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Magnetic DEMO, CTF fusion reactors and their strategy

Leonid E. Zakharov,

Princeton University, Princeton Plasma Physics Laboratory

NSTX Physics Meeting

January 06, 2003, PPPL, Princeton NJ

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

Abstract

The basic aspects of a strategy leading to a DEMO magnetic fusion reactor are formulated. The strategy makes a clear distinction between ignition (high-τ_E) and operation (high-β) points of the reactor and is focused on development of the Operational Power Reactor Regime (OPRR) and its technology. Without diminishing the importance of the ITER program, this strategy considers the FESAC-2002 focus on low β "burning plasma" experiments as a strategic mistake missing the DEMO objectives.

The proposed strategy relies on compact, low-recycling (LiWall) Spherical Tokamak (ST) configurations where ignition can be reached with a modest external heating power at the OPRR relevant β. On the technology side, the strategy relies on development of the low activation first wall with the Li based plasma facing components and the FLiBe blanket and development of the full tritium cycle at pre-DEMO stages.

Three phases are envisioned with a strong coupling between plasma physics R&D of the OPRR and technology of the first wall and the self-sufficient tritium cycle. The objective of the first, DD phase is to develop and demonstrate the DD OPRR relevant, beam heated plasma with a full bootstrap current drive. Next, Component Test Facility (CTF) phase is based on a compact ($<$30 m^3) non-inductive, ignited ST ($\simeq$0.5 GW) with the neutron wall loading $>$5 MW/m^2 and tritium breeding first wall.

Third, DEMO phase merges the development of the ignition, OPRR, first wall and tritium cycle of CTF with the ITER experience of operating a reactor scale fusion facility and its infrastructure. The objective of DEMO is demonstration of consistency of the OPRR, first wall and tritium cycle with the safety and economics aspects of the power reactor.

Contents

Present times for magnetic fusion are distinguished by two things:

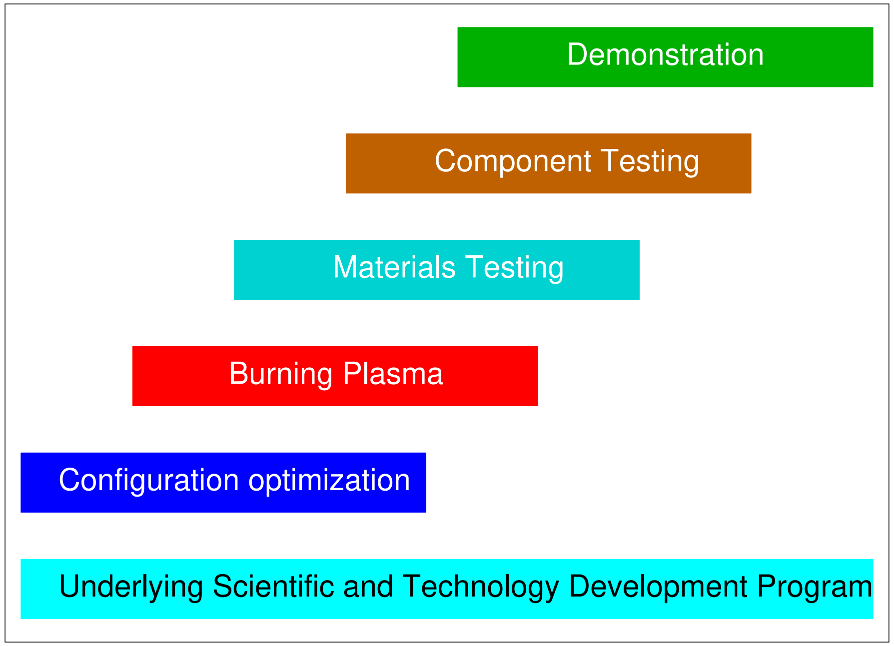
1. ITER project has been concluded
2. DOE requested a plan to develop a DEMO for demonstration the net electricity production from fusion in $\simeq$ 34.7 years

"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



Do we really know that fusion can produce the electricity in 35 years ?

The positive answer of FESAC Development Plan (DP) is not supported by a clear vision, strategy and by a focused R&D fusion reactor program.

Is it really possible to expect a positive answer ? Or to get any answer ?

Let us try, starting from the elementary things.

There are 3 specific objectives of magnetic fusion as a power source:

1. Stable, reactor relevant plasma regime with

$$\boxed{n T \tau_E = 50 \cdot 10^{20},}$$

2. Low activation, tritium breeding, energy extracting first wall
3. Self-sustained tritium cycle

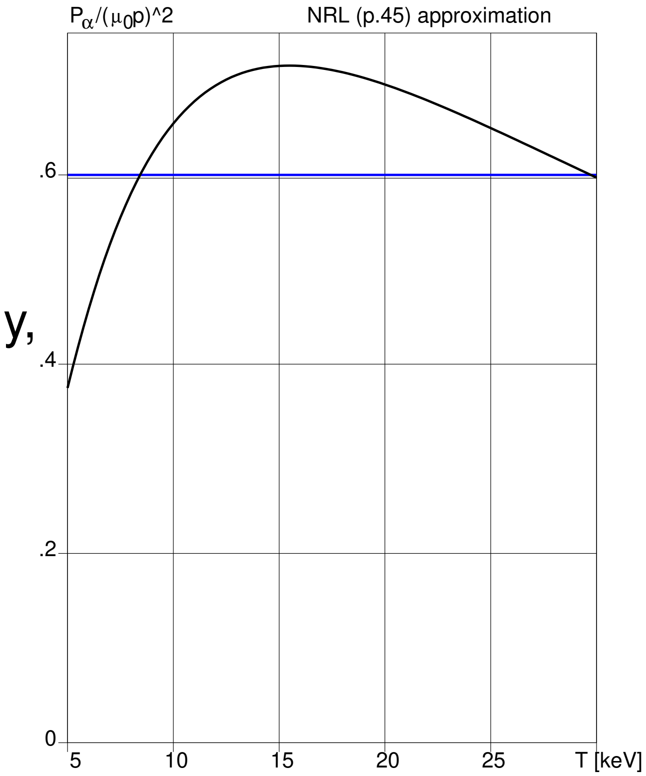
DEMO objectives are essentially in demonstration that all three can be developed and work together in consistency with safety and economics of the power reactor.

In the reactor α-particles fusion power covers all losses from the plasma

Ignition/operational regime:

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

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



Useful approximation:

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

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

Ignition criterion is a fusion specific requirement for the reactor operation

$$n \cdot T \cdot \tau_E > 5 \cdot 10^{21} \quad \left[\frac{1}{\mathrm{m}^3} \cdot \mathrm{keV} \cdot \mathrm{sec}\right] \tag{2.1}$$

Substitution

$$n \cdot T = B^2 \cdot \beta \cdot 1.25 \cdot 10^{21} \tag{2.2}$$

converts it into a suitable form

$$\boxed{B^2 \cdot \beta \cdot \tau_E > 4 \quad \left[\mathrm{T}^2 \cdot \mathrm{sec}\right]}$$

for the reactor design analysis.

Other forms are equivalent:

$$\begin{aligned} &\mu_0 p \cdot \tau_E > 2 \quad [\mathrm{MPa} \cdot \mathrm{sec}], \quad \mu_0 = 0.4\pi, \\ &p \cdot \tau_E > 16 \quad [\mathrm{atm} \cdot \mathrm{sec}] \end{aligned} \tag{2.3}$$

(β_N is not relevant for the basic level of the reactor physics).

Power of the fusion reactor is determined solely by τ_E and V.

$$P_{DT} = 5P_\alpha = 3(\mu_0 p)^2 V. \tag{2.4}$$

Combining with

$$\mu_0 p \tau_E = 2 \tag{2.5}$$

the power is simply

$$\boxed{P_{DT}\ [\mathrm{GW}] = 12\frac{V}{\tau_E^2}} \quad \text{or} \quad \boxed{P_{DT}\ [\mathrm{GW}] = \frac{3}{4}\beta^2 B^4 V}$$

Fusion power is inverse proportional to τ_E.

The total stored thermal plasma energy

$$P_{DT} = 5P_\alpha = \frac{5E_{pl}}{\tau_E}, \quad E_{pl} = \frac{P_{DT}\tau_E}{5} \tag{2.6}$$

is proportional to τ_E.

High-τ_E is highly unfavorable for operation regime !!!

from both reactor power and stored energy points of view

$$\boxed{P_{DT}\ [\mathrm{GW}] = 12\frac{V}{\tau_E^2},} \qquad \boxed{E_{pl} = \frac{P_{DT}\tau_E}{5}.}$$

Unfortunately, at present, the leading tendency in magnetic fusion is to follow the road of enhancing τ_E (at the negligible level of β).

FESAC DP essentially suggests the same road of low-β&high-τ for the next 34.7 years.

Ignition phase imposes different requirements on τ_E

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

$$\frac{dE_{pl}}{dt} = P_{ext} + P_\alpha - \frac{E_{pl}}{\tau_{E@ignition}} \simeq P_{ext} + P_{\alpha@ign}(x^2 - x),$$
$$x \equiv \frac{E_{pl}}{E_{pl@ign}} \qquad (2.7)$$

gives an estimate for the external heating power P_{ext}

$$P_{ext} > \frac{1}{4} P_{\alpha@ign} \simeq \frac{1}{20} P_{DT@ign} \simeq 0.6 \frac{V}{\tau^2_{E@ign}}. \qquad (2.8)$$

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

It is impossible to count on igniting reactor at its operation point

For typical

$$\boxed{P_{DT} \simeq 4 \text{ [GW]},}$$

the necessary external power installed would be

$$\boxed{P_{ext} > 0.2 \text{ [GW]},}$$

while being used for only 10-15 seconds.

Together with beta-tau aspects the cost affects the reactor strategy.

The most obvious limitation on the cost C of the reactor is given by the $$-value of the electricity produced

$$\begin{aligned} C &<(?)\frac{P_{DT}}{4}\cdot(30 \text{ years})\cdot 365.25\cdot 24\cdot(0.04 \text{ \$/kWh})\cdot 10^6 \\ &= 10.5\frac{P_{DT}}{4}\,[10^9\$]. \end{aligned} \quad (2.9)$$

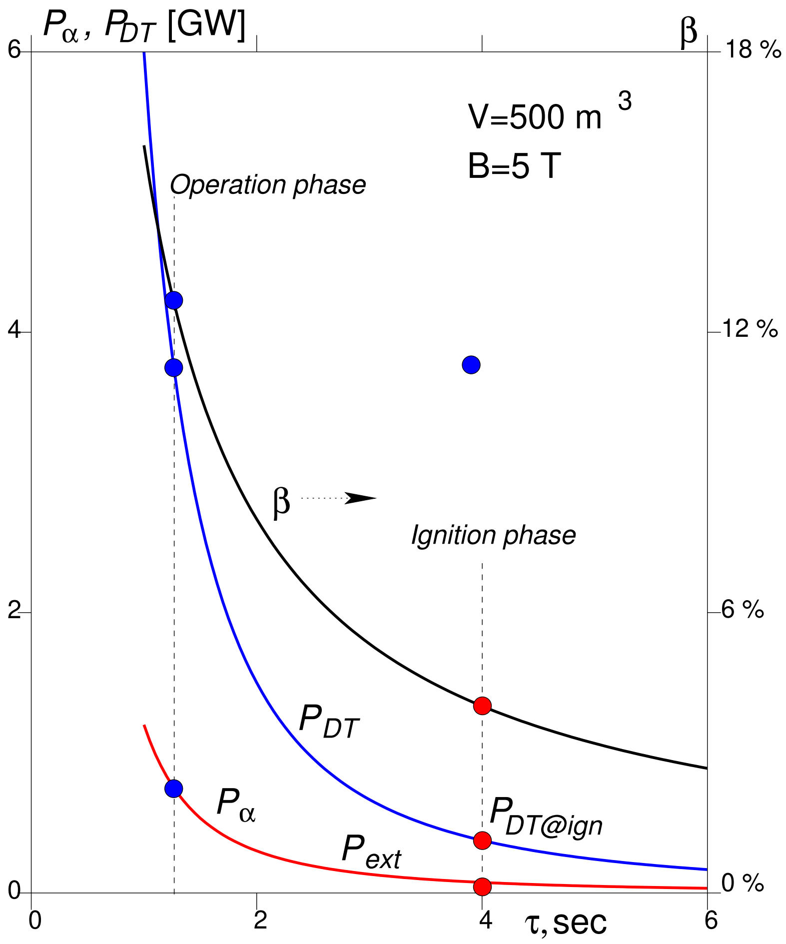
At present, the dominant approach relies on enhanced τ_E (3.7 sec for ITER), and low β (0.025 for ITER). It is inconsistent with the reactor strategy.

ITER (event if it will be ignited and magically not destroyed by the ignited plasma)

$$C_{ITER} < 10.5\cdot 12\frac{0.837}{3.7^2\cdot 4} \simeq 2.3\,[10^9\$] \quad (2.10)$$

shows this inconsistency in the obvious way.

Ignition and operation phase have totally different plasma regimes.



Beta-tau of the reactor strategy:

- Ignition/burning 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

$$C\ [10^9\$] < 10.5 \frac{P_{DT}}{4}\ [\mathrm{GW}],$$

- Ignition external power

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

Beta-tau aspects essentially give an approximate size of the FPR.

Thus, a reference Fusion Power Reactor (FPR) with

$$\boxed{B = 5\ \text{T}, \quad V = 400\ \text{m}^3,}$$

operational parameters

$$\boxed{P_{DT} = 4\ \text{GW}, \quad \tau_E = 1.1\ \text{sec}, \quad \beta = 15\ \%,}$$

ignition parameters

$$\boxed{\tau_{E@ign} = 3\ \text{sec}, \quad P_{ext} \simeq 30\ \text{MW}.}$$

and the cost

$$\boxed{C = \$(2-3)\cdot 10^9.}$$

satisfies the basic requirements.

4 simple but fundametal relationships determine the plasma physics aspects of the strategy of the power reactor.

Notion of two distinct regimes

- one is a short term, ignition phase, which needs a high $\tau_{E@ign}$, and
- another is the Operational Power Reactor Regime (OPRR), which requires high β and reduced τ_E,

is the key point of the strategy of the power reactor and its design.

The notion of OPRR is missed in FESAC Development Plan, which does not envision the ignition in the nearest future.

Presence of OPRR as the key plasma physics objective is the major distinction between the power reactor strategy and the FESAC DP.

OPRR is a key plasma physics objective of the DEMO strategy.

After 30 years of efforts, the reactor relevant plasma β remains an unresolved problem of magnetic fusion.

ITER, FIRE, or other low-β "burning" plasma experiments are incapable to contribute to the solution of this crucial for DEMO problem.

With low power extraction capabilities, they also cannot contribute to the solution of other crucial problems for the magnetic usion.

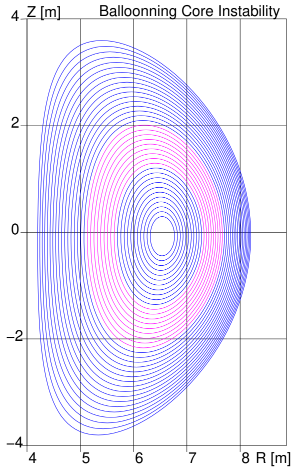
For high-β new, low recycling plasma physics regimes are required.

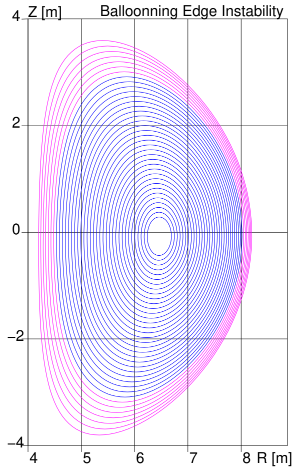
The logic of such a regime is:

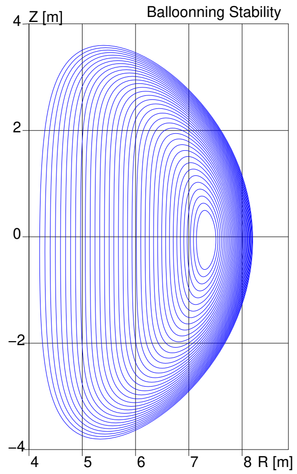
1. The only way of enhancing β is to develop a wall stabilized plasma.
2. This alone is not sufficient. Troyon criterion still limits β at unacceptably low level.
3. The only way to bit it is to develop a low recycling regime with either
   (a) Lithium plasma facing renewable wall, or
   (b) pumping divertor (a la Mike Kotschenreuter, DIII-D)
4. Absence of the tendency of the temperature peaking eliminates the necessity of the "profile" control, incompatible with the reactor.
5. Low recycling regime is the only one consistent with both high-$\tau_{E@ign}$ at ignition and high-β at OPRR.

Low recycling regime gives an access to the second stability β

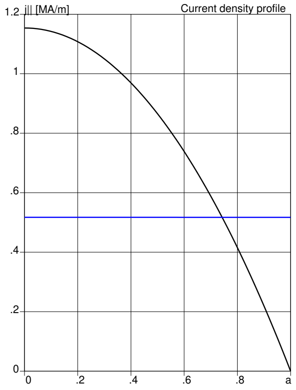
ITER-like plasma (I_{pl}=15 MA, B=5.3 T)

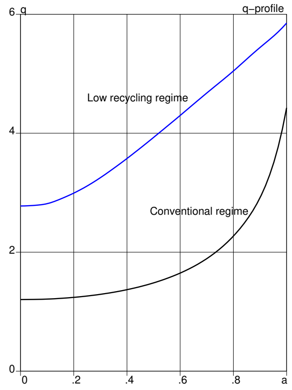


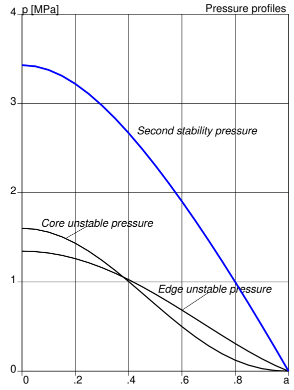




Core unstable, $\beta = 4.6$ % Edge unstable $\beta = 5.3$ % Second stability, $\beta = 16.0$ %

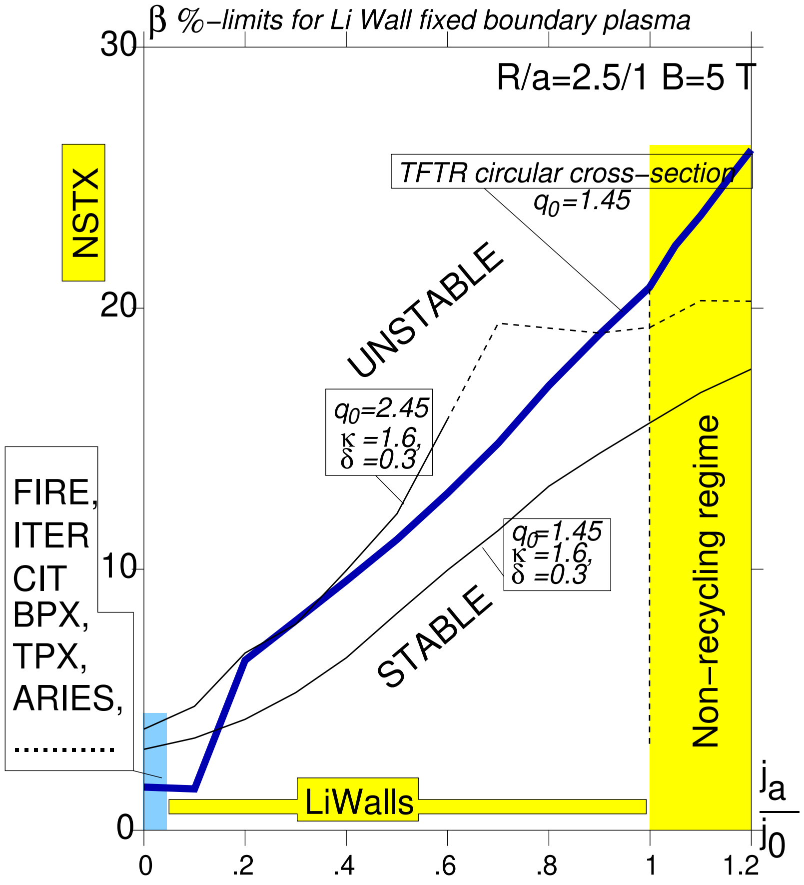






$j_{||}(a)$ $q(a)$ $p(a)$

LiWalls lead to the (core second stability)/(wall stabilized) plasma



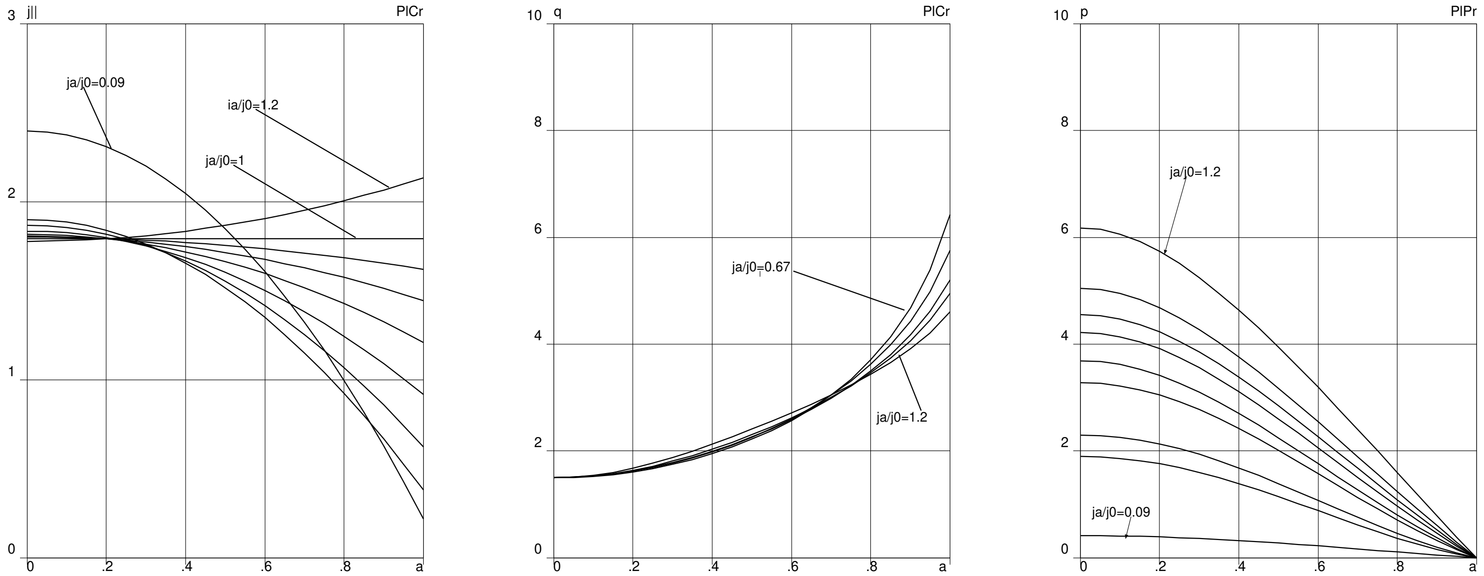
- no sawtooth oscillations;
- no Troyon limit;
- the second stability core;

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

$$\mathrm{j}_{\parallel} = j_a + (j_0 - j_a)\left(1 - \frac{r^2}{a^2}\right)$$

LiWalls give an additional parameter, $j_{\|}(a)/j_{\|}(0)$, for optimization

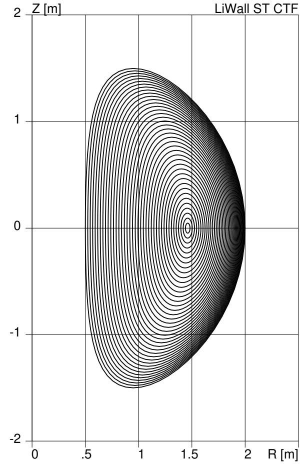


$j_{||}$-profiles $\quad$ q-profiles $\quad$ p-profiles

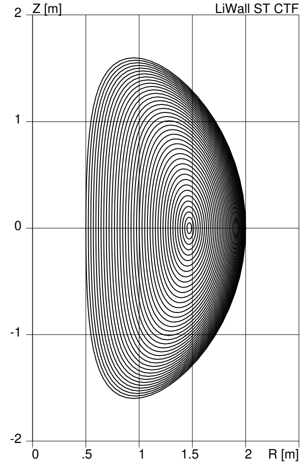
$$\frac{dp}{d\Psi} = const, \quad a = \sqrt{\frac{\Phi}{\Phi_{edge}}}, \quad \Phi \text{ is the toroidal flux.} \qquad (2.11)$$

In ST LiWalls can utilize high-β by eliminating the IRE

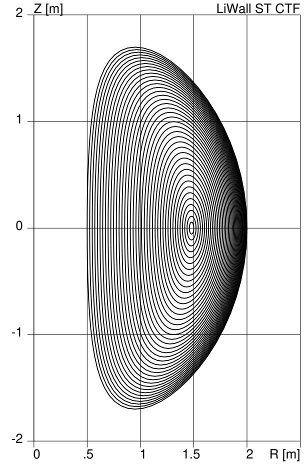
Ignited LiWall ST CTF plasma (I_{pl}=11 MA, B=3 T at R=1.25 m)



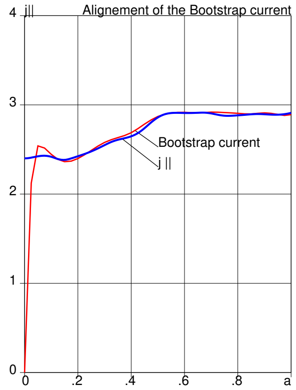
$\beta = 0.41,\ P_{DT} = 388$ MW



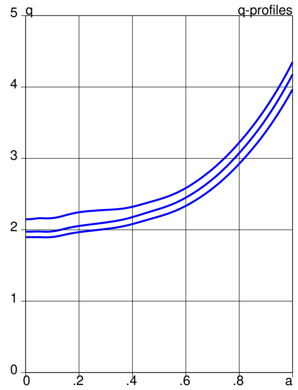
$\beta = 0.45,\ P_{DT} = 490$ MW



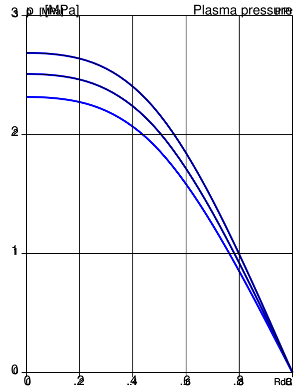
$\beta = 0.48,\ P_{DT} = 606$ MW



$j_{||}(a)$



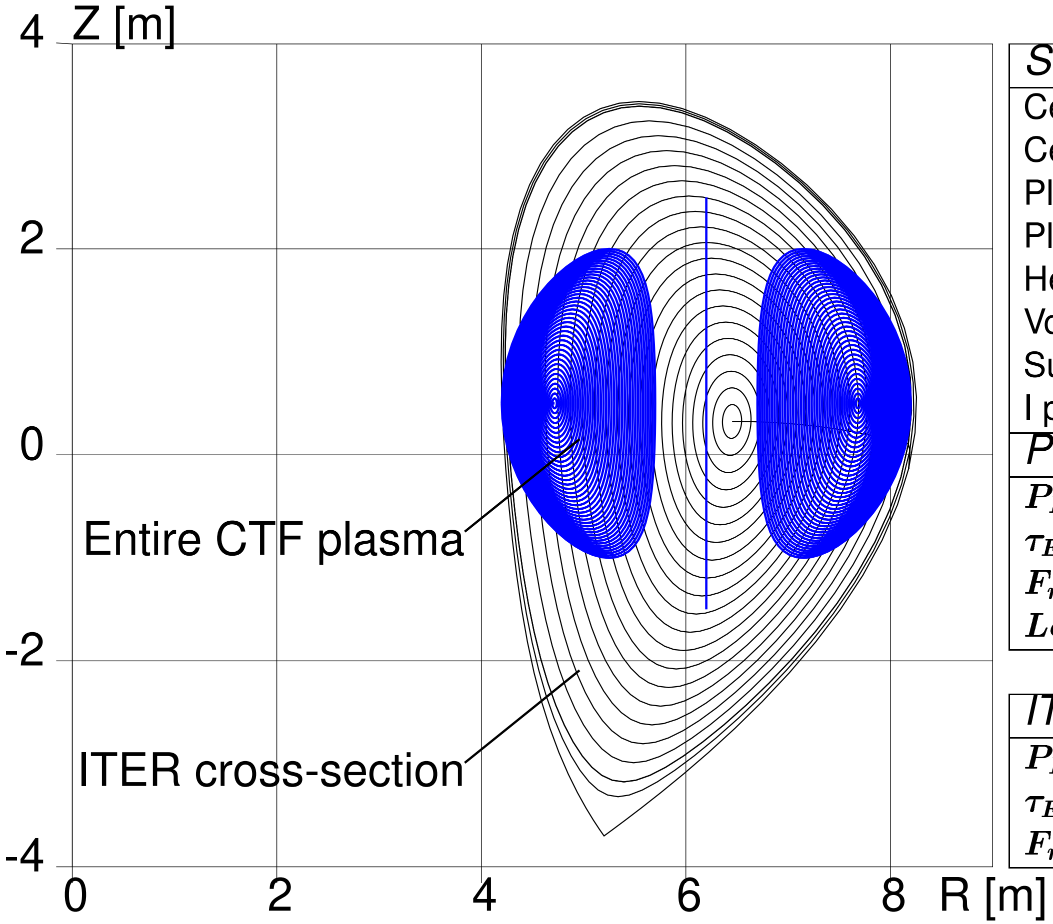
$q(a)$



$p(a)$

LiWalls + high-β ST make CTF consistent with the DEMO strategy

Ignition is a key requirement for CTF not envisioned by FESAC DP.



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

The "first wall" (first 10-15 cm) is the most challenging element of the fusion reactor.

Its functions:

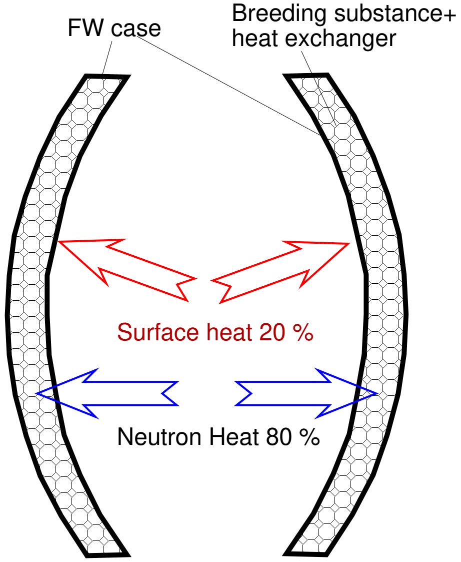
- surface absorption of 1/5 of the fusion power
- absorption of most of remaining 4/5 of the neutron fusion power
- be compatible with a high-temperature coolant/breeder
- tritium breeding
- withstanding deterioration of mechanical properties
- be easily accessible, do not not produce activation

Structural materials loose their mechanical properties presumably after

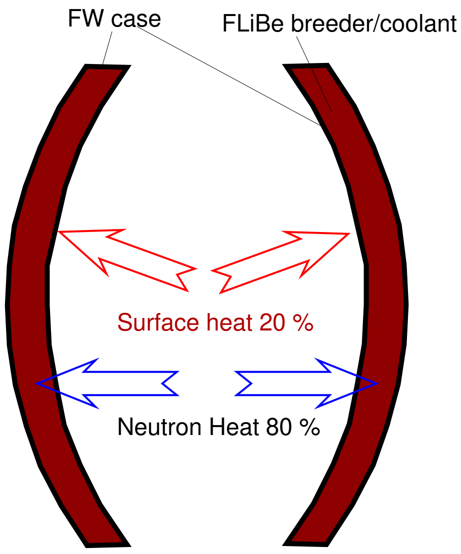
$$\boxed{\int Q_{neutron} dt \simeq 15 \, \frac{\mathrm{MW \cdot year}}{\mathrm{m}^2}.}$$

Cost of electricity corresponding to 1 life time $\boxed{C_{FW} = \frac{5.25}{4} \cdot 10^6 \frac{\$}{\mathrm{m}^2}.}$

Solid FW designs are incompatible with the Fusion Power Reactor.



Conventional Solid FW



FLiBe based Solid FW

Requires divertor.

Incompatible with L.Recycling edge.

Good for exp. devices.

bad for CTF and FPR.

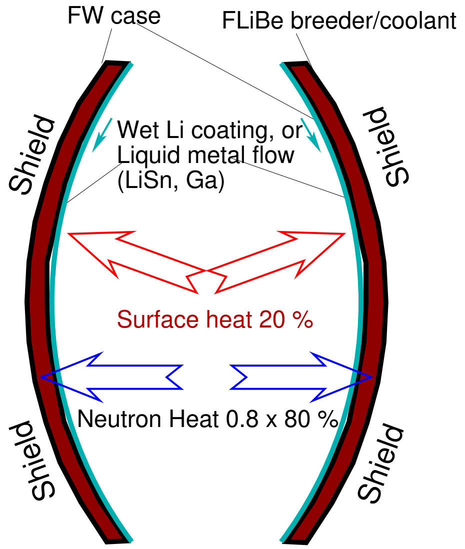
Requires divertor,.

Incompatible with L.Recycling edge.

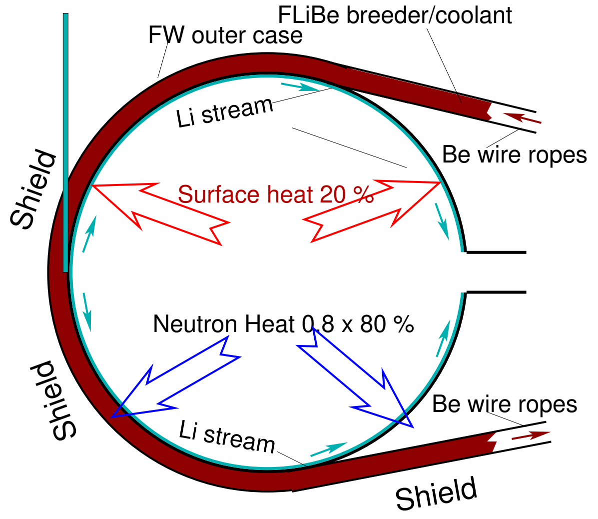
Good for exp. devices, CTF.

Bad for FPR.

New FW designs ideas, compatible with FPR, are necessary.



High T, FLiBe based
actively cooled FW



LiWall, dynamically balanced,
FLiBe based Yacht Sail FW

Compatible with divertor.

Compatible with L.&H.Recycl. edge.

excellent for CTF, good for DEMO.

problematic for FPR.

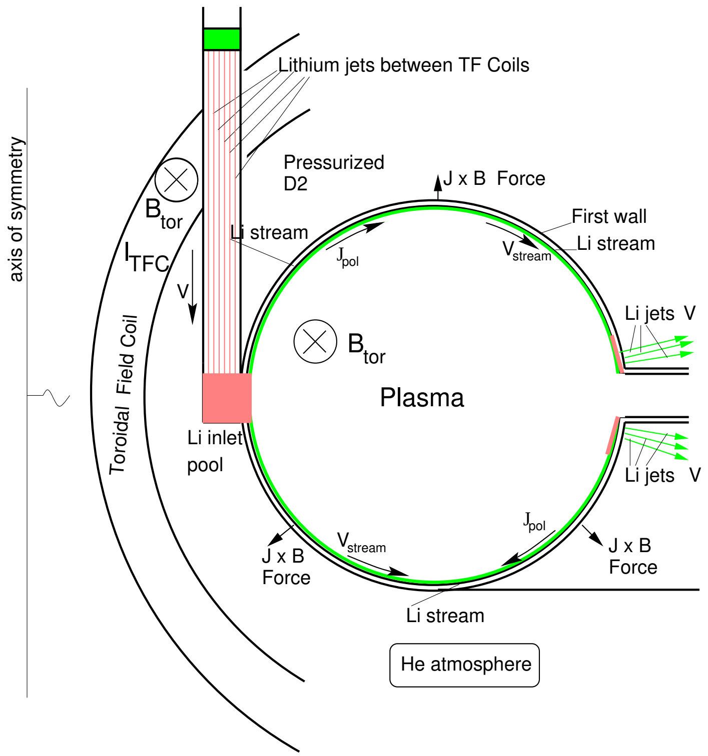
Requires Li MHD development.

Has an accessible neutron zone.

Excellent for FPR.

Magnetic propulsion opens the possibility for Intense Li Streams

$$p_{\mathrm{j}\times\mathrm{B}}\big|_{inlet} - p_{\mathrm{j}\times\mathrm{B}}\big|_{outlet} \gg \Re_2 \frac{B_{tor}^2}{2\mu_0}, \quad \Re_2 \equiv \mu_0\sigma\frac{h^2}{R}V \simeq 0.0015$$



- Driving electromagnetic pressure

$$p_{\mathrm{j}\times\mathrm{B}}\big|_{outlet} > 1\ atm$$

$$p_{\mathrm{j}\times\mathrm{B}}\big|_{inlet} - p_{\mathrm{j}\times\mathrm{B}}\big|_{outlet} \simeq 1.5 - 3\ [atm]$$

- Flow parameters

$$V \simeq 20\ m/sec, \quad h \simeq 0.01\ m$$

- Magnetic Reynolds numbers

$$\Re_1 \equiv \mu_0\sigma h V \simeq 0.8, \quad \Re_2 \simeq 0.0015$$

- Stream are stable if

$$\rho\frac{\langle V^2\rangle}{2} > \frac{a}{2R}p_{wall}n_r$$

Intense Lithium Streams have FPR relevant power extraction capability

$$
\begin{aligned}
&t_{exposure} \equiv t_{flight}, \quad (k_T \rho c_p)_{Li} = 1.00 \left[\frac{J^2}{sec \cdot K^2 cm^4} \right], \\
&\Delta T_{Li} = 200^o \frac{q_{wall}}{3.5\ MW/m^2} \sqrt{4 t_{flight}}, \\
&d_{skin} = 2.4 \sqrt{4 t_{flight}}\ \text{mm}.
\end{aligned} \tag{3.1}
$$

With $t_{flight} = 0.25$ sec, even with no vortices in the streams

$$\boxed{q_{wall} \simeq 3.5\ \text{MW/m}^2, \quad (+14\ \text{MW/m}^2\ \text{in neutrons}),}$$

while keeping wall heating low, $\Delta T < 200^o$ C.

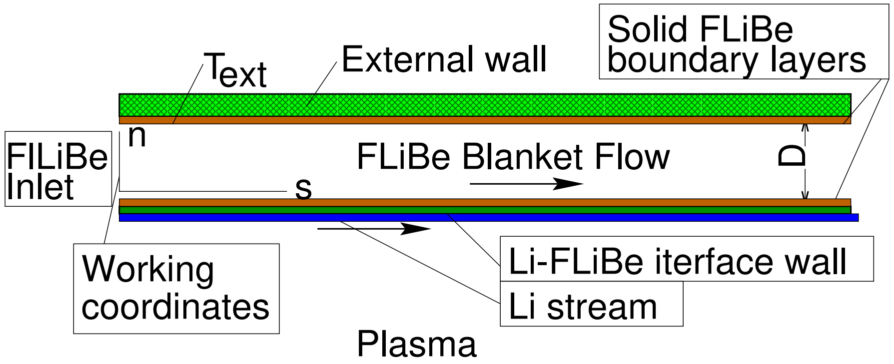
E.g., for a middle size tokamak-reactor

$$\boxed{R = 6\ \text{m}, \quad a = 1.6\ \text{m}, \quad P_{wall} = 4\pi^2 R a q_{wall} \simeq 1.3\ GW}$$

(more than order of magnitude higher than any divertor).

FLiBe has unique thermal transport properties for the fusion reactor

Stratified geometry of the FLiBe Blanket/Lithium streams.

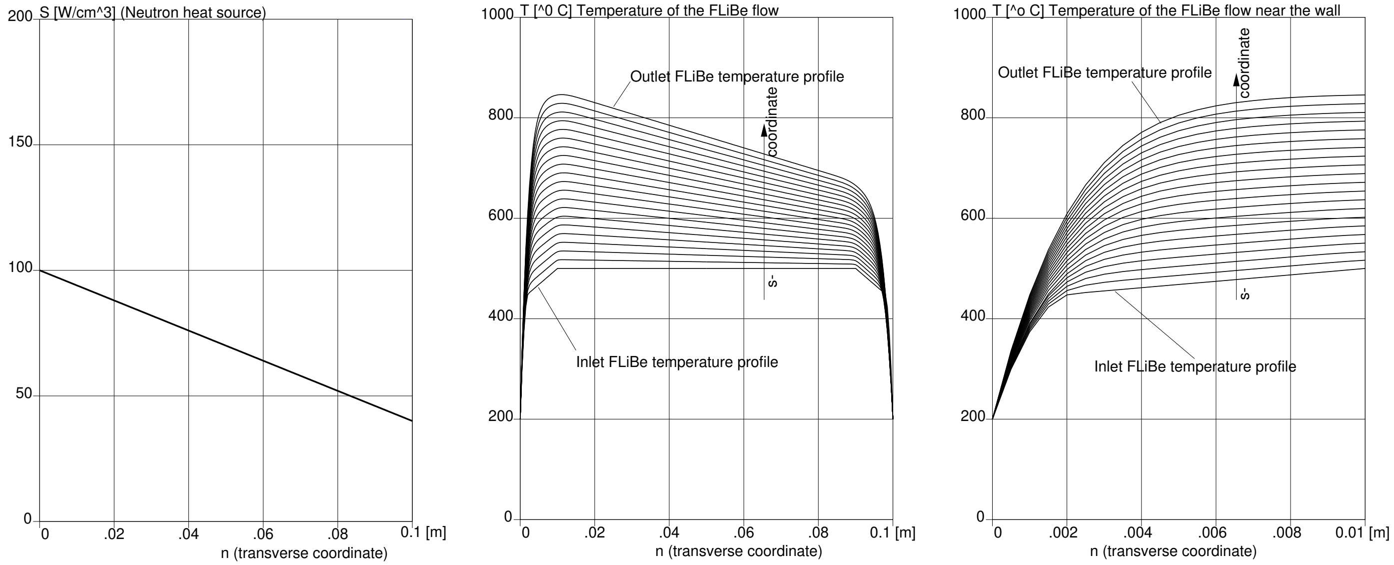


D	m	0.1
L	m	10
V	$\frac{m}{sec}$	0.5
$S(n)$	$\frac{W}{cm^3}$	100-40
$T_{side\ wall}$	C^o	200
FLiBe parameters		
ρ	$\frac{kg}{m^3}$	2240
c_p	$\frac{J}{kg \cdot C^o}$	2380
κ	$\frac{W}{m \cdot C^o}$	1
T_{melt}	C^o	450

Heat source S corresponds approximately to 10 MW/m^2 in neutrons.

FLiBe removes the neutron heat by convection

Profiles of the (neutron) heat source and T in the FLiBe channel



Inside FLiBe the temperature of the flow is determined solely by the heat source power, not by thermo-conduction.

FLiBe blanket requires active cooling of the plasma facing surface

With low wall temperature (Zinkle, Nelson, 2000)

$$\boldsymbol{T_{wall} \simeq 250^o} \text{ C} \boldsymbol{< T_{melt} = 450^o} \text{ C.}$$

two solid FLiBe boundary layers of the order of 1-2 mm are formed on inner walls of the channel, protecting wall from the chemical reactions.

Side heat losses are small even for high, $\simeq \mathbf{800^o}$ C, FLiBe temperature

In the example the averaged energy losses are $\boldsymbol{0.26\ MW/m^2}$ through the plasma side wall and $\boldsymbol{0.16\ MW/m^2}$ through the outer wall, which constitute approximately 4 % of the incoming neutron energy.

FLiBe is a perfect coolant/breeder for the fusion power reactor:

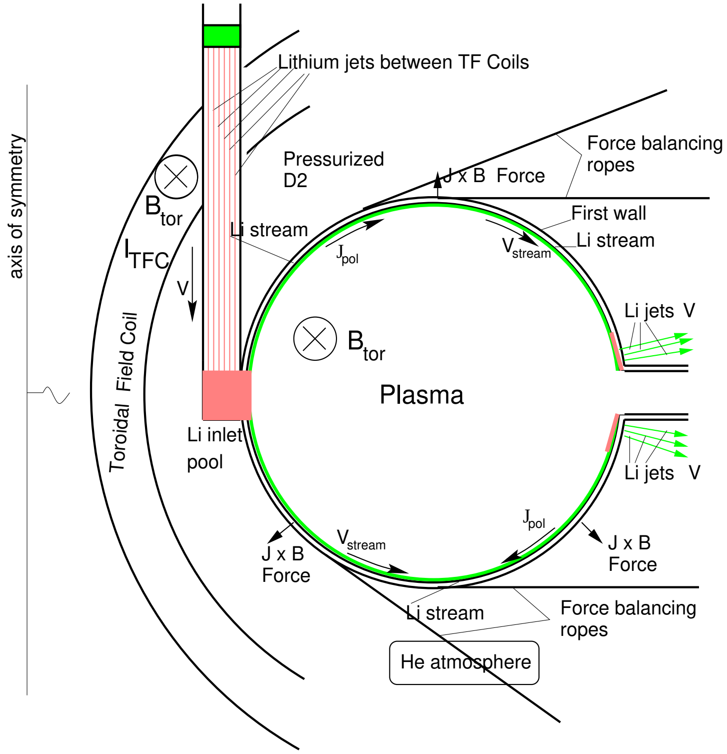
- liquid
- light weighted
- easily flowing
- non-damageable
- easy for designing
- capable of tritium breeding
- capable of extracting a high temperature heat
- not activatable
- transparent for low frequency electromagnetic fields and compatible with plasma feedback stability control

Active cooling of the plasma side of the first wall is required.

FLiBe based first wall blanket is a focus of the fusion reactor strategy.

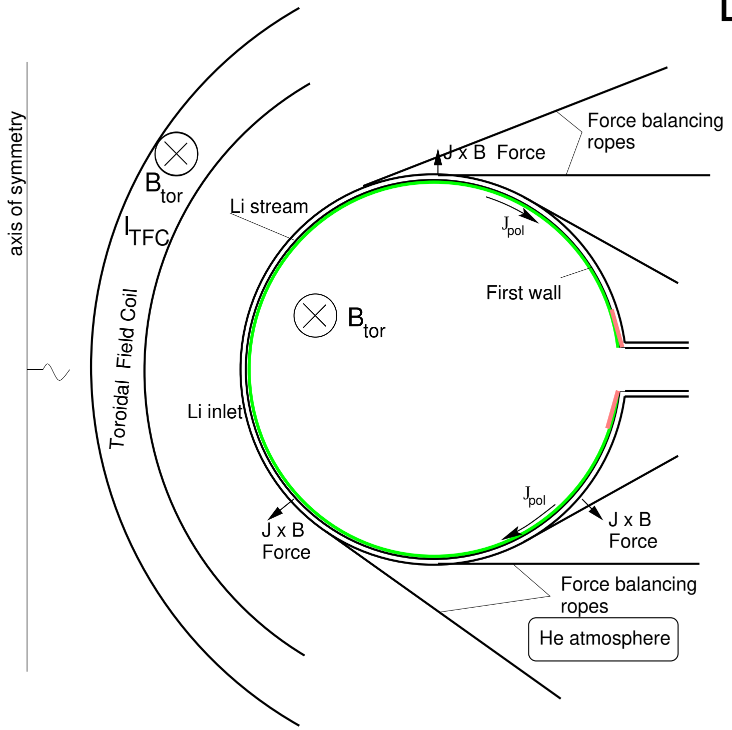
Intense Li Streams affect the very fundamentals of reactor design.

Electrodynamic pressure creates a stable situation for the first wall.



- Guide wall works against expansion $\Longrightarrow$
- Guide wall can be made as a thin shell (like a car tire).
- Inner surface is sealed by the lithium streams (insensitive to cracks) $\Longrightarrow$
- Vacuum barrier can be moved to the plasma boundary (giving access to the neutron zone).

Wire ropes can control the shape of the patchy guide wall.



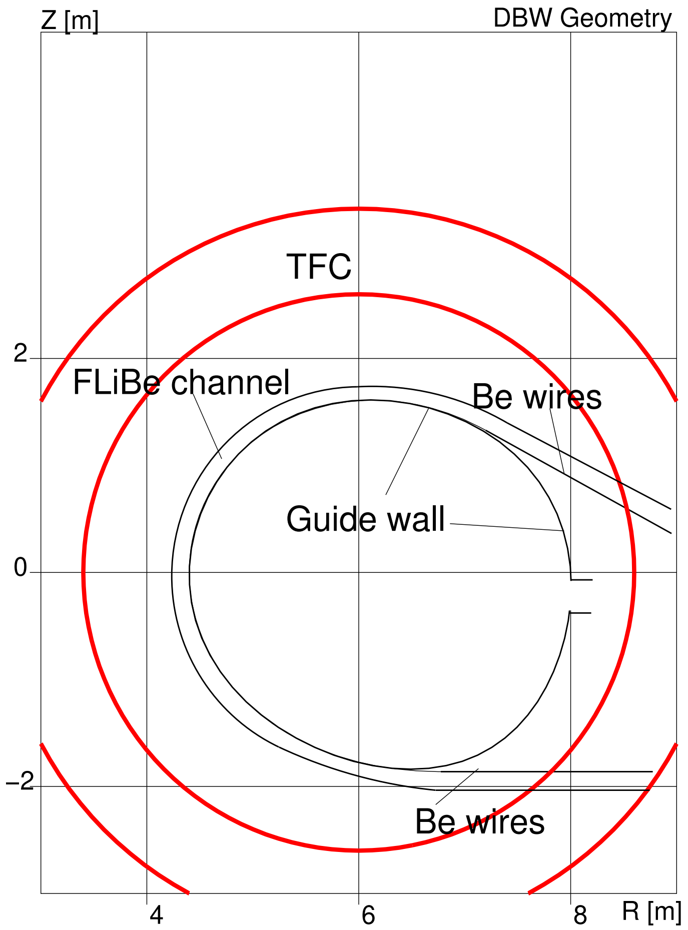
Danamic balancing (a la Yacht Sail):

- Radial component of the electromagnetic force can be balanced by a set of external wire ropes

$$\left(p_{\mathrm{j}\times\mathrm{B},outlet}\frac{r^2_{outlet}}{r^2} - p_{atm}\right)\frac{r}{r_{inlet}} = Td,$$

where T is the tension of ropes, $d(r)$ is the total thickness as a function of position of the touch point.

Topology of Be wires can be made consistent with the presence of the FLiBe Blanket



Equation for poloidal curvature of the guide wall

$$d\frac{T}{\rho} = p_{JxB} - p_{ext} - g\rho_{FLiBe}(z - z_0).$$

Both radial force on both lines of wires

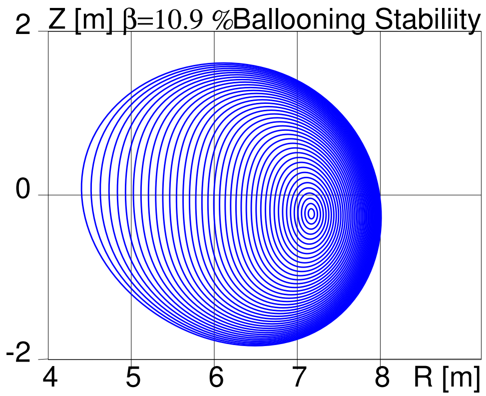
$$F = 1.5 \text{ [MN/m]}$$

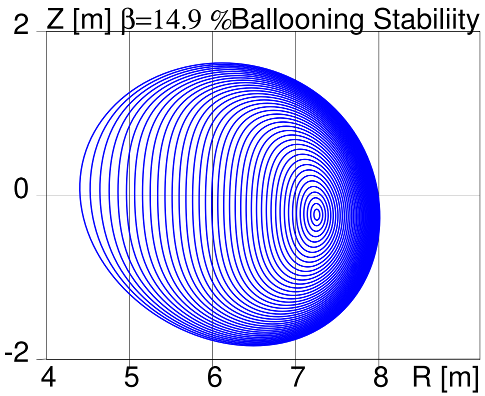
and tension in wires

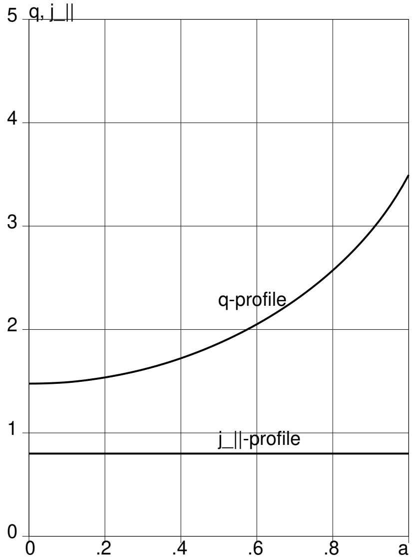
$$d \cdot T = 0.75 \text{ [MPa} \cdot \text{m]}$$

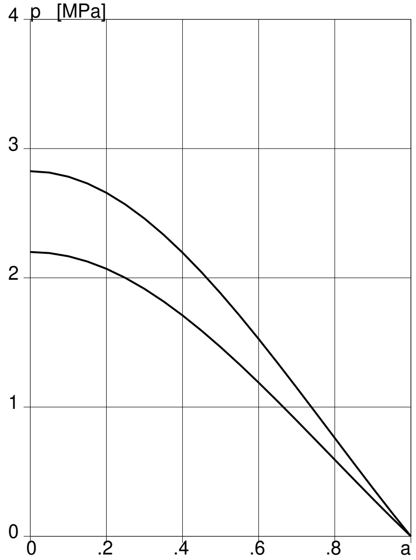
are reasonable.

Plasma shape remains consistent with the wall stabilized high-β.

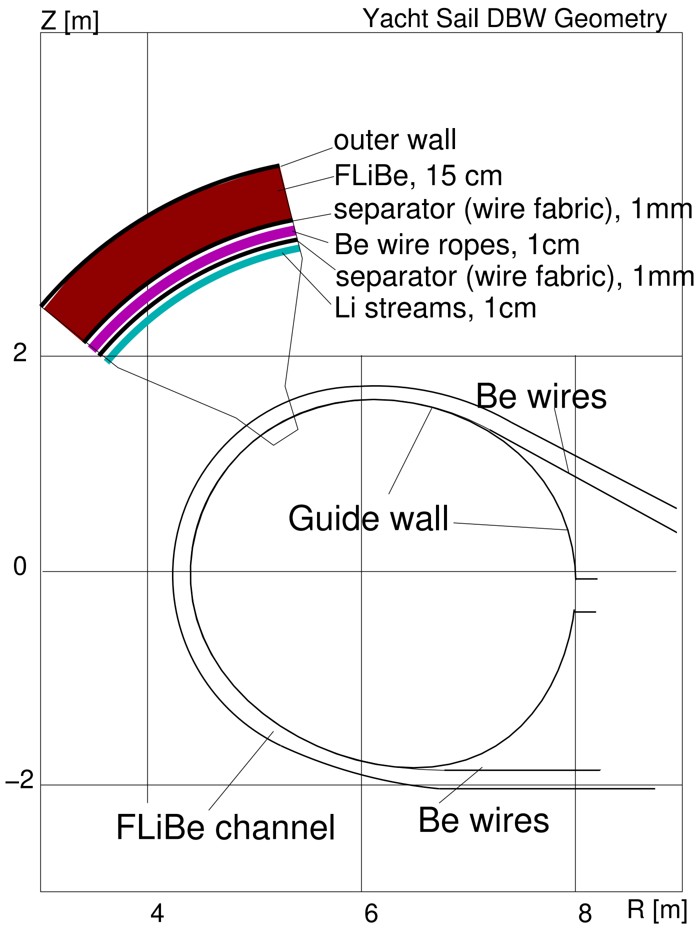








Yacht Sail FW design concept is the only one consistent with the FPR



- Intense Li Streams keep low temperature of the FW plasma side
- Guide (patchy wire fabric) wall serves as a separator between Li streams and wire ropes.
- Wire ropes provide the FW force balance.
- Second patchy wire fabric layer separates the wire ropes from FLiBe.
- FLiBe blanket is an element of FW.

Consistency with the FPR is outstanding:

- Excellent energy extraction from the plasma and the blanket.
- Wires can withstand any plasma disruptions.
- Be wire ropes multiply neutrons.
- Minimal ammount of high-Z materials.
- Vacuum barier at the plasma boundary.
- Extremely high reliability, no damage, replacement on the fly.

Yacht Sail FW provides stationary plasma boundary conditions.

At the same time it is insensitive to thermal deformations.

Yacht Sail FW eliminates the necessity in the stationary tokamak regime.

Fusion as an “inexhaustible” source of energy has, in fact, no fuel

Price of tritium

$$c_T \simeq (25-30)\cdot 10^3\,\frac{\$}{\mathrm{g}}.$$

with \$-value of electricity (0.04 \$/kWh)

$$W_T = (452+112)\,\frac{\mathrm{GJ}}{\mathrm{g}}, \quad C_T \simeq \frac{6.25}{4}\cdot 10^3\,\frac{\$}{\mathrm{g}} \ll c_T.$$

Testing the First Wall with the 15 MW·year/m^2 fluence requires tritium and money consumption

$$m_T = 1046\,\frac{\mathrm{g}}{\mathrm{m}^2}, \quad c_{T4FW} = 30\cdot 10^6\,\frac{\$}{\mathrm{m}^2}.$$

Only ignited CFT is consistent with the DEMO strategy

With a surface area $\boldsymbol{S_{FW} \simeq 50}$ m^2 the cost of tritium necessary would be

$$\boxed{\boldsymbol{C_{T4FW} = 1.5 \cdot 10^9 \ \$.}}$$

The behemoth^3 size CTFs (V > 500 m^3) are unaffordable due to price and low availability of tritium. ITER ($\boldsymbol{S = 678}$ m^2) is useless as a CTF.

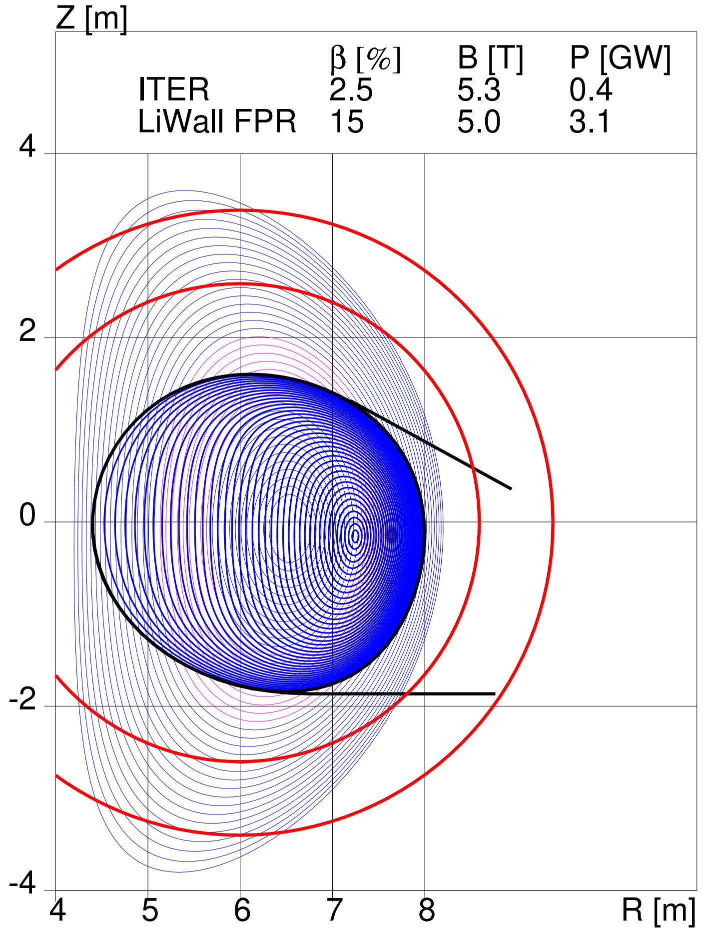
In order to fulfill the mission, the compact CTF

- should be ignited in order to utilize every DT neutron during the operation stage (with all NB ports filled with the breeding material)
- should be ST (rather than FIRE) for the same reason
- should be self-sustained in tritium with breeding at $>$100 % level

Besides the FW design and plasma size and geometry,

CTF should be, essentially, a mini- fusion reactor !

Fundamentally new approaches are required for the power reactors



Conceptual consistency with FPR physics

Objective	ITER-like	LiWall	M.Kotsch
High-β	-	+	+
Low recycl	-	+	+
High-$\tau_{E@ign}$	-	+	+
Pl.Heat Extr.	-	+	+
Neutron P.Extr.	-	+	+
FLiBe Blanket	-	+	+
Low Activation	-	+	-+
Mechanics	-	+	-+
Energy conversn	-	-+	+
Cost	-	+	-+

Mimicking plasma physics experiments does not work

LiWall ST is the only option to solve interrelated problems of CTF

Distinguished properties of ST

1. high-$\beta \simeq 40$ % in the first stability regime.
2. small plasma volume.
3. high fraction of the bootstrap current.

Low recycling LiWalls complement ST with

1. wall stabilized plasma
2. second stability high-$\beta \simeq 40$ %.
3. enhanced confinement
4. full or over- drive of the boorstrap current.

and make ST consistent with the mission of developing OPRR and the Component Test Facility as a mini fusion reactor.

ST lays down the path to the DEMO

Spherical Tokamak ignited CTF can develop all 3 objectives of magnetic fusion:

- Operational Power Reactor Regime in a minimal volume facility
- First Wall with reactor relevant wall loading
- Tritium cycle

Being a mini-reactor, CTF leaves to DEMO the extention to the

- 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.

With OPRR power density, fusion technology is as important as physics

R&D would include

- PFC components for a wall controled and stabilized plasma
- Low recycling power extraction and particle control
- FLiBe technology
- Liquid metal technology
- Materials and a concept of the FW and TC for CTF
- Dynamic balanced FW
- . . . , etc.

Development of OPRR is the starting point on the path to DEMO

Three phases are reasonable

- DD phase: development and simulation of OPRR on existing and a series of new DD ST.
- CTF phase: development of the DT OPRR, FW and TC on ignited, quasi-stationary ST based CTF.
- DEMO phase: full scale demonstration of the DT OPRR, first wall and tritium cycle on ignited, stationary, low activation non-ST based DEMO.

Plasma physics, fusion engineering and technology are involved on an equal basis in all three phases of the strategy.

Once fusion missed a brilliant opportunity given by government in 1987 to develop an experimental reactor.

It would be unforgivable to miss the second one and rely on old stuff, i.e.,

divertors, low-β/high-τ_E, Troyon limits, peaked temperature, sawtooth oscillations, gigantic facilities with inefficient use of plasma volume, profile “control”, “burning” (not ignited) plasma with losses of neutrons, solid FW walls (full of activation), “broad” fusion science with ignorance of technology and economics.

Well “established”, ideas, contradictory to the basic aspects of the FPR strategy, will fail for DEMO.

The "present state of understanding" of fusion requires a DEMO strategy relying on innovations in all basic aspects.

Development of both plasma physics and technology of

- wall stablized plasma with low-recycling edge
- high-β OPRR at the second stability zone
- flattened temperature with full use of the plasma volume for fusion
- lithium plasma facing surfaces and intense lithium streams,
- Yacht-Sail design of the first wall
- high-temperature FLiBe coolant/breeder

together with focus on

- the ingited Spherical Tokamak CTF and
- the matching technology program

for material and design testing have a good chance to meet the challenge of making DEMO as a power reactor within the time frame and the budget.

Coherent Plasma Physics and Technology R&D should be a basis of DP