Current Profile Control for High Performance, Steady State Tokamaks: Considerations from C-Mod LHCD Program

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with thanks to Paul Bonoli for input

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Shape and Aspect Ratio Optimization for High Beta, Steady-State Tokamak
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General Atomics, CA

Outline of talk

- **Overview of C-Mod LHCD and Advanced Tokamak Program**

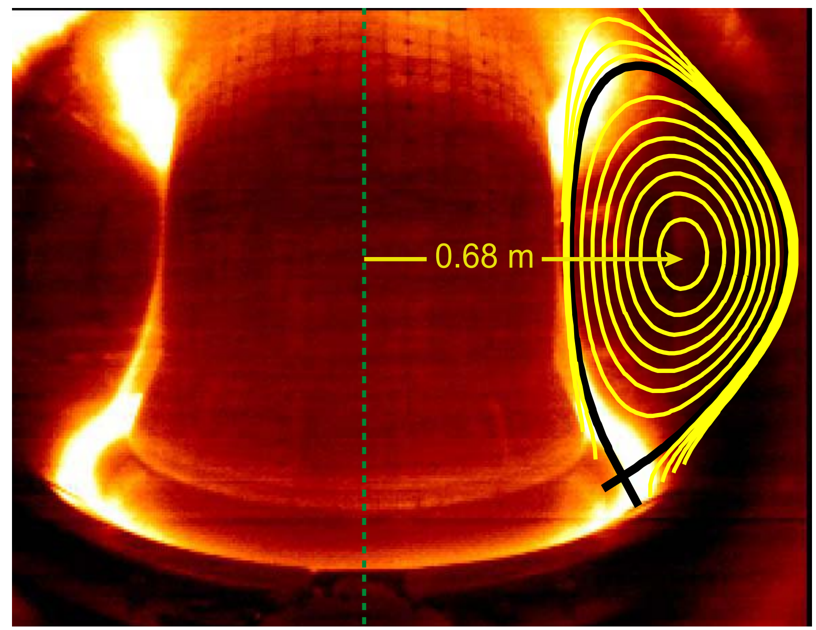
- **Some considerations for current profile control in high performance scenarios**
  - Shaping optimization.
  - Density profile optimization.

- **Recent developments in modelling** of current drive and integrated scenarios.

  (I will talk about C-Mod case, but believe these issues are all relevant to other, and future, experiments, though details differ).
- **Summary**

Alcator C-Mod: Compact, High Field

- Toroidal Magnetic Field = 4 to 8 Tesla
- Plasma Current to 2.0 MA
- Plasma Volume = 1 m^3
- Temperature: 1 to 6 keV
- **Density: 10^{20} to 10^{21} m^{-3}**
- All metal plasma-facing components
- 6 MW ICRH (8 MW source)
- **Shaping: $\kappa \leq 1.85$, $\delta \leq 0.85$**



Overview of AT program on C-Mod

- Advanced Tokamak research is one of two main ‘integrating thrusts’ on C-Mod, and growing in emphasis (the other focuses on high performance ‘conventional’ H-mode scenarios.) *Both* focus on burning-plasma relevant regimes.
- Major new tool, coming on line this year, is a **Lower Hybrid Current Drive** system.

Main research areas/5 year goals are:

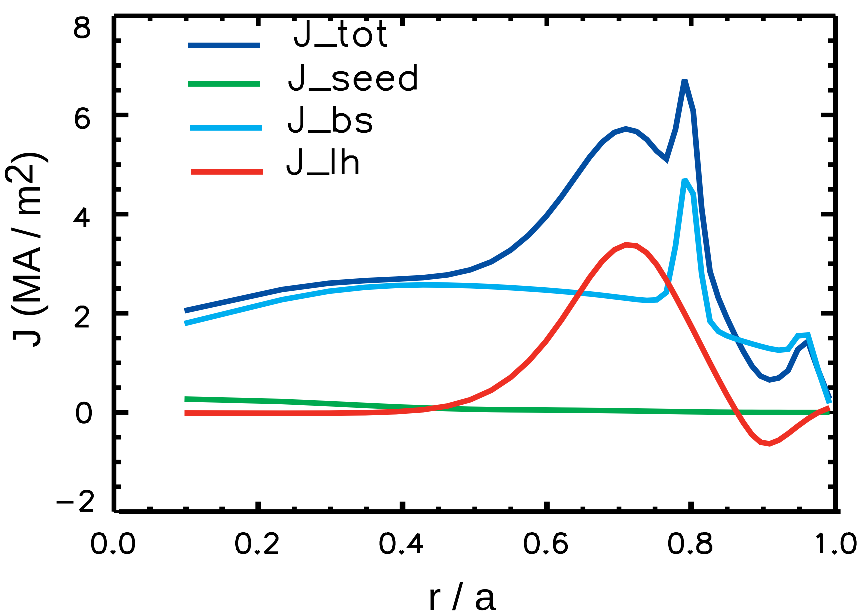
1. **Current profile control using LH and ICRF waves**, at high densities (>10^{20} m^{-3}; *relevant range for ITER and reactors*).
2. Understanding, control and sustainment of **Internal Transport Barriers**, with coupled ions and electrons, $\tau^{e\text{-}i} << \tau_E$ ($T_e \sim T_i$) and without momentum input (RF only).
3. **Full non-inductive current drive, with high bootstrap fraction and pulse length near steady state (5 sec, 4-6 τ_{CR})**
4. **Attain and optimize no-wall β to MHD limit (β_N ~ 3)**. Longer term, consider means to exceed limit.

Example of fully non-inductive AT target scenario

Alcator C-Mod

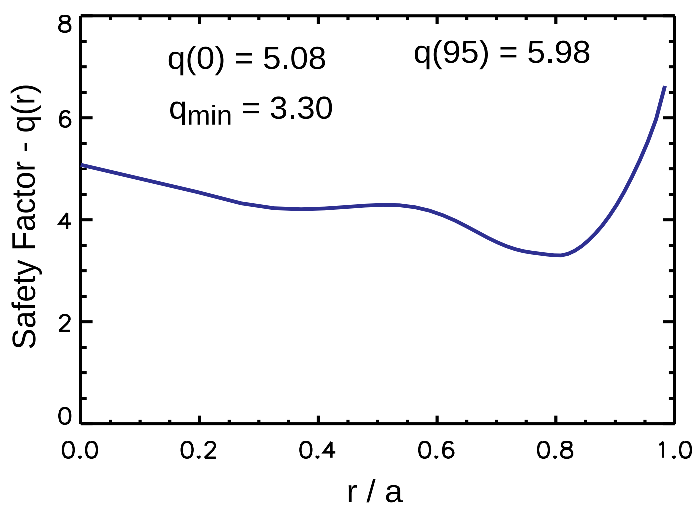
- **One of many optimized scenarios modelled with ACCOME.**
  - I_{LH}=240 kA
  - I_{BS}=600 kA (70%)

I_p = 0.86 MA I_{lh} = 0.24 MA f_{bs} = 0.7



- **Double transport barrier**
  - B_T=4 T
  - ICRH: 5 MW
  - LHCD: 3 MW, $N_{//0}$=3
  - $n_e(0)$= 1.8e^{20} m^{-3}
  - $T_e(0)$=6.5 keV (H=2.5)
  - β_N=2.9

Scenarios without barrier, or only an ITB, have similar performance.



P. Bonoli, Nucl. Fus. 20(6) 2000.

Unique Features of C-Mod for AT

Alcator C-Mod

Active advanced tokamak programs on several tokamaks (eg. DIII-D, JT60-U, AUG, JET, Tore-Supra, others).
What will C-Mod contribute that is new?

1. In physics terms, "Steady-state" current drive implies pulse lengths >> current relaxation time τ_{CR}.

   C-Mod can run 5 second pulses, vs τ_{CR}~ 0.2-1.4 s [Z_{eff}=1.5; T_e= 2-7.5 keV]
   Have already run 3 secs. We *routinely* run pulse lengths >> τ_{CR}..
   (Unlike typical scenarios on larger devices, can't rely on rampup tailoring, transient effects to freeze in j(r).)

2. Most AT expts have $T_i > T_e$, $\tau^{e-i} > \tau_E$ and use NBI for core fuelling and rotation drive in ITBs.

   Reactor scenarios have $\tau^{e-i} << \tau_E$ ($T_e > T_i$), no core fuelling, no momentum input, RF heating and CD.
   ITER going in this direction; high n_e, limited NB fuelling….

   C-Mod can test feasibility of AT scenarios with all these features simultaneously.

C-Mod Profile Control Tools

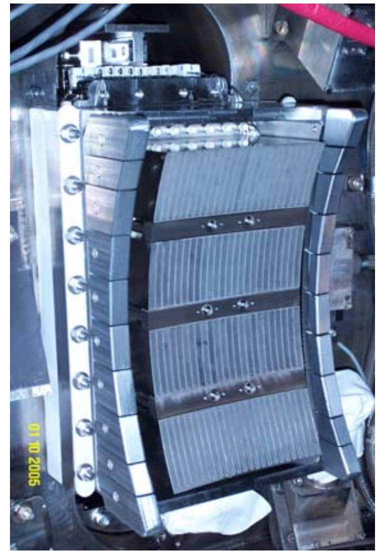
"The crucial distinguishing feature of an Advanced Tokamak over a conventional tokamak is …the use of active control of the current or shear profile, and of the pressure profile or transport characteristics" *(AT Workshop, GA, 1999)*

Tools available or *under development*:

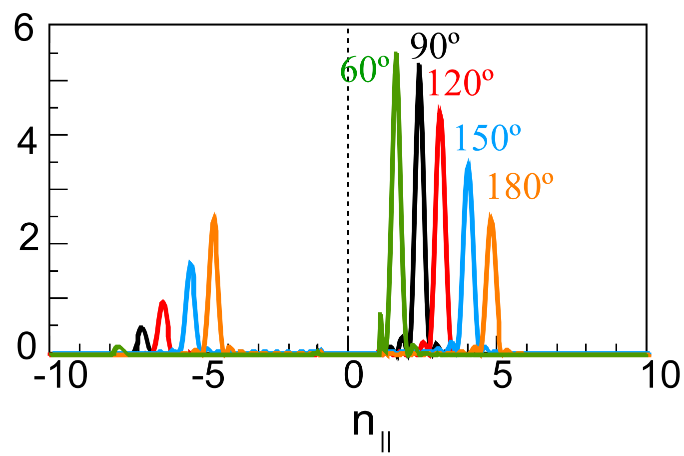
- **Current profile:**
  - **Lower Hybrid Current Drive.** *(*Phase I 2005. *Phase II ~2007). 4 MW, 4.6 GHz, 2 launchers with independent phasing, $N_{//}$.*
  - Mode Conversion Current Drive. (initial tests were promising)
  - Bootstrap current drive via pressure profile control.
- **Density profile.**
  - Control of core transport, peaking.
  - *Cryopump controls edge source. (2006)*
  - D_2 and Lithium pellet injectors.
- **Temperature Profiles**
  - 8 MW ICRH, 40-80 MHz, 2 independently variable deposition locations.
  - LHCD.
  - Control of core transport, peaking (RF, *magnetic shear)*
- **Shear Flow** - MC flow drive *(tests and modeling underway).*

C-Mod Lower Hybrid System

- f=4.6 GHz
- Launchers have 4 x 24 guides.
  - Designed for well controlled spectrum with flexible $N_{//}$, variable over range 2-4.
- First stage of system has one launcher ,12 klystrons, 3 MW source (coupled power will be lower).
  - *Commissioning expts will start in a few weeks.*
- Later plan to add second launcher.
  - Will allow two different $N_{//}$, utilization of full 3 MW.
- Finally will add 4 more klystrons to raise source power to 4 MW total.



LH launcher installed in C-Mod (01/05)

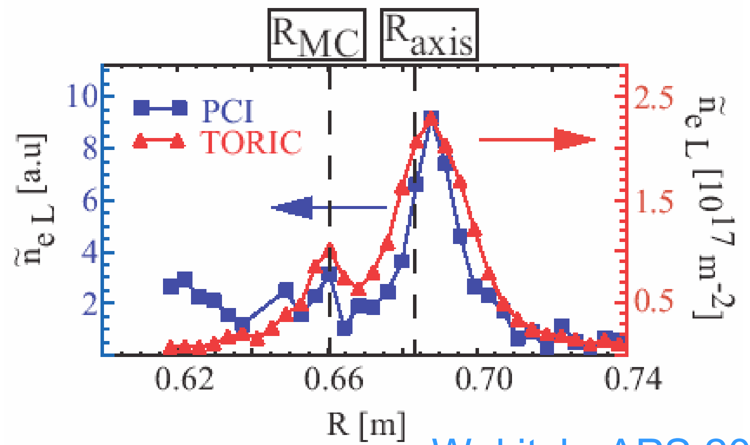


Mode Conversion Current Drive

- Current can also be driven by **mode-converted IBW and/or ICW waves.**
- **Remarkable progress in measuring and modeling the waves** in these conversion processes!
  This means we can now *use* models with high confidence.

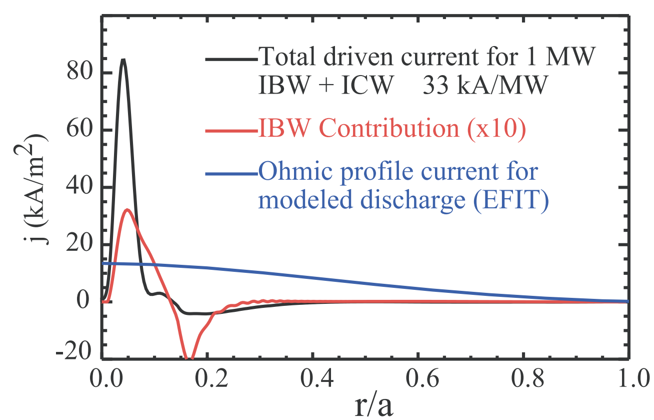
- Could provide a useful extra tool for localized CD, particularly on axis where up to 100 kA is predicted. Complementary to LH.

- Indications of some local current drive near q=1 in recent experiments, to be followed up in 2005.



Wukitch, APS 2004

TORIC Prediction for **On-axis MCCD**
(5.4 T, 50+80 MHz)
I_{MCCD} = 100 kA for P_{ICRF} = 3 MW

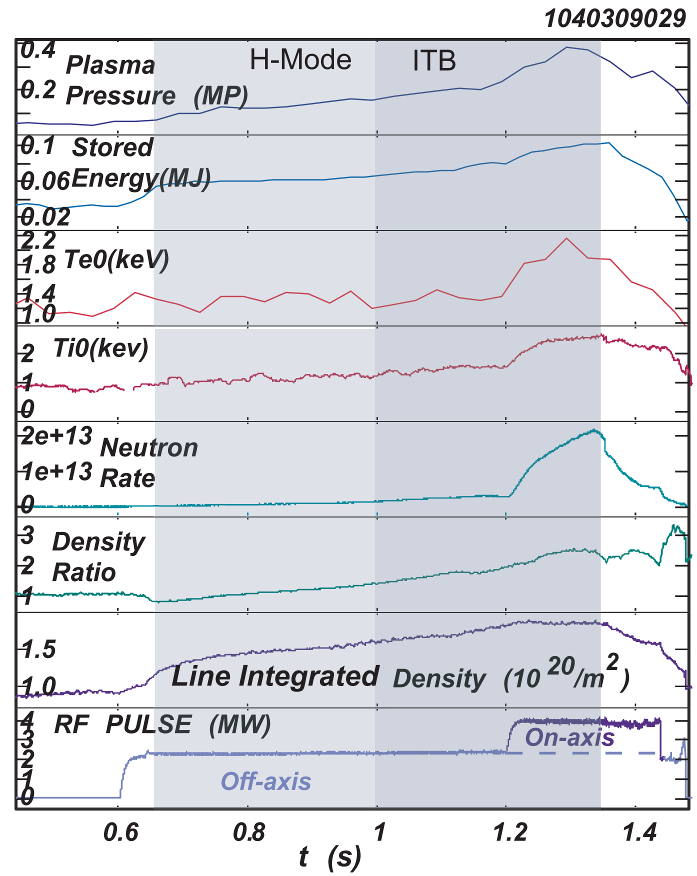


Control of core transport, profiles (Internal Transport Barriers)

- C-Mod has found ITB's triggered by **off-axis ICRH**, at r/a ~0.5, in plasmas *without* reversed shear.
  - Core barriers co-exist with edge pedestal (EDA H-mode.)
  - Also seen in *ohmic H-mode*.
  - Core χ_{eff} drops to neoclassical.

- Adding *central* ICRH tends to increase transport. Its level is adjusted to control density and impurity rise.
- Recently increased ICRF powers up to **3 MW off-axis**, **1.8 MW on-axis** (earlier limit ~0.6 MW). There does *not* seem to be an absolute limit, rather a dependence on relative powers.

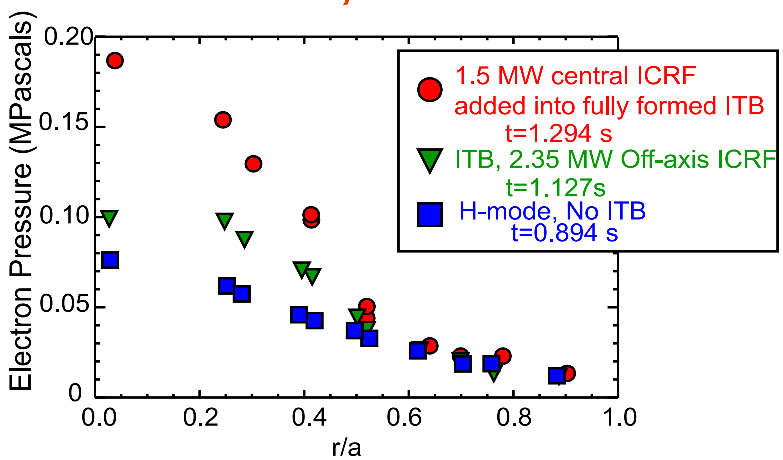
Fiore, EPS 2004 (invited), APS 2004

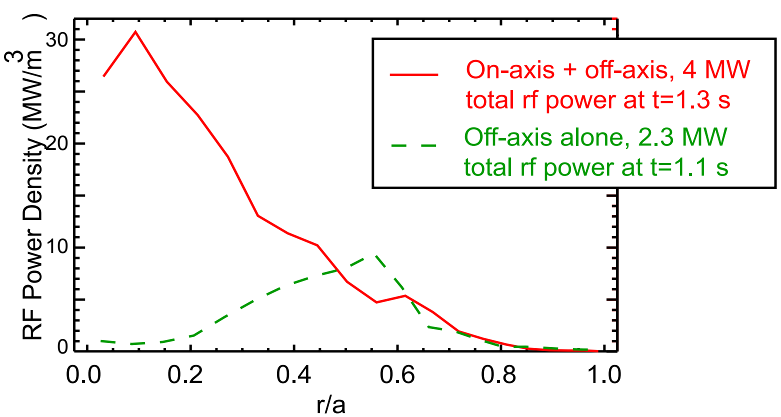


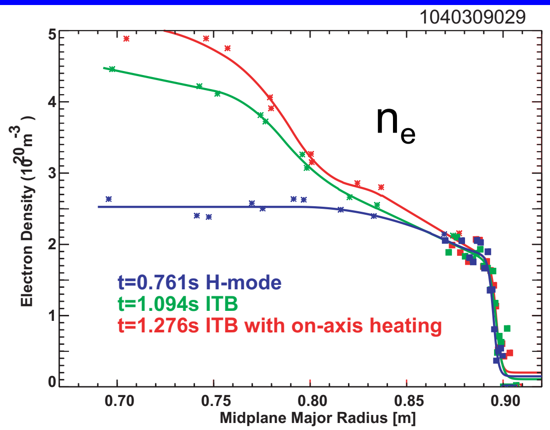
We can *control* the degree of energy and particle transport within the barrier!

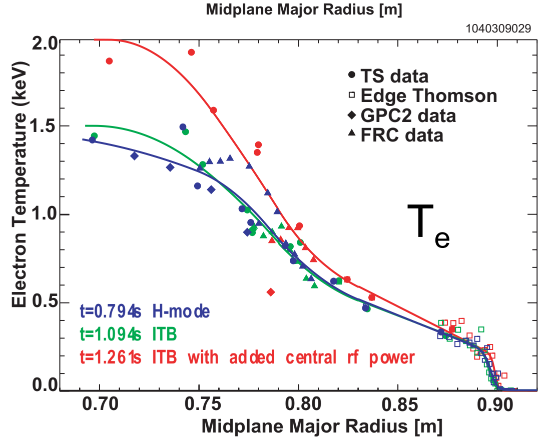
High pressures (n *and T*) achieved

- OFF-axis heating alone causes density peaking, ~ const T.
- ON-axis heating clamps n, but increases T, neutron rate.









- As j(r) control becomes available, we will add off-axis LHCD to assess effects of weak/reversed shear.

ISSUES AFFECTING CURRENT PROFILE CONTROL in ADVANCED SCENARIOS

Studies find **shaping** key to optimizing β, performance for C-Mod AT scenarios

Alcator C-Mod

- Highly shaped plasmas ($\kappa \approx 1.8$, $\delta \approx 0.7$) with broad pressure profiles ($p_0 / p_{av} \approx 3.0$) are needed to produce attractive AT operating modes with high β and bootstrap fraction (f_{BS}):
  - A. Turnbull *et al*., Nucl. Fusion **38**, 1467 (1998).
  - P.T. Bonoli *et al*., PPCF **39**, 223 (1997).
- C-Mod has capability of strong shaping (now up to κ=1.85, δ=0.85)

- Current profile control is necessary to achieve these operating modes:
  - Shear reversal with $q(r) > 2$ everywhere and $r(q_{min}) > 0.5a$.
- Attractive AT operating modes at the no-wall β-limit have been identified in C-Mod using:
  - LH current profile control modeled by the ACCOME code
  - Ideal MHD stability analysis using:
    - JSOLVER / PEST-II
    - CAXE / KINX
- $f_{BS} = 0.7$, $I_p = 0.8$ MA, $\beta_N \approx 3.0$, $H_{89}=2.5$, $P_{LH} = 2.5 - 3$ MW

Highly Shaped Plasma δ = 0.7 has highest β limit

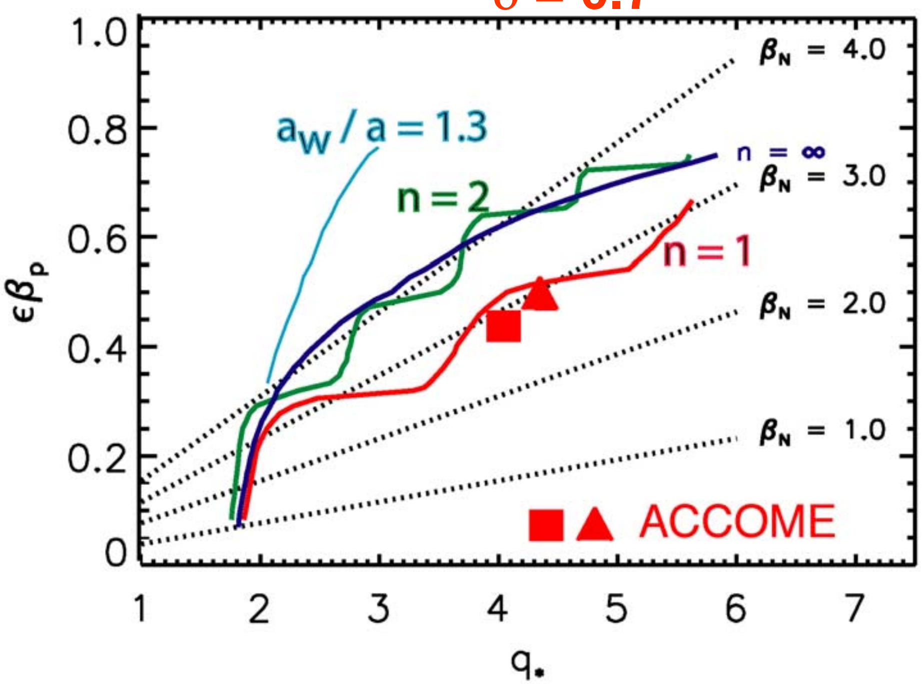
Alcator C-Mod

- Without a conducting wall the ideal stability is set by the n=1 external kink mode
- Reduced triangularity (δ=0) lowers the ideal β-limit significantly (from 3.0 to 2.0)

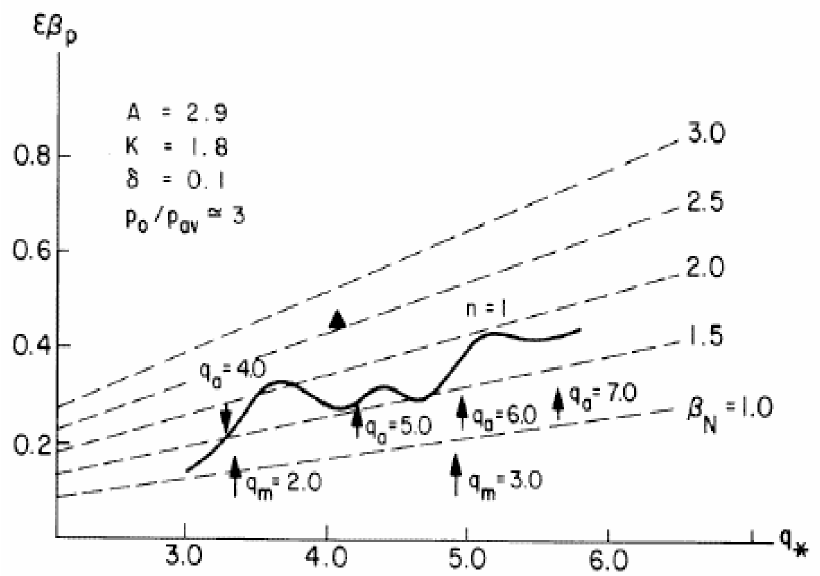
Parameters:

- A = 2.9
- κ = 1.8
- $p_0 / p_{av} \approx 3.0$

δ = 0.7



δ = 0.0

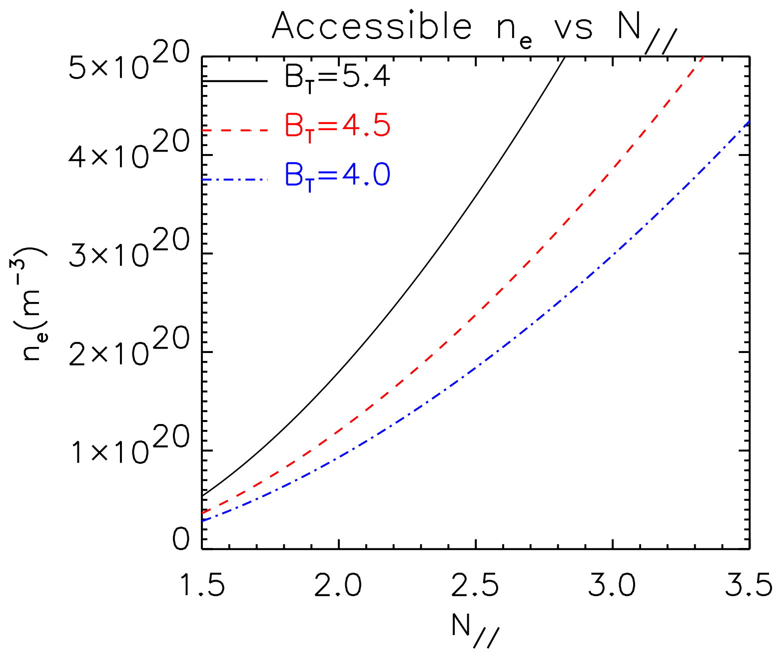


Density Profile Control is Key to j(r) Control with LHCD

Alcator C-Mod

Local $n_e(r)$ affects driven current in several ways:

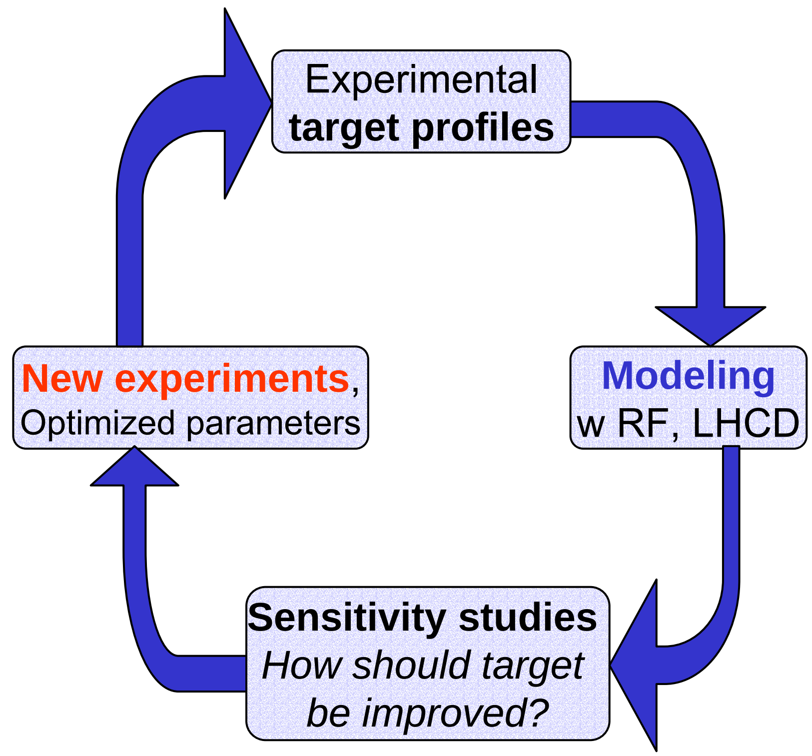
- For *fixed* efficiency η, $I_{LH} \sim 1/n_e$.
- η increases with T_e.
- $\eta \sim 1/N_{//}^2$
  - LH wave accessibility is a strong function of B field, $N_{//}$, *local* density,
  - At higher n_e, may need higher $N_{//}$, ie. reduced η.
- **For fixed pressure, B (β), I_{LH} varies *at least* as n_e^{-2} .**
- On the positive side, the ability to control $N_{//}$, B, $n_e(r)$ and $T_e(r)$ gives several useful 'knobs' to control deposition profile, and get localized off-axis CD.



Because of same B, similar n_e, C-Mod and ITER are in similar ω_p/ω_{ce} regimes, both will run close to accessibility limit.

Density Control is Linked to Plasma Physics

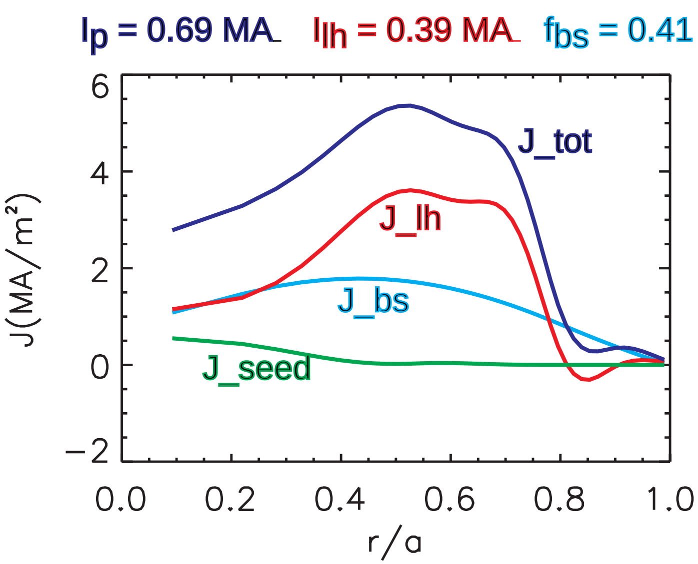
- In models, easy to input desired $n_e(r)$, (and $T_e(r)$)
  - Not so easy in experiment.
- Density control *not just a matter of pumping,*
- Also need to consider plasma physics (ELM type, ITBs…)
  - eg, on C-Mod, find minimum n_e for steady EDA or ELMy H-mode, thus for double barriers.
- Often conflicting demands for confinement (bootstrap current) and LHCD.
- We have an active program of making, modelling target discharges for LHCD.
  I will give some examples of (non-optimized) scenarios to illustrate the issues.

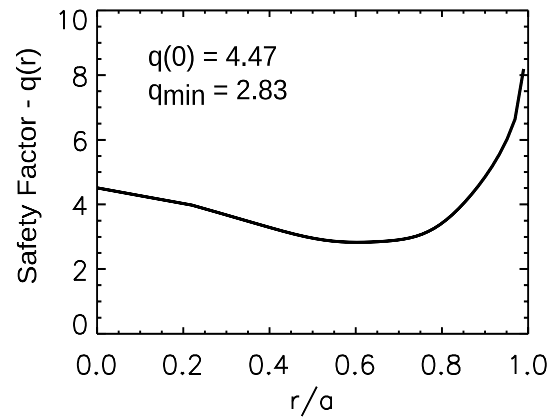


Low density L-Modes give strong LHCD, but modest confinement

Alcator C-Mod

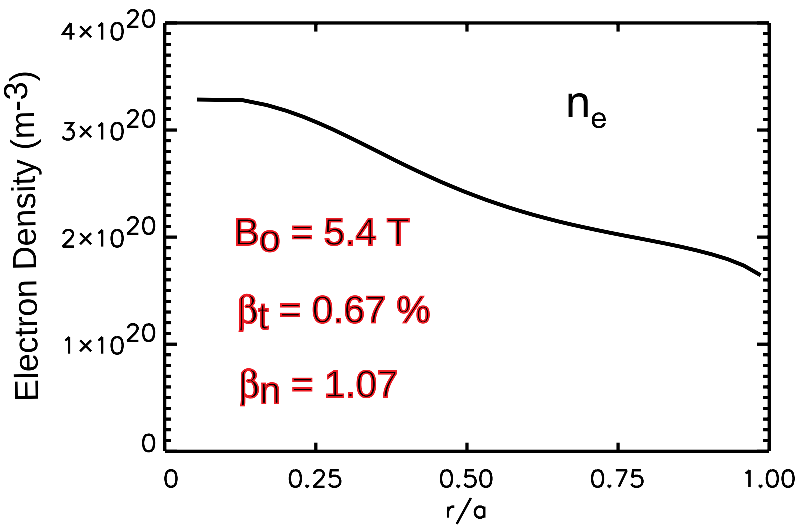
- Based on experiments with ICRF heating in current rise phase, with T_{e0} > 5 keV.
- **Model predicts I_{LH} = 390 kA, strong shear reversal.**
  - *Lower n_e cases gave I_{LH} up to 660 kA.*
- Reversed shear may well lead to improved core confinement, which would make this scenario attractive.





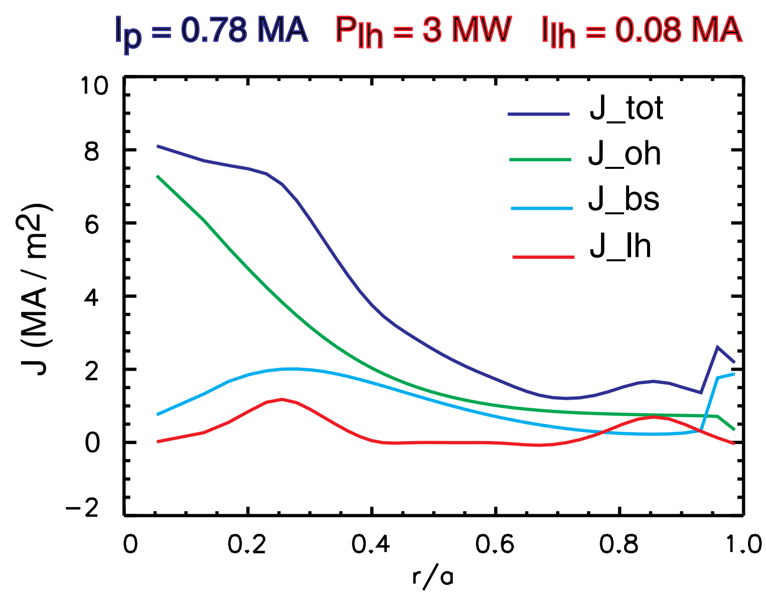
Standard high density H-modes give modest LHCD

5.4 T, 800 kA, steady EDA H-mode, n_{ped}~$2.0x10^{20}$ m^{-3}



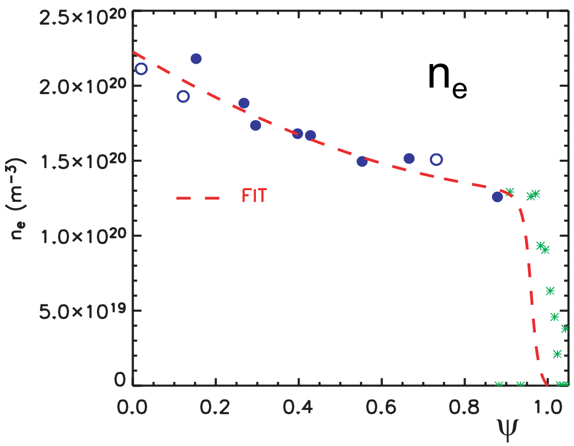
Density range in H-mode regimes is set by pedestal physics!

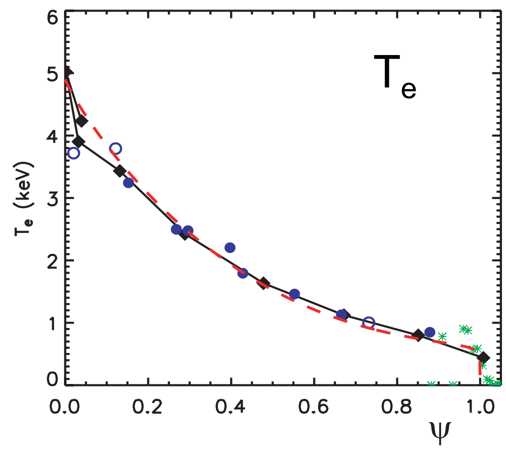
ACCOME finds LH waves accessible, but I_{LH} only ~80 kA, broadly distributed



Low(er) density H-modes improve scenarios

Experimental profiles from 5.4 T, 600 kA, steady EDA H-mode





n_{ped}~$1.3x10^{20}$ m^{-3}.

ACCOME predicts:

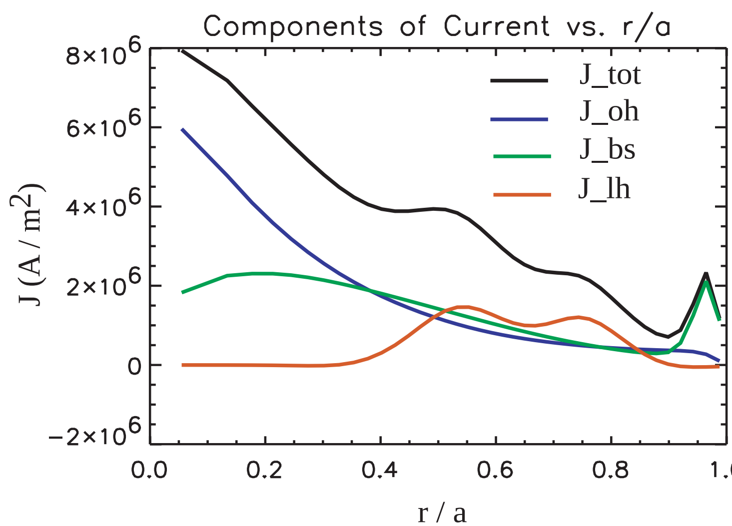
I_{LH} 131 kA, r/a 0.5-0.8

I_{BS} 234 kA

62% non-inductive

(with P_{LH}=3 MW)

- A good starting point; we plan further optimization, including use of cryopump.



Double Barrier Mode

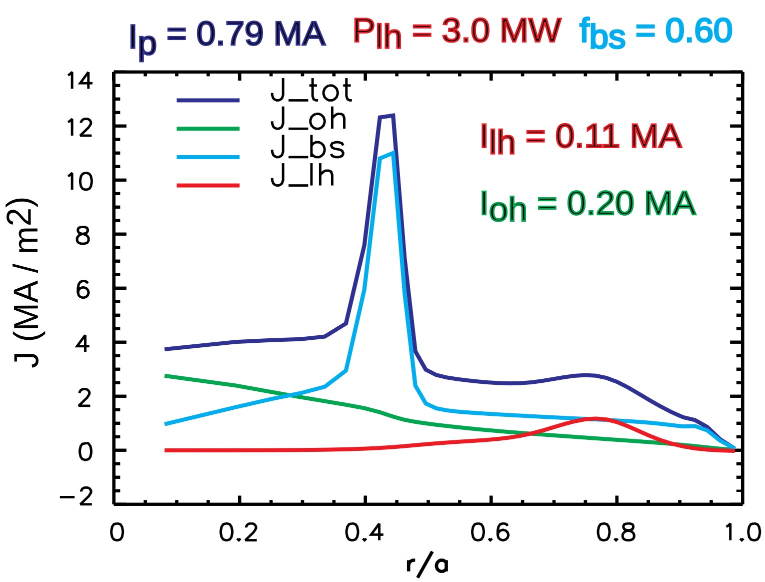
Density profile similar to ITB discharge with off-axis ICRH. T_e =3 keV

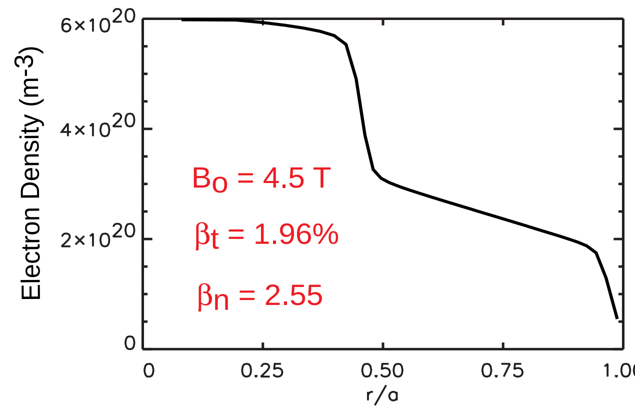
ACCOME predicts 60% bootstrap current (470 kA)

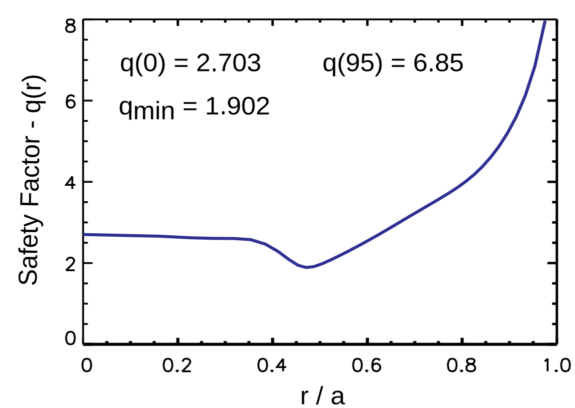
 - ***But, at radius smaller than optimum.***

110 kA LHCD (lower due to high n_e)

Our upcoming expts aim to expand barrier radially, reduce n_e, increase T_e.



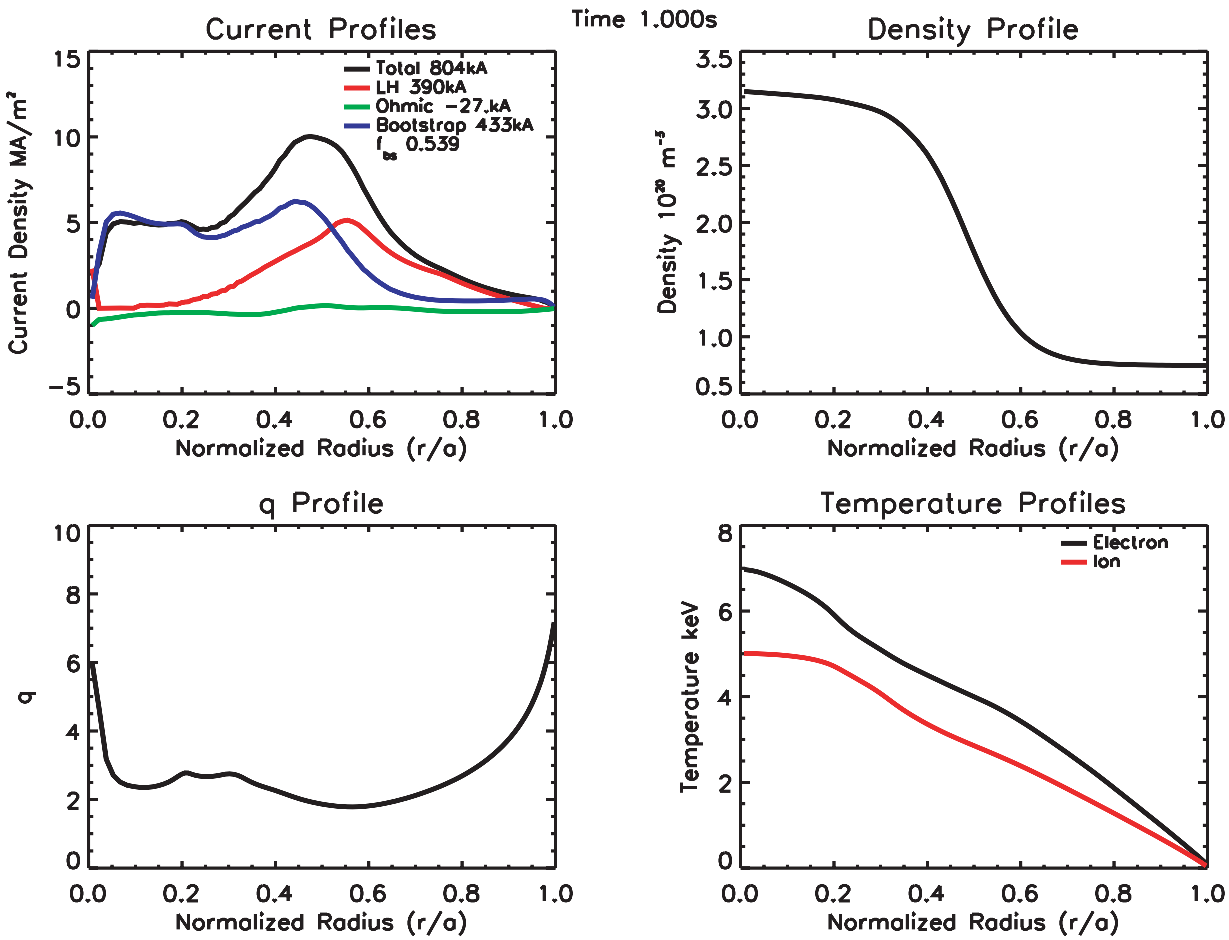




ITB with L-mode edge:
Time-dependent TRANSP simulation

Alcator C-Mod

- T_e, current profiles evolve in time, slice shown at t=1.0 sec
- Full non-inductive current drive.



P_{ICRF}=3 MW

P_{LH}=1.65 MW

$N_{//}$=2.75

TRANSP using input n_e, $\chi(r)$

LSC for LHCD

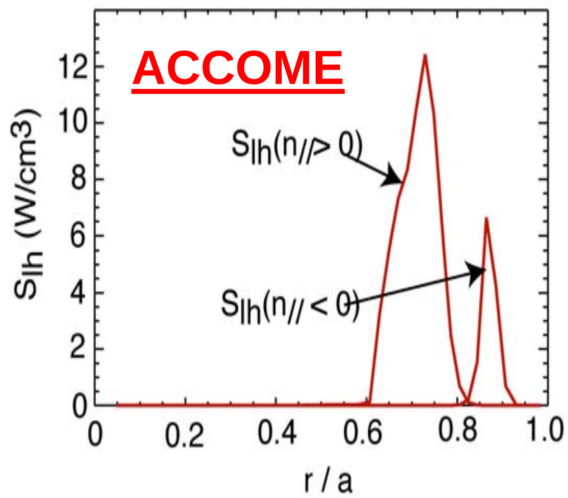
J. Liptac, APS 2002

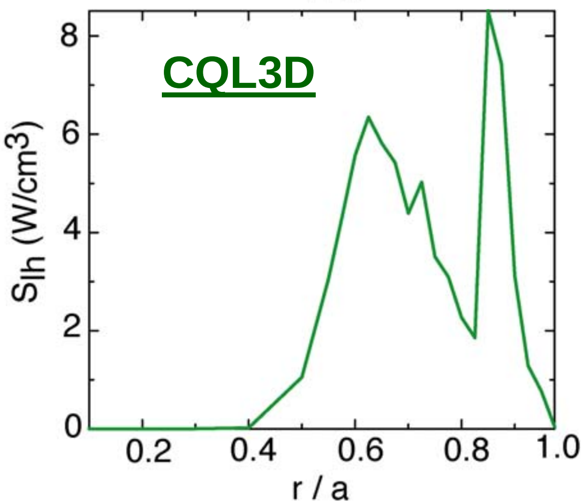
Looks very good –
***If* we can make**
these profiles.

Recent developments in current drive modelling

- **Benchmarking effort compared LHCD models** (as part of an ITPA - SS Activity):
  - **CQL3D:** exact numerical 2-D ($p_\perp$, $p_{//}$) solution of the FPE.
  - **ACCOME:** combines an adjoint solution of the FPE with a 1-D ($p_{//}$) damping model which includes an analytic model for 2-D pitch angle scattering effects.
    - Works well for the broad quasilinear plateaus characteristic of past LHCD experiments BUT,
    - Less accurate as the quasilinear plateau narrows, **a situation typical of Alcator C-Mod *and ITER***

Benchmarking for 4.5 T C-Mod case with double barrier

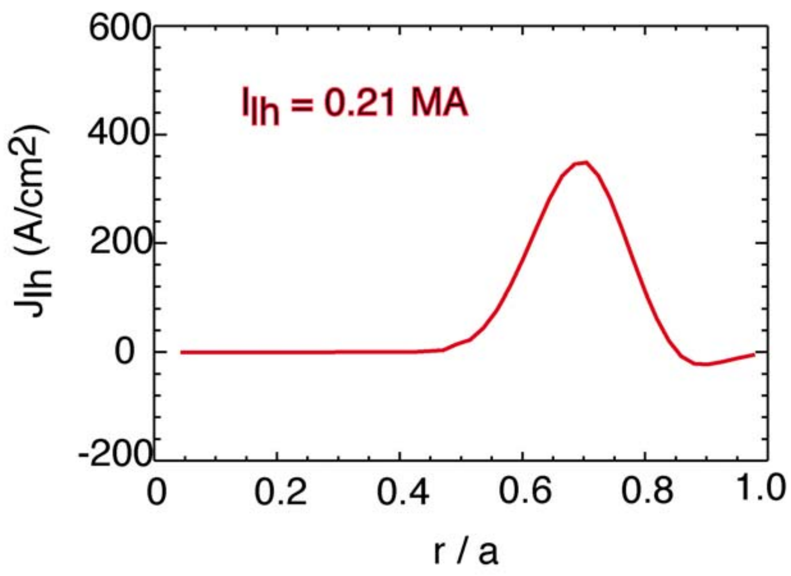




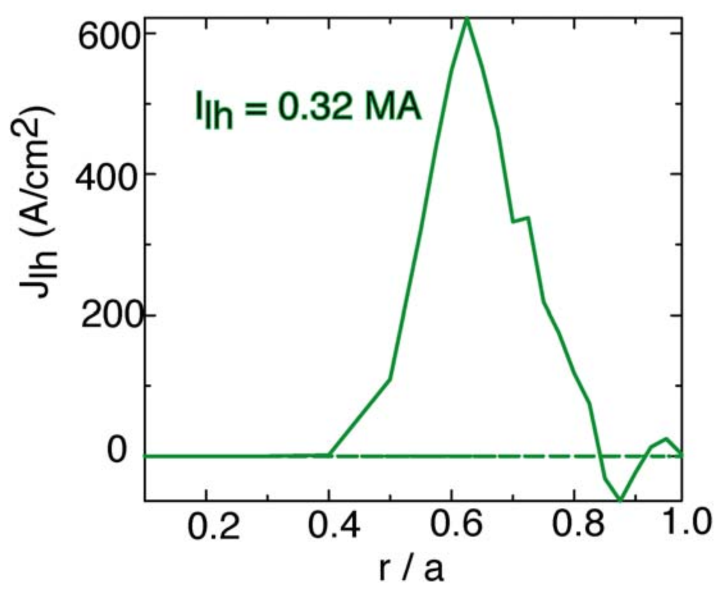
CQL3D predicts 50% more LH current than ACCOME

Alcator C-Mod

<u>ACCOME</u> I_{LH} = 0.21 MA



<u>CQL3D</u> I_{LH} = 0.32 MA



Bottom line: **Driven current in C-Mod scenarios shown is likely *underpredicted by ACCOME.***

Need to incorporate 2-D solution in future scenario modelling

Planned Modeling Activities in Support of the LH Current Profile Control Program on C-Mod

Alcator C-Mod

- Implementing **CQL3D** on the parallel cluster at MIT
- Will couple a LH **full-wave solver** to CQL3D (both rf SciDac Projects).
  - **These will provide accurate assessment of LHCD in C-Mod discharges.**

- **There is a need to include the latest RF models (as well as transport models), in time dependent scenario modelling.** (eg TRANSP, TSC); (LSC has several limitations even compared to ACCOME.)

- **Many complex interactions, especially in scenarios with barriers.** eg:
  - n_e, T_e profiles determine j(r) from LHCD, which changes shear.
  - Shear affects transport which affects profiles, which affect both LHCD and bootstrap current, which further affect shear….
  - Time dependent modelling shows it takes at least 1 τ_{CR} for profiles to ‘settle’ to equilibrium.

C-Mod AT and LHCD program will focus on ITPA high-priority tasks

Alcator C-Mod

Steady State Operation:

- Investigate **hybrid scenarios** for prolonged plasma operation and **develop full current drive plasmas with significant bootstrap current**: assess beta limits.
- Develop **real time current profile control** using heating and CD actuators: assess predictability, in particular **for off-axis CD.**

Transport Physics:

- Improve experimental characterization and understanding of **critical issues for reactor relevant regimes with enhanced confinement**, by:
  - Obtaining **physics documentation for transport modeling of ITER hybrid and steady-state demonstration discharges.**
  - **Addressing reactor relevant conditions, e.g., electron heating, Te~Ti, impurities, density, edge-core interaction, low momentum input...**
- Contribute to and utilize international experimental ITPA database for tests of the commonality of hybrid and steady state scenario transport physics across devices.

This alignment is no accident;
The features which make LHCD and advanced scenarios *unique and challenging* on C-Mod are the same as will need to be addressed in a burning plasma.
Need to make use of near-term experiments to learn to deal with them before ITER operates! Results should help clarify whether LHCD is useful for ITER.

Summary: Current Profile Control Considerations for High Performance Steady-State Tokamaks

Alcator C-Mod

- C-Mod is near the beginning of a program to achieve higher performance, quasi-steady state plasmas through current profile control.
  - Key new tool, Lower Hybrid Current Drive system, just installed. To be commissioned during 2005, hope to use it for j(r) modification experiments in 2006.
  - Mode Conversion Current Drive also seems promising and would be a valuable complement.

- Localization and efficiency of current drive depends strongly on plasma parameters (notably $n_e(r)$ and $T_e(r)$). Control of kinetic profiles (heating, transport, particles) is thus a key consideration.
  - These dependencies must be considered when designing scenarios for present and future experiments. Not enough to simply specify ideal p(r), j(r) profiles for performance, stability, then say 'we need *x* kA at r/a=y'!
- Recent advances in RF modelling allow more accurate prediction of LHCD and MCCD. Now need to couple these codes to integrated, time dependent models. Also important to include in design studies for future machines (ARIES etc).