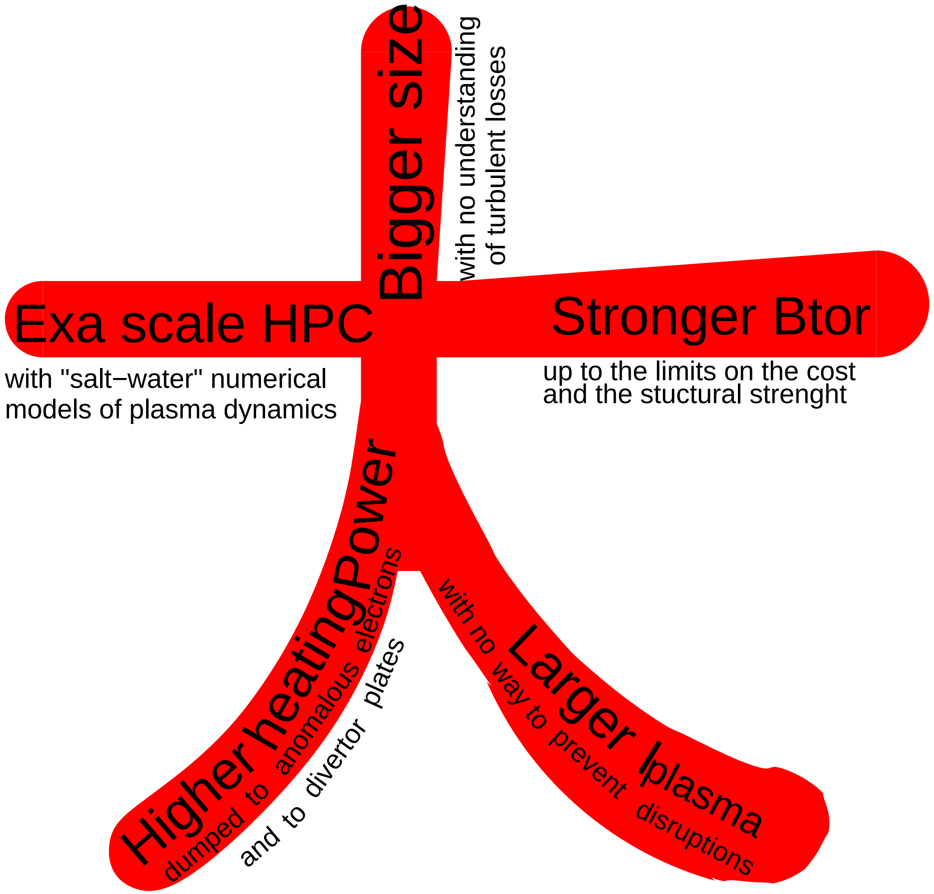
Q_{DT}	P_{DT} MW	t s	Machine
0.27	10.7	0.3	TFTR, 1994
0.62	16.1	0.7	JET, 1997
0.18	21.7/5	5	JET, 1997

(Jet Experiments in Deuterium-Tritium Keilhacker, Watkins, JET Team Europhysics News November 1998)

	TFTR	JET	ITER
R, m	2.5	2.9	6.2
a, m	1	1	2
B, T	5	4	5.6
I_{pl}, MA	3	3.5	15
P^{ext}, MW	40	20	$>$80+40

After this, DT power was not produced for more than decade

Conventional (5) approach relies on 5 “Bigs”



Every “Big” creates additional plasma physics and technology problems.

Chinese character “Big” 5 has no enough legs for all “Bigs” of magnetic fusion:

+ Massive (Big # 6 !) Gas Injection (MGI)
+ Big promises of fusion power to the grid in 2035, etc

++ The cost of 5 is not simply Big. It is **astronomical**.

One of them:

ITER → DEMO → PROTO → Pilot plant → . . . → and no destination point.

The fundamental problem of magnetic fusion is that the life time of the First Wall (first 15 cm of material structure) can be expressed in terms of electricity produced:

$$\begin{aligned} 200\ \textit{dpa} &\simeq 15\ \textit{MWa/m}^2 = 1\ \textit{kg T/m}^2 = 566 \cdot 10^{12}\ \textit{J/m}^2 \\ &\simeq \$2.2\textit{M/m}^2 \cdot \frac{P_{electric}/P_{DT}}{0.33} \cdot \frac{\$Cost_{1\ kW \cdot hour}}{\$0.04}. \end{aligned} \tag{2.1}$$

It is highly questionable (in fact, impossible) to cover the replacement

of first 15 cms of the FW (full of pipes, channels, joints, etc)

in toroidal (activated) device

by the limited value of electricity produced

(even if all materials are taken from a Home Depot)

Regarding this big problem of magnetic fusion, both tokamaks and stellarators are equivalent (with stellarators being worse).

The real situation with 5-fusion is worse than this

With no realistic destination, 5-fusion has no even a good STARTING point for its roadmaps

Fundamental problems of plasma physics remain unsolved for decades, e.g.:

1. ***No understanding of anomaly of core electron transport (the root reason of 5): every new experiment is in conflict with existing (still electro-static) theory.***
2. ***Misinterpretation ("egde transport barrier" and shear flow stabilization) of the plasma edge and temperature pedestal, which is outside the confinement zone.***
3. ***Big gaps in understanding the global stability (e.g., Greenwald density limit, ELMs).***
4. ***Misinterpretation ("halo" currents) of disruption measurements.***
5. ***Existing for 4 (!!!) decades a fundamental flaw in 3-D MHD codes (including M3D, NIMROD in the US), which with their boundary condition on the wall***

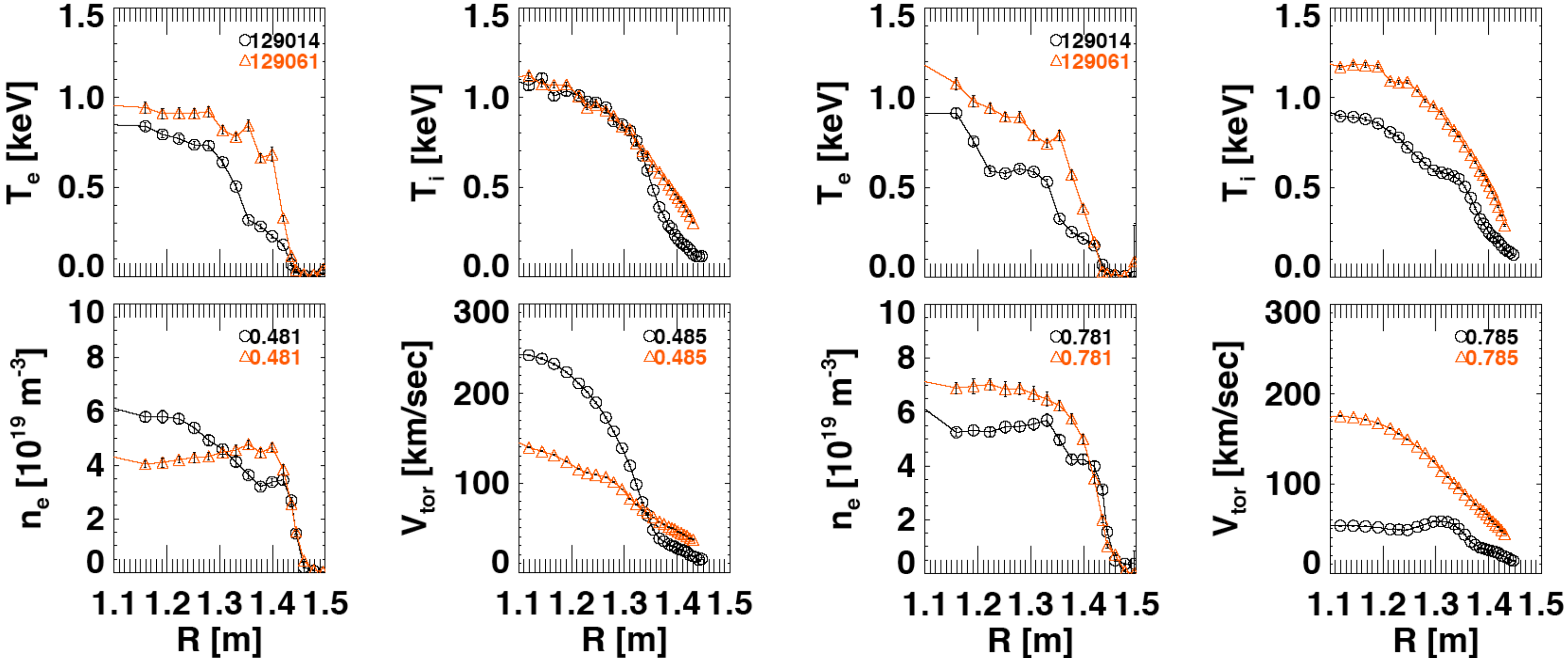
   $$V_{normal} = 0$$

   treat the tokamak plasma as water in the pipe ("the salt-water" numerical model)
6. ***No concept of stationary plasma (unpredictable long term plasma-wall interaction)***

It is not possible to move forward anymore by relying almost exclusively on the adopted in 5-fusion empirical approach

Lithium Edge Conditions Increased Pedestal Electron and Ion Temperature

NSTX



R. Maingi, ORNL

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Confinement is not consistent with "profile consistency"

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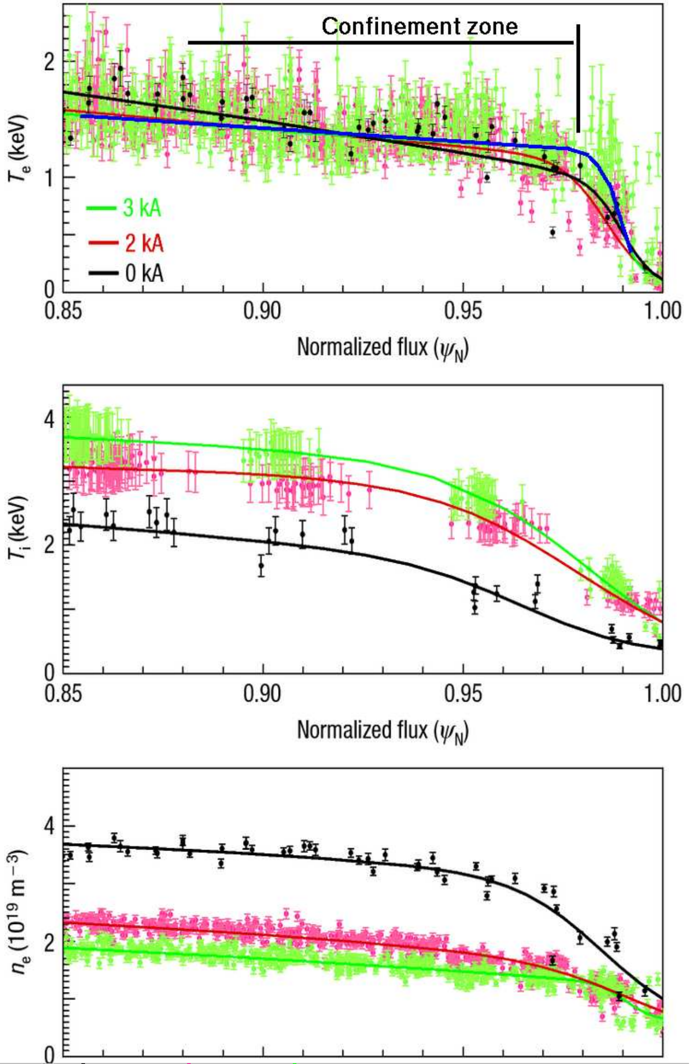
DIII-D confirmed the basic edge theory of LiWF

RMP experiments on DIII-D have determined the size of the confinement zone



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

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

1. ***The pedestal $T_e^{pedestal}$ is found insensitive to RMP $\longrightarrow$ $T_e^{pedestal}$ is the T_e^{edge} $\longrightarrow$ The tip of the T_e pedestal is the boundary of the confinement zone for electrons.***
2. ***RMP do penetrate into the confinement zone: The gradients***

$$n'(x),\ T'_e(x)$$

in the core are reduced by RMP - indication of "screening".

3. ***Different positions of the "edge" for T_e, T_i, n_e are possible***

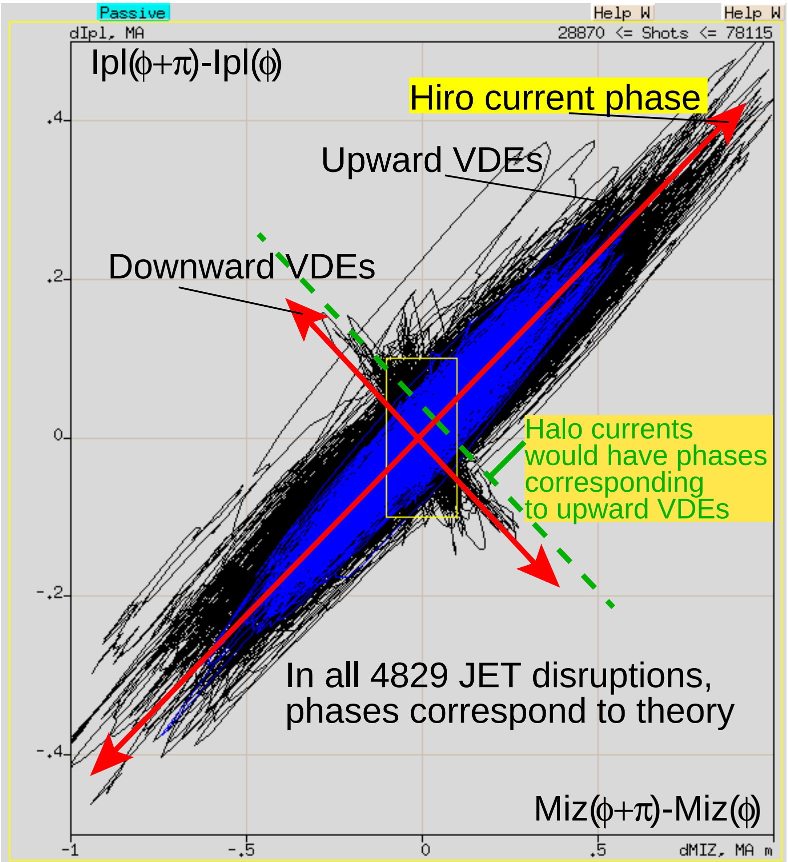
Claims about flow shear "stabilization" of turbulence and suppressed transport in the pedestal are baseless.

It is just opposite: there is no electron confinement in the pedestal region.

The pedestal is situated outside the confinement zone

Our disruption theory is validated by JET data base

High quality of JET data was critical for validation. In 2009 JET Disruption data base (DdB) was created (Cbdsr code) and used for validation of theory



Phase diagram for all 4829 disruption shots (May 2009) based on all dB data from octants

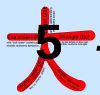
7,3 ($\varphi_7 = 270^o,\ \varphi_3 = 90^o$), black color and
5,1 ($\varphi_5 = 150^o,\ \varphi_1 = \ \ 0^o$),7 blue color

$$I_{pl}(\varphi+\pi,t) - I_{pl}(\varphi,t)$$ ***(vertical axis)***

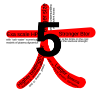
vs

$$M_{IZ}(\varphi+\pi,t) - M_{IZ}(\varphi,t)$$ ***(horizontal axis)***

$(M_{IZ} \simeq I_{pl}\delta z$ ***- measured signal***$)$

***-fusion interpretation of toroidal asymmetry based on "halo" currents contradicts even the sign of measured signals***

Without exceptions JET disruption data are consistent with theory of Hiro currents, rather than "halo" currents (having opposite direction)

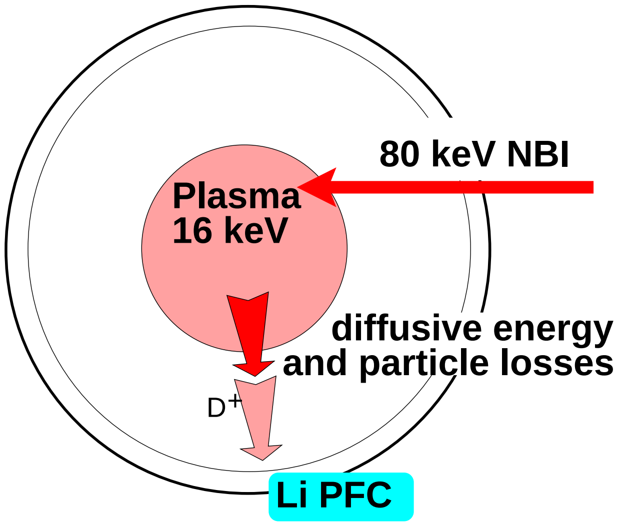
With numerous plasma physics problems unresolved, the  approach has been essentially exhausted at the level of TFTR and JET.

What kind of reserves is still not utilized ?

3 The LiWall Fusion (LiWF) concept of magnetic fusion

NBI for core fueling & heating + Pumping LiWall conditions

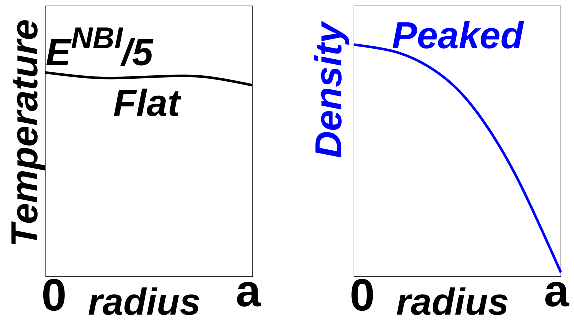
(Limited plasma edge cooling: $R^{ecycling} < 0.5$, $\Gamma^{gasI} < \Gamma^{NBI}$)



The BEST possible confinement regime: energy losses are determined only by particle diffusion

The plasma physics is much simpler

In LiWF high edge T is OK



No ∇T-driven turbulence (ITG/ETG)

Potential TEMs affect only the density level with NBI as a source

No Greenwald limit, saw-teeth, ELMs.

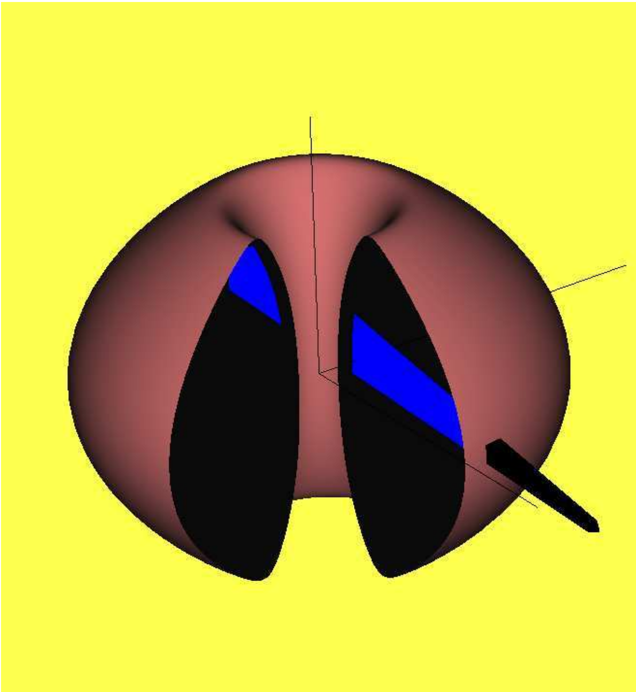
Entire plasma volume produces fusion

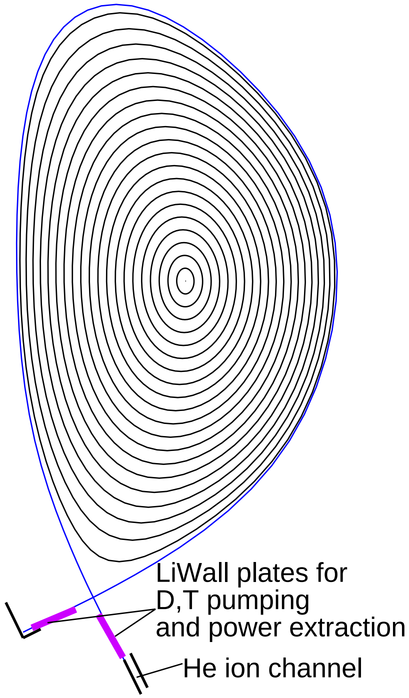
Anomalous electron thermal conduction plays no role

This simplest and best possible approach is suggested for the Chinese next step FFRF

FFRF stands for Fusion-Fission Research Facility, which is an option of the next 100-200 MW fusion device in China.

Implementation is straightforward





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

$$\frac{T_i+T_e}{2} = \frac{E_{NBI}}{5}$$

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

$$\rightarrow (T_e+T_i)/2 \simeq 16\ keV$$

Familiar "hot-ion" regime:

$$T_i > T_e$$

Thermalization of the beam is much faster than the particle diffusion.

Plasma temperature will be uniform automatically (plasma physics is not involved)

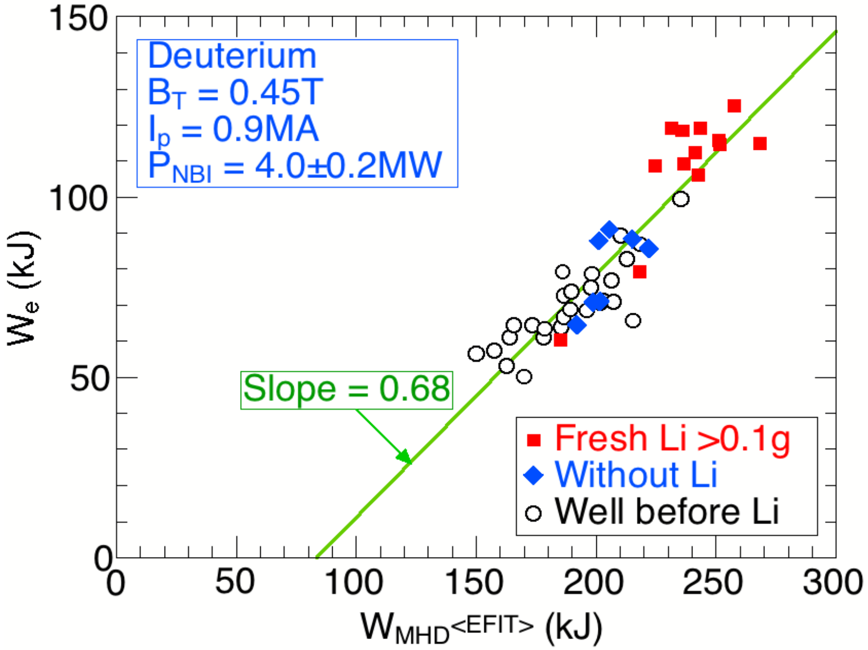
No mystery, no tricks. LiWF implements a very simple idea:

For toroidal plasma it is much more efficient to prevent plasma cooling by neutrals from the wall than to rely on overwhelming heating power.

LiWF had no single failure so far in its predictions

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

NSTX



M. G. Bell

PPPL

• Data sampled at time of peak W_e

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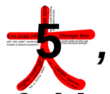
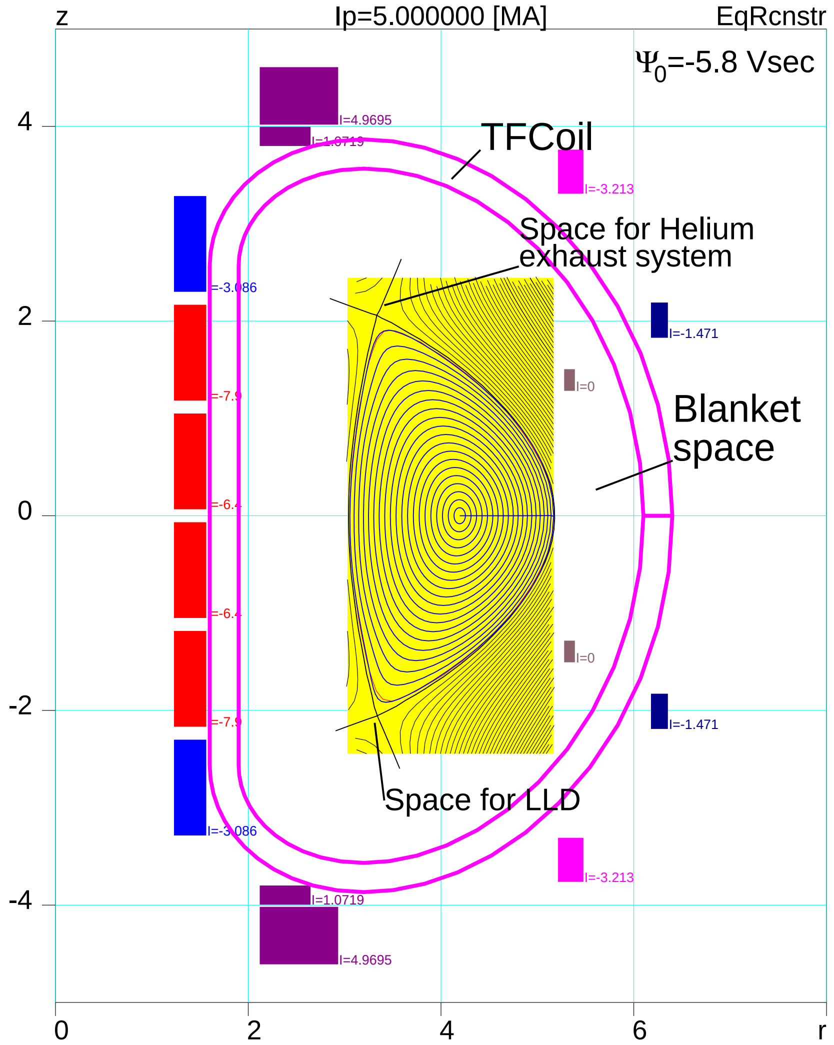
Unlike  ***, which is full of embarrassing failures, the LiWF theory is exceptionally successful in its prediction:***

1. ***enhanced confinement (at least, 4-fold increase in CDX-U, douled in NSTX)***
2. ***Enhanced MHD stability (all MHD disappeared in CDX-U with liquid lithium (LiLi)).***
3. ***no Greenwald density limit (1.4-1.8 excess over Greenwald in averaged density FTU)***
4. ***Edge stability (ELMs were easily stabilized on NSTX by Li conditioning)***

4 Parameters of FFRF and mission



Parameter	FFRF
$d_{blanket,m}$	1
a_m, R_m	1.0, 4.0
$V^{pl}_{m^3}, S^{pl}_{m^2}$	130, 230
n_{20}	0.4
E^{NBI}_{keV}	120
$\frac{T_i+T_e}{2}\Big\|_{keV}$	24-27
$B_{t,T}$	4-6
$I_{pl,MA}$	5
$\Delta\Psi_{f-top,Vsec}$	40
$W_{th,MJ}$	42
$\tau^{ind}_{E,sec}$	20-7
P^{NBI}_{MW}	2-5
P^{DT}_{MW}	50-100

Active fission core power 80-4000 MW. He cooling is possible.

FFRF can be potentially the next step device in PRC

Mission

The mission of FFRF is to advance fusion to the level of a (quasi-)stationary neutron source and to create a technical, scientific, and technology basis for utilization of 14 MeV fusion neutrons for needs of nuclear energy and technology.

FFRF is a research, rather than application device.

For its justification, FFRF does not need to compete with, e.g., fast breeder reactors

FFRF has both fusion and FFH missions

5 Burning plasma regime of FFRF

In burning plasma 90 % of α-particle energy goes to electrons, which do not produce fusion but contribute to MHD β.

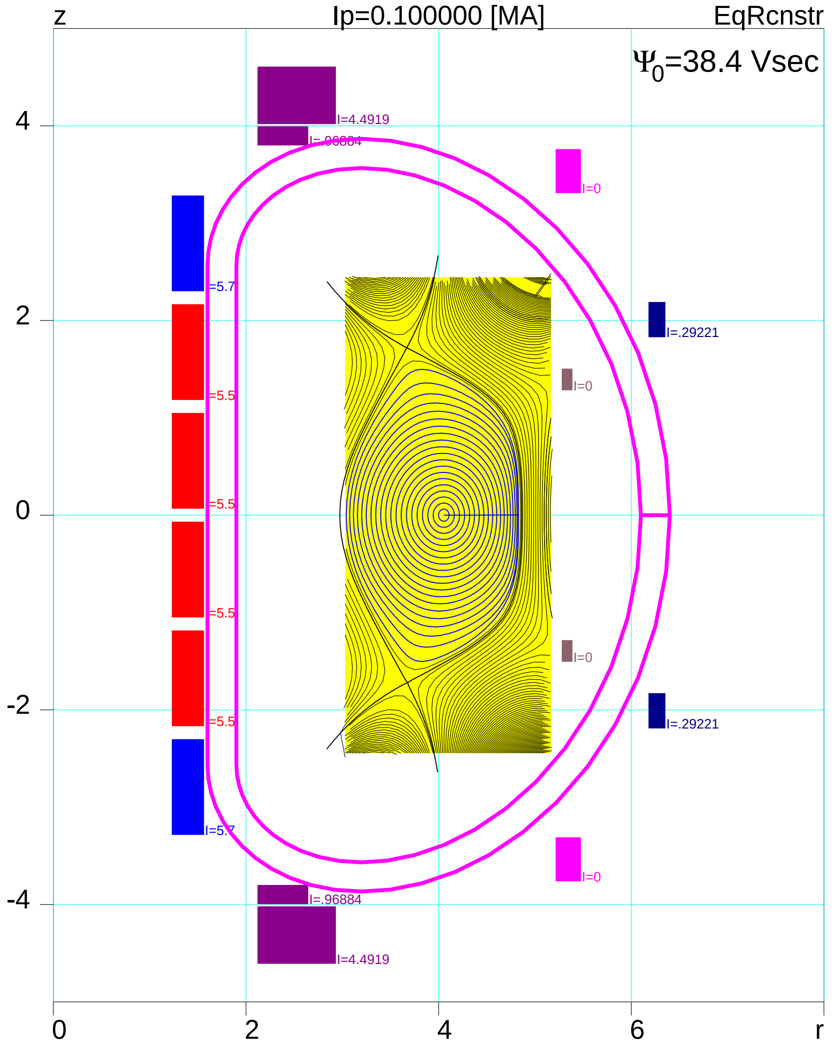
The LiWF regime does not need α-particle heating.

The question is: will the hot-ion regime survive in the burning plasma ?

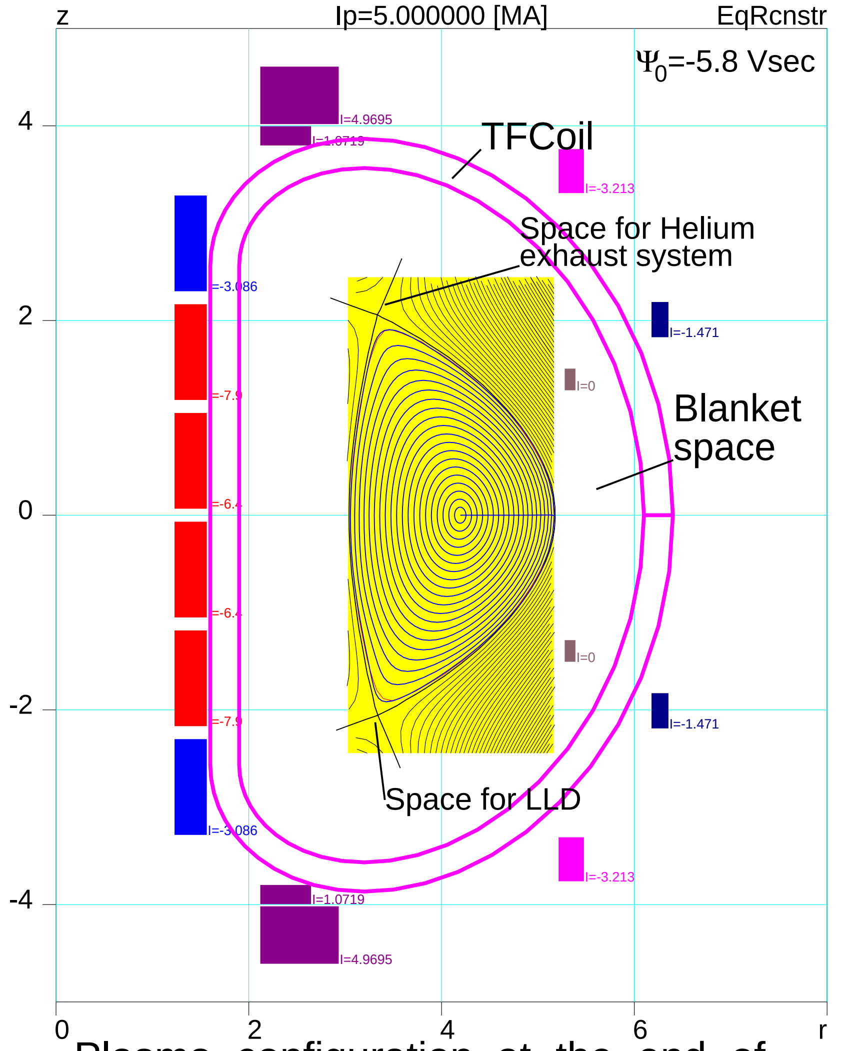
For spherical tokamaks the answer is almost for certain "Yes". Even for $I_{pl} = 8.4$ MA, 60 % of α-particles can be intercepted at first orbits.

Is the LiWF regime applicable to the burning plasma with $I_{pl} = 5$ MA in conventional tokamaks, like FFRF ?

5.1 Volt-second capacities of FFRF: 40 V-sec



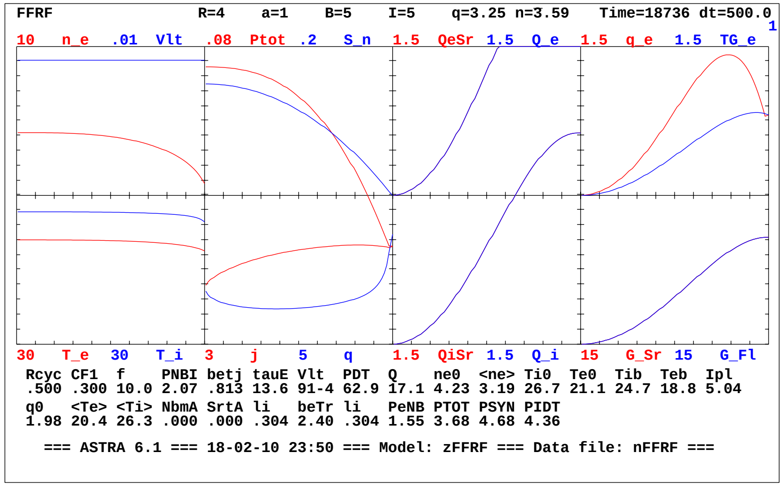
Initial plasma configuration



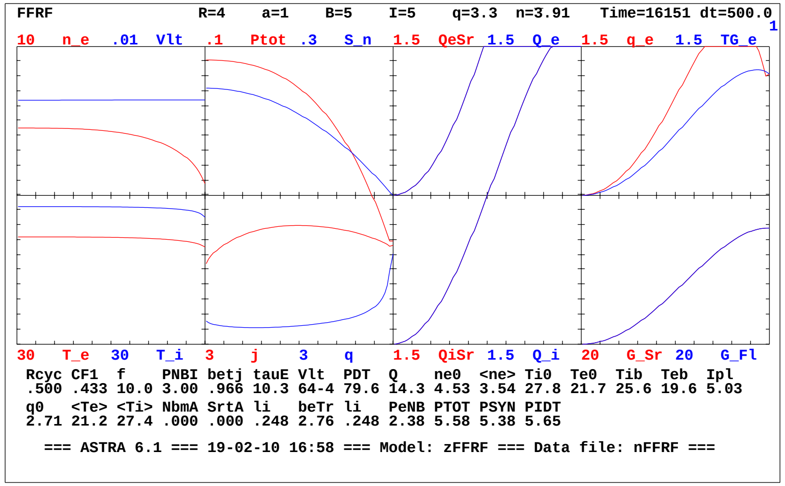
Plasma configuration at the end of End of flat-top

About 40 V-sec is available for the flat-top of inductively driven plasma current. ($-6\ T \leq B^{CS} \leq 6\ T$)

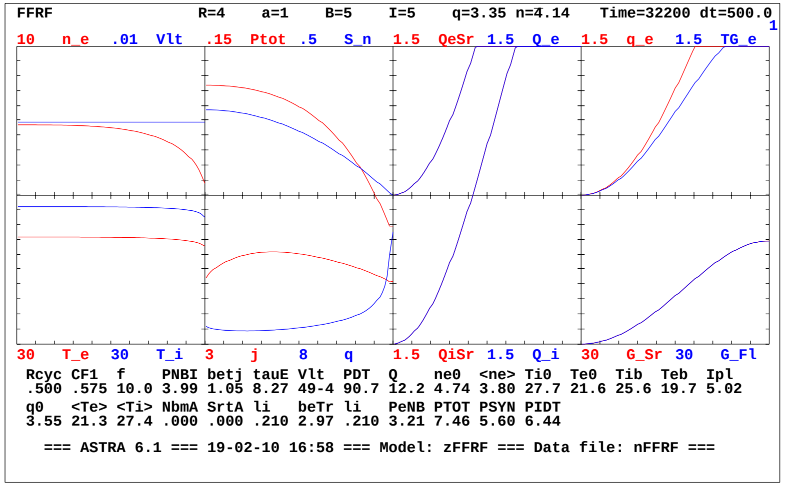
Examples of stationary hot-ion burning plasma regimes in FFRF with $R^{ecycl} = 0.5,\ \Gamma^{gas} = 0,\ f = 10$ (factor of anomaly of $\chi_e = f\chi_i$)



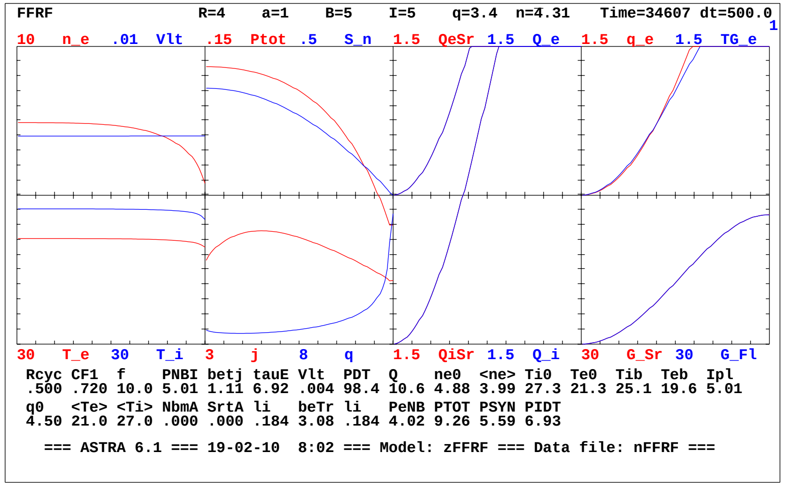
$P^{NBI} = 2$ MW



$P^{NBI} = 3$ MW



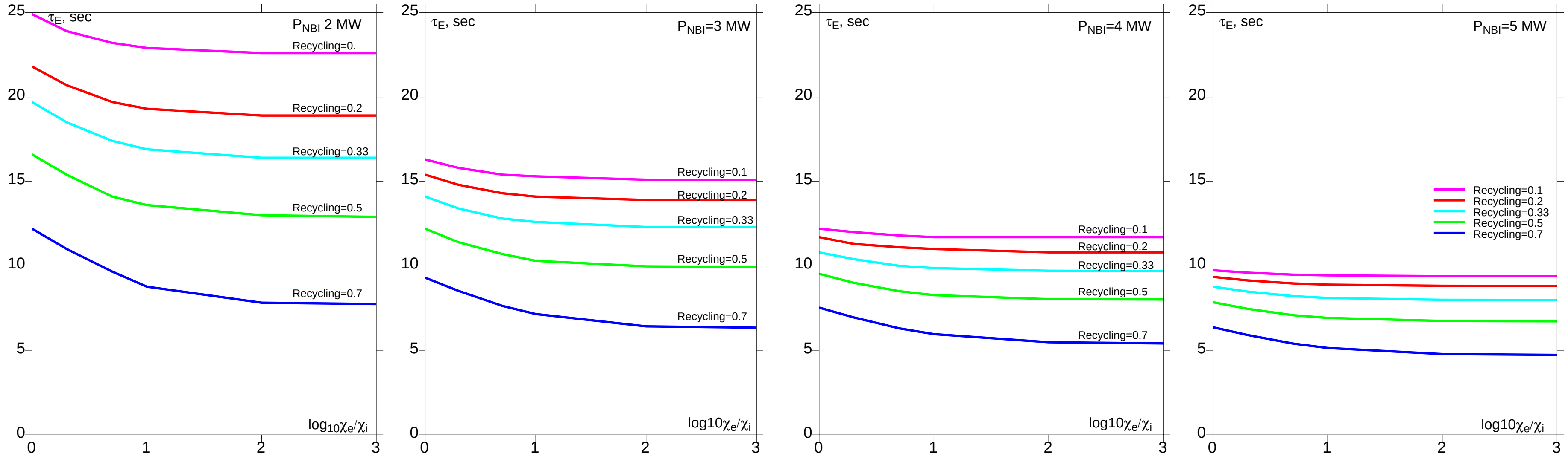
$P^{NBI} = 4$ MW



$P^{NBI} = 5$ MW

5.2 Energy confinement time: 7-20 s

In calculations 50 % of α-particle energy was released in the plasma (assuming loss of energetic particles). Dilution of plasma was neglected.



$P^{NBI} = 2$ MW $\quad P^{NBI} = 3$ MW $\quad P^{NBI} = 4$ MW $\quad P^{NBI} = 5$ MW

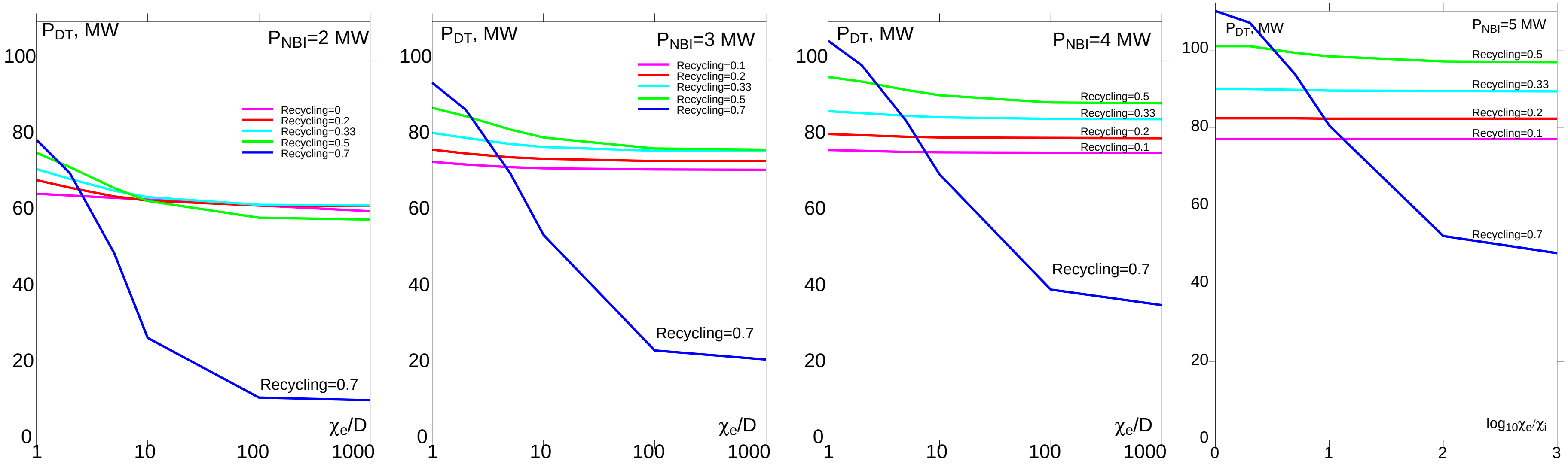
Energy confinement time in LiWF regime for different R^{ecycl} as function of

$0 \leq \log_{10} \chi_e/\chi_i \leq 3 \; (1 \leq \chi_e/\chi_i \leq 1000)$.

LiWF regime is not sensitive to anomalous electron thermal conduction, which is the root reason of problems in magnetic fusion.

5.3 Fusion power: 50-100 MW

High recycling $R^{ecylc} > 0.6$ (as in conventional fusion) is devastating for fusion power production.



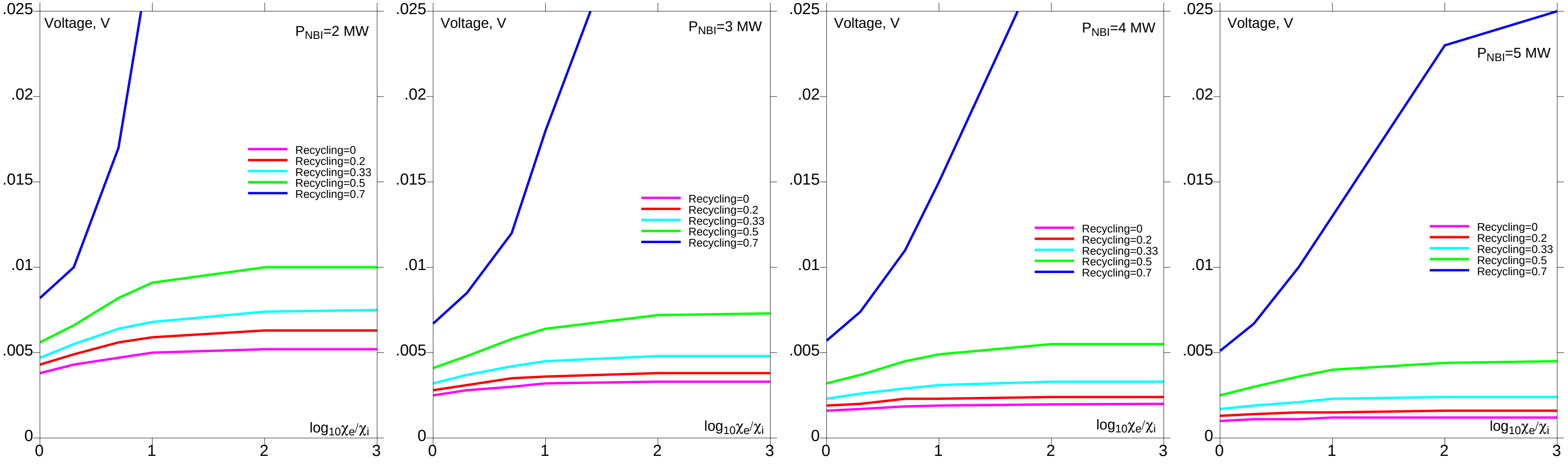
$P^{NBI} = 2$ MW $P^{NBI} = 3$ MW $P^{NBI} = 4$ MW $P^{NBI} = 5$ MW

Fusion power time in LiWF regime for different R^{ecycl} as function of

$0 \le \log_{10} \chi_e/\chi_i \le 3$ $(1 \le \chi_e/\chi_i \le 1000)$.

At the practical level of recycling coefficient $R^{ecycl} < 0.5$, the burning plasma regime with $P^{DT} = 50 - 100$ MW is possible in FFRF

With limited recycling $R^{ecylc} < 0.5$ the loop voltage in FFRF is smaller than 0.01 V.



$P^{NBI} = 2$ MW $\quad P^{NBI} = 3$ MW $\quad P^{NBI} = 4$ MW $\quad P^{NBI} = 5$ MW

Loop voltage in stationary stage for different R^{ecycl} as function of
$0 \leq \log_{10} \chi_e/\chi_i \leq 3$ $(1 \leq \chi_e/\chi_i \leq 1000)$.

With 40 Vsec of the flux swing, a simple 1-2 hour inductive regime is possible in FFRF. This makes FFRF exceptionally consistent with its mission

6 Summary

The LiWF suggests the Best possible burning plasma regime for FFRF, which makes it realistic as a 100-200 MW fusion device:

1. ***the best possible (diffusion based) confinement***
2. ***the best possible core MHD stability (no saw-teeth)***
3. ***the best possible plasma edge stability (no ELMs)***
4. ***the best possible stationary plasma-wall interaction (no thermo-force, stationary plasma facing wall surface)***
5. ***the comprehensive plasma control by NBI and edge conditions (not a hostage of plasma unknowns)***
   - ***(a) hours long inductive regime***
   - ***(b) the best possible conditions for non-inductive current drive***
   - ***(c) the best possible power extraction approach - synchrotron radiation***
   - ***(d) no reliance on α-heating***
   - ***(e) the best possible use of plasma volume for fusion***
   - ***(f) the best possible helium ash exhaust regime***

The real question is "How good is the Best ?"

Plasma physics and fusion technologies, which have to be developed in parallel with the design work on FFRF in order to answer this question, are well specified.

With LiWF we are on the right track

Achievements based on LiWF theory:

- ***Enhancement of the energy confinement time was predicted in Dec. 1998.***
  - *More than 4 fold enhancement was demonstrated on CDX-U with LiLi tray in 2005.*
  - *NSTX enhanced energy confinement time by factor of 2 (from 50 to 100 msec) using Li evaporators (2006-2010).*
  - *EAST obtained the H-mode in 2010 using Li conditioning.*
- ***Enhanced global stability predicted in 1999.*** *All MHD activity disappears in CDX-U since introduction of LiLi in 2003.*
- ***Absence of the density limit (Greenwald limit) was predicted in 2003.*** *Confirmed by experiments on FTU in 2006.*
- ***Stabilization of Edge Localized Modes (ELM) was predicted in 2005.*** *Confirmed in experiments with Lithium evaporation on NSTX in 2007.*
- ***New understanding of the plasma edge (e.g., temperature pedestal) was created in 1999.*** *Confirmed by experiments with Resonant Magnetic perturbations on DIII-D in 2006.*

Still, all experiments so far are limited by Li conditioning, which is only a partial implementation of LiWF.

ASIPP is moving toward to make EAST in 3-4 years the first machine operating in the LiWF regime with combination of NBI and Flowing LiLi system.