Design window analysis of LHD-type Heliotron DEMO reactors

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LHD-type Heliotron DEMO is foreseeable

- Helical system with net-current free plasma:
  - No disruptive event ➔ **steady-state** easily achievable
  - No current drive power ➔ **self-ignition state (Q = ∞)** is attainable

- LHD has achieved:
  - High beta (~5% by volume average for ~100 τ_E)
  - Extremely high central density (IDB-SDC, $n_{e0} = 1.2 \times 10^{21} \mathrm{m}^{-3}$)
  - Steady state wo/ disruptive events
  - Other remarkable observations
    - Impurity hole
    - Divertor detach scenario

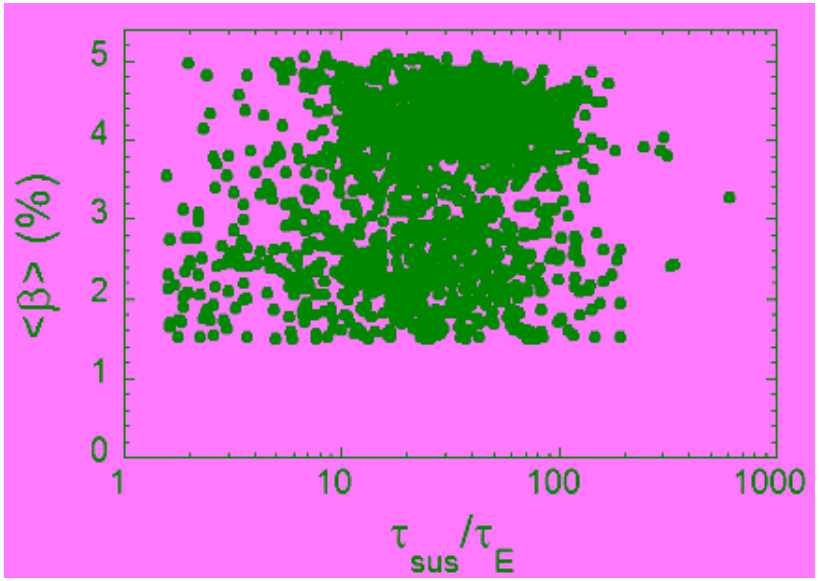


*Figure from A. Komori *et al.*, Fusion Science and Technology **58** (2010) 1.

- The LHD-type Heliotron DEMO reactor is foreseeable.

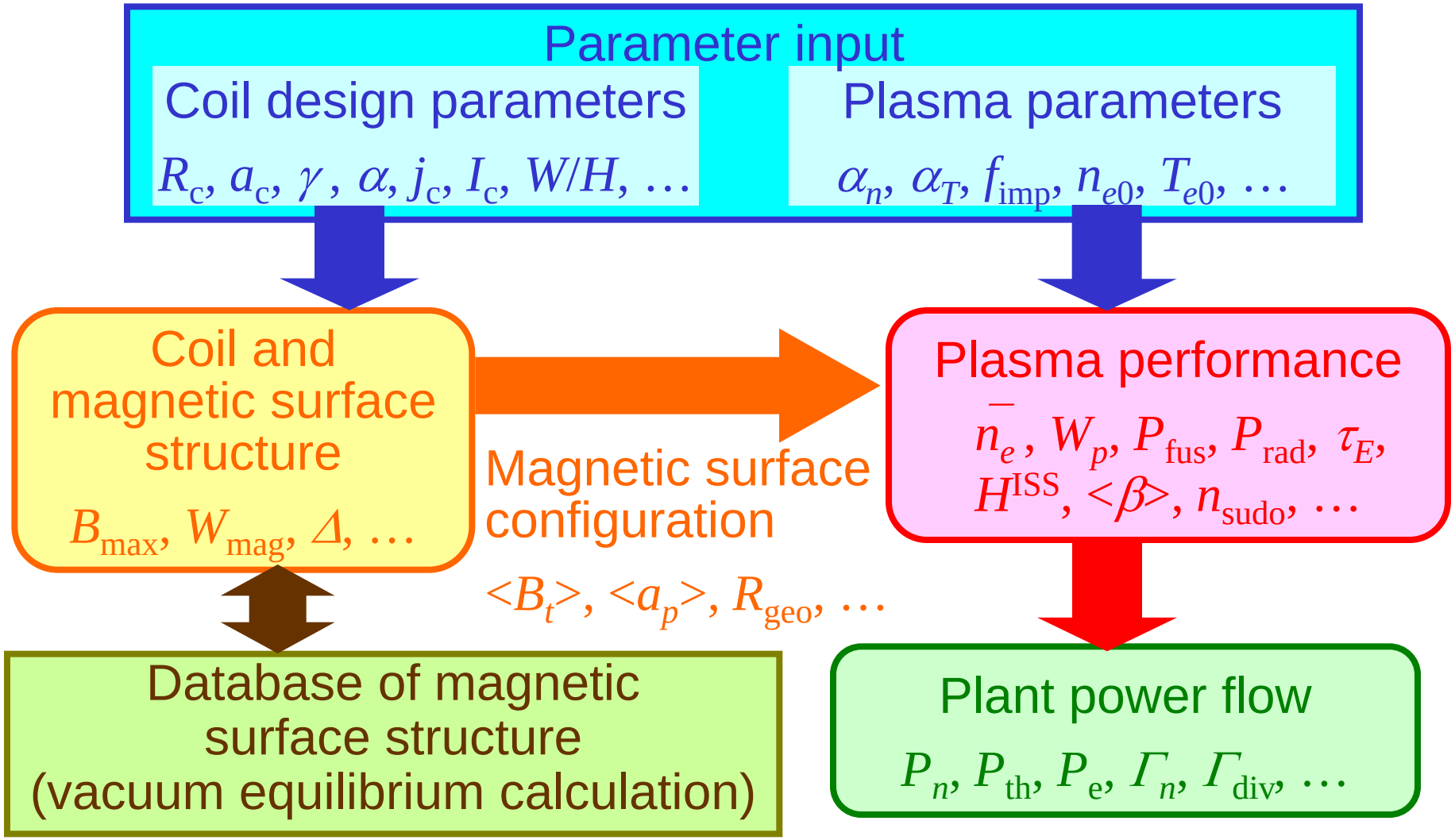
Not optimum but 'robust' design

- There are several uncertainties in the physics conditions of a burning plasma.
  - Density and temperature profiles
  - Impurity fraction (especially helium ash fraction f_α)
  - Alpha heating efficiency η_α
- DEMO is the next step reactor
  - high reliability is required in its design

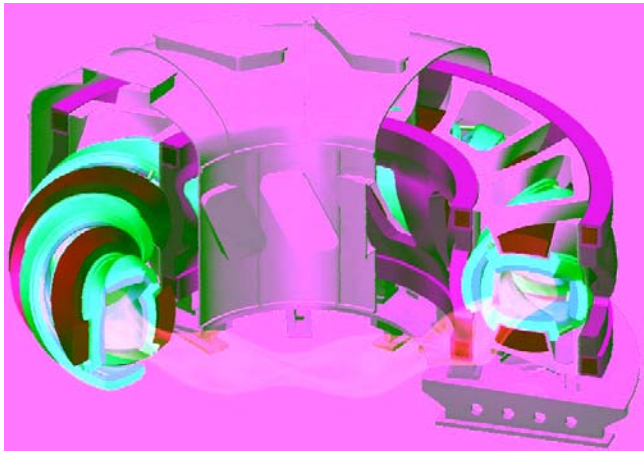
- Direct extrapolation of experimentally-obtained plasma properties (presented by Dr. Miyazawa)
- Finding of robust (insensititive to the change of uncertain parameters) design window

System Design Code HELIOSCOPE

HELIOtron System design COde for Performance Evaluation



LHD-type Heliotron Reactor FFHR-2m2



- FFHR-2m2* is the LHD-type Heliotron reactor
  - Based on LHD high-beta discharge
  - designed for the use in both a DEMO and commercial reactor
- Design policy:
  - P_{fus} = 3GWth ($P_{e,net}$ = 1GWe)
  - Long-term (~30 FPYs) operation with high plant availability
    - →Average neutron wall load $<\Gamma_{nw}> \leq 1.5$ MW/m^2 is assumed
  - Technology can be extrapolated from the present knowledge
    - →Stored magnetic energy $W_{mag} \leq 160$ GJ is assumed**

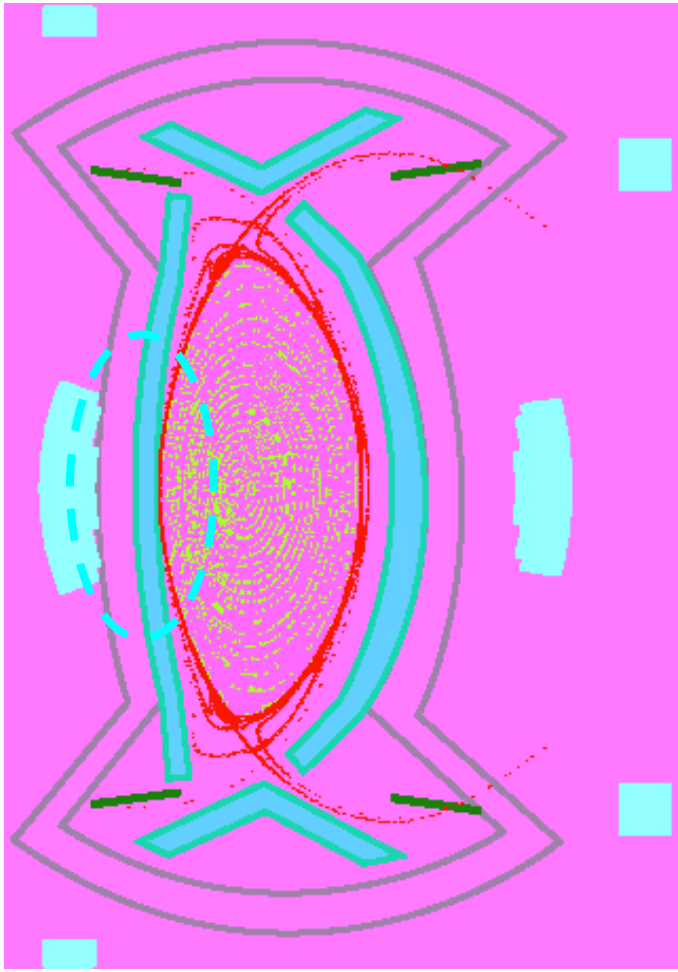
* A. Sagara *et al.*,. Fus. Eng. Des. **83**, 1690 (2008), A. Sagara *et al.*,. Nucl. Fusion **45**, 258 (2005).

** S. Imagawa *et al.*,. Nucl. Fusion **49**, 075017 (2009).

Blanket space is a key design issue

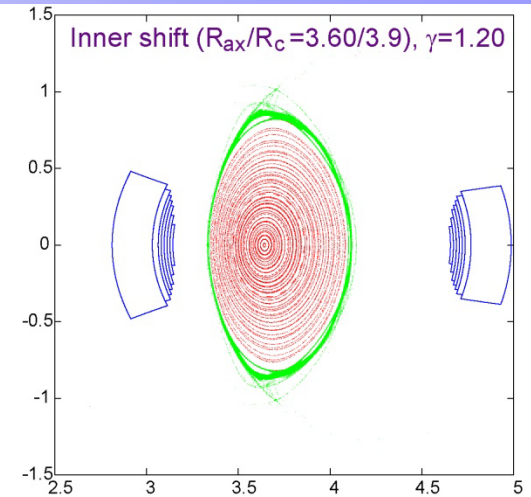
- Inboard side blanket space on vertically-elongated cross-section is limited for the LHD-type heliotron reactor

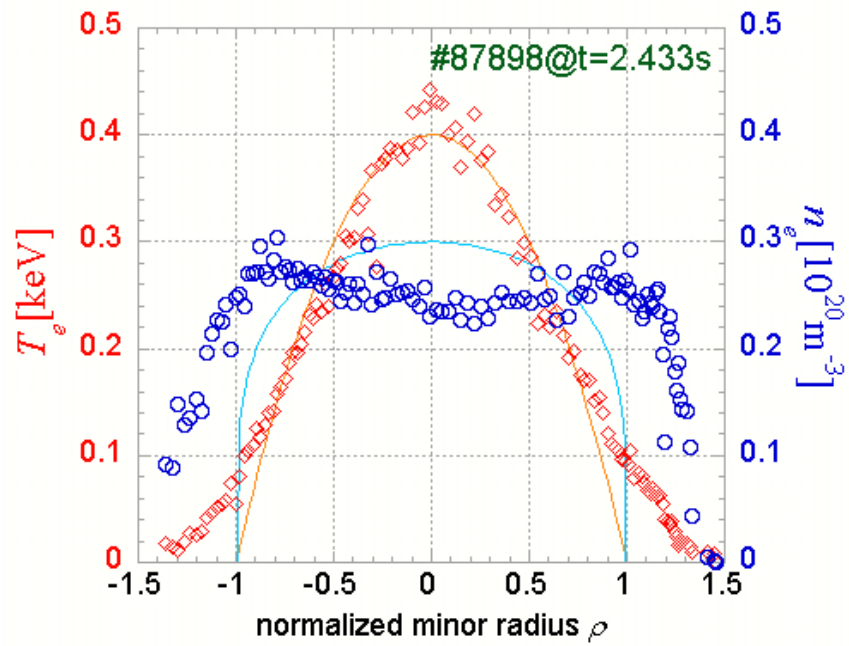
- Inboard minimum blanket space $\Delta_{in} \geq 1.0$m is assumed in FFHR-2m2
  - assure the sufficient net TBR (>1.05) with ~40cm breeding layer
  - suppress fast neutron damage on superconducting coil < 10^{22}n/cm^2 after 30FPYs with ~60cm radiation shield



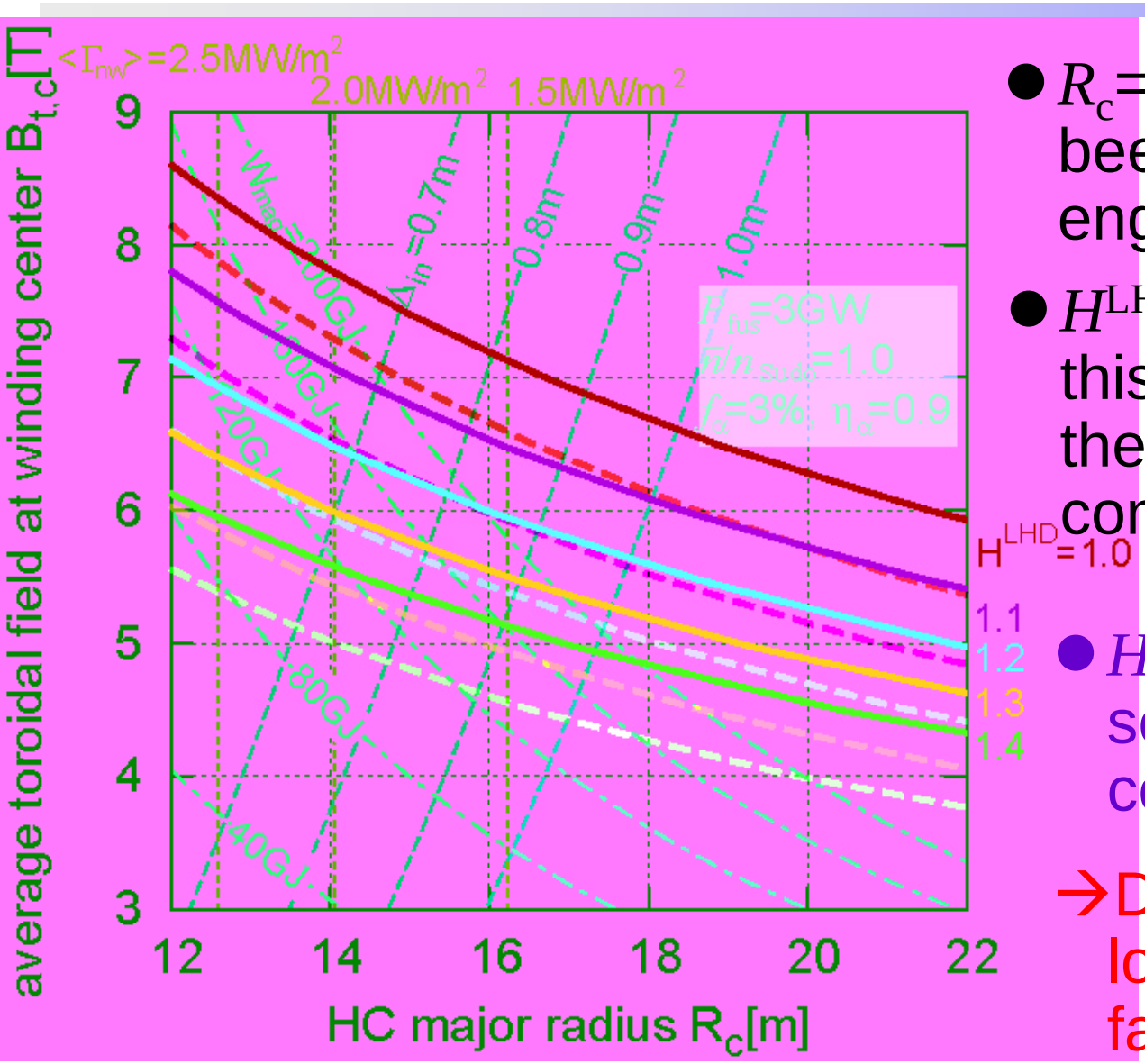
Physic conditions of FFHR-2m2

- Physics conditions:
  - Mainly based on LHD high-beta discharges
    - Inward-shifted magnetic axis position R_{ax}/R_c = 3.6/3.9
    - Helical pitch parameter γ=1.2 (plasma aspect ratio A_p ~ 6.3)
    - Density/temperature profiles as $n(\rho) = (1-\rho^2)^{\alpha_n}$, $T(\rho) = (1-\rho^2)^{\alpha_T}$ with α_n=0.25, α_T =0.75
  - Density limit: $\bar{n}_e \leq 1.5\, n_{\mathrm{sudo}}$
  - <u>Assuming</u> f_α=0.03 and η_α=0.9





Design point of FFHR-2m2



- R_c=17m, $B_{t,c}$=4.7T has been selected by engineering constraints
- H^{LHD}~1.3 can realize this design point with the assumed physics conditions
- H^{LHD} is quite sensitive to physics conditions

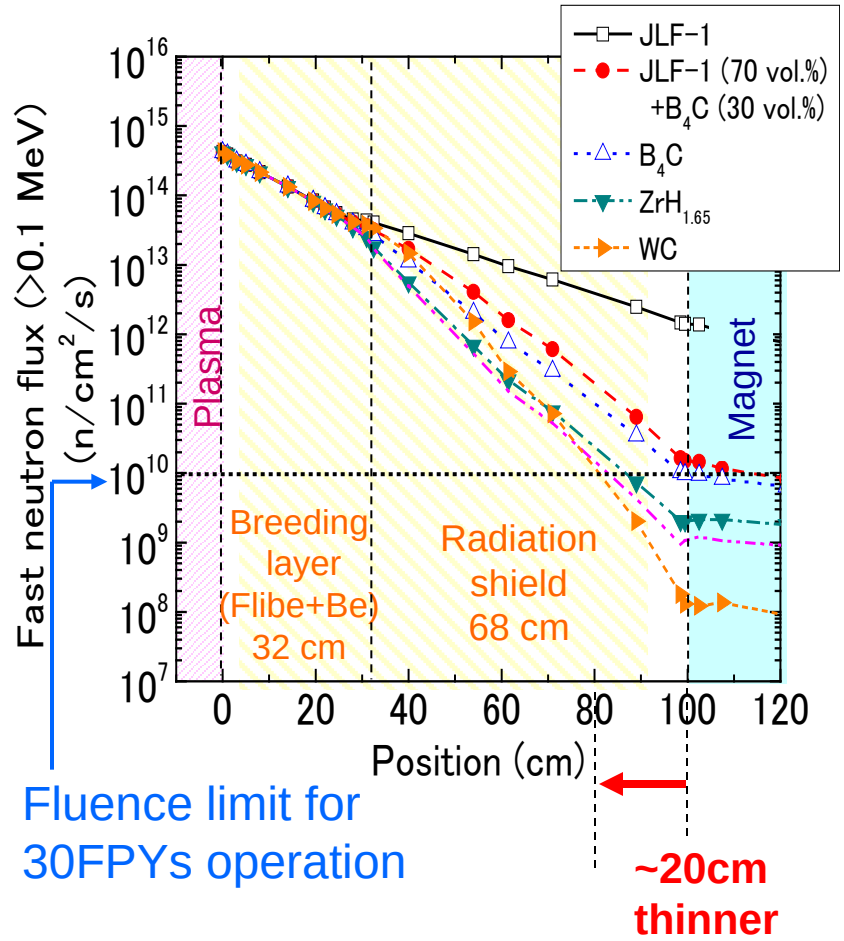
→Design point with lower H^{LHD} is favorable

Flexible DEMO design concept can reduce the minimum blanket space

- DEMO should demonstrate;
  - steady-state, self-ignition plasma operation and electric power generation
  - integrity of engineering components

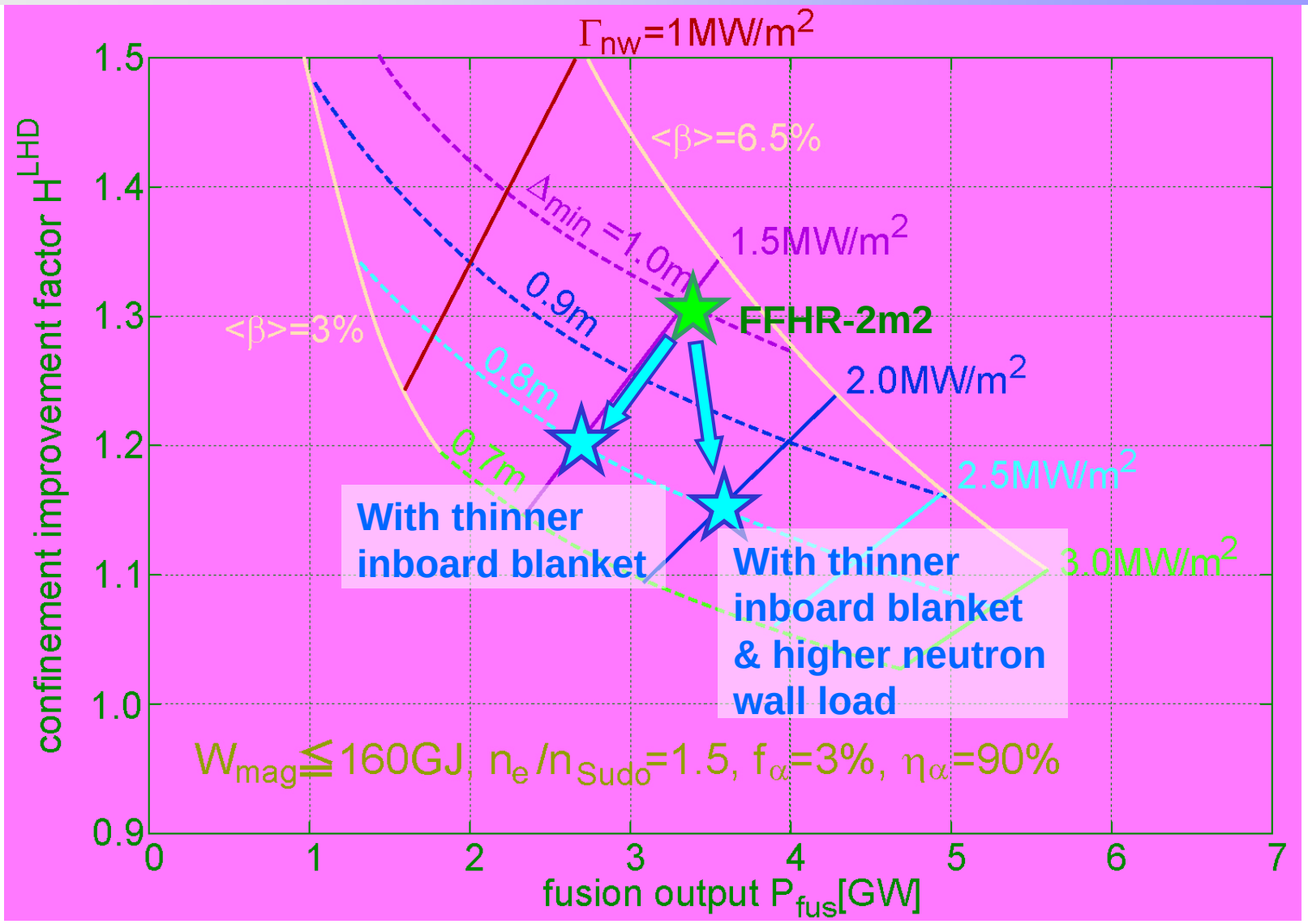
➔30FPYs operation is not needed and higher neutron flux can be accepted

- Thinner inboard blanket can be realized by
  - Using special material ($ZrH_{1.65}$, WC, etc)
  - accepting higher neutron flux on superconducting coil



Courtesy of Dr. Teruya Tanaka
(original figure is found in
A. Sagara *et al.*, FED **83**, 1690 (2008))

Reduction in inboard blanket thickness can expand design window



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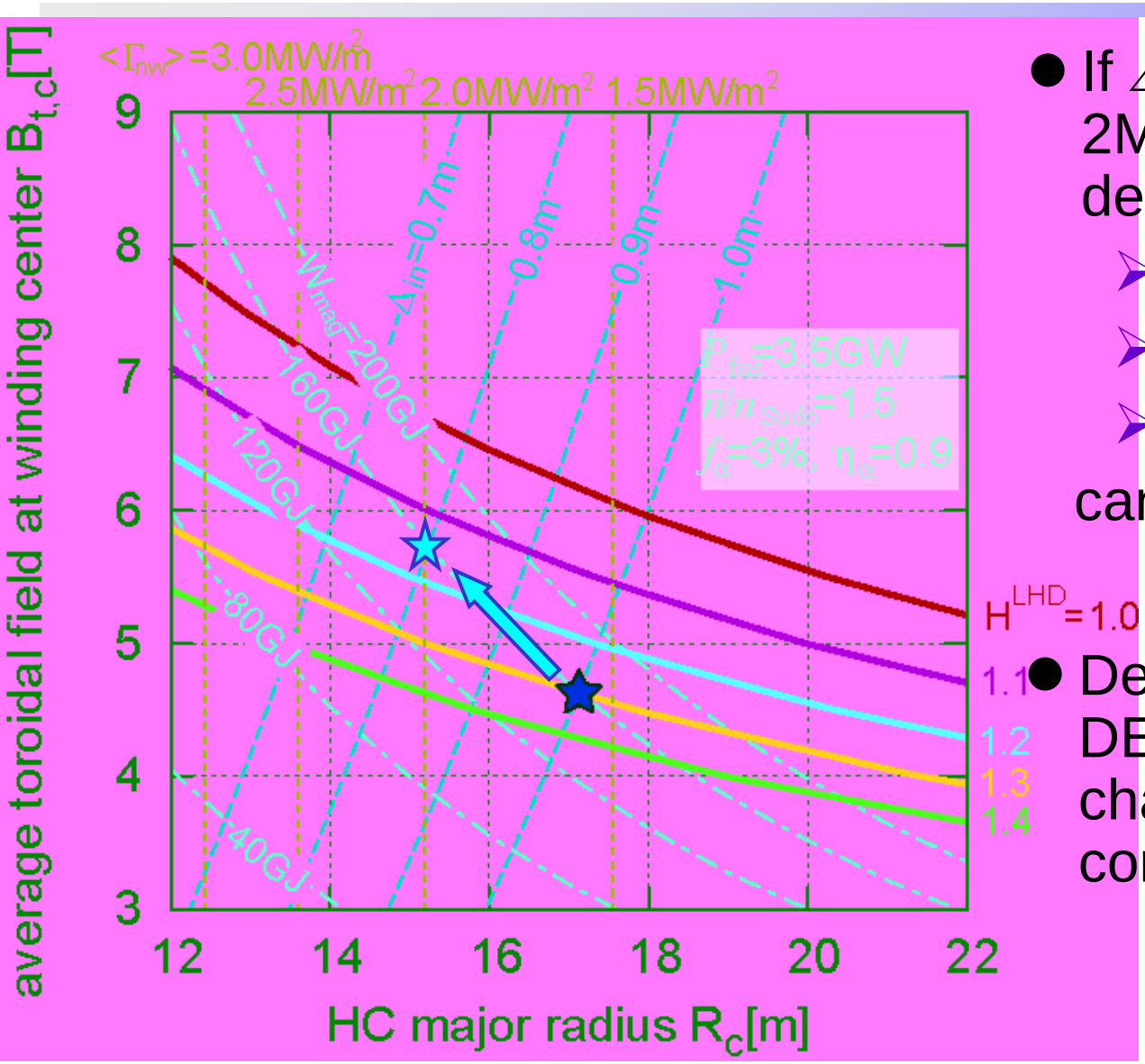


- If Δ_{in}=0.8m and $<\Gamma_{nw}>$ = 2MW/m^2 is accepted, design points with
  - R_c ~ 15 m
  - P_{fus} = 3.5 GW
  - H^{LHD} ~1.15

  can be selected

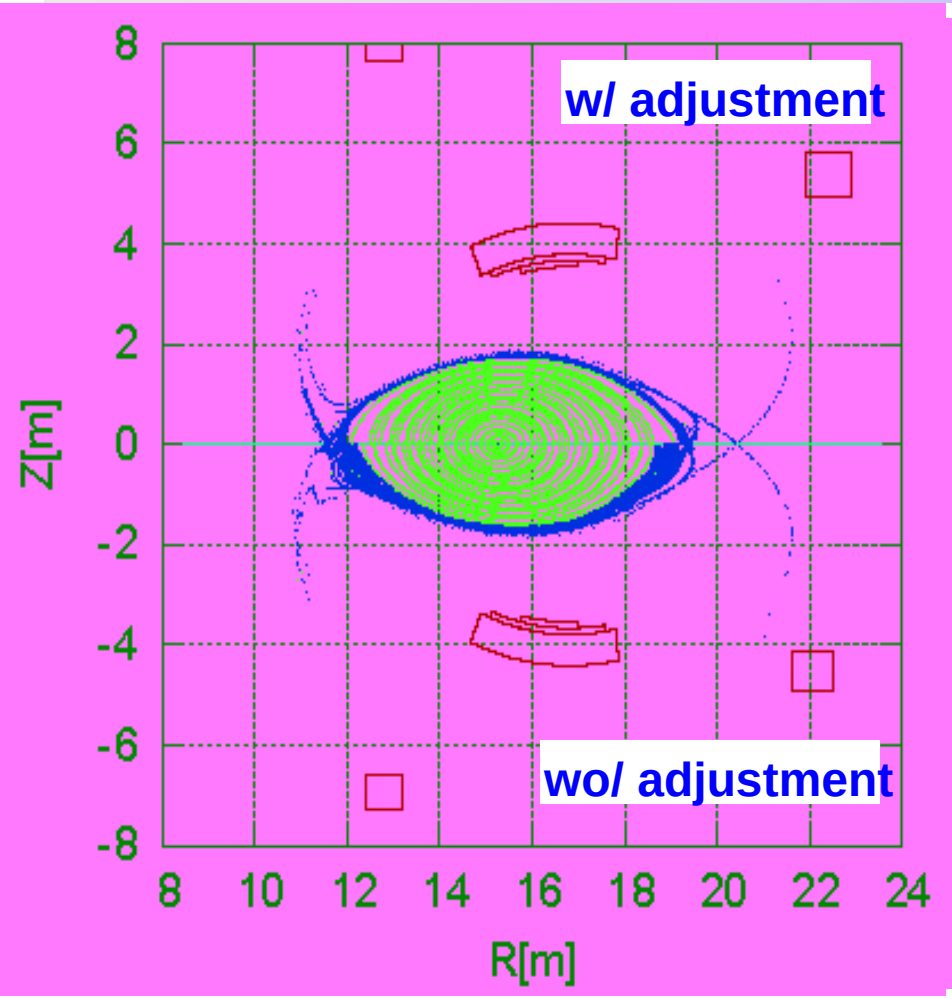
- Design robustness of DEMO reactor to the change in the physics conditions

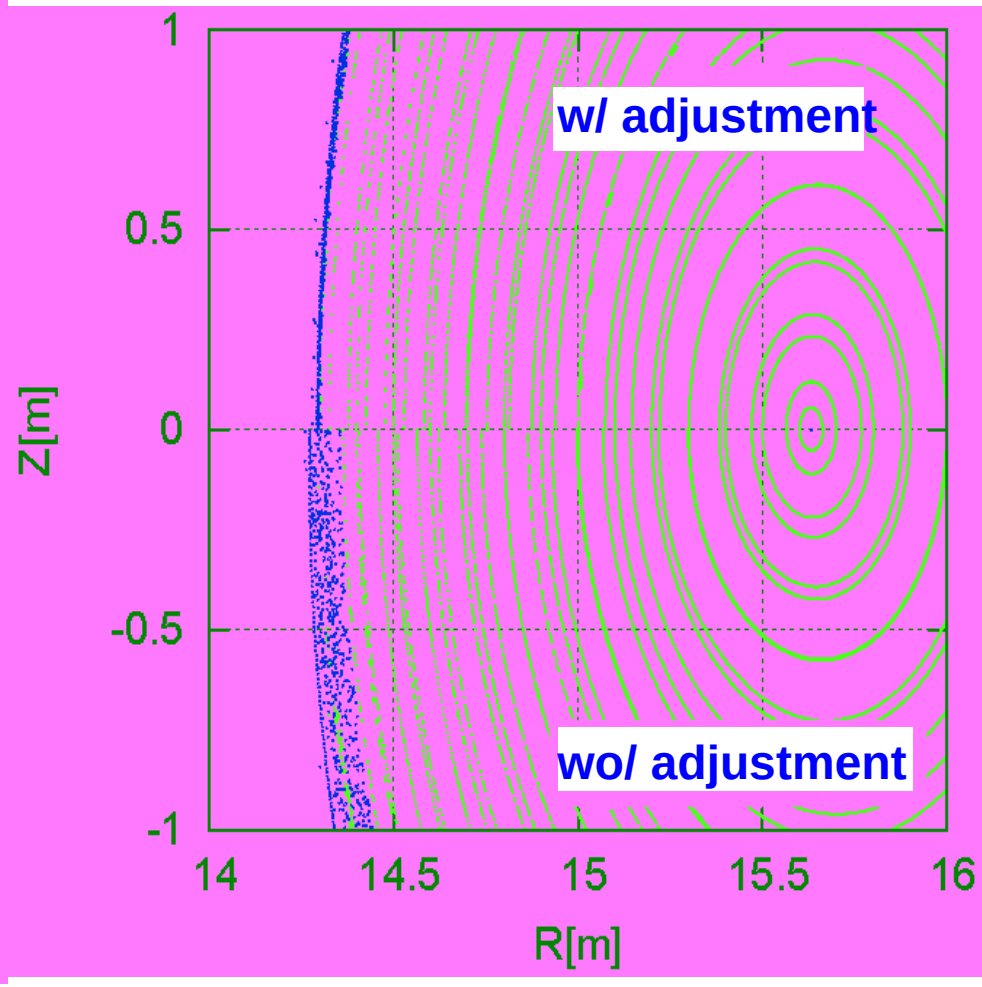
Summary

- Reduction in the minimum blanket thickness can greatly expand the design window
  - Major radius can be reduced by ~2m
    - give the robustness to the change in physics conditions
    - can adopt flexible magnetic configurations

- Progress in engineering research that enables the reduction of the minimum blanket space and acceptance of higher neutron wall load is expected.
- Larger confinement improvement is also expected to make DEMO and commercial reactors more economically attractive

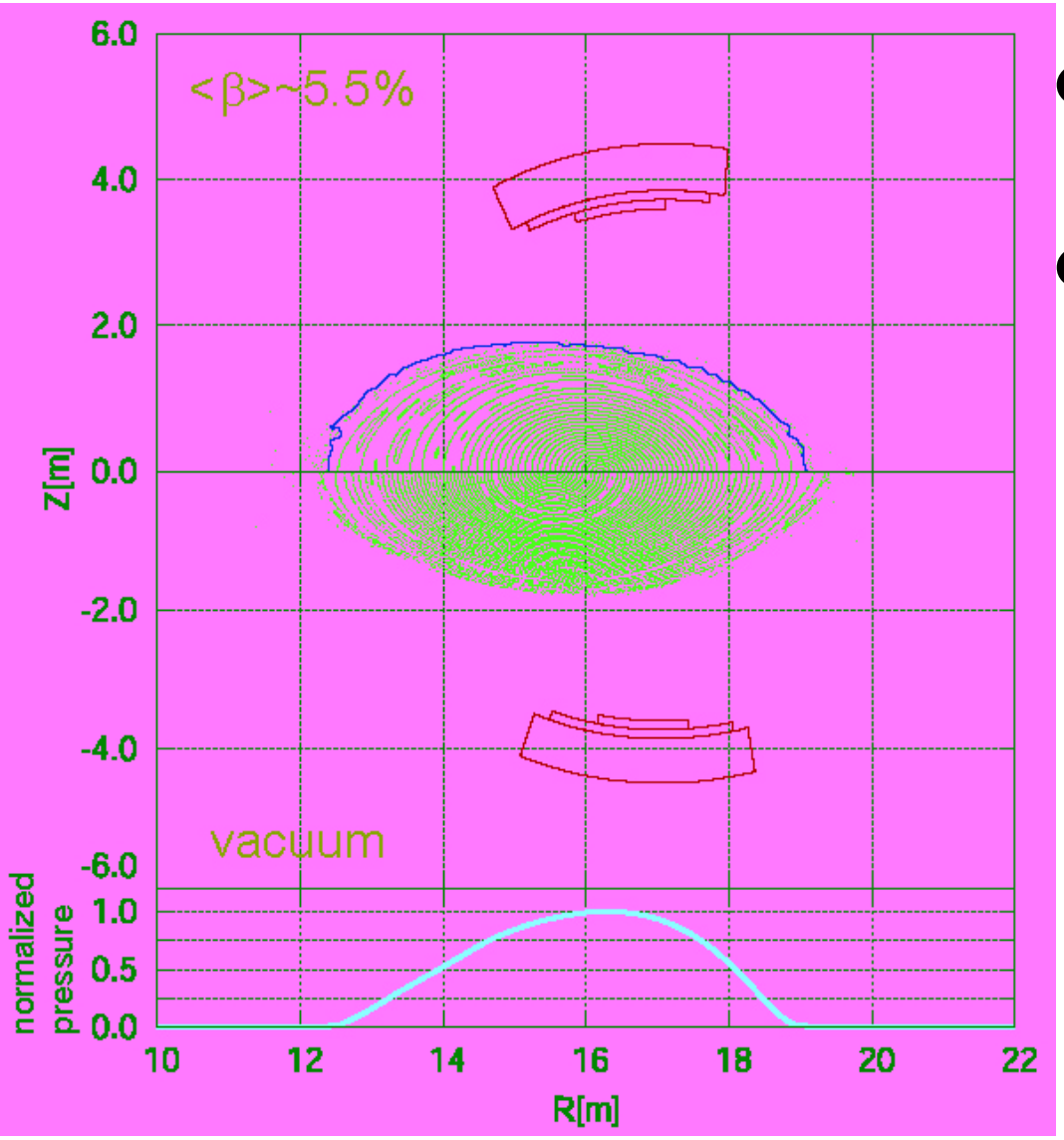
Adjustment of poloidal coil position





- Adjustment of poloidal coil position enables the increase of blanket space as well as increase of plasma volume（~22%）.

High-beta equilibrium analysis



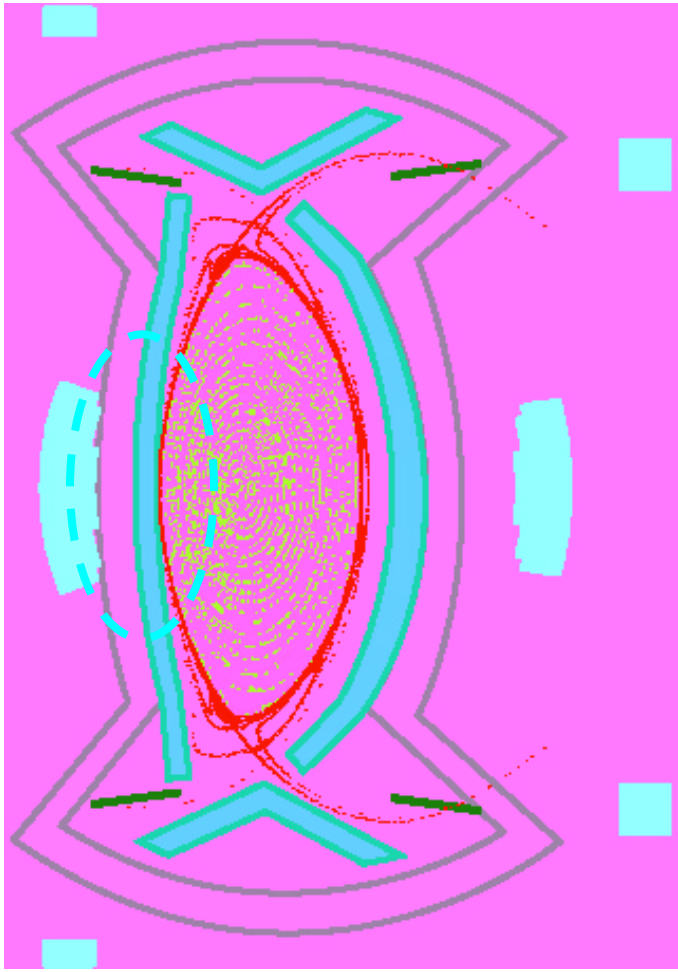
- Calculation by HINT2 code.
- <β>~6.5% equilibrium with the almost same volume as that in the vacuum condition can be obtained by applying an appropriate vertical field.

Courtesy of Dr. Yasuhiro Suzuki

Heliotron Reactor Design FFHR-2m2

- LHD-type Heliotron reactor which can be utilized as both a DEMO and commercial reactor

- Design policy:
  - P_{fus} = 3GWth ($P_{e,net}$ = 1GWe)
  - Long-term (~30 years) operation with high plant availability
  - Technology can be extrapolated from the present knowledge



Design constraints of FFHR-2m2

- Engineering constraints :
  - Magnet system based on the ITER-relevant technology
    - Helical coil current density: j_c=25 A/mm^2
    - Magnetic stored energy: $W_{mag} \leq 160$ GJ
  - Minimum blanket space: $\Delta_{min} \geq 1$m
    - *Assure the sufficient net TBR (>1.05)*
    - *Suppressing fast neutron fluence on SC coil <10^{22}n/cm^2 after 30FPY operation)*
  - Averaged neutron wall load: $<\Gamma_{nw}> \leq 1.5$ MW/m^2
    - *Suppressing neutron damage on the structural material <100dpa after 30 FPY operation with long-life blanket concepts*
- Physics condition :
  - Based on LHD high-beta discharges
  - Assuming $n_e \leq 1.5\, n_{sudo}$, f_α=0.03 and η_α=0.9.

3 Key Elements in the LHD-type Heliotron Reactor Designs

Increase in magnetic field strength vs. Reduction in stored magnetic energy

Maximization of plasma volume, Increase in output vs. Blanket space, Reduction of Wall and divertor loading

Plasma

- Beta value
- Confinement improvement

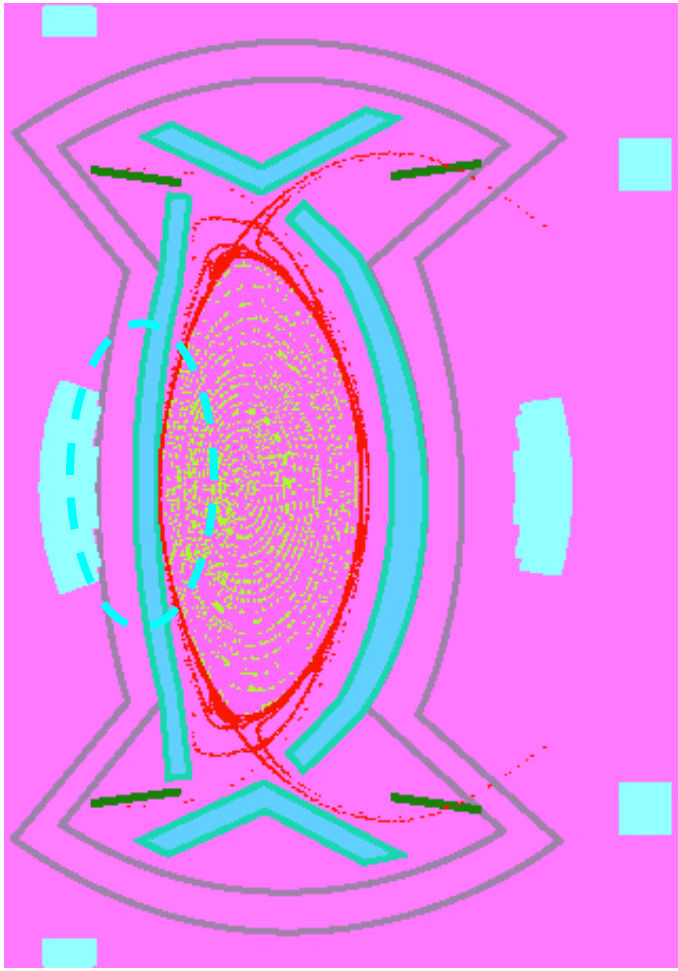
SC Coil

- Max. field on coil
- Coil current density
- Stored magnetic energy
- Neutron fluence
- Nuclear heating

Blanket/ Shield

- Neutron flux
- Thickness
- Materials

Increase in the coil cross-sectional area vs. Blanket space



- System analysis is necessary to identify design window.