Numerical analysis of electron distribution function under electron cyclotron heating during tokamak start-up

N. Tsujii, A. Ejiri, K. Shinohara, Y. Peng, Y. Lin, Z. Jiang, Y. Tian, F. Adachi, Y. Jiang, S. Wang, M. Yoshida and Y. Takechi

The University of Tokyo

Abstract

- Electron cyclotron (EC) heating is useful to assist start-up of large superconducting tokamaks with low loop voltage
- Trapped-particle configuration (TPC) that confine collisionless electrons was found to be effective for EC assisted start-up
- Fokker-Planck simulation and extended MHD equilibrium reconstruction was used to analyze the electron distribution function before and around closed-flux-surface formation
- Finite-orbit and relativistic effects were included

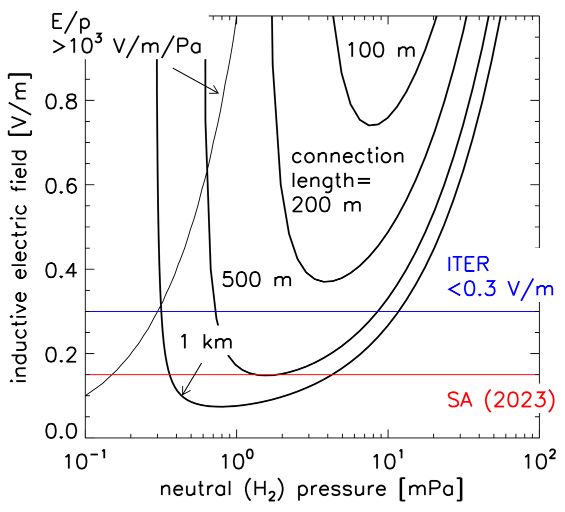
Assistance by EC waves is useful for low loop voltage start-up of large superconducting tokamaks

Ohmic breakdown

- DC E-field
  - → parallel acceleration
  - ↔ collisional slowing down
- Operation in collisional regime
- Maximize connection length
- – Field-null configuration (FNC)

EC assisted start-up

- DIII-D: >0.15 V/m*
- KSTAR: >0.3 V/m†
- JT-60SA: >0.15 V/m‡

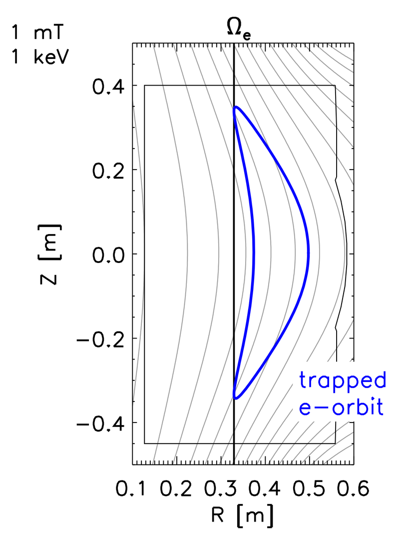


Phase space for Ohmic breakdown

*B. Lloyd et al., Nucl. Fusion **31**, 2031 (1991)
†J. Lee et al., Nucl. Fusion **57**, 126033 (2017)
‡T. Wakatsuki et al., Nucl. Fusion **64**, 104003 (2024)

Improvement of EC assisted start-up with TPC* observed in devices including KSTAR† and JT-60SA‡

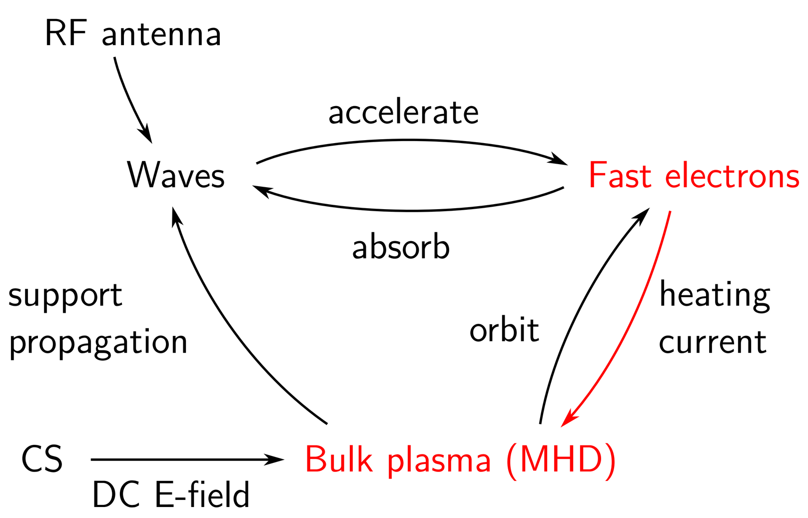
- EC waves
  - → generate collisionless fast electrons
- Optimization of collisionless orbits
- – Trapped-particle configuration (TPC)
- ↔ Field-null configuration (FNC)
  - – collisional confinement
- Comprehensive understanding of rf assisted start-up
- → Robust start-up with compact CS



Electron orbit in TPC of TST-2

*C.B. Forest et al., Phys. Plasmas **1**, 1568 (1994)
†J. Lee et al., Nucl. Fusion **57**, 126033 (2017)
‡T. Wakatsuki et al., Nucl. Fusion **64**, 104003 (2024)

Tokamak configuration forms through interactions of waves, fast electrons and MHD equilibrium



- Fast electron transport by Fokker-Planck simulation
- Extended MHD equilibrium reconstruction to include fast electron current

Collisionless fast electron distribution described with the orbit-averaged distribution function $f(\mathbf{K})$

- Constants of motion used for orbit labels $\mathbf{K} = (\mathcal{E}, \Lambda, P_\phi)$

$$\mathcal{E} = mc^2(\gamma-1) \simeq \frac{mv^2}{2} \quad : \text{kinetic energy}$$

$$\Lambda = \frac{2\mu B_0}{mu^2} = \frac{B_0}{B}\frac{u_\perp^2}{u^2} \quad : \text{velocity pitch } (B_0\text{: arbitrary B-field const.})$$

$$P_\phi = q\left(\psi + \frac{RB_\phi}{\gamma\Omega}u_\parallel\right) \quad : \text{toroidal angular momentum}$$

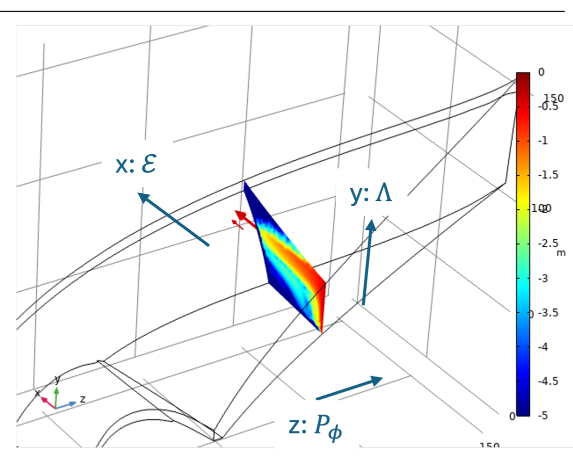
FEM software COMSOL* was used to implement the orbit-averaged Fokker-Planck simulation†

Transport drive

- Coulomb collisions with background plasma
- Quasilinear diffusion by waves
- Inductive DC electric field

Boundary conditions

- $f = 0$ at limiter
- No flux otherwise



Electron distribution in TST-2

*www.comsol.com
†N. Tsujii et al., Plasma Fusion Res. **18**, 1402051 (2023)

Equilibrium reconstruction was performed using extended MHD with kinetic electron current*

- Bulk plasma force balance

$$-\Delta^*\psi = \mu_0 j_\phi = \mu_0 R\frac{dP}{d\psi} + \frac{H}{R}\frac{dF}{d\psi} + \mu_0 j_{k\phi}$$

$$H = RB_\phi = F(\psi) + G$$

$P(\psi)$: bulk pressure
$F(\psi)$: bulk poloidal current

- Kinetic toroidal current $j_{k\phi}(R,Z)$
- Kinetic poloidal current $G(R,Z)$

$$j_{kR} = -\frac{1}{R}\frac{\partial G}{\partial Z}, \quad j_{kZ} = \frac{1}{R}\frac{\partial G}{\partial R}$$

*N. Tsujii et al., Nucl. Fusion **61**, 116047 (2021)

$f(\mathbf{K})$ parametrized analytically to be used in the extended MHD equilibrium reconstruction

- Analytic orbit-averaged distribution function

$$f(\mathcal{E},\Lambda,P_\phi) = \exp\left(-\frac{\mathcal{E}}{T} + \frac{\Lambda-\Lambda_{EC}}{\delta\Lambda}\right)\cos^2\left(\frac{\pi}{2}\frac{P_\phi - P_{EC}}{\delta P}\right)$$

T	: fast electron temperature
$\Lambda_{EC} = \frac{eB_0}{m_e\omega}$	: resonant velocity pitch
$\delta\Lambda = 0.1\Lambda_{EC}$	: width in velocity pitch
P_{EC}	: $q\psi$ at EC resonance on midplane
δP	: difference in $q\psi$ from top limiter to midplane

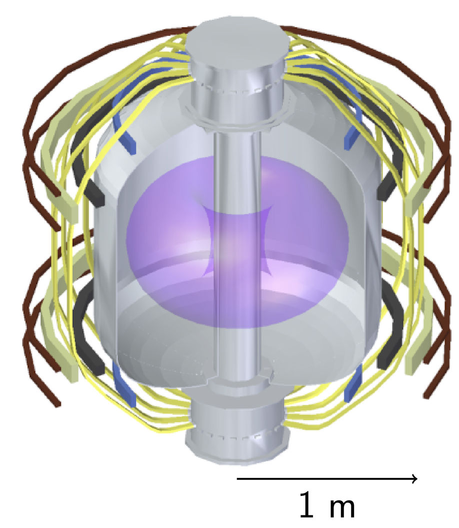
- Drift-kinetic current evaluated from the three moments $j_\parallel$, $P_\parallel$ and $P_\perp$

$$\mathbf{j}_k \simeq j_\parallel \mathbf{b} + \frac{P_\parallel - P_\perp}{B}\nabla\times\mathbf{b} + \frac{\mathbf{b}\times\nabla P_\perp}{B}$$

TST-2 spherical tokamak

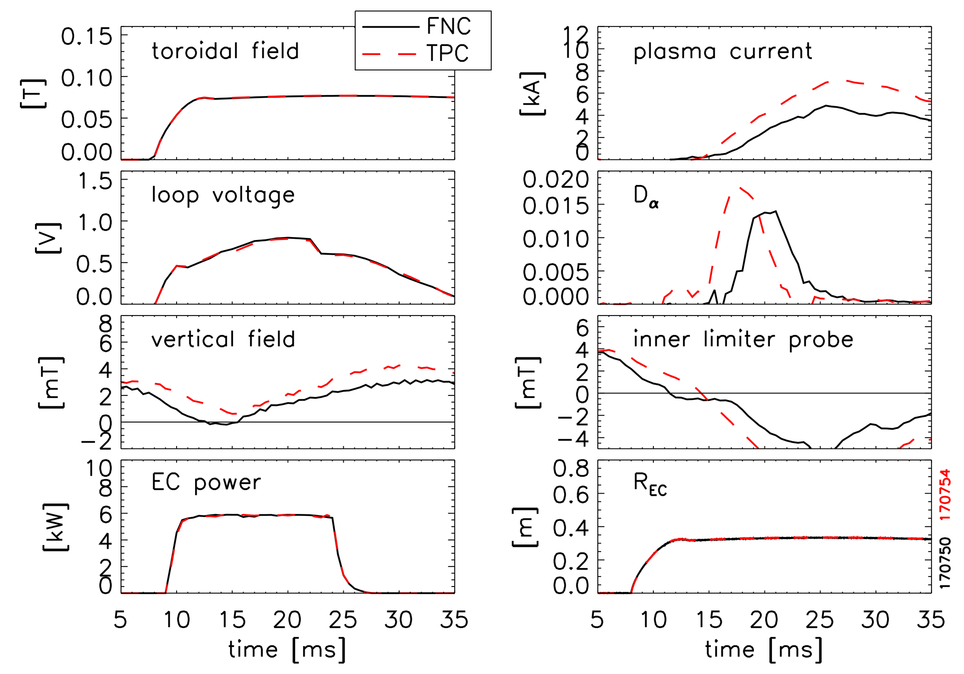
Major radius	0.36 m
Minor raduis	0.23 m
Toroidal field	<0.16 T
Plasma current	<27 kA
Electron density	$<1\times10^{18}\,\mathrm{m^{-3}}$
Electron temperature	<100 eV
LH power (200 MHz)	100 kW × 4
Discharge duration	80 ms

RF (CS-free) operation parameters



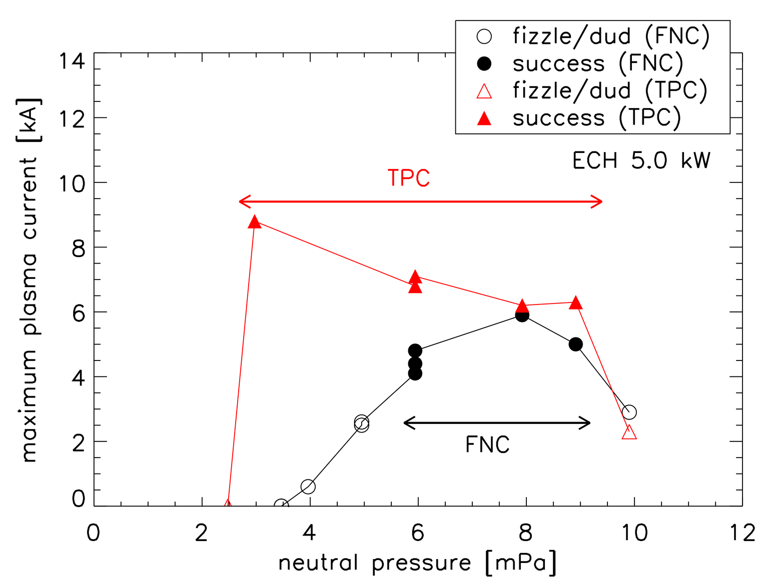
- Ohmic operation: 110 kA, $2\times10^{19}\,\mathrm{m^{-3}}$, 500 eV

Faster plasma current rise was observed for start-up with TPC compared to FNC



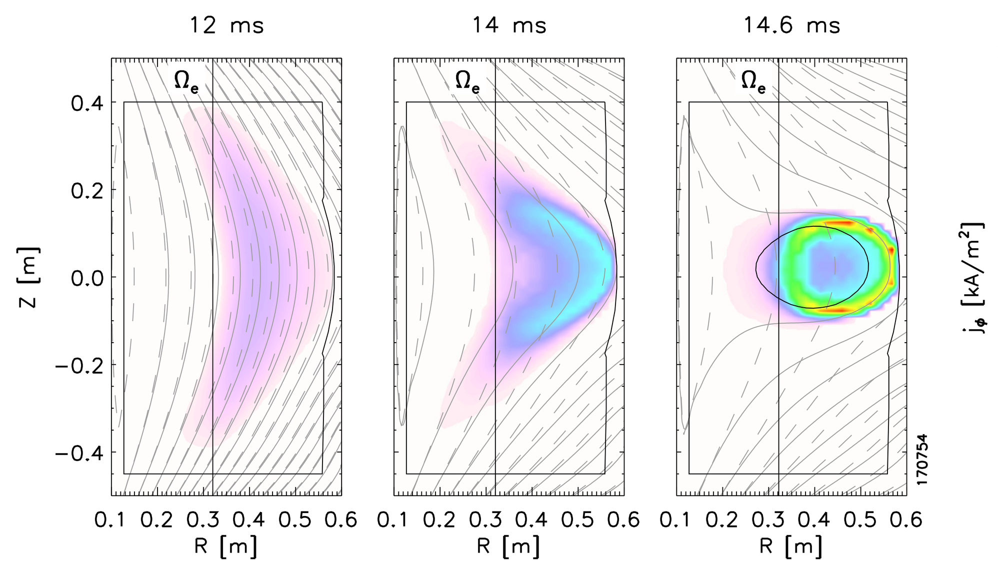
- Time of closed-flux-surface formation slightly earlier for the TPC

Higher plasma current was achieved with TPC compared to FNC at low neutral pressure



- Neutral pressure scan at:
  EC power: 5 kW (~8 kW/m³)
  CS flux swing: 0.013 Vs
- Start-up substantially improved with TPC at low neutral pressure
  - → strong impact of orbit optimization in the collisionless regime
- Small difference between TPC and FNC at high pressure
  - → weak magnetic configuration dependence in the collisional regime

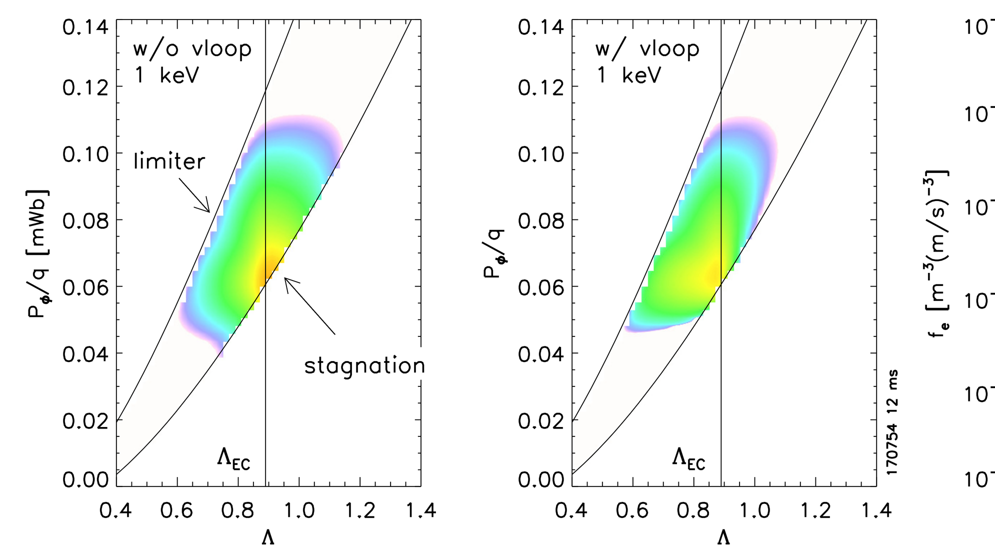
Extended MHD equilibrium reconstructed from vacuum to closed-flux-surface formation



Dashed curves: vacuum field

- Consistent MHD equilibrium field and global electron distribution function that match the magnetics measurements were obtained
- Closed-flux-surfaces formed by kinetic electron current

Fast electrons were generated around the resonant velocity pitch

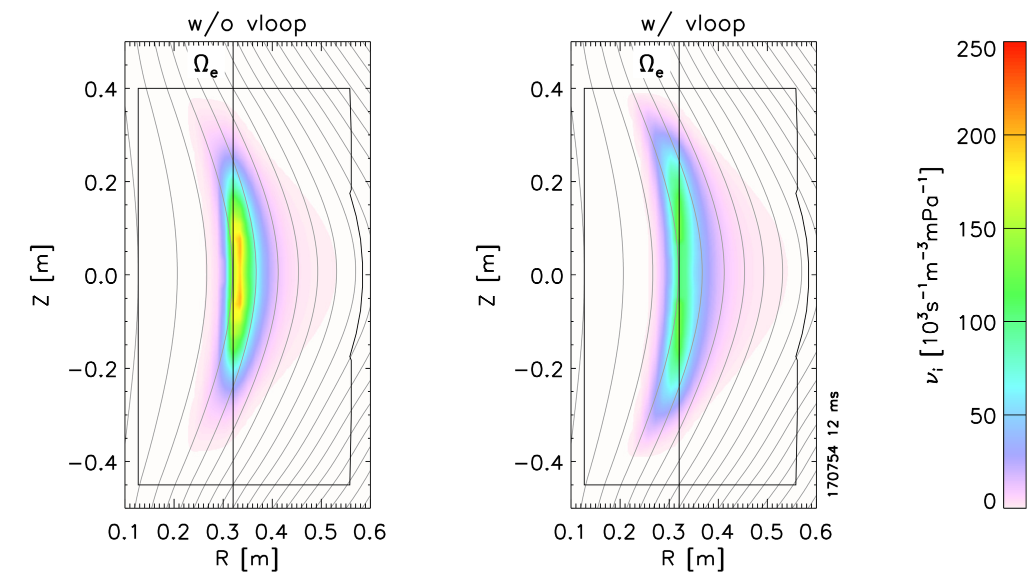


w/o loop voltage   w/ loop voltage

Phase space distribution at 1 keV

- Resonant velocity pitch Λ_{EC}
  - – turning point at EC resonance layer
- Loop voltage shifted the distribution to smaller velocity pitch Λ

Electron distribution expanded vertically when loop voltage was applied

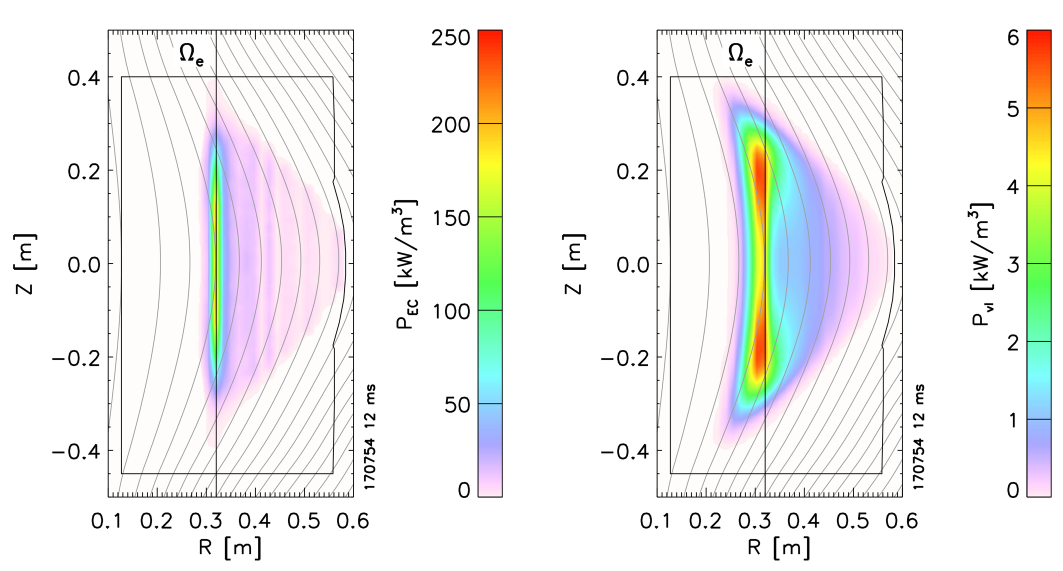


w/o loop voltage   w/ loop voltage

Ionization profile

- Loop voltage: transport towards smaller velocity pitch Λ
- EC waves: transport towards larger velocity pitch up to Λ_{EC}
- Improved synergistic acceleration at greater P_ϕ/q

Ohmic heating localized around EC resonance layer



EC heating power   Ohmic heating power

- Efficient DC E-field acceleration of EC generated energetic electrons
- EC heating dominated over Ohmic heating during early start-up phase

Conclusions

- Extended MHD equilibrium reconstruction was applied to EC assisted Ohmic start-up discharge
- Equilibrium field and electron distribution function consistent with magnetics were reconstructed
- Kinetic electron current was sufficient to close flux surfaces
- EC heating dominated over Ohmic heating up to closed-flux-surface formation