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Operational Power Reactor Regime, ignited CTF, and Lithium Tokamak Experiment (LTX)[1]

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Abstract

The Operational Power Reactor Regime (OPRR) (which is distinct from the Ignition phase) is introduced as a major challenge for magnetic fusion. The necessity for a low recycling regime and a wall-stabilized plasma for OPRR is emphasized.

For development of the OPRR, Spherical Tokamaks (ST) are uniquely positioned as high-β small volume devices with good plasma confinement and stability. It is shown that LiWall ST devices with a low-recyling plasma and wall stabilization have the opportunity for ignited operation in a self-sustained magnetic configuration driven by the bootstrap current.

The use of the ST in developing the OPRR would provide a new vision for a Component Test Facility (CTF) as a compact (30 m^3) ignited ST (0.5 GW of fusion power) with high (5-8 MW/m^2) neutron wall load and maximum (up to 95 %) use of fusion neutrons for tritium breeding.

A compact Lithium Tokamak Experiment (LTX) is being proposed to address the basic plasma physics and technology issues of the low recycling regime, controlled by a lithium wall surface.

Contents

Important approximation for the fusion power

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

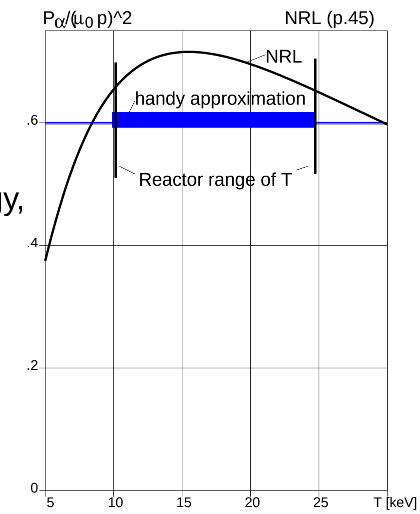
$$P_\alpha \ge \frac{E_{pl}}{\tau_E}, \quad E_{pl} = \frac{3}{2} pV,$$

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])

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

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)*

Typical examples of Fusion Power Reactor parameters:

With 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

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

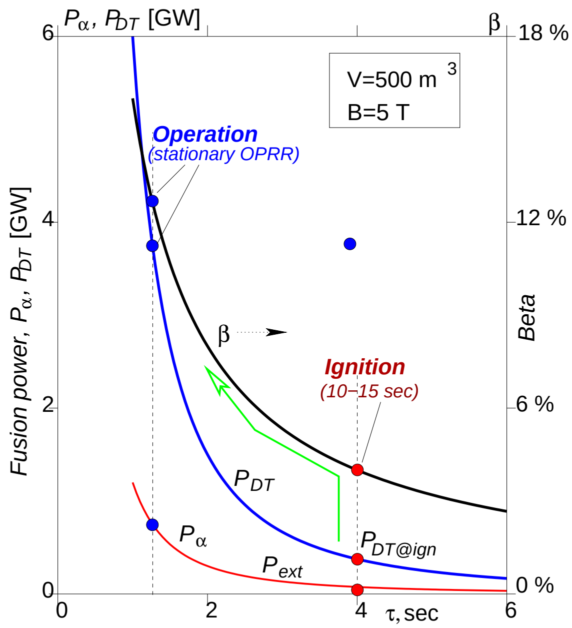
in order to fit the "betatau" requirements.

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 and operation phase have totally different plasma regimes.



"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

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

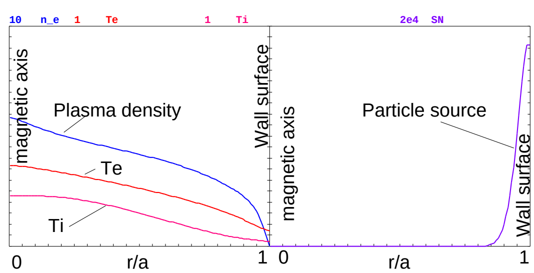
- Ignition external power

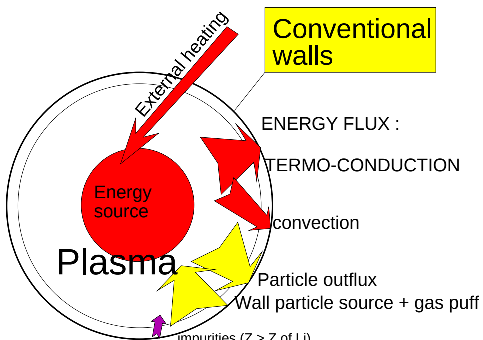
$$P_{ext} = \frac{1}{20} P_{DT@ign}.$$

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





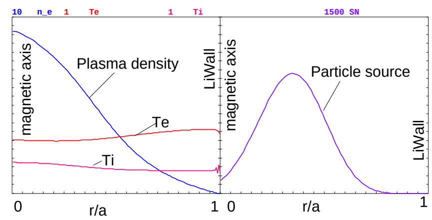
Peaked temperature:

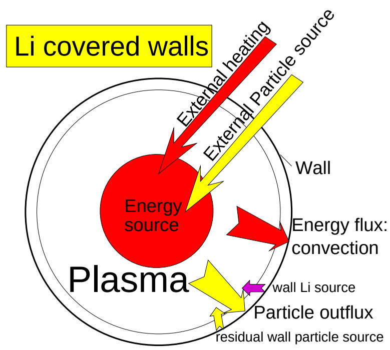
- ITG turbulence,
- thermo-conduction is a dominant energy loss channel,
- peakedness of the current density,
- $q(0) \to 1$ - sawtooth oscillations,
- $q(0) \to 1$ - low β and Troyon beta limit,
- low bootstrap current,
- influx of impurities,
- poor utilization of plasma volume

OPRR needs a different regime.

Core fueling + Li absorbing wall offers enhanced edge temperature.

LTX simulations





Flatten temperature

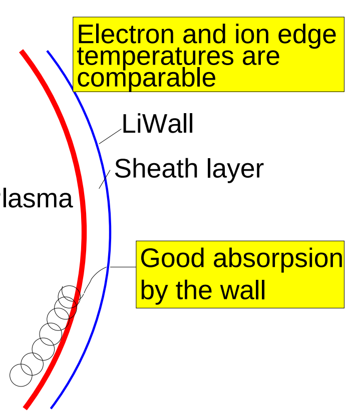
- no ITG turbulence,
- convection is a loss channel for particles and energy,
- no sawtooth oscillations,
- second stability regime (no Troyon limit),

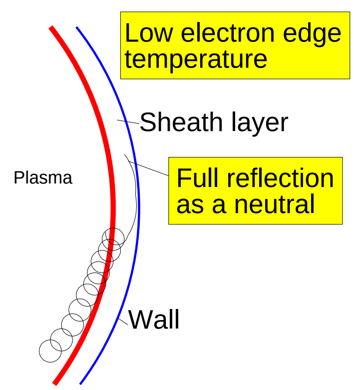
LiWalls add more:

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

LiWalls are promising for OPRR.

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



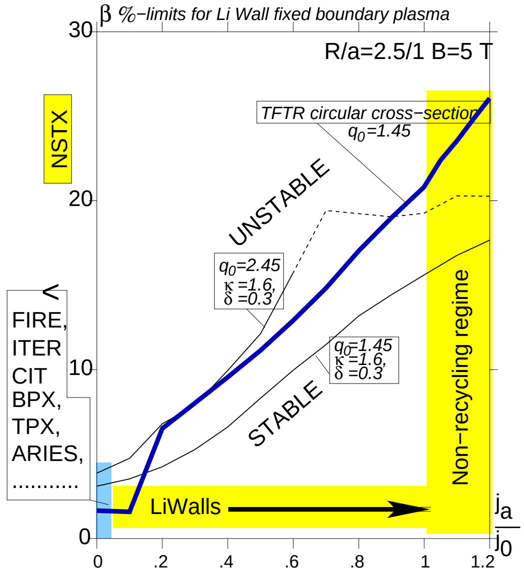


Good for LiWalls *Bad for LiWalls*

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

LTX targets comprehensive studies of plasma-LiWall physics.

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



- no sawtooth oscillations;
- no Troyon limit;

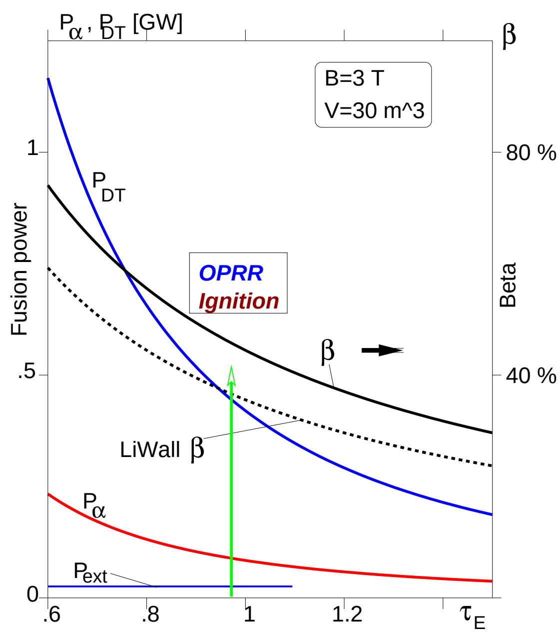
β - limits for the second stability regime

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

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

LTX may potentially observe the effect of LiWalls on sawteeth

Spherical Tokamaks are unique in merging OPRR and Ignition Phase



Betatau mini-reactor parameters:

- Ignition & operation condition

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

- Total power

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

- Igniting external power

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

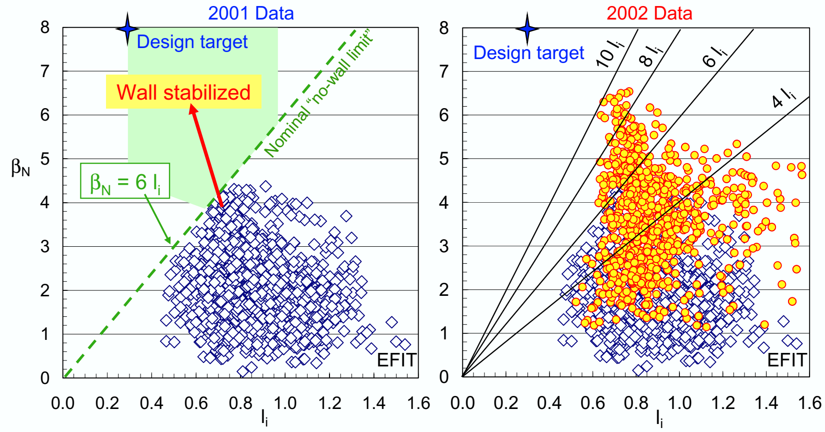
- Cost limitation

  $C < 1$ [\$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



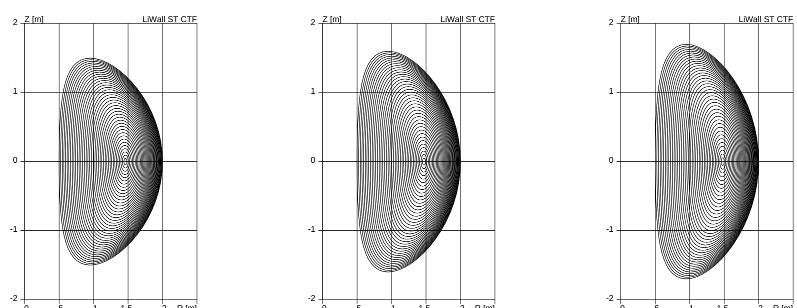
- Normalized beta, β_N = 6.5, with β_N/l_i = 9.5; β_N up to 35% over $\beta_{N\ no\text{-}wall}$
- Toroidal beta has reached 35% ($\beta_t = 2\mu_0\langle p\rangle / B_0^2$)

NSTX

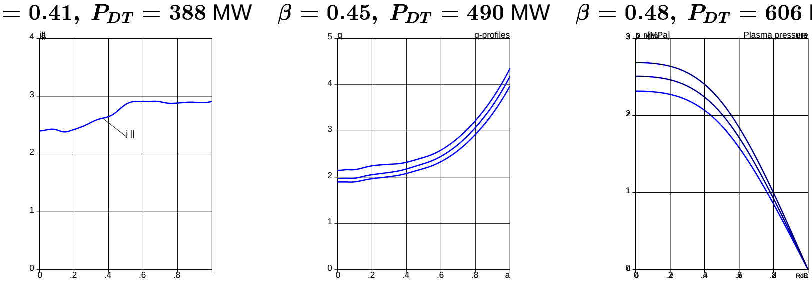
By eliminating Te-peaking and IRE, LiWalls can make high-β robust

High-β Spherical Tokamaks are naturally suitable for ignition

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

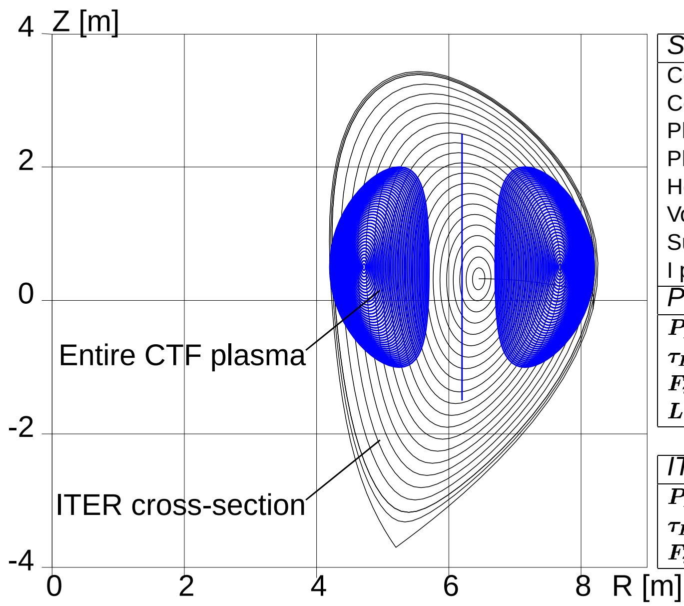


$\beta = 0.41,\ P_{DT} = 388$ MW $\beta = 0.45,\ P_{DT} = 490$ MW $\beta = 0.48,\ P_{DT} = 606$ MW



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

Tritium breeding, in fact, requires ignition for compact CTFs

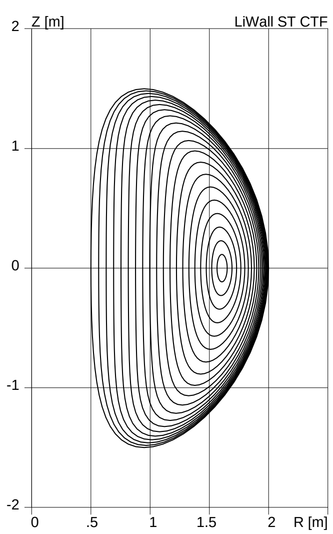


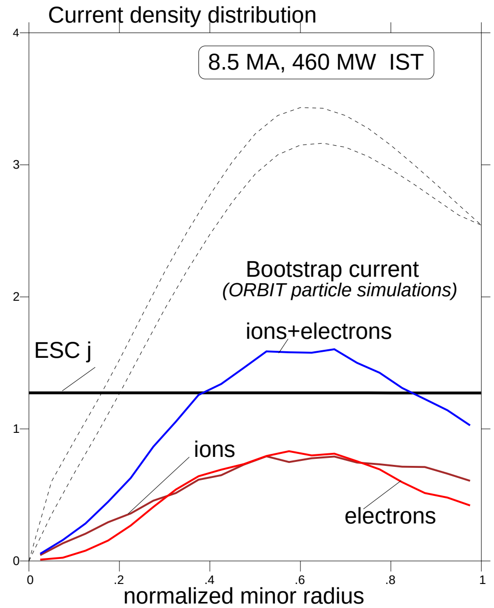
ST CTF Parameters			
CenterPole R m	0.5	0.5	0.5
CenterPole B T	7.5	7.5	7.5
Plasma R_1 m	0.5	0.5	0.5
Plasma R_2 m	2.0	2.0	2.0
Height m	3.0	3.2	3.4
Volume m^3	26.1	27.8	29.6
Surface m^2	53.4	55.9	58.5
I plasma MA	11.1	11.9	12.7
Plasma performance			
P_{DT} MW	388	490	606
τ_E sec	0.75	0.69	0.64
$F_{neutron}$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

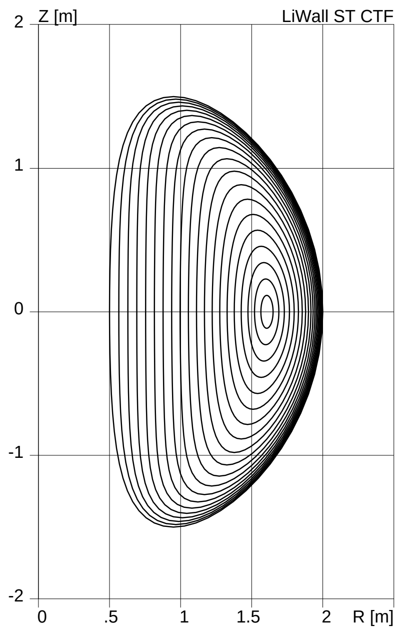
IST appears to be consistent with the necessary bootstrap current

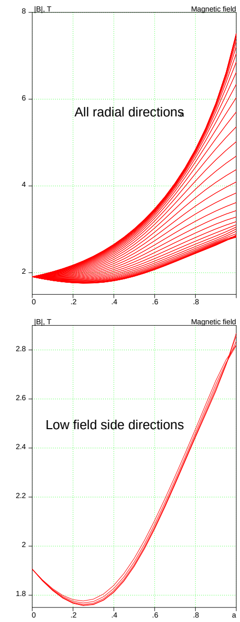




Only the central region may cause a problem

IST has the best magnetic configuration for pellet injection





Field gradient

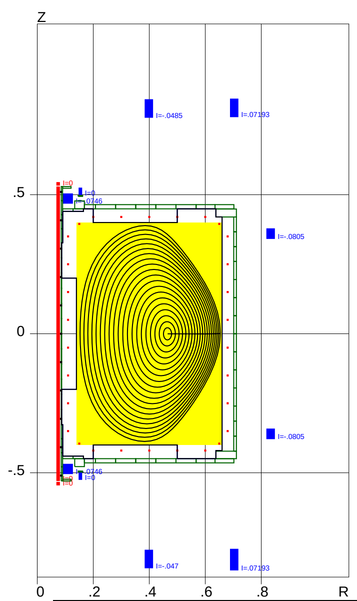
$$\frac{d|B|}{dR} \simeq 2.5\ \frac{T}{m}$$

is higher than in "high-field" side conventional tokamak fueling.

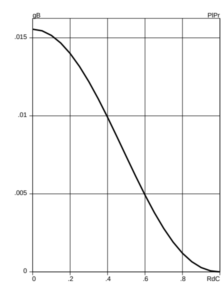
In addition:

High speed of pellets can be utilized (3 km/s)

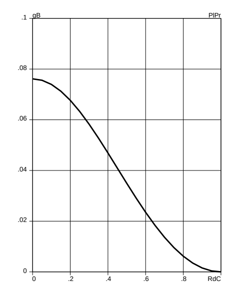
LTX is a very first step for developing a wall controlled plasma



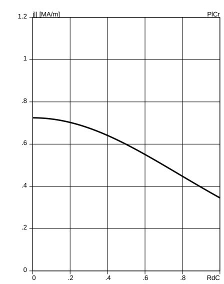
Wall is designed for different $j(r), p(r)$ and I_{pl}



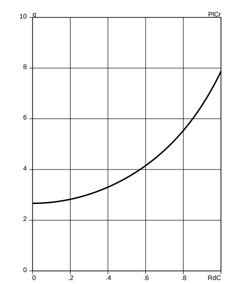
peaked $j_{||}$



pressure profile



flattened $j_{||}$

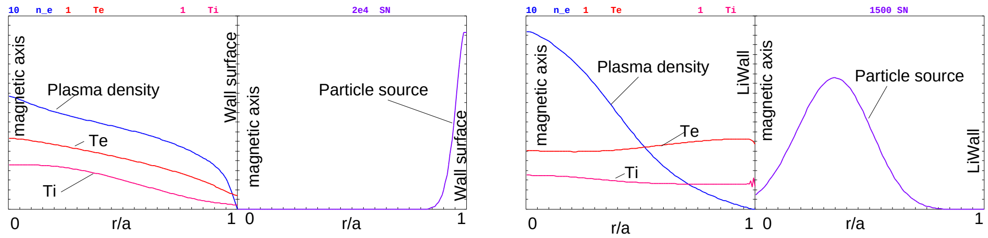


q- profile

Core fueled plasma is a key physics objective of LTX

It includes:

- studies of recycling, sheet potential and other plasma-wall physics
- identification of the basic scale lengths for the plasma edge (charge exchange, ionization, ion larmor radius, banana width, etc).
- elimination of the wall dominance in the plasma fueling,

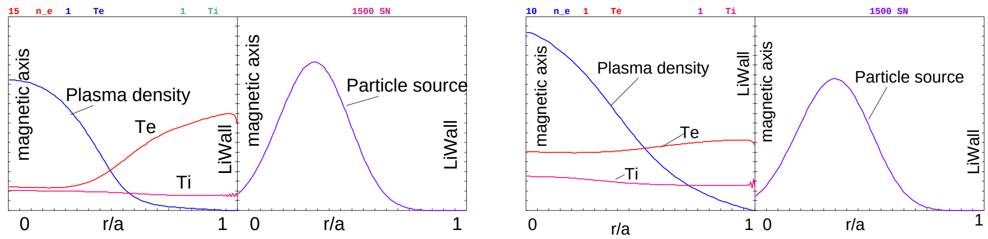


- development of a start-up scenario in presence of absorbing walls,
- development of a quasi-steady, pellet fueled plasma.

Flowing lithium is not a target of LTX.

Scientific objectives of LTX are unique particle transport studies:

- Neoclassical physics can be illuminated in a low recycling LTX (all trapped particles are predominantly at the plasma edge).
- elimination of the dominance of thermo-conduction in energy losses,
- test of Okhawa's type dependence $(1/n)$ in the particle transport,



- low edge q (< 3) regimes in presence of a pumping wall

High-β is not a present target of LTX.

Advanced tools are necessary for challenging physics of LTX plasma

- ESC equilibrium and reconstruction code
- TRANSP, ASTRA transport simulation and analysis code
- DCON, BALLOON stability codes
- ORBIT particle orbit code

all already are linked together.

In addition collaboration with LLNL (UEDGE code) will provide the plasma edge analysis.

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

1. Operational Power Reactor Regime (in a minimal volume facility)
2. First Wall with reactor relevant wall loading
3. Tritium cycle

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

- 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.

At this moment,

experimental tests and calibrations are desperately needed.

LTX is proposed as a first device extending lithium technology research

to systematic studies of low recycling plasma physics.

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)

$$\frac{dE_{pl}}{dt} = P_{ext} + P_\alpha - \frac{E_{pl}}{\tau_{E@ignition}} \simeq P_{ext} + P_{\alpha@ign}(x^2 - x), \qquad x \equiv \frac{E_{pl}}{E_{pl@ign}} \tag{4.1}$$

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)