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# High beta and high bootstrap current equilibria with internal and external transport barriers

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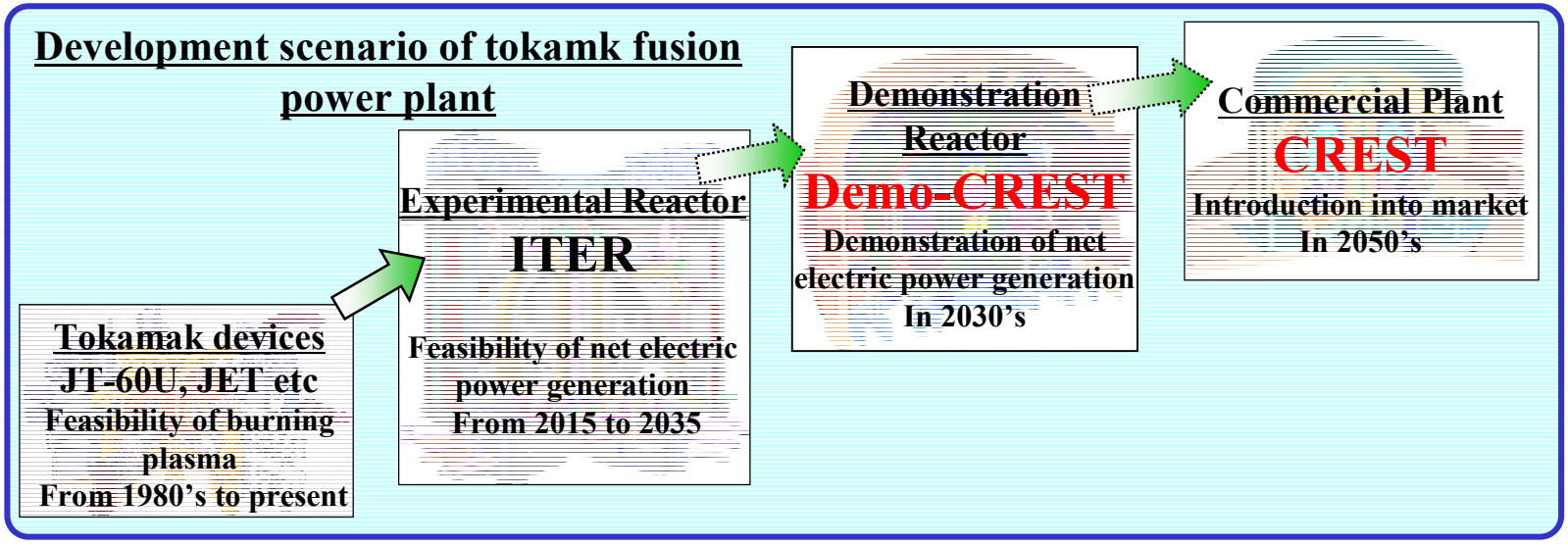
This presentation is based on Kimura's master thesis at the University of Tokyo.

# Overall Feature of Development Scenario of CREST




- The demonstration of electric power generation in the 2030's is focused on. That means Demo-CREST has to be constructed just after or during the ITER project
- Testing by ITER is an important policy in this development scenario of Demo-CREST and CREST. This leads to the selection of A=3.4.
- This development scenario is characterized by a advanced tokamak plasma reactor with a water cooled RAF (Reduced Activated Ferritic Steel) blanket system.

# Demonstration Plant : Demo-CREST

**Principles for the Demo-CREST Design**

1. To demonstrate electric power generation as soon as possible in a plant scale, with moderate plasma performance which will be achieved in the early stage of the ITER operation, and with foreseeable technologies and materials (**Demonstration Phase OP1~OP4**)
2. To show a possibility of an economical competitiveness with advanced plasma performance and high performance blanket systems, by means of replacing breeding blanket from the basic one to the advanced one (**Development Phase OP4, OPRS**)

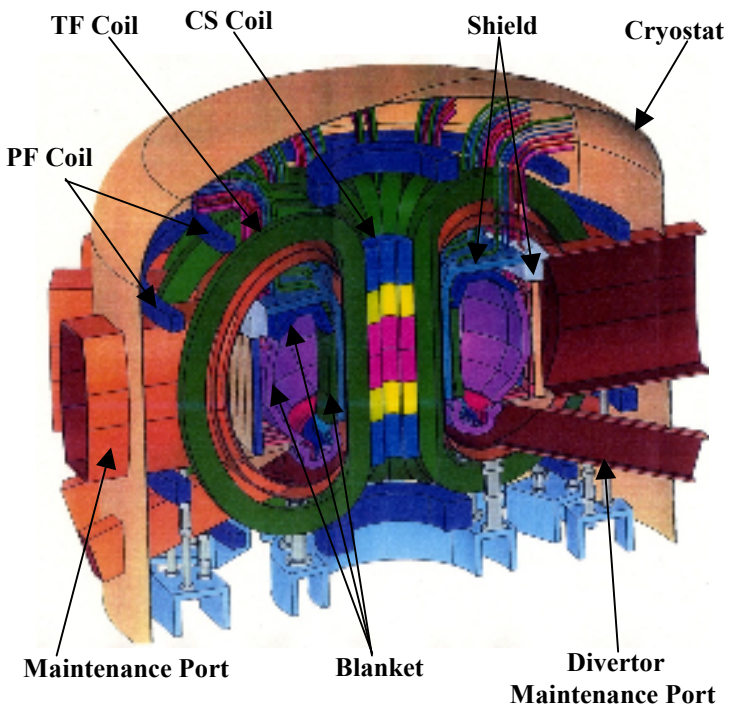



Figure:Bird's-eye of Demo-CREST

| | | OP1 | OP2 | OP3 | OP4 | OPRS |
|---|---|---|---|---|---|---|
| R (m) / A | | 7.25 / 3.4 | | | | |
| $\kappa/\delta$ | | 1.85/ 0.35 | | | | |
| $q_{min}/q_{95}$ | | -/5.0 | | | -/5.2 | 3.6 / 6.5 |
| $\beta_N$ | | **1.9** | **2.5** | **3.0** | **3.4** | **4.0** |
| HH | | **0.96** | **1.1** | **1.2** | **1.2** | **1.4** |
| $fn_{GW}$ | | **0.56** | **0.73** | **0.80** | **1.02** | **1.31** |
| $P_b$ (MW) | | 188 | 190 | 185 | 191 | 106 |
| $P_f$ (MW) | | 1260 | 1940 | 2460 | 2840 | 2970 |
| $P_{enet}$ (MWe) | **Basic Blanket** | **30** | **230** | **390** | **490** | - |
| | **Advanced Blanket** | - | - | - | **850** | **1090** |

# Commercial Plant : CREST

**The aim of CREST design is to show the typical development goal to get the economic competitiveness.**

| | | | |
|---|---|---|---|
| High beta<br>$\beta_N$~5.5 | Reversed Shear<br>Profile control and high speed plasma rotation | High efficiency<br>$\eta_{th}$>40% | High thermal efficiency $\eta_{th}$~41%<br>Advanced ferritic steel component with water cooled system |
| High κ and δ<br>κ~2.0,δ~0.5 | Active and passive feedback coils | Quick Maintenance | Full sector removal design for blanket (14 sectors)<br>High availability (>80%) |

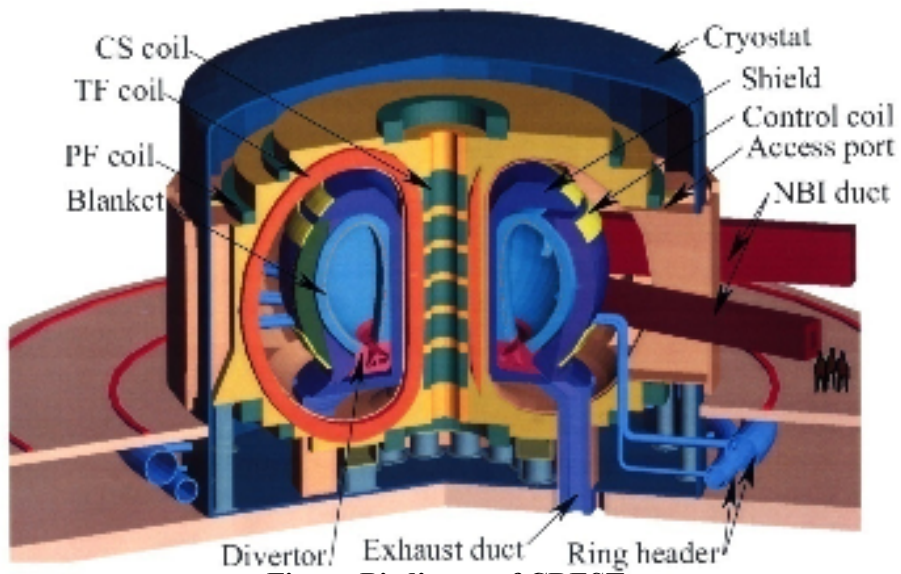


**Figure:Bird's-eye of CREST**

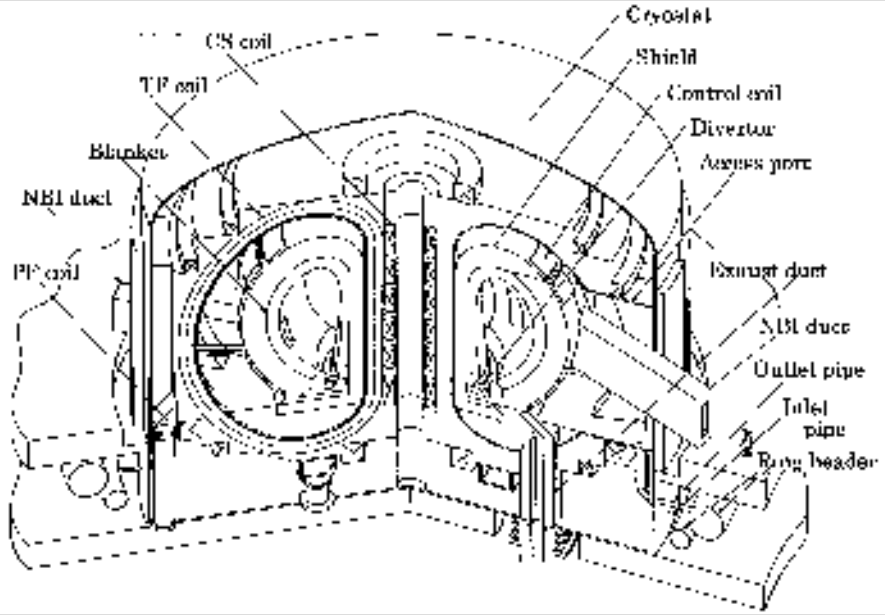
| | |
|---|---|
| R (m) /A | 5.4 / 3.4 |
| κ / δ | 2.0 / 0.5 |
| Bt (T) / Ip (MA) | 5.6 / 12 |
| $q_o$ / $q_{min}$ / $q_{95}$ | 2.9 / 2.4 / 4.3 |
| $\beta_N$ | 5.5 |
| HH | 1.5 |
| $fn_{GW}$ | 1.3 |
| $f_{bs}$ | 0.83 |
| $P_b$ (MW) / $E_b$ (MeV) | 97 / 2.5 |
| $P_f$ (MW) | 2970 |
| $P_e/P_{enet}$ (MWe) | 1385 /1163 |

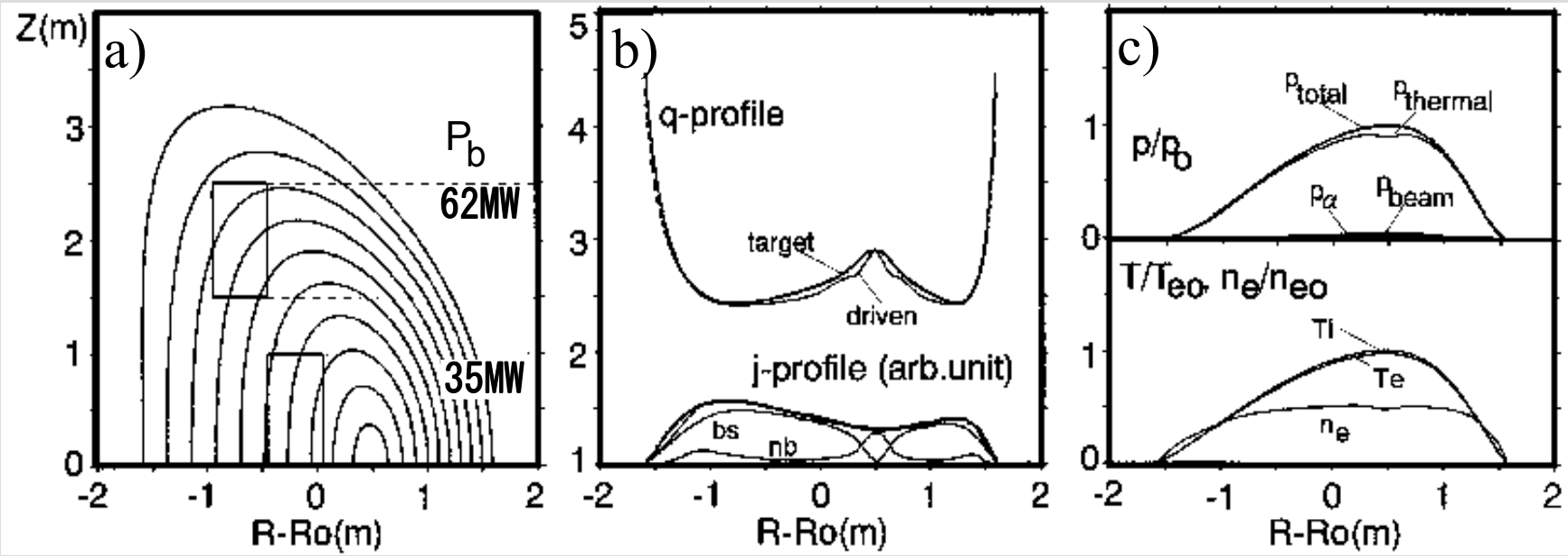
# Original high beta NBCD equilibrium of CREST with no pedestal

## $\beta n$=5.5 (by NBCD)

is stable against low-n (1,2,3) kink modes and high-n ballooning modes with a closed conductive shell ($a_w/a$ = 1.15) . RWM is stabilized by fast toroidal rotaion.

K. Okano et al., Nuclear Fusion **40**(2000)635



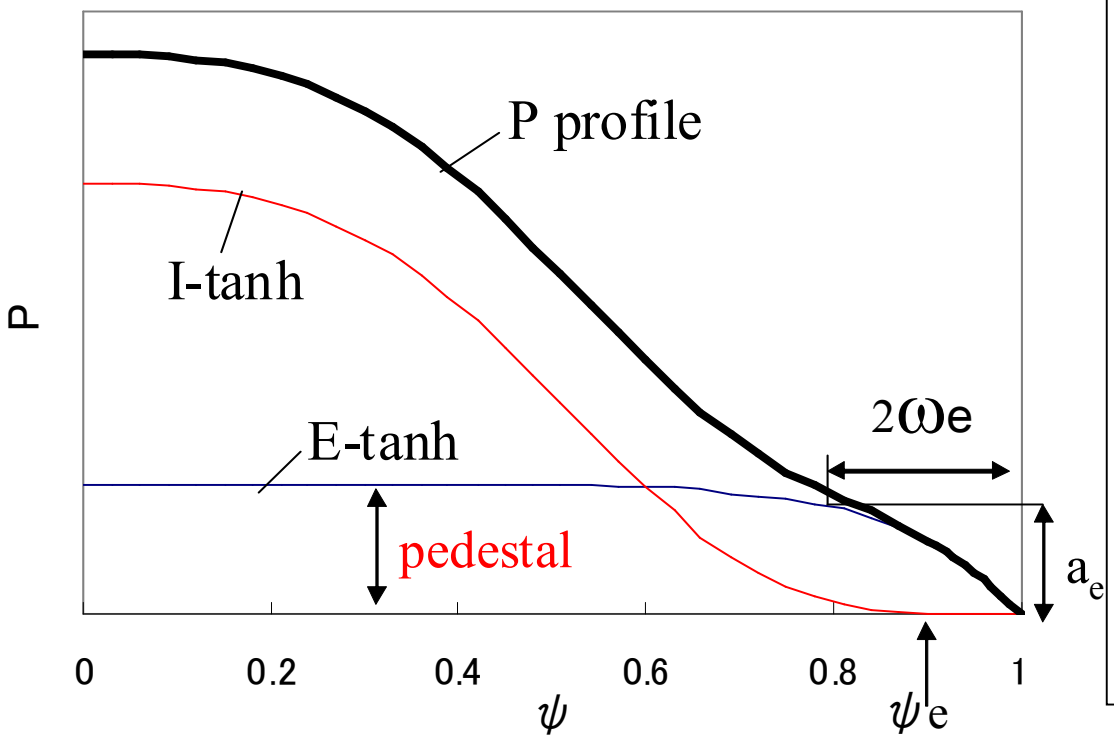
# High beta (NB+RF)CD equilibrium of CREST with pedestal

## βn-max = ???

$$P(\psi) = a_{\text{int}} c\left(1+\tanh\left(\frac{-(\psi-\psi_{\text{int}})}{\omega_{\text{int}}}\right)\right) + a_{ext} c\left(1+\tanh\left(\frac{-(\psi-\psi_{ext})}{\omega_{ext}}\right)\right) - const$$

$$TdT/d\Psi = cR_0^2\left(1-\psi^{t2}\right)\left[t_3+\left(1-t_3\right)\psi^{t4}\right] - R_0^2 P' t_5$$

T( = R jφ)




In most of present tokamak experiments, pressure profile with a pedestal has been observed in the improved confinement discharges.

The purposes of this study:
To investigate the effect of the pedestal on the attainable high beta steady-state equilibria driven by the non-inductive current drive and the BSC.

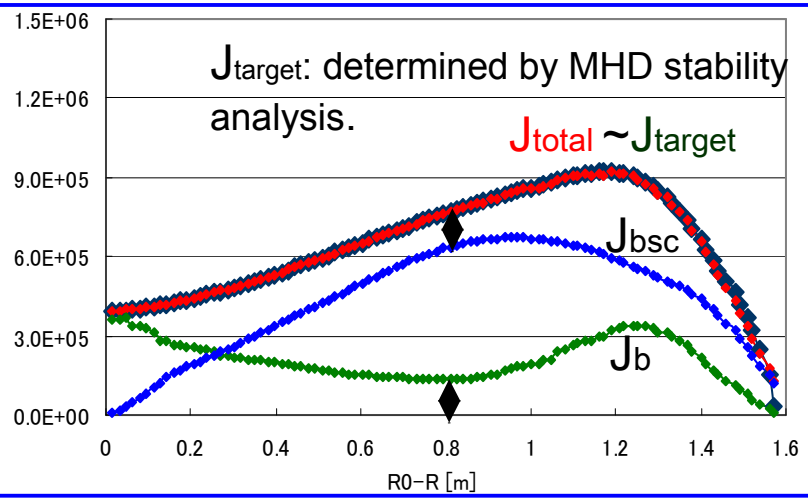
The pedestal height is determined by a-int/a-ext. The width of barrier is determind by $\omega_{ext}$ and $\omega_{int}$.

# High beta equilibria sustained by CD may be restricted by following three kinds of limits:

1. MHD limit
   Simply, MHD beta limit restricts the maximum $\beta_n$ (= conventional beta limit)

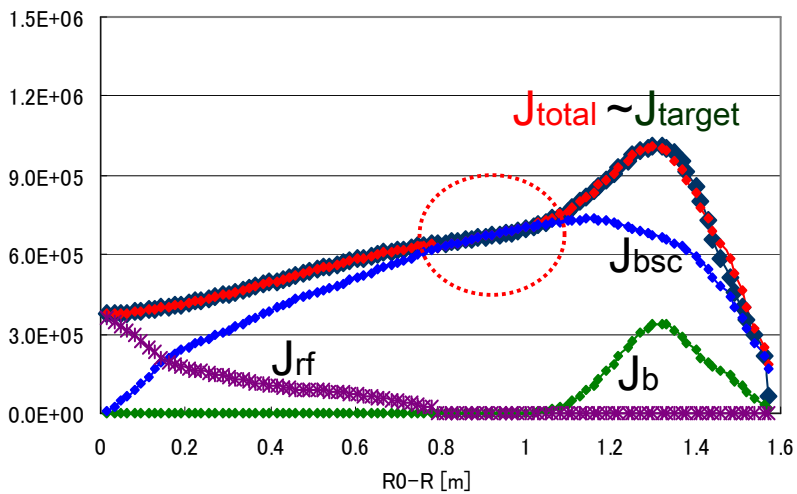
2. Beam driven limit
   $J_{total}$ (=$J_{beam}$+$J_{bsc}$) may exceed the required current density when $\beta_n$ is increased further, even if $\beta_n$ is less than MHD limit.

The CREST NBCD equilibrium is just the case.

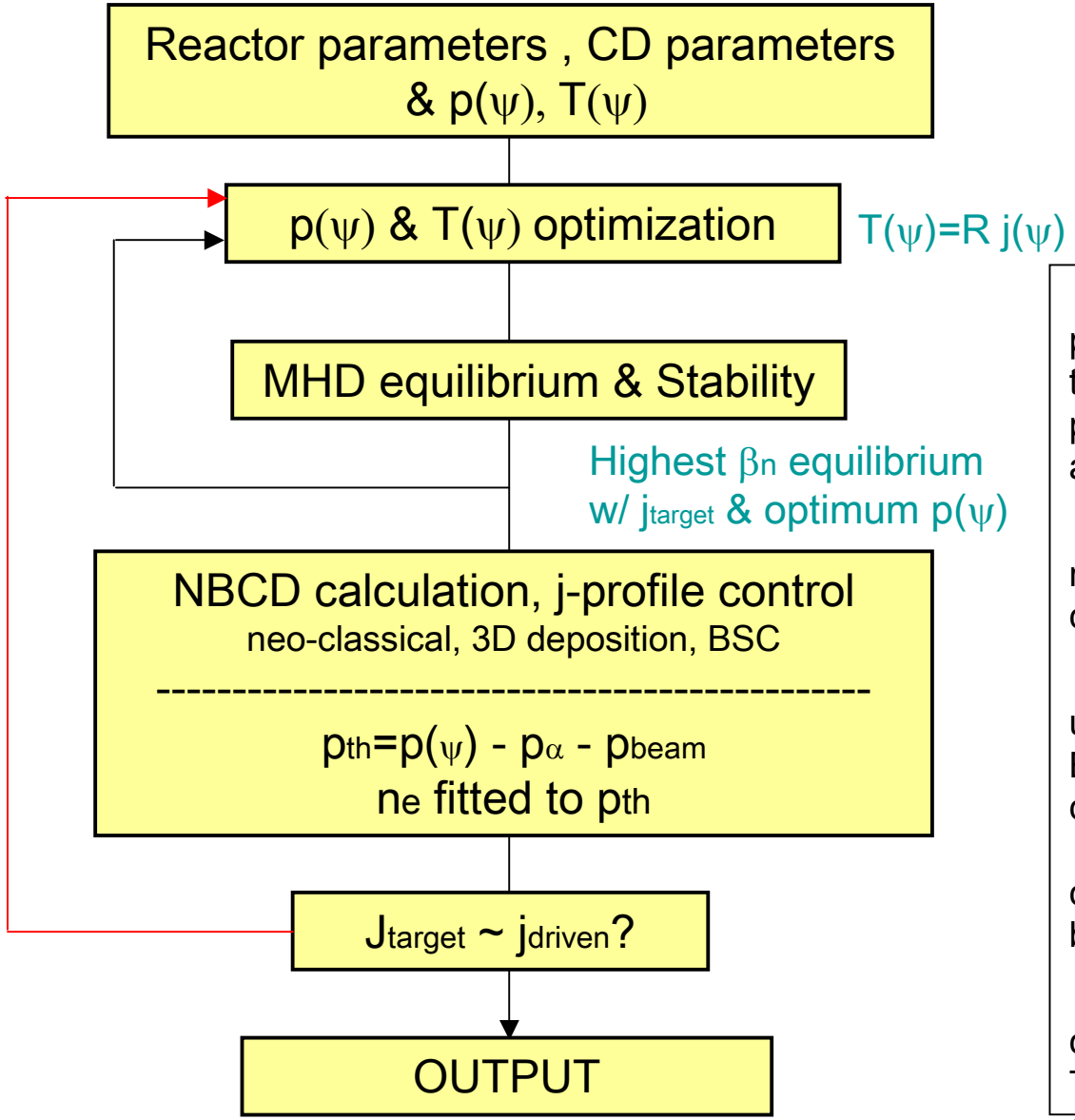



3. CD limit
   $J_{bsc}$ may exceed the target current density when $\beta_n$ is increased further, even if $\beta_n$ is less than MHD limit.

The current near axis never be driven by NBCD. RFCD will be required.



# Steady state tokamak analysis code system




In this code system, the reactor parameters & CD parameters like the beam energy and pressure profile, temperature profiles, etc. are given.

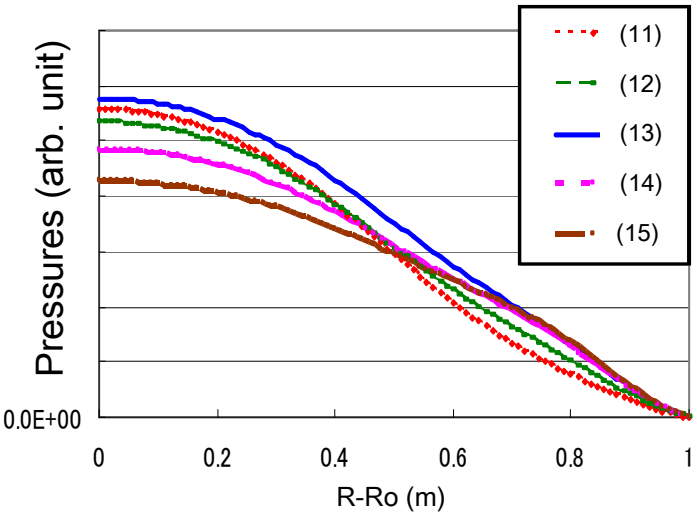
The current profile is optimized to maximize beta-n. This is the target current profile for CD calculation.

The highest beta equilibrium is used to calculation for NBCD and BSC. The NBCD parameters may change so that j-driven = j-target.

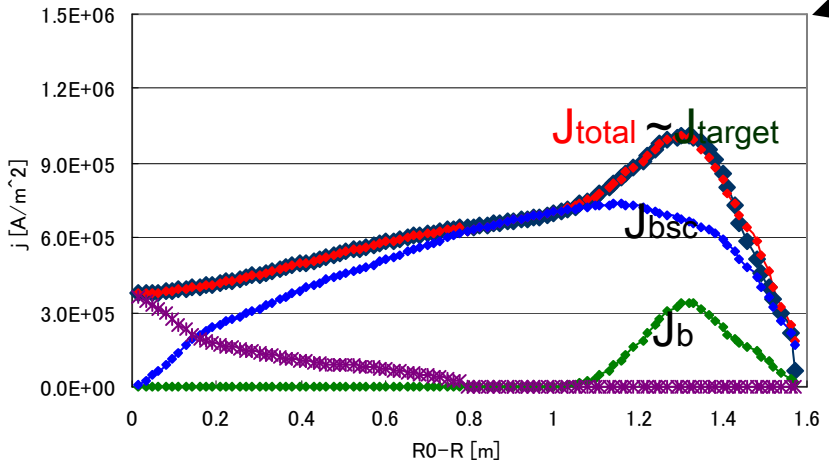
The thermal pressure profile is calculated considering alpha & beam pressures.

If the deviation of the driven current profile is not small enough, T(ψ) will be modified & MHD equilibrium is optimized again.

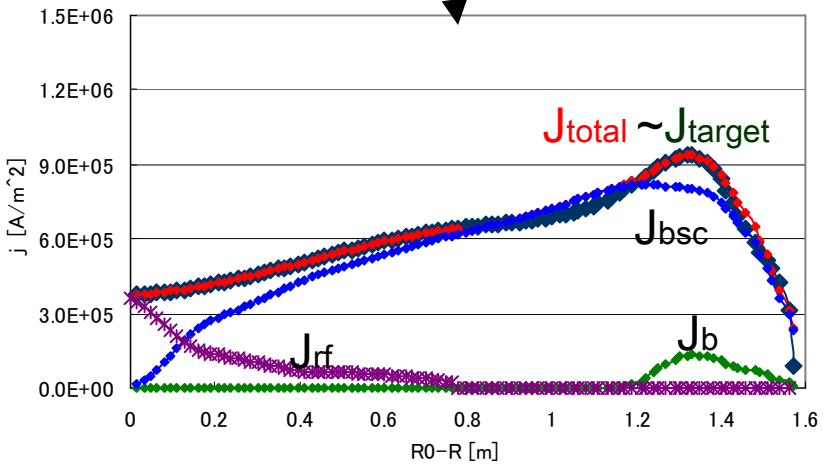
# Survey of high beta equilibria with weak pedestals




| $\omega_{ext}$=0.2 | (11) | (12) | (13) | (14) | (15) |
|---|---|---|---|---|---|
| $a_{-int}$ / $a_{-ext}$ | 8/1 | 8/2 | 8/3 | 8/4 | 8/6 |
| $\beta_{n\text{-}max}$ $a_w/a$=1.15 | 4.0 | 4.2 | 4.8 | 4.4 | <3.8 |
| restricted by | CD limt | CD limt | CD limt | CD limt | MHD limit |

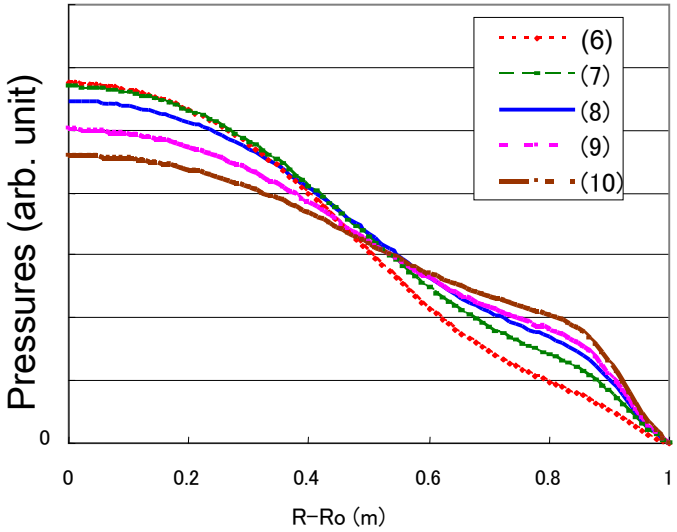



Equilibrium (12) (at BSC limit)

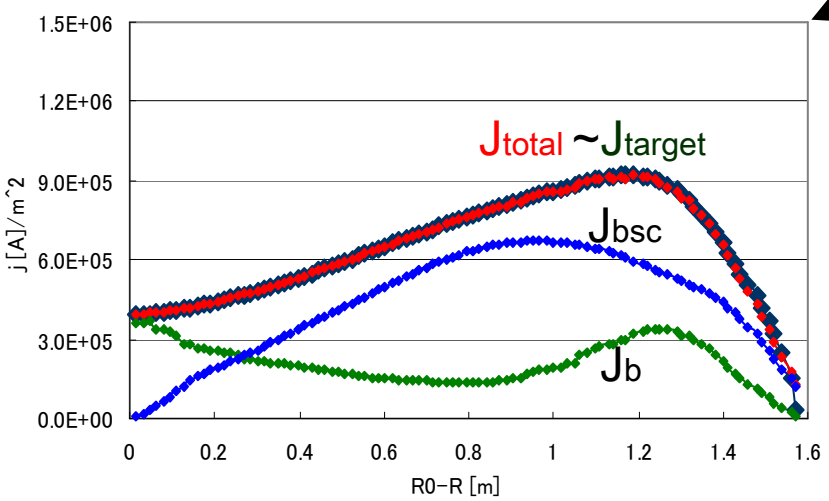



Equilibrium (13) (at BSC limit)

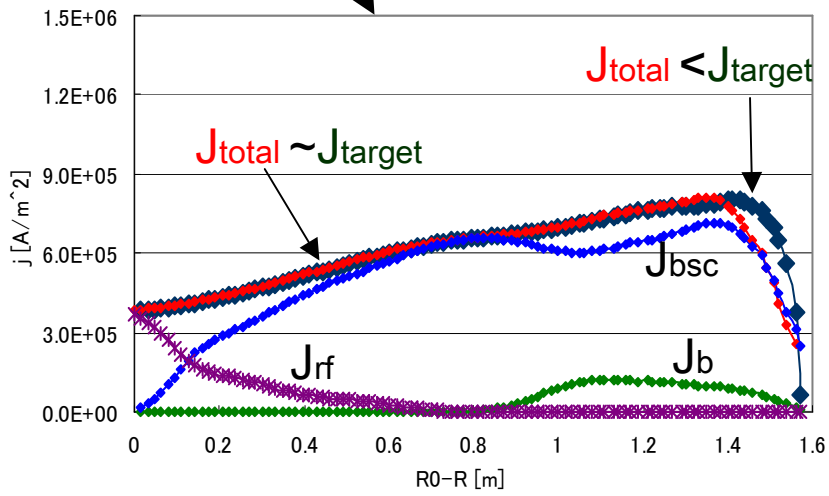
# Survey of high beta equilibria with sharp pedestals




| $\omega_{ext}$=0.1 | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|
| $a_{-int}$ / $a_{-ext}$ | 8/1 | 8/2 | 8/3 | 8/4 | 8/6 |
| $\beta_{n\text{-}max}$ $a_w/a$=1.15 | 3.3 | 4.5 | 4.1 | 3.6 | <2.0 |
| restricted by | MHD limt | CD limt | MHD limt | MHD limt | MHD limit |

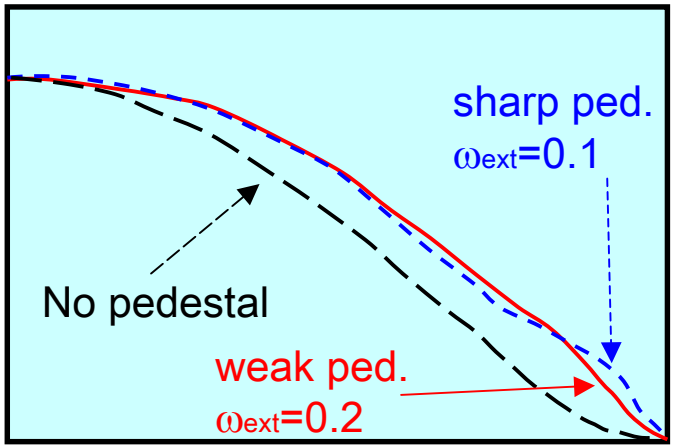



Equilibrium (6) (at MHD limit)




Equilibrium (7) (at BSC limit, j-driven is not aligned at periphery)

# Summary of the highest beta equilibrium for each profile (1)




@ Addition of any pedestal tends to result in a lower βn limit.

@ After optimization of CD parameters, the highest βn's are restricted by CD limit rather than MHD limit.

@ NBCD (off-axis) + RFCD (on-axis) will widen the operation windows toward a higher βn.

| | no pedestal | weak pedestal | sharp pedestal |
|---|---|---|---|
| $a_{-int}$ / $a_{-ext}$<br>$\omega_{ext}$ | --<br>-- | 8/3<br>0.2 | 8/4<br>0.1 |
| $\beta_{n-max}$<br>w/ optimized CD | 5.5 | 4.8 | 4.5 |
| Driver(s) | NB only | NB+RF | NB+RF |
| $I_{bsc}/I_p$ | 83% | 95% | 91% |
| restricted by | NBCD limit | CD limit | CD limit |

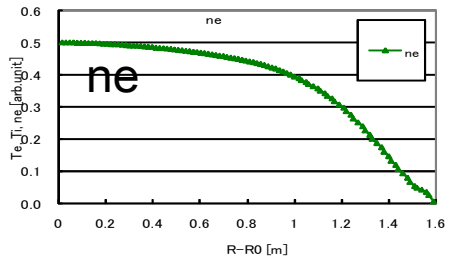
# Summary of the highest beta equilibrium for each profile (2)

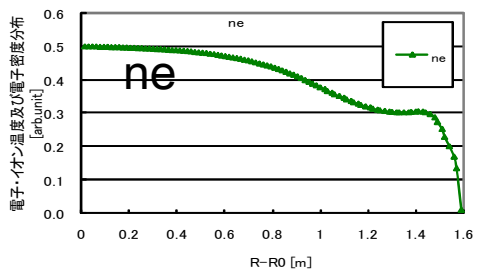
@ The beam power and the beam energy can be reduced with pedestal.
‘1 MeV’ is much more feasible than ‘2.5 MeV’.

@ BUT, the fusion power w/ pedestal decreases down to 1.2-1.3 GW, not only due to the lower beta, but also due to the broad ne profile.

@ Thanks to lower Eb, the toroidal rotation velocities are not small.

| | no pedestal | weak pedestal | sharp pedestal |
|---|---|---|---|
| $\beta_{n\text{-}max}$ | 5.5 | 4.8 | 4.5 |
| Beam power | 97 MW | 14.4MW+RF? | 31.3MW+RF? |
| Beam Energy | 2.5 MeV | 1.0 MeV | 1.0 MeV |
| Tor. rotation vel. | 1.2x10^5 m/s | 0.8x10^5 m/s | 1.9x10^5 m/s |
| Fusion power | 2.97 GW | 1.34 GW | 1.17 GW |



# Conclusion

Although the results are just tentative (further optimization will be possible), the findings of this study are as follows:

@ The high beta equilibria for original CREST ($\beta n$ = 5.5) may not be attainable if a sharp pedestal in the pressure profile is required for advanced tokamak operation.

@ When NBCD (off-axis) + RFCD (near axis) are available:

* The highest beta-n with a sharp pedestal profile has been $\beta n$ =4.5 at CD limit.

* The BSC rate over 90% will be possible, while it was 83% at NBCD limit of the CREST original equilibrium ($\beta n$=5.5) without pressure pedestal.

@ Because of lower $\beta n$ and broad ne profile, the fusion power decreases down to1.2-1.3 GW.
Re-optimization of the reactor design will be necessary (for example, to increase the major radius from 5.4 m).

How about DEMO with 1 GWth?