

Studies of fast electron dynamics in rf start-up plasmas on the TST-2 spherical tokamak

N. Tsujii, A. Ejiri, K. Shinohara, S. Jang, O. Watanabe, Y. Peng,
K. Iwasaki, Y. Ko, Y. Lin, T. Hidano, Y. Shirasawa, Y. Tian,
F. Adachi and C.P. Moeller¹

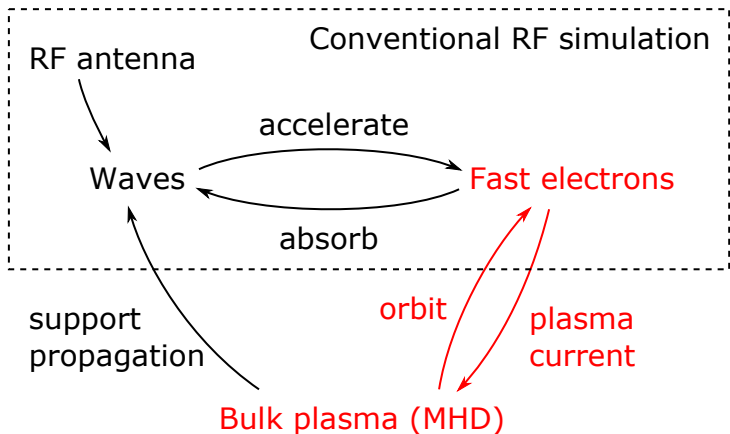
The University of Tokyo, ¹General Atomics

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THE UNIVERSITY OF TOKYO

LH driven plasma is a self-organized system that arises from interactions between waves, fast electrons and MHD



- Fast electron current dominates in rf start-up plasmas
→ Fast electron and MHD model needs to be improved

Outline

- 1 Extended MHD equilibrium reconstruction
- 2 The TST-2 experiment
- 3 Analysis of LH start-up experimental results
 - Outer-midplane launch scenario
 - Top launch scenario
- 4 Development of the off-midplane launch antenna
- 5 Summary

Extended MHD equilibrium reconstruction¹: bulk MHD fluid and collisionless fast electrons

Force balance of bulk plasma

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

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

$P(\psi)$: bulk pressure

$F(\psi)$: bulk poloidal current

$\nabla \cdot \mathbf{j}_{\text{fast}} = 0 \rightarrow$ define stream function G

$$j_{\text{fast},R} = -\frac{1}{R} \frac{\partial G}{\partial Z}, \quad j_{\text{fast},Z} = \frac{1}{R} \frac{\partial G}{\partial R}$$

¹E.V. Belova et al., Phys. Plasmas **10**, 3240 (2003).

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Fast electron current obtained from moments of the orbit-averaged distribution function

$$f_{\text{fast}} = f_{\text{fast}}(\mathcal{E}, \mu, \psi^*, \sigma)$$

$$\mathcal{E} = \frac{m_e v^2}{2} \quad : \text{total energy}$$

$$\mu = \frac{m_e v_{\perp}^2}{2B} \quad : \text{magnetic moment}$$

$$\psi^* = \psi + \frac{RB_{\phi}}{\Omega_e} v_{\parallel} \quad : \text{toroidal angular momentum per charge}$$

$$\sigma = \frac{v_{\parallel}}{|v_{\parallel}|} \quad : \text{parallel velocity sign}$$

$\mathbf{j}_{\text{fast}}$ can be written in terms of moments of f_{fast}

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

Fit the parametrized fast electron distribution function in the equilibrium reconstruction¹

$$f_{\text{fast}}(\mathcal{E}, \mu, \psi^*, \sigma; T_{\text{e0}}, R_0, R_1, I_{\text{fast}}, \mathcal{E}_{\text{min}}, \mathcal{E}_{\text{max}}, \sigma_0) \\ = \begin{cases} \mathcal{N} \exp\left(-\frac{\mu B_0}{T_{\text{e0}}}\right) \exp\left(-\frac{(\psi^* - \bar{\psi})^2}{\Delta\psi^2}\right) & \text{if } \mathcal{E}_{\text{min}} < \mathcal{E} < \mathcal{E}_{\text{max}}, \sigma = \sigma_0 \\ 0 & \text{otherwise} \end{cases}$$

$$\Delta\psi = (\psi_0 - \psi(R_1))/2$$

$$\bar{\psi} = \bar{\psi}(\mathcal{E}; R_0) \text{ (depends on the scenario)}$$

$$I_{\text{fast}} = \int dR dZ j_{\text{fast},\phi}$$

Subscript 0 denotes value at $R = R_0$

- $v_{\parallel}$: plateau from $\mathcal{E}_{\text{min}} = 9T_{\text{e0}}$ to $\mathcal{E}_{\text{max}} = m_e c^2 / 2n_{\parallel}^2$
- $v_{\perp}$: Maxwellian at $T_{\text{e0}} \leftarrow$ measured bulk temperature
- Spatial profile determined by R_1 : inner edge, R_0 : center

¹N. Tsujii et al., Nucl. Fusion **61**, 116047 (2021).

Outline

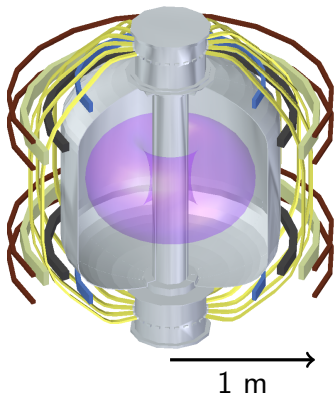
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TST-2 spherical tokamak device

Major radius	0.36 m
Minor radius	0.23 m
Toroidal field	< 0.16 T
Plasma current	< 27 kA
Electron density	$< 1 \times 10^{18} \text{ m}^{-3}$
Electron temperature	< 100 eV
LH power	$100 \text{ kW} \times 4$
Discharge duration	80 ms

Non-inductive operation parameters

- Ohmic operation: 110 kA , $2 \times 10^{19} \text{ m}^{-3}$, 500 eV

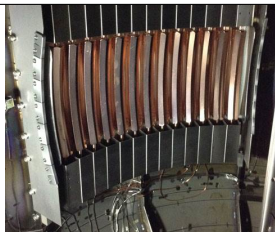


Capacitively coupled combline antennas are used to excite LH waves at 200 MHz

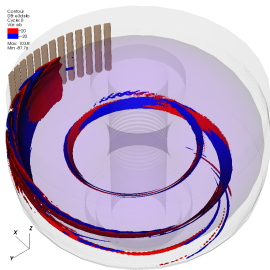
Top launch



Outer-midplane launch



- Two feeders (in & out)
- Transmission line in vacuum
- Couples to LH waves in the presence of plasma

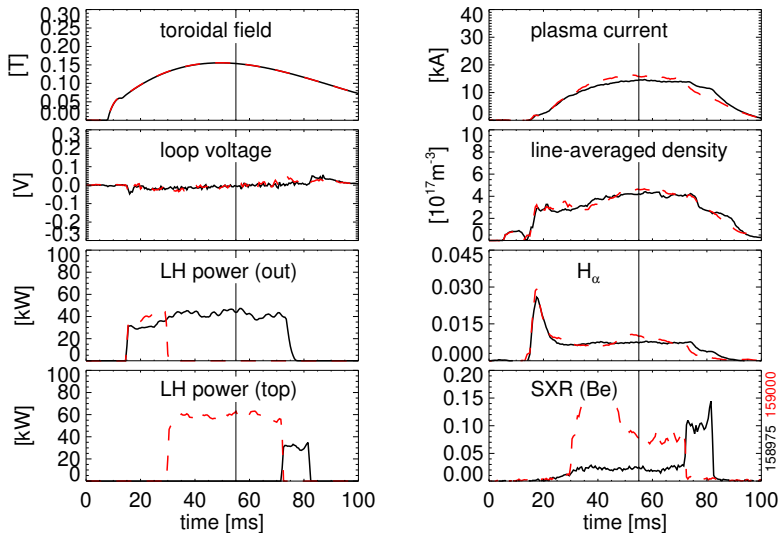


LH waves simulated by AORSA

Trigger Time 17/12/13 13:39:26.704054 Frame +00000100



Fully non-inductive operation using LH waves

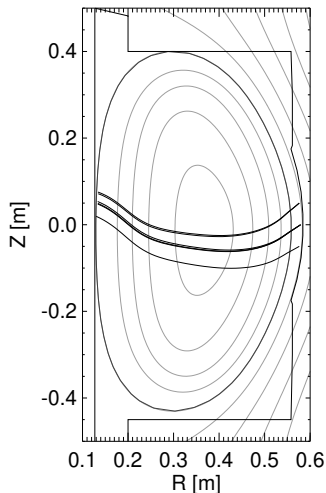
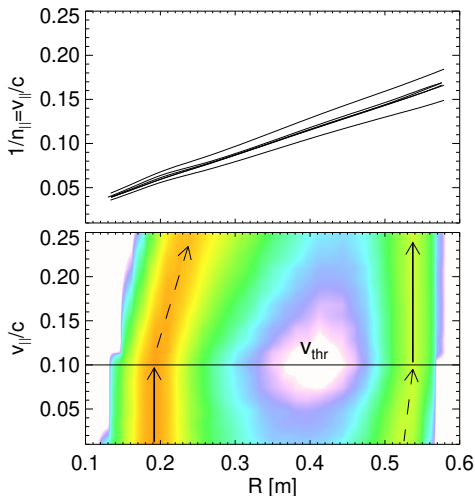


- Substantially higher x-ray radiation during top launch

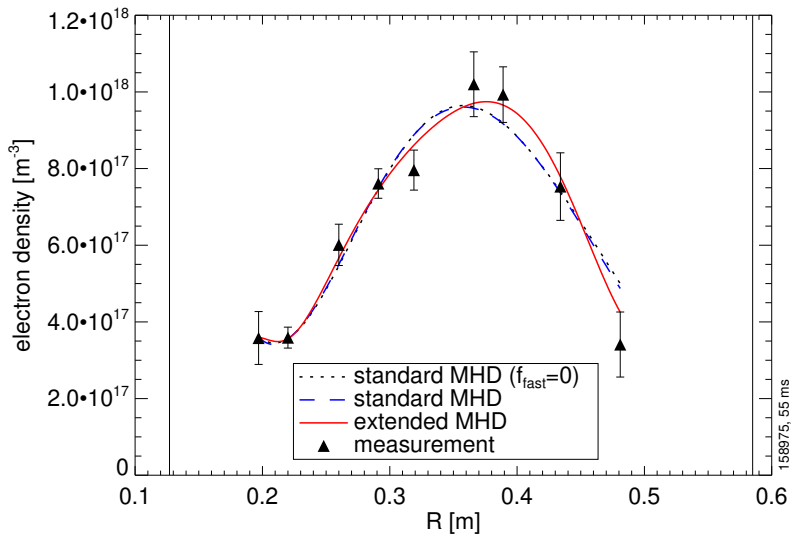
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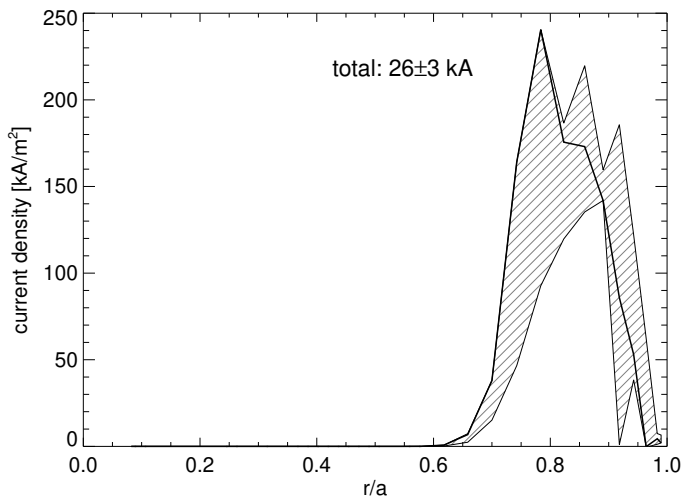
Outer-midplane launch: assume HFS acceleration at low energy, LFS acceleration at high energy



Outer-midplane launch: electron density profile fit improved with extended MHD

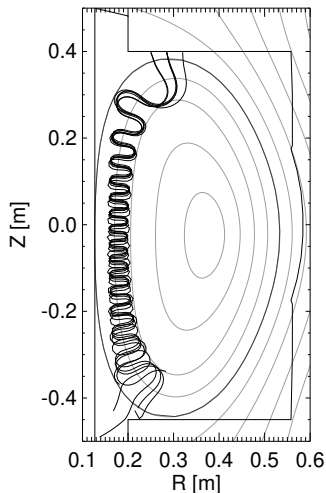
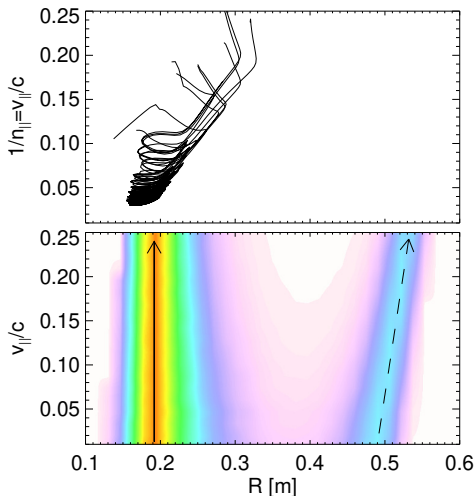


Outer-midplane launch: simulation¹ within a factor of two of the experimental result

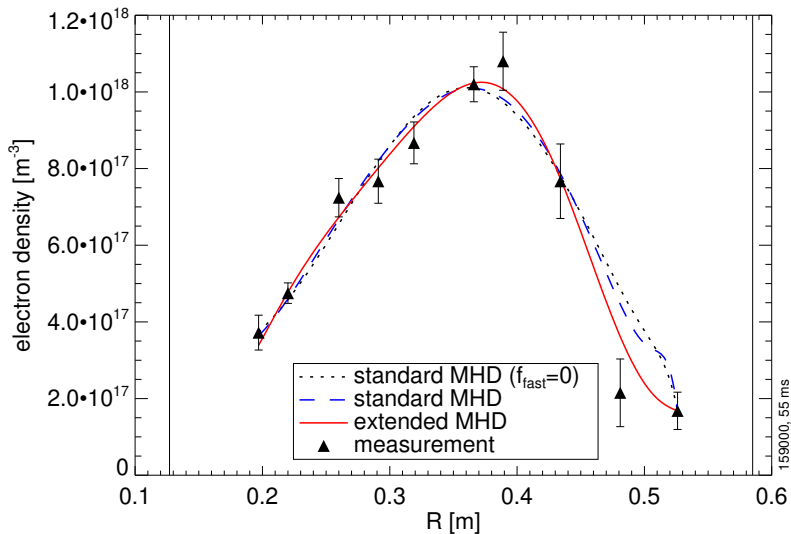


¹Simulation by GENRAY-CQL3D (<https://www.compxco.com/>).

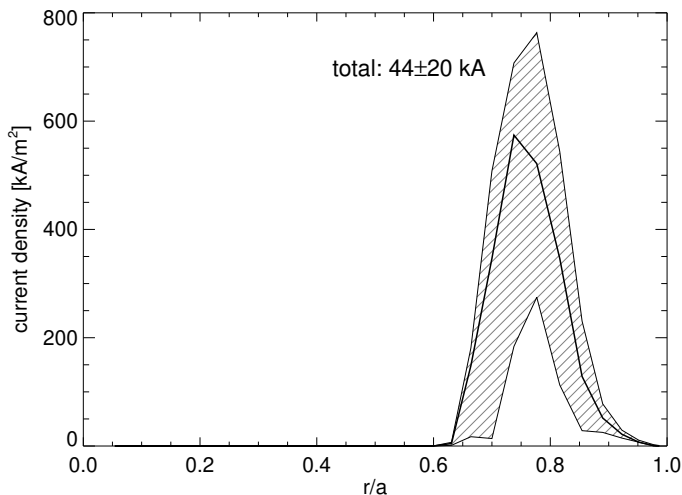
Top-launch: assume HFS acceleration regardless of the energy



Top-launch: electron density profile fit improved with extended MHD



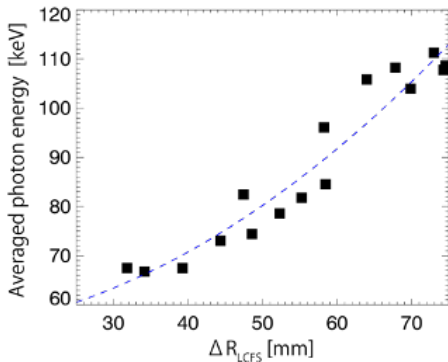
Top launch: simulation overestimates the experiment by a factor of three



- Orbit loss not fully simulated

The measured hard x-ray energy increases strongly as a function of the outer gap during top launch operation

- Not expected from zero orbit width model
- Radiation intensity too large for coming from core plasma
→ Thick-target radiation?
- Radial transport due to finite orbit effects may be responsible

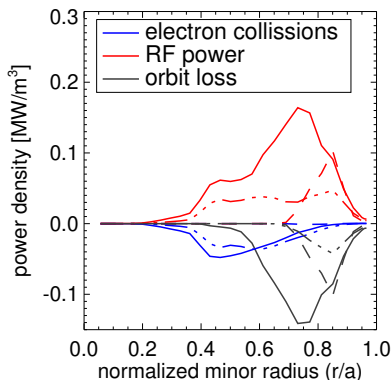
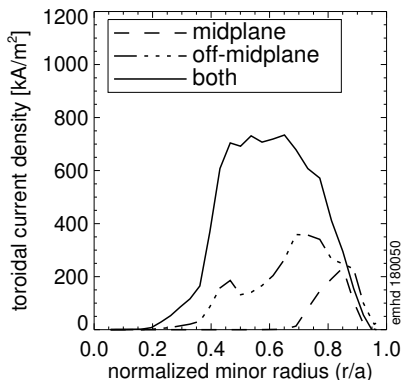


H. Yamazaki

Outline

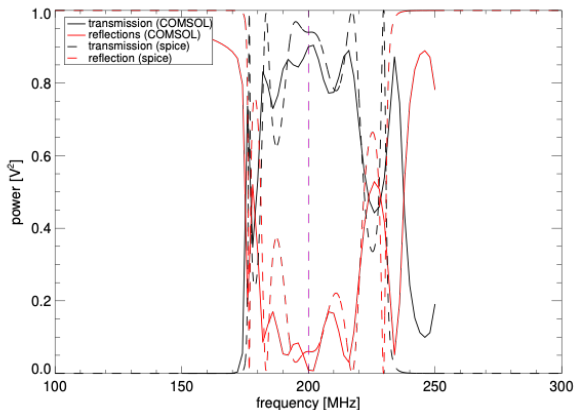
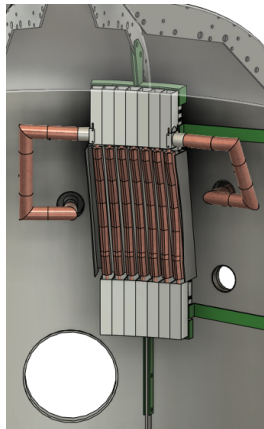
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Off-midplane launch is expected to drive more current than the midplane launch



- Synergy between off-midplane and midplane launch
- Improved heating power density

The off-midplane launch antenna has been installed in TST-2 and experiment is about to start



- Predicted reflection/transmission characteristics confirmed in bench-test

Y. Ko

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Summary

- Extended MHD reconstruction was developed to better describe the fast electron current dominated plasma
 - ▶ Outer-midplane launch scenario: simulation was within a factor of two of the experiment
 - ▶ Top launch scenario: simulation overestimated the experiment by a factor of three → finite-orbit simulation may be required
- Off-midplane launch antenna was newly developed
 - ▶ Mid-radius current drive
 - ▶ Strong single pass absorption
 - ▶ Synergy with outer-midplane launch

Acknowledgements

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