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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

1 Basics of Opereational Power Reactor Regime.

Important approximation for the fusion power

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

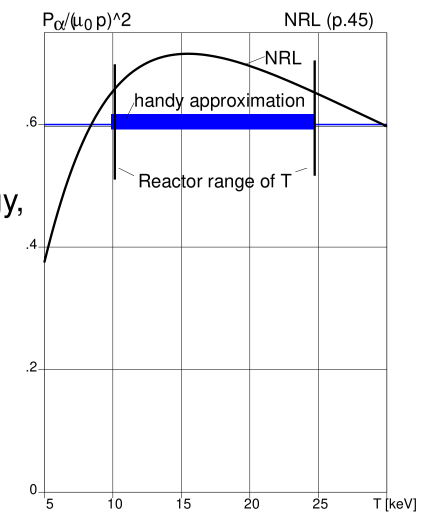
$$\boxed{P_\alpha \geq \frac{E_{pl}}{\tau_E}, \quad E_{pl} = \frac{3}{2}pV,}$$

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

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

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



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

1. $\boxed{B^2 \cdot \beta \cdot \tau_E > 4}$ — 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. $\boxed{P_{DT} = 12 \frac{V}{\tau_E^2}}$ — DT power of the fusion reactor
(high $\tau_E > 1.5$ sec is bad for power production)

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

together with

4. $\boxed{C\ [\$B] + \ldots < 10.5 \frac{P_{DT}}{4} \frac{\$/kWh}{0.04}}$ - 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:

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

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

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

and then must operate at an enhanced β and reduced τ_E

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

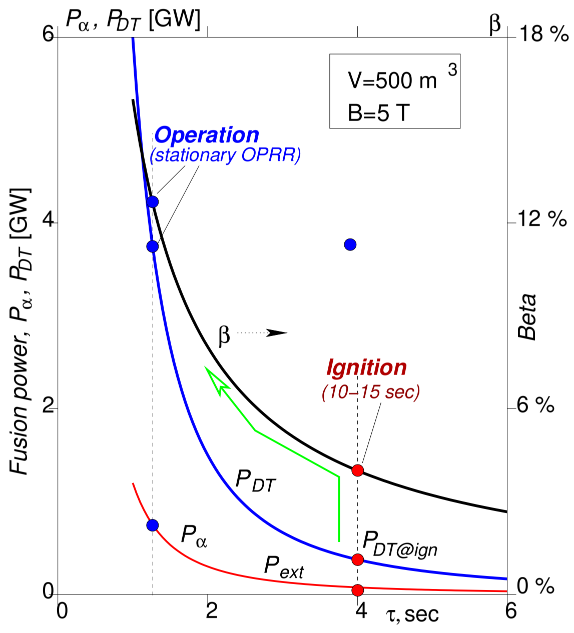
in order to fit the "betatau" requirements.

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

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

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

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

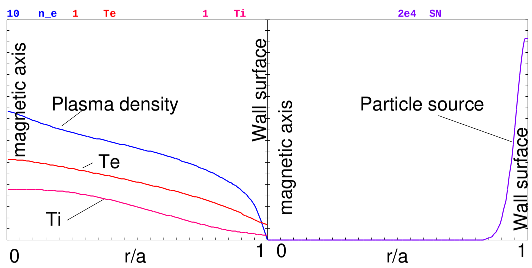
- Ignition external power

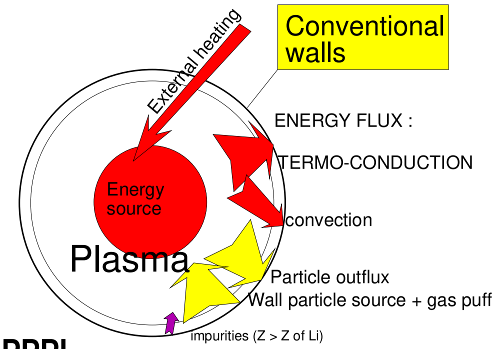
$$P_{ext} = \frac{1}{20} P_{DT@ign}.$$

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





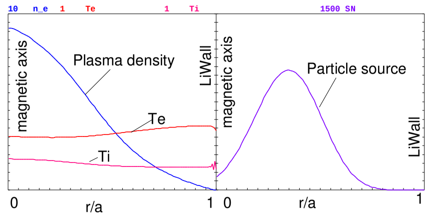
Peaked temperature:

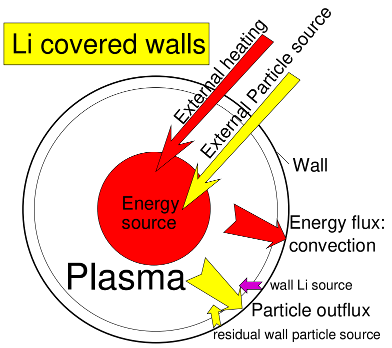
- ITG turbulence,
- thermo-conduction is a dominant energy loss channel,
- peakedness of the current density,
- $q(0) \to 1$ - sawtooth oscillations,
- $q(0) \to 1$ - low β and Troyon beta limit,
- low bootstrap current,
- influx of impurities,
- poor utilization of plasma volume

OPRR needs a different regime.

Core fueling + Li absorbing wall offers enhanced edge temperature.

LTX simulations





Flatten temperature

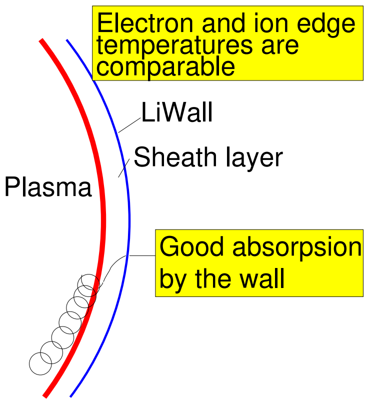
- no ITG turbulence,
- convection is a loss channel for particles and energy,
- no sawtooth oscillations,
- second stability regime (no Troyon limit),

LiWalls add more:

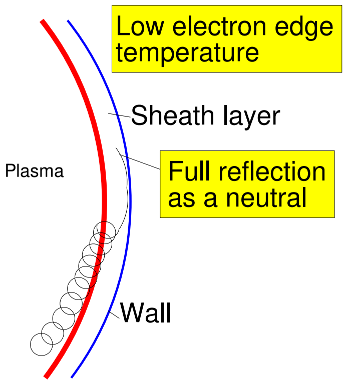
- wall stabilized plasma,
- high-β,
- high bootstrap current,
- outflux of impurities,
- ...

LiWalls are promising for OPRR.

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



Good for LiWalls

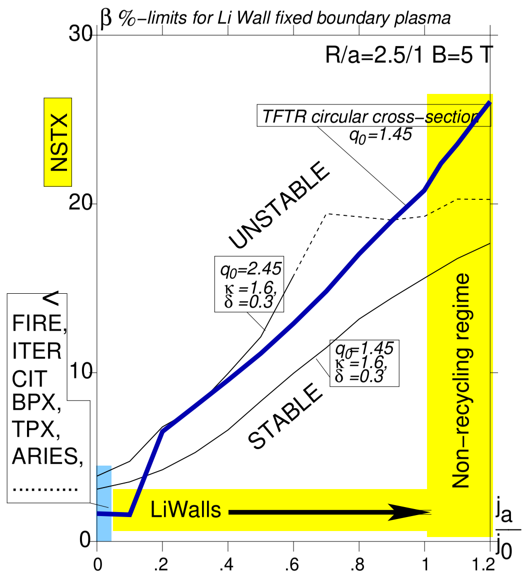


Bad for LiWalls

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

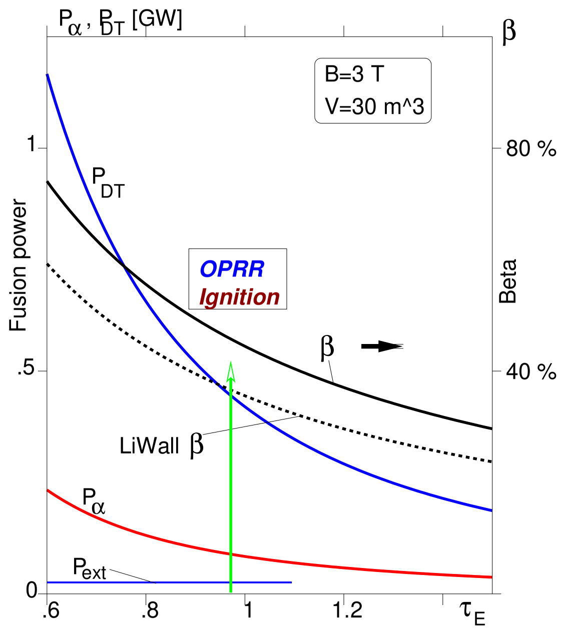
- fixed boundary plasma
- n=1,2,3 + ballooning modes (DCON,PEST-2,BALLON,ESC)
- current density with an edge pedestal

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

LTX may potentially observe the effect of LiWalls on sawteeth

2 Ignited ST (IST) and the Component Test Facility (CTF).

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

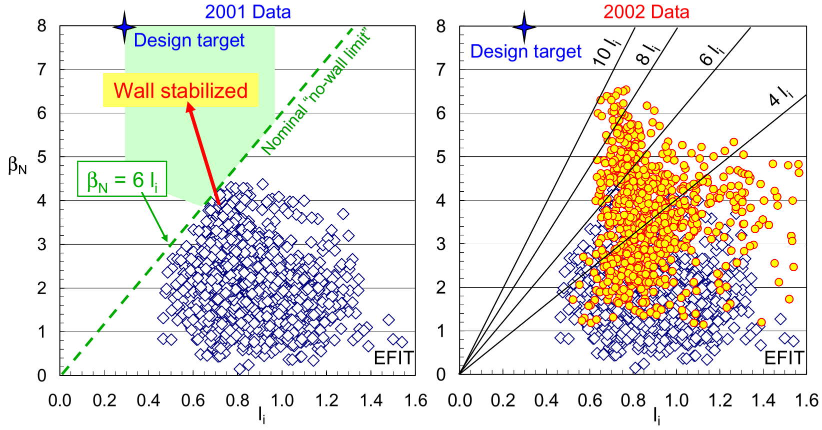
  $C < 1$ [\$B],

Ignited ST is a practical approach for development of OPRR

2.1 High-β are achieved experimentally on ST.

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 $\beta_{N\ \text{no-wall}}$
- Toroidal beta has reached 35% ($\beta_t = 2\mu_0\langle p\rangle / B_0^2$)

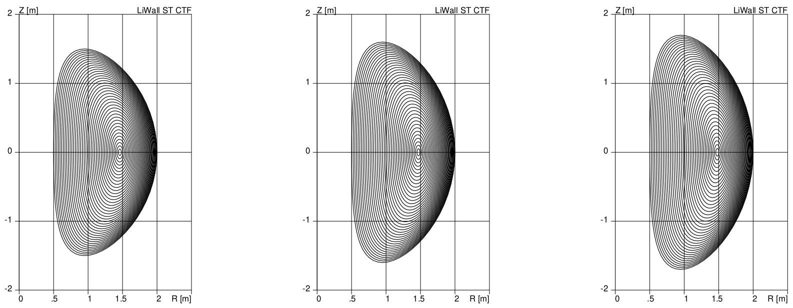
NSTX

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

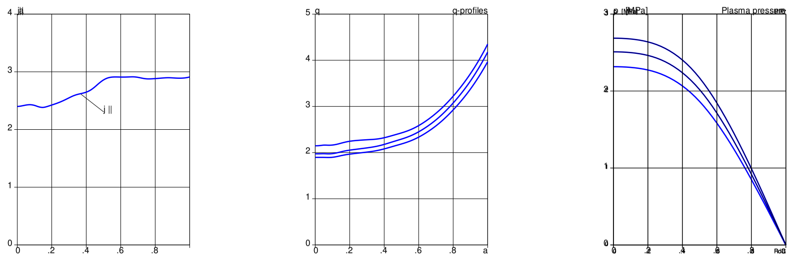
2.2 Ignited CTF rather than externally driven "burning" device.

High-β Spherical Tokamaks are naturally suitable for ignition

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

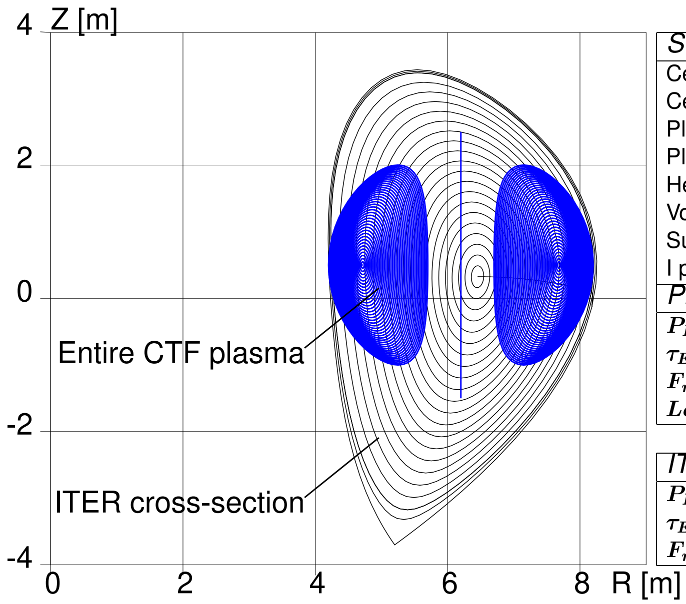


$\beta = 0.41,\ P_{DT} = 388$ MW $\quad \beta = 0.45,\ P_{DT} = 490$ MW $\quad \beta = 0.48,\ P_{DT} = 606$ MW



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

Tritium breeding, in fact, requires ignition for compact CTFs

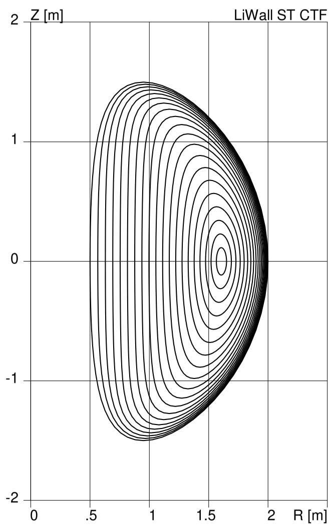


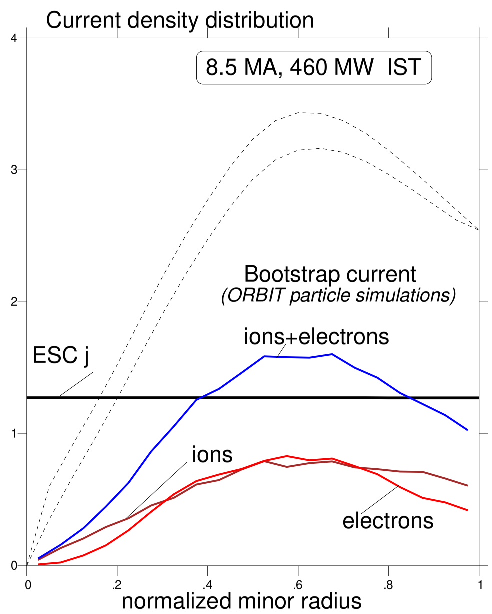
ST CTF Parameters				
CenterPole R	m	0.5	0.5	0.5
CenterPole B	T	7.5	7.5	7.5
Plasma R_1	m	0.5	0.5	0.5
Plasma R_2	m	2.0	2.0	2.0
Height	m	3.0	3.2	3.4
Volume	m^3	26.1	27.8	29.6
Surface	m^2	53.4	55.9	58.5
I plasma	MA	11.1	11.9	12.7
Plasma performance				
P_{DT}	MW	388	490	606
τ_E	sec	0.75	0.69	0.64
$F_{neutron}$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

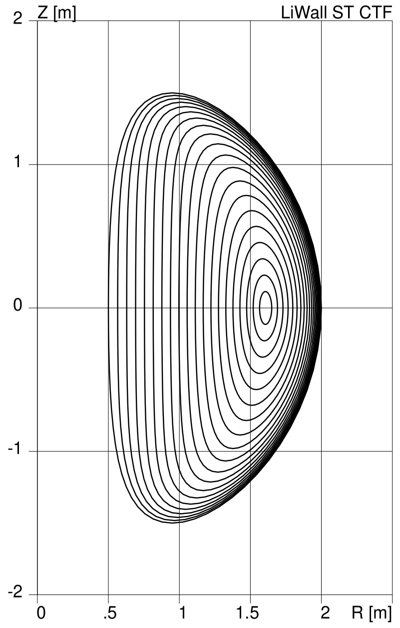
IST appears to be consistent with the necessary bootstrap current

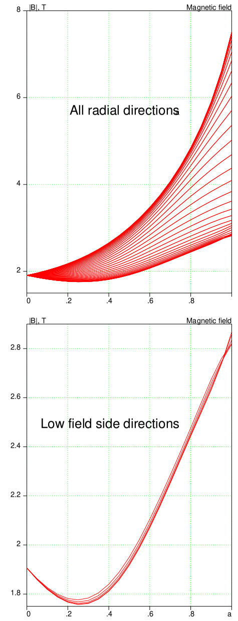




Only the central region may cause a problem

IST has the best magnetic configuration for pellet injection





Field gradient

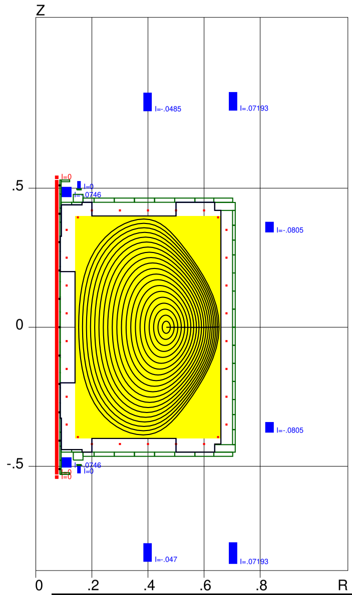
$$\boxed{\frac{d|B|}{dR} \simeq 2.5 \frac{T}{m}}$$

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

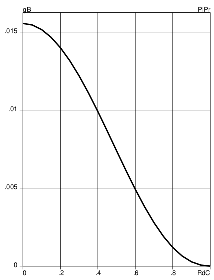
In addition:

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

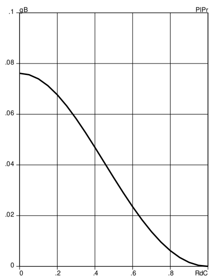
LTX is a very first step for developing a wall controlled plasma



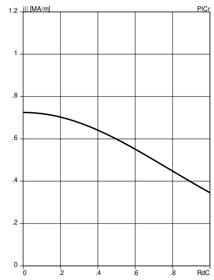
Wall is designed for different $j(r), p(r)$ and I_{pl}



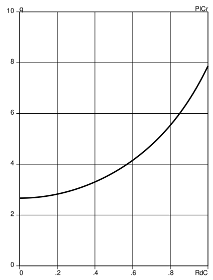
peaked $j_{||}$



pressure profile



flattened $j_{||}$

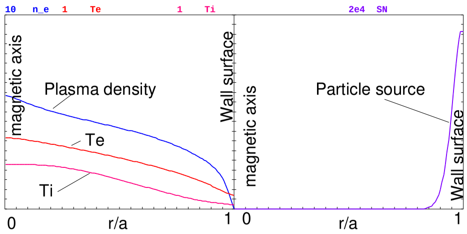


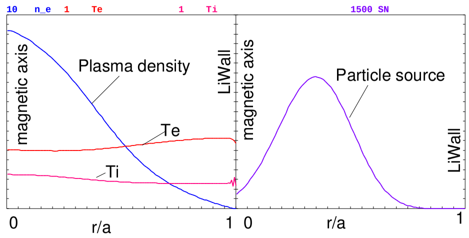
q- profile

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,



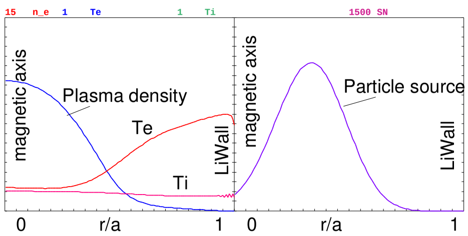


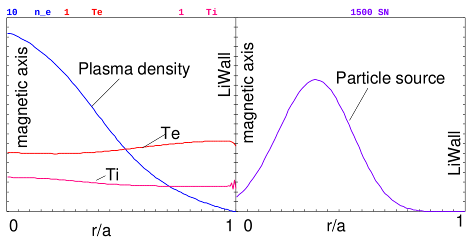
- development of a start-up scenario in presence of absorbing walls,
- development of a quasi-steady, pellet fueled plasma.

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.

4 New vision of mission of CTF, based on an Ignited ST

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.

Appendix. Ignition power estimate.

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

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

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

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