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Tokamak reactors, their strategy, operational regime, fueling and control[1]

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Abstract

The talk outlines objectives and ten basic rules of magnetic fusion strategy.

The low recycling Ignited Spherical Tokamaks (IST) are specified as the magnetic fusion devices capable of developing the Operational Power Reactor Regime (OPRR), First Wall (FW) and the Tritium Cycle (TC). At present, only ISTs are consistent with the reactor relevant high-betas, stationary regime (maintained by the bootstrap current and by LiWall pumping), high fusion power density and neutron flux.

The Diamagnetic "Hot Dog" (DHD) mechanism for refueling and controlling the low-recycling, high edge temperature OPRR is outlined. DHD fueling is consistent with controlling fusion power deposition, density and pressure profiles as well as with helium ash exhaust from the plasma of power reactors.

The theory of DHD controlled LiWall IST essentially concludes the plasma physics concept of tokamak based DT magnetic fusion and emphasizes the growing role of fusion technology. After 4 years the LiWall-DHD development became a practical theory, requiring technology and experimental implementation.

Contents

Half year ago DoE expressed very specific interest in practical fusion.

A plan to develop a DEMO for demonstration the net electricity production from fusion in $\simeq$ 34.5 years

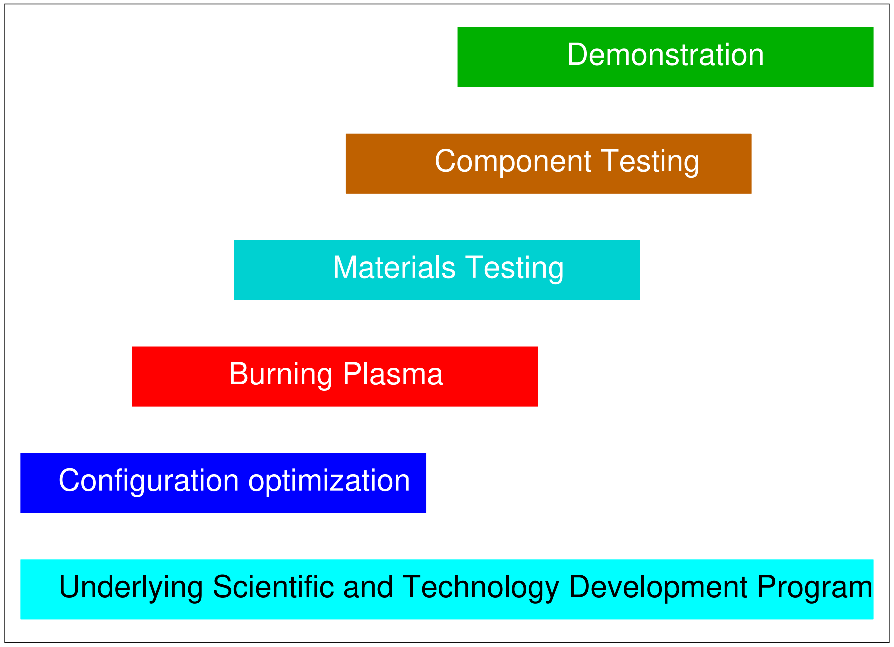
"I would like the Fusion Energy Sciences Advisory Committee (FESAC) to comment, from our present state of understanding of fusion, on the prospects and practicability of electricity into the U.S. grid from fusion in 35 years."

"In addition, I would like FESAC to develop a plan with the end goal of the start of operation of a demonstration power plant in approximately 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



Magnetic fusion should fulfill the following 3 R&D objectives:

- Demonstrate the ignition and then transition to the Operational Power Reactor Regime (OPRR)
- Resolve the "unresolvable" problem of the First Wall (FW)
- Develop the safe and efficient Tritium Cycle (TC)

all compatible with safety and economics of the power reactors.

Physics and technology basic aspects of OPRR (low recycling high-beta plasma, edge control, refueling, technology of the LiWalls and the power extraction, etc) should be developed at the DD phase of R&D.

Only after meeting all 3 objectives, the fusion physics and technology may go to the business.

Fusion strategy is not a mystery and is determined by 10 guiding rules.

3 beta-tau rules can be derived from approximation $P_\alpha \propto p^2$.

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

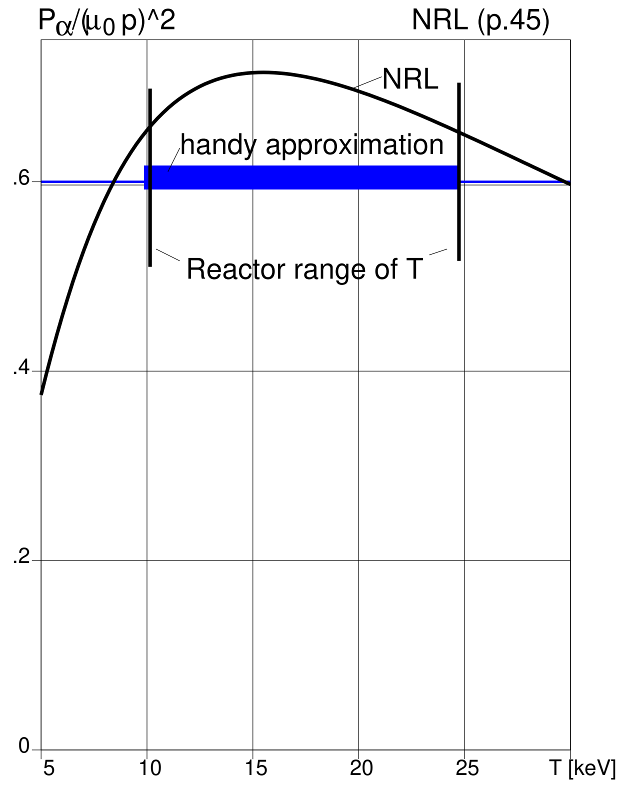
$$\boxed{P_{DT} = 5P_\alpha = 3(\mu_0 p)^2 V.}$$

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

α-particle fusion power covers all losses

$$\boxed{P_\alpha = 0.6(\mu_0 p)^2 V \geq \frac{E_{pl}}{\tau_E} = \frac{3\,pV}{2\,\tau_E}}$$

$$\boxed{p \cdot \tau_E \text{ [MPa} \cdot \text{sec]} \simeq 1.6}$$



1-4th guiding rules of magnetic fusion strategy:

1. "Ignition" condition should be fulfilled during both ignition and OPRR

$$p\tau_E \text{ [MPa} \cdot \text{sec]} \simeq 1.6, \quad \text{or} \quad B^2 \cdot \beta \cdot \tau_E \text{ [T}^2 \cdot \text{sec]} \simeq 4$$

2. Operational τ_E ($\simeq 1$ sec) is determined by

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

and then translated to $\beta \simeq 0.15$ for $B \simeq 5$ T.

3. $\tau_{E@ign}$ at the ignition phase (several secs long) is determined by

$$P_{ext} > \frac{1}{4}\,P_{\alpha@ign} = \frac{12}{20}\,\frac{V}{\tau_{E@ign}^2}$$

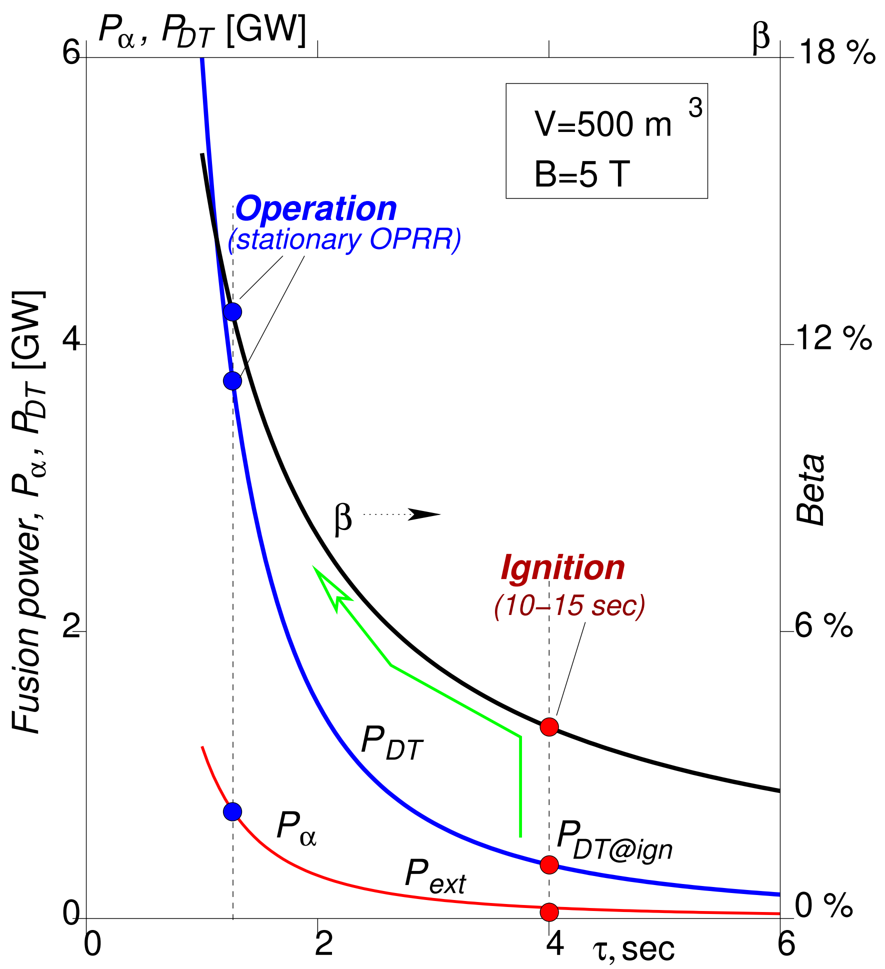
($\simeq 4$ sec for the reactor, $\simeq 0.7$ sec for Ignited ST).

4. Appropriate cost of electricity ($\simeq \$0.04$/kWh) should be a target.

The cost C of the reactor should be within the limits of \$\$-value of electricity produced (given assuming 30 years of uninterrupted operation)

$$C + \ldots\ [\$B] < 10.5\,\frac{P_{DT}}{4}\quad\frac{\$/kWh}{0.04}$$

Ignition requires high τ_E, operation requires high β.



"Beta-tau" parameters

- Ignition/operation condition

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

- Total power

$$P_{DT} = 4\ \mathrm{GW}, \quad \tau_E = 1.2\ \mathrm{sec},$$

- Igniting external power

$$P_{ext} \simeq 20\ \mathrm{MW}, \quad \tau_{E@ign} = 4\ \mathrm{sec}.$$

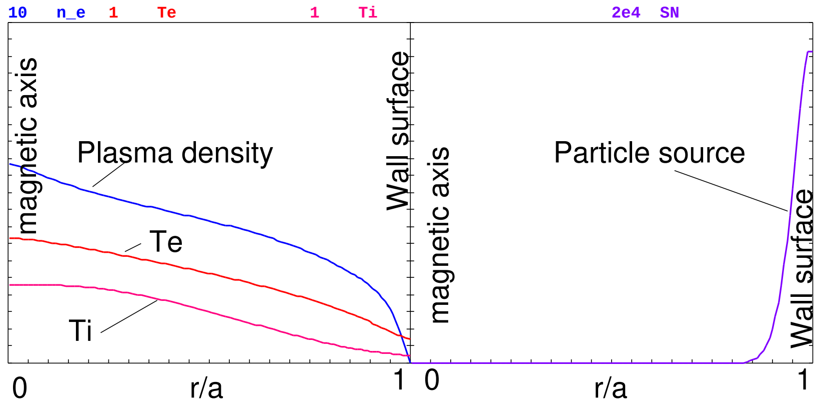
- Cost limitation

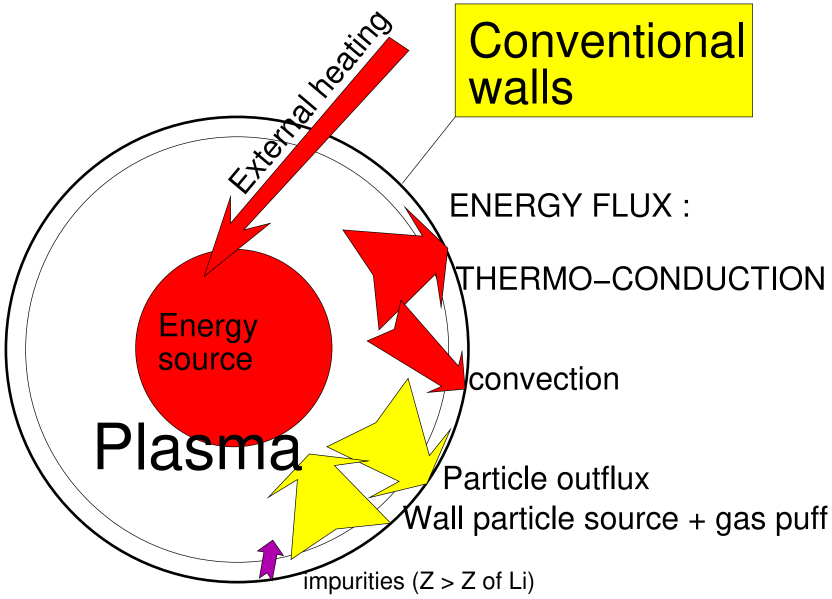
$$C \simeq 2 - 3\ \$B \ll 10.5\ \$B,$$

Achieving OPRR remains the major unresolved problem for magnetic fusion.
New regimes are absolutely necessary.

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

LTX simulations, no Li at walls



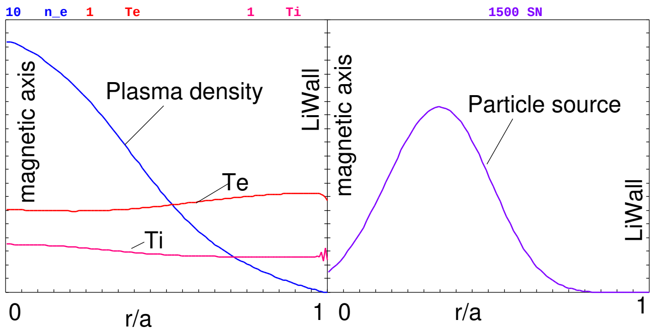


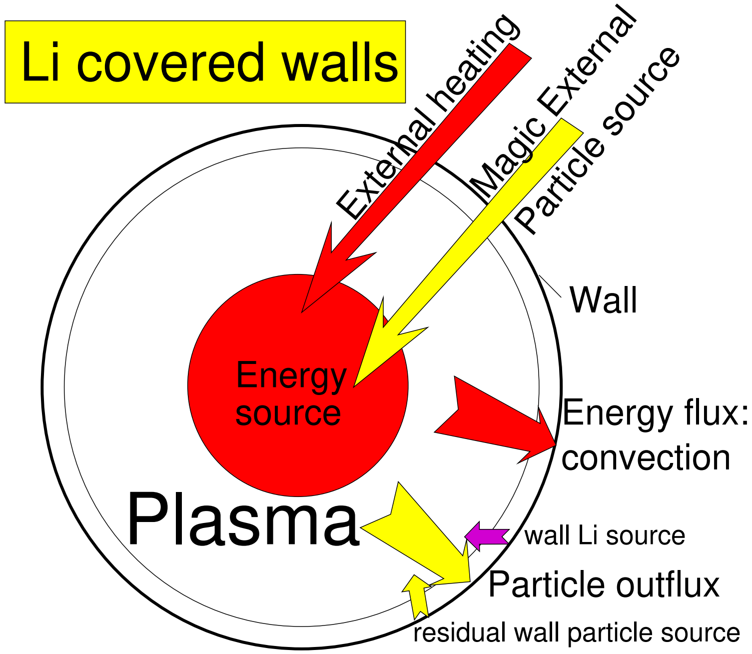
Peaked temperature and pile of problems:

- 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
- scalings instead of right regimes

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

LTX simulations





Flatten temperature

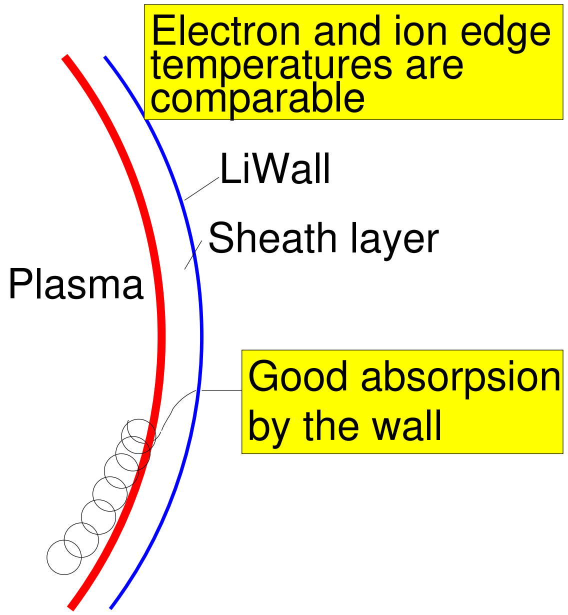
- no ITG turbulence,
- particle transport is the only energy loss channel
- no sawtooth oscillations,
- second stability regime
- control of density, power and BS current

LiWalls add more:

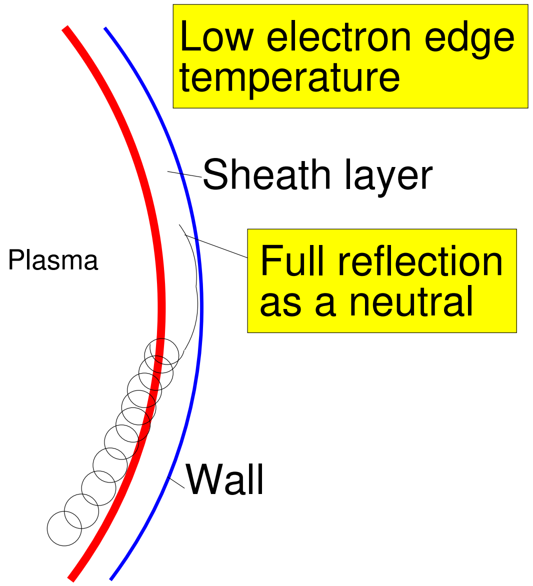
- wall stabilized plasma,
- high-β,
- high bootstrap current,
- outflux of both impurities and He
- no place for scalings

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 confinement*
- *consistent with the core DHD plasma fueling*
- *consistent with controlling*
  - *the density profile*
  - *the fusion power deposition*
  - *the bootstrap current profile*
- *having no problem with helium accumulation inside the plasma.*

6-7th rules of magnetic fusion strategy

This Earth has no tritium for our "inexhaustible and clean" energy source

6. During the entire DT development of OPRR, FW and TC tritium should be breeded with $> 100\%$ efficiency

- *The cost C_T of tritium is* $\boxed{C_T \left[\frac{\$B}{kg}\right] = 0.026 - 0.030}$
- *"Large" machines ($\simeq$835 m^3) are not suitable for developing the OPRR.*
- *Small machines ($\simeq$30 m^3, 0.5 GW) should convert every neutron into tritium and must be ignited.*
- *There is no physics reasons for high-β compact machine not to be ignited*
- *There is no sense for a "compact" machine not to be high-β ($\simeq$ 40%)*
- *Only Ignited STs (IST) are of interest for OPRR.*

7. Fluence of 15 MW$\cdot$year/m^2 should be provided for developing FW.

- *Testing the first wall requires $\boxed{\simeq 1\ kg/m^2}$ of tritium and costs $\boxed{0.030\ \$B/m^2}$.*
- *"Large" machines ($\simeq$650) m^2 are not suitable ($\simeq$650 kg of T) for developing the FW.*
- *ISTs ($\simeq$ 55 m^2, 7-8 MW/m^2 neutron load) are well suitable for developing the FW.*
- *So called "controlled burning" is a meaningless idea of LPPP*

8th rule of magnetic fusion strategy

New design approaches are necessary for the FW

8. FW design should be consistent with

- low activation
- tritium breeding
- power extraction and
- and replacement cost.
  - *The replacement cost C_{FW} should be within \$\$-value of electricity corresponding to 1 life time of the FW* $$C_{FW} \quad \frac{\$B}{m^2} < 0.001 \cdot \frac{5.25}{4}.$$
  - *Solid walls with the "neutron" zone inside the vacuum barrier cannot fit the requirements*
  - *FLiBe is the coolant consistent with the FW requirements*
  - *Active cooling (by liquid metal) of the plasma facing FW surface is required (Zinkle, Nelson)*
  - *"Yacht Sail" low activation approach is the only known option consistent with the FW requirements*

9-10th rules of magnetic fusion strategy

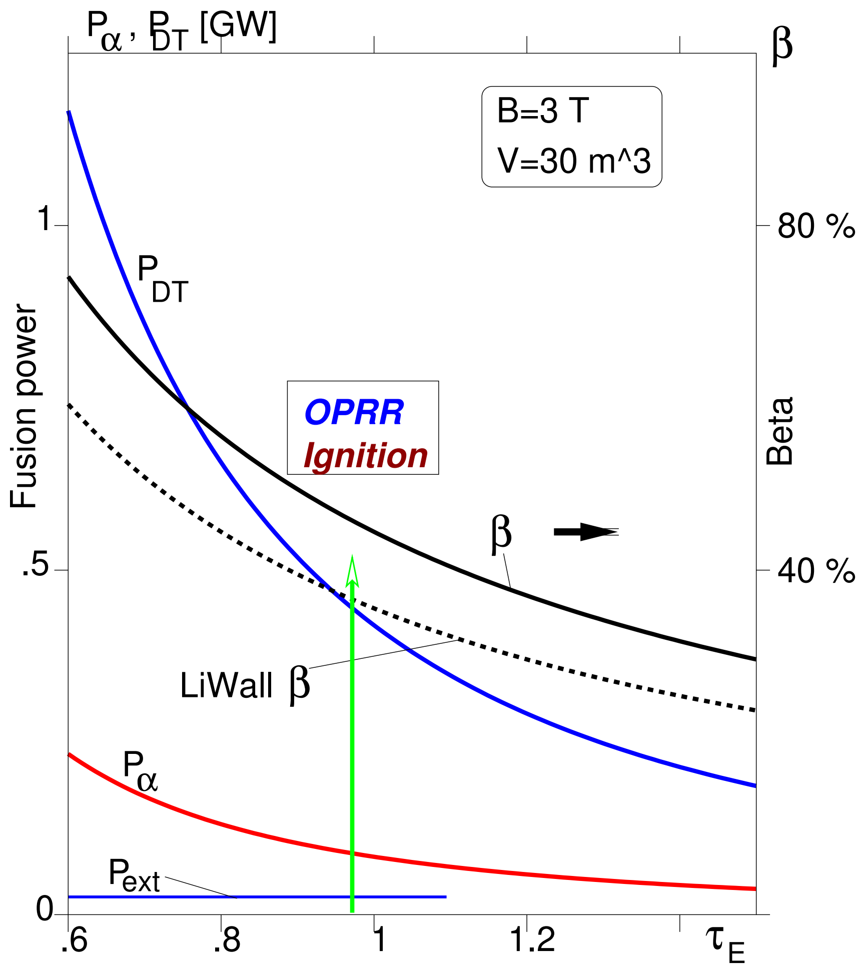
Shield determines the geometry of tokamak reactors

9. Tokamak reactor should have full neutron shielding and minimal activation.

- *LiWall ISTs are the only tokamaks which can be ignited at the operational point and be stationary. ISTs are crucial for developing OPRR, FW and TC for the power reactors.*
- *On the other hand, STs have unresolvable (so far) problems with activating the central pole and are out of consideration as the power reactor.*
- *Conventional aspect ratio $\simeq 4$ is the most probable.*

10. Do not waste the life time on fake ideas. But if you were stupid and already wasted, just make things happen.

Spherical Tokamaks are unique in merging OPRR and Ignition Phase



$\beta - \tau_E$ parameters of IST:

- Ignition & operation condition

  $$B^2 \cdot \beta \cdot \tau_E \simeq 4,$$

- Total power

  $$P_{DT} \simeq 0.5 \text{ GW},$$

- Igniting external power

  $$P_{ext} \simeq 25 \text{ MW}.$$

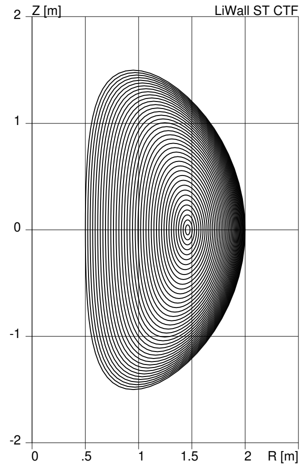
- Cost limitation

  Not relevant, $\ll 1$ \$B

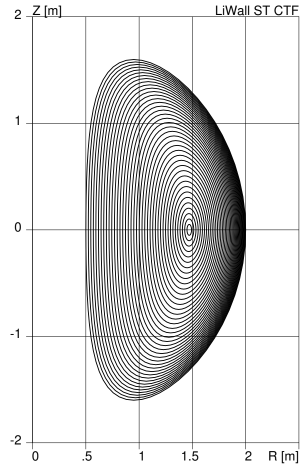
Ignited ST is a practical approach for development of OPRR, FW and TC

IST are naturally suitable for Component Test Facility

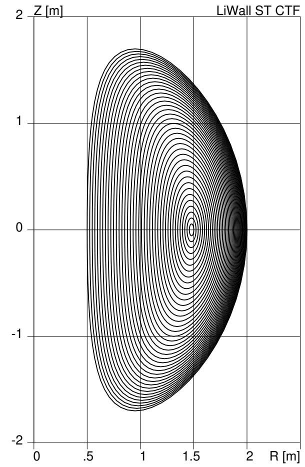
LiWall IST ($\boldsymbol{I_{pl}}$=11 MA, $\boldsymbol{B}$=3 T at R=1.25 m) are not a tech. challenge



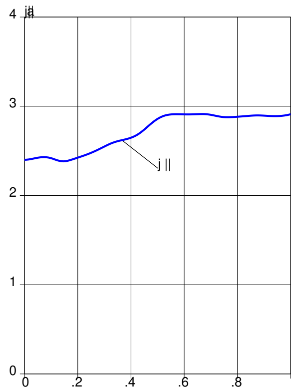
$\beta = 0.41,\ P_{DT} = 388$ MW



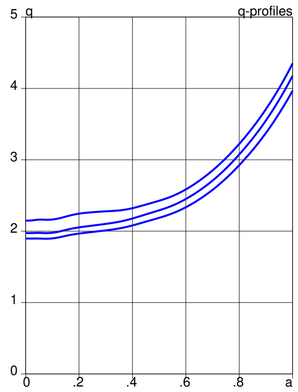
$\beta = 0.45,\ P_{DT} = 490$ MW



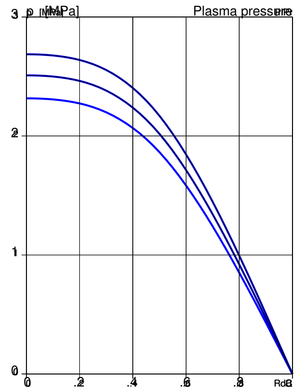
$\beta = 0.48,\ P_{DT} = 606$ MW



$j_{||}(a)$

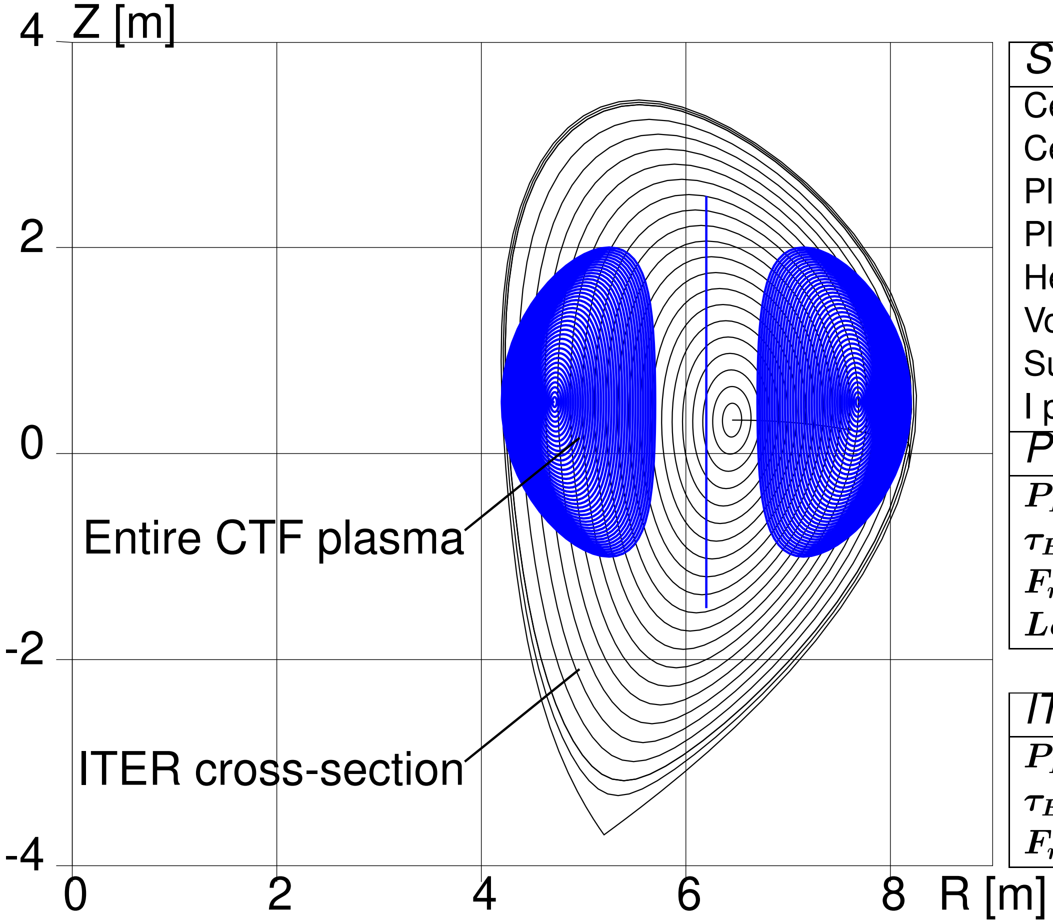


$q(a)$



$p(a)$

Tritium breeding, in fact, requires ignition for compact CTFs

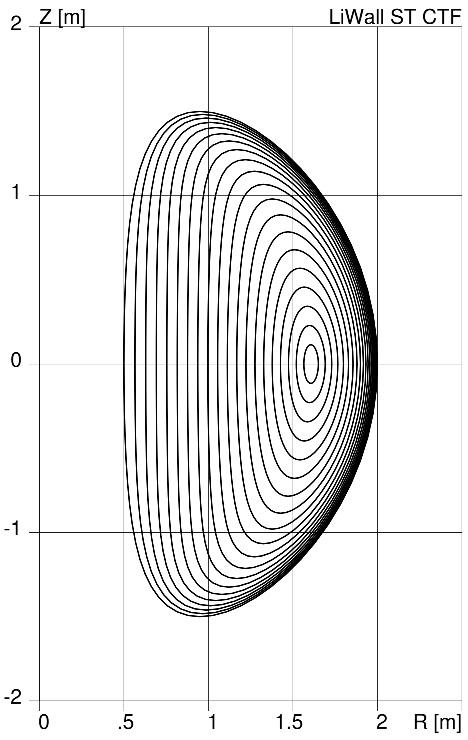


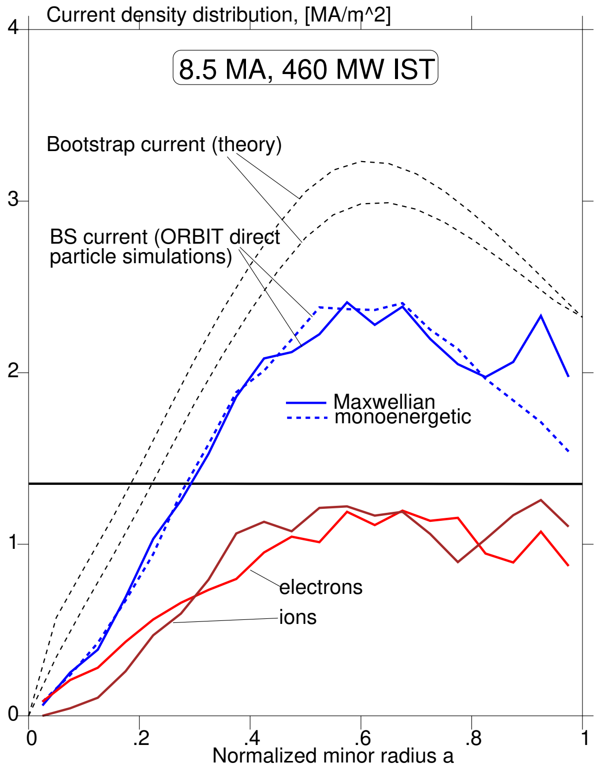
ST CTF Parameters				
CenterPole R	m	0.5	0.5	0.5
CenterPole B	T	7.5	7.5	7.5
Plasma R_1	m	0.5	0.5	0.5
Plasma R_2	m	2.0	2.0	2.0
Height	m	3.0	3.2	3.4
Volume	m^3	26.1	27.8	29.6
Surface	m^2	53.4	55.9	58.5
I plasma	MA	11.1	11.9	12.7
Plasma performance				
P_{DT}	MW	388	490	606
τ_E	sec	0.75	0.69	0.64
$F_{neutron}$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

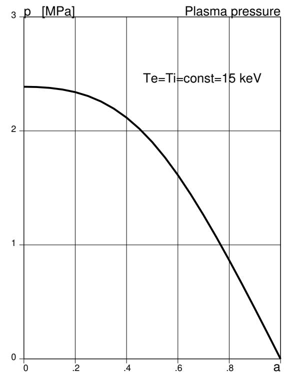
ITER		
P_{DT}	MW	410
τ_E	sec	3.7
$F_{neutron}$	MW/m^2	0.5

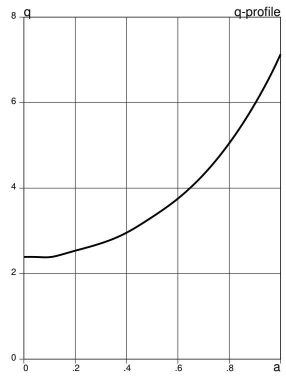
IST can provide 95 % utilization of neutrons for tritium breeding

ISTs are reliably overdriven by bootstrap current (R. White)



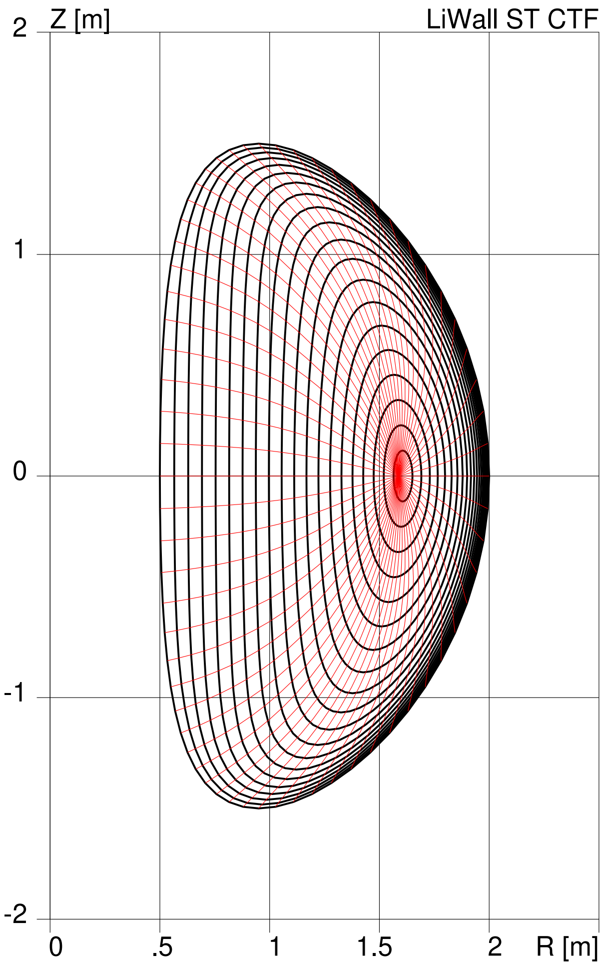


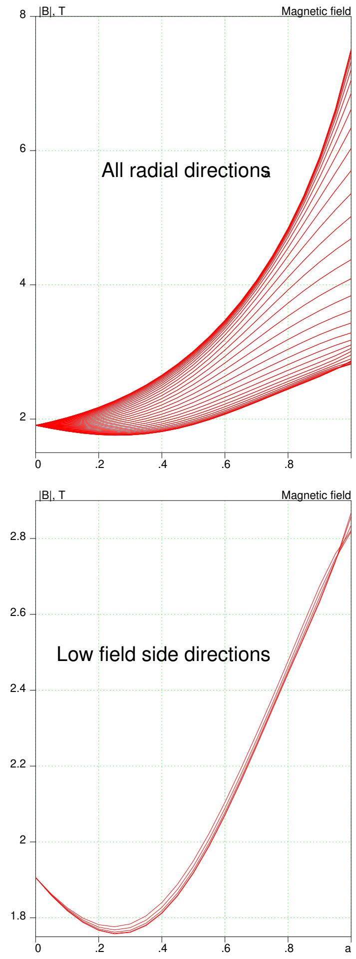




With DHD fueling even the central region is not a potential problem

IST has the best magnetic configuration for fueling





Field gradient in IST

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

is more than an order of magnitude higher than in "high-field" 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 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*

DHD has extremely simple equations of motion

The length of DHD is determined by

$$L = 2c_s t. \tag{5.1}$$

The cross-section of DHD is defined by

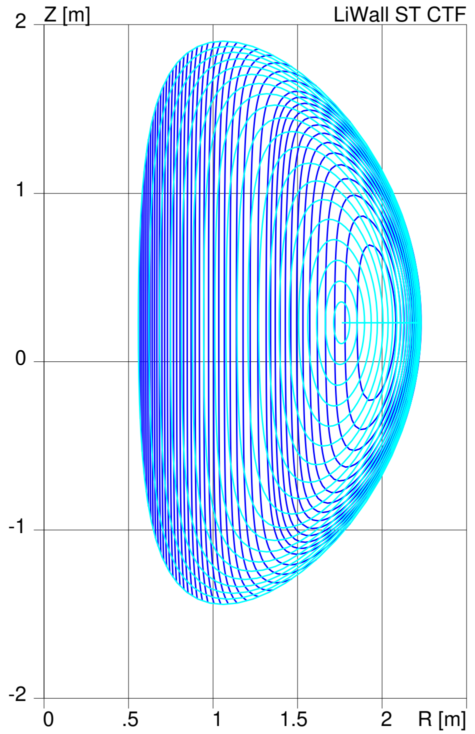
$$\pi\rho^2 L = const. \tag{5.2}$$

The velocity across the field is given by

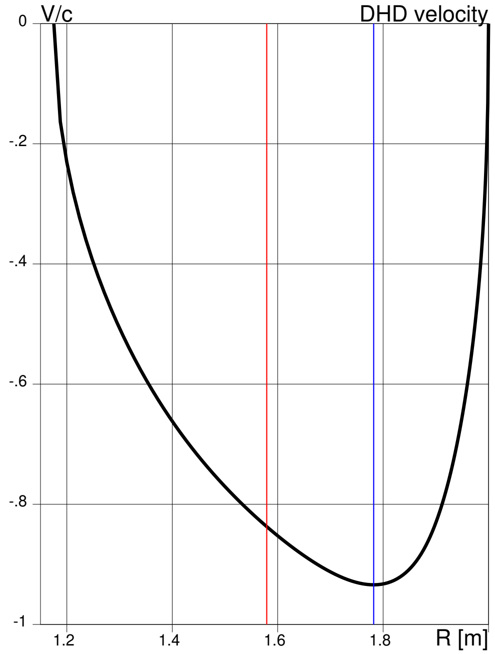
$$\frac{dv_\perp}{dt} = c_s^2 \frac{1}{B}\frac{dB}{dr}, \quad v_\perp = c_s\sqrt{\ln\frac{B^2_{launch}}{B^2}}, \tag{5.3}$$

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

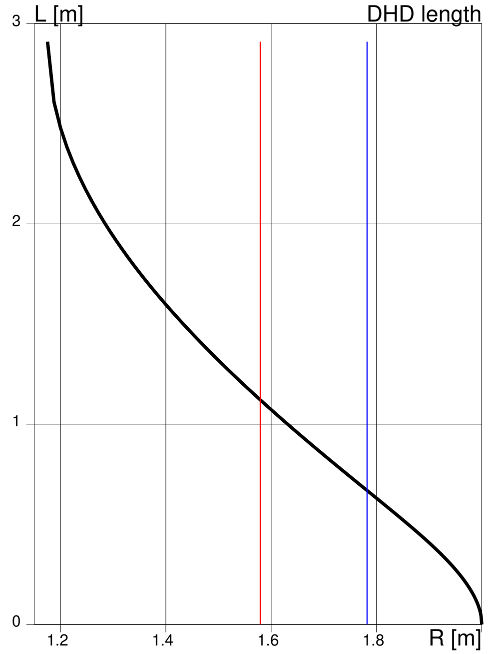
In 3 μs DHD tunnels the particles from the edge to the plasma center



B =const lines



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



$L(R)$

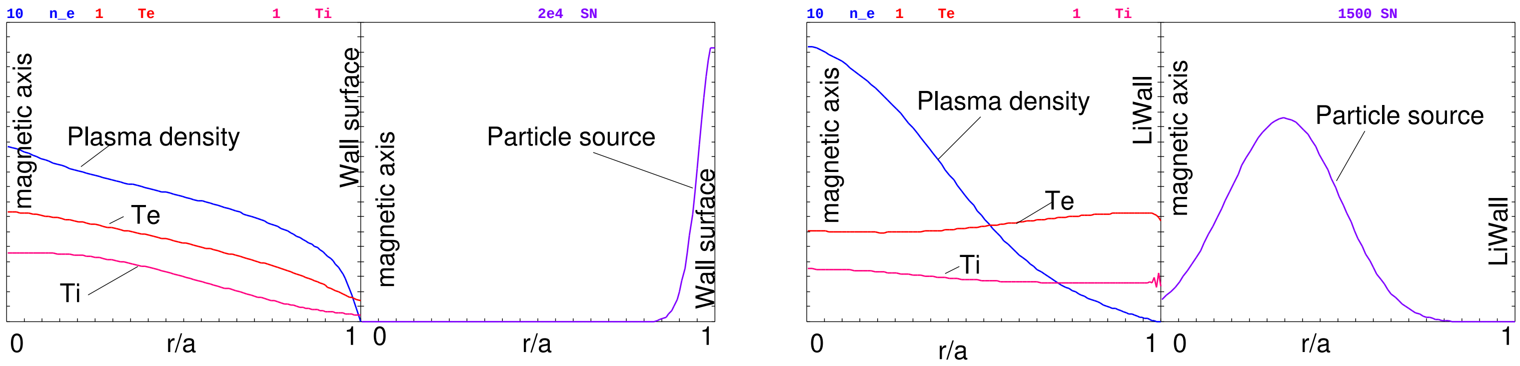
DHD fueling creates the plasma physics matching to low recycling wall/divertor ideas of ALPS/APEX technology programs

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

Edge plasma temperature is determined by (S. Krasheninnikov)

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

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



By returning hot electrons from the edge to the center, DHD effectively enhances the plasma heating power by 50 % with respect to the "magic" central fueling (ASTRA code was set up just this morning for showing this.)

DHD theory contains also the reversed effect of pumping by DHD

This part is not yet ready for presentation.

The DHD pumping idea sonsists 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 only the low energy plasma and helium

As a result, the low recycling high (15 keV) edge plasma temperature will be consistent with ITER (redesigned) divertor and

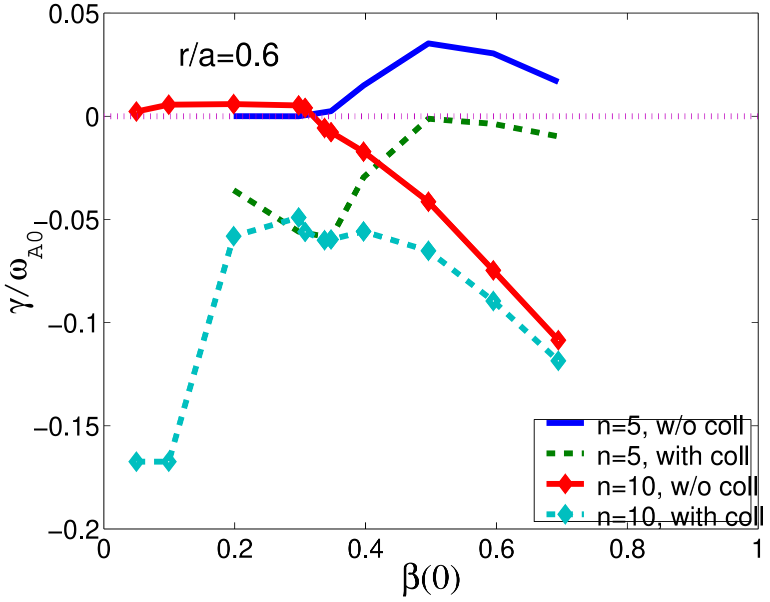
Ignition will happen in ITER *with tritium supply from a couple of US (?) ISTs*

See the rule #10.

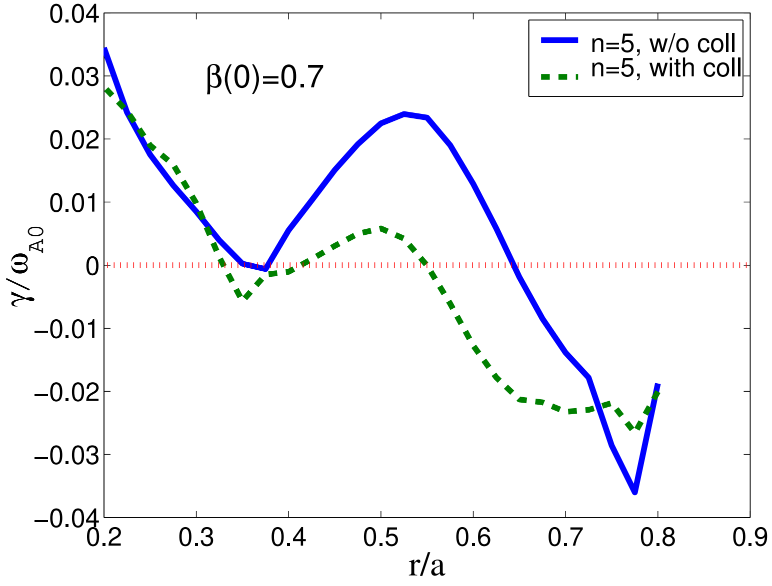
In LiWall plasma energy losses are determined by particle losses

Particle losses in tokamaks are determined by the best confined component.

Gorelekov's HINST calculations of stability



Increase in β stabilizes modes



Even $n = 5$ mode is stable at $a > 0.6$

Electron trapped modes are stabilized by reversed particle precession

With no microturbulence DD is easily possible (needs $\tau_E \simeq 20$ sec)

but probably unpractical because of low power.

Invention of DHD fueling culminates 4 years of LiWall concept

For "present state of understanding of fusion" the LiWall-DHD theory opens the way to

- *achieving the ignition in low-recycling IST*
- *designing and operating the IST based Component Test Facility*
- *electric power generation in the tokamak power reactor.*

ISTs are suitable for developing 3 major objectives of magnetic fusion

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

This theory specifies the appropriate plasma physics concept for a practical magnetic fusion.

It just needs experimental and technology implementation

Any fusion Lab, having 25 MW of NBI power, would be capable of igniting the IST