Higher Off-Axis Electron Cyclotron Current Drive Via ‘Top Launch’ Approach Demonstrated on the DIII-D Tokamak

by
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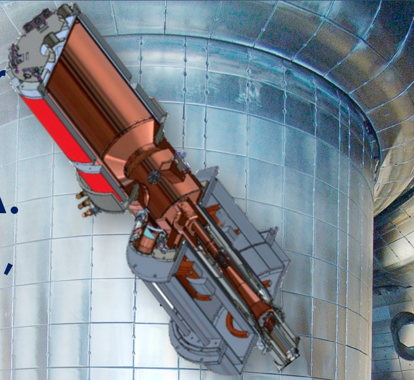
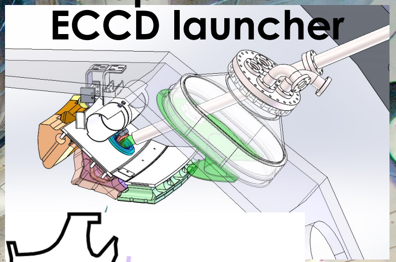
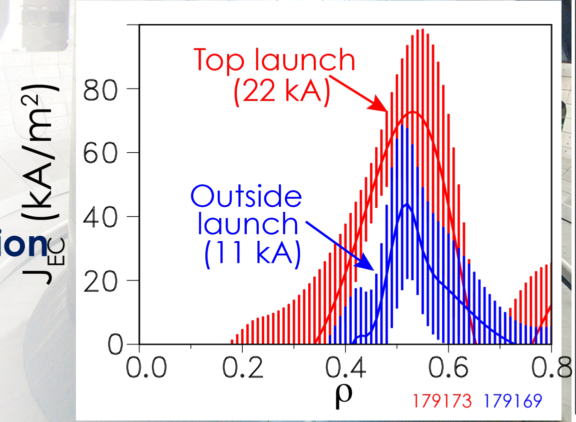
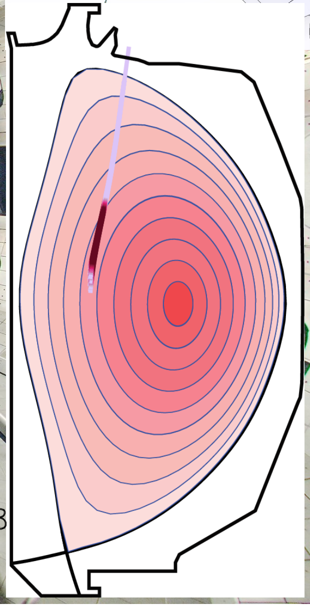
[4]Oak Ridge National Laboratory
[5]University of California-Los Angeles









Presented at the

21st Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Resonance Heating
ITER Organization HQ, France

June 20 – 24, 2022

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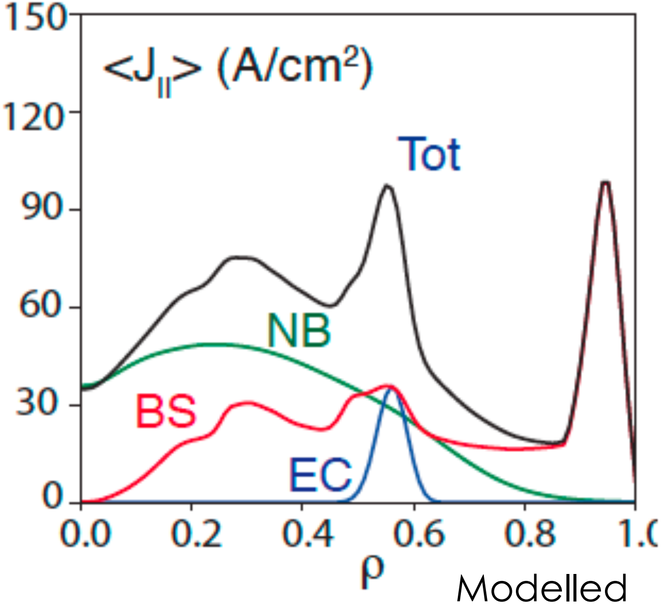
GENERAL ATOMICS

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

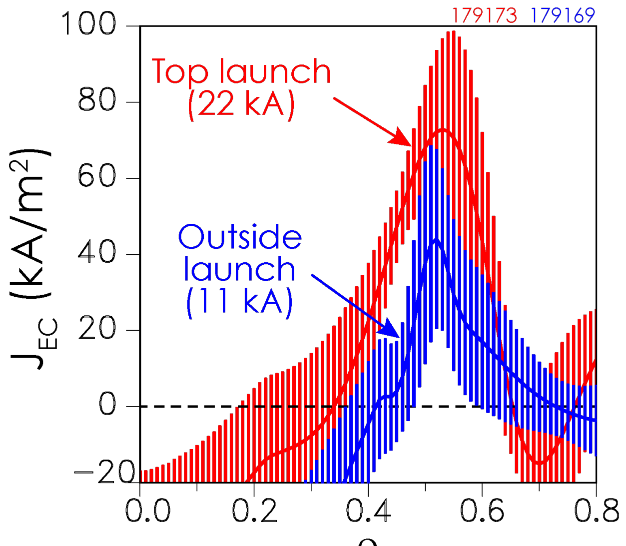
$f_{NI}=1$, $\beta_N>4$, high q_{min}



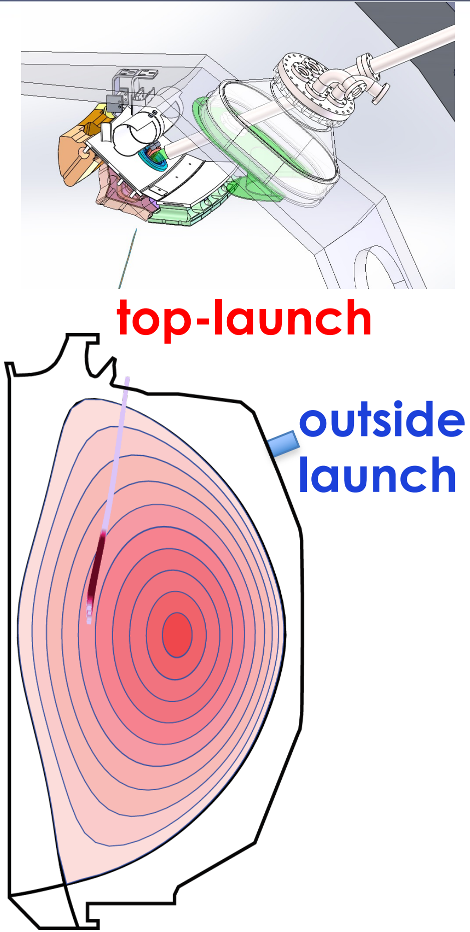
Modelled DIII-D shot

Doubling of Off-axis ECCD Achieved on DIII-D via Top Launch Approach

- **A top launch ECCD system installed on DIII-D to allow experimental validation**
- **Experiments have 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 $V_{||}$



Xi Chen/EC-21/June 2022



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

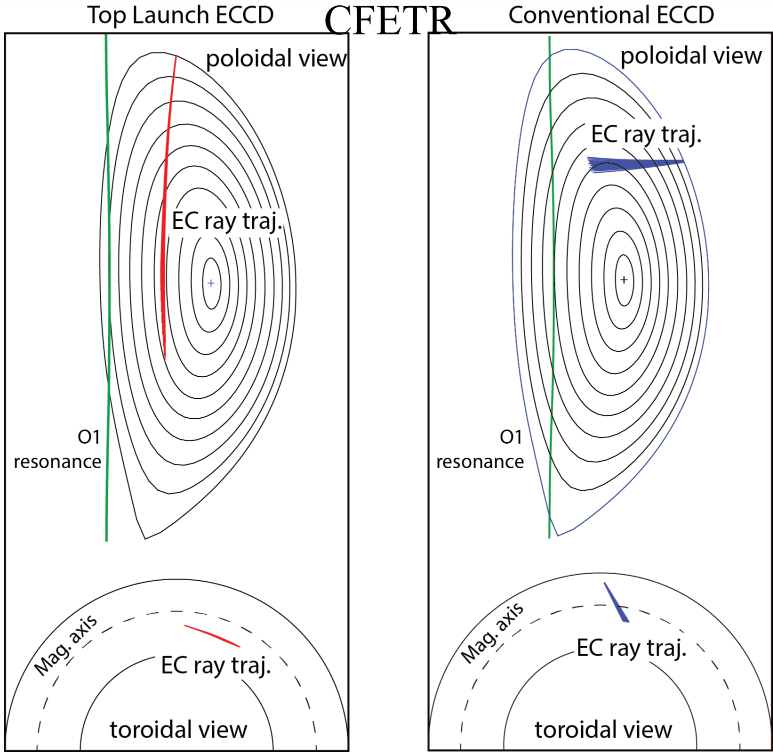
Top Launch ECCD injects EC wave[1]:

❶ nearly parallel to the resonance plane

❷ with strong toroidal steering

❸ on HFS of the plasma

❹ either O1 or X2-mode



Ray Tracing TORAY Calculation

[1] K. Hamamatau and A. Kukuyama, PPCF (2000); R.W. Harvey and F.W. Perkins, NF 2001; R. Prater, et al, APS (2012); E. Poli, et al, NF 53 (2013) 013011; Y. Bae, et al, EC-19; Xi Chen, et al, EC-20

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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

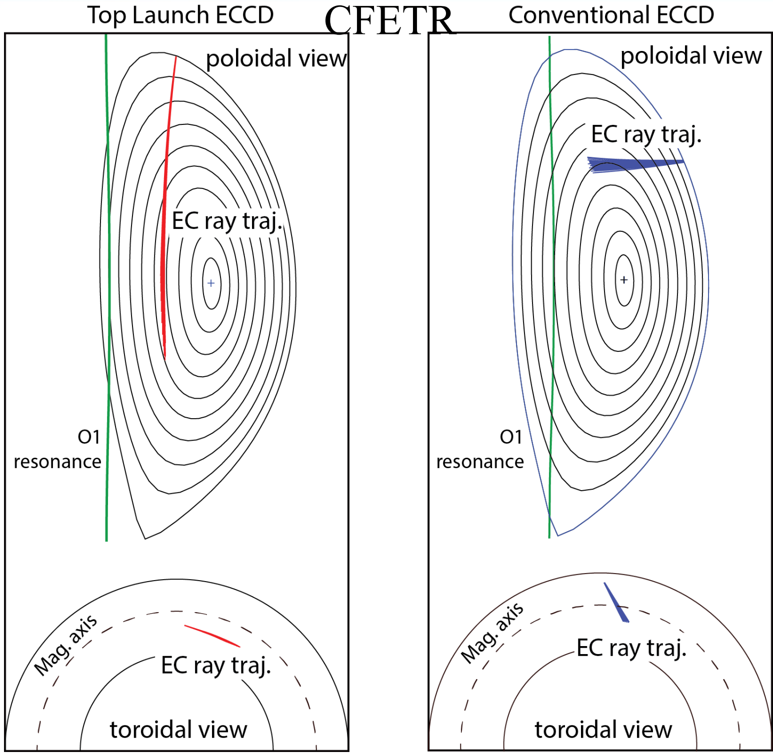
➢***increased Doppler shift*** ensures EC wave power is absorbed by higher energy (less collisional) electrons throughout long interaction zone

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>1keV



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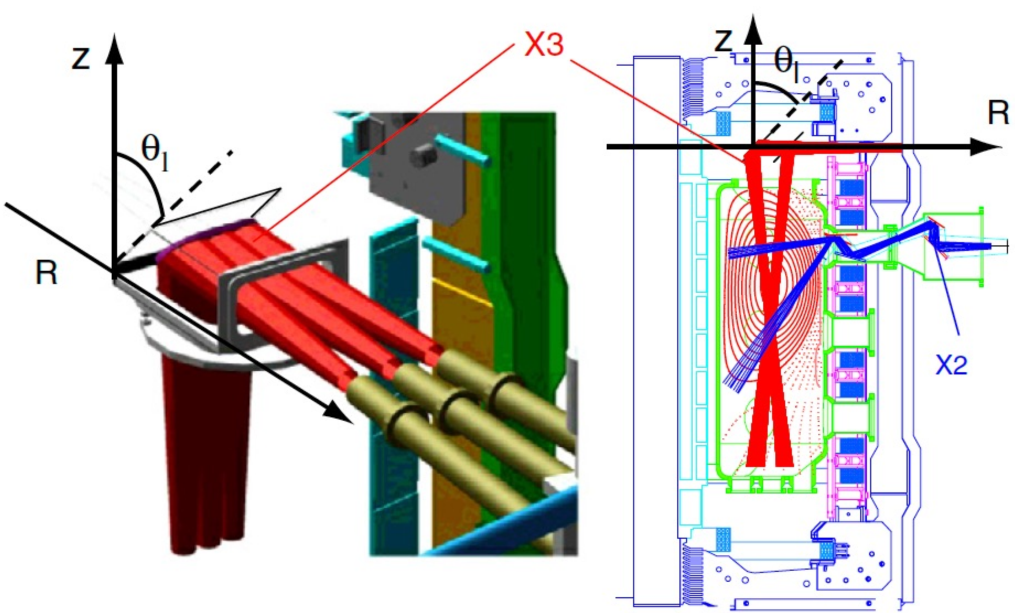
Top Launch ECCD Differs From TCV Top Launch ECH

- **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

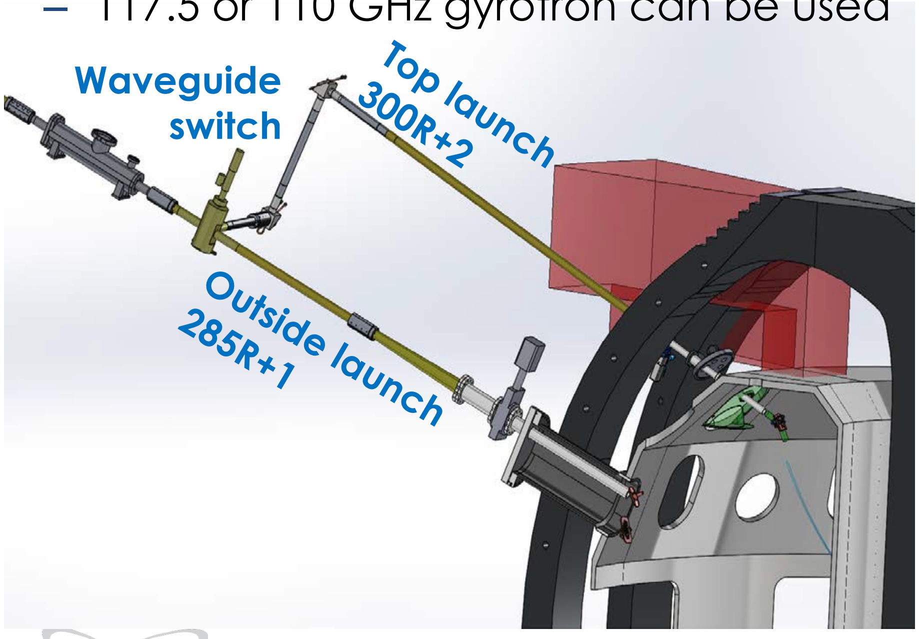
Third-harmonic, top-launch, ECRH experiments on TCV tokamak

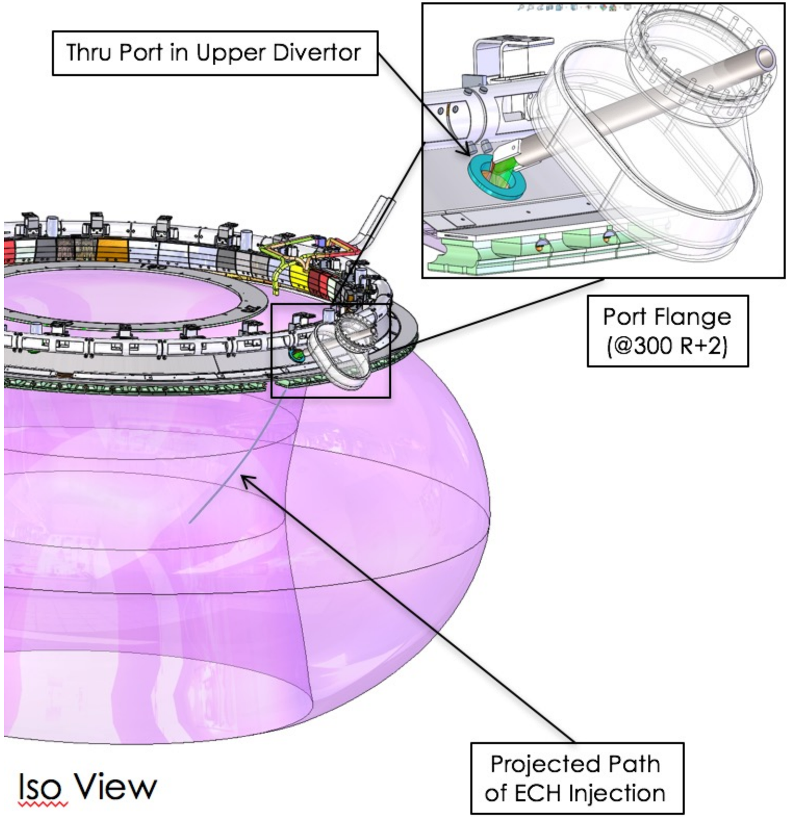


[1] S. Alberti, et al, NF 45 (2005) 1224

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
  - 2^{nd} harmonic X-mode damping
  - 117.5 or 110 GHz gyrotron can be used





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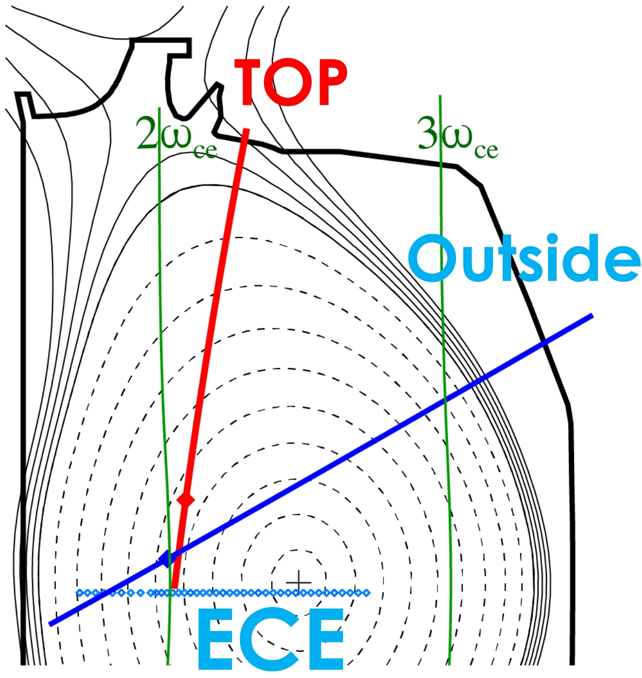
EC Power Deposition Profile is Measured by Modulating Gyrotron Power and Observing T_e Oscillations

- **EC source and T_e response are related through Fourier-transformed energy conservation equation**

$$-D\nabla^2\tilde{T}_e + V\nabla\tilde{T}_e + \frac{1}{\tau}\tilde{T}_e + i\frac{3}{2}\omega_M\tilde{T}_e = \frac{\tilde{S}_{ECH}}{n_e}$$

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



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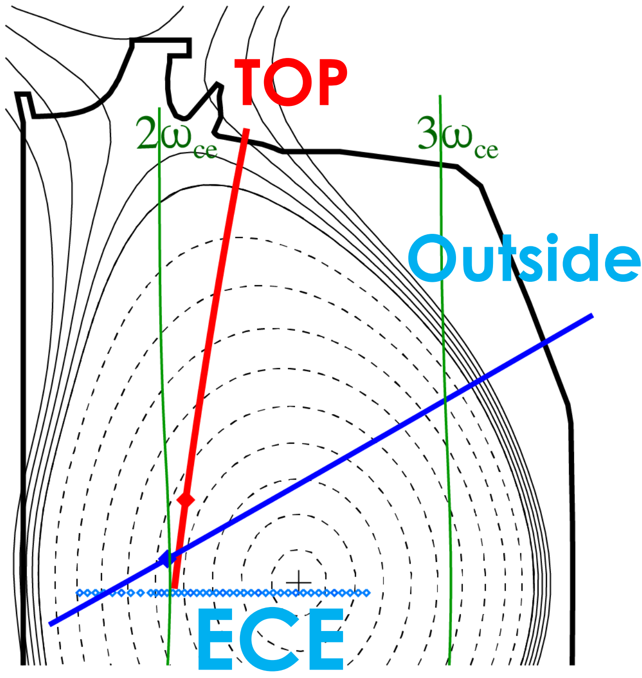
Gyrotron modulation frequency



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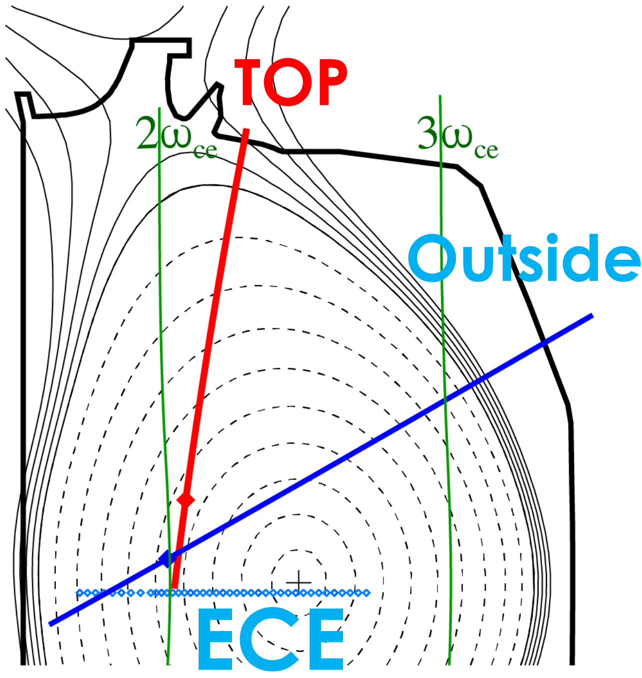
D, V, τ are transport coefficients



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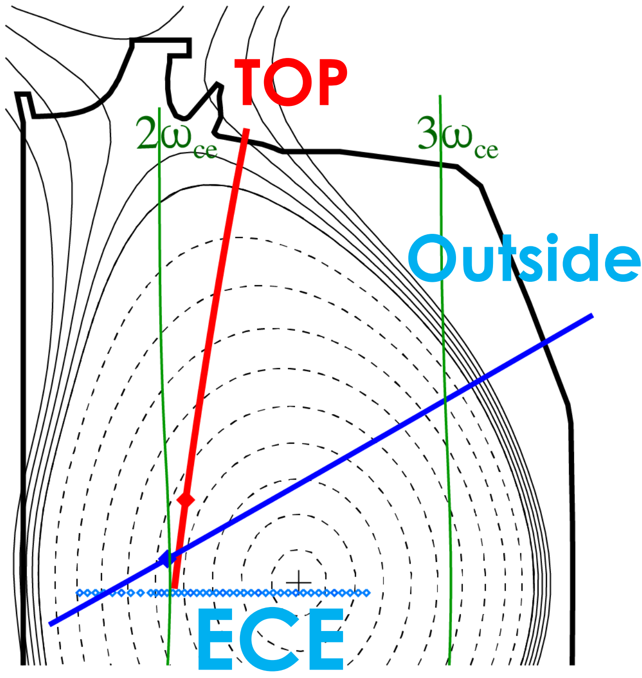
High frequency limit



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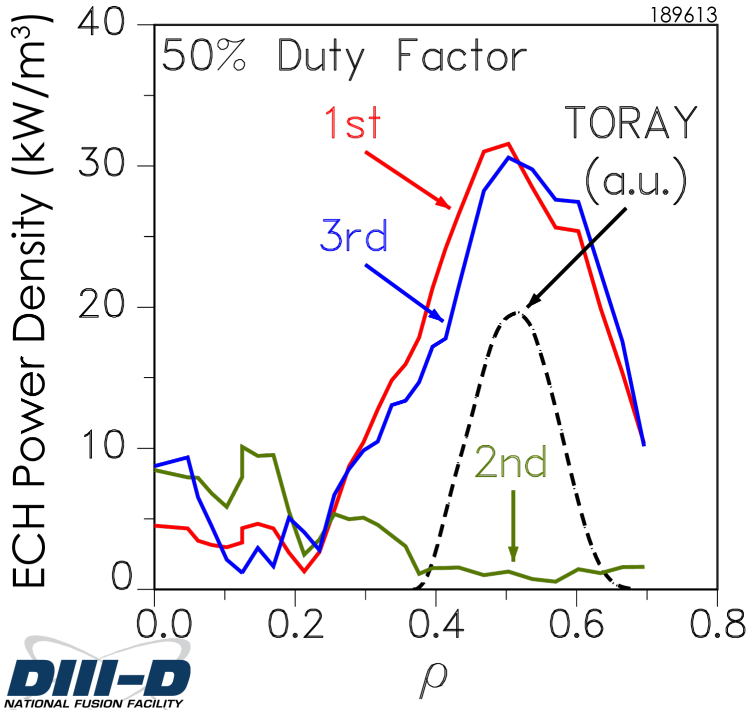
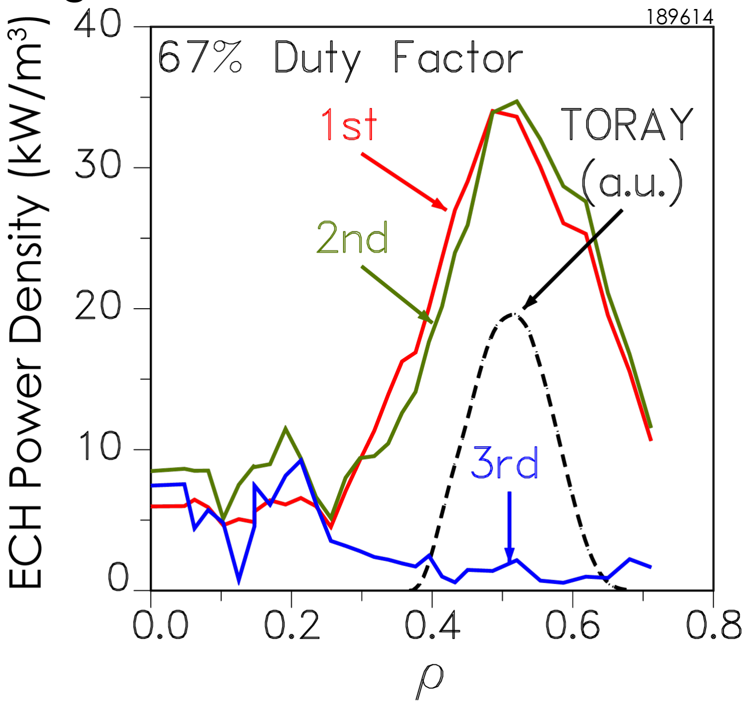
- **Experiments utilized various gyrotron modulation frequencies (ω_M)**

Plasma Response to Modulated ECH Confirmed

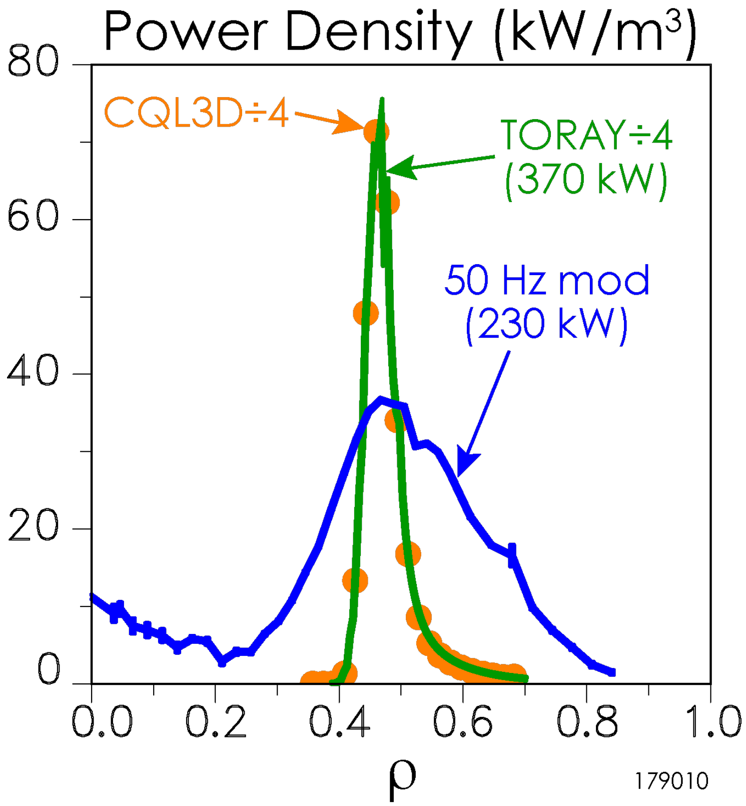
- **Measurements confirm the expected harmonic response from modulation**
  - Single gyrotron modulated in a plasma with sawteeth
  - Measured EC power deposition is real signal, not due to sawteeth





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

- **Good agreement found between experimental and theoretical locations of top launch EC absorption**



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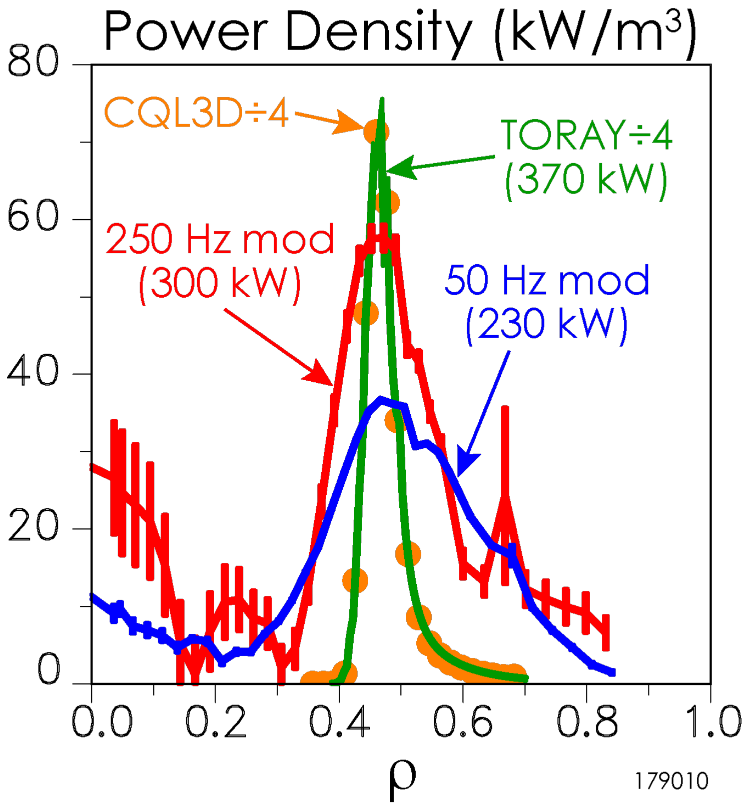
Measured Power Deposition of Top Launch ECCD Generally Agrees with TORAY and CQL3D Predictions

- **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)**



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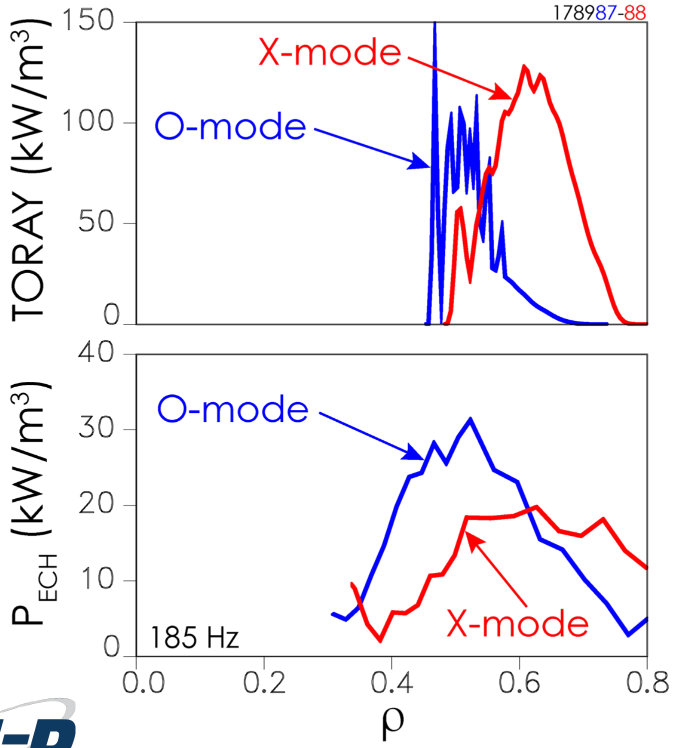
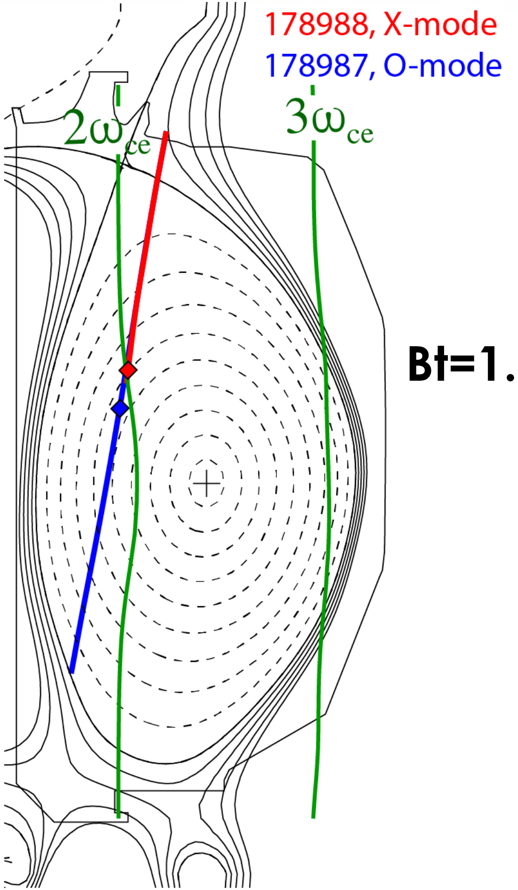
Shifted Radial Deposition Between O-mode and X-mode can Verify Vertical Path Trajectory of Top-Launch ECCD

- **O2 has weaker absorption than X2 and has longer damping path**





Bt=1.6T

Below Midplane, O-Mode Profile Switches Places with X-Mode Because Longer Vertical Path Ends at Larger ρ

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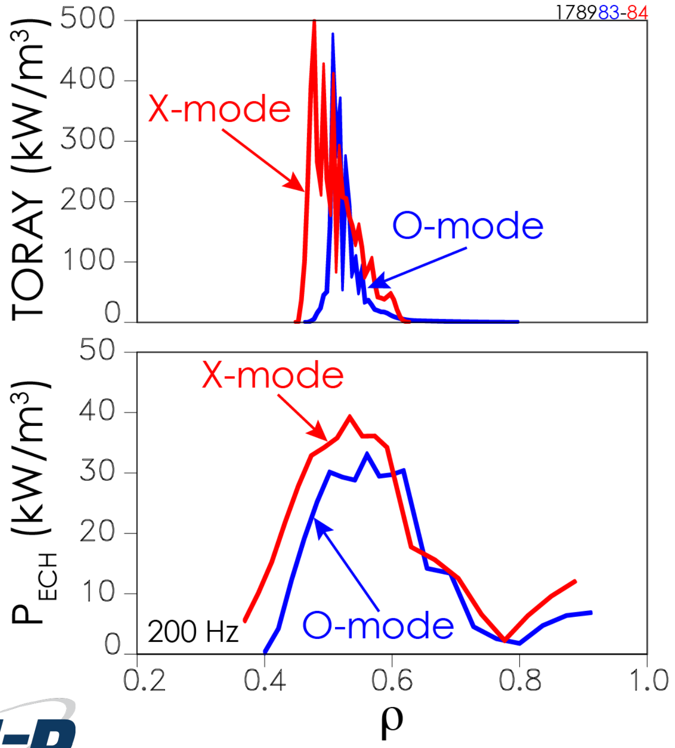
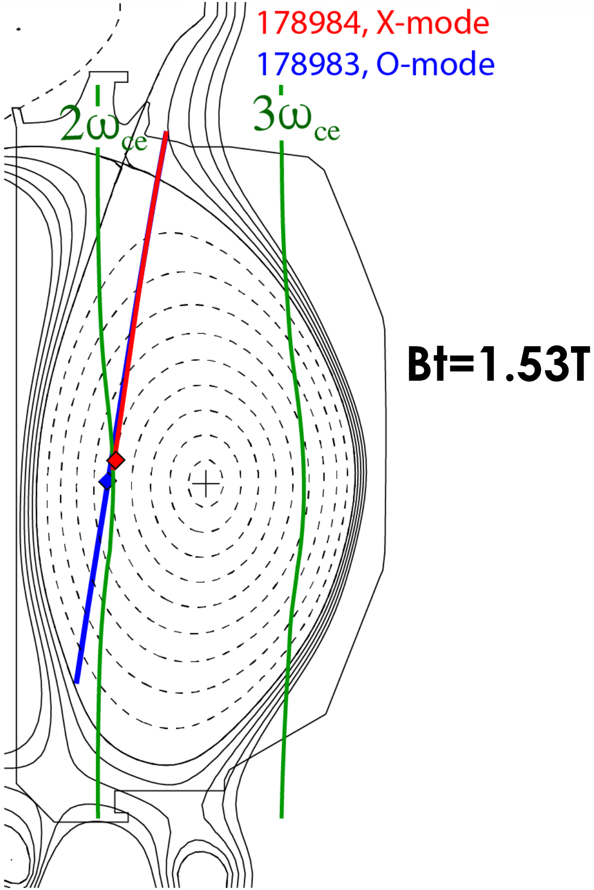
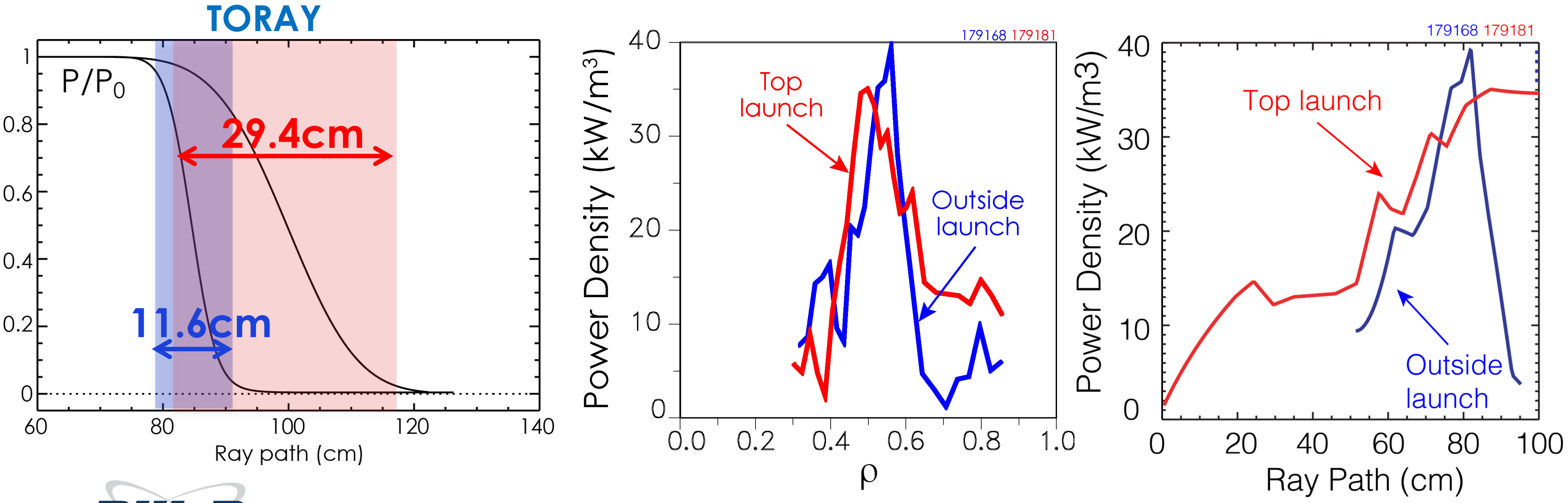




Broader Power Deposition Profile of Top Launch Confirms the Predicted Longer Absorption Zone

- **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**



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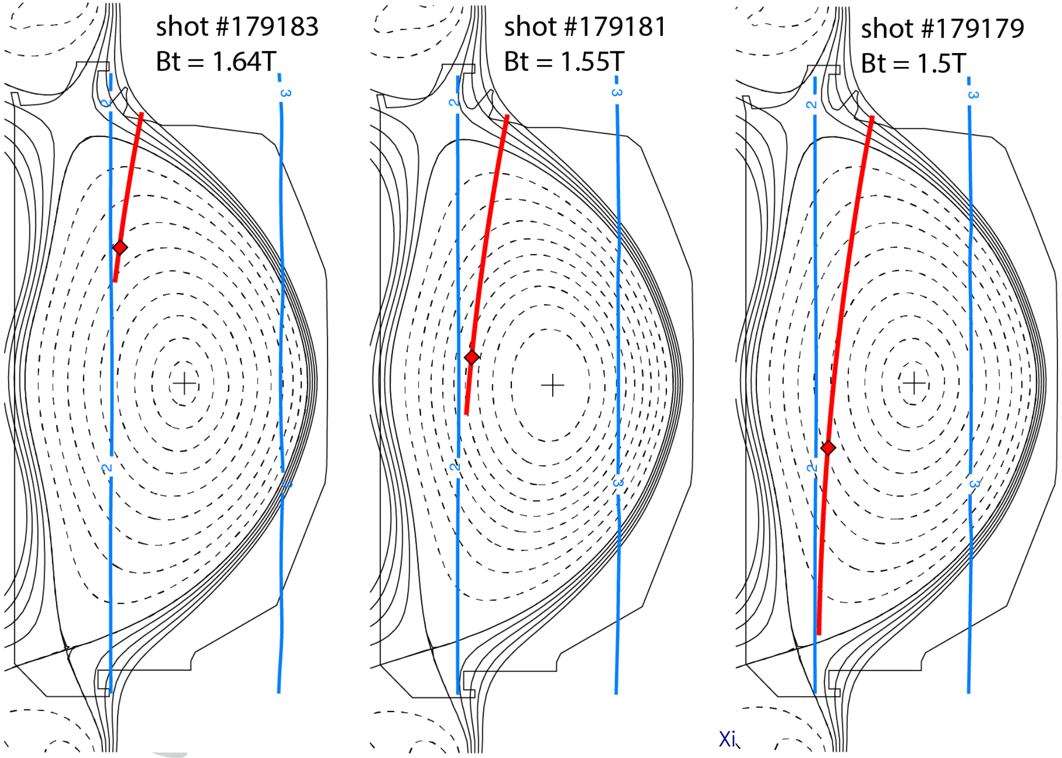
Power Deposition Location of Top Launch ECCD Moves with Magnetic Field

- **Magnetic field (B_t) is scanned with fixed-injection to move the cold resonance location closer to or further away from the EC trajectory**

TORAY Prediction



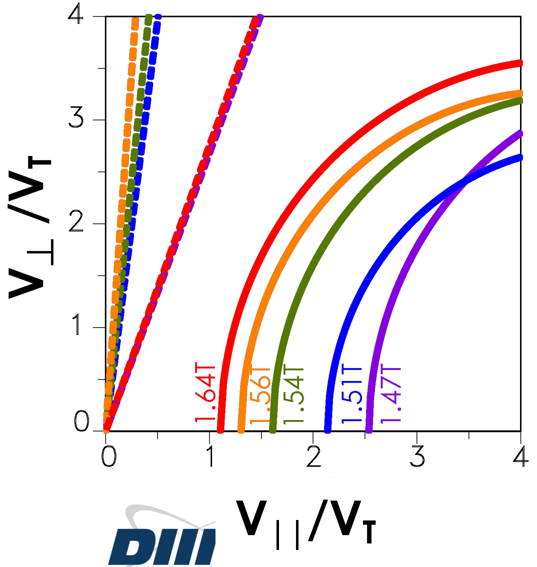
Measurement (ECE)

shot	Bt(T)	ρ_{EC}
179183	1.64	0.56
179181	1.55	0.48
179179	1.50	0.50

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

- **At fixed-injection, varying the magnetic field alters the wave-electron interactions in the velocity space**
  - Lower B_t pushes resonance to higher $V_{||}$

    Cyclotron resonance $\omega - \omega_{ce}/\gamma = k_{||} v_{||}$



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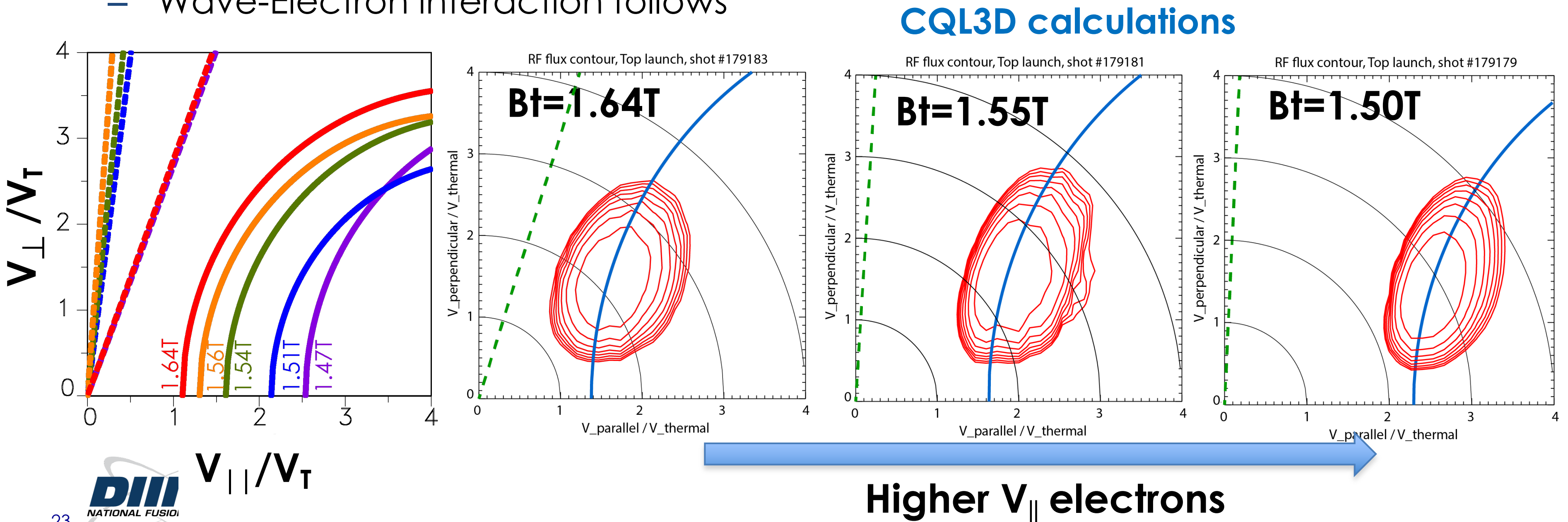
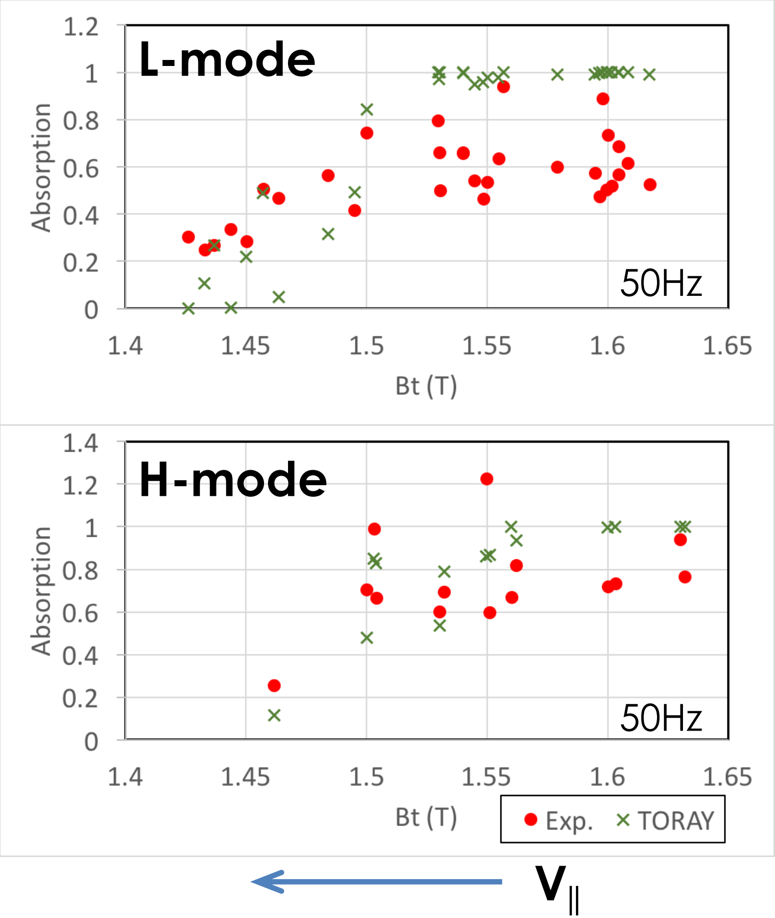
    Cyclotron resonance $\omega - \omega_{ce}/\gamma = k_{||} V_{||}$
  - Wave-Electron interaction follows



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

- **Measured absorption fraction decreases with lower B_t (higher $V_{\parallel}/V_t$), in agreement with TORAY, when the damping on tail electrons is too weak**
  - Higher B_t cases were tried but the ECE array couldn't cover the entire deposition profile



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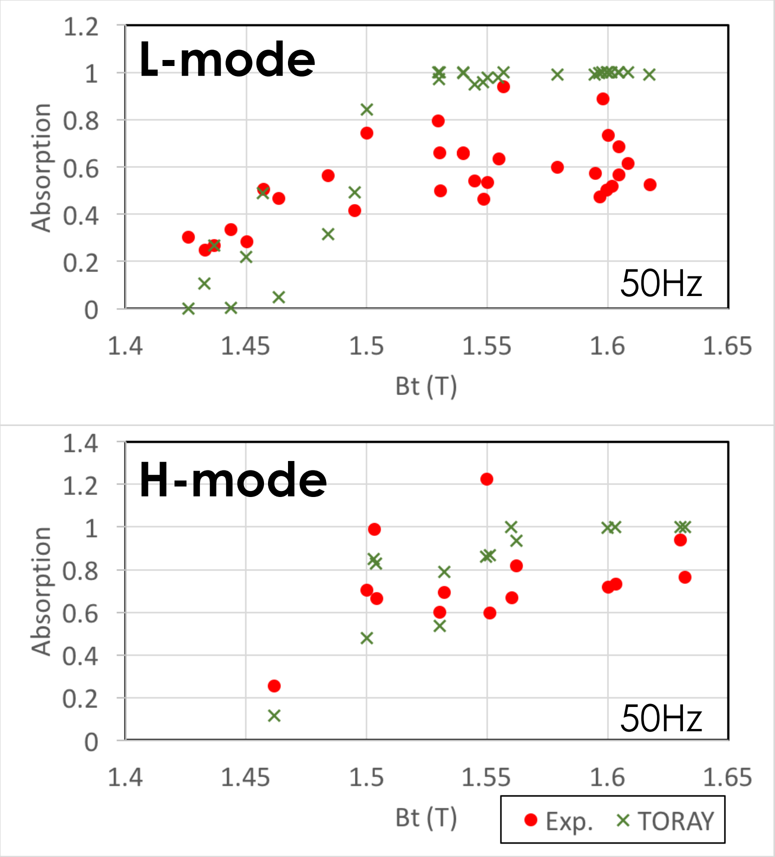
  - Higher B_t cases were tried but the ECE array couldn't cover the entire deposition profile
- **Since higher energy electrons drive current more efficiently, there is a optimum (optimal B_t) for top launch ECCD:**

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



← $V_{\parallel}$

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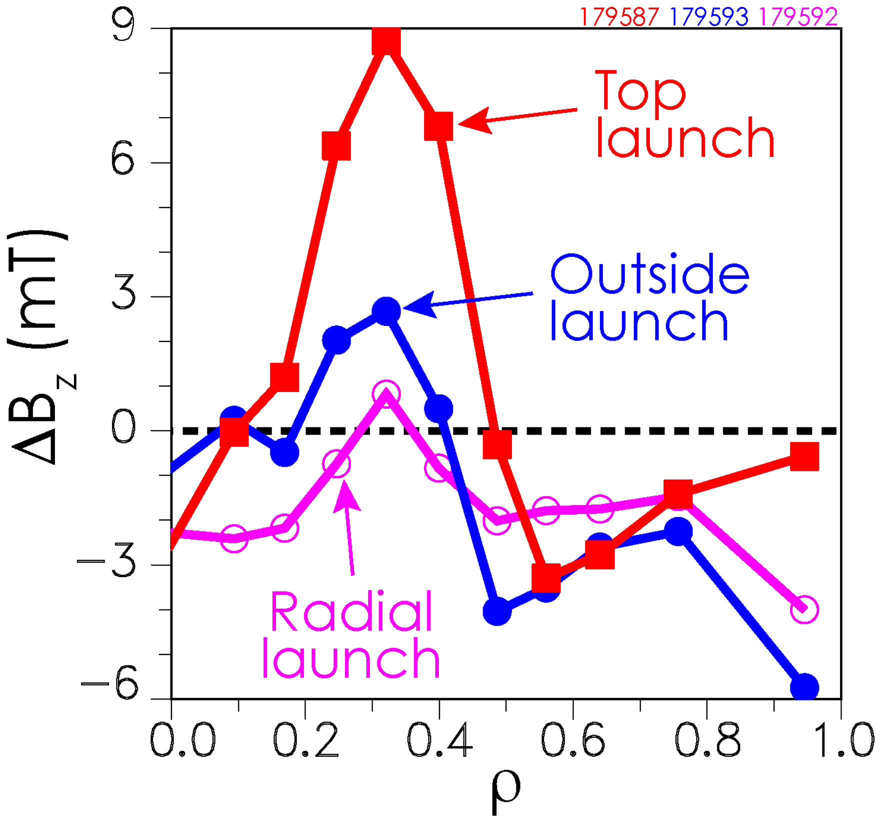
Larger Change in MSE Pitch Angles Observed for Top Launch Than for Outside Launch ECCD

- **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:**

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

neoclassical conductivity

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

- **Pure heating effect is eliminated by**

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

- **Two analysis methods are 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

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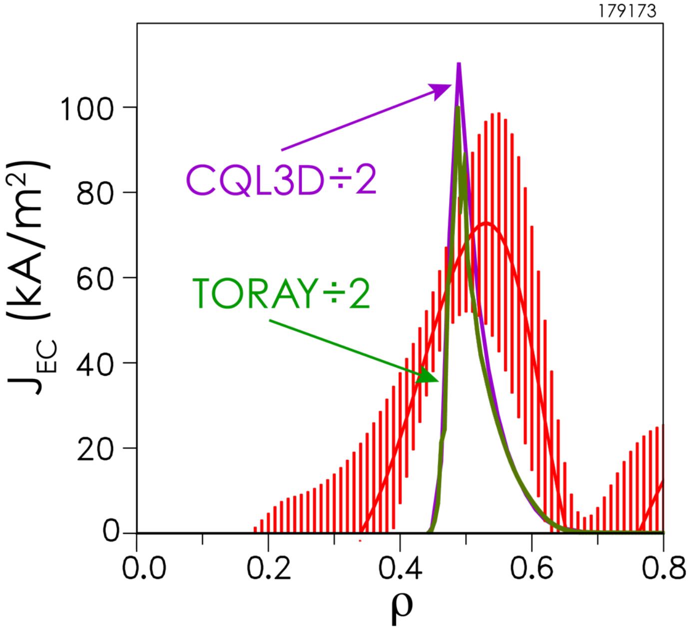
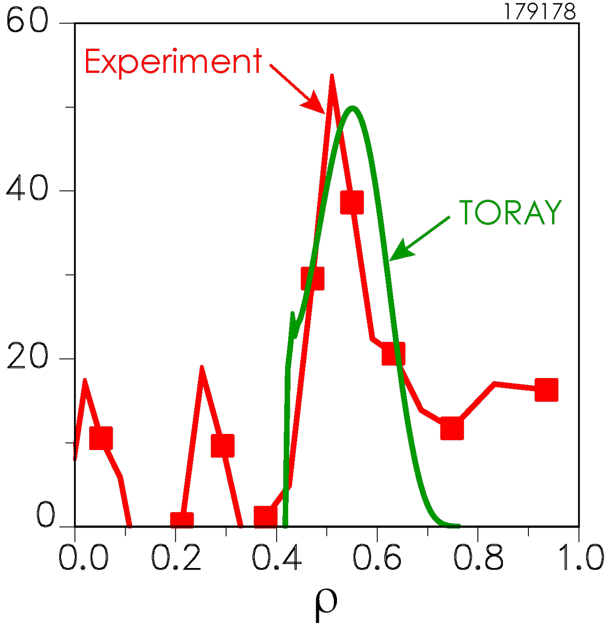
Measured Off-axis Current Profile via Top Launch ECCD is Generally Consistent with Theoretical Prediction

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



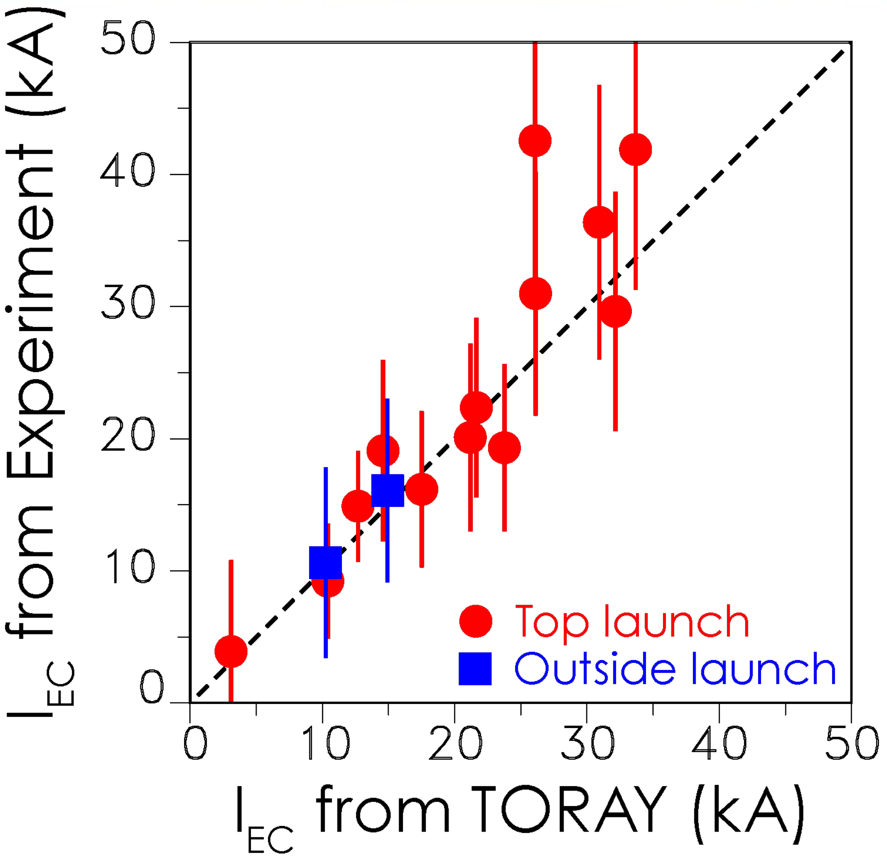
ELMing H-mode plasma, I_p = 0.6 MA, $T_e(0)$ = 2.3 keV, n_e = $1.6\text{x}10^{19}$ m^{-3}

Direct MSE analysis method



ELMing H-mode plasma, I_p = 0.6MA, $T_e(0)$ = 2.5keV n_e = $1.7\text{x}10^{19}\text{m}^{-3}$

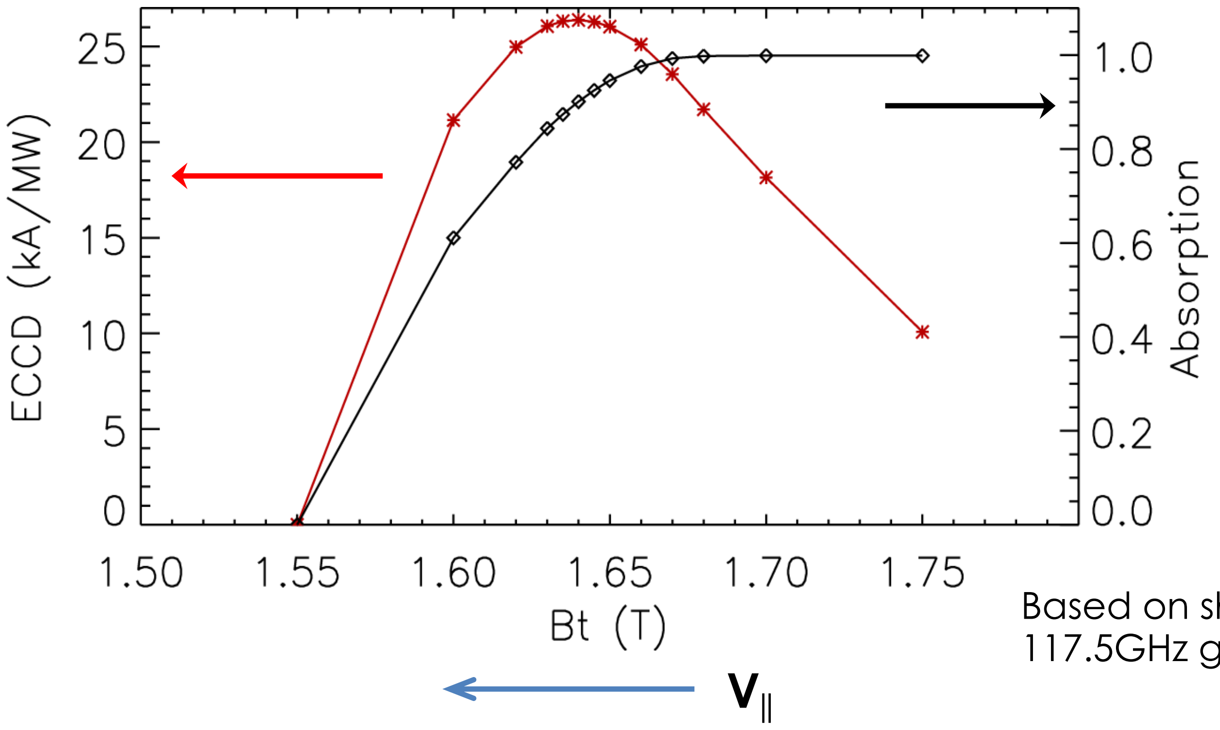
Integrated ECCD Magnitude in Good Agreement with Theory



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

- **TORAY modeling typically predicts highest ECCD efficiency occurs for less than 100% absorption**

TORAY Prediction



Based on shot 147634, using 117.5GHz gyroton

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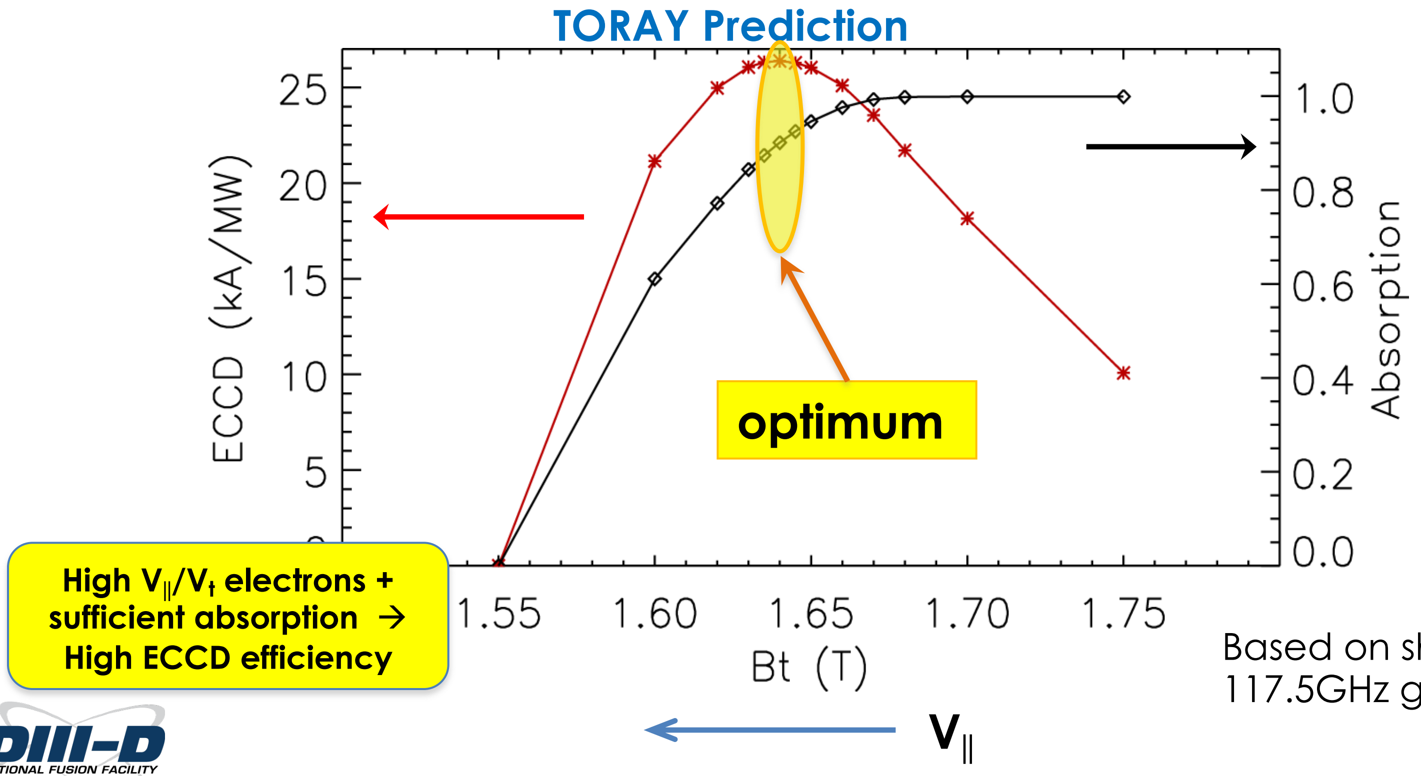
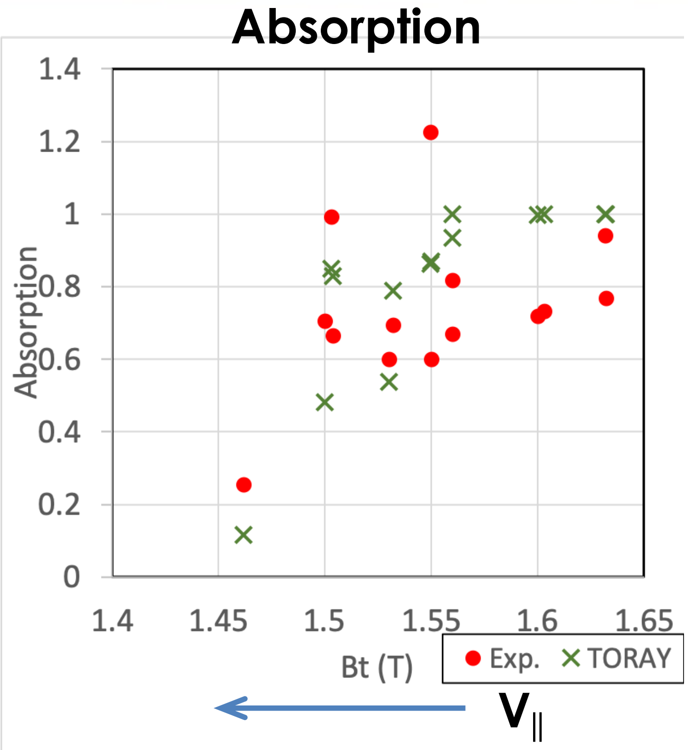
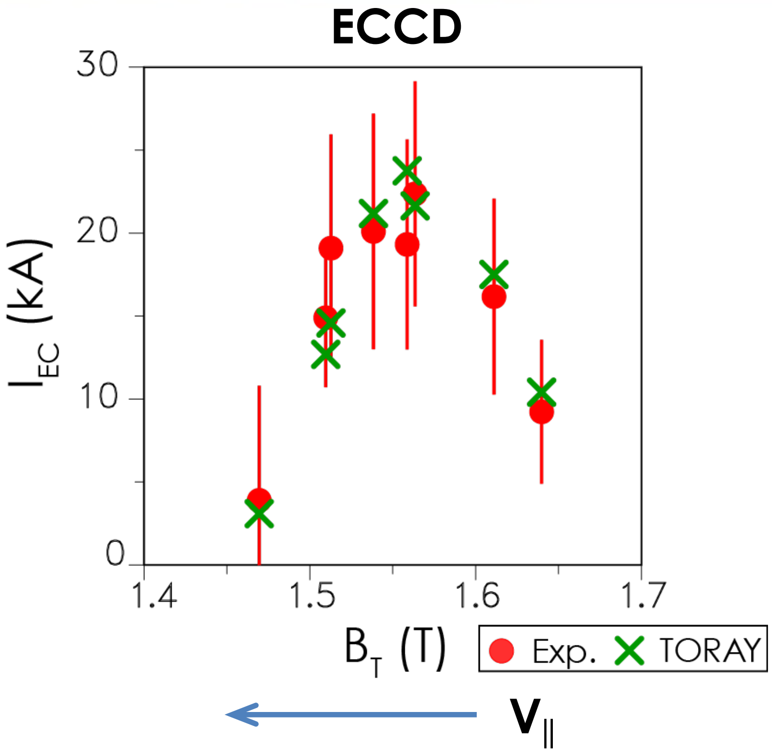


Based on shot 147634, using 117.5GHz gyroton

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





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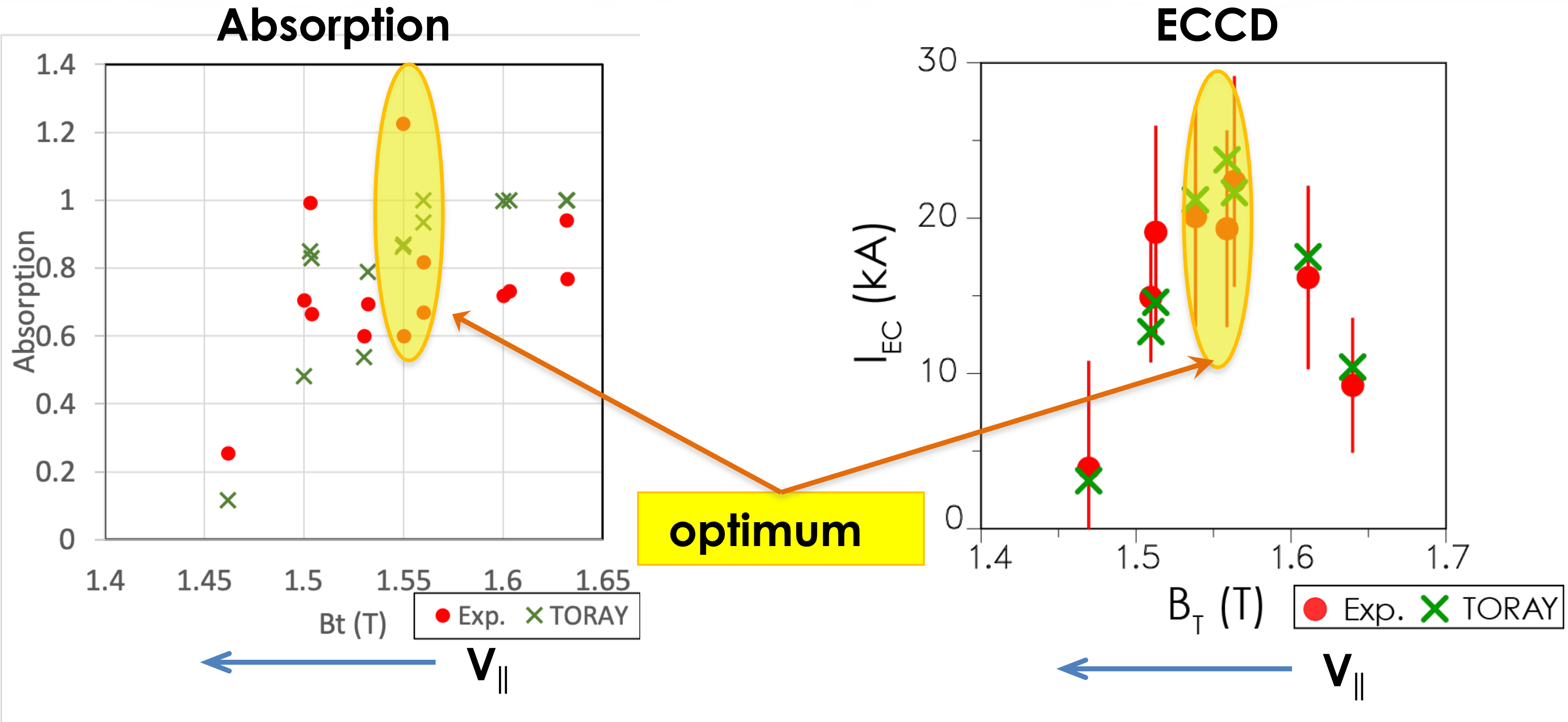

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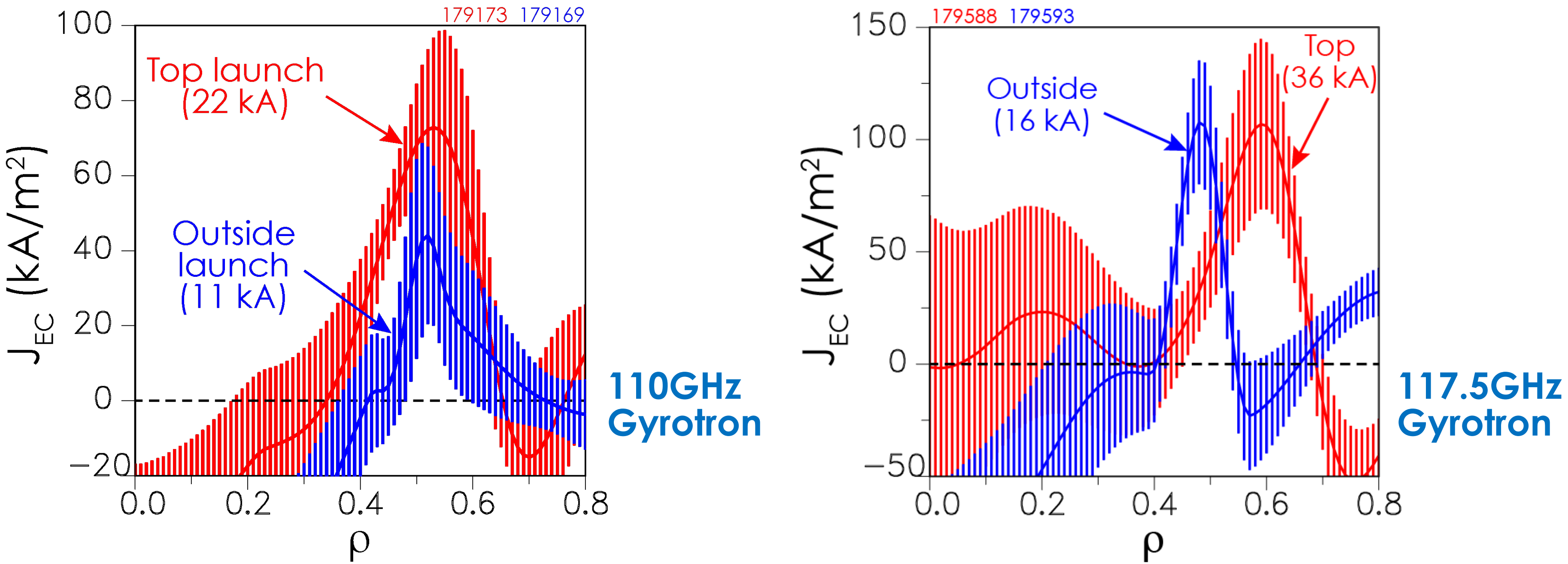
Greatly Enhanced ECCD in Mid-Radii Observed via Top Launch ECCD Compared to Outside Co-ECCD Launch

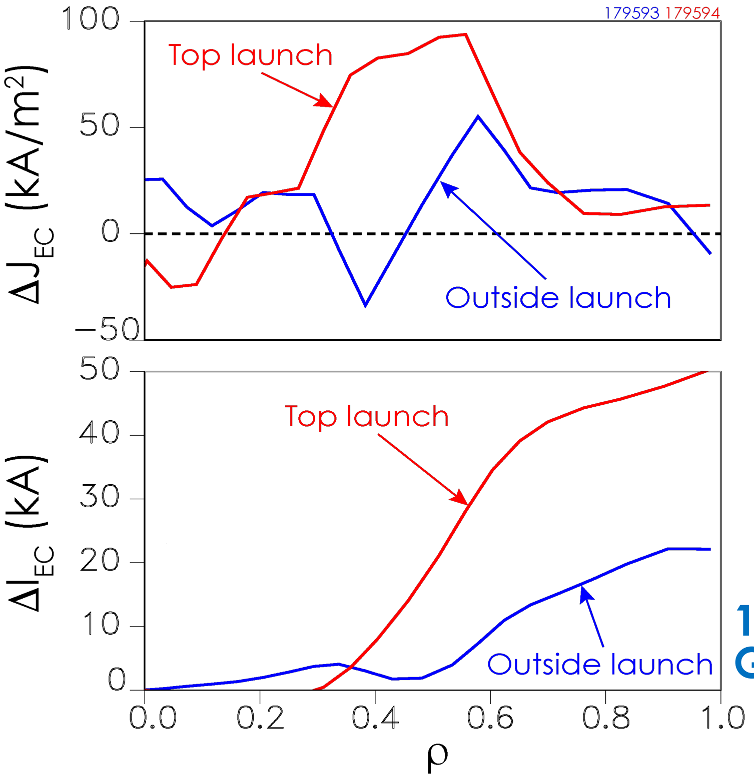
Loop voltage analysis for MSE Efits with local cos²(kψ) representation



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

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

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



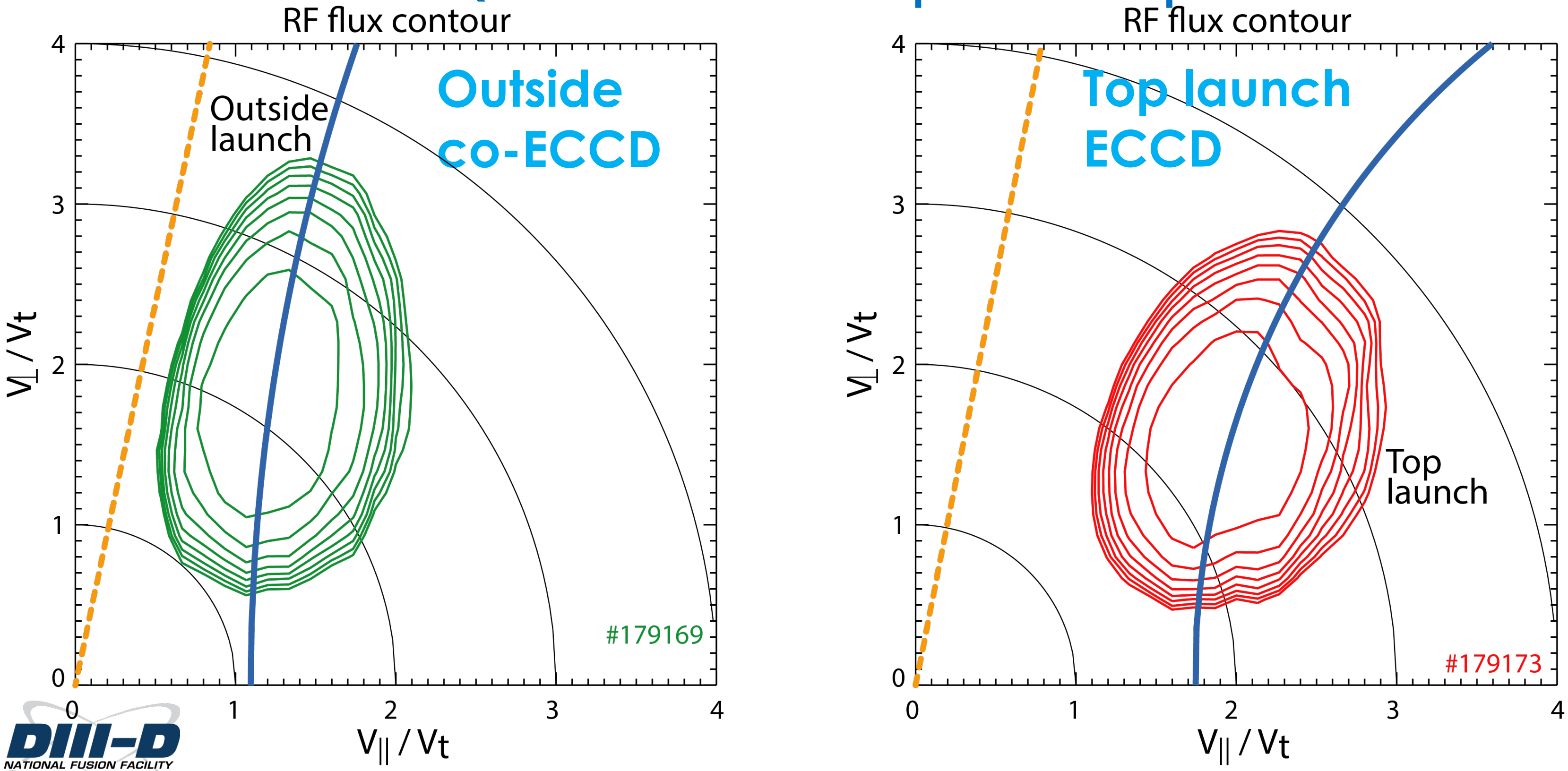
117.5GHz Gyrotron

ELMing H-mode plasma, I_p = 600kA, $T_e(0)$ = 3.5keV, n_e = 1.9x10^{19}m^{-3}, P_{EC} = 0.60MW

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

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

CQL3D calculations at peak absorption



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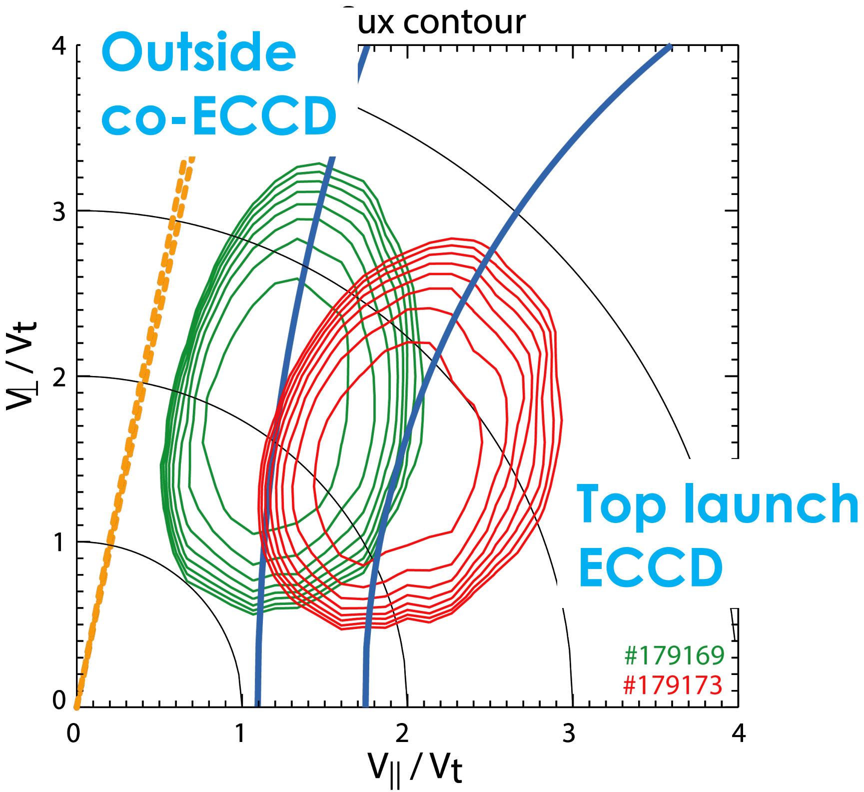
EC Wave via Top Launch Interacts with Higher $V_{||}$ Electrons, Further Away from Trapping Boundary

CQL3D calculations at peak current drive



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Outline

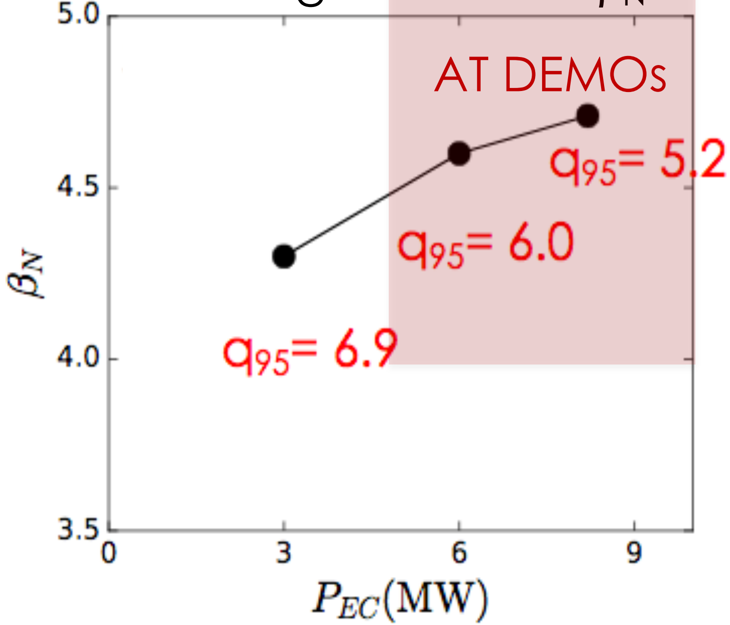
- What's top launch ECCD?
- Longer absorption zone with top launch ECCD
- Strong damping on high $v_{||}$ electrons
- Significantly higher off-axis ECCD measured on DIII-D
- **Top launch ECCD for reactors**

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

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

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

FASTRAN Modeling: Steady State Highest Stable β_N



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

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- **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 3MW TOP as 6 MW OUTSIDE

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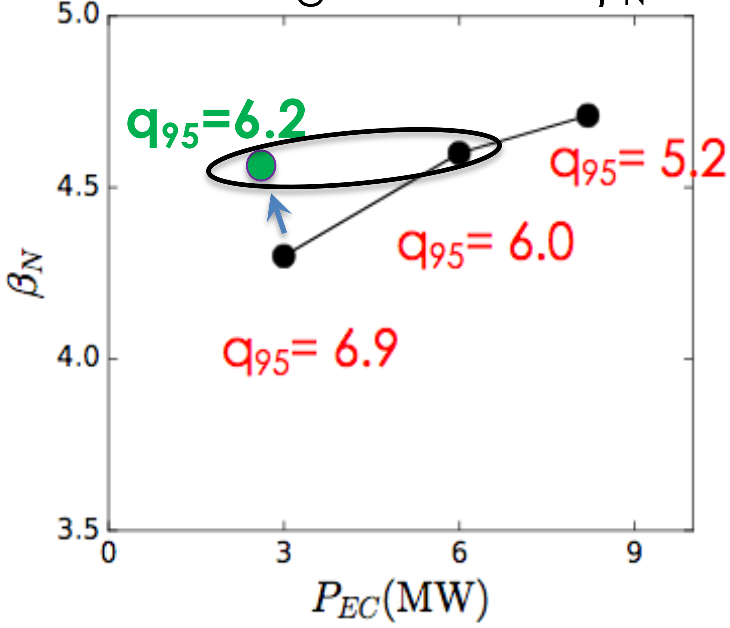

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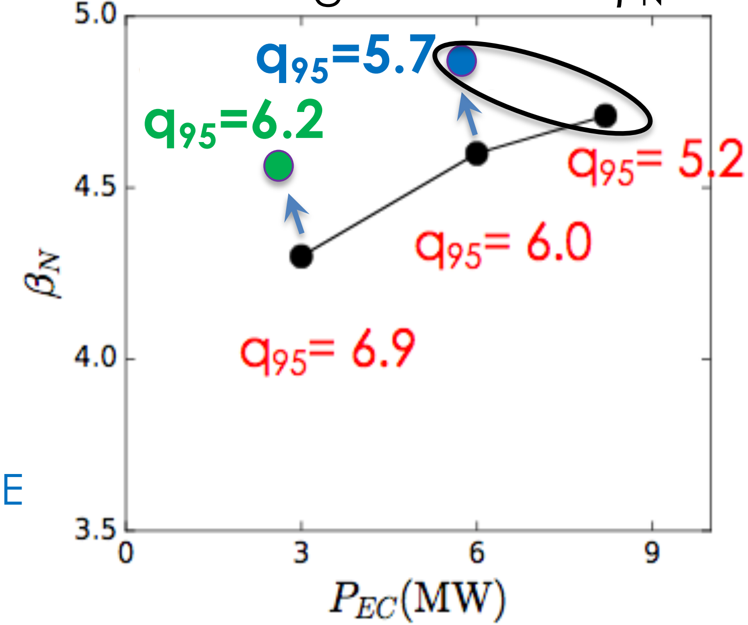
  - ➢Nearly the same performance with 3MW TOP as 6 MW OUTSIDE
  - ➢3MW TOP 117.5 GHz + 3MW OUTSIDE 110 GHz would be a reasonable alternative to 9MW OUTSIDE

FASTRAN Modeling: Steady State Highest Stable β_N

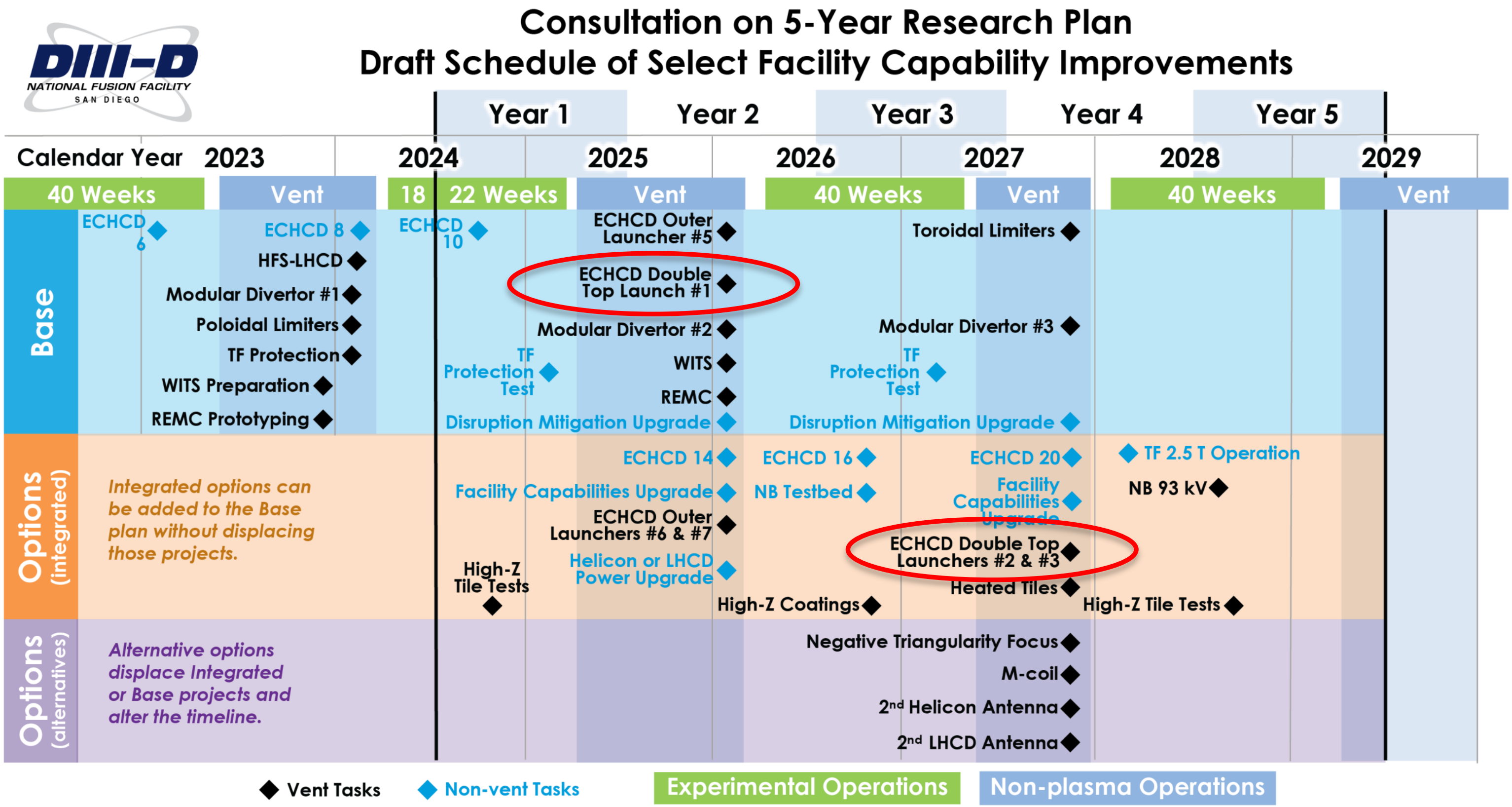


[1] J.M. Park, et al., POP (2018)

DIII-D NATIONAL FUSION FACILITY

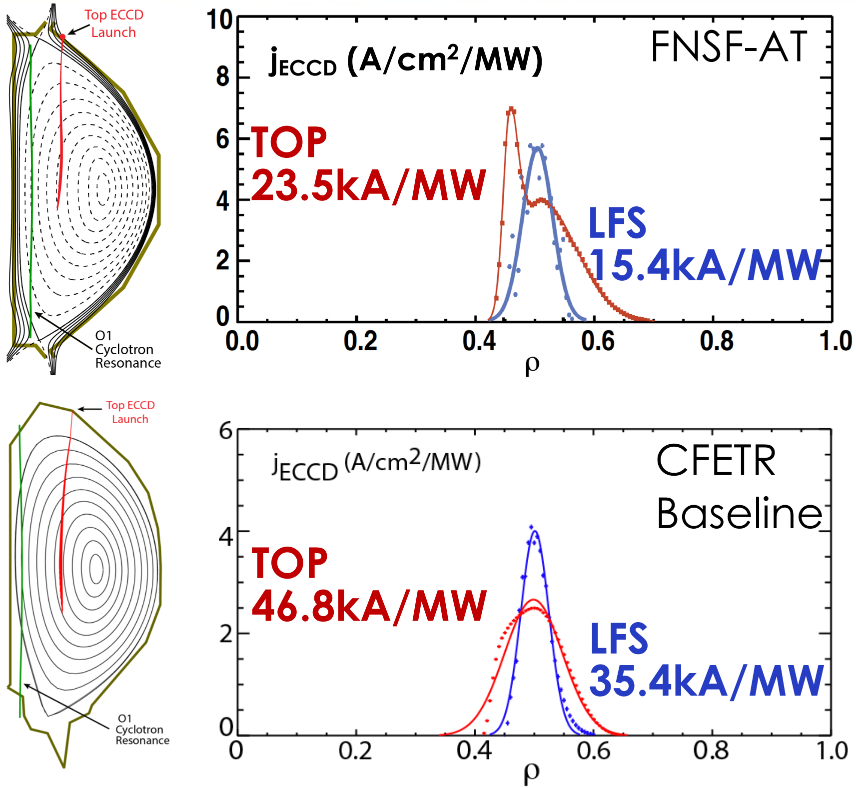
Increasing Top Launch Lines in DIII-D to Advance Towards High-β AT Scenario Physics Goals

- **2nd top launch system installed and operating, 3rd pre-funded, and more proposed**
  – waveguide switch utilized and dedicated gyrotron is not needed



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

- **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 is found in initial modeling for CFETR baseline scenario[3]**



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

Higher Off-Axis Electron Cyclotron Current Drive Via 'Top Launch' Approach Demonstrated on the DIII-D Tokamak

- **New top launch ECCD system installed on DIII-D to test this high ECCD efficiency approach**

- **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**
  - Top Launch Lines in DIII-D is increasing to advance towards high-β AT scenario physics goals