ITER as a prototype of a Fission Fusion Hybrid . The fastest way to fusion power .

V. Chuyanov

First Workshop on MFE Development Strategy in China

January 5-6, 2012

Content

1. Possible missions of nuclear fusion.
2. Possible parameters of a blanket with natural /depleted Uranium.
3. Power balance of a fusion/fission hybrid reactor and requirements to the fusion part.
4. ITER as hybrid fusion /fission reactor.
5. Safety considerations.
6. Some planning considerations.
7. Conclusions.

Possible Missions of Fusion Reactors. 1

Possible Missions of Fusion Reactors	Pro	Con	Time frame
Pure fusion	Practically inexhaustible fuel resource. Wastes are easy to manage. No criticality risks from a safety point of view: small fuel or radioactive inventory, minimal afterheat . Pure fusion has the potential to be essentially qualitative superior to fission environmentally Fusion plants will have tritium, but no fissile fuel cycle and no actinides on site. In regard to proliferation inspections would be technically straightforward.	Net energy production has not yet been demonstrated. Even not all the physics problems have been solved. Problems with materials (first-wall heat handling, thermo-mechanical loads and 14 MeV neutron damage) High complexity . The very large scale of fusion devices make it difficult to realize small-scale, energy-producing prototypes.	Long term . > 40- 50 years

Possible Missions of Fusion Reactors.2

Possible Missions of Fusion Reactors	Pro	Con	Time frame
Fusion -fission hybrids Three potential hybrids missions: Energy production, Fuel supply and Waste management.	To support fission energy through breeding fuel and/or burning fission wastes. To reduce the requirements on the fusion system first-wall loading , reduce 14 MeV neutron damage - and as a result - accelerate the deployment of fusion energy.	No qualitative difference with fission to justify public acceptance : The same (general) resource limitation. The same fission wastes. Similar with fission safety concerns . Major proliferation concerns	May be shorter than for pure fusion - 15-20 years if needed.
Waste transmutation Actinides burners	In comparison with breeders the total system cost may be lower.	Not a technical but political problem . There are cheaper ways to do it	Probably , not needed
Energy production (blankets with high energy amplification)	No criticality requirements . Minor safety advantages relative to fission . Deep burnout	Will be always more expensive than fission . High initial loading of fissile material. Long doubling time if used as breeder.	May be developed for 15-20 years , but probably , not needed
Fuel supply (Nat. U^{238} or depleted U^{238}) , low energy multiplication	Deep burnout or fuel supply for fission reactors without limitation of doubling time .	Not important now for some countries. BUT May be important for others	Depends on a country 15-100 years

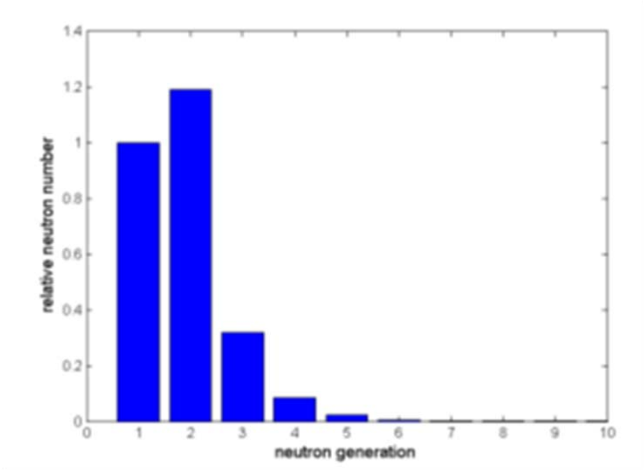
Blanket with natural /depleted Uranium

- Fusion produces fast (14 MeV) neutrons.
- These neutrons can fission U238 with energy release 196 MeV
- Each fission produces ~ 4.5 neutrons .
- At least one of them must be used for reproduction of Tritium burned in a fusion reactions. Others will leak out, captured by construction materials or by U_{238} with production of Pu_{239} These neutrons can also fission U_{238} , however in blankets with depleted or natural U_{238} the probability of fission is not high and the addition to the fission by fast neutrons is relatively small
- Fission is the main source of energy in such blankets . Generation of energy by other processes is relatively small and in the first approximation the energy multiplication factor can be written as

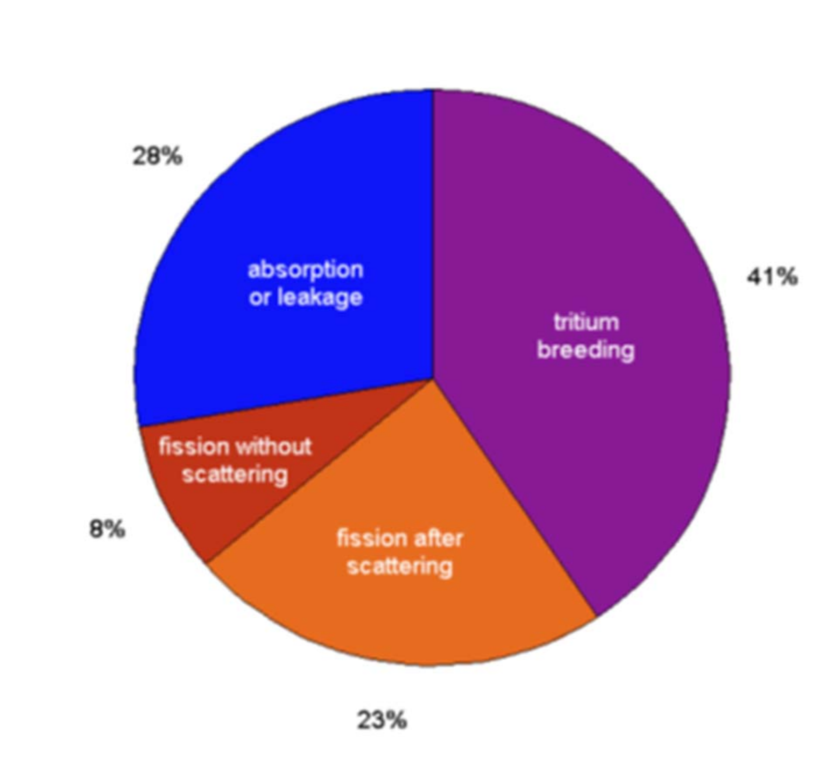
$$M \sim (200\text{MeV}/14\text{Mev})^* K_f$$

- Here K_f is a number of fission events per one fusion neutron. **It strongly depends on the selection of materials and blanket design** but for deeply subcritical blanket $K_f < 1$ (0.2-0.5) and M ~3- 8.
- The number of Pu_{239} produced per a fusion neutron is ~0,5.

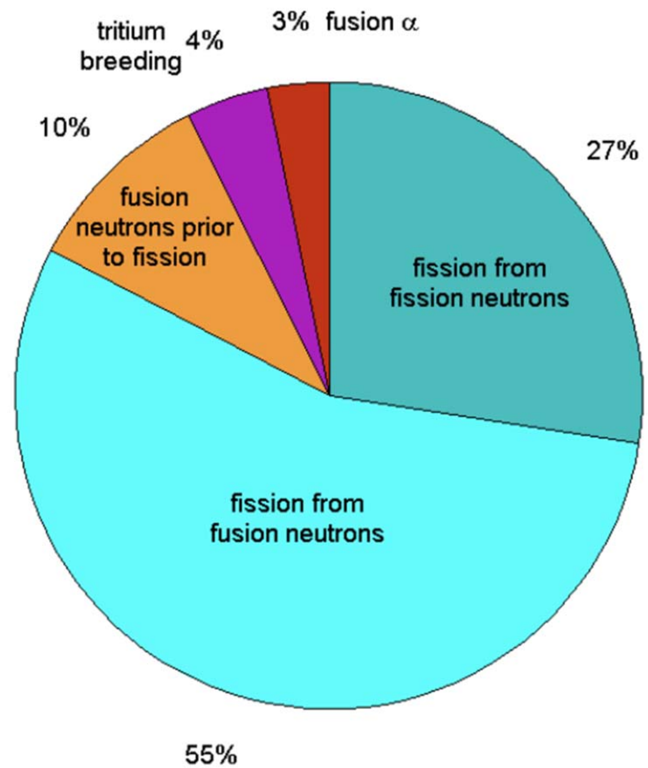
In a deeply subcritical blanket the fate of fusion 14 MeV neutrons determine the characteristics of the blanket.
Total number of secondary neutrons ~1.7 per a fusion neutron is small.
The fusion neutrons directly generate 2/3 of fissions



The number of neutrons in each generation throughout the hybrid system.



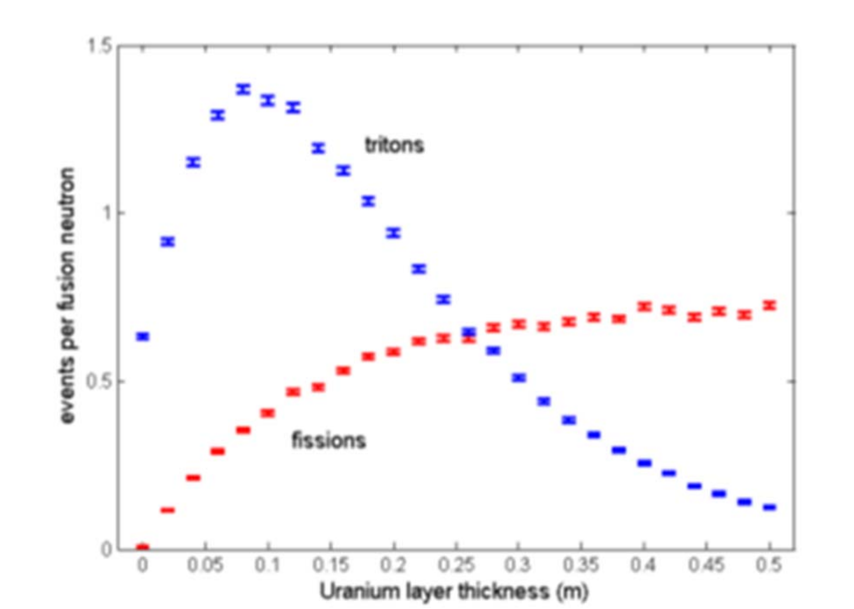
The fate of fusion-born (1st generation) neutrons.



The composition of the total hybrid power from various sources.

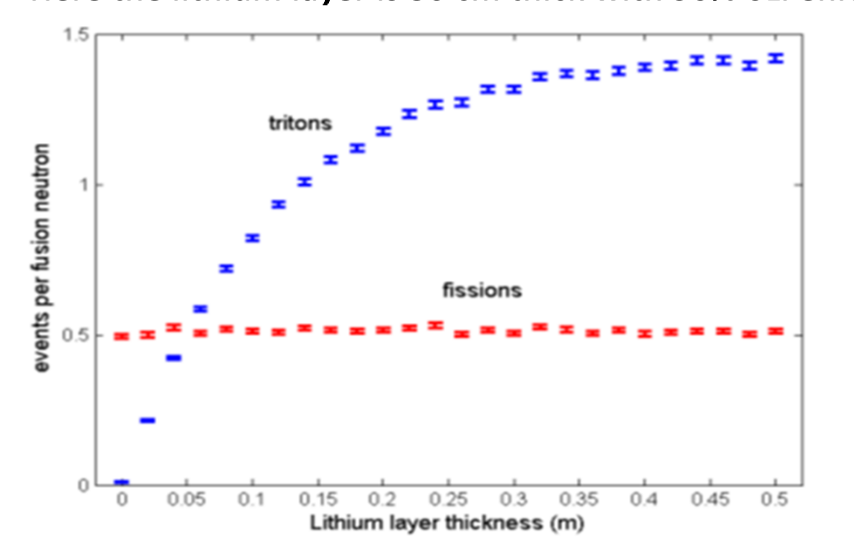
PSFC/RR-11-1
A Fission-Fusion Hybrid Reactor in Steady-State L-Mode Tokomak Configuration with Natural Uranium
Reed, M., Parker, R., Forget, B.
MIT January 2011

One Example of Blanket Parameters



UO_2 pebble layer thickness 18 cm
Li-Pb layer thickness 25 cm
Li enrichment 90%
Li atomic fraction in Li-Pb 10%
Fission ratio K_f 0.47
M ~7.7
Tritium breeding ratio 1.05

Fissions and bred tritons per fusion-born neutron as a function of uranium pebble layer thickness. Here the lithium layer is 30 cm thick with 90% 6Li enrichment. TBR>1 with 20cm of U layer.



Fissions and bred tritons per fusion-born neutron as a function of lithium layer thickness. Here the uranium layer is 15 cm thick, and the 6Li enrichment is 90% . K_f~constant

PSFC/RR-11-1
A Fission-Fusion Hybrid Reactor in Steady-State L-Mode Tokomak Configuration with Natural Uranium
Reed, M., Parker, R., Forget, B.*
MIT January 2011

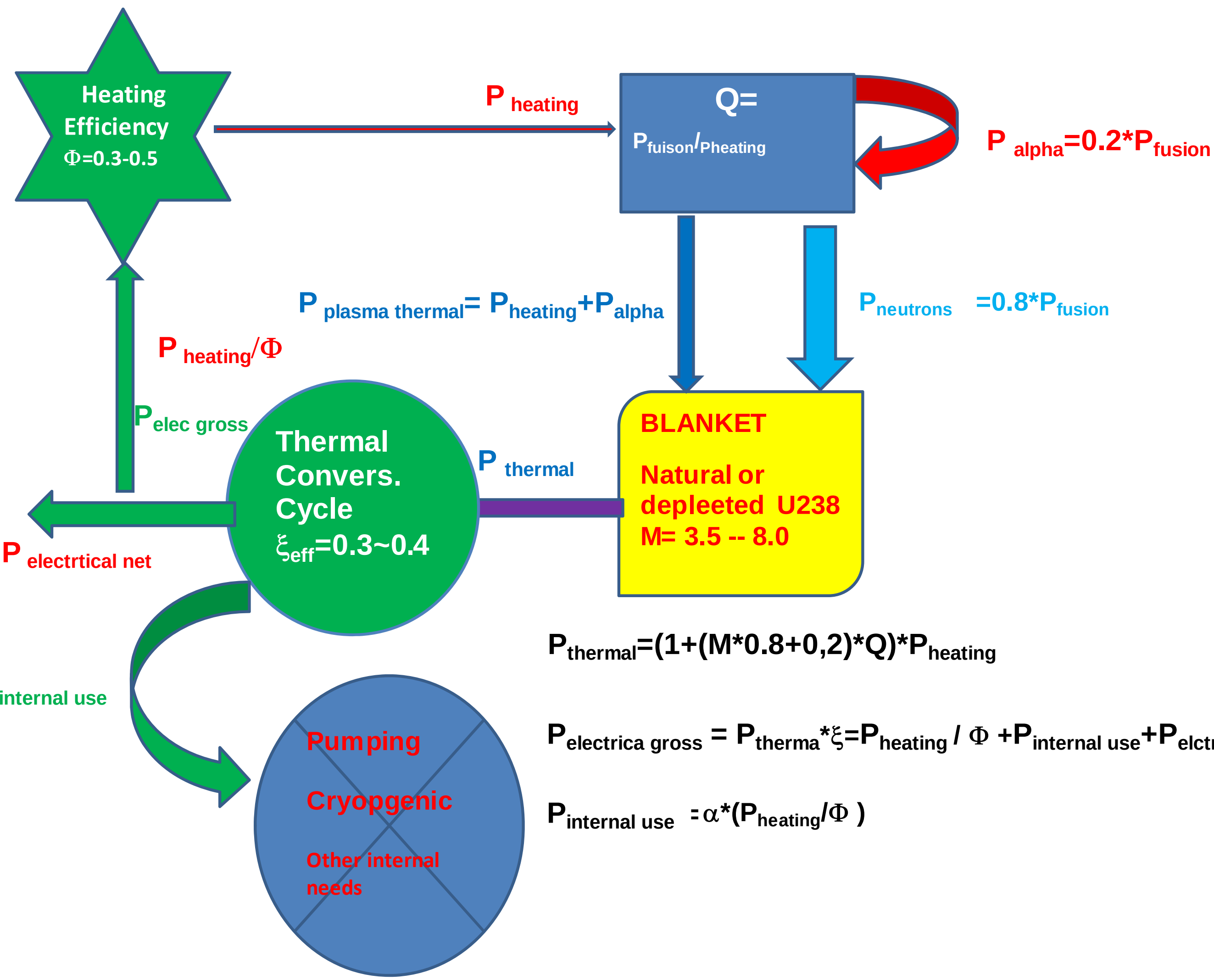
Fusion neutron wall loading requirement for a blanket with natural /depleted Uranium

- The mean free path of the fast (14Mev) neutrons in the solid materials is of the order 10-12 cms .
- Energy multiplication of fusion power M ~3-8.
- The density of energy W generated inside of the blanket is proportional to Fusion power wall loading

$$W\ (MW/m^3) = P_{fusion}(MW/m^2) * M / 0.1m$$

- Afterheat , generated in the fission blanket, proportional to density of the thermal power .
- Removal of this afterheat in the case of loss of coolant event is the main safety concern for fission-fusion blanket. The ability to remove the afterheat without melting of the blanket limits permissible wall loading
- If in case of pure fusion high wall loadings like 5-10 MW/m^2 are desirable, but in the fission fusion case, **the fusion neutron wall loading must be limited by <1 MW/m^2** .
- It gives W <30- 70 MW/m^3, compare the numbers with
  - PWR 75 MW/m^3
  - BWR 50MW/m^3
  - HTGR 7MW/m^3
  - LMFBR 530MW/m^3

Power balance of a fusion/fission reactor



$P_{thermal}=(1+(M*0.8+0,2)*Q)*P_{heating}$

$P_{electrica\ gross} = P_{therma}*\xi=P_{heating} / \Phi +P_{internal\ use}+P_{elctrical\ r}$

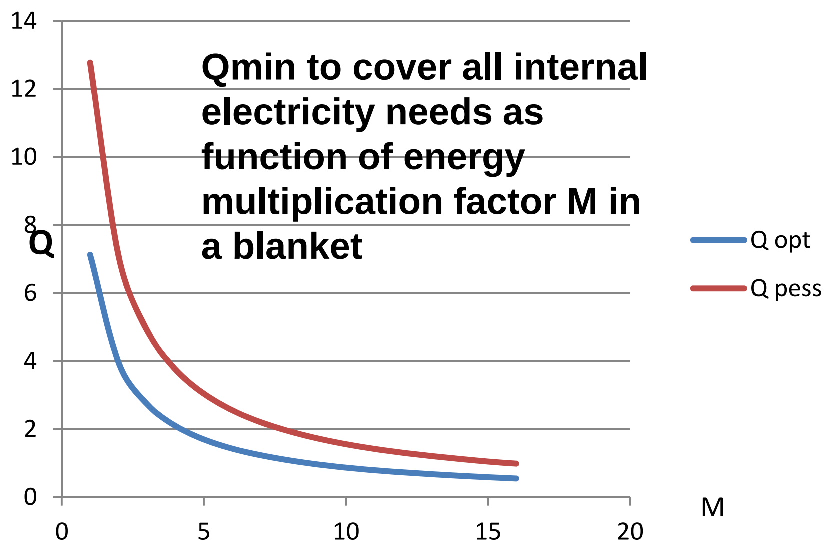
$P_{internal\ use} = \alpha*(P_{heating}/\Phi)$

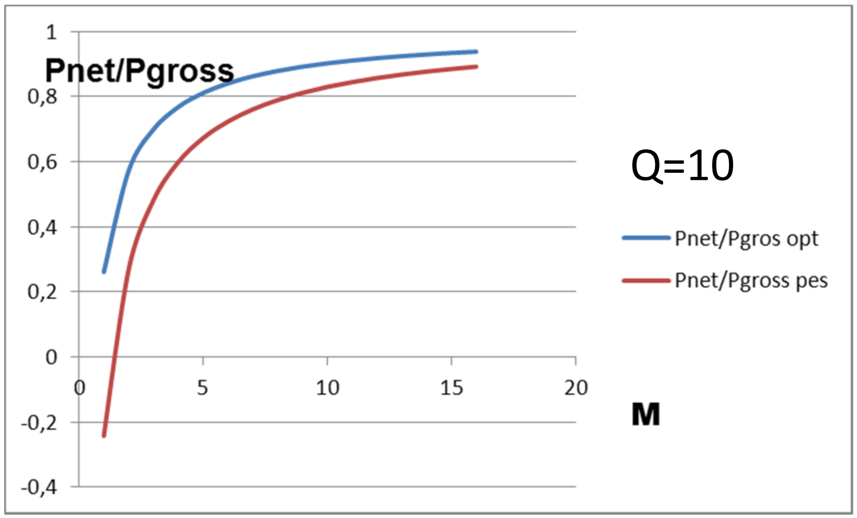
Requirements to the plasma part of a hybrid reactor as functions of blanket energy multiplication M

Pessimistic case	α=0.5	ξ=0,33	Φ=0,33	P $_{heating}$=70MW; P $_{heating}/\Phi$=212MW; P int =106MW (as ITER)
Optimistic case	α=0,3	ξ=0,4	Φ=0.4	50MW 125 MW 37.5 MW

For Pnet >0 Q>((1+a)/(ξ*Φ)–1)/(M*0.8+0.2)

$P_{net}=P_{heat}$*((1+(M*0.8+0.2)*Q)*ξ-(1+α)/Φ





Q pes (M=7) > 2,2
Q opt (M=7.7) >1,1

For Q=10 $P_{net}/P_{gross\ pess}$ (M=7)= 0,766;
$P_{net}/P_{gross\ opt}$ (M=7.7)= 0.866

ITER

Main Plasma Parameters and Dimensions

Total fusion power 500 MW *(700MW)*
Q = fusion power/auxiliary heating power ~10
Average neutron wall loading 0.57 MW/m2 *(0.8 MW/m2)*
Plasma inductive burn time >300 s
Plasma major radius 6.2 m
Plasma minor radius 2.0 m
Plasma current (Ip) 15 MA *(17.4 MA)*
Vertical elongation @95% flux surface/separatrix - 1.70/1.85
Triangularity @95% flux surface/separatrix 0.33/0.49
Safety factor @95% flux surface 3.0
Toroidal field @6.2 m radius 5.3 T
Plasma volume 837 m3
Plasma surface 678 m2
Installed auxiliary heating/current drive power73 MW *(100 MW)*
Operation equivalent to a few 10000 inductive pulses of <500 s.
Average fluence > 0.3 MWa/m2.
Device operation ~ 20 years. Tritium to be supplied from external sources

The inductively-driven pulse has a nominal burn duration of 300-500 s, with a pulse repetition period as short as 1800 s. (dwell time ~1000s for a series of short pulses)

For burn periods greater than 600 s. ITER shall operate with a duty factor of at least 25% (dwell time 1800s)

ITER shall be designed for an operational machine availability of at least 32% on average over ITER lifetime

Site Electrical power source must be able to provide up to 500 MW for pulsed loads as well as 120 MW for continuous loads.

ITER as Hybrid Fusion /fission reactor

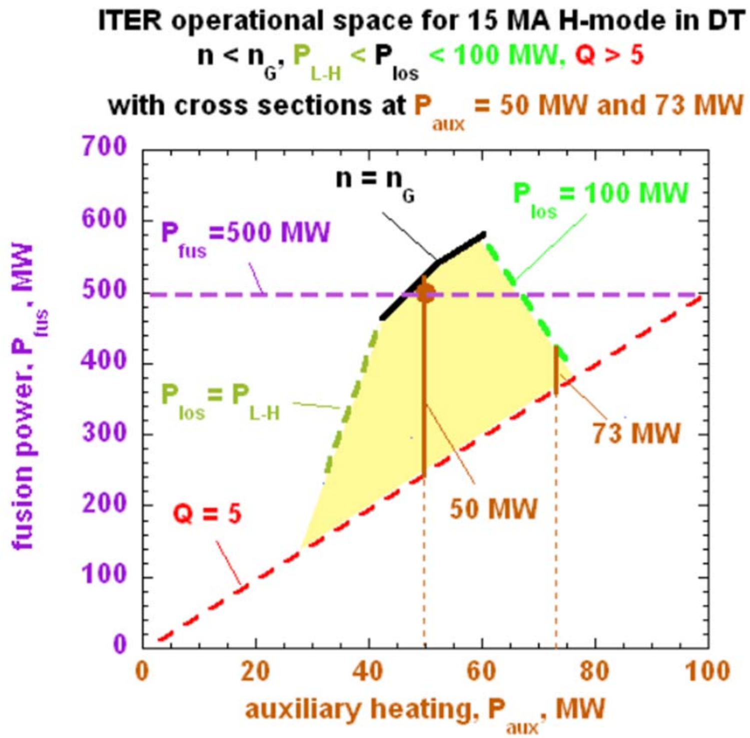
- *Heating Power 50 MW*
- *Fusion power 500 MW*
- *Blanket energy multiplication 7*
- *Total thermal power 2950 MW*
- *Electric Power Gross 973.5 MW*
- *Electric power for heating 150 MW*
- *Electric power for cryogenic/cooling 50 MW*
- *Electric power net 773 MW*
- *P net/P gross 0.794*
- *Availability in hybrid regime (3000s pulse, 1000s dwell) < 0.75 It is not sufficient .*
- *Electricity production 5E9 kWh /y*
- *(with price 2c/kWh 100 M$*
- *Plutonium production 861 kg/y*

(Weapon grade Pu costs 4000$/gram. Not cleaned plutonium is much cheaper . If the price of this plutonium >120E/gram, the cost of Pu will be higher than the cost of electricity)

- *Number of pulses per year 7884*
- *Possible operational time 30 y (15MWY/m2)*
- *Total number of pulses 236000 pulses*
- *ITER is designed for 30000 pulses (* ***8 times less****).*
- *Steady state operation is an important advantage but not strictly necessary*

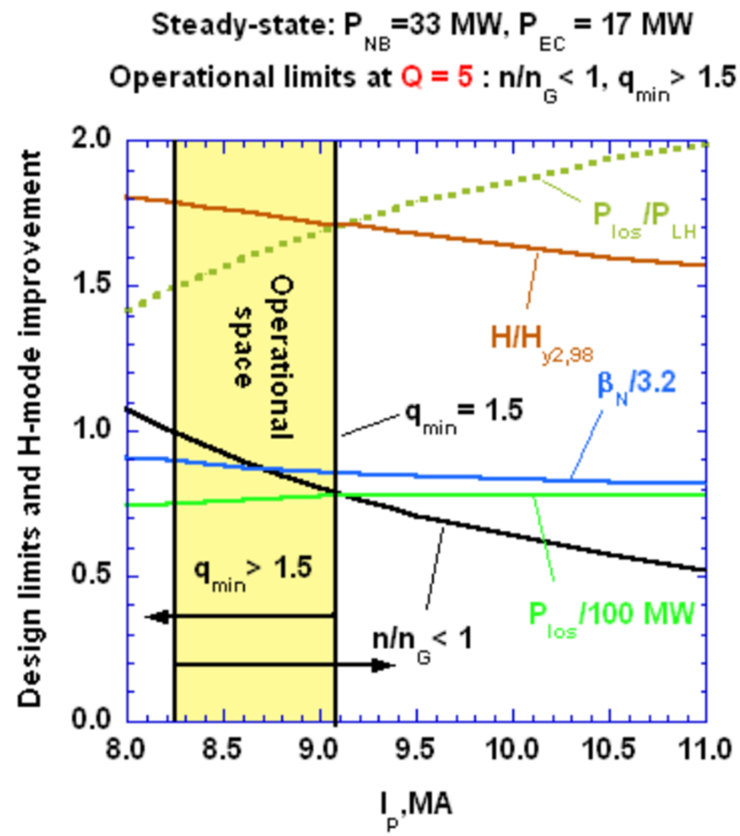
Operational space for ITER(1)

Inductive scenarios



Inductive mode15 MA :
Pfusion 500 MW; Q ~10 , H=1
but pulse length <400 s

Steady state scenarios

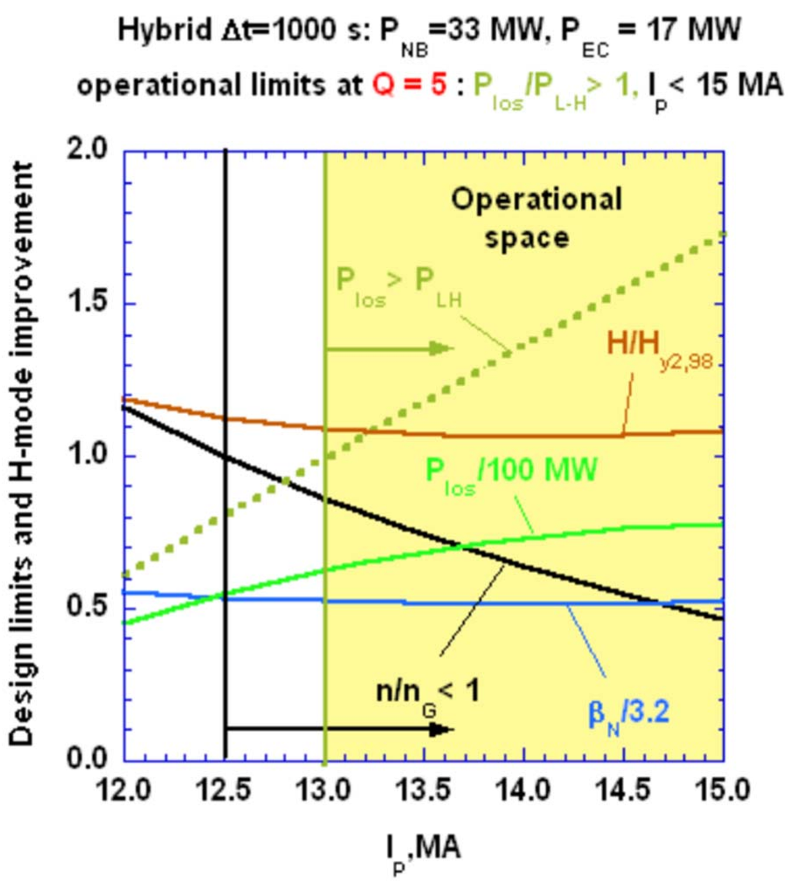


Steady state mode : I~8,5 MA , Pfusion=` 250 MW , Q=5 , β_N<1.5 but H = 1,7.
In the range of 8-10 MA, to get a Q of 3-6 and fully not inductive current drive the H-multiplier must be of order ~ 1.7

(A.Polevoy37th EPS Plasma Physics Conf. (Dublin, Ireland, 2010) P2.187)

Operational space for ITER (2)

Hybrid scenarios



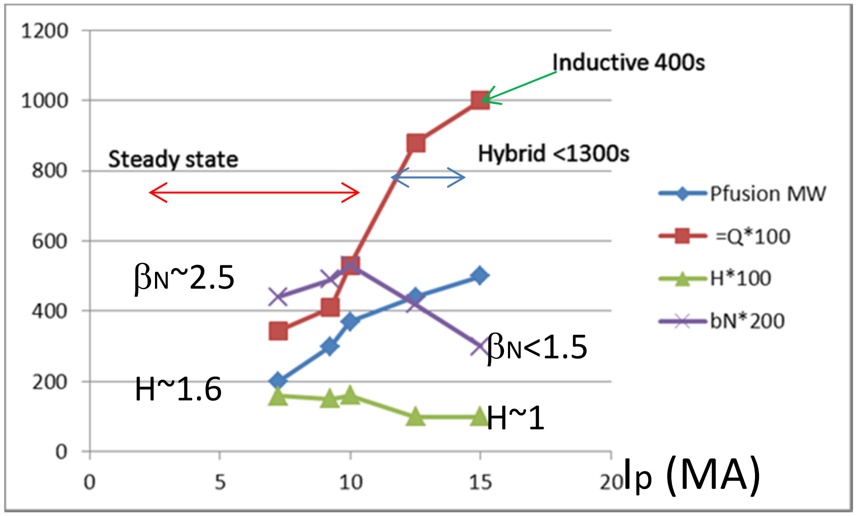
Hybrid mode of operation: I>13MA, Pfusion 250 MW, H~1,1 but only pulse length only 1000s

- **Hybrid scenarios: Q ≥ 5, ∆t = 1000s, Paux = 50 - 73 MW do not require enhanced energy confinement H~1, Ip= 13 - 15 MA.**
- **The hybrid scenario at 12.5 MA can access 900-1300 s flattop burn times and Q~7 with H~1.25. (The non-inductive current fraction is about 0.35, β_N ~ 2-2.2)**
- **With enhanced confinement (H>1) much longer pulses (>3000s) with Q >5 are possible.**
- **Enhanced confinement is necessary to achieve long pulses in all regimes. But hybrid regimes promise higher Q.**

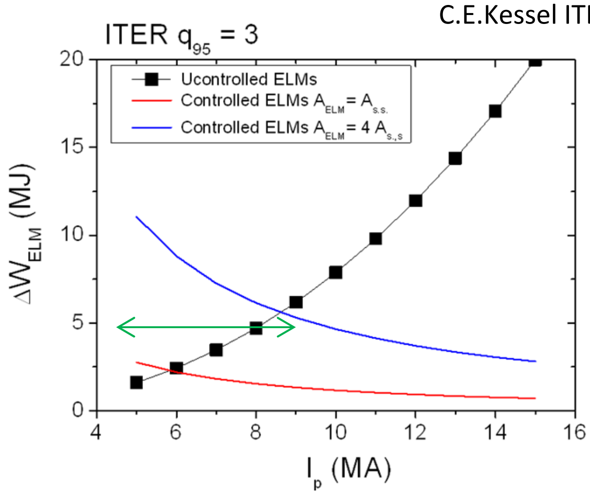
(A.Polevoy . 37th EPS Plasma Physics Conf. (Dublin, Ireland, 2010) P2.187)

Summary of modeling of ITER scenarios

- **Inductive scenarios permit to achieve Q>10 with a β_N <1.5 and H~1 at Ip~15 MA with a pulse flat top duration ~400s**
- **Hybrid scenarios permit to get similar Qs with currents ~12.5 MA and a pulse flat top duration ~<1300 s, the same confinement and higher β_N.**
- **Better confinement (H~1.6) permits to achieve fully non inductive scenarios with β_N ~2.5 , currents <~10 MA and Q~<5**
- **Achievements of good confinement and high β are key elements for steady state high Q operation.**
- **Uncontrolled ELM operation with low erosion possible up to Ip = 6.0–9.0 MA depending on A_{ELM} (ΔW_{ELM}).**
- **ITER physics to day is a good basis to design the plasma part of Fusion/Fission Hybrid**



C.E.Kessel ITER_D_437B7E



(A. Loarte)

Safety considerations

- **Safety considerations are of paramount importance for a fusion/fission hybrid** .

A hybrid combines high free energy typical for a fusion device with high amount of radioactivity typical for a fission device. **The combination can be extremely dangerous**. A proper choice of design , taking safety considerations first , is absolutely necessary.

- **The main safety problems in tokomaks are connected with disruptions** . To avoid these problems the operational space must be selected far from stability boundaries and the maximum plasma current must be selected <15 MA . ITER design shows that this plasma current may be safely achieved, but for a hybrid devise extra precautions will be needed and the current must be reduced with additional benefits of lower cost and longer pulses. Lower current will also simplify problems of ELMs and run away electrons. The decision how to deal with run away electrons must be taken at the conceptual stage .The design must be capable or to confine the beam of run away electrons and to kill them slowly or to prevent their formation.
- **The main fission safety problem of a hybrid is the after heat** . The afterheat is proportional to fission power and to make the problem solvable the fusion neutron wall loading and the power density of fission reactions inside the blanket must be limited . The fusion neutron wall loading must be << 1 MW/m2**. Passive ways to cool the blanket in the case of a loss of coolant accident must be found even if it will lead to lower economical efficiency of the station.**

Some planning considerations.

- **The blanket design is complex and crucial for the success of the project – a prototype blanket must be designed , developed and fully tested.**
  - **ITER will not be able to test fission blanket modules**
  - **A new test stand is necessary.**
  - **ITER physics is already sufficient to build such long pulse test stand.**
- **The same stand may be used to**
  - **test and improve efficiency and reliability of all the plant systems .**
  - **develop and test additional plasma physics in a full scale device without any future extrapolations .**
  - **achieve and investigate steady state regimes necessary for the fusion-fission hybrid.**
- **There are two possible ways to go forward:**
  - **One step development : to build a test stand capable to accept full blanket coverage and step by step develop it up to demo stage**
  - **Two step development : start with a smaller test stand , capable to accept only a partial blanket (say , only in ports) and on the basis of the result build later full scale demo hybrid reactor.**
- **The second approach permits to safe time . Development of blanket will take more time that design and construction of the test bed which can use all ITER experience and can go in parallel**

  Two step approach will also permit to design more optimized demo.

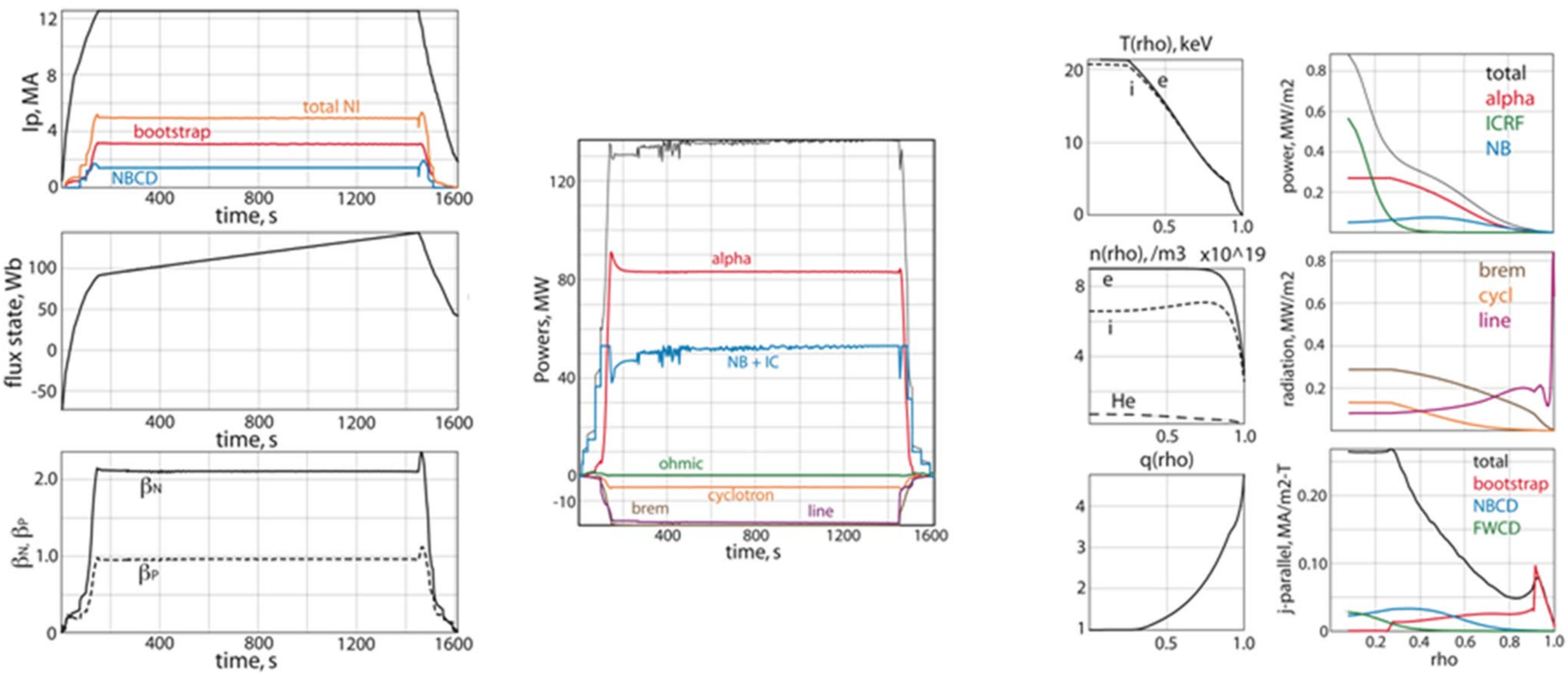
Conclusions

- **ITER is close to fulfill some physics requirements to the fusion part of fusion-fission hybrid:**
    - **Sufficient Q**
    - **Sufficient fusion power**
    - **Sufficient wall loading.**
- **In the same time significant technical improvements are needed:**
    - **Improved availability**
    - **High energy efficiency of heating and plant systems .**
    - **Steady state or very long pulses (>10000sec).**
- **ITER is optimized for inductive operation . A better optimization for SS/long pulse operation is possible. The optimization can also lead to a significant cost reduction.**
- **Some physics advances are also could be very welcomed .**
    - **Better confinement and**
    - **higher β**

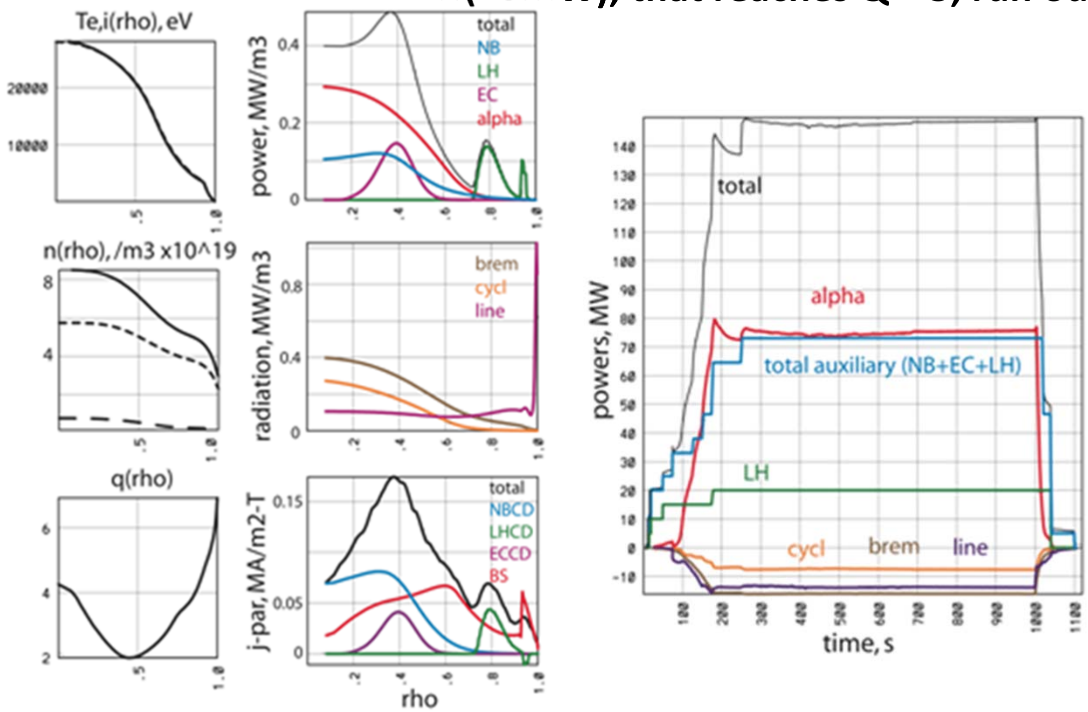
  will help to achieve long pulses and higher Q.
- **Optimized ITER will be a perfect fusion basis of a fusion/fission hybrid and a useful step in development a pure fusion steady state power reactor.**

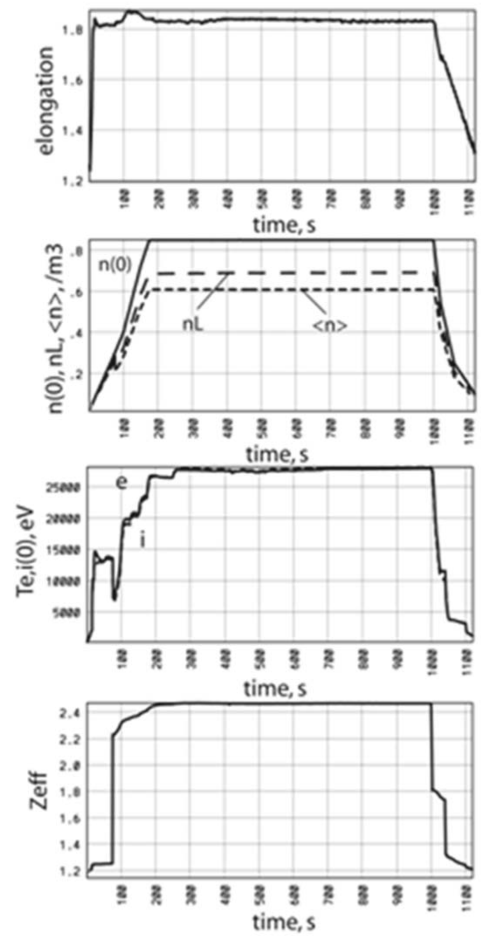
Supporting slides

An example of a hybrid scenario, with a 1300 s flattop burn phase



Time histories of an example of a steady state scenario with NB (33MW), EC(20MW), and LH(20MW), that reaches Q = 5, run out to 1000s





The steady state scenario consumes about 85-100 Wb to ramp up the plasma current to 7.5-10 MA, with external heating and current drive assisting.

The SS scenario is significantly dependent on the H/CD sources, since the current deposition profiles in combination with the bootstrap current determine the safety factor profile.