Introduction condition of a tokamak fusion power plant as an advanced technology in world energy scenario

US-Japan Workshop on Fusion Power Plant and Related Advanced Technology with participation of EU

Center for Promotion of Computational Science and Engineering, JAERI
Jan. 11, 2005, Tokyo, Japan

°R.Hiwatari, K.Tokimatsu, Y.Asaoka, K.Okano, S.Konishi and Y.Ogawa

Central Research Institute of Electric Power Industry (CRIEPI), Tokyo, Japan

Research Institute for Innovative Technology for the Earth (RITE), Tokyo, Japan

Institute of Advanced Energy, Kyoto Univ., Kyoto, Japan

High Temperature Plasma Center, the Univ. of Tokyo, Tokyo, Japan

Contents

1. Introduction and objectives

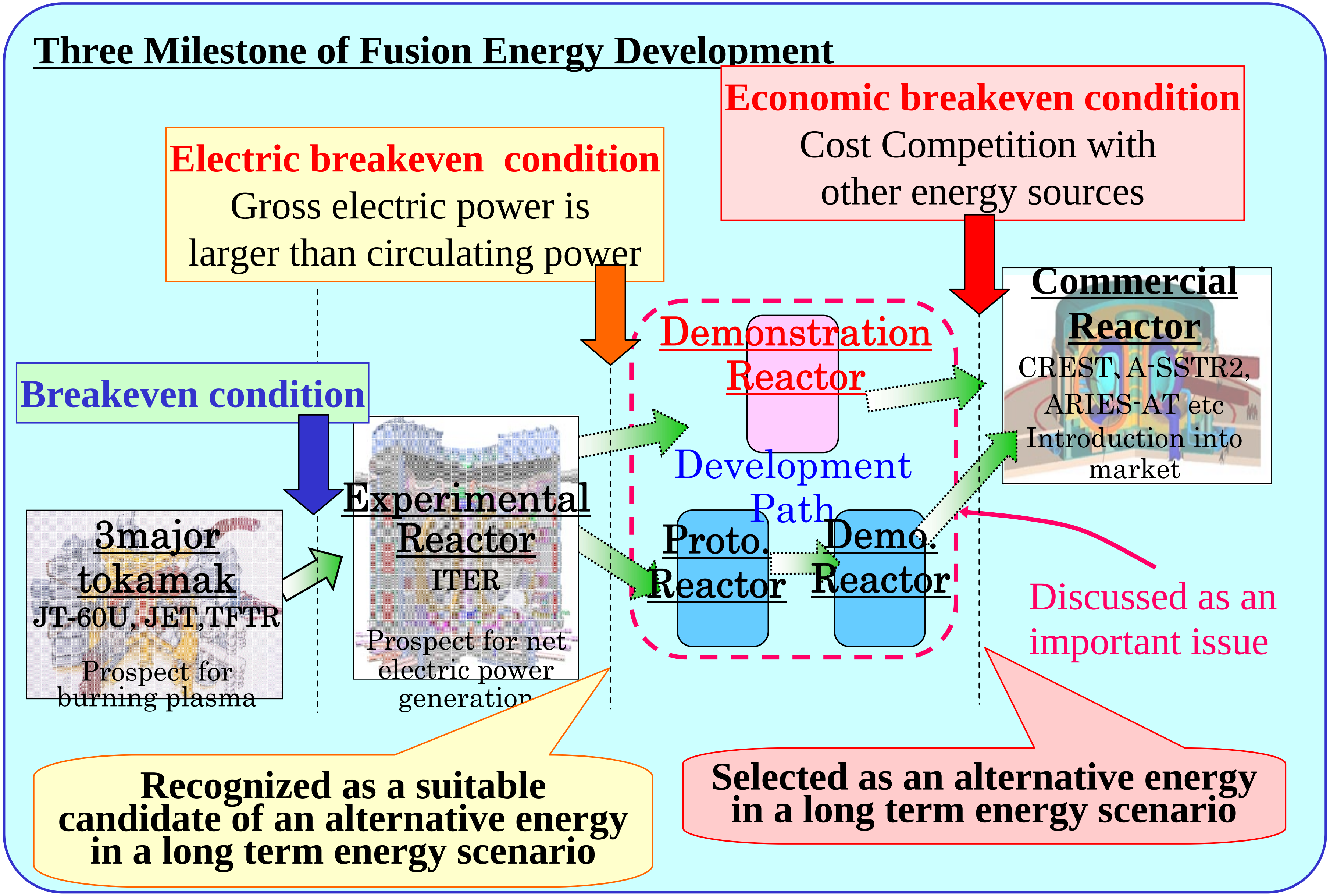
   electric and economic break-even conditions in the fusion energy development
2. World energy scenario and break-even price of fusion energy
3. Analysis method of electric and economic break-even condition
4. Electric break-even condition

   Completion of this condition leads to recognize fusion energy as a suitable candidate of an alternative energy source in world energy scenario.
5. Economic break-even condition

   Completion of this condition leads for fusion energy to be selected as an alternative energy source
6. Summary

"Electric Power, Promise for Tomorrow" CRIEPI Central Research Institute of Electric Power Industry

Introduction



Objectives

The present study reveals the following two introduction conditions of a tokamak fusion power plant in a long term energy scenario.

(1)**Electric breakeven condition**, which is required for the fusion energy to be recognized as a suitable candidate of an alternative energy

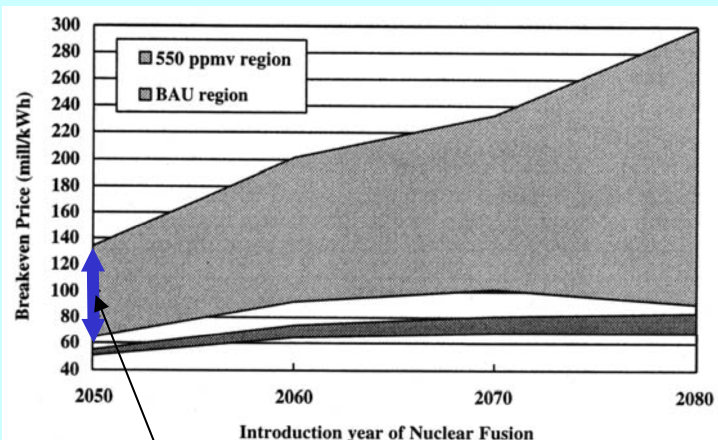
(2)**Economic breakeven condition**, which is required to selected as an alternative energy source

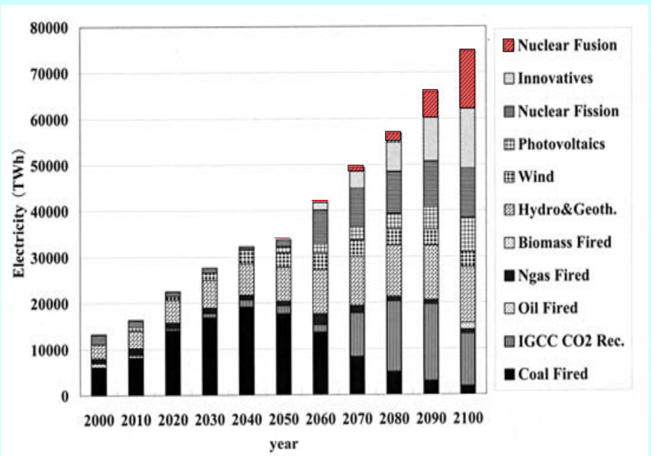
World Energy Scenario

Long term world energy and model (Linearized DNE21) is applied to the fusion energy. (This model is used for IPCC post SRES activity.)

Under the condition of 550 ppm CO_2 concentration in atmosphere, breakeven price and introduction year are analyzed.

If the COE for the fusion energy can achieve the 65mill/kWh, **20% share of the fusion energy in all produced electricity in 2100** is expected.





Break-even Price（ＢＰ）in 2050 is estimated at **<u>65mill/kWh ~ 135mill/kWh</u>**

Economic Breakeven condition in this study.

Analysis Method

FUSAC (FUsion power plant System Analysis Code)

- 0D plasma model of ITER Physics Guidelines
- simple engineering model based on TRESCODE(JAERI)
- Generomak Model for economic analysis

Database of 10,000 operation points for a tokamak

Plasma size(major radius，aspect ratio)，major physical parameters，shape and location of reactor component（TF・CS coil，radial build），weight of each component, construction cost，cost of electricity (COE)

Electric and economic break-even condition

β_N, f_{nGW}, HH required to achieve electric and economic break-even condition

"Electric Power, Promise for Tomorrow"
CRIEPI
Central Research Institute of Electric Power Industry

Parameter Region

Plasma size

Maximum is ITER-FDR(～8.5m).

Max. Magnetic field

The outlook of R&D for Ni_3Al ⇒ 16T

Thermal efficiency

The coolant conditions of ITER test blanket module ⇒ 30%

NBI system efficiency

The outlook of NBI system in ITER (～40%) ⇒ 50%

R (m)	5.5～8.5
A	2.6～4.0
κ	1.8, 1.9, 2.0
δ	0.35, 0.45
Te(=Ti) (keV)	12～20
q_ψ	3.0～6.0
B_{tmax} (T)	**13, 16**, 19
η_e (%)	**30**, 40
η_{NBI} (%)	**30, 50**, 70

Other conditions

- NBI power for current drive restricted to 200MW.
- 1.4m for blanket and shield region was kept.
- Current ramp-up is induced by CS coils.

Plasma Performance Required to Generate Net Electric Power ---β_N---

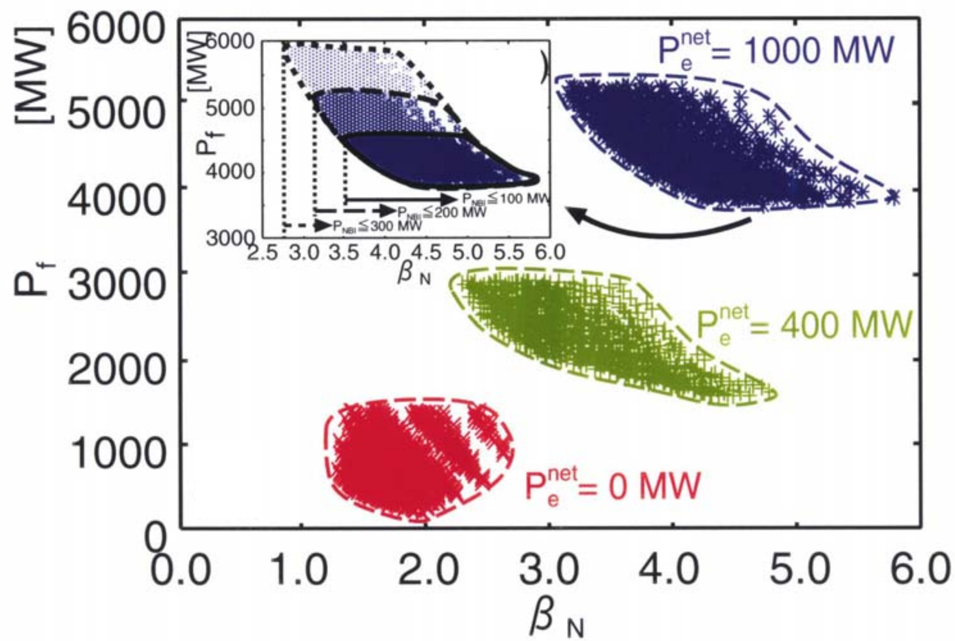
β_N required for net electric power

P_e^{net}=0 MW

$1.2 \leqq \beta_N \leqq 2.7$

P_e^{net}=1000 MW

$3.0 \leqq \beta_N \leqq 5.8$



ITER inductive operation mode(β_N=1.8) corresponds to P_e^{net}=0MW region

Effect of restriction P_{NBI}

The operational region is enlarged with the increasing the restriction PNBI

P_e^{net}=1000 MW case

$P_{NBI} \leqq 100$ MW and $3.5 \leqq \beta_N$ ⇒ $P_{NBI} \leqq 300$ MW and $2.7 \leqq \beta_N$

Plasma Performance Required to Generate Net Electric Power ---HH---

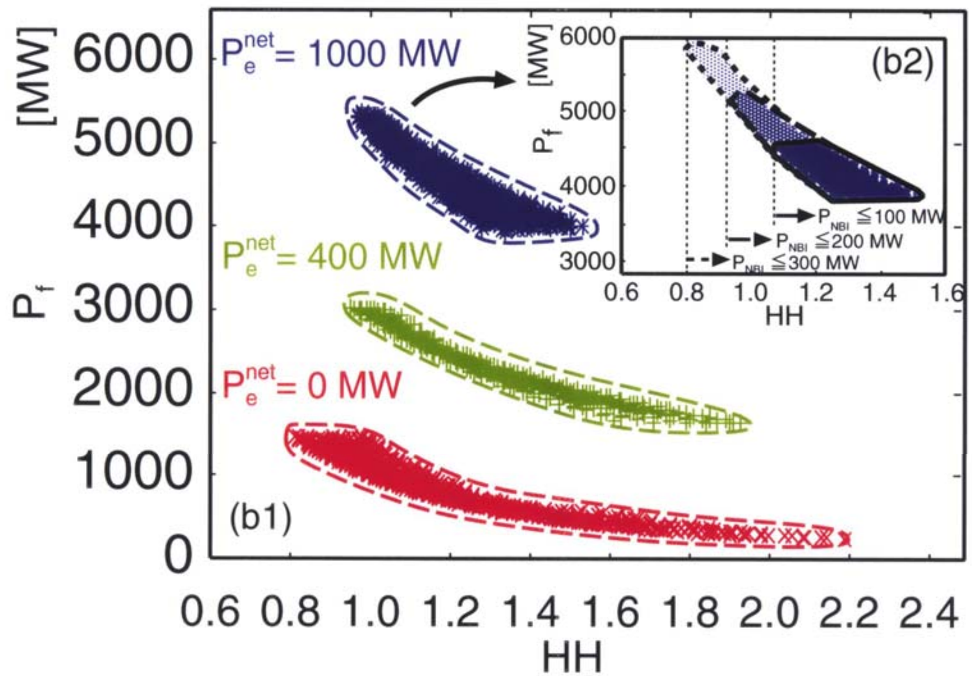
HH required for net electric power

P_e^{net}=0 MW

0.8≦HH≦2.2

P_e^{net}=1000 MW

0.9≦HH≦1.6



ITER inductive operation mode(HH=1.0) is included in P_e^{net}=0MW region

Effect of restriction P_{NBI}

The operational region is enlarged with the increasing the restriction PNBI

P_e^{net}=1000 MW case

P_{NBI}≦100 MW and 1.1≦HH ⇒ P_{NBI} ≦300 MW and 0.8≦ HH

"Electric Power, Promise for Tomorrow"
CRIEPI
Central Research Institute of Electric Power Industry

Plasma Performance Required to Generate Net Electric Power ---fn_{GW}---

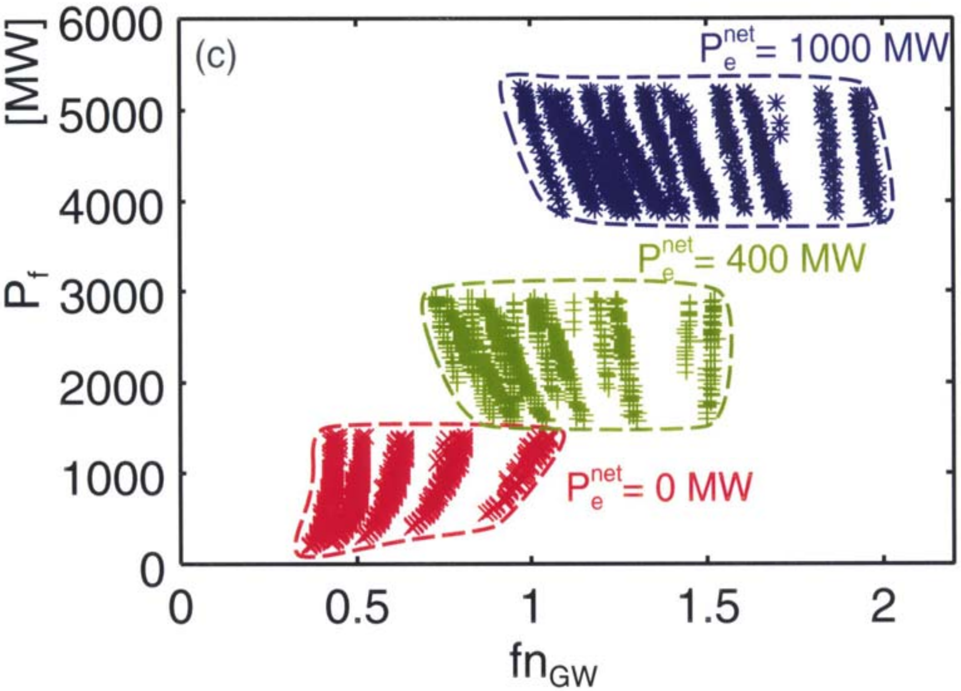
fn_{GW} required for net electric power

P_e^{net}=0 MW

$0.4 \leqq fn_{GW} \leqq 1.1$

P_e^{net}=1000 MW

$0.9 \leqq fn_{GW} \leqq 2.0$

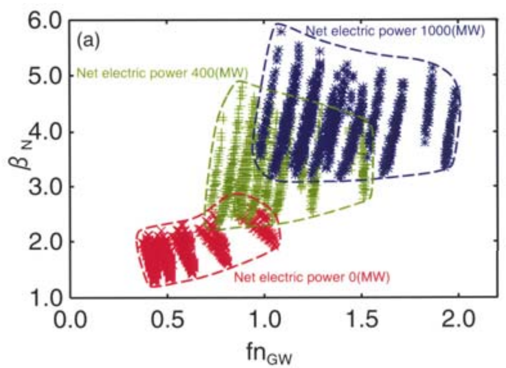


ITER inductive operation mode(fn_{GW}=0.85) corresponds to P_e^{net}=0MW region

Effect of restriction P_{NBI}

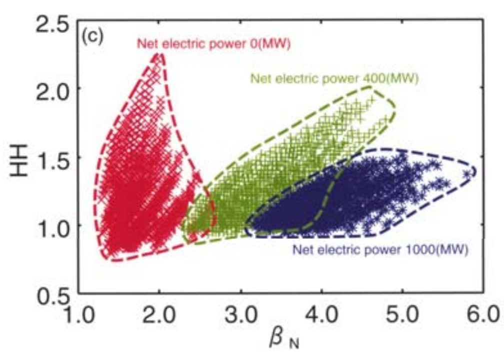
The effect of restriction P_{NBI} is not described in case of the required fn_{GW} .

Correlation between Plasma Performances



$f\ n_{GW}$ and β_N

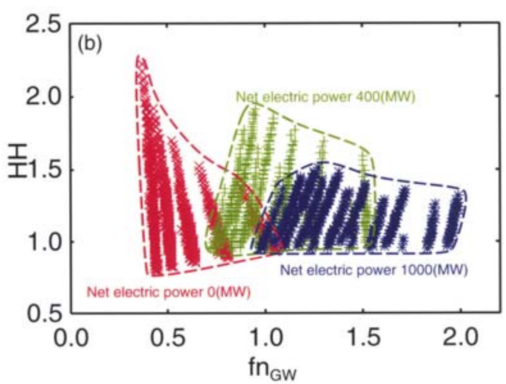
Both $f\ n_{GW}$ and β_N have to be increased together so as to increase the net electric power



$f\ n_{GW}$ and H H

No clear relationship

There is no operational point under HH≦0.8, of course, which is depending on the ristriction P_{NBI}



β_N and H H

No clear relationship

Existence of inevitable HH value

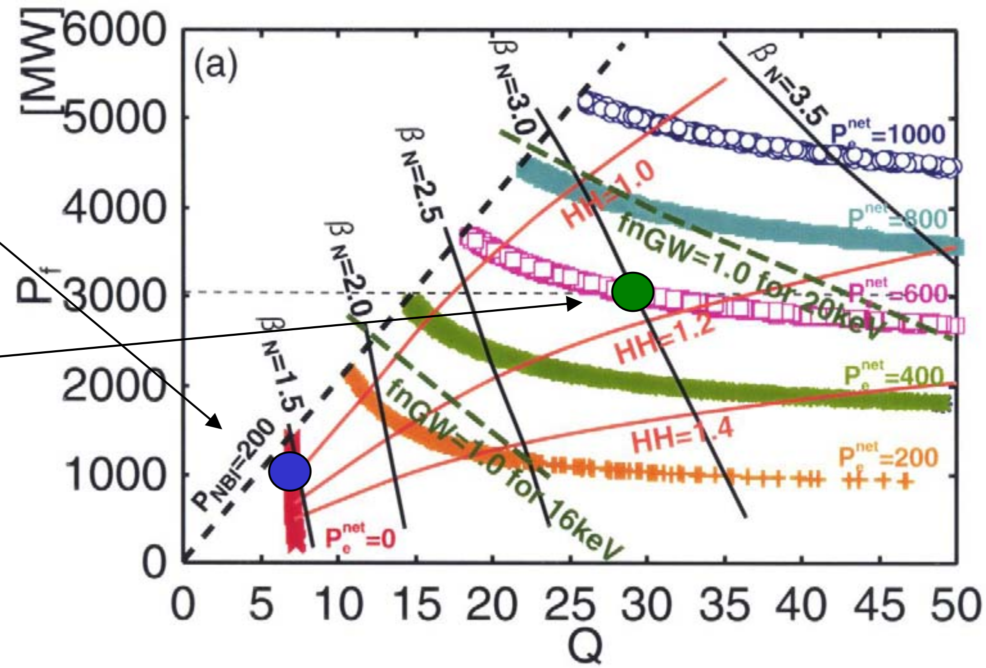
Plasma Performance Diagram for the Net Electric Power Generation ---R=8.5m---

P_e^{net}=0 MW and P_f=1000 MW

βN=1.5, HH=1.0

P_e^{net}=600 MW and P_f=3000 MW

βN=3.0, HH=1.15



Requirement to increase P_e^{net}

β_N and fn_{GW}

- Increase together

HH

- Not necessary to increase
- Depending on the restriction P_{NBI}

In comparison with the present ITER experimental plan

The outlook of both Penet =0MW and Penet=600 MW will be obtained.

"Electric Power, Promise for Tomorrow"
CRIEPI
Central Research Institute of Electric Power Industry

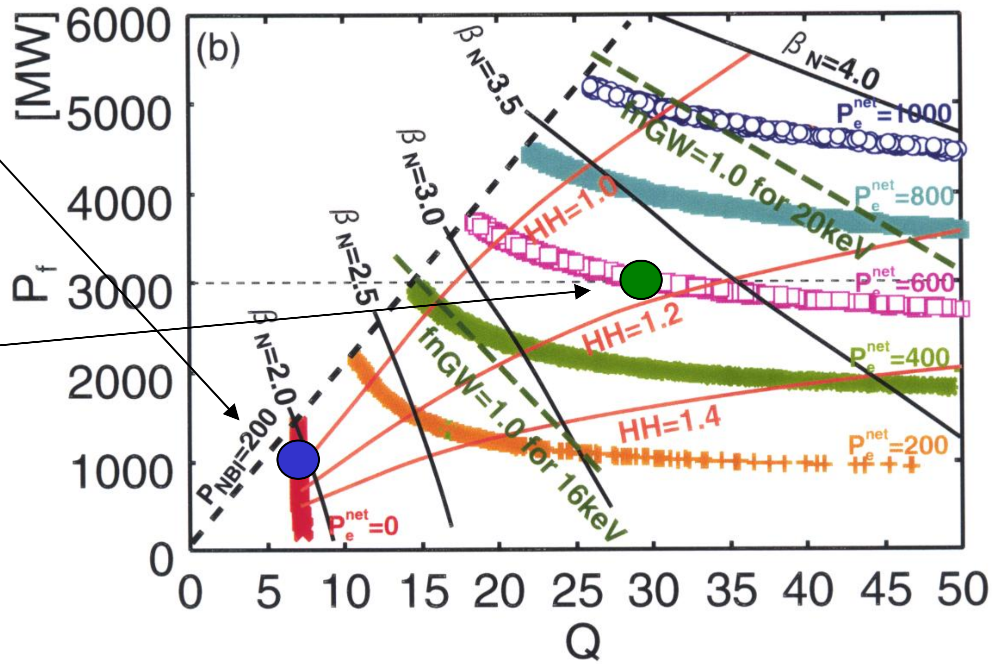
Plasma Performance Diagram for the Net Electric Power Generation ---R=7.5m---

P_e^{net}=0 MW and P_f=1000 MW

βN=1.9, HH=1.0

P_e^{net}=600 MW and P_f=3000 MW

βN=3.4, HH=1.15



In comparison with the present ITER experimental plan

The outlook of both Penet =0MW and Penet=600 MW will be obtained.

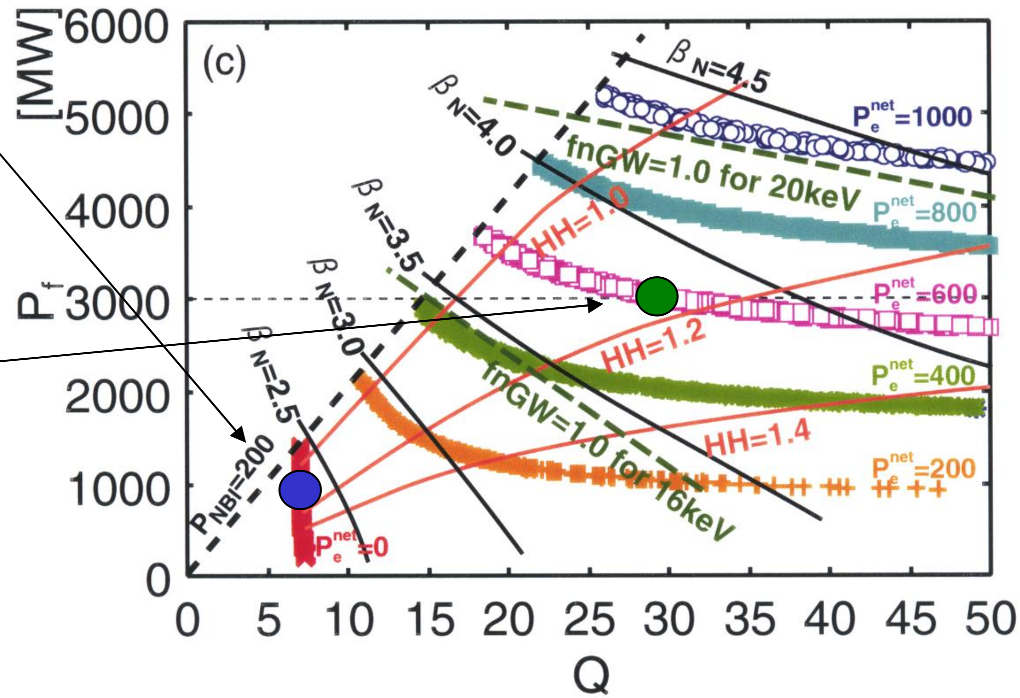
Plasma Performance Diagram for the Net Electric Power Generation ---R=6.5m---

P_e^{net}=0 MW and P_f=1000 MW

βN=2.3, HH=1.0

P_e^{net}=600 MW and P_f=3000 MW

βN=3.8, HH=1.15



In comparison with the present ITER experimental plan

The outlook of Penet =0MW will be obtained, but it is difficult to achieve Penet=600MW.

Electric break-even condition

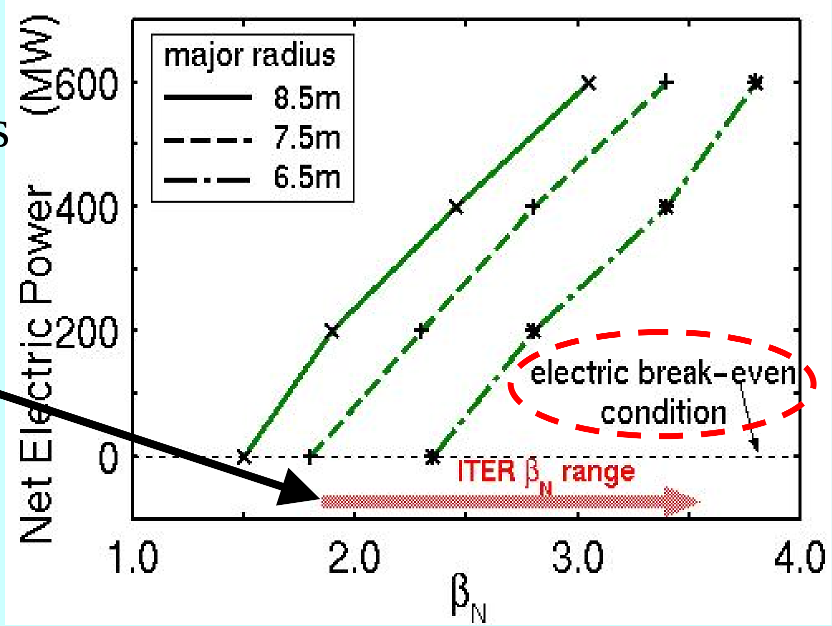
Typical electric breakeven condition

Typical operation point for each major radius and each net electric power in the previous figures.

HH ~ 1.0 for P_e^{net}=0MW operation points

HH ~ 1.2 for P_e^{net}=600MW operation points

κ= 1.9、B_{tmax}=16 T、ηe=30%、η_{NBI}=50%



ITER experimental region covers wide range of operation point from β_N=1.8 to β_N= 3.6.

How small device is feasible for Demo depends on how high plasma performance is achieved in ITER

Advancement of engineering condition

Engineering Conditions for economic break-even condition

◆B_{tmax}=16T、η_e=**40%**、P_e^{net}=1000MWe、other condition are the same as the previous electric breakeven analysis.

◆Plant availability 60%, an unexpected outage is considered

◆Including **without CS coil case(CS-less case)**, Note that full non-inductive current ramp-up is required

Economic break-even condition β_N

β_N required for breakeven price

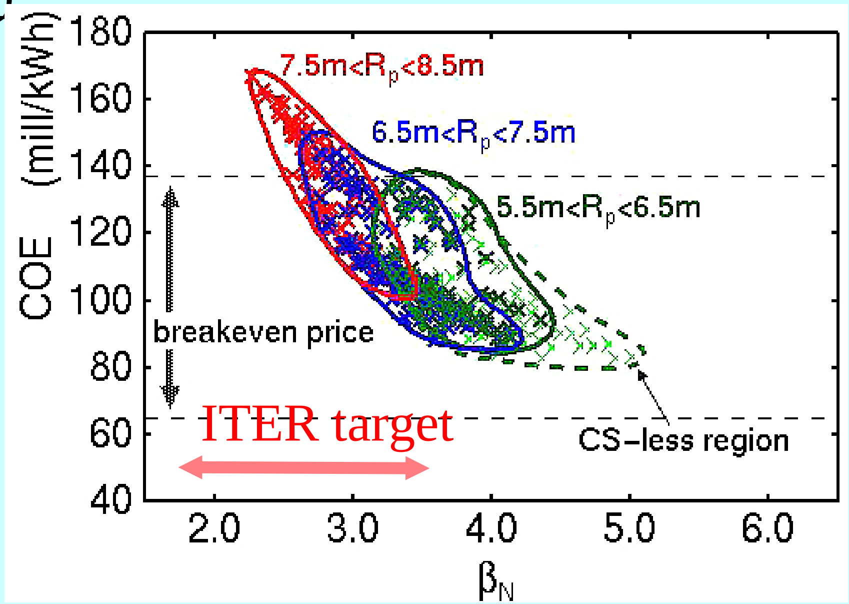
κ= 1.9、B_{tmax}=16 T、ηe=40%、η_{NBI}=50%

Higher limit of breakeven price (135mil/kWh)

$\beta_N \geqq 2.5$ is required

Lower limit of breakeven price (60mil/kWh)

$\beta_N \geqq 5.0$ and R_p<5.5 m is required.

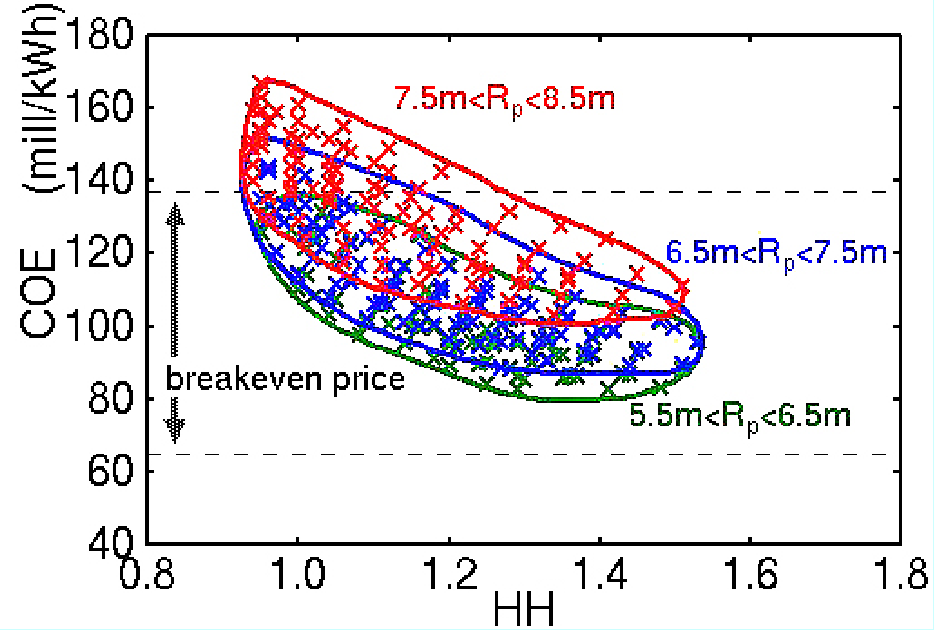


- ◆In the lower limit of 5.5m<R_p<6.5m, simplified radial build without CS coil is required.
- ◆Upper limit of breakeven price is possible to be attained by $\beta_N \geqq 2.5$, which is examined in the ITER advanced operation model.

Economic break-even condition HH

HH required for breakeven price

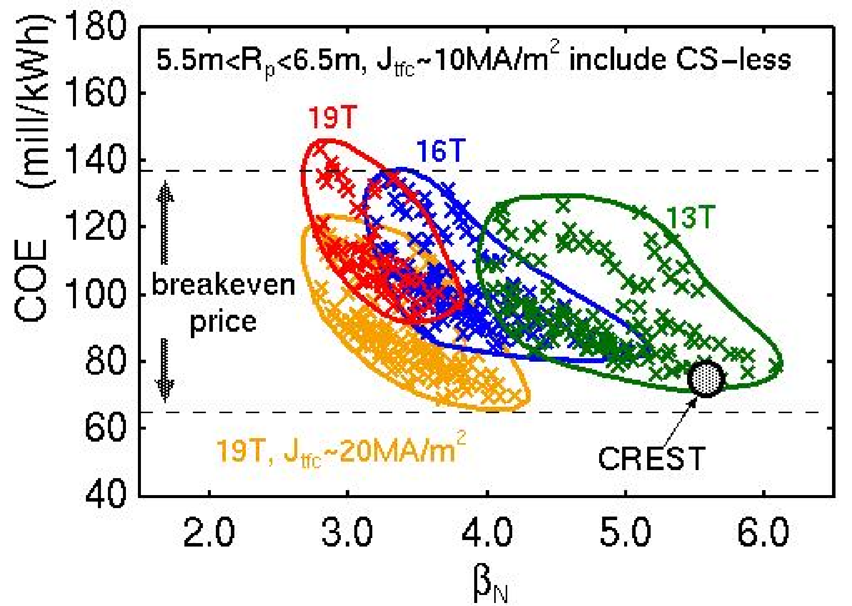
- ◆The higher HH is the lower COE is, because of reduction of the cost for the current drive system.
- ◆In contrast with β_N, the required HH region is almost the same through the range of 5.5m <R_p<8.5m.
- ◆The important suggestion is that there is no path with HH<0.9 to introduction of the tokamak fusion reactor into the long term world energy scenario.



"Electric Power, Promise for Tomorrow"
CRIEPI
Central Research Institute of Electric Power Industry

Dependence of COE on B_{tmax}

- The increase of B_{tmax} is very effective for the mitigation of the required β_N under the condition of including the simplified radial build without a CS coil.
- The increase of B_{tmax} increases the lowest limit of COE under the condition of the same critical current density of TF coils, because the increase of the coil volume or the device size, and the lower limit of COE range of 19T increases up to 90mill/kWh.
- CREST (Rp=5.4, η_e41%, B_{tmax}=13T) is near the breakeven price of 65mill/kWh



To get the merit of high magnetic field, the current density of super conductor also has to be improved. When current density about 20MW/m^2 of TF coils is feasible with the same cost as a 10MA/m^2 coil, the merit of high field is clearly seen.

"Electric Power, Promise for Tomorrow"
CRIEPI
Central Research Institute of Electric Power Industry

Summary

Electric Breakeven condition

β_N≧2.0, HH≧1.0、steady state operation technique、max. magnetic field 16T、thermal efficiency η_e=30% lead to achieve the electric breakeven condition.

The electric breakeven condition requires the simultaneous achievement of $1.2<\beta_N<2.7$, $0.8<HH$, and $0.3<fn_{GW}<1.1$ under the condition of B_{tmax}=16T, η_e=30%, and P_{NBI}<200MW. It shuold be noted that the relatively moderate conditionns of β_N~1.8, HH=1.0, and fn_{GW}~0.9, which correspond to the ITER reference operation parameters, have a strong potential to achieve the electric breakeven condition

Economic Breakeven condition

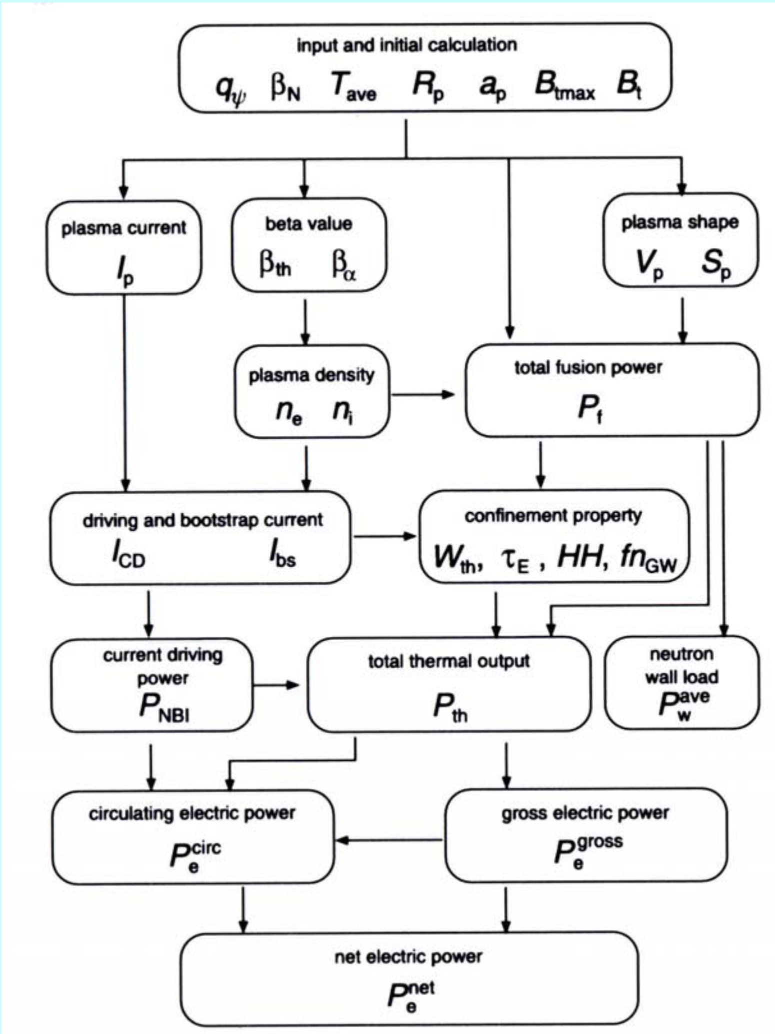
β_N≧3.0, HH≧1.0、η_e>40% leads to the upper limit of breakeven price and to the possibility for fusion energy to be introduced into the world energy scenario. To prepare for a severe breakeven price(65mill/kWh), β_N>5.0 with R_p<5.5m should be aimed at.

The economic breakeven condition requires β_N~2.5 for 135mill/kWh of higher breakeven price case and β_N~5.0 for 65 mill/kWh of lower breakeven price case under the conditions of B_{tmax}=16T, η_e=40%, plant availability 60%, and feasibleness of a simplified radial build without CS coils. The demonstration of steady state operation with β_N~3.0 in the ITER project leads to the prospect to achieve the upper region of breakeven price in the world energy scenario. This β_N requirement will be somewhat mitigated with higher B_{tmax}.

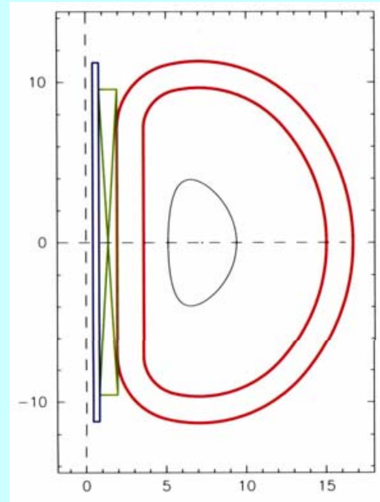
"Electric Power, Promise for Tomorrow"
CRIEPI
Central Research Institute of Electric Power Industry

System Analysis Code (FUSAC)

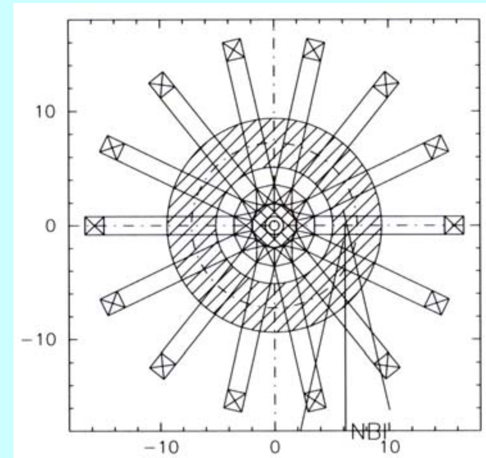
Calculation Flow



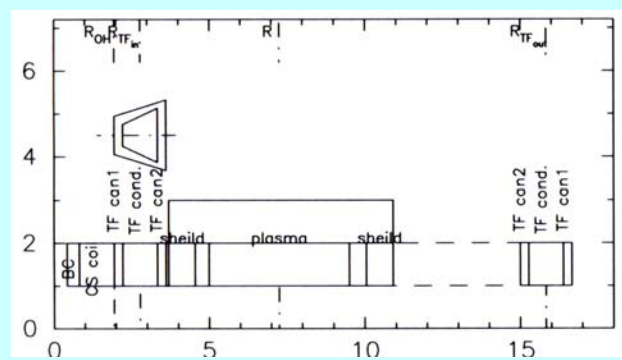
Output of Result



elevation view



plane view



radial build

fn_{GW} and Operation Temperature

- The required fn_{GW} decreased with increasing operation temperature.
- β_N is almost constant.

fnGW

Confinement and MHD property

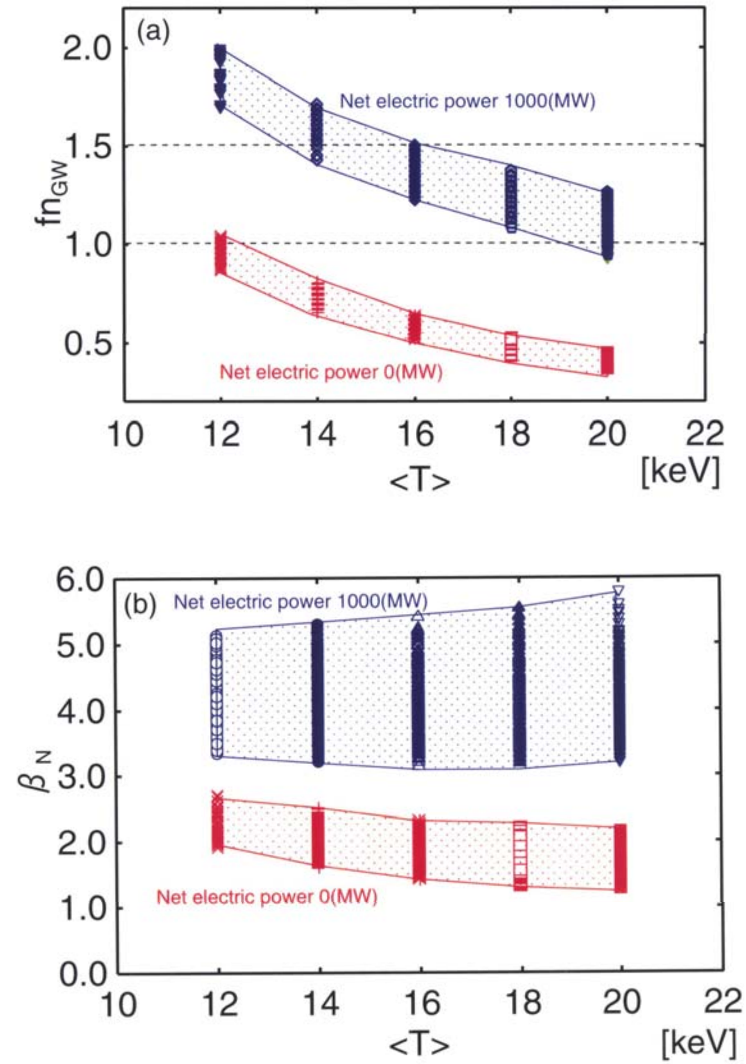
consistency

<T>

NBI current drive property

Divertor operation condition

The operation temperature will be optimized



The effect of thermal efficiency

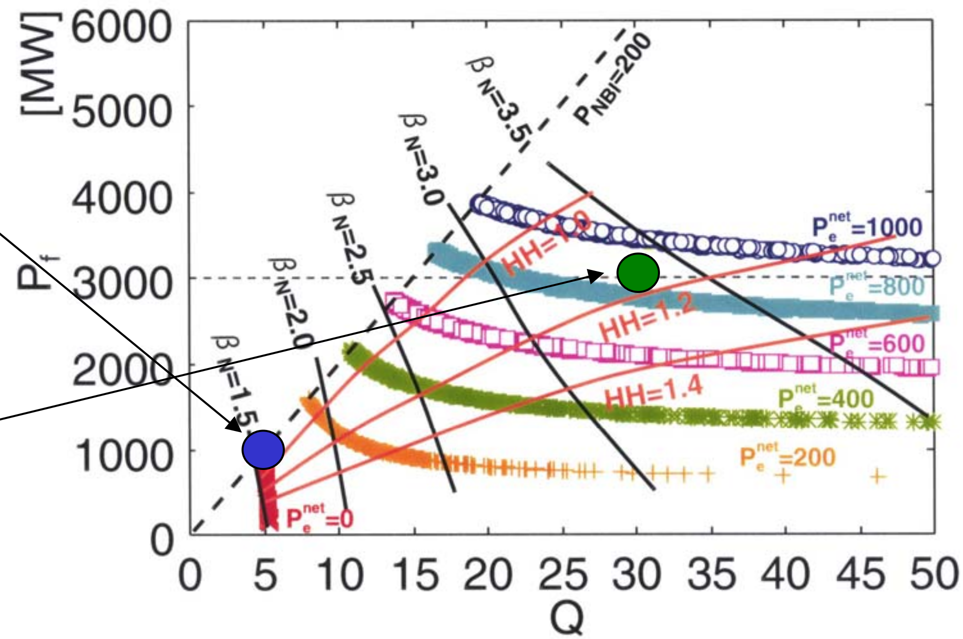
R=7.5 m and η_e=40 % case

P_e^{net}=0 MW and P_f=1000 MW

βN=**1.5**, HH=0.9

P_e^{net}=900 MW and P_f=3000 MW

βN=3.4, HH=1.15



The η_e progress will decrease the required plasma performances with the same P_e^{net}, or increase the net electric power with the same plasma performance

To get the economical outlook, the η_e progress is inevitable.

The effect of NBI system efficiency

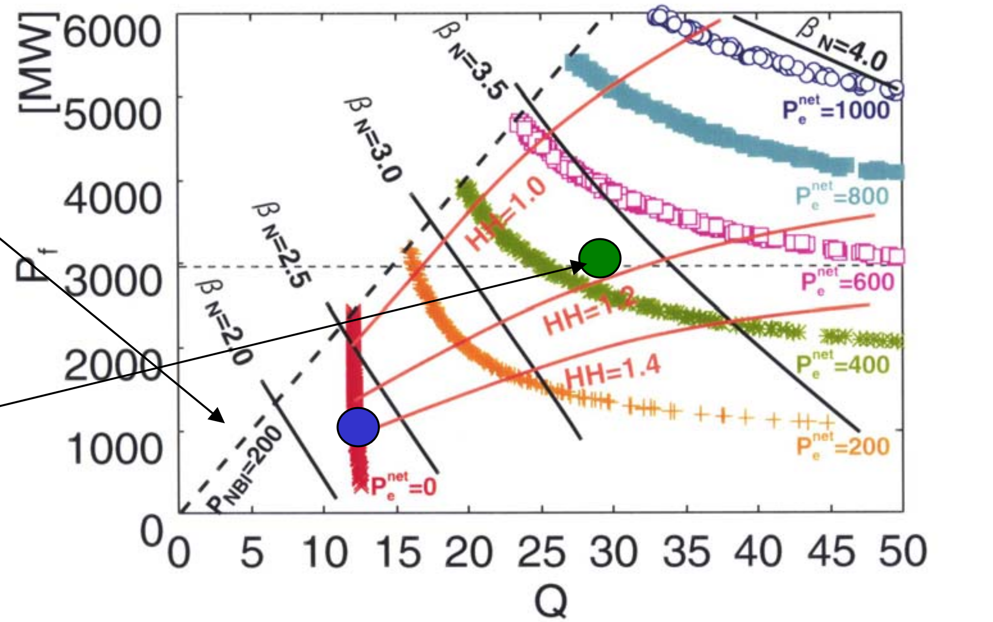
R=7.5 m and η_{NBI}=30 % case

P_e^{net}=0 MW and P_f=1000 MW

βN=**1.8**, HH=1.4

P_e^{net}=450 MW and P_f=3000 MW

βN=3.4, HH=1.15



The η_{NBI} is critical to the required HH, especially, in the low Penet region.

The η_e progress should be almost completed by the demo reactor stage.

The effect of Max. magnetic field

Increase of B_{tmax} from 13T to 19T

- The required βN decrease
- The operational region is shrank

In case of B_{tmax}=19T, the current ramp-up is not possible by CS coil, or 1.4m space for blanket and shield can not be accommodated (R<7.5).