D-^{3}He HA tokamak device for experiments and power generations

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Contents

1．Motivation

2．Formalism, control algorithm, and hot ion mode criterion

3．Calculated results

4．Summary and further issues

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1. Motivation

ST has a large potential for D-^{3}He fusion.
Although the large plasma current required for ignition can be ramped up by the vertical field and heating power even without the central solenoid, the following concerns may appear:

[1]the plasma current itself is very large,
[2]the plasma current changes when the plasma energy changes.
[3]the current hole produced in the initial phase does not shrink due to long resistive decay time, leading to the high energy particle confinement problems, and q_{min}=2 limitation of the plasma current.

Purpose of this study:
@ Using the central solenoid in the high aspect ratio tokamak, disadvantageous point of ST is removed. Namely, the current hole is removed in the initial low temperature phase, leading to improving the high energy particle confinement, q_{min} limit, and the plasma current change.
@ Feasibility of D-^{3}He HA

2. Formalism, Control algorithm, and Hot ion mode criterion

2.1. 0-dimensional particle and power balance equations

Deuterium

$$\frac{dn_D(0)}{dt} = (1+\alpha_n)S_D(t) - \frac{n_D(0)}{\tau_D^*}$$

$$-(1+\alpha_n)\left[n_D(0)n_T(0)\overline{\langle\sigma v\rangle_{DT}(x)} + n_D(0)^2\left\{\overline{\langle\sigma v\rangle_{DDPT}(x)} + \overline{\langle\sigma v\rangle_{DDHE3N}(x)}\right\} + n_D(0)n_{He3}(0)\overline{\langle\sigma v\rangle_{DHE3}(x)}\right]$$

Helium-3

$$\frac{dn_{HE3}(0)}{dt} = (1+\alpha_n)S_{HE3}(t) + (1+\alpha_n)\left\{\frac{n_D(0)}{2}\overline{\langle\sigma v\rangle_{DDHE3N}(x)} - n_D(0)n_{He3}(0)\overline{\langle\sigma v\rangle_{DHE3}(x)}\right\} - \frac{n_{He3}(0)}{\tau_{HE3}^*}$$

Tritium

$$\frac{dn_T(0)}{dt} = (1+\alpha_n)\left\{\frac{n_D(0)}{2}\overline{\langle\sigma v\rangle_{DDPT}(x)} - n_D(0)n_T(0)\overline{\langle\sigma v\rangle_{DT}(x)}\right\} - \frac{n_T(0)}{\tau_T^*}$$

Alpha ash

$$\frac{dn_\alpha(0)}{dt} = (1+\alpha_n)\left\{n_D(0)n_T(0)\overline{\langle\sigma v\rangle_{DT}(x)} + n_D(0)n_{He3}(0)\overline{\langle\sigma v\rangle_{DHE3}(x)}\right\} - \frac{n_\alpha(0)}{\tau_\alpha^*}$$

Proton ash

$$\frac{dn_p(0)}{dt} = (1+\alpha_n)\left\{\frac{n_D(0)}{2}\overline{\langle\sigma v\rangle_{DDPT}(x)} + n_D(0)n_{He3}(0)\overline{\langle\sigma v\rangle_{DHE3}(x)}\right\} - \frac{n_P(0)}{\tau_P^*}$$

Electron density

$$n_e(0) = n_D(0) + n_T(0) + 2n_{He3}(0) + 2n_\alpha(0) + n_p(0) + (1+\alpha_n)Zn_{imp}$$

Power balance (T$_i$/T$_e$=1.5)

$$\frac{dT_i(0)}{dt} = \frac{1+\alpha_n+\alpha_T}{1.5e\left(f_D + f_T + 1/\gamma_i + f_{He3} + f_\alpha + f_P\right)n_e(0)} \times$$

$$\left[\left\{P_{EXT}/V_o + \overline{P}_{oh} + \overline{P_{DHE}} + \overline{P_{DDPT}} + \overline{P_{DDHE3N}} + \overline{P_{DT}}\right\} - \left\{\overline{P_L} + \overline{P_b} + \overline{P_s}\right\}\right]$$

$$-\frac{T_i(0)}{\left(f_D + f_T + 1/\gamma_i + f_{He3} + f_\alpha + f_P\right)} \times$$

$$\left[\left\{1+\frac{1}{\gamma_i\left(1-(1+\alpha_n)Zf_{imp}\right)}\right\}\frac{1}{n_e(0)}\left[\frac{dn_D(0)}{dt}+\frac{dn_T(0)}{dt}+\frac{dn_P(0)}{dt}\right]+\left\{1+\frac{2}{\gamma_i\left(1-(1+\alpha_n)Zf_{imp}\right)}\right\}\frac{1}{n_e(0)}\left[\frac{dn_\alpha(0)}{dt}+\frac{dn_{He3}(0)}{dt}\right]\right]$$

where
$T_i(x)/T_i(0) = T_e(x)/T_e(0) = (1-x^2)^{\alpha_T}$
$n(x)/n(0) = n_\alpha(x)/n_\alpha(0) = (1-x^2)^{\alpha_n}$

Tokamak:

$$\begin{cases} \tau_{IPB(y,2)} = 0.0562A_i^{0.19}I_p^{0.93}[MA]\overline{n}_{19}^{0.41}[\times 10^{19}m^{-3}]R_o^{1.97}[m]\varepsilon \\ \qquad\qquad \times \kappa^{0.78}B_{to}^{0.15}[T]/P_{HT}^{0.69}[MW] \\ \tau_{AUX} = \gamma_{HH}\tau_{IPB(y,2)} \end{cases}$$

IPB98(y,2) confinement law with $\tau_E = \min\{\tau_{NA}, \tau_{AUX}\}$
where the mass factor:

$A_i = \{2n_D(0) + 3n_{HE3}(0) + 3n_T(0)\}/\{ n_D(0) + n_{HE3}(0) + n_T(0)\}$

2.2. Hot ion mode criterion.

Energy transfer from ion to electron :

$$\bar{P}_{ie}\left[W/m^3\right] = \frac{2.4\times 10^5 \left(n_e(0)[m^{-3}]/10^{20}\right)^2}{1+2\alpha_n - 0.5\alpha_T}\left(\frac{f_D}{A_D}+\frac{4f_{He3}}{A_{He3}}+\frac{f_p}{A_p}+\frac{4f_{He4}}{A_{He4}}+\frac{f_T}{A_T}\right)\ln\Lambda_j \frac{\left(\frac{T_i(0)}{T_e(0)}-1\right)}{T_e(0)[keV]^{0.5}}$$

Ion power balance $P_f\, f_i = P_{ie} + P_{Li}$

Electron power balance $P_f\,(1-f_i) + P_{ie} = P_b + (P_{sw} + P_{sv}) + P_{Lie}$

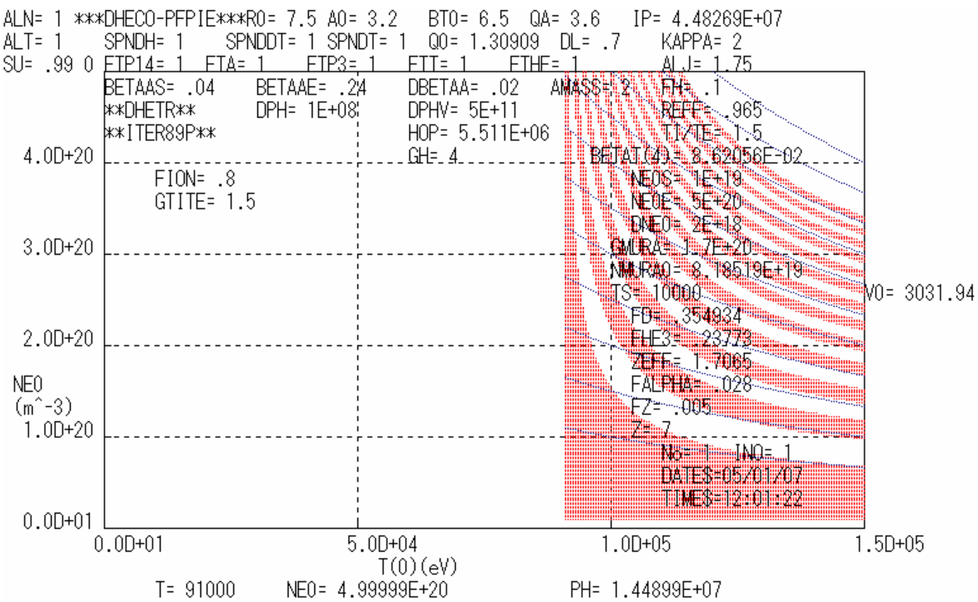
where f_i is the energy transfer fraction of the fusion power to ion.

$P_f\, f_i > P_{ie}$ must be satisfied to have ion and electron power balances .

The contour map of ($P_f\, f_i - P_{ie}$) is drawn on the n-T_i plane with 100 MW.

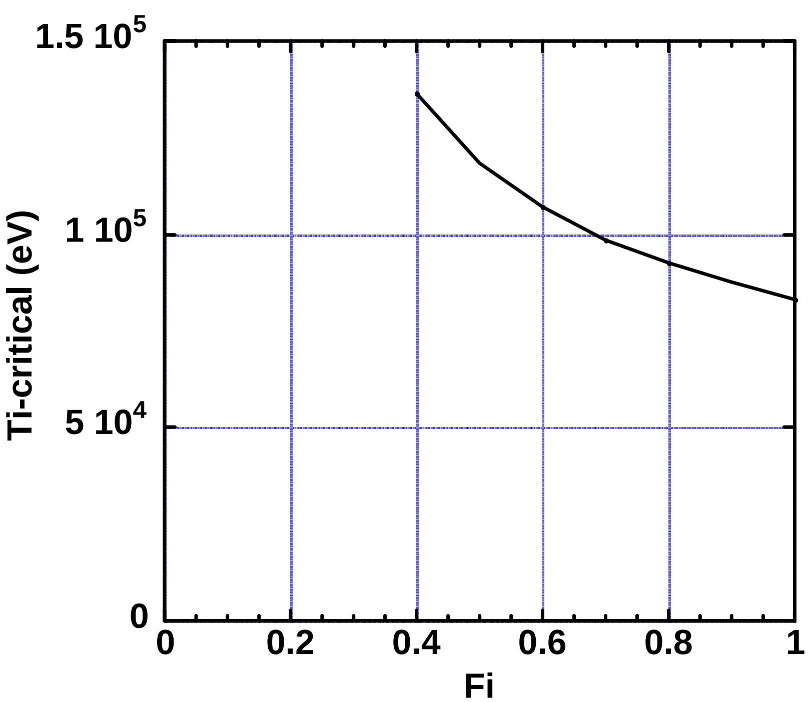
[1] T_i/T_e=1.5, f_i=0.8,
f_D=0.354,f_{HE3}=0.238,f_T=0.0015,f_p=0.003,f_{HE4}=0.0288, lnΛ=20

T_i>90 keV is necessasry



[2]Critical ion temperature vs ion energy fraction f_i for T_i/T_e=1.5

Higher temperature is required for the hot ion mode.



Even when the global power balance analysis gives us the answer, it is sometimes rejected by this criterion.

[1] Improper case: R_{eff}=0.9

Fusion power P_f = 2323-60 MW(neutron) = 2263 MW

Brems rad. P_b = 952 MW

Synchrotron rad. P_s=325+112 MW

Plasma conduction P_L=865 MW

n(0)=3.62x10^{20} m^{-3}

T_i= 83.5 keV, T_e= 55.6 keV, T_i-T_e= 27.9 keV → P_{ie}=2800 MW

$$2263f_i = 2800 + 0$$
$$2263(1-f_i) + 2800 = 952+325+112+665$$

$f_i > 1$ →Impossible

[2] Proper case R_{eff}=0.99

Fusion power P_f = 2323-60 MW(neutron) = 2170 MW

Brems rad. P_b = 792 MW

Synchrotron rad. P_s=148.3+165 =313 MW

Plasma conduction P_L=1069 MW

n(0)=3.08x10^{20} m^{-3}

T_i=98 keV, T_e=65.3 keV, T_i-T_e=32.7 keV → P_{ie}=1798 MW

$$2171\, f_i = 1798 + 0$$
$$2171\,(1-f_i) + 1788 = 792+313+1069$$

For the limit of P_{Li} = 0, f_i > 0.8 is obtained.

This criterion with f_i=0.8 gives us n(0) < 3.0x10^{20} m^{-3},

$T_i(0) > 98$ keV for HA D-^{3}He fusion reactor.

2.3. External heating power:

$$P_{EXT}(HL)\ [W] = M_{HL0}(t) x 10^6\ \overline{P}_{thresh} - \left(\overline{P}_{oh} + \overline{P}_F - \overline{P}_b - \overline{P}_s\right) V_o$$

where

$$\overline{P}_{thresh}\ [MW] = 2.84\ \overline{n}^{0.58}\ [10^{20}\ m^{-3}]\ B_t^{0.82}\ [T]\ R^{1.0}[m]\ a^{0.81}/A_i$$

2.4. Fueling

Total fueling is controlled by the minimum error between the three signals

$$e_{DHE3}(p_f) = (1 - P_f / P_{fo})$$

$$e_{DHE3}(n) = (1 - n(0)/n(0)_{GW})$$

$$e_{DHE3}(<\beta>) = (1 - <\beta>/<\beta>_{MAX})$$

$$e_{DHE3}(\min) = \min\left\{e_{DHE3}(p_f), e_{DHE3}(n), e_{DHE3}(<\beta>)\right\}$$

$$S_{DHE3} = S_{DHE30}\left\{e_{DHE3}(\min) + \frac{1}{T_{INT}}\int e_{DHE3}(\min)dt + T_d\frac{de_{DHE3}(\min)}{dt}\right\}$$

where Integration time: T_{int}= 10 sec, Derivative time: T_d=0,1

D-^{3}He Fuel ratio is controlled by

$$S_D(t) = \left\{\left[\frac{n_D(0)}{n_D(0)+n_{He3}(0)}\right]_o + G_{NDHE3}\left(e(n_D/n_{He3}) + \frac{1}{T_{DHE3int}}\int_0^t e(n_D/n_{He3})dt\right)\right\}S_{DHE3}(t)$$

$$S_{HE3}(t) = \left\{\left[\frac{n_{He3}(0)}{n_D(0)+n_{He3}(0)}\right]_o + G_{NDHE3}\left(e(n_{He3}/n_D) + \frac{1}{T_{DHE3int}}\int_0^t e(n_{He3}/n_D)dt\right)\right\}S_{DHE3}(t)$$

where $e(n_D/n_{He3}) = \left[\frac{n_D(0)}{n_D(0)+n_{He3}(0)}\right]_o - \frac{n_D(0)}{n_D(0)+n_{He3}(0)}$

$$e(n_{He3}/n_D) = \left[\frac{n_{He3}(0)}{n_D(0)+n_{He3}(0)}\right]_o - \frac{n_{He3}(0)}{n_D(0)+n_{He3}(0)}$$

@ The fuel ratio: $n_D : n_{He3}$ = 2 : 1 ~ 0.42 : 0.58〜0.3 : 0.7

@The particle confinement time ratio : $\tau_D^*/\tau_E = \tau_{HE3}^*/\tau_E = \tau_T^*/\tau_E = \tau_p^*/\tau_E = \tau_\alpha^*/\tau_E$ = 2 ~ 4

@The prompt loss of fusion products is to be zero.

2.5. Plasma circuit equation:

Plasma circuit equation:

$$L_p \frac{dI_p}{dt} + R_p(I_p - I_{CD} - I_{BS}) = -\left(M_{PV}\frac{dI_V}{dt} + M_{Psh}\frac{dI_{sh}}{dt} + M_{Pdiv}\frac{dI_{div}}{dt} \right) + V_{OH} \quad \textbf{(1)}$$

and the vertical field

$$B_{VE} = B_{zoV}\, I_V - B_{zodiv}\, I_{div} + B_{zosh}\, I_{sh} \quad \textbf{(2)}$$

provides the equivalent circuit equation with $\alpha_{div} = I_{div}/I_p$ and $\alpha_{sh} = I_{sh}/I_V$,

$$L_{peff}\frac{dI_p}{dt} = -R_{peff} I_p - \left\{ \frac{M_{PV} + M_{Psh}\alpha_{sh}}{B_{zoV} + B_{zosh}\alpha_{sh}} \right\} \frac{dB_{VE}}{dt} + V_{OH} \quad \textbf{(3)}$$

where

$$L_{peff} = L_p + \left\{ M_{Pdiv} - \left\{ \frac{M_{PV} + M_{Psh}\alpha_{sh}}{B_{zoV} + B_{zosh}\alpha_{sh}} \right\} B_{zodiv} \right\} \alpha_{div}$$

$$R_{peff} = -R_p(1 - f_{CD} - f_{BS})$$

$$f_{BS} = I_{BS}/I_p = C_{BS}\sqrt{\varepsilon}\beta_p$$

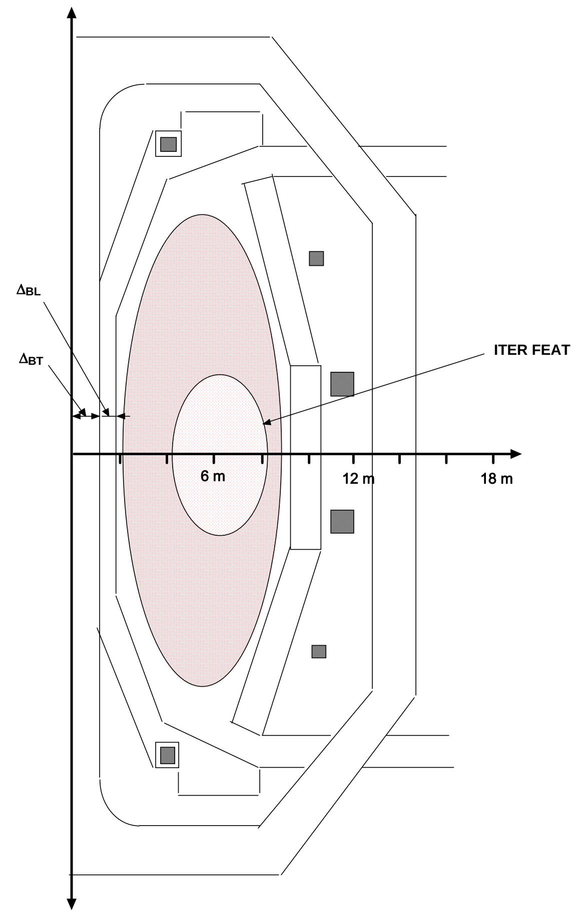
C_{BS}=0.5

α_{div} =0.2 , α_{sh} = 1

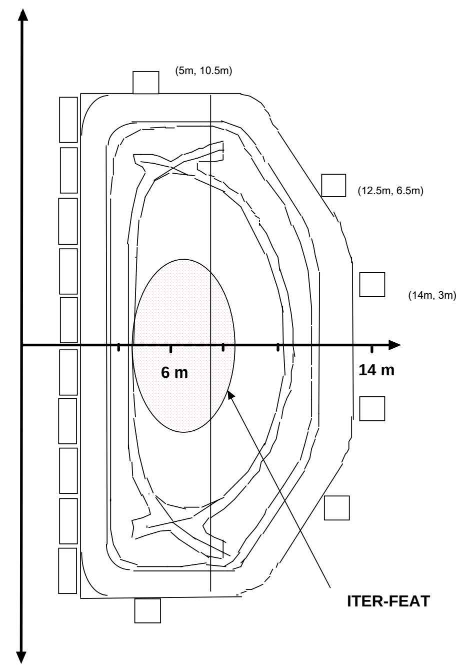
Feedback controlled OH by V_{OH}=200(1-I_p/I_{po})

As the vertical field drives the plasma current, the OH contribution is reduced during the fusion power rise-up phase.

2.6. D-^{3}He Tokamak device



Cross section of D-^{3}He ST "Thermonuclear Boiler Plant"



Final ST **D-^{3}He HAT**

Although machine sizes of D-^{3}He HAT are slightly larger than the present ITER, it may be constructed with the present technology in spite of the larger plasma parameters.

<u>Radial build:</u>

$R=7.5$ m, $a=3.2$ m, $\Delta_{SO}=0.2$ m, $\Delta_{BL}=0.8$ m, $\Delta_{SP}=0.2$ m, $\Delta_{BT}=1.0$ m, $\Delta_{OH}=0.8$m (total gap =0.4 m)

<u>OH coil:</u>$R_{OH}=R - a - \Delta_{SO} - \Delta_{BL} - \Delta_{SP} - \Delta_{BT} - \Delta_{OH}/2 = 1.7$ m

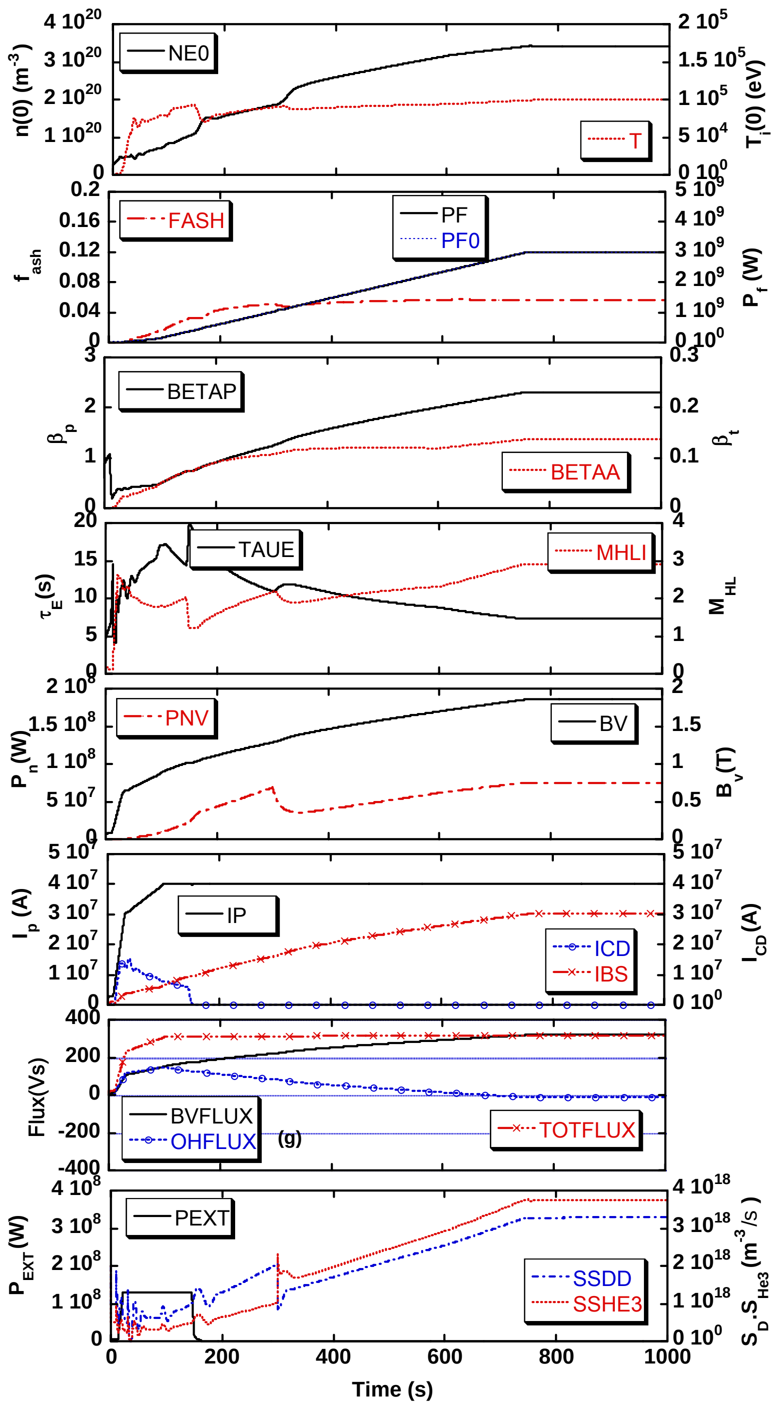
$B_{OH}=12.0$ T, $\Phi_{OH}= \pi R_{OH}^2(2B_{OH})=9.07\text{x}(2B_{OH}) = 217$ Vs

3. Calculated results of temporal evolution

3.1. Power generation plant without parameter constraints

[1] Wall reflection $R_{eff}=0.95$, $n/n_{GW}=1.83$, $\beta_{max}=13.7\%$, $T_i/T_e=1.5$, $\tau_p^*/\tau_E=2$, $D:{}^3He=0.46:0.54$, $f_{ash}=5.7\%$, $P_f=3.0$ GW, Ignition, $P_n=75$ MW, $P_e=1000$ MW [40%]

$n(0)=3.4\times10^{20}$ m^{-3}, $T_i(0)=99.9$ keV, $P_f f_i=2340$ MW$>P_{ie}=2235$ MW

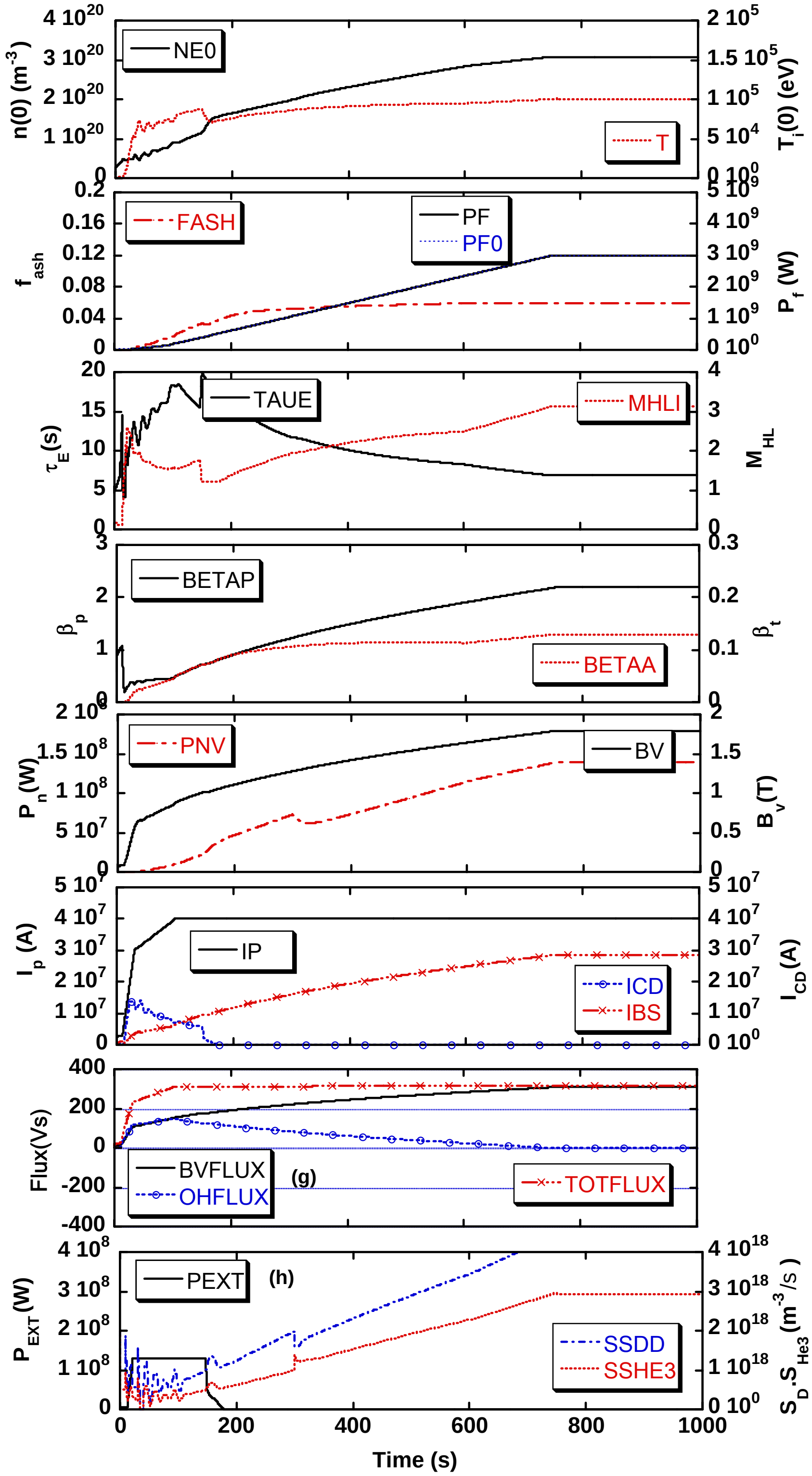


[2] Worse wall reflection $R_{eff}=0.9$, $n/n_{GW}=1.65$, $\beta_{max}=12.9\%$

$T_i/T_e=1.5$, $\tau_p^*/\tau_E=2$, $D:^3He = 0.6:0.4$, $f_{ash}=5.9\%$, , $P_f=3.0$ GW, Ignition,

$P_n=140$MW, $P_e=1000$ MW [40%]

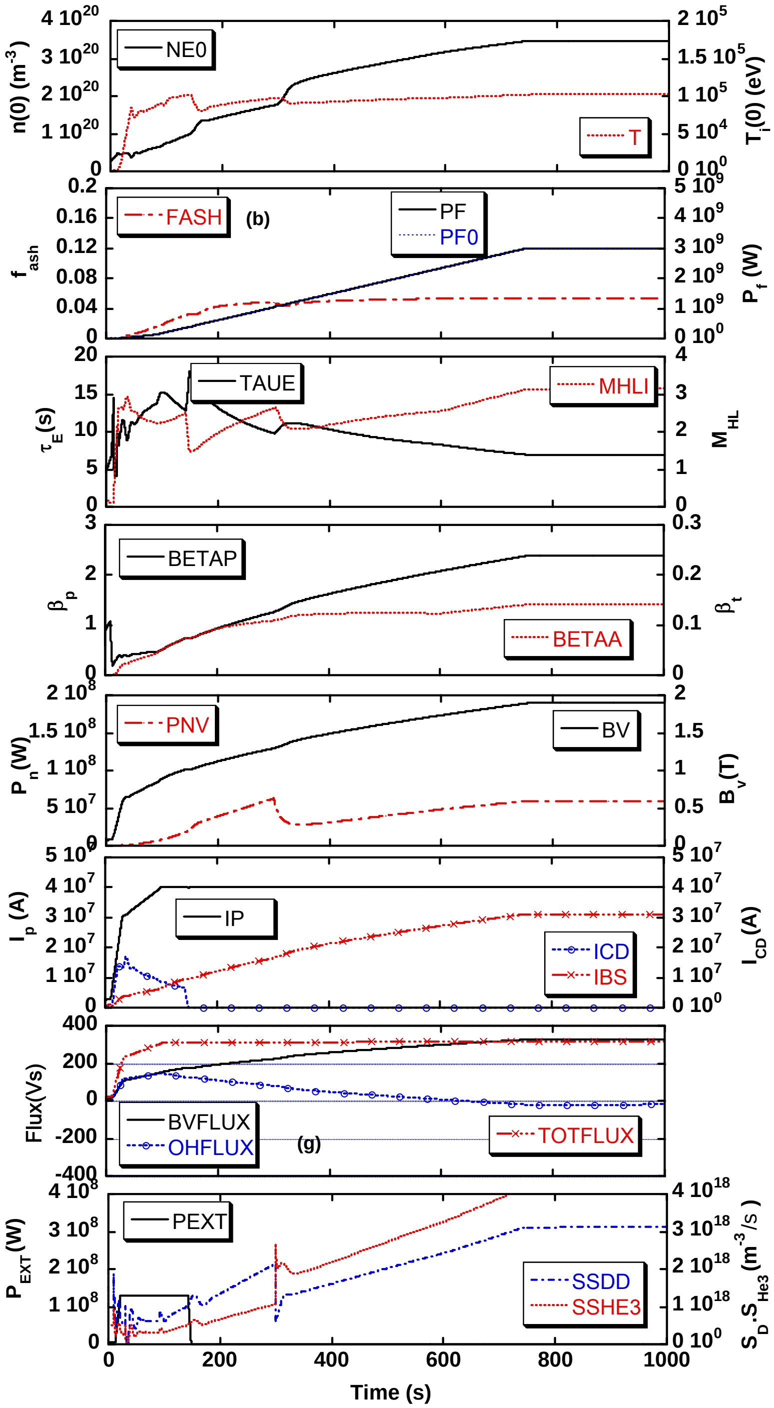
$n(0)=3.07\times10^{20}$ m^{-3}, $T_i(0)=100$ keV, $P_f f_i=2289$ MW $>P_{ie}=1762$ MW



[3] Good wall reflection R_{eff}=0.99, n/n_{GW}=1.85, β_{max}=14.1%, T_i/T_e=1.5, τ_p^*/τ_E=2, D:^{3}He = 0.42:0.58, f_{ash}=5.4%, P_f=3.0 GW, Ignition, P_n=60MW, P_e=1100 MW [40%],

$n(0)=3.46\times10^{20}$ m^{-3}, $T_i(0)$=103 keV, $P_f f_{ion}$=2352 MW>P_{ie}=2309 MW

If a wall reflection is good, the neutron power can be further reduced.

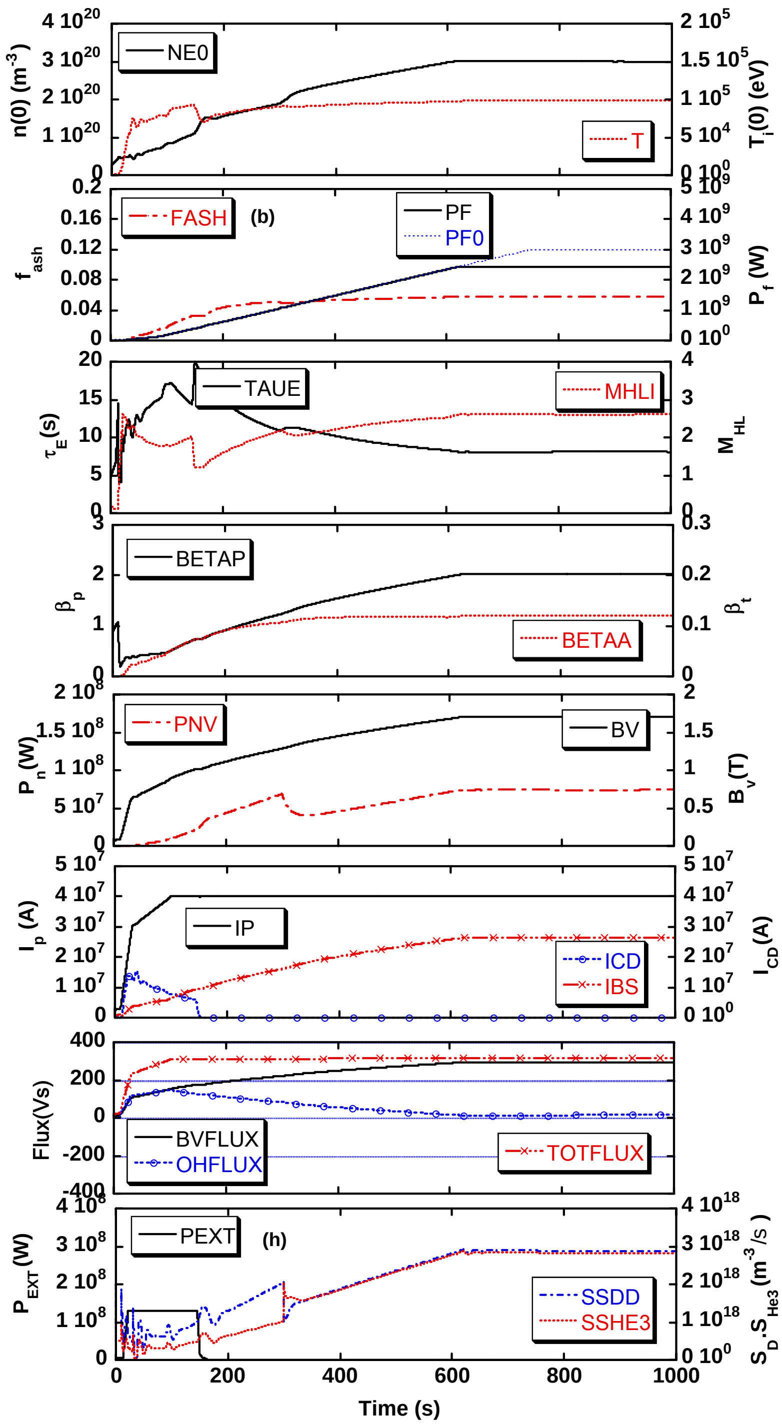


3.2. Possible power generation experiments with parameter constraints :

[4] The beta limit: β_{max}=12.0% , n/n_{GW}=1.6,

R_{eff}=0.95, T_i/T_e=1.5, τ_p^*/τ_E=2, D:^{3}He = 0.5:0.5, f_{ash}=5.5%, P_f=2.4 GW, Ignition, P_n=74MW, P_e=877 MW [40%]

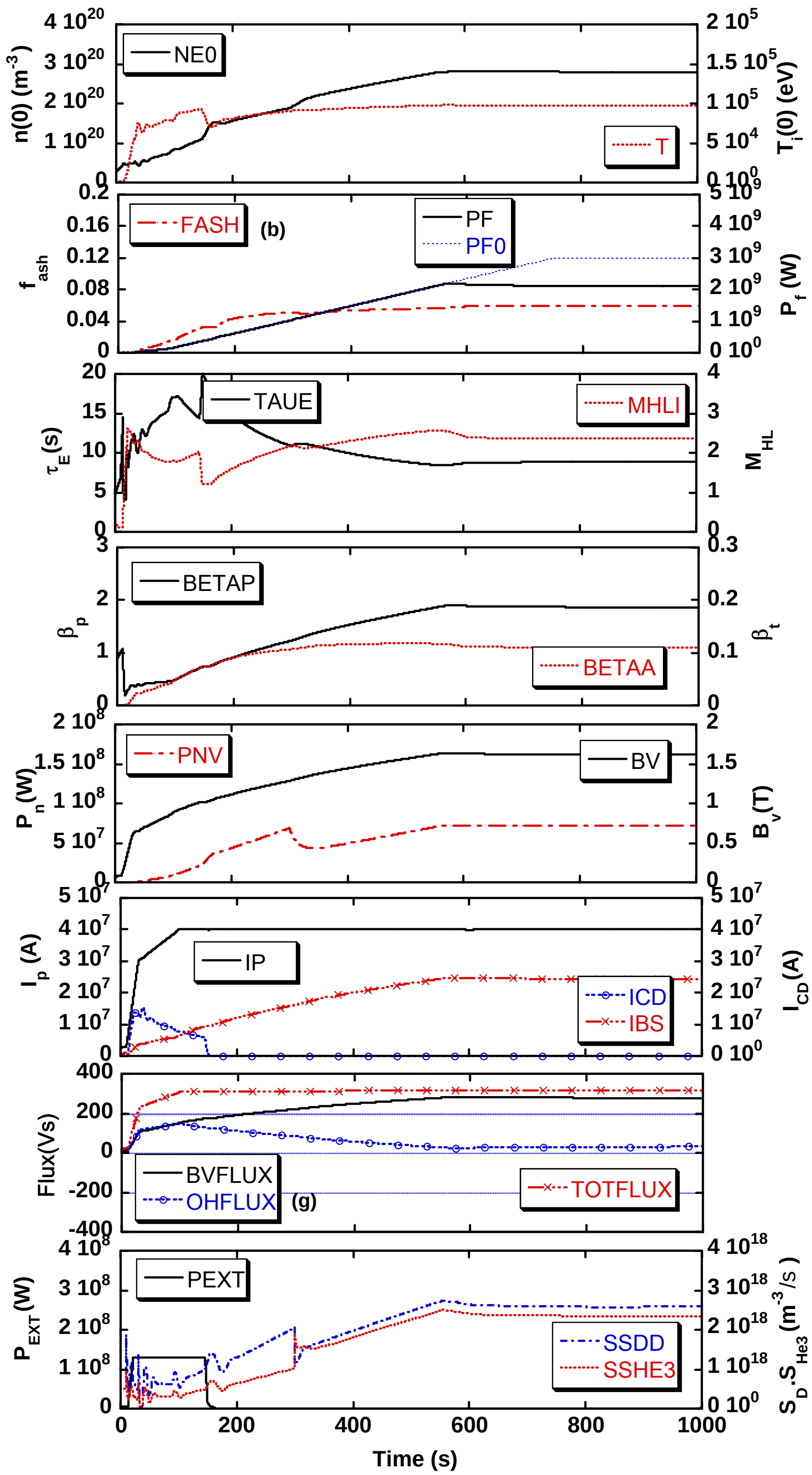
n(0)=3.00x10^{20} m^{-3}, $T_i(0)$=98.5 keV, $P_f f_i$=1887 MW>P_{ie}=1739 MW



[5] Additional density limit : n/n_{GW}=1.5, β_{max}=11.0%,

R_{eff}=0.95, T_i/T_e=1.5, τ_p^*/τ_E=2, D:^{3}He=0.52:0.48, f_{ash}=5.5%, P_f=2.1

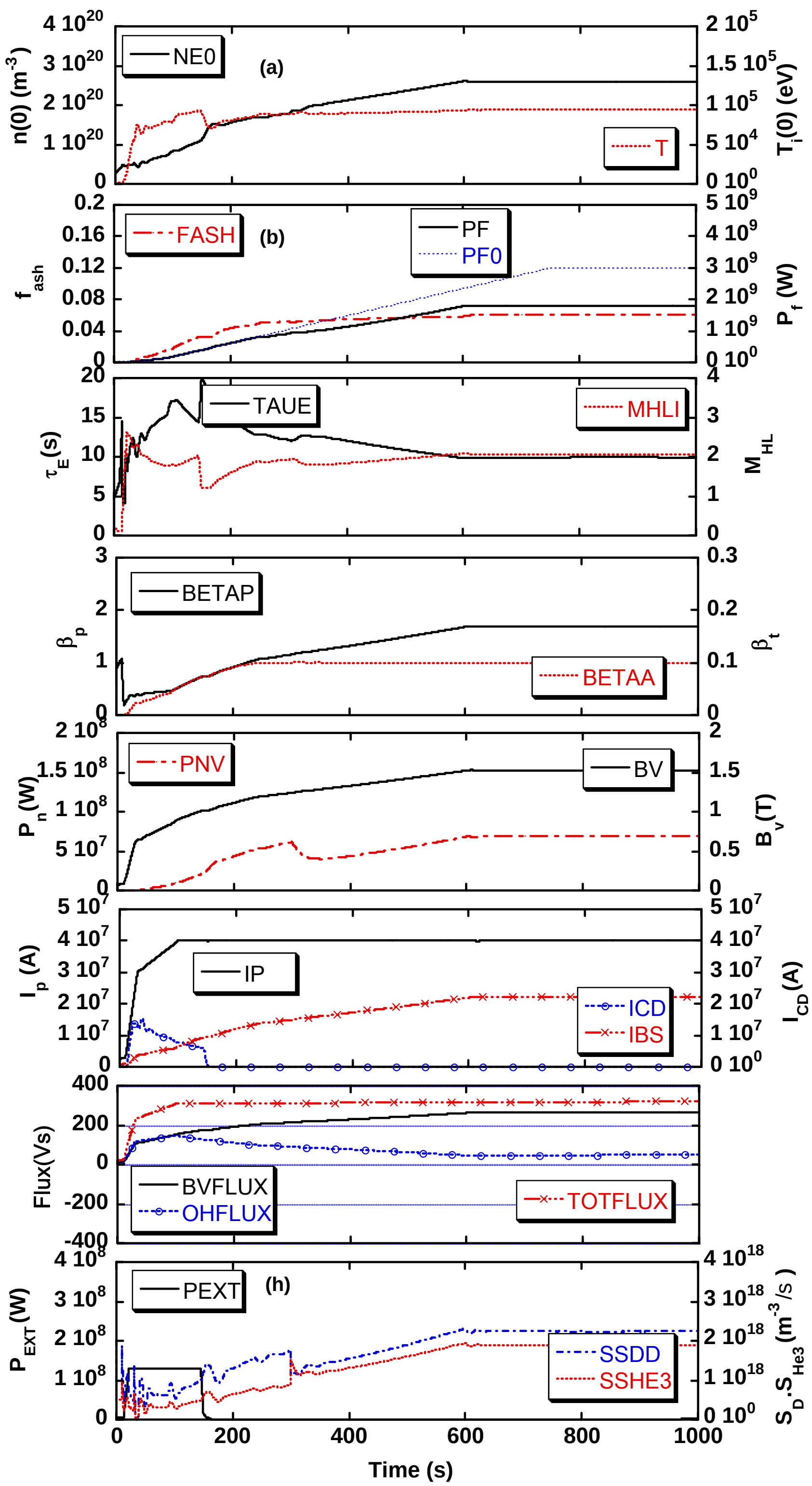
GW, Ignition, P_n=72W, P_e=755 MW [40%]
n(0)=2.79x10^{20} m^{-3}, $T_i(0)$=97 keV, $P_f f_i$=1634 MW >P_{ie}=1518 MW



[6] The beta limit : β_{max}=10.0%, n/n_{GW}=1.4,

R_{eff}=0.95, T_i/T_e=1.5, τ_p^*/τ_E=2, D:^{3}He = 0.54:0.46, f_{ash}=5.9%, P_f=1.8 GW, Ignition, P_n=68MW, P_e=630 MW [40%]

n(0)=2.59x10^{20} m^{-3}, T_i(0)=94 keV, $P_f f_i$=1373 MW>P_{ie}=1317 MW

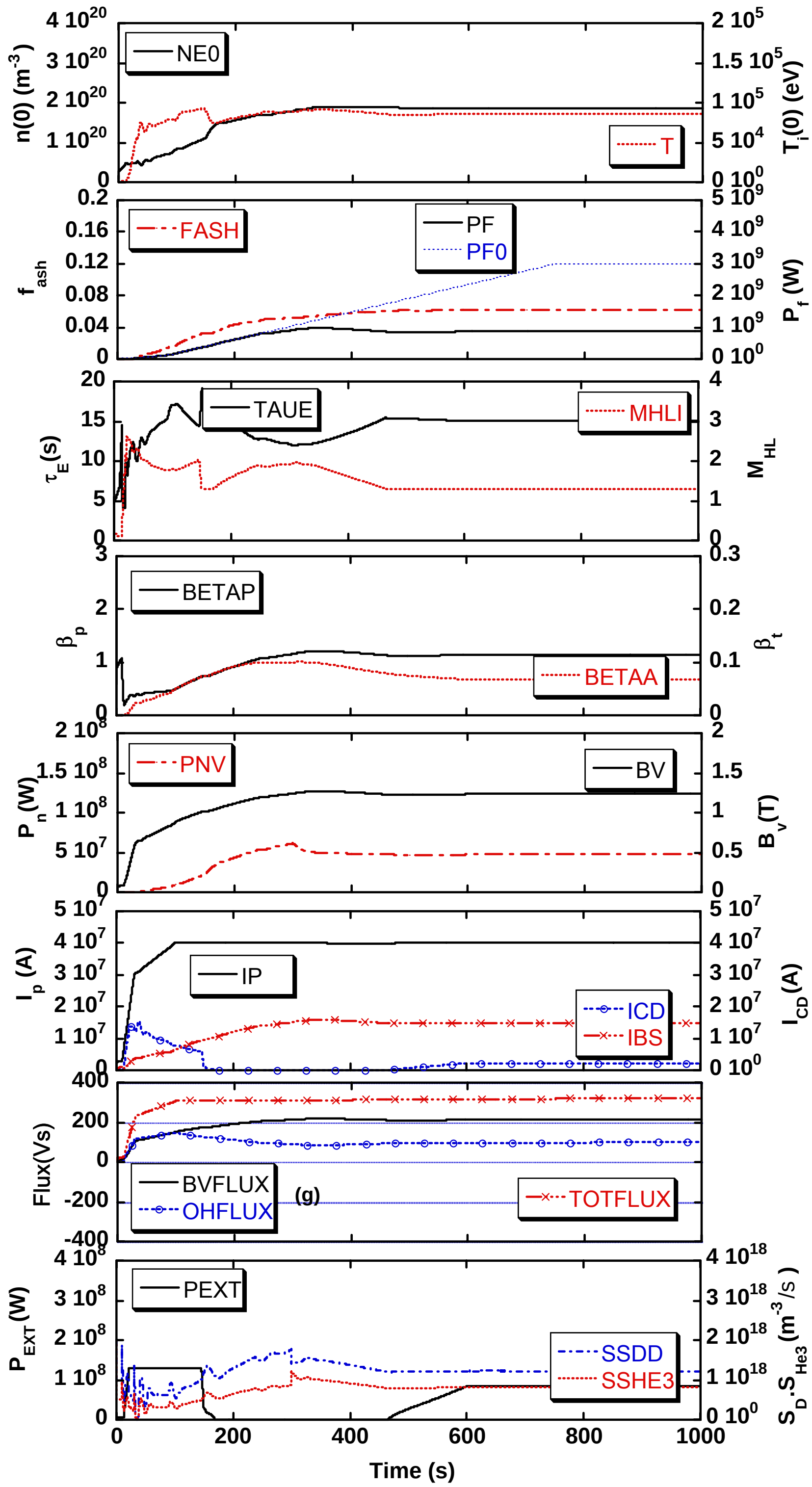


[7] Additional density limit : $n/n_{GW}=1.0$, $\beta_{max}=6.8\%$

$R_{eff}=0.95$, $T_i/T_e=1.5$, $\tau_p^*/\tau_E=2$, $D:^3He=0.6:0.4$, $f_{ash}=6\%$, $P_f=0.87$ GW,

Sub-Ignition, $P_n=47MW$, $P_e=320$ MW [40%], $Q_E=3.7$

$n(0)=1.86\times10^{20}$ m^{-3}, $T_i(0)=87$ keV, $P_f f_{ion}=728$ MW$>P_{ie}=696$ MW

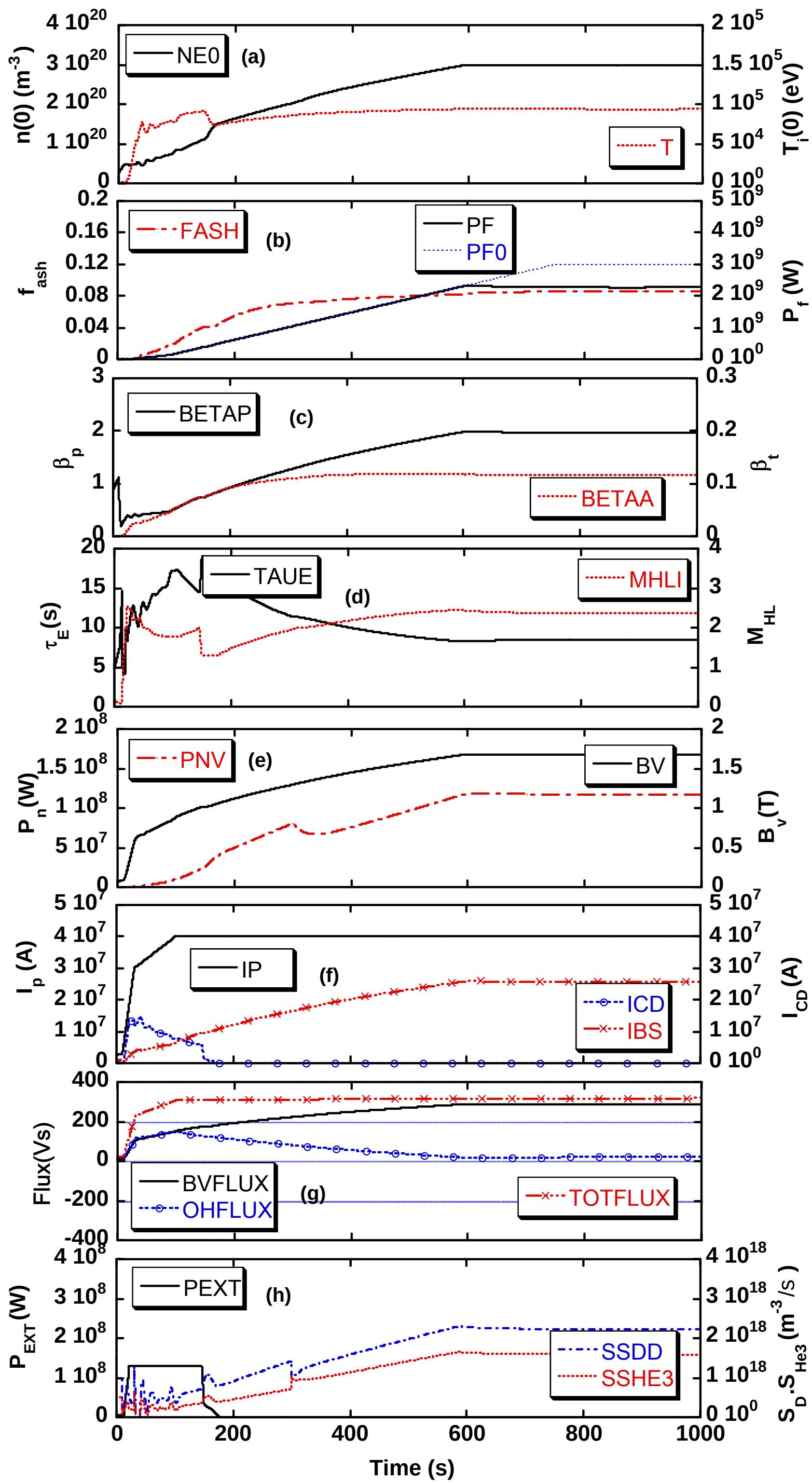


[8] Long particle confinement time : $\tau_p^*/\tau_E=3$, $f_{ash}=8.5\%$

$R_{eff}=0.95$, $T_i/T_e=1.5$, D:^{3}He = 0.58:0.42, $n/n_{GW}=1.6$, $\beta_{max}=11.8\%$,

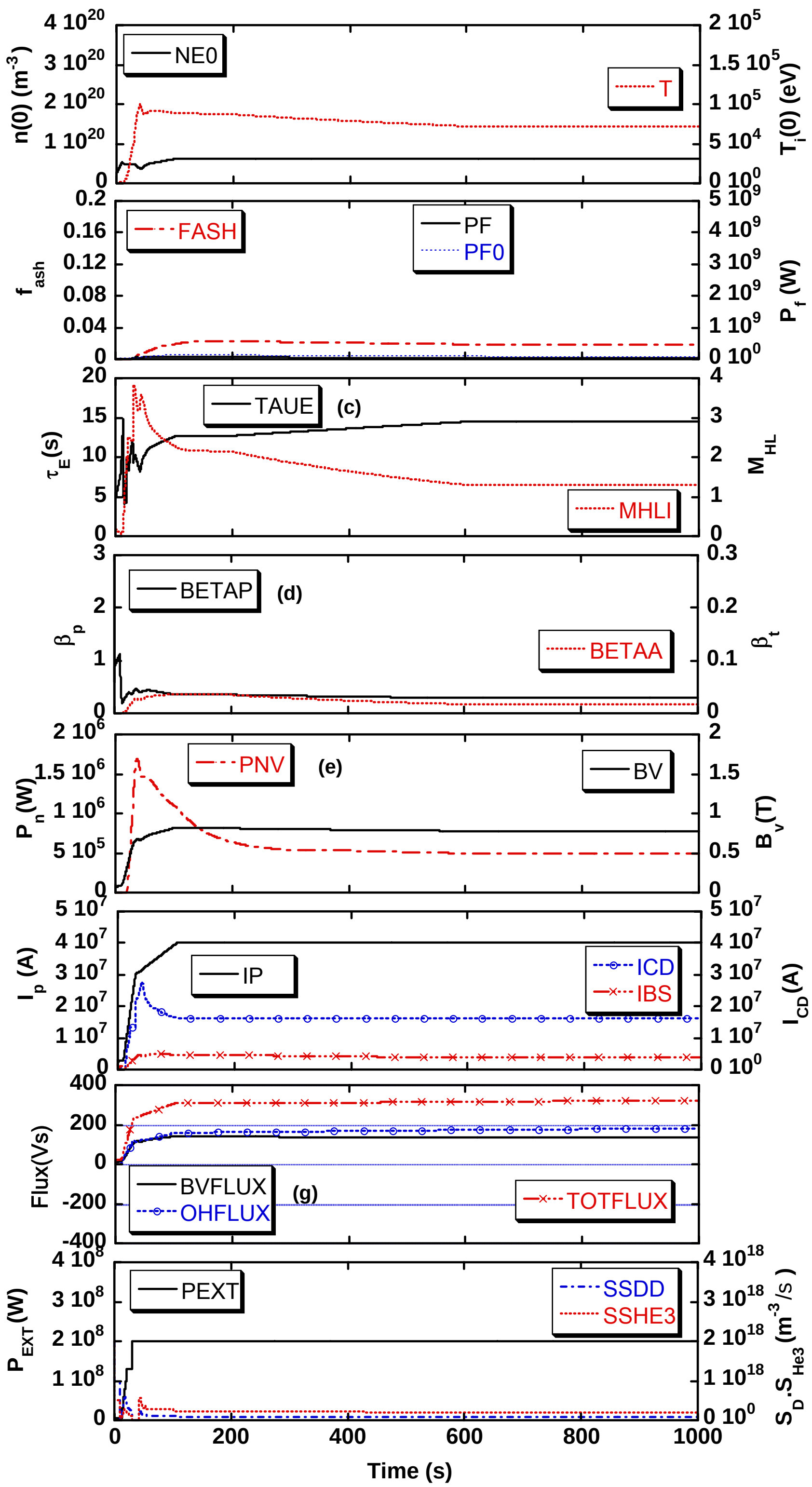
$P_f=2.37$ GW, Ignition, $P_n=132$MW, $P_e=838$ MW [40%]

$n(0)=2.98\text{x}10^{20}$ m^{-3}, $T_i(0)=95$ keV, $P_f f_i=1795$ MW>$P_{ie}=1674$ MW



NE0
(a)
T
n(0) (m^-3)
T_i(0) (eV)
FASH
(b)
PF
PF0
f_ash
P_f (W)
BETAP
(c)
BETAA
β_p
β_t
TAUE
(d)
MHLI
τ_E(s)
M_HL
PNV
(e)
BV
P_n (W)
B_v (T)
IP
(f)
ICD
IBS
I_p (A)
I_CD (A)
BVFLUX
OHFLUX
(g)
TOTFLUX
Flux(Vs)
PEXT
(h)
SSDD
SSHE3
P_EXT (W)
S_D.S_He3 (m^-3/s)
Time (s)

[9] ^{3}He rich operation (Possibly ^{3}He plasma +D-beam with E>1 MeV) , τ_p^*/τ_E=4, D:^{3}He=0.3:0.7, f_{ash}=1.67%, H-mode operation, P_f=44 MW, P_n=0.5 W, P_{EXT}=200 MW, P_e=81 MW[40%], Q_E=0.4, n(0)=6.2x10^{19} m^{-3}, T_i(0)=72 keV, $P_f f_i$=97 MW>P_{ie}=93 MW



NE0
T
n(0) (m^-3)
T_i(0) (eV)
FASH
PF
PF0
f_ash
P_f (W)
TAUE
(c)
MHLI
τ_E(s)
M_HL
BETAP
(d)
BETAA
β_p
β_t
PNV
(e)
BV
P_n (W)
B_v (T)
IP
ICD
IBS
I_p (A)
I_CD (A)
BVFLUX
OHFLUX
(g)
TOTFLUX
Flux(Vs)
PEXT
SSDD
SSHE3
P_EXT (W)
S_D,S_He3 (m^-3/s)
Time (s)

3.3. Parameters of D-^{3}He HAT:

Parameter	Symbol	No Limit	Beta limit $\beta \le 12\%$	Density limit $n/n_{GW} \le 1.5$	Beta limit $\beta \le 10\%$
Major radius:	R	7.5 m	7.5	7.5	7.5
Minor radius:	a	3.2 m	3.2	3.2	3.2
Toroidal field:	B_o	5-6.5 T	5-6.5	5-6.5	5-6.5
Maximum field:	B_{max}	12.1 T	12.1	12.1	12.1
Radius B_t coil :	Δ_{BT}	0.8m	0.8m	0.8m	0.8m
Plasma Current:	I_p	40 MA	40	40	40
Safety factor:	Q_{MHD}	2.98-3.8	2.98-3. 8	2.98-3. 8	2.98-3.8
Internal inductance	ℓ_i	0.5	0.5	0.5	0.5
Plasma inductance:	L_p	7.4 μH	7.4	7.4	7.4
Heating power:	P_{EXT}	130->0 MW	130->0	130->1.6	130->1.7
Plasma volume:	V	3031m^3	3031	3031	3031
Confinement factor over IPB(y,2) scaling :	γ_{HH}	2.0	2.0	2.0	2.0
Confinement time:	τ_E	7.2 s	8.1	8.8	9.9
Ash density fraction:	f_{ash}	5.7%	5.8	5.9	6.0
Be impurity fraction:	f_{Be}	2 %	2	2	2
Effective charge:	Z_{eff}	1.7	1.7	1.7	1.7
Particle confinement time ratio:	$\tau_\alpha^*/\tau_E = \tau_p^*/\tau_E$ …	2	2	2	2
Fuel ratio:	$n_D:n_{He3}$	0.46:0.54	0.5:0.5	0.52:0.48	0.54:0.46
Fusion product heating efficiency:	$\eta_\alpha = \eta_p =$..	1	1	1	1
Wall reflectivity:	R_{eff}	0.95	0.95	0.95	0.95
Hole fraction ;	f_H	0.1	0.1	0.1	0.1
Density profile:	α_n	1.0	1.0	1.0	1.0
Temperature profile:	α_T	1.0	1.0	1.0	1.0
Electron density:	$n(0)$	3.4x10^{20} m^{-3}	2.87x10^{20}	2.8x10^{20}	2.8x10^{20}
Greenwald factor	$n(0)/n(0)_{GW}$	1.82	1.6	1.5	1.4
Ion temperature:	$T_i(0)$	100 keV	99	97	78.3
Tmperature ratio:	$T_i(0)/T_e(0)$	1.5	1.5	1.5	1.5
Toroidal beta value:	$<\beta>$	13.7%	12.0	11.0	10.0
Poloidal beta value:	$<\beta_p>$	2.3	2.03	1.9	1.7
Normalized beta value:	$\beta_{\square}$	7.1	6.24	5.7	4.5
Fusion power:	P_f	3000 MW	2430	2110	1780
Neutron power:	P_n	75 MW	74	72	69
Bremsstrahlung loss:	P_b	958MW	731	621	517
Synchrotron radiation loss to the wall:	P_s	347 MW	332	313	289
for energy conv.:	P_s				
Plasma conduction loss:	P_L	438 MW	1132	954	770
Electric power (η_c=40%)	P_e	1100	877	725	630
Average neutron wall loading	Γ_n	0.047 MW/m^2	0.046	0.045	0.043
Average heat flux:	Γ_h	0.94 MW/m^2	0.77	0.68	0.59
Divertor heat load $P_L/(2\pi R$x1 m)	Γ_{div}	30.5MW/m^2	24.0	20.2	16.3
Energy multiplication	Q_F	∞	619	449	350

		Density limit $n/n_{GW} \leq 1.0$	Worse p/e ratio		3He rich operation
Major radius:	R	7.5 m	7.5	7.5	7.5
Minor radius:	a	3.2 m	3.2	3.2	3.2
Toroidal field:	B_o	5-6.5 T	5-6.5	5-6.5	5-6.5
Maximum field:	B_{max}	12.1 T	12.1	12.1	12.1
Radius B_t coil :	Δ_{BT}	0.8m	0.8m	0.8m	0.8m
Plasma Current:	I_p	40 MA	40	40	40
Safety factor:	Q_{MHD}	2.98-3.8	2.98-3. 8	2.98-3. 8	2.98-3.8
Internal inductance	ℓ_i	0.5	0.5	0.5	0.5
Plasma inductance:	L_p	7.4 μH	7.4	7.4	7.4
Heating power:	P_{EXT}	130->85.3 MW	130->0	130->1.5	200->200
Plasma volume:	V	3031m^3	3031	3031	3031
Confinement factor over IPB(y,2) scaling :	γ_{HH}	2.0	2.0	2.0	2.0
Confinement time:	τ_E	15.0 s	7.8	8.0	14.5
Ash density fraction:	f_{ash}	6.2%	11.0	8.5	1.8
Be impurity fraction:	f_{Be}	2 %	2	2	2
Effective charge:	Z_{eff}	1.6	1.6	1.6	1.8
Particle confinement time ratio:	$\tau_\alpha^*/\tau_E = \tau_p^*/\tau_E$ …	2	4	3	4
Fuel ratio:	$n_D{:}n_{He3}$	0.6:0.4	0.6:0.4	0.58:0.42	0.3:0.7
Fusion product heating efficiency:	$\eta_\alpha = \eta_p =$..	1	1	1	1
Wall reflectivity:	R_{eff}	0.95	0.99	0.95	0.95
Hole fraction ;	f_H	0.1	0.1	0.1	0.1
Density profile:	α_n	1.0	1.0	1.0	1.0
Temperature profile:	α_T	1.0	1.0	1.0	1.0
Electron density:	$n(0)$	1.86×10^{20} m^{-3}	3.0×10^{20}	2.98×10^{20}	0.62×10^{20}
Greenwald factor	$n(0)/n(0)_{GW}$	1.0	1.6	1.6	0.33
Ion temperature:	$T_i(0)$	87 keV	95	94	72
Tmperature ratio:	$T_i(0)/T_e(0)$	1.5	1.5	1.5	1.5
Toroidal beta value:	$<\beta>$	6.8	12.0	11.6	1.7
Poloidal beta value:	$<\beta_p>$	1.1	2.0	2.0	0.3
Normalized beta value:	β_N	3.5	6.2	6.0	0.9
Fusion power:	P_f	660 MW	2264	2276	44
Neutron power:	P_n	47 MW	134	117	0.5
Bremsstrahlung loss:	P_b	245 MW	691	674	264
Synchrotron radiation loss to the wall:	P_s	215 MW	136	292	85.5
for energy conv.:	P_s				
Plasma conduction loss:	P_L	343 MW	1155	1051	91
Electric power (η_e=40%)	P_e	320 MW	790	800	80
Average neutron wall loading	Γ_n	0.03 MW/m^2	0.08	0.073	0.0002
Average heat flux:	Γ_h	0.36 MW/m^2	0.61	0.7	0.1
Divertor heat load $P_L/(2\pi R\times1$ m)	Γ_{div}	7.3 MW/m^2	24.5	22.3	1.9
Energy multiplication	Q_E	3.7		537	0.4

4. Summary and issues

[1] D-^{3}He HA Tokmak device is proposed with CS.

@ R= 7.5 m, a= 3.2m, B_{to}= 5~6.5 T, (5.5 T in ITER)
@ Plasma current of ~40MA (17 MA in ITER)
@ IPB98y2 confinement factor γ_{HH}= 2.0 (2.2 in JT60)
@ Wall reflectivity 0.95
@ Low ash confinement ratio of 2 -->low neutron power of 75 MW
Ash confinement time ratio of 4 is possible
@ Neutron wall loading 0.04 MW/m^2 ,
@ Heat flux=0.87 MW/m^2 ($\leq$1.0 MW/m^2)
@ Greenwald factor<1.8 (1.5 in DIII-D,ASDEX)
@ β=12.0 % (10～13.8%) (β=12.6 % in DIII-D)

A D-^{3}He tokamak reactor would be possible within small extension of the present data base.

* For reference D-^{3}He ST reactor 1 GW power generation
@R= 5.6 m, a= 3.4m, B_{to}= 4.4 T,
@heating power and vertical field ramp to 90 MA (NSTX <1.5 MA)
@IPB98y2 confinement factor γ_{HH}= 2.5 ~ 1.8 (NSTX ~1.6)
@heat flux =0.99 MW/m^2 ($\leq$1.0 MW/m^2)
@Greenwald factor = 0.9 (1.5 in DIII-D,ASDEX)
@β=39.2 % (β=38 % in NSTX)
@Initial heating power$\leq$ 300 MW
@Maximum toroidal field B_{max} = 20.5 T(Bi-high temperature superconductor B_{max} = 22 T)

@ash confinement time ratio up to 5 (4 at present)

@low wall reflection ($R_{eff} \geq 0.35$)

@low ash confinement time ratio down to 2 -->low neutron power of 35 MW, low neutron wall loading of 0.02 MW/m^2 .

[2] Common issues in D-^{3}He reactors

(1) A large fraction (80 %) of the fusion power should go to ions to keep the hot ion mode of T_i/T_e =1.5.

[1] Nuclear elastic scattering (Nakao and Matsuura) may provide 40 %.

[2] The rest of 40 % should be provided by the stochastic ion heating (D.Gates et al) as observed in NSTX,

NSTX:	$T_i/T_e = 2$ for $V_{NBI} \sim 4V_A$
D-^{3}He ST reactor:	$V_\alpha \sim 3.8V_A, V_p \sim 7.5V_A$
D-^{3}He HA tokamak reactor :	$V_\alpha \sim 2.7V_A$, $V_p \sim 5.5V_A$

and gyro-stream cyclotron instability as proposed by Cheng.

(2) Divertor heat flux is very large

→ Pebble divertor by Nishikawa

→ Ga Liquid divertor