Advanced Tokamak Scenarios for the Fusion Ignition Research Experiment

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Fusion Ignition Research Experiment

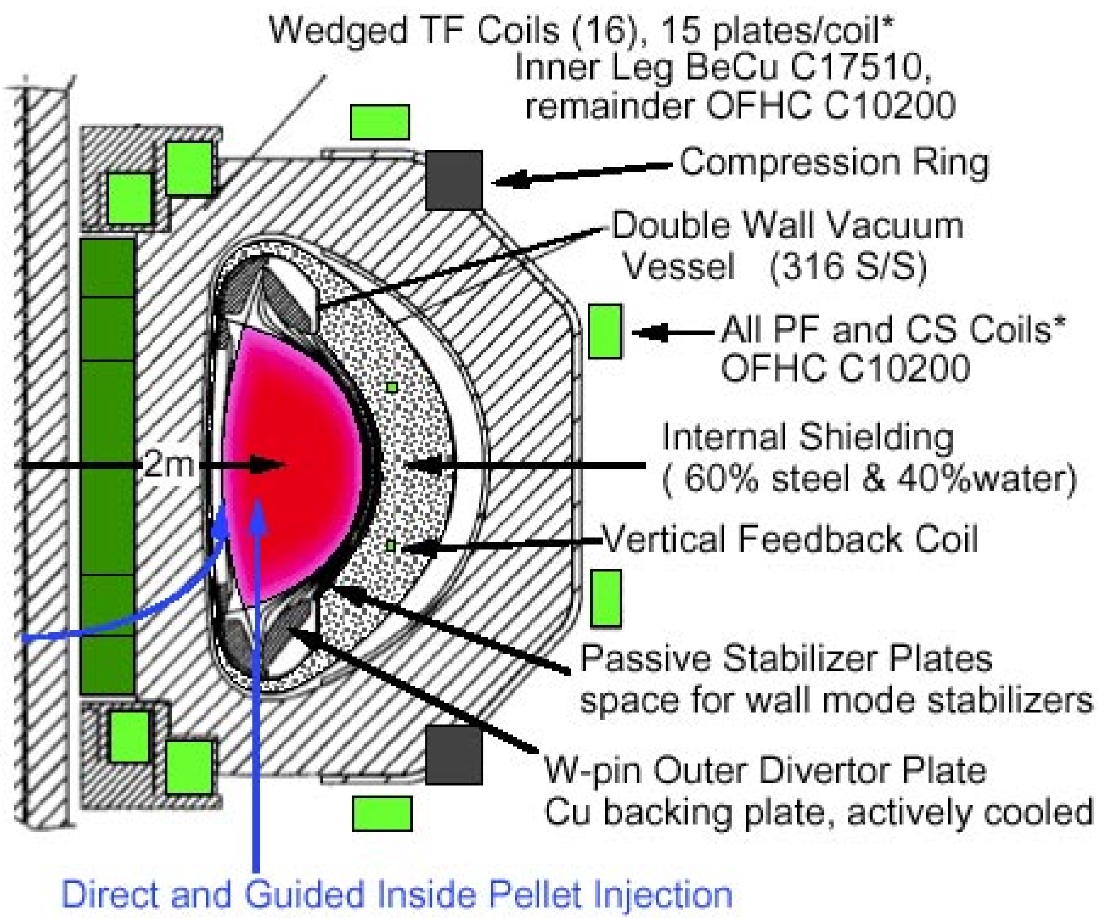
- FIRE is a compact high field tokamak, using copper coils, for the study of burning plasma physics
  - Q (P_{fus}/P_{aux}) = 5-10
  - Flattop times ≥ 2 current diffusion times
  - Study and resolve both standard (H-mode) and advanced tokamak burning physics issues
  - Keep the device cost at ≈ $1 B

Fusion Ignition Research Experiment

R = 2.0 m, a = 0.53 m, Bt = 10 T, Ip = 6.5 MA, κ_x = 2.0, δ_x = 0.7

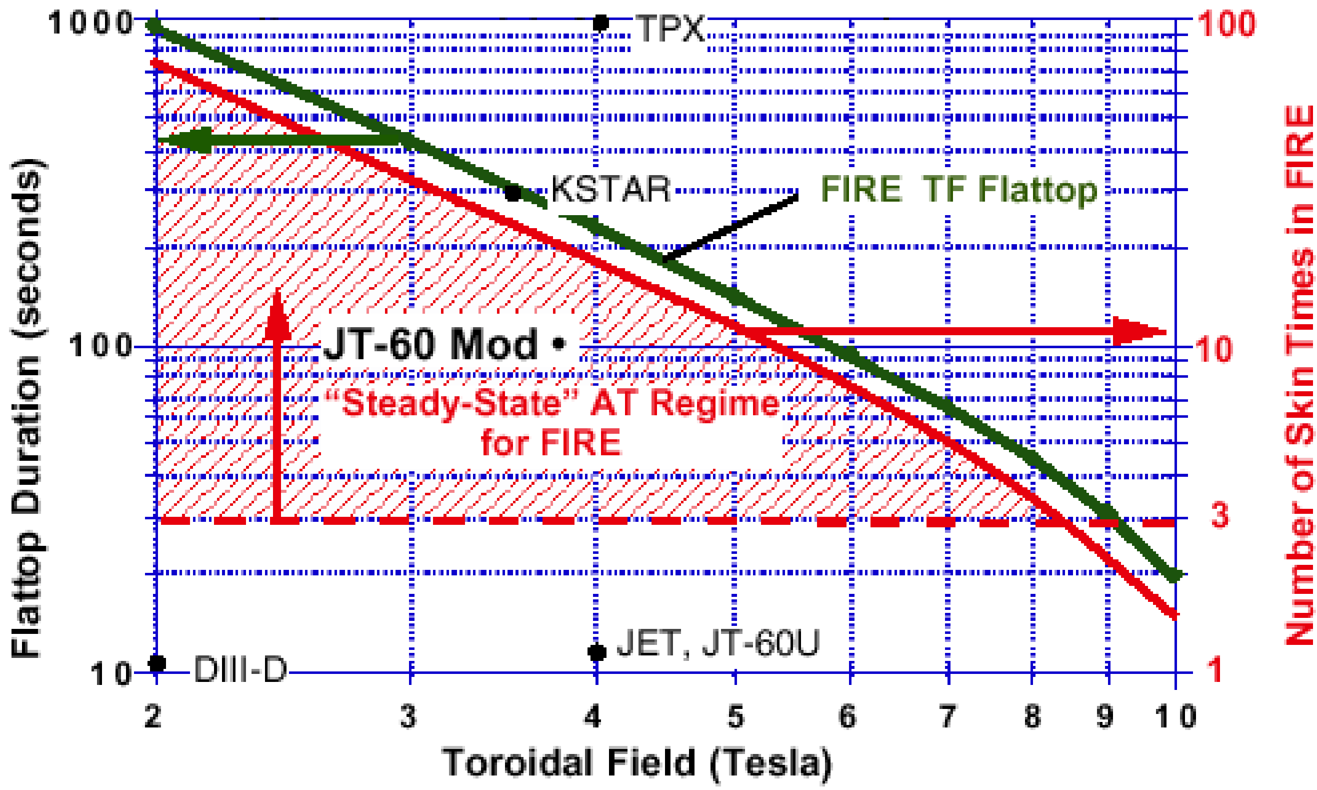
AT Features

- DN divertor
- strong shaping
- very low ripple
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



*Coil systems cooled to 77 °K prior to pulse, rising to 373 °K by end of pulse.

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 .

FIRE's Advanced Tokamak Development is a Sequence of Improvements

Increase β_N

Stabilize NTM's

Stabilize n=1 RWM

Stabilize n>1 RWM's

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

Increase β_N

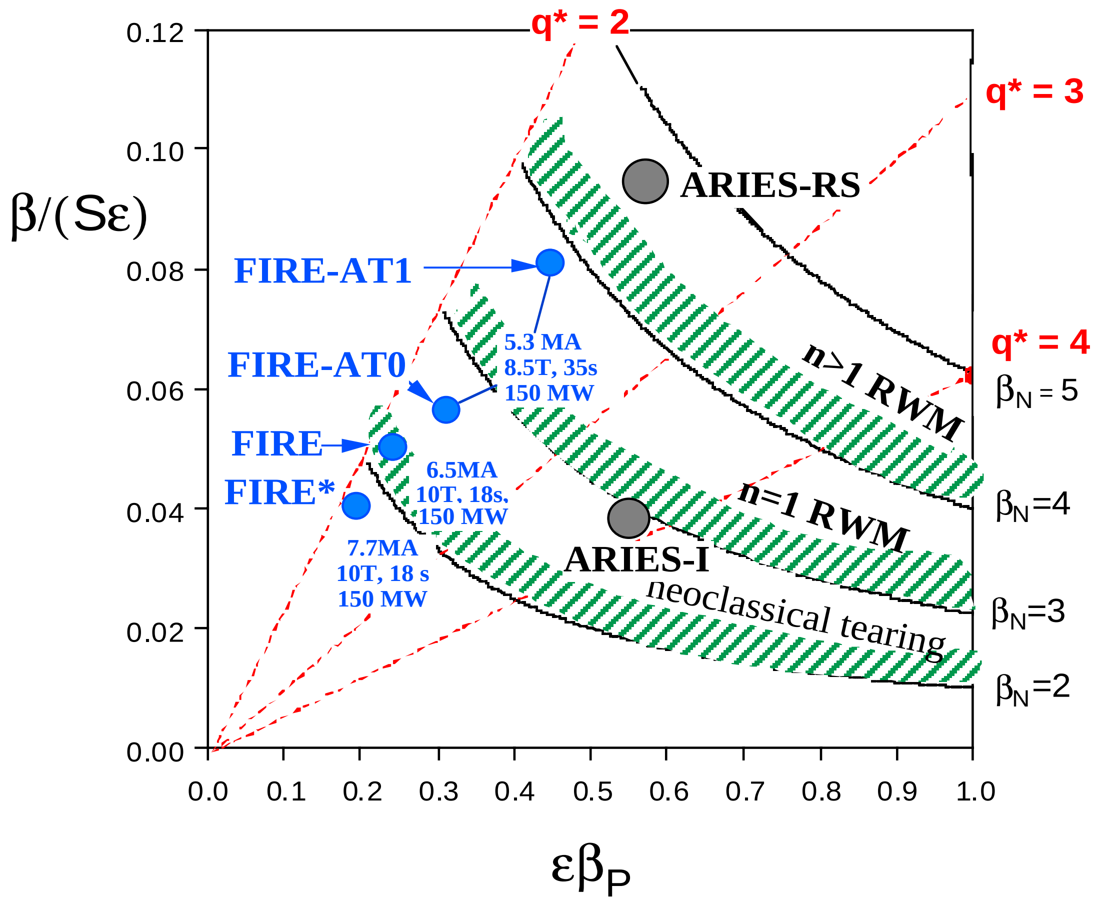
Current drive

Control of n and T profiles

Extend pulse lengths

More sophisticated control

Plasma edge/SOL/divertor



FIRE Efforts to Self-Consistently Simulate Advanced Tokamaks

<u>0-D Systems Analysis</u>:

Determine viable operating point global parameters that satisfy constraints

<u>Plasma Equilibrium and Ideal MHD Stability</u>:

Determine self-consistent stable plasma configurations to serve as targets

<u>Current Drive</u>:

Determine current drive efficiencies and deposition profiles

<u>Transport</u>:(GLF23 and pellet fueling models to be used in TSC)

Determine plasma density and temperature profiles consistent with heating/fueling and plasma confinement

<u>Dynamic Evolution Simulations</u>:

Demonstrate self-consistent startup/formation and control including transport, current drive, and equilibrium

<u>Edge/SOL/Divertor</u>:

Find self-consistent solutions connecting the core plasma with the divertor

Systems Analysis Shows That H98 > 1.1 for Q=5

Varying parameters:

β_N = 2.0-5.0

q_{95} = 3.1-4.7

n(0)/<n> = 1.25-2.0

n/n_{Gr} = 0.35-0.95

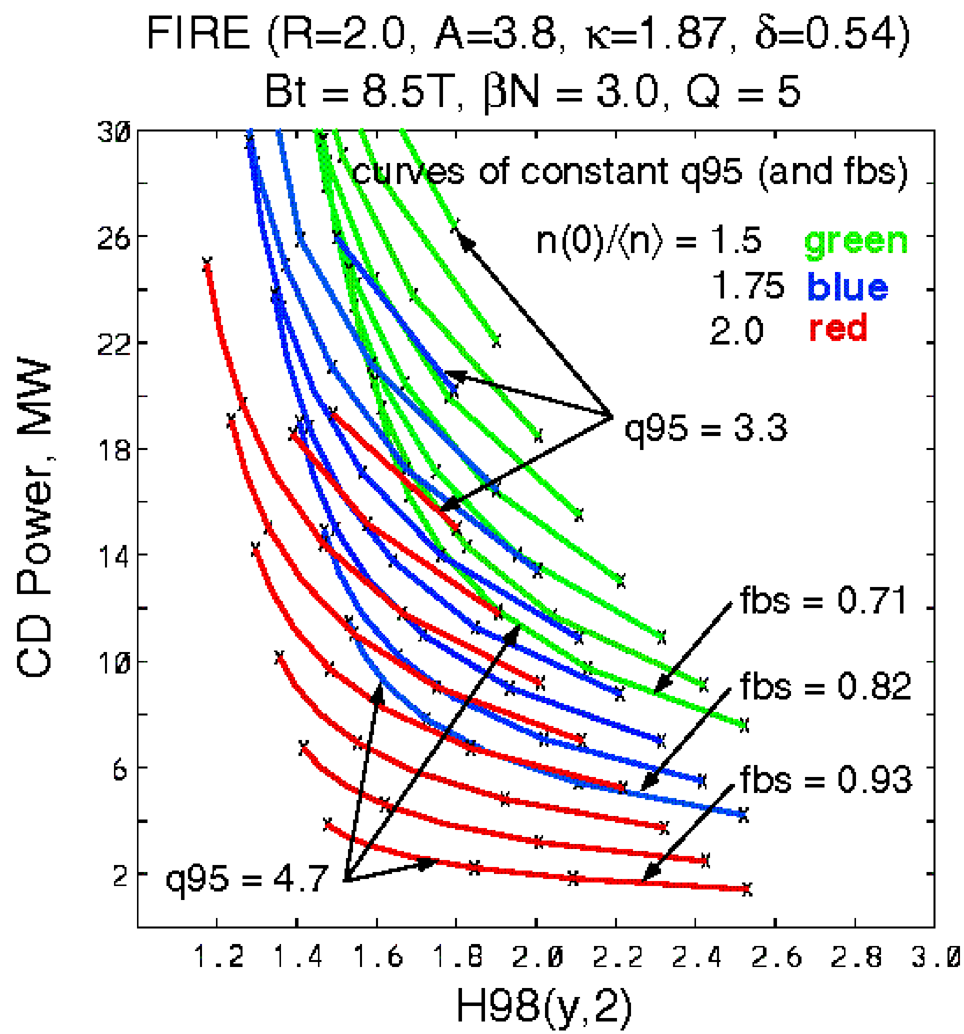
B_t = 6.5 - 9.5 T

Constrained to obey:

Power balance with Q=5

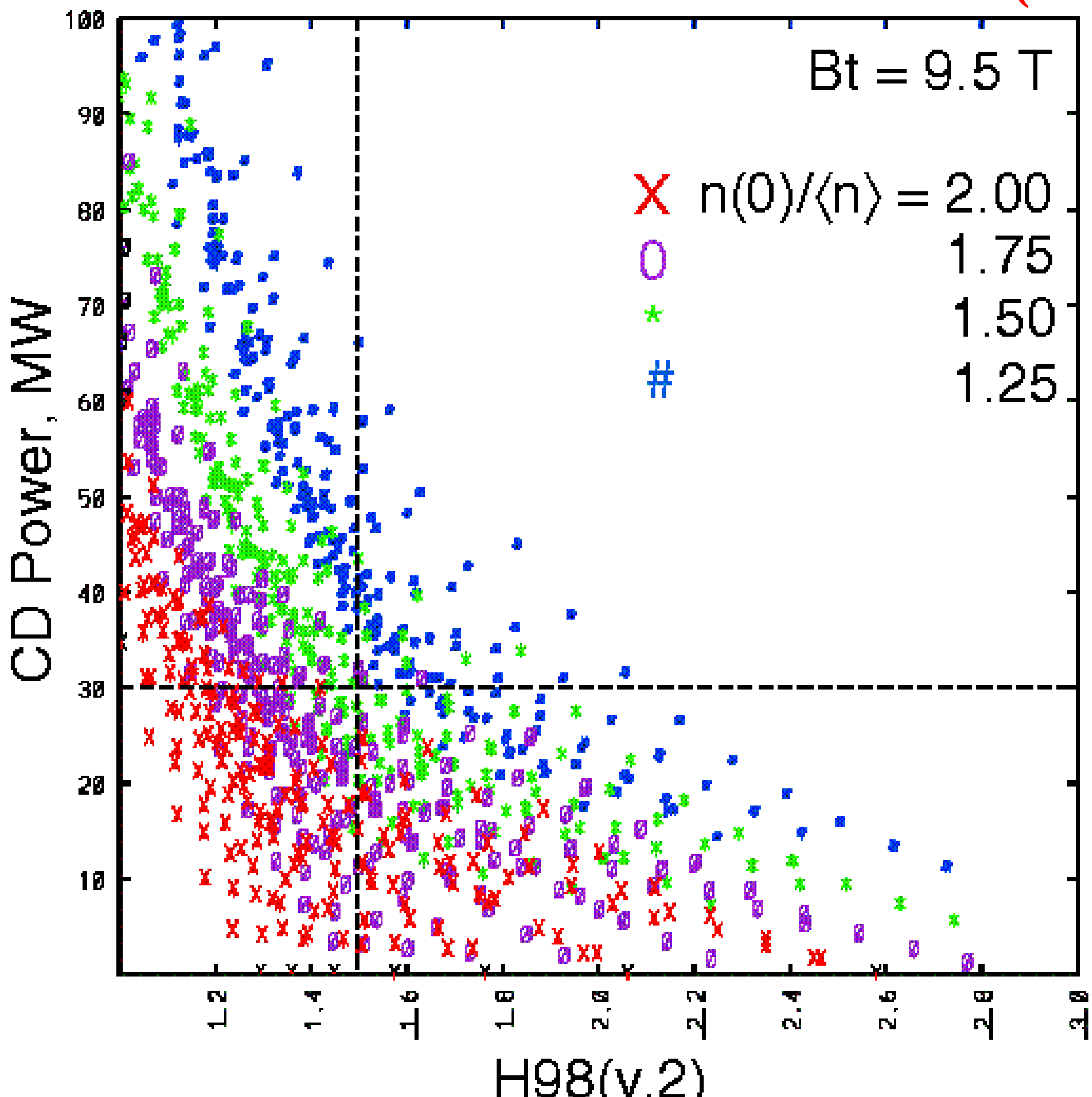
$P_{CD} < P_{aux}$, η_{CD} = 0.45 A/Wm^2, Pcd < 35 MW

P_{fusion} < 250 MW



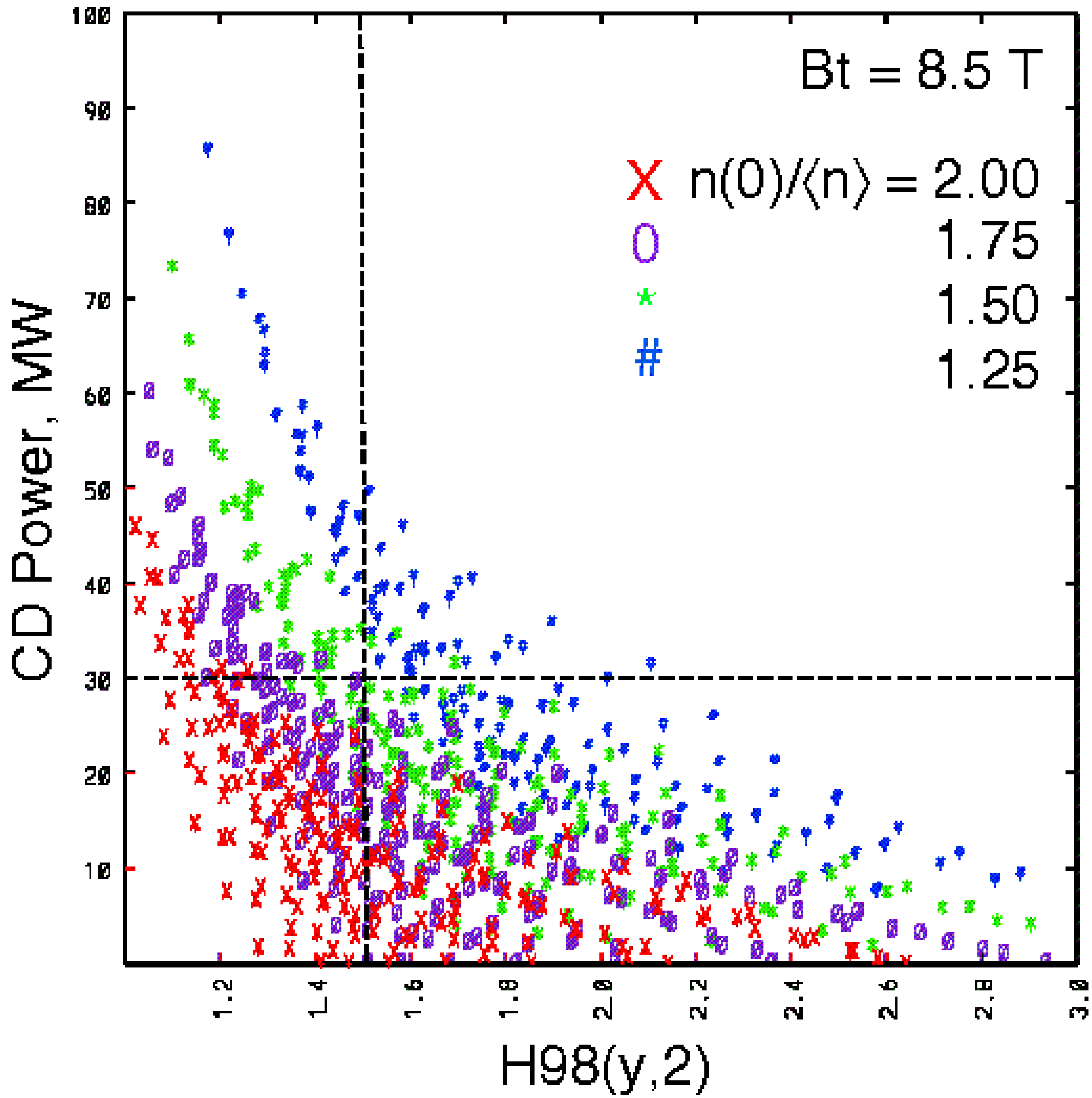
Q=5, 100% Non-inductive AT Plasmas

t(flattop) = 26 s



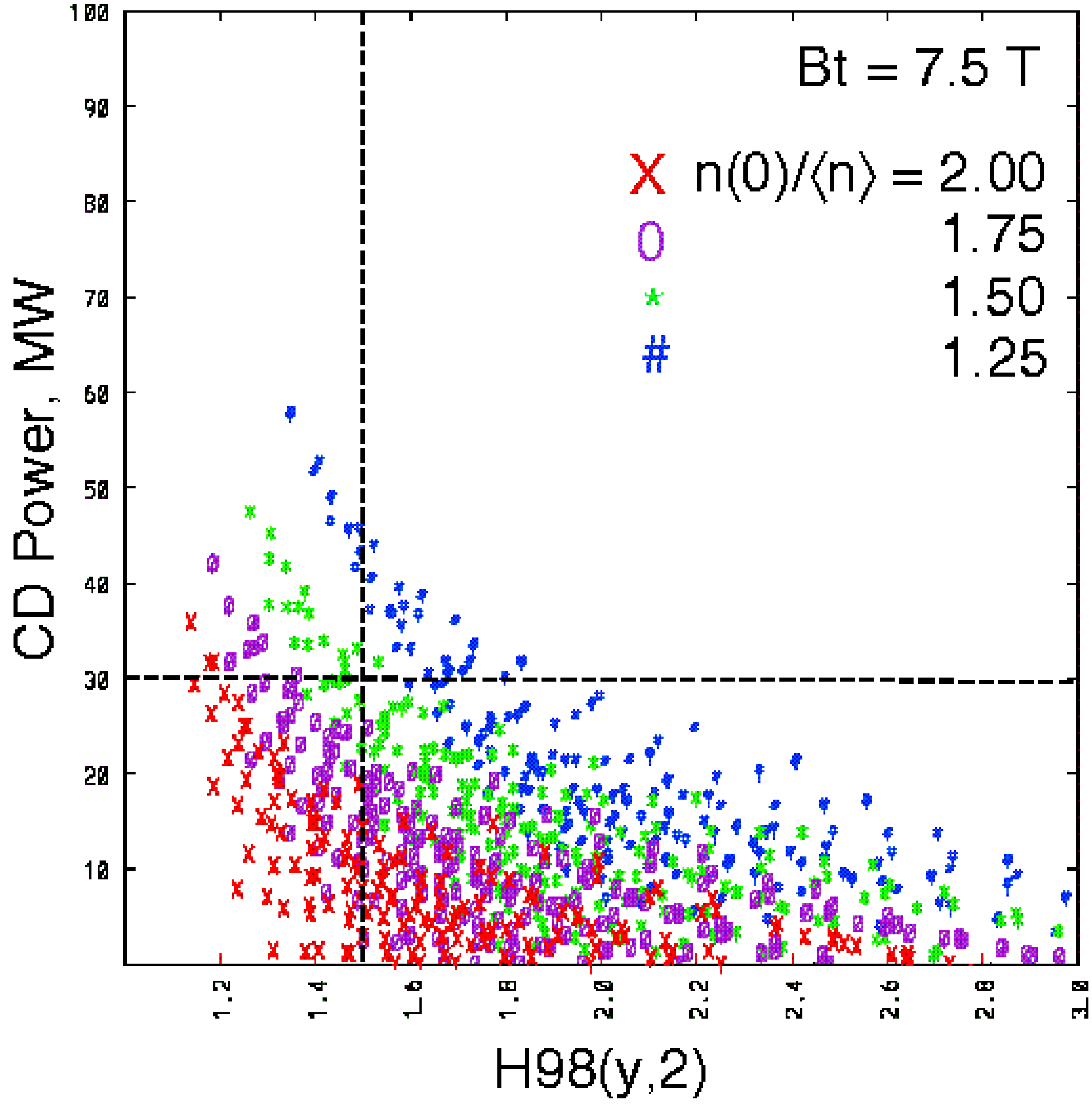
Q=5, 100% Non-inductive AT Plasmas

t(flattop) = 35 s



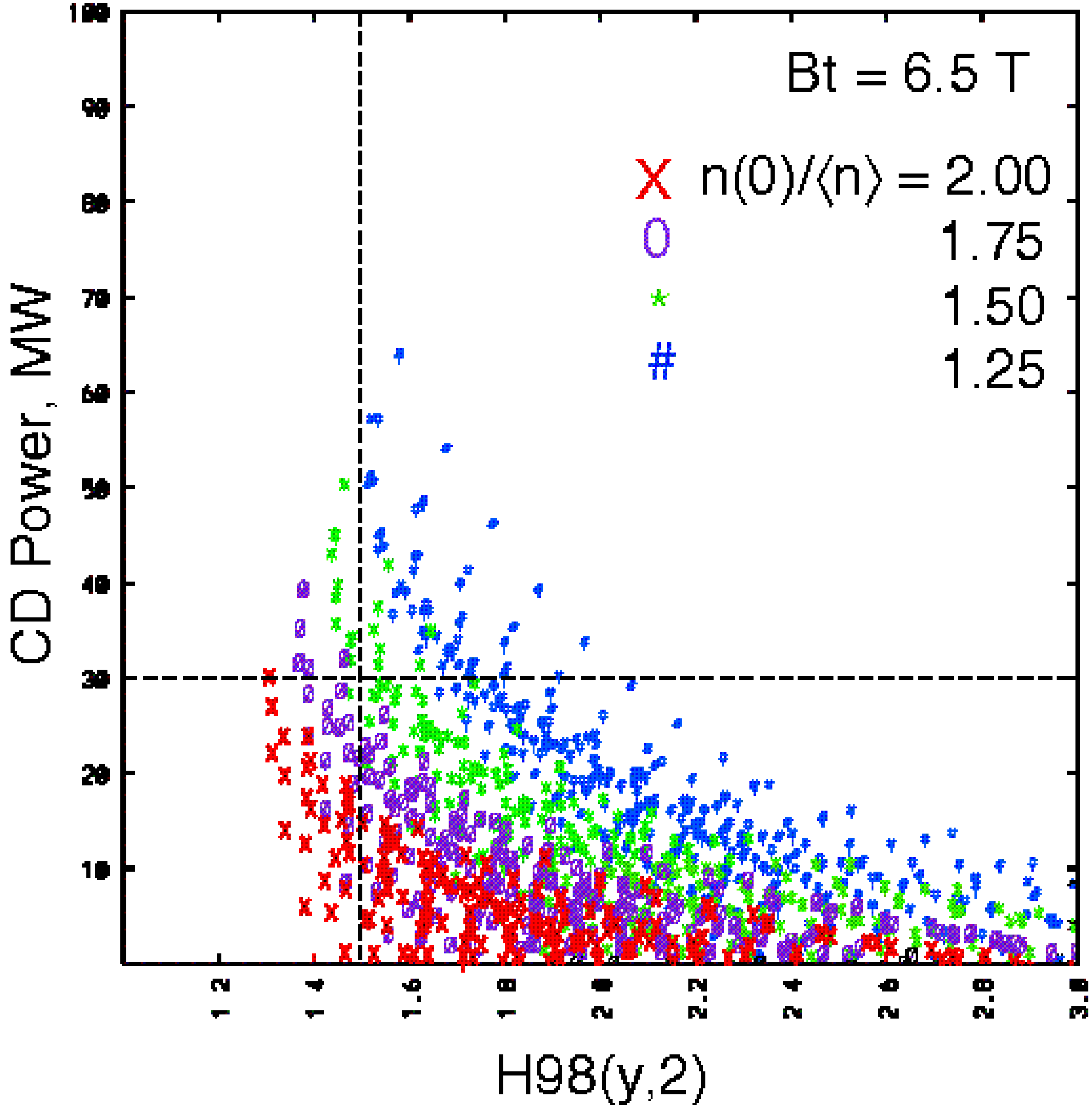
Q=5, 100% Non-inductive AT Plasmas

t(flattop) = 49 s



Q=5, 100% Non-inductive AT Plasmas

t(flattop) = 69 s



Systems Analysis Shows That H98 > 1.4 for Q=10

Varying parameters:

β_N = 2.0-5.0

q_{95} = 3.1-4.7

n(0)/<n> = 1.25-2.0

n/n_{Gr} = 0.35-0.95

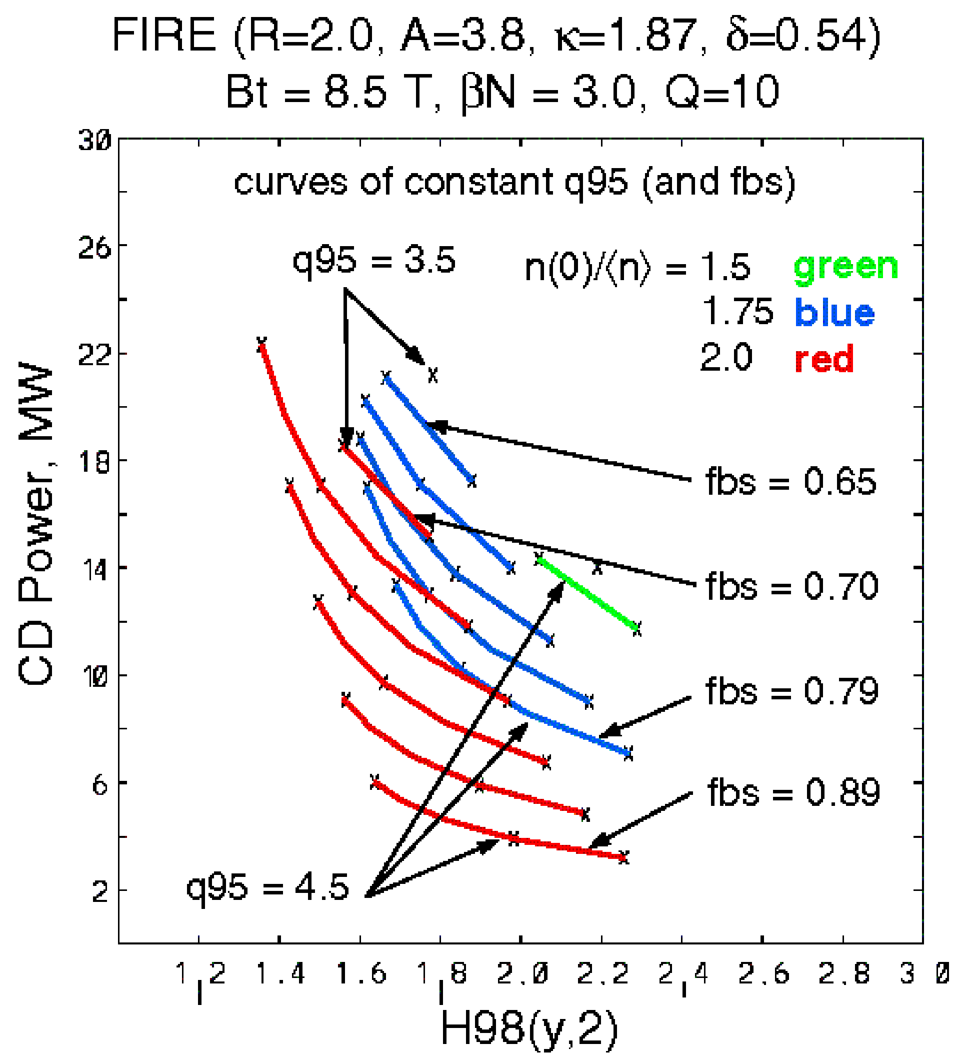
B_t = 6.5 - 9.5 T

Constrained to obey:

Power balance with Q=10

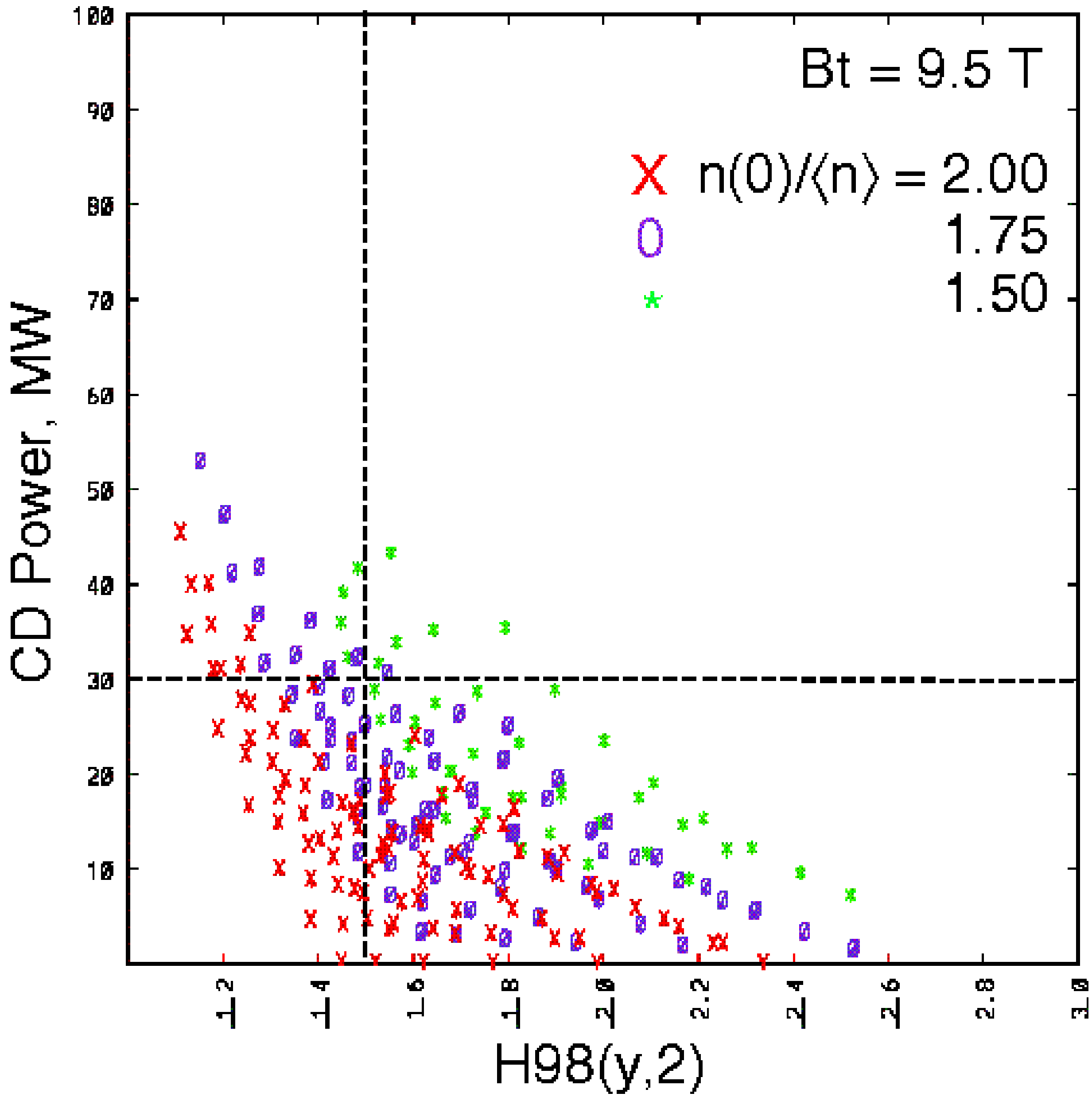
$P_{CD} < P_{aux}$, η_{CD} = 0.45 A/Wm^2, Pcd < 35 MW

P_{fusion} < 250 MW



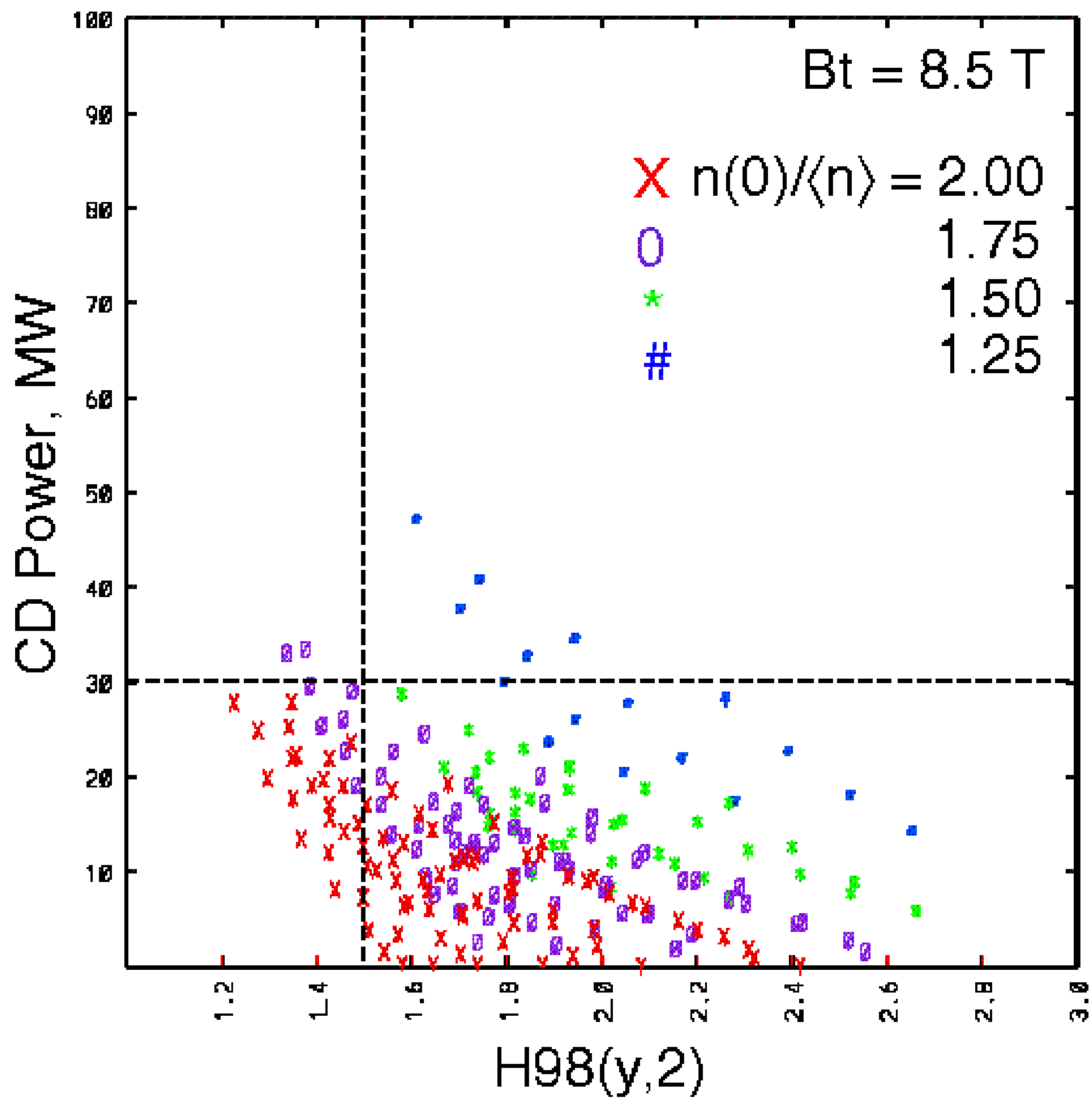
Q=10, 100% Non-inductive AT Plasmas

t(flattop) = 26 s



Q=10, 100% Non-inductive AT Plasmas

t(flattop) = 35 s



Q=10, 100% Non-inductive AT Plasmas

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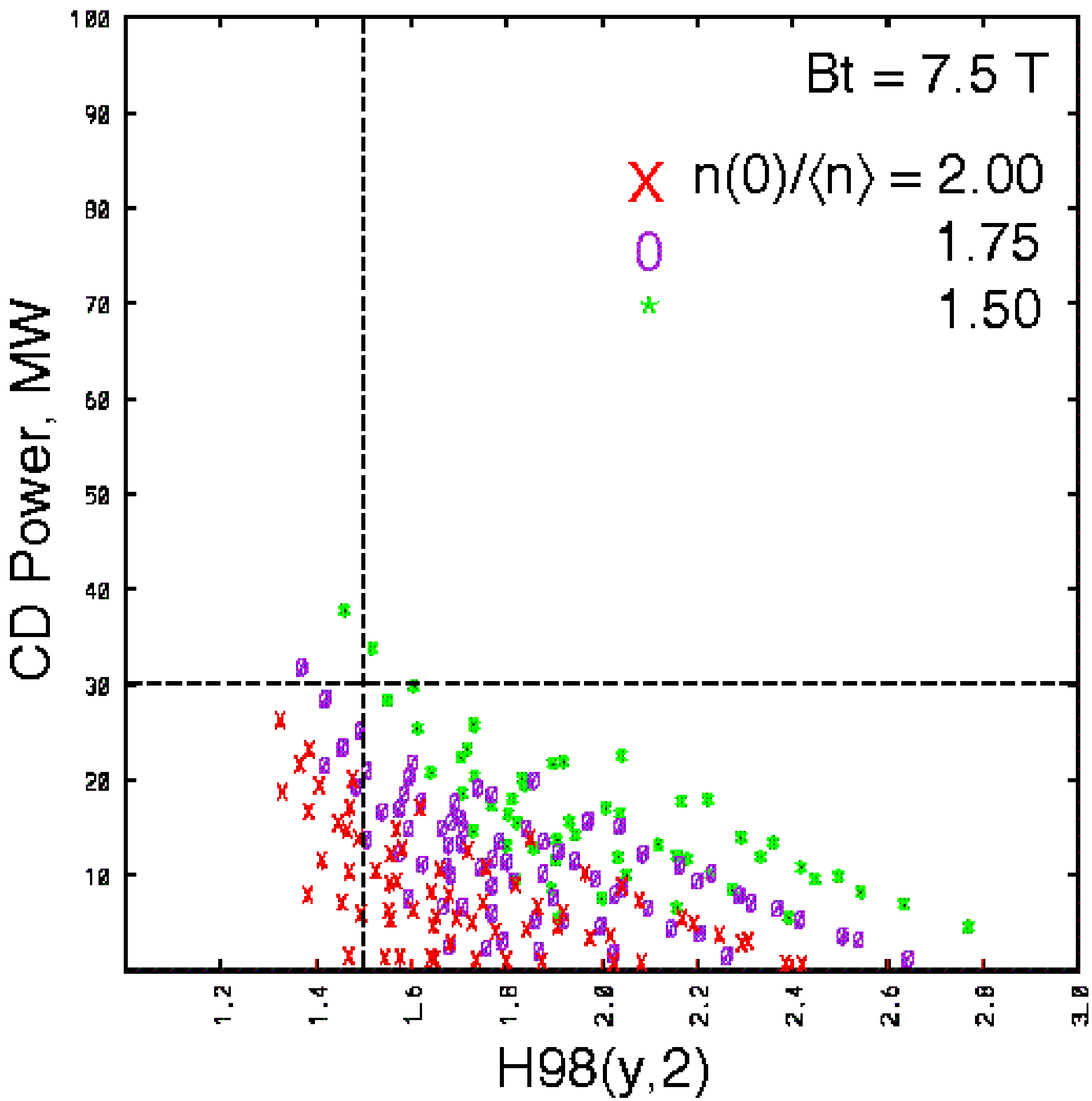
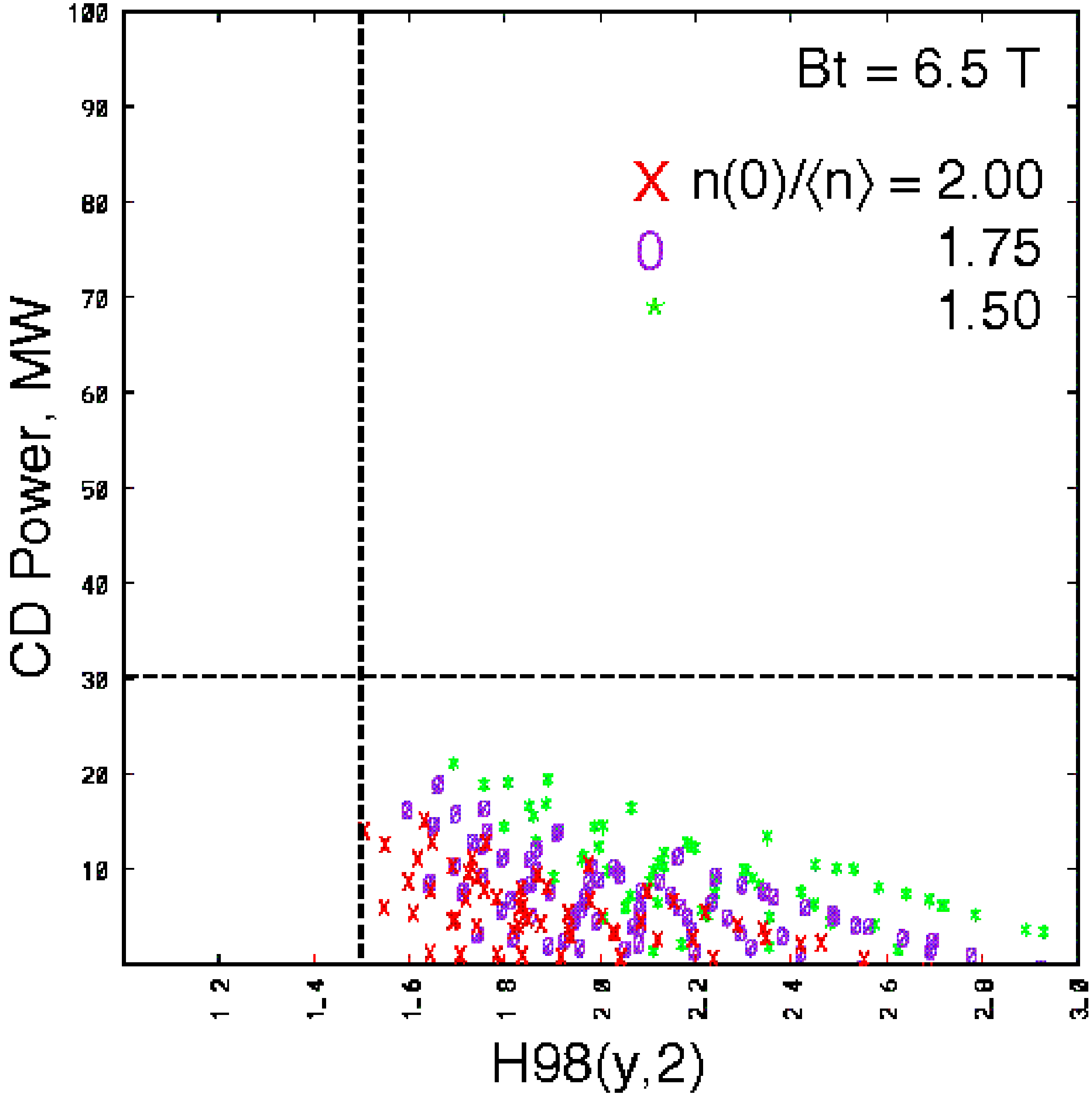


Q=10, 100% Non-inductive AT Plasmas

t(flattop) = 69 s



Systems Analysis Show Critical Requirements for Burning AT Plasmas

- Burning AT plasmas must simultaneously meet
  - Plasma power balance (a given Q)
  - Pcd ≤ Paux
  - Can't operate at very low density to make CD efficiency higher
- Density profile peaking
  - Pellet fueling
  - ITB in particle channel
  - Very broad density profiles require high H98 and Pcd
- Ability to approach or exceed Greenwald density limit
  - Provides low H98
  - Requires high bootstrap fraction
  - High n/nGr reduces required H98 and increases required Pcd
- Optimal combination of Bt, q95, and βN
  - achieves the lowest H98

Minimum H98 Cases in Q=5 Database

n(0)/<n>	Bt (T)	q95	Ip (MA)	H98(y,2)	n/nGr	fbs	Pcd(MW)	βN
2.00	9.50	3.90	5.72	1.10	0.85	0.65	33.6	2.50
2.00	8.50	3.50	5.70	1.13	0.75	0.58	34.9	2.50
2.00	7.50	3.10	5.68	1.18	0.75	0.62	31.7	3.00
2.00	6.50	3.10	4.92	1.31	0.95	0.72	22.0	3.50
1.75	9.50	4.10	5.44	1.24	0.75	0.60	33.3	2.50
1.75	8.50	3.70	5.40	1.25	0.85	0.65	32.6	3.00
1.75	7.50	3.30	5.34	1.26	0.95	0.67	33.0	3.50
1.75	6.50	3.10	4.92	1.39	0.85	0.63	28.3	3.50
1.50	9.50	4.30	5.19	1.35	0.85	0.65	33.1	3.00
1.50	8.50	3.70	5.40	1.40	0.65	0.56	34.3	3.00
1.50	7.50	3.50	5.00	1.42	0.85	0.61	34.0	3.50
1.50	6.50	3.10	4.92	1.47	0.95	0.70	28.4	4.50

$$H_{98}\left[\frac{(1+\alpha_n+\alpha_T)^2}{(1+2\alpha_n+2\alpha_T)}\right]^{0.31}\frac{Bt^{0.73}(n/nGr)^{0.41}}{q_{95}^{0.96}\,\beta_N^{0.38}}=const$$

$$P_{CD}\propto\frac{(n/nGr)Bt^2}{q_{cyl}^2\eta_{CD}}(1-f_{bs})$$

$$f_{bs}=(0.525+0.5\alpha_n)5\beta_N q_{cyl}/\sqrt{\varepsilon}$$

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

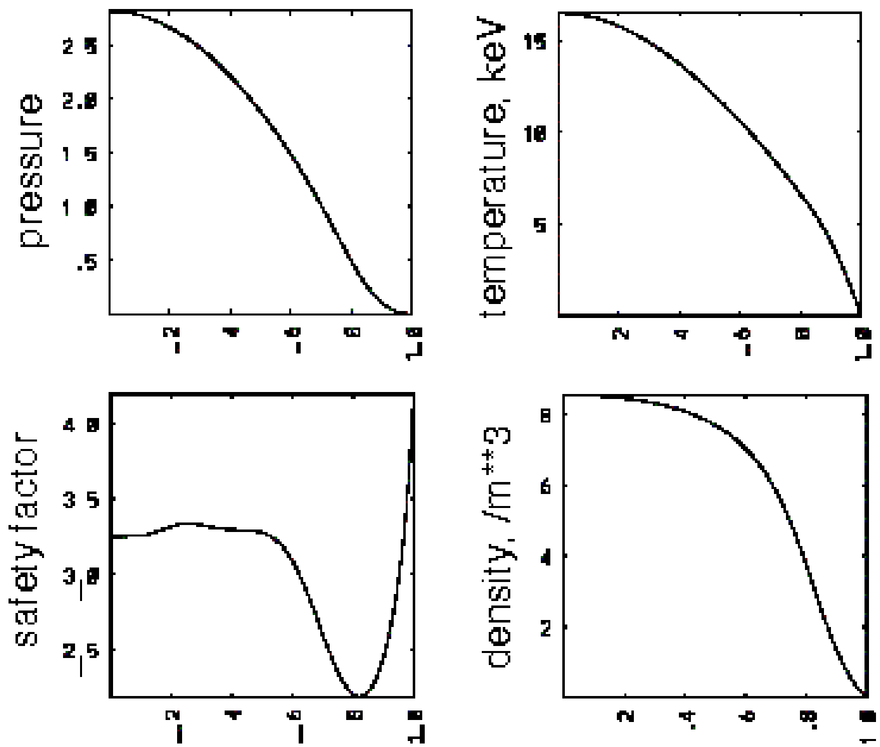
qmin=2.1-2.2		n=1 stabilized	lower of 4*li or 1.15*βN
r/a(qmin)=.50	Ip=3.25		
	βN=3.0	βN=3.4	βN=3.45
q*=4.15	qmin=2.16		
βp=2.37	li(3)=0.68		
	li(1)=0.88		
	fbs=0.62	fbs=0.65	fbs=0.65
r/a(qmin)=.65	Ip=4.71		
	βN=2.8	βN=3.45*	βN=2.8
q*=2.88	qmin=2.13		
βp=1.55	li(3)=0.54		
	li(1)=0.70		
	fbs=0.52	fbs=0.63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

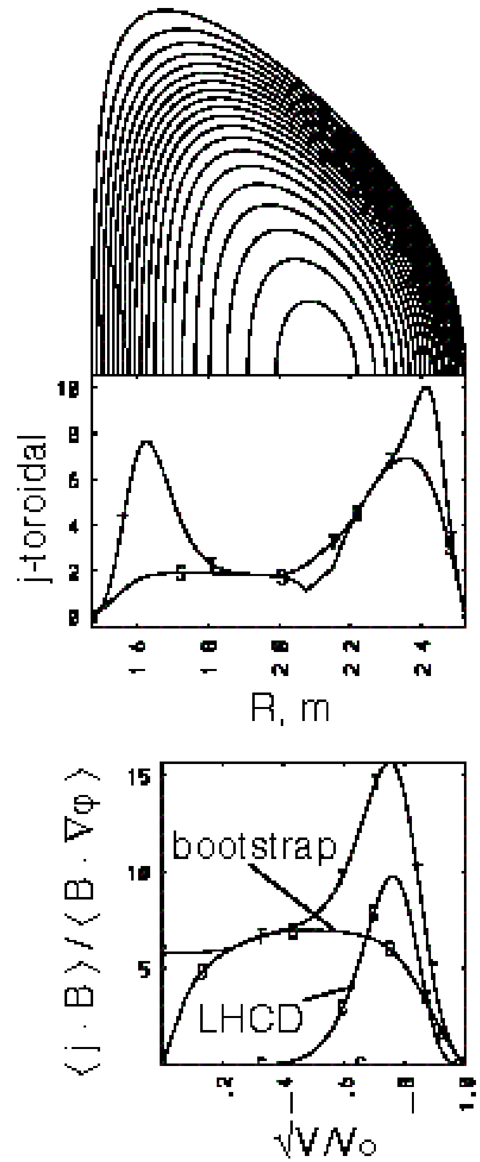
Target for FIRE AT analysis

FIRE AT Mode

r/a(qmin)=0.8, qmin=2.19, Ip=5.4 MA,

βN=2.54, I(LH)=2.2 MA, fbs=0.58



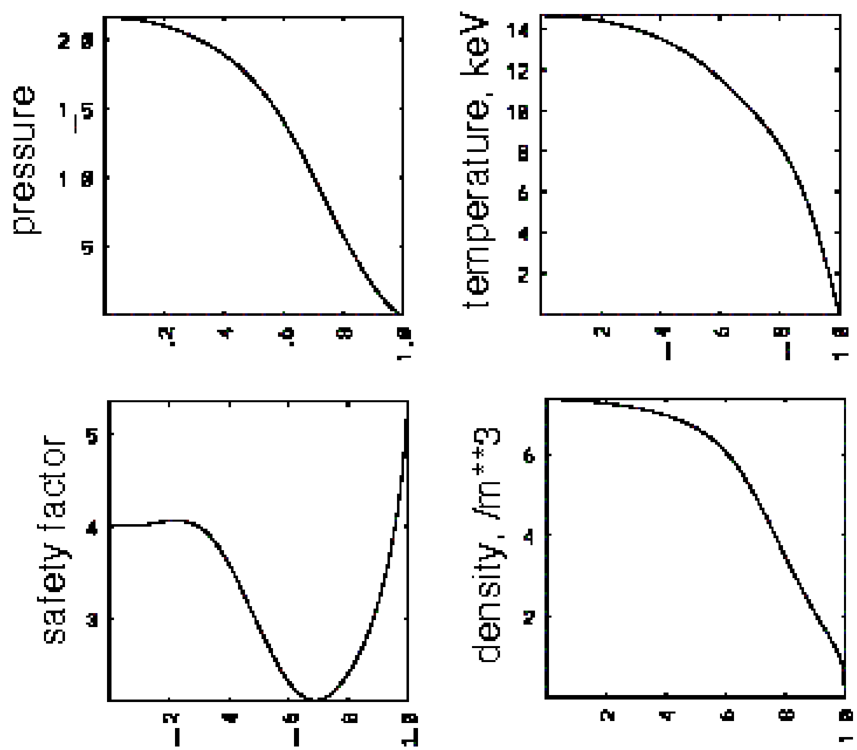


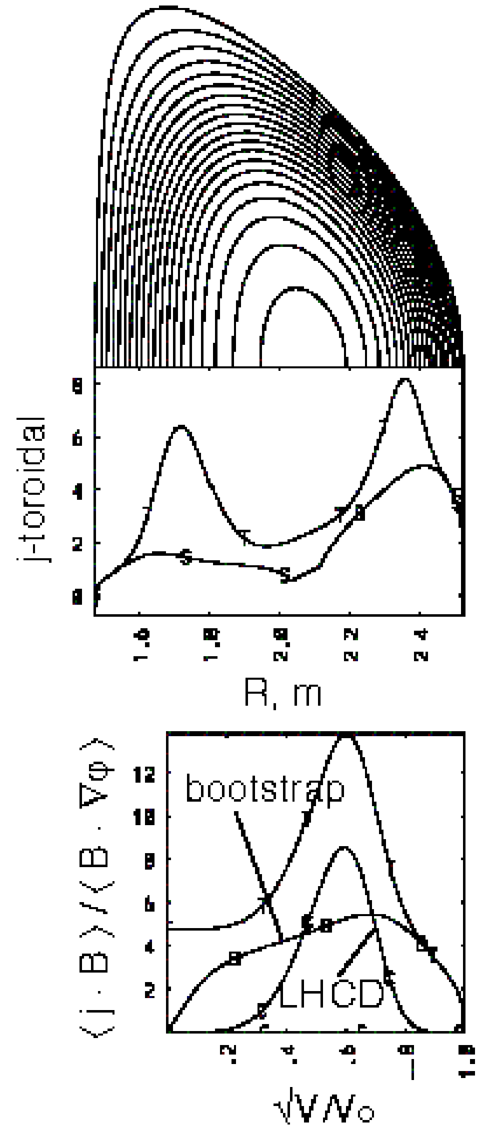
JSOLVER bootstrap self-consistent equilibria

FIRE AT Mode

r/a(qmin)=0.65, qmin=2.12, Ip=4.54 MA

βN=2.8, I(LH)=1.7 MA, fbs=0.58



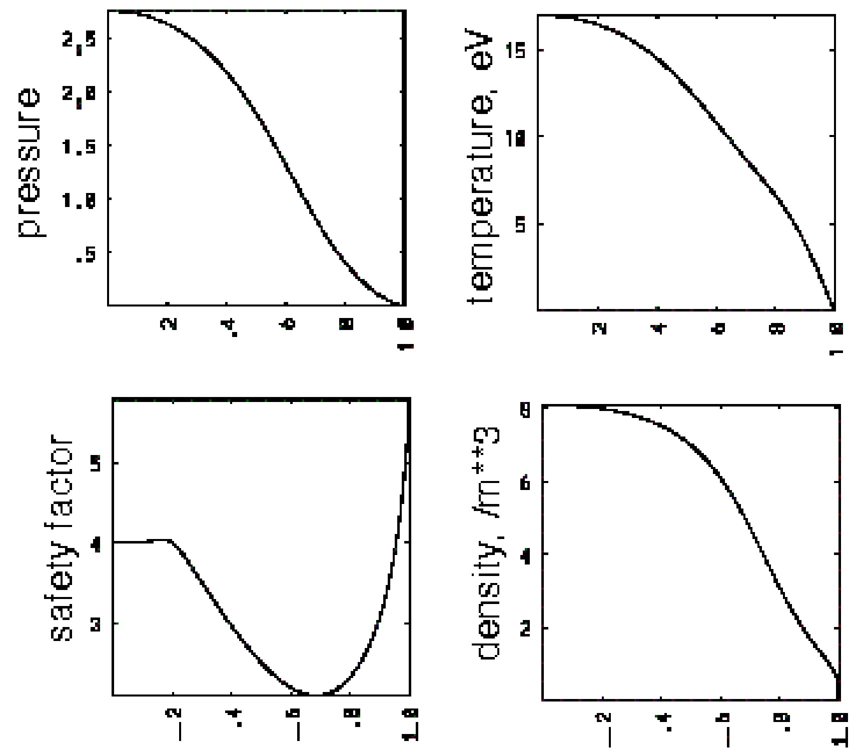


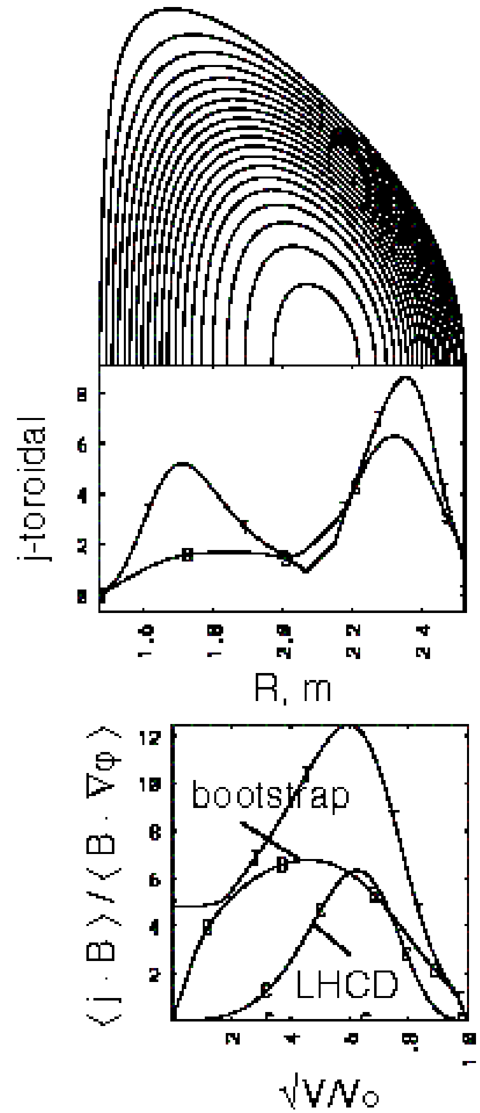
more broad pressure

FIRE AT Mode

r/a(qmin)=0.65, qmin=2.10, Ip=4.5 MA,

βN=2.85, I(LH)=1.75 MA, fbs=0.59





more peaked pressure

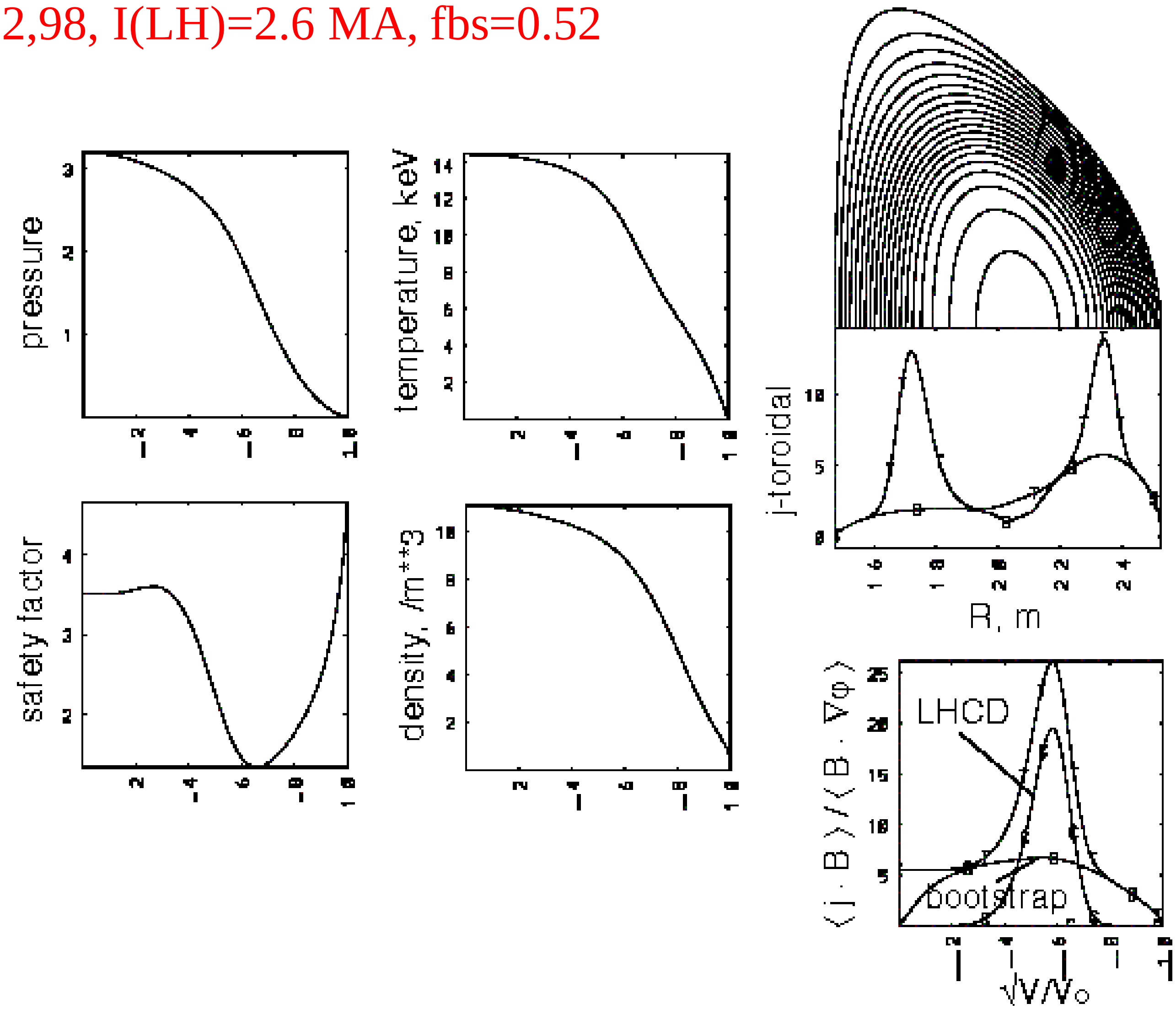
FIRE AT Modes; Bt=8.5 T, A=3.8, κ=1.9, δ=0.65

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

FIRE AT Mode

r/a(qmin)=0.65, qmin=1.34, Ip=5.67 MA,
βN=2,98, I(LH)=2.6 MA, fbs=0.52



Equilibrium, Ideal MHD Stability and Current Drive Identify AT Target Plasmas

q(min) = 2.1-2.2

r/a(qmin) = 0.8

n(0)/<n> = 1.5

Ip = 5.5 MA

Bt = 8.5 T

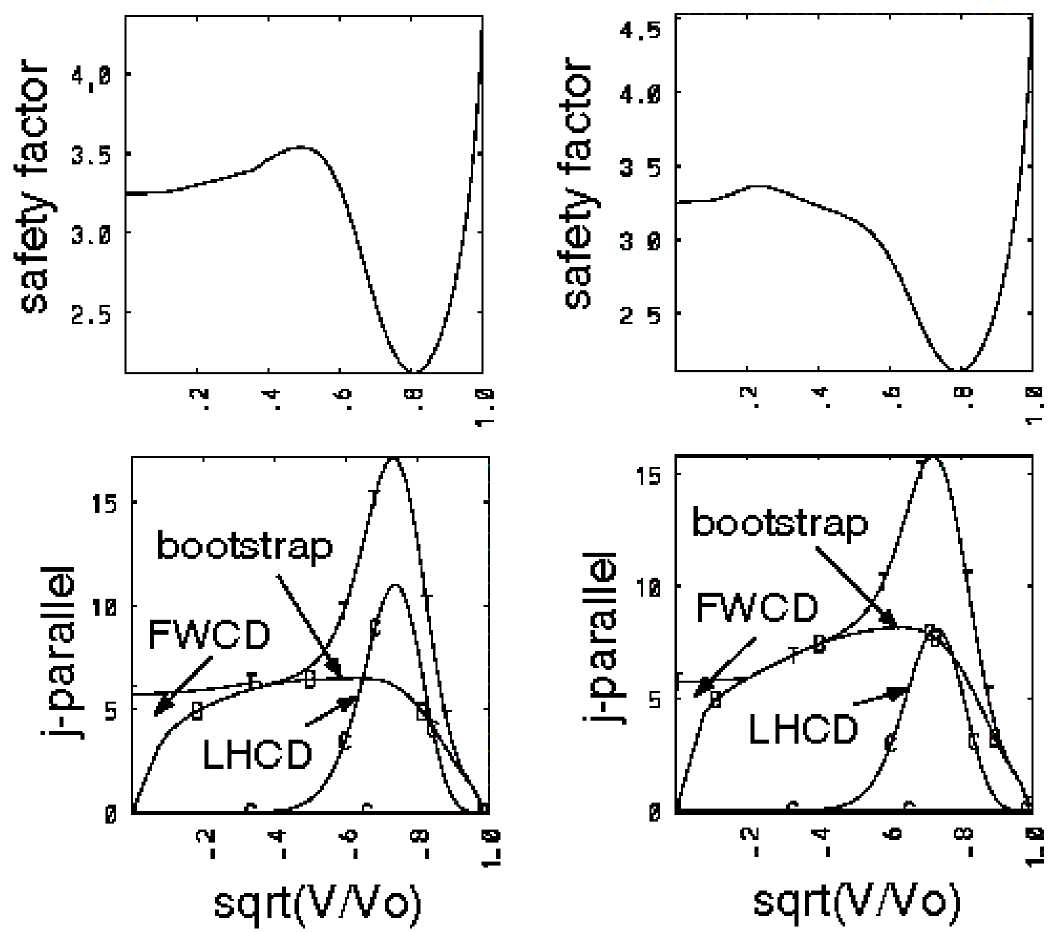
No wall stabilization

$\beta N = 2.5$

n=1 RWM stabilized

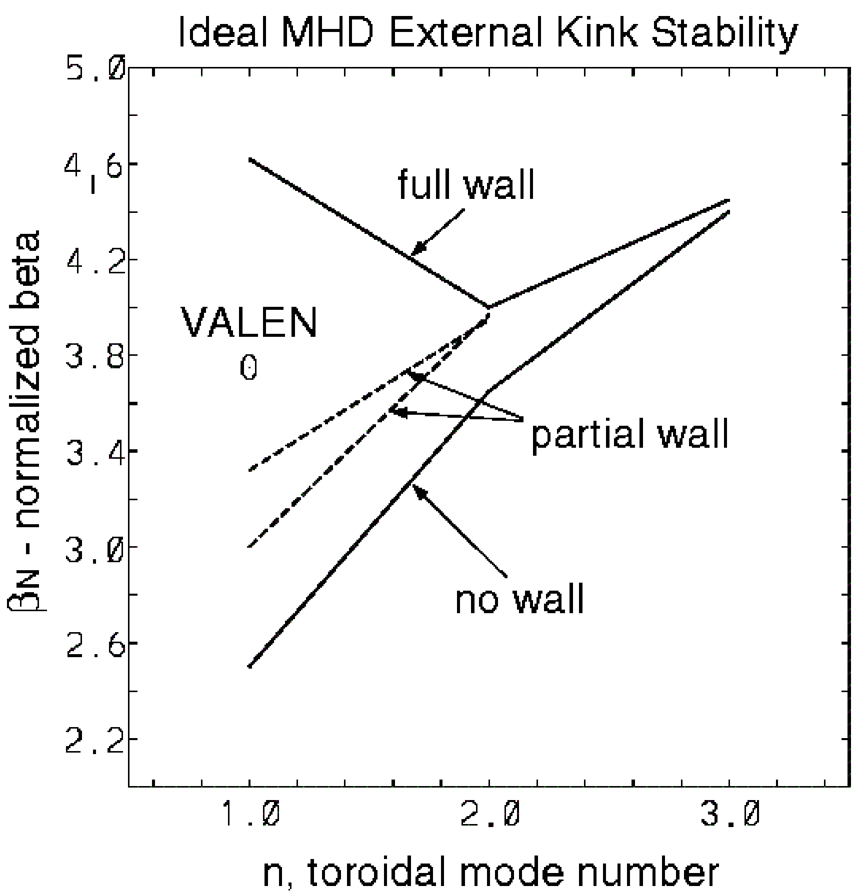
$\beta N = 3.65$

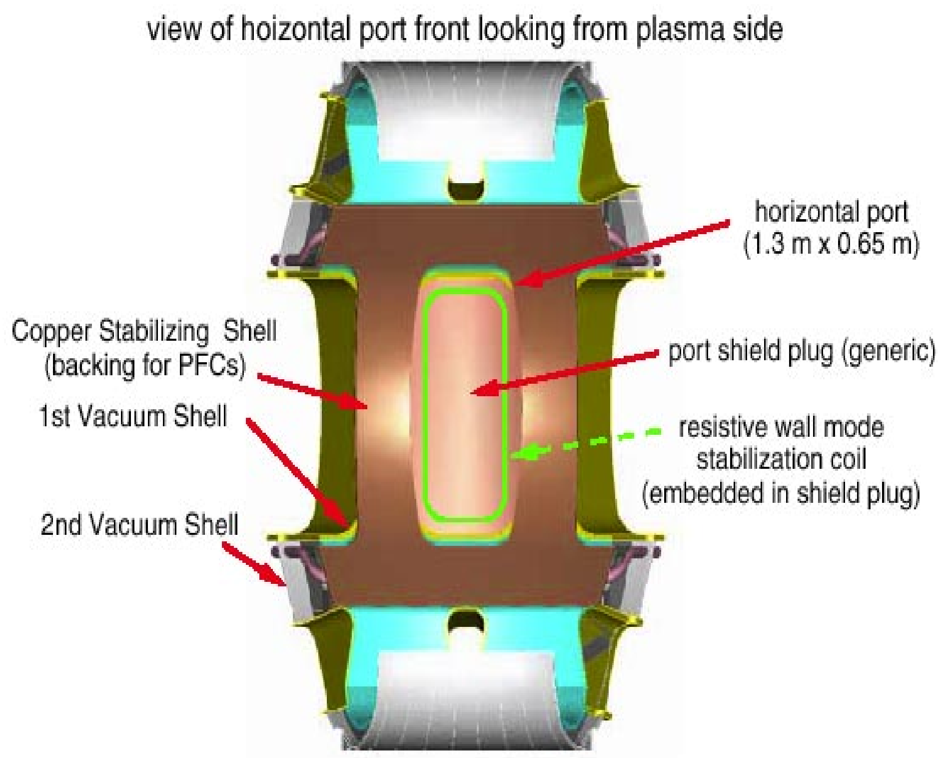
$\beta_N = 2.5, f_{bs} < 0.55$ $\beta_N = 3.65, f_{bs} < 0.75$



Stabilization of the n=1 RWM on FIRE

PEST2 and VALEN analysis used to determine possible strategies for raising β by feedback stabilization based on DIII-D experience





ICRF/FW Viable for FIRE On-Axis CD

PICES analysis (ORNL)

ω = 115 MHz

n|| = 2.0

n(0) = 5x10^20 /m3

T(0) = 14 keV

40% power in good part of spectrum

----> 0.02 A/W

CURRAY analysis (UCSD)

ω = 100 MHz

n|| = 2.0

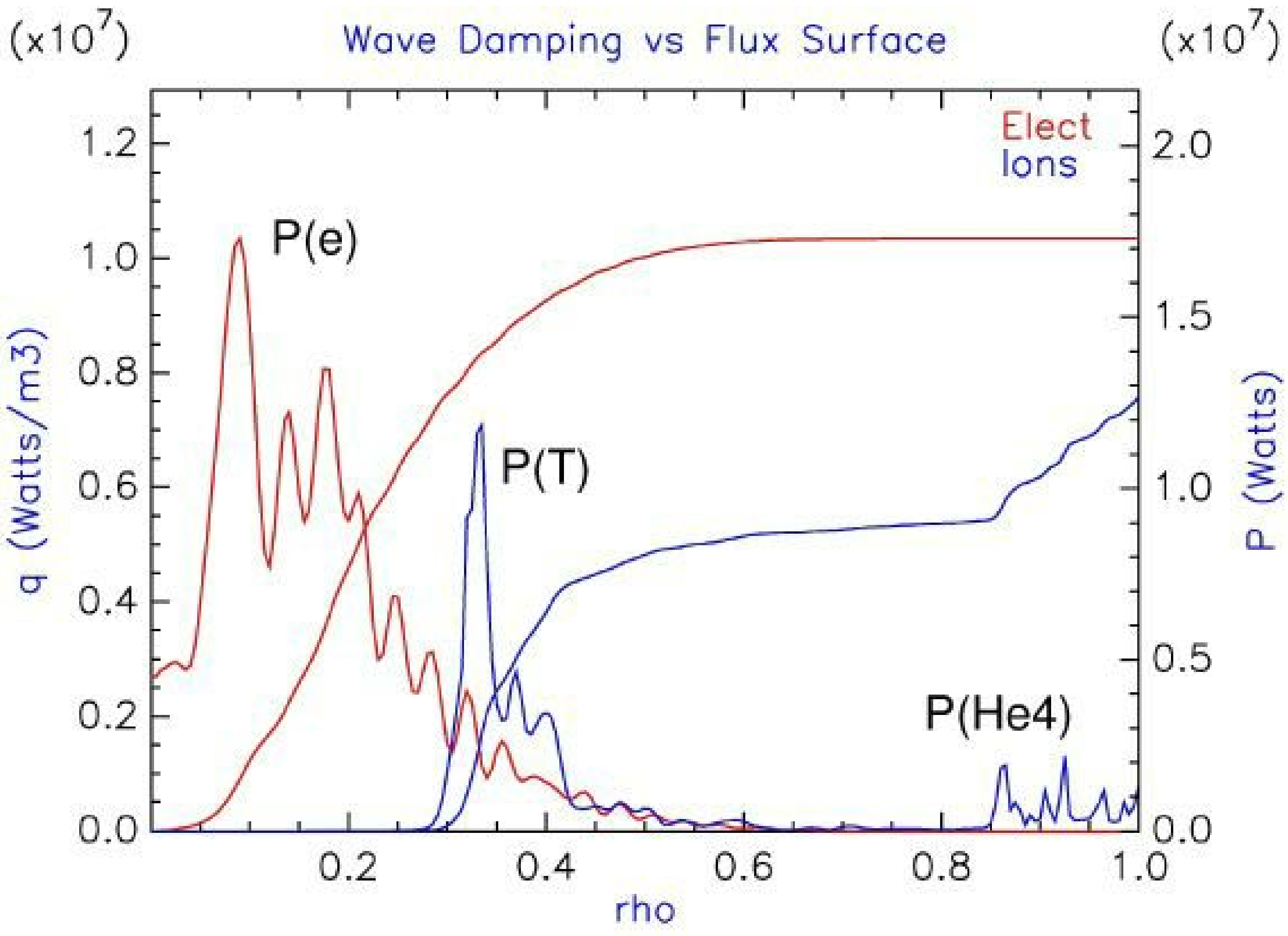
n(0) = 3.5x10^20 /m3

T(0) = 20 keV

100% power into good part of spectrum

----> 0.08 A/W

Need more detailed antenna design, include all impurities, address multiple AT scenarios, final ηcd expected to be between those found

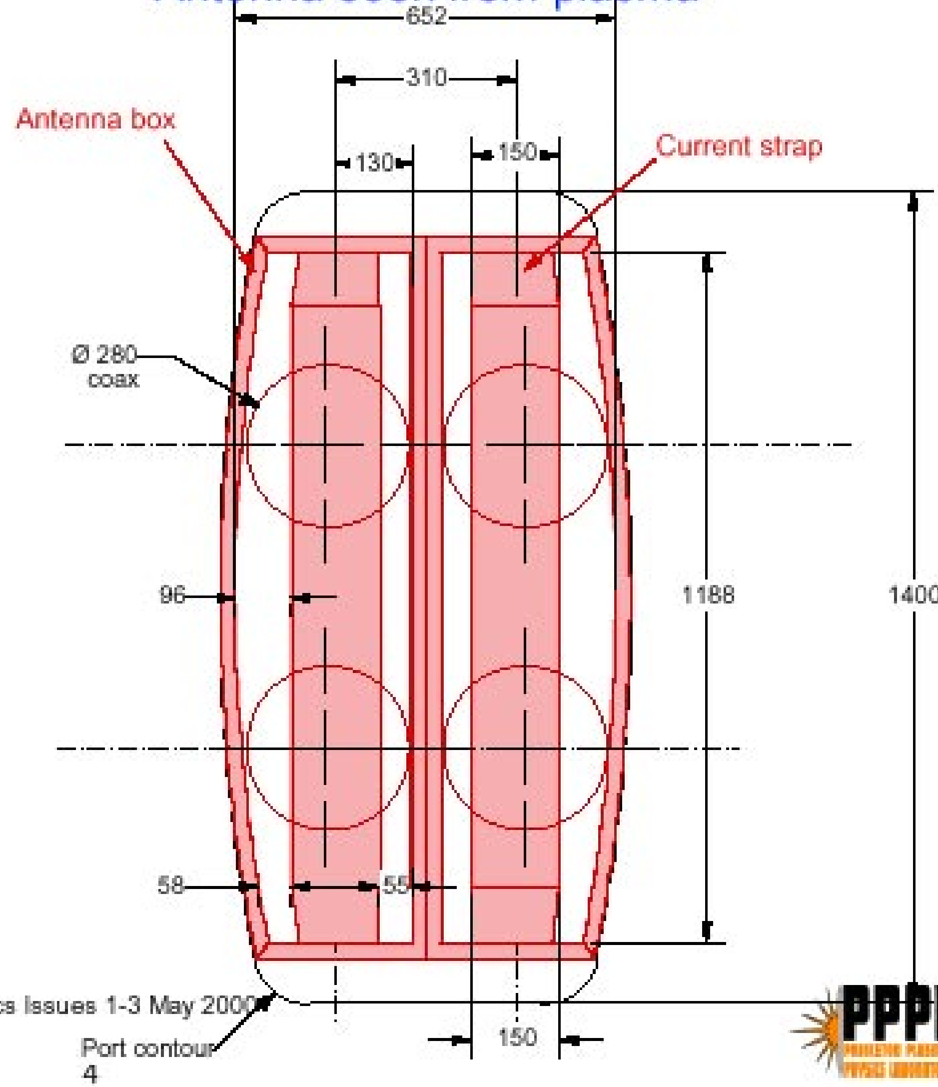


Preliminary ICRF Antenna Design

Antenna characteristics:

- Two current straps
- Straps grounded at each end
- Each strap fed by 2 coax feeders
  - Feeds at midpoint between center and ends
  - Driven out of phase
- Antenna covered by Faraday shield (not shown)
  - Single-layer tubes
  - Probably connected to frame at center
- Active water cooling may be required during a shot (particularly on FS tubes).

Antenna seen from plasma



LHCD Viable for FIRE Off-Axis CD

C-Mod LH Launcher Design: ω = 4.6 GHz, n|| = 2-4, Δn|| = 0.3

TSC-LSC analysis, PPPL

ω > 2ω(LH), ω = 4.6 GHz

n|| = 2.0, Δn|| = 0.3

n(0) = 4.5x10^20 /m3

T(0) = 22 keV

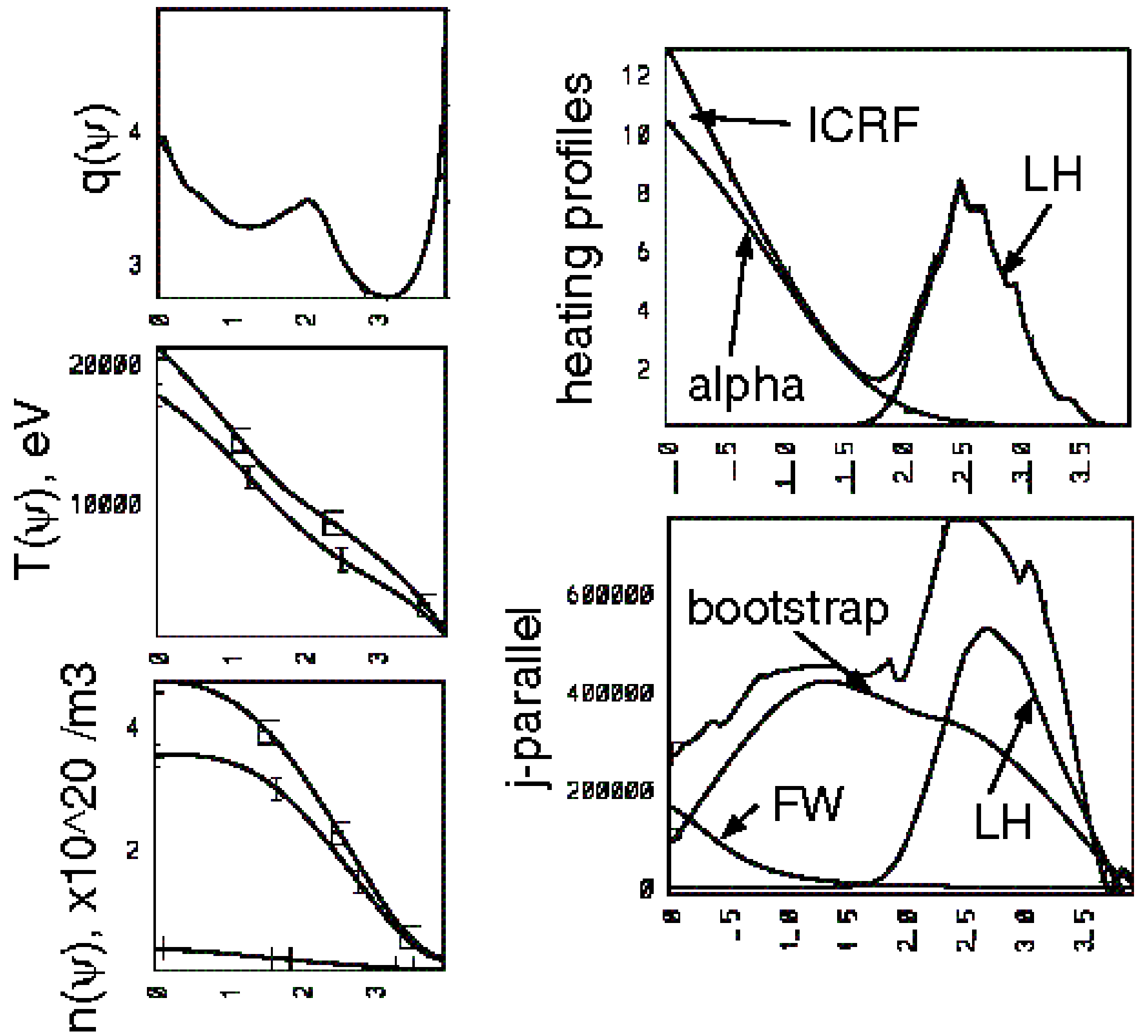
n(0)/<n> = 1.5

Bt = 8.5 T

----> 0.085 A/W

Alpha particle absorption needs to be determined

All rays launched from outboard midplane



Preliminary LH Launcher Design

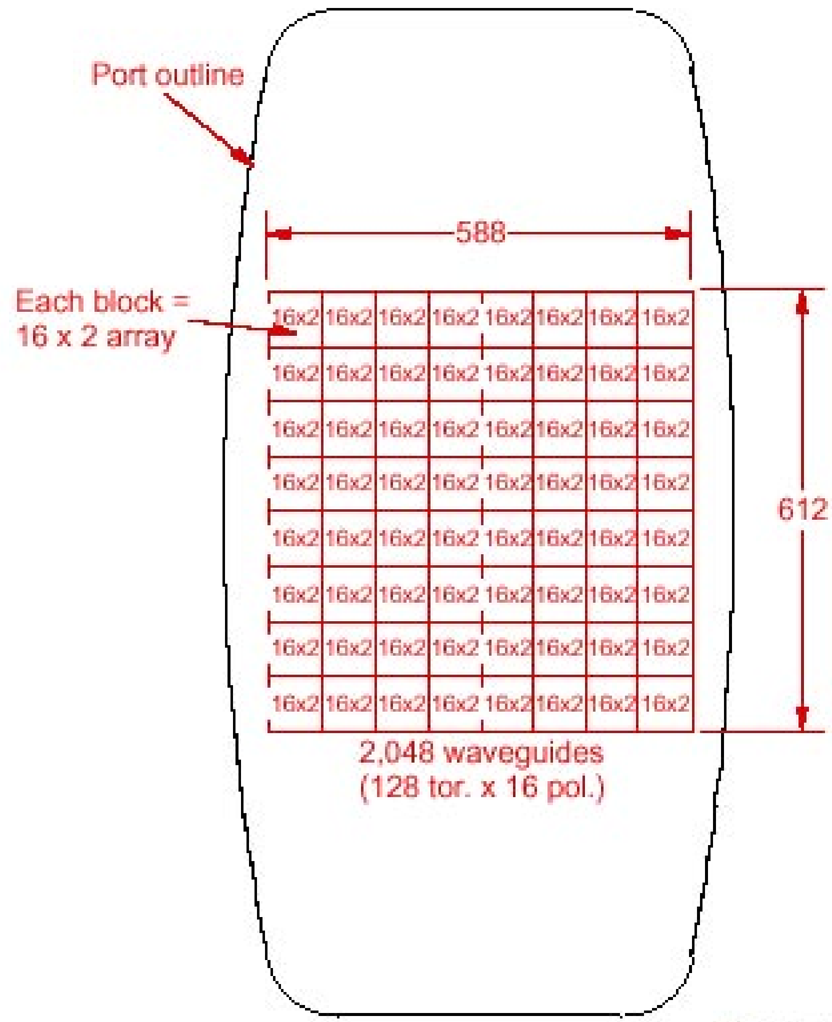
For one port, put array as shown.

- Array area ≈ 0.33 m², so
- P_{LH} ≈ 12.8 MW/port.

-> Need two LH ports to deliver 25 MW.

LH launcher contour must conform very closely to the plasma contour for good coupling. The higher the coupler, the greater the constraint on the plasma outer separatrix.

Issue: How much change will there be in the plasma shape during a shot, or under different experimental conditions?



LHCD Efficiency is Sensitive to Local Density and Temperature

TSC-LSC, PPPL

P(LH) = 20 MW

ω = 4.6 GHz

n|| = 2.0

Δn|| = 0.3

n(0)/<n> = 1.25-1.6

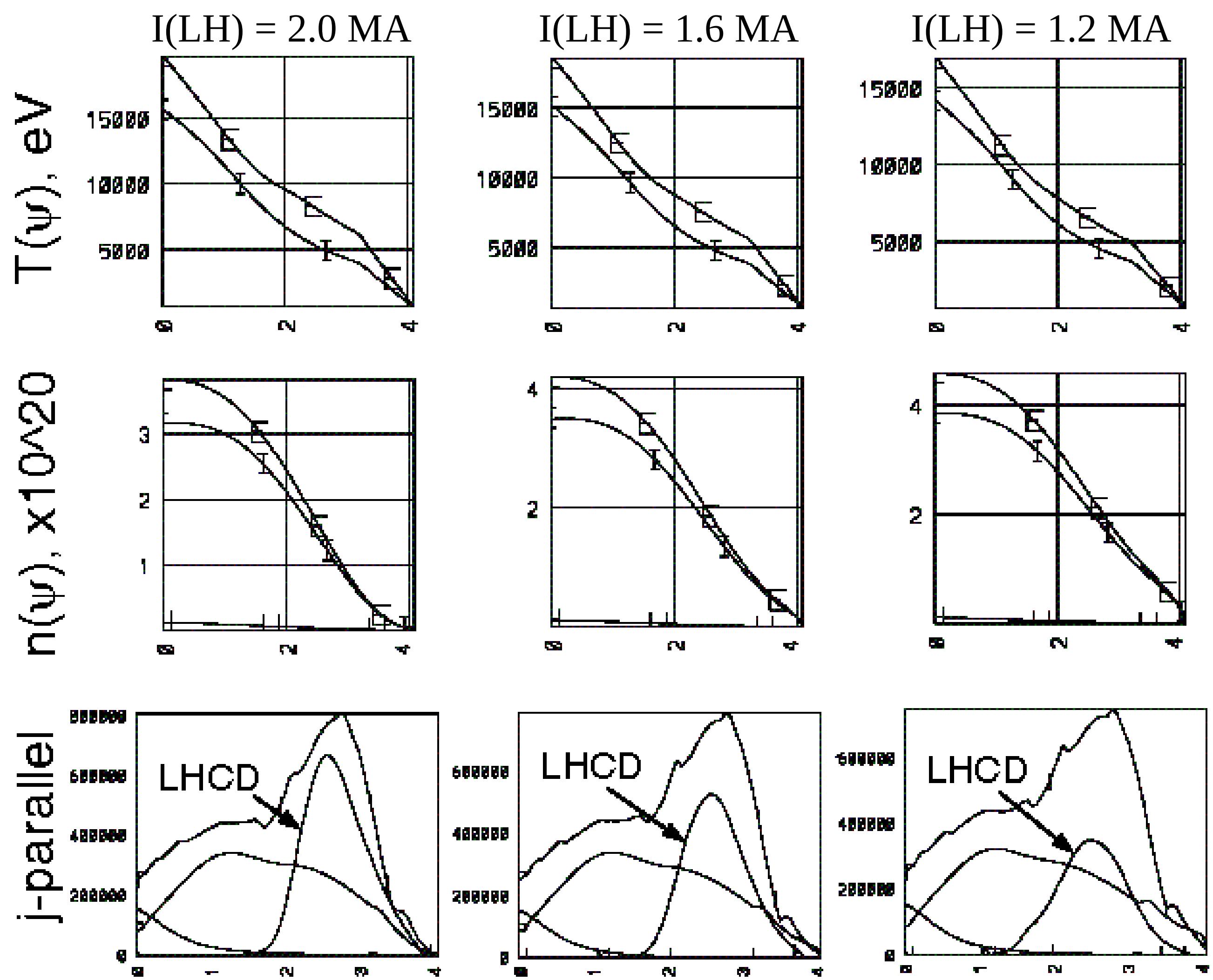
Deepest penetration

T(ψ) an n||

Avoid mode conversion

Maximum A/W

T(ψ)/n(ψ)



Quasi-Stationary AT Burning Plasmas are the Primary Focus

- Plasma current is ramped up with inductive and non-inductive current to produce a quasi-stationary plasma at the beginning of flattop
- The safety factor in flattop is held by non-inductive current
  - Bootstrap current
  - LHCD off-axis
  - ICRF/FW on axis
- Flattop times 2-4 x τ_{jdiff} (30-60 s)
- Q=5-10
- 1.0 < H(y,2) < 1.8

transient burning AT plasmas can be produced with inductive current

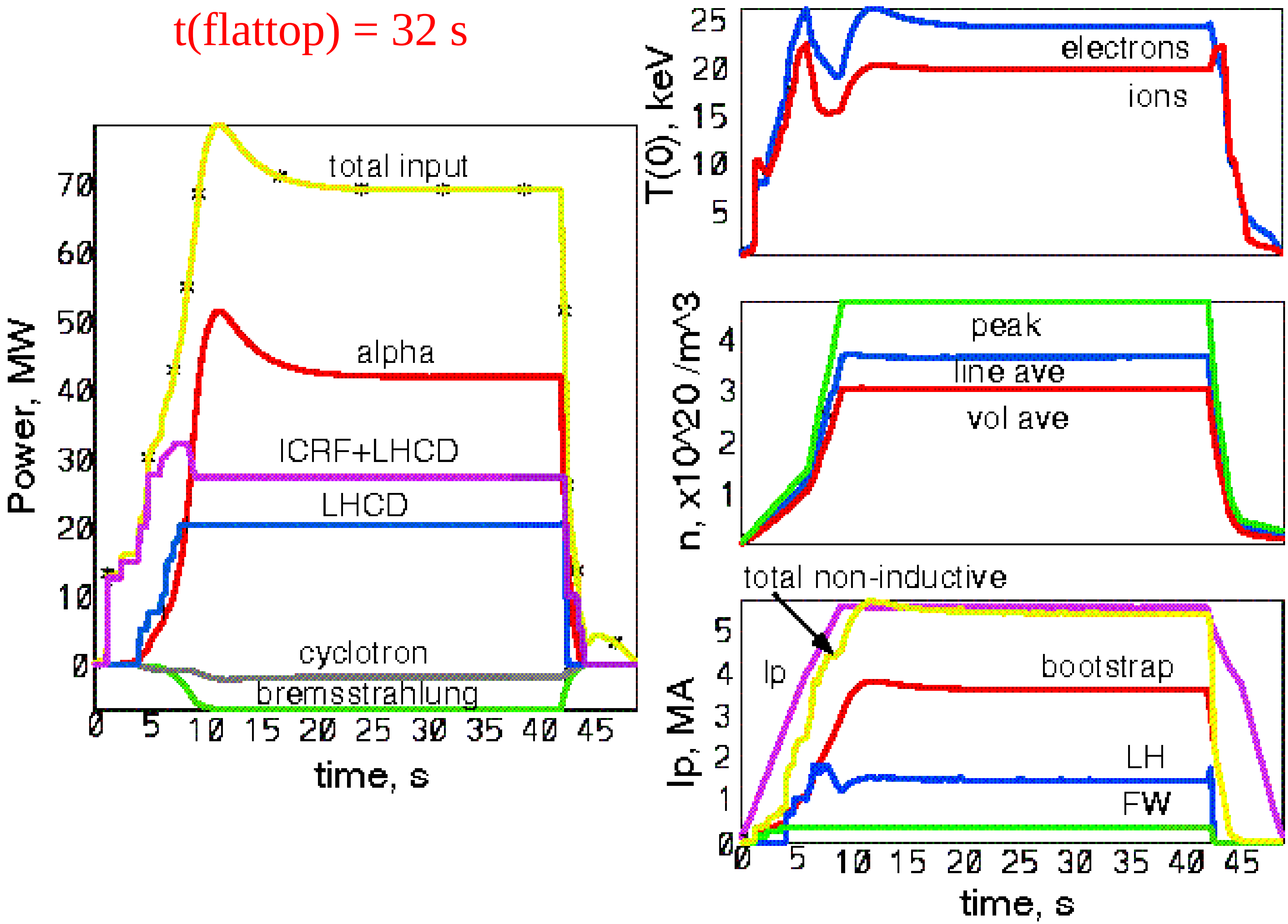
long pulse DD (non-burning) plasmas can be created with pulse lengths up to >200 s at Bt=4 T, Ip=2 MA

TSC-LSC Simulation of Burning AT Plasma in FIRE

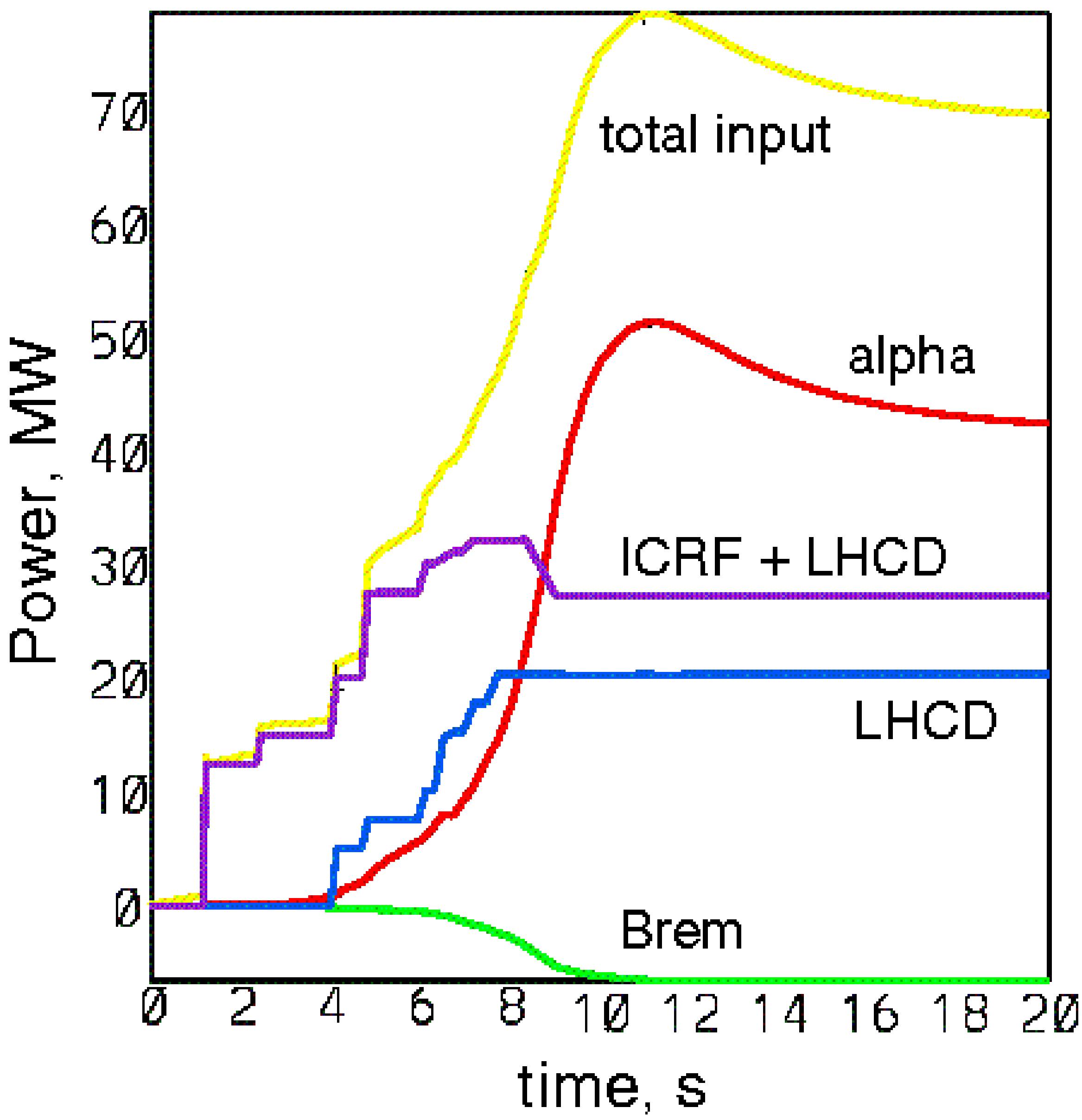
- Bt = 8.5 T, Ip = 5.5 MA
- q(0) = 3.0, q(min) = 2.25, q(95) = 3.5, li = 0.45
- β = 4.5 %, βN = 3.5, βp = 1.77
- n/nGr = 0.5, n(0)/<n> = 1.57
- n(0) = 4.7x10^20, n(line) = 3.6, n(vol) = 3.0
- Wth = 36.5 MJ
- τE = 0.6 s, H98(y,2) = 1.6
- Ti(0) = 20 keV, Te(0) = 24 keV
- $\Delta\psi$(total) = 22.5 V-s, $\Delta\psi$(res) = 1.2 V-s, $\Delta\psi$(int. ind) = 4.4 V-s
- Pα = 42 MW
- P(LH) = 20 MW
- P(ICRF/FW) = 7 MW
  - Up to 20 MW ICRF used in rampup
- P(brem) = 6.6 MW
- Q = 7.8
- I(bs) = 3.6 MA, I(LH) = 1.5 MA, I(FW) = 0.35 MA

TSC-LSC Simulation of Q=7.8 Burning AT Plasma

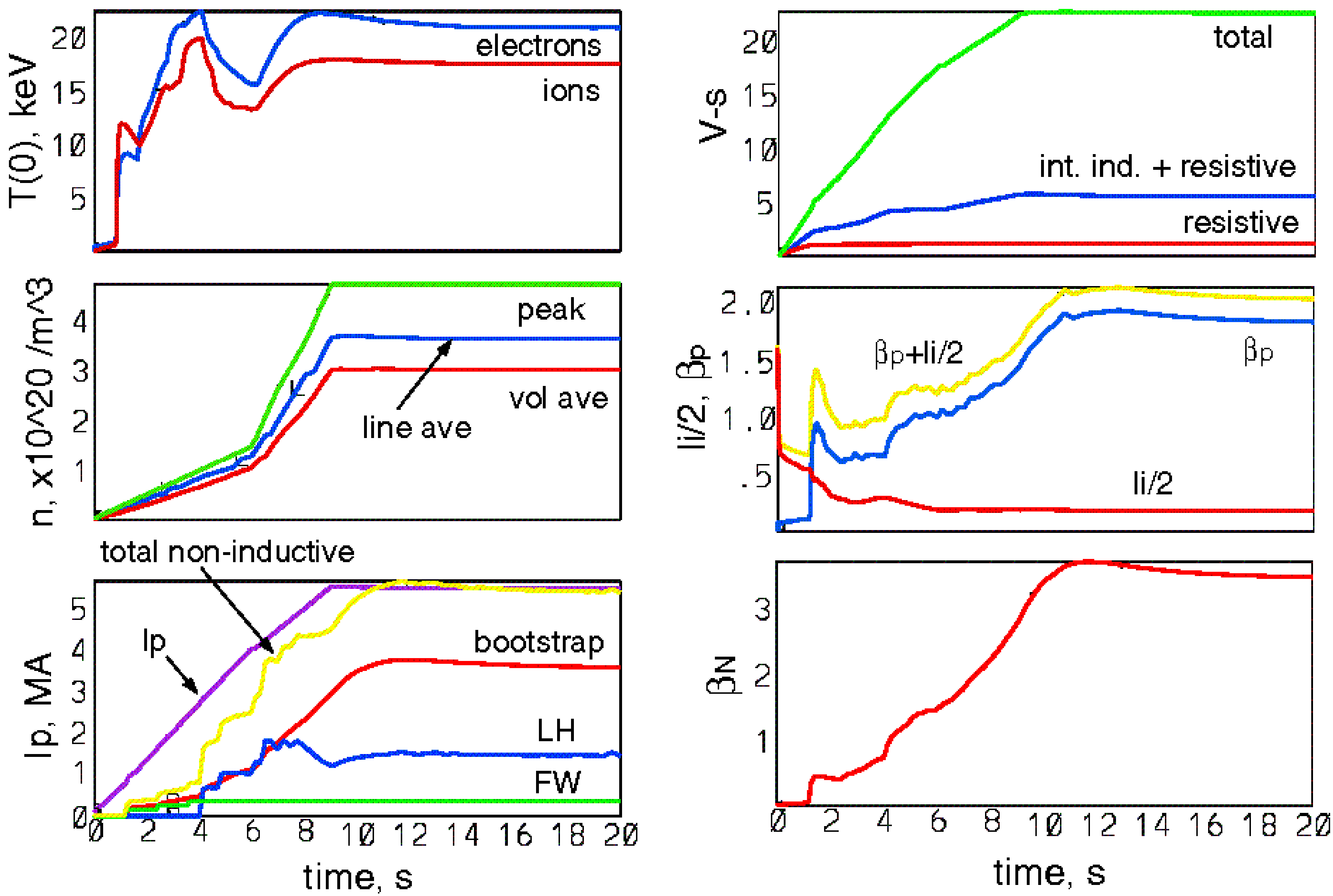
t(flattop) = 32 s



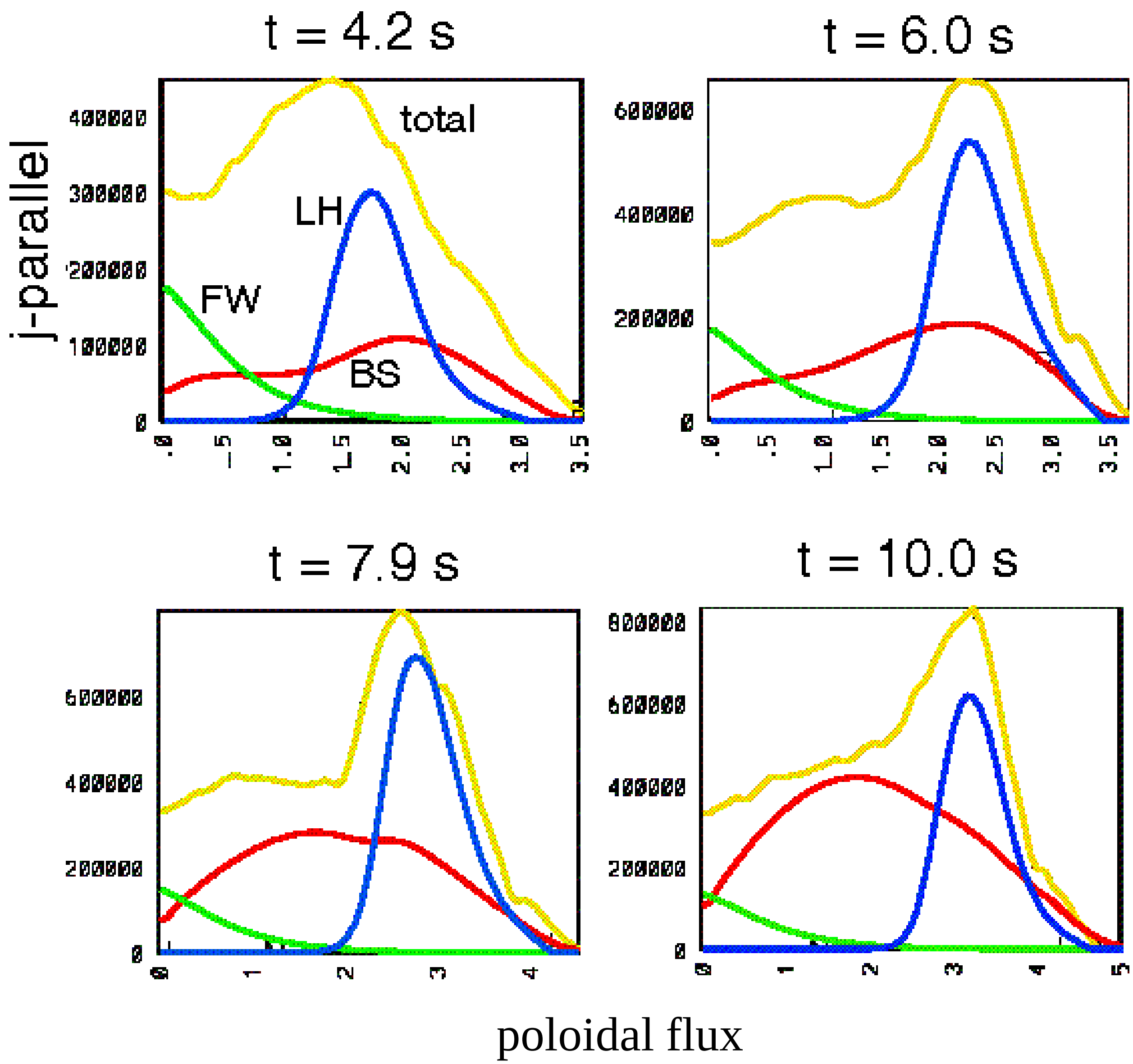
TSC-LSC Simulation of Q=7.8 Burning AT Plasma



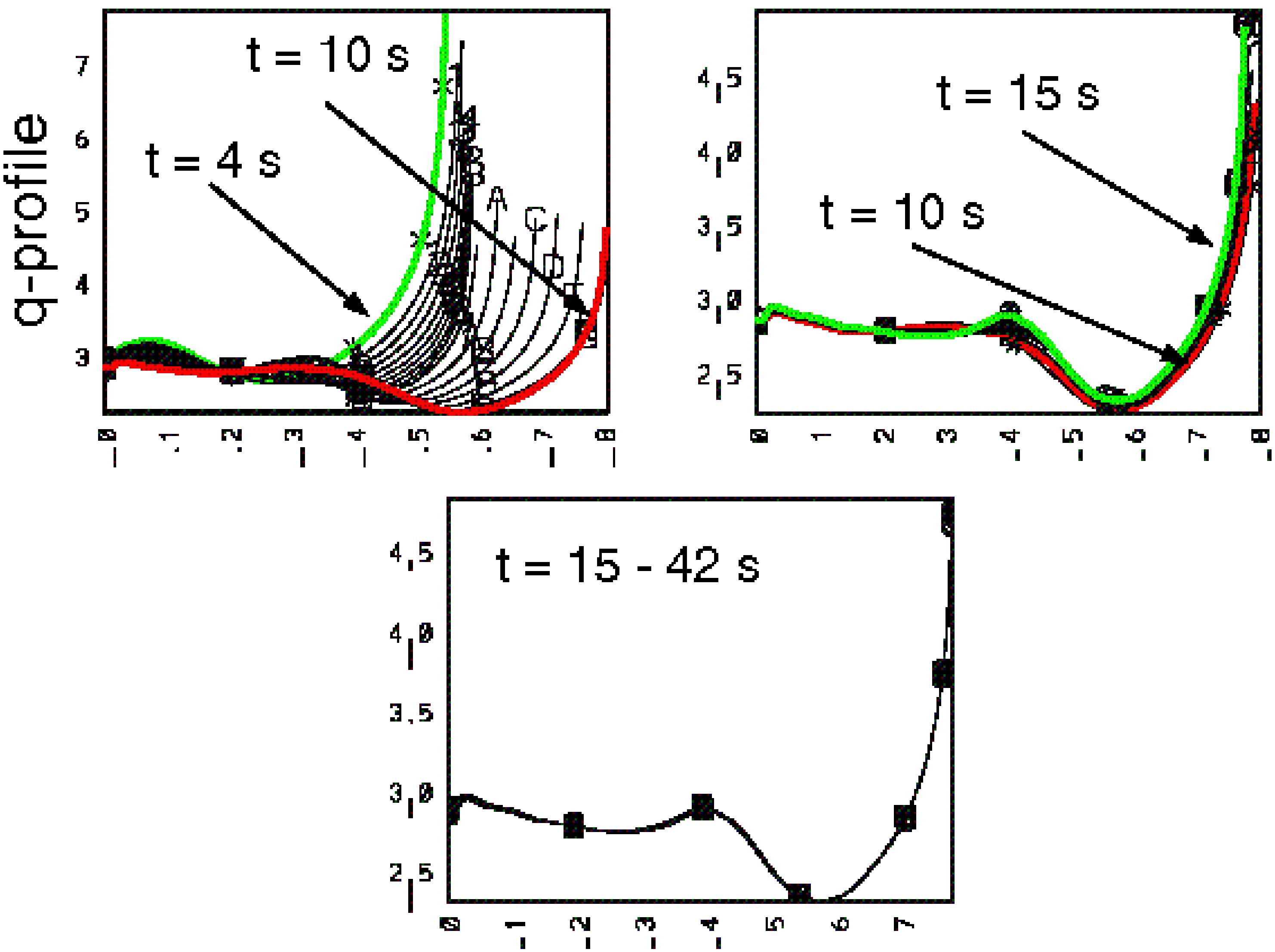
TSC-LSC Simulation of Q=7.8 Burning AT Plasma



TSC-LSC Simulation of Q=7.8 Burning AT Plasma



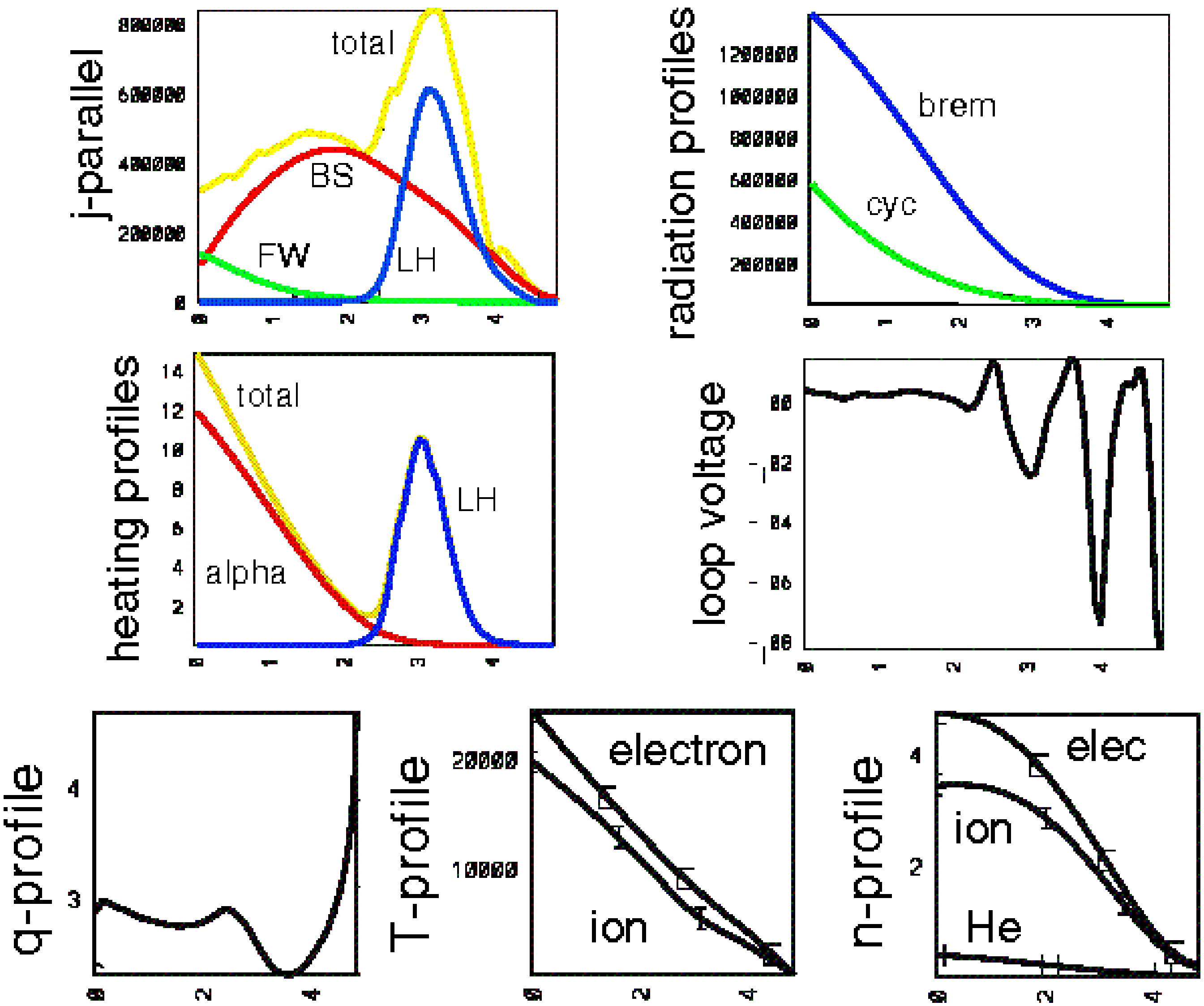
TSC-LSC Simulation of Q=7.8 Burning AT Plasma



poloidal flux

TSC-LSC Simulation of Q=7.8 Burning AT Plasma

Flattop profiles



poloidal flux

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