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ECH-assisted Plasma Start-up Experiment using Trapped Particle Configuration in VEST and KSTAR

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Contents

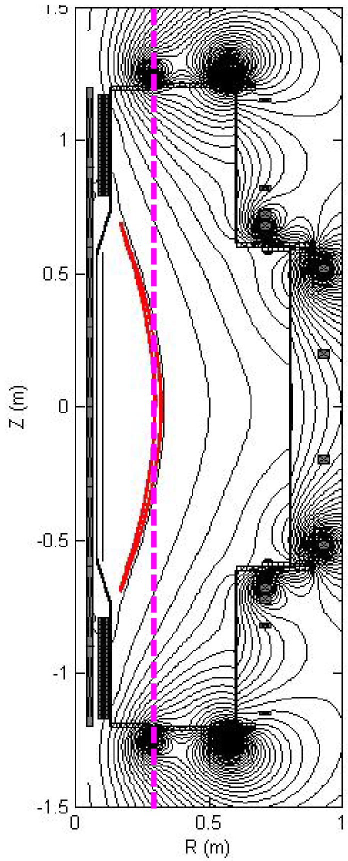
Start-up with ECH pre-ionization

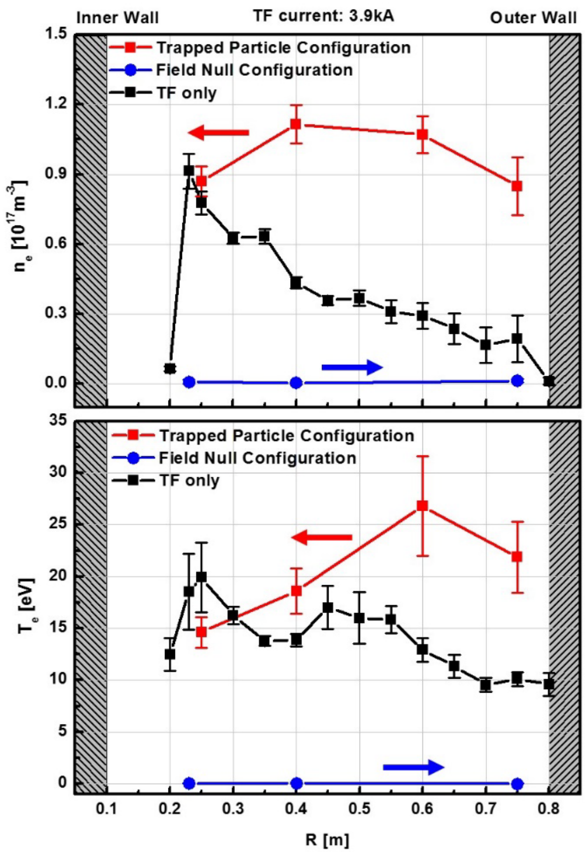
- Pre-ionization: the plasma provided by the ECH power, before the onset of the toroidal electric field
- Advantages of pre-ionization
    1. Reduce the required loop voltage
    2. Reduce the flux consumption
    3. Efficient and fast plasma current initiation
    4. Reduce the startup runaway electrons
    5. Assist burn-through
    6. Non-inductive current drive

➢ **But in VEST, severe degradation of the pre-ionization plasma under field null configuration (FNC) has been generally observed.**

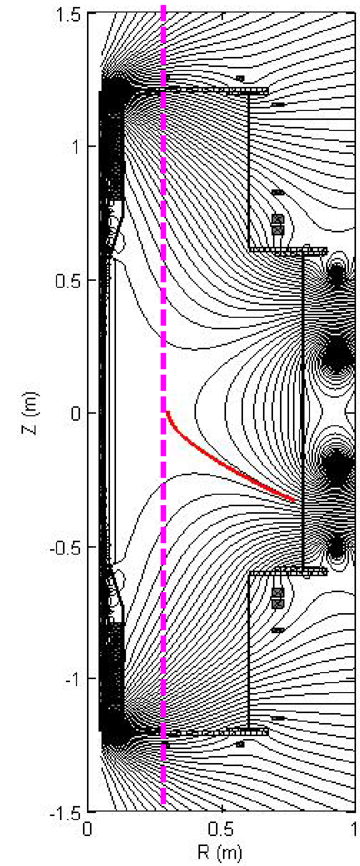
Enhancement of pre-ionization plasma under TPC in VEST*

Trapped particle





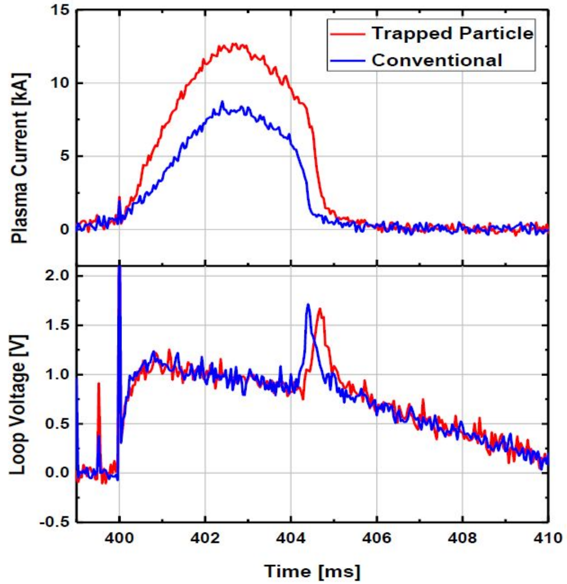
Field null



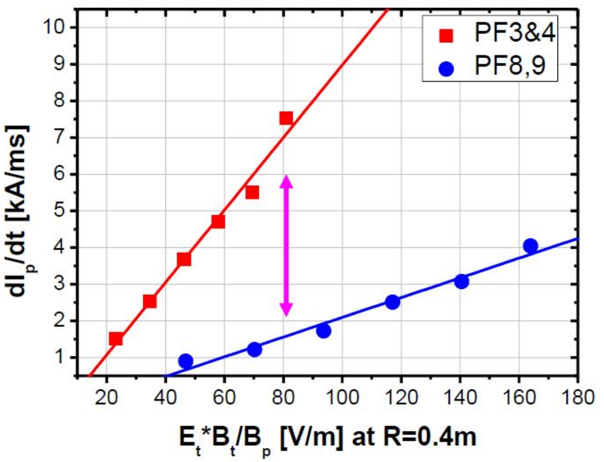
- Significant enhancement of pre-ionization plasma with trapped particle configuration
- Significant degradation of pre-ionization plasma with field null configuration

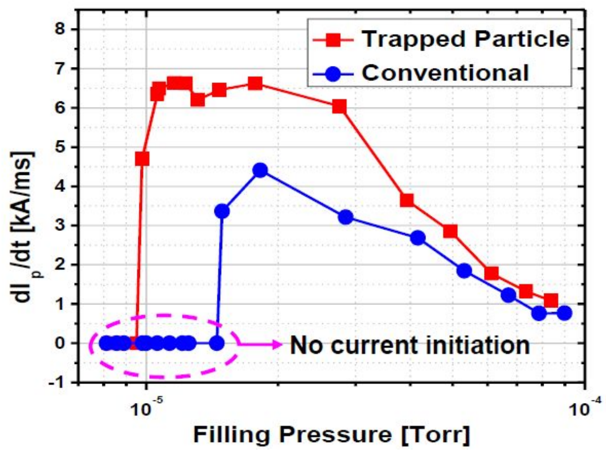
* Y.H. An *et al, Proc. of FEC 2015*, ICC/P8-19

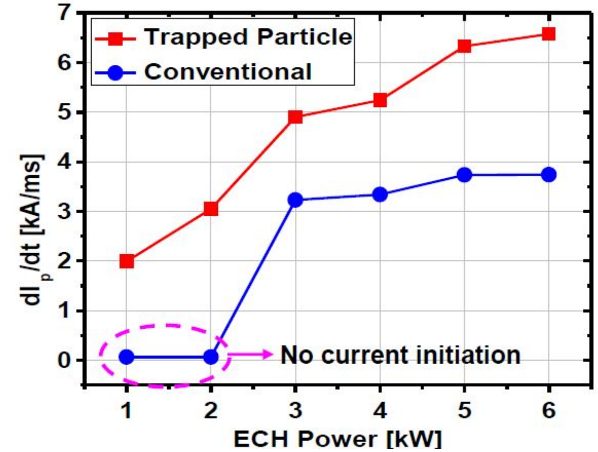
Plasma start-up using TPC & FNC in VEST*



- **Advantages of plasma current initiation using TPC**
  - ✓ **High plasma current compared with the field null start-up**
  - ✓ **Higher dI_p/dt at the same electromagnetic field condition represented by $E_t \cdot B_t / B_p$**
  - ✓ **Wide operation range in terms of prefill gas, ECH power**







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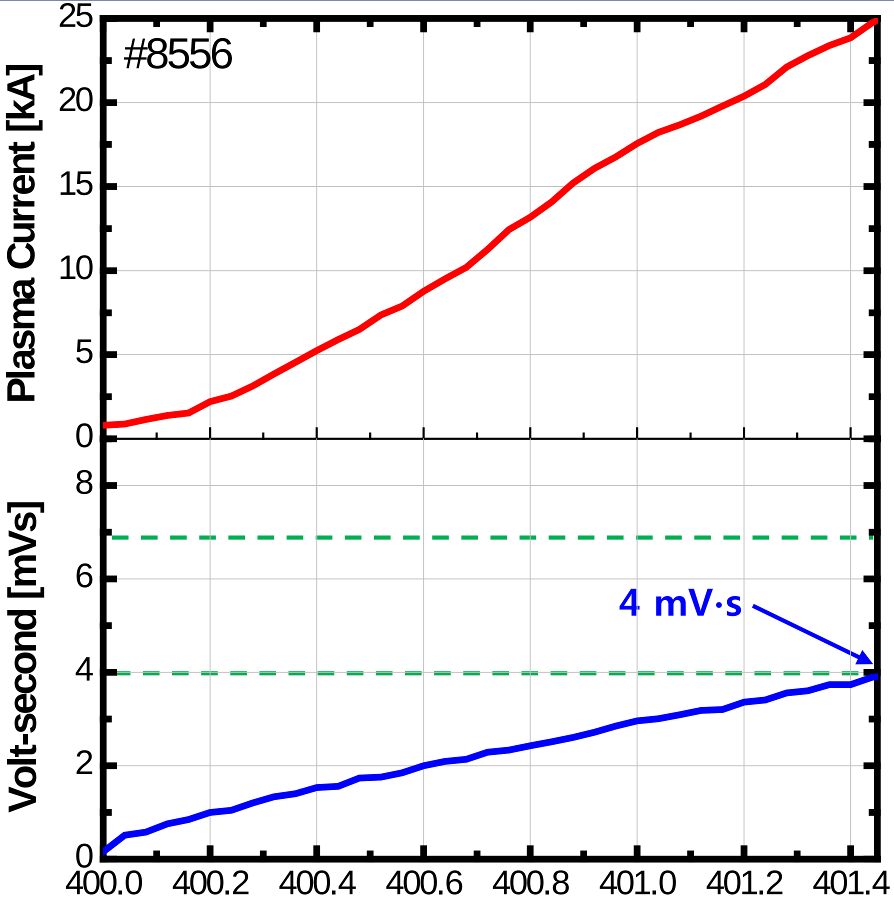
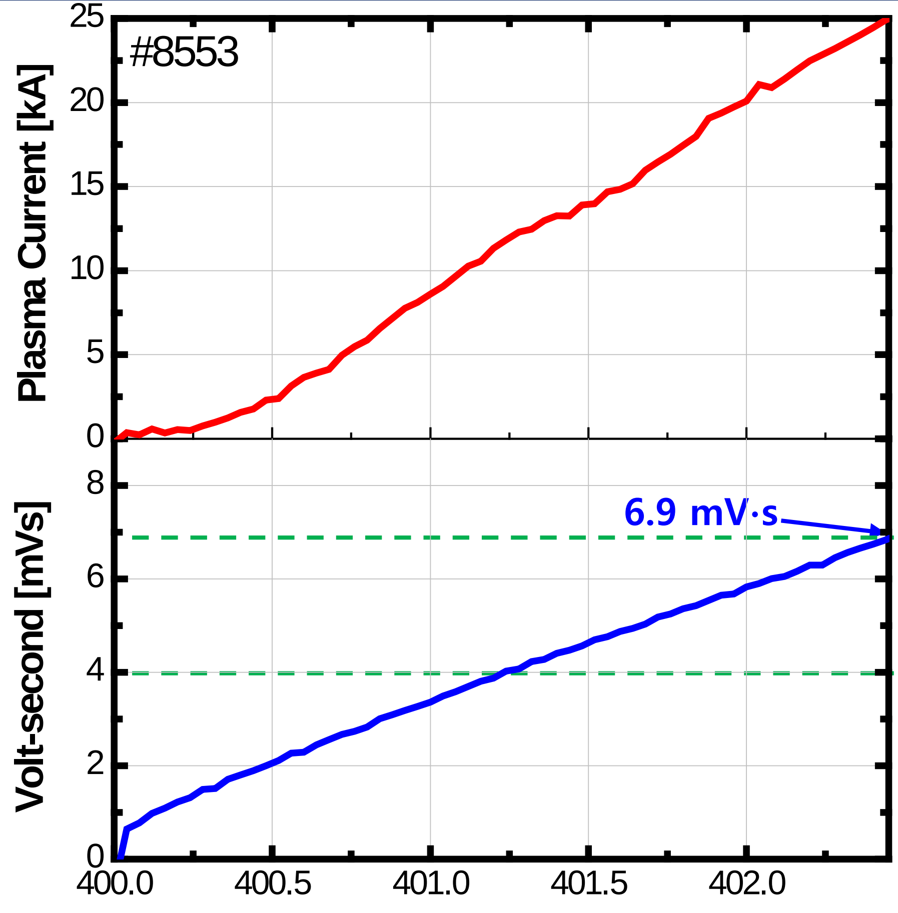
Plasma start-up using TPC & FNC in VEST*



Trapped Particle Configuration
with PF1 Single Swing



Field Null Configuration
with PF1 Single Swing

Only half of volt-second is required with trapped particle configuration compared with that with filed null configuration.

* Y.H. An *et al, Proc. of FEC 2015*, ICC/P8-19

Motivation

- **The TPC shows better plasma startup performance than the FNC, but..**
  - ✓ DIII-D[1] already shown the B_v effect of the ECH-assisted startup
  - ✓ **Performing TPC with difference mirror ratio, ~1 and ~3**
    : Magnetic field curvature effect

- **The TPC shows good in spherical torus, VEST, but..**
  - ✓ Could it be applied to the conventional, superconducting tokamak like ITER?
  - ✓ **Performing TPC startup in KSTAR 2015 campaign,**
    : Feasibility of TPC in conventional tokamak as well as ST

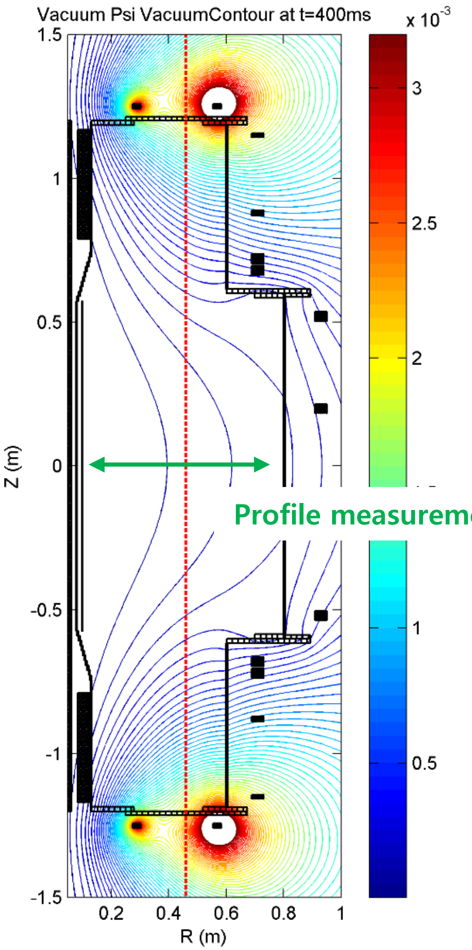
1) G.L. Jackson, *et al., Fusion Science and Technology*, **57** pp.27-40 (2010)

Mirror ratio effect of the plasma start-up in VEST

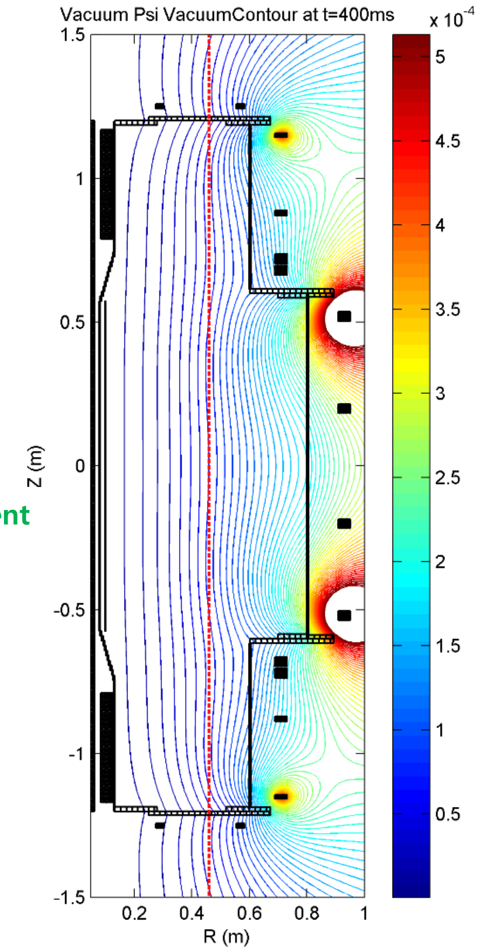
- Enhanced pre-ionization plasma under TPCs with different mirror ratio (R_m)
- Plasma startup with different mirror ratio TPC
- Startup simulation using circuit approximation with n_e, T_e, R_0 measurement

TPC configuration with different R_m

R_m ~ 3

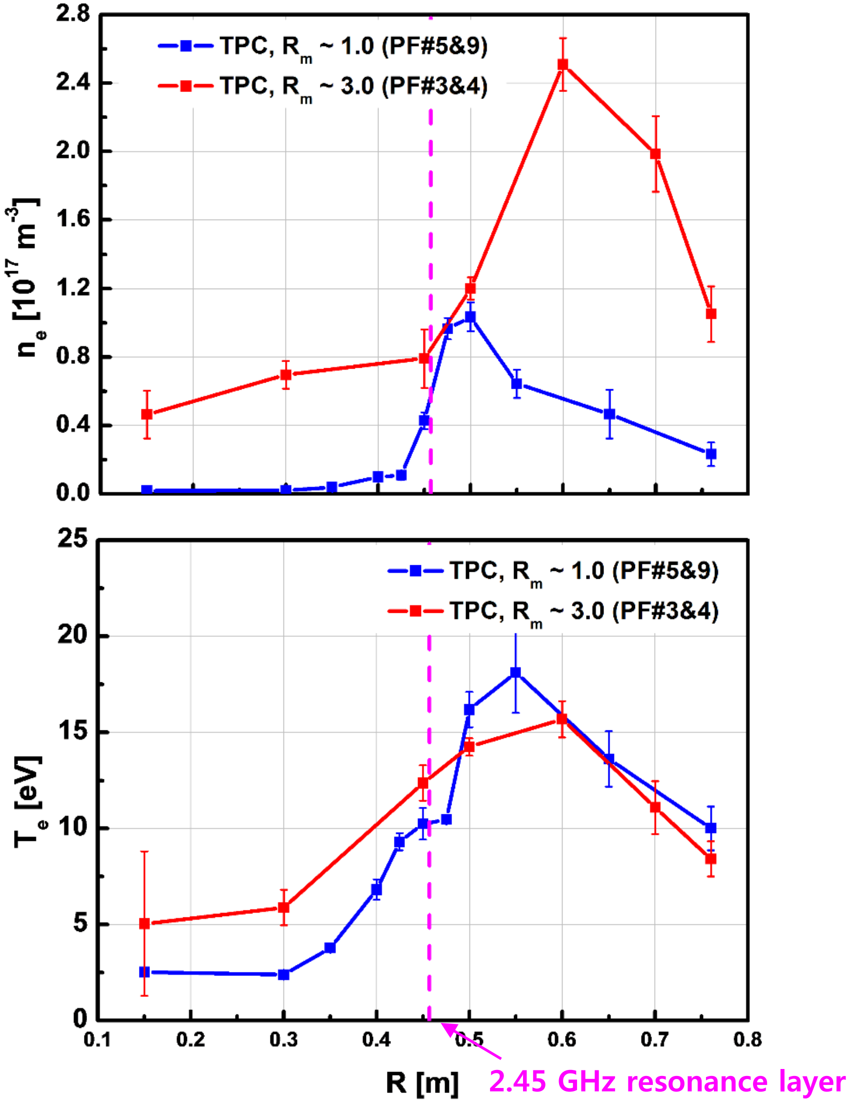


R_m ~ 1



- B_T = 0.1 T at R = 0.4 m
- Prefill gas = 2 x 10^{-5} Torr
- ECH for pre-ionization
  2.45 GHz, X-mode fundamental
  P_{ECH} = 6 kW, CW
  R_{RES} = 0.43 m
  Perp. Injection
- TPC (by PF#3&4, PF#5&9)
  Mirror ratio ~ 3, 1
- *Movable triple Langmuir probe*
  n_e, T_e measurement, mid-plane
- Plasma radial position from single filament approximation

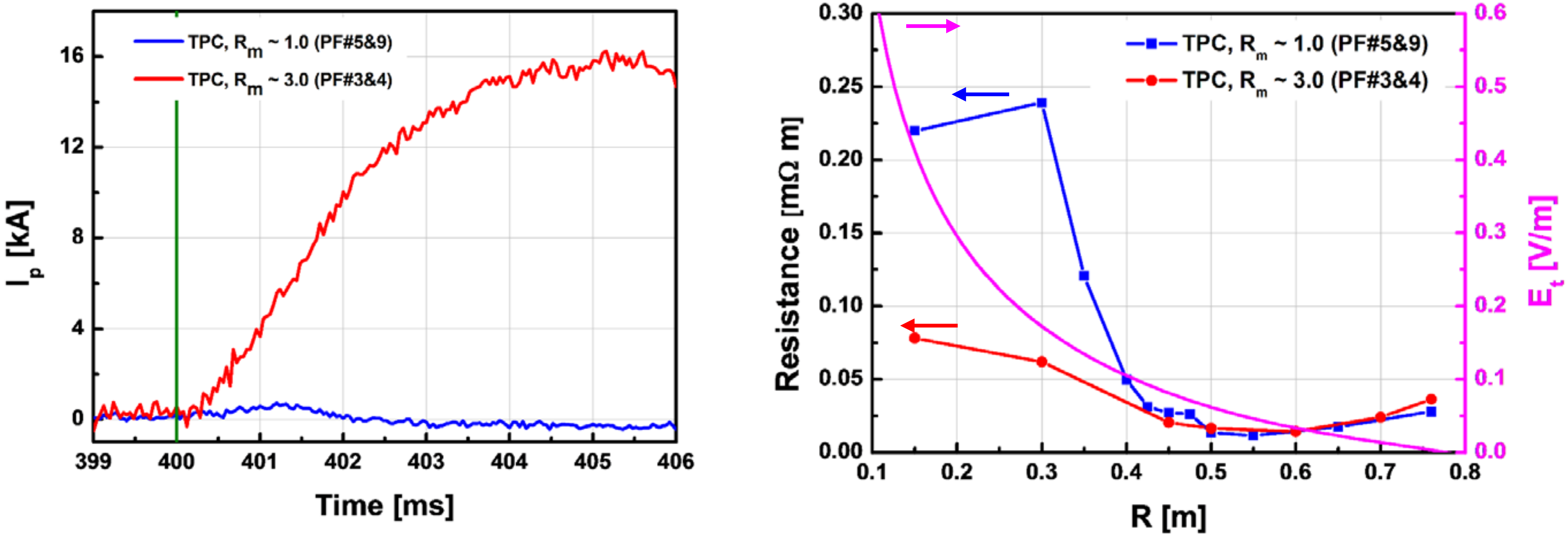
n_e, T_e profile of the pre-ionization plasmas



- In R_m ~ 1.0 case, the pre-ionization plasma was formed near the resonance layer.
- The electron density diffuses to the LFS(low Et region), but not to the HFS (high E_t region)
- In R_m ~ 3.0 case, the pre-ionization plasma accumulated at the LFS, factor of 2 comparing with the resonance layer.
- Even HFS, density exist order of 10^{16} m^{-3} and higher electron temperature than R_m ~ 1.0

➢ *More enhanced pre-ionization density and temperature is observed in the R_m ~ 3 than the R_m ~ 1, both inboard and outboard side.*

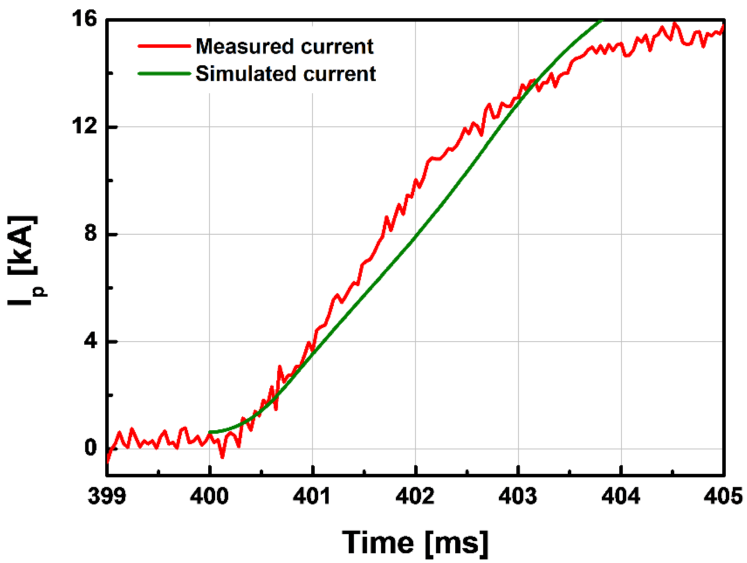
Plasma startup with different R_m



- The Spitzer resistivity is used to calculate the resistance of the pre-ionization plasmas with $Z_{eff} = 1$ and $\ln \Lambda = 17$.
- Startup fails with R_m ~ 1.0 TPC because of its high resistivity and low electron density.
- Successful startup with ~ 4.5 kA/ms ramp up speed is achieved with R_m~3.0 TPC with i ts low plasma resistance at the high E_t region.

➢ *Low resistance and sufficient electron density at the high E_t region allows immediate, fast plasma start-up in VEST.*

Circuit approximation of plasma current evolution



- **RL circuit equation,**

$$L\frac{dI}{dt} + RI = V_{ext}$$

- **Resistivity**
  - ✓ Spitzer formula w/ n_e, T_e measurement
  - ✓ Assume $Z_{eff} = 1$ and $\ln \Lambda = 17$
- **Inductance**
  - ✓ Plasma shape from single filament fitting (from magnetics data)
  - ✓ Assume $l_i = 0.5$
- **External voltage**
  - ✓ From eddy current solver

- **Circuit simulation of R_m ~ 3.0 shows good agreement of the measured current.**
- **Based on the n_e, T_e profile measurement, the plasma startup capability could be estimated.**

➢ *Based on the noble pre-ionization plasma measurement, the plasma current initiation under the TPC is successfully simulated.*

Plasma Start-up using TPC in KSTAR

- ECH-assisted, FNC vs. TPC
- Trapped field strength effect to plasma start-up

Experimental set-up for KSTAR TPC start-up

- B_T = 2.7 T at R = 1.8 m
- Prefill gas = 2 x 10^{-5} mbar
- ECH/ECCD for pre-ionization

  170 GHz, X-mode 2^{nd} harmonic

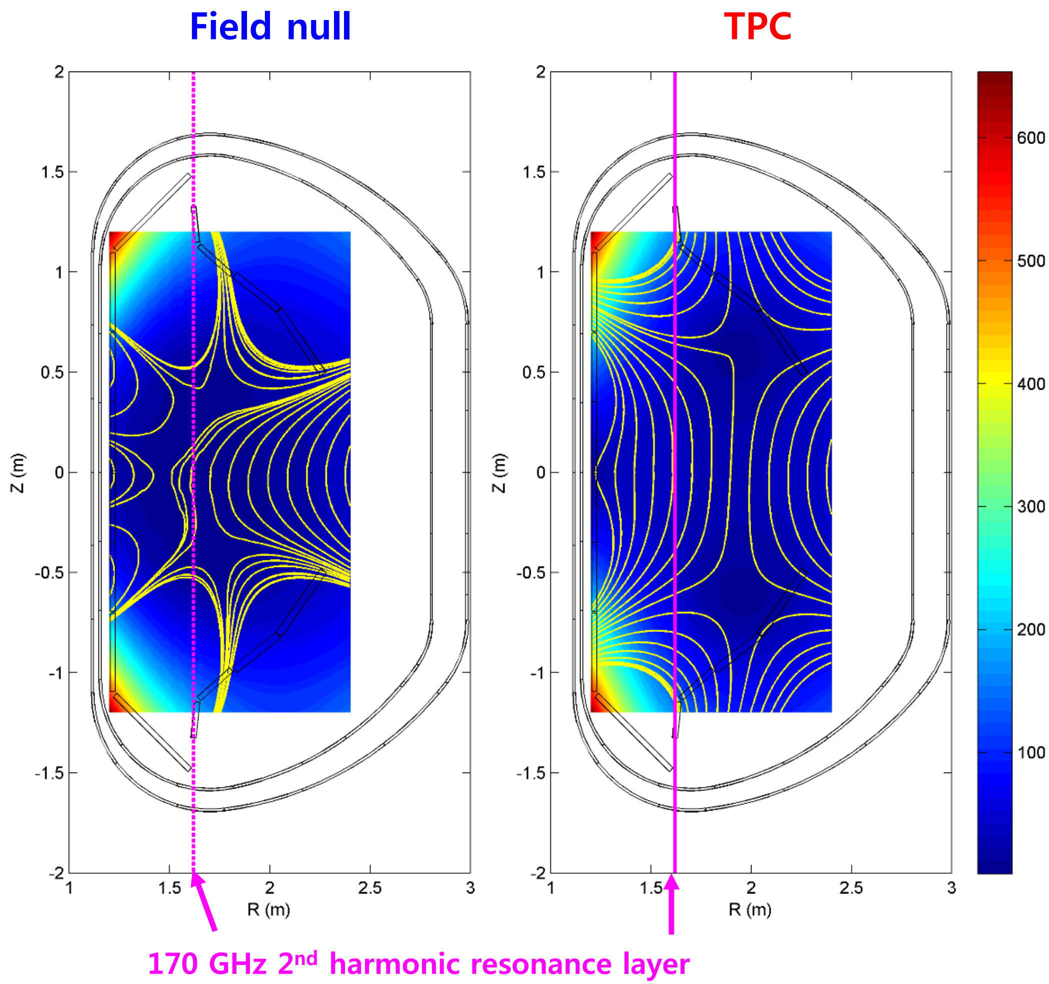
  P_{ECH} = 500 ~ 600 kW

  R_{RES} = 1.62 m

  θ_{TOR} = 20 °
- Superimpose TPC structure

  (by PF#5) on the field null

  Mirror ratio = 1.4



✓ Magnetic field strength and *psi* contour at the pre-ionization phase

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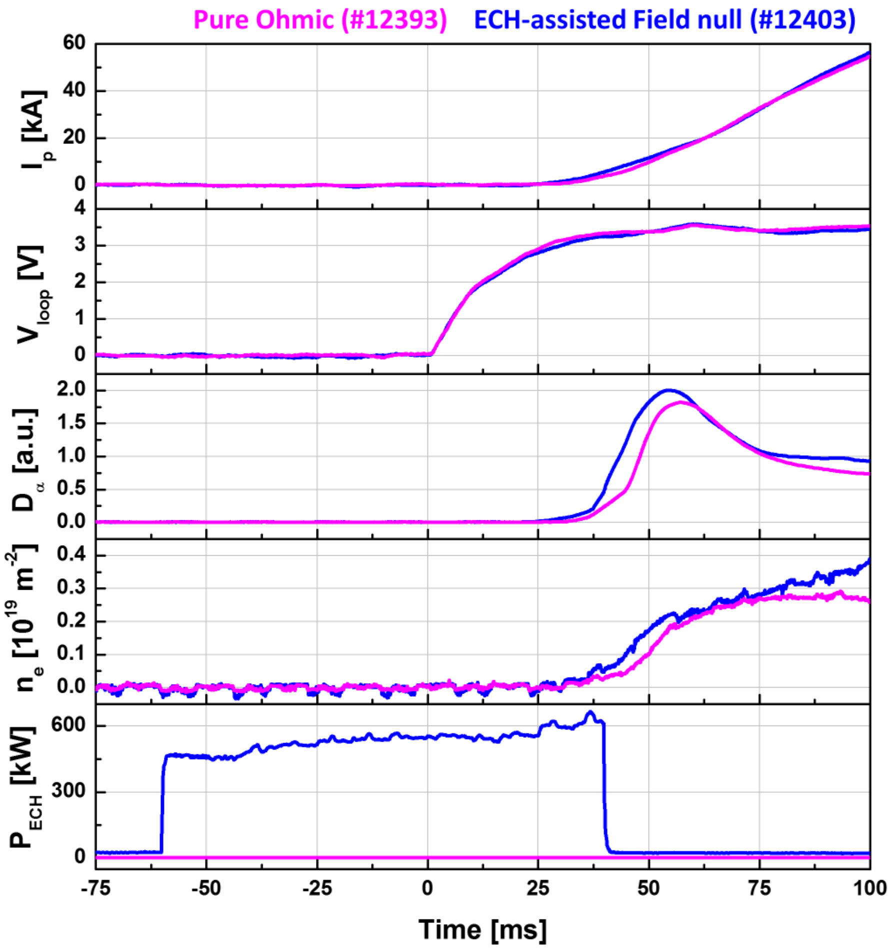
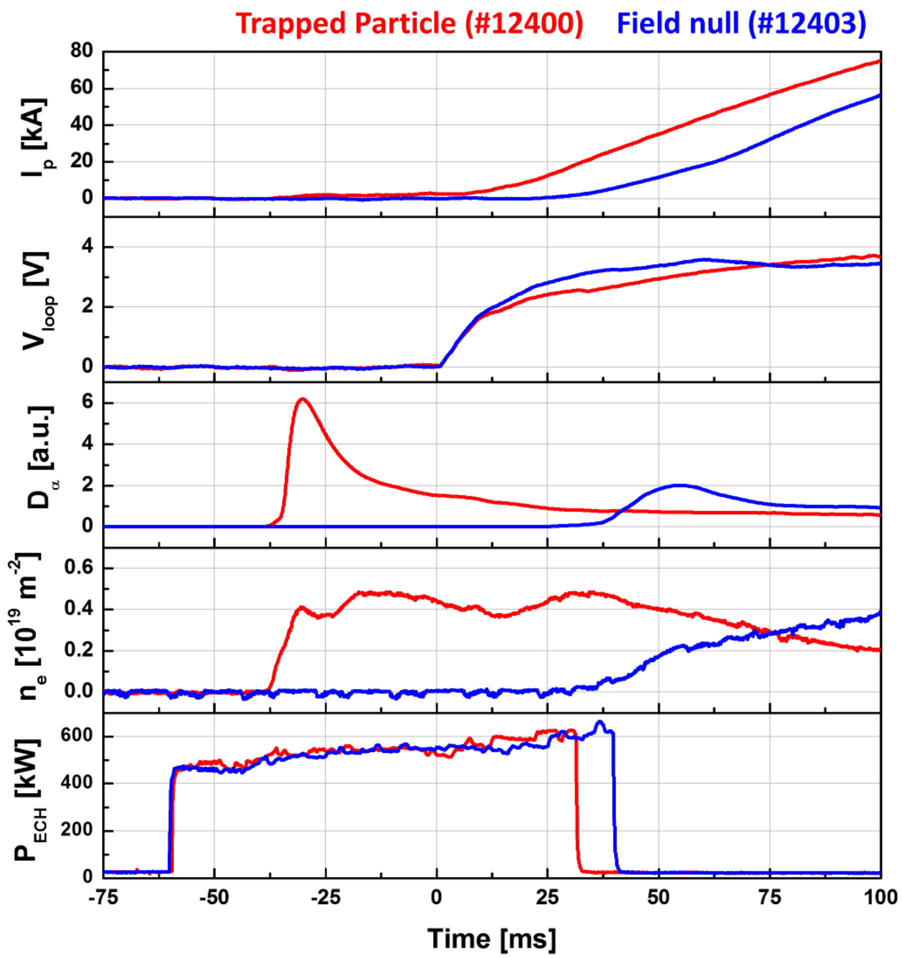
FNC vs. ECH-assisted FNC



- **Up to 600 kW ECH/ECCH injected 60 ms before the loop voltage onset**
- **Negligible plasma density in the pre-ionization phase**
- **Delay in current ramp up with limited ECH pre-ionization, similar to the pure ohmic**

➢ *There are no advantages of the ECH/ECCH injection to the field null configuration(FNC).*

ECH-assisted FNC vs. ECH-assisted TPC

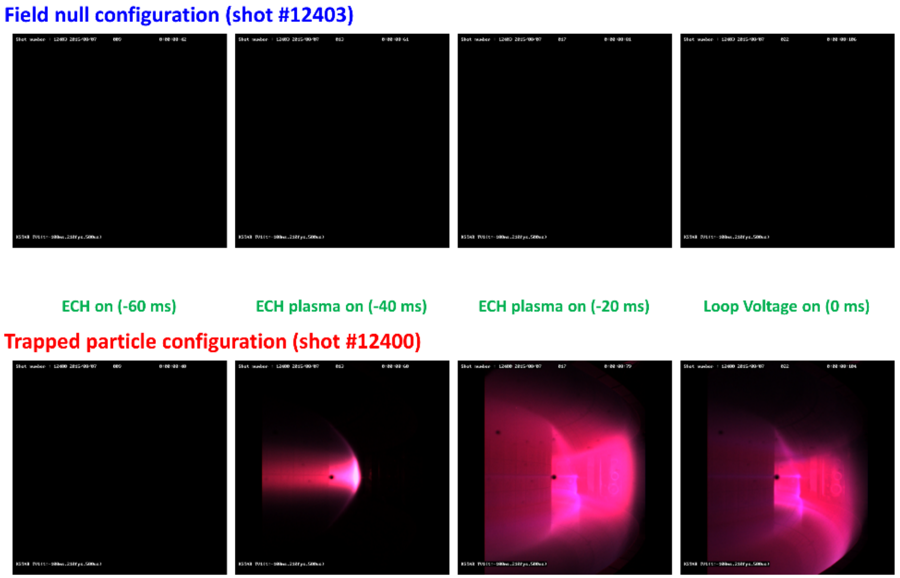


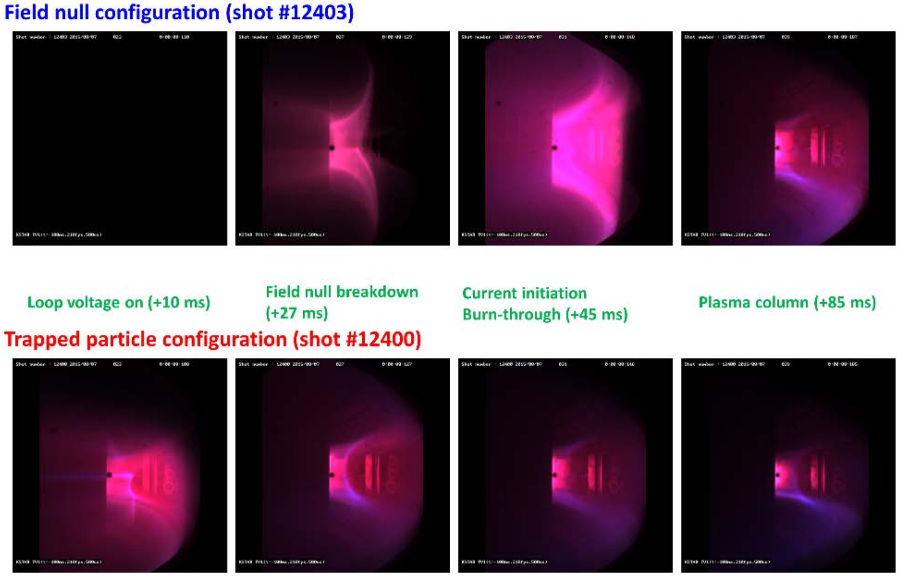
- <u>"Only poloidal magnetic field different"</u>
- TPC shows many advantages of the plasma startup:
  - ✓ Average pre-ionization density of 4 x 10^{18} m^{-2} with improved particle confinement
  - ✓ Immediate current initiation after the loop voltage on
  - ✓ Higher current ramp-up rate with efficient loop voltage consumption

➢ *Improved tokamak startup by the TPC in KSTAR with the enhanced pre-ionization (R_m ~ 1.4)*

Fast camera images of ECH-assisted FNC and TPC

- **Pre-ionization phase (→)**
  - ✓ No pre-ionization plasmas under field null
  - ✓ After 20 ms delay of ECH on, pre-ionization plasma occurs
  - ✓ Expanded from the resonance layer





- **(←) Plasma current formation phase**
  - ✓ Delayed breakdown of 25 ms after V_{loop} on
  - ✓ Burn-through ~ 85 ms
  - ✓ Early and fast plasma current formation

➢ *Improved tokamak startup by the TPC is also clearly confirmed by the fast camera images.*

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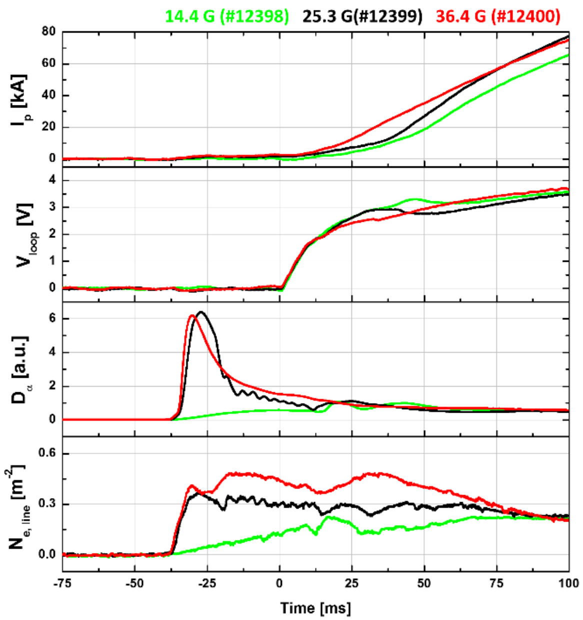
Robust, efficient ECH-assisted startup



- ✓ **Robust startup can be achieved in KSTAR:**

  ex) after many plasma disruption experiments (dirty wall)

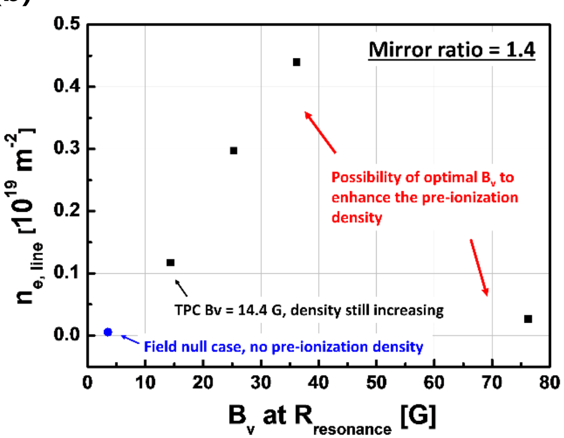
- ✓ **Startup efficiency improvement for <u>low loop voltage start-up</u>**
  - **Pre-ionization density ← poloidal field strength (fig b)**

    Current ramp-up rate ← pre-ionization density (fig c)

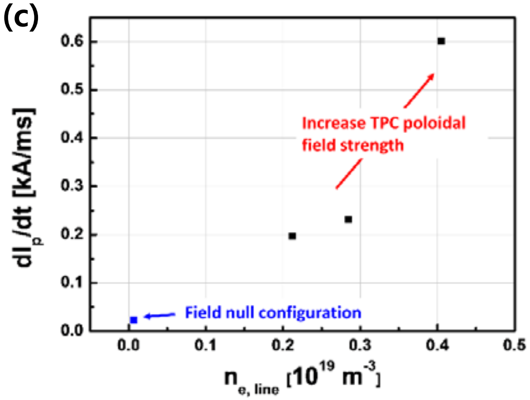
  - → **<u>Good for low loop voltage start-up for future devices (ITER)</u>**

- ➢ ***Tokamak startup performance can be improved furthermore by the enhanced pre-ionization with TPC instead of the Lloyd condition. (fig (d))***

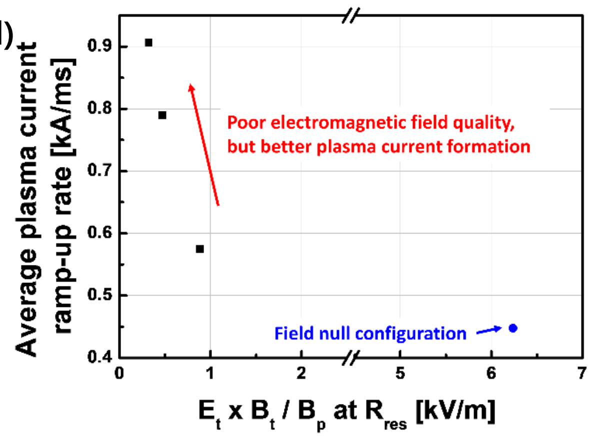
(b)



(c)



(d)



Summary

➢ **Enhanced plasma startup using TPC has been validated in VEST and KSTAR**
  - ✓ **In VEST, mirror ratio effect of TPC is clearly shown from the startup experiment with different R_m, ~1 and ~3.**
  - ✓ **With n_e, T_e and R_0 measurement of the plasma, the plasma current initiation is precisely calculated by the plasma-RL circuit approximation.**
  - ✓ **In KSTAR, TPC shows more enhanced ECH-assisted startup than the conventional FNC with identical experimental condition.**
  - ✓ **The superiority of TPC is also validated in conventional, superconducting tokamak, which has intrinsically low mirror ratio than spherical torus.**
  - ✓ **The TPC could improve the startup scheme in ITER, especially in terms of the low loop voltage startup which comes from the limitation of the superconducting solenoid coils.**
  - ✓ **The TPC will be applied to the outer PF startup scheme, one of the solenoid-free startup methods for ST, which have required much pre-ionization power to overcome the pure magnetic field null condition.**