Progress on Advanced Tokamak Scenario Modeling for FIRE

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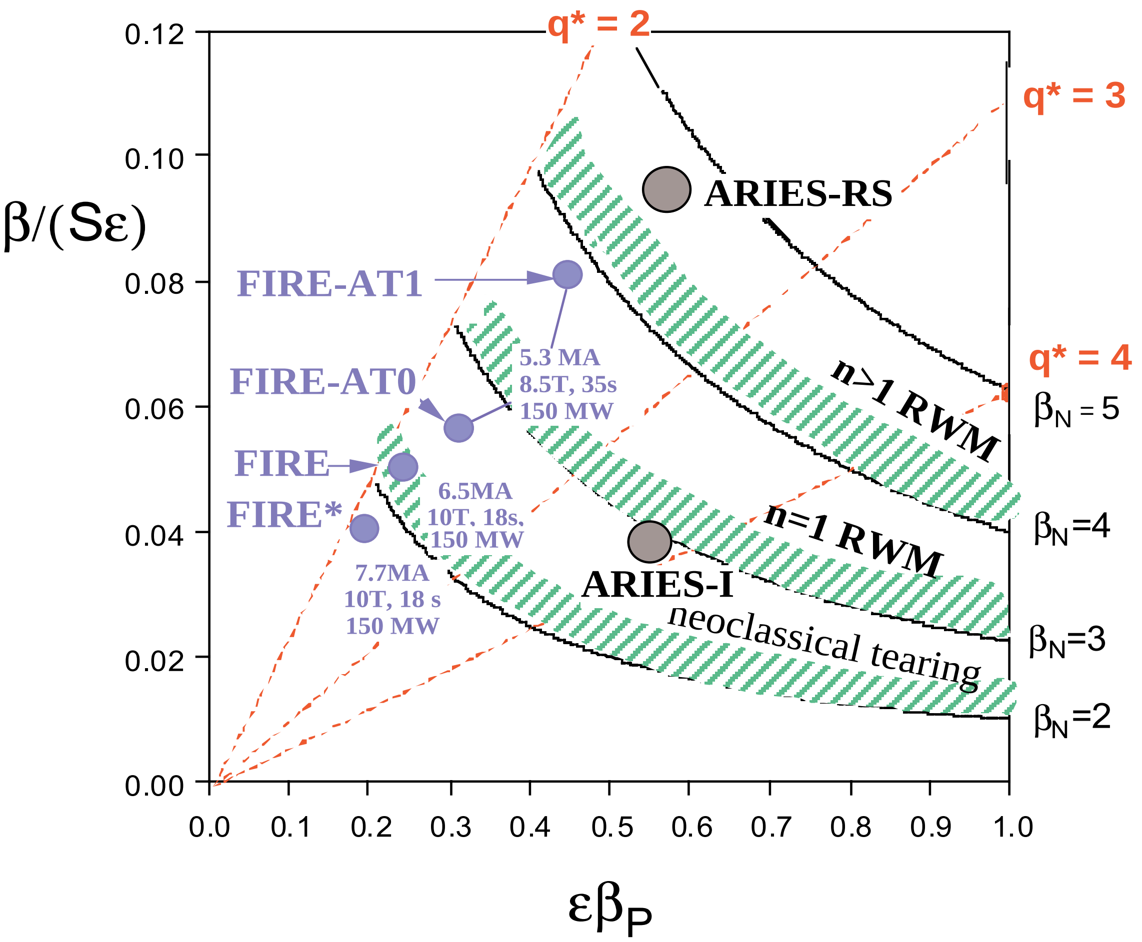
Advanced Tokamak Development is Viewed as a Sequence of Improvements*

Increase β_N

- Stabilize NTM’s
- Stabilize n=1 RWM
- Stabilize n>1 RWM

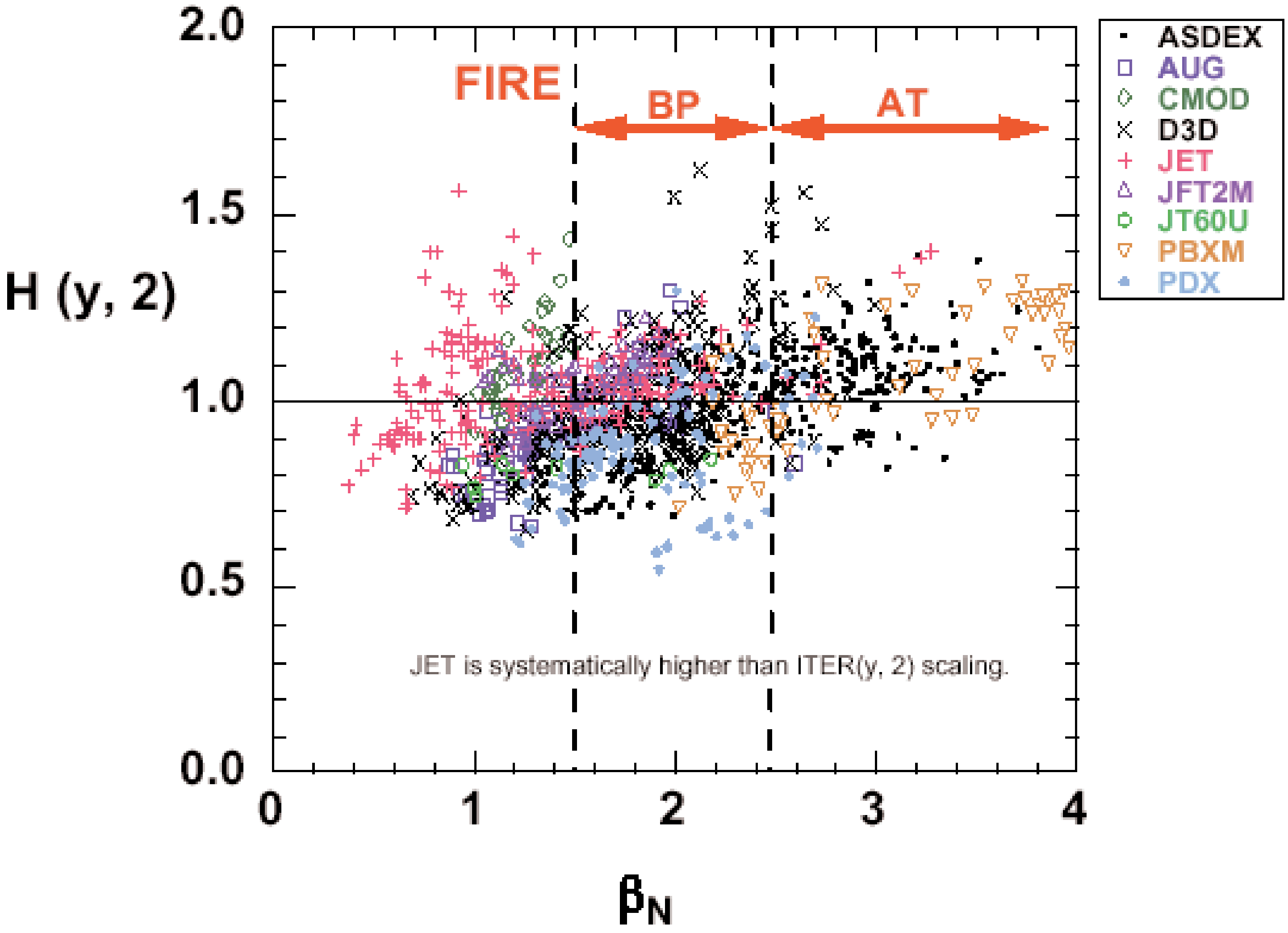
Increase f_{bs} and $f_{noninductive}$

- Increase β_N
- Current drive
- Control of n and T profiles



*includes simultaneous plasma edge/SOL/divertor improvements

Access to Higher β AT Plasmas



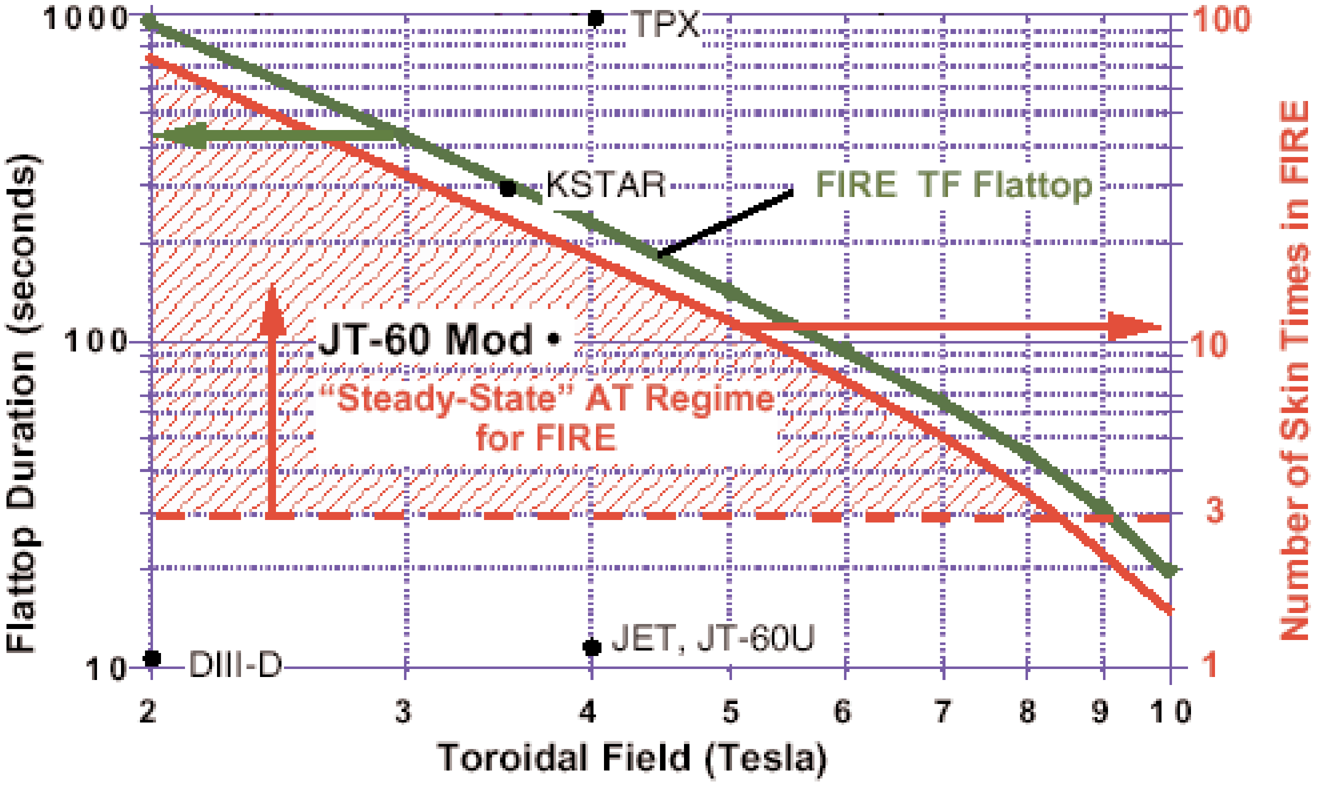
Quasi-Stationary AT Burning Plasmas are the Primary Focus

- The safety factor is held by non-inductive current
  - Bootstrap current
  - LHCD off-axis (other possibilities are NBI and HHFW)
  - ICRF/FW on axis
- Pulse lengths 3-5 x τ_{jdiff} (30-50 s)
- Q=5
- $1.0 < H(y,2) < 1.8$

transient burning AT plasmas can be produced with inductive current

long pulse DD (non-burning) plasmas can be created with pulse lengths up to >200 s at Bt=4 T, Ip=2 MA

FIRE Can Access Various Pulse Lengths by Varying B_T



Note: FIRE is ≈ the same physical size as TPX and KSTAR.
At Q = 10 parameters, typical skin time in FIRE is 13 s and is 200 s in ITER-FEAT .

Ideal MHD Stability Identifies Attractive AT Plasmas

- No n=1 stabilization
  - q_{min} = 2.1-2.2
  - $2.5 < \beta_N < 3.0$
  - $0.5 < r/a(q_{min}) < 0.8$
  - $3.3 < I_p(MA) < 5.5$
  - $0.3 < f_{bs} < 0.5$

- With n=1 stabilization --> strong benefit
  - q_{min} = 2.1-2.2
  - $3.4 < \beta_N < 3.6$
  - $0.5 < r/a(q_{min}) < 0.8$
  - $3.3 < I_p(MA) < 5.5$
  - $0.5 < f_{bs} < 0.75$

*plasmas with q_{min} = 1.3-1.4 also identified, but these have (3,2) and (2,1) NTMs, and no improvement in β_N when n=1 is stabilized

**pockets of n=1 stability at q_{min} just above integer values are found, although the depth of the pocket is unclear

FIRE AT Modes; $Bt=8.5$ T, $A=3.8$, $\kappa=1.9$, $\delta=0.65$

n(0)/<n>=1.5; * balloon limited; n=1,2,3 checked for n=1 stabilized

qmin=2.1-2.2		n=1 stabilized	lower of 4*li or 1.15*βN
r/a(qmin)=.50	Ip=3.25		
	$\beta N=3.0$	$\beta N=3.4$	$\beta N=3.45$
q*=4.15	qmin=2.16		
$\beta p=2.37$	li(3)=0.68		
	li(1)=0.88		
	fbs=0.62	fbs=0.65	fbs=0.65
r/a(qmin)=.65	Ip=4.71		
	$\beta N=2.8$	$\beta N=3.45$*	$\beta N=2.8$
q*=2.88	qmin=2.13		
$\beta p=1.55$	li(3)=0.54		
	li(1)=0.70		
	fbs=0.52	fbs=0.63	fbs=0.52
r/a(qmin)=.80	Ip=5.45		
	$\beta N=2.5$	$\beta N=3.60$	$\beta N=2.32$
q*=2.48	qmin=2.20		
$\beta p=1.18$	li(3)=0.45		
	li(1)=0.58		
	fbs=0.54	fbs=0.75	fbs=0.50

FIRE AT Modes; Bt=8.5 T, A=3.8, κ=1.9, δ=0.65

n(0)/<n>=1.5; * balloon limited; n=1,2,3 checked for n=1 stabilized

qmin=1.3-1.4		n=1 stabilized	lower of 4*li or 1.15*βN
r/a(qmin)=.50	Ip=5.02		
	βN=3.55	βN=3.55	βN=3.68
q*=2.69	qmin=1.37		
βp=1.89	li(3)=0.71		
	li(1)=0.92		
	fbs=0.50	fbs=0.50	fbs=0.52
r/a(qmin)=.65	Ip=5.85		
	βN=3.15	βN=3.15	βN=3.44
q*=2.32	qmin=1.37		
βp=1.38	li(3)=0.67		
	li(1)=0.86		
	fbs=0.38	fbs=0.38	fbs=0.42

Benefit of n=1 RWM Stabilization

q_{min} = 2.1, r/a(q_{min}) = 0.8, I_p = 5.3 MA, B_T = 8.5 T, R/a = 3.8, (5,2) and (3,1) NTM’s, allows wider range for value of q_{min}, n(0)/<n> = 1.4-1.5

LHCD shape and location modeled from ray-tracing calculations

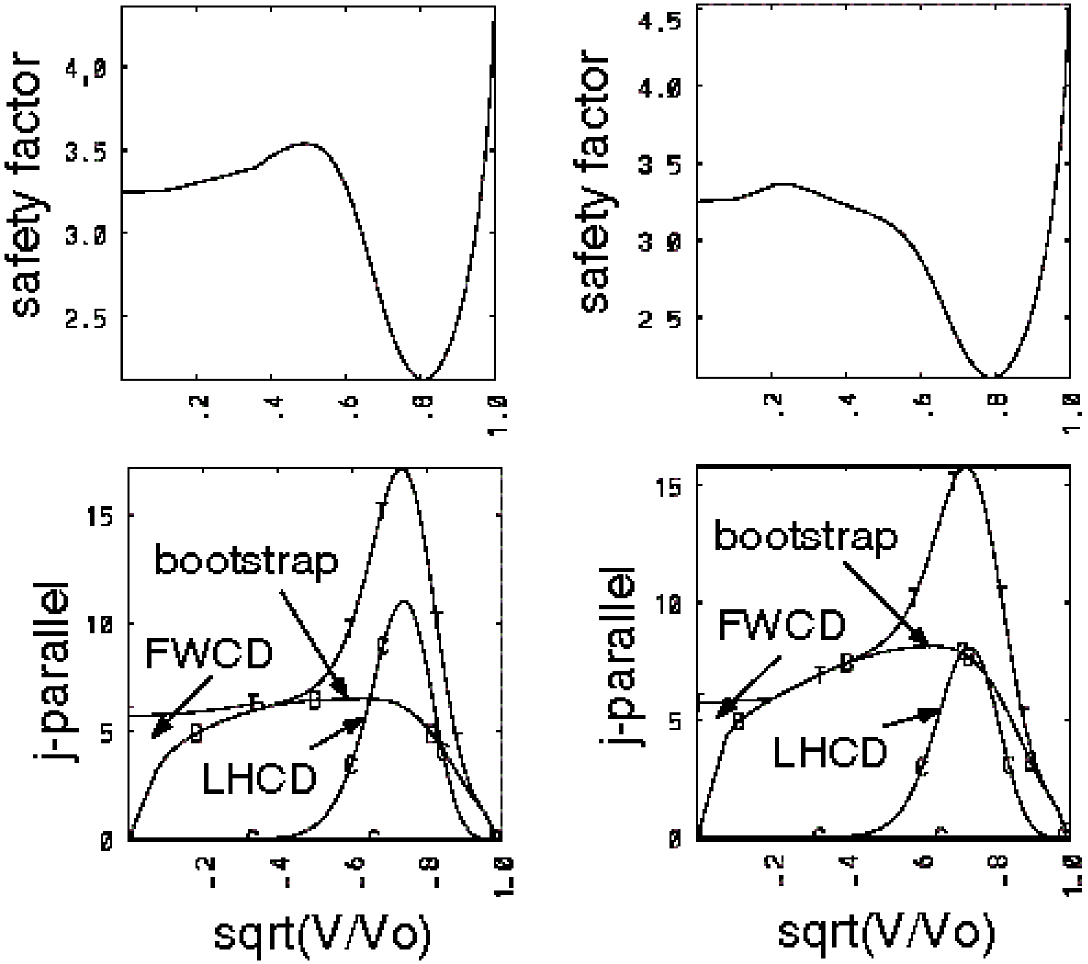
n=1 not stabilized

β_N = 2.55

f_{bs} = 0.55

I_{LH} = 2.2 MA

I_{BS} = 3.0 MA



n=1 stabilized

β_N = 3.6

f_{bs} = 0.75

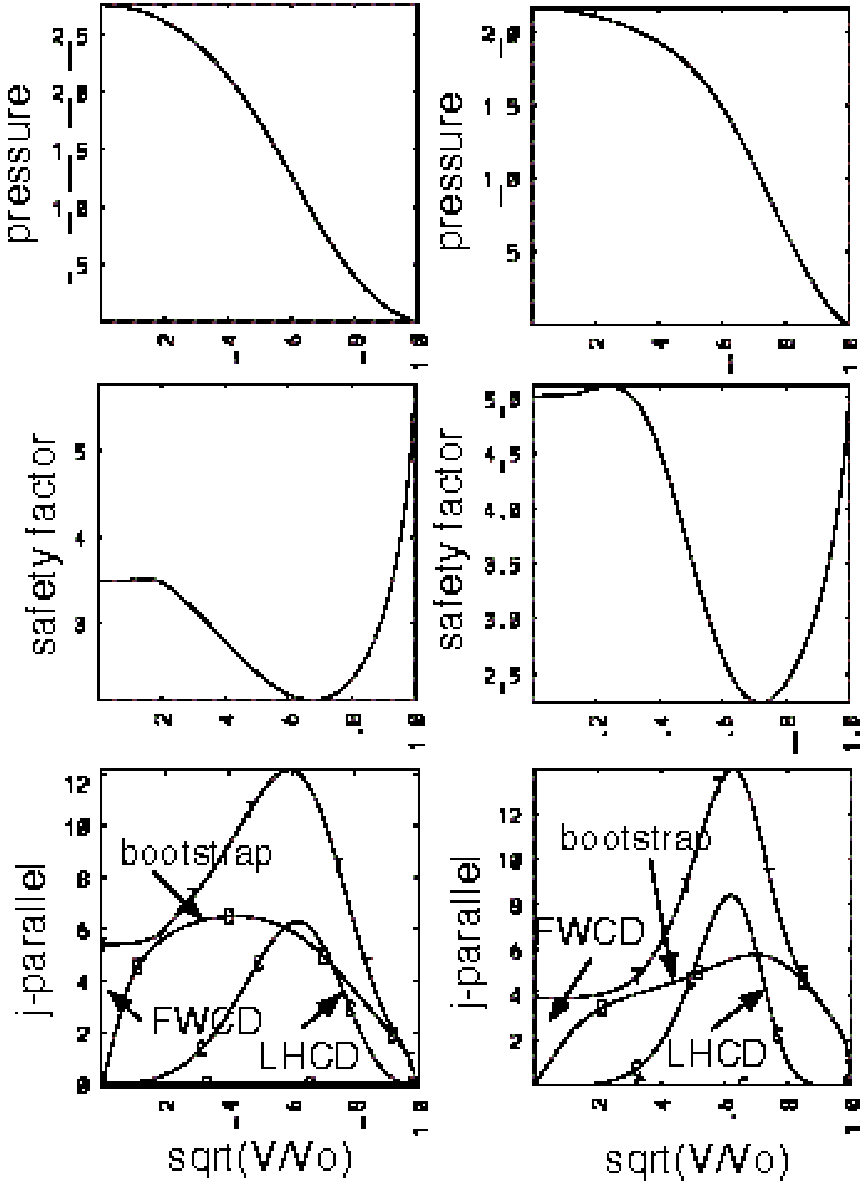
I_{LH} = 1.4 MA

I_{BS} = 3.8 MA

Bootstrap Current and the q Profile

Both cases have q_{min}=2.1-2.2, stable up to β_N=2.85, r/a(q_{min}) = 0.65, same n profiles n(0)/<n>=1.45, f_{bs}=0.6

- Bootstrap current profile determined by n, T profiles--> q
- There are points with fixed f_{bs} as a function of β_N and n(0)/<n>
- At what f_{bs} do we need to control n and T profiles?



External Current Drive and Heating for FIRE

- 30 MW ICRF (ion heating) for ELMy H-mode;
  - 4 ports, 100-150 MHz
- <10 MW ICRF/FW (electron heating/CD) for AT mode;
  - 1 (or 2) ports, 90-110 MHz??, phasable
  - Want to use same ICRF equipment

- 20-30 MW LHCD (electron heating/CD) for AT mode;
  - 2-3 ports, 5.6 GHz, $n_{||}$ =2.0-2.5
  - For NTM control
- ?? MW ECH/ECCD (electron heating/CD) for startup and NTM control (issue is high B_T and high density)

Lower Hybrid for Off-Axis Current Drive on FIRE

LSC lower hybrid ray tracing calculation

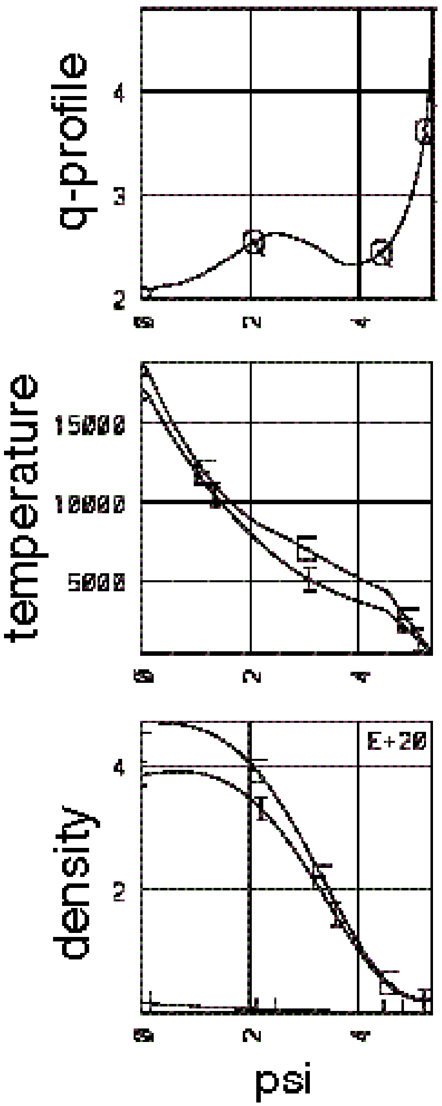
$P_{LH} = 30$ MW

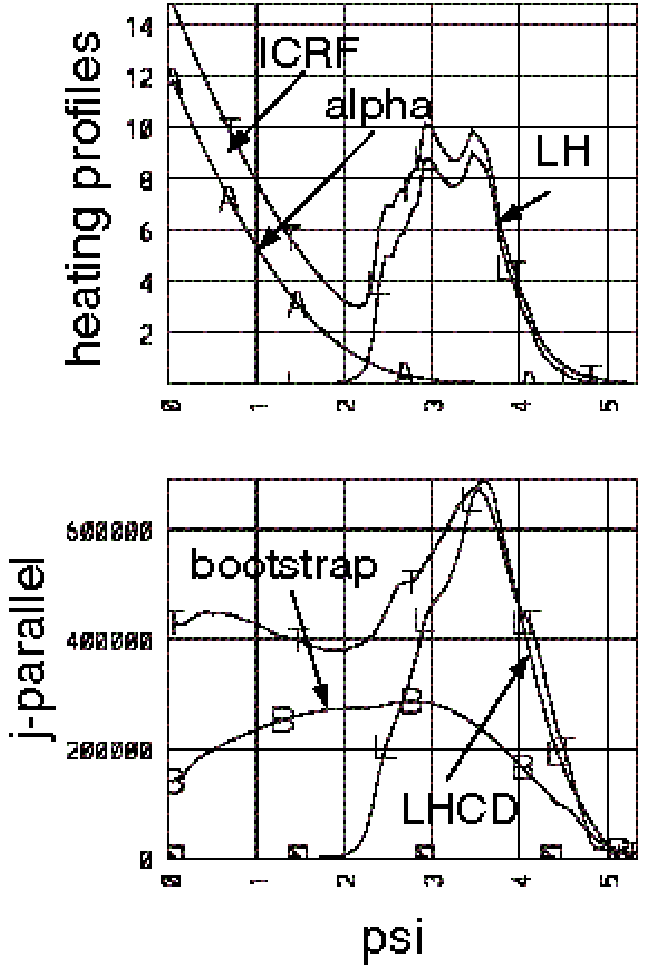
$I_{LH} = 2.4$ MA

$N_{\|} = 2.0$, $\Delta N_{\|} = 0.3$

$I_{BS} = 2.6$ MA

*alpha particle absorption of LH power? -- ripple loss of alphas may mitigate this



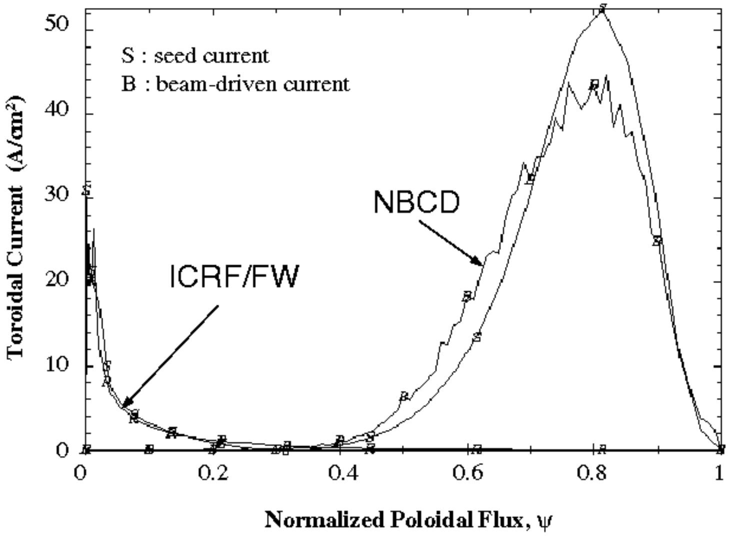


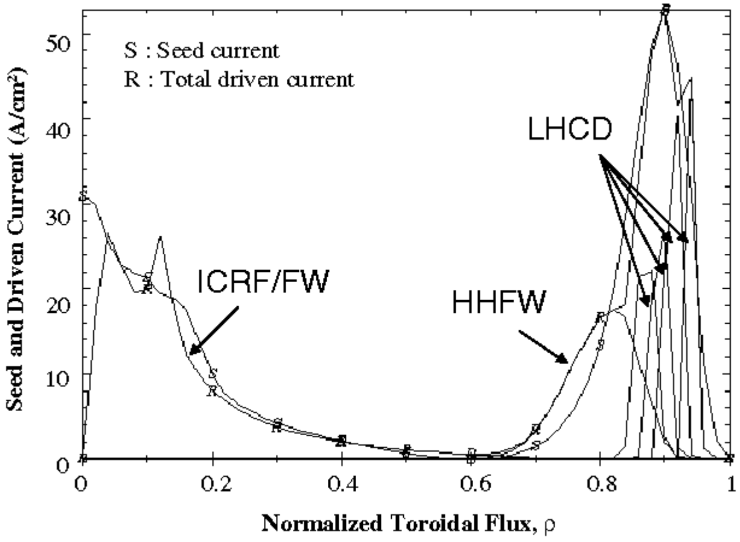
Note radial coordinate is poloidal flux

External Current Drive and Heating for FIRE (other possibilities)

- 120 keV NBI (positive ion); deposition to ρ>0.7; good off-axis current profile and rotation
- HHFW (300-800 MHz); deeper penetration than LH

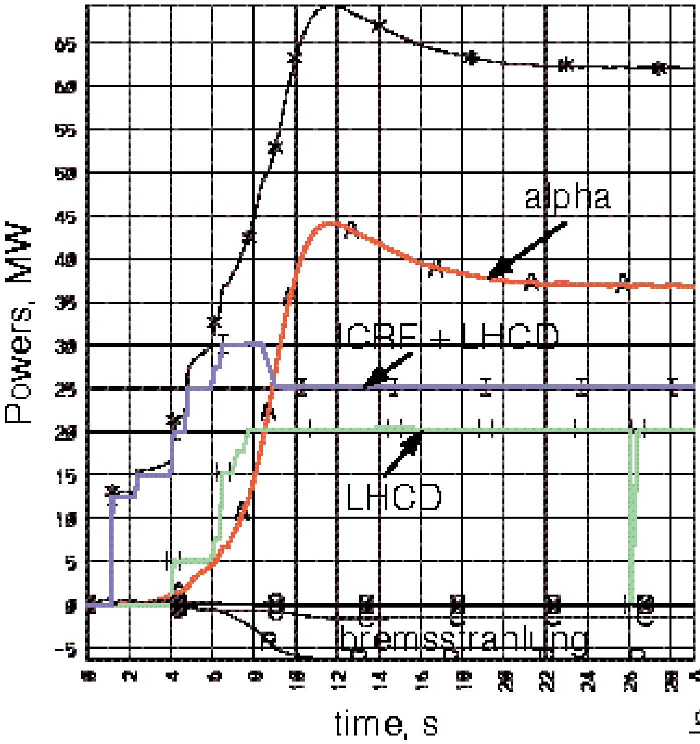
CD analysis by T.K.Mau for ARIES-AT

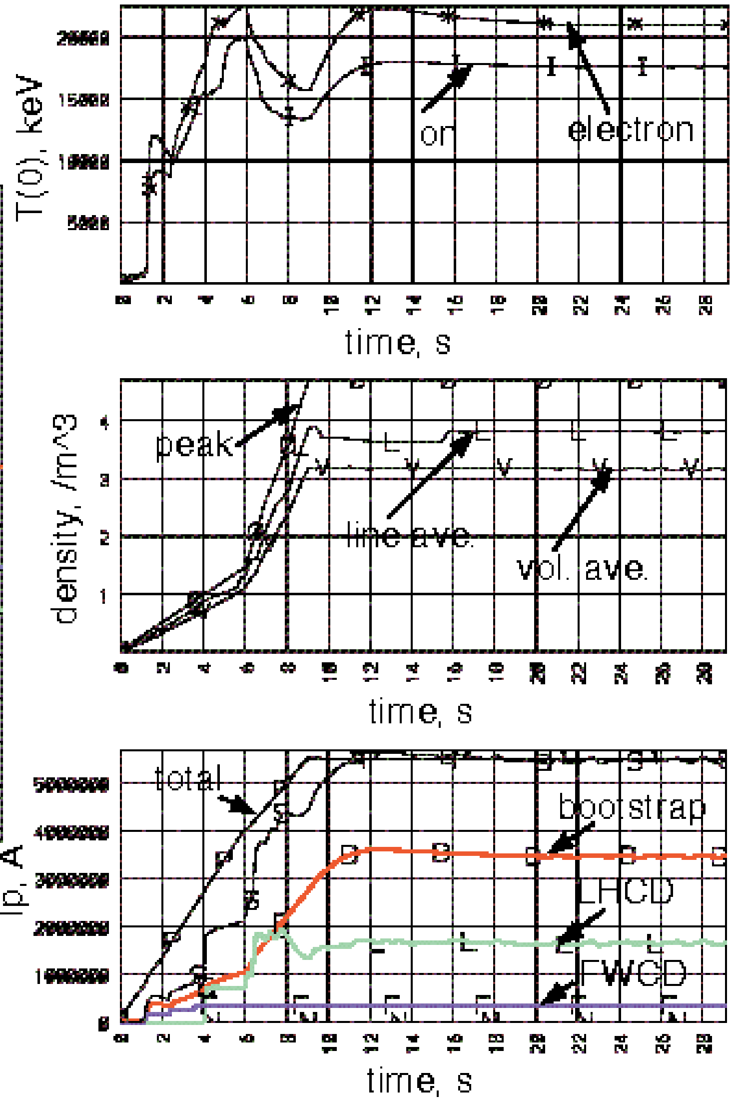




Dynamic Burning AT Simulations with TSC-LSC for FIRE

Ip=5.5 MA, Bt=8.5 T, Q=7.5,
β_N=3.0, β=4.4%, P_{LH}=20 MW,
I_{LH}=1.7 MA, I_{BS}=3.5 MA, I_{FW}=0.35 MA

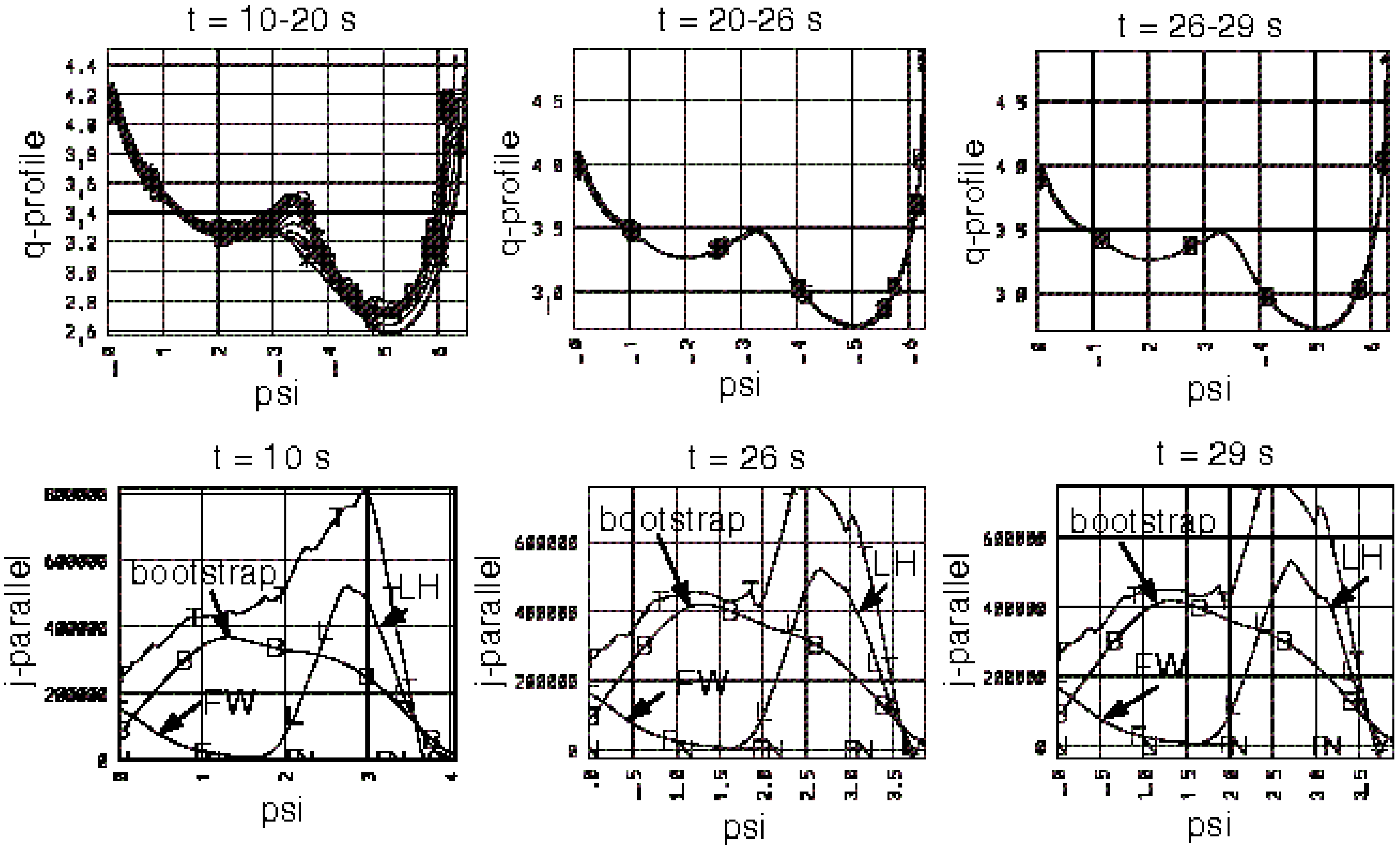




H(y,2)=1.6

Dynamic Burning AT Simulations with TSC-LSC for FIRE

Plasma becomes quasi-stationary after 10 s



Conclusions

- q_{min} around 2.1-2.2 is found to provide a good combination of
  - Beta limit with and without n=1 stabilization--increase these
  - High plasma current--not too high
  - Elimination of (3,2) and (2,1) NTM's--but (5,2) and (3,1) exist
  - Lower CD power --need to reduce this
- Less than 2 MA of LHCD is required, leading to powers of 20-30 MW from LSC lower hybrid calculations
- Stabilization of n=1 RWM would yeild attractive configuratons
- Need to find techniques for density profile peaking to enhance bootstrap current
- TSC-LSC simulations indicate that we can create quasi-stationary plasmas for flattop burn

Future Work for FIRE Burning AT Plasma Development

- Continue ideal MHD stability search
  - Pressure profile and q* variations
  - Edge profile effects
  - n=1 stabilized plasmas
- NTM requirements
- Examine DIII-D AT experiments
- Examine C-Mod AT experiments

- CD analysis
  - Reduce $P_{CD,}$ raise f_{bs}
  - LHCD, HHFW, NBI
  - ICRF/FW
  - ECCD
- TSC-LSC dynamic discharge simulations
  - Plasma formation in shortest time
  - Energy and particle transport models
  - Control of j, n, T

Experimental AT Observations to Guide FIRE AT Development

- DIII-D
  - NBI strong rotation source
  - ITB/turbulence suppression--->profiles
  - Edge plasma conditions/pumped divertor
  - n=1 RWM feedback
  - NTM stabilization
- C-Mod
  - Anomalous ICRF rotation
  - ITB/turbulence suppression--->profiles
  - LHCD/current profile control
  - High density core/edge
  - Detached divertor

The differences between the devices are likely to be the most important

Burning AT Plasma Issues

- Ripple losses are larger due to high q, low I_p and low B_T
- Alfven eigenmodes are expected to be more severe
- NTM suppression
  - LHCD and/or ECCD
- RWM stabilization
  - n=1 feedback
  - Then what for n>1 RWM's
- Impurities for control
- T,n profile control
  - Density peaking vs β_N for bootstrap current
  - ITB relaxation, or turbulence suppression without ITB
- Plasma rotation
  - Bulk rotation for RWM stability
  - Sheared rotation for turbulence suppression
- Plasma edge conditions
  - L-mode or H-mode
  - Radiation characteristics

FIRE can Test Advanced Regimes of Relevance to ARIES-AT

Confinement Required to access this regime

Q = 10, HH = 1.2

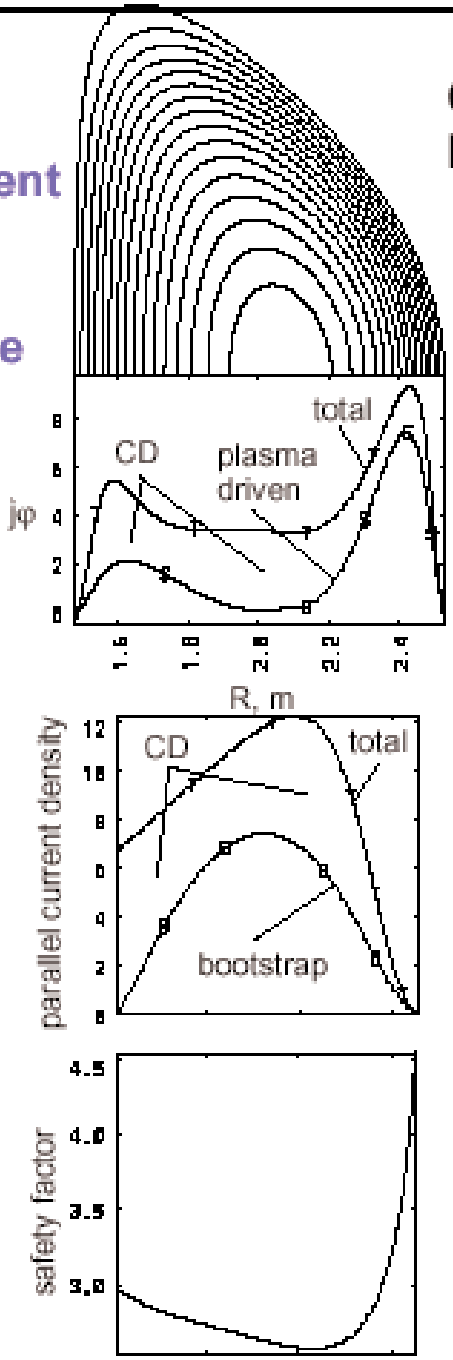
or

Q = 5, HH = 1.06

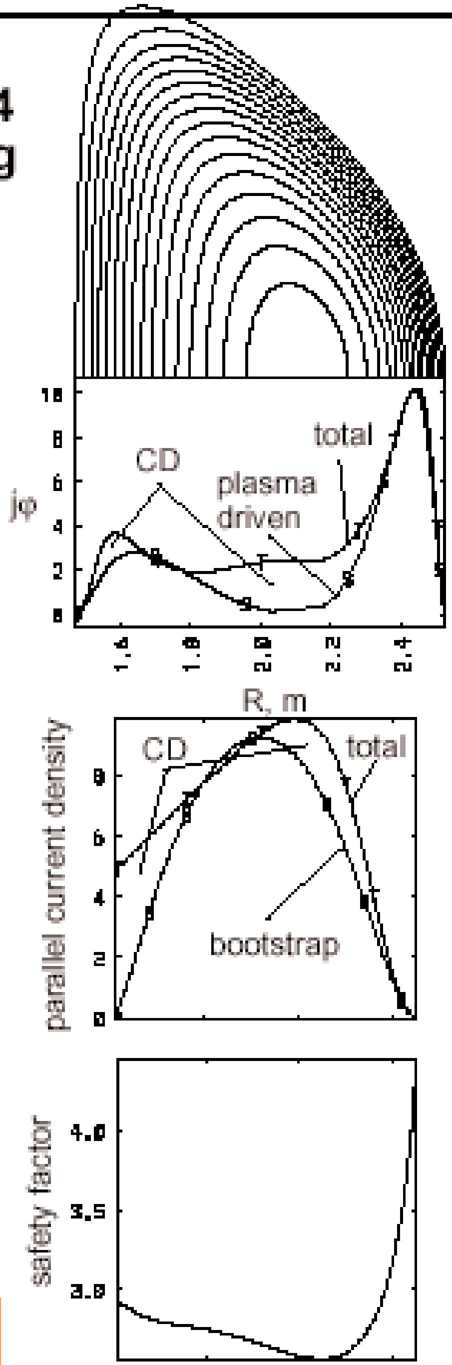
Needs self-consistent current drive power

Duration

~2 tau_skin



Case 1 Modest AT		Case 4 Strong AT
30	Flat top(s)	60
5.65	Ip(MA)	4.50
9.00	B_T(T)	6.75
2.90	q_o	2.90
2.60	q_{min}	2.60
1.31	β_p	2.11
2.60	β_N	4.50
3.10	β(%)	5.70
0.42	li	0.39
0.50	f_{bs}	0.82
165	P_{fus}(MW)	170
29.4	W_{th}(MJ)	30.1
0.65	n_e/n_{Gr}	0.81
2.40	α-loss(%)	9.40



Confinement Required to access this regime

Q = 10, HH = 1.56

or

Q = 5, HH = 1.36

Duration

~ 4 tau_skin