Current drive system of SlimCS on the basis of current ramp scenario

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1. Introduction

Fusion DEMO design at JAEA directs toward compactness of the reactor with the fusion output of 3 GW level.

A small CS has a large impact on reducing the reactor size. The CS can not ramp-up to the flat top of plasma current (Ip).

Candidate of current drive(CD):

Neutral beam injection (NBI) and electron cyclotron wave (ECW)

Merit of use of ECW compared with NBI

- Easy transportation by a wave-guide
- Easy equipment of a shield
- Widely permissable location of port
- High locality of CD profile
- Easy maintenance

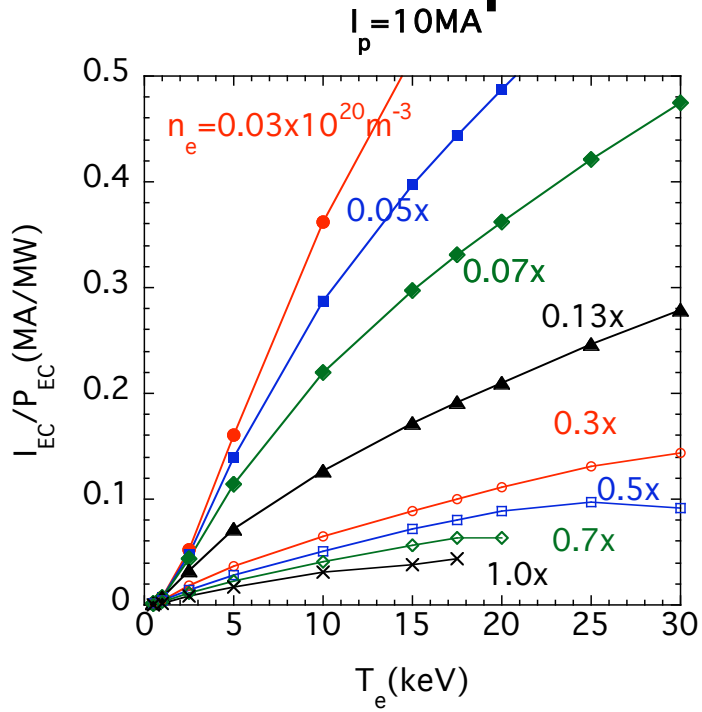
NBI & ECW are compared from viewpoints of CD efficiency, Ip ramp-up scenari, & necessary power.

	DEMO
Rp(m)	5.5
a(m)	2.1
A	2.6
κ	2.0
δ	0.44
Bt/Bmax(T)	6.0/16.4
Ip(MA)	16.6
q_{95}	5.6
β_N	4.3
I_{bs}/I_p	78%
HH	1.3
n/n_{GW}	0.98
P_{fus}	3.0
$P_n(MW/m^2)$	3.5
Q(NBI/EC)	52/27
Weight(tons)	17,500

2.1 I_{EC} /P_{EC}

- ACCOME(Analyzer for Current Drive Consistent with MHD Equilibrium)
- EC ray trace code
  - Dispersion relation: Cold plasma approximation.
  - Wave damping : Weakly relativistic Maxwellian plasma
  - Driven current: Linearized relativistic Fokker-Planck eq.
- High I_{EC} /P_{EC} in low n_e & high T_e

⇨ Low n_e & high T_e approach



2.2 I_{CD}/P_{CD}

I_{CD}/P_{CD} at the steady state fusion reaction (Ip=16.7MA, T_e=17.5keV, n_e=1.18 x$10^{20}m^{-3}$)

$I_{Bootstrap}$ /Ip = 78%

NBI (Mikkelsen formula)

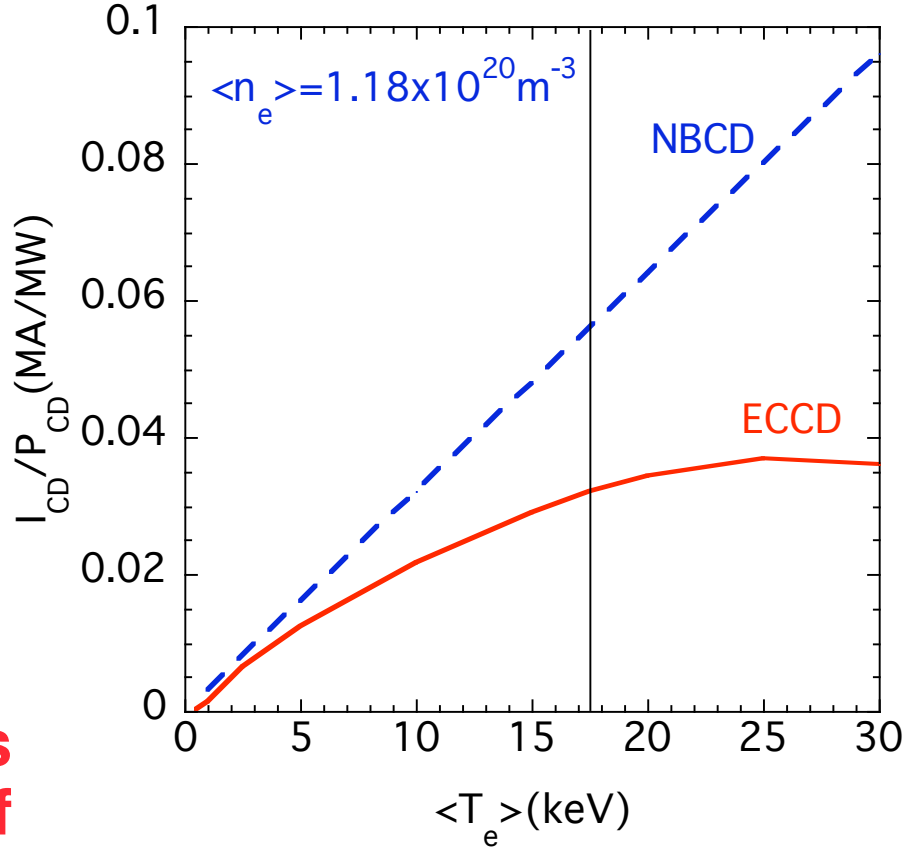
- **P_{NBI}=60MW is needed.**

ECW

- **P_{ECW}=115MW is needed.**

- **I_{CD}/P_{CD} in the case of ECW is about half of that in the case of NBI at the steady state fusion reaction.**

P_{fus}=3GW



3.1 Constraint for plasma region

Plasma operational parameters during I_p ramp-up are limited from the plasma requirements in DEMO reactor.

Plasma performance

- $n_e \leq n_{GW}$ ($10^{20}m^{-3}$) $\equiv I_p$ (MA)/(πa^2)
  n_{GW} :Greenwald density limit
  $f_{GW} \equiv n_e/n_{GW} \leq 1$
- HH factor ≤1.3 at $n_e = n_{GW}$

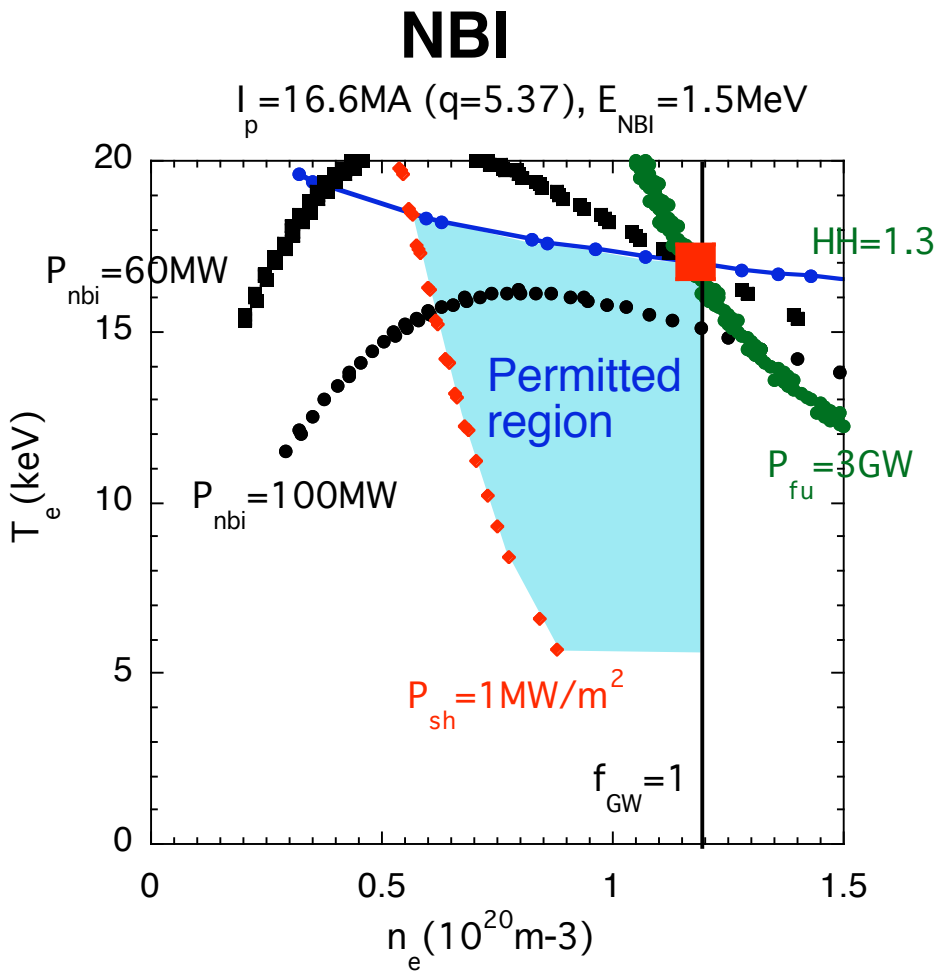
Equilibrium condition

- $\beta_p \varepsilon \leq 1$

Guard of first wall (Only for NBI)

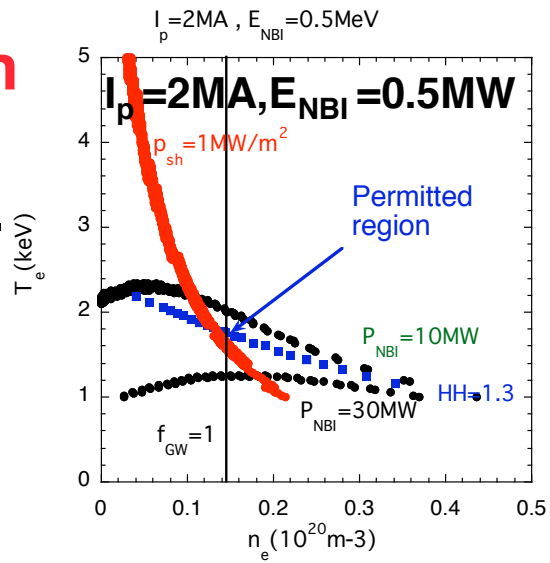
- Shine through of NBI
  p_{sh} <1.0~2.0 MW/m^2,
  p_{rad} ~0.5 MW/m^2 , $p_{total} = p_{sh} + p_{rad}$

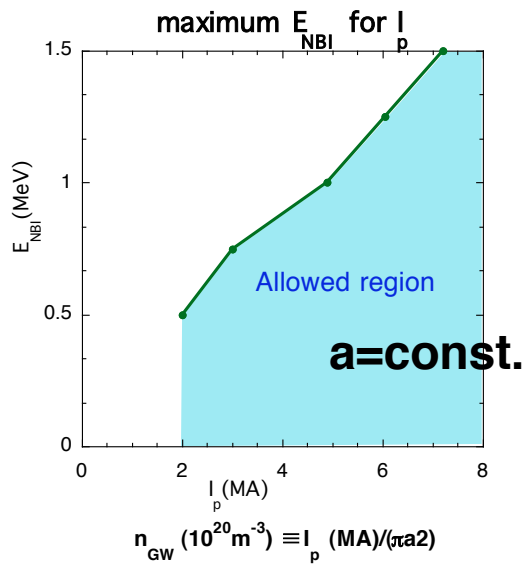
→ Permitted plasma region in popcon diagram



3.1 Constraint for E_{NBI}

- **Plasma requirements result in the constraint for E_{NBI} & P_{NBI}.**
  - **Ex. $E_{NBI} \leq 0.5$ MeV for I_p = 2MA.**





<u>E_{NBI} for steady state</u>.

- **In the final state of P_{fus}=3GW, NBI system efficiency is good for $E_{NBI} \leq 1.5$ MeV.**

Maximum E_{NBI} is selected to be 1.5MeV.

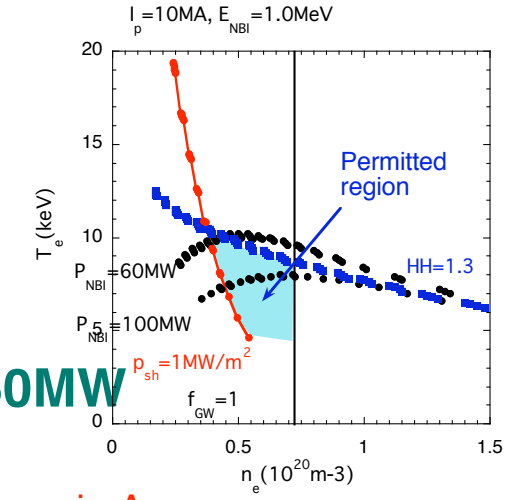
So, E_{NBI} is required to be changed in the more than two stages.

- **In order to inject sufficient power in the low E_{NBI} phase, a new technology Constant Current Variable Voltage (CCVV ($P_{NBI} \propto E_{NBI}$))for changing E_{NBI} is necessary, instead of the present technology (Perveance Match ($P_{NBI} \propto E_{NBI}^{5/2}$)).**

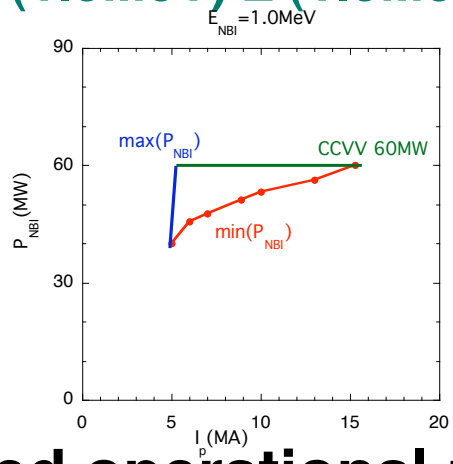
3.3 Constraint for P_{NBI}

Power constraints

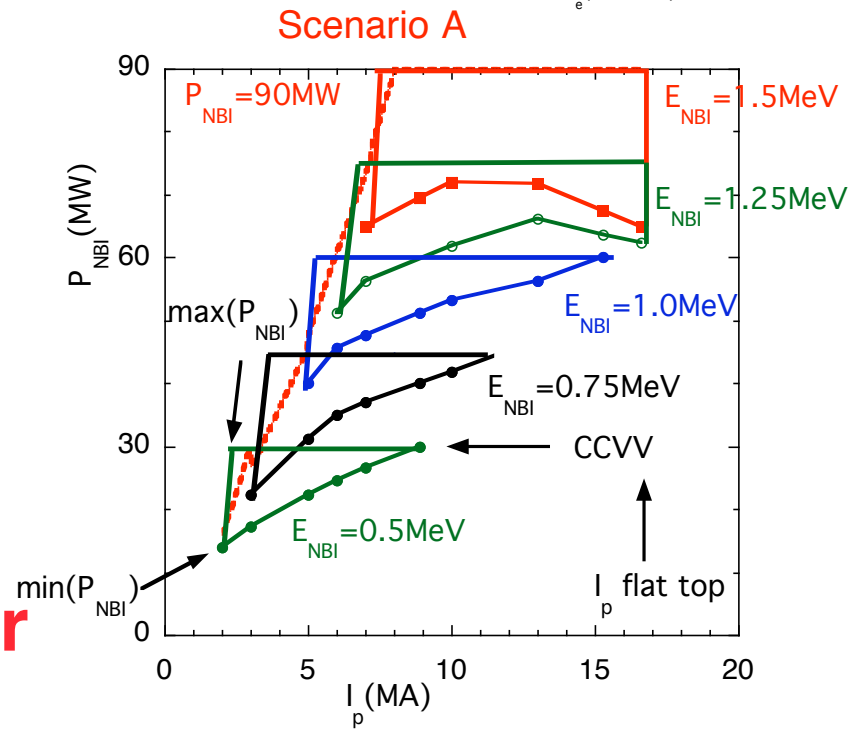
- **Plasma Requirements**
  - min (P_{NBI}) ~ HH factor =1.3 & P_{sh} =1MW/m^2
  - max (P_{NBI}) => f_{GW} =1 & P_{sh} =1MW/m^2
- **Requirement from CCVV ($P_{NBI} \propto E_{NBI}$)**
  - P_{NBI} (1.0MeV) ≤ (1.0MeV/1.5MeV) * max(P_{NBI} (1.5MeV))=60MW



90MW



- **Allowed operational region of NBI parameters (E_{NBI} & P_{NBI}) depends on the I_p.**
- **There is no critical constraint for ECW.**



4 Calculation method

I_p ramp-up scenario is evaluated by using circuits eq.

<u>Basic equation</u>

Calculation of I_p by NBCD, ECCD and Bootstrap current.

$$\frac{dI_p}{dt} = \frac{R_\Omega}{L_p}\left(I_{BS}+I_{NB}+I_{EC}-I_p\right) + 2\frac{d(I_{BS}+I_{NB}+I_{EC})}{dt}$$

I_p:Plasma current, I_{BS} : bootstrap current, I_{NB}:NBCD,

I_{EC}:ECCD, R_Ω:Resistivity, L_p:Inductance

I_{NB}:Mikkelsen formula

$$I_{NB}/P_{NB} = 2.675\, C_p (R_{tang}/R_p)\ Z_p (1-f_s)(T_e/n_{20}) J_b(x,y)\ \{1-F(Z_b, Z_{eff}, \varepsilon)\}$$

I_{EC}: ACCOME results

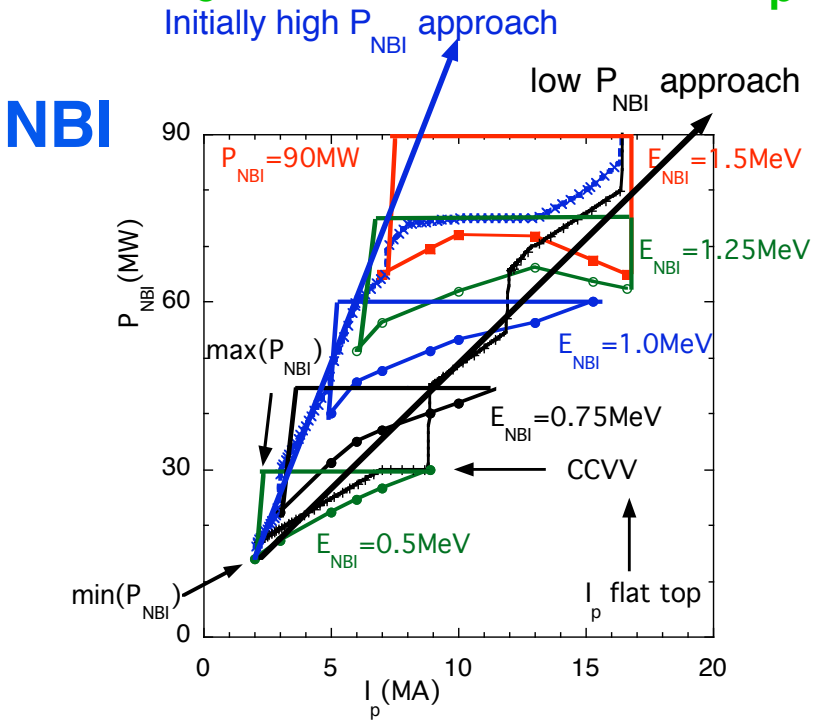
I_{BS}: $I_{BS}/I_p = C_{BS}\,(\varepsilon^{0.5}\beta_p^*)^{1.3}$

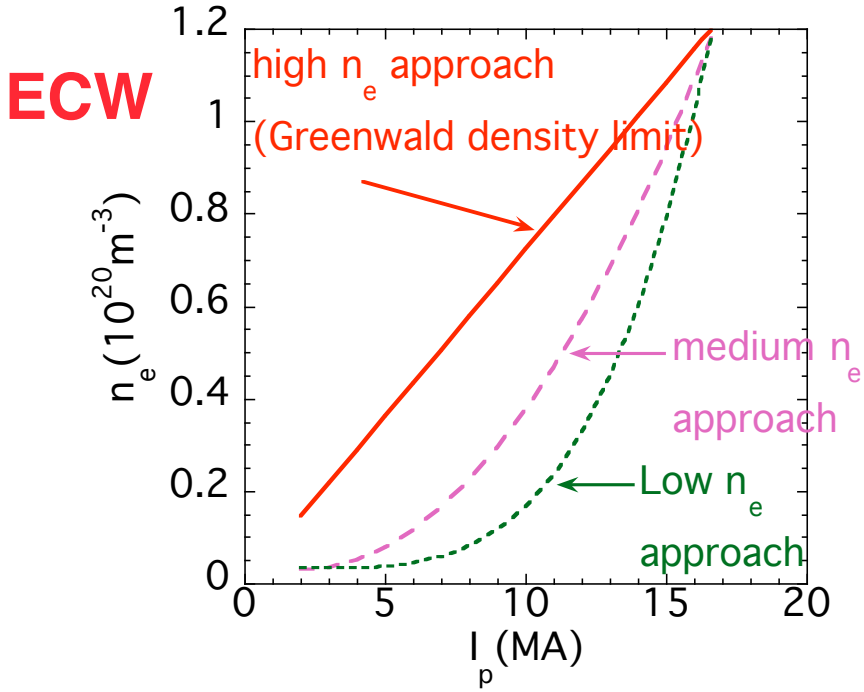
n_e, T_e:Stationary solution in 0-D particle & power balance eqs.

I_p is assumed to be ramped up to 2MA by the CS.

5.1 I_p ramp-up scenario

- **NBI**
  - Initially high P_{NBI} approach in low I_p ~ f_{GW}=1 & P_{sh}~1MW/m^2
  - Initially low P_{NBI} approach in low I_p ~ HH=1.3 & P_{sh}~1MW/m^2
- **ECW**
  - High n_e approach in low I_p (Greenwald density limit)
  - medium n_e approach in low I_p
  - Low n_e approach in low I_p -> High I_{EC} /P_{EC}





Final state of P_{fus} = 3GW from 2MA can be reached in both NBI & ECW scenarios.

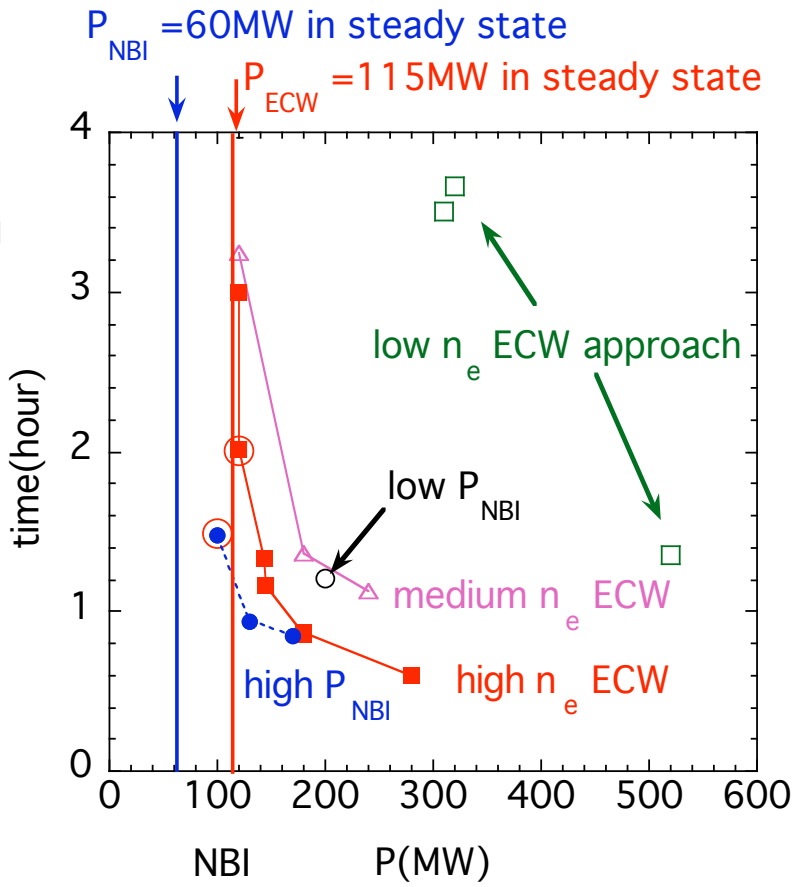
NBI

- Lower power and shorter time are needed in the NBI cases compare with ECW cases.
- Initially high power approach is a candidate.
- P_{NBI} =100MW is needed. P_{steady}=60MW

ECW

- There are many candidates for scenarios due to the small constraint for P_{ECW}.
- Initially high density approach is a candidate.
- P_{ECW} =120MW is needed.

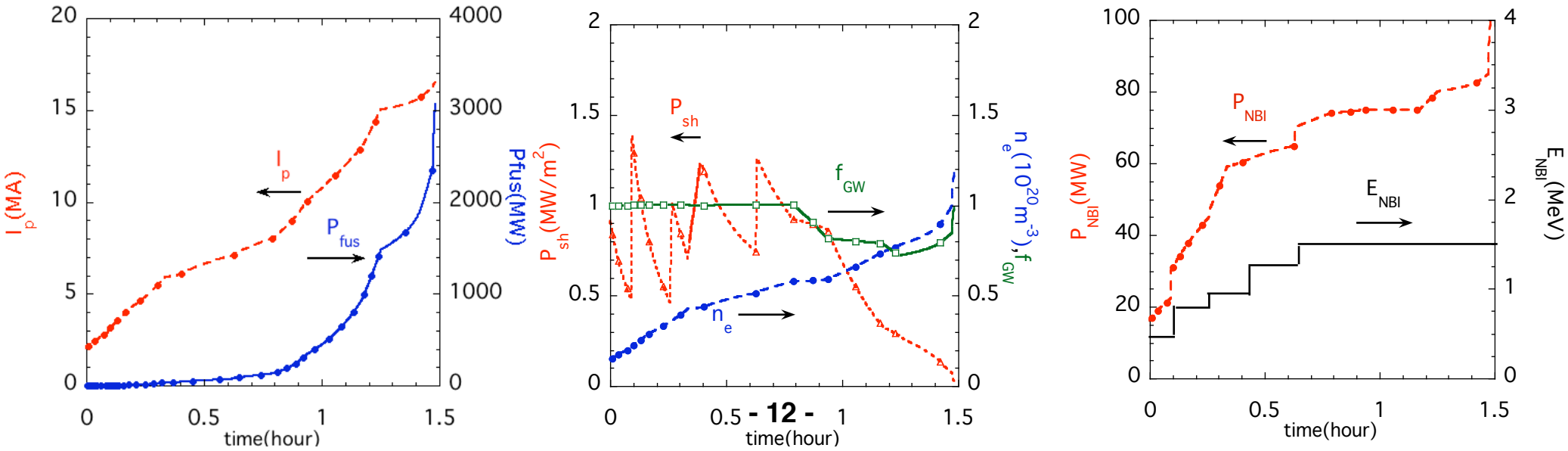
  ~ P_{steady}=115MW



5.2 I_p ramp-up scenario (NBI)

Initially high P_{NBI} approach (high n_e approach)

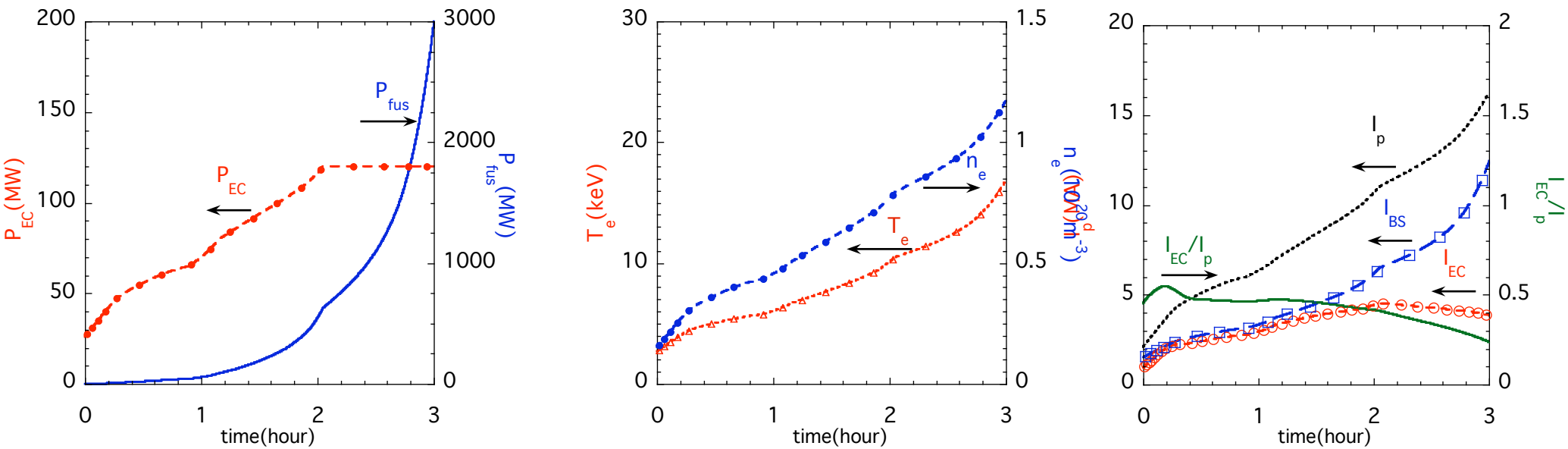
- **Final state can be reached by changing E_{NBI} using CCVV method ($P_{NBI} \propto E_{NBI}$). E_{NBI}=0.5MeV→0.75MeV→1MeV→ 1.25MeV→1.5MeV.**
- **There are strong constraints of shine through& changing E_{NBI}.**
- **max(p_{sh}) = 1.4MW/m^2, P_{NBI} (1.5MeV) = 100MW**
- **It takes 1.5 hours to reach the final state from 2MA.**



5.3 I_p ramp-up scenario (ECW)

Initially high n_e approach(Greenwald density limit)

- **Needed power is about 120MW due to the low ECCD fraction (I_{EC}/I_p) during ramp-up phase.**
  - **$I_{EC}/I_p \leq 50\%$ @ I_p=2MA->16.7MA**
- **It takes 3 hours to reach the final state from 2MA.**
- ***There is a possibility of I_p ramp-up by ECW at DEMO plant.***



6. Layout plan for ECW

Assumption

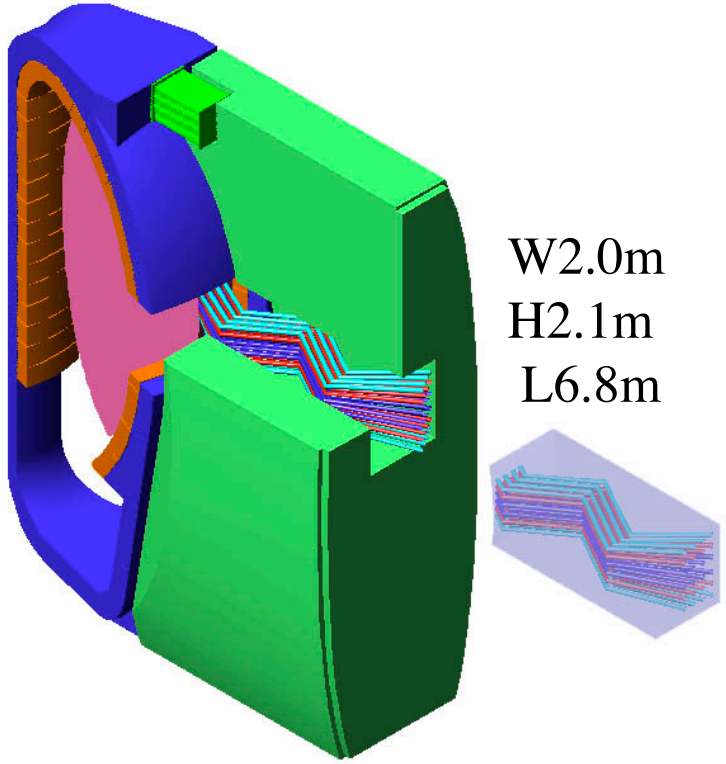
- n flux(at window) / n flux(at first wall) ≤ 10^{-6} for DEMO (= 10^{-4} for ITER)
- Power density(DEMO) = 2 x Power density(ITER)
  - 2MW/ Gyrotron

Specifications

- Total power:150MW, 50MW/unit
- 3 Units are located in 3 toroidal sections.
- WG, Mirror, window: water cooling.

Maintenance

- ECW unit: a removable assembly.



7. Summary

- Current drive methods are evaluated for SlimCS DEMO reactor at JAEA.
- Two candidates of NBI & ECW are compared from viewpoints of current ramp-up scenario, CD efficiency & necessary power.
- HH factor & Greenwald density limit affect on the current ramp-up scenario.
- Final state of P_{fus} = 3GW from 2MA can be reached in the cases of NBI (P_{NBI}=100MW) and ECW (P_{ECW}=120MW).
- I_{CD}/P_{CD} in the case of ECW is about half of that in the case of NBI at the steady state fusion reaction.

NBI

- Since the shine through condition is added, there is strong constraint for ramp-up scenario.
- Final state of P_{fus} = 3GW from 2MA can be reached by changing E_{NBI} using CCVV method ($P_{NBI} \propto E_{NBI}$).
- Initially high power approach is the candidate.

ECW

- Although CD efficiency is lower than that in the NBI case, there is flexibility of current ramp-up scenario.
- Moreover, there is merits of easy maintenance, high CD locality etc. So, ECW should be adopted as main CD method in SlimCS DEMO Plant at JAEA.
- Initially high density approach is the candidate.