On Operational Power Reactor Regime and Ignited Spherical Tokamaks[1]

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Abstract

While recent Really Great 35 year Development Plan (RG35DP) suggests a new, 2003 version of the "cold" magnetic "Fusion without ignition" in the next 35 years, the talk was focused on achieving ignition in tokamaks in the nearest future.

It introduced the Operational Power Reactor Regime (OPRR) as a power producing phase distinct from the ignition. Being a major challenge for magnetic fusion, OPRR requires a low recycling and wall-stabilized high-β plasma.

Because of the small plasma volume and high-β, spherical tokamaks are uniquely suitable for development of OPRR. It was shown that in the low recycling regime, spherical tokamaks not only are capable for OPRR relevant high-beta, but also are overdriven with the bootstrap current, calculated now for the first time using direct Monte Carlo particle orbit simulations with the pitch angle scattering.

The Diamagnetic "Hot Dog" (DHD) mechanism for refueling and controlling the low-recycling, high edge temperature OPRR has been reported for the first time. DHD fueling has all properties for providing full control of the fusion power deposition, density and pressure profiles in the low recycling tokamak power reactors.

It gives the physics basis for the development of the DHD controlled tokamak fusion, including:

- *fusion demonstration at a compact (30 m^3) Ignited Spherical Tokamak (IST) (0.5 GW of the fusion power),*
- *an IST based Component Test Facility with high (5-8 MW/m^3) neutron wall load and maximum (up to 95 %) utilization of neutrons for tritium breeding.*

The theory of DHD controled LiWall IST essentially concludes the plasma physics concept of the tokamak based DT magnetic fusion and now requires a phase of its focused experimental and technology development, contrary to the eclectic RG35DP "configuration optimization".

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Present times for magnetic fusion are distinguished by two things:

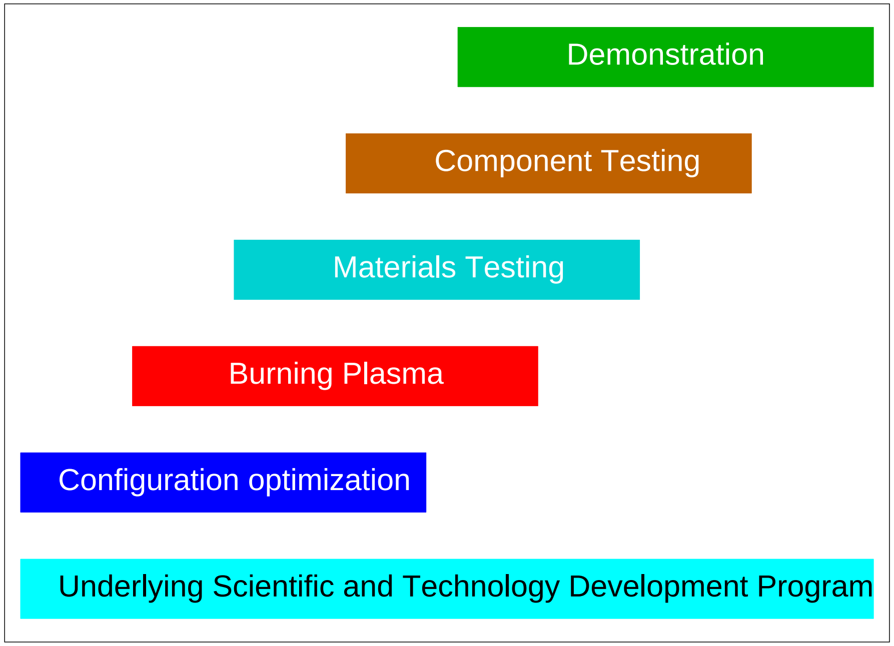
1. ITER project has been concluded
2. DOE requested a plan to develop a DEMO for demonstration the net electricity production from fusion in $\simeq$ 34.7 years

"I would like the Fusion Energy Sciences Advisory Committee (FESAC) to comment, from our present state of understanding of fusion, on the prospects and practicability of electricity into the U.S. grid from fusion in 35 years."

- Raymond L. Orbach
Director
Office of Science
Sept. 10, 2002

"It is the judgment of the Panel that the plan illustrated here can lead to the operation of a demonstration fusion power plant in about 35 year and enable the commercialization of fusion power"

- FESAC
Nov. 25, 2002



The answer makes the recent Development Plan Really Great (RG35DP)

In particular, this RG35DP contains:

- Promise of commercial fusion and no a single ignited machine for 35 years.
- Broad and comprehensive “configuration optimization” and no clear money source for such a great scientific endeavor.
- Promise of fusion technology development and no single machine, which would be able to accumulate the necessary fluence during the next 100-150 years.
- Promise of electricity production and no mentioning of Ampere-Volt-meters (for El.Power measurement) at the end of 35 years.
- . . .

This is and indovative Really Great new definition of (Fusion without ignition) comparable only with "cold" fusion in its mix of lie with incompetence

Targeting more plasma scaling RG35DP can be scaled in its own turn.

It is sufficient to just repeat the trick of replacing $\beta \ll 1$ by beta-looking $\beta_N \simeq 1$, and switch from years to dimensionless units

$$\bar{t}_{RGDP} \equiv t - (09/10/2002), \quad \tau_{RGDP} \equiv \frac{\bar{t}_{RGDP}/35}{1 + C_M \bar{t}/35}, \quad C_M = \frac{10}{35},$$

where C_M is E. Mazzucato correction (well-known in PPPL), reflecting the experimental fact, that in 80-s fusion was promised in 25 years, and now in 35.

Now, the prediction of when RG FESACting Fusion will be delivered can be written in a scientific form

$$\tau_{RGDP} < C_M^{-1} \simeq O(1) \ll O(10). \tag{1.1}$$

The nicest thing is that for RGDP the fusion technology will not be necessary, at least, for

$$\tau_{RGDP} < 0.5 \ll O(1). \tag{1.2}$$

There is only one bothering problem

The RG35DP scaling for future funding should be based on experimental facts of past 3 decades, i.e, $-1 < \tau_{RGDP} < 0$ (rather than on simplistic theory)

$$\frac{d\,(\$\$)}{d\tau_{RGDP}} > \frac{C_{\$\$}}{(1 - C_M\tau_{RGDP})^2} \tag{1.3}$$

After saving pressurous money from the technology programs, (see (1.2)), the really colossal job is to educate public and other institutions that

FESACting ("cold") Fusion is absolutely necessary (e.g., for public H-cars) and by no means

$$\frac{d\,(\$\$)}{d\tau_{RGDP}} \neq const\ (!) \tag{1.4}$$

In this regard

FF propaganda, colored pictures, . . . should be emphasized, not tech.

Although it is boring, let us return to the old, ignited view on fusion

Important approximation for the fusion power (old fashioned)

In the reactor, α-particles fusion power covers all losses

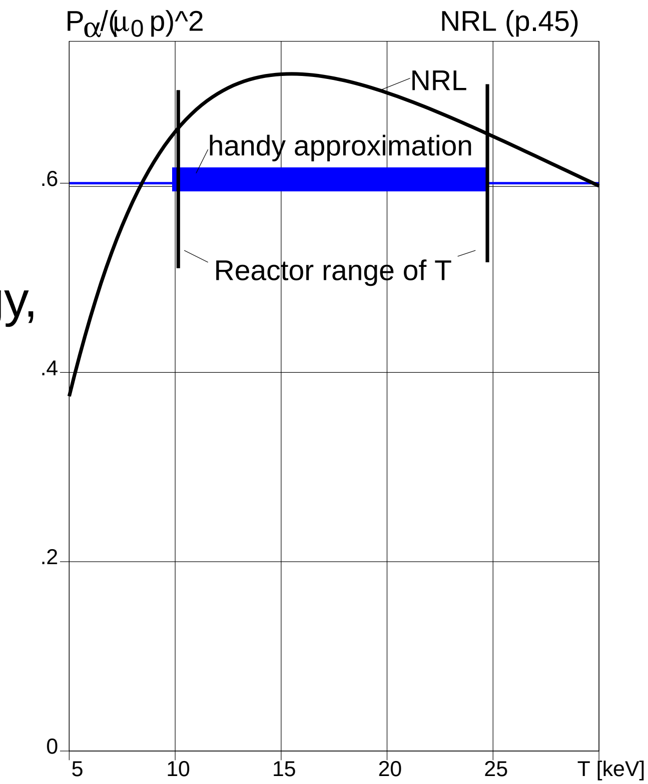
$$P_\alpha \geq \frac{E_{pl}}{\tau_E}, \quad E_{pl} = \frac{3}{2} pV,$$

P_α	[GW]	-	power in α-particles,
E_{pl}	[GJ]	-	thermal plasma energy,
p	[MPa]	-	averaged pressure,
V	[1000 m^3]	-	plasma volume.

Fusion power is proportional to the plasma pressure

$$P_\alpha = 0.6(\mu_0 p)^2 V, \quad \mu_0 = 0.4\pi,$$

$$P_{DT} = 5P_\alpha = 3(\mu_0 p)^2 V.$$



Four important formulas come immediately from $P_{DT} \propto p^2$

1. $$B^2 \cdot \beta \cdot \tau_E > 4$$ — ignition condition (B is in [T])

$\left(p \cdot \tau_E = 1.6 \text{ [MPa} \cdot \text{s]}, \quad n \cdot T \cdot \tau_E = 5 \cdot 10^{21}\right)$

2. $$P_{DT} = 12 \frac{V}{\tau_E^2}$$ — DT power of the fusion reactor

(high $\tau_E > 1.5$ sec is bad for power production)

3. $$P_{ext} > \frac{1}{4} P_{\alpha @ ign} = \frac{3}{5} \frac{V}{\tau_{E@ign}^2}$$ — needed external igniting power *(high $\tau_E \simeq 3$ sec is necessary for 10-15 sec of ignition phase)*

together with

4. $$C\ [\$B] + \ldots < 10.5 \frac{P_{DT}}{4} \frac{\$/kWh}{0.04}$$ - cost C of a reactor vs $\$$-value of electricity produced *(assuming 30 years of uninterrupted energy production)*

Ignition phase requires high τ_E and low-β

The best scenario of ignition (e.g., low recycling regime with a flat T and a raising density)

$$\frac{dE_{pl}}{dt} = P_{ext} + P_\alpha - \frac{E_{pl}}{\tau_{E@ignition}} \simeq P_{ext} + P_{\alpha@ign}(x^2 - x), \quad x \equiv \frac{E_{pl}}{E_{pl@ign}} \qquad (2.1)$$

leads to third important formula

$$P_{ext} > \frac{1}{4} P_{\alpha@ign} \simeq \frac{1}{20} P_{DT@ign} \simeq 0.6 \frac{V}{\tau^2_{E@ign}},$$

which gives a minimal estimate for the external heating power P_{ext}

(The subscript $_{@ign}$ specifies parameters at the ignition phase)

RG35DP vision of the Fusion Power Reactor parameters:

With RG35DP achievements in confinement (in accordance with lovely plasma confinement scalings)

$$\tau_E \simeq 4\,[sec],$$

the reactor

$$P_{DT} = 4\ \text{GW},$$

would acquire an attractive (for menagement) size

$$V = \frac{16}{4} \cdot 1000\ \text{m}^3,$$

and a very “modest” installed ignition power (useful for only 10 secs)

$$P_{ext} > 200\ \text{MW},$$

Such a commercial product is just very hard to apprehend for non-professionals in the RG35DP cold fusion.

Special efforts are required in future in educating utility people.

Typical example of Fusion Power Reactor parameters:

With the reasonable design parameters:

$$P_{DT} = 4 \text{ GW}, \quad B = 5 \text{ T}, \quad V = 400 - 500 \text{ m}^3,$$

a Fusion Power Reactor should be ignited at high τ_E and moderate β

$$\tau_{E@ign} = 3 \text{ sec}, \quad P_{ext} > 27 - 34 \text{ MW},$$

and then must operate at an enhanced β and reduced τ_E

$$\tau_E = 1.1 - 1.22 \text{ sec}, \quad \beta = 0.15 - 0.13$$

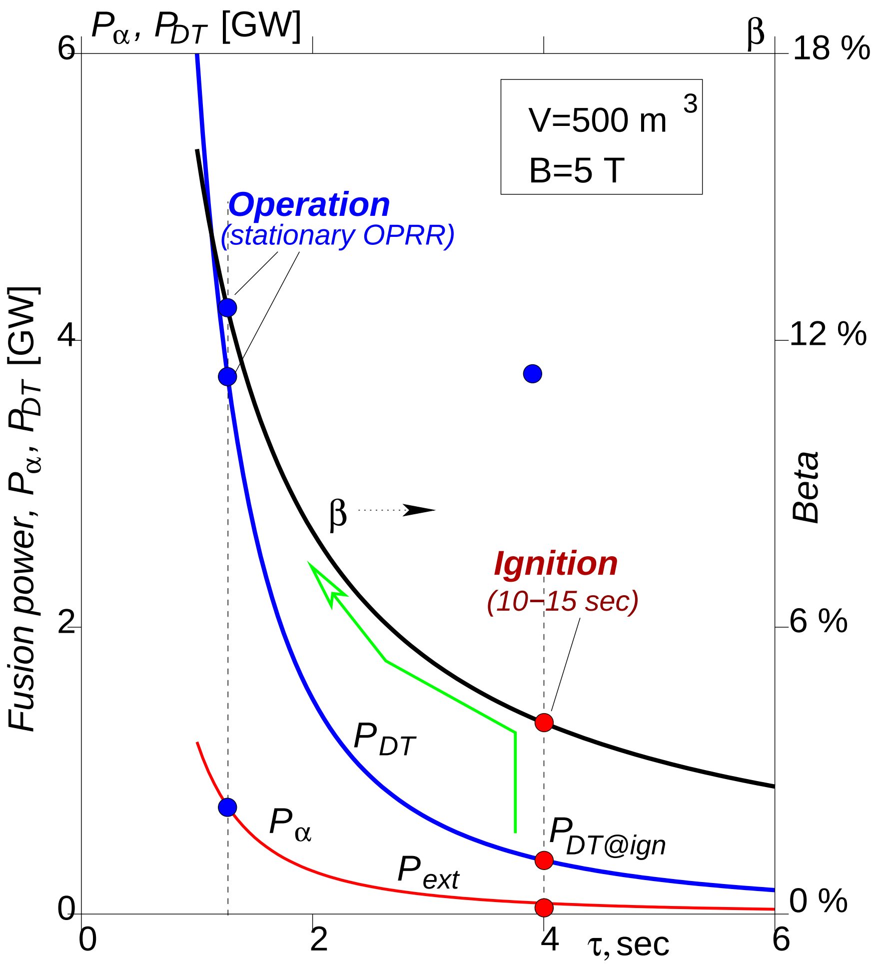
in order to fit the "betatau" requirements.

Having twice smaller volume than, e.g., ITER, it would be 10 times more powerful in order to fit a cost

$$C = \$(2 - 3) \cdot 10^9$$

consistent with $-value of electricity produced.

Ignition requires high τ_E, operation requires high β.



"Betatau" of the reactor strategy:

- Ignition/operation condition

$$B^2 \cdot \beta \cdot \tau_E \; [\mathrm{T}^2 \cdot \mathrm{sec}] = 4,$$

- Total power

$$P_{DT} \; [\mathrm{GW}] = 12 \frac{V}{\tau_E^2} \left[\frac{10^3 \mathrm{m}^3}{\mathrm{sec}}\right],$$

- Cost limitation

$$C \; [\$\mathrm{B}] < 10.5 \frac{P_{DT}}{4} \frac{\$/kWh}{0.04} \; [\mathrm{GW}],$$

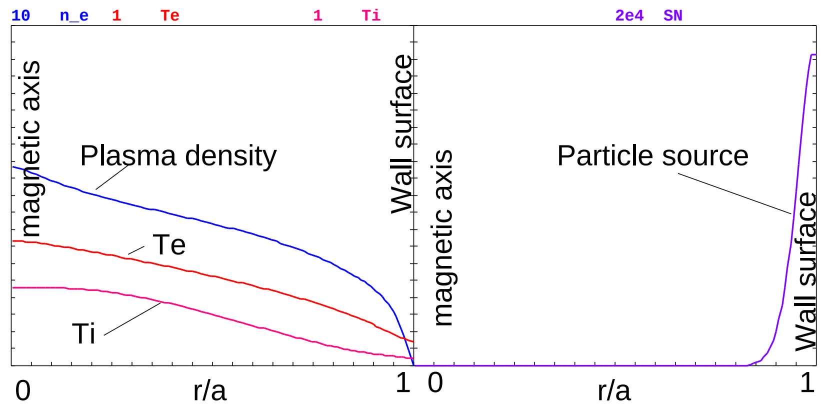
- Ignition external power

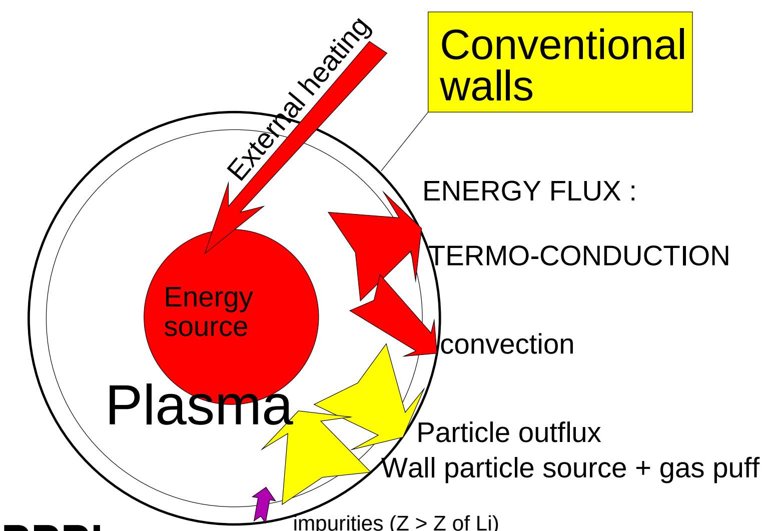
$$P_{ext} = \frac{1}{20} P_{DT@ign}.$$

Development of OPRR remains a challenge for magnetic fusion. New regimes are necessary.

Conventional plasma is controlled by wall fueling.

LTX simulations, no Li at walls



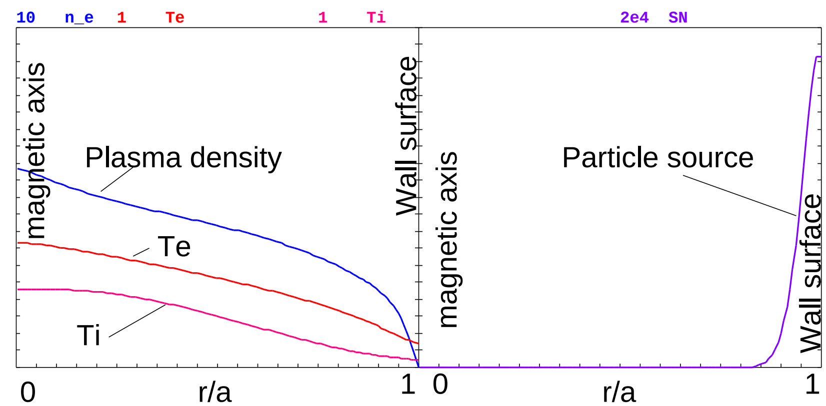


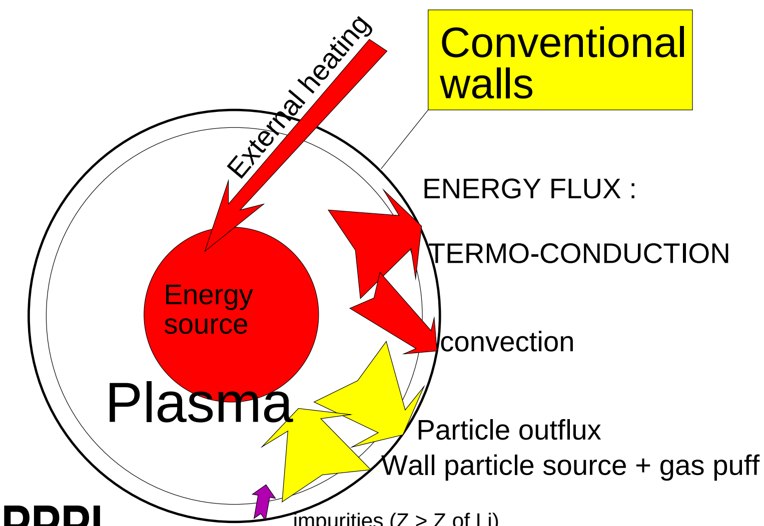
Peaked temperature:

- ITG turbulence,
- thermo-conduction is a dominant energy loss channel,
- peakedness of the current density,
- $q(0) \to 1$ - sawtooth oscillations,
- $q(0) \to 1$ - low β and Troyon beta limit,
- low bootstrap current,
- influx of impurities,
- poor utilization of plasma volume
- ... and a lot of scalings

Peaked temperature is perfectly consistent with RG35DP.

LTX simulations, no Li at walls



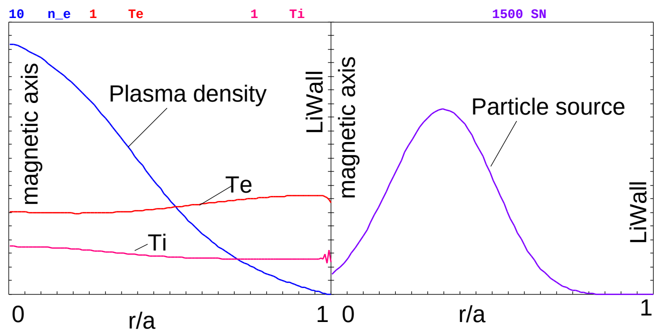


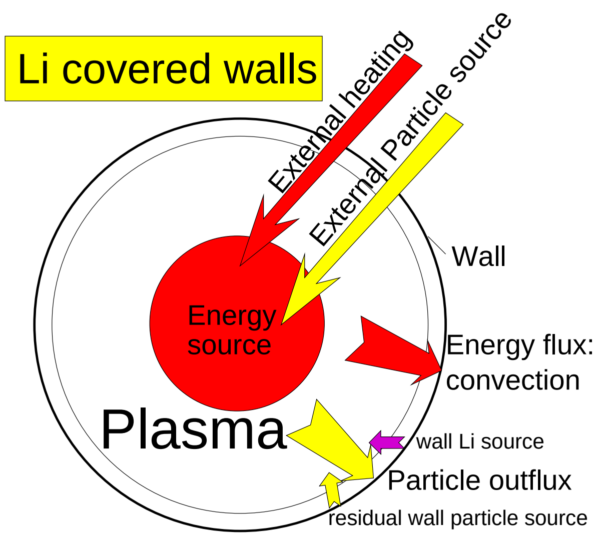
- ITG - no confi ment but many scalings and vast computer simulations,
- thermo-conduction is unpredictable - a challenging problem for theory,
- peakedness of the current density - rich MHD,
- $q(0) \rightarrow 1$ - 30 years of simulations and no understanding,
- $q(0) \rightarrow 1$ - $\beta \ll 1$, instead β_N which is beta-looking
- low bootstrap current - good for neocalssi-cal modes,
- influx of impurities - rich spectroscopy,
- poor utilization of plasma volume - more money for projects

OPRR needs a different regime.

Dull, Heristic and Diletant (DHD) plasma physics model.

LTX simulations





Flatten temperature

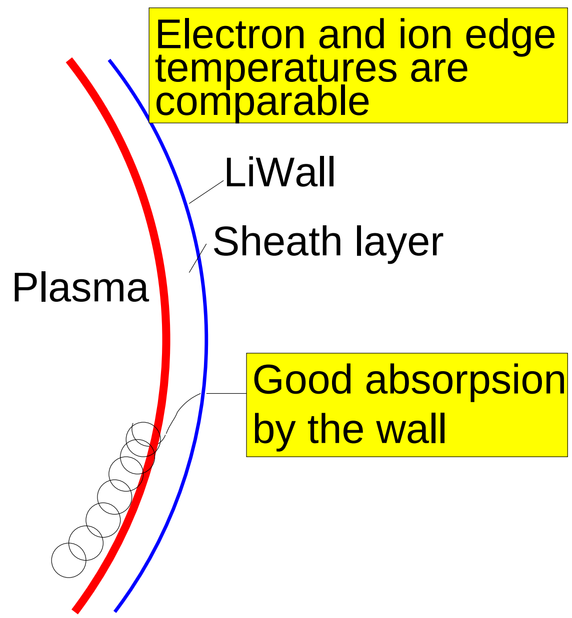
- no ITG turbulence,
- convection is a loss channel for particles and energy,
- no sawtooth oscillations,
- second stability regime (no Troyon limit),

LiWalls add more:

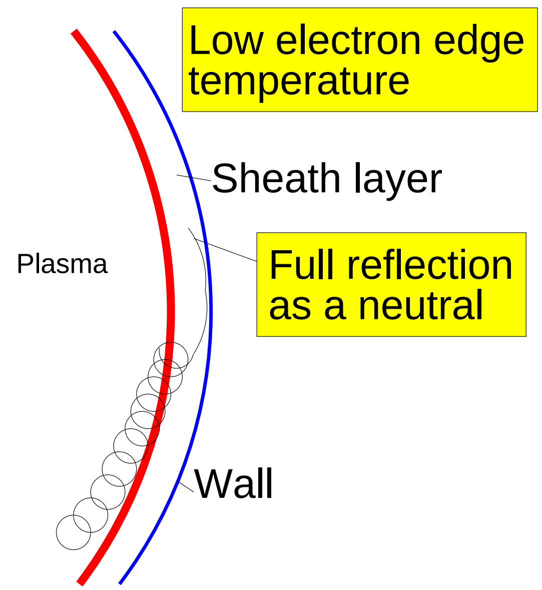
- wall stabilized plasma,
- high-β,
- high bootstrap current,
- outflux of impurities,
- . . .

Almost no core physics, but is promising for OPRR.

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



Good for LiWalls

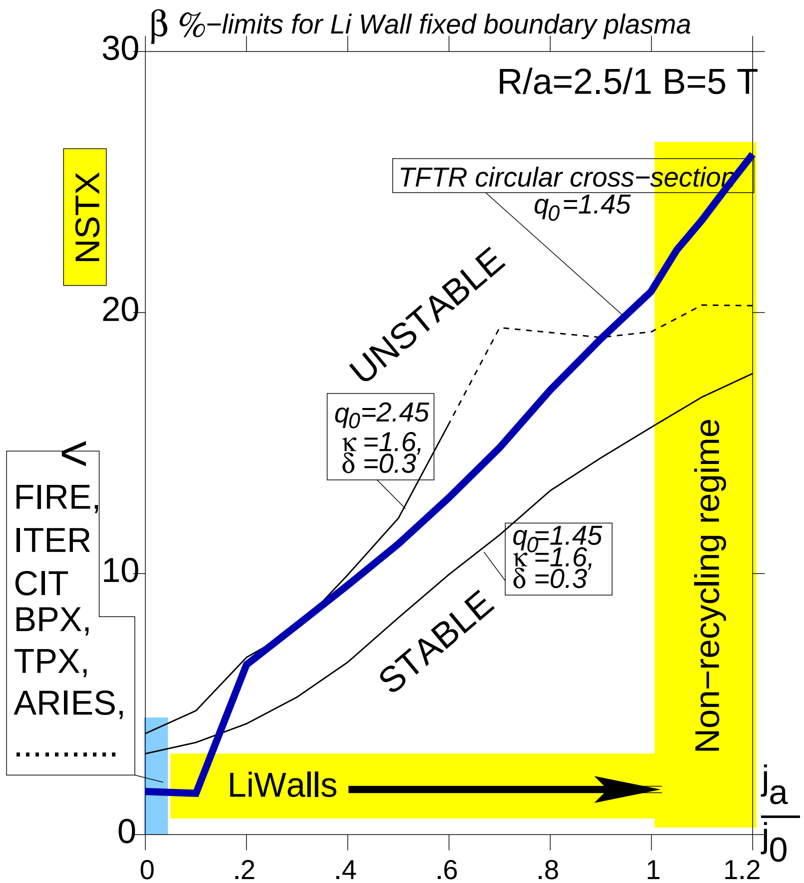


Bad for LiWalls

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

Plasma-wall interaction is a key issue for DHD plasma.

LiWalls offer (second stability core) + (wall stabilized) plasma



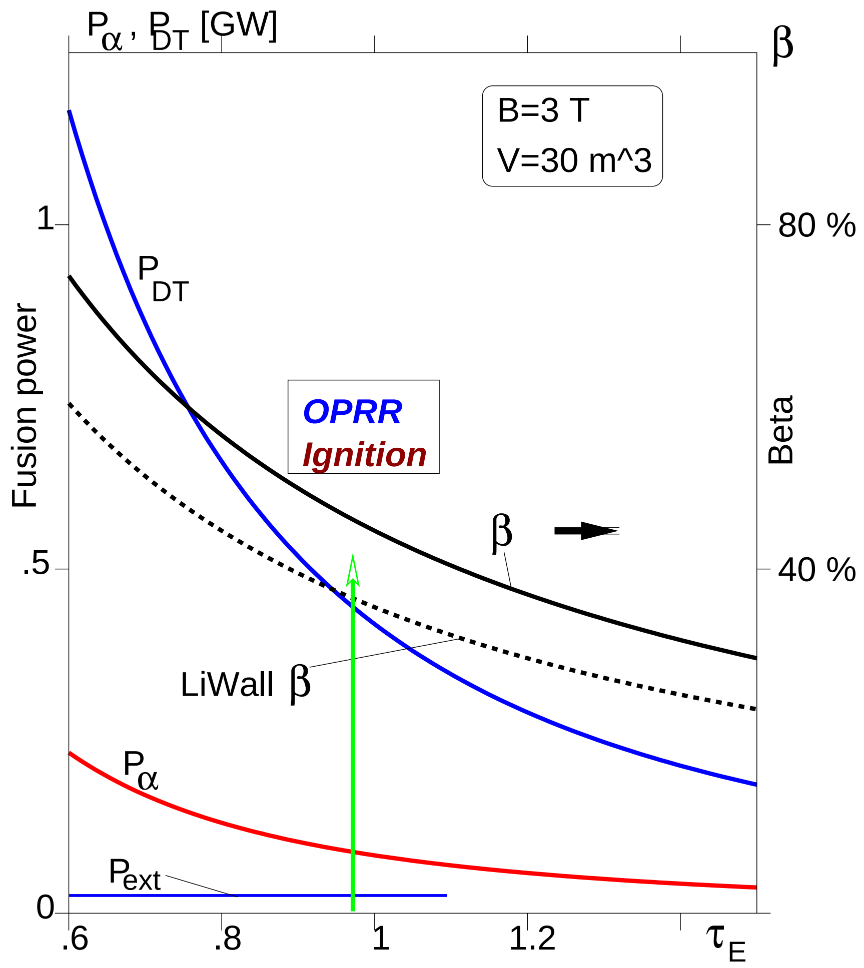
- no sawtooth oscillations;
- no Troyon limit;

β - limits for the second stability regime

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

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

Spherical Tokamaks are unique in merging OPRR and Ignition Phase



$\beta - \tau_E$ parameters of mini-reactor:

- Ignition & operation condition

  $$B^2 \cdot \beta \cdot \tau_E \ [\mathrm{T}^2 \cdot \mathrm{sec}] = 4,$$

- Total power

  $$P_{DT} \simeq 0.5 \ [\mathrm{GW}],$$

- Igniting external power

  $$P_{ext} \simeq 25 \ [\mathrm{MW}].$$

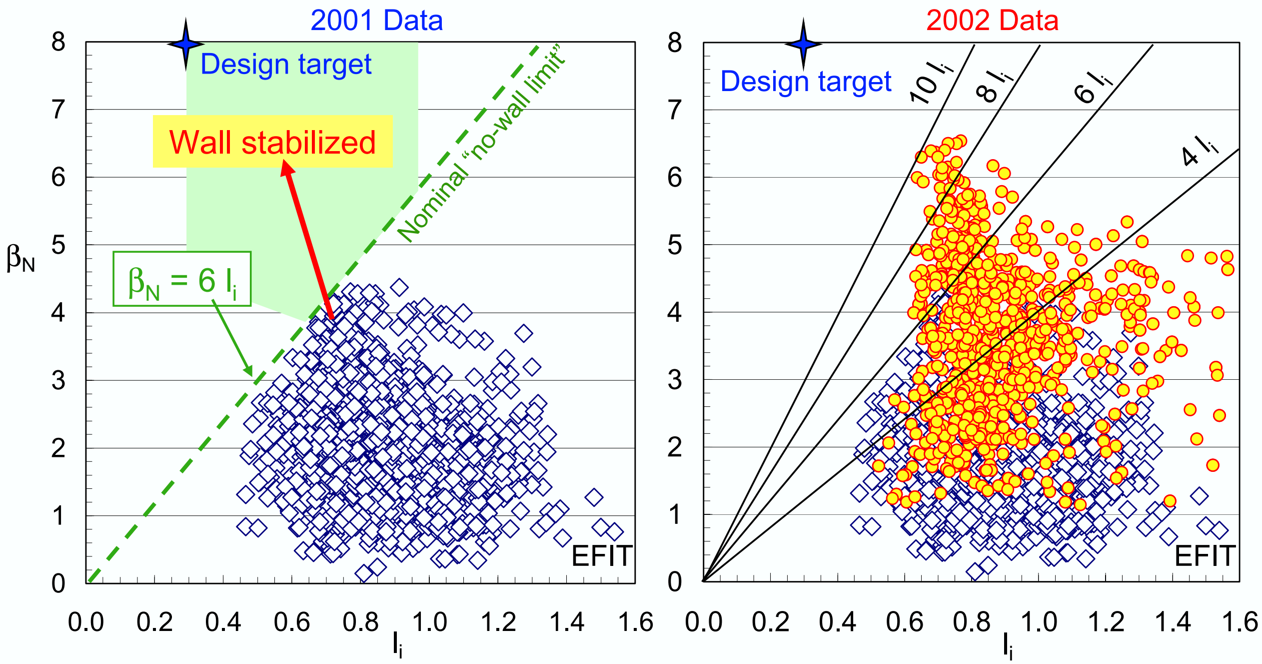
- Cost limitation

  $$C < 1 \ [\$\mathrm{B}],$$

Ignited ST is a practical approach for development of OPRR

START, NSTX, MAST demonstrated OPRR relevant beta (35 %)

Plasma operation in low l_i, wall-stabilized space



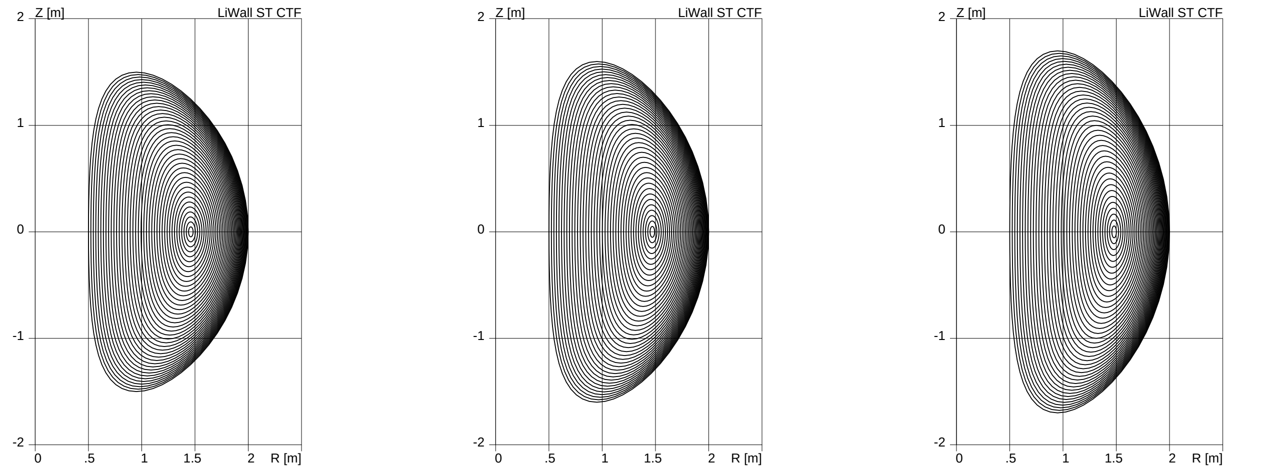
- Normalized beta, $\beta_N = 6.5$, with $\beta_N/l_i = 9.5$; β_N up to 35% over $\beta_{N\ \text{no-wall}}$
- Toroidal beta has reached 35% ($\beta_t = 2\mu_0 \langle p \rangle / B_0^2$)

NSTX

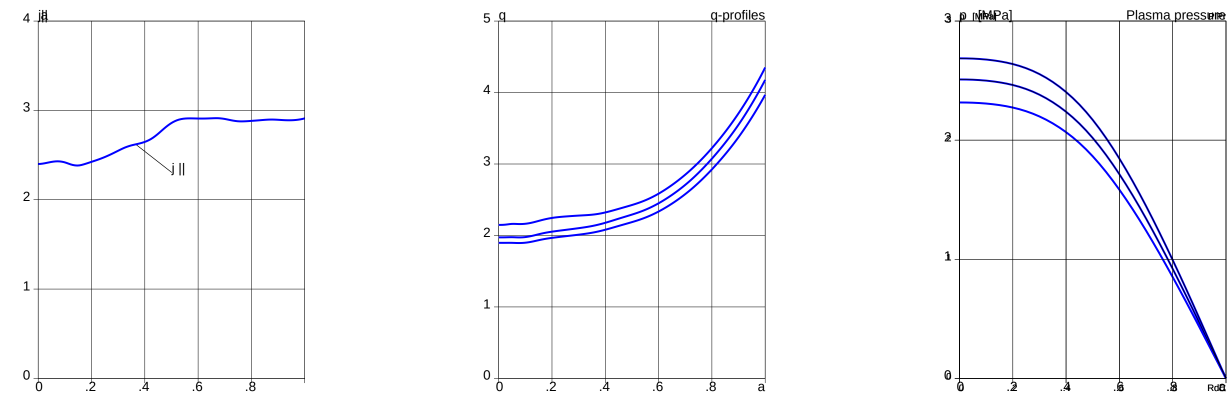
By eliminating Te-peaking and IRE, LiWalls can make high-β robust

High-β Spherical Tokamaks are naturally suitable for ignition and CTF

LiWall Ignited ST ($\boldsymbol{I_{pl}}$=11 MA, $\boldsymbol{B}$=3 T at R=1.25 m)

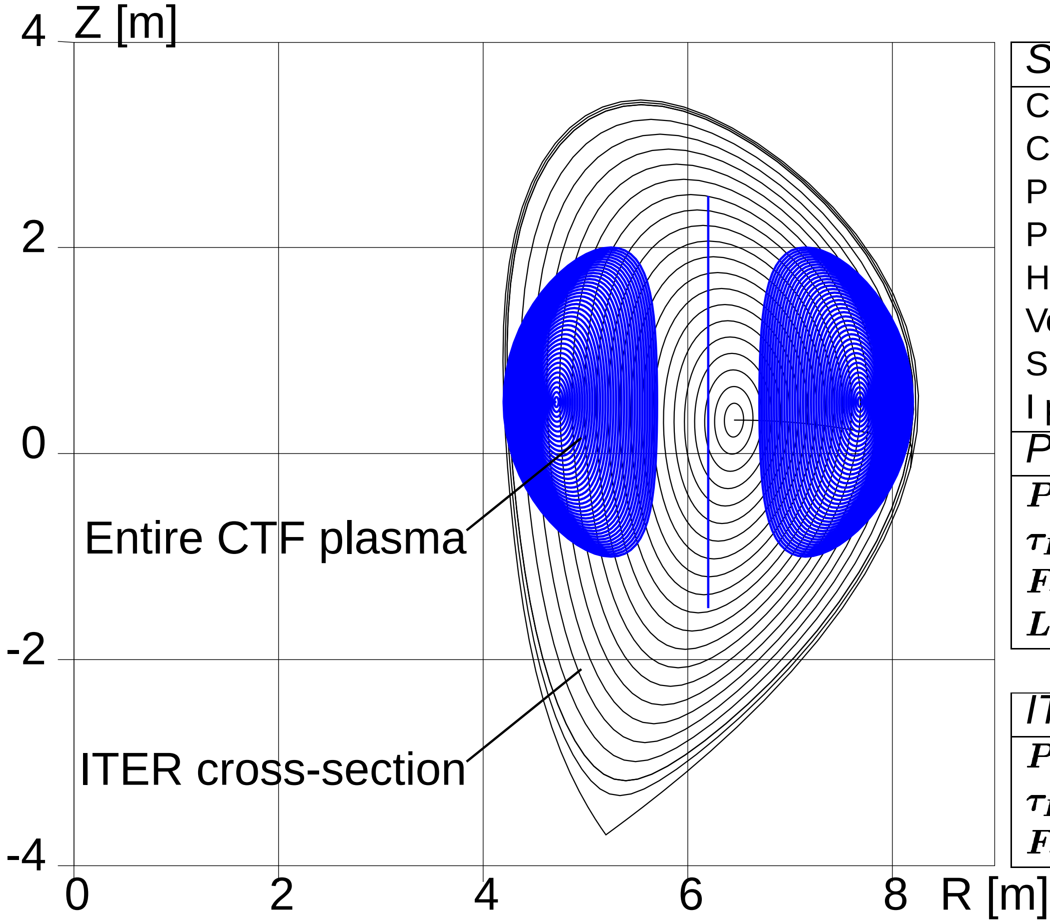


$\beta = 0.41,\ P_{DT} = 388$ MW $\beta = 0.45,\ P_{DT} = 490$ MW $\beta = 0.48,\ P_{DT} = 606$ MW



$j_{||}(a)$ $q(a)$ $p(a)$

Tritium breeding, in fact, requires ignition for compact CTFs

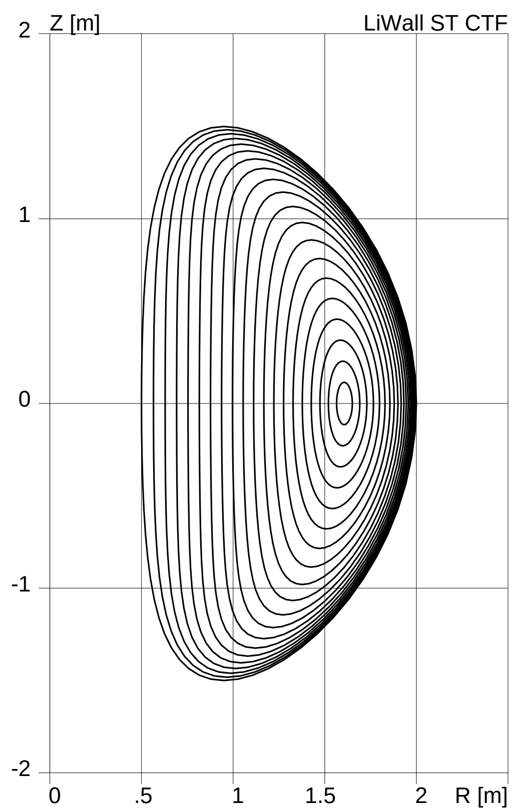


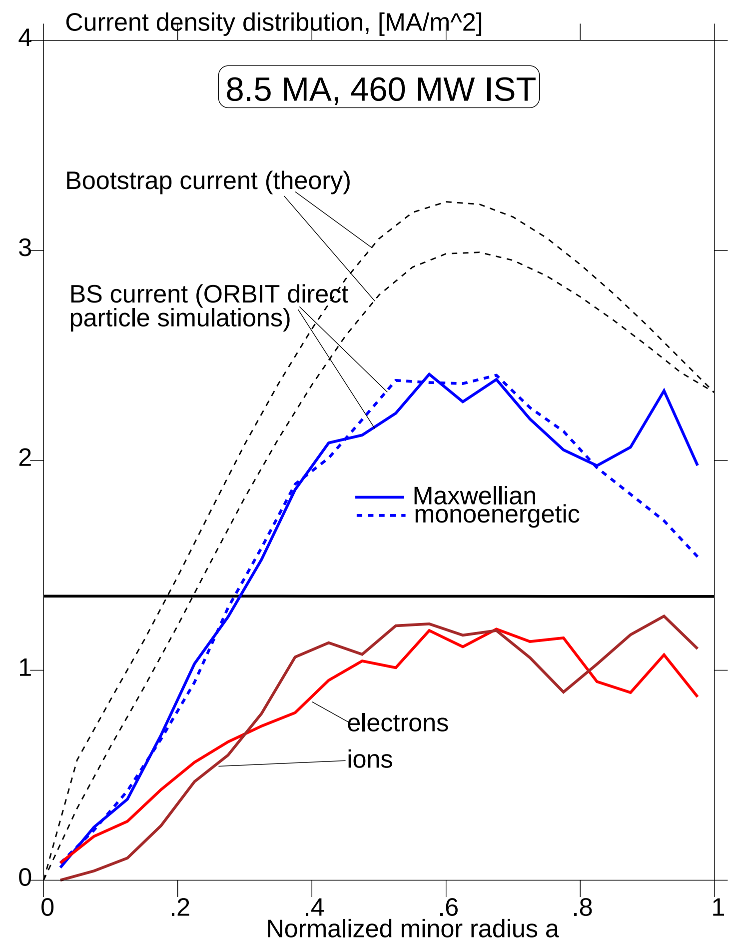
ST CTF Parameters				
CenterPole R	m	0.5	0.5	0.5
CenterPole B	T	7.5	7.5	7.5
Plasma R_1	m	0.5	0.5	0.5
Plasma R_2	m	2.0	2.0	2.0
Height	m	3.0	3.2	3.4
Volume	m^3	26.1	27.8	29.6
Surface	m^2	53.4	55.9	58.5
I plasma	MA	11.1	11.9	12.7
Plasma performance				
P_{DT}	MW	388	490	606
τ_E	sec	0.75	0.69	0.64
$F_{neutron}$	MW/m^2	5.8	7.0	8.3
$Loss_{neutron}$	%	4.7	4.8	4.9

ITER		
P_{DT}	MW	410
τ_E	sec	3.7
$F_{neutron}$	MW/m^2	0.5

IST can provide 95 % utilization of neutrons for tritium breeding

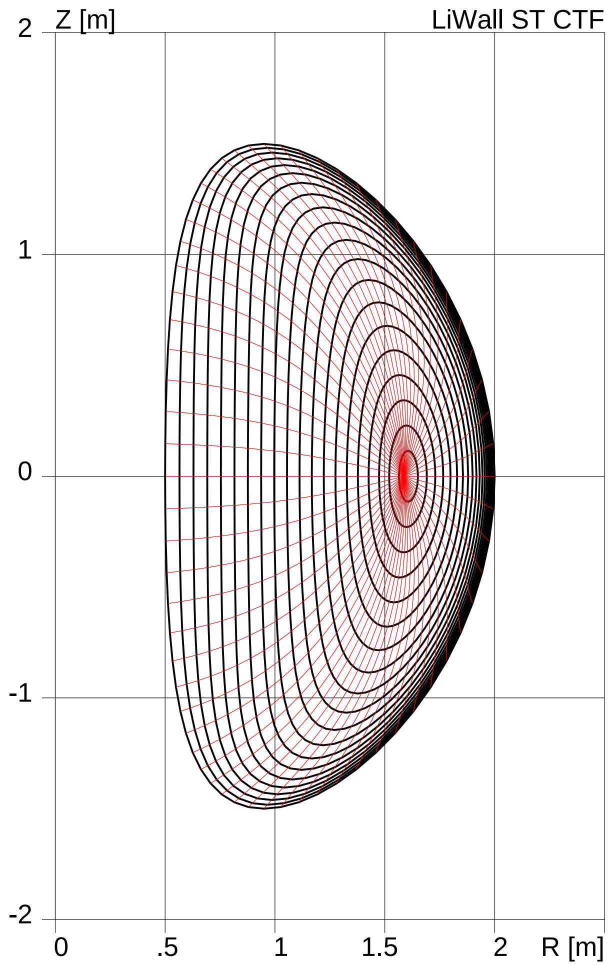
IST is reliably overdriven with bootstrap current

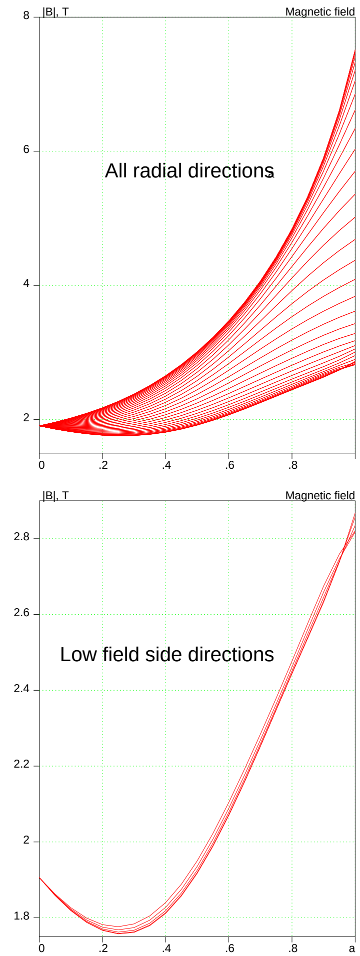




With DHD fueling even the central region is not a potential problem

IST has the best magnetic configuration for fueling





Field gradient in IST

$$\left.\frac{d|B|}{|B|dR}\right|_{\theta=0} \simeq 2.8\,\frac{T}{m}$$

is more than an order of magnitude higher than in "high-fi eld" side conventional tokamak fueling, ($\theta = \pi$).

Because of $\theta = 0$:

Various DHD technologies can be used

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

Invention of Diamagnetic “Hot Dog” (DHD) mechanism, revealed now for the first time, resolves the issue.

Contrary to conventional wisdom, the low recycling, high edge temperature plasma is the only one which has, at present time, precise mechanism for fueling and for reliable power reactor control.

The principle and detailes were explained on the blackboard

DHD has extremely simple equations of motion

The length of DHD is determined by

$$L = 2c_s t. \tag{4.1}$$

The cross-section of DHD is defined by

$$\pi \rho^2 L = const. \tag{4.2}$$

The velocity across the field is given by

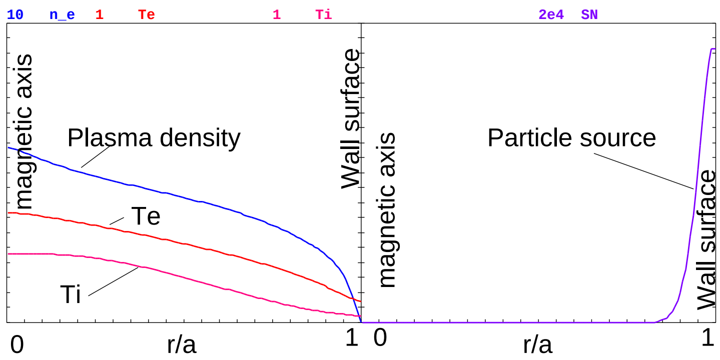
$$\frac{dv_\perp}{dt} = c_s^2 \frac{1}{B}\frac{dB}{dr}, \quad v_\perp = c_s \sqrt{\ln \frac{B_{launch}^2}{B^2}}, \tag{4.3}$$

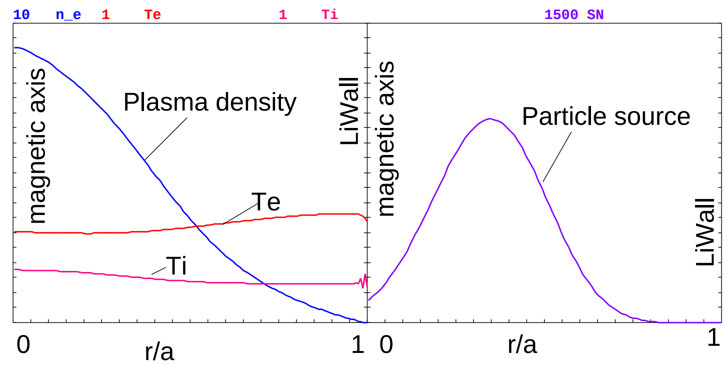
like in a potential field, corresponding to practically instantaneous delivery of the fuel into any desirable place in the plasma core.

4.2 Plasma temperature profi le with DHD fueling

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

Was explained using ASTRA simulations for LTX proposal





Invention of DHD fueling culminates the development of LiWalls

LiWall IST can potentially develop all 3 major objectives of magnetic fusion, i.e.

1. Operational Power Reactor Regime and its DHD control
2. First Wall (FW) with reactor relevant wall loading
3. Tritium cycle

Being a mini-reactor, IST will leave to DEMO an extension to

- DHD controlled OPRR in a full size plasma configuration (conventional aspect ratio)
- FW with the full reactor functionality and a shielded neutron zone
- Full scale Tritium Cycle with the reactor scale power and rate.

This theory of DHD controled LiWall IST essentially concludes the plasma physics concept of entire DT magnetic fusion and requires a phase of its focused experimental and technology development.

The DHD “present understanding of fusion” has no common points with RG35DP

Powered by both physics and technology (rather than by “scalings”) DHD suggests totally different time scales for the US fusion power development.

If expressed in RG35DP dimensionless units

$$\begin{aligned} &\tau_{RGDP} < C_{Mazzucatto} && \text{for demonstration ignition at IST} \simeq \mathbf{10} \text{ years,} \\ &\tau_{RGDP} < (C_{Mazzucatto})^{2/3} && \text{for CTF} \simeq \mathbf{15-20} \text{ years,} \\ &\tau_{RGDP} < (C_{Mazzucatto})^{1/3} && \text{for DEMO} \simeq \mathbf{20-25} \text{ years.} \end{aligned} \quad (5.1)$$

4 years (since formulation of LiWall concept) of permanent blocking of LiWall experimental development by champions of RG35DP suggests that DHD controlled Fusion and STELLArating RG35DP “Fusion retirement” plan are orthogonal to each other.

In fact, DHD controlled Fusion and RG35DP are on colliding cources.