Fission-Fusion Research Facility (FFRF) as a Practical Step Toward Hybrids[1]

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15th International Conference on Emerging Nuclear Energy Systems

May 17, 2011, San Francisco, CA

[1]This work is supported by US DoE contract No. DE-AC02-09-CH11466.

Contents

1 Fusion energy from magnetic fusion

Top magnetic fusion achievements:

$Q_{DT} = 0.27$ $P_{DT} = 10.7$ ***MW 0.3 s 1994 TFTR***
$Q_{DT} = 0.62$ $P_{DT} = 16.1$ ***MW 0.7 s 1997 JET***
$Q_{DT} = 0.18$ $E_{DT} = 21.7$ ***MJ 5 s 1997 JET***

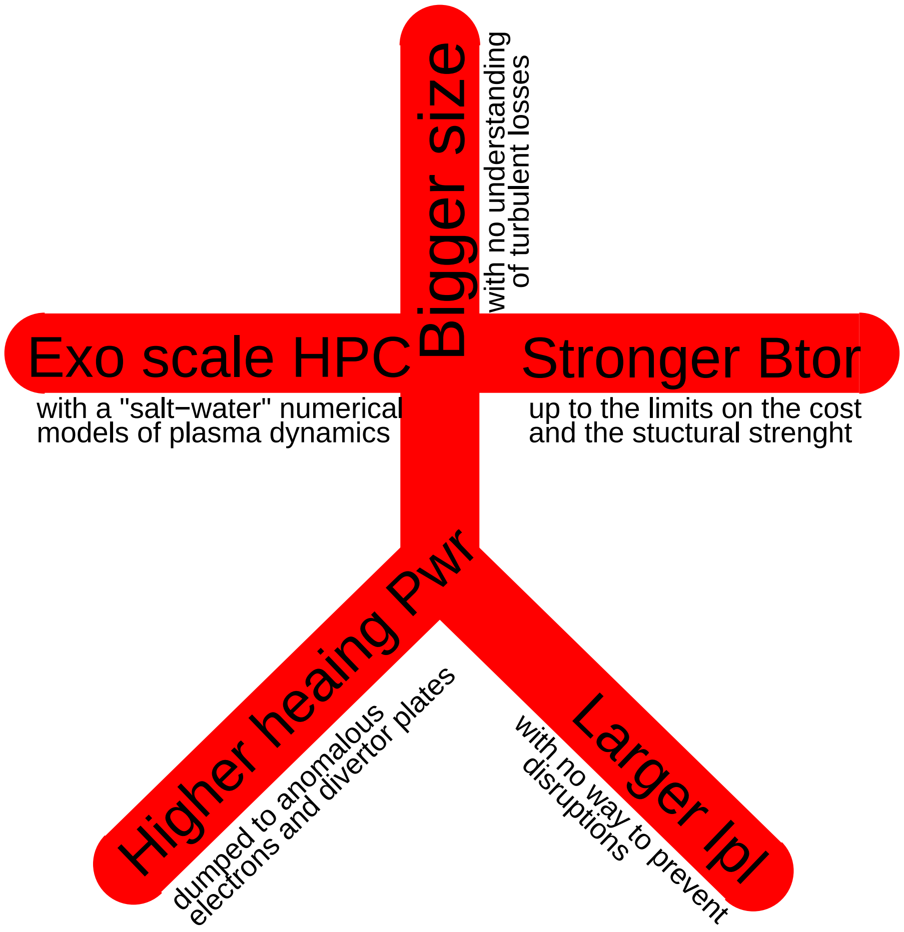
(Jet Experiments in Deuterium-Tritium Keilhacker, Watkins, JET Team Europhysics News November 1998)

After this, DT power was not produced for more than decade

The question is:

Instead of a "noble" goal ITER → DEMO → PROTO → . . . → inexhaustible energy source can magnetic fusion become a 30-100 MW neutron source for potential applications in nuclear energy and technology ?

Conventional approach relies on 5 “Bigs”



+ Massive (Big # 6 !) Gas Injection (MGI)
+ Big promises of fusion power to the grid

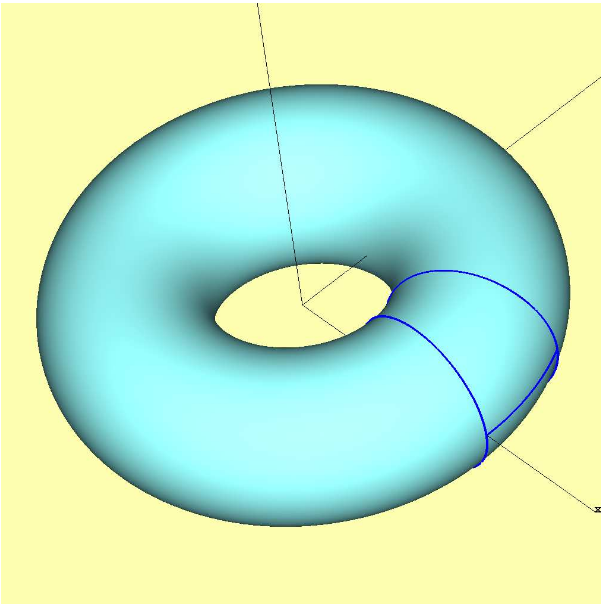
Chinese character “Big” has no legs for all “Bigs” of fusion

Every “Big” creates additional plasma physics and technology problems.

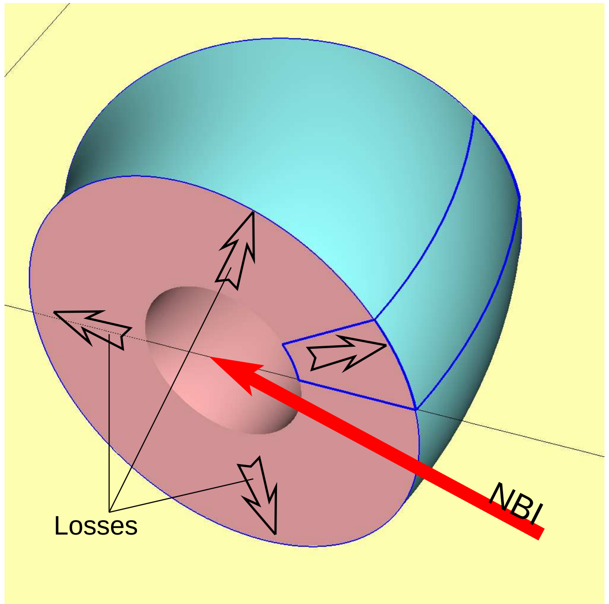
With numerous plasma physics problems unresolved, the conventional approach has been essentially exhausted at the level of TFTR and JET.

Can we still go forward ?
What kind of reserves is still not utilized ?

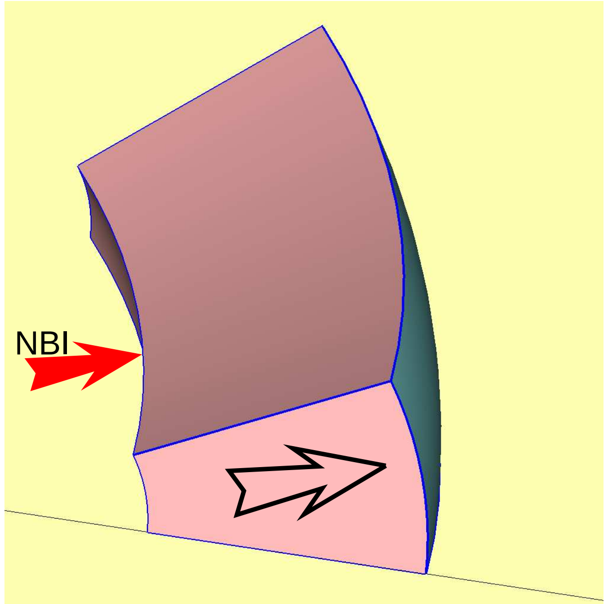
2 Revealing intrinsic potential of magnetic fusion



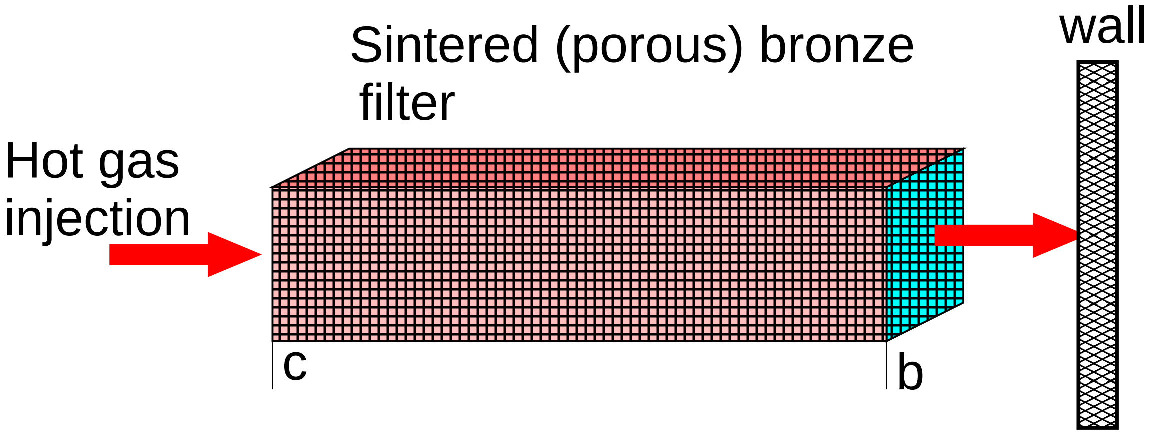
Full tokamak plasma column



A sector of a tokamak plasma with NBI delivering energy and particles to the core



Fraction of plasma sector for easy analysis



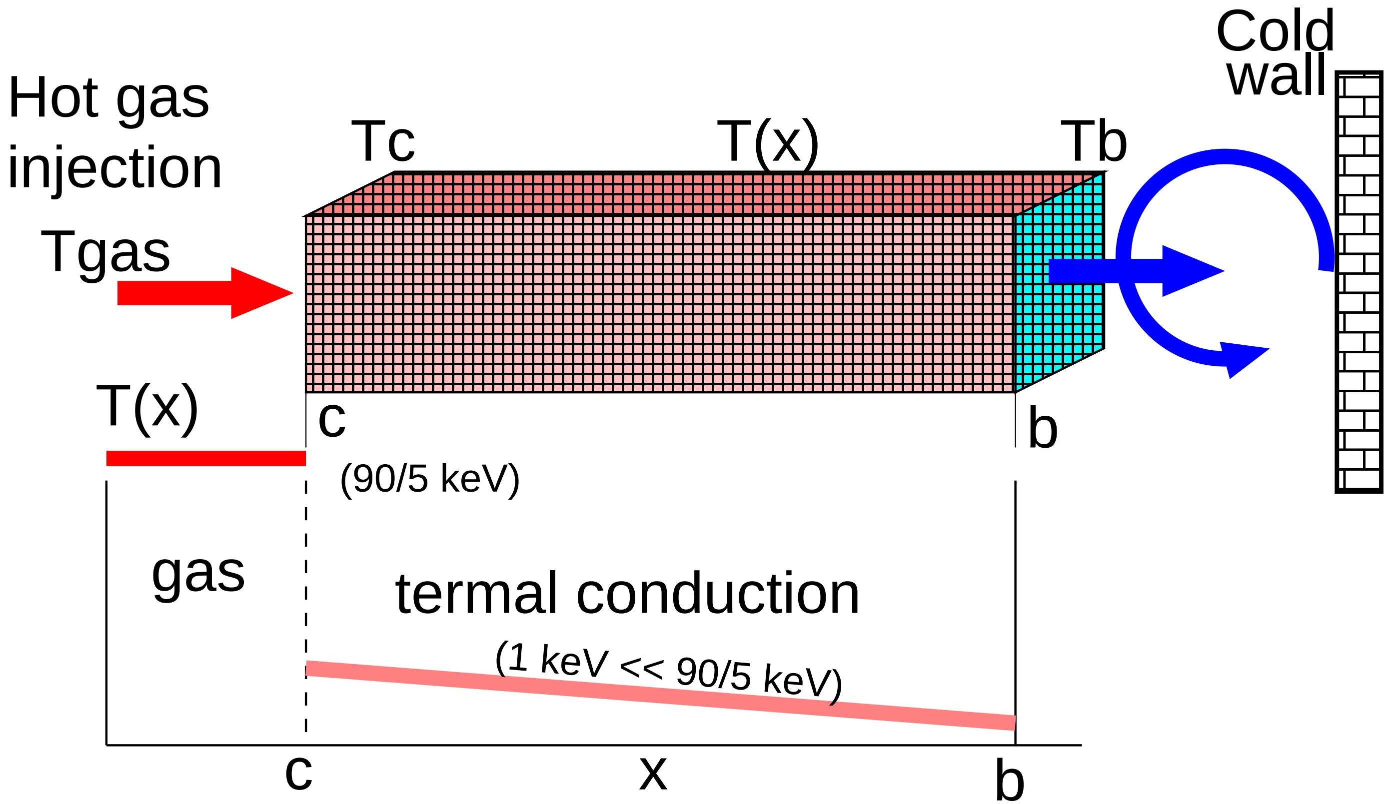
Close analogy with tokamak confinement

Tokamak plasma	*Sintered bronze filter*
high χ_e	*high metal* χ_e
modest χ_i	*modest gas* χ_g
modest diffusion D	*modest diffusion* D_g
core NBI fueling	*left-side gas supply*
core NBI heating	*left-side heat supply*

Regime controlled by thermal conduction

Two fundamentally different regimes are possible

Case 1 (analogous to conventional plasma regimes).

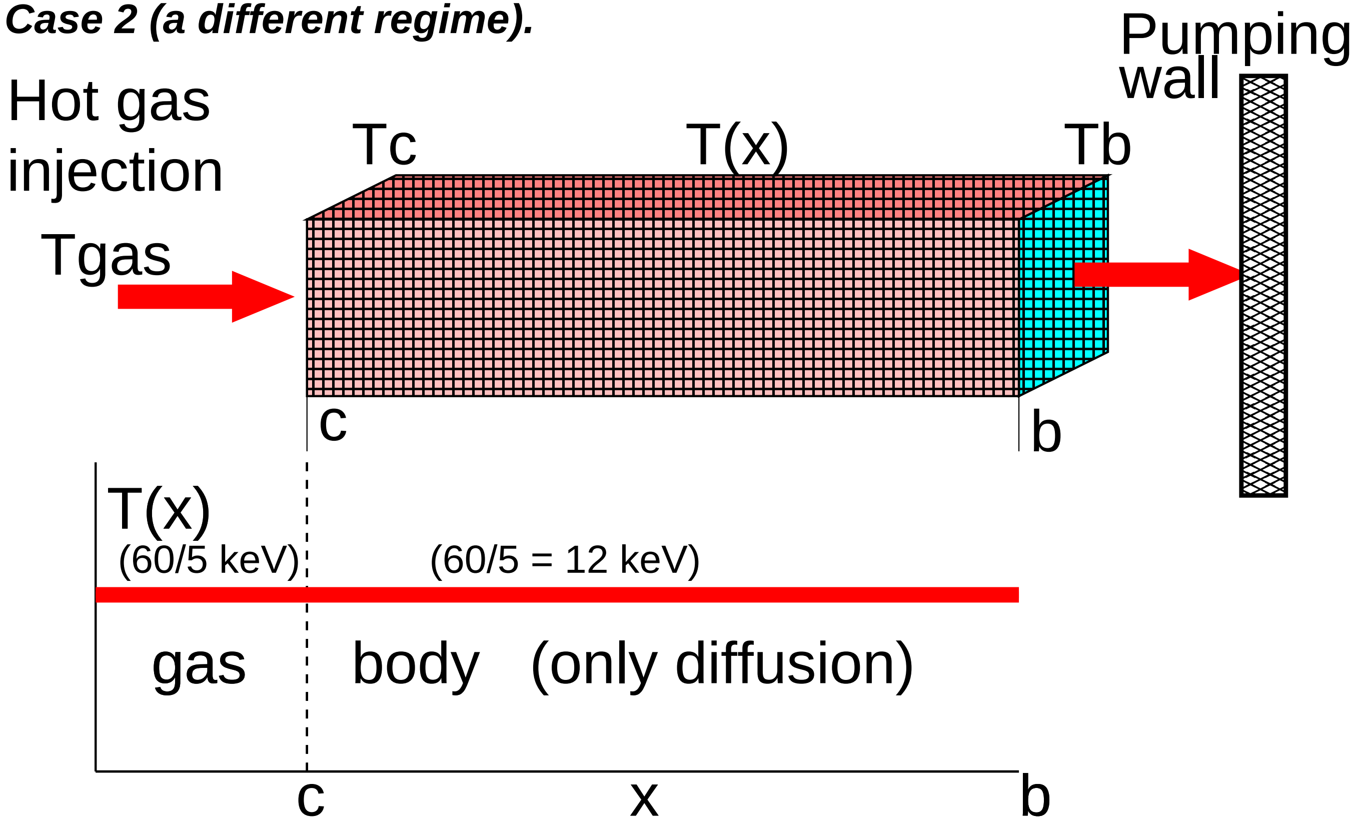


$$\Gamma^{edge\to wall} \gg \Gamma^{\to core}, \qquad \frac{5}{2}\Gamma^{edge\to wall}T_b = \frac{5}{2}\Gamma^{\to core}T_{gas}, \qquad T_b \ll T_{gas}$$

$$\rho c_p\frac{\partial T}{\partial t} + \rho c_p V\frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\kappa\frac{\partial T}{\partial x}, \quad \rho c_p V(T_{gas} - T_c) = \kappa\frac{T_c - T_b}{x_c - x_b}, \quad \rho c_p V \ll \frac{\kappa}{x_c - x_b}.$$

Diffusion based confinement regime

Case 2 (a different regime).



$$\Gamma^{edge\rightarrow wall} = \Gamma^{\rightarrow core}, \qquad \frac{5}{2}\Gamma^{edge\rightarrow wall} T_b = \frac{5}{2}\Gamma^{\rightarrow core} T_{gas}, \qquad T_b = T_c = T_{gas}$$

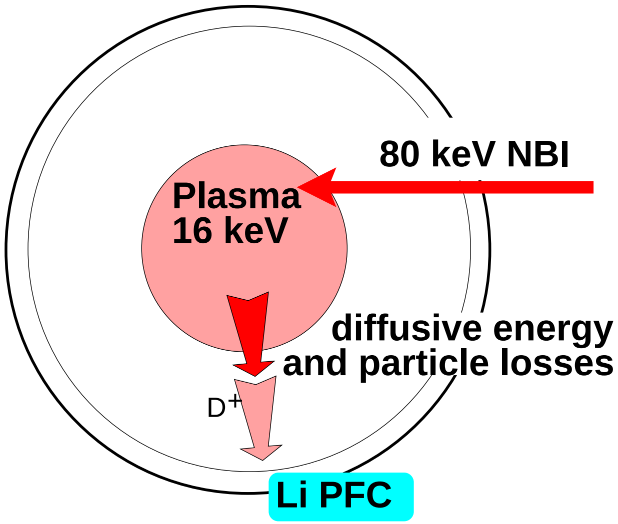
$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p V \frac{\partial T}{\partial x} = \frac{\partial}{\partial x}\kappa\frac{\partial T}{\partial x} = 0.$$

Right boundary, rather than the core, is the key to good confinement

The LiWall Fusion (LiWF) concept

NBI for core fueling & heating + Pumping LiWall conditions

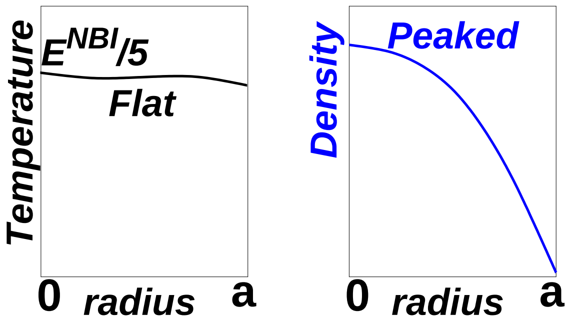
(Limited plasma edge cooling: $R^{ecycling} < 0.5$, $\Gamma^{gasI} < \Gamma^{NBI}$)



The BEST possible confinement regime: energy losses are determined only by particle diffusion

The plasma physics is much simpler

In LiWF high edge T is OK



No ∇T-driven turbulence (ITG/ETG)

Potential TEMs affect only the density level with NBI as a source

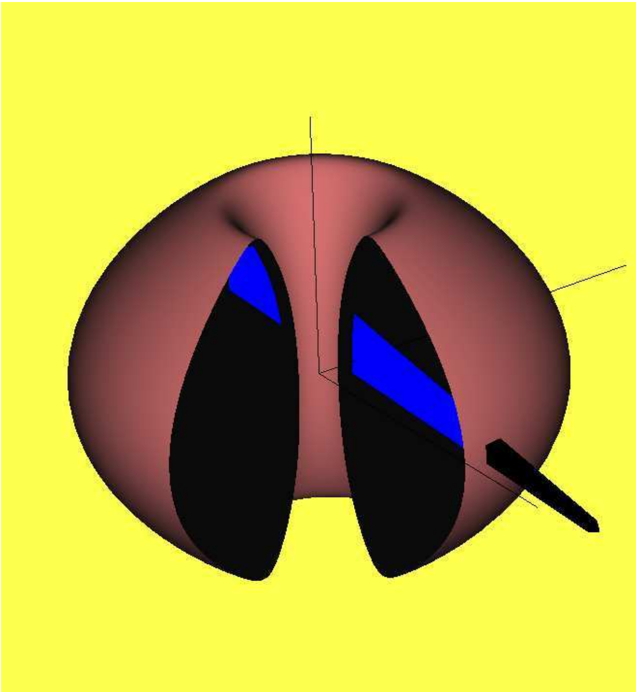
No Greenwald limit, saw-teeth, ELMs.

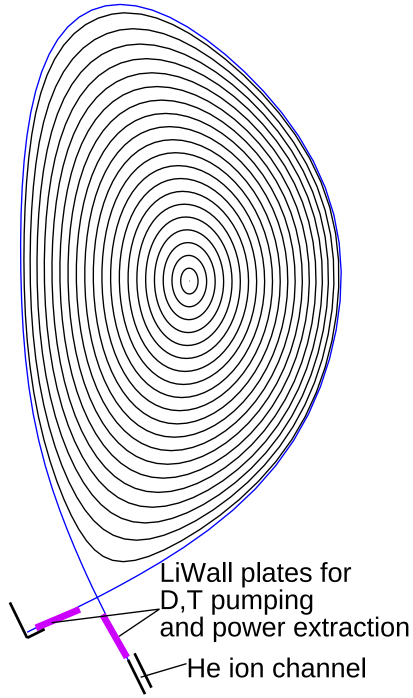
Entire plasma volume produces fusion

Anomalous electron thermal conduction plays no role

This simplest and best possible approach is suggested for FFRF

Implementation is straightforward





$$E_{NBI} = \left(\frac{3}{2}+1\right)(T_i+T_e),$$

$$\frac{T_i+T_e}{2} = \frac{E_{NBI}}{5}$$

$$E_{NBI} = 80\ keV \rightarrow$$

$$\rightarrow (T_e+T_i)/2 \simeq 16\ keV$$

Familiar "hot-ion" regime:

$$T_i > T_e$$

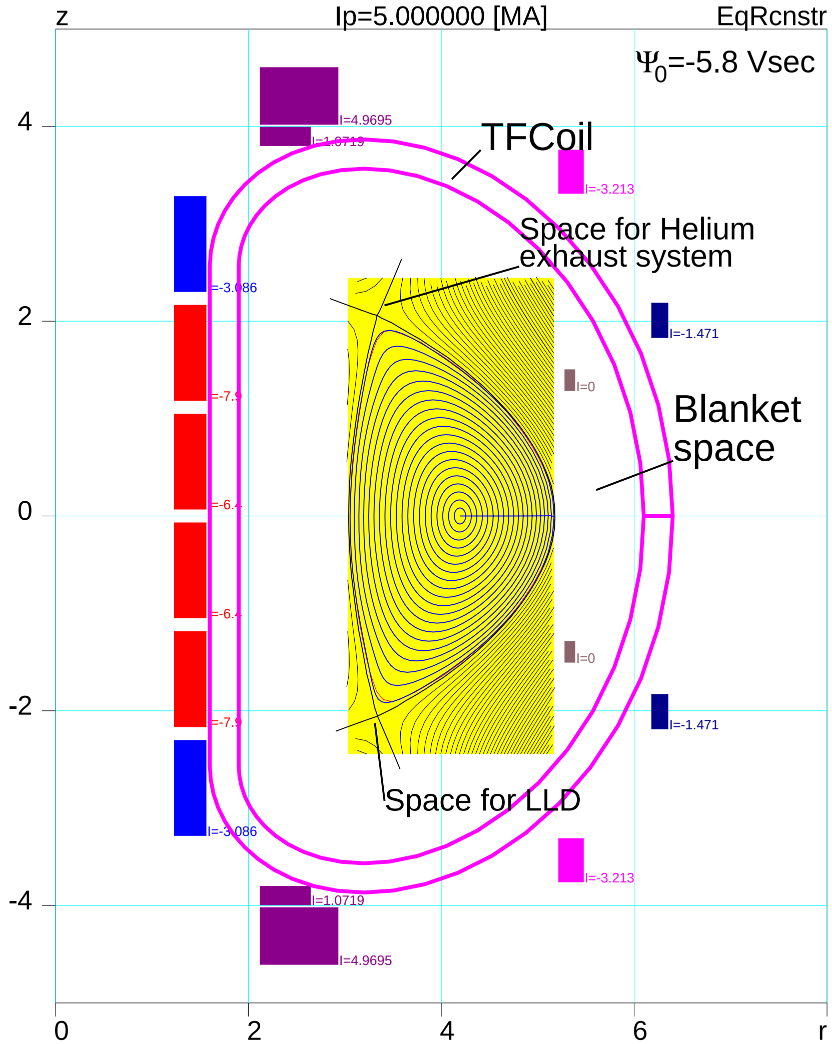
Thermalization of the beam is much faster than the particle diffusion.

Plasma temperature will be uniform automatically (plasma physics is not involved)

No mystery, no tricks. LiWF implements a very simple idea:

For toroidal plasma it is much more efficient to prevent plasma cooling by neutrals from the wall than to rely on overwhelming heating power.

3 Parameters of FFRF and mission



Parameter	FFRF
$d_{blanket,m}$	1
a_m, R_m	1.0, 4.0
$V^{pl}_{m^3}, S^{pl}_{m^2}$	130, 230
n_{20}	0.4
E^{NBI}_{keV}	120
$\frac{T_i+T_e}{2}\Big\vert_{keV}$	24-27
$B_{t,T}$	4-6
$I_{pl,MA}$	5
$\Delta\Psi_{f-top,Vsec}$	40
$W_{th,MJ}$	42
$\tau^{ind}_{E,sec}$	20-7
P^{NBI}_{MW}	2-5
P^{DT}_{MW}	50-100

Active fission core power 80-4000 MW. He cooling is possible.

FFRF can be potentially the next step device in PRC

Mission

The mission of FFRF is to advance fusion to the level of a (quasi-)stationary neutron source and to create a technical, scientific, and technology basis for utilization of 14 MeV fusion neutrons for needs of nuclear energy and technology.

FFRF is a research, rather than application device.

For its justification, FFRF does not need to compete with, e.g., fast breeder reactors

FFRF has both fusion and FFH missions

4 Burning plasma regime of FFRF

In burning plasma 90 % of α-particle energy goes to electrons, which do not produce fusion but contribute to MHD β.

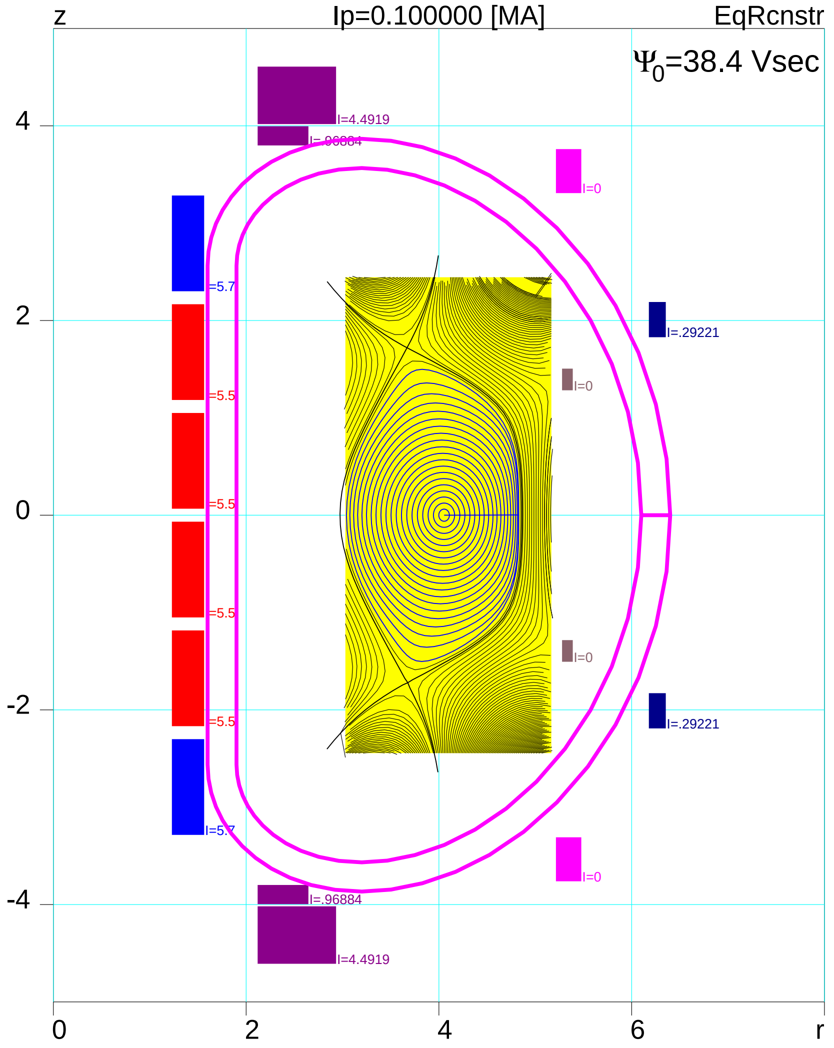
The LiWF regime does not need α-particle heating.

The question is: will the hot-ion regime survive in the burning plasma ?

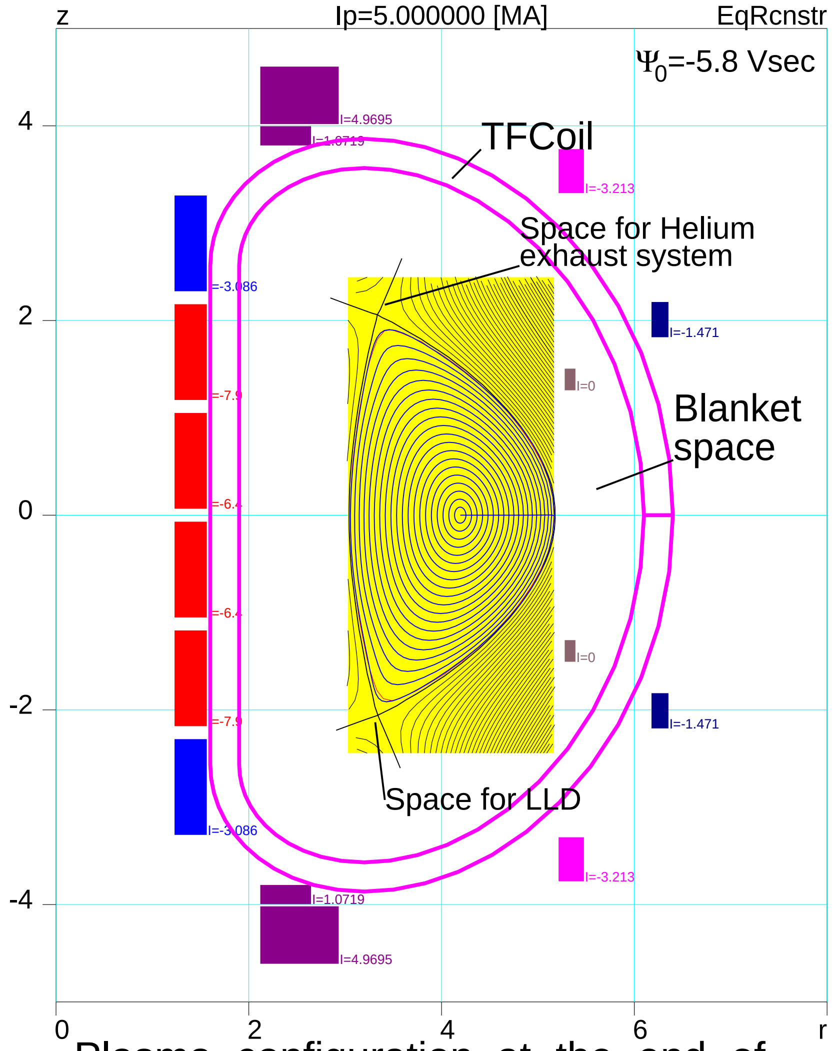
For spherical tokamaks the answer is almost for certain "Yes". Even for $I_{pl} = 8.4$ MA, 60 % of α-particles can be intercepted at first orbits.

Is the LiWF regime applicable to the burning plasma with $I_{pl} = 5$ MA in conventional tokamaks, like FFRF ?

4.1 Volt-second capacities of FFRF: 40 V-sec



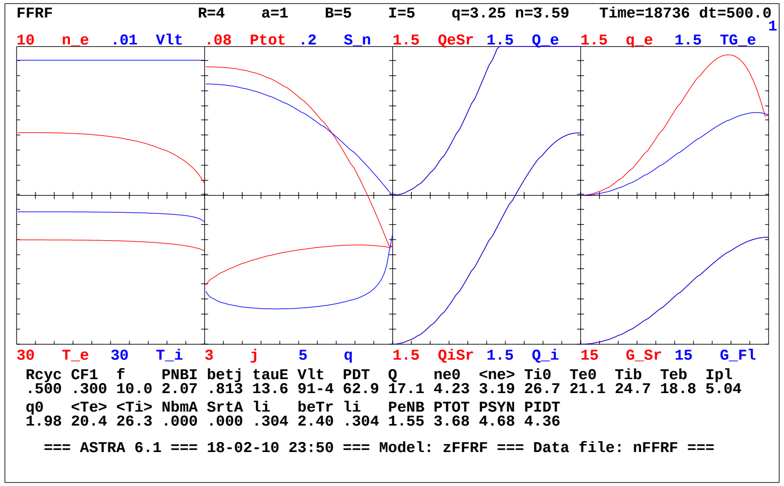
Initial plasma configuration



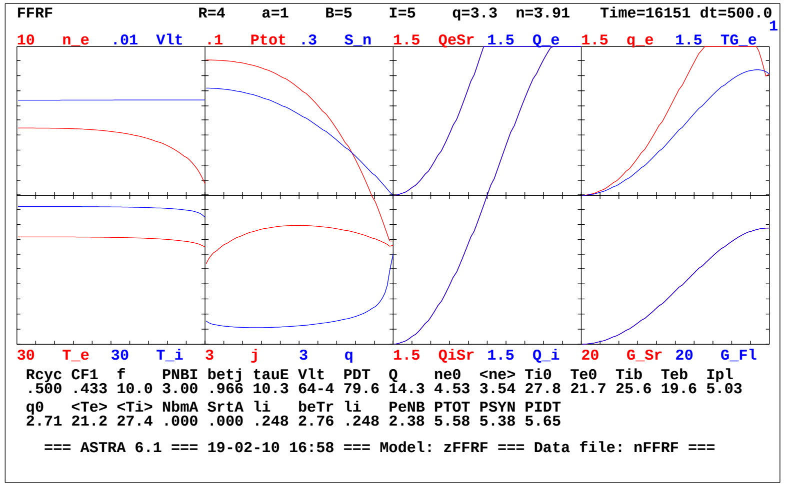
Plasma configuration at the end of End of flat-top

About 40 V-sec is available for the flat-top of inductively driven plasma current.
($-6\ T \le B^{CS} \le 6\ T$)

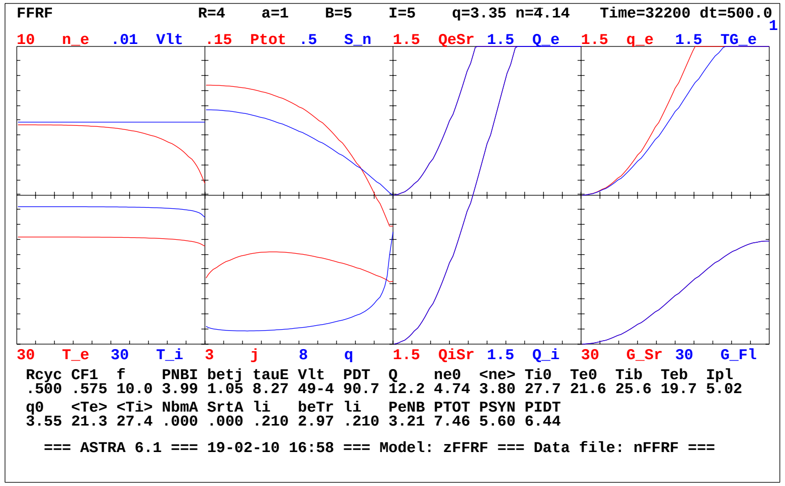
Examples of stationary hot-ion burning plasma regimes in FFRF with
$R^{ecycl} = 0.5, \ \Gamma^{gas} = 0, \ f = 10$ (factor of anomaly of $\chi_e = f\chi_i$)



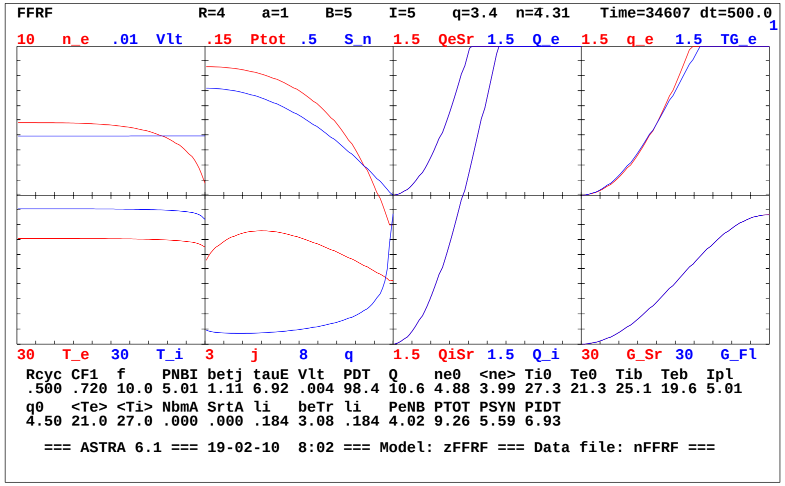
$P^{NBI} = 2$ MW



$P^{NBI} = 3$ MW



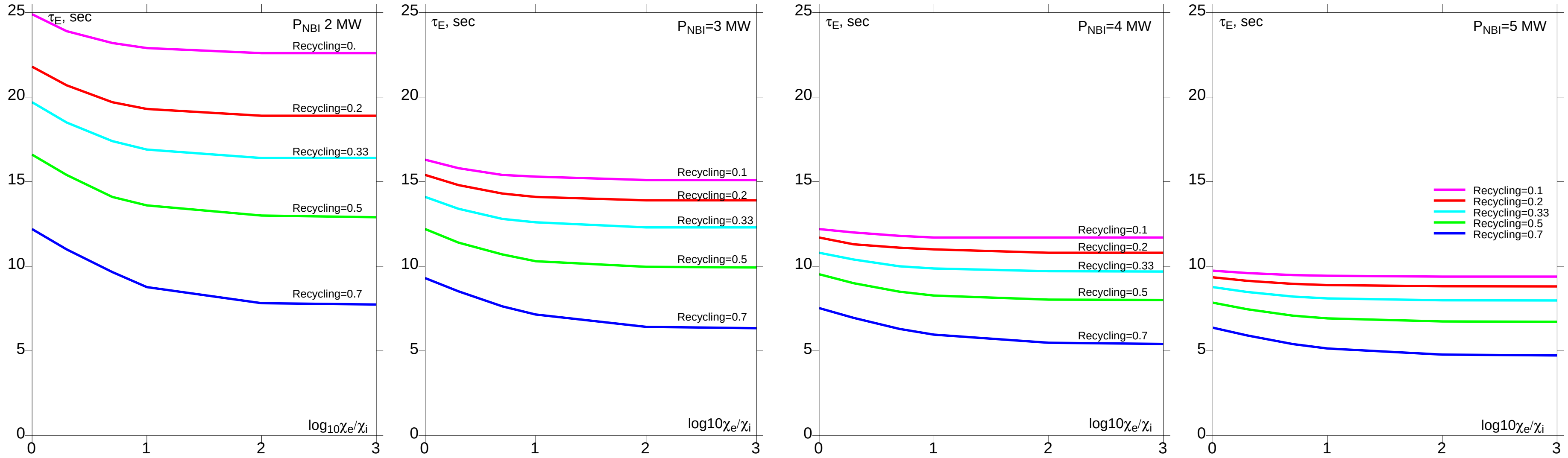
$P^{NBI} = 4$ MW



$P^{NBI} = 5$ MW

4.2 Energy confinement time: 7-20 s

In calculations 50 % of α-particle energy was released in the plasma (assuming loss of energetic particles). Dilution of plasma was neglected.



$P^{NBI} = 2$ MW $\quad P^{NBI} = 3$ MW $\quad P^{NBI} = 4$ MW $\quad P^{NBI} = 5$ MW

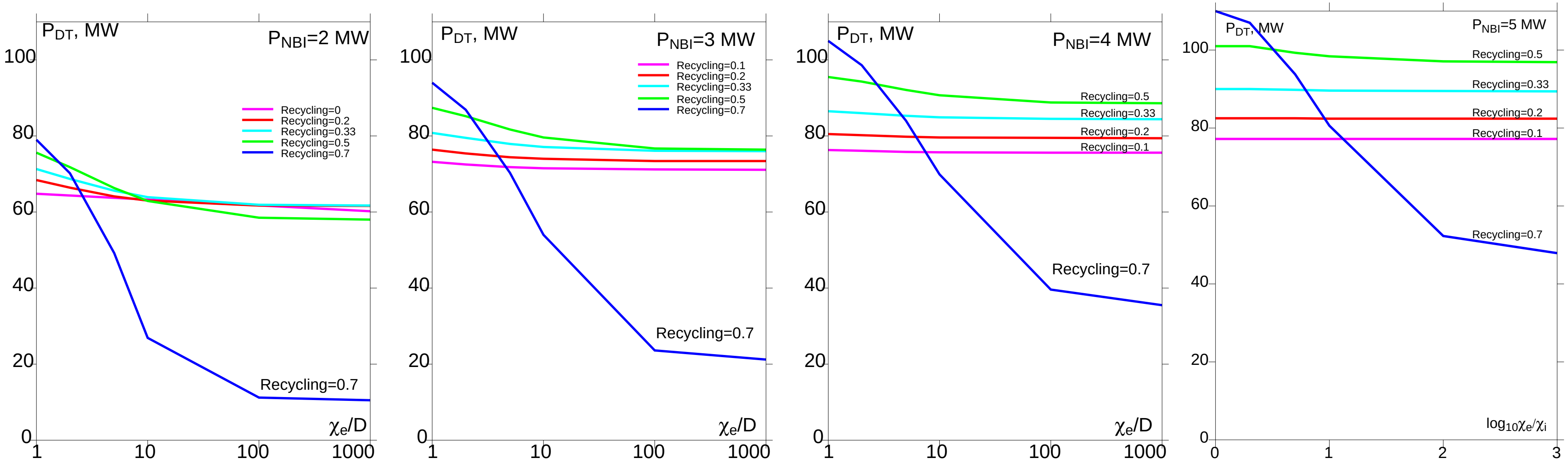
Energy confinement time in LiWF regime for different R^{ecycl} as function of

$0 \le \log_{10}\chi_e/\chi_i \le 3$ $(1 \le \chi_e/\chi_i \le 1000)$.

LiWF regime is not sensitive to anomalous electron thermal conduction, which is the major root reason of problems in magnetic fusion.

4.3 Fusion power: 50-100 MW

High recycling $R^{ecylc} > 0.6$ (as in conventional fusion) is devastating for fusion power production.



$P^{NBI} = 2$ MW　$P^{NBI} = 3$ MW　$P^{NBI} = 4$ MW　$P^{NBI} = 5$ MW

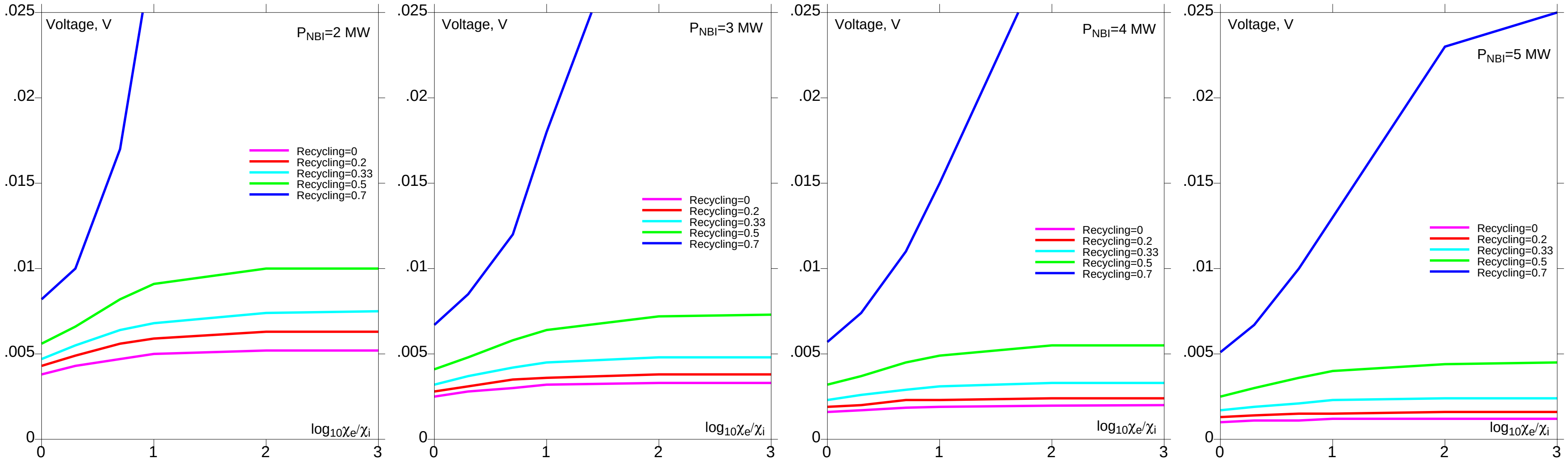
Fusion power time in LiWF regime for different R^{ecycl} as function of

$0 \leq \log_{10} \chi_e/\chi_i \leq 3$ $(1 \leq \chi_e/\chi_i \leq 1000)$.

At the practical level of recycling coefficient $R^{ecycl} < 0.5$, the burning plasma regime with $P^{DT} = 50 - 100$ MW is possible in FFRF

4.4 Duration of the inductive regime: 1-2 hours

With limited recycling $R^{ecylc} < 0.5$ the loop voltage in FFRF is smaller than 0.01 V.



$P^{NBI} = 2$ MW $P^{NBI} = 3$ MW $P^{NBI} = 4$ MW $P^{NBI} = 5$ MW

Loop voltage in stationary stage for different R^{ecycl} as function of

$0 \leq \log_{10} \chi_e/\chi_i \leq 3$ $(1 \leq \chi_e/\chi_i \leq 1000)$.

With 40 Vsec of the flux swing, a simple 1-2 hour inductive regime is possible in FFRF. This makes FFRF exceptionally consistent with its mission

5 Summary

The LiWF suggests the Best possible burning plasma regime for FFRF, which makes it realistic as a fusion device:

1. ***the best possible (diffusion based) confinement***
2. ***the best possible core MHD stability (no saw-teeth)***
3. ***the best possible plasma edge stability (no ELMs)***
4. ***the best possible stationary plasma-wall interaction (no thermo-force)***
5. ***the comprehensive plasma control by NBI and edge conditions (not a hostage of plasma unknowns)***
   - ***(a) hours long inductive regime***
   - ***(b) the best possible conditions for non-inductive current drive***
   - ***(c) the best possible power extraction approach - synchrotron radiation***
   - ***(d) no reliance on α-heating***
   - ***(e) the best possible use of plasma volume for fusion***
   - ***(f) the best possible helium ash exhaust regime***

The real question is "How good is the Best ?"

Crucial and well specified plasma physics and fusion technologies have to be developed in parallel with the design work on FFRF in order to answer this question.