Doubling the Efficiency of Off-Axis Current Drive Using Reactor-relevant 'Top Launch ECCD' on the DIII-D Tokamak

by

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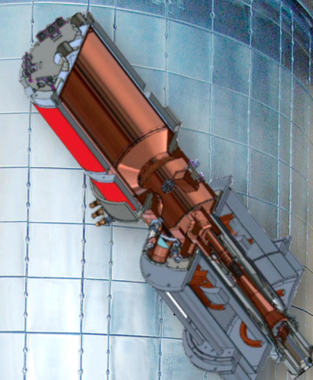

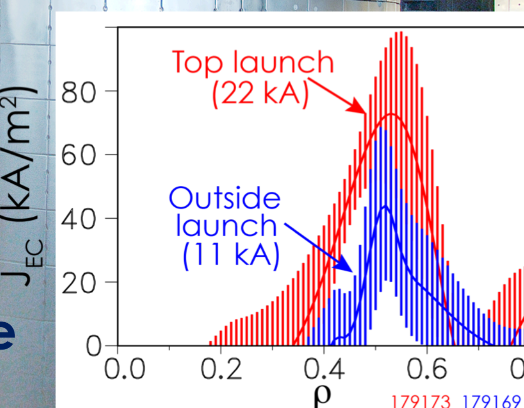

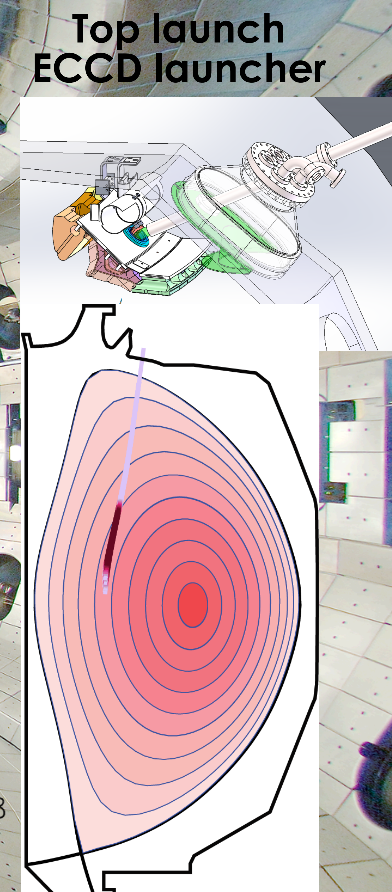

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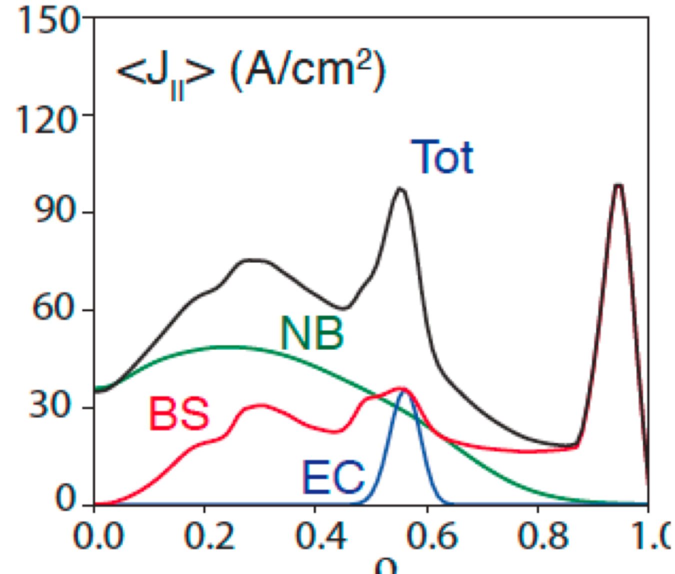
Steady-State Advanced Tokamak (AT) Operation Requires Efficient Off-Axis Current Drive

- **Off-axis current drive is needed to achieve the broad "AT" current profile favorable for stability and transport**
  - High CD efficiency (ξ_{CD}) is needed for high fusion gain → $Q = P_{fus}/P_{aux} \sim \xi_{CD}$

- **Efficient methods of off-axis current drive need to be demonstrated in ongoing fusion experiments**
  - Top launch ECCD is one of the reactor-relevant techniques being developed on DIII-D to efficiently drive current at the right location

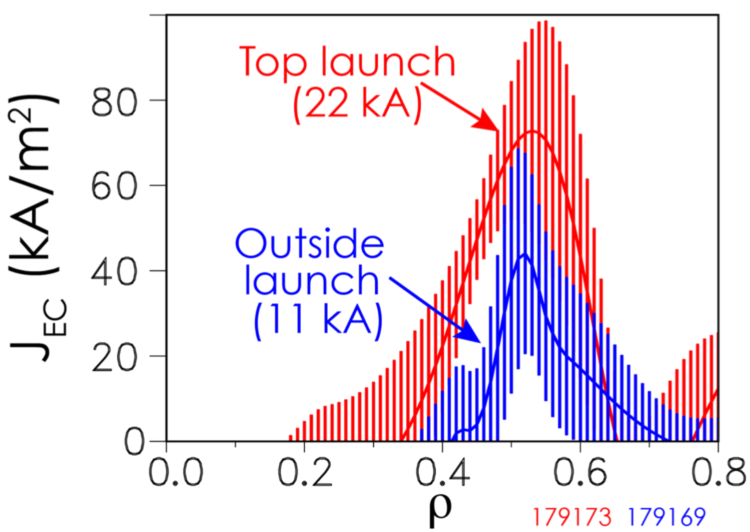
$f_{NI}=1$, $\beta_N>4$, high q_{min}

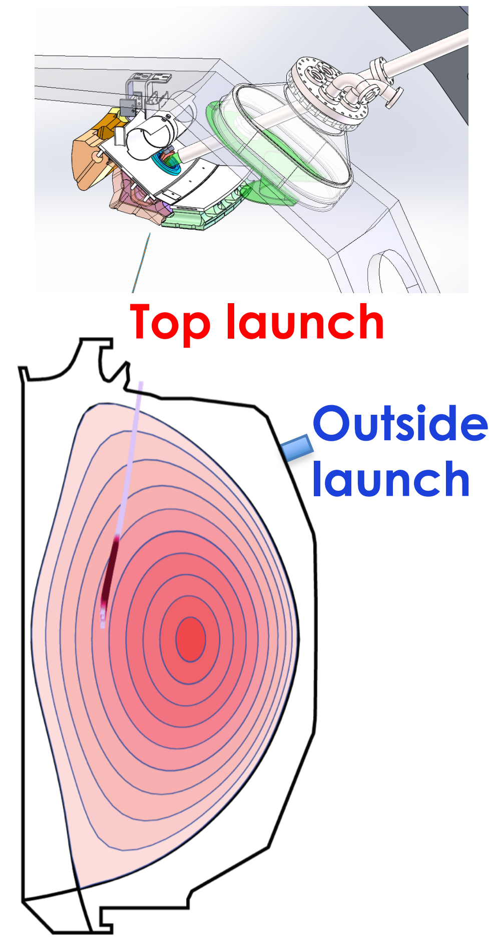


Modelled DIII-D shot

Doubling of Off-axis ECCD Achieved on DIII-D via Reactor-relevant ‘Top Launch ECCD’ Approach

- **New top launch ECCD system is installed on DIII-D to allow experimental validation**
- **Experiments tested main tenets of top launch ECCD**
  - Geometry allows selective wave interaction with high $V_{||}$ electrons having high CD efficiency
  - Long absorption path compensates for inherently weak damping at high $V_{||}$





Outline

- **What's top launch ECCD?**
- Longer absorption zone with top launch ECCD
- Strong damping on high $v_{||}$ electrons
- Significantly higher off-axis ECCD measured on DIII-D
- Top launch ECCD for reactors

Top Launch ECCD with a Large Doppler Shift Ensures Strong Damping on Tail Electrons Leading to Higher ECCD

Top Launch ECCD injects EC wave[1]:

❶ nearly parallel to the resonance plane

➢***longer absorption path*** arises from EC trajectory that gradually approaches the resonance

❷ with strong toroidal steering

➢***increased Doppler shift*** ensures EC wave power is absorbed by higher energy (less collisional) electrons throughout long interaction zone

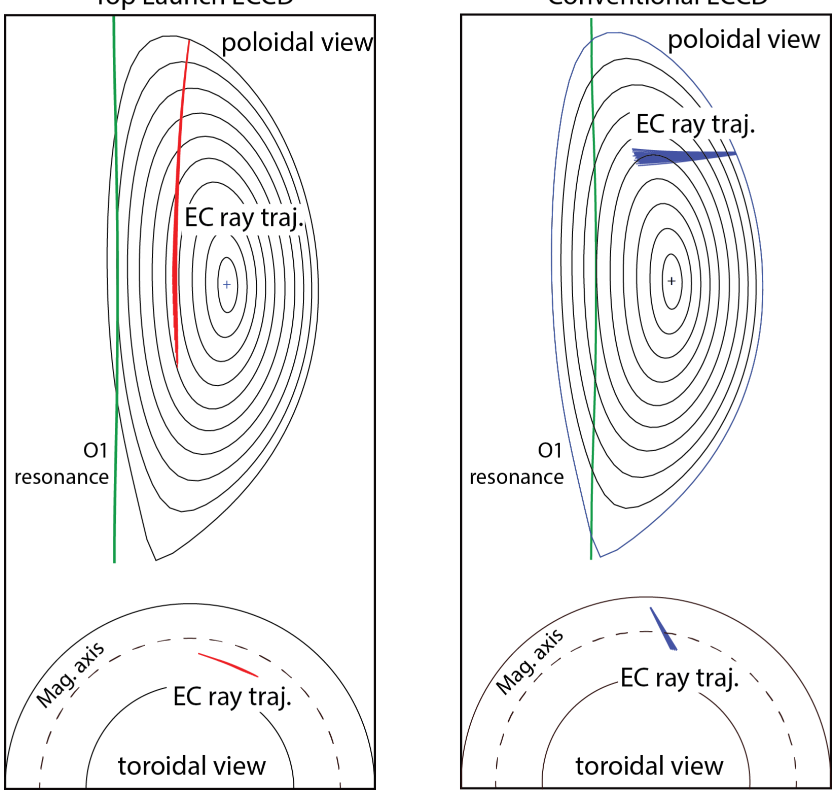
❸ on HFS of the plasma

➢***reduce trapping effects*** (reduce the cancellation of Ohkawa counter current)

❹ either O1 or X2-mode

➢Strongly absorbed for Te>1 keV

Ray Tracing Code TORAY Calculation

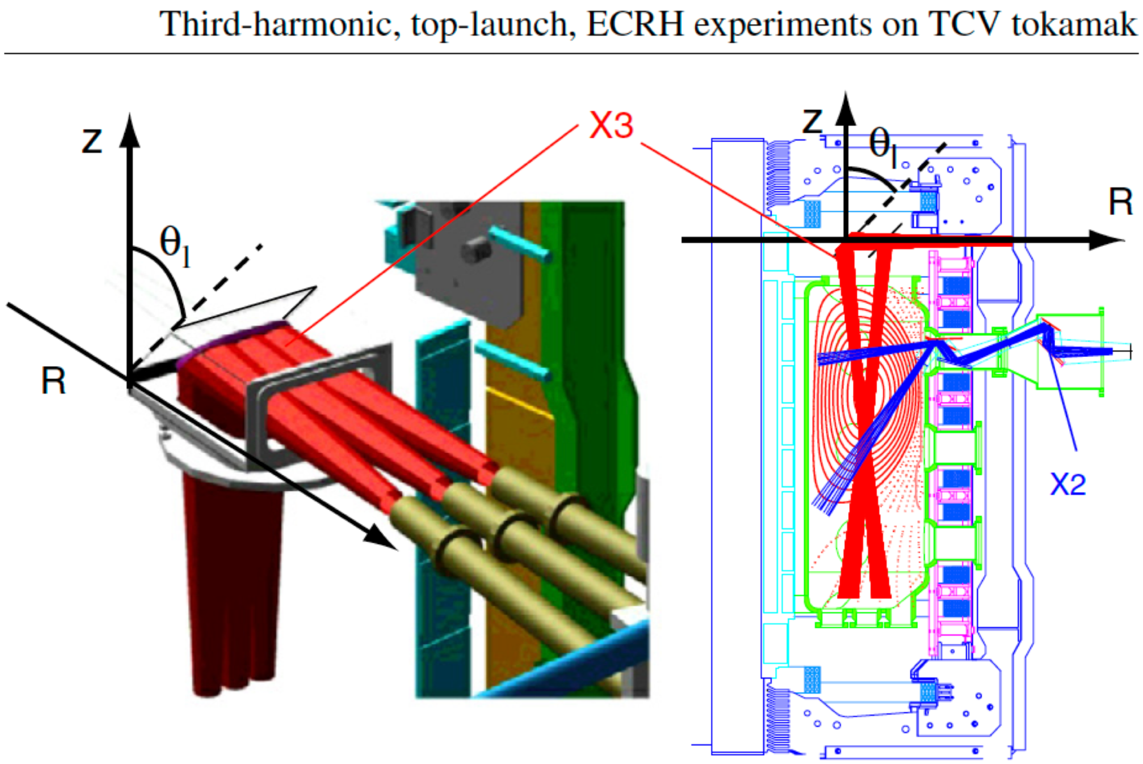


CFETR

[1] R. Prater, et al., APS (2012); E. Poli, et al., NF 53 (2013) 013011
[2] Xi Chen, et al., EPJ Web of Conferences, 203, 01004 (2019)

Top Launch ECCD Differs From TCV Top Launch ECH

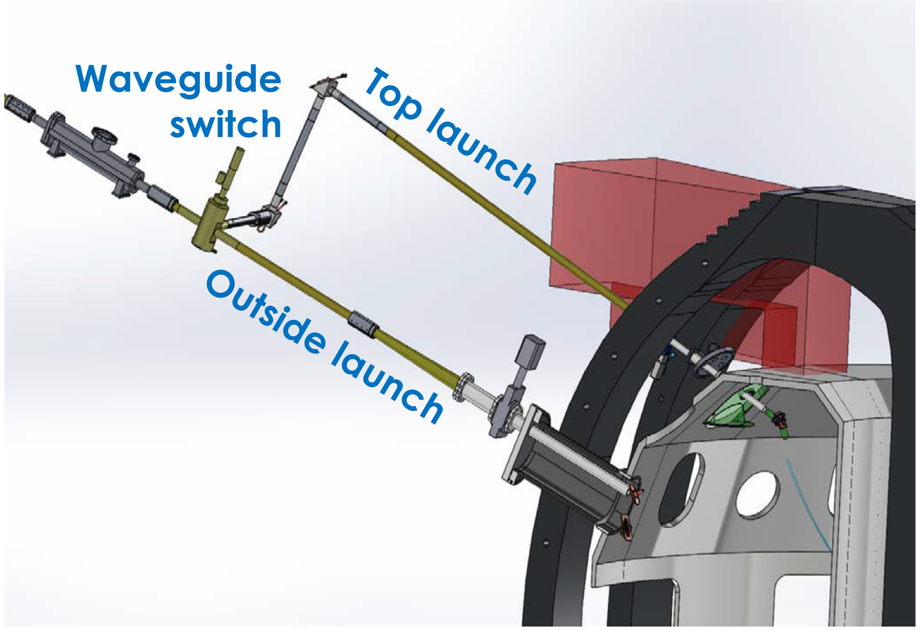
- **Important high density heating experiments have been done on TCV tokamak using top launch ECH[1]**
  - Launch EC wave with nearly zero toroidal steering
  - Use X3 to heat high density (> X2 cutoff) plasmas
  - Current drive not studied

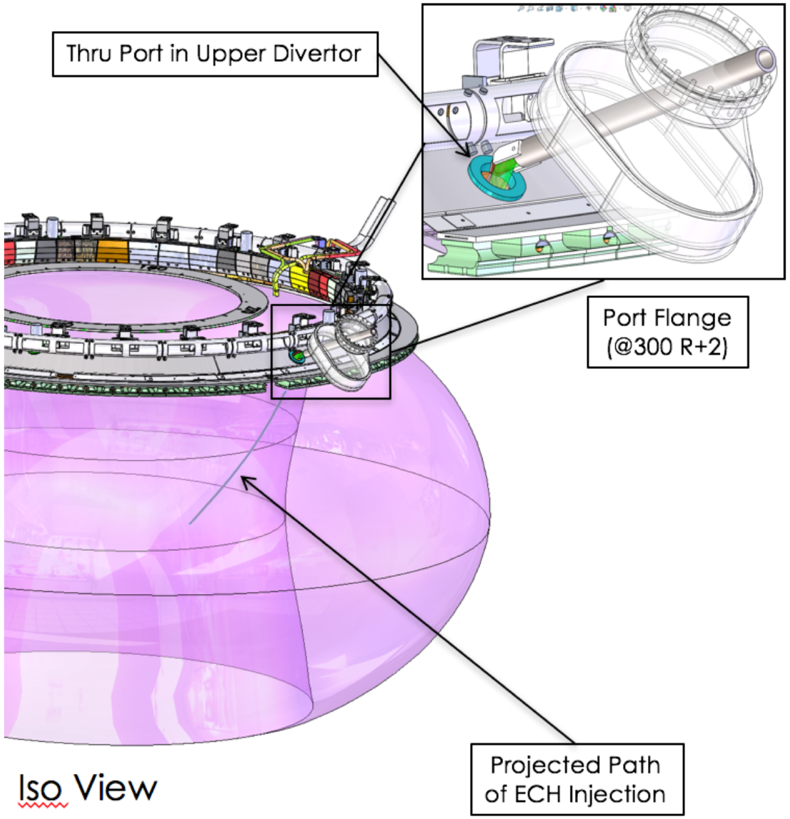


[1] S. Alberti, et al, NF 45 (2005) 1224

Fixed-injection Prototype System Installed on DIII-D to Evaluate and Characterize Top Launch ECCD Approach

- **New top launcher can be switched into existing waveguide**
  - Dedicated gyrotron is not needed
  - 2nd harmonic X-mode damping
  - 117.5 or 110 GHz gyrotron can be used





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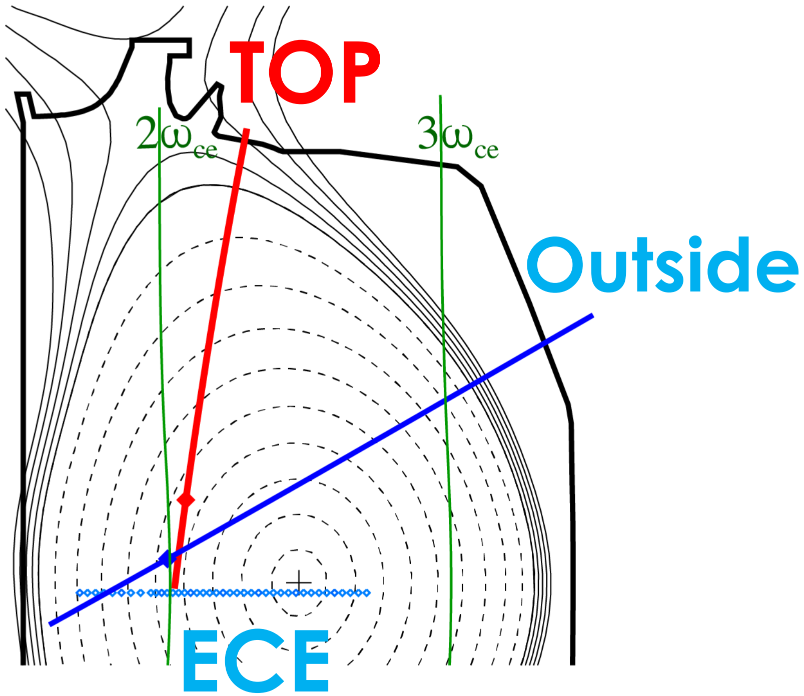
EC Power Deposition Profile Measured by Modulating Gyrotron Power and Observing T_e Oscillations

- **EC source and T_e response are related through Fourier-transformed energy conservation equation. In high frequency limit,**

$$\tilde{S}_{ECH} = \frac{3\pi}{4} \omega_M n_e \tilde{T}_e$$

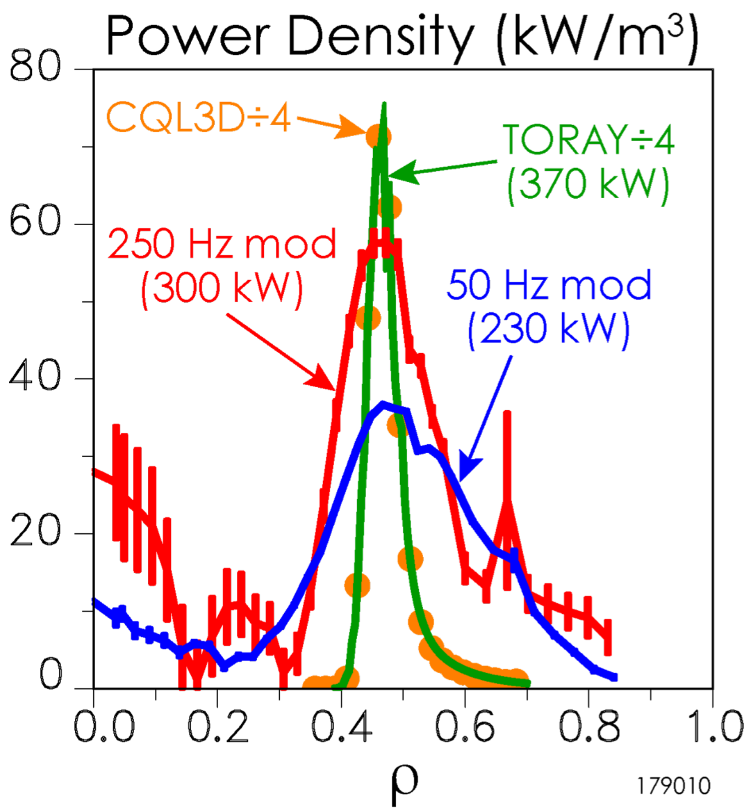
- **T_e response measured by Electron Cyclotron Emission (ECE) with high spatial and temporal resolution**

- **Experiments utilized various gyrotron modulation frequencies (ω_M)**



Measured Power Deposition of Top Launch ECCD Generally Agrees with TORAY and CQL3D Predictions

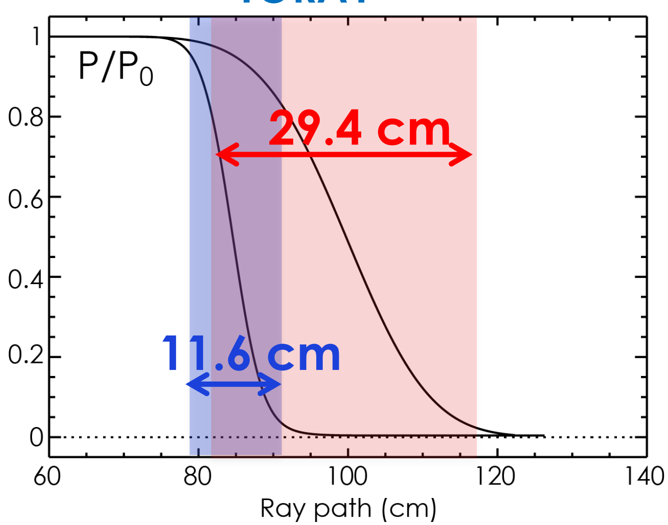
- **Ray tracing code TORAY models the Gaussian EC beam using a number of rays**
- **Quasi-linear Fokker-Planck CQL3D code calculates bounce-averaged electron distribution function and velocity-space fluxes**
- **Good agreement found between experimental and theoretical locations of top launch EC absorption**
- **Measured EC power deposition profile is in better agreement with theory for higher modulation frequencies (weaker transport effects)**



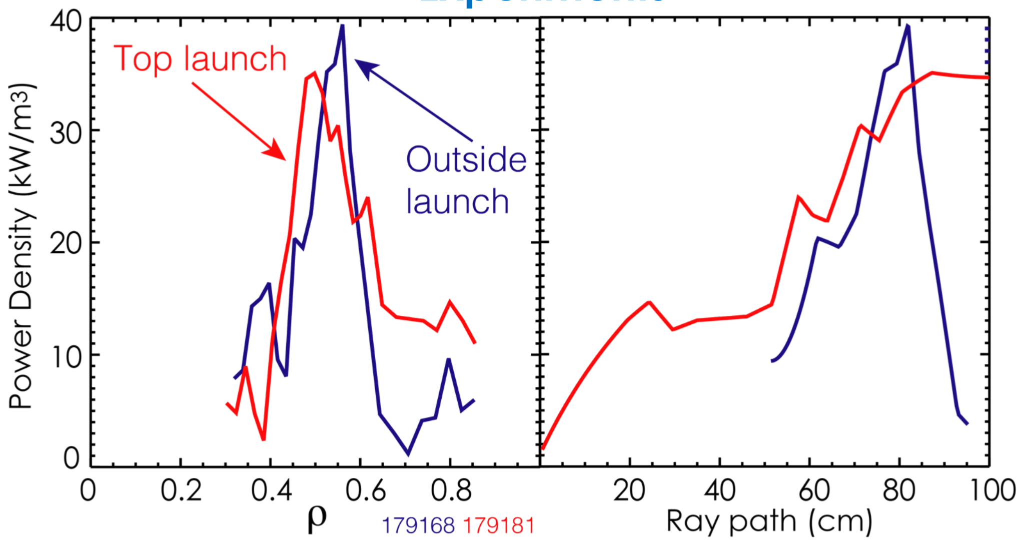
Broader Power Deposition Profile of Top Launch Confirms the Predicted Longer Absorption Zone

- **Theory predicts a *longer absorption path* for top launch, a result of EC waves approaching the resonance more gradually than for conventional outside launch**
- **Along ray path, the FWHM of EC power deposition profile measured by ECE is ~3x longer for top launch than outside launch ECCD**

TORAY



Experiments



110 GHz Gyrotron

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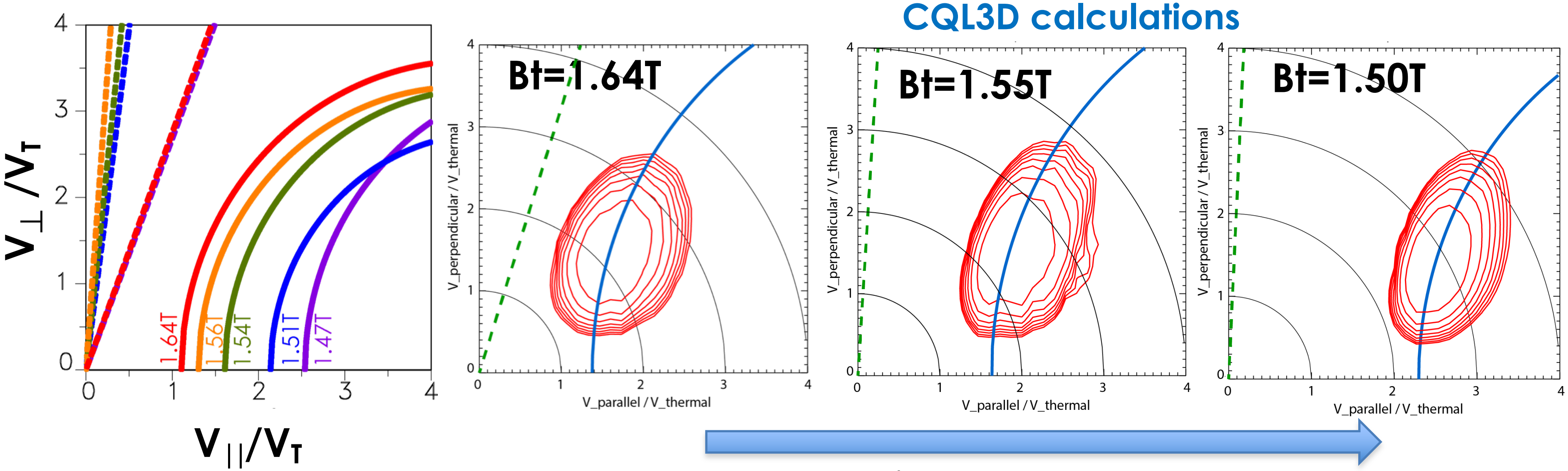
Top Launch ECCD Wave Interacts with Higher $V_{||}$ Electrons for Lower Magnetic Fields

- **Magnetic field (B_t) is scanned with fixed-injection to move the cold resonance location closer to or further away from the EC trajectory**
- **With fixed-injection, varying the magnetic field alters the wave-electron interactions in velocity space**
  - Lower B_t pushes resonance to higher $V_{\|}$
    Cyclotron resonance $\boxed{\omega - \omega_{ce}/\gamma = k_{\|}v_{\|}}$ where $\omega_{ce} \propto B$
  - Wave-Electron interaction follows

CQL3D calculations



Higher $V_{\|}$ electrons

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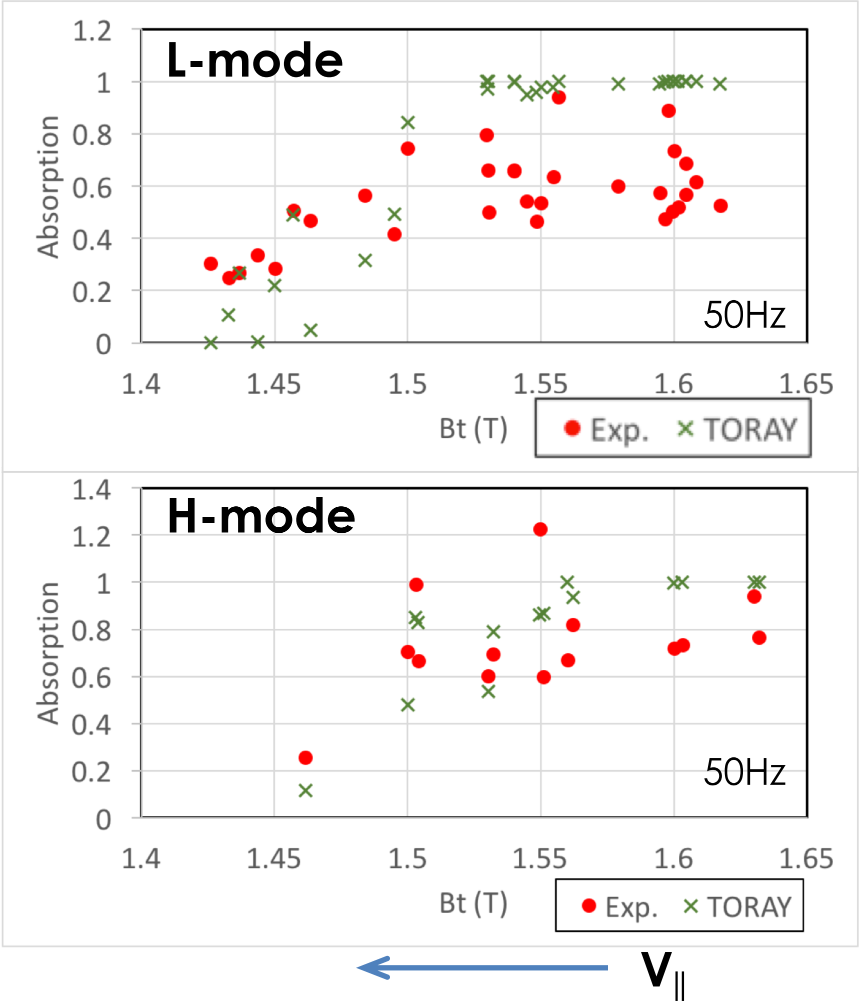
Top Launch EC Absorption is Reduced When Wave Interacts with Too Few High $V_{||}$ Electrons

- **Measured absorption fraction decreases with lower B_t (higher $V_{||}/V_t$), in agreement with TORAY, when the damping on tail electrons is too weak**

- **Since higher energy electrons drive current more efficiently, there is a optimum (optimal B_t) for top launch ECCD:**

High $V_{||}/V_t$ electrons + sufficient absorption → High ECCD efficiency



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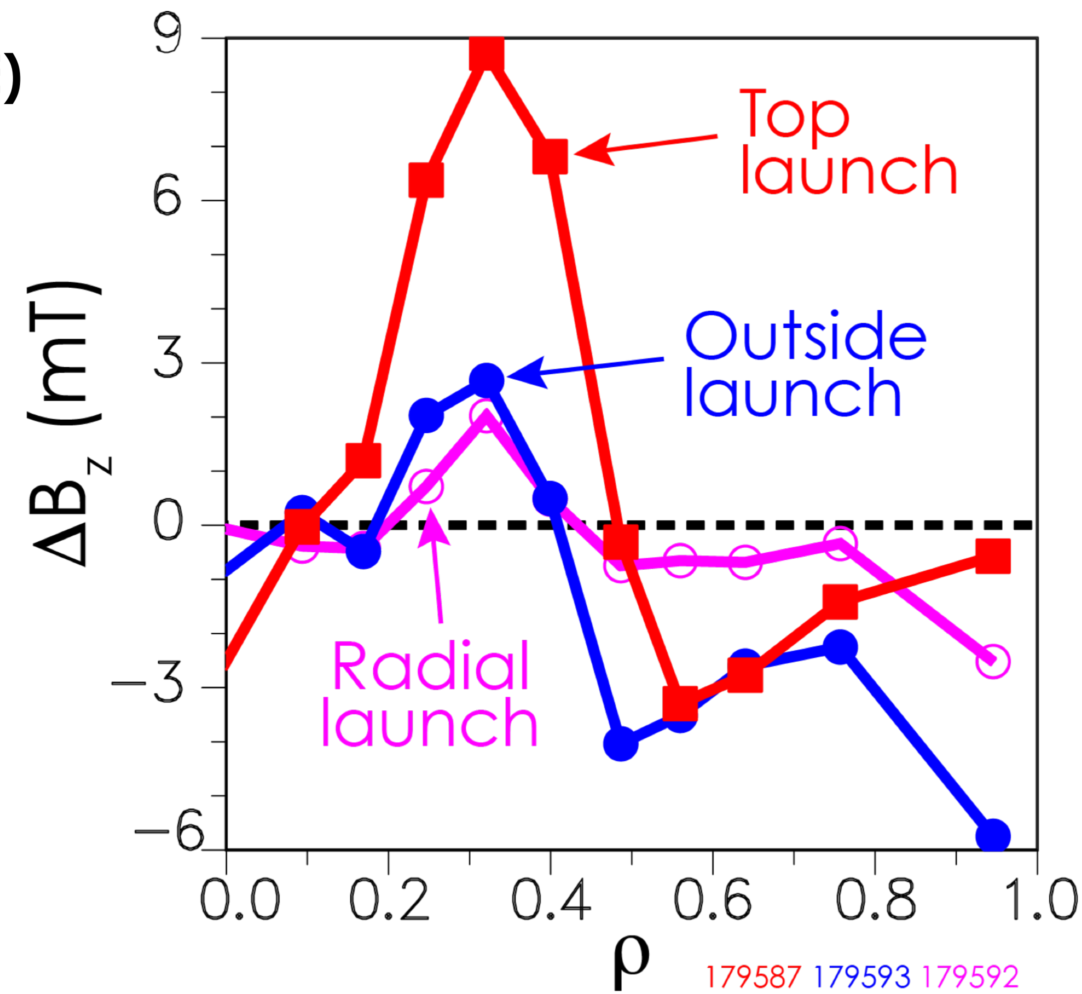
Larger Change in MSE Pitch Angles Observed for Top Launch Than For Outside Launch ECCD

- **Motional Stark effect (MSE) polarimetry measures vertical component of magnetic field (Bz) as a function of plasma radius**
- **Change in MSE signal compared to similar “no ECH” discharge shown**



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ECCD Profile Determined from Difference Between Oblique Launch and Radial Launch

- **Non-inductive current drive determined using Ohm's law:**

$$J_{\mathrm{NI}} = J_{\|} - \sigma_{\mathrm{neo}} E_{\|}$$

neoclassical conductivity

$$E_{\|} \sim \frac{1}{R_0} \frac{\partial \psi}{\partial t}$$

- **Pure heating effect eliminated by**

$$J_{\mathrm{EC}} = J_{\mathrm{NI}}(\mathrm{ECCD}) - J_{\mathrm{NI}}(\mathrm{ECH})$$

- **Two analysis methods used:**

Ⓐ determining $J_{\|}$ and $E_{\|}$ from equilibrium reconstruction with MSE data

➢narrow ECCD profile measured by using $\cos^2(k\psi)$ term in current reconstruction[1]

Ⓑ determining $J_{\|}$ and $E_{\|}$ directly from MSE data

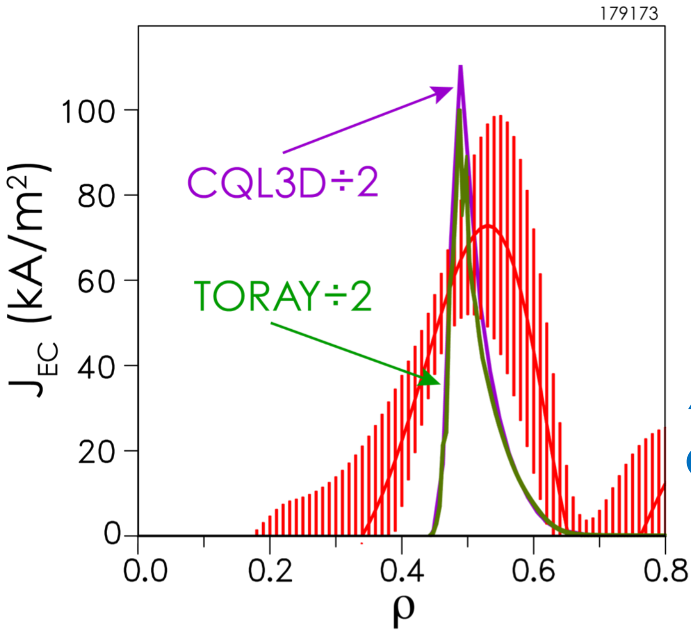
➢direct application of Ampere's and Faraday's laws to B_z profile[2]

[1] L.L. Lao, et al., Proc. 14th Top. Conf. on Radiofrequency Power in Plasmas (2001) p 310

[2] C.C. Petty, et al., PPCF **47** (2005) 1077

Measured Off-axis Current Profile via Top Launch ECCD is Generally Consistent with Theoretical Prediction

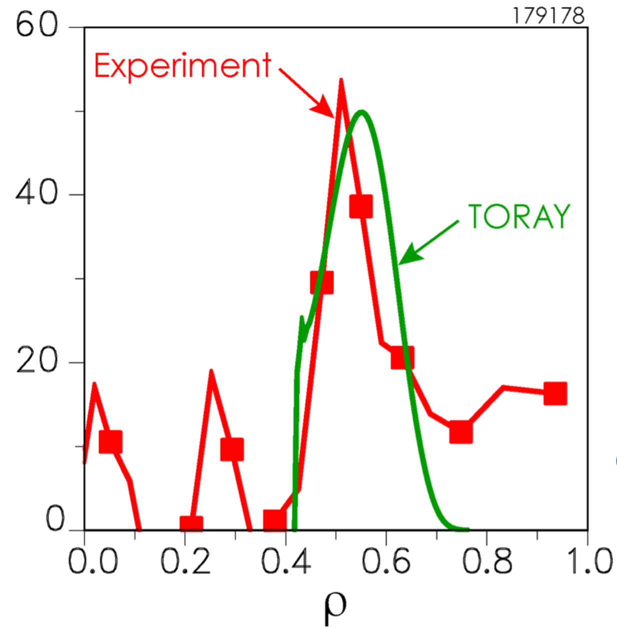
Loop voltage analysis for MSE EFITs with local $\cos^2(k\psi)$ representation



117.5 GHz Gyrotron

ELMing H-mode plasma, I_p = 0.6 MA, $T_e(0)$ = 3.3 keV, n_e = 1.7x10^{19} m^{-3}

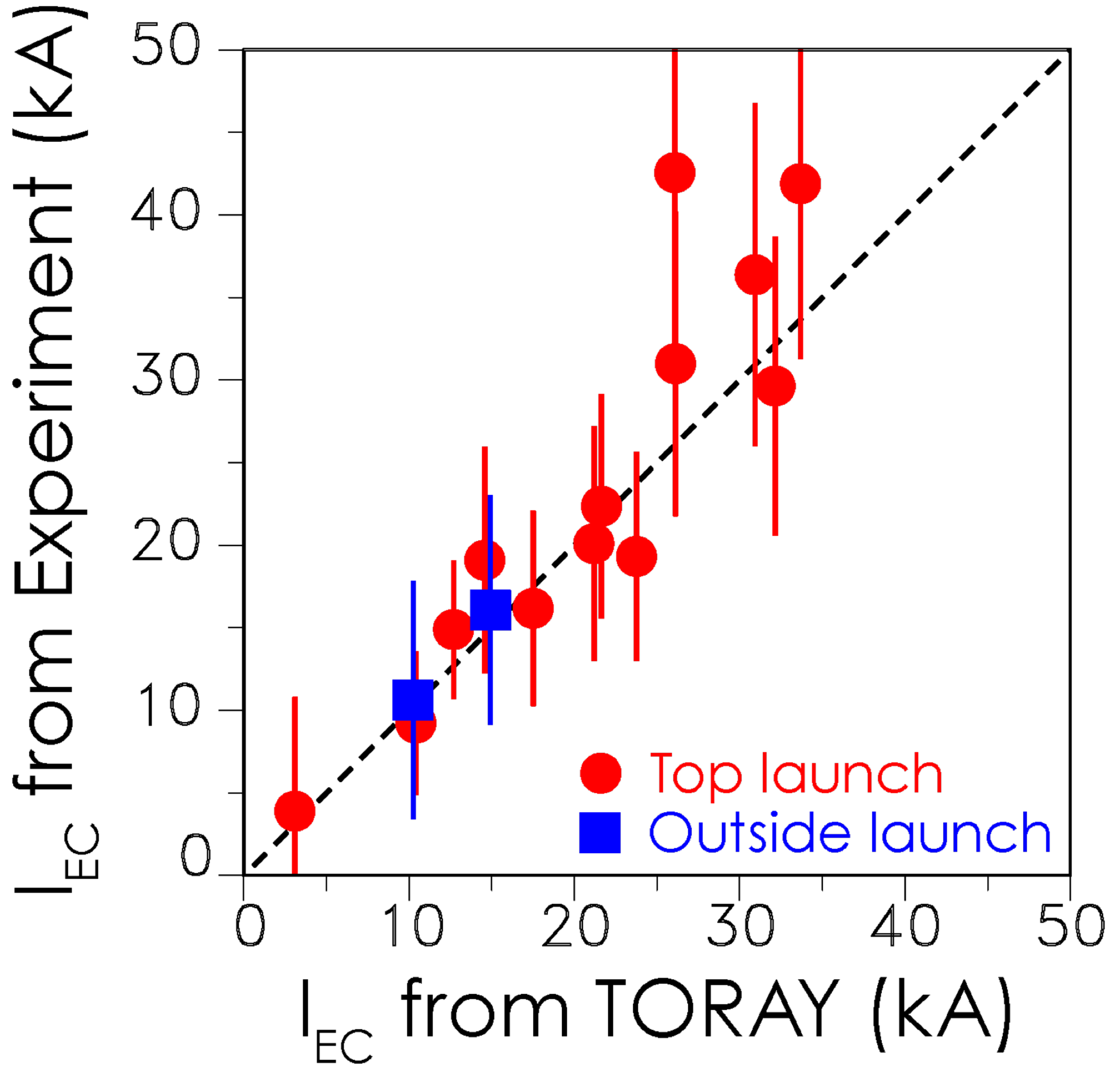
Direct MSE analysis method



110 GHz Gyrotron

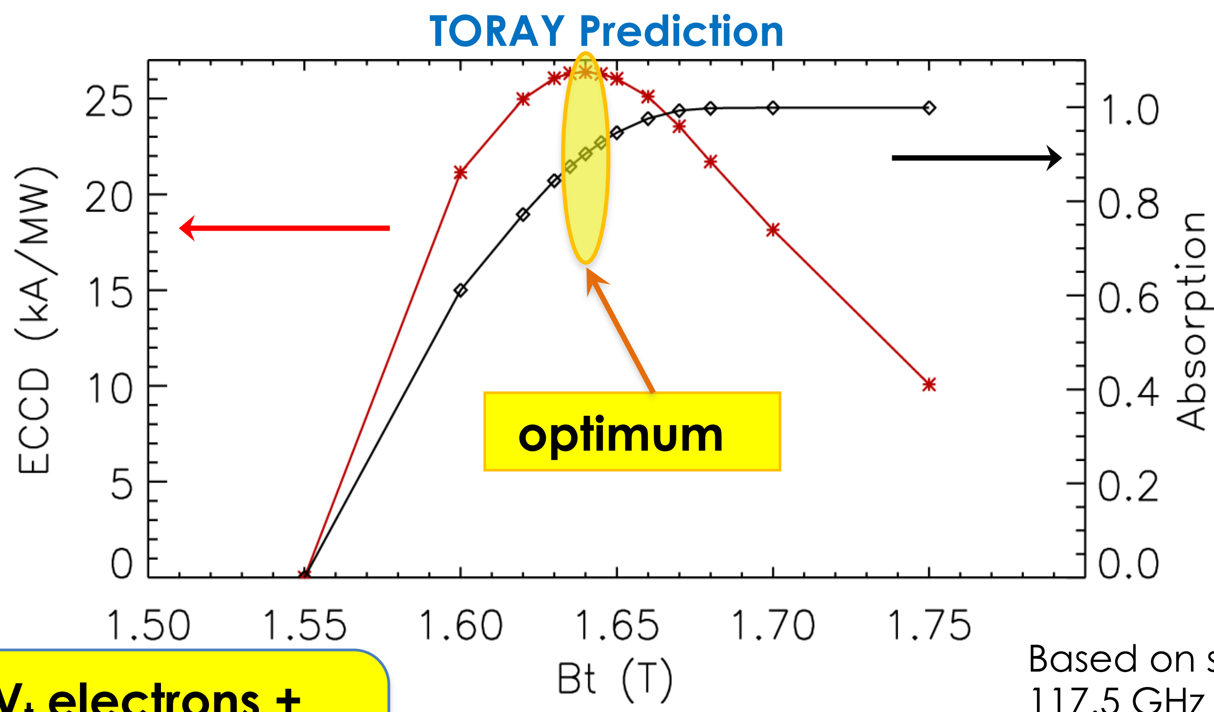
ELMing H-mode plasma, I_p = 0.6 MA, $T_e(0)$ = 2.5 keV, n_e = 1.7x10^{19} m^{-3}

Integrated ECCD Magnitude in Good Agreement with Theory



For Top Launch, Highest ECCD Predicted for Optimal Tail Electron Absorption

- **TORAY modeling of typical DIII-D 'AT' plasma predicts highest ECCD with absorption < 100 %**

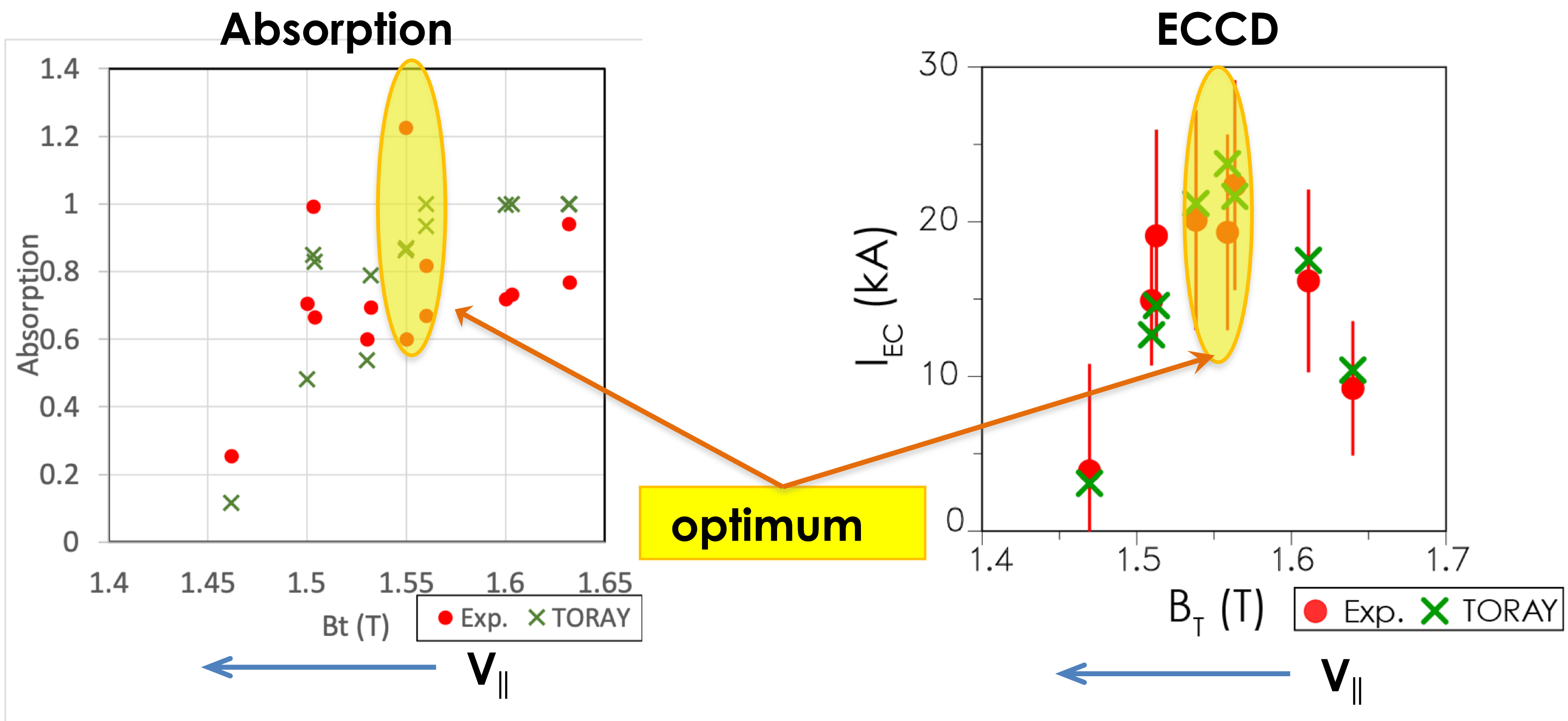


High $V_{\|}/V_t$ electrons + sufficient absorption → High ECCD efficiency

$V_{\|}$

Based on shot 147634, using 117.5 GHz gyroton

Highest ECCD via Top Launch Obtained for Bt Optimized for Sufficient Damping on Tail Electrons

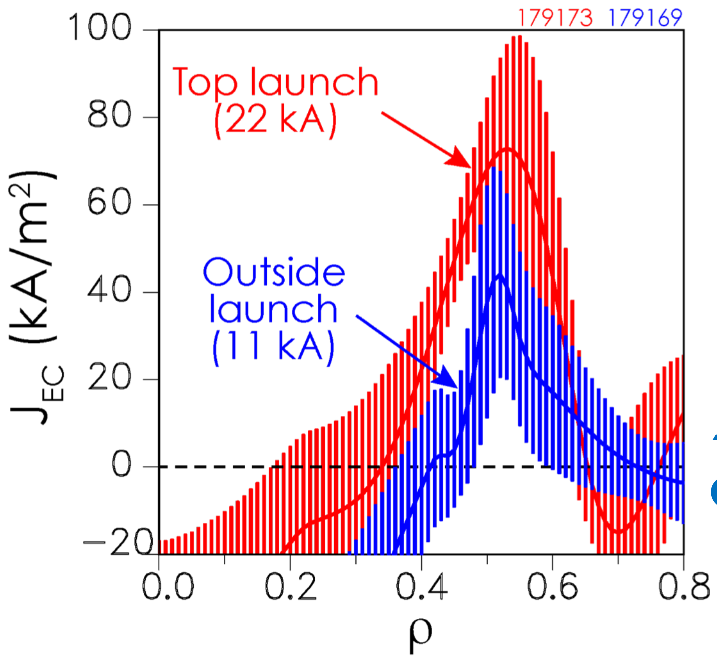


ELMing H-mode plasma $\langle I_p \rangle = 0.6$ MA, $\langle T_e(0) \rangle = 2.3$ keV, $\langle n_e \rangle = 1.5\times10^{19}$ m^{-3}

110 GHz Gyrotron

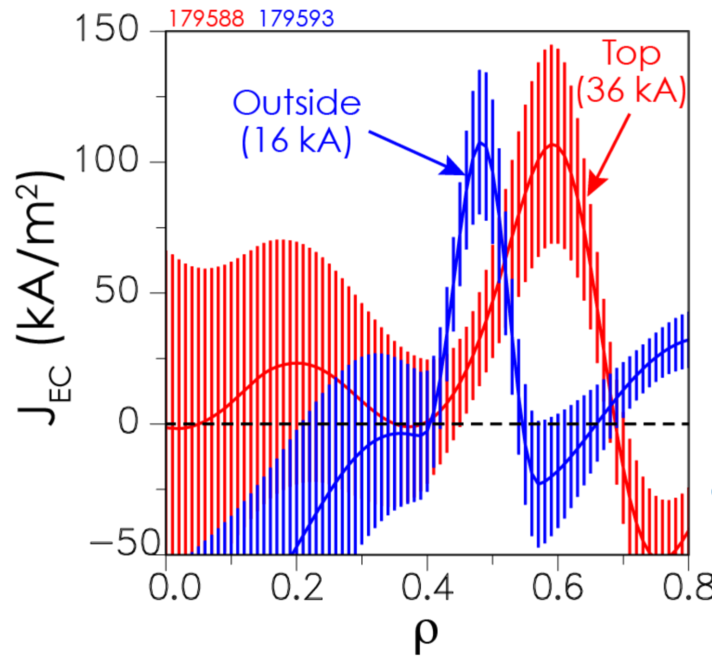
Greatly Enhanced ECCD at Mid-Radii Observed via Top Launch ECCD Compared to Outside Co-ECCD Launch

Loop voltage analysis for MSE EFITs with local $\cos^2(k\psi)$ representation



110 GHz Gyrotron

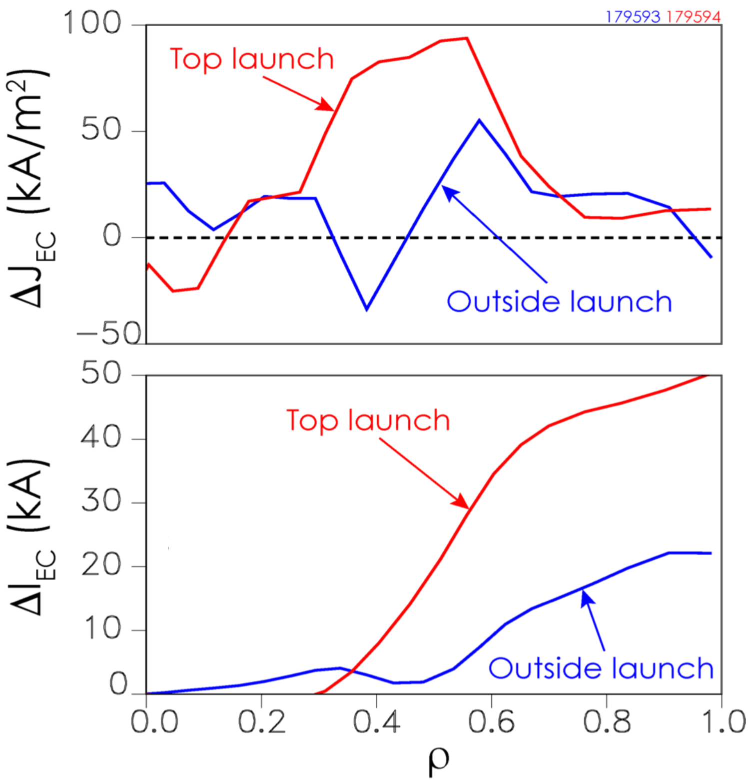
ELMing H-mode plasma, I_p = 0.6 MA, $T_e(0)$ = 2.3 keV, n_e = 1.6×10^{19} m^{-3}



117.5 GHz Gyrotron

ELMing H-mode plasma, I_p = 0.6 MA, $T_e(0)$ = 3.0 keV, n_e = 1.8×10^{19} m^{-3}

Direct MSE Analysis Confirms ECCD is More than Double for Top Launch, Consistent with TORAY and CQL3D



ECCD (kA/MW)	Top launch	LFS co-ECCD
Measured	70	25
TORAY	63	27
CQL3D	68	31

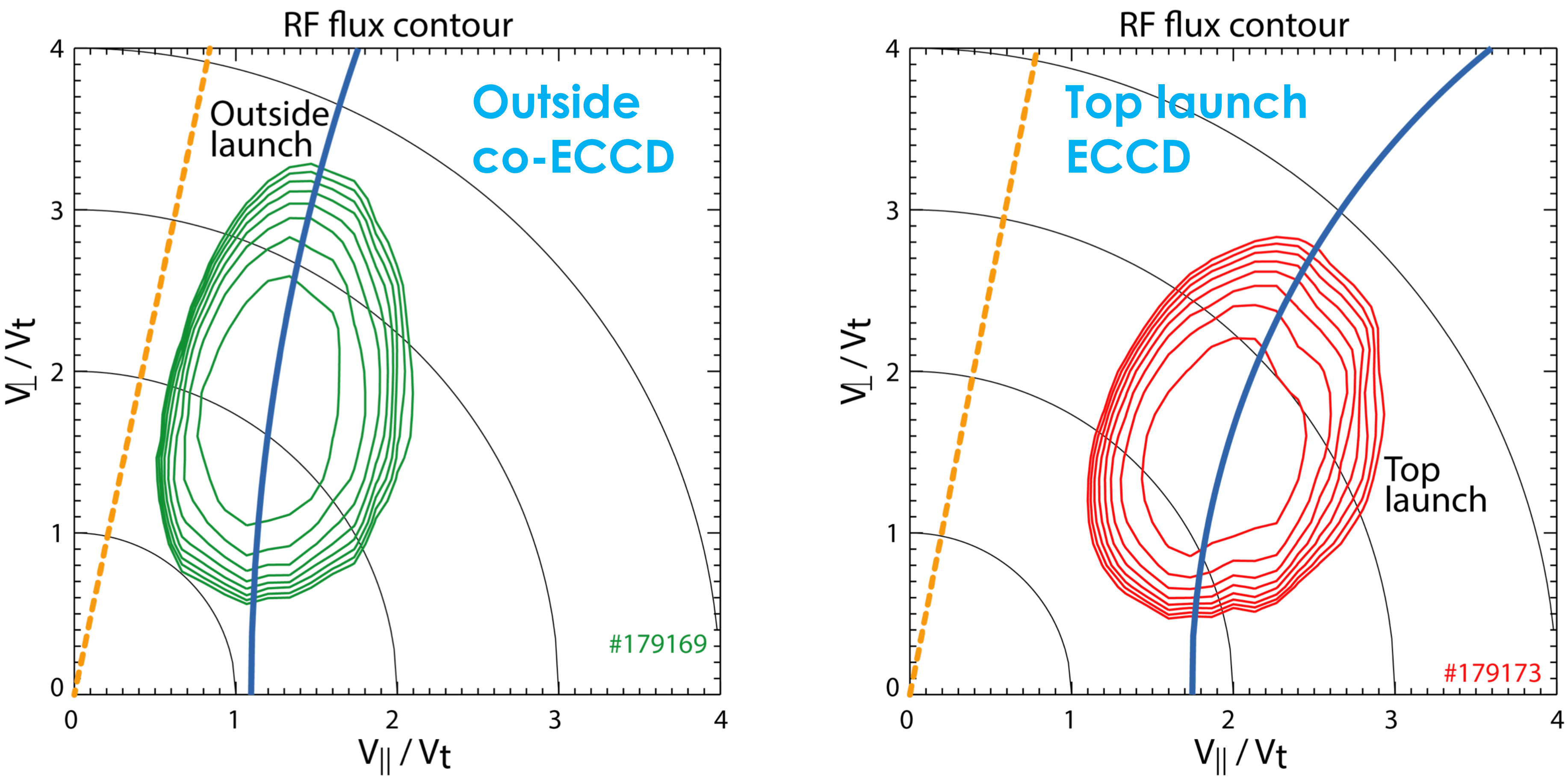
ELMing H-mode plasma, I_p = 0.6 MA, $T_e(0)$ = 3.5 keV, n_e = 1.9x10^{19} m^{-3},

P_{EC} = 0.60 MW

117.5 GHz Gyrotron

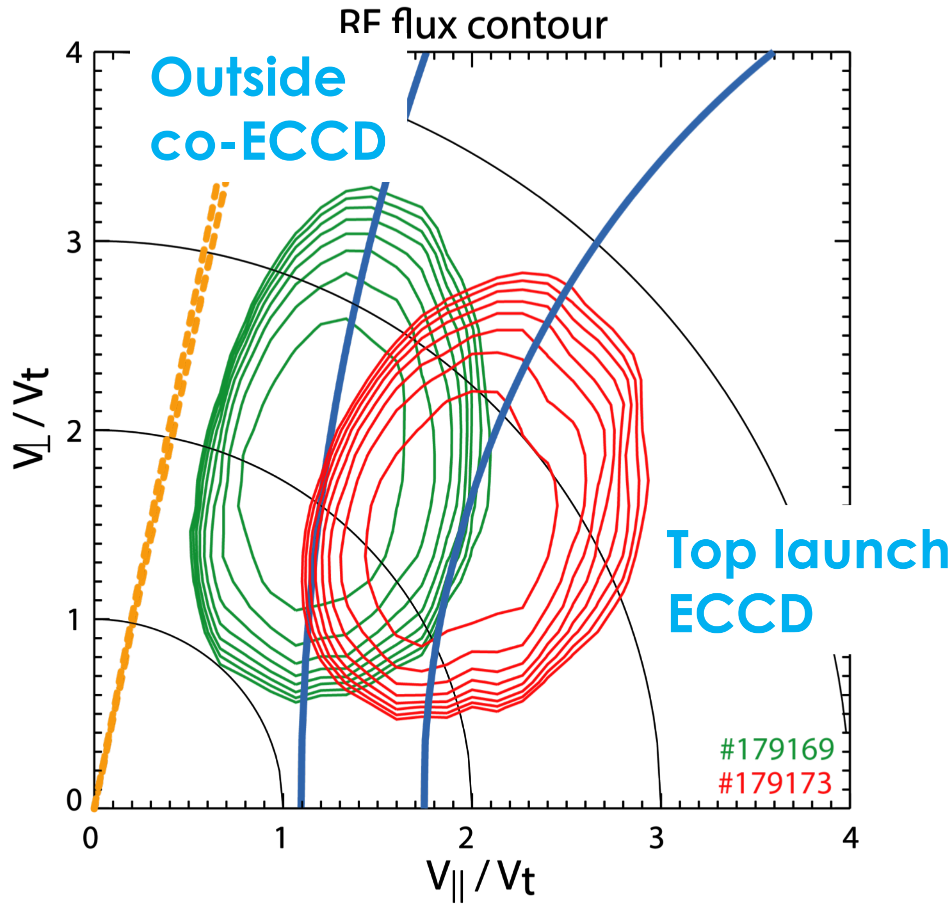
EC Wave via Top Launch Interacts with Higher $V_{||}$ Electrons, Farther From Trapping Boundary

CQL3D calculations at peak current drive



EC Wave via Top Launch Interacts with Higher $V_{||}$ Electrons, Further Away from Trapping Boundary

CQL3D calculations at peak current drive



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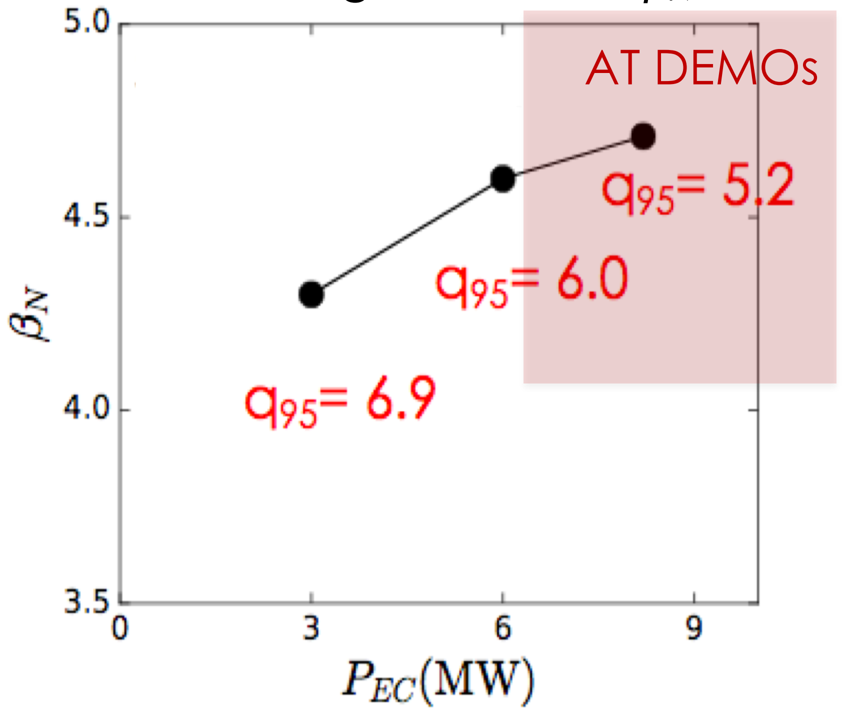
Two New Top Launch Lines Planned in DIII-D to Advance Towards High-β AT Scenario Physics Goals

- **Most DEMO design studies (e.g. Aries-AT, ACT1, CAT-DEMO) operate at β_N=4-6, q_{95}=4-6**

- **Traditional approach with *outside launch 110 GHz gyrotrons* predicted to require 6+ MW for DIII-D to reach target range of DEMO designs[1]**

FASTRAN Modeling: Steady State Highest Stable β_N



[1] J.M. Park, et al., POP 25 (2018) 012506

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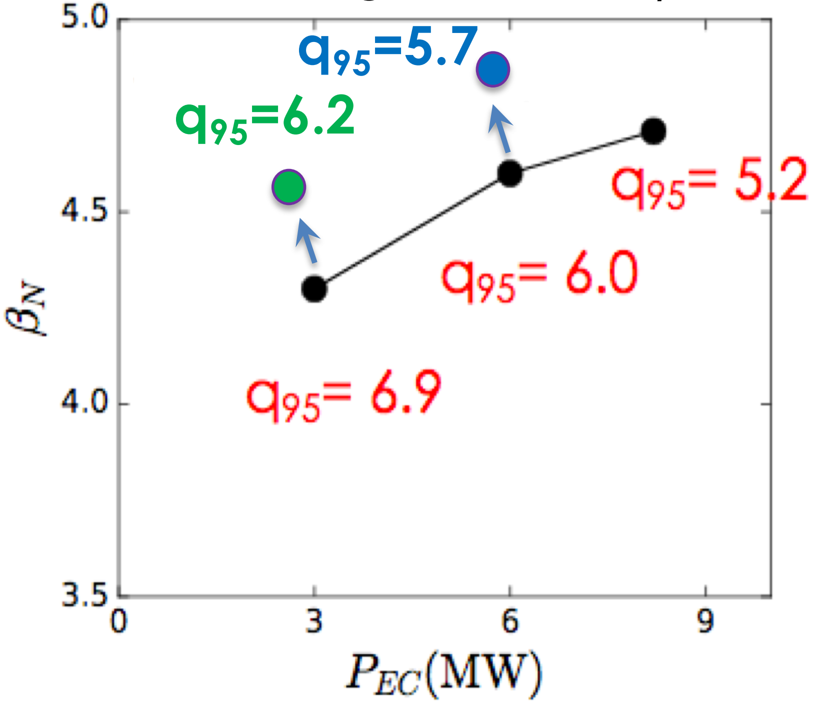
- **Traditional approach with *outside launch 110 GHz gyrotrons* predicted to require 6+ MW for DIII-D to reach target range of DEMO designs**[1]

- **Instead, apply the same power using ~2x more efficient top launch, broader *j*, higher β_N , lower q_{95} can be accessed**
  - **Nearly the same performance with 3 MW TOP as 6 MW OUTSIDE**
  - **3 MW TOP 117.5 GHz + 3 MW OUTSIDE 110 GHz would be a reasonable alternative to 9 MW OUTSIDE**

FASTRAN Modeling: Steady State Highest Stable β_N

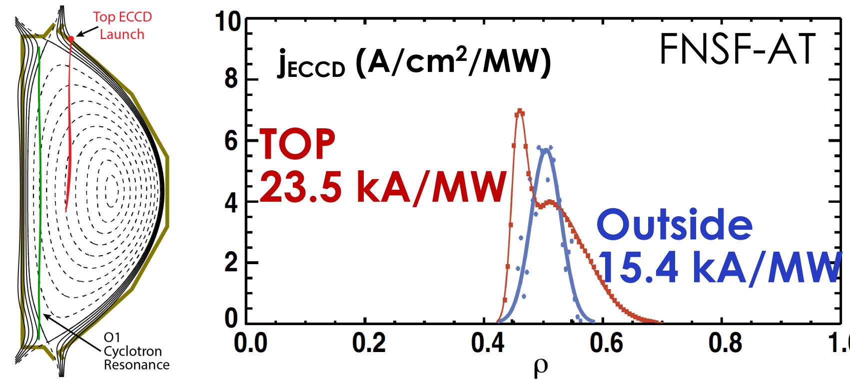


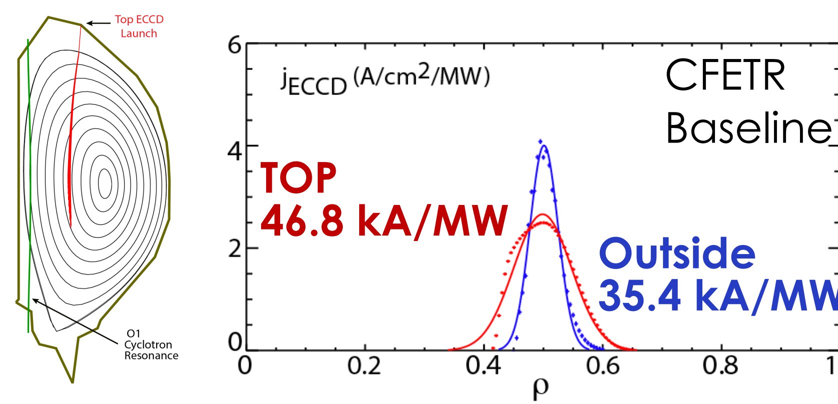
- **Two new top launch installations planned: first in FY22 campaigns**

[1] J.M. Park, et al., POP 25 (2018) 012506

Predictions for FNSF-AT, DEMO, CFETR Suggest Substantial Improvement in Efficiency via Top Launch ECCD

- **Studies of many tokamak reactors show current drive around ρ ~ 0.5-0.7 is required for steady-state AT regime**
- **Modeling for FNSF-AT shows > 50% higher off-axis CD efficiency for top launch ECCD[1], similarly for DEMO[2]**
- **35% improvement in ECCD efficiency at ρ~0.5 found in initial modeling for CFETR baseline scenario[3]**





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[3] Xi Chen, et al., EPJ Web of Conferences, 203, 01004 (2019)

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- **Experiments validated main tenets of top launch ECCD**
  - Geometry allows selective wave interaction with high $V_{||}$ electrons yielding high CD efficiency
  - Long absorption path compensates for inherently weak damping at high $V_{||}$
  - ➢ Highest ECCD efficiency for optimal absorption on high $V_{||}$ tail electrons
- **Simulations of FNSF-AT, DEMO and CFETR support top launch ECCD as an improved efficiency off-axis current drive technique for future reactors**