Ignition Characteristics of a D-^{3}He Helical Reactor

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collaboration with A.Sagara, S.Imagawa, K.Watanabe, T.Watanabe, and Y.Tomita (NIFS)

1. Motivation

1.1. Relative advantage and disadvantage of D-T and D-^{3}He reactor :

@ Nuclear waste: large amounts <--> smaller (?)
@ Blanket: frequent replacement <--> life time use
@ T accidental release: possible <--> less possible
@ Fuel breeding of tritium <--> Moon
@ Operation limit serious <--> less serious
(small
due to the allowable tritium production (<10 g /day)
tritium quantities at site
(~0.35 kg)
@ Public acceptance lower <--> higher

@ Machine size smaller <--> larger
@ Plasma parameters easier <--> difficult
(Larger first wall heat flux, higher temperature, higher density, higher beta, longer confinement, larger divertor heat flux)

1.2. Personal motivation

(1) Hostile environment to fusion--> attempt to design a cleaner fusion reactor

(2) Recent successful conceptual design of the D-^{3}He ST reactor by myself
——＞D-^{3}He helical reactor conceptual design.

(3) Challenge to the more demanding reactor study provides new insight into fusion study.
It can also be fed back to a D-T reactor.

1.2. Successful D-^{3}He ST reactor conceptual design

(1) High beta in NSTX β~35 %

(2) Successful plasma current ramp-up without CS coil in JT-60U, MAST and TST-2,

-->

@ R_o = 5.6 m, a=3.4 m, A=1.64, P_e~1 GW

@ Maximum toroidal field: B_{max} = 20.5 T for B_{to}= 4.4 T (Bi2124 high temperature superconducting coil)

@ Low neutron power of 35 MW is possible.

@ Plasma current of 90 MA is induced by the heating power and vertical field.

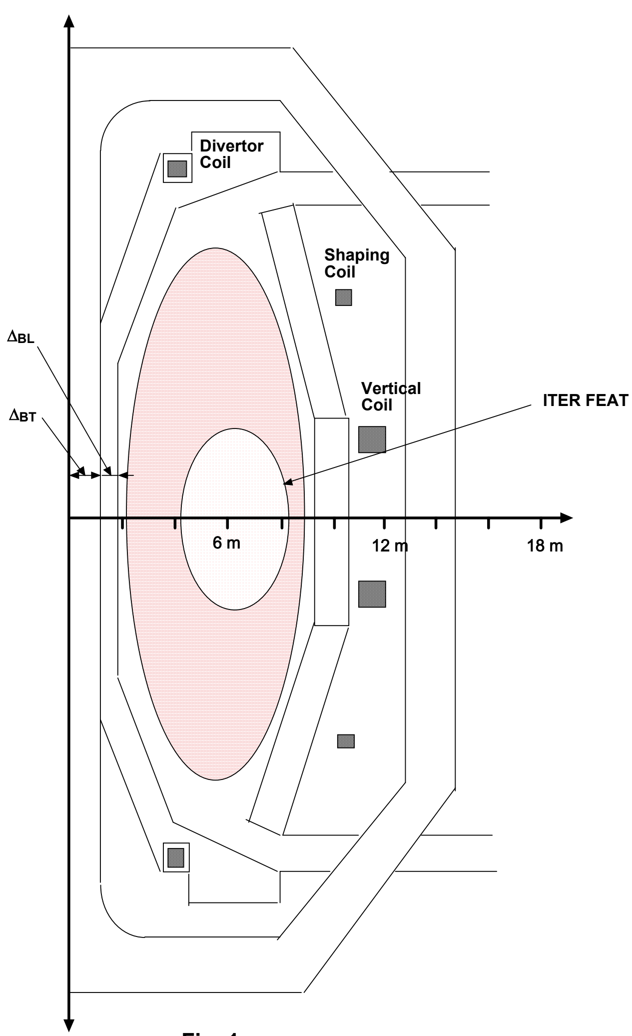


Fig. 1

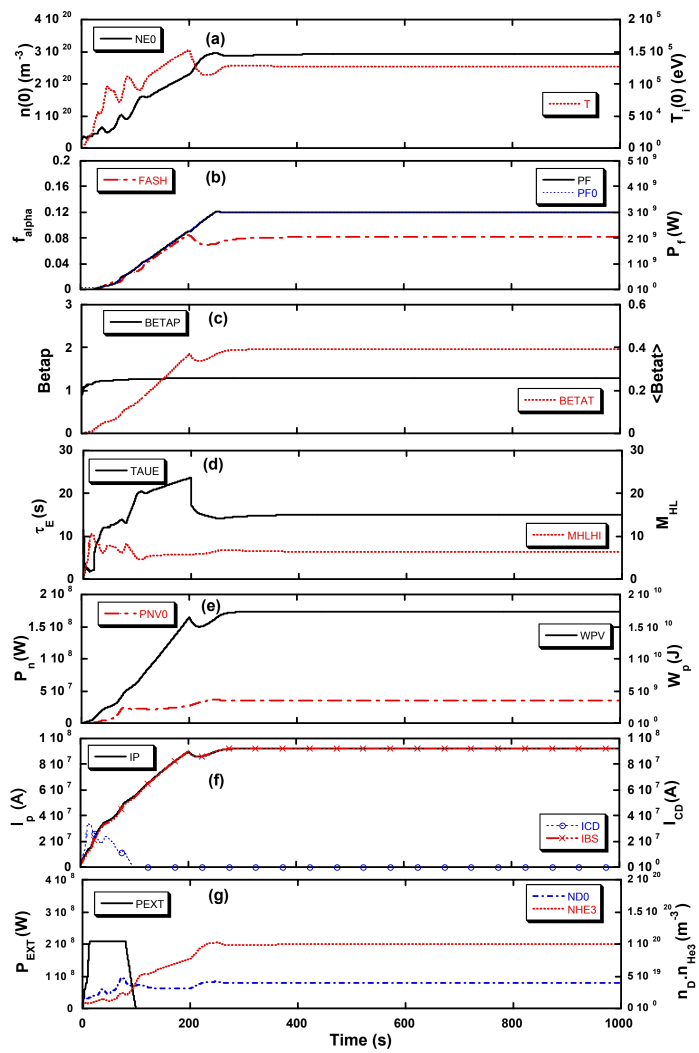


Fig. 6

Parameters of D-^{3}He Final ST:
Final (Fusion Ignitor with Neutron Alleviated) ST

		Constant I_p mode	I_p ramp-up mode: Low reflectivity	Long particle confinement	Low neutron mde
Major radius:	R	5.6 m	5.6	5.6	5.6
Minor radius:	a	3.4 m	3.4	3.4	3.4
Toroidal field:	B_o	4.4 T	4.4	4.4	4.4
Maximum field:	B_{max}	20.6 T	20.6	20.6	20.6
Radius B_t coil :	Δ_{BT} :	1.2 m	1.2	1.2	1.2
Plasma Current:	I_p	53 MA	85.7	86	92.5
Safety factor:	Q_{MHD}		5.3	5.3	4.98
Internal inductance	ℓ_i		0.42	0.42	0.42
Plasma inductance:	L_p		2.78 H	2.78	2.78
Heating power:	P_{EXT}	300 MW	300	220	210
Confinement factor over IPB(y,2) scaling :	γ_{HH}	2.5	2.5 to 1.7	2.5 to 1.6	2.5 to 1.8
Confinement time:	τ_E	6.1 s	14.5	11.3	15.0
Ash density fraction:	f_{ash}	5 %	14.7	11.1	8.2
Be impurity fraction:	f_{Be}	2 %	2	2	2
Effective charge:	Z_{eff}	1.55	1.74	1.75	1.86
Particle confinement time ratio:	$\tau_\alpha^*/\tau_E = \tau_p^*/\tau_E$ …	2	4	5	2
Fuel ratio:	$n_D:n_{He3}$	2:1	1:1	0.85:1	0.4:1
Fusion product heating efficiency:	$\eta_\alpha = \eta_p =$..	1	1	1	1
Wall reflectivity:	R_{eff}	0.9	0.35	0.99	0.99
Hole fraction ;	f_H	0.1	0.1	0.01	0.1
Density profile:	α_n	1.0	0.5	0.5	0.5
Temperature profile:	α_T	1.0	1.0	1.0	1.0
Electron density:	n(0)	2.55×10^{20} m^{-3}	3.1×10^{20}	3×10^{20}	2.9×10^{20}
Greenwald factor	$n(0)/n(0)_{GW}$	1.85	1.03	0.99	0.9
Ion temperature:	$T_i(0)$	105 keV	98	100	127
Tmperature ratio:	$T_i(0)/T_e(0)$	1.4	1.4	1.4	1.4
Toroidal beta value:	$<\beta>$	26 %	33.7	34.4	39.2
Poloidal beta value:	$<\beta_p>$	2.6	1.28	1.29	1.29
Normalized beta value:	β_N		5.9	6.0	6.3
Fusion power:	P_f	3 GW	3	3	3
Neutron power:	P_n	170 MW	123	113	35.4
Bremsstrahlung loss:	P_b		1457	1440	1682
Synchrotron radiation loss to the wall:	P_s		350	48	62
for energy conv.:	P_s		48	53	70
Plasma conduction loss:	P_L		1024	1350	1153
Electric power (η_c=50%)	P_e		~1000	~1000	~1000
Average neutron wall loading	Γ_n	0.12 MW/m^2	0.07	0.06	0.02
Average heat flux:	Γ_h	0.9 MW/m^2	1.02	0.83	0.99
Divertor heat load	Γ_r		1350/(2πRx1) ~39 MW/m^2		

2. Ignition control algorithm in a helical reactor

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

$T_i(x)/T_i(0) = T_e(x)/T_e(0) = (1-x^2)^{\alpha_T}$

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

ISS95 confinement law: As γ_H~1.6 in LHD, γ_{HH} is the further required confinement factor over the present LHD

$$\begin{cases} \tau_E[s] = \gamma_{HH} \times 1.6\ \tau_{ISS95}[s] \\ \tau_{ISS95}[s] = 0.079 \iota_{2/3}^{0.4} \overline{n}_{20}^{0.51}[\times 10^{20} m^{-3}] B_o^{0.83}[T] \\ \qquad \times \overline{a}^{2.21} R^{0.65}[m] / P_{HT}^{0.59}[MW] \end{cases}$$

2.2. External heating power:

As clear transition from L to H mode in LHD has not been observed, the density limit has been used for control of the heating power.

The external heating power is applied to expand the density limit, not to maintain the H-mode regime.

Density limit :

$$\gamma_{DL0} n(0) \le n(0)_{\lim}[m^{-3}] = \frac{0.25\times 10^{20}}{\gamma_{pr}} \sqrt{\frac{\{\overline{P}_{h,net} V_o [MW]\times 10^6\} B_o[T]}{\overline{a}^2 R\ [m]}}$$

where

Density limit set value : $\gamma_{DL0} = n(0)_{lim}/n(0) = 1.02 > 1.0$

Density limit is slightly higher than the operation density.

Profile factor $(\gamma_{pr} = \bar{n}/n(0) = 2/3$ **parabolic profile),**

External heating power :

$$P_{EXT}(DL)[W] = \left\{\frac{\gamma_{DL0}\gamma_{pr} n(0)[m^{-3}]}{0.25\times 10^{20}}\right\}^2 \frac{\overline{a}^2 R\ [m]}{B_o[T]} \times 10^6 - (P_\alpha - P_B - P_S)$$

2.3. Fueling

D, ^{3}He fueling are controlled by the fusion power signal P_f and fueling rate.

PID control for continuous gas puffing

$$S_{DHE3}(t) = S_{DHE30}\left\{e(P_f) + \frac{1}{T_{\text{int}}}\int_0^t e(P_f)dt + T_d\frac{de(P_f)}{dt}\right\}G_{fo}(t)$$

$e(P_f) = 1 - P_f / P_{fo}(t)$

Here, PI control was employed.
Integration time: T_{int}> 20 sec
Derivative time: T_d=0

Fuel ratio control

@ Initially, the fuel ratio: n_D / n_{He3} = 2 / 1,
@ Later, feedback control of fuel ratio (n_D / n_{He3} ~ 1) to reduce neutron power

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

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

where

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

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

PI control was employed: Integration time:$T_{DHE3int}$= 100 sec

@ The particle confinement time ratio:

$$\tau_D/\tau_E = \tau_T/\tau_E = \tau_p/\tau_E = \tau_T/\tau_E = \tau_{HE3}/\tau_E = \tau_\alpha/\tau_E = 2$$

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

@ As the beta value is lower than that in ST, ignition is sensitive to the wall reflectivity.
-->$R_{eff}=0.99$ has been chosen.

2.4. Helical reactor based on the LHD size scaling to estimate the blanket thickness (calculated by Dr. Imagawa)

Based on the shifted LHD plasma (R=3.6 m) with the good thermal and super-thermal confinement, three sizes of a helical reactor have been chosen.

(1) R=14.77 m, a=2.585 m, Δ_B=0.930 m
(2) R=16.62 m, a=2.908 m, Δ_B=1.115 m
(3) R=18.46 m, a=3.232 m, Δ_B=1.297 m

3. Temporal evolution

D-^{3}He Ignition is possible for a helical reactor with R = 14.47m, a = 2.585 m, B_o = 6 T, high beta of $\langle\beta\rangle \sim 18$ %

□□□□□□□□□□□□□□□□□□:

□γ_{LHD} = 2.4 ->2.4, P_{EXT}= 300 MW, D:^{3}He = 2: 1--> P_n=184 MW

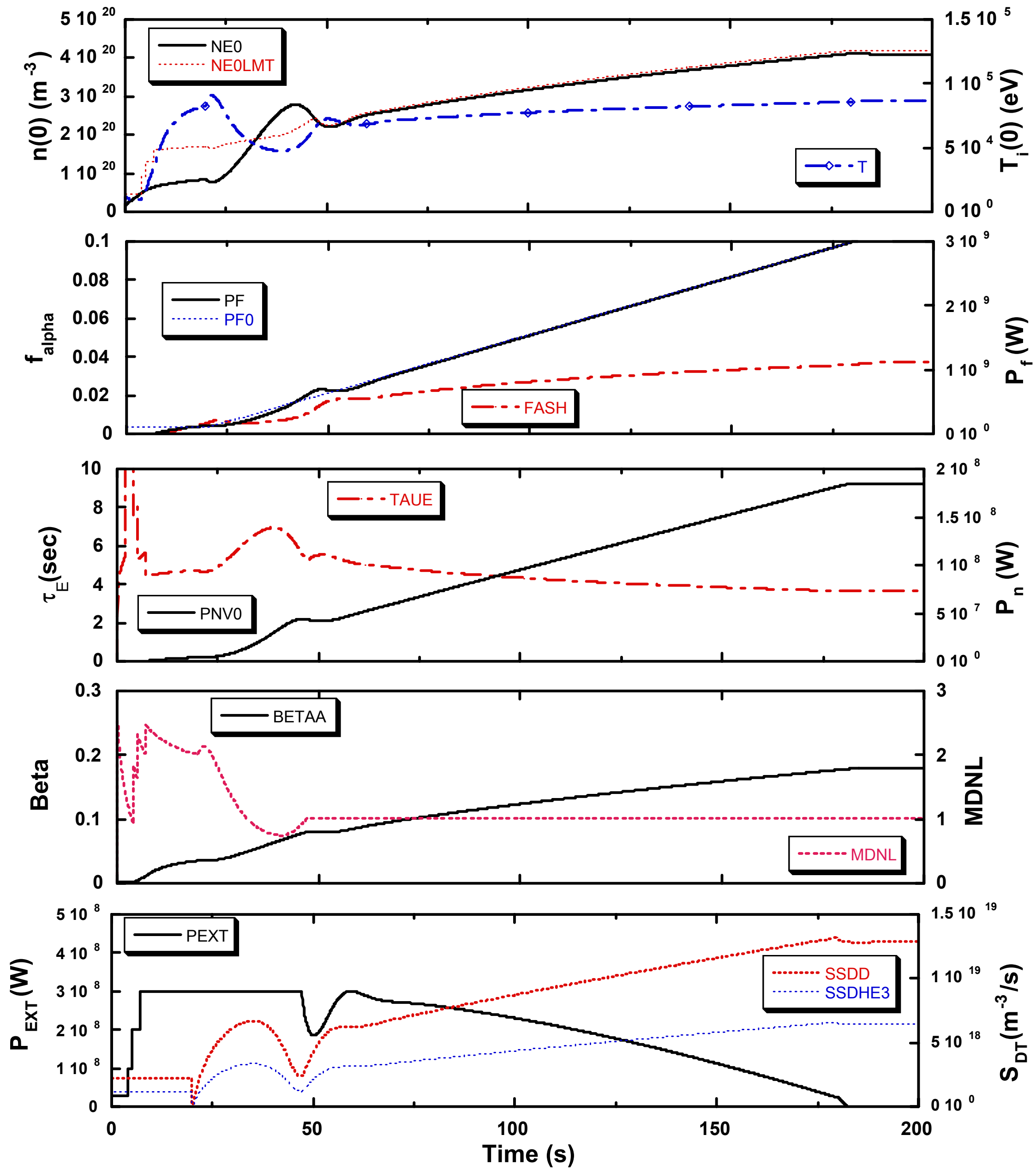
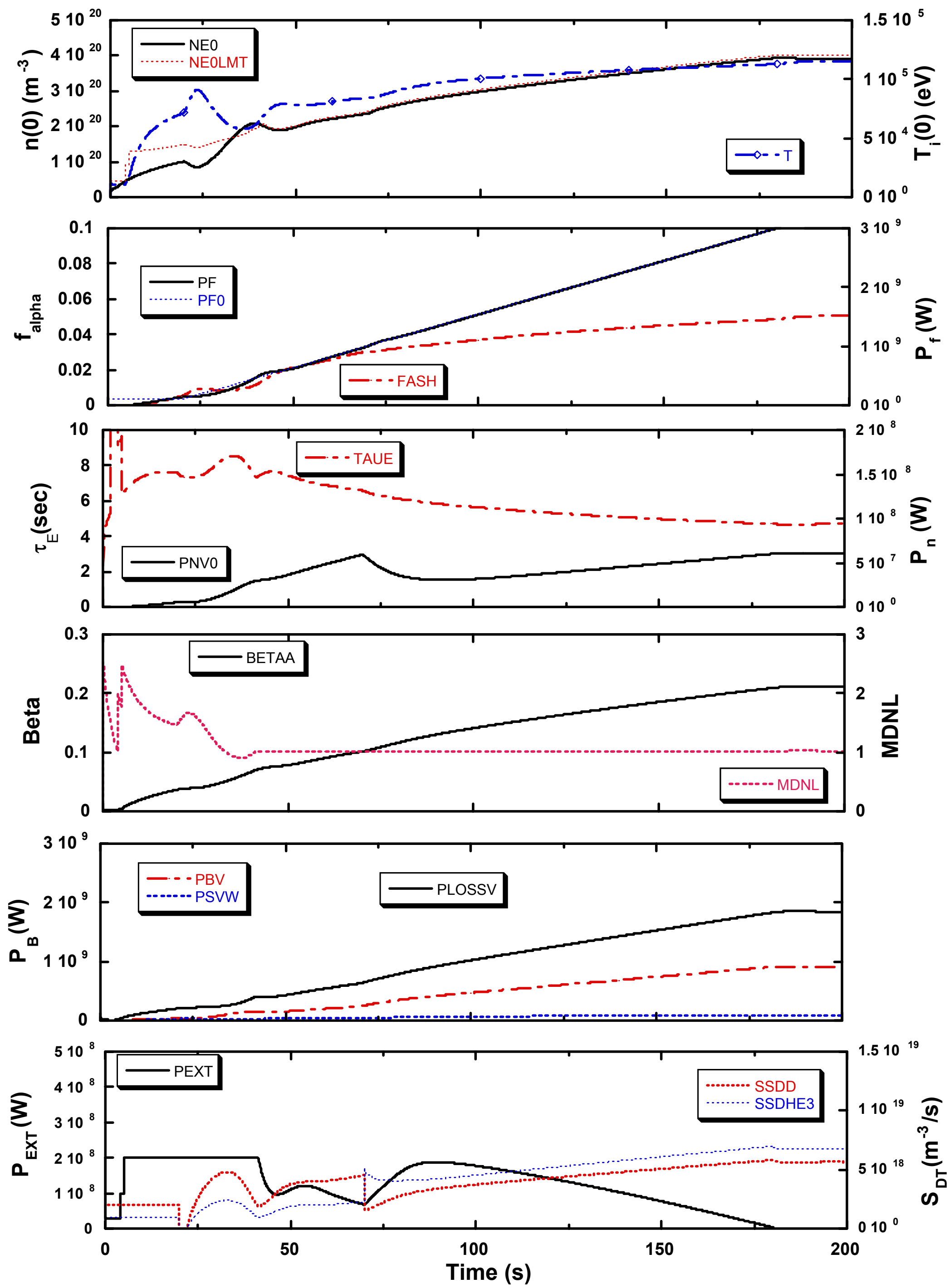


Fig. 1

Low neutron mode: R/a=14.47 m/2.585 m, $\langle\beta\rangle$ ~ 21 %
γ_{LHD} = 3 ->3, P_{EXT}= 200 MW,D:^{3}He = 0.45:0.55--> P_n=61 MW



NE0
NE0LMT
T
n(0) (m^{-3})
$T_i(0)$ (eV)
PF
PF0
FASH
f_{alpha}
P_f (W)
TAUE
PNV0
τ_E(sec)
P_n (W)
BETAA
MDNL
Beta
MDNL
PBV
PSVW
PLOSSV
P_B (W)
PEXT
SSDD
SSDHE3
P_{EXT} (W)
S_{DT}(m^{-3}/s)
Time (s)

Fig. 2

The larger machine-1: **R/a=16.62 m/2.908 m**

τ_D/τ_E = ... = 2, $\langle\beta\rangle \sim 16$ %

1. γ_{LHD} = 3.0 ->2.5 and P_{EXT}= 250 MW   D:^{3}He = 0.52:0.48
2. γ_{LHD} = 2.5 ->2.5 and P_{EXT}= 300 MW   --> P_n=87 MW

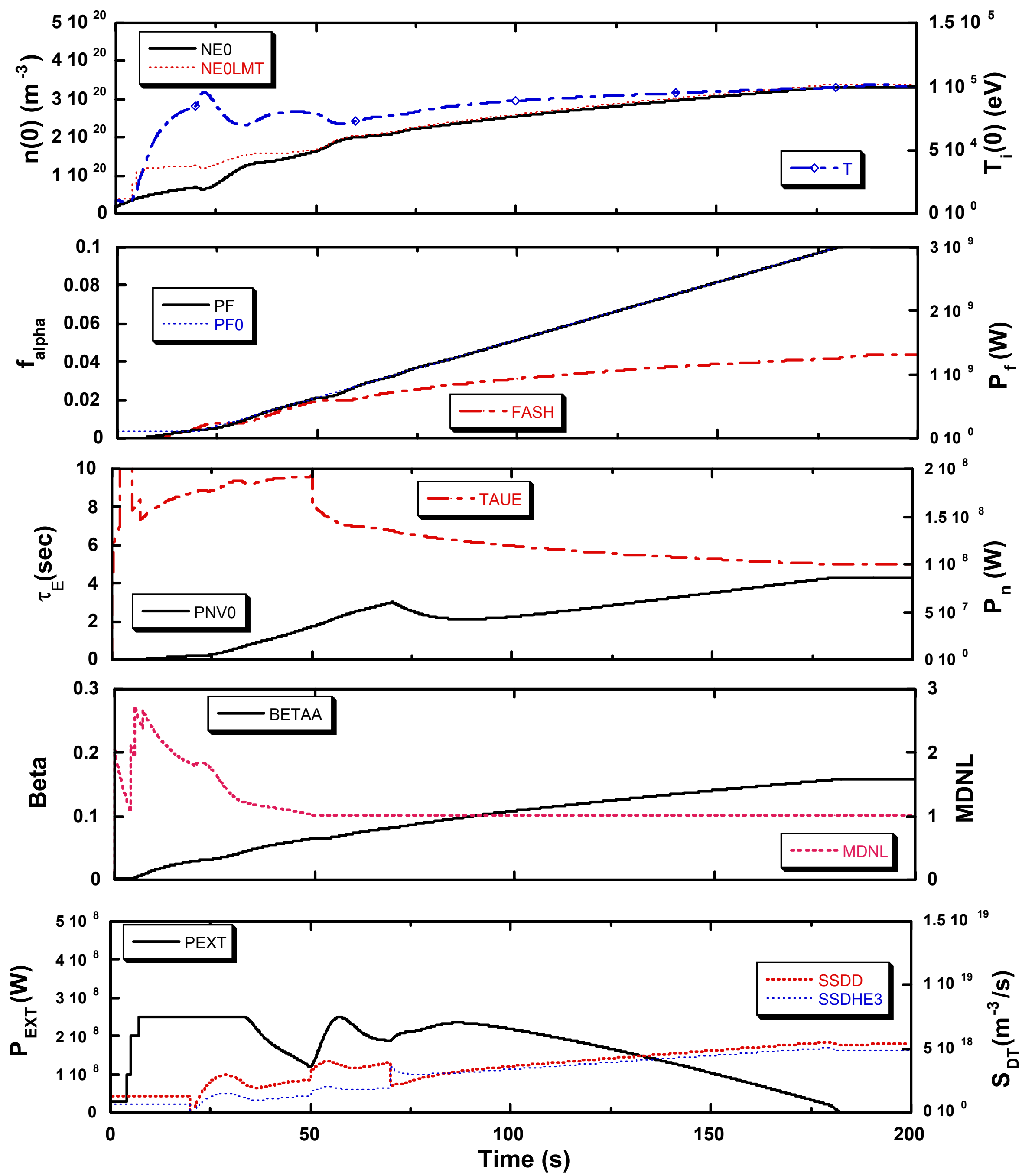


Fig. 3

The larger machine-2: **R/a=18.46 m/3.232 m**

τ_D/τ_E = ... = 2, $<\beta>$ ~ 14 %

..!γ_{LHD}= 3.0 ->2.5 and P_{EXT}= 250 MW D:^{3}He = 0.52:0.48

. 2γ_{LHD} = 2.5 ->2.5 and P_{EXT}= 300 MW --> P_n=86 MW

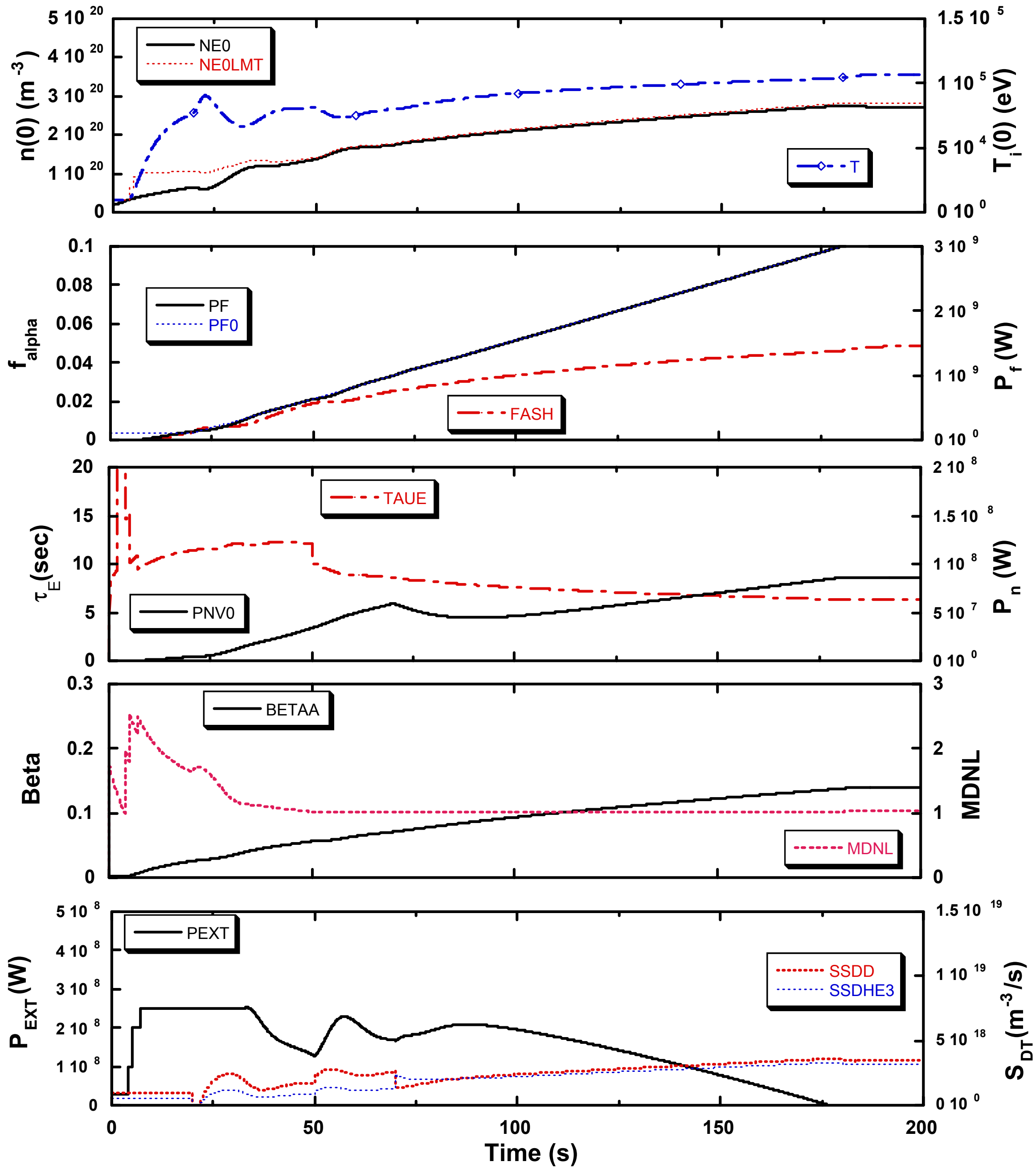


Fig. 4

Parameters D-^{3}He Helical Reactor

		Lower confinement	Low neutron mode		
Major radius:	R	14.47 m	14.47	16.62	18.46
Effective minor radius:	a	2.585 m	2.585	2.908	3.232
Toroidal field:	B_o	6.0 T	6.0	6.0	6.0
Maximum field:	B_{max}	T			
Plasma volume	V_o	1908 m^3	1980	2774	3806
Plasma surface area	S_o	1476 m^2	1476	1988	2355
Vessel surface area	S_w				
Blanket thickness :	Δ_{BT} :	0.933 m	0.933	1.115	1.297
Rotational transform:	$\iota_{2/3}$	0.92	0.92	0.92	0.92
Heating power:	P_{EXT}	300 MW	200	250 (300)	250 (300)
Confinement factor over 1.6xISS95 scaling : γ_{LHD}		2.4->2.4	3.0->3.0	3->2.5 (2.5->2.5)	3.0-> 2.5 (2.5->2.5)
Confinement time:	τ_E	3.7 s	4.7 -->	5.0 -->	6.3
Ash density fraction:	f_{ash}	3.75 %	5.1	4.4	4.9
Be impurity fraction:	f_{Be}	1 %	1	1	1
Effective charge:	Z_{eff}	1.54	1.73	1.68	1.68
Particle confinement time ratio:	$\tau_\alpha^*/\tau_E = \tau_p^*/\tau_E$ …	2	2	2	2
Fuel ratio:	$n_D:n_{He3}$	2:1	0.45:0.55	0.52:0.48	0.52:0.48
Fusion product heating efficiency:	$\eta_\alpha = \eta_p =$..	1	1	1	1
Wall reflectivity:	R_{eff}	0.99	0.99	0.99	0.99
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)	4.10×10^{20} m^{-3}	3.92×10^{20} -->	3.3×10^{20}-->	2.72×10^{20}
Density limit factor	$n(0)/n(0)_{LIMIT}$	1.02	1.02	1.02	1.02
Ion temperature:	$T_i(0)$	87 keV	115	100	107
Temperature ratio:	$T_i(0)/T_e(0)$	1.5	1.5	1.5	1.5
Toroidal beta value:	$<\beta>$	18 %	21.1 -->	15.9 -->	14.0
Fusion power:	P_f	3 GW	3	3	3
Neutron power:	P_n	184 MW	61	87	86
Bremsstrahlung loss:	P_b	717 MW	906	818	803
Synchrotron radiation loss to the wall:	P_{sw}	46.5 MW	89.3	94.6	143
for energy conv.:	P_{sH}	51.6 MW	99.2	105.1	158
Plasma conduction loss:	P_L	2000 MW	1847	1897	1810
Electric power (η_c=40%)	P_e	~1100 MW	~1100	~1000	~1000
Average neutron wall loading Γ_n		0.12 MW/m^2	0.04	0.046	0.036
Average heat flux:	Γ_h	0.55 MW/m^2	0.74	0.53	0.47
Divertor heat load $=P_L/(2\pi R x 1m x 2leg)$	Γ_r	11 MW/m^2	~10	9	7.8

For reference: **The same size of D-T reactor (R = 14.47 m, a = 2.585 m, B_o = 6T) does not require any improvement in confinement and beta value for D-T ignition.**

(γ_{LHD} = 1.0, the beta of <β> ~ 2.7 %, η_α =1, τ_D/τ_E = ... = 3 and the heating power of 70 MW) --> P_n=2400 MW

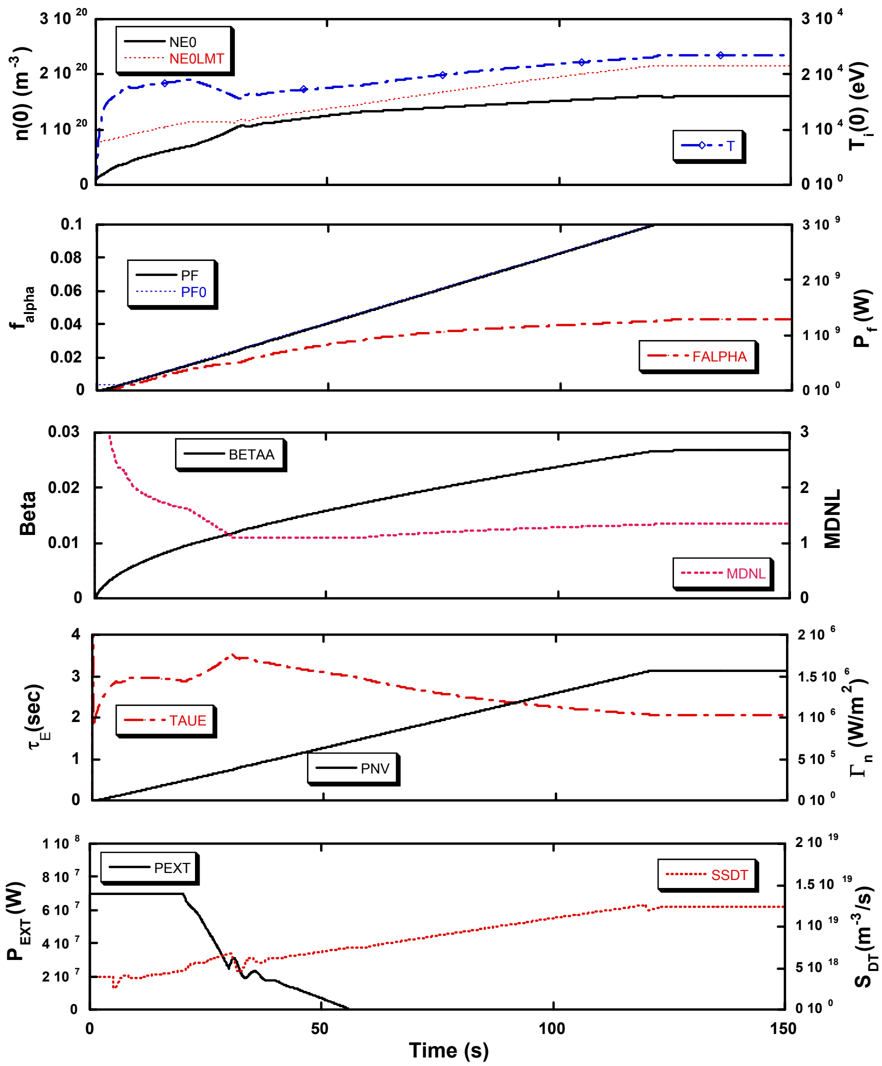


Fig. 5

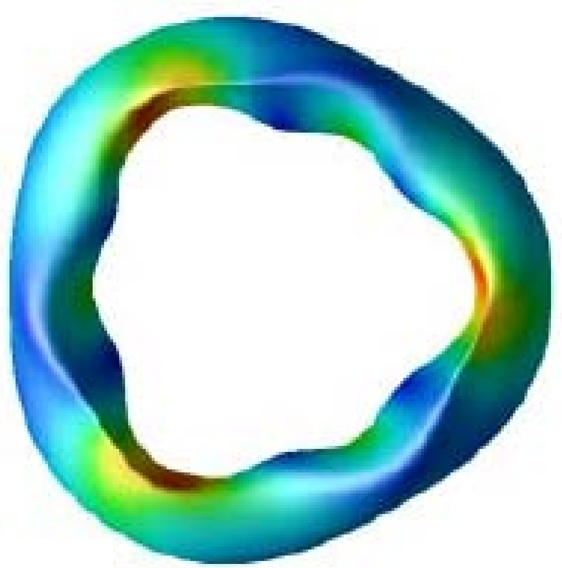
However, D-^{3}He helical reactor is demanding in

beta, confinement factor and divertor heat flux when LHD type machine is assumed.

Quasi-poloidal stellarator (QPS) proposed by Oak Ridge Group is interesting for D-^{3}He helical reactor.

(D.A.Spong et al., Nuclear Fusion, 41 (2001) 711)

β=15~23 %, τ_E~ 6 xτ_{ISS95} -> <u>3.75</u> (1.6xτ_{ISS95}) are predicted for the aspect ratio A=3.7.



Cited from "The ORNL Quasi-Poloidal Stellarator (QPS)" by J. F. Lyon, ORNL
Auburn Univ., Feb. 7, 2002

One example of QPS D-^{3}He reactor

$A=3.7$, $R=11.1$ m, $a=3.0$ m, $B=6$ T, $\gamma_{LHD}=3.0$ and $\eta_p=97\%$, D:^{3}He = 0.45:0.55 ---> $P_n=62$MW, $\Gamma_n=0.04$ MW/m^2, $\Gamma_h=0.85$ MW/m^2, $\beta=22.8$ %, $f_{ash}=6.24$ %, $P_L=1.74$ GW, $P_B=0.94$ GW, $P_s=0.25$ GW, $\tau_E\sim5.5$ s

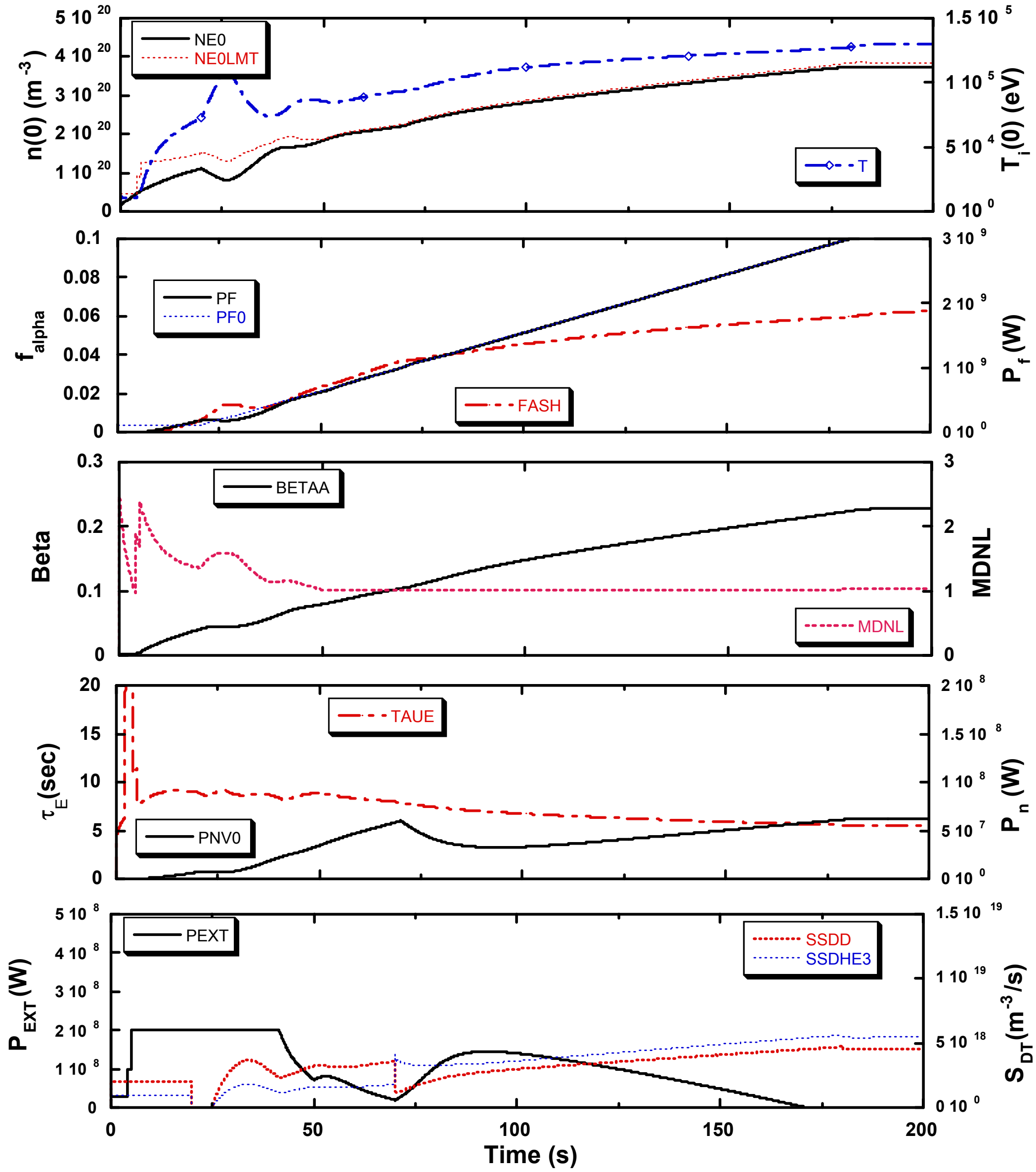


Fig. 6

4. Summary and issue

(1) To achieve ignition in a D-^{3}He helical reactor with R = 14.47 m, a = 2.6 m and B=6 T, the confinement should be improved up to >2.4 times than the present LHD confinement, and β=14~21 %, heating power of 200~300 MW are necessary. Neutron power is ~60 MW.

(2) Larger machine has a lower beta due to the lower density and larger confinement time.

(3) Further parameter improvement is required for LHD type machine. This result provides us "Challenge" or "Give-up".

(4) QPS is interesting for D-^{3}He fusion.

Problems for LHD type reactor

[1] Can 14 MeV proton is confined in a LHD helical field?
[2] Is it possible to achieve such a high beta in LHD type machine? (Increase in the rotational transform by bootstrap current may decrease Shafranov shift and increase beta.)
[3] Can Hot ion mode is maintained?

In ST：The hot ion mode T_i/T_e = 1.4 is necessary to maintain the ignition. Stochastic heating by super-Alvenic instability (V_α~$3.8V_A$,V_p~$7.5V_A$) may heat ion preferentially as in NSTX.

[4] Divertor heat load