The Alcator C-Mod Program - and Plans for AT Scenario Development

NSTX Five Year Planning Forum
June 24-26, 2002
Princeton Plasma Physics Laboratory

Presented by Paul Bonoli
MIT Plasma Science and Fusion Center,
for the C-Mod team

Program Structure

Unique Aspects and Strengths of C-Mod $\Rightarrow$ Address Key Questions

Alcator C-Mod

- Unique long pulse capability (relative to skin and L/R times) in highly shaped, diverted plasma; B > 4 T
  - $\rightarrow$ Quasi-steady lower hybrid driven AT scenarios
- High performance, compact, high field capability
  - $\rightarrow$ Address issues for compact, high-field ignition approaches
- Exclusively RF driven
  - – Heating decoupled from particle sources
  - – No external momentum sources
  - $\rightarrow$ Reactor-relevant regimes for Transport, MHD, AT studies
- Unique dimensional parameters, but comparable to larger tokamaks in dimensionless parameters
  - – Key points on scaling curves
  - – Test sensitivities to non-similar processes (radiation, neutrals, etc.)
- Very high scrape-off layer power density (~1 GW/m^2)
  - – Unique divertor regimes, reactor prototypical
- Advanced materials (also reactor prototypical)
  - – Unique recycling properties; generic MFE challenge

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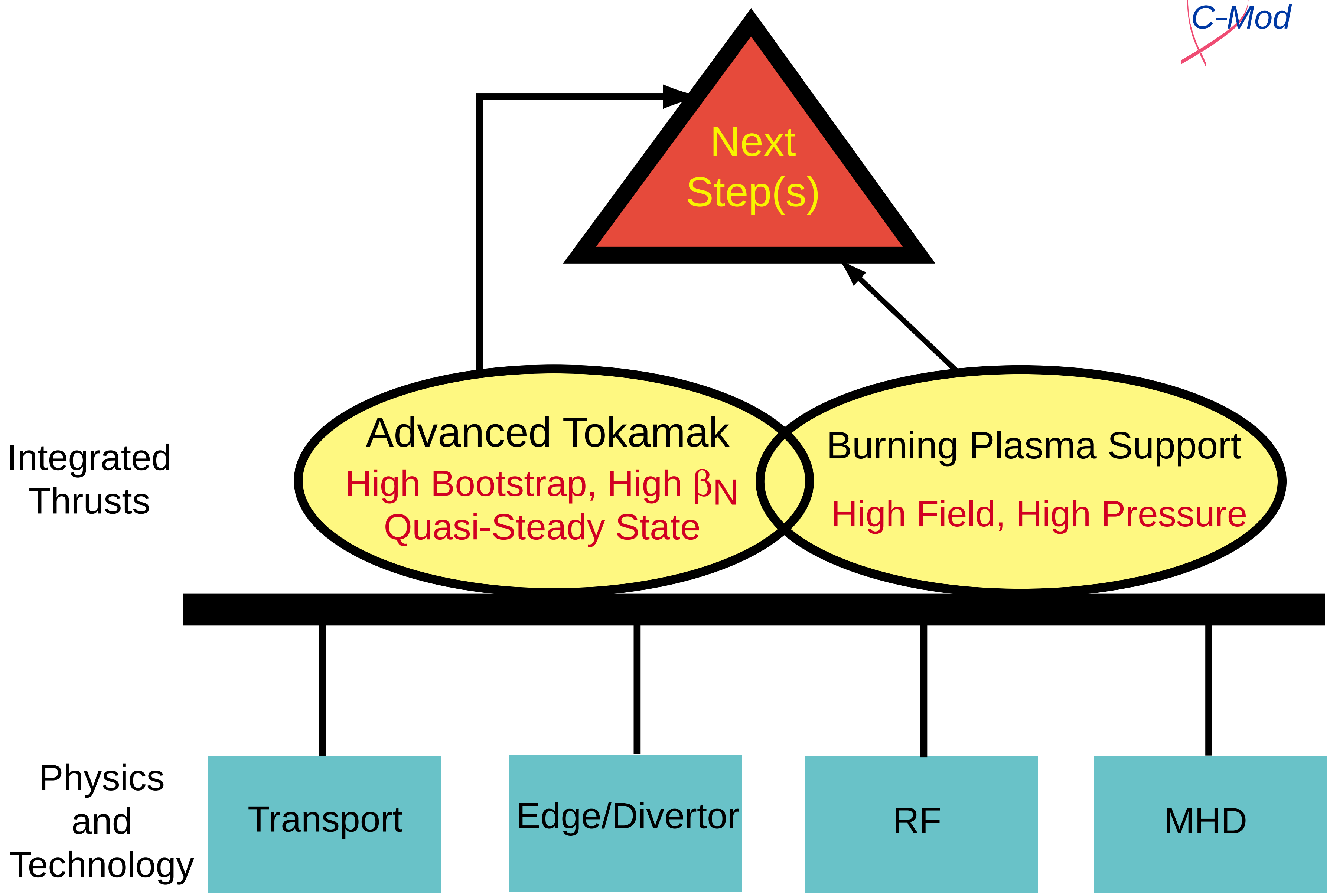
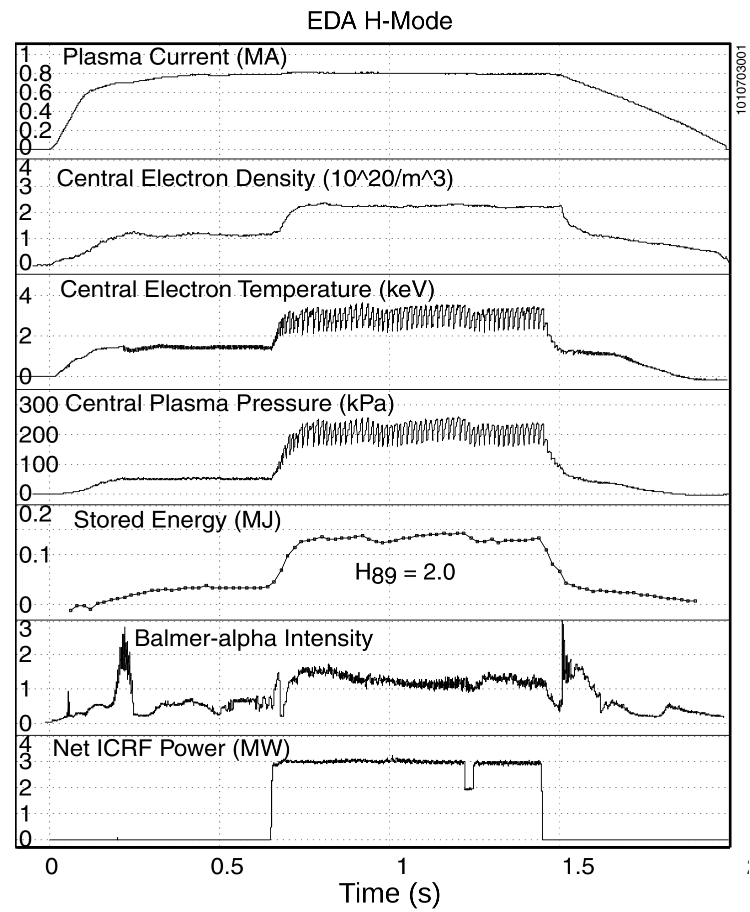


Burning Plasma Support Research

Develop and Validate Physics Basis for Tokamak Burning Plasma Experiments

Develop and Demonstrate Scenarios for BPX Optimization

- High Priority Topics
  - H-Mode Pedestal Physics
    - Threshold; Pedestal height; Edge relaxation mechanisms
  - Particle and power handling at high plasma and power densities
  - RF physics and technology (ICRF, Lower Hybrid): heating, current drive and plasma control
  - Shape and topology (δ, κ, SN/DN/Lim)
  - Sawtooth and NTM stabilization
  - High-current disruptions



Main goals of the AT physics program

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1. **Current profile control via LHCD**, at reactor-relevant densities.

2. Understanding, control and sustainment of **Internal Transport Barriers**, with $T_e \sim T_i$ and without momentum input.

3. Use non-inductive current drive (LHCD and bootstrap) to **extend pulse length to near steady state (5 sec, 4-6 τ_{CR})**
   - *divertor power handling and wall particle issues.*

4. **Increase β to MHD limit**, and maximize through profile optimization, possibly stabilization.

Program involves *all physics areas* (RF, transport, divertor, MHD) and has broad participation from the C-Mod team.

Profile Control Tools

Alcator C-Mod

"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 2003. Phase II 2005). 4 MW, 4.6 GHz, 2 launchers with independent phasing, $N_{//}$.*
  - *Mode Conversion Current Drive*. *(on-axis, tests 2002-3)*
  - Bootstrap current drive via pressure profile control.
- **Density profile.**
  - Control of core transport, peaking.
  - *Cryopump controls edge source. (2004)*
  - D_2 and Lithium pellet injectors.
- **Temperature Profiles**
  - 8 MW ICRH, 40-80 MHz, 2 independently variable deposition locations.
  - *4 MW LHCD.*
  - Control of core transport via RF deposition, *magnetic shear*.
- **Shear Flow** - *MC flow drive.*

Lower Hybrid Current Drive system

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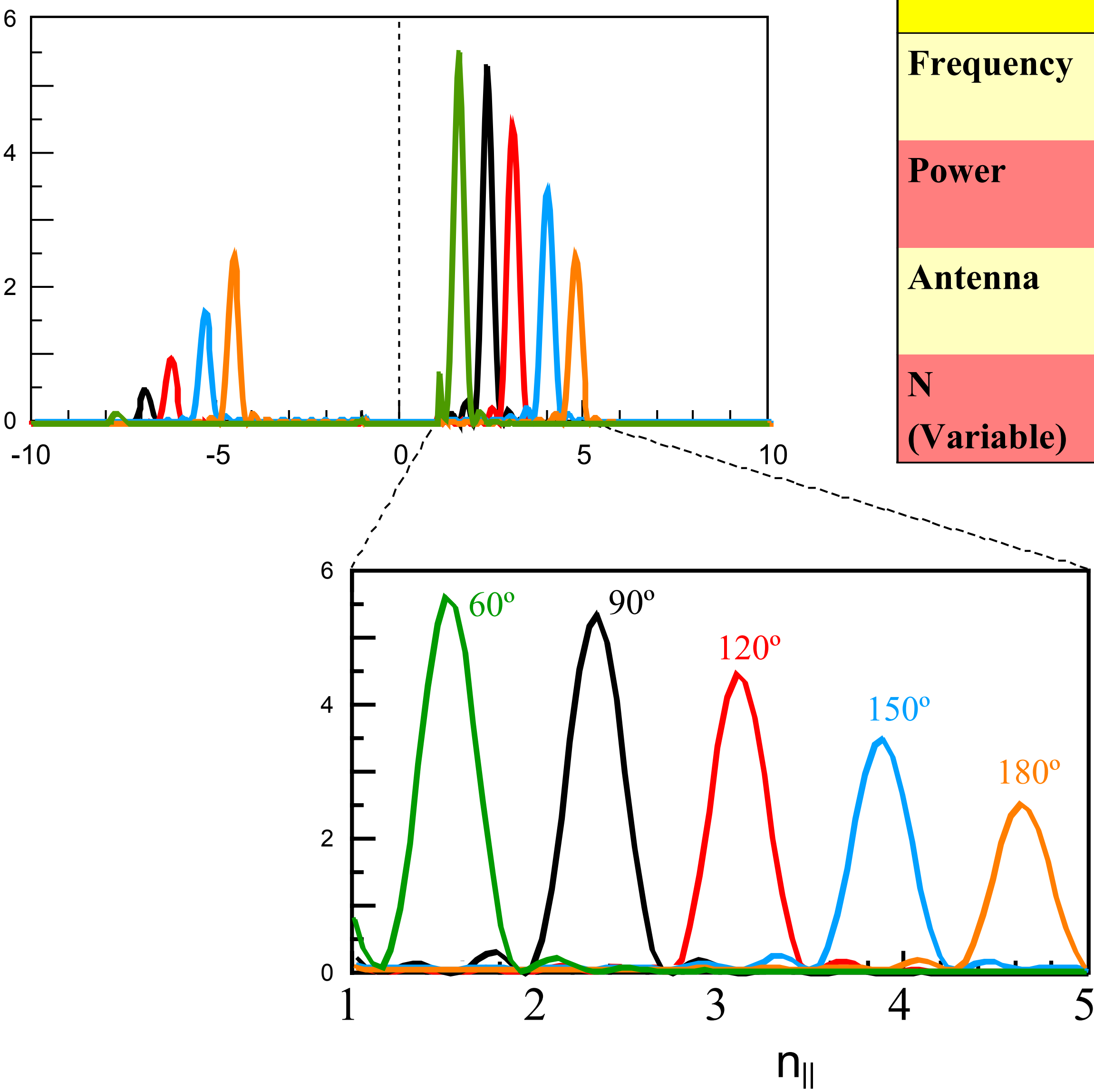


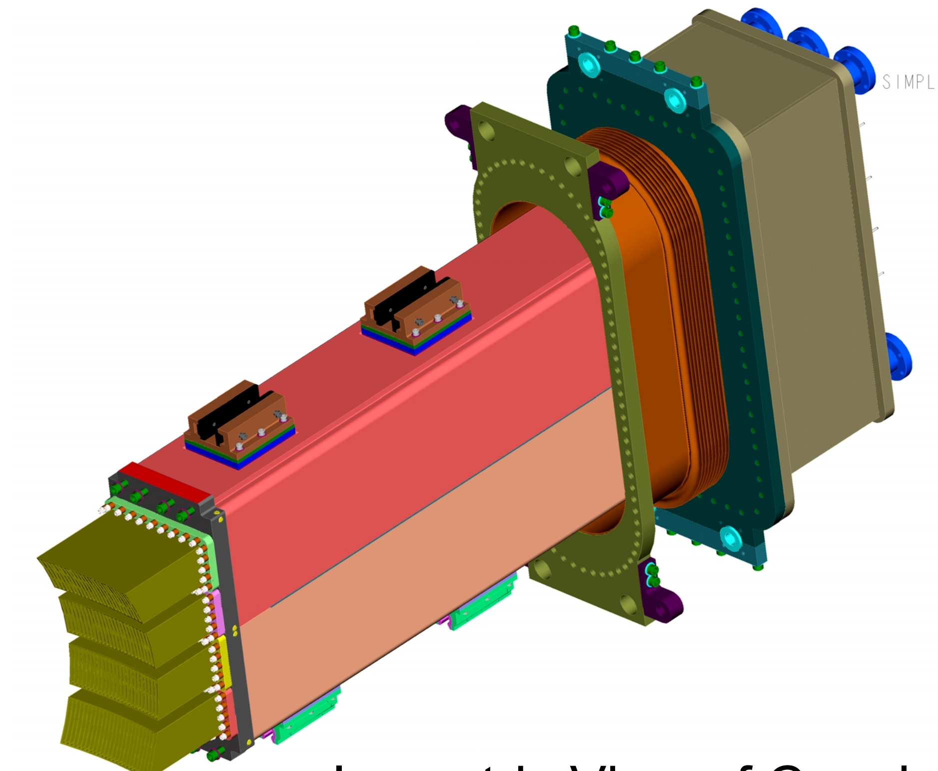
	Phase I	*Phase II*
Frequency	**4.6 GHz**	**4.6 GHz**
Power	**3 MW**	**4 MW**
Antenna	**4X24 Waveguide Grill (1)**	**4X24 Waveguide Grills (2)**
N (Variable)	**2-4**	**2-4**

- Each antenna will have **flexible $N_{//}$** ,
- Variable between or during discharges using phase shifters.

LH hardware preparation well advanced

- **RF sources, power supplies, WG being prepared by MIT.**
  - 12 Klystrons (3 MW) have been tested and installed in C-Mod cell.
- First LH expts summer 2003

- **LH Coupler and splitter are being fabricated by PPPL**
  - Many components in-house.
  - Testing of grill modules in progress.
- **Delivery to MIT March 2003**



Isometric View of Coupler

Research Highlights

Internal Transport Barriers

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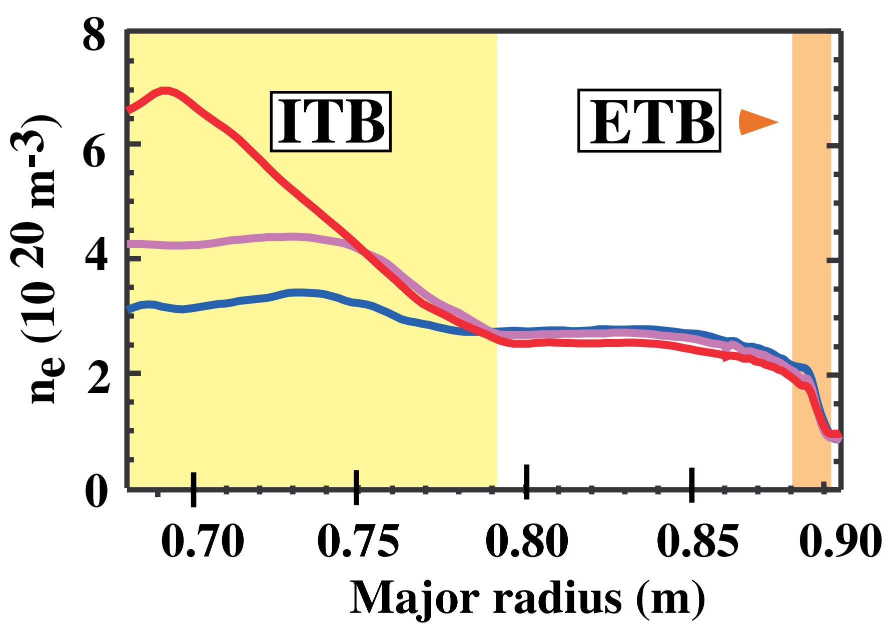
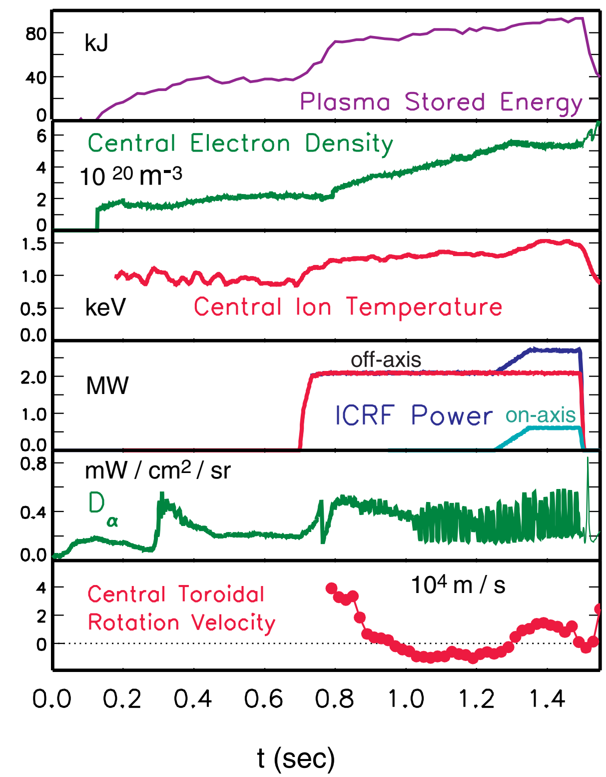
- ITB's are routinely triggered by **off-axis ICRH**, at r/a ~0.5.
- Core barriers co-exist with edge pedestal (EDA H-mode.)
- Also seen in *ohmic H-mode*.
- Reversed shear not needed.



S. Wukitch, APS 2001, PoP 2002.

Stable conditions were reached for ~15 τ_E, through addition of modest on-axis ICRH.

We can control the degree of transport within the barrier!



Barriers are formed with heating on high *or* low field side.

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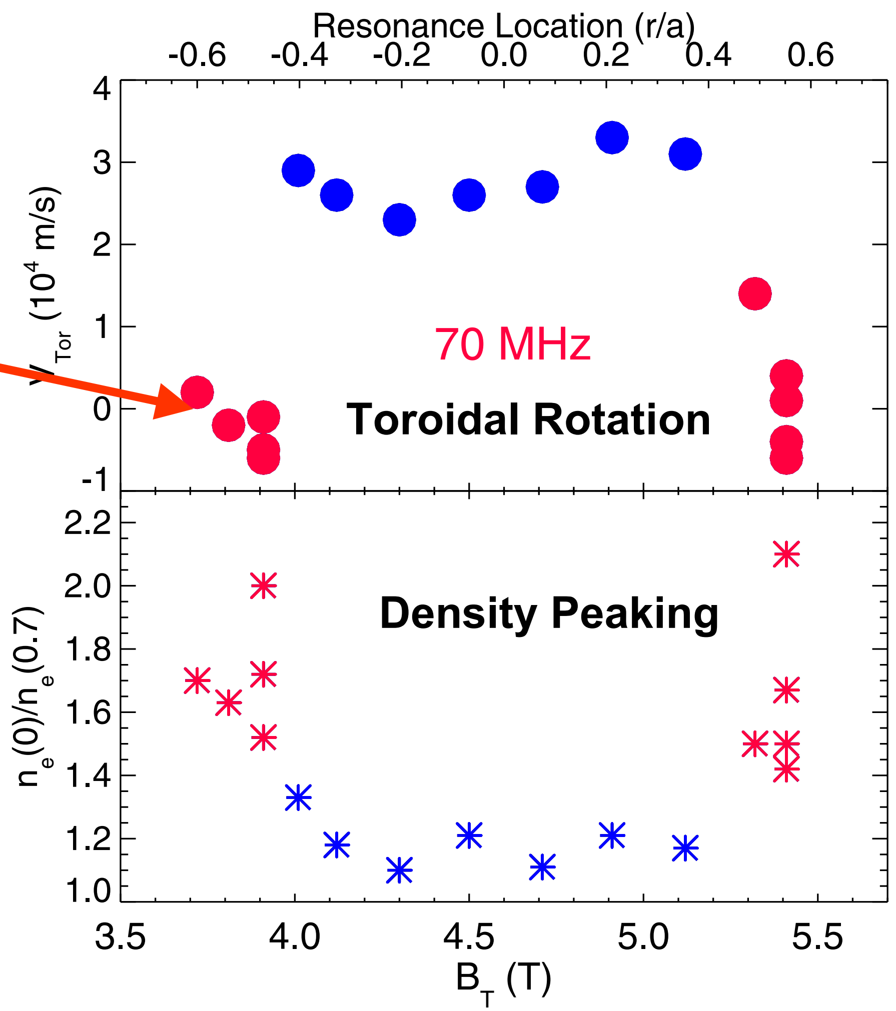
- Scenarios tested:

  F= 80 MHz, B=4.5 T

  F= 70 MHz, B=3.8 or 5.4 T

- Same condition $r_{res}/a = \pm 0.5$ in all cases.
  - With HFS heating at 80 MHz, used 70 MHz core heating to stabilize barrier
  - With LFS heating at 70 MHz, used 80 MHz core heating to stabilize barrier.



J. Rice et al, Nucl. Fusion 42, 510(2002)

TRANSP analysis confirms energy and particle transport barrier

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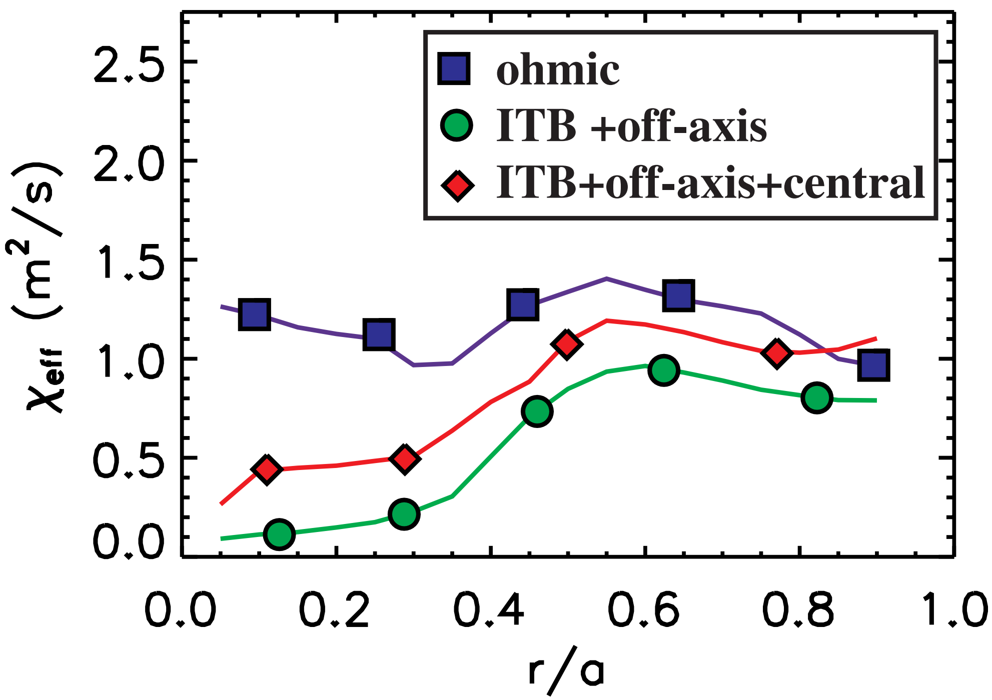
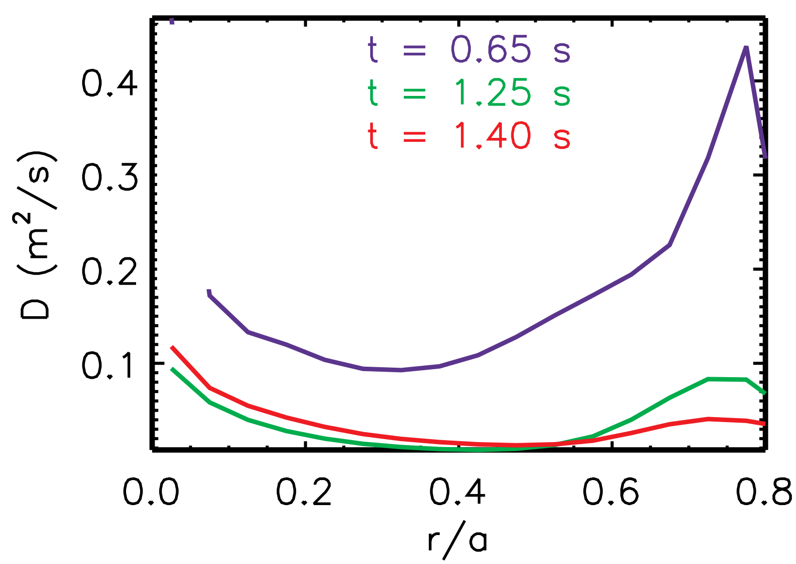
- **Strong decrease in χ_{eff} as well as D** when barrier forms.
- Ware pinch is large enough to peak $n_e(R)$ once D is reduced.
- With central heating, core χ_{eff} and D increase somewhat but are still less than without barrier.
  - Can **control barrier strength**, avoid impurity accumulation as well as MHD limits.
- Localized energy transport barrier is also seen clearly in sawtooth heat propagation.





Emerging understanding of ITB mechanism from GS2 simulations

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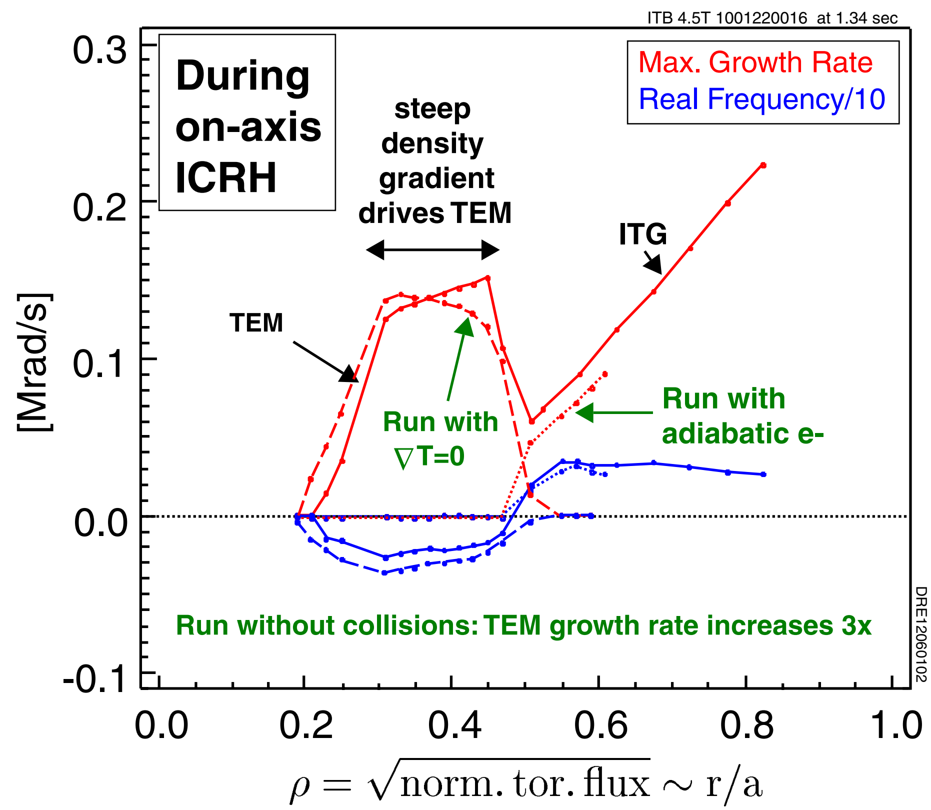
- Formation starts with decrease in ITG mode (note low η_e , R/L_T).
  - At transition time, ExB shear does not appear dominant.
- Ware pinch peaks n_e, p_e.
  - n_e gradient then further stabilizes ITG (positive feedback), but can drive weak TEM in barrier.
- When on-axis heating is applied, TEM increases (lower ν^*).
  - Nonlinear simulations show enough transport to balance Ware pinch, arrest peaking.
  - Too much heating erodes the barrier.
- **Preliminary Picture; need many tests in models, experiments!**

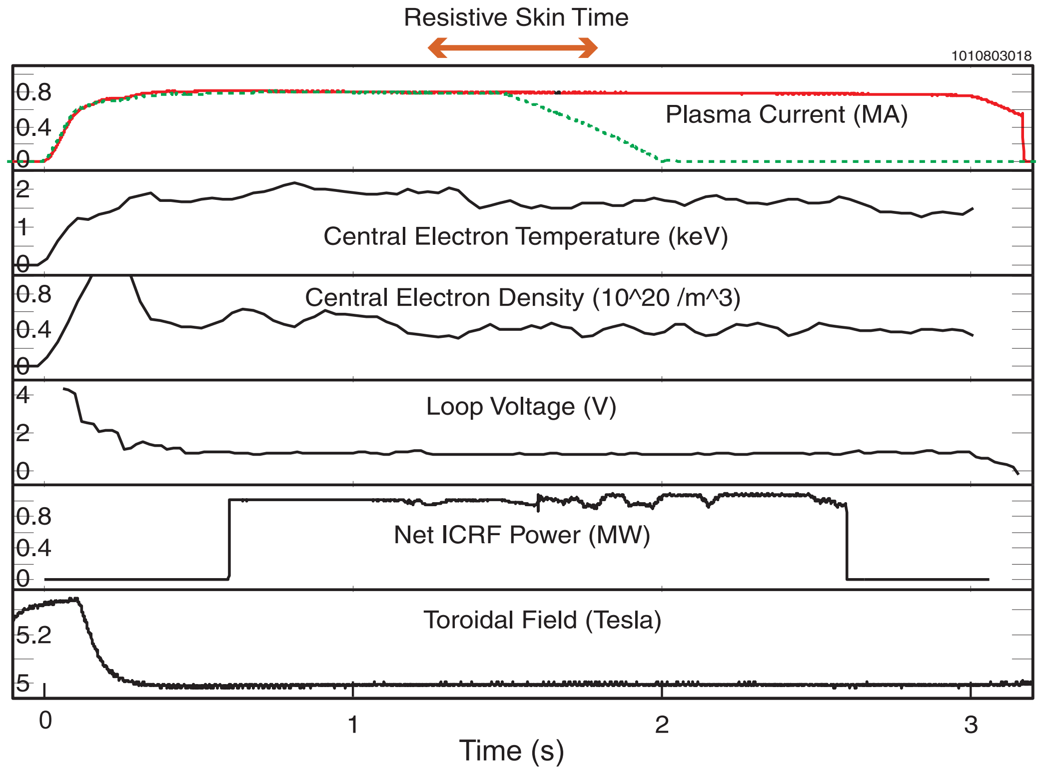


D. Ernst, Sherwood 2002

M. Redi, TTF 2002, EPS 2002
C. Fiore, PoP 2001, TTF 2002

Long pulse operation demonstrated for 3 seconds

Alcator C-Mod



- 5 T, 800 kA.
- L and H-mode discharges, with ICRF.
- Densities were controlled. ~ 4×10^{19} m^{-3} (L), 2×10^{20} m^{-3} (H)
- T_{e0}~ 2 keV **t_{pulse}~ 15 τ_{CR}** *(would be ~ 4 τ_{CR} at 5 keV).*
- No engineering problems (details by Jim Irby).

Mode conversion heating is efficient, well localized

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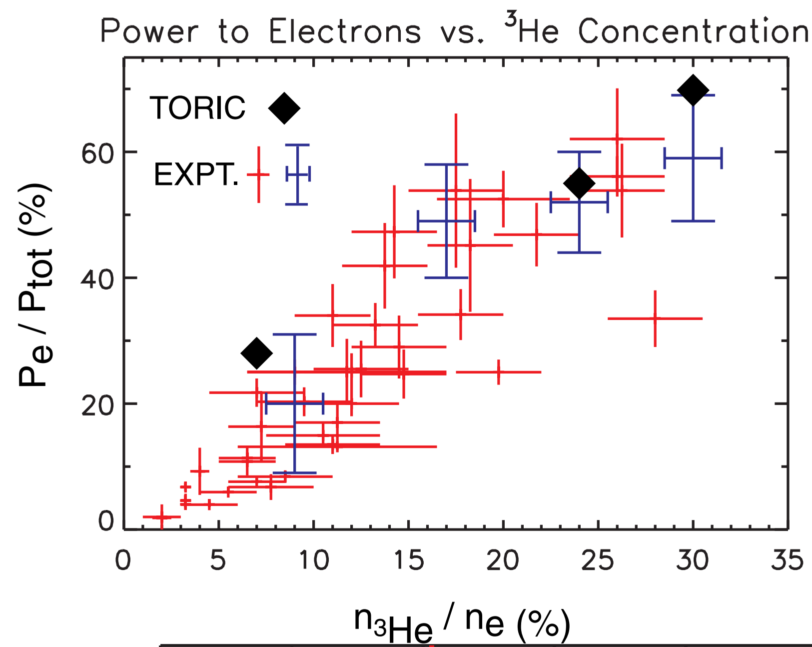
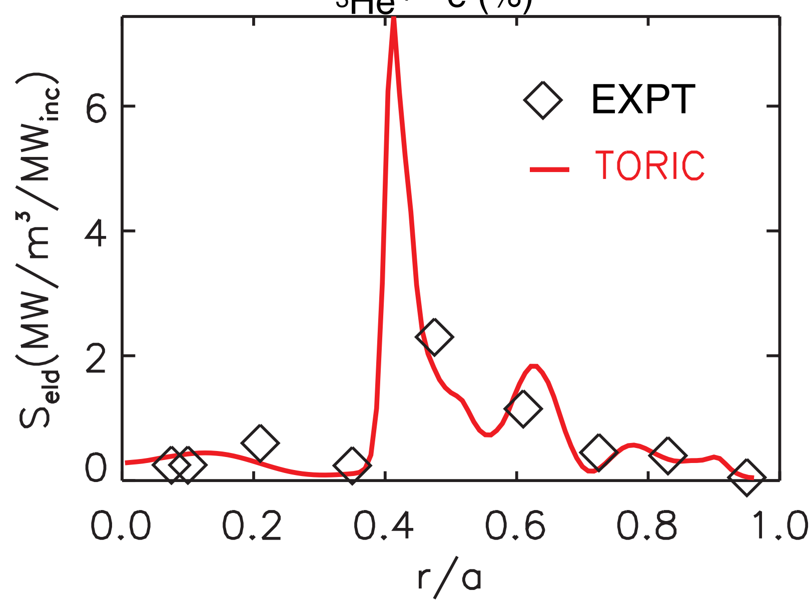
- Electron HEATING by mode-converted IBW/IC waves has been measured in several experiments, scenarios.
- Efficiency up to 60%.
- Localized radially, can be placed on or off-axis by varying B_T, concentrations.
- Increasing understanding of physics through high mode-number TORIC simulations, PCI measurements.

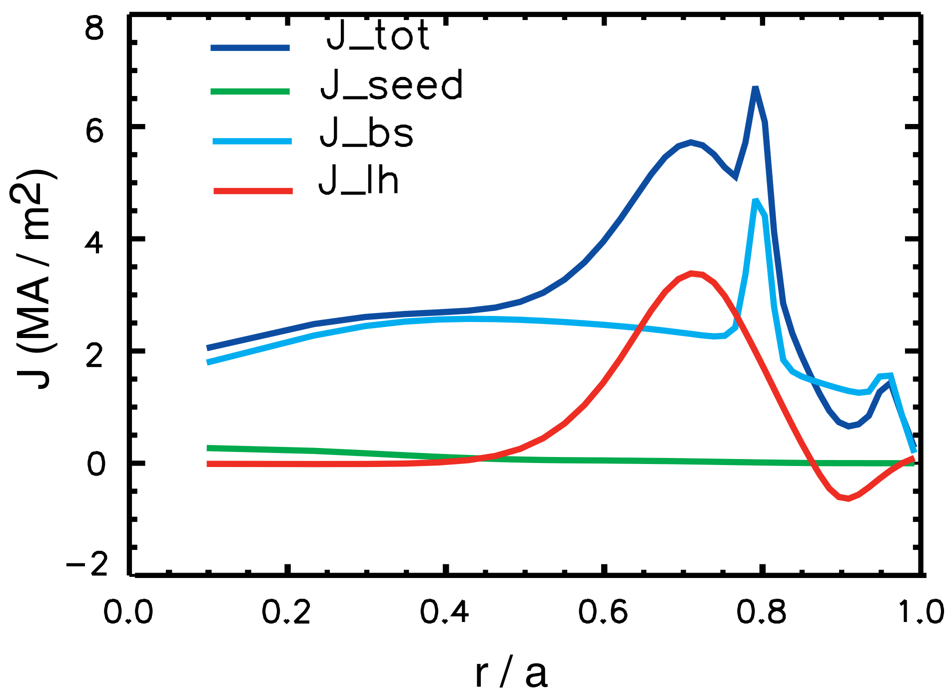




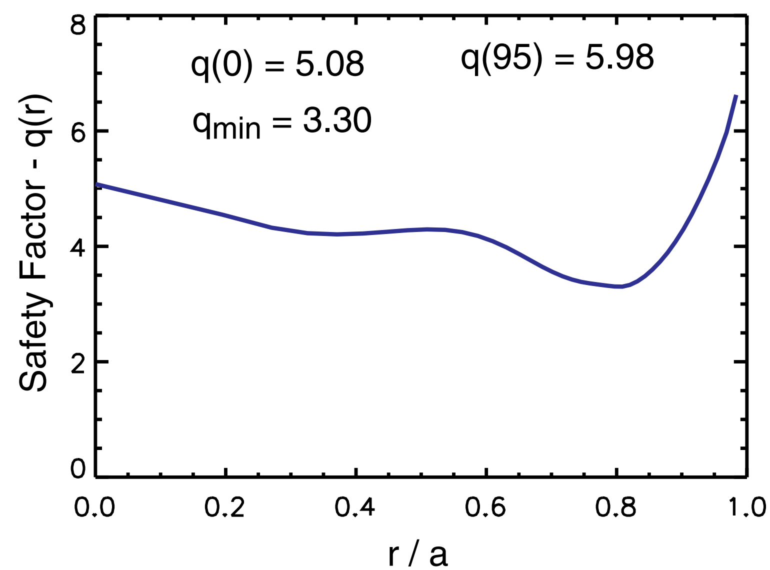
ACCOME modelling has identified several promising AT scenarios

- **Example of an optimized scenario.**
  - I_{LH}=240 kA
  - I_{BS}=600 kA (70%)
- MHD stable, β_n=2.9

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



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

Target Plasma Development and Scenario Modelling closely linked.

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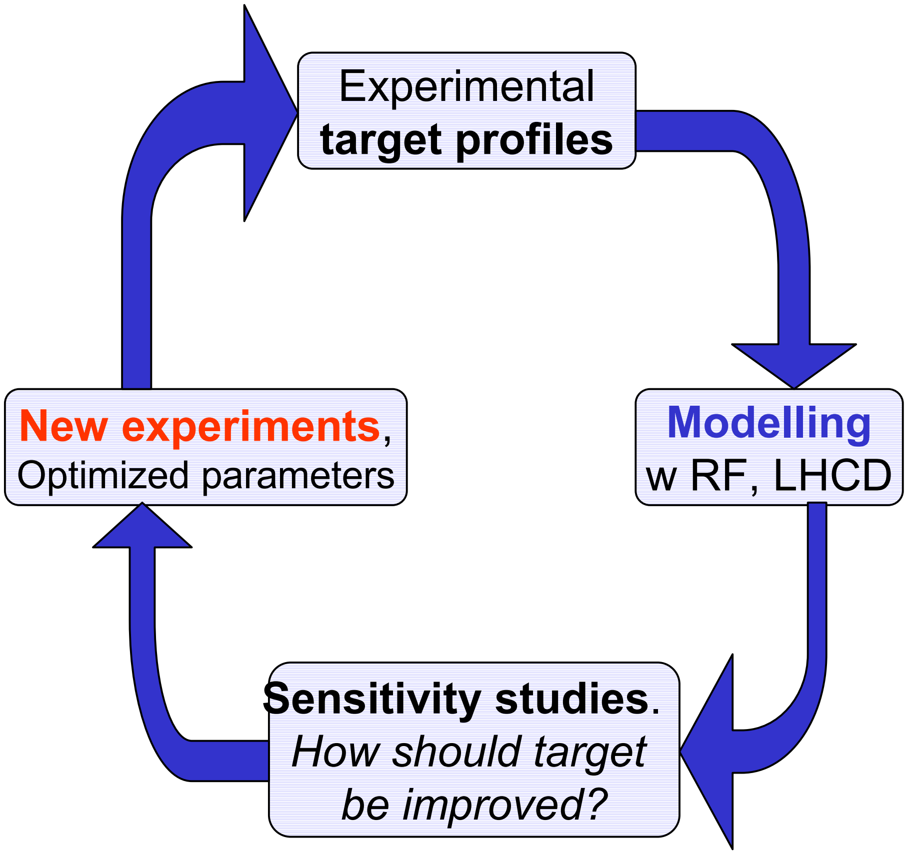
- Modelling is used to assess wave accessibility, damping, and CD efficiency, and guide target plasma development toward more optimal scenarios.
- Exploring several different regimes:
  - Rampup,
  - L-mode,
  - H-mode and
  - Double-barrier.



Current ramp, low density L-Mode.

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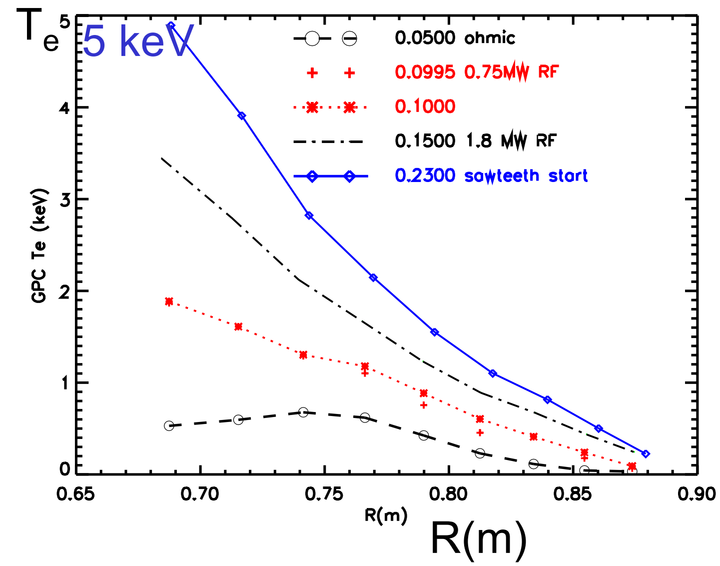
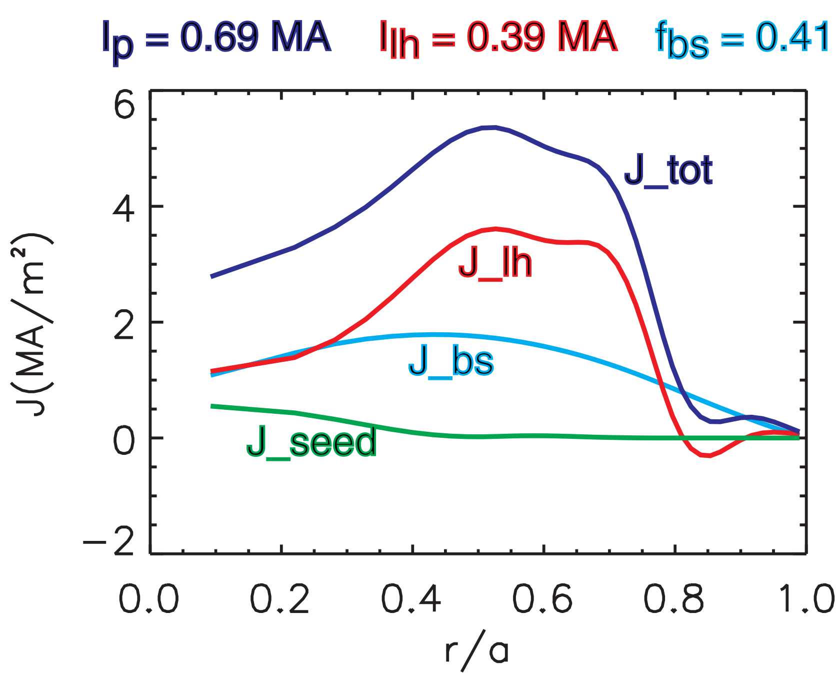
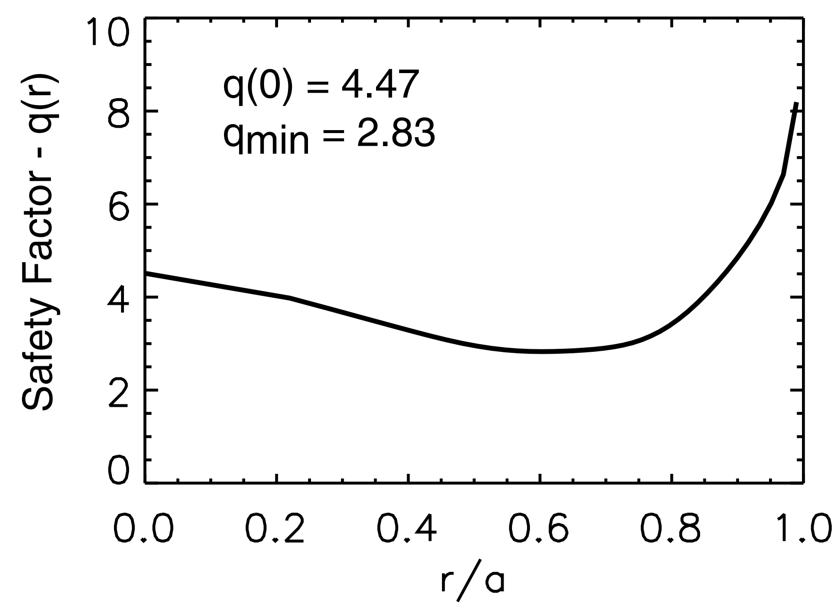
- Based on an expt with T_{e0} = 5 keV, $n_{e0} = 1.5 \times 10^{20}\ m^{-3}$, 1.8 MW ICRH.
- **Model predicts I_{LH} = 390 kA, strong shear reversal.**
- ***Also have dynamic simulations with TRANSP+ LSC***
  http://www.psfc.mit.edu/people/jliptac/amanda/2203anim.html





P_{LH}=3 MW, $N_{//}$=2.75

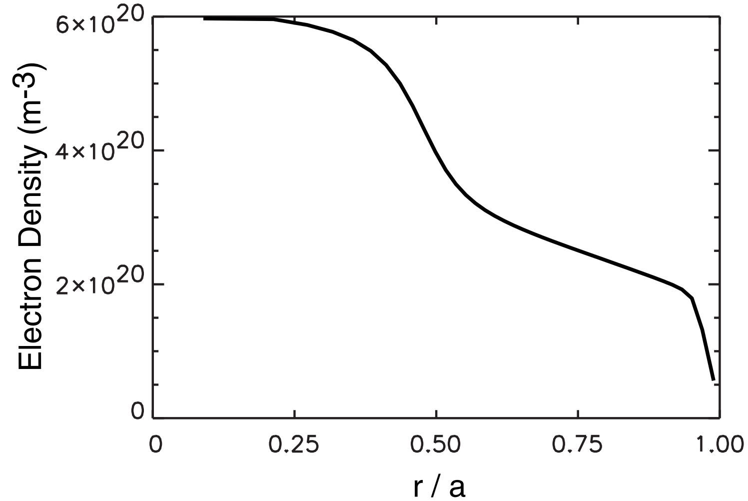


Double Barrier Mode

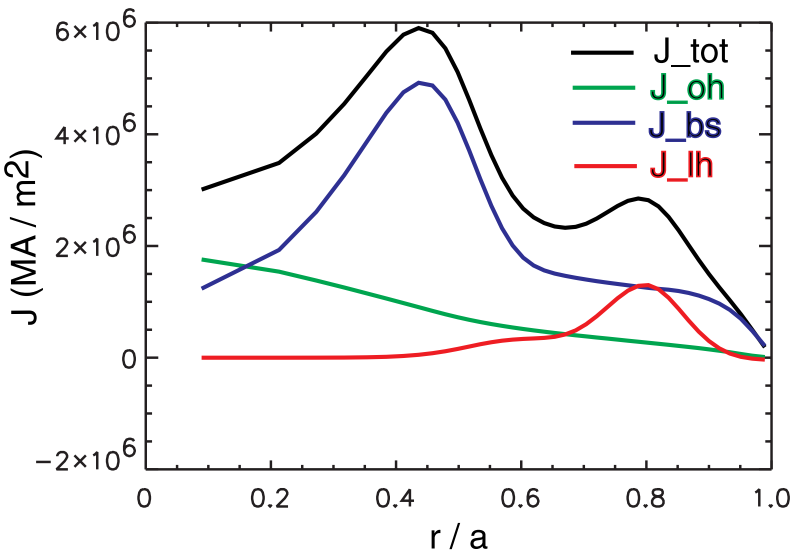
Density profile from an ITB discharge with off-axis ICRH. T_e has been raised to 3 keV
ACCOME predicts 60% bootstrap current (470 kA) (I_{BS} ~100 kA in actual discharge).
But, at radius smaller than optimum.
- Expts aim to expand barrier, increase T_e.

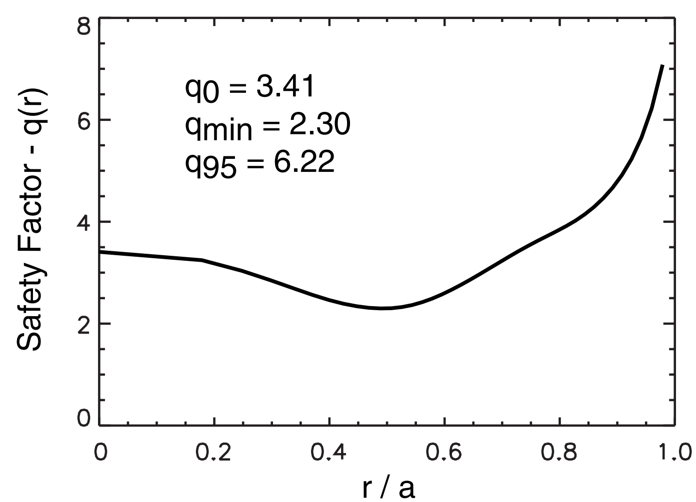
Good LH penetration even with H-mode pedestal.
Adding LHCD increases q_{min}, bootstrap fraction at fixed I_p. f_{bs}, q_{min} increase at lower I_p.

$6x10^{20}$ m^{-3}



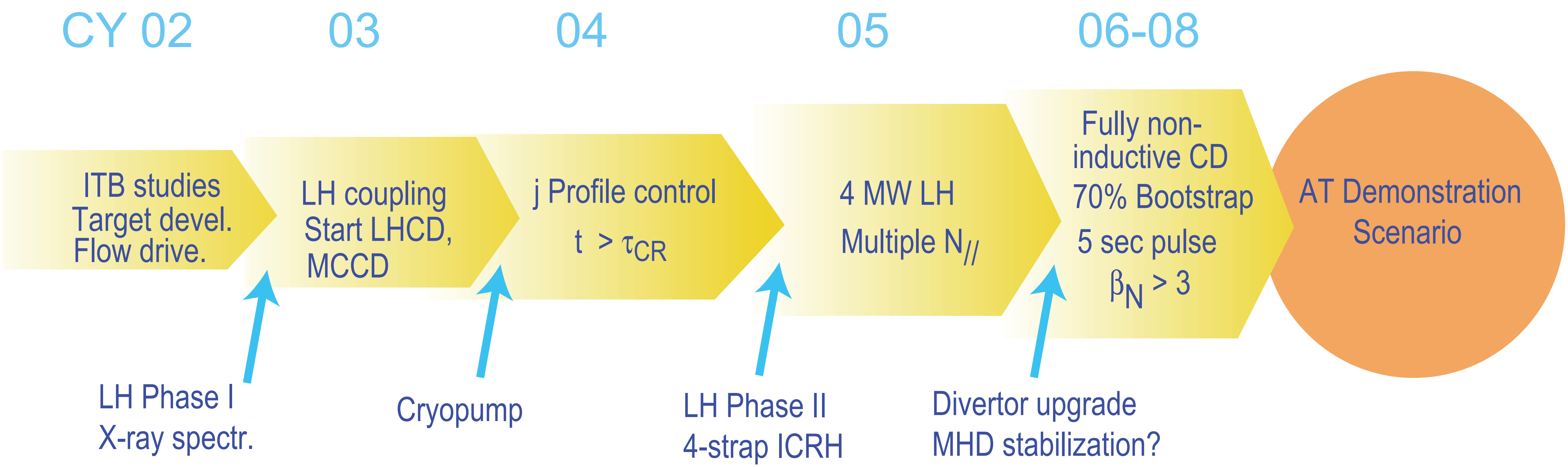
I_p=750 kA, I_{LH}=110 kA f_{BS}=0.68





Research Issues and Plans

Long Term Advanced Tokamak Program



Current Profile Control: LHCD

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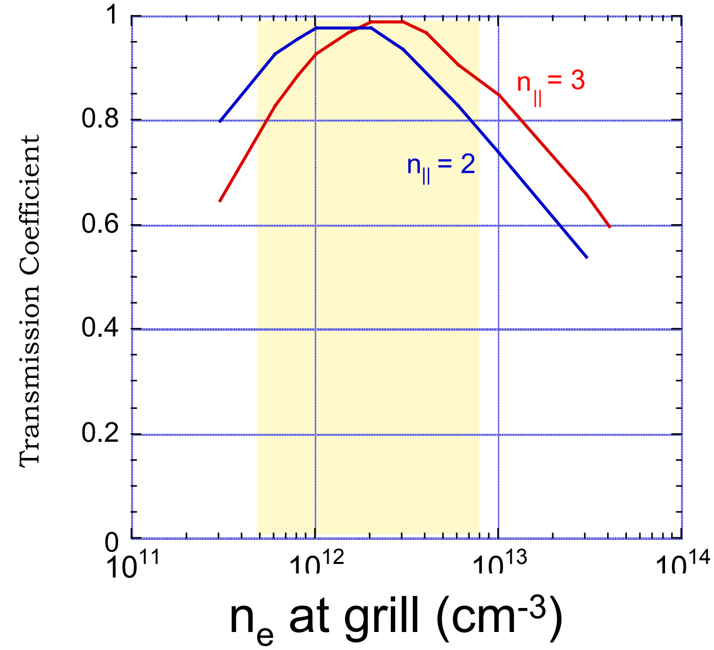
- **2002: Demonstrate optimized target plasmas:**
  - High power L-mode.
  - Lower density H-modes.

- **2003: Commission Phase I.**
  - **Assess power handling.** *What is the limit for short, long pulses?*
  - Focus on **LH coupling, wave physics studies**.
  - Measure coupling efficiency, reflectivity vs density, launcher and limiter position.
  - LHCD and heating efficiency and deposition profile studies vs density, $N_{//}$. Both on and off-axis CD
  - ***Imaging Hard X-ray Spectrometer for fast electron profile and MSE for j(r) are important diagnostics.***

TRANSMISSION COEFFICIENT

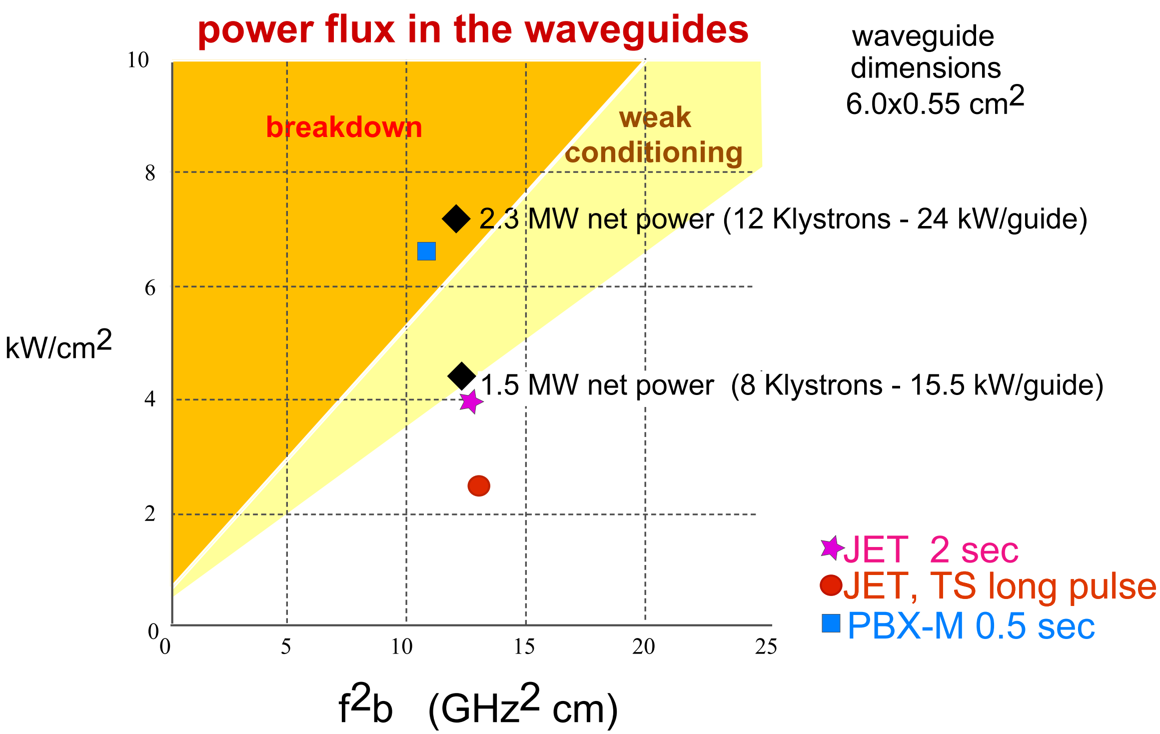


S. Bernabei, PPPL

Current Profile Control: LHCD

2004: Combine LHCD and ICRH.

- Combine LHCD with barriers, optimize total current profiles.

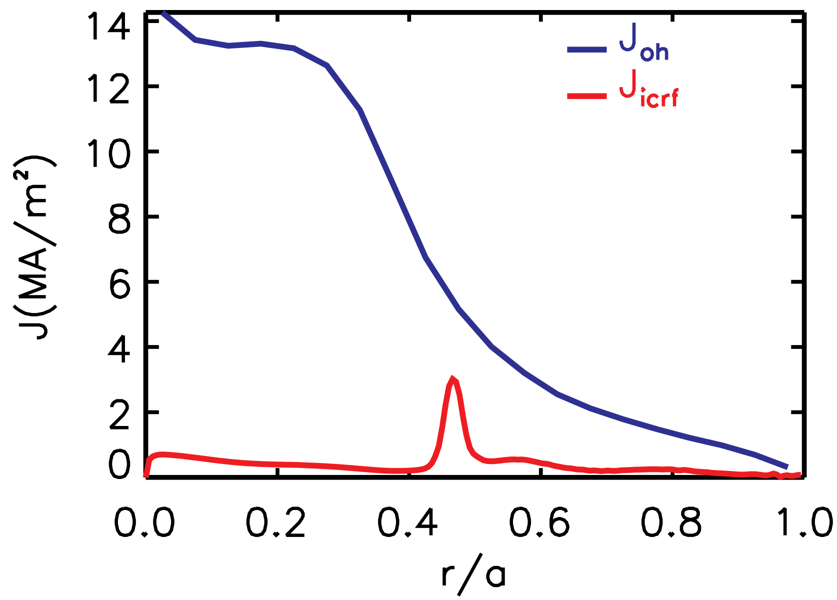


2005: Commission LHCD Phase II.

- 2nd antenna allows 4 MW source,
- **3 MW coupled** for modest power density, **5 sec pulse** .
- Add new 4-strap ICRF antenna.
- **Use flexibility of two launchers to create spectrum with two $N_{//}$ peaks.**
  - *Modelling and other experiments (eg ASDEX) show that a high $N_{//}$ component increases off-axis absorption and localization.*

Current Profile Control: MCCD

- MCCD was demonstrated on TFTR (Majeski et al, 1996)
- Modelling predicts MCCD has best efficiency at high T_e (ie on-axis).
  - Good complement to LHCD, may provide 'seed current' ~ 100 kA.



- **2003: Initial tests of MCIBW with current drive phasing.**
- **2004**: **If successful, combine with LHCD.** Synergism??

TORIC - Adjoint Code Prediction for Off-axis MCCD in C-Mod (N_m=161, 5.5 T, 60 MHz)

I_p=800 kA **I_{RF} = 90 kA**

P_{ICRF} = 3 MW

$n_e(o) = 2 \times 10^{20}$ m^{-3}

$T_e(o)$ = 3.5 keV

$n_{He\text{-}3} / n_e = 0.15$

Flow Profile Control

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- Already observe large toroidal rotation, (up to 120 km/s), without momentum input (ohmic or RF).
- Not well understood; appears related to transport, W_{plasma}.
- Shear flow is known to affect transport, barriers; *an active RF control tool is of great interest to all experiments*.

2002-3

- Improving V_ϕ, V_θ diagnostics in (X-ray and CXRS).
- **Will look for evidence of localized poloidal flow drive by mode converted IC waves.**
- If flow drive proves significant, will later test influence on transport, ITBs.

Transport and Pressure Profile Control

Alcator C-Mod

2002 (planned expts)

- **Improve understanding of ITBs in ohmic plasmas and with off-axis ICRH.**
  What is the threshold condition? Is there hysteresis?
  Role of rotation? Detailed profiles, time behaviour of χ, D?
  - R/L_T , η variation, B_T scans, heat and impurity pulses.
- **Barrier location control.**
  What determines the barrier location (usually r/a~0.5)?
  Can bootstrap current be expanded for more attractive AT scenario? Does it respond to changes in magnetic shear?
  - Current scan, fast current ramps.
- **Improving performance.**
  How can we maximize energy confinement, bootstrap current?
  Does regime extend to higher T, lower ν?*
  - Higher B (5.4 or 6.2 T) , higher power ITBs.

Transport and Pressure Profile Control

Alcator C-Mod

2003-7

- **Investigate influence of magnetic shear on ITB formation, location and transport profiles.**
  - Use LHCD and MCCD to control j(r).

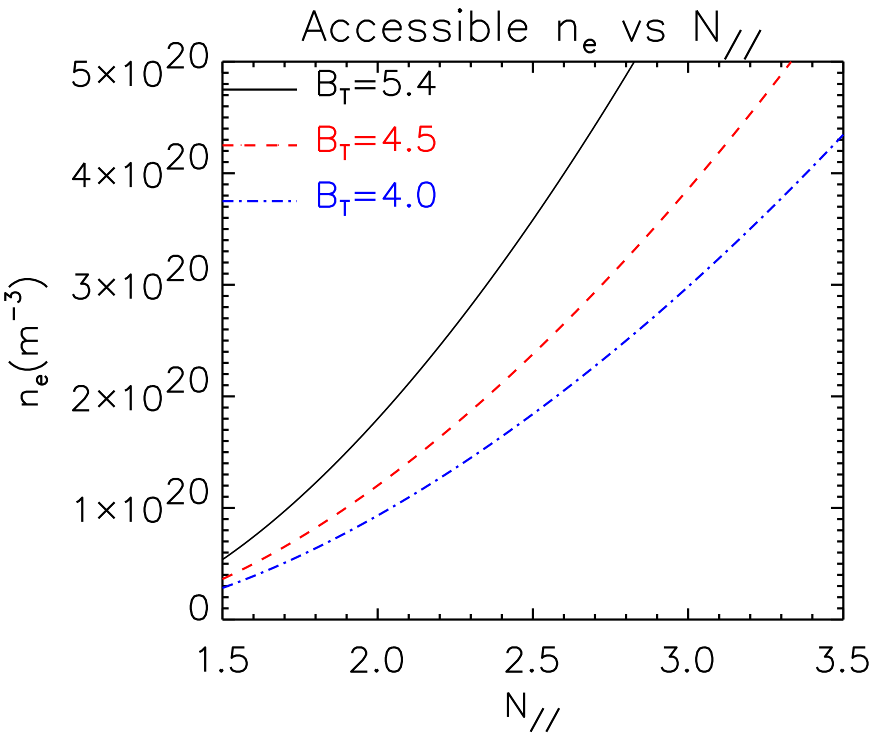
- **Study effect of flow drive on barriers.**
  - Depends on MCIBW flow drive tests.
  - Can it be an active barrier control tool?

- **Adjust heating profile to modify $T_e(R)$**
  - Two ICRF frequencies.
  - LH Heating

- **Optimize density, temperature, bootstrap profiles** for compatibility with LHCD, maximum non-inductive CD scenario.
  - Goal is 50% non-inductive in 2004 (Phase I LHCD)
  - **100% non-inductive by 2007 (Phase II LHCD)**

Density Profile Control.

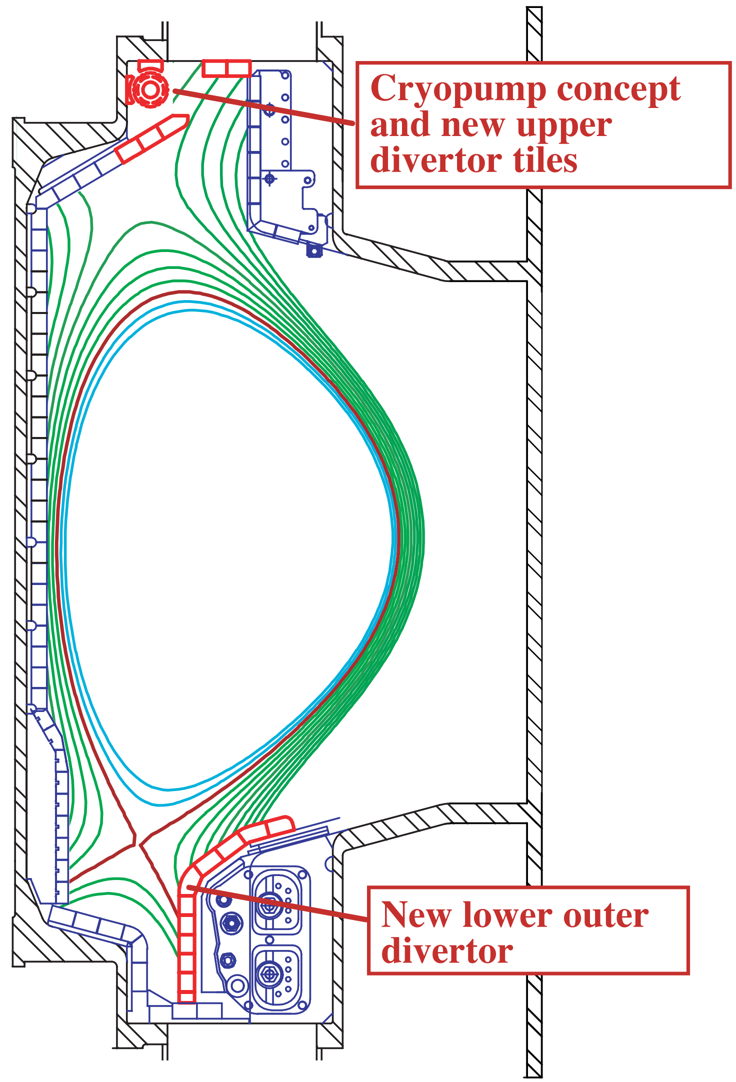
Density is critical for LHCD accessibility, efficiency and deposition profile.



- For fixed efficiency, $I_{LH} \sim 1/n_e$.
- $\eta \sim 1/N_{//}^2$, and increases with T_e.
- **LH wave accessibility is a strong function of local density, field, $N_{//}$.**
  - This gives several useful ‘knobs’ to control deposition profile, and get localized off-axis CD

Density Profile Control.

- **Cryopump will be installed in 2004.**
  - Tests show high neutral pressure with unbalanced DN.
  - Planning upper cryopump.
- **Transport control** will be the best tool for density peaking.
  - Also have Li, D pellet injectors.
- Will assess **impurity accumulation, wall saturation effects** for long-pulses.



Power Handling in Long Pulse AT

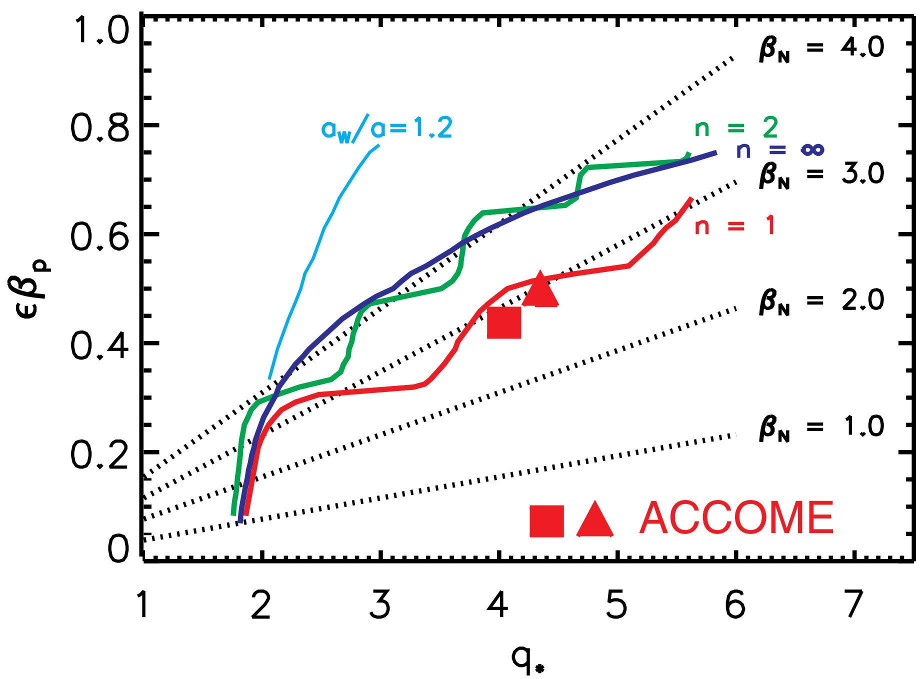
- Divertor/SOL power handing will also be a major challenge as power, pulse length increase.
- Requirement for fairly low edge n_e ($1\text{-}2 \times 10^{20}$ m^{-3}) for LHCD makes radiative divertor difficult.

- **2003-4:**
  - 6 MW ICRH + 2 MW LH (coupled)
  - ~3 second pulses.
  - Add IR cameras to monitor LH antenna, hot spots
  - Try strike point sweep.

- **2005-7:**
  - 6 MW ICRH+3 MW LH
  - 5 s pulses.
  - Upgrade outer divertor, plus other areas as required.

MHD Stability of non-inductive plasmas

- Expect core MHD stability to be more important as power, β raised.
- Ideal no-wall limit β_n~3.
  - With *optimized* p(r), j(r).
  - Strong shaping.
- **Installed antennas for active core MHD spectroscopy** to measure linear growth rates.
  - Feedback to avoid limit.
- Study ELM, core MHD interaction.
- Try stabilization of NTM using LHCD and/or MCCD.
- Plan to carry out a **design/feasibility study of active stabilization methods** to allow β > no-wall limit, in collaboration with Columbia.
- *May install such a system ~ 2007.*



AT-Related Modelling

Alcator C-Mod

RF near term, longer term

- Sensitivity studies of LHCD current profile using ACCOME (vary n_e, B, T_e, $N_{//}$) *(Collaboration with R. Dumont, PPPL)*
- 2-D (V_{perp}, $V_{//}$) Fokker Planck simulations of LHCD *(R.W. Harvey – CompX, P. Bonoli) - preliminary results show increased CD*
- LHCD efficiency, distribution simulations, X-ray diagnostic design *(Y. Peysson, Cadarache, A. Bers, J. Decker, MIT).*
- Full Wave simulations of LHCD (1-D) and IBW (3-D) *(R. Dumont, and C.K. Phillips, PPPL, P. Bonoli, J. Wright, MIT).*
- Full Wave LH simulations in 2-D *(R. Dumont and C.K. Phillips, PPPL, P. Bonoli, J. Wright, MIT; part of SciDac effort)*

AT-related Modelling

Alcator C-Mod

TRANSPORT

- Couple current drive and transport modelling using TRANSP in predictive mode *(J. Liptac, P. Bonoli).*
  - Use χs obtained from analysis of C-Mod ITBs, simplified criteria for barrier formation.
- Gyrokinetic analysis (GS2) of ITB discharges. *(M. Redi, PPPL, D. Ernst)*
- Couple LHCD model from ACCOME to TRANSP. (MIT, PPPL)
- Use evolving capabilities of TRANSP for more theory-based predictive modelling. Eg. assessing ω_{ExB} vs $\gamma_{ITG.}$
- Develop and incorporate improved **particle transport modelling** (critical for ITB simulations).

MHD

- Low n and ballooning stability analysis of modeled scenarios with PEST-2, Keldysh code and MARS *(J. Ramos, MIT PSFC)*

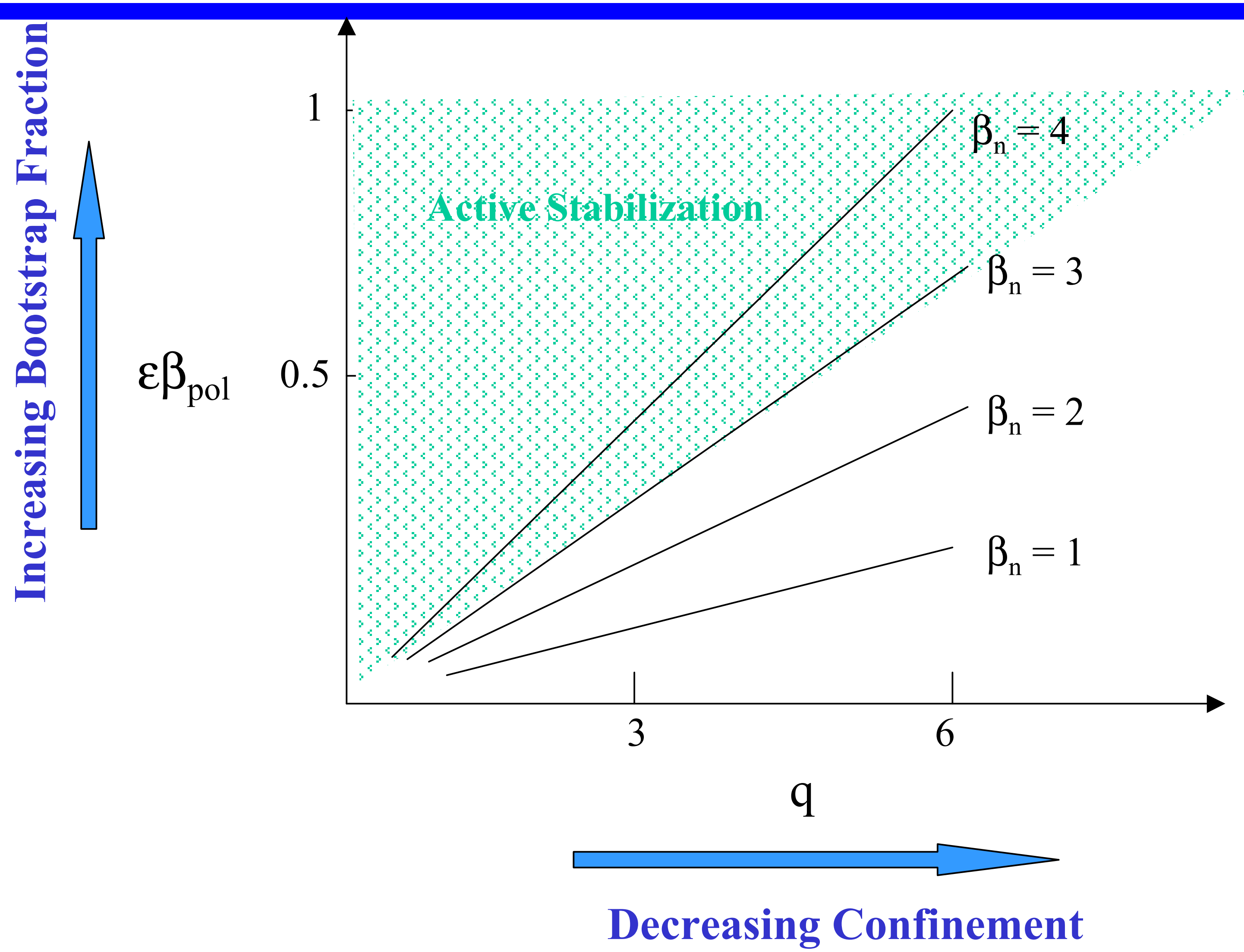
Integrated AT Scenario Demonstration

Alcator C-Mod

- **A successful AT demonstration must *combine* all of the control tools and physics/technology areas discussed.**
  - Eg. LHCD *and* high bootstrap *and* high β *and* long-pulse divertor.
  - Integration and parameter optimization will be an important part of the program from the beginning. For example, tradeoffs necessary in I_p, density.
  - With so many tools, regimes to explore and exploit, increased run-weeks will be essential.
  - Scenario modelling is critical to make efficient use of run time, and is closely coupled to expt!

- **Goal is fully non-inductive current drive, from LHCD plus bootstrap current, at β_N=3.0 (or higher), for 5 second pulse length** (~6 τ_{CR} at 5 keV).

Optimized Steady-State Scenario Requires a Tradeoff Between Bootstrap Fraction and Confinement



Also tradeoffs in density:

low n for maximum LHCD, high grad-n favours bootstrap.

Summary

Alcator C-Mod

- Advanced Tokamak thrust will be an increasingly important part of the C-Mod program.
- Focusses on **RF control of current, transport and pressure profiles** in high density regime, for **t >>** τ_{CR}, to make unique contributions to world AT program.

- We have succeeded in modifying core transport without momentum input or reversed shear.
- LHCD is well underway - Phase I on schedule for March 2003.

- Long term program leads progressively to a **non-inductive, steady state, advanced tokamak demonstration in a unique regime highly relevant to any BPX.**
  – *all RF drive,* $B_T = 4\text{-}6$ *T,* $T_i \sim T_e$*,* $n_e \sim 1\text{-}5 \times 10^{20}$ m^{-3}.