CHARACTERISTICS OF A TOKAMAK FUSION NEUTRON SOURCE FOR SPENT NUCLEAR FUEL TRANSMUTATION

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OUTLINE
SYSTEMS STUDY OF ELECTRICAL POWER CHARACTERISTICS
CONCEPTUAL DESIGN STUDY OF TOKAMAK NEUTRON SOURCE
(CONCEPTUAL DESIGN STUDY OF SUBCRITICAL FAST REACTOR)

PRESENTED AT *INTERNATIONAL WORKSHOP ON BLANKET AND FUSION CONCEPTS FOR THE TRANSMUTATION OF ACTINIDES*, SAN DIEGO, CA, 3/21-23/01

SYSTEMS STUDIES*

The effective transmutation (fission) rate is

$$TR = \mathrm{v}\Sigma_f N = \frac{S}{1-k}\frac{\Sigma_f}{\Sigma_a} \approx \frac{Sk}{\nu(1-k)}$$

The input electrical power required to produce S fusion neutrons per second is

$$P_{in,e}^{fus} = \frac{E_{fus}S_{fus}}{\eta_b^{fus}Q_p} + \frac{P_{aux}^{fus}}{\eta_{aux}^{fus}} = \frac{E_{fus}S_{fus}}{\eta_b^{fus}Q_p}\left[1+\left(\frac{P_{aux}^{fus}}{E_{fus}S_{fus}}\right)Q_p\left(\frac{\eta_b^{fus}}{\eta_{aux}^{fus}}\right)\right]$$

The electrical energy amplification (Q_e) factor is

$$Q_e^{fus} = \eta_e^{fus}\eta_b^{fus}\left\{\frac{\left[1+Q_p\left(1+\frac{(1+\varepsilon)\frac{k_{fus}}{\nu}}{(1-k_{fus})}\left(\frac{E_{fis}}{E_{fus}}\right)\left(\frac{\eta_e^{blkt}}{\eta_e^{fus}}\right)\right)\right]}{\left[1+Q_p\left(\frac{P_{aux}^{fus}}{S_{fus}E_{fus}}\right)\left(\frac{\eta_b^{fus}}{\eta_{aux}^{fus}}\right)\right]}\right\}$$

where

Q_p = plasma Q

E_{fus} = 17.6 MeV/fusion

E_{fis} = 195 MeV/fission

ε = enhancement of fission energy by other exoergic reactions

P_{aux}^{fus} = power required to operate auxiliary systems

η_b^{fus} = heating energy into plasma/electrical energy into heating system

η_{aux}^{fus} = efficiency of converting electrical power to power to auxiliary systems

η_e^{fus} = efficiency of converting fusion plus auxiliary heating energy to electricity

η_e^{blkt} = efficiency of converting fission energy to electricity

Similar expressions can be written for an ATW facility.

* Nuclear Fusion, 41, 135 (2001).

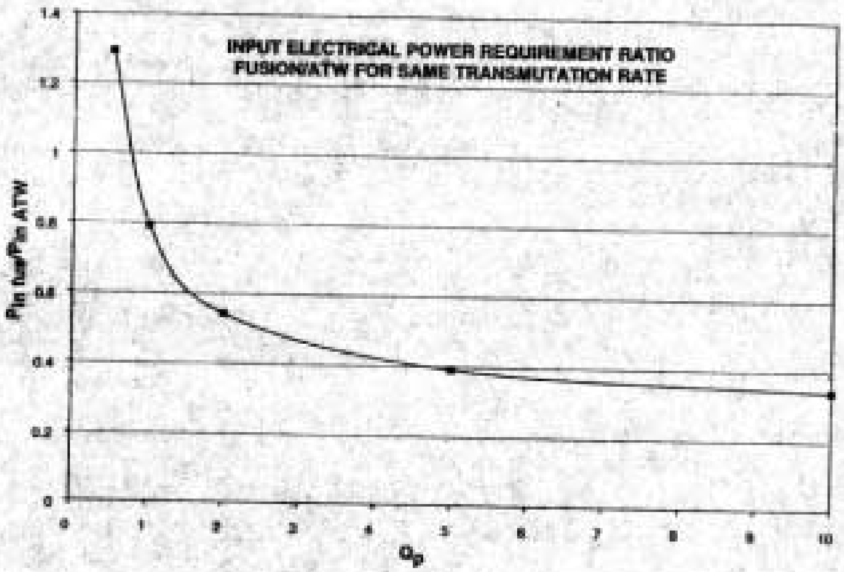


Figure 1. Ratio of input electrical power required for the operation of fusion and ATW neutron sources which produce the same transmutation rate in a subcritical transmutation reactor. ($E_{spall} = 25$ MeV/n, $E_{fus} = 17.6$ MeV/n, $P_{aux}/S = 12.5$ MeV/n, $\nu = 2.9$, $\gamma = 1.05$, $\eta_b^{fus} = \eta_b^{atw} = \eta_e^{fus} = \eta_e^{atw} = 0.40$, $\eta_e^{fus}/\eta_e^{blkt} = \eta_e^{atw}/\eta_e^{blkt} = 0.9$, $\eta_b^{atw}/\eta_{aux}^{atw} = \eta_b^{fus}/\eta_{aux}^{fus} = 0.8$. $k = 0.90$ is the same with fusion and ATW neutron sources.)

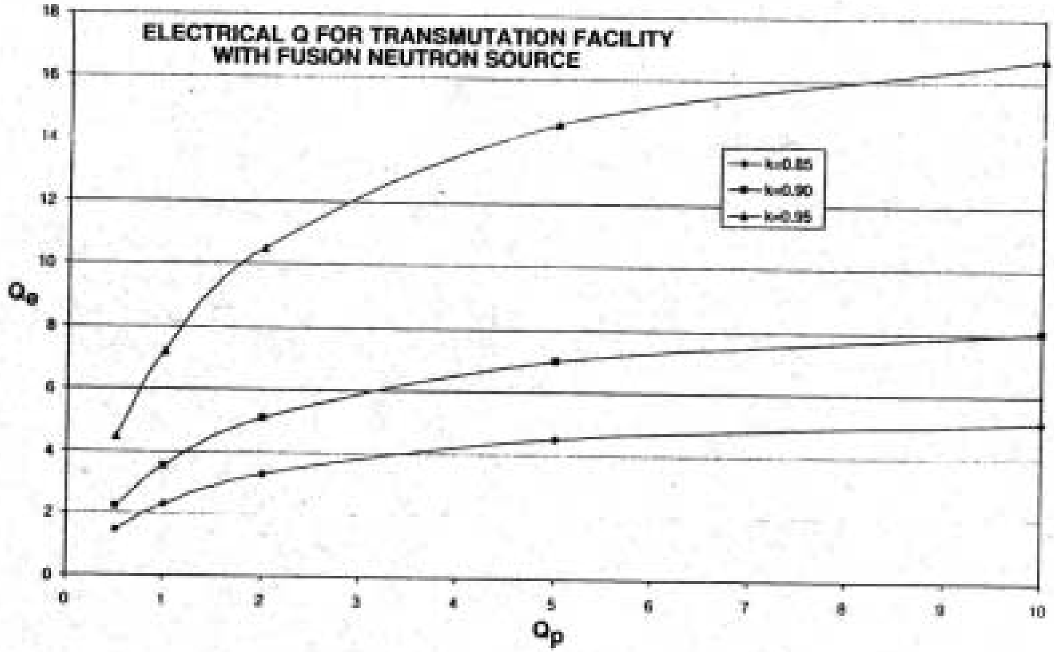


Figure 2. Electrical energy gain Q_e^{fus} for a subcritical transmutation reactor plant with fusion neutron source. (E_{fis} = 195 MeV/fis, E_{fus} = 17.6 MeV/n, P_{aux}/S = 12.5 MeV/n, $\nu = 2.9$, $\gamma = 1.05$, $\varepsilon = 0.05$, $\eta_b^{fus} = \eta_e^{fus} = 0.40$, $\eta_e^{fus}/\eta_e^{fiss} = 0.9$, $\eta_b^{fus}/\eta_{aux}^{fus} = 0.8$.)

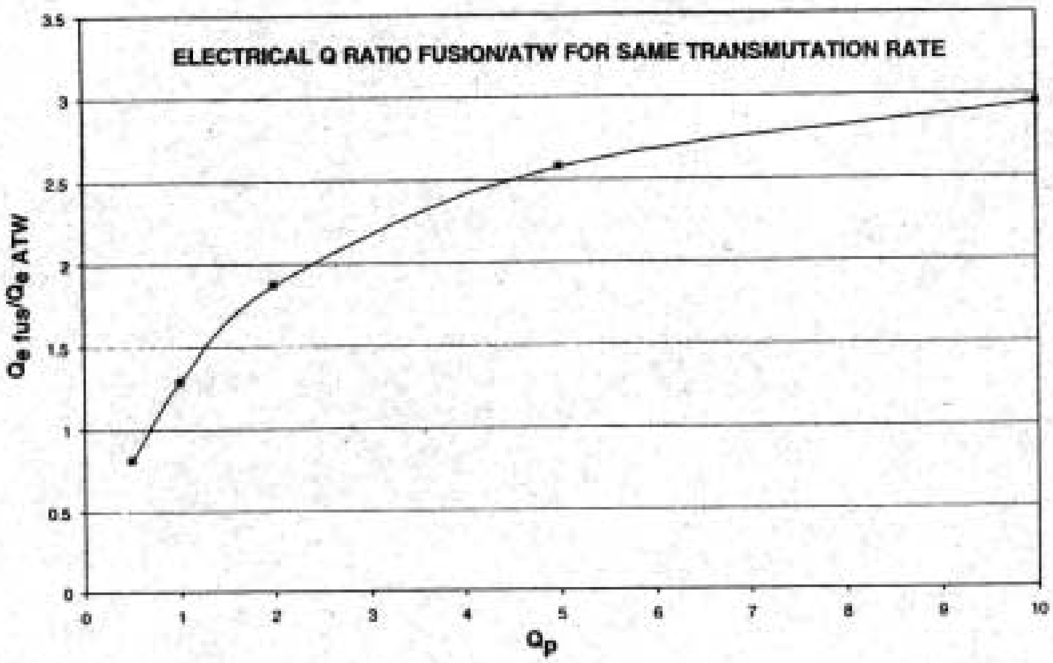


Figure 3. Ratio of subcritical transmutation reactor plant electrical energy gain for the same transmutation rate with fusion and ATW neutron sources. (E_{fis} = 195 MeV/fis, E_{spall} = 25 MeV/n, E_{fus} = 17.6 MeV/n, P_{aux}/S = 12.5 MeV/n, $\nu = 2.9$, $\gamma = 1.05$, $\varepsilon = 0.05$, $\eta_b^{fus} = \eta_b^{atw} = \eta_e^{fus} = \eta_e^{atw} = 0.40$, $\eta_e^{fus}/\eta_e^{blkt} = \eta_e^{atw}/\eta_e^{blkt} = 0.9$, $\eta_b^{atw}/\eta_{aux}^{atw} = \eta_b^{fus}/\eta_{aux}^{fus} = 0.8$; $k = 0.90$ is the same with fusion and ATW neutron sources.)

PHYSICS SYSTEMS STUDIES WERE PERFORMED TO IDENTIFY RANGE OF TOKAMAK PARAMETERS FOR A NEUTRON SOURCE TO DRIVE A SPENT FUEL TRANSMUTATION REACTOR

Parameter	Nominal Database	Advanced Database
H-confinement	1.0	1.5
β_N	2 -- 3	2 – 3
Q_p	2 -- 5	2 – 5
B (T)	5.5	5.5
τ_{ign} (s)	5	5
κ,δ	1.7, 0.5	2.0, 0.8
q_{95}	4	4
n/n_{GW}	0.4 – 1.0	0.2 – 0.6
R (m)	3 - 5	2 – 3
I (MA)	6 - 10	6 – 10
P_{fus} (MW)	10s – 100s	10s – 100s

Table 1. Characteristic Parameters of Tokamak Fusion Neutron Sources That Could Produce Transmutation Rates of Hundreds-to-Thousands of Kg/FPY in Transmutation Reactors with k = 0.9.

ENGINEERING SYSTEMS STUDIES HAVE NOT BEEN PERFORMED, BUT ON THE BASIS OF PREVIOUS WORK IT IS ESTIMATED THAT THE MINIMUM SIZE OF A SUPERCONDUCTING TOKAMAK FOR THE TRANSMUTATION MISSION IS R_0 = 4.5--5.5m.

IN ORDER TO REALIZE THE MINIMUM SIZE ALLOWED BY THE PHYSICS CONSTRAINTS ($R_0 \approx 3.0$m), IT APPEARS TO BE NECESSARY TO USE NORMAL MAGNETS.

GEORGIA TECH DESIGN STUDY
TOKAMAK-DRIVEN
SUBCRITICAL TRANSMUTATION REACTOR

- IN JANUARY, 2001 A FACULTY-STUDENT CONCEPTUAL DESIGN STUDY OF A TOKAMAK-DRIVEN SUBCRITICAL TRANSMUTATION REACTOR WAS INITIATED AT THE GEORGIA TECH FUSION RESEARCH CENTER.

- OBJECTIVE—IDENTIFY THE PHYSICAL PARAMETERS AND PERFORMANCE CHARACTERISTICS OF A SUBCRITICAL FAST TRANSMUTATION REACTOR DRIVEN BY A TOKAMAK FUSION NEUTRON SOURCE.

- DESIGN BASIS

    - EXISTING TOKAMAK PHYSICS DATABASE, BUT WITH ADVANCES IN CURRENT DRIVE FOR LONG PULSES

    - EXISTING FUSION TECHNOLOGY

    - ADAPTATION OF NUCLEAR TECHNOLOGY (METAL FUEL, PB-BI COOLING, PYROMETALLURGICAL PROCESSING) THAT IS BEING DEVELOPED FOR ATW PROJECT. ADAPTATIONS FOR
        - TRITIUM BREEDING
        - TOKAMAK GEOMETRY

- DESIGN ANALYSIS EMPHASIS

    - TOKAMAK PHYSICS

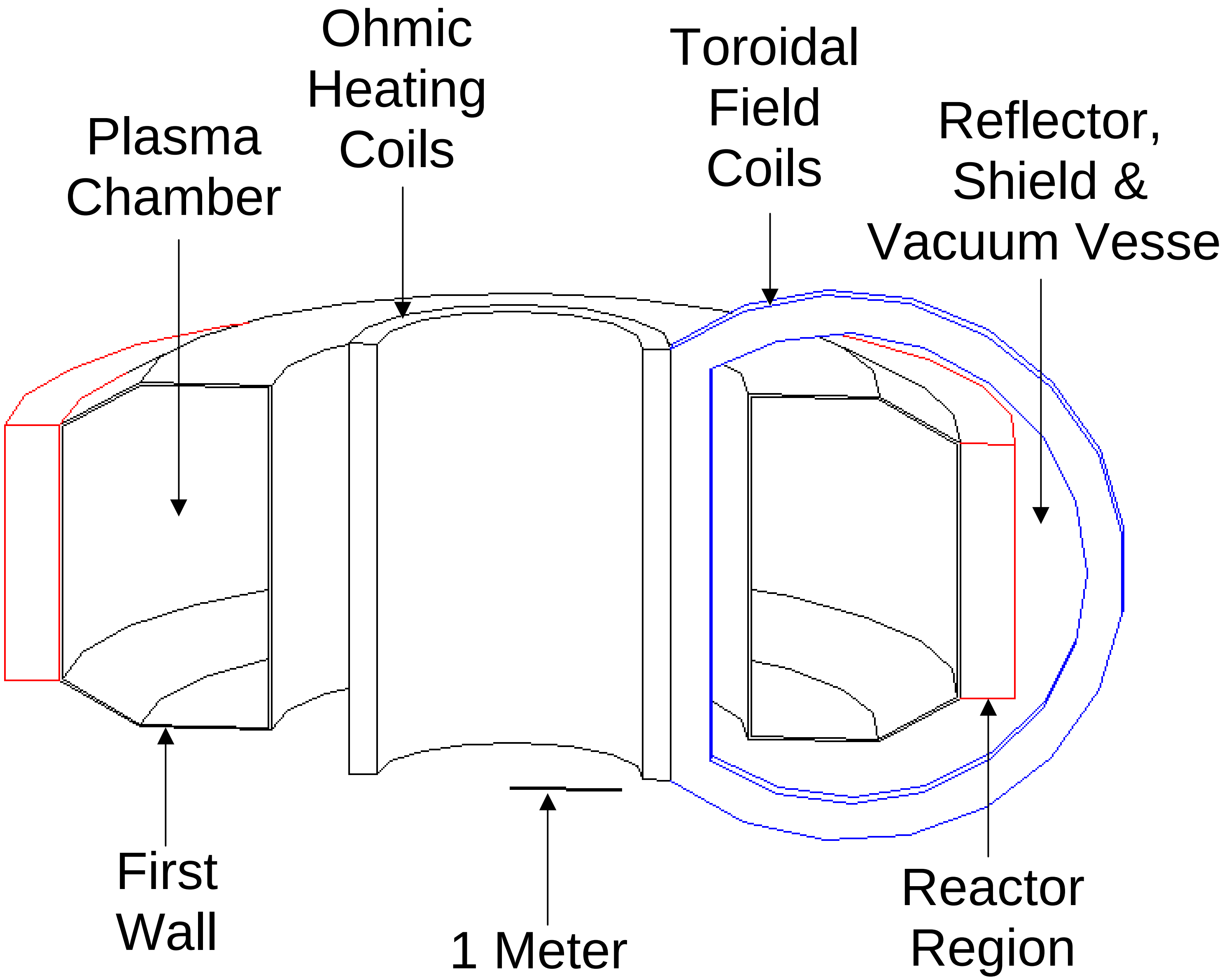
    - LONG-BURN COPPER MAGNET SYSTEM

    - SUBCRITICAL REACTOR PHYSICS*

    - TRANSMUTATION FUEL CYCLE ANALYSIS*

* PAPER BY E. A. HOFFMAN, et al. AT THIS WORKSHOP.

Tokamak Design



Methodology for determining tokamak reactor parameters

- Starting from the performance and power balance equation,

$$nT\tau_E = \frac{(nT\tau_E)_\infty}{\left(1+\frac{5}{Q_p}\right)}$$

  where $(nT\tau_E)_\infty$ is the $nT\tau_E$ value required for ignition (~ 5×10^{21} m^{-3} keV.s), Q_p is the plasma Q, and using the ITER IPB98(y,2) scaling for τ_E:

$$\tau_E = 0.0562 H I^{0.93} B^{0.15} n_{19}^{0.41} R^{1.97} A^{-0.58} P^{-0.69} M^{0.19} \kappa^{0.78}$$

  and using the following physics and radial build constraints:

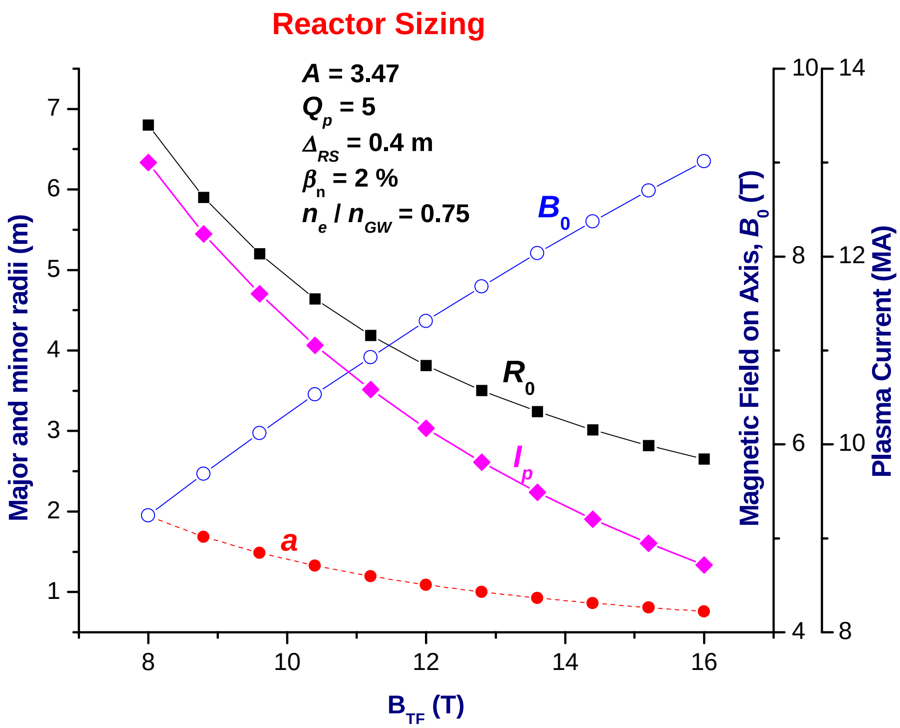
  - $q_{95} \geq 3$, where

$$q_{95} = \frac{5B_0 R}{A^2 I_{MA}}\left[\frac{1+\kappa^2\left(1+2\delta^2-1.2\delta^3\right)}{2}\frac{1.17-0.65\varepsilon}{\left(1-\varepsilon^2\right)^2}\right]$$

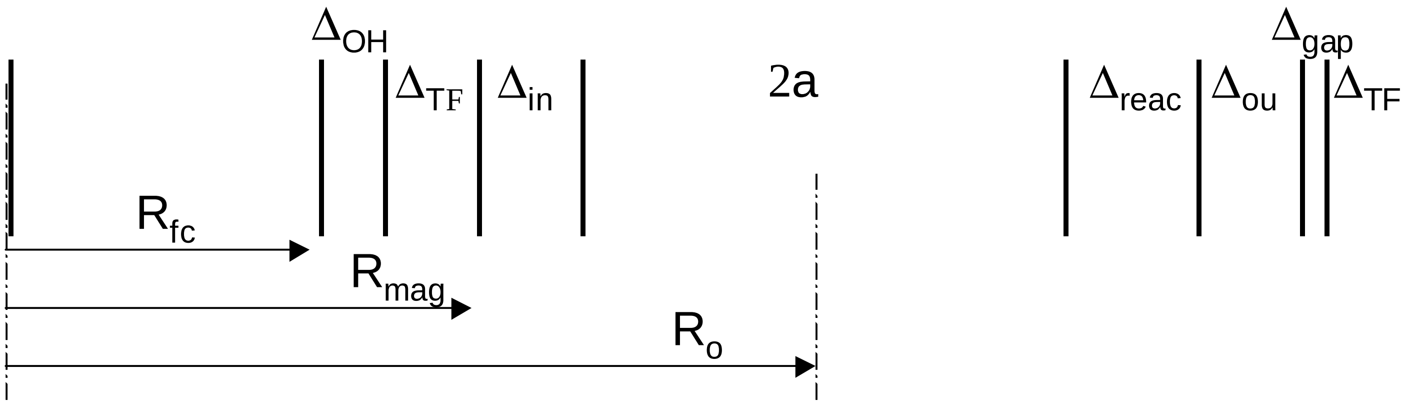
  - $\beta \leq \beta_N \, {I_{MA}}/{aB}$ (β limit)
  - $\bar{n}_{20} \leq G_n \frac{I_{MA}}{\pi a^2}$ (Greenwald density limit)
  - $B_0 = \frac{B_{TF}}{A}\left(A-1-\frac{\Delta_{rs}}{a}\right)$ (radial build limit)

- For a given set of κ, δ, H, G_n, β_n, q_{95}, B_{TF} and A we can solve for the plasma current, I, and then all the other basic tokamak parameters (R, a, B_0, P_{fus}, etc.) are fully determined.

- Since the various inequality constraints have been treated as equality constraints in this formulation, the performance characteristics of the resulting design should be regarded as an upper limit. Sufficient operational flexibility should exist by operating below the various limits (β limit, Greenwald density limit, etc.)

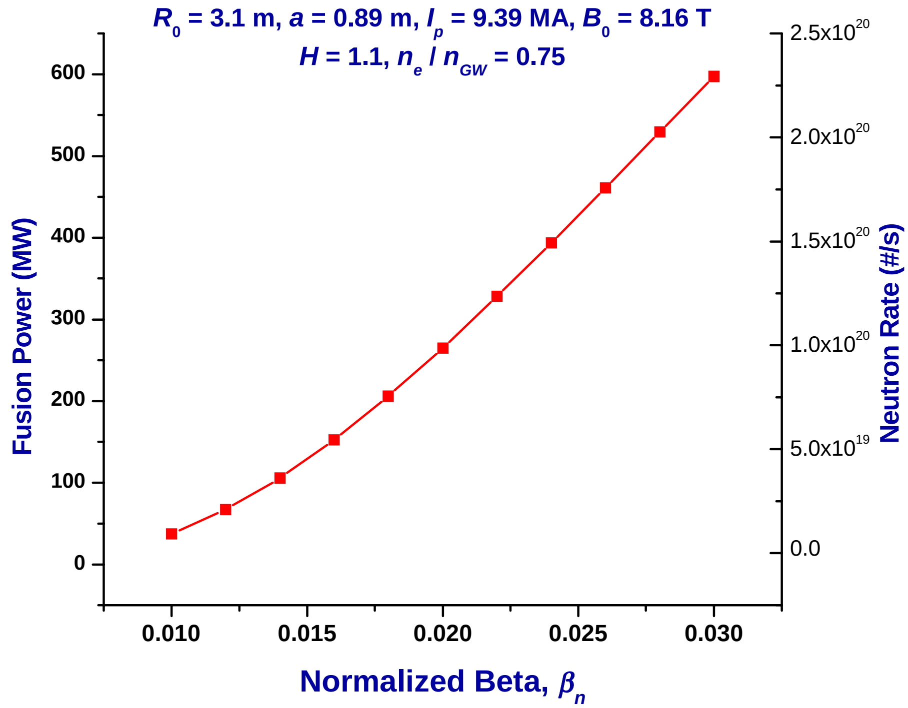

Reactor Sizing
A = 3.47
Q_p = 5
Δ_RS = 0.4 m
β_n = 2 %
n_e / n_GW = 0.75
B_0
R_0
I_p
a
Major and minor radii (m)
Magnetic Field on Axis, B_0 (T)
Plasma Current (MA)
B_TF (T)
1
2
3
4
5
6
7
8
10
12
14
16
4
6
8
10
8
10
12
14

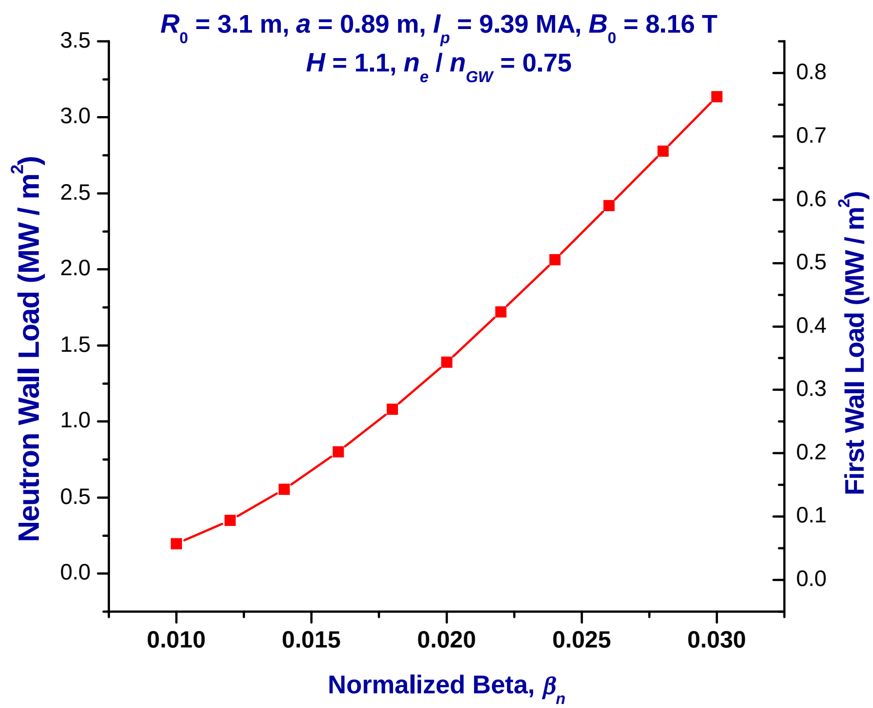
Midplane Radial Build

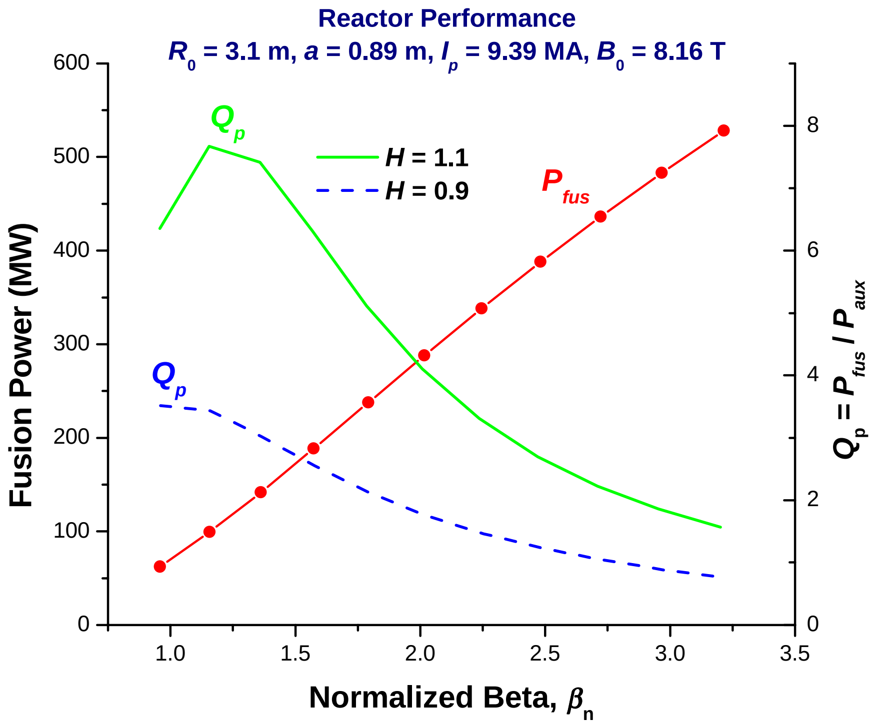


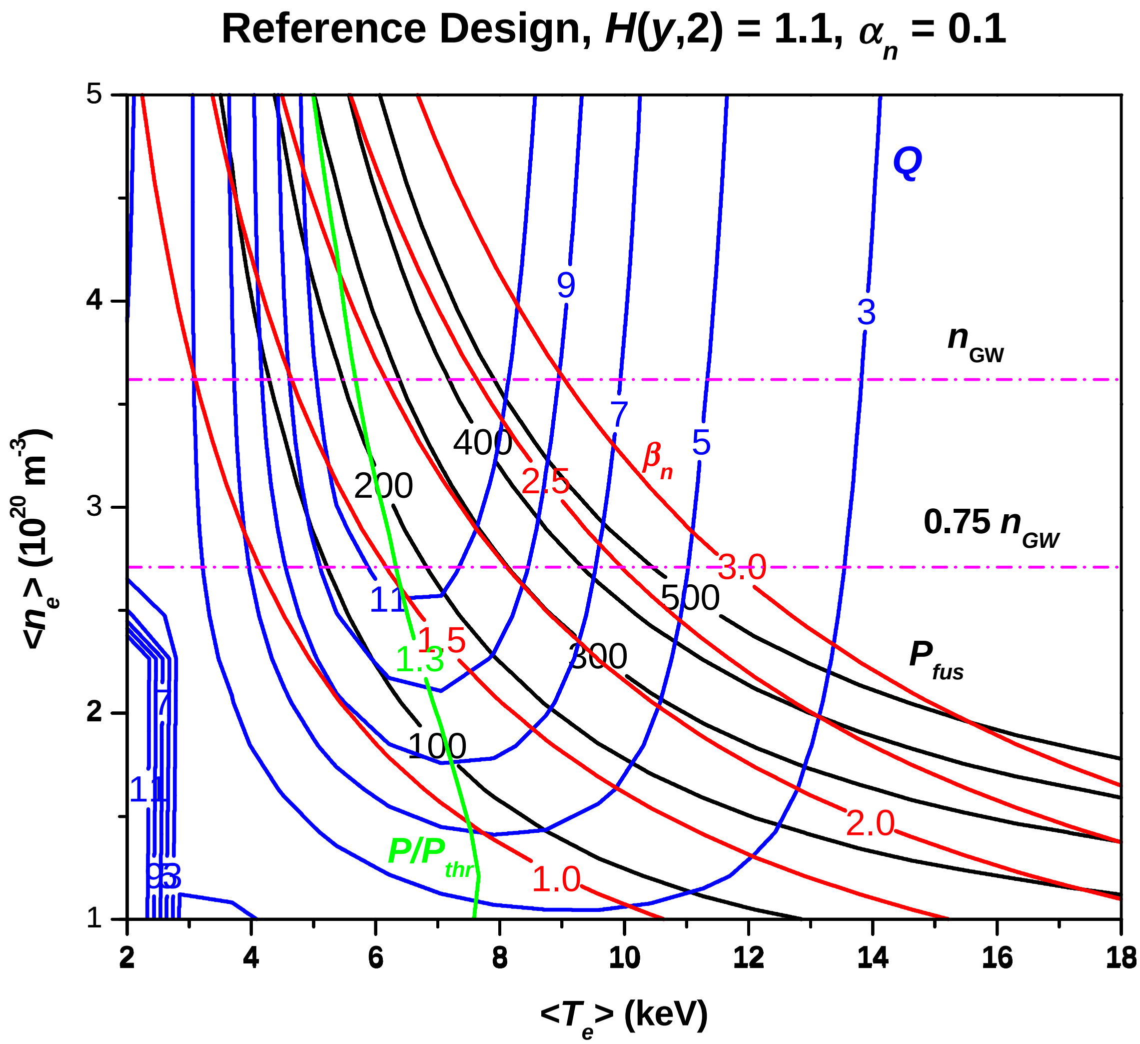
R_{fc}	=	flux core radius	=	1.20 m
Δ_{OH}	=	OH solenoid Δ	=	0.25
Δ_{TF}	=	TF coil Δ	=	0.35
Δ_{in}	=	inner refl/shld	=	0.40
a	=	minor radius	=	0.90
Δ_{reac}	=	reactor	=	0.40
Δ_{ou}	=	outer refl/shld	=	0.30
Δ_{gap}	=	outer gap	=	tbd
R_o	=	major radius	=	3.10
R_{mag}	=	magnet radius	=	1.80

Note: refl/shld includes first wall, reflector, shield, and vacuum vessel


R_0 = 3.1 m, a = 0.89 m, I_p = 9.39 MA, B_0 = 8.16 T
H = 1.1, n_e / n_{GW} = 0.75
Fusion Power (MW)
Neutron Rate (#/s)
Normalized Beta, β_n
0
100
200
300
400
500
600
0.0
5.0x10^19
1.0x10^20
1.5x10^20
2.0x10^20
2.5x10^20
0.010
0.015
0.020
0.025
0.030


R_0 = 3.1 m, a = 0.89 m, I_p = 9.39 MA, B_0 = 8.16 T
H = 1.1, n_e / n_{GW} = 0.75
Neutron Wall Load (MW / m^2)
First Wall Load (MW / m^2)
Normalized Beta, β_n
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.010
0.015
0.020
0.025
0.030


Reactor Performance
R_0 = 3.1 m, a = 0.89 m, I_p = 9.39 MA, B_0 = 8.16 T
Q_p
H = 1.1
H = 0.9
P_{fus}
Q_p
Fusion Power (MW)
$Q_p = P_{fus} / P_{aux}$
Normalized Beta, β_n
0
100
200
300
400
500
600
0
2
4
6
8
1.0
1.5
2.0
2.5
3.0
3.5


Reference Design, H(y,2) = 1.1, α_n = 0.1
<n_e> (10^20 m^-3)
<T_e> (keV)
Q
n_GW
0.75 n_GW
P_fus
β_n
P/P_thr
1.3
100
200
300
400
500
1.0
1.5
2.0
2.5
3.0
3
5
7
9
11

COPPER MAGNET DESIGN CONSTRAINTS

OH SOLENOID

Provide $1/2$ start-up V-s

$$\Delta\phi = \pi r_{fc}^2 B_{OH} = 1/2\ \Delta\phi_{ind} = 1/2\ \mu_o R\left[\ell n\left(\frac{8R_o}{a}\right) - 1.75\right] I_{plasma}$$

ASME stress limits

$$B_{OH} = \mu_o NI/L$$

$$\sigma_{ten} = \mu_o\left(\frac{NI}{L}\right)^2 \frac{1}{2}\left(\frac{r_{fc}}{\Delta r} + \frac{1}{3}\right) < S_m = larger\begin{cases}\frac{1}{3}\sigma_u \\ \frac{2}{3}\sigma_y\end{cases}$$

Heat removal

$$P_{ohm} = I^2\left(\frac{\rho L_T}{A_c}\right) = L_p h\left(T_{cond} - T_{cool}\right) L_T$$

TOROIDAL FIELD COILS

$$B_\phi = \mu_o NI/2\pi R$$

ASME stress limits

$$\sigma_{ten} = \frac{1}{2}\left(\frac{\mu_o NI^2}{4\pi}\right)\ell n\left(\frac{1+\left(R_{bore}/R_o\right)}{1-\left(R_{bore}/R_o\right)}\right)\Big/ A_c < S_m$$

Heat removal

PRELIMINARY MAGNET PARAMETERS

	OH Solenoid	TF Coils
Conductor	BeCu	OFHC Cu
Coolant	LN2	LN2
Field @ Conductor (T)	10	14
Volt-sec capability	46	
Cross section area (m^2)	0.8	0.22/coil
coolant fraction (%)	15	20
structure fraction (%)	tbd	25
Maximum tensile stress (MPa)	273	226
ASME allowable Sm (MPa)	280	268
Ohmic heating (MW)	tbd	407
Coolant mass flow (kg/s)	tbd	185

SUMMARY

TOKAMAK NEUTRON SOURCE ELECTRICAL POWER REQUIREMENTS MORE FAVORABLE THAN FOR AN ACCELERATOR NEUTRON SOURCE

PHYSICS DESIGN BASIS

—PRESENT TOKAMAK DATABASE

---EXTENDED DATABASE FOR LONG PULSE NON-INDUCTIVE CURRENT DRIVE.

TOKAMAK PARAMETERS

- $R_0 \approx 3$ m
- $B_0 \approx 8$ T
- $\beta_N < 2$
- $Q_P \approx 2 - 5$
- $P_{fus} \approx 200$ MW
- $S \approx 10^{20}$ n/s
- $\Gamma_n \approx 1.0$ MW/m^2
- $q_{fw} \approx 0.25$ MW/m^2

COPPER MAGNETS

- $B_{TFC} \approx 14$ T
- $B_{0H} \approx 10$ T