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Low recycling ITER operational regime, its fueling, pumping and He control[1]

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Abstract

A recent theory of island held equilibria in tokamaks explains existence of a slow evolution phase in the tokamak core even when the plasma is "ideally unstable" with respect to m/n=1/1 internal kink mode. Consistent with TFTR data, this theory predicts unavoidable major disruptions in the reference high performance regimes of ITER and, thus, requires their considerable revision.

As a result, ITER tentantively should implement the low recycling plasma regime, which would not only eliminate the danger of internal disruptions but would significantly enhance the ITER performance and lead to its ignition.

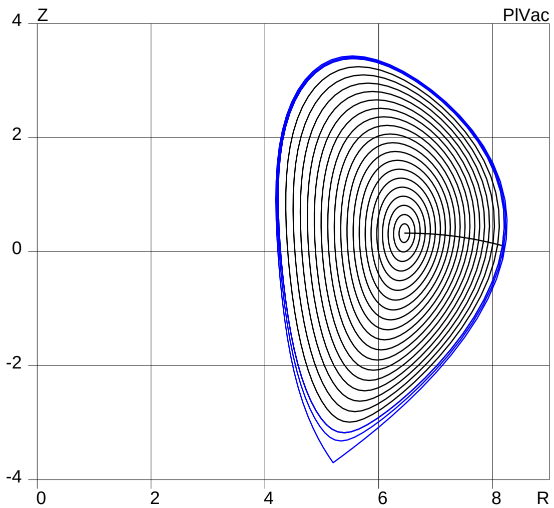
The Diamagnetic "Hot Dog" (DHD) mechanism for refueling and controlling the low-recycling high edge temperature ITER operational regime is outlined. This mechanism provides control of fusion power deposition, density and pressure profiles as well as the helium ash exhaust from the plasma.

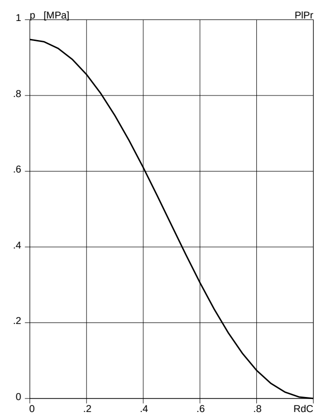
The DHD pumping (inverse to fueling) provides transport of hot edge plasma particles to Li coated wall panels (suggested in this regard for ITER wall design), thus making divertor consistent with the high plasma edge temperature. At the same time, the DHD pumping directs the He ions into the divertor for their pumping, thus, suggesting entirely new ITER divertor functionality.

Contents

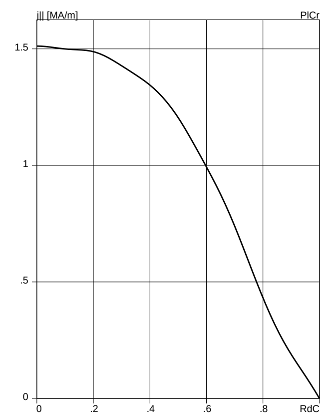
Plasma stability with $q_0 < 1$ remains to be a big issue for ITER

Internal relaxations ($q_0 < 1$) are considered as a "stabilized" transitional process with periodic collapses. There is no firm experimental/theory supported model.

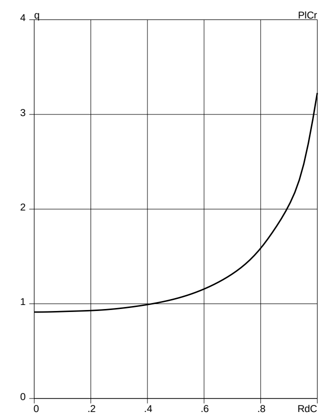




pressure

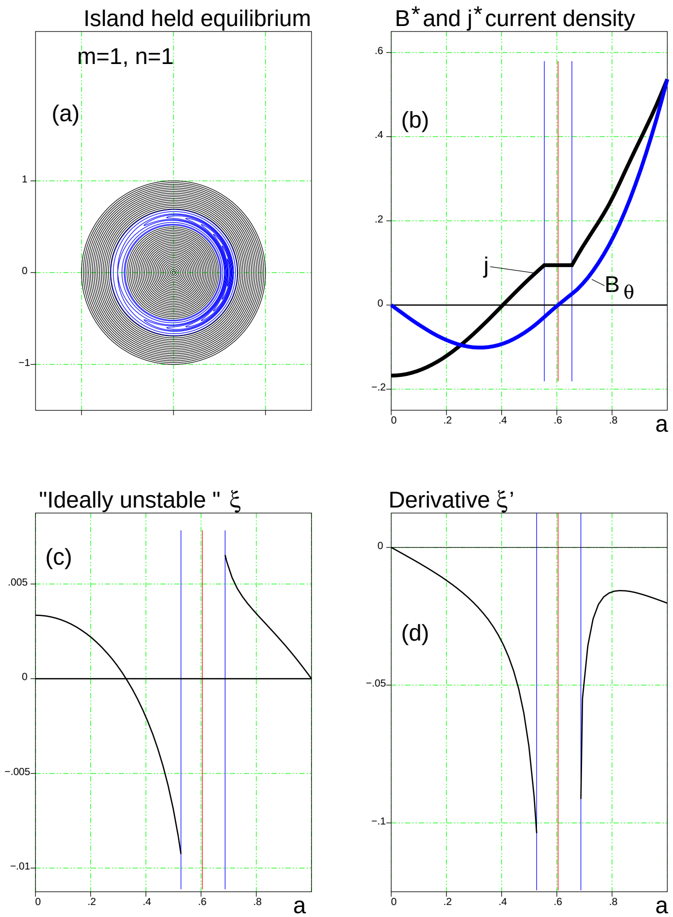


current density



q-profile

New theory suggests that internal disruptions are unavoidable in ITER



Width of island is a sensitive function

$$\sqrt{e}\alpha_e w = e^{-\frac{1}{2\alpha_e\lambda_H}}$$

$$\alpha_{c,e} = -\frac{j'R}{q'B_{tor}} - \frac{3}{2}$$

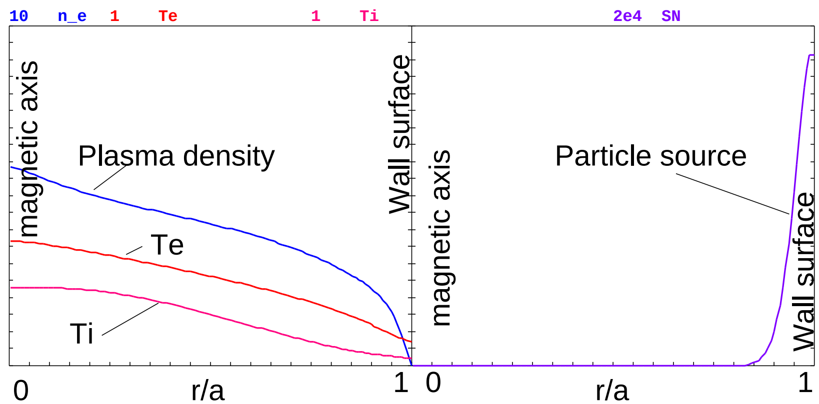
$$\lambda_H \equiv \frac{a}{R^2 q'^2}\left[\frac{c}{1-c}{\beta_j}^2 - \frac{13}{16}\left(l_i - \frac{1}{2}\right)\right]$$

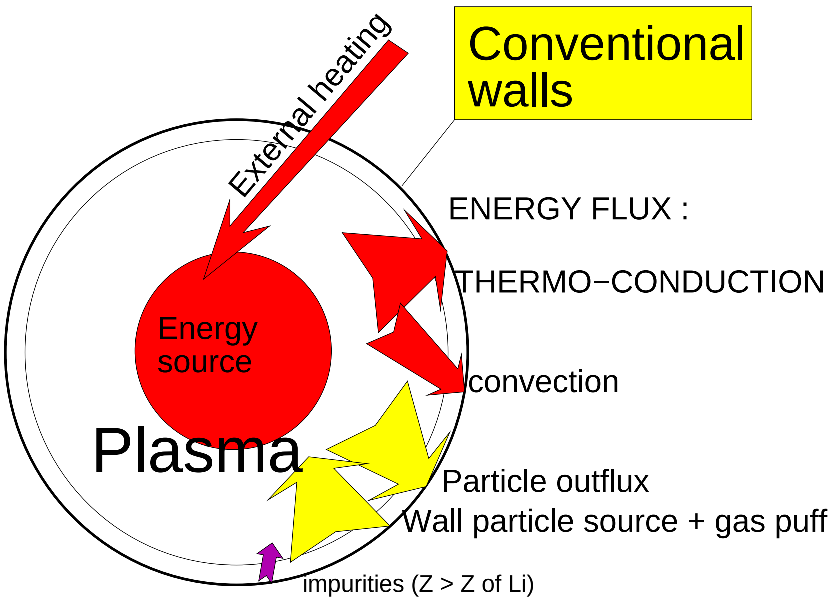
Triggering at $q'^2 \simeq 2(1-q_0) \propto \beta_j^2$

LPPP in high performance lead to internal collapses rather than to relaxations

First concept belongs to Lazy Physicists of Pumping Plasma (LPPP)

LTX simulations, no Li at walls



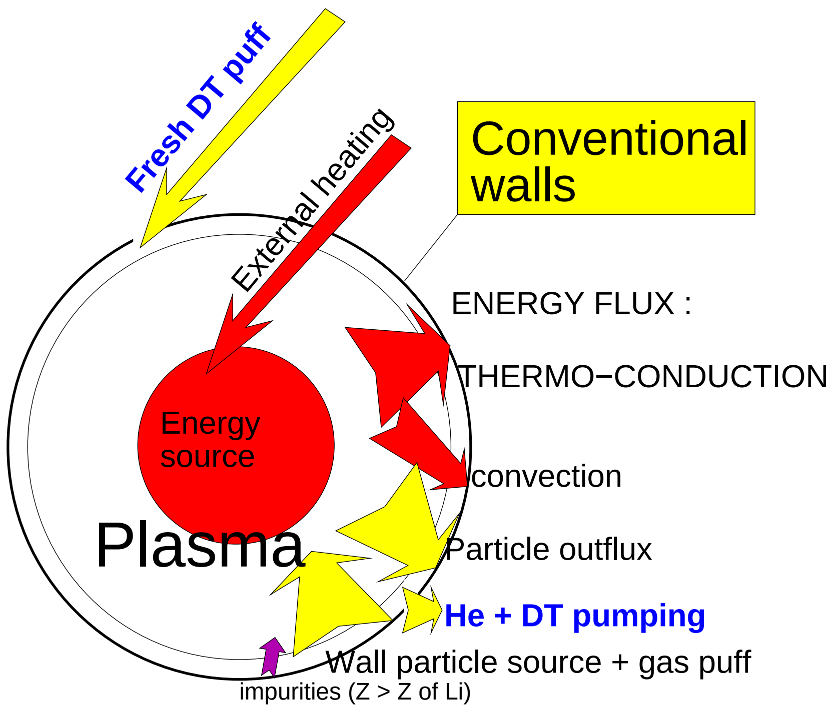


Peaked temperature and pile of problems:

- ITG turbulence,
- thermo-conduction is a dominant energy loss channel,
- peaked current density instead of wall stabilization,
- $q(0) \longrightarrow 1$ - sawtooth oscillations, unreliable stability,
- $q(0) \longrightarrow 1$ - low β and Troyon beta limit,
- low bootstrap current,
- influx of impurities, He accumulation
- poor utilization of plasma volume
- **LPPP leads to disruptions**

One "good" thing about LPPP

LPPP has two pairs of holes in the wall and is "ready" to pump helium



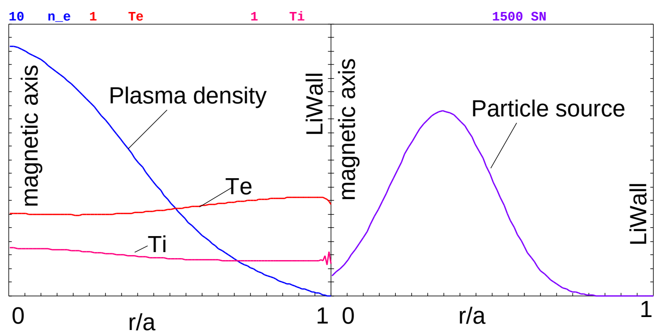
Pumps are the only things ready to pump He with no idea if He will go from the plasma core

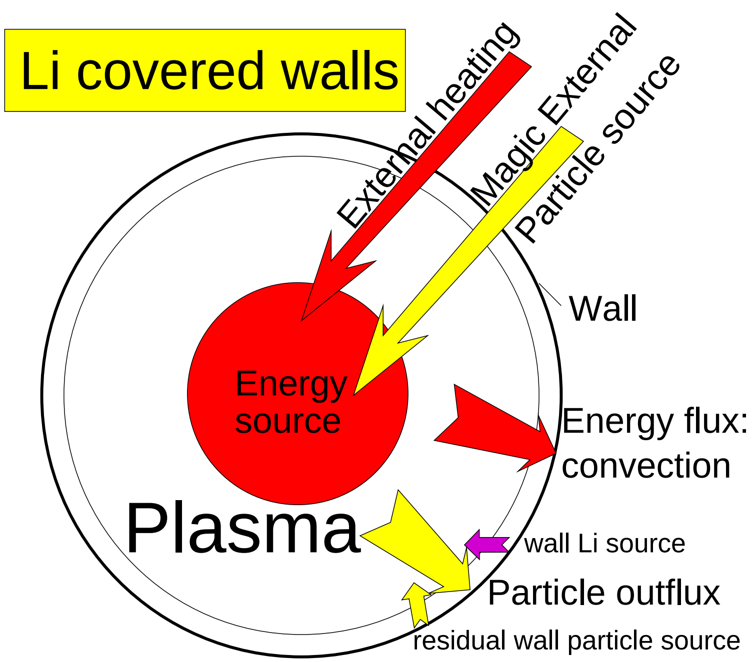
LPPP has the worst arrangement for He+DT handling

- edge DT fuel source
- no control of the fusion power deposition
- no control of the density
- central He source
- uncontrolled contamination of wall by T

Second is LiWall pumping + Diamagnetic "Hot Dog" (DHD) core fueling

LTX simulations





Flatten temperature

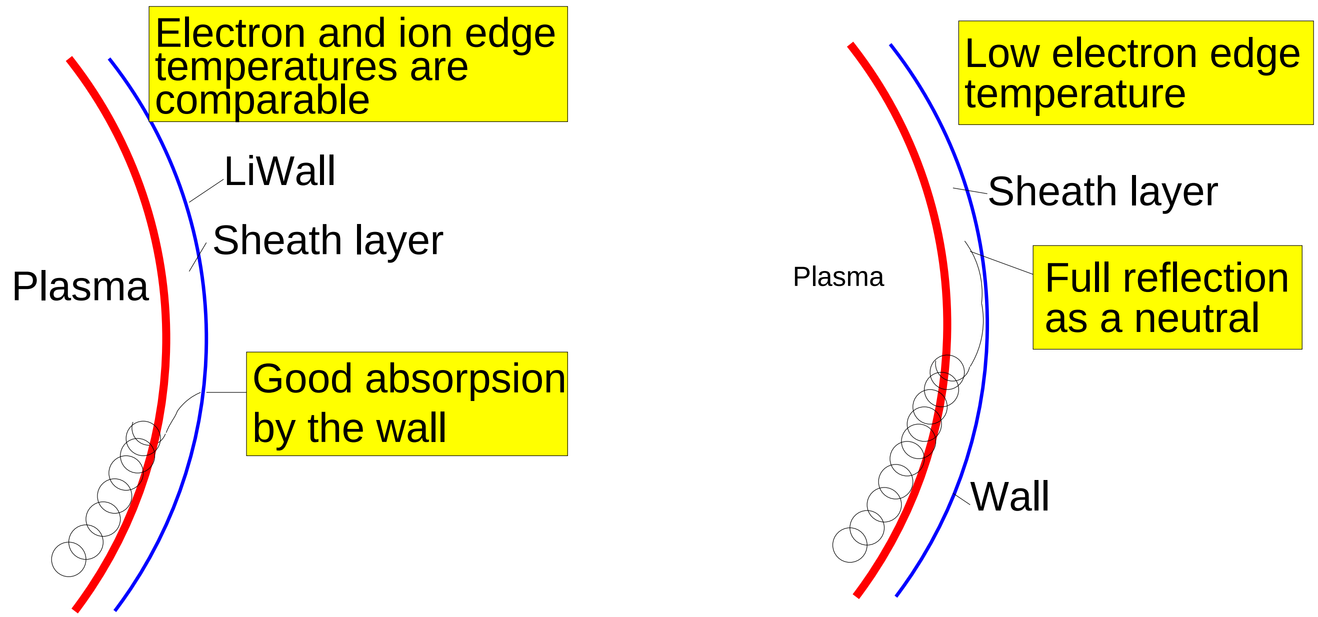
- no ITG turbulence,
- particle transport is the only energy loss channel
- no sawtooth oscillations,
- second stability regime
- control of density, power and BS current

LiWalls add more:

- wall stabilized plasma,
- high-β,
- high bootstrap current,
- outflux of both impurities and He
- no place for scalings

No scalings but perfect for OPRR.

LiWalls require plasma aligned with the wall surface (no divertor)



Good for LiWalls *Bad for LiWalls*

Sheath potential near the walls is determined by the electron energy, $E \simeq 3T_e/\rho_i$.

Plasma-wall interaction is the key physics for LiWall-DHD plasma.

Low recycling regime is necessary (and sufficient) for the reactor

5. Low recycling regime is the only OPRR relevant plasma regime:

- *capable of the reactor relevant high beta*
- *consistent with the full use plasma volume for fusion power*
- *fully maintained by the bootstrap current*
- *capable of controlling the confi nement*
- *consistent with the core DHD plasma fueling*
- *consistent with controlling*
  - *the density profi le*
  - *the fusion power deposition*
  - *the bootstrap current profi le*
- *having no problem with helium accumulation inside the plasma.*

Plasma physicists should NOT be allowed to speak about fusion reactor until they learn HOW TO PUMP the plasma edge.

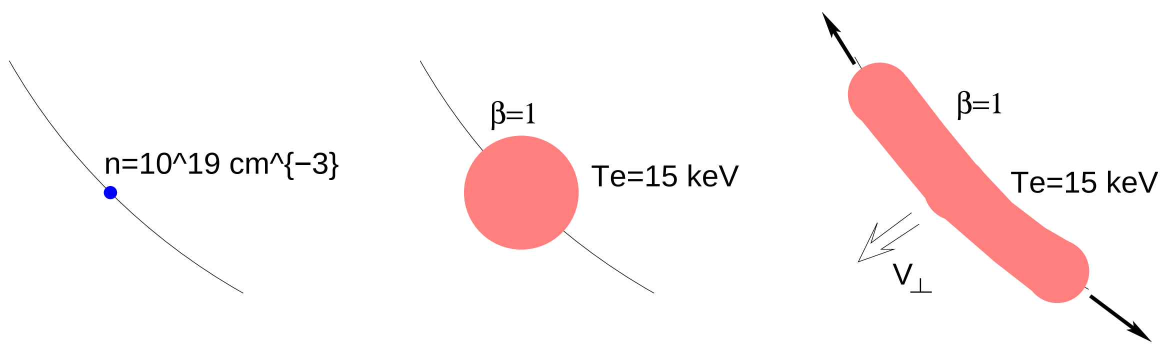
Core fueling was the most inflamatory "assumption" of LiWall concept.

Invention of Diamagnetic “Hot Dog” (DHD) mechanism resolves the issue.

DHD (contrary to a pellet) is a much smaller, neutral gas object, which, when inserted into the high-T edge plasma,

- *is getting instantaneously ionized (rather than ablated).*
- *acquires the same electron temperature as the plasma (e.g., 15 keV),*
- *explodes into a diamagnetic ball with* $\beta = 1 + \beta_{plasma}$
- *expands along the field lines (forming a hot dog like diamagnetic sausage) and accelerates from the high magnetic field to the lower field*

Not for discussion



Not for discussion

DHD has simple equations of motion

The length of DHD is determined by

$$L = 2c_s t. \tag{3.1}$$

The cross-section of DHD is defined by

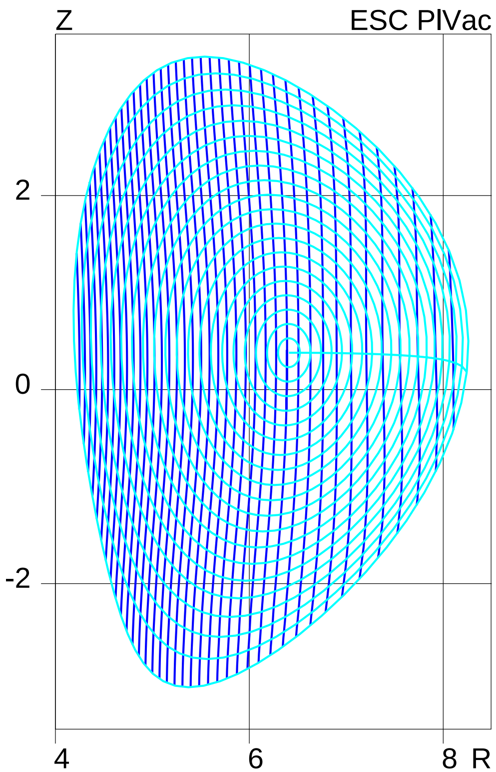
$$\pi\rho^2 L = const, \quad L < \frac{n_{gas}}{n_{DHD}} L_{gas} \simeq 10^5 L_{gas}. \tag{3.2}$$

The velocity across the field is given by

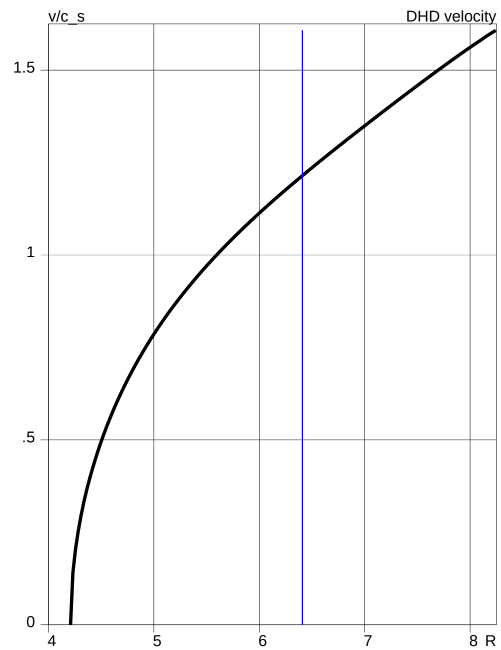
$$\begin{aligned} \frac{dv_\perp}{dt} &= -c_s^2 \frac{d}{dr} \ln(B^2 + 2\mu_0 p) - k v_s^2, \\ v_\perp &> c_s \sqrt{2 \ln \frac{B^2_{launch}}{B^2 + 2\mu_0 p}}, \end{aligned} \tag{3.3}$$

corresponding to practically instantaneous delivery of the fuel into the plasma core.

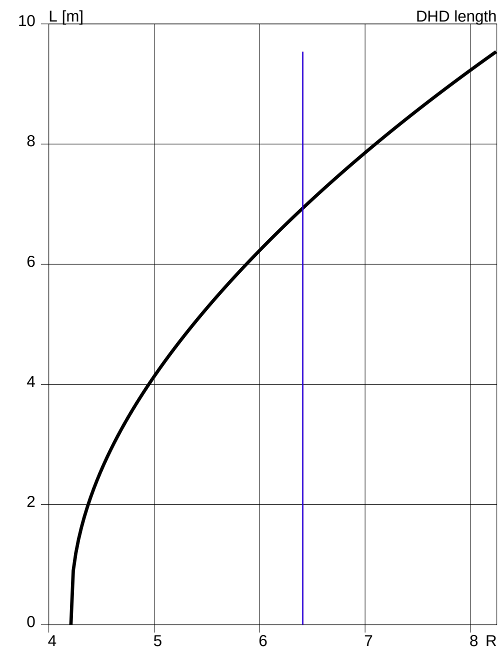
In 2-3 μs DHD tunnels the particles from the edge to the plasma center



$B^2 + 2\mu_0 p =$const lines



$$\frac{v_\perp(R)}{c_s}$$



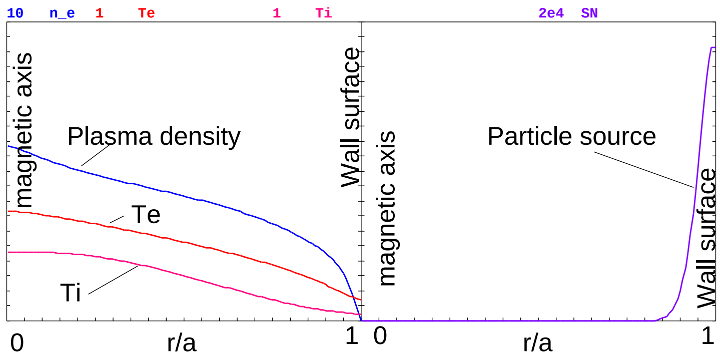
$$L(R)$$

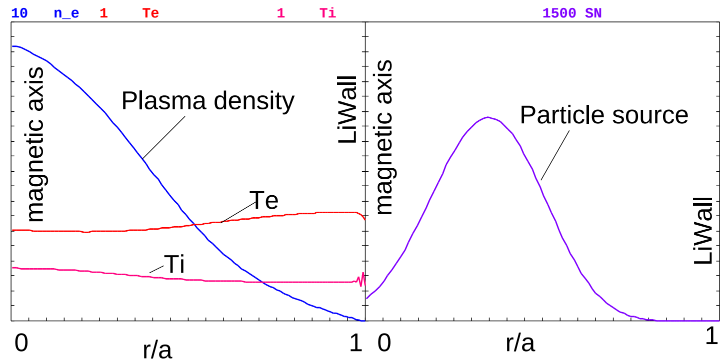
DHD fueling makes high performance plasma consistent with its reliable control. DHD desintegration TBD.

Edge plasma temperature is predetermined (S. Krasheninnikov) by

$$\frac{5}{2}\Gamma_{wall}T_{edge} = P, \quad T_{edge} = \frac{2P}{5\Gamma_{wall}}$$

- In LPPP situation $\Gamma_{wall} \gg \Gamma_{pl}, \quad T_{edge} \ll T(0)$
- In LiWall-DHD situation $\Gamma_{wall} \simeq \Gamma_{pl}, \quad T_{edge} >= T(0)$



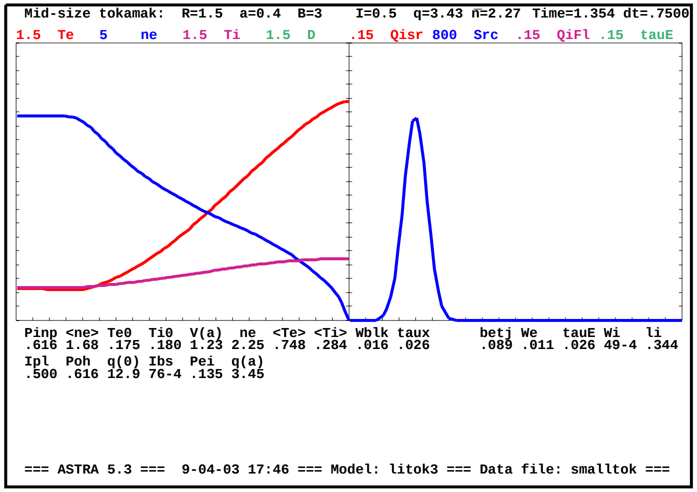


In Ohmic plasma the effect of "better" low-recycling confinement is obscured by redistribution of the power deposition toward the edge.

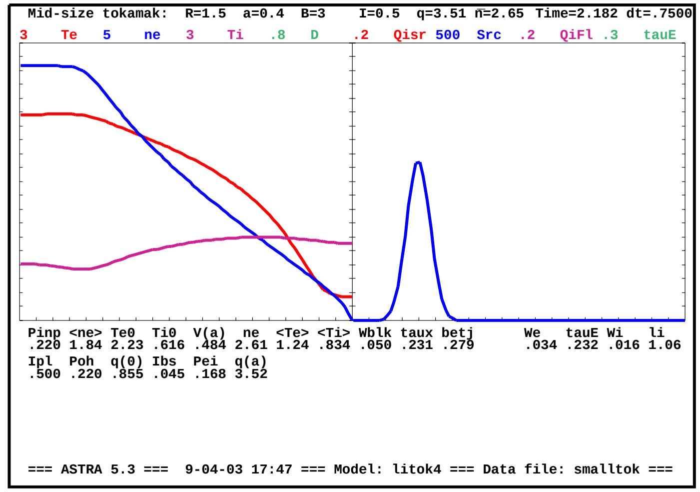
DHD returns $\simeq$ 50 % of the energy flux from the edge to the core

Without affecting edge plasma temperature $\boxed{\frac{5}{2}\Gamma_{wall} T_{edge} = P, \quad T_{edge} = \frac{2P}{5\Gamma_{wall}}}$

Compared with a pellet, DHD delivers half heated fuel to the core.



"Magic" core fueling



DHD fueling

DHD fueling effectively enhances the plasma heating power by 50 % with respect to the "magic" central fueling. In Ohmic heated plasma the number is $>$ 50 % !!!

DHD theory contains also the reversed effect of pumping by DHD

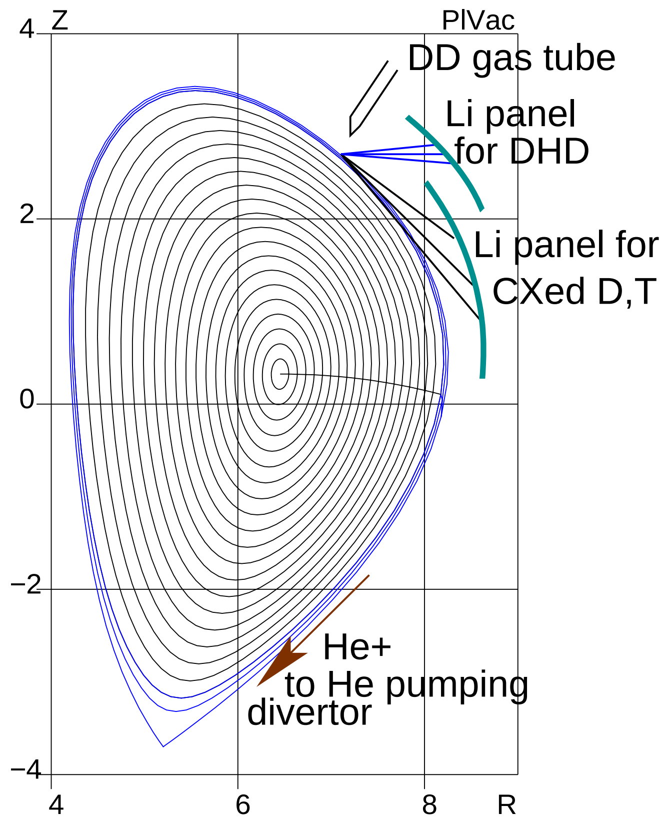
The DHD pumping idea consists of

- Cooking the DHD at the low field side
- Transmitting the hot ion plasma energy to LiWalls by charge exchange
- Transmitting the hot electron plasma energy to LiWalls by DHD
- Leaving for the divertor the low (rather than high) energy plasma
- Leaving for the divertor the helium flux

Deuterium (not DT) gas should be used for DHD pumping

DHD pumping. Low recycling regime and ignition in ITER.

DHD fueling/pumping makes necessary modifications of ITER modest



In addition to DHD "cooking" device, others should be installed:

- *D_2 (rather than DT) gas tubes*
- *Li panels for pumping energetic CXed DT (perfect tritium control)*
- *Li panels for pumping DHD with energetic electrons*
- *Redesigned divertor plates for He pumping*
- *Heat extraction systems from Li panels*

With DHD pumping low recycling high (15-20 keV) edge plasma temperature can be made consistent with ITER divertor (redesigned for He)

DHD pumping. Low recycling regime and ignition in ITER.

Present, disruption prone ITER regime has no chance for performance

On the other hand, there is nothing unrealistic with DHD pumping and low recycling. For ITER plasma

$$\begin{aligned} & n_e \simeq 1.5 \cdot 10^{20}\ [\mathrm{m}^{-3}], \quad V \simeq 835\ [\mathrm{m}^3], \quad \tau_{pl} \simeq 4\ [\mathrm{s}], \\ & \frac{dN}{dt} \simeq 3 \cdot 10^{22}\ [\mathrm{s}^{-1}] \end{aligned} \tag{3.4}$$

the following gas jets capacity is required

$$n_g \simeq 3 \cdot 10^{19}\ [\mathrm{cm}^{-3}], \quad v \simeq 10^5\ [\mathrm{cm/s}], \quad \sum_i S_i \simeq 1\ [\mathrm{mm}^2] \tag{3.5}$$

together with pumping by Li coated wall panels.

Instead of wasting resourses on fighting unpredictable disruptions, it is better to establish the LR ITER plasma regime and its full control.

With a core stable plasma and LR ignition will happen in ITER (KPZ-2002) *(with future tritium supply from a couple of US (?) ISTs)*

Participation in ITER is not the achievement of fusion. It is its life-preserver.

It is an attempt (probably last one) of the US government of saving the fusion program, which failed to develop fusion for 35 years (counting since T_e measurements on T-3 tokamak in 1968).

For US fusion community involvement in ITER is

- *Punishement for the previous failure*
- *Opportunity for reestablishing credibility*
- *Message that without development of our own fusion power reactor nobody needs us*

While being a "minor partner", US can (and should) be a leader in key aspects of ITER physics and technology.

Summary

Invention of DHD fueling/pumping opens unprecedented opportuniites

In this regard

- *Real steps should be made in implementing efficient (Li based) pumping techniques on existing tokamaks (NSTX, DIII-D, CDX/LTX)*
- *The dominance of LPPP approach should be drastically reduced in both ITER and fusion reactor R&D*
- *All efforts should be made for developing DHD fueling/pumping on existing high-edge temperature tokamaks (DIII-D, JET, ASDEX, etc)*
- *Development of the tokamak regime control should shift the emphasis from the core plasma physics to edge physics and technology*
- *The ignited operational ITER regime has be considered as a high priority target for making ITER successful*

ALPS/PFC area of expertize in low recycling technology is consistent with streamline tendencies in fusion.

Summary

By contributing into ITER ALPS/PFC has unique opportunities

for developing (together with the US plasma physics community), e.g.,

- *core fueling and regime control of ITER,*
- *optimum tritium fuel cycle (rather than breeder)*
- *reactor-relevant divertor/wall operation*

which are crucial for the US power reactor.

We should make ITER ignited in the low recycling regime.

We should make sure that ITER will be not the first one to be ignited.