JUST

A Conceptual Design of Super Conducting Spherical Tokamak Reactor

presented by **Yoshio Nagayama***

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Our object is to present a fusion reactor concept that can be realized with present technologies. (by Satoshi Nishio)

In memory of Dr. Satoshi Nishio (1952 – 2009) (2007/3/2 at NIFS)

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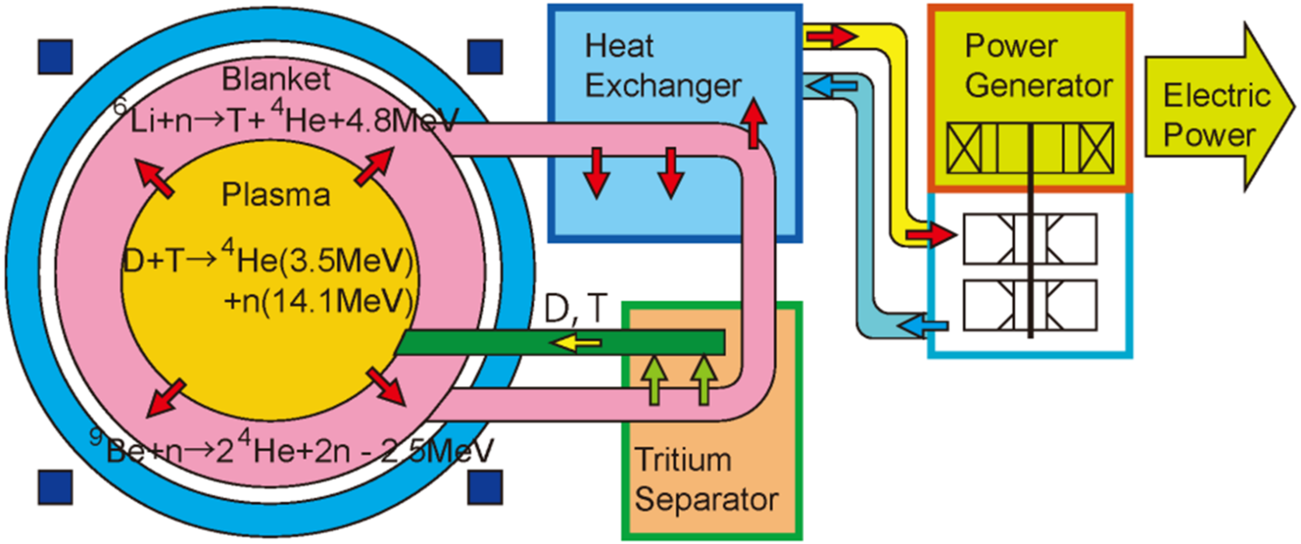
Tutorial

Fusion Power Plant

- Fusion reaction (D+T) in a high temperature plasma (10keV) makes fast neutron (14MeV) and fast He ion (3.5MeV).
- Neutron energy is transferred to thermal energy to produce electricity
- Reaction of neutrons with Be and Li generates T again.



Contents

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I. Why we consider ST as a fusion reactor.

Major Issues to realize a fusion reactor:

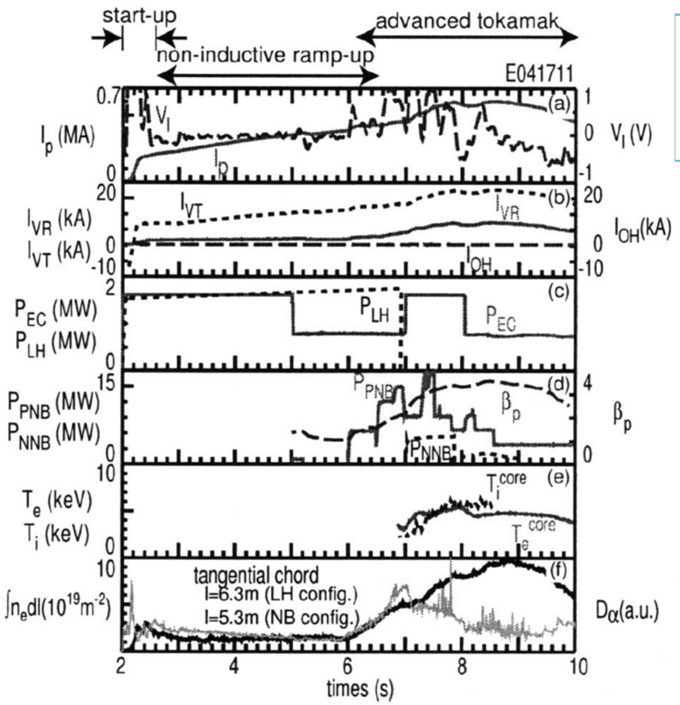
1. Plasma confinement
2. Steady state
   - High bootstrap fraction (f_{BS}>80%)
3. Neutron damage
   - Neutron damage used to be the weakest point of fusion reactor.
4. Cost
   - ITER costs 15 B$, while a fission reactor costs 3-5 B$.

II. Conceptual design of superconducting ST reactor

I. Why we consider ST as a fusion reactor.

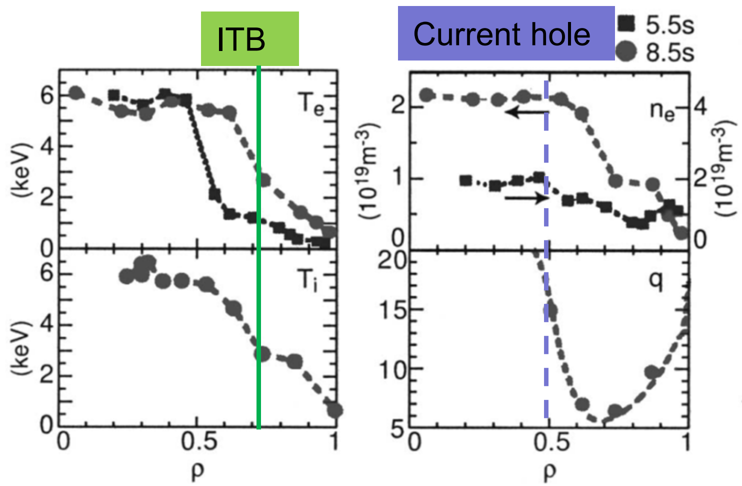
1. Steady state
2. High beta
3. Neutron damage

Steady State Tokamak with ITB and 90% BS current fraction.



Non-inductive current start up in JT-60U

- Non-inductive current start up in JT-60U simulate the steady state tokamak, as no OH current remains.



S. Shiraiwa, et al.: "Formation of Advanced Tokamak Plasmas without the Use of an Ohmic-Heating Solenoid", PRL92, 035001 (2004).

ST can be stable at 99% BS fraction.

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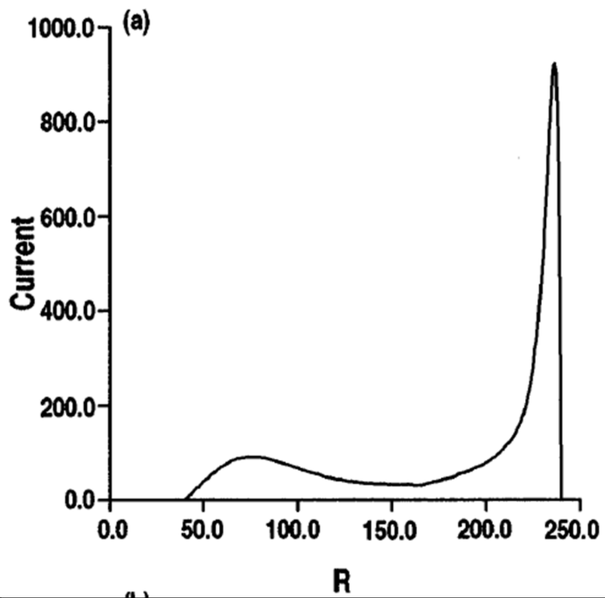
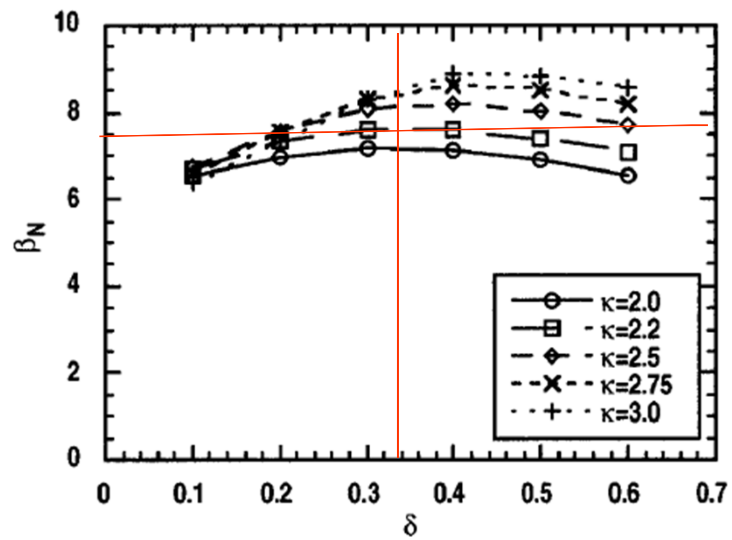
- ST configuration (hollow current profile) is consistent with the high BS current plasma.





R. Miller, et al., "Stable equilibria for bootstrap-current-driven low aspect ratio tokamaks", Phys. Plasmas 4, 1062 (1997).

High bootstrap current can be obtained in ST.

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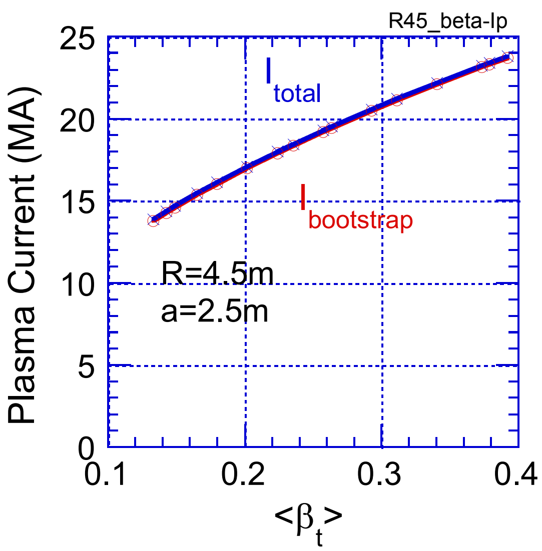

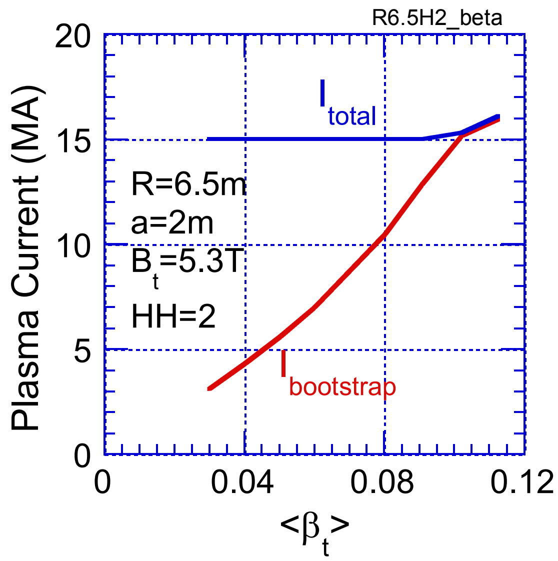

- High plasma current is required to confine alpha ions.
- In high beta plasma (ST), the BS current can be high enough.
- In conventional tokamak, the beta is too low.

Neutron damage problem can be solved in ST.

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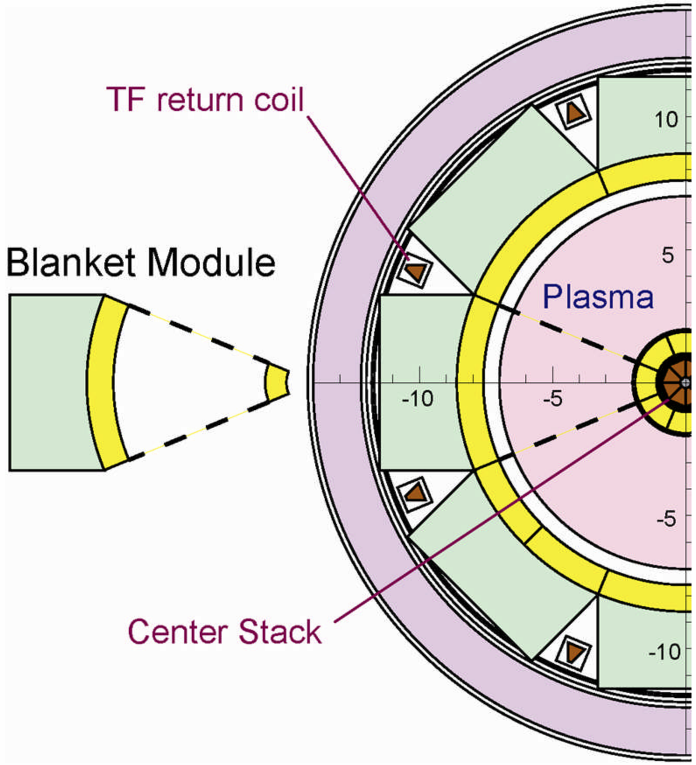
- Total (time integrated) neutron flux < 10 MW-year/m^2.
  - Life time of the first wall is 2-3 years, if the neutron wall load is 3-5 MW/m^2.
- Easy replacement of blanket module solves the neutron damage problem.
- The wide separation between TF return coils in ST enables the quick replacement of the blanket cassette.
- Large port is a weak point to support TF coils.



Can ST be a reactor?

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Strong points

1. Low cost
   – High beta
2. Quick replacement of neutron damaged wall
3. Steady state
   – High BS fraction

Weak (Questionable) points

1.Neutron flux in the inboard side?

2.No space to protect CS?

3.No superconducting magnet?

4.No space for OH solenoid?

5.Weak structure due to big port for the wall replacement.

6.How about heat flux?

The neutron flux is similar in any aspect ratio.

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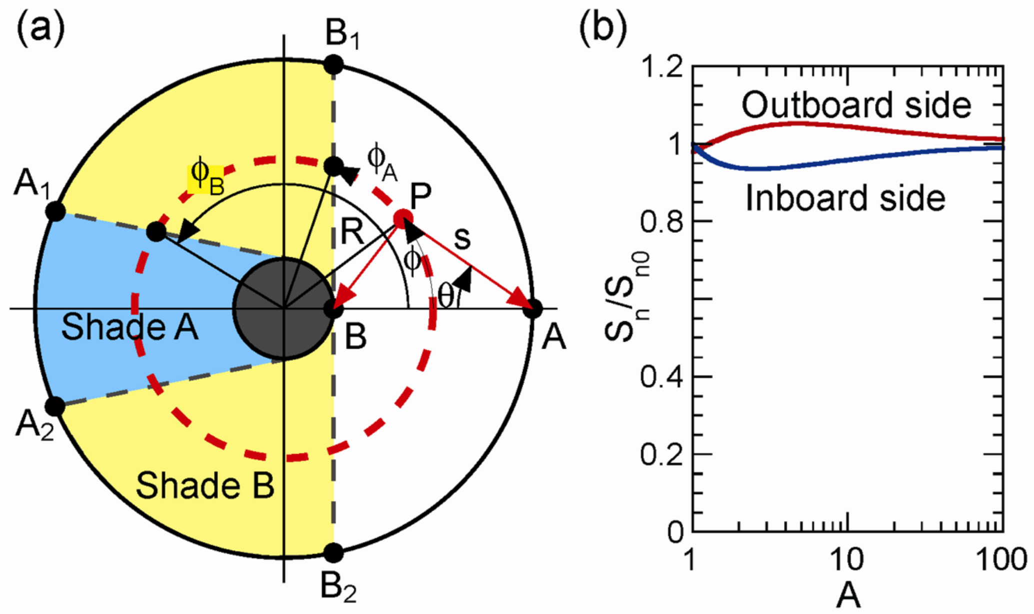
- Some misunderstand that neutron accumulate to the center stack.
- However, neutron flux is similar both in inboard and outboard sides.



Blanket (80cm thick) protects super conductor.

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- Thickness of the most effective neutron shield (V-VH_2/W cooled by lithium) is 58 cm.

Table 1 Total shield thickness to decrease neutron flux within criteria on the super-conducting coil.

Case	Structural Material	Shield Material	Coolant	Thickness (cm)
A	V Alloy (17)	VH_2 (61)/W (11)	Li (10)	58
B	F82H (17)	VH_2 (51)/W (11)	He (20)	66[53]
C	V Alloy (17)	VH_2 (51)/W (11)	Li (20)	65
D	F82H (17)	VH_2 (51)/W (11)	Water(20)	57
E	F82H (16)	VH_2(75.6)	He (8.4)	74[68]
F	F82H (12)	VH_2 (58)/LiPb/Be	He (6.4)	76[70]

Note. Values in ( ) : Volume Ratio [%], A～D : One- dimensional calculation, E and F : Three-dimensional calculation (In the case of F, plasma-facing inner shield 18 cm in thickness is a neutron reflector composed of LiPb and Be), Values in [ ] : Substantial thickness except He (Cases B, E, F)

M. Yamauchi, T. Nishitani, S. Nishio, "Neutron Shielding and Blanket Neutronics Design", J. Plasma Fus. Res. 80, 952 (2004)

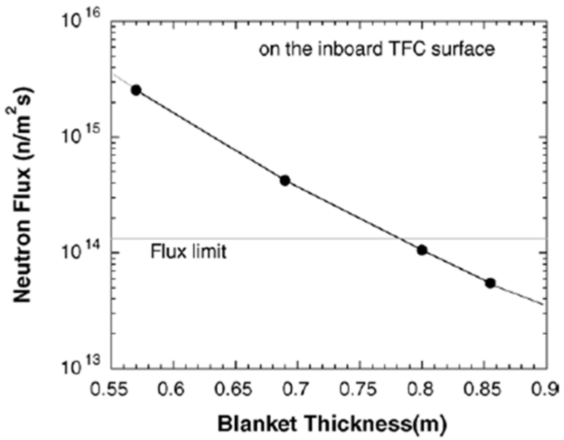

Fig. 3. The fast neutron flux ($E > 100$ keV) on the surface of the inboard TFC as a function of the inboard blanket thickness consisting of F82H and VH_2.

T. Nishitani, et al., "Neutronics design of the low aspect ratio tokamak reactor, VECTOR", FED 81, 1245 (2006).

II. Conceptual design of superconducting ST reactor

1. Plasma Model
2. Equilibrium
3. Magnetic Field
4. Radial build
5. Superconducting Magnet
6. Diverter, Fueling and Exhausting
7. Blanket (Primitive)

Assumptions to design the ST reactor

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1. Box type ITB
2. ITER scaling (IPB98y2) with the improvement factor, γ_{HH}

$$\tau_E = \gamma_{HH} \square 0.0562 R^{1.97} A^{-0.58} \kappa^{0.78} B_t^{0.15} I_p^{0.93} n^{0.41} M^{0.19} P^{-0.69}$$

3. High aspect ratio approximation for the BS current
4. Lin Liu-Stambaugh's beta limit

$$\beta_N = \beta_{N0}\left(c_0 + c_1\kappa + c_2\kappa^2 + c_3\kappa^3\right)\coth\left(\frac{d_0 + d_1\kappa}{A^m}\right)\frac{1}{A^n}$$

Here, β_{N0}=10, c_0=-0.7748, c_1=1.2869, c_2=-0.2921, c_3=0.0197, d_0=1.8524, d_1=0.2319, m=0.6163, n=0.5523

5. Ellipticity scaling:

$$\kappa = 1 + \frac{3}{A}$$

6. Ejima-Wesley, $C_{E\text{-}W}$=0.4
7. Particle confinement time: $\tau_p = 4\tau_E$

A=1.8, κ=2.5, β_N=7.2

Design parameters are calculated with the 0D transport code.

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1. Energy balance equation: $\frac{dW}{dt} = P_{ext} + P_{alpha} - P_{Brems} - P_{syn} - \frac{W}{\tau_E}$

(α: H, D, T, ^{3}He, ^{4}He, C)

2. Particle balance equation: $\frac{dn_\alpha}{dt} = \nu_\alpha + \frac{1}{V}\sum_\beta s_{\alpha\beta} N_{\alpha\beta} - \frac{n_\alpha}{\tau_p}$

ν_α: Fueling rate

Number of nuclear reaction $N_{\alpha\beta} = \int_V \delta_{\alpha\beta} \langle \sigma v \rangle_{\alpha\beta} n_\alpha n_\beta dV$

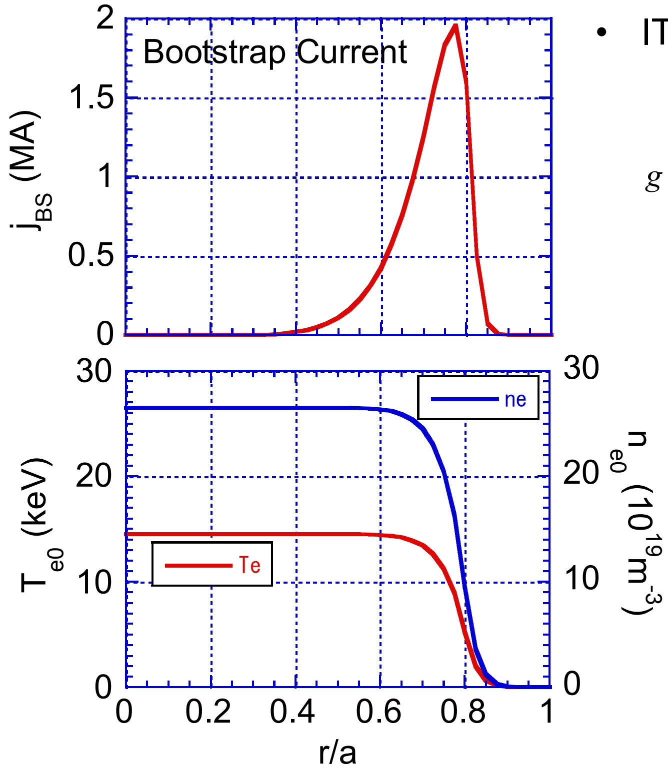
Alpha Heating $P_{alpha} = \int_V Q_{\alpha\beta}^{alpha} \delta_{\alpha\beta} \langle \sigma v \rangle_{\alpha\beta} n_\alpha n_\beta dV$ $\delta_{\alpha\beta} = \begin{cases} 0.5 & (\alpha = \beta = D) \\ 1 & (others) \end{cases}$

Bremsstrahlung $P_{Brems} = \frac{32\pi e^6 Z^2 n_e n_i}{3(4\pi\varepsilon_0)^3 c^3 m_e h}\sqrt{\frac{2\pi T_e}{3m_e}} = 1.5\times 10^{-38} Z^2 n_e n_i \sqrt{T_e[eV]}$ $[W/m^3]$

Synchrotron radiation (Trubnikov formula) $W_{sy} = V_p \frac{n}{3\pi\varepsilon_0}\frac{e^2}{c}\frac{\omega_{ce}}{\zeta}\frac{K_3(\zeta)}{K_2(\zeta)}\frac{60}{\zeta^{3/2}}\sqrt{(1-R_f)\left(1+\frac{2a}{R}\sqrt{\frac{2\pi}{\varsigma}}\right)\frac{c\omega_{ce}}{a\omega_{pe}^2}}$ $\zeta = \frac{m_e c^2}{eT_e}$

Bootsrap current density is (high A model) $j_b = \frac{p_e}{B_p}\sqrt{\frac{r}{R}}\left\{-2.44\left(1+\frac{T_i}{T_e}\right)\frac{1}{n_e}\frac{dn_e}{dr} - \frac{0.69}{T_e}\frac{dT_e}{dr} + \frac{0.42}{T_e}\frac{dT_i}{dr}\right\}$

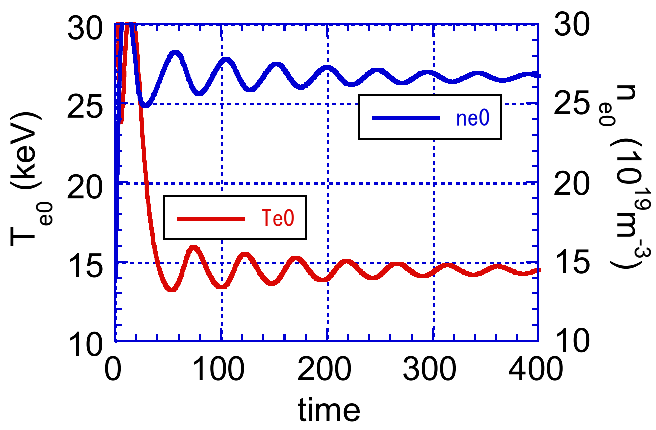
Steady state solution of 0-D equations with fueling rate.



- ITB profiles for $n_e(r)$ and $T_e(r)=T_i(r)$.

$$g(x;b,m)=\begin{cases}1-\dfrac{x^{2m}}{b^{2(m-1)}} & (0\le x\le b)\\[2ex] \dfrac{\left(1-x^2\right)^m}{\left(1-b^2\right)^{m-1}} & (b\le x\le 1)\end{cases}$$

$b_1=b_2=0.8,\ m_1=m_2=8$



The beta limit determine the machine parameters for ST reactor

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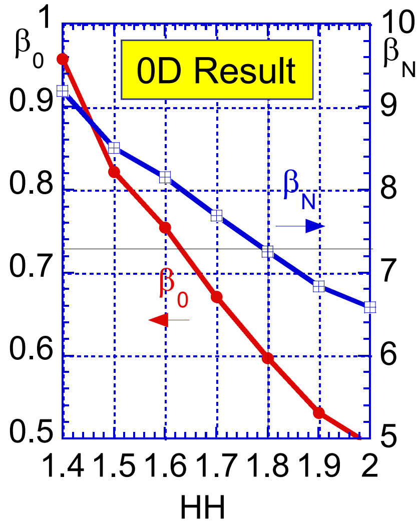
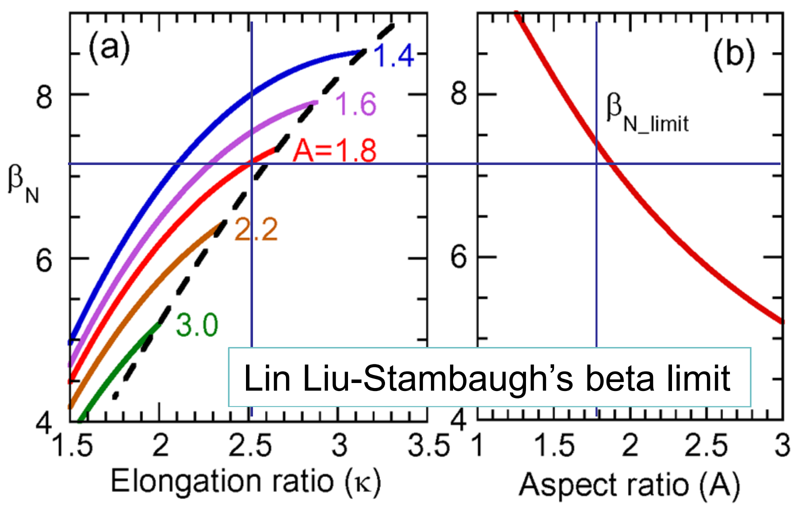
- From Lin Liu-Stambaugh's beta limit and the ellipticity scaling

$$\beta_N = \beta_{N0}\left(c_0 + c_1\kappa + c_2\kappa^2 + c_3\kappa^3\right)\coth\left(\frac{d_0 + d_1\kappa}{A^m}\right)\frac{1}{A^n} \qquad \kappa = 1 + \frac{3}{A}$$

Here, β_{N0}=10, c_0=-0.7748, c_1=1.2869, c_2=-0.2921, c_3=0.0197, d_0=1.8524, d_1=0.2319, m=0.6163, n=0.5523

- We assume R/a=4.5/2.5m, B=2.3T, κ=2.5, HH=1.8 β_N=7.2.





Plasma parameters for ST reactor (R/a=4.5/2.5m, B=2.3T)

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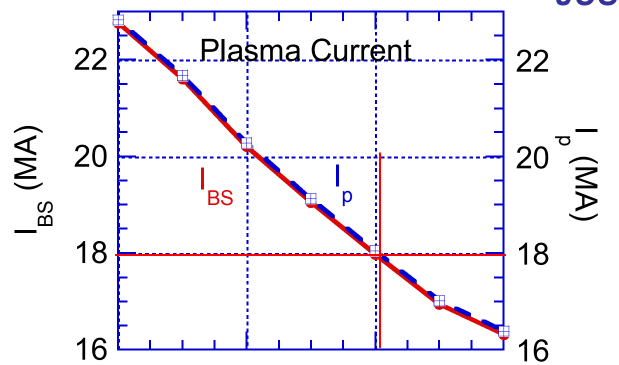
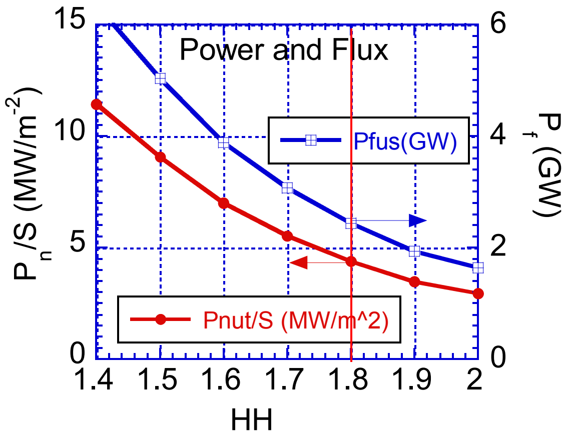
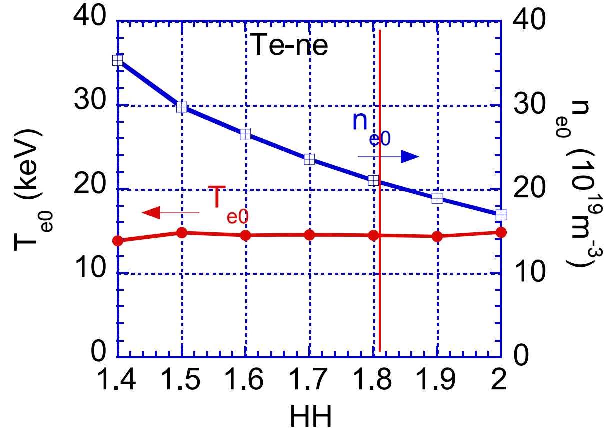
- The fusion power is 2.5 GW, and the neutron flux is 4.5 MW/m^2.
- I_p=I_{BS}=18 MA, n_{e0}=2x10^{20}m^{-3} (HH=1.8)
- T_{e0}=T_{i0}=15keV for any HH factor



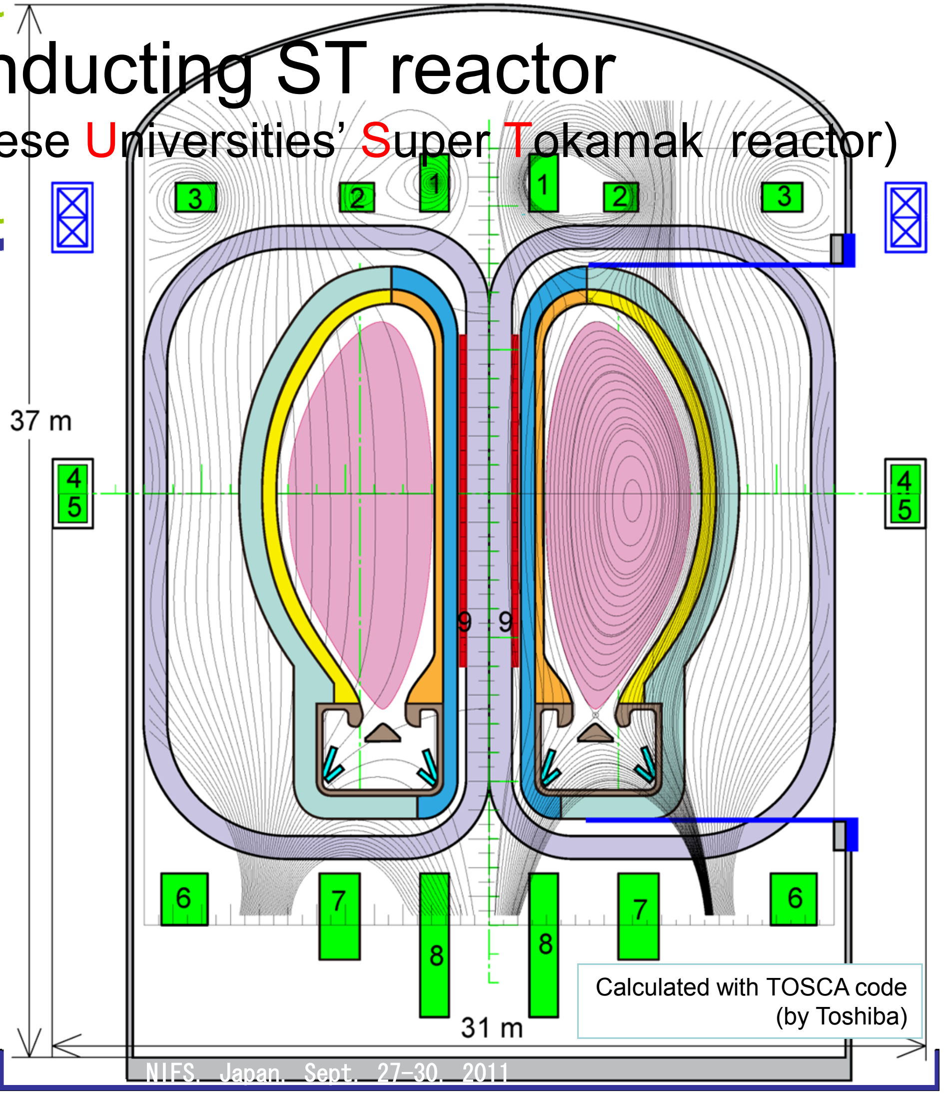




Superconducting ST reactor

JUST (Japanese Universities' Super Tokamak reactor)

R/a	4.5/2.5 (m)
κ/δ	2.5/0.35
B_{t0}/B_{coil}	2.36/12.7 (T)
U_{TF}	24 (GJ)
j_{coil}	24 (MA/m^2)
Φ_{OH}	20 (V-sec)
I_{BS}/I_{OH}	18/7 (MA)
T_{e0}/T_{i0}	15/15 (keV)
n_{e0}	17 ($10^{19}m^{-3}$)
n_e/n_{GW}	1.5
β_t/β_N	0.22/7.2
τ_E/τ_p	2.7/11 (sec)
Neutron flux	4.4 (MW/m^2)
P_f/P_α	2.4/0.5 (GW)

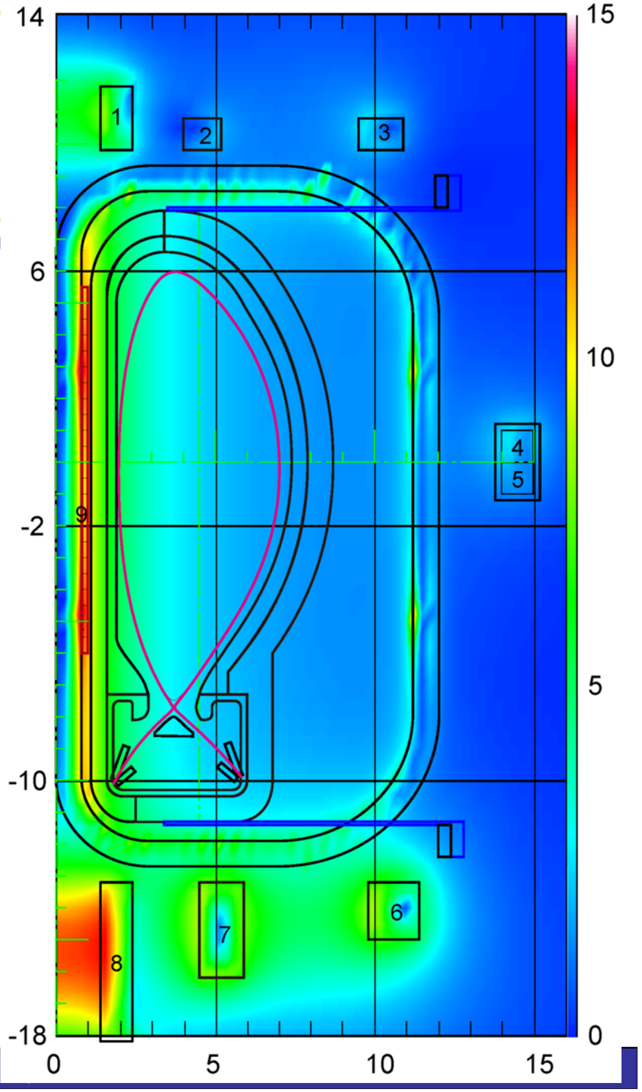


Magnetic Field

calculated with Biot-Savart law

- Magnetic energy:
  - TF: 24GJ
  - PF: 36 GJ

Coil items	current	(unit)
TF coil current	53	(MA-T)
OH solenoid current	6.5	(MA-T)
PF1	21.7	(MA-T)
PF2	3.683	(MA-T)
PF3	-7.296	(MA-T)
PF4	-7.299	(MA-T)
PF5	1.666	(MA-T)
PF6	-3.331	(MA-T)
PF7	50.83	(MA-T)
PF8	43.74	(MA-T)
PF9	0.079	(MA-T)



From ripple, N_{TF}=12

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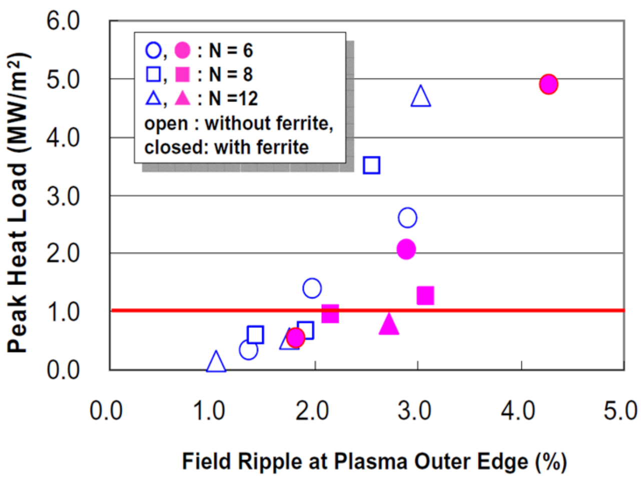
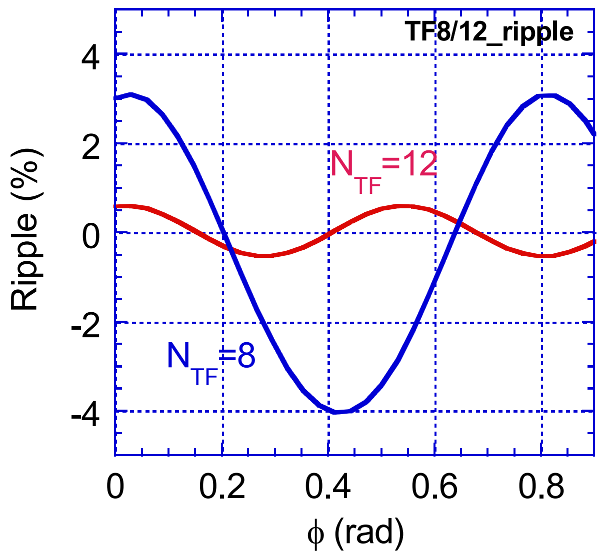
- The TF ripple should be less than 2% in order to reduce the heat load due to alpha particle.
- This condition gives the number of TF return coils as N_{TF}=12.



Peak heat load vs. edge field ripple
(K. Tani, et al., IEEJ Tans. FM, 129, 569 (2009))



Top View (1/12 section)

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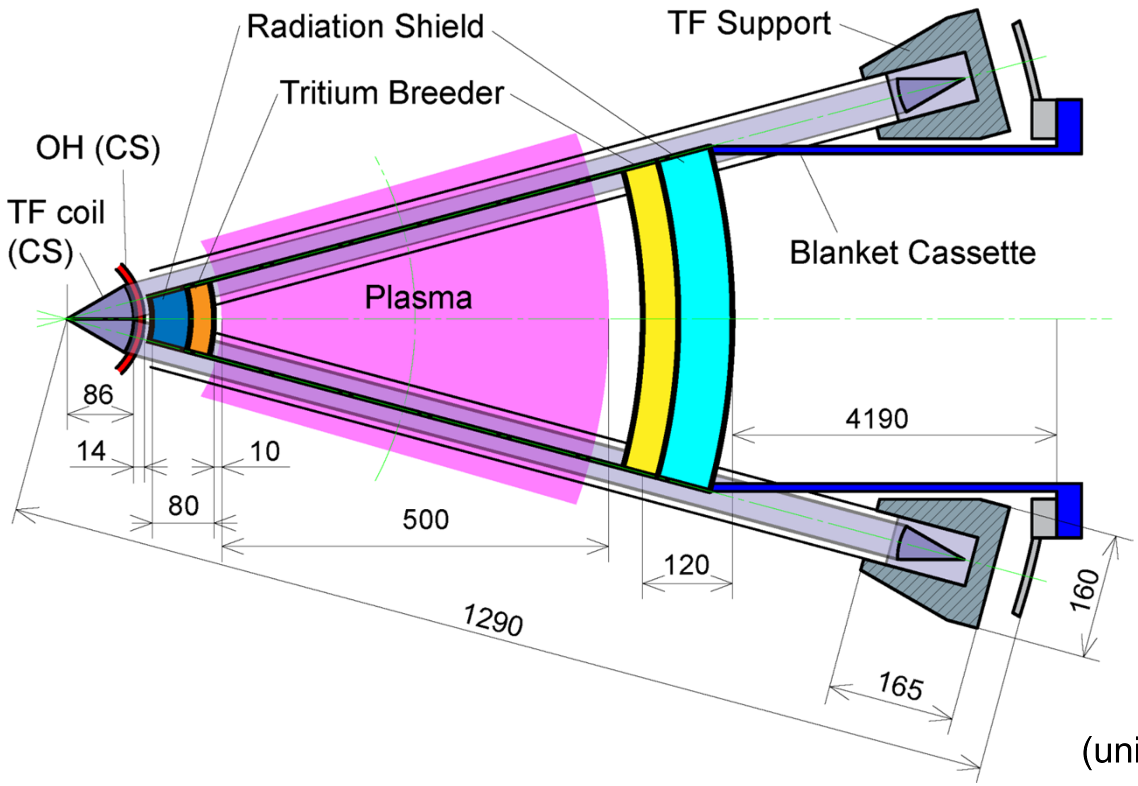

(unit: cm)

Superconducting Center Stack

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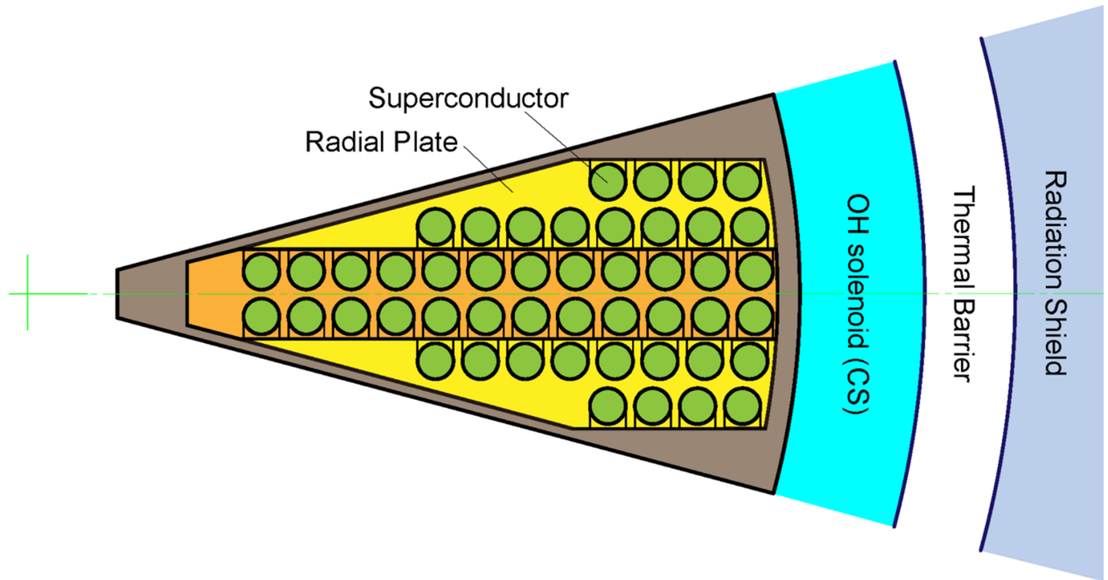
- TF coil is made of double-pan-cake superconductor on a radial plat.
- Center solenoid is wound over the TF core.
- CS is separated by 10 cm thermal shield from the 80cm thick blanket.



How to wind the center (OH) solenoid

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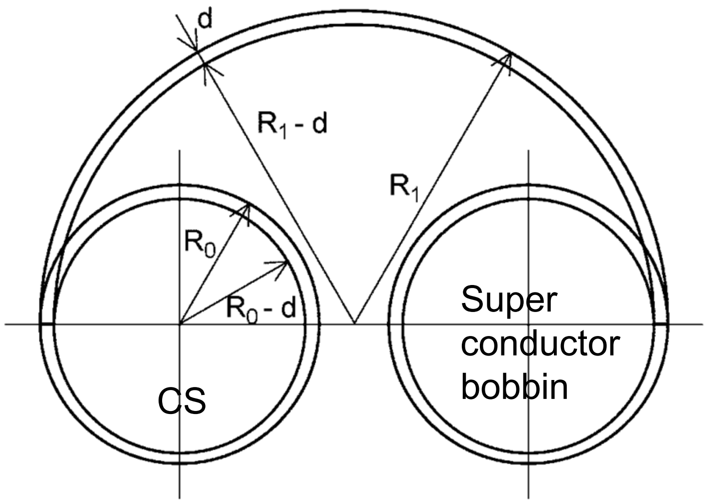
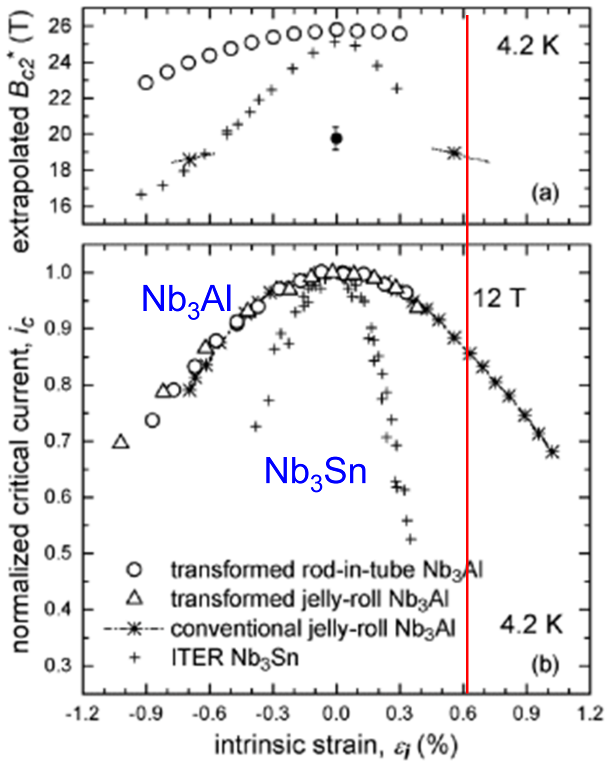
- Winding strain $\varepsilon = \dfrac{d}{2R_0}$
  - ε=0.6% if R_0=84cm, d=1cm
- Nb_3Al is a good superconductor.

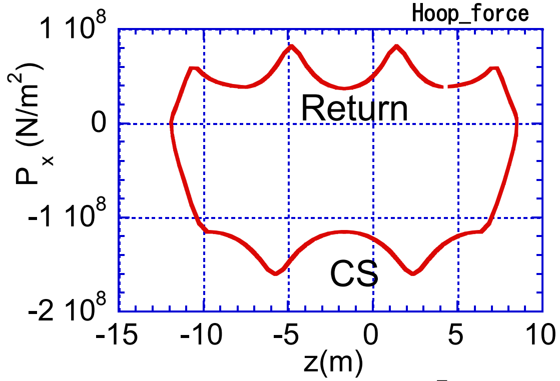


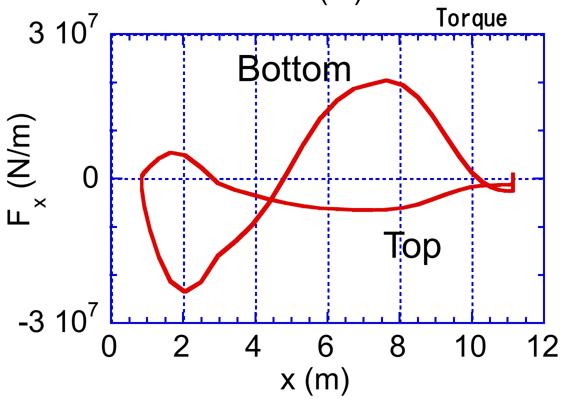


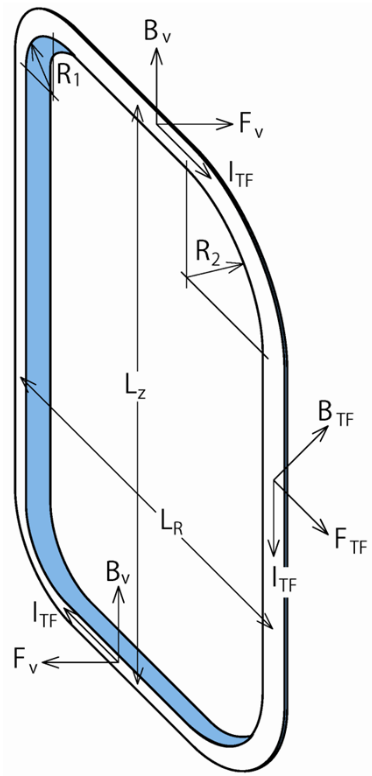
Force on TF Coil

- Hoop force
  - $B_{TF} \times I_{TF}$
  - 160 [MPa]
- Limit of steel
  - 200/500 [MPa]
- Torque due to vertical field
  - $B_V \times I_{TF} \times L^2 \times 2$

    = 700 [MN-m]







TF Coil Support

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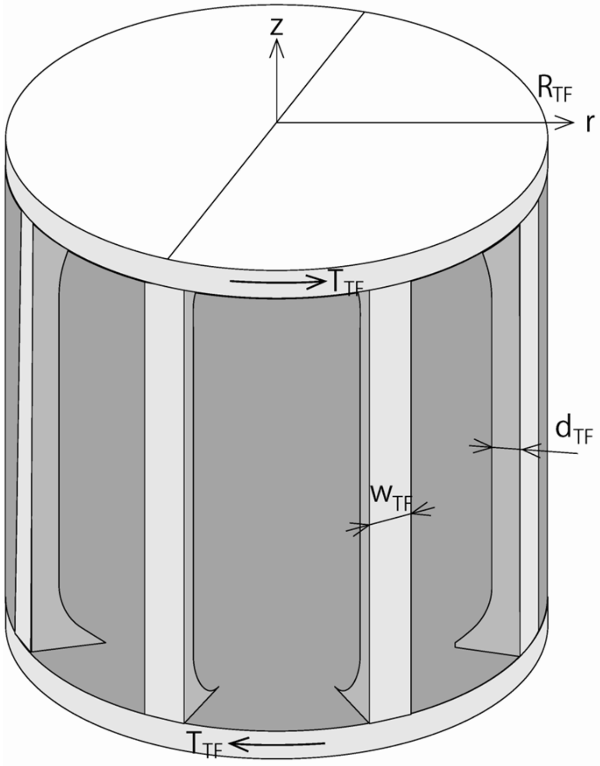
- Large port abandons standard TF coil support, such as compression plate between TF return coil
- Shear stress (τ)

$$\tau = \frac{R_{TF} T_{TF}}{I_\tau}$$

Second polar moment of inertia = 0.1 [Mm^4]

$$I_\tau = \int_r r^2 dA$$

- Support parameters
  - w_{TF}=1.6 [m], d_{TF}=2 [m]
  - τ= 60 [MPa]
  - Strain: 0.3 mm
- The torque can be supported.



Heat load on the diverter plate is one of the most serious problems.

- No solid material can receive the heat load on the diverter plate
  - 200 MW/m^2
- Solutions
  - Detachment
  - Liquid diverter plate (Li, Ga, Sn)

The heat flux into the scrape-off layer, per unit toroidal length, can be written

$$h \simeq -2\pi a n \chi \frac{\mathrm{d}T}{\mathrm{d}r} \simeq \frac{2\pi a n \chi T}{\lambda}, \qquad 13.3.4$$

where λ is the scrape-off layer thickness. This must equal the heat flux along the scrape-off layer to the divertor, which can be written

$$h \simeq 3nT\left(\frac{a}{L}c_s\right)\lambda, \qquad 13.3.5$$

where L is the connection length along the magnetic field and c_s is the sound speed. The quantity $(a/L)c_s$ can be thought of as the component of the parallel flow speed in the poloidal plane. From eqns 13.3.4 and 13.3.5 the scrape-off thickness is given by

$$\lambda \simeq \left(\frac{2\chi L}{c_s}\right)^{1/2}. \qquad 13.3.6$$

For $L = 30$ m, $\chi = 2\ \mathrm{m^2\,s^{-1}}$ and $c_s = 10^5\ \mathrm{m\,s^{-1}}$ the scrape-off layer thickness $\lambda \sim 3$ cm.

Taking 3 GW of fusion power the thermal heat flux is 600 MW. Thus for a toroidal circumference of 50 m and hence a scrape-off area of $2 \times 50 \times 0.03\ \mathrm{m^2} = 3\ \mathrm{m^2}$, the power load would be 200 MW m^{-2}. This is a

J. Wesson: "Tokamaks 3rd ed", Oxford Science Publishing (2004), p.710.

Diverter

Heat load is received by the liquid diverter plate and detachment plasma.

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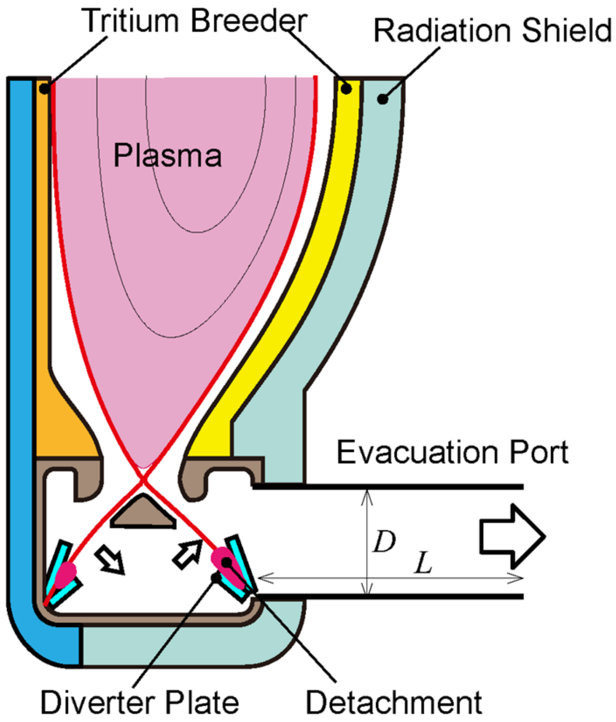
- Heat load
  - Area of diverter plate ($A=2\pi Rw$)
  - R=5 m, w=0.03m then $A=0.9\ m^2$
  - 50% of alpha heating = 270 MW.
  - Heat flux = 300 [MW/m^2]
- Liquid Diverter plate
  - Li (Hydride)
  - LiSn (Effect to Plasma)
- Detachment
  - V-shape diverter target limits the volume and makes high density diverter plasma.
  - Large area (100 m^2: w=1.5 [m])
- Intense development is required!



Fueling and Exhausting

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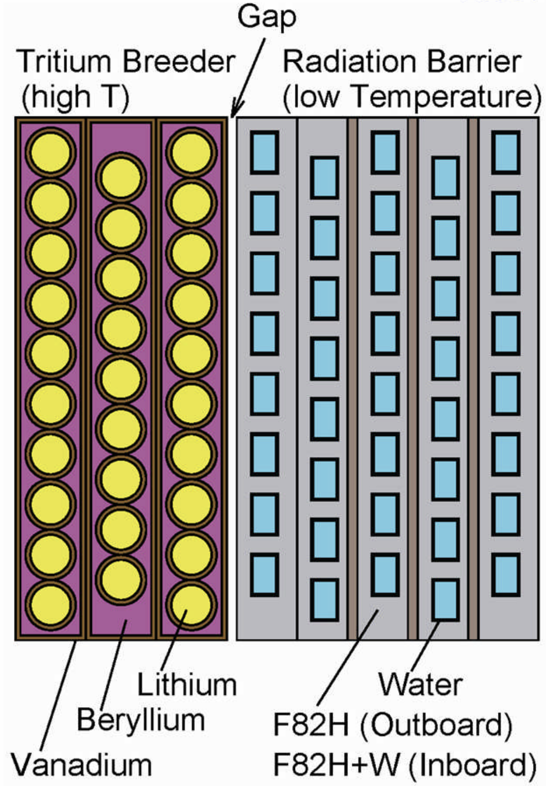
- Fueling
  - Fueling rate (D+T): 13 (10^{21}atoms/sec); Burning rate: 1.7 (10^{21}atoms/sec)
  - Ice pellet injection (Core: 30cc)
    - Puffed gas cannot pass through the SOL
- Exhaust gas
  - Assume fueling efficiency of 10%
  - 6 (10^{22}molecules/sec)=0.1 (mol), which is 220 (Pa-m^3/sec)
- Evacuation pump
  - Conduction of 12 ports (D=2 m, L=6m)
    2000 (m^3/sec) (molecular flow)
    2000 (m^3/sec) (viscous flow)
- Pressure at diverter chamber is 0.11 (Pa)
  - High compression rate of diverter leg is necessary.

Blanket (primitive)

T-Breeder: (Be+Li)/V, Shield: F82H(W)+H_2O

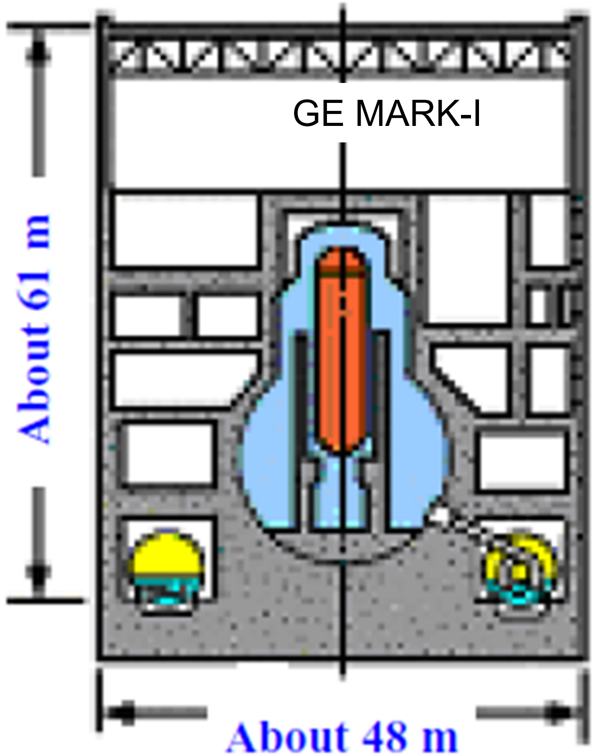
JUST

- Neutron breeding by Beryllium (T_{melt}=1560K)
  $^9Be+n \rightarrow {}^8Be+2n$ (E_n>2.7MeV)
  $^9Be+n \rightarrow {}^6He+{}^4He$ (E_n>1.4MeV)
  $^8Be \rightarrow 2\ {}^4He$ ($T_{1/2}$=0.067 fsec)
  $^6He \rightarrow {}^6Li+b$ ($T_{1/2}$=0.808 sec)
- Tritium breeding by Lithium (T_{melt}=454K)
  $^6Li+n \rightarrow T+{}^4He$+4.8MeV (940barn)
  $^7Li+n \rightarrow T+{}^4He+n$-2.5MeV ($E_n$>2.8MeV; 0.355barn)
- Strong point
  - High breeding ratio
  - High cooling rate for neutron power (4.5 MW/m^2)
  - Free from melt down in the case of power off
- Needs
  - Insulator coating inside the pipe of lithium fluid
  - T separation from lithium

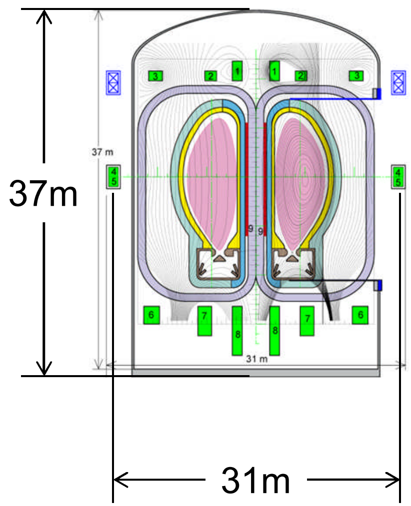


Comparison of fusion and fission reactors

JUST



- Size of fusion reactor (JUST: 850MWe) is not much bigger than a fission reactor (GE MARK-I: 840MWe).



CONCLUSION

ST can be a fusion power reactor.

JUST

- ST may be able to have solutions for most issues to realize a fusion reactor.
- Since ST experiment is not sufficient, most physics solutions need proof.

Issues	ST	status
Plasma confinement	ITB	(need proof)
Disruption control	Margin in β and q-value	(need proof)
Steady state	High BS current	(need proof)
Cost	High β	(need proof)
Superconducting magnet	Space of neutron shield for CS	(need design)
Neutron damage	Easy wall replacement with blanket cassette	(need design)
Heat load	Liquid wall (+ detachment)	(need proof and technology to separate Tritium)

Conclusion

JUST

- Major issues for fusion reactor are not very serious in ST.
  - Confinement, Steady state, Disruption,
  - Neutron damage, Cost (Low field),
- We made a conceptual Design of superconducting ST reactor
  - R=4.5 m, a=2.5 m, B_t=2.3 T,
  - Fusion power: 2.5 GW (Electric power: 0.85GW)
  - U_{TF}=24 GJ: half of ITER
- Further efforts are required
  - Proof of steady state operation, high BS current, high T_e,
  - Diverter
  - Tritium
  - Liquid metal