Ignited Spherical Tokamaks for developing a power reactor[1]

Leonid E. Zakharov

[1] *Princeton Plasma Physics Laboratory, MS-27 P.O. Box 451, Princeton NJ 08543-0451*

PPPL Research Seminar

Jan. 11, 2006, PPPL, Princeton NJ, 2006

[1] This work is supported by US DoE contract No. DE–AC020–76–CHO–3073.

Abstract

On the way to power reactors, there are three, mutually linked objectives, specific to magnetic fusion, i.e., (a) development of the high fusion power density operational power reactor regime (OPRR), (b) design and development of low activation first wall (i.e., the first 15 cms of the material faced by 14 MeV neutrons) together with power extraction and helium ash exhaust, and (c) development of the tritium cycle.

This triple-objective cannot be meet based on present reactor concept (essentially non-existing). Because of lack of tritium only compact devices are suitable for reactor development, and the only candidates are spherical tokamaks (ST).

For the purposes of the first wall R&D and accumulating the necessary 15 MW•year/m^2 fluence of 14 MeV neutrons even ST require a special plasma regime, which would provide a self-generating plasma current, ignition and a self-sufficient tritium operation.

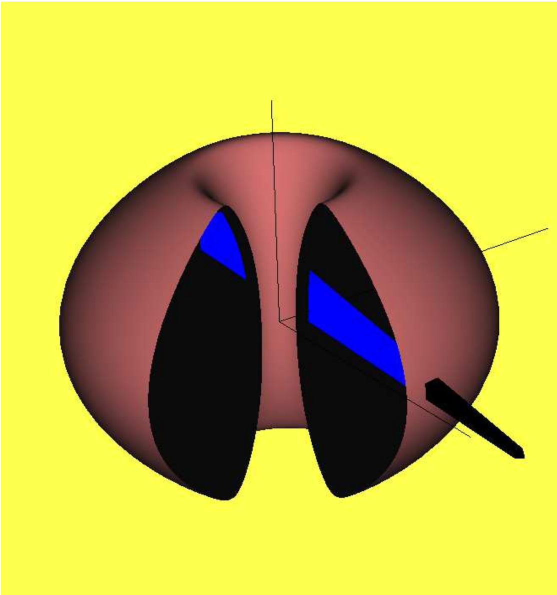
The talk compares two approaches for magnetic fusion: (a) the conventional one, based on the high recycling plasma, and (b) the LiWall approach, which utilizes the unique lithium capacity of pumping hydrogen isotopes.

Despite its dominance during the last 35 years, the conventional approach did not resolve several basic problems of magnetic fusion even at the plasma physics level. It never approached the real, nuclear issues of the fusion power reactor. In contrast, the 7 years old LiWall concept (1999) has opened a way for achieving the triple objectives of magnetic fusion in a form of Ignited Spherical Tokamaks (0.5 GW of fusion power in 30 m^3).

Contents

1 "Flat" temperature in presence of absorbing walls

Perfectly absorbing walls (no cold particles) would lead to a "flat" temperature, relevant to the reactor



E.g, the beam energy 45 keV will be converted into a plasma

$$E_b = \frac{3}{2}(T_i + T_e), T_i = T_e = 15\ keV$$

with collision frequencies

$$\begin{aligned} \nu_i &= 68\frac{n_{20}}{T_{i,10}^{3/2}}, \\ \nu_e &= 5800\frac{n_{20}}{\sqrt{T_{e,10}^3}}, \\ \rho_i &= 1.44\frac{\sqrt{T_{i,10}}}{B}\ [cm], \\ D_{ban} &\simeq 0.016\frac{n_{20}}{B_p^2\sqrt{T_{i,10}}}\sqrt{\frac{a}{R}}\left[\frac{m^2}{sec}\right]. \end{aligned} \tag{1.1}$$

When the density level becomes stationary, $T_i = T_e = const$

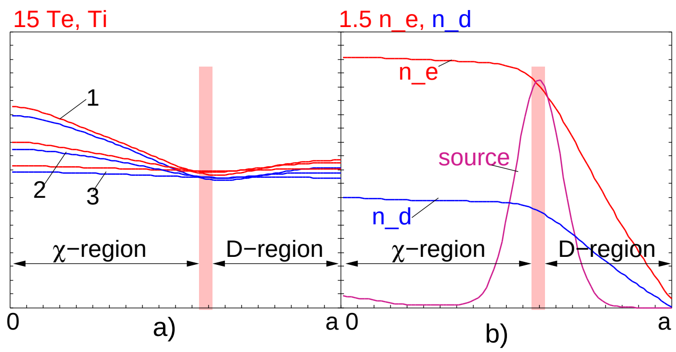
In "flat" temperature there is no mistery nor the plasma physics

Edge temperature is determined by microscopic particle flux

$$T_{edge} \simeq \frac{1}{5\Gamma^{micro}_{edge\to wall}} \int P_{heat} dV. \qquad (1.2)$$

In conventional plasma with a lot of recycled cold particles from the wall

$$\Gamma^{micro}_{edge\to wall} \gg \Gamma_{convective}, \quad T_{edge} \ll T_{core}. \qquad (1.3)$$



χ- and D- confinement regions in the low recycling regime. (a) Electron and ion temperatures for three values of thermo-conduction coefficients. (b) Electron, ion density and the particle source.

$$\Gamma^{micro}_{edge\to wall} \simeq \Gamma_{convective}, \quad T_{edge} = \frac{1}{5\Gamma_{convective}} \int P_{heat} dV \simeq T_{core}$$

Absorbing walls lead to the best possible confinement situation

1. Energy confinement time is determined by particle confinement

2. Particle confinement is always determined by the best confined component.

3. No reasons for ITG or other turbulence

4. Thermo-conduction losses are essentially eliminated

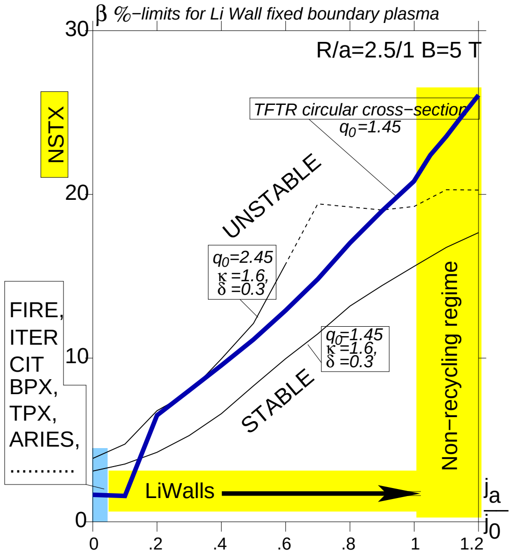
Neo-classical diffusion coefficient

$$D_{ban} \simeq 0.016 \frac{n_{20}}{B_p^2 \sqrt{T_{i,10}}} \sqrt{\frac{a}{R}} \left[\frac{m^2}{sec}\right], \quad \tau_p \simeq \frac{a^2}{D_{ban}} \qquad (1.4)$$

suggests the energy confinement time $\tau_E \simeq \tau_p > 10$ ***sec for*** $a \simeq 0.4$.

To my knowledge, there is no indication of turbulence related "profile-consistency" for the density profile

Stabilizing conducting wall can be placed at the plasma boundary



High edge plasma temperature leads to
(a) high current density at the edge, and
(b) second stability in the plasma core

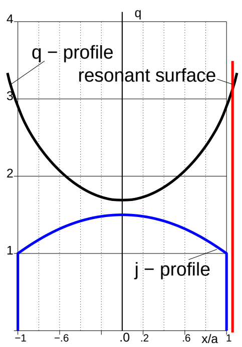
β - limits for the second stability regime

- *fixed boundary plasma*
- *n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON)*
- *current density with an edge pedestal*

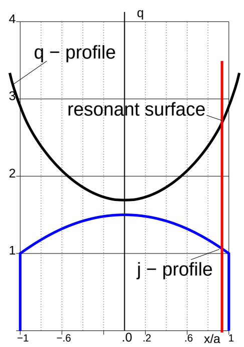
$$j_{\|} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$

High tokamak beta can be consistent with high fusion power density

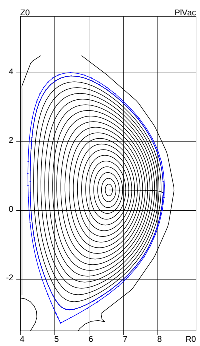
A widespread belief in MHD theory is that the high edge current density is destabilizing



case 1: $mq_a < n$
Ideally unstable



case 2: $mq_a > n$
Tearing stable

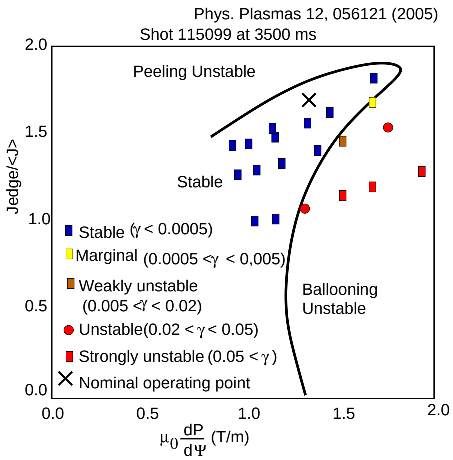


LiWall + Separatrix: $q_a = \infty$
Ideally & tearing stable

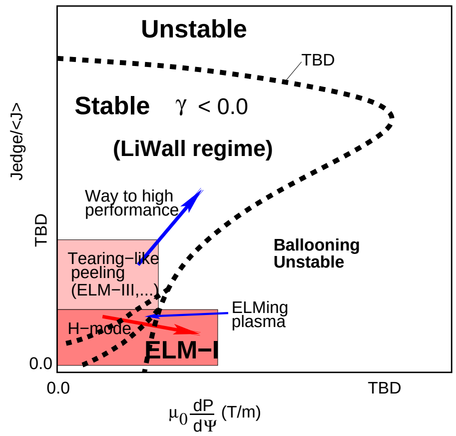
In presence of separatrix, the high edge current density is stabilizing

At present, NO numerical codes exist to analyze the edge stability.

High edge temperature is stabilizing for ELMs.

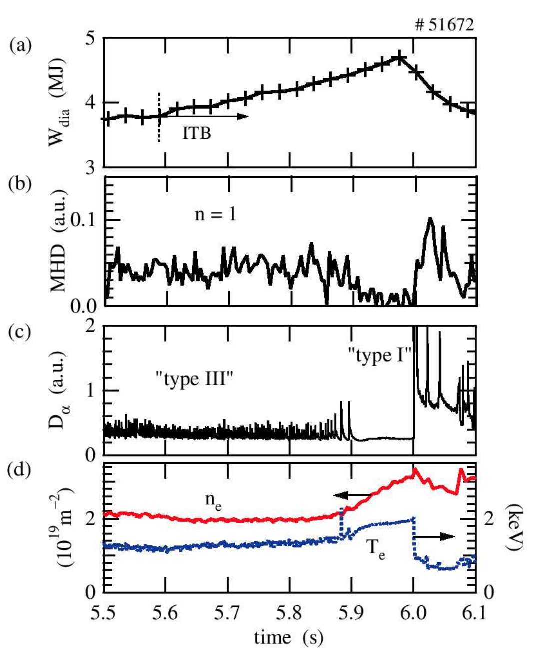


DIII-D interpretation



"Zakharov's" diagram (TBD)

There is no "peeling" modes for the separatrix limited plasma and $T_{edge} \neq 0$



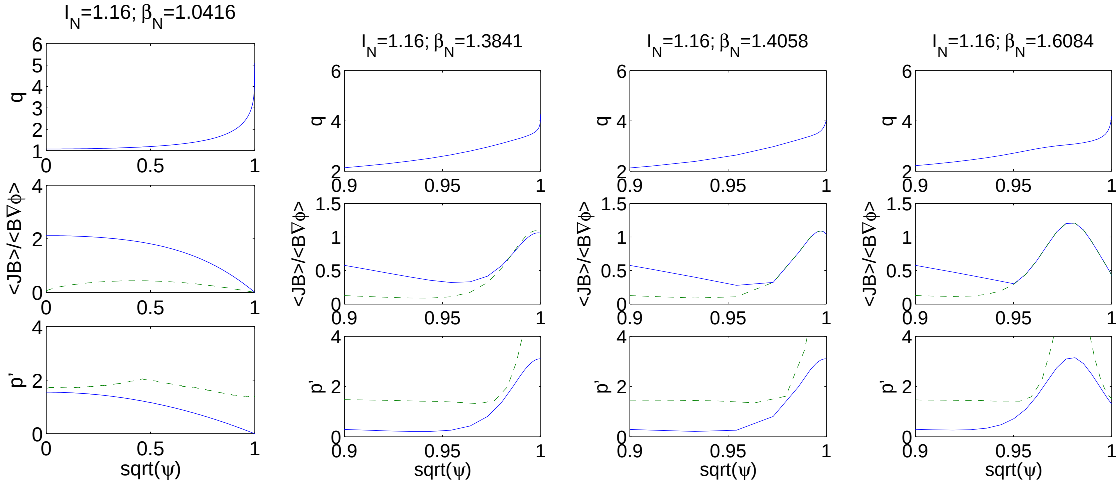
JET has a quiescent regime as transient phase from ELM-III to ELM-I

"Edge issues in ITB plasmas in JET"

Plasma Phys. Control. Fusion 44 (2002) 2445-2469 Y. Sarazin, M. Becoulet, P. Beyer, X. Garbet, Ph. Ghendrih, T. C. Hender, E. Joffrin, X. Litaudon, P. J. Lomas, G. F. Matthews, V. Parail, G. Saibene and R. Sartori.

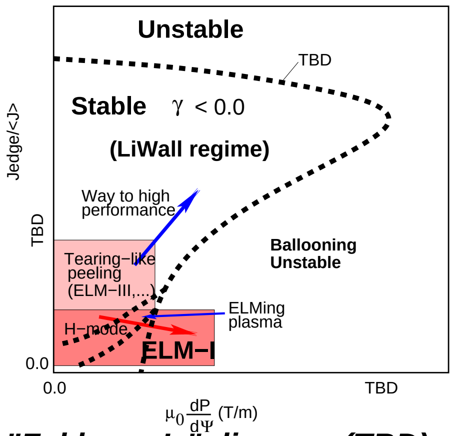
Crucial role of the edge current density was emphasized

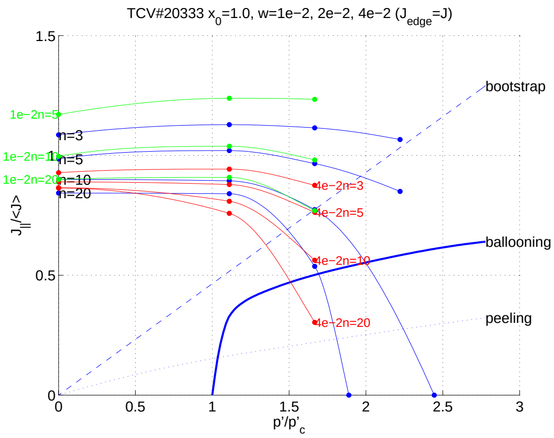
In fact, there is a single ideal MHD code to handle the stability



TCV profiles were uses as a reference

In fact, there is a single ideal MHD code to handle the stability

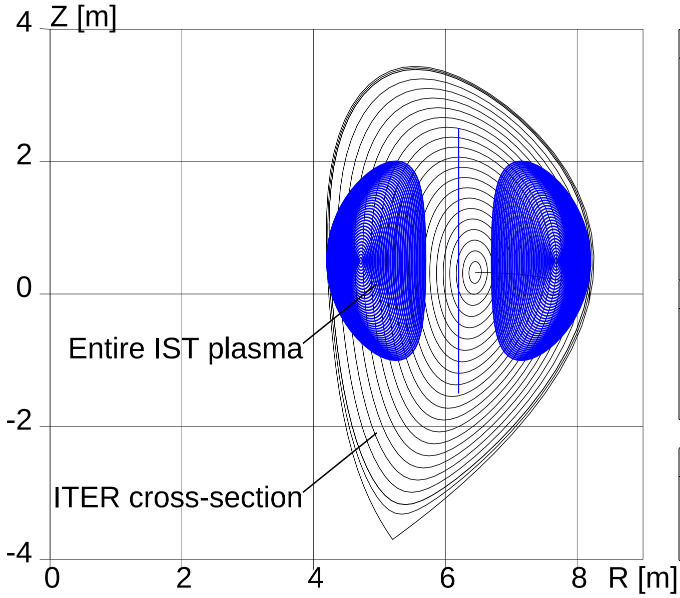




"Zakharov’s" diagram (TBD) ***Keldysh Institute calculations***

“Flat” temperature makes plasma stability robust and independent from the core physics

Only compact devices are suitable for R&D of the reactor

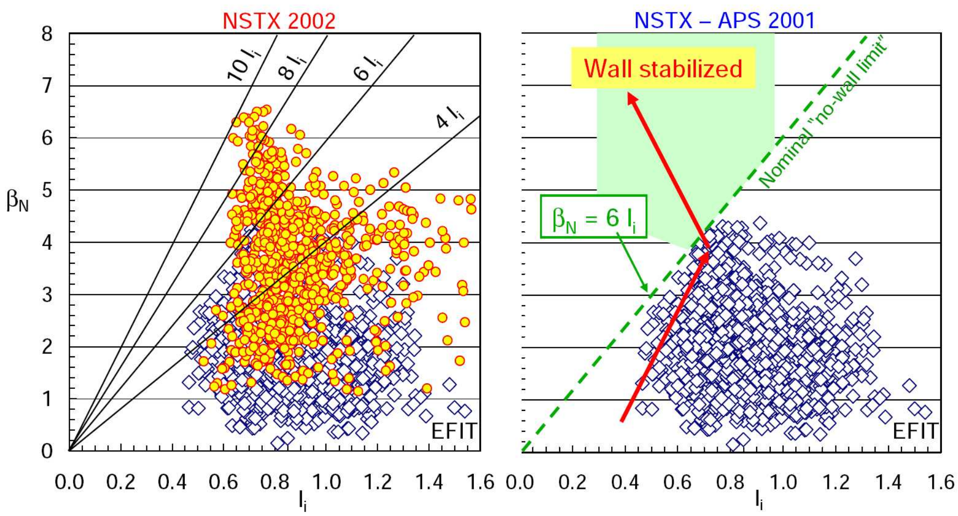


IST Parameters			
CenterPole R m	0.5	0.5	0.5
CenterPole B T	7.5	7.5	7.5
Plasma R_1 m	0.5	0.5	0.5
Plasma R_2 m	2.0	2.0	2.0
Height m	3.0	3.2	3.4
Volume m^3	26.1	27.8	29.6
Surface m^2	53.4	55.9	58.5
I plasma MA	11.1	11.9	12.7
IST Plasma performance			
P_{DT} MW	388	490	606
τ_E sec	0.75	0.69	0.64
$F_{neutron}$ MW/m^2	5.8	7.0	8.3
$Loss_{neutron}$ %	9.4	9.6	9.8

ITER			
P_{DT} MW	410	V	834 m^3
τ_E sec	3.7	S	680 m^2
$F_{neutron}$ MW/m^2	0.5		

IST on β=0.4 and in "flat" $T_{i,e}$ $\simeq$15 keV. Ignition is a necessity

START, NSTX achieved the reactor R&D levels of beta

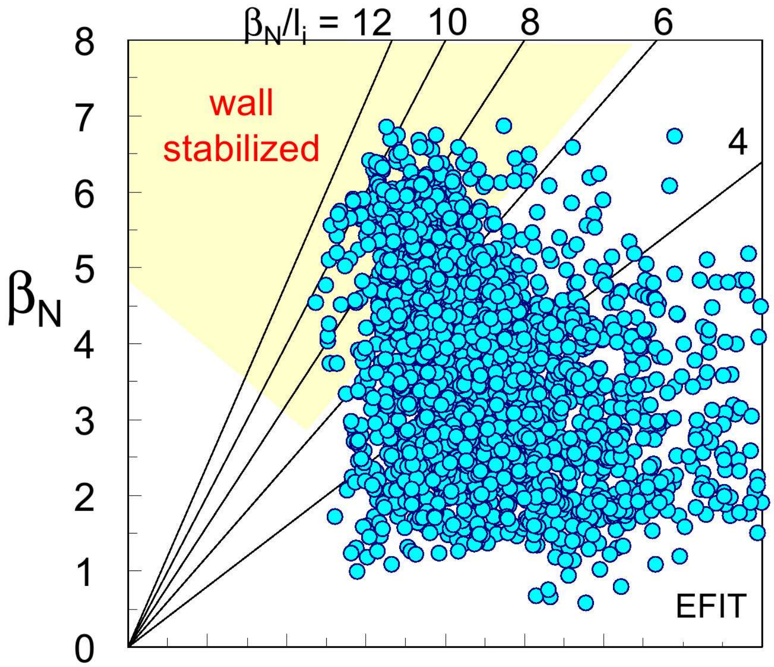


- Normalized beta, β_N = 6.5, with β_N/l_i > 9.5; β_N > 30% over $\beta_{N\ no\text{-}wall}$
- Toroidal beta has reached 34%

NSTX

Tendencies in stability in NSTX are consistent with the LiWall concept

STs already have a relevant stability data base



In 2004 beta in NSTX approached the necessary 40 % ($\beta = 39\%$)

Large Shafranov shift makes core fueling possible

"Core" fueling is crucial for the density profile control.

The charge-exchange penetration length

$$\lambda_{cx} \simeq \frac{0.3}{n_{e,20}} \frac{V_b}{V_{b,40\ keV}} \, [m] \tag{2.1}$$

The distance between magnetic axis and plasma surface in IST

$$R_e - R_0 = 0.3 - 0.5 \, [m] \tag{2.2}$$

The cylindrical geometry works in favor of the core fueling:

$$\frac{d\dot{N}_b}{dx} = -\lambda_{cx} N_b, \quad S_{particles} \equiv \frac{d\dot{N}_b}{dVolume} = \frac{d\dot{N}_b}{dx}\frac{dx}{dVolume} \propto \frac{1}{a}, \tag{2.3}$$

where a is the minor radius of magnetic surface.

Even in the case that other fueling ideas will not work,

ISTs allow a variety of NBI combinations for flexible fueling

New ignition regime could be possible with absorbing walls

Notations for full fusion power, α-particle, and beam powers:

$$P_{DT} = 5P_\alpha, \quad \int P_\alpha dV = E_\alpha n_D n_T \langle \sigma v \rangle_{DT}, \quad P_{NBI} = E_b \frac{dN_b}{dt}. \tag{2.4}$$

The power balance in the plasma

$$f_\alpha \int P_\alpha dV + P_b = \frac{E_{pl}}{\bar{\tau}_E}, \tag{2.5}$$

where E_{pl} is the plasma energy and $\bar{\tau}_E$ is the overall energy confinement time, and $f_\alpha \le 1$ is a fraction of used α-particles.

In IST a rather small energy confinement time is sufficient for ignition

$$f_{pk} \langle p_{pl} \rangle \bar{\tau}_0 = 1, \quad f_{pk} \equiv \frac{\langle 4 p_D p_T \rangle}{\langle p \rangle} \simeq 1, \quad \bar{\tau}_0 \simeq 0.7\ sec. \tag{2.6}$$

Because in a "flat" temperature regime it can be expected that

$$\bar{\tau}_E >> \bar{\tau}_0 \tag{2.7}$$

"Excessive" τ_E would lead to a super-critical ignition (SCI) regime in IST

Super-critical regime would change the philosophy of ignition

In SCI regime:

1. ***No confinement of α-particles is necessary. They can be expelled to the wall at full energy. Good burnup of tritium***

$$f_\alpha = 0, \quad \langle \sigma v \rangle_{DT,16keV} \bar{\tau}_E = 0.03 n_{20} \bar{\tau}_E \rightarrow 1. \tag{2.8}$$

2. ***Power regime and fueling are externally controlled by NBI***

$$P_b = \frac{E_{pl}}{\bar{\tau}_E}, \quad \text{e.g.,} \quad P_{DT} = 0.5\ GW, \quad P_\alpha = 100\ MW, \quad \bar{\tau}_E = 10\tau_0, \quad P_b = 10\ MW. \tag{2.9}$$

3. ***Bootstrap current control by NBI.***
4. ***Extracted power is distributed over wall surface without reliance on irradiation.***
5. ***No issue with the Helium dilution of DT fuel in the plasma.***
6. ***Natural "Hot ion mode" with NO high-tech involved.***

$$T_i > T_e \tag{2.10}$$

7. ***Similarity of α-particle expulsion with DIII-D QHM counter injection.***

Only compact ISTs can take full advantage of SCI regime

"So-far-unbeatable" objection against LiWalls was their apparent inconsistency with He pumping

Helium ash production

$$\frac{dN_{He}}{dt} = 3.5 \cdot 10^{20} \left[\frac{1}{GW}\right]$$
$$\frac{dVolume_{He}}{dt} = 350 \left[\frac{m^3}{GW}\right] \quad \textit{at} \quad n_{He} = 10^{18} \left[\frac{1}{m^3}\right]. \tag{2.11}$$

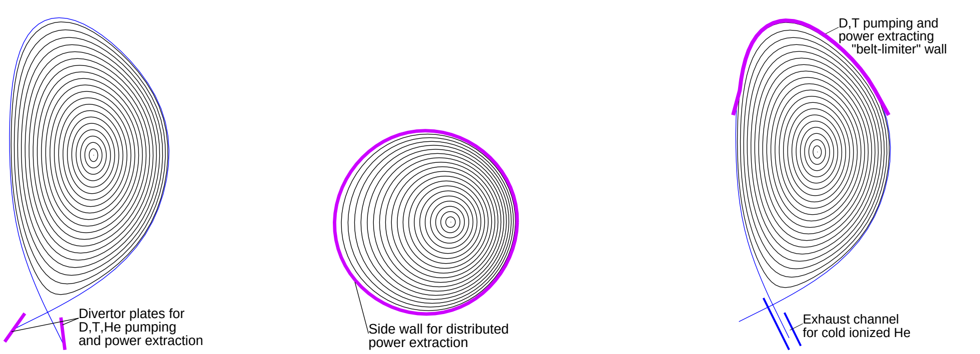
Even with no compression of He (but with a proper design), it would be required only

$$\frac{50}{GW} \quad \text{[units]} \tag{2.12}$$

of V-6000 turbo-pumps from Varian.

Helium pumping problem would be more suitable for Varian rather than for plasma physicists

The entire tokamak program is built around the single idea of a divertor



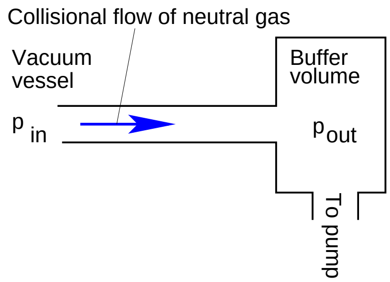
(a) **(b)** **(c) LiWalls case**

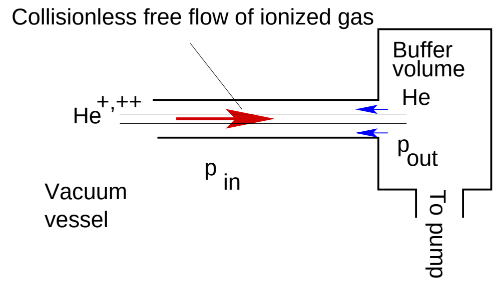
(a) conventional divertor: *all problems are well known; Not scalable to reactor*
(b) the side walls: *inconsistent with particle, impurities and helium pumping:*

both requiring low edge plasma temperature (turbulence, ELMs, disruptions, etc).

LiWalls absorb the power and D,T from the plasma and automatically distill from D,T the Helium ash (as a cold gas)

The program is kept as a hostage of the gas-dynamic scheme of He exhaust





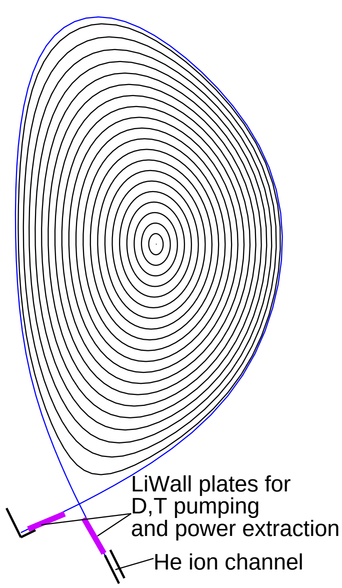
Conventional, gas-dynamic scheme:
a) collisional neutral gas in "pipe",
b) requires pressure drop

$$p_{in} > p_{out}$$

A scheme for ionized gas in tokamaks:
a) Free stream of $He^{+,++}$ *along* $\mathbf{B}$,
$\lambda \simeq \frac{1}{n\sigma_{cx0+}} \simeq \frac{1}{10^{12}\cdot 3\cdot 10^{-15}} \simeq 30\ [\mathrm{m}]$
b) Back flow is limited by
$\Gamma_{He} = D n'_x, \quad D = hV_{thermal}$
c) Helium density in the chamber plays no role, while D *is in the hands of engineers.*

LiWall concept is consistent with pumping He using the second scheme

With no ability to pump helium, LiWalls do the 95 % of job for helium pumping



LiWall divertor would contain two 0.5 m wide plates (30 m^2) with 0.1 mm of LiLi.

1. *LiWalls distill the He ash from the power and D,T from the plasma. Tritium is kept in the concentrated form in LiLi.*
2. *He is released cold. Assuming* $V_{He} \simeq$ *1 km/sec and* $n_{He} =$*10^{18} the channel gap is <1 cm to pump the ITER He ash.*
3. *Total inventory of Li is 3 L or 1.5 kg (10 kg/hour rate of refreshing).*
4. *Without refreshing is capable to pump ITER for 2 hours.*
5. *Gravity and Marangoni effects provide sufficient speed for refreshing Li surface*

$$V_g \simeq 5[\mathrm{cm/sec}], \quad V_M \simeq 1[\mathrm{mm/sec}] \text{ at } \Delta T \simeq 50^o\mathrm{C}$$

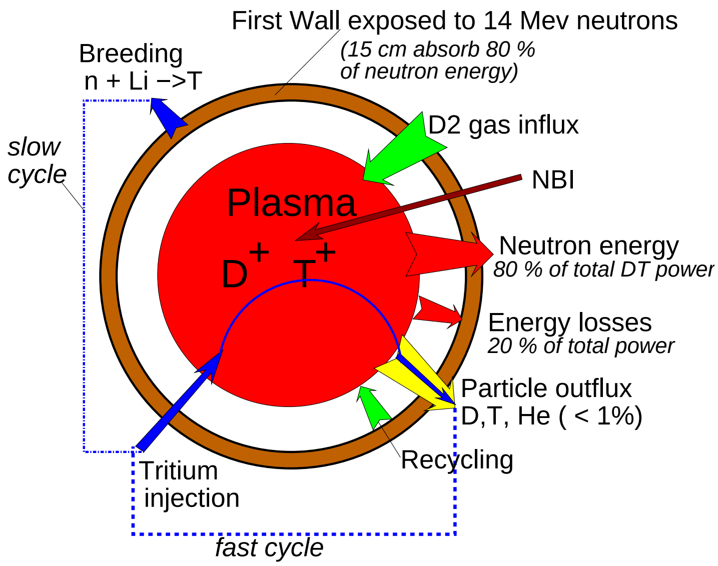
LiWall helium pumping is consistent with stable, safe and ignited ITER regime

The LiWall concepts is superior over the conventional fusion in all its basic aspects

It relies as little as possible on plasma physics

3 The number 1 kg/m^2 of T in fusion strategy

The problems of First Wall and Tritium Cycle are specific for DT fusion



Two loops of tritium cycle are present. First wall is being damaged by 14 Mev neutrons

The FW is the most challenging part of the fusion reactor

Neutron fluence $\simeq$15-20 MW·year/m^2 in necessary for destruction as well as for designing the First Wall of the reactor

15 MW·year/m^2 corresponds to consumption of 1 kg/m^2 of tritium.

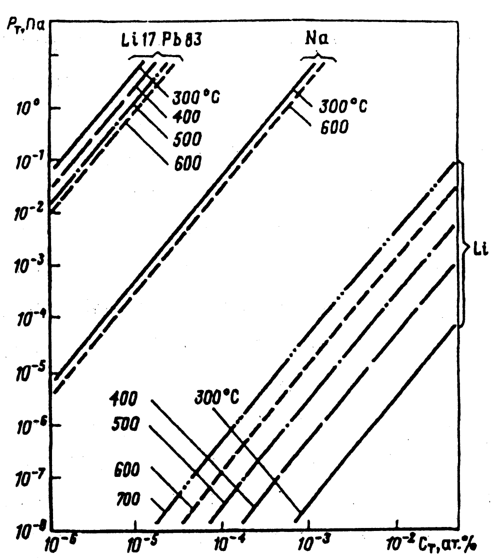
Frequently referred as an "inexhaustible" energy source, in fact,

Fusion has NO tritium fuel even for designing the reactor

(*E.g., with ITER wall surface $\simeq$ 650 m^2 650 kg of T would be consumed for designing the First Wall*)

The number 1 kg/m^2 of T specifies uniquely the fusion strategy and its reliance on IST for the reactor R&D

Tritium Cycle is an untouched challenge

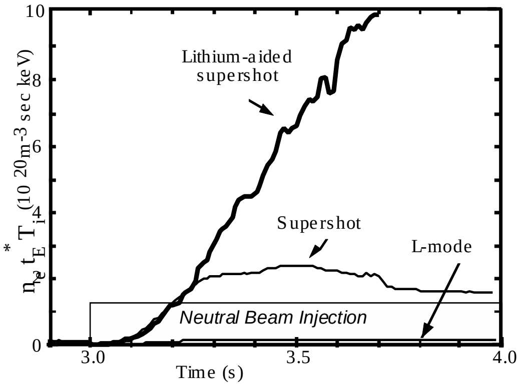


Li-, LiPb-, Na-T vapor pressure [Pa].

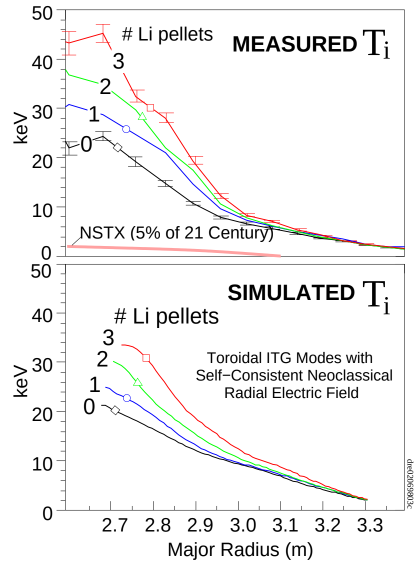
1. ***In the fast loop 97 % of injected T should be recycled. Lithium based PFC can do the job.***
2. ***In the breeding loop every neutron should be converted into tritium. Then tritium should be extracted from Lithium at concentration of 0.0001 atomic %.***

   In the case of Li, tritium cycle needs 480 MW of power for a reactor unit. *"Lithium in thermonuclear and space energetics",B.N.Mikhailov et al, Moscow, Energoizdat, 1999*

The current fusion program does not follow the basic requirements of reactor strategy



(TFTR # 83546 D.Mansfield, C.Skinner)



Depute an obvious Li effect, TFTR was not even close to its full potential

Typical for programming is the problem of matching your understanding of the code with its control parameters

#	Control parameters user has in mind	FORTRAN namelist
0	promotion to AL	`igrid`
1	promotion to group leader	`rleft`
2	major monetary award	`rright`
3	promotion within the rank	`zbotto`
	...	`ifcoil`
	...	`iecoil`
	...	...
	...	`af2`
	...	`fcturn`
95	minor disciplinary actions	`he`
96	suspension for a week	`ecid`
97	layoff	`vsid`
98	torture	`rvs`
99	electric chair	`zvs`

In science we match what was encoded by the nature with our knowledge

The total number N_0 of possible sporadic matches of n items is

$$N_0 = n! \tag{4.1}$$

with entropy

$$S_0 \equiv \ln N_0 \simeq n(\ln n - 1) + \frac{1}{2}\ln(2\pi n)$$

Suppose both sides subdivide each set on n/k mutually consistent sections with k elements in each.

$$\underbrace{\cdots\cdots\cdots\cdots\cdots}_{physics\ program's\ n} = \underbrace{\underbrace{\cdots}_{k}\ \underbrace{\cdots}_{k}\ \underbrace{\cdots}_{k}\ \cdots\ \underbrace{\cdots}_{k}}_{n/k}$$
$$\underbrace{\cdots\cdots\cdots\cdots\cdots}_{nature's\ n} = \underbrace{\underbrace{\cdots}_{k}\ \underbrace{\cdots}_{k}\ \underbrace{\cdots}_{k}\ \cdots\ \underbrace{\cdots}_{k}}_{n/k} \tag{4.2}$$

The job is reduced to matching k parameters inside each group.

Organizing the job can be made in two ways, corresponding to logical `'|' = 'or'` and `'&' = 'and'` relations

Uncorrelated permutations (`'|'` choice) inside each section is the easiest way. The total number of actions N_1 in this case

$$N_1 = \underbrace{k!\ k!\ k!\ \ldots\ k!}_{n/k\ times} = (k!)^{\frac{n}{k}},$$
$$S_1 = \ln N_1 \simeq \frac{n}{k}(k\ln k - k) = n(\ln k - 1) \quad \simeq \quad n(\ln n - 1) \tag{4.3}$$

Simple grouping of physicists (with no management control of the job) has a little effect on entropy of the system,

while being deceptively "efficient" for small n, k

As a rule, k and n rise in time (with n/k fixed) and initial "effect" disappears

$$S_1 = n\left(\ln n - \ln\frac{n}{k} - 1\right) \quad \rightarrow \quad n(\ln n - 1) \tag{4.4}$$

"Organizing" job as uncorrelated "parallel" processes is a typical mistake in management

Imposing correlations ('&' type) is crucial for reducing entropy

Matching one section after another in sequence reduces the number N_2 to

$$N_2 = \underbrace{k! + k! \ldots + k!}_{n/k \text{ times}} = (k!)\frac{n}{k},$$
$$S_2 = \ln N_2 \simeq (k-1)\ln(k-1) + \ln n \quad \ll \quad n(\ln n - 1) \tag{4.5}$$

Any coherency in action results in dramatic reduction in entropy for any n.

```
{ Step0;
  { Step1;
    { Step10;
    }
    { Step11;
    }
  }
  { Step2;
  }
}
```

Coherency requires a rigorous control. Mistake at the top may cost a lot.

Organization of '&' and '|' types have different properties

Type '|' ('or')

1. Is stable although inefficient
2. Results in further fragmentation, rather than reaching success
3. Going out of the control into "activity trap"

Type '&' ('and')

1. Is metastable. Stability is provided by the competence and creativity of leaders.
2. Is prone to destruction as soon as unresolvable problem is faced.
3. Self-destructive. Requires external control for maintenance.

An optimal mixture of a hierarchical structure with parallel groups can provide both stability and efficiency

Management structure can be mapped to C-code structure and can be computer assisted

```
Box0{
  BIGLEADER b0,b1,b2,b3; /* list of control parameters*/
  JobBox0();
   Box1{
    MIDDLELEADER a0,a1,a2;
    JobBox1();
    ----------------------------------------------------------
     Lab0[              |    Lab1[              |    Lab2[
      LEADER h0,h1,h2;|    LEADER h0,h1,h2; |    LEADER h0,h1,h2;
      JobLab0();        |    JobLab1();        |    JobLab2();
    ]                   |  ]                    |  ]
   ------------------------------------------------------------
    Box2{
      SELLP h0,h1,h2;
      JobBox2();
    }
  }
}
```

The entire structure and its functionality should be transparent

Functional position of control parameters (or leaders) inside the structure is crucial

The typical structural a single element can be shown as

$$\begin{aligned} &\{ \\ &\quad \texttt{LEADER}\quad \texttt{L0,L2,L3;}\quad \text{/* providing correlations across the parallel sections */} \\ &\quad [\,\texttt{CX}_0] \mid [\,\texttt{CX}_1] \mid [\,\texttt{CX}_2] \mid [\,\texttt{CX}_3] \mid [\,\texttt{CX}_4] \mid [\,\texttt{CX}_5] \\ &\quad \texttt{MONITOR}\quad \texttt{M0,M2,M3;}\quad \text{/* monitoring and selling the output */} \\ &\} \end{aligned} \tag{4.6}$$

It includes both "leading" and "monitoring" control parameters.

In management "leaders" are the meta-stable, "inverse population" with a tendency of conversion into monitors, and loss of functionality.

Business relying on uncorrelated "CX"s is inefficient and falls into "activity trap"

Thermodynamically, the activity trap is the same as a thermostat

The thermostat is characterized by:

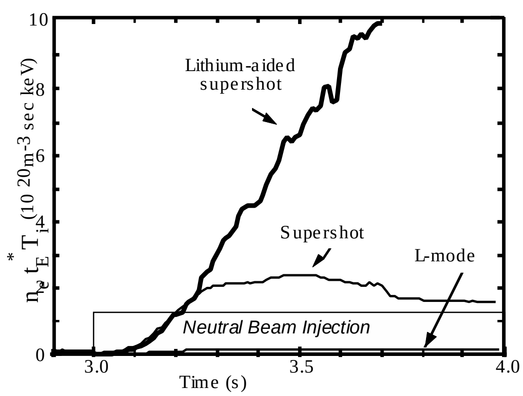
1. ***Large amount of total thermal energy with no "free" energy***
2. ***Equipartition distribution.***
3. ***Destruction of any non-thermal fluctuation.***
4. ***Dissolving to non-existence any externally injected negative entropy (information) or attempts to generate a coherence.***
5. ***Extreme stability: cannot be shaken, destroyed, can be only gradually deflated.***

In the "thermostatic" fusion community

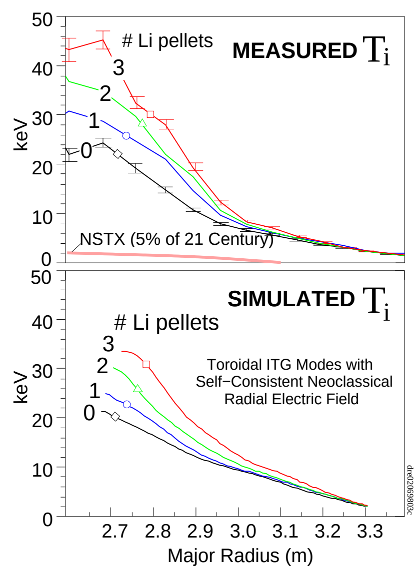
1. ***Each believes in contributing to a fusion power reactor***
2. ***Illusion is created that the "long range correlations" are provided by a sort of a "super-natural" force at the top of the program.***
3. ***"Inquisition" is in place for monitoring "rules of behavior", preserving the thermostatic happiness.***

Science is still not a progress. Progress is made by leaders in science.

Not a single basic problem is resolved in a reactor consistent manner



(TFTR # 83546 D.Mansfield, C.Skinner)



Most of machines capable for new research were destroyed during last 7 years

There is no visible fundamental plasma physics or technology problems to develop the high power density regime, first wall, and tritium cycle for the fusion power reactor.
IST is a key tool.

Entrapment of the convention fusion program into a single, reactor irrelevant plasma physics concept, represents the real obstacle, which made fusion an extraordinary failure in physics of the 20 century.

Essentially in middle of 1980s, when the plasma physicists were not capable of providing the neutron fluence for the ITER project, the fusion program felt down into "activity trap".

The reactor relevant problems were put under the "rug", while the research was fragmented in uncorrelated activities covered by intense propaganda of scientific achievements.

7 years since the formulation of the LiWall concept lead to a firm indication that the current fusion program is essentially in an irreversible state of "thermal death" with scientific leadership structure vanished.

It is time for a separate program relying on new plasma regimes, new management approach, and explicitly targeting the power reactor development