SELF-CONSISTENT ADVANCED TOKAMAK SCENARIO MODELING FOR DIII-D

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with contributions from

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Presented at
the Advance Tokamak Scenario Workshop
General Atomics, San Diego, CA

March 10, 1999

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ADVANCE TOKAMAC SCENARIO MODELING

OBJECTIVES OF SCENARIO MODELING:

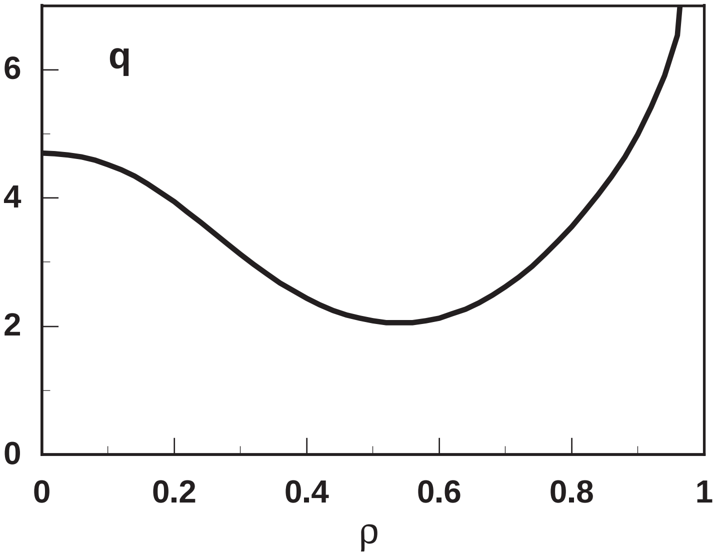
- Perform predictive calculations of DIII-D AT scenarios using time-dependent transport codes to answer the questions:
  - What is the optimum q and pressure profiles and scenarios to obtain them?
  - Can we maintain the desired q and pressure profiles?
- Use transport modeling to help planning experiments and to understand physics involved

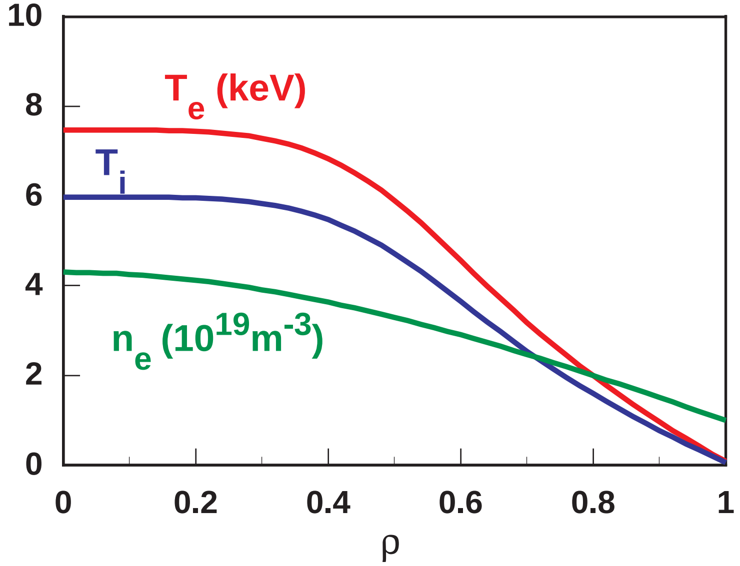
Goals of the DIII-D AT Scenarios:

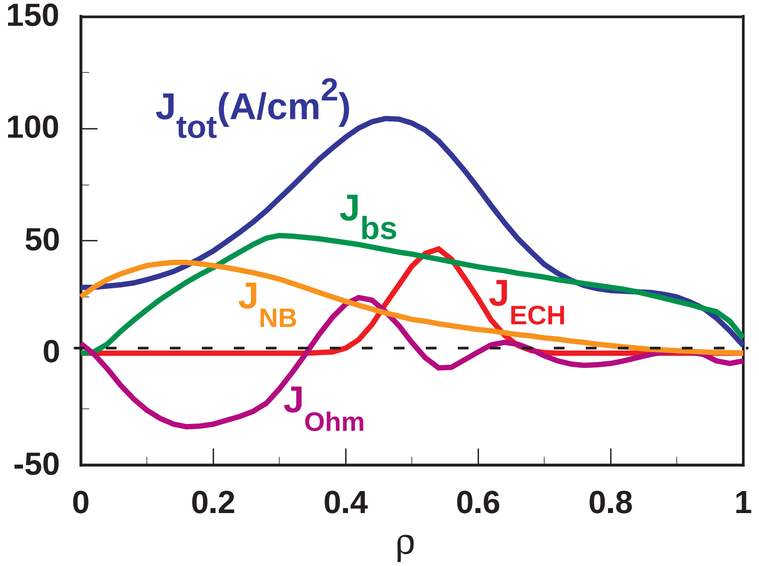
- High normalized performance better than twice the conventional ELMing H-mode ($\beta_N H > 10$)
- Consistent with steady state (I.e., non-inductively)
- High bootstrap fraction

A BASE-LINE TARGET FOR ECH SUSTAINED NCS SCENARIO BASED ON FIXED KINETIC PROFILES

P_{EC} (MW)	2.3	β_T (%)	4.0
P_{FW} (MW)	3.6	β_N	4.0
P_{NBI} (MW)	4.1	H_{89P}	2.8
I_p (MA)	1.0	n (10^{20} m^{-3})	0.32
I_{Boot} (MA)	0.65	n/n_G	0.3
$I_{E\ CCD}$ (MA)	0.15	$T_i(0)$ (keV)	6.0
B_T (T)	1.6	$T_e(0)$ (keV)	7.5







- Satisfies MHD stability
- Density profile based on pumped ELMing H-mode

QUESTIONS REGARDING THE ADVANCED TOKAMAK SCENARIO MODELING

1. Can we reproduce the baseline target scenarios using self-consistent transport modeling?

2. Can we extend the AT scenarios to steady state with the available ECH power in near terms?

3. Which edge condition is more favorable in achieving the goals?

4. How can we use the transport modeling to help planning experiments and understand physics involved?

AT SCENARIO MODELING IS BASED ON TIME-DEPENDENT SIMULATIONS USING TRANSPORT COEFFICIENTS DERIVED FROM EXISTING DISCHARGES

PROCEDURE

1. Obtain profiles of $\chi_e(r)$, χ_i (r) from existing discharges
   - — 92668: 2.1T, NBI, L-mode edge NCS with ITB at H~2
   - — 87087; 1.6T, NBI, H-mode edge, β_N~4, ITB at H~2.5
2. Scale χ_e, χ_i to preserve H factor
   - — $\chi \propto P^{0.5}/(I^{0.85}n^{0.1}B^{0.2})$

     [Use of H_{98y} (GyroBohm) instead changes little]
3. Solve heat equations and current diffusion equations, consistent with fixed-boundary MHD equilibrium -- Density profile fixed
4. Apply off-axis ECH/ECCD
   - — Optimize bootstrap alignment
   - — Optimize ECCD
5. Extend modeling duration to near steady state
6. Test MHD stability

ONETWO

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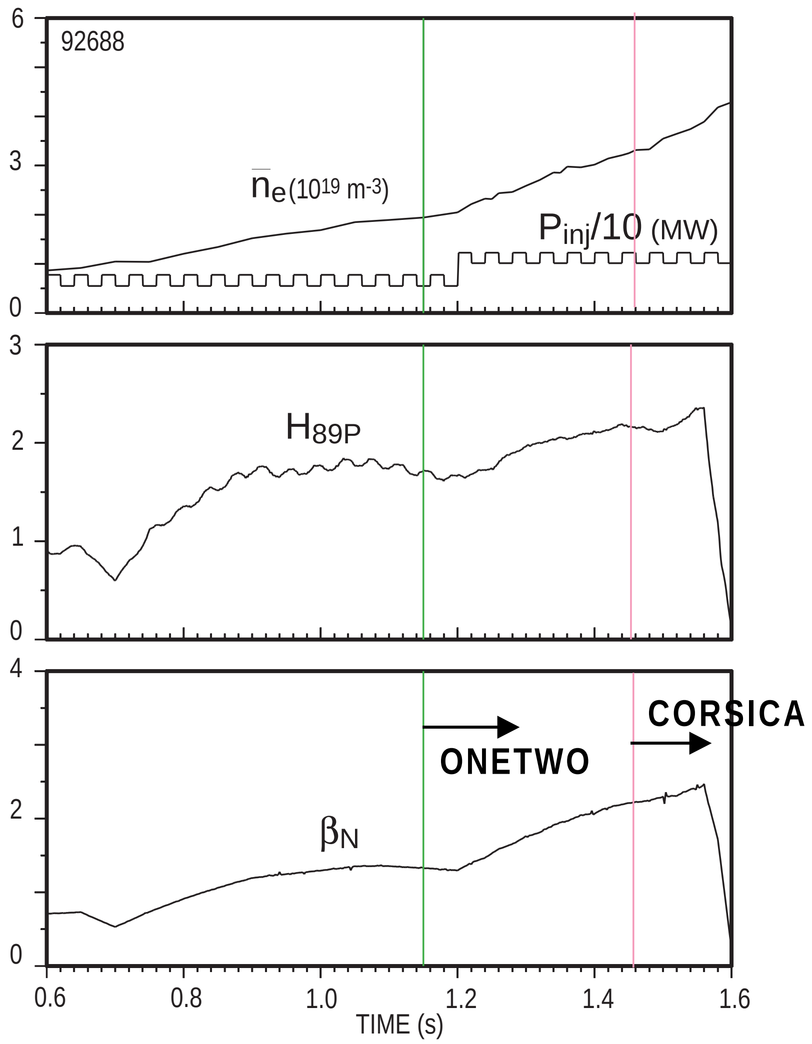
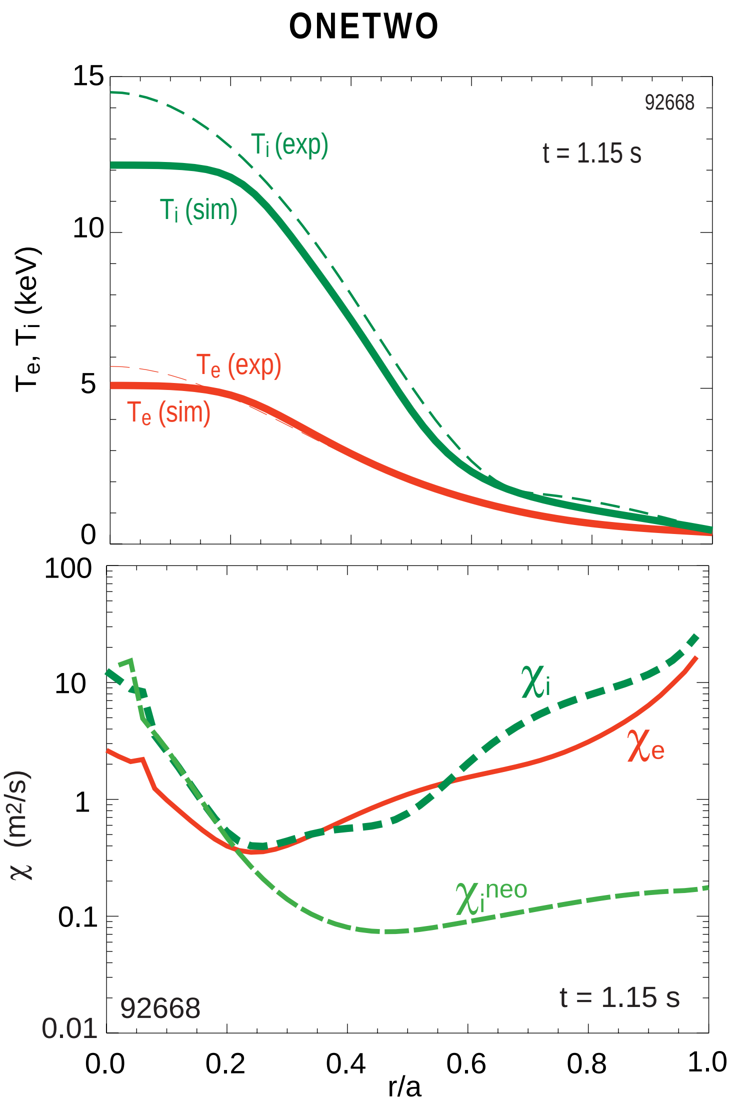
THE STARTING POINT IS AN EXISTING L-MODE EDGE INTERNAL TRANSPORT BARRIER SHOT AT 2.1 T

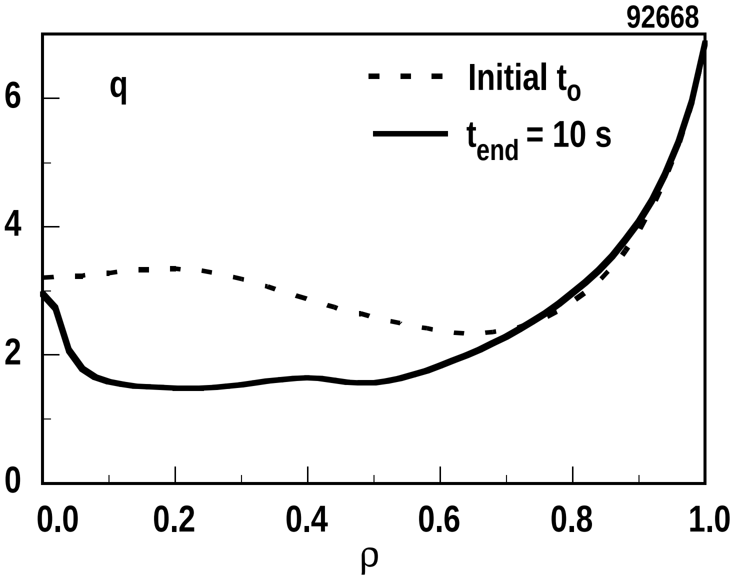
$B_T = 2.1\ \mathrm{T},\ I_p = 1.3\ \mathrm{MA},\ \overline{n}_e = 2.9\times10^{19}\ \mathrm{m}^{-3}$

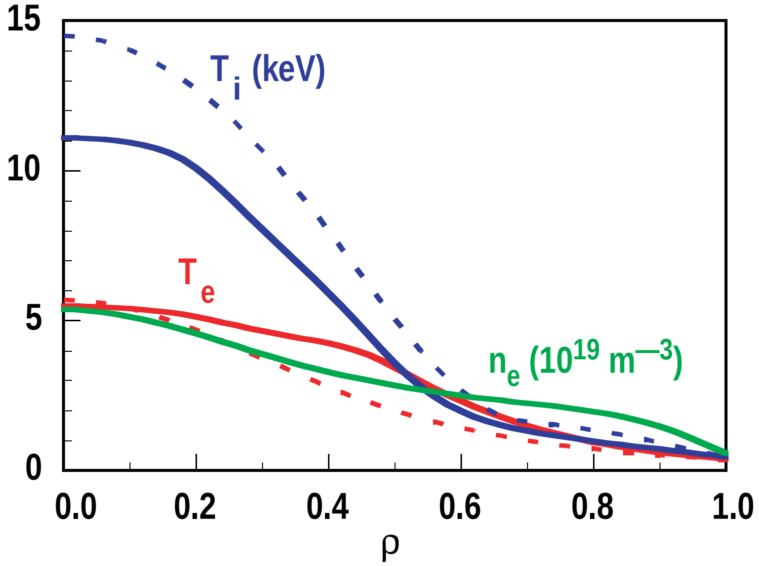


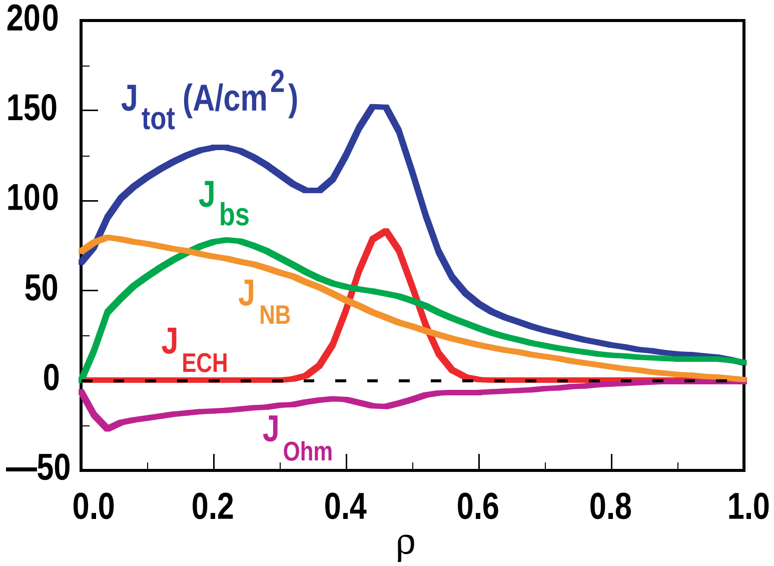


3-MW ECCD MAINTAINS q>1 FOR 10 s with β_NH~6

	Sim.	(Exp.)			
P_{EC} (MW)	3.0	(0)	β_T (%)	3.1	
P_{FW} (MW)	0		β_N	2.7	(1.5)
P_{NBI} (MW)	6.2		H_{89P}	2.2	(1.9)
I_p (MA)	1.11	(1.33)	n (10^{20} m^{-3})	0.29	
I_{Boot} (MA)	0.59		n/n_G	0.32	(0.27)
I_{ECCD} (MA)	0.18		T_i(0) (keV)	11.2	
B_T (T)	1.6	(2.1)	T_e(0) (keV)	5.4	







- 92668 scaled to B_T = 1.6 T and I_p = 1.0 MA
- NCS could not be sustained due to peaked $J_{bs}(\rho)$ resulting from peaked $n_e(\rho)$

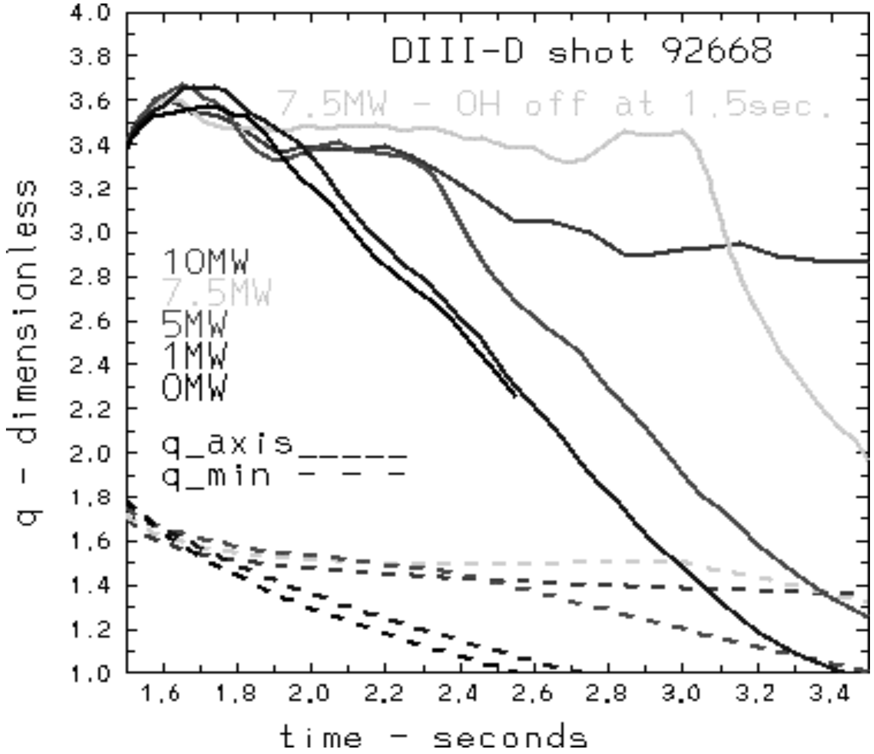
CORSICA SIMULATIONS EMPHASIZES THE TIME-DEPENDENT BARRIER DYNAMICS

PROCEDURE

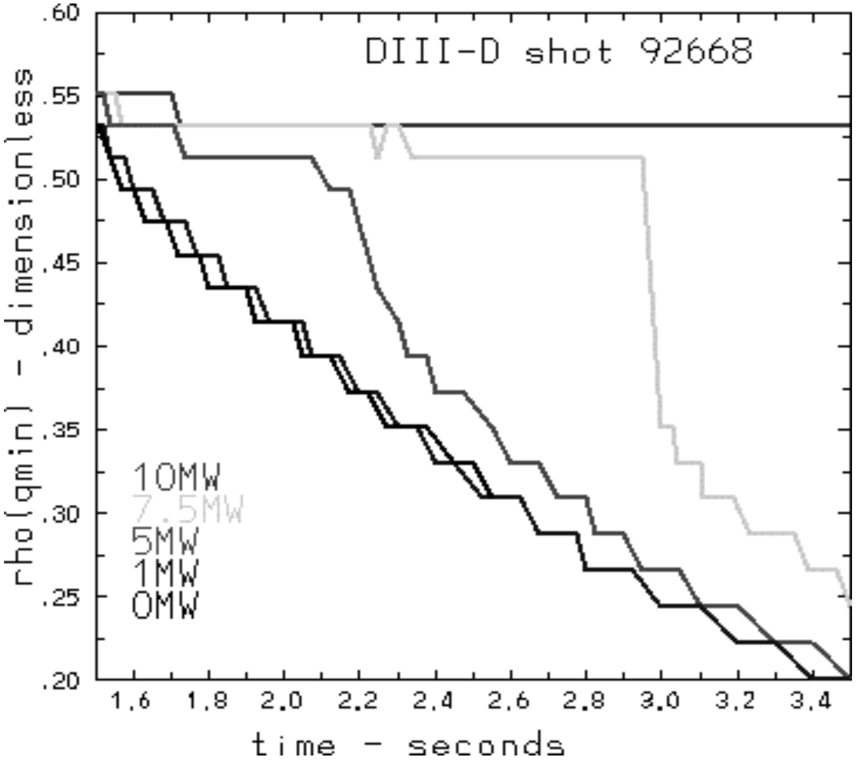
- **Existing ITB discharge – NCS with an L-mode edge:**
  - **— 92668 at 2.1T with H~2 and β_N~2.2**
- **Transport model ➠ modified gyro-Bohm**
  - — $\chi_e = \chi_0 \times (T_e^{3/2} / B_T^2) \times (T_e/T_i)^{\alpha} \times f(s) \times q^2$
    - $s = r\nabla q/q$ = shear parameter & $\alpha = 1$ or 2
  - — $f(s) = 1/[1+(9/4) \times (s-2/3)^2]$
    - shape profile from transport simulation
  - — $\chi_i = c_1\chi_{neo} + c_2\,\chi_e \times Z_{eff} \times (T_e/T_i)^{1/2} \times H(\nabla q)$
    - H = Heaviside function ➠ strong ion barrier
    - c_0, c_1, and c_2 (~1) are free parameters based on measured profiles
- **Add off-axis ECH and scans in power and heating location**
- **Evolve until q < 1 anywhere or 5 sec.**

10 MW simulation shows that ρ_{qmin} is sustained for full heating interval (CORSICA)

q_0 and q_{min} vs. time



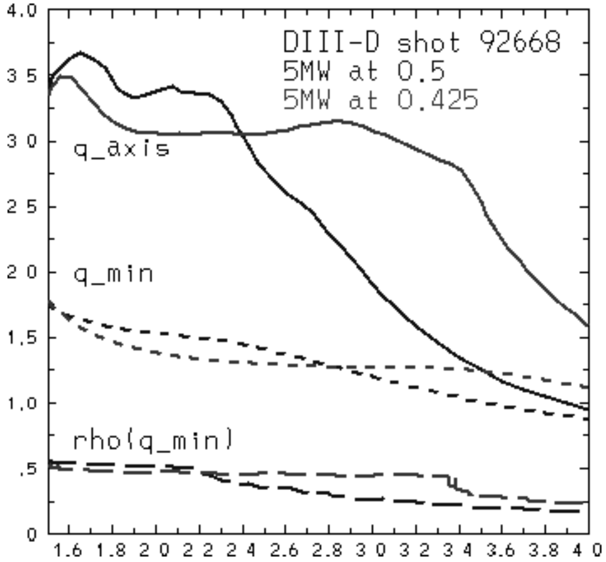
$\rho(q_{min})$ vs. time



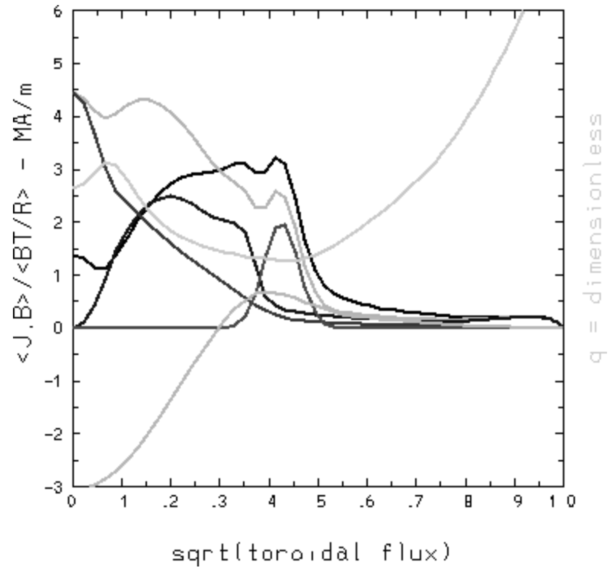
ρ_{ECCD} = 0.5
with $\delta\rho$ = 0.05

BETTER ALIGNMENT OF ECCD WITH J_{BS} REDUCES POWER TO SUSTAIN BARRIER (CORSICA)

q0, q_{min} and $\rho(q_{min})$ comparison for 5MW applied at r=0.5 and r=0.425



Current profiles at 3.0 seconds



- At r=.425, sustain barrier to 3.5 sec.
- Moving P_{EC} location to ρ = .425 ➠ on steep ∇n region ➠ better alignment of J_{ECCD} with J_{BS}

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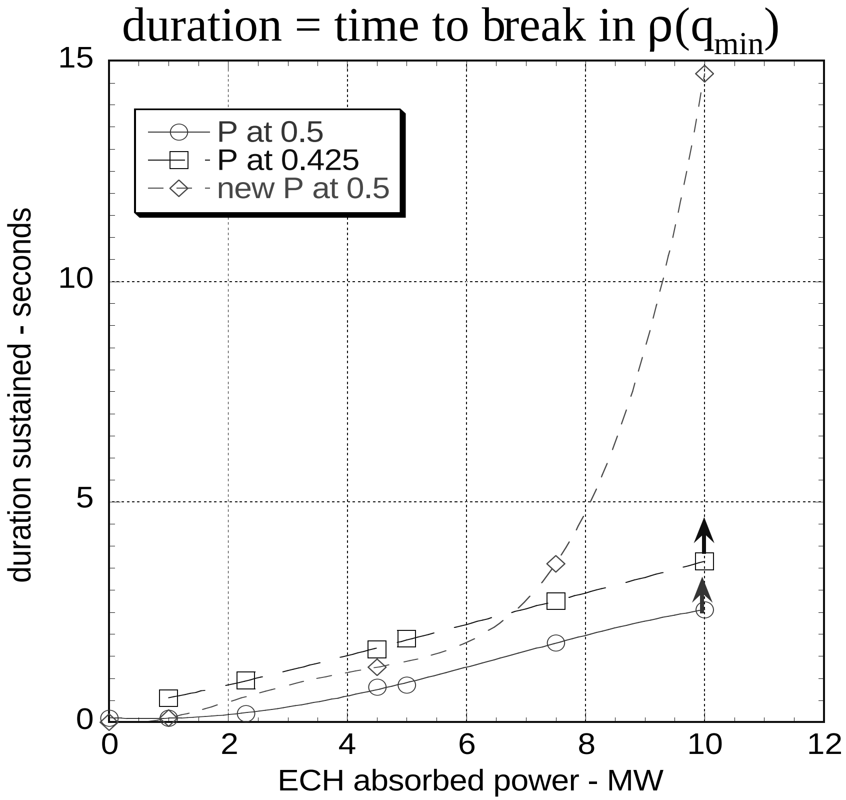
SUSTAINED BARRIER DURATION INCREASES WITH ABSORBED P_{EC} FOR MODIFIED GYRO-BOHM MODEL (CORSICA)



- ✶ Simulations sustain ρ_{qmin} for > 15 s at 10MW
- ✶ At higher power (e.g. ~ 5MW) simulations show that long pulse NCS discharges are sustained at high β
- ✶ Results are critically dependent on the transport model used

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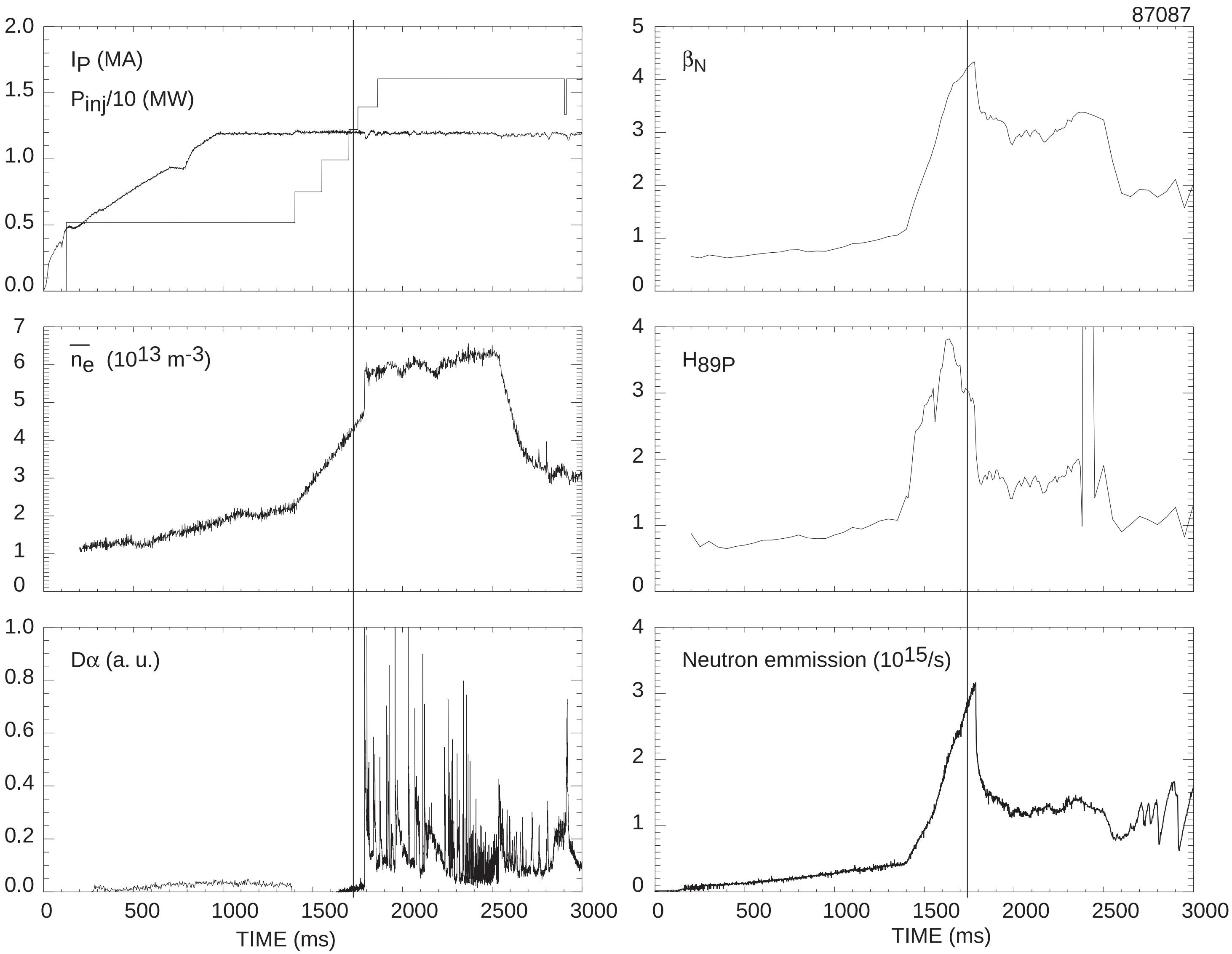
POSSIBLE β_NH~10 STARTING POINT -- H-mode edge ITB



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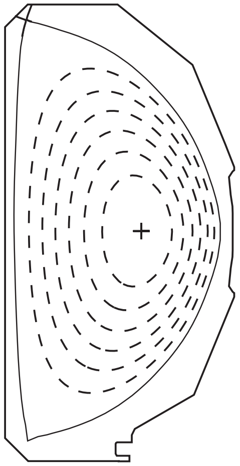
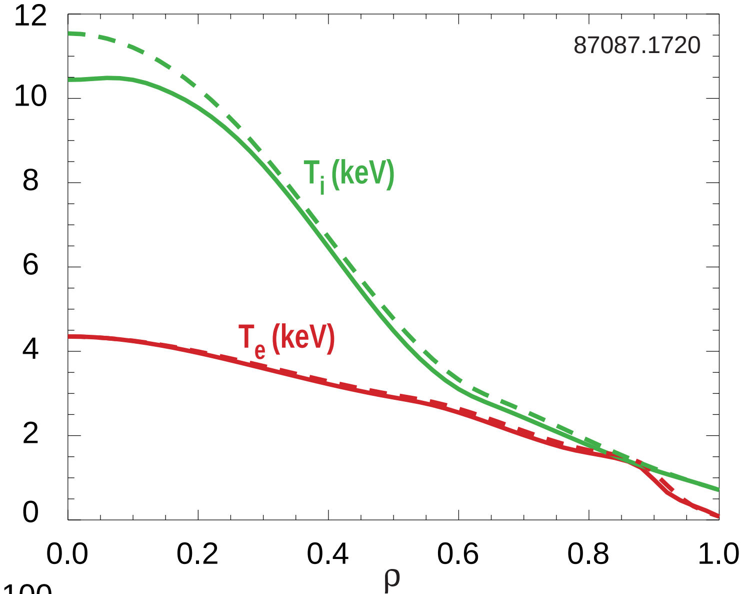
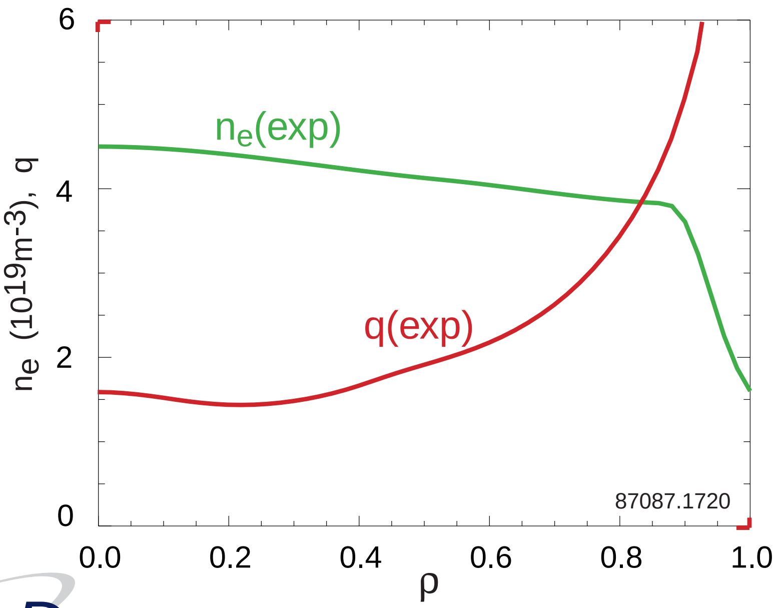
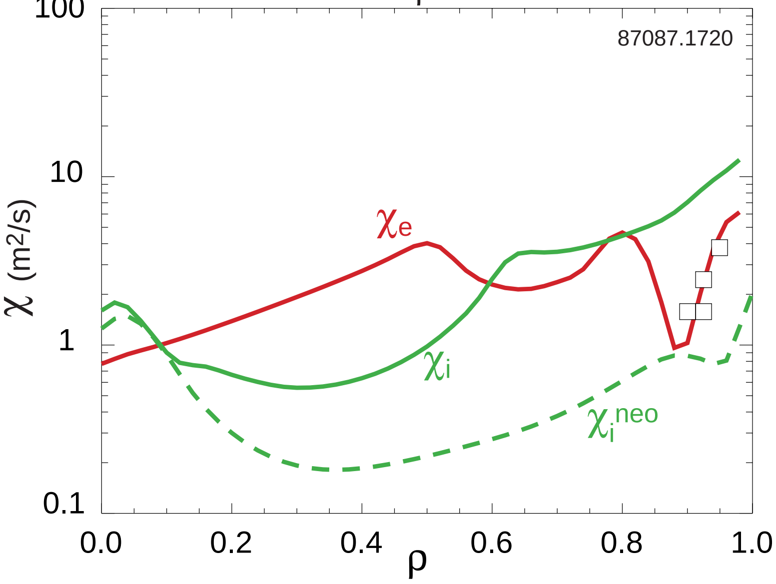
SIMULATIONS ARE BASED ON AN EXISTING H–MODE EDGE DISCHARGE WITH INTERNAL TRANSPORT BARRIER AT 1.6 T



B_T = 1.58 T
I_p = 1.2 MA

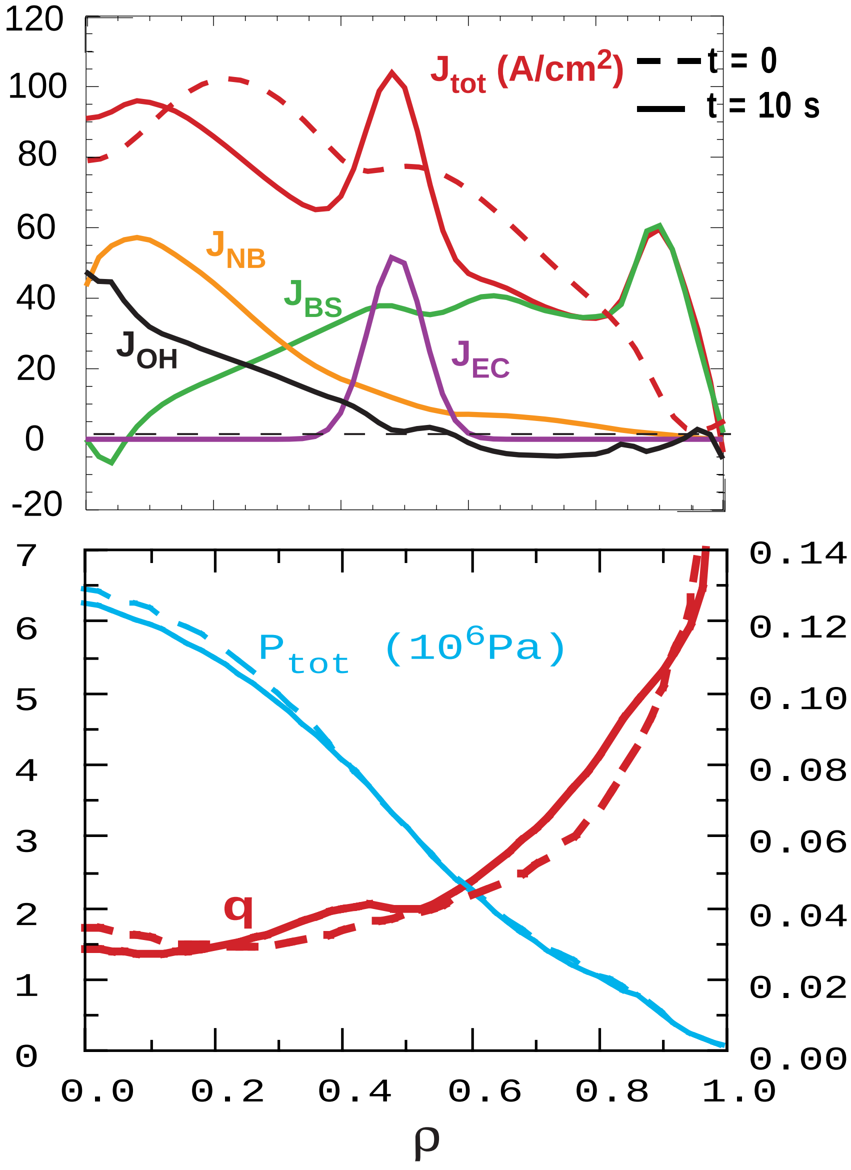






SIMULATION RESULTS FOR ITB WITH H–MODE EDGE AT 1.6 T AND 3 MW ECH

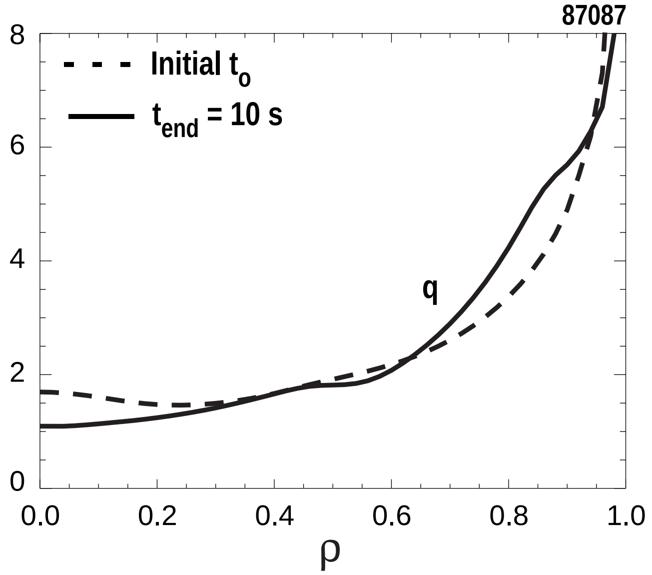
	Sim. (Exp.)		
P_{EC} (MW)	3.0 (0)	β_T (%)	4.6
P_{FW} (MW)	0	β_N	3.7 (3.7)
P_{NBI} (MW)	9.2 (12)	H_{89P}	2.5 (2.4)
I_p (MA)	1.20	n (10^{20} m^{-3})	0.45
I_{Boot} (MA)	0.70	n/n_G	0.45
I_{ECCD} (MA)	0.14	T_i(0) (keV)	10.4
B_T (T)	1.6	T_e(0) (keV)	4.7

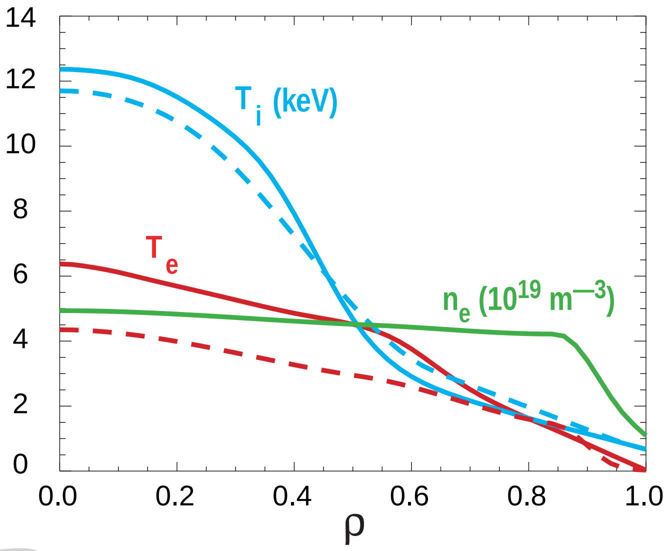


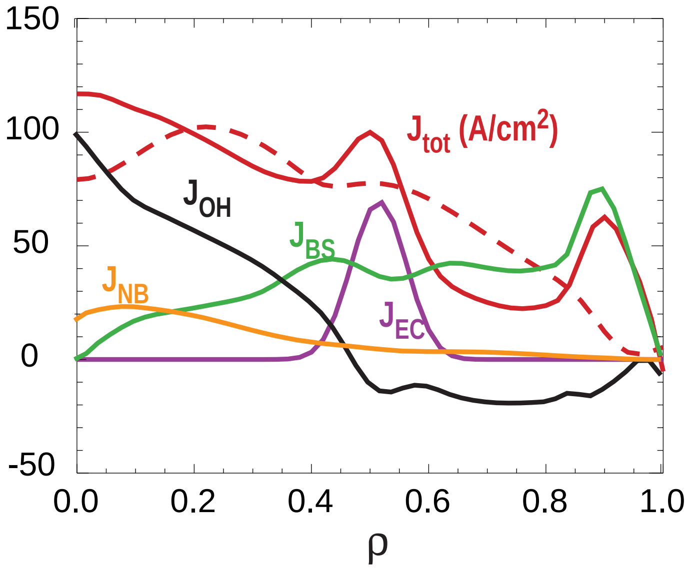
- Evolved for 10 s with fixed-boundary MHD equilibria
- Stable to n=1 with a conducting wall at 1.5a (very unstable without wall)
- 2nd ballooning stability access for most of plasma volume

4.5-MW ECCD with FAST WAVE HEATING ACHIEVES $\beta_N H$~12 AND BOOTSTRAP CURRENT FRACTION OF ~70%

	Sim. (Exp.)		
P_{EC} (MW)	4.5 (0)	β_T (%)	5.2
P_{FW} (MW)	3.6	β_N	4.2 (3.7)
P_{NBI} (MW)	4.1 (12)	H_{89P}	2.8 (2.4)
I_p (MA)	1.20	n (10^{20} m^{-3})	0.45 (0.38)
I_{Boot} (MA)	0.84	n/n_G	0.45
I_{ECCD} (MA)	0.20	T_i(0) (keV)	12.4
B_T (T)	1.6	T_e(0) (keV)	6.4







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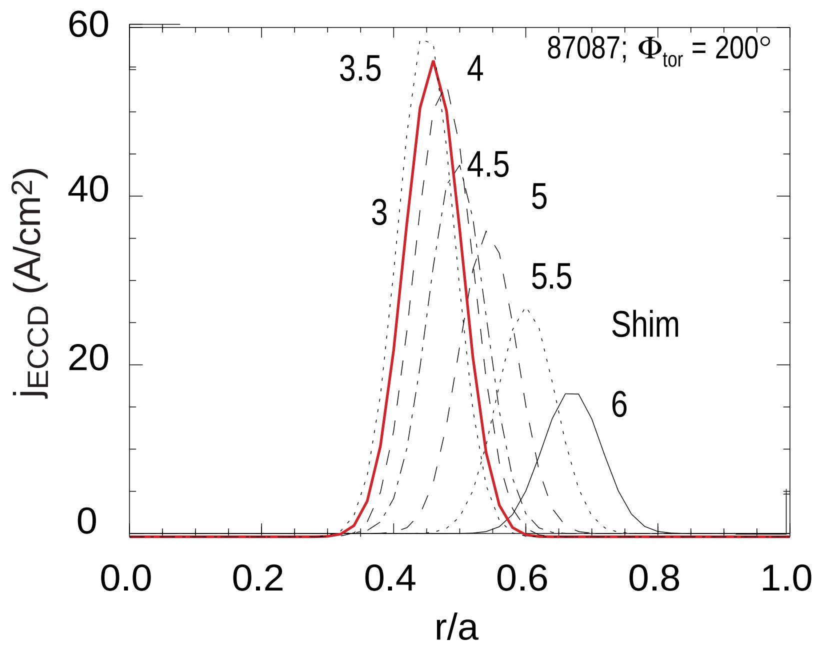
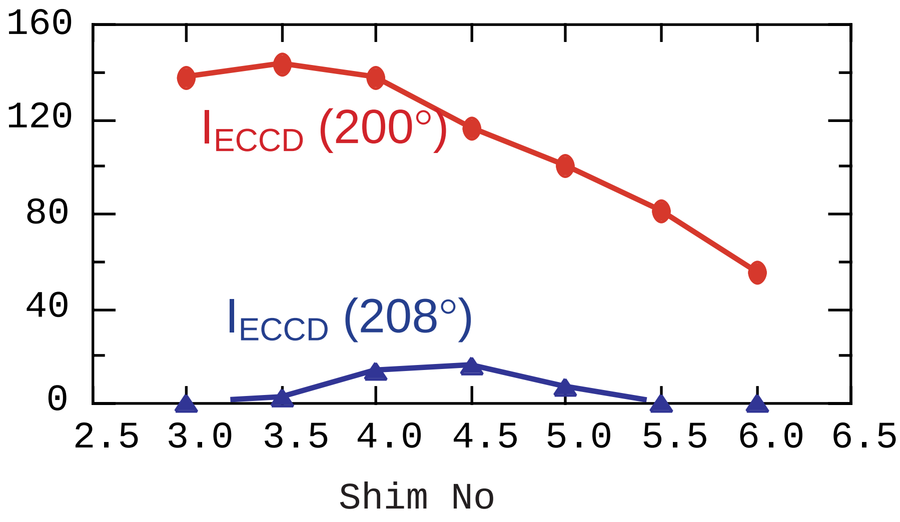
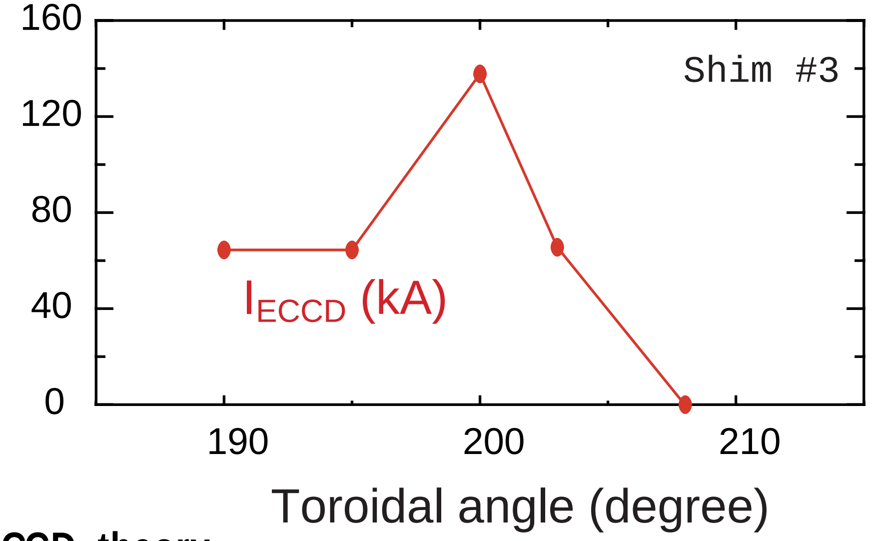
ECH POLOIDAL AND TOROIDAL AIMING ARE OPTIMIZED FOR ECCD EFFICIENCY AND BOOTSTRAP ALIGNMENT







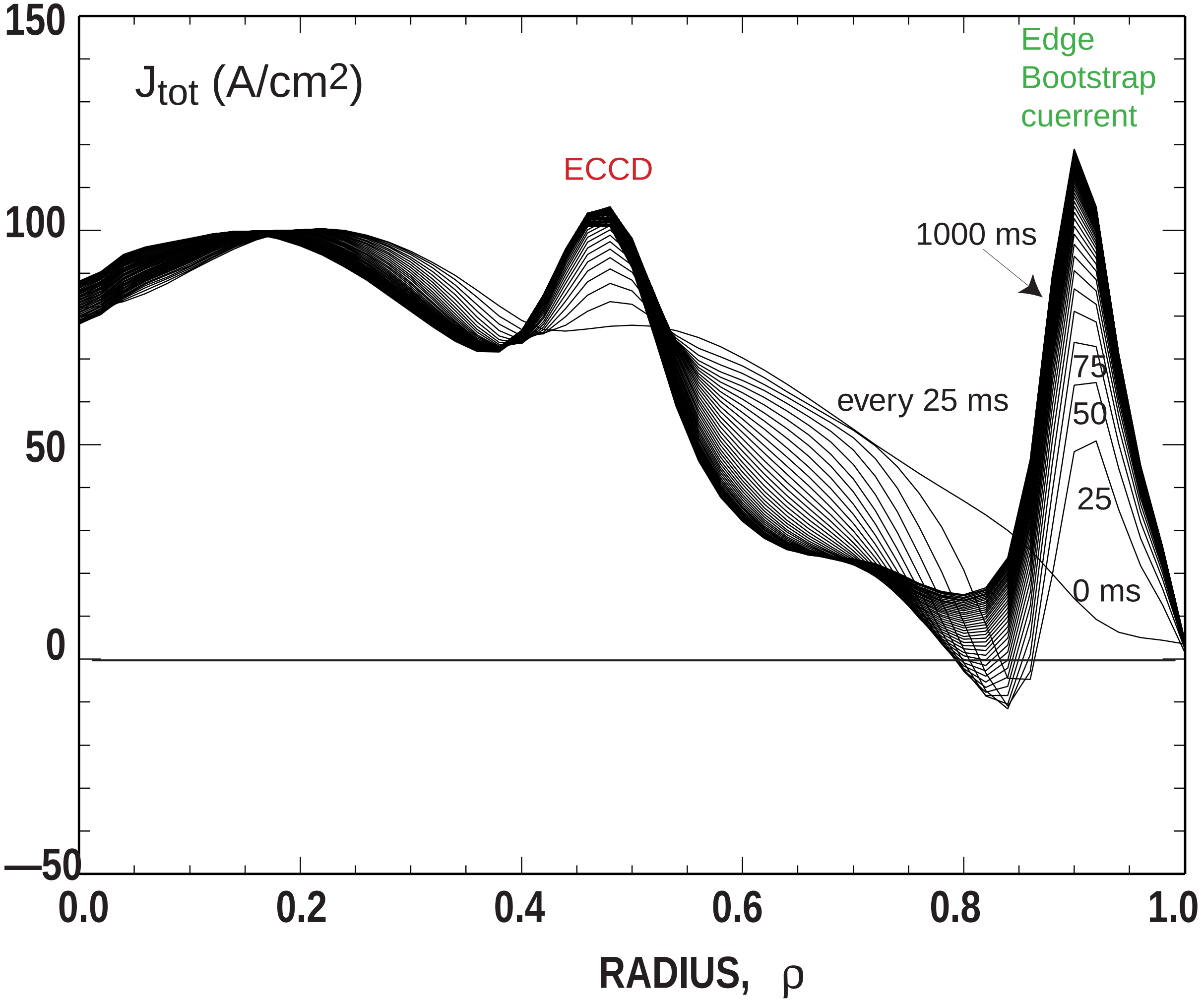
- **Toroidal aiming are quite different from L-mode case due to refraction at edge**

- **Issues to be resolved:**
  - **— Collisionality effects in ECCD theory**
  - **— Mode conversion between X- and O-mode at edge**

SUMMARY OF AT SCENARIO MODELING WITH ECCD

	Fixed Profiles	Transport Simulation		
P_{C} (MW)	2.3	3.0	3.0	4.5
P^{E}_{W}(MW)	3.6	0	0	3.6
P^{F}_{BI} (MW)	4.1	9.2	9.2	4.1
I^{N}(MA)	1.0	1.1	1.2	1.2
(MA) I^{p}_{OOT}	0.65	0.59	0.74	0.84
I^{B}_{CCD} (MA)	0.15	0.18	0.14	0.20
γ^{E}_{c} (10^{20}A/W/m)	0.035	0.038	0.034	0.051
B (T)	1.6	1.6	1.6	1.6
β^{T}(%)	4.0	3.1	4.6	5.2
β	4.0	2.7	3.8	4.2
4^{N}li	3.4	4.5	3.4	3.2
H_{9P} $^{-3}$	2.8	2.2	2.5	2.8
$n^{8}(10^{20}$ m)	0.32	0.29	0.38	0.38
n/n_{G}	0.3	0.32	0.38	0.38
T (0)	6	11.2	10	12.4
T^{i} (0) $_{e}$	8	5.4	4.5	6.4

EDGE BOOTSTRAP CURRENT IS MODIFIED BY THE BACK EMF

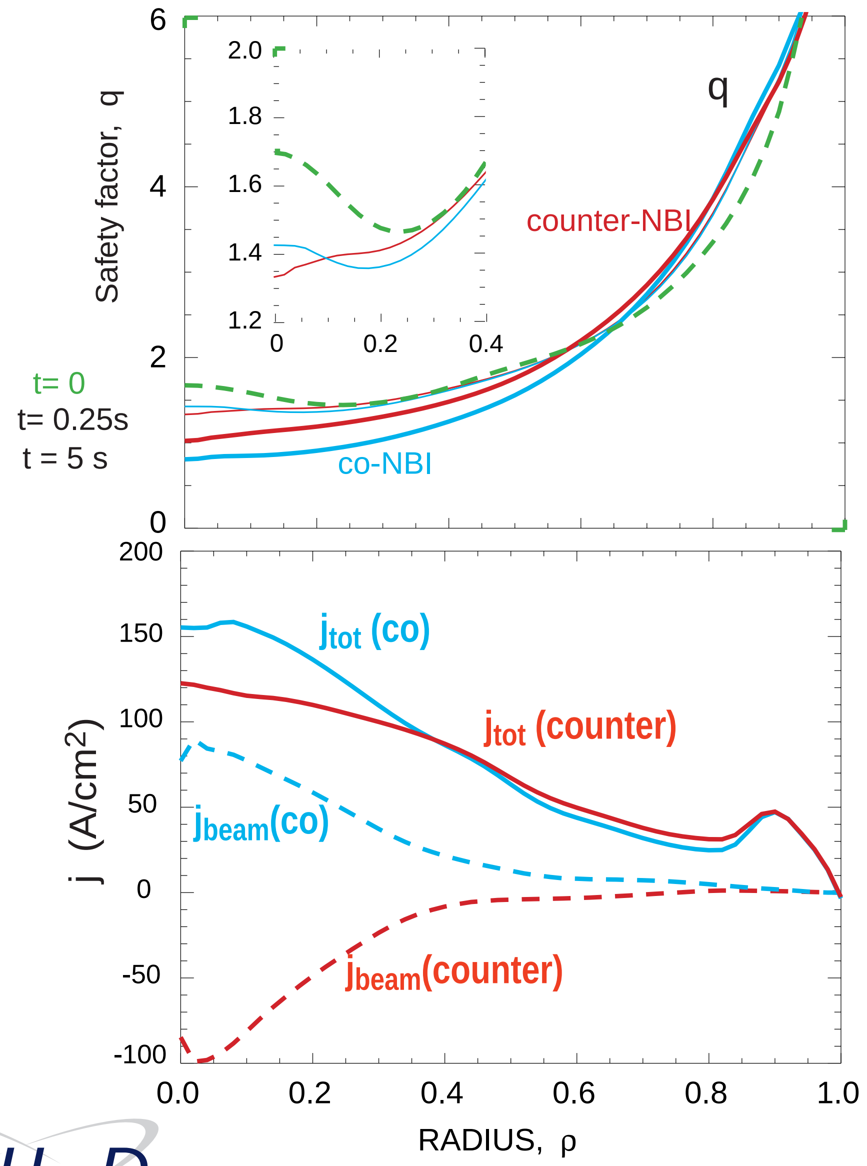


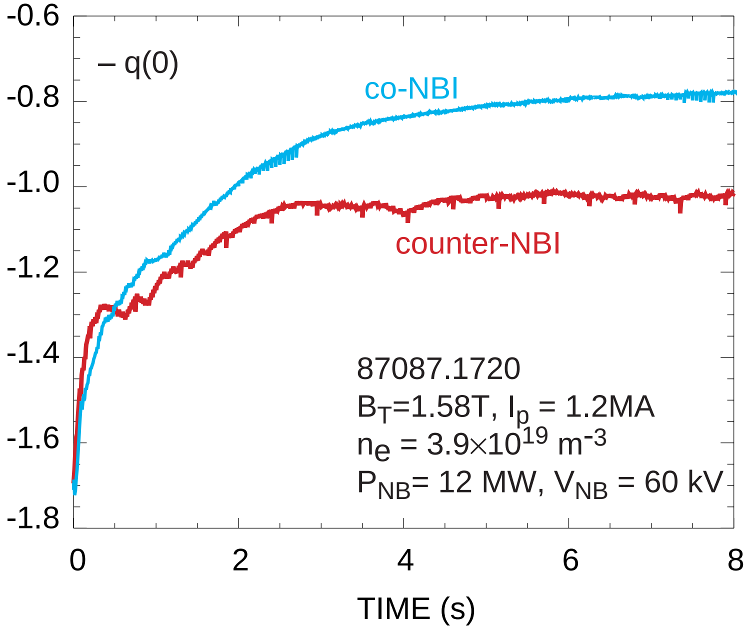
- A usual ELM period is much shorter than the time for edge current to grow to a full amplitude of bootstrap current.

TRANSPORT SIMULATIONS HELP PLAN EXPERIMENTS AND UNDERSTAND ITB PHYSICS

- Counter Injection
- Initial ECH/ECCD with NBI [C. Greenfield]

SIMULATIONS INDICATE THAT COUNTER-NB INJECTION MAINTAINS q>1 FOR FULL HEATING DURATION





- **Back EMF decreases q(0) with counter-injection during the initial first second**

FUTURE DIRECTIONS

- Apply physics models to self-consistent ITB dynamics
  - Magnetic shear and ExB flow shear effects
  - Particle and momentum evolution

- Models -- IFS/PPPL with ExB shearing, Mixed shear model, GLF23

- Increase the portfolio of the target discharges
  - Thrust 2: NCS scenario using ECCD
  - Thrust 7: ITB expansion and duration -- Counter injection campaign

CONCLUSION

- ONETWO and Corsica simulations indicate that ECCD can sustain NCS/WNS discharges
- Modeling used transport coefficients derived from existing discharges
- Scaling of existing shots indicates a path to higher performance steady-state conditions (high β_NH and higher bootstrap fraction)
- Combined ECH/FWH and ECCD in simulations maintain NCS/WNC from several τ_E to steady-state -- somewhat dependent on the model χ used
- Transport simulations help plan experiments and better understand physics involved