Plasma Current: Start-up and Ohmic Heating

- How to make required plasma current?
  - Start-up
  - Ohmic heating and current drive

- Tokamak start-up and Ohmic heating
  - ✓ Ohmic solenoid start-up
  - ✓ Solenoid-free start-up
  - ✓ Ohmic heating and current drive

Ohmic Solenoid Start-up

- Ohmic solenoid start-up
  - Ohmic breakdown and pre-ionization
  - Closed flux surface formation: field null and trapped particle configurations
  - Plasma current ramp-up and volt-second consumption

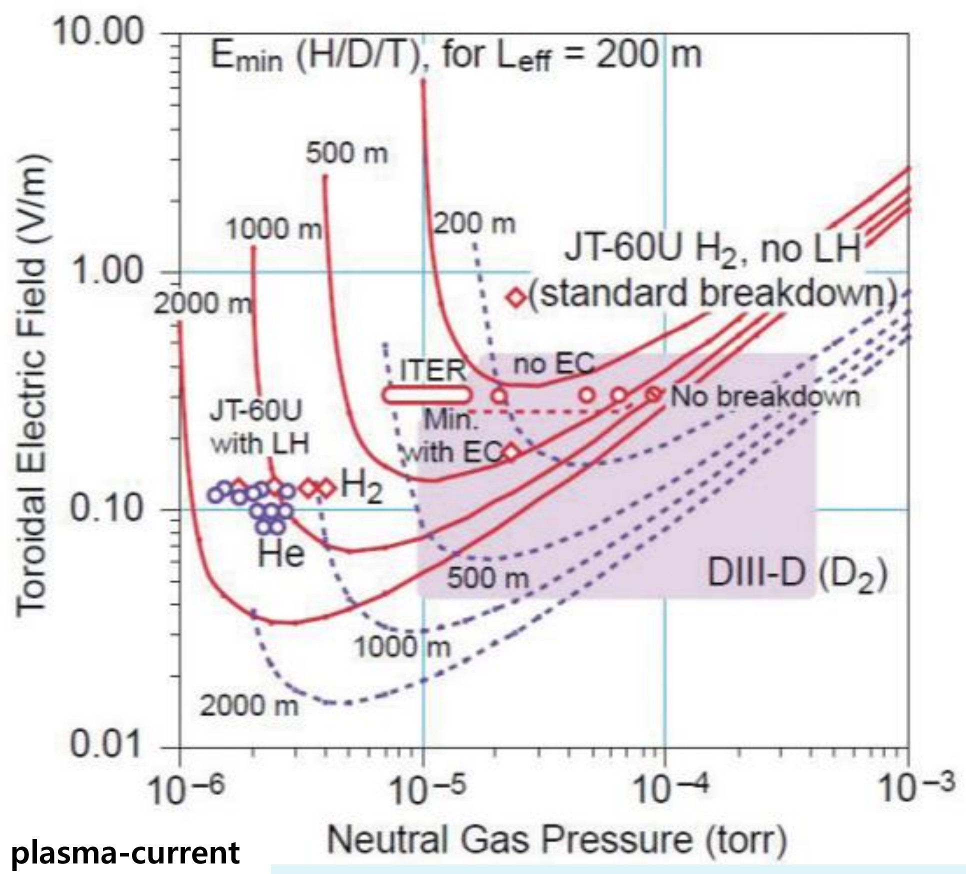
Gas breakdown condition and loop voltage

✓ Townsend Avalanche
✓ Magnetic Connection Length

$$E_{min}(V/m) = 1.25\times10^{-4}\, p(Torr)/ \ln[510\, p(Torr)\, L\, (m)]$$

Pre-ionization

✓ Electron cyclotron heating:
low-pressure resonant heating
enhanced particle trapping with mirror field
✓ Low loop voltage breakdown feasible



R. Yoshino, M. Seki, "Low electric field (0.08 Vm-1) plasma-current start-up in JT-60U", Plasma Phys. Control. Fusion 39 (1997) 205

Ohmic Solenoid Start-up

- **Ohmic solenoid start-up**
  - Ohmic breakdown and pre-ionization
  - **Closed flux surface formation: field null and trapped particle configurations**
  - Plasma current ramp-up and volt-second consumption

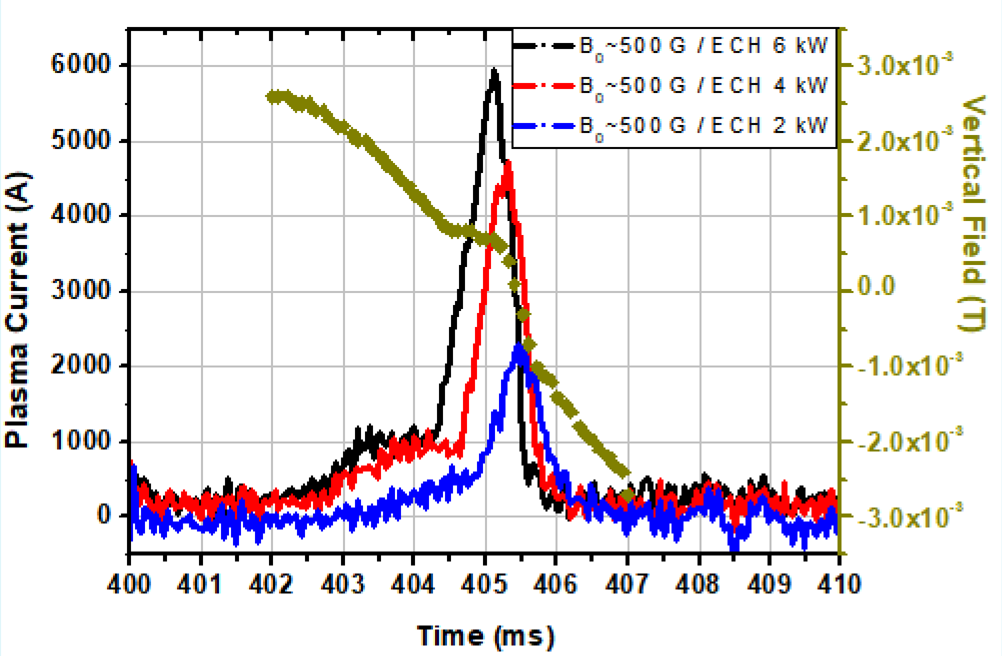
Close flux surface formation

✓ **Successful ohmic start-up at low loop voltage depends on vertical field strength, loop voltage, and plasma resistivity**

✓ **Close flux formation criterion can be set simply by finding when poloidal field from initial current exceeds vertical field**

$B_v\,(G) < B_p = 2 * I_p(kA) / a(m)$

$$\frac{E_t a}{B_v \rho} > 1.6 \times 10^2 \;\left[\frac{V}{G\,\Omega m}\right]$$



To lower resistivity for low loop voltage start-up,

✓ Large loop voltage with small stray field

✓ Impurity burn-through (heating power or wall isolation)

✓ Effective pre-ionization: trapped particle configuration

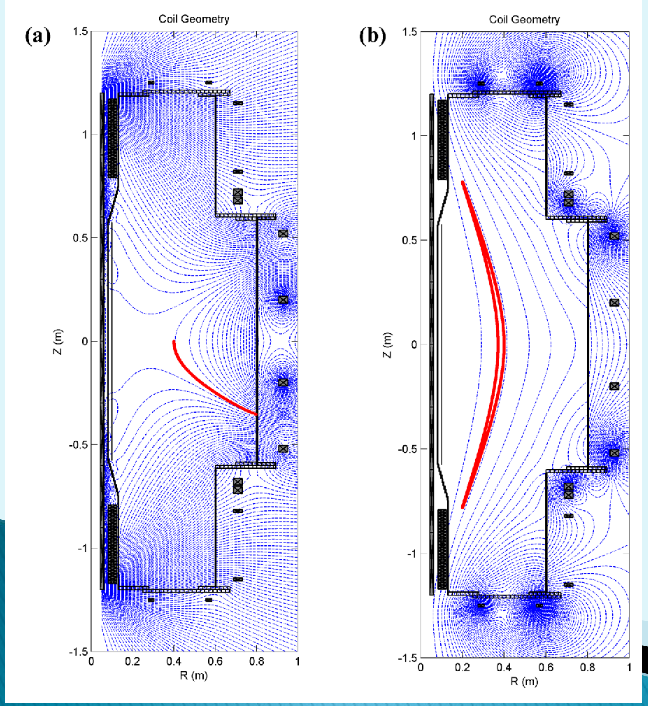
Ohmic Solenoid Start-up

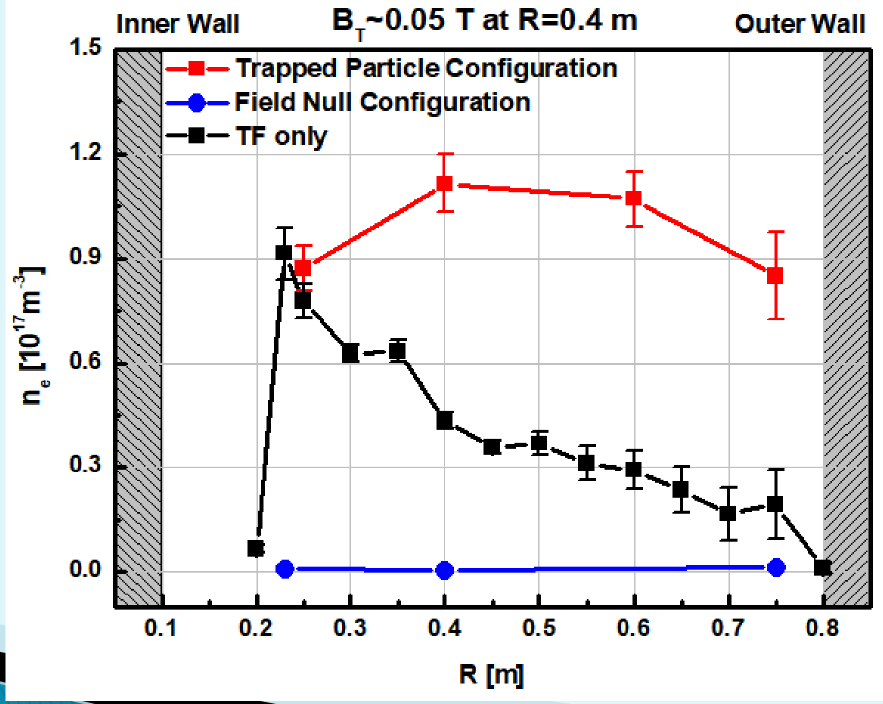
Y. An *et al.*, *Nucl. Fusion* 57 016001 (2017)

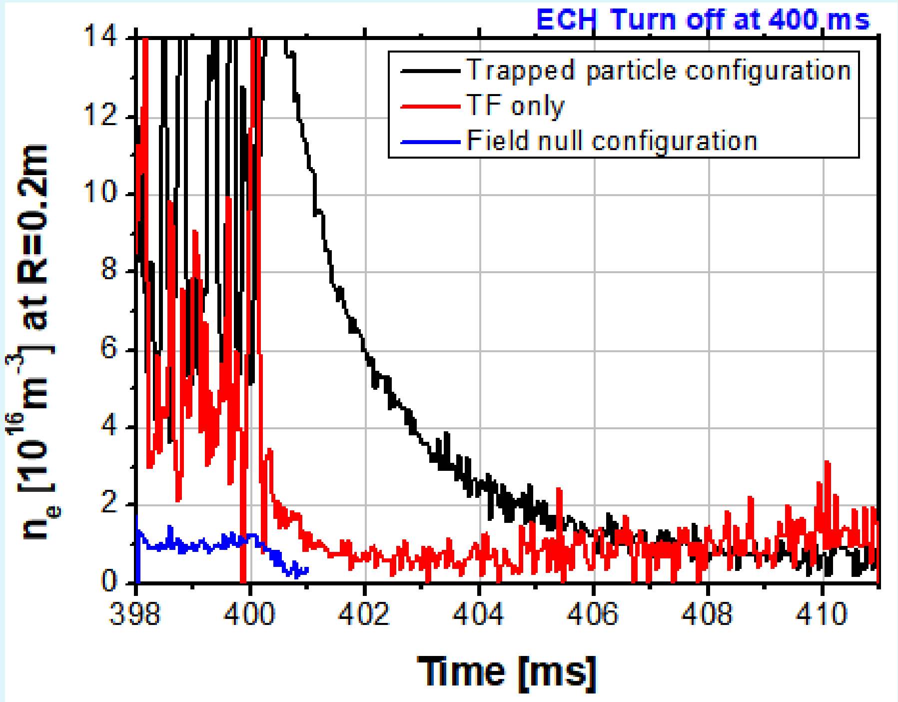
- **Ohmic solenoid start-up**
  - Ohmic breakdown and pre-ionization
  - Closed flux surface formation: field null and trapped particle configurations
  - Plasma current ramp-up and volt-second consumption

Field Null and Trapped Particle Configurations (FNC & TPC)

Large-size high-density plasma formation with TPC effectively

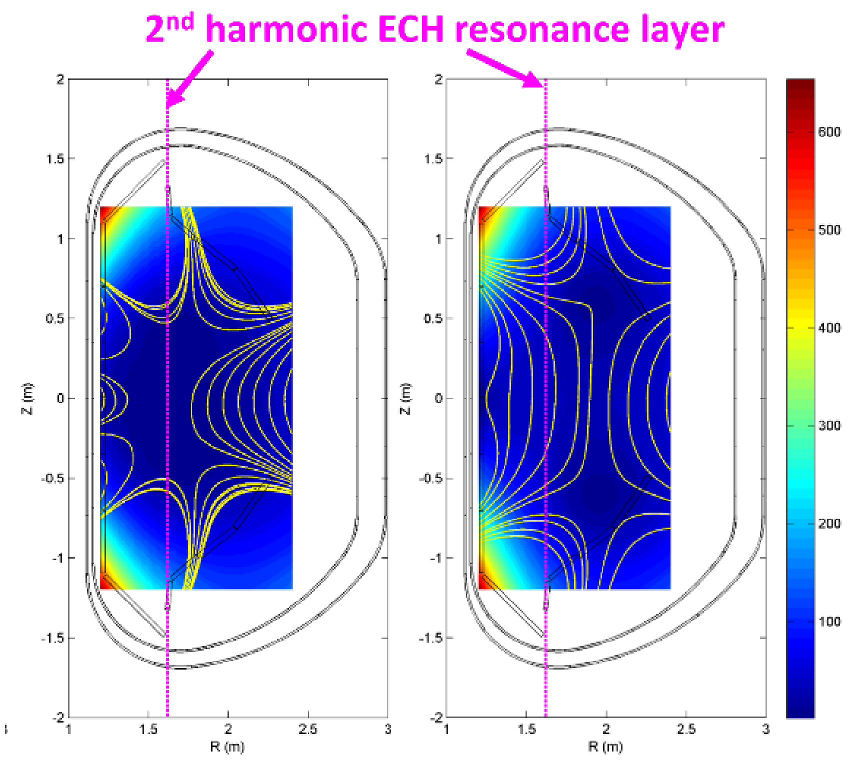






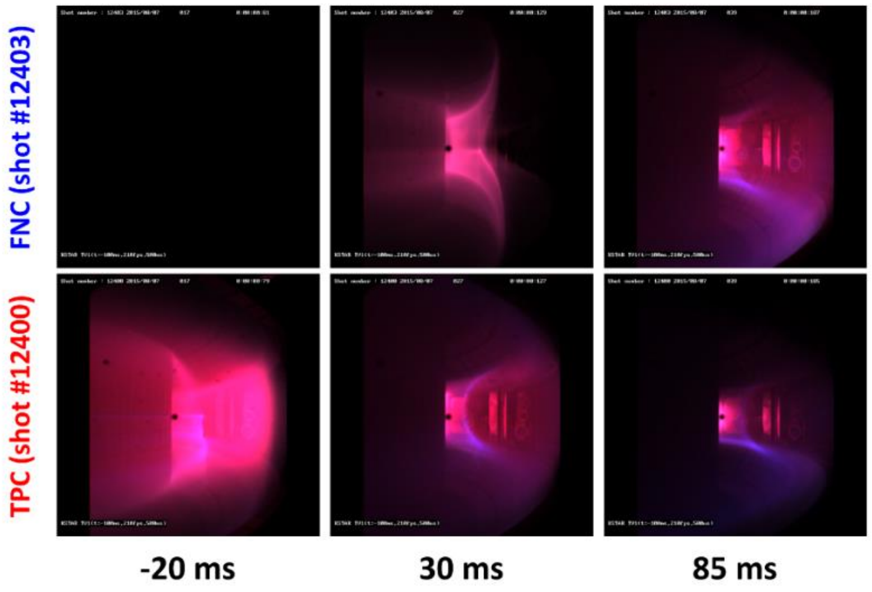
Robust and Reliable TPC Start-up Applied to KSTAR Successfully

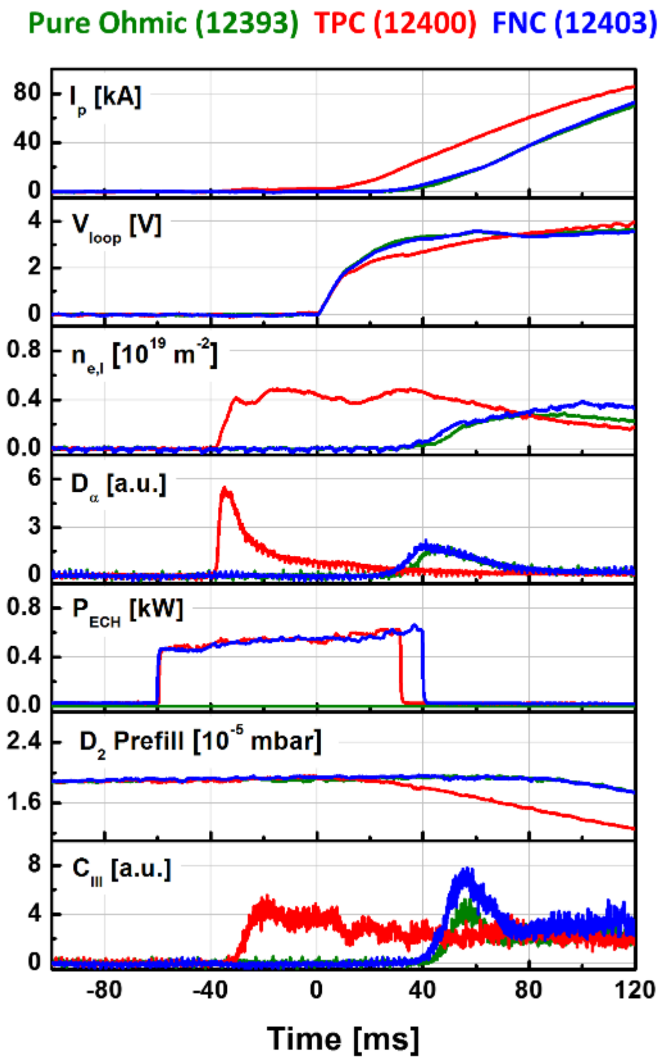
J.W. Lee *et al., Nucl. Fusion* 57, 126033 (2017)



Reference field null   Reference TPC

Earlier plasma column formation than field null





- **Feasibility study of TPC in *KSTAR***
  - Even though low mirror ratio than ST, achieving efficient start-up with TPC
  - 2nd harmonic delay of 20 ms and ECH plasma density of 4×10^{18} m^{-2}
  - I_p formation with low E_t *less than 0.2 V/m*

In collaboration with NFRI National Fusion Research Institute

Ohmic Solenoid Start-up

- **Ohmic solenoid start-up**
  - Ohmic breakdown and pre-ionization
  - Closed flux surface formation: field null and trapped particle configurations
  - **Plasma current ramp-up and volt-second consumption**

Plasma current ramp-up

$$L_p \frac{dI_p}{dt} = V_l - I_p \left(\frac{dL_p}{dt} + R_p \right) > 0$$

High aspect ratio

$$L_p = \mu_o R_o \left(\ln \frac{8R_o}{a} + \frac{l_i}{2} - 2 \right)$$

$$\frac{dR_o}{dt} < 0 \rightarrow \frac{dL_p}{dt} < 0$$

Volt-second consumptions

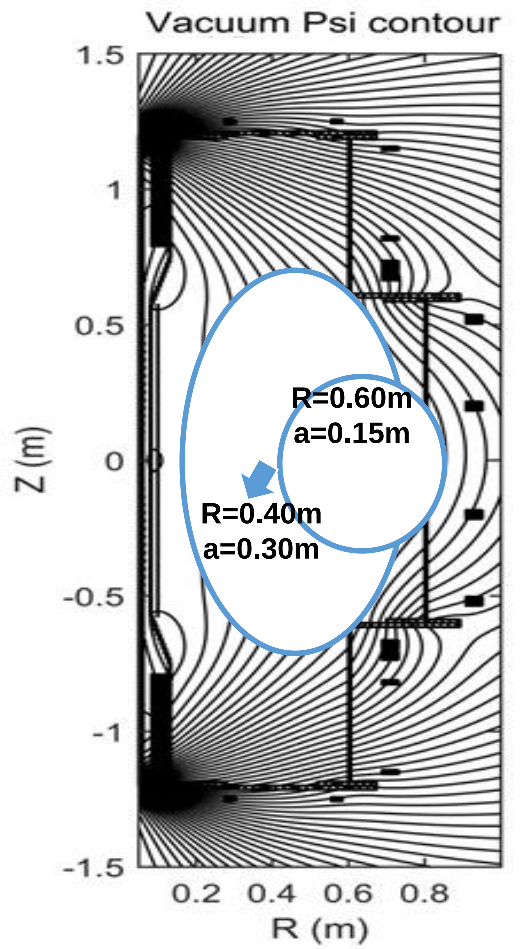
$$\int V_l dt = \int R_p I_p dt + \int \left(L_p \frac{dI_p}{dt} + I_p \frac{dL_p}{dt} \right) dt$$

$$= C_E \mu_o R I_p + L_p I_p$$

Ejima coefficient

$$\frac{L_e}{\mu_0 R_0} = \frac{f_a (1-\epsilon)}{(1-\epsilon) + \kappa f_b}$$

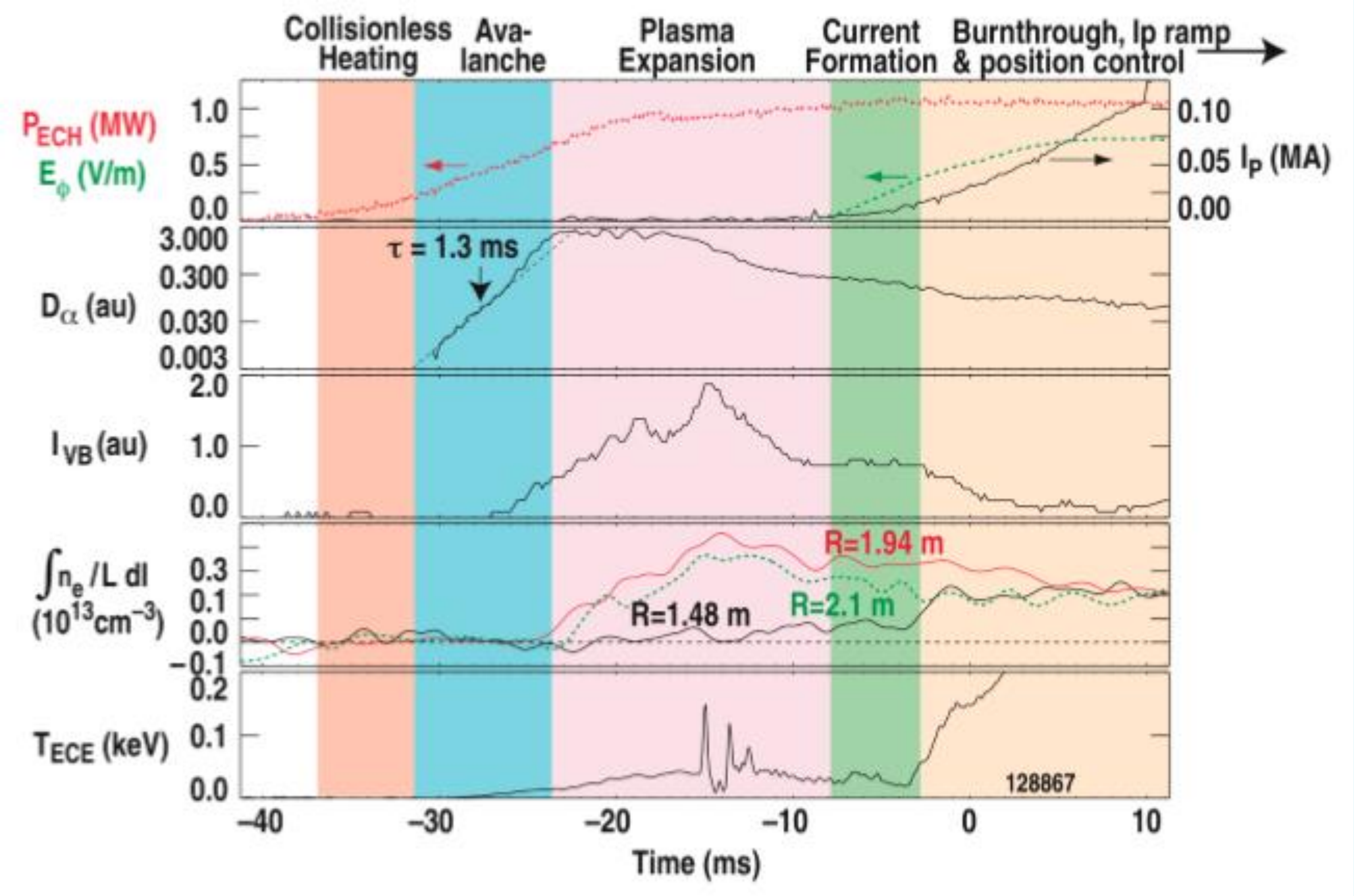
Low aspect ratio



Pre-ionization and Burn-through

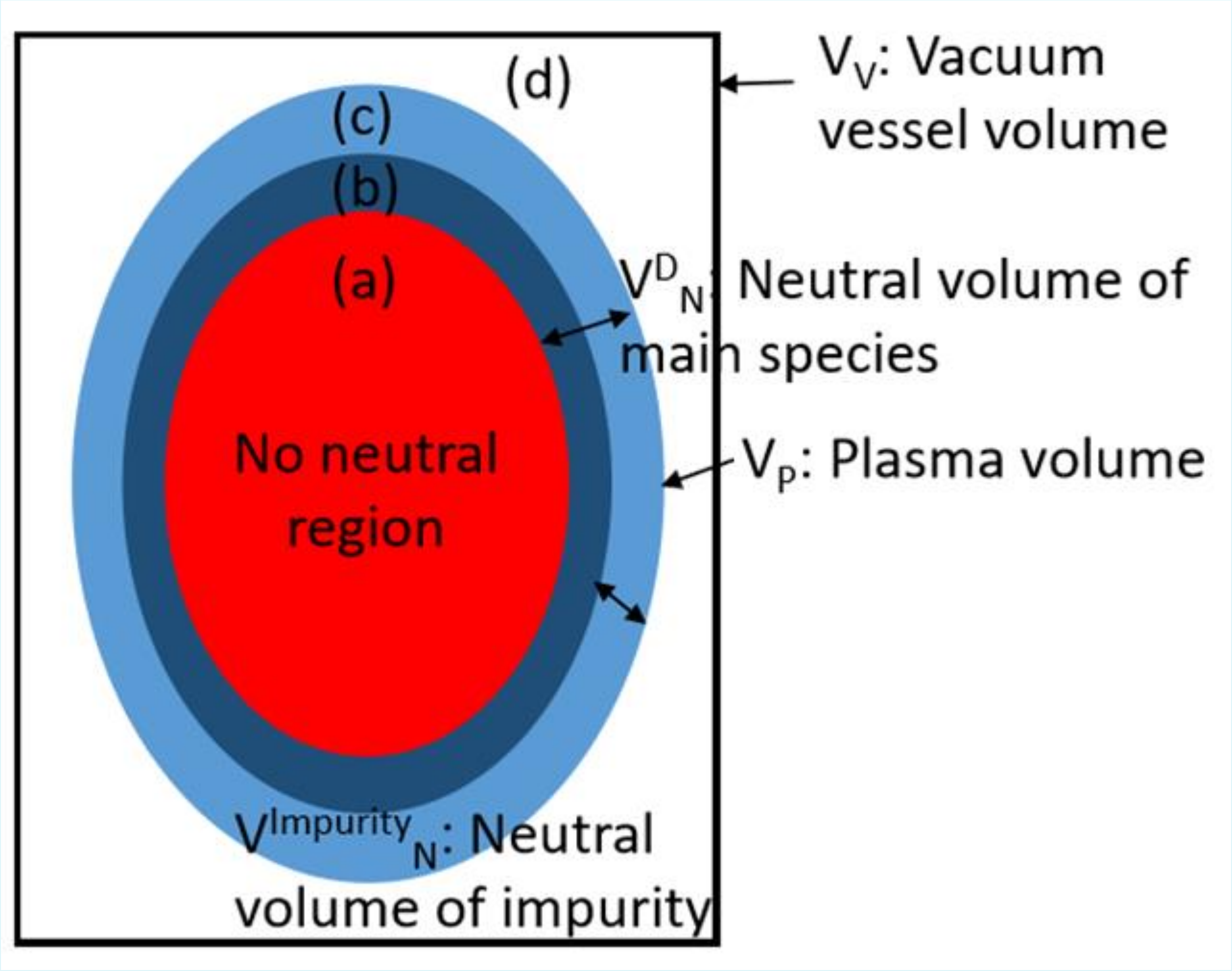
- Once closed flux surface is formed, burn-through becomes important for the success of tokamak start-up

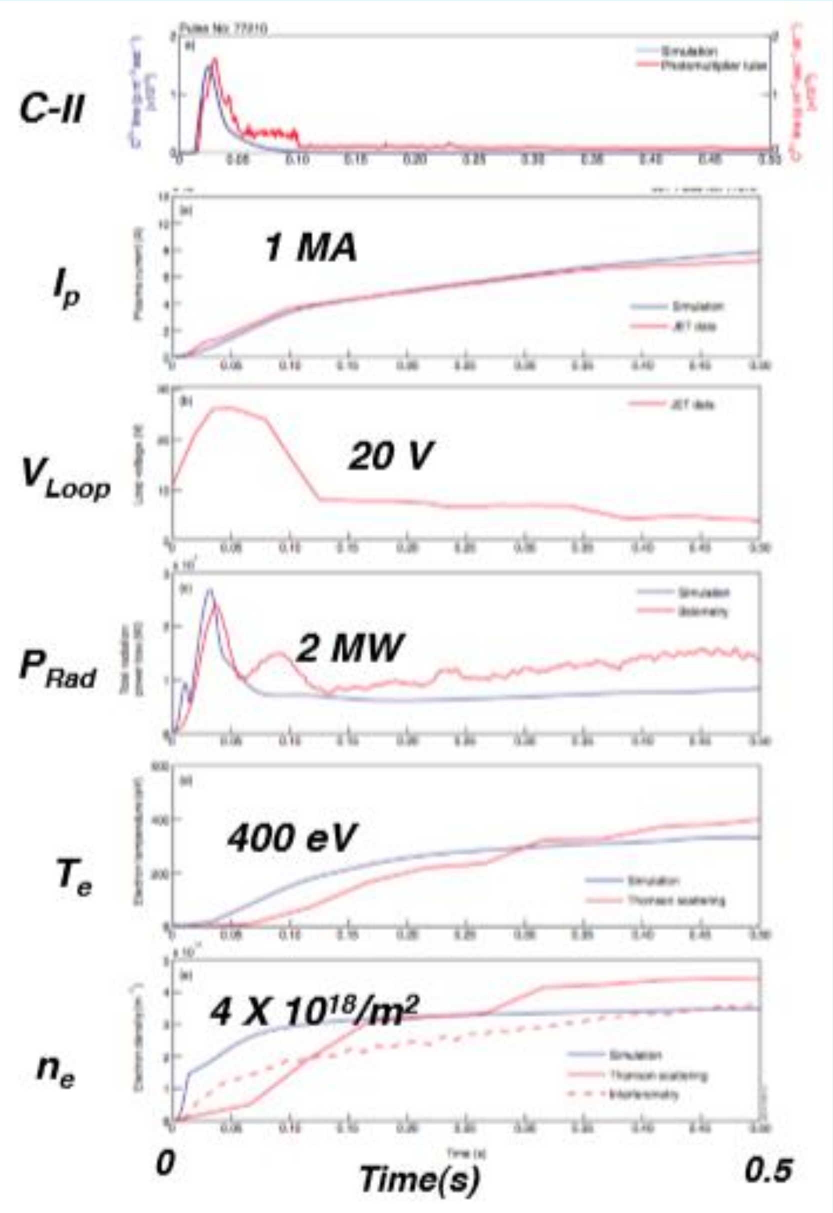
  - ➢ Sufficient ohmic and ECH heating by considering reduced ohmic power with higher electron temperature
  - ➢ Wall conditioning for minimal impurity radiation power loss
  - ➢ Reduced MHD activities



Jackson, et. al., Fusion Sci. & Tech. 57, 27(2012)

Start-up Modelling with Burn-through





Hyun-Tae Kim, W. Fundamenski, A.C.C. Sips et al.,
Nucl. Fusion 52 (2012) 103016

Ohmic Heating and Current Drive

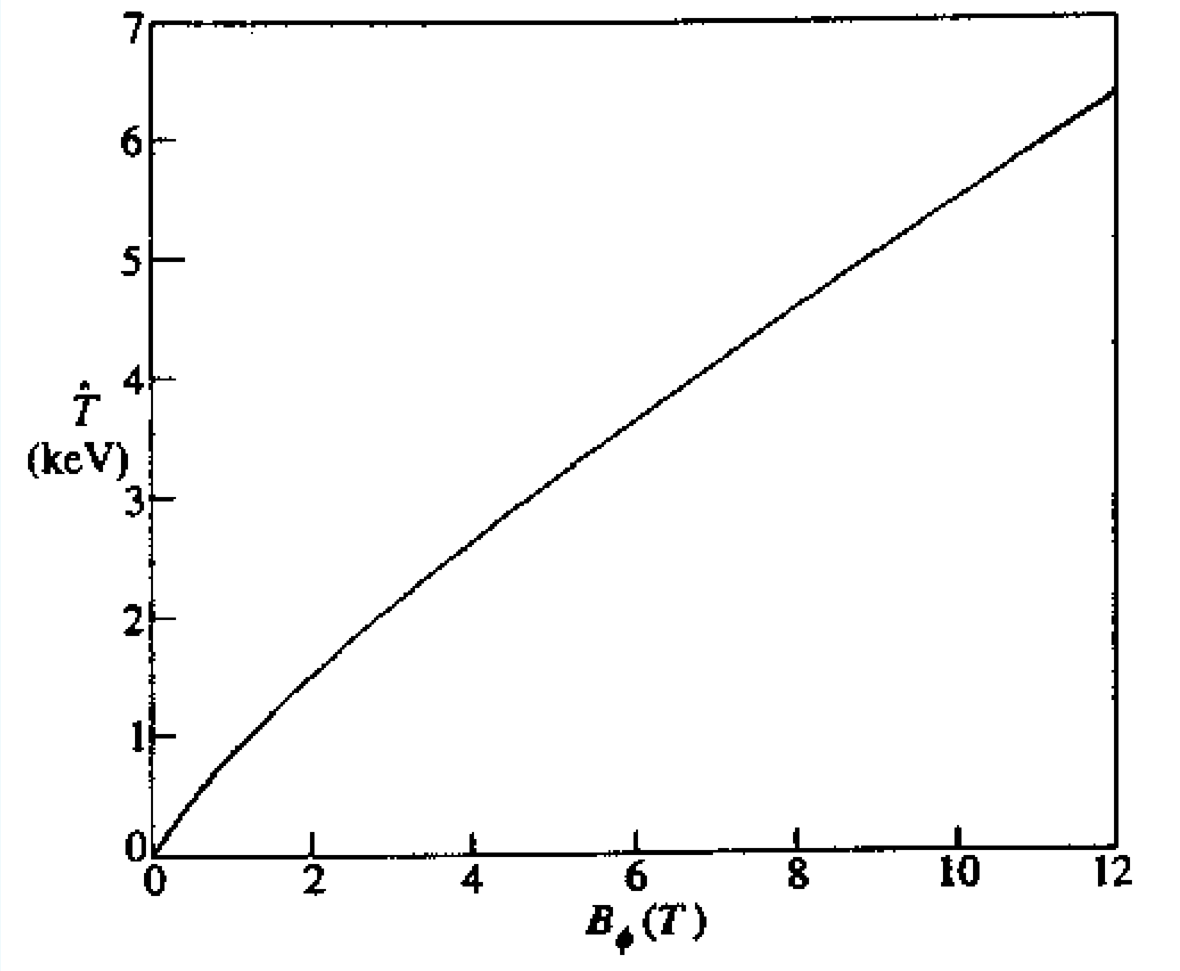
Ohmic heating

$$P_\Omega = \eta\left\langle j^2 \right\rangle = 1.0\times10^5\left(\frac{Z_{eff}}{T^{3/2}}\right)\left[\frac{1}{q_o(q_a - q_o/2)}\right]\left(\frac{B_\phi}{R}\right)^2$$

$$P_{loss} = 3nkT/\tau_E \qquad \tau_E = (n/10^{20})a^2/2$$

Alcator scaling

$$T = 2.7\times10^8\left(\frac{Z_{eff}\tau_E}{nq_aq_0}\right)^{\frac{2}{5}}\left(\frac{B_\phi}{R}\right)^{\frac{4}{5}}$$

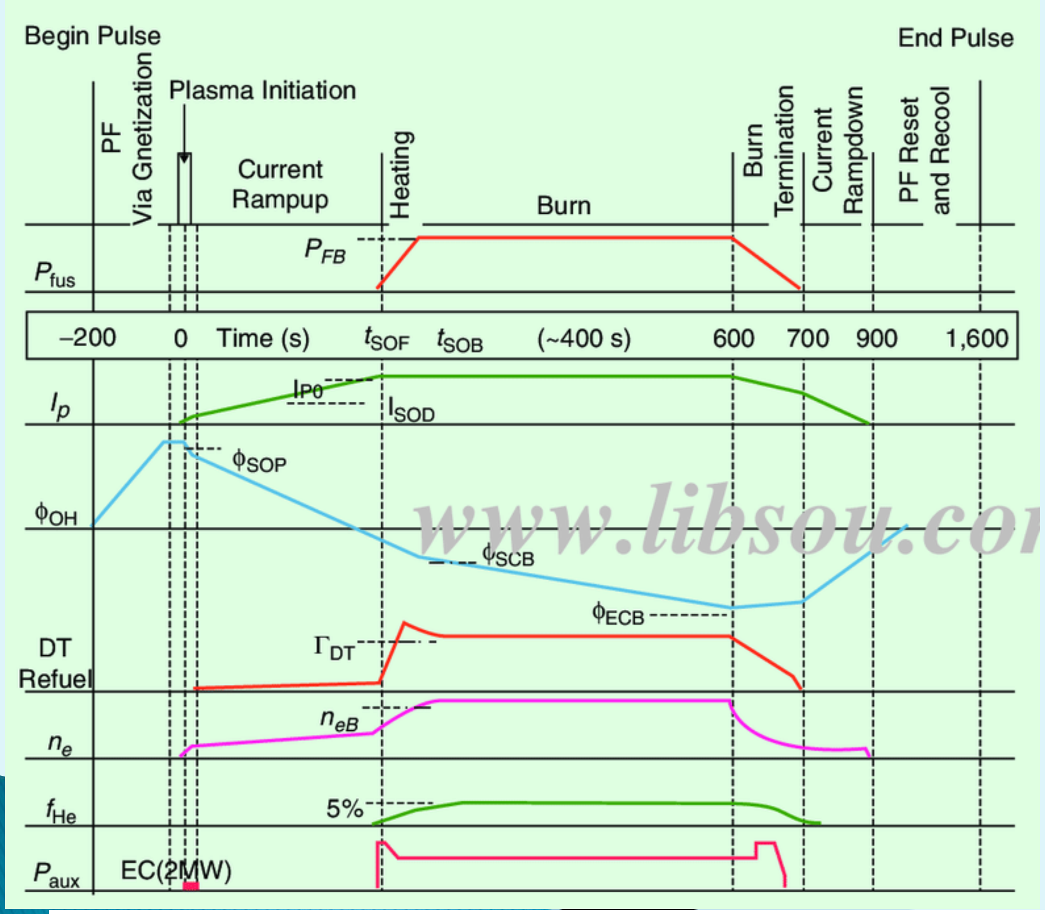


Ohmic Heating and Current Drive

Volt-second consumptions

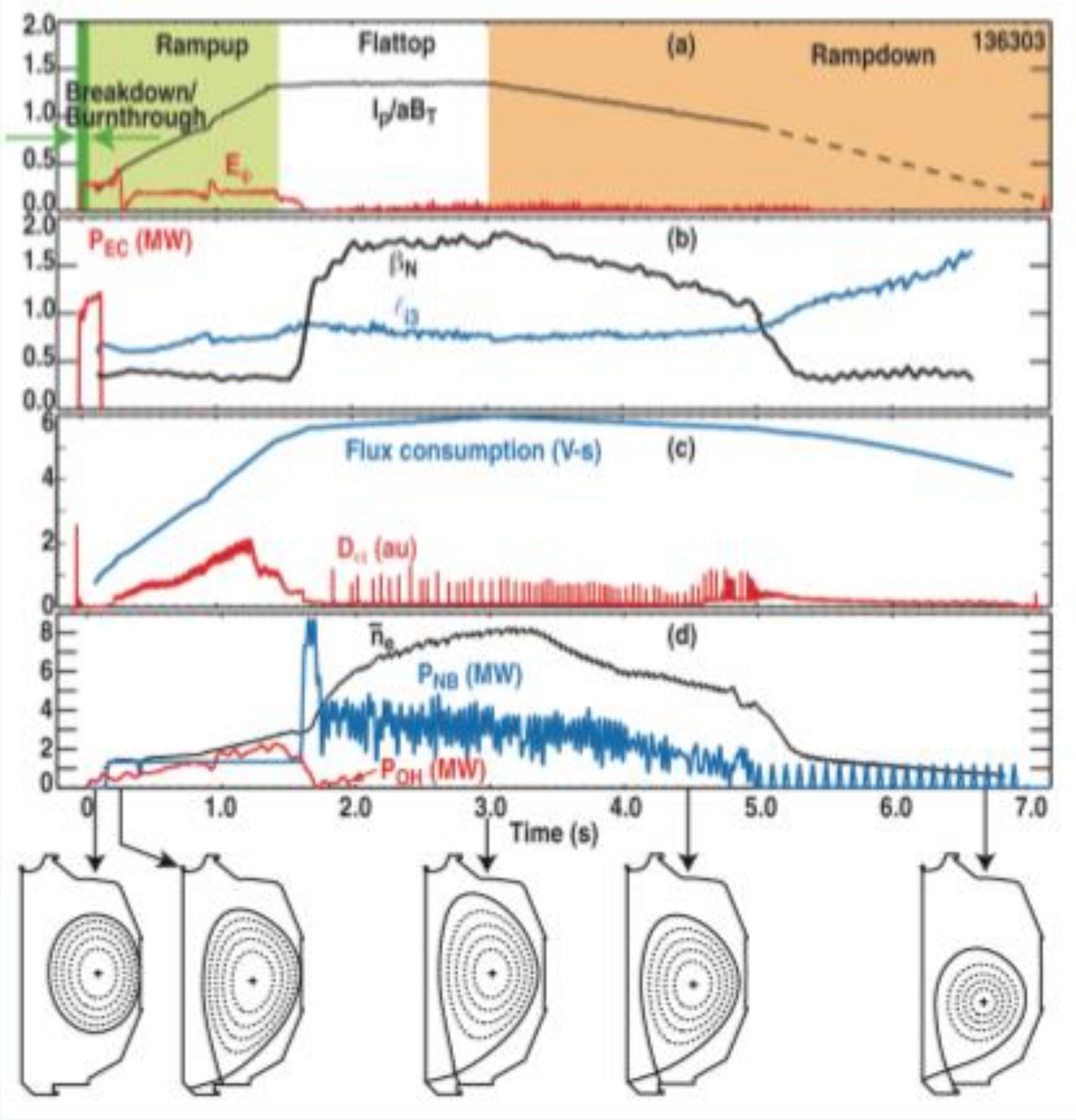
$$\int V_l dt = \int R_p I_p dt + \int (L_p \frac{dI_p}{dt} + I_p \frac{dL_p}{dt}) dt$$

$$= C_E \, \mu_o R I_p + L_p I_p + R_p \, I_p \Delta t$$



[Lister, et. al., IEEE control systems](#) 26, 79(2006)

DIII-D ITER Scenario



Jackson_exs_p2-11_2011FEC

Homework # 2-1

1. **Find out a criterion for successful ohmic current ramp-up after closed flux surface formation from power and particle balances.**