Time-dependent Modeling of Sustained Advanced Tokamak Scenarios

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We are modeling time-dependent behavior of advanced tokamak operating modes sustained by electron cyclotron heating and current drive for a variety of plasma conditions and heating locations. Using experimentally achieved DIII-D discharge conditions with either theory-based or experimentally fitted transport models, we investigate techniques to control the hollow current profiles required for steady-state AT operation. For negative shear conditions, we include the effects of strong heating and variations in ion and electron temperatures and density profiles. We find that, at moderate levels of microwave power for the DIII-D system, we can sustain transport barriers for long intervals with evolution to non-inductively current-driven conditions under many scenarios. At the high temperatures representative of high performance discharges in DIII-D, the equilibration time is fairly long, taking several seconds to reach the non-inductively driven state. We will present details of these time-dependent simulations investigating methods for current profile control including effects of temporal variations of neutral beam and electron cyclotron heating.

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Motivation: development of advanced tokamak scenarios

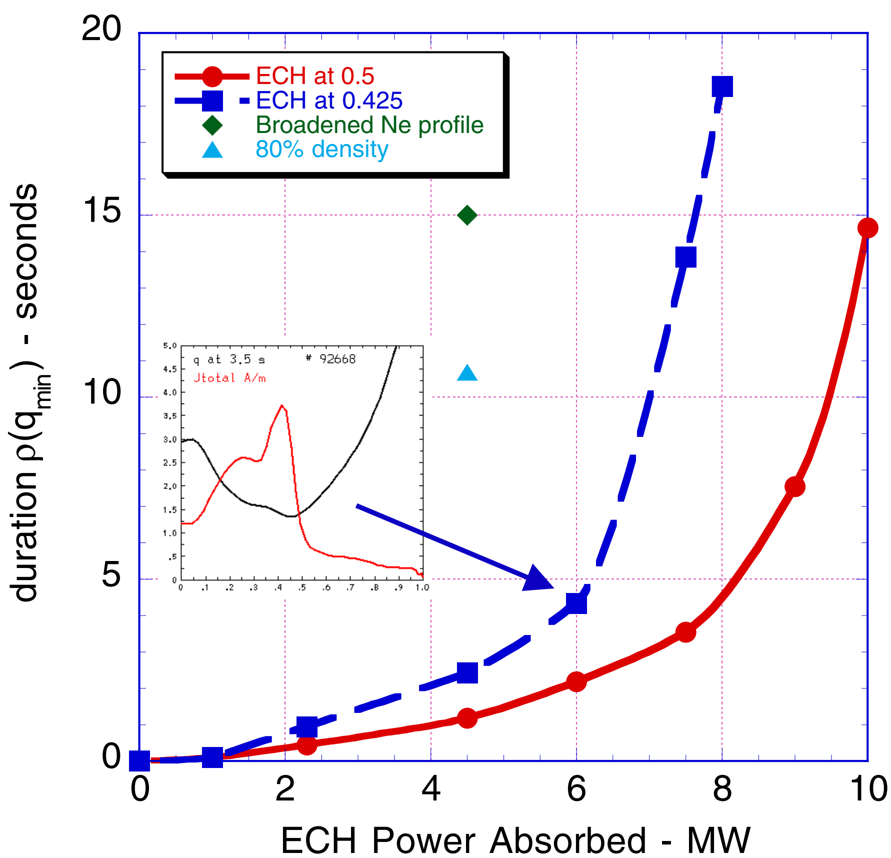
- Negative central shear (NCS) discharges require a non-inductively sustained hollow current profile in steady state.
- High performance, $\beta_n H \sim 10$, with high bootstrap current fraction, $f_{BS} \sim 50\%$, may be more easily achieved in H-mode-like operation.
- Electron cyclotron heating (ECH) power in DIII-D is being increased and operating scenarios need to be explored.
- Development of tools to explore optimization and use of ECH and neutral beam injection (NBI) power
  - Feedback modification of plasma parameters
  - Combined use of ECH and NBI heating and current drive
  - Stability control
  - Guide for experiments

Time-dependent simulations

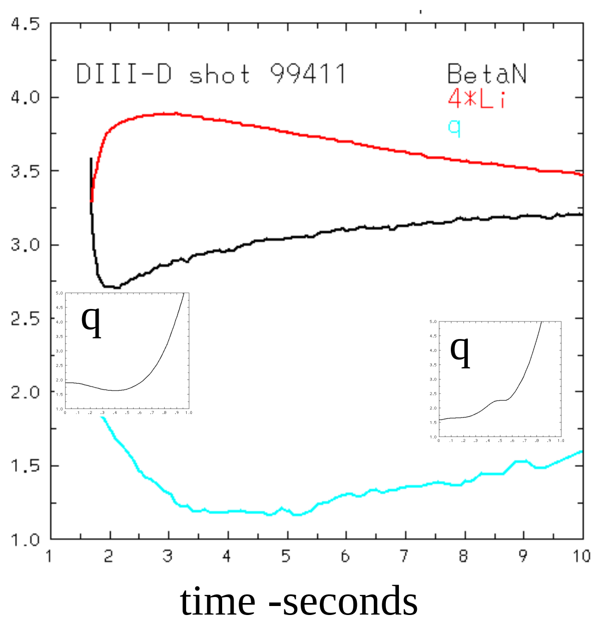
- Energy transport models for χ_i and χ_e used in Corsica to evolve plasma from known experimental state
  - Self-consistent equilibrium and transport converged at each time step
  - Time-dependent NBI and EC heating and current drive sources
  - Stability assessment
- Simulation of internal transport barrier (ITB) dynamics in Corsica
  - χ_i and χ_e from a parametric, gyro-Bohm model for ITB
  - High performance NCS with L-mode edge
  - shot #99268
- Target studies for ECH control in Corsica & ONETWO
  - Measured χ_i and χ_e for shot #99411, a high performance H-mode shot without an ITB
  - Transport coefficients fixed in time are used to evolve H-mode ECH target shot

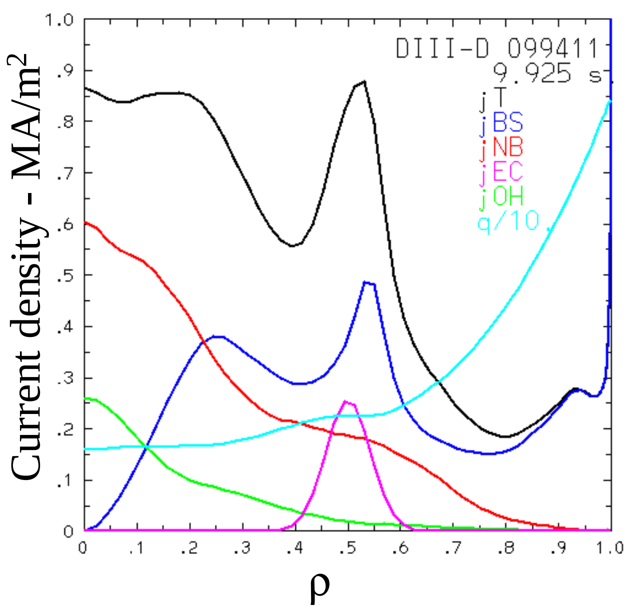
For high performance NCS with L-mode edge, ECH/ECCD increases the duration the barrier is maintained

- At P_{ECH} comparable to that available on DIII-D, strong modification of the q-profile increases barrier duration
- Density control optimizes performance ➠ control of peak density for heating/current drive efficiency and profile for bootstrap alignment



ECH/ECCD modification of current profile in high performance H-mode target shot

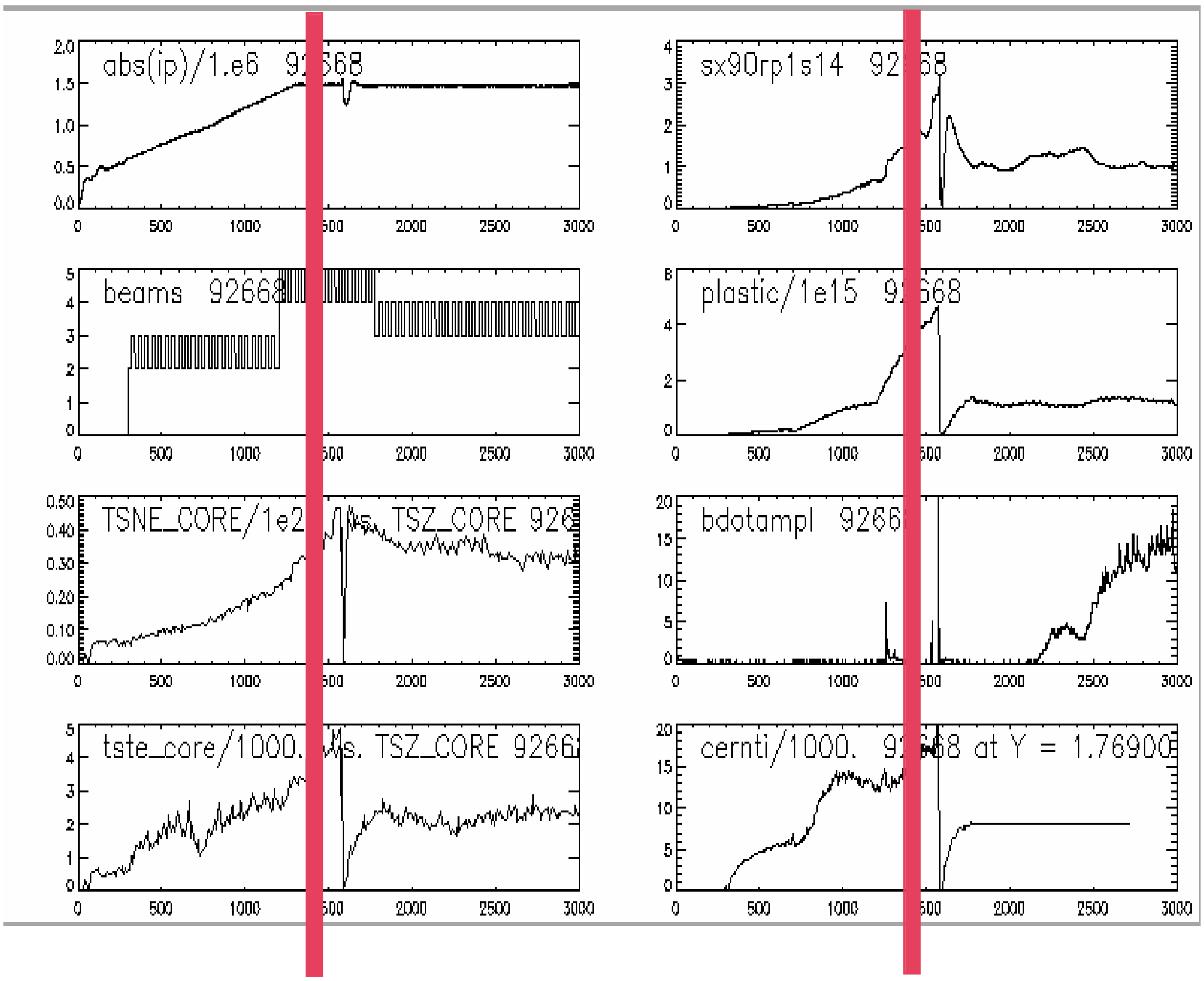




- ECH provides an ability to modify the current profile , e.g. raise q, during evolution to steady state
- Optimization of NBI and EC heating and current drive is important
- Density control provides some control of q_0 at fixed β_n ➠ need for core-edge coupled simulations

Shot #92668 simulation ➟ Extend duration of negative shear plasma

- β collapse due to peaked pressure profiles
- Corsica: density profile, I_p, B_T and P_{NBI} fixed



Corsica simulations initialized with measured profiles at 1.45 sec

Transport model used for barrier dynamics simulations

- $\chi_e = c_{0e} (T_e^{3/2}/B_T^2) (T_e/T_i)^\alpha f(s) q^2$

  $+ c_{1e} \chi_e^{neo} + \chi_{edge}$ ➠ $c_{0e} = 1.4$, $c_{1e} = 1.0$, $\alpha = 1$

  Based on gyro-Bohm scaling

  $s = r\nabla q/q$ = shear parameter

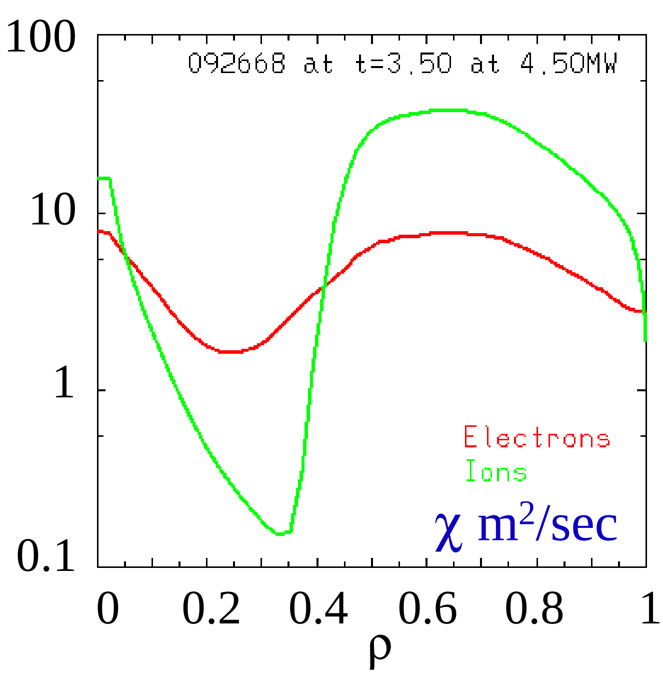
  $f(s) = 1/[1+(9/4) \times (s-2/3)^2]$

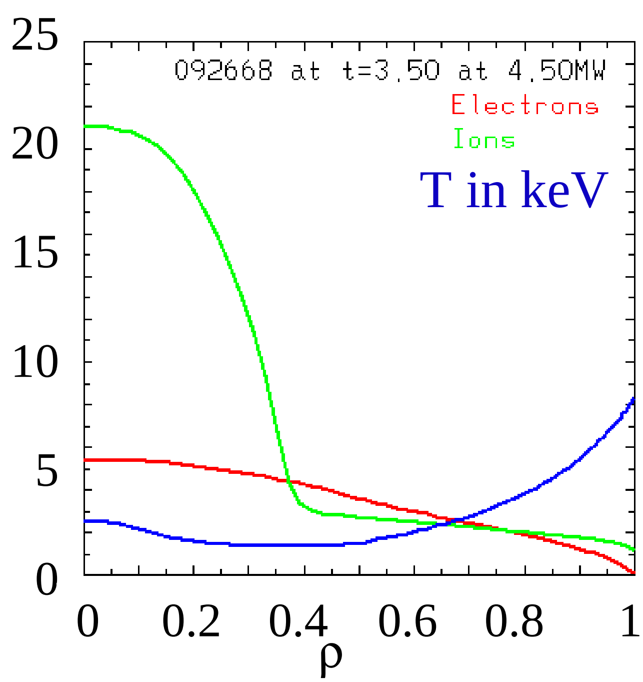
  shape profile from transport simulation

- $\chi_i = c_{0i} \chi_e Z_{eff} (T_e/T_i)^{1/2} H(\nabla q)$

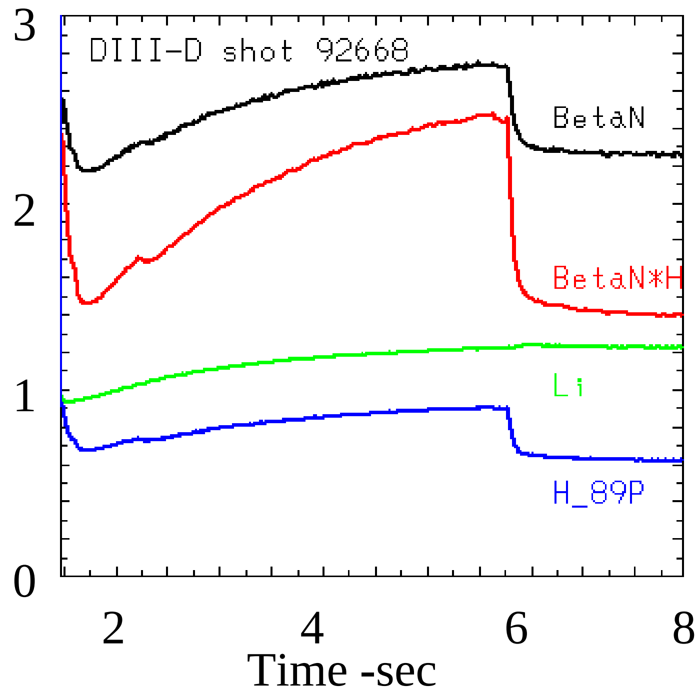
  $+ c_{1i} \chi_i^{neo}$ ➠ c_{0i}, $c_{1i} = 1.0$

  strong ion barrier ➠ H = Heaviside function



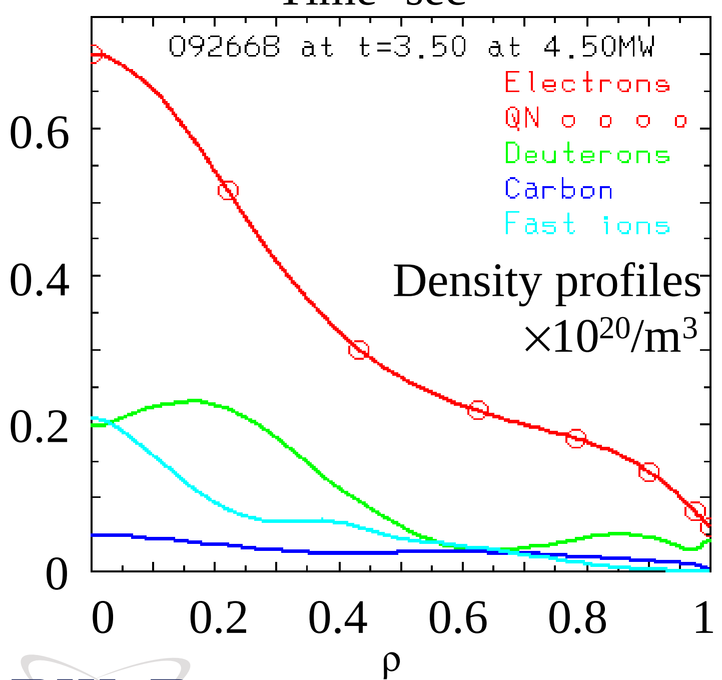


Evolve plasma equilibrium, current distribution and temperatures



β_N, H_{iter89} and l_i evolution for P_{ECH}=4.5MW at ρ=0.425

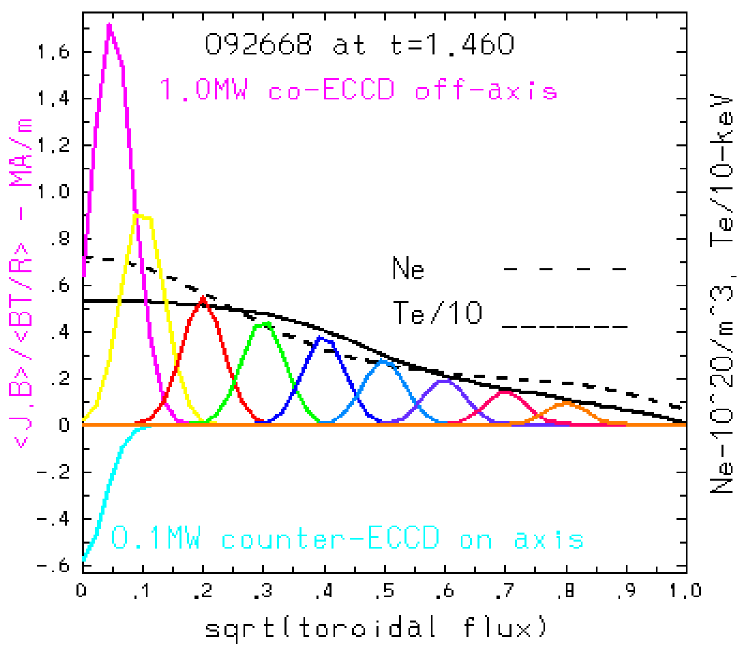
ITB "lost" at ~ 5.75 sec.



Electron density and Zeff held fixed at measured profiles for #99268

Fast & thermal ion densities from Monte-Carlo NBI model and quasi-neutrality

Use Gaussian approximation to EC power deposition profile from TORAY



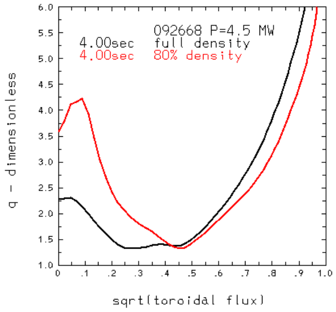
Current density variation for Heating at Different ρ at P_{EC}=1MW for N_e and T_e profiles shown

TORCH ray tracing code is in Corsica but not yet exercised

- $I_{ECCD} = \gamma P_{ECH} T_e / n_e R$
  efficiency, γ, from measurements
- Current drive contributions at 2.0 sec. for power absorbed at ρ=0.5

P_{ECH}	I_{ECCD}	I_{BSCD}	I_{NBCD}	I_P
1 MW	28kA	480kA	307kA	1.48MA
5 MW	185kA	640kA	321kA	1.48MA
7.5MW	320kA	726kA	300kA	1.38MA
10 MW	460kA	660kA	340kA	1.49MA

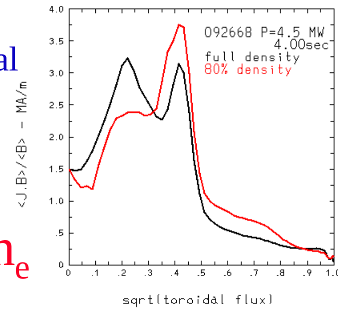
Summary NCS simulations: Increasing P_{EC} and decreasing n_e increase the duration $\rho(q_{min})$ is maintained

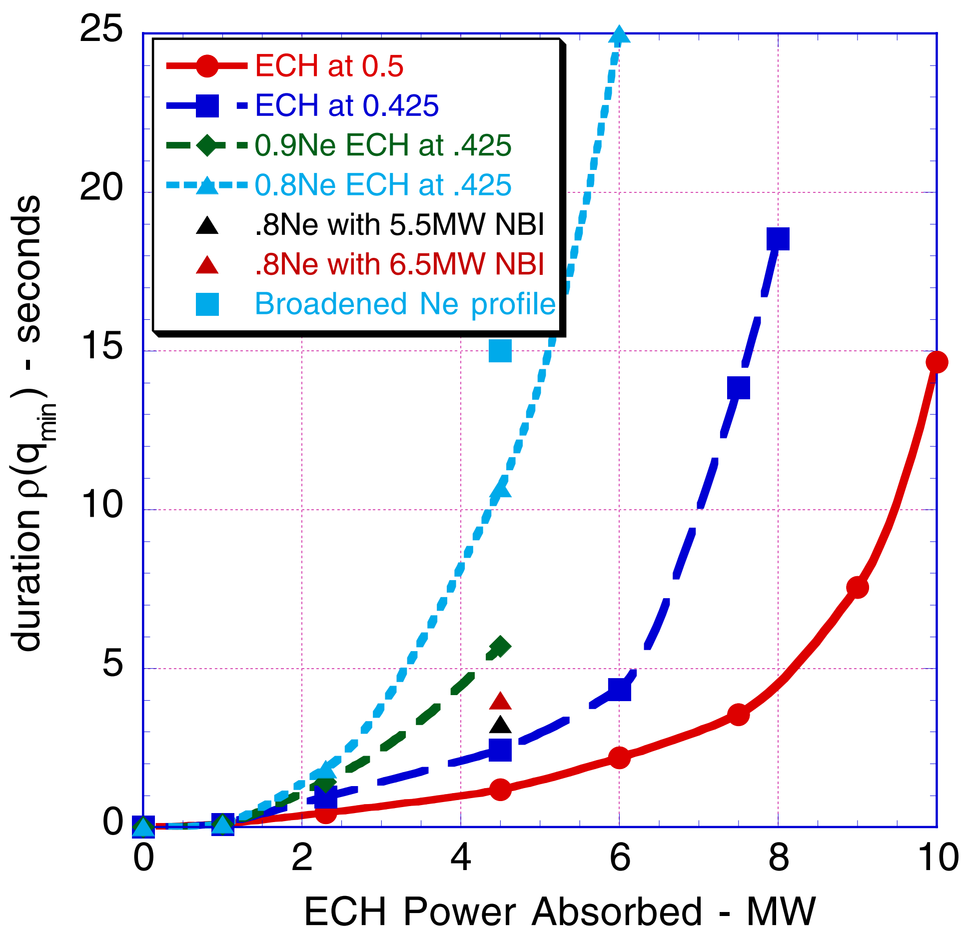


q

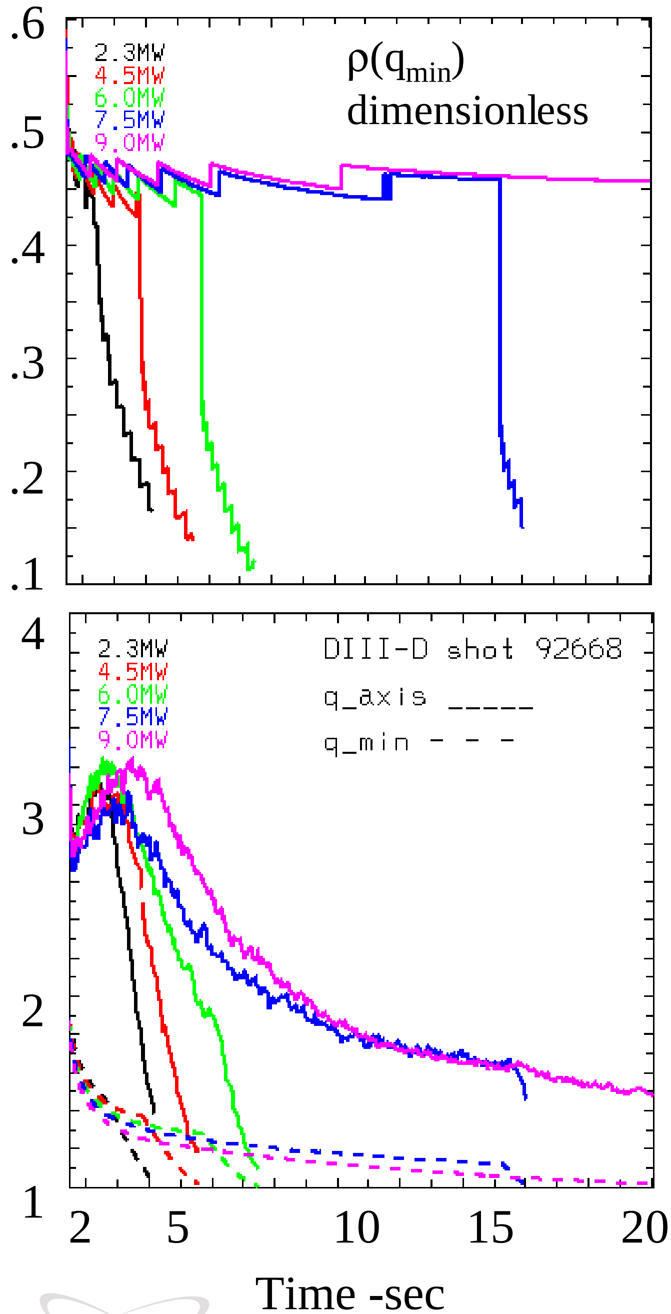
Profiles at 4 sec with 4.5MW ECH for experimental n_e and .8 n_e

J_{total}



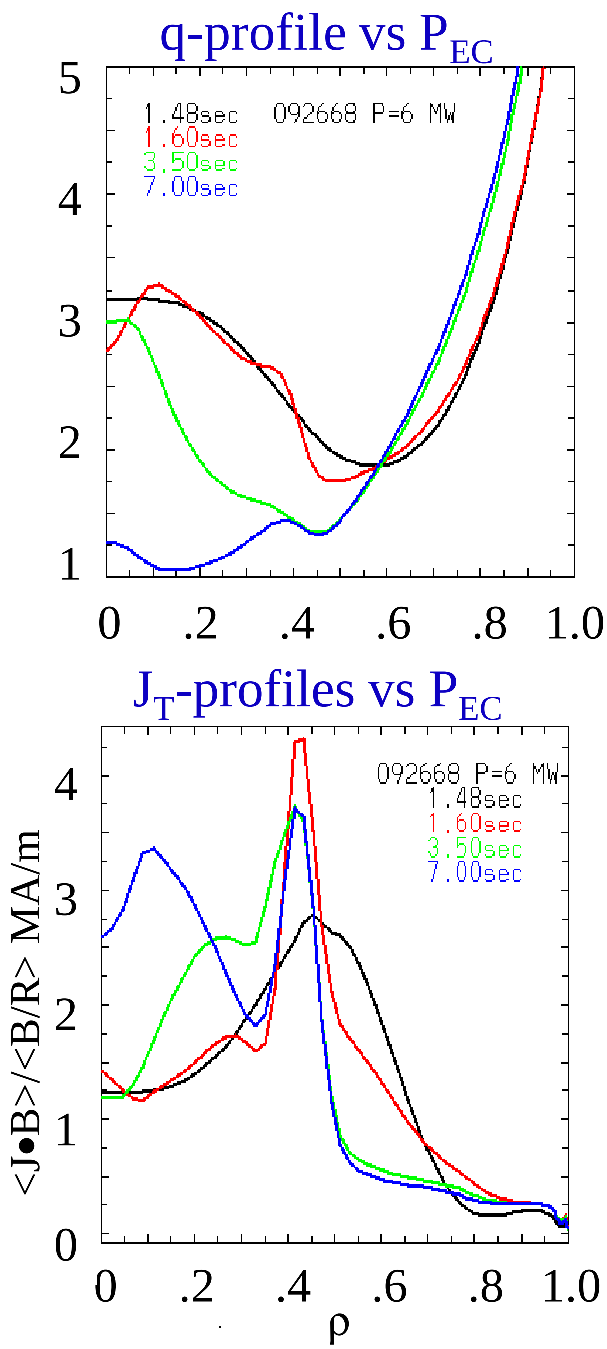


At power > ~ 8MW, simulations indicate $\rho(q_{min})$ is sustained for times > 20sec.



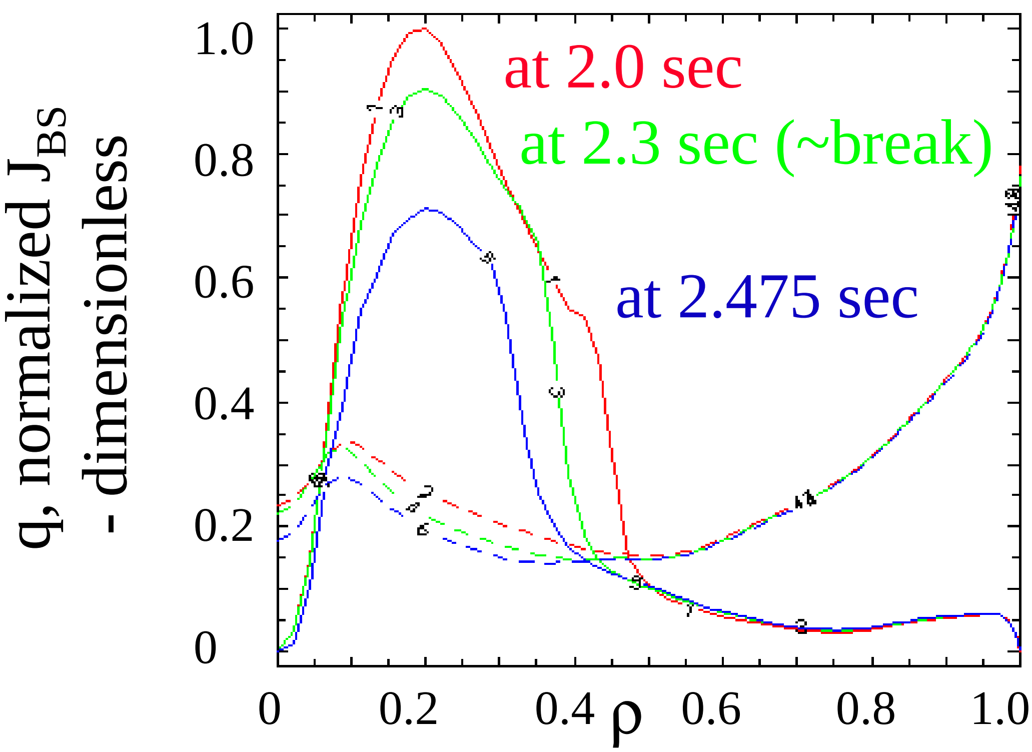
- $\rho(q_{min})$ held constant by ECCD until OH current diffusion pushes q_{min} inside the heating location
- Current profiles at steady-state are non-inductively driven, e.g. I_{OH} ~ 0.
- q-profile evolution ➡ NCS sustained by ECH/ECCD

ECCD locally modifies q-profile to maintain barrier



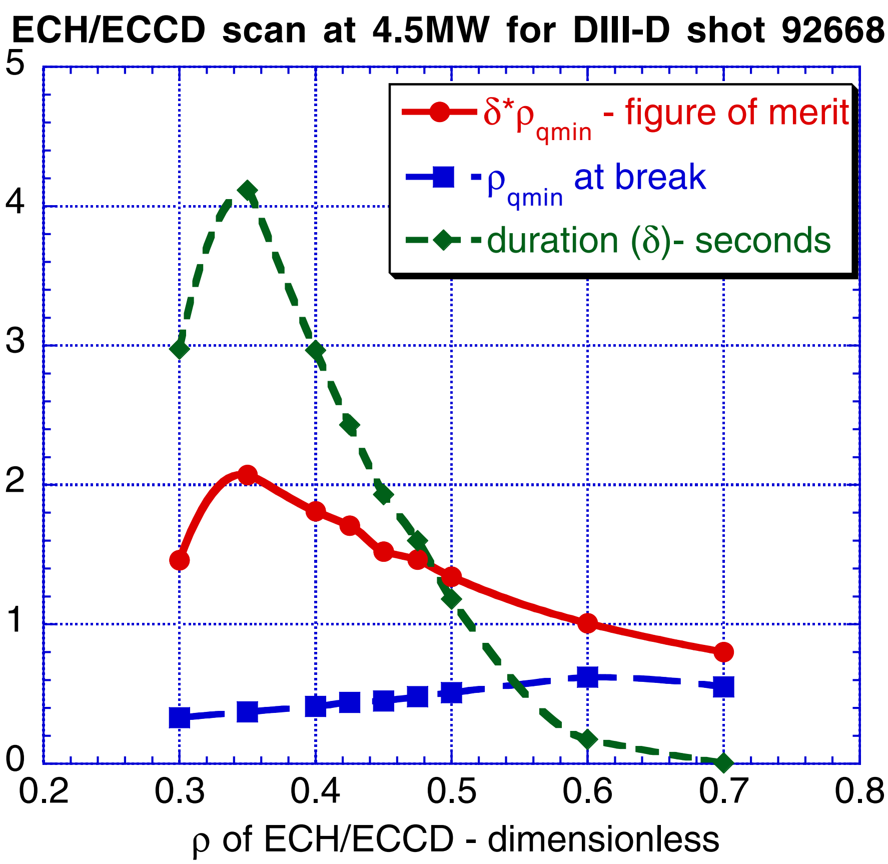
- ECCD locally depresses q profile to maintain barrier
- Eventually, J_{OH} diffuses inward and pulls q_{min} down & the barrier is lost
- Late in time, non-inductive current is peaked on axis due to NBI geometry and results in a monotonic q profile
- Solution is off-axis NBI or trade-off of NBI for heating source near the axis without current drive.

Barrier moves inward after OH current diffusion moves $\rho(q_{min})$ inside heating location



As $\rho(q_{min})$ moves in, the NB heating efficiency and, therefore, bootstrap current drive decreases ➠ T_i and β_N drop.

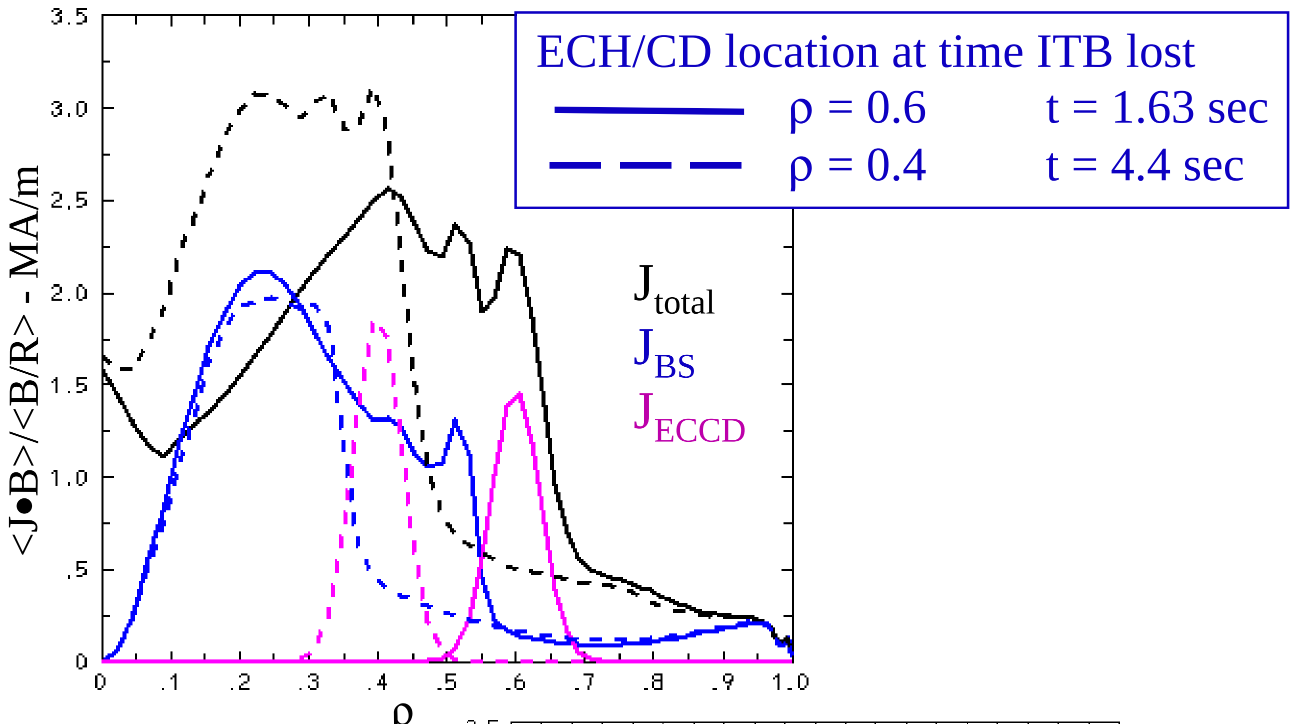
Maximum "figure of merit" obtained when heating at ρ ª .35

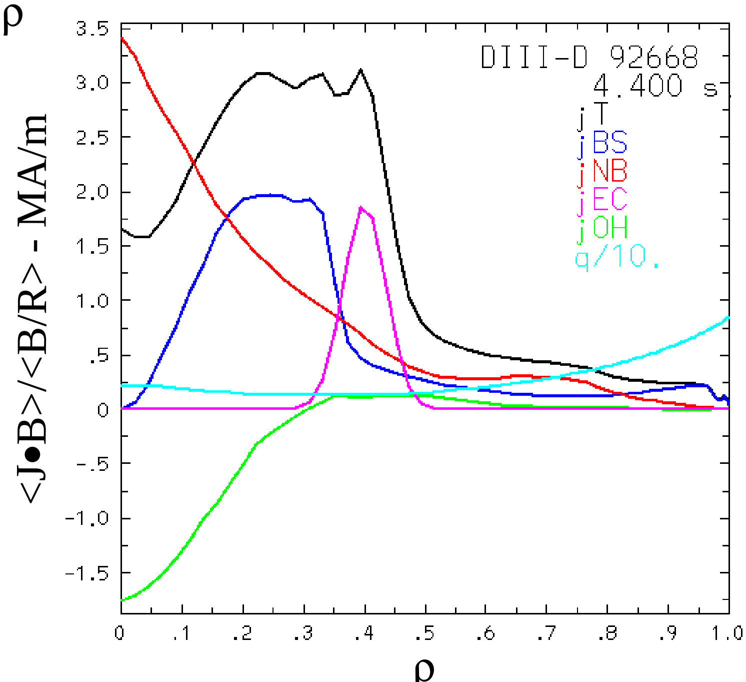


Optimization runs: vary heating/current drive location at P_{EC} = 4.5MW

- Duration (τ) to break in ρ_{qmin}
- Value of ρ_{qmin}
- Figure of merit = $\tau^*\rho_{qmin}$

ECCD at ρ=.4 is well aligned with J_{BS} ➠ "good" total current profile



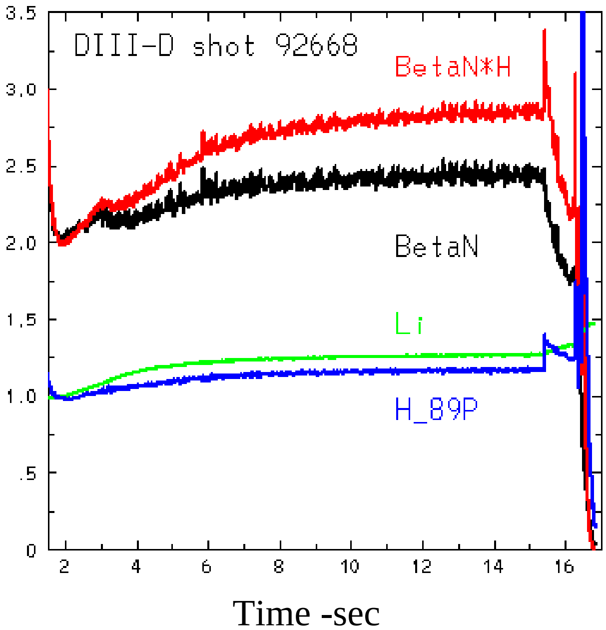


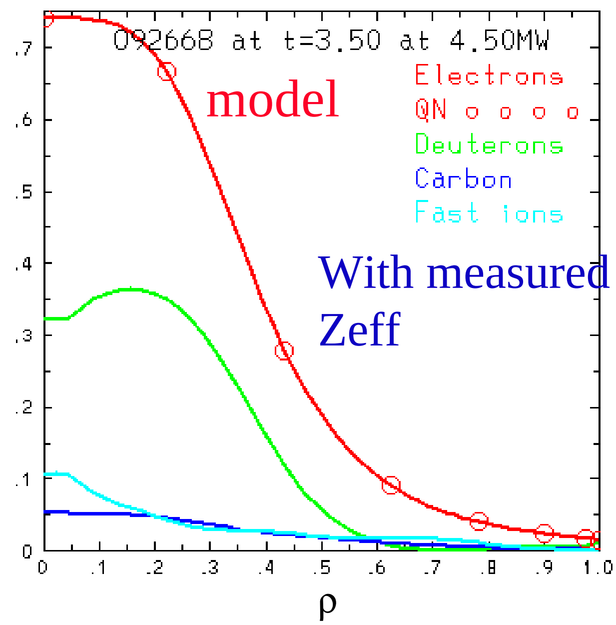
Current components for ECH at ρ=.4

Discussion: NCS with L-mode edge

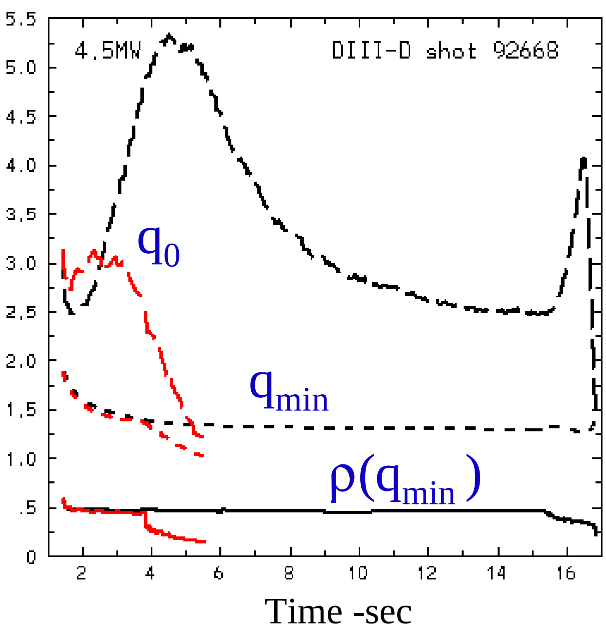
- At high power, ECH/ECCD provides a means to sustain $\rho(q_{min})$ for long durations in NCS discharges with an L-mode edge for stability
  - 8 MW inside barrier maintains $\rho(q_{min})$ for times > several hundred τ_E
  - Heating in the ∇n region at 4.5MW improves capability to maintain $\rho(q_{min})$
  - Lower n_e reduces the ECH power required
- High temperature and neutral beam current overdrive make late-time q-profile control difficult ➠ require innovative control of heating and current drive.
- Density profile control ➠ bootstrap current alignment is critical for maintaining $\rho(q_{min})$ at low ECH power.

Broadening the density profile sustains $\rho(q_{min})$ for long duration at lower P_{EC} due to ∇n bootstrap





Model density profile Used with ∇n near q_{min}

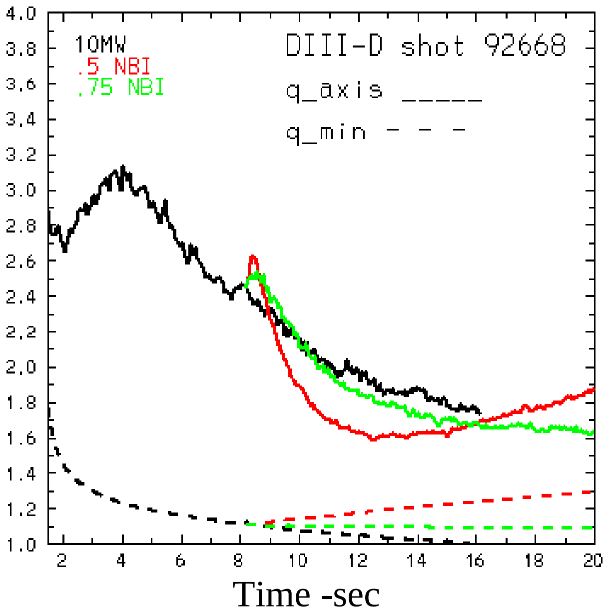


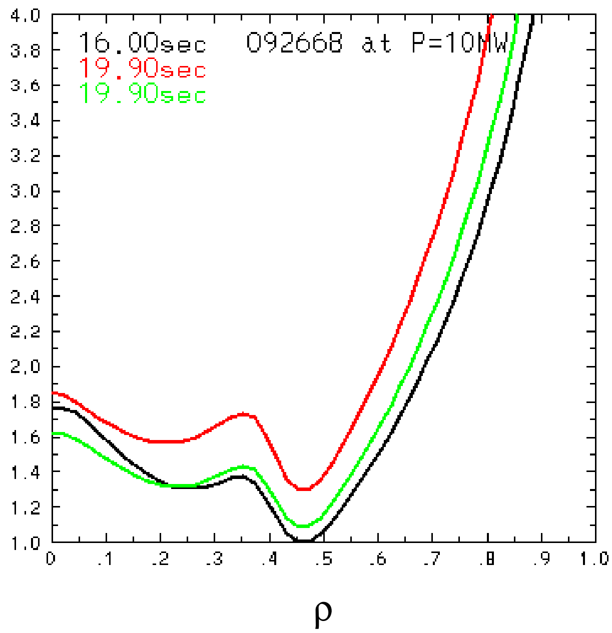
Evolution of q – comparison between model profile and more peaked measured profile

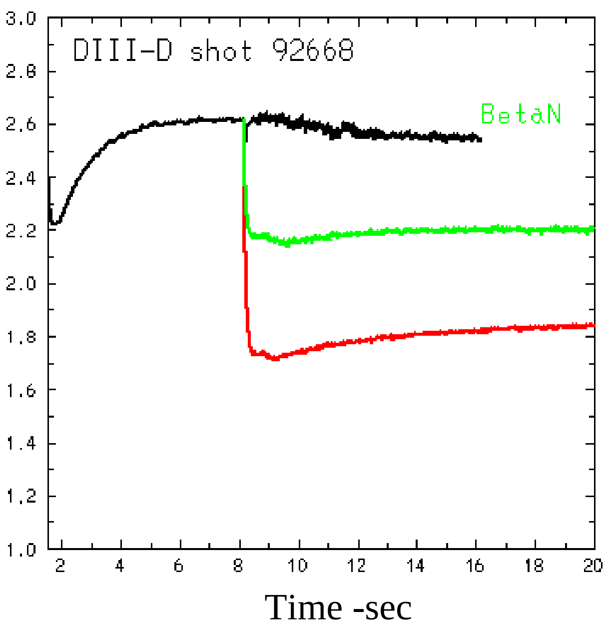
Developing methods to control the current and q profiles

- Integrated modeling ➠ Corsica provides an efficient way to explore methods to control profile evolution
- Time-dependence ➠ equilibrium and transport converged including current diffusion, heating and fueling sources
- New interactive stability assessment ➠ Glasser's DCON package – many thanks to Glasser and Pearlstein for adding this package to Corsica and, with Turnbull, for benchmarking it with other codes.
- Efficient computations ➠ runs on workstations reasonably fast
- Interactive ➠ parameters, sources and calculations modified in "real" time (or batch if you want)

Reducing P_{NB} controls q-profile late in time - holds $q_{min}>1$







At high power levels, q_{min} drops to 1 before $\rho(q_{min})$ starts to move inward.

Reducing the NBI, reduces the (on-axis) NB current drive and allows q to rise, at the expense of heating ➡ β_N

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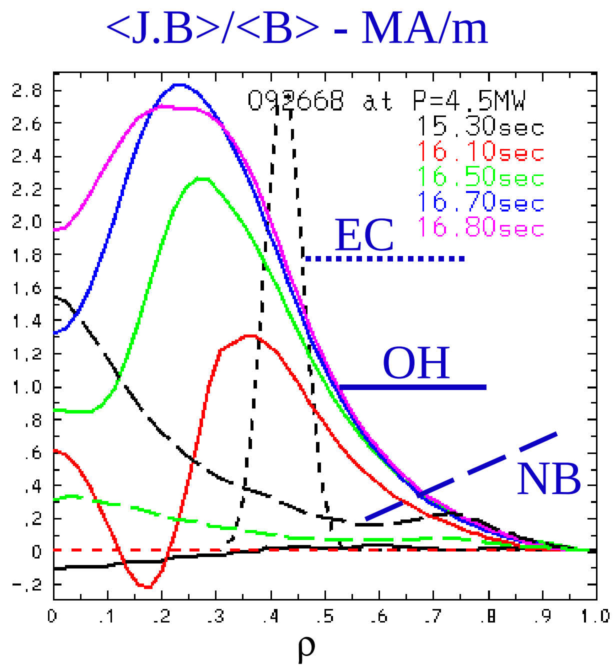
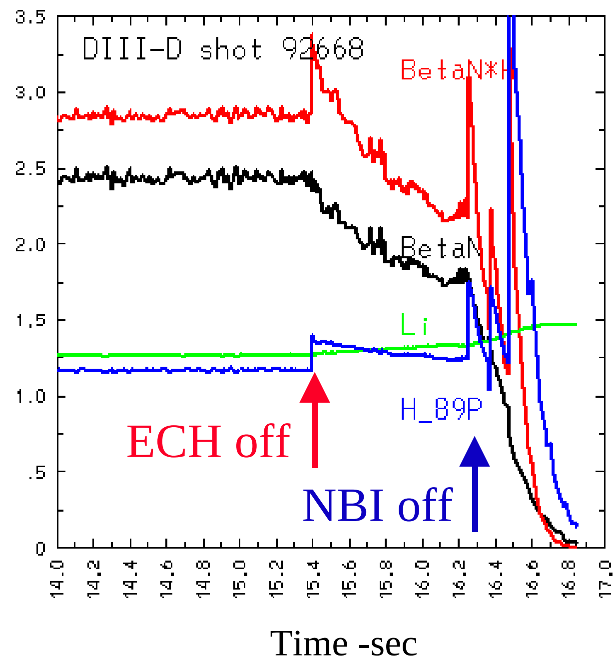
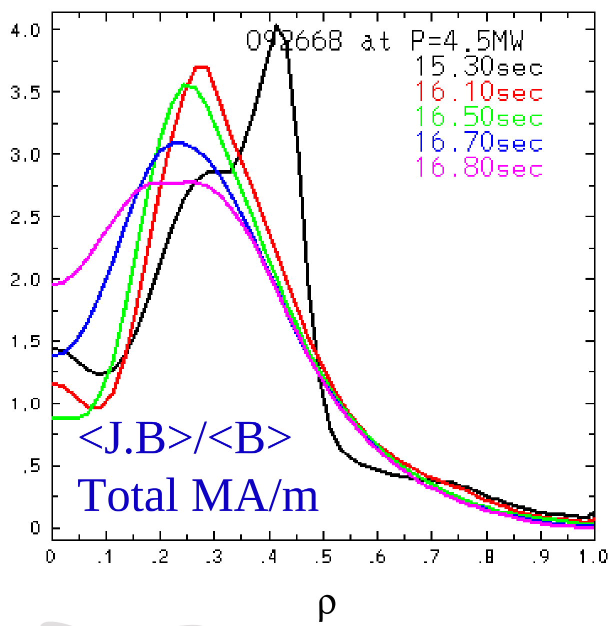
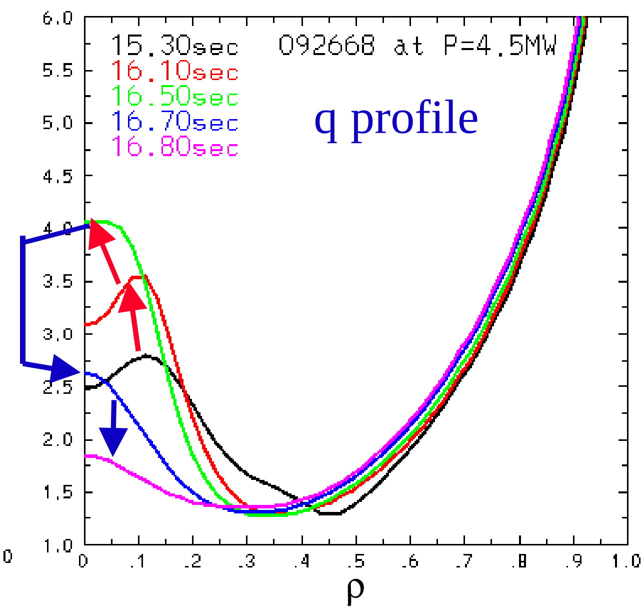
ECH maintains $\rho(q_{min})$ late in time barrier shrinks to bootstrap supported region when ECH is off





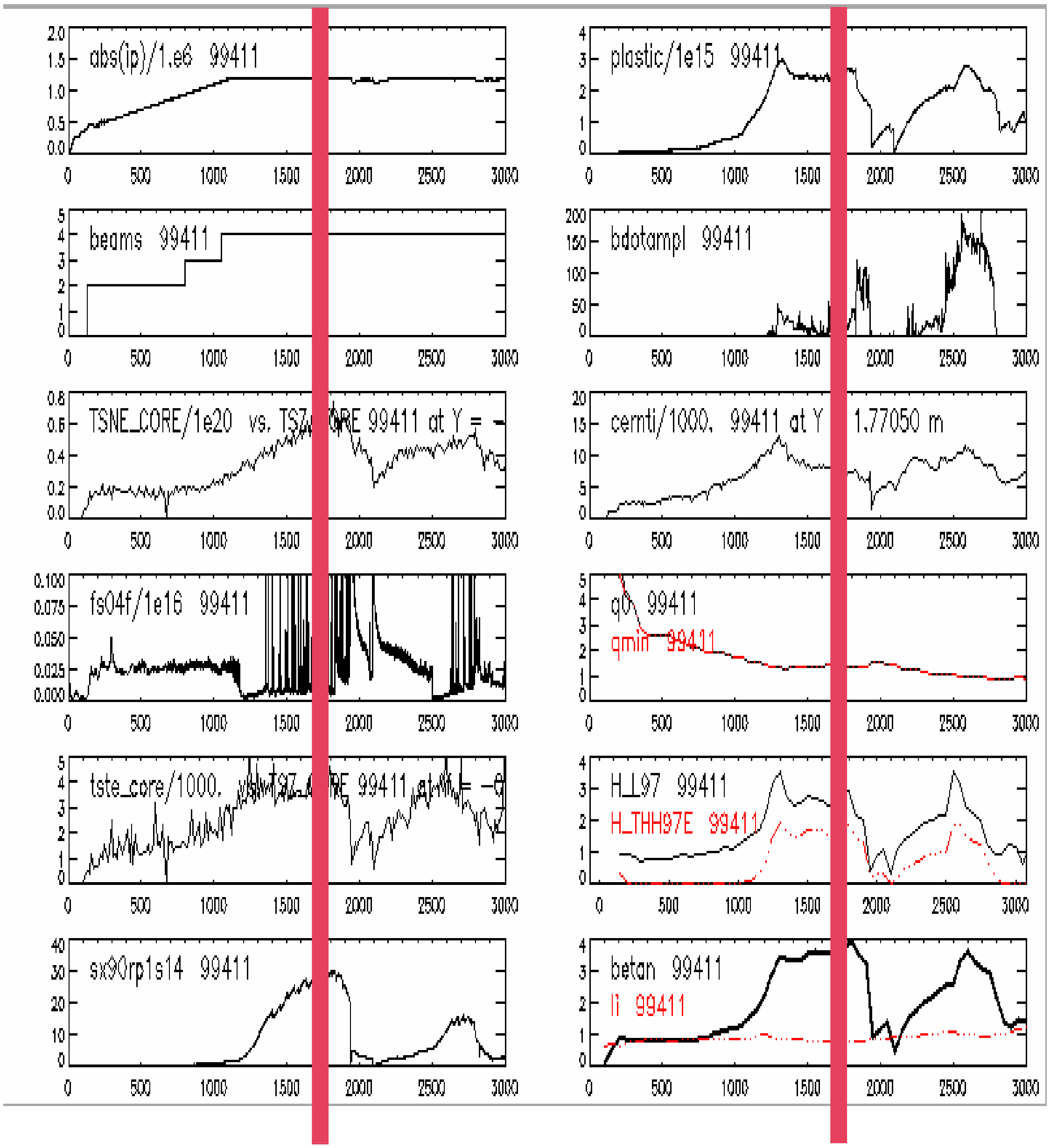




Development and optimization of ECH and NBI – ECH/ECCD target shot (99411)

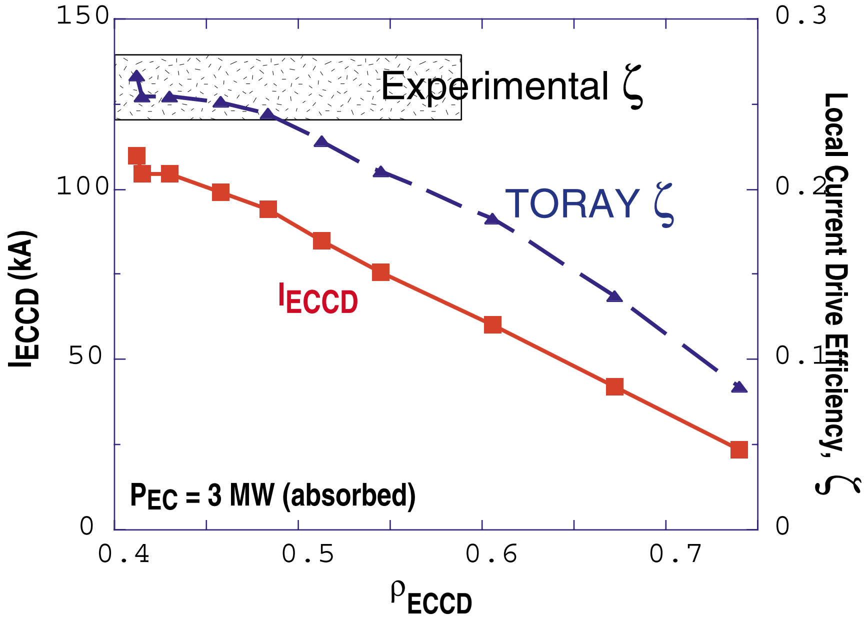
- DIII-D shot 99411: high performance ELMing H-mode at β_N*H_{89P} ~ 9
- Combined role of ECH/NBI in sustaining such a discharge at steady-state
  - Time-dependent variation in the mix of power
  - Stability
- Measured χ_i and χ_e used in simulations chi's based on onetwo/Corsica analysis
  - χ held fixed in time and space
  - Scaled for confinement
- Ohmic drive turned off to look for non-inductively driven steady state
  - ➡ I_p drops (a little) in time

Shot #99411 simulation ➠ Role of electron cyclotron and neutral beam heating and current drive



Corsica simulations initialized with measured profiles at 1.7 sec

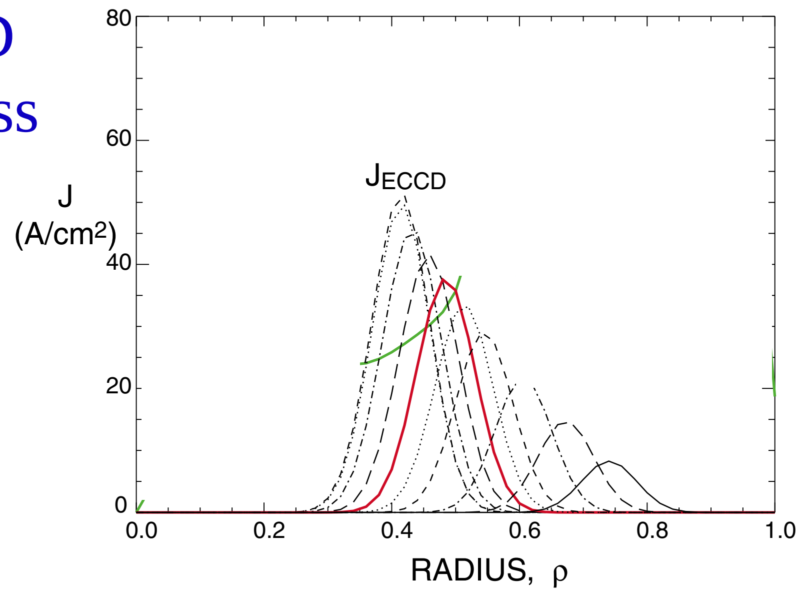
TORAY-predicted EC current drive deposition and measured efficiency



$$\zeta = \frac{33\, n_{20} I_A R_m}{P_W T_{keV}}$$

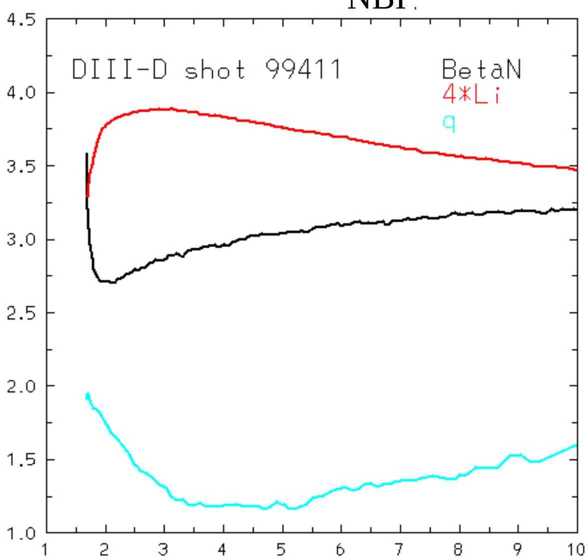
Experimental CD efficiency ζ is less sensitive to the off-axis position than theoretical estimate

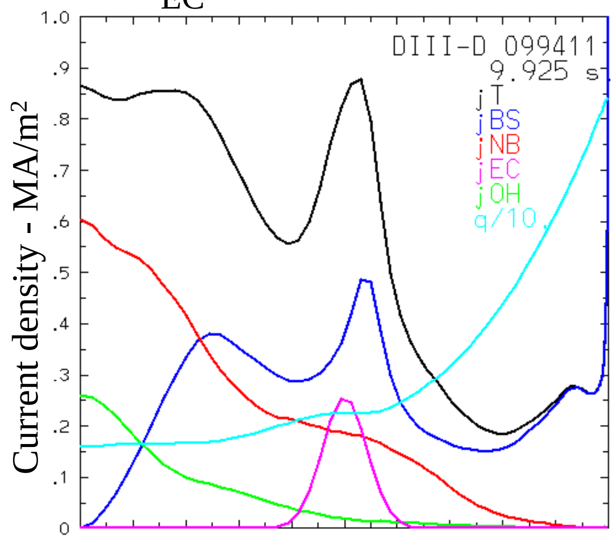
[Luce; Lin-Liu]

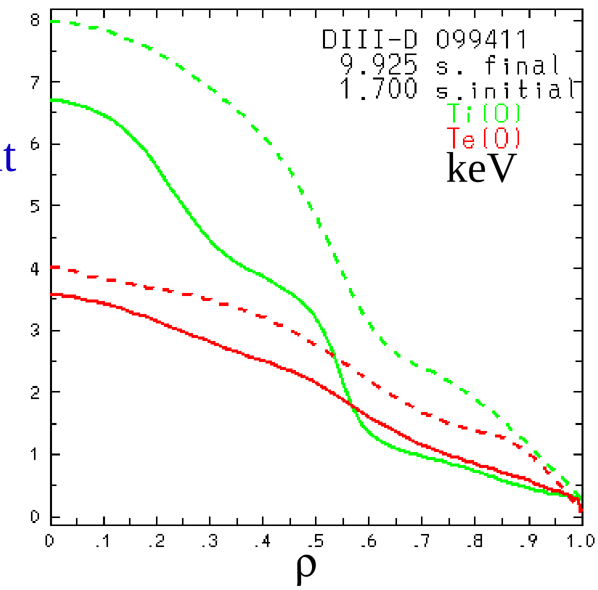


Time-dependent simulations indicate off-axis ECH modification of the current profiles

$P_{NBI} = 7MW$ with $P_{EC} = 3MW$





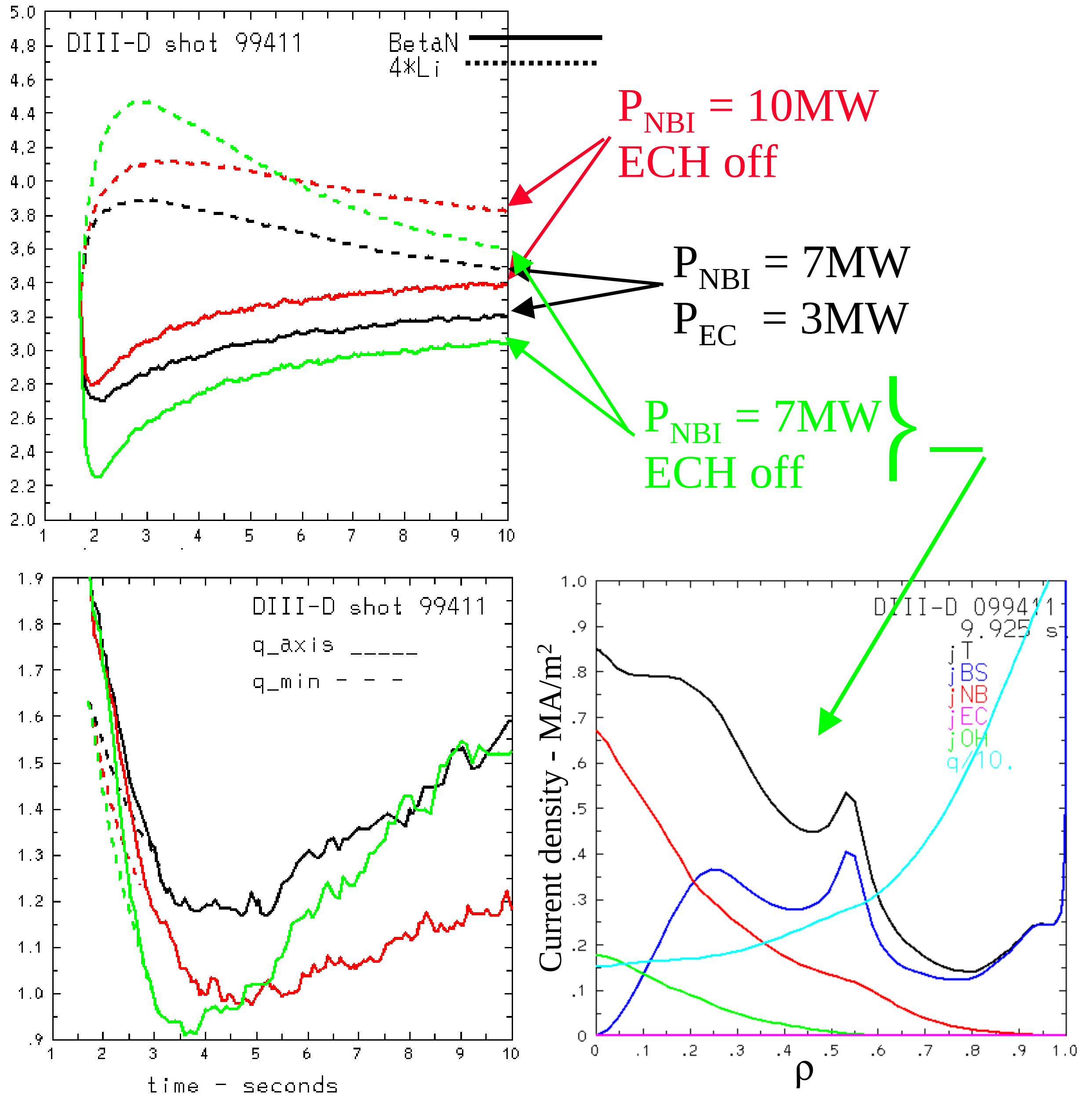


ECCD role seems to be one of controlling details of the current profile rather than strongly perturbing the local q profile as in the NCS condition.

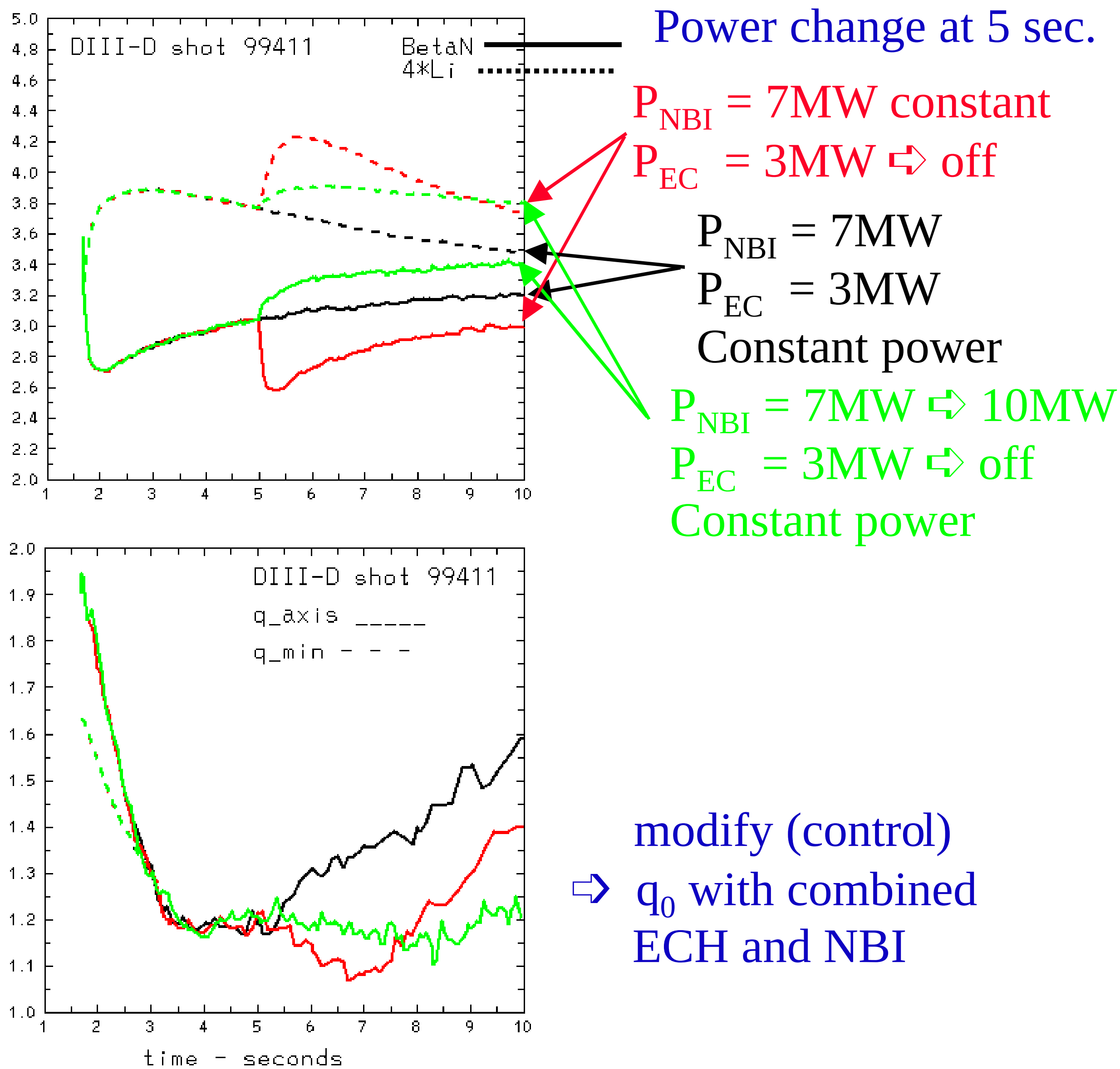
The H-mode case has considerably more current drive due to NBI and bootstrap

Control of multiple sources, density and stability become the issues.

ECH provides a route to maintaining higher q_0 operation

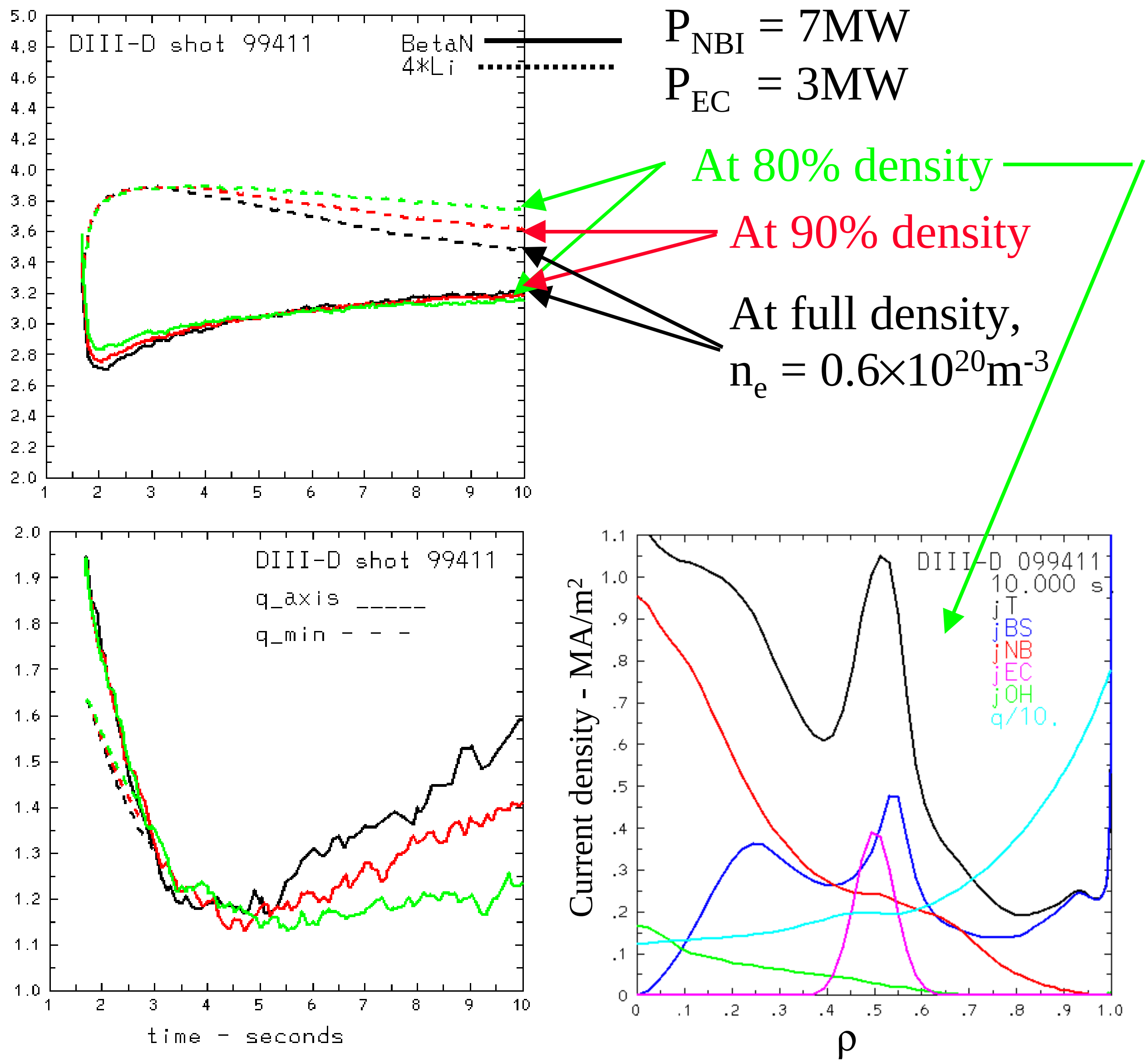


Demonstration of effects of ECH power on current profile with power change at 5 seconds.

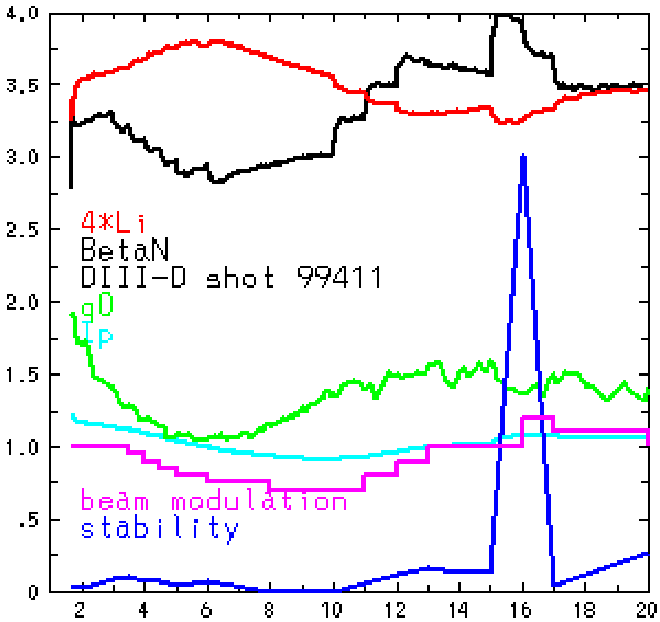


⇨ modify (control) q_0 with combined ECH and NBI

Peak density scan ⇨ ability to modify current profile at constant βn



Time-dependent stability simulation ⇨ P_{EC} = 3MW with P_{NBI} varied to change β_N



time - seconds

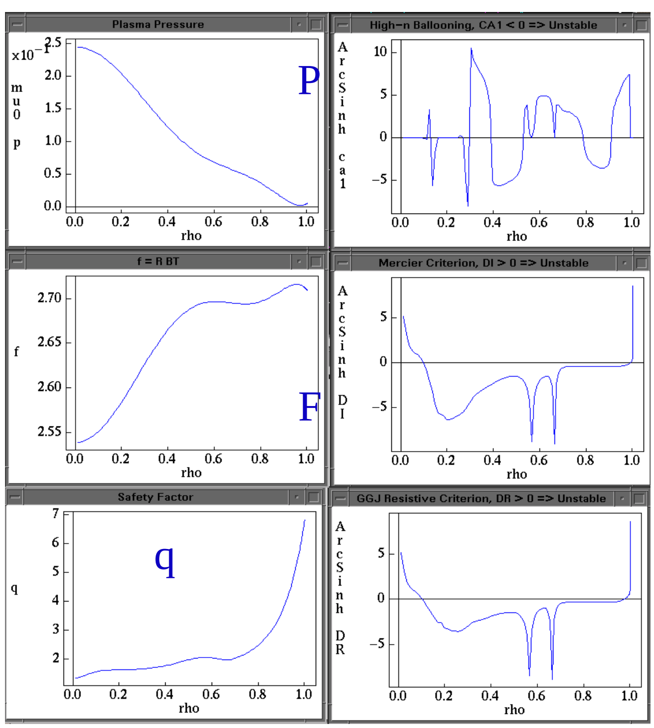
β_N and $4l_i$ response ⇨ Measure of expected stability

I_p and q_0 to track changing equilibrium

Modulation of P_{NBI} over range .7 to 1.2*7MW

Normalized plot of -Energy ⇨ > 0 unstable

Profiles from Corsica simulation used to evaluate stability criteria



Stability criteria at t = 17 sec ⇨

ballooning unstable

Mercier stable

and

MHD stable

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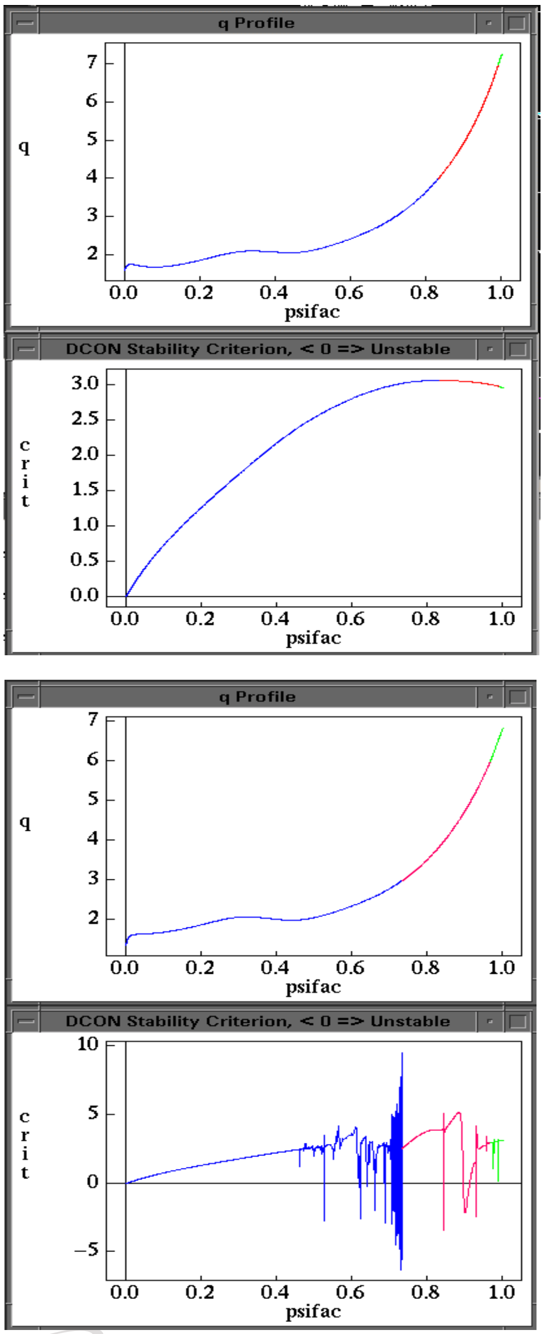
APS tac Nov99

Comparison of internal stability at 15 sec. and at 17 sec.



- q-profile at 15 sec.
- Stability parameter ⇨ No internal modes
- Similar conditions over entire evolution except at high bn conditions
- q-profile at 17 sec.
- Possible internal modes predicted at 17 sec.

Packages currently available for integrated modeling with Corsica

corsica> list packages

Priority	Name	Long Name	Status
3	par	Basis System	-- up --
34	eq	eq: calculate an equilibrium	generate
23	ceq	ceq: constrained equilibria via	-- up --
22	meq	meq: minimize eq with constraint	-- up --
25	eqt	eqt: equilibrium temporaries	-- up --
24	vpf	vpf: vertical stability	-- up --
33	ctr	ctr: core transport	-- up --
19	nbi	nbi: NB heating & CD	-- up --
32	csc	csc: inter-package communication	-- up --
17	mth	mth: mathematical routines	-- up --
16	uec	Core-edge coupling package	-- up --
15	rfl	rfl: reflectometry diagnostics	-- up --
14	dcn	dcn: MHD global stability	-- up --
13	ctl	Run Controller Package	-- up --
12	svd	Singular Value Decomposition	-- up --
11	hst	History Package	-- up --
10	pfb	PFB Interface	-- up --
9	ezc	EZCURVE/NCAR Graphics	-- up --
8	ezd	Device Package	-- up --
7	iso	3-D Isosurface Plotting Routine	-- up --
6	srf	3-D Surface Plotting Routine	-- up --
5	bes	Bessel builtins	-- up --
4	fft	Fast Fourier Transforms	-- up --

corsica>

Summary / Conclusions

- Simulations with the gyro-Bohm model indicate that moderate ECH powers in DIII-D can have a significant effect on NCS discharges with L-mode edge.
- ECH appears to have a more subtle effect on the H-mode target discharges indicating that dominant effects may enter through the q-profile or stability.
- We are developing control concepts in Corsica using time-dependent equilibrium, transport, heating and current diffusion.
- The DCON stability package (Glasser) is now functional for assessing MHD stability of simulated discharge evolution.