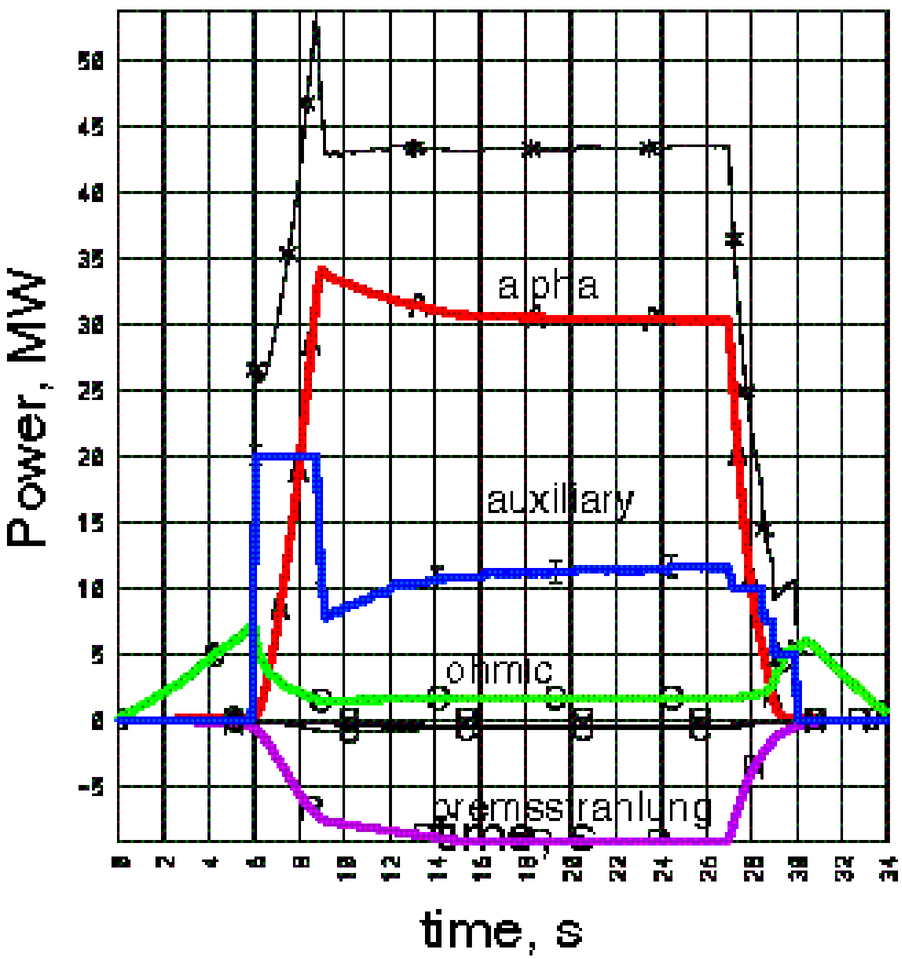
FIRE Physics/AT Progress

C. Kessel
Princeton Plasma Physics Laboratory

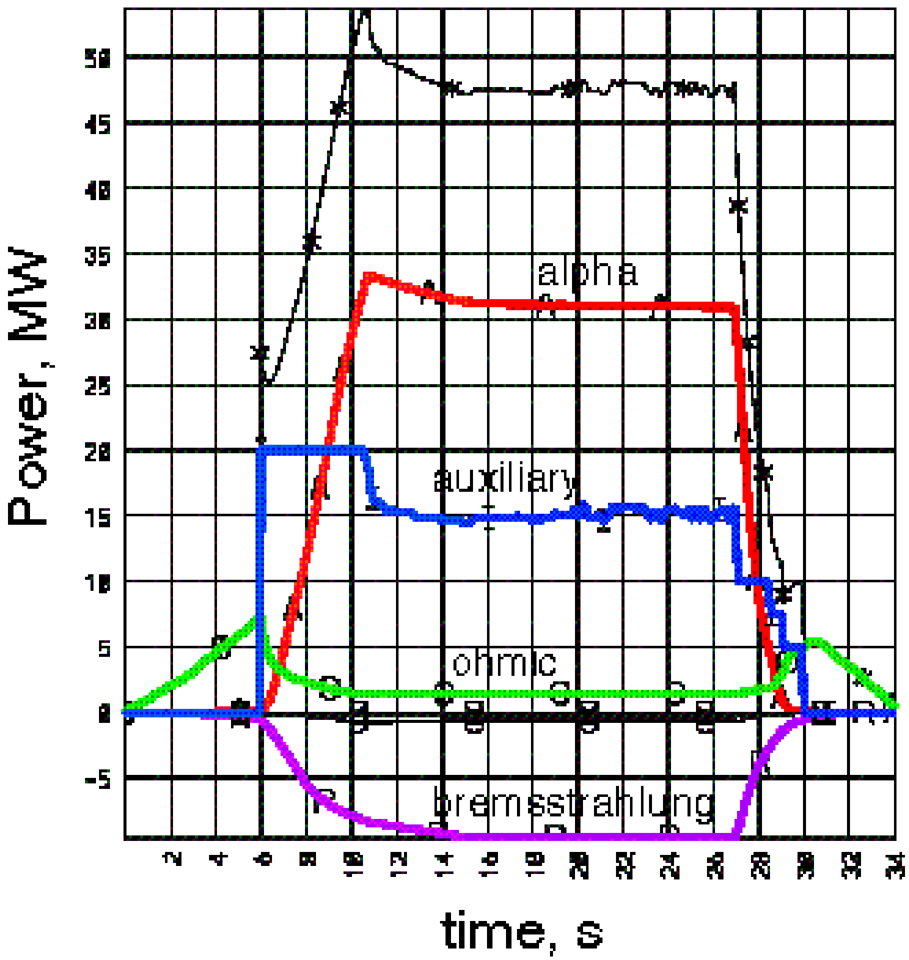
NSO/PAC Meeting, LLNL, November 29-30, 2001

FIRE* Reference Discharge With GLF23 Transport Model

Coppi-Tang L-mode Chi-model

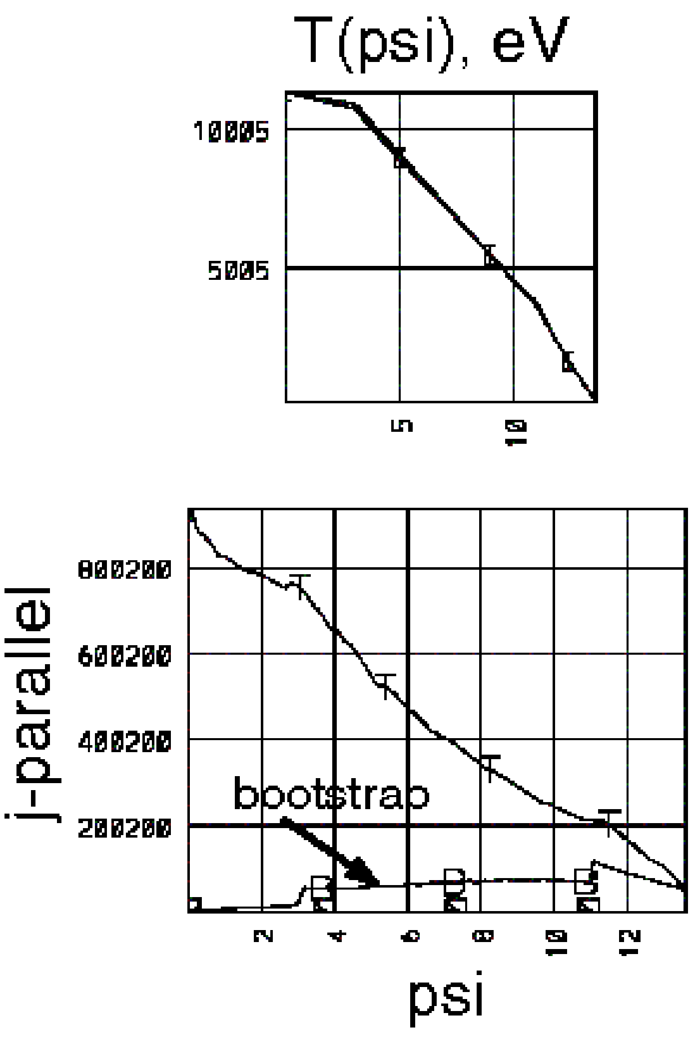


GLF23 Chi-model

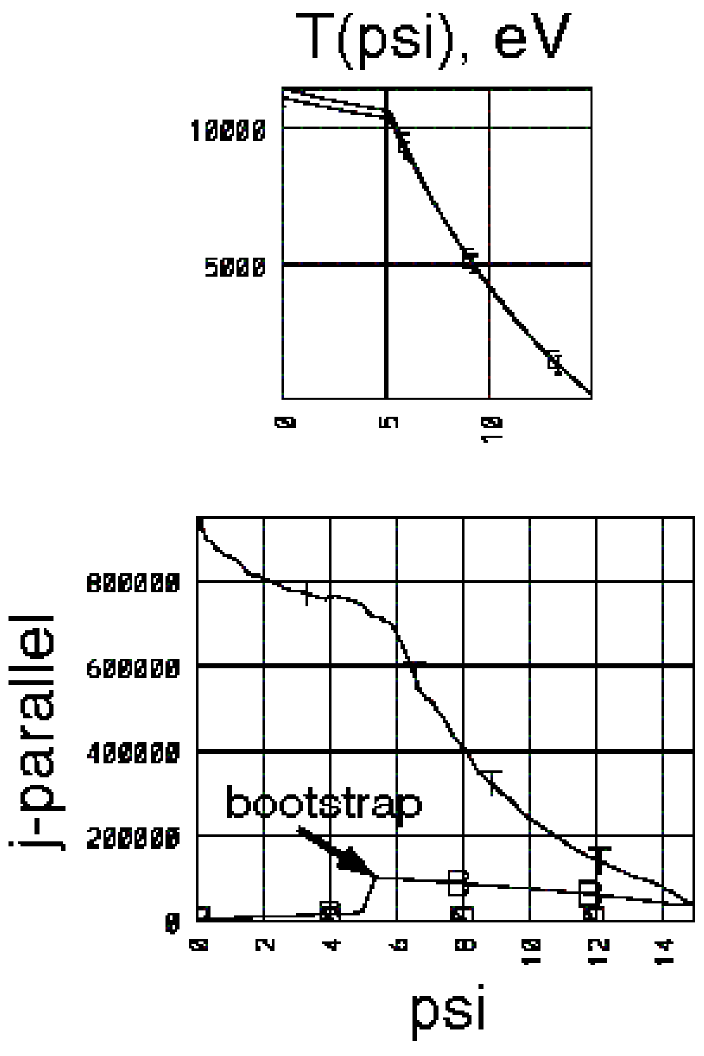


FIRE* Reference Discharge With GLF23 Transport Model

GLF23 Chi-model

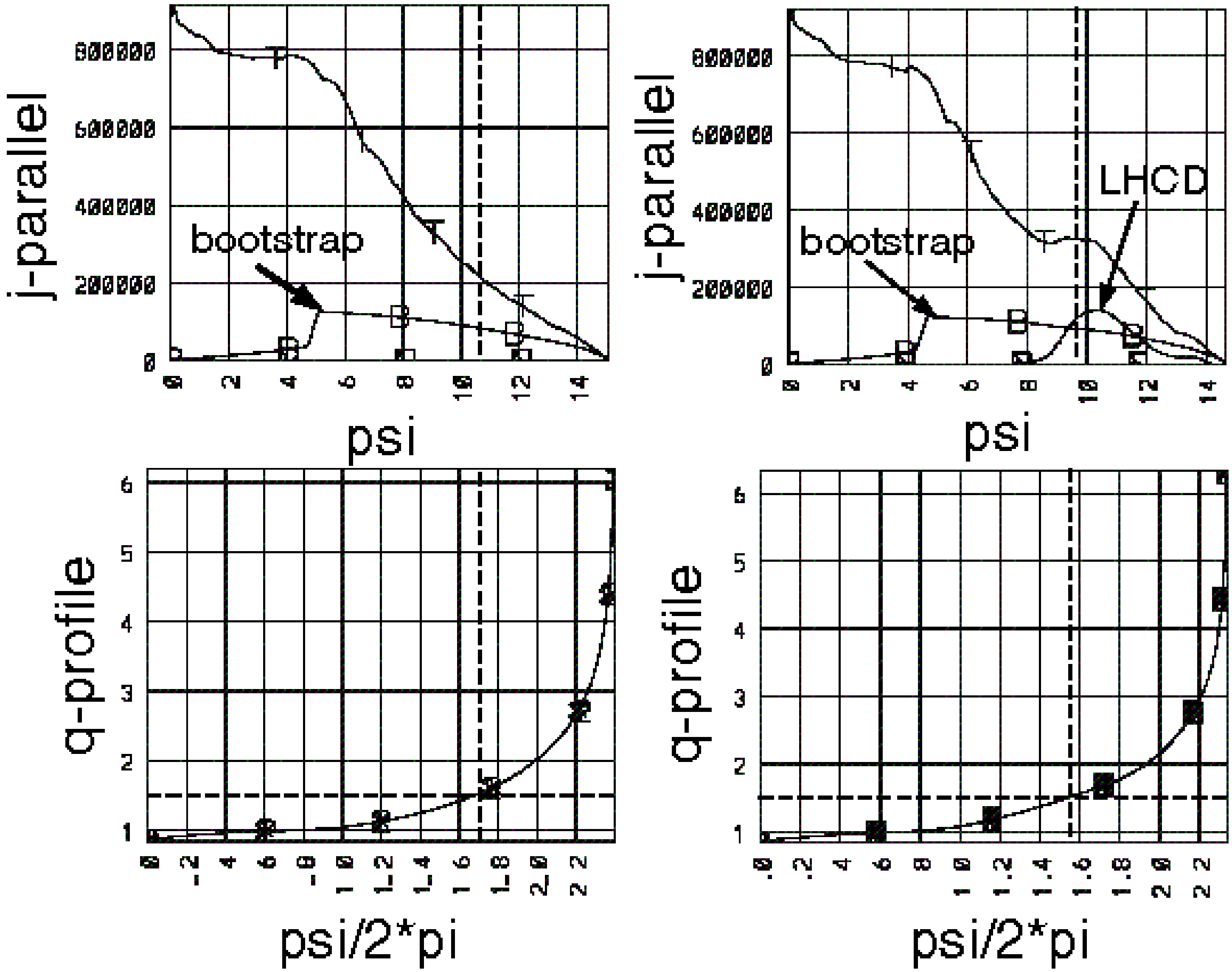


L-mode Chi-model

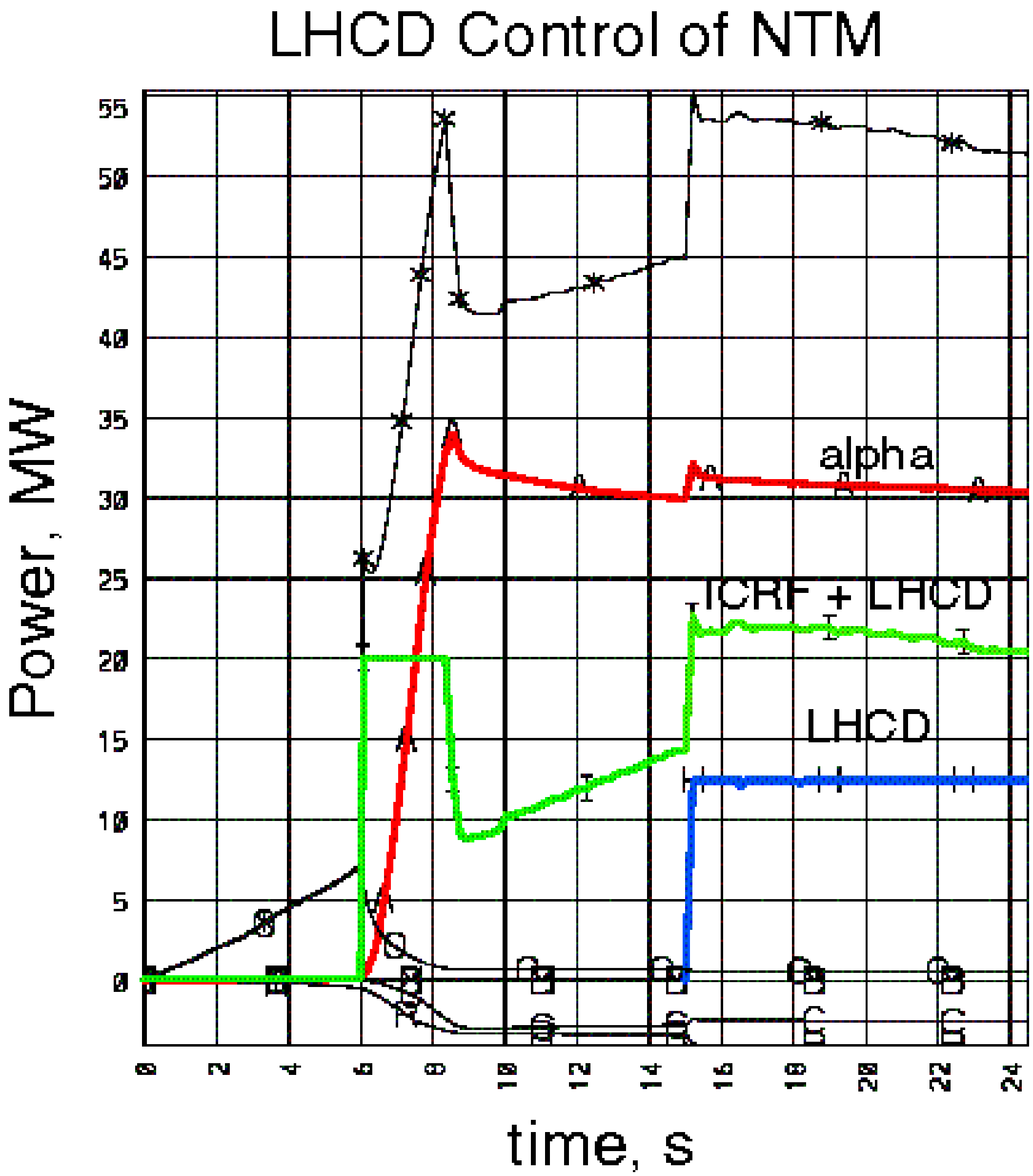


NTM Control With LHCD

12.5 MW LHCD, I(LH)=650 kA, at (3,2) surface



NTM Control With LHCD



12.5 MW LHCD producing 0.65 MA

n/nGr = 0.35 to improve CD efficiency

Current profile modification to alter Δ’, will be examined with PEST3

Injected LH power reduces Q to 5-7

FIRE Efforts to Self-Consistently Simulate Advanced Tokamaks

0-D Systems Analysis:

Determine viable operating point global parameters that satisfy constraints

Plasma Equilibrium and Ideal MHD Stability:

Determine self-consistent stable plasma configurations to serve as targets

Current Drive:

Determine current drive efficiencies and deposition profiles

Transport:(GLF23 and pellet fueling models to be used in TSC)

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

Dynamic Evolution Simulations:

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

Edge/SOL/Divertor:

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

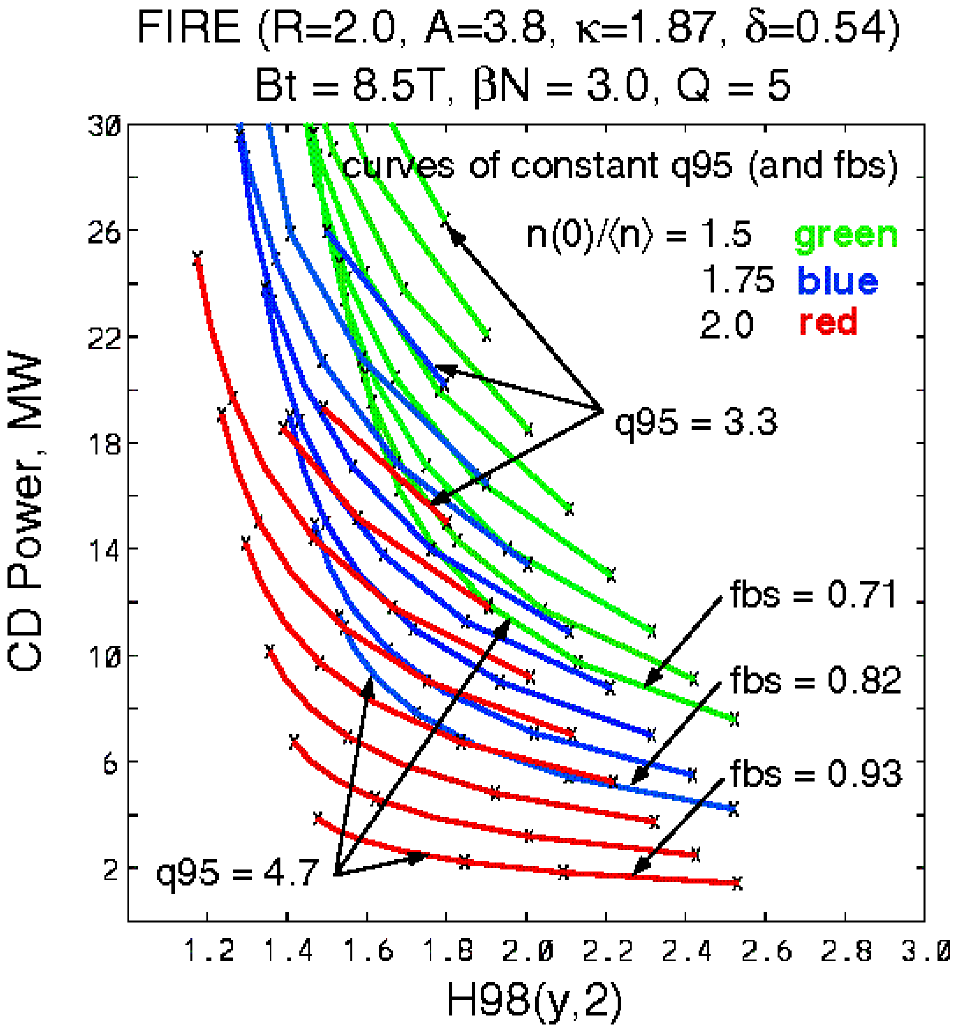
B_t = 6.5 - 9.5 T

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



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

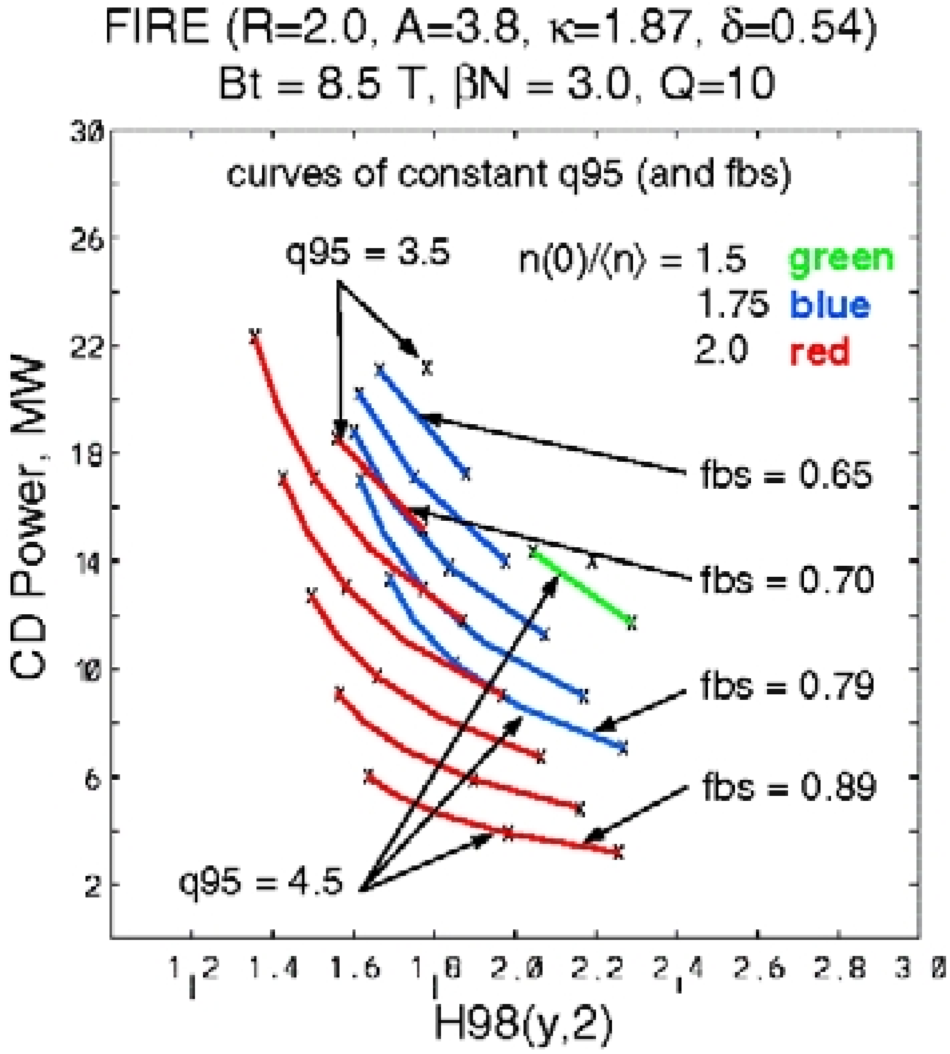
B_t = 6.5 - 9.5 T

Constrained to obey:

Power balance with Q=10

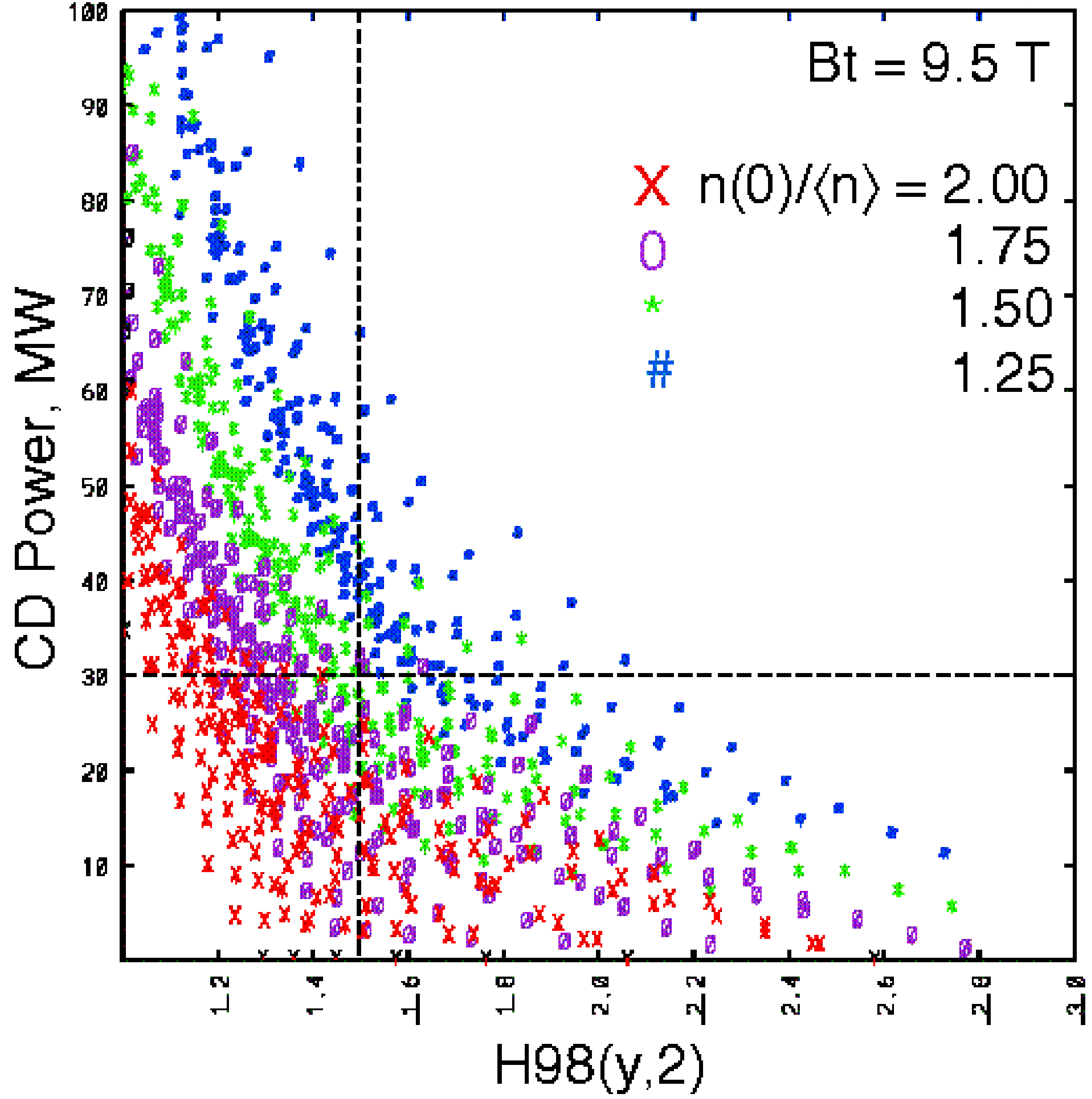
$P_{CD} < P_{aux}$, η_{CD} = 0.45 A/Wm^2, Pcd < 35 MW

P_{fusion} < 250 MW



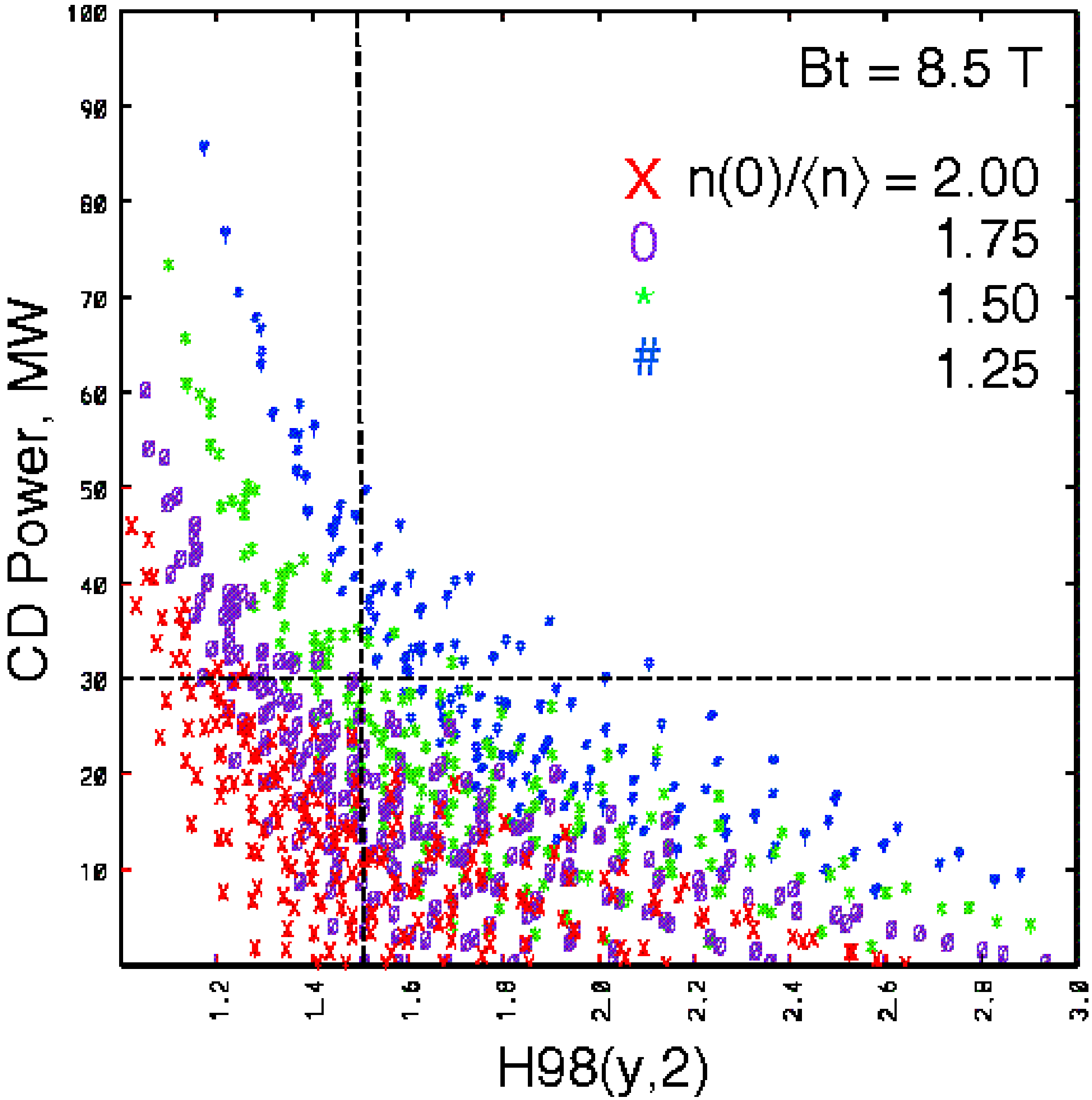
Q=5, 100% Non-inductive AT Plasmas

t(flattop) = 26 s



Q=5, 100% Non-inductive AT Plasmas

t(flattop) = 35 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

P(fus) ≤ 250 MW

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

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

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

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

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

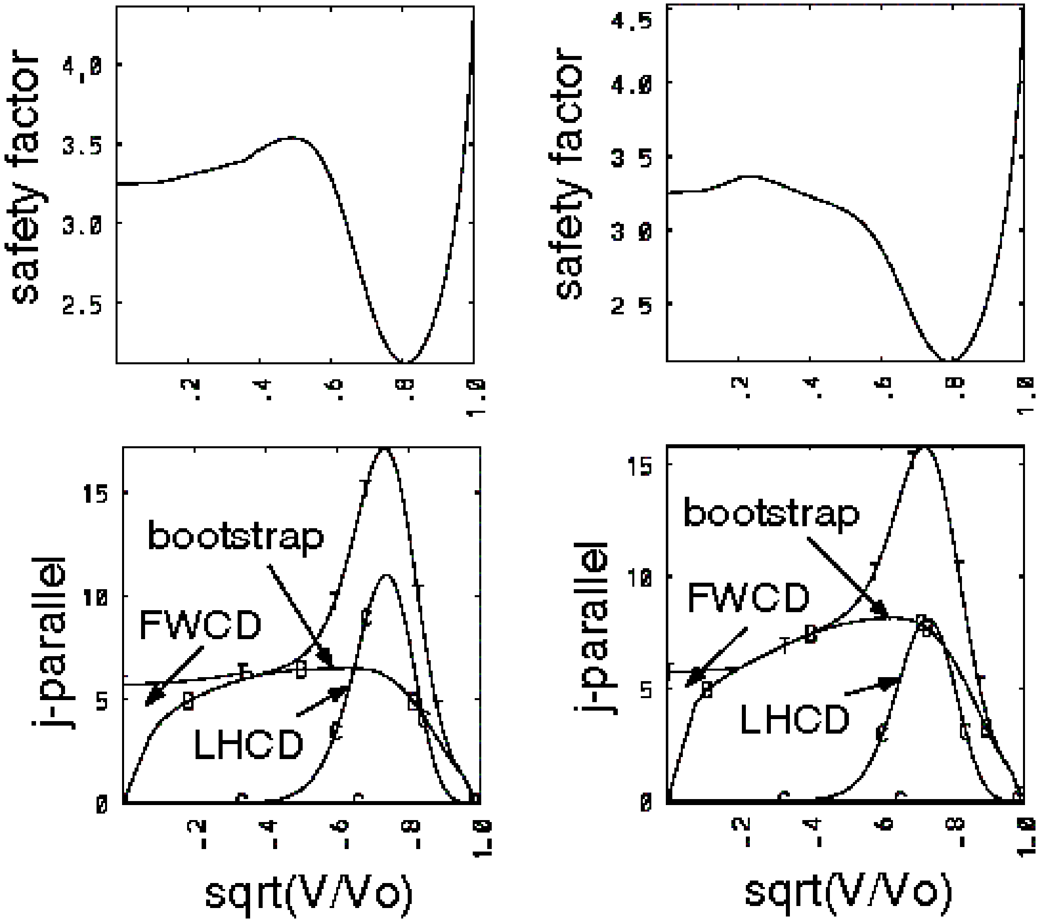
No wall stabilization

βN = 2.5

n=1 RWM stabilized

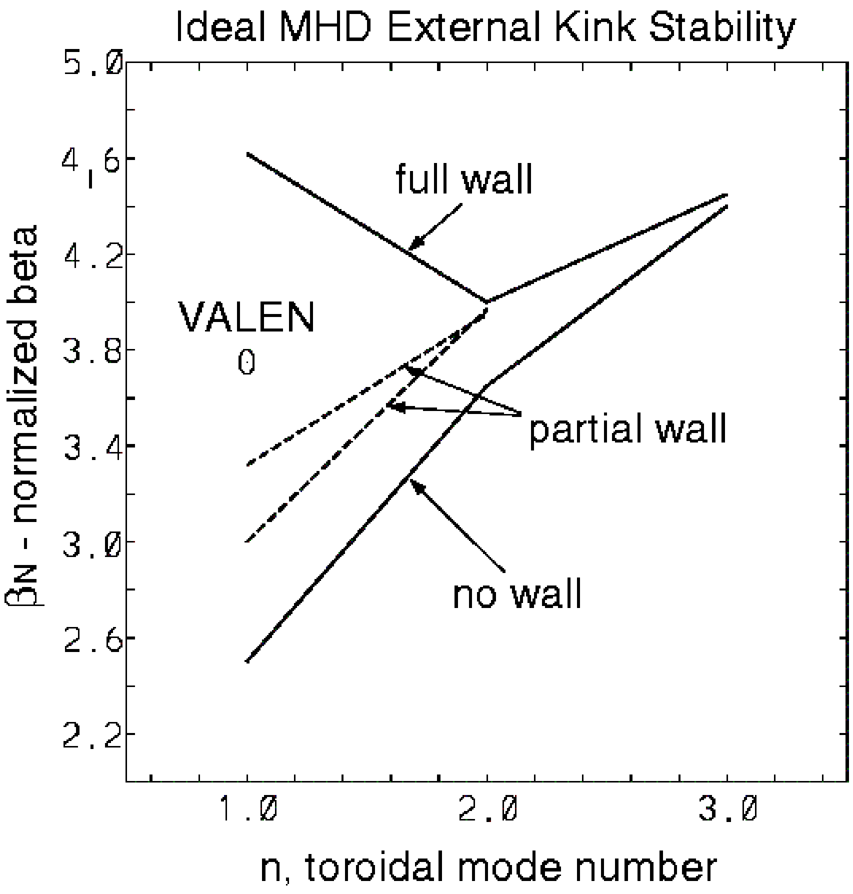
βN = 3.65

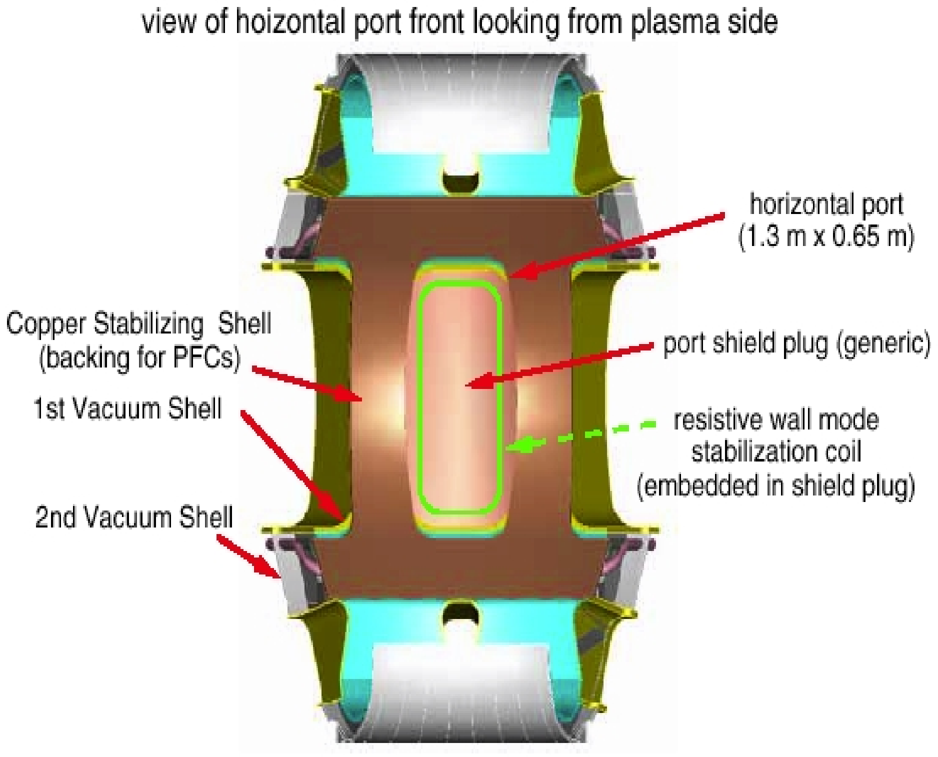
$\beta_N = 2.5$, $f_{bs} < 0.55$ $\beta_N = 3.65$, $f_{bs} < 0.75$



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

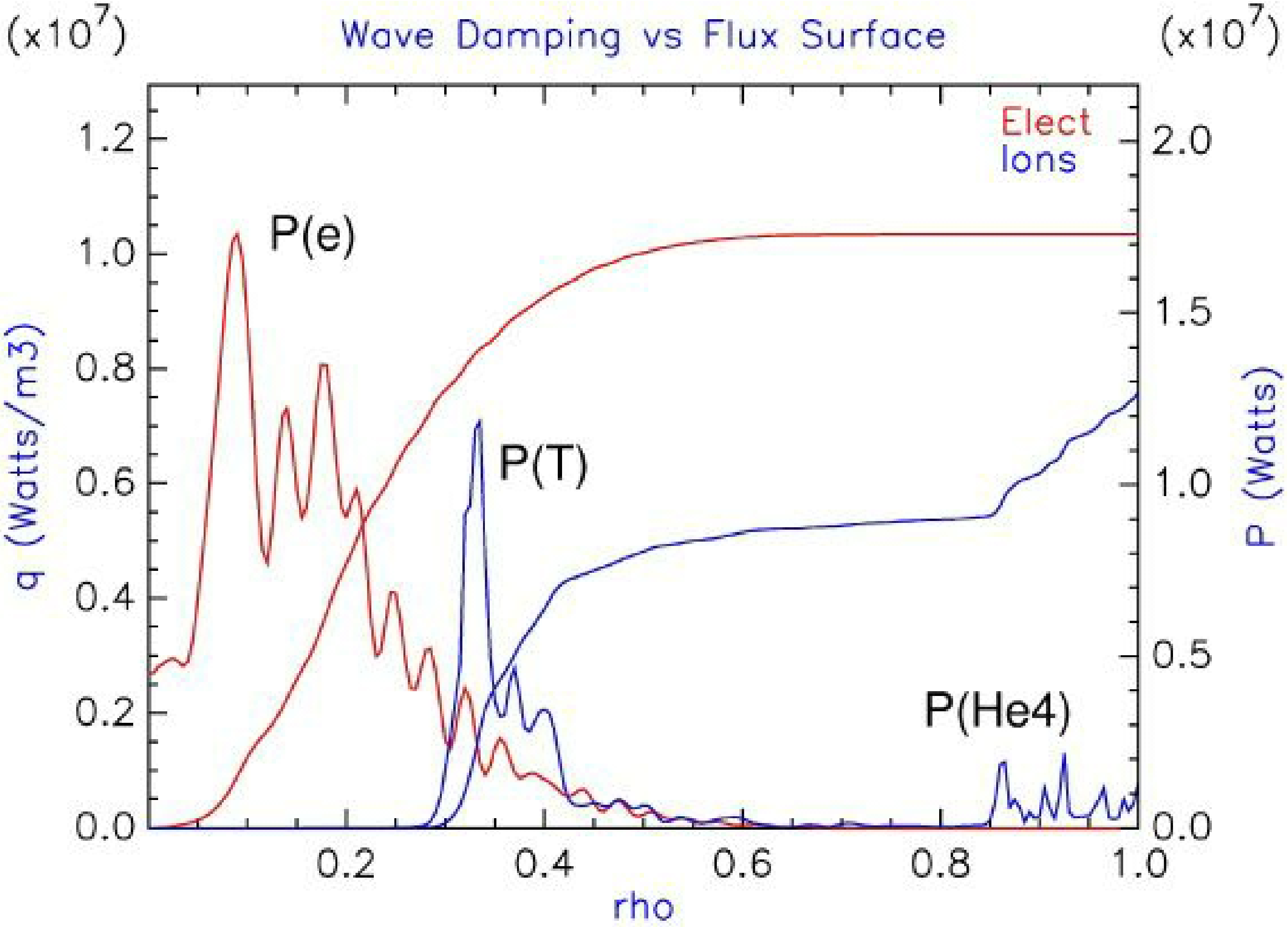
n(0) = 3.5x10^20 /m3

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



ICRF Heating and Current Drive

f = 80-120 MHz, P(ICRF) = 20 MW, 4 strap antennas, 4 ports

- Ion heating for Bt = 6.5-10 T
  - 2T resonance, requires 100 MHz at Bt = 10 T
  - Below Bt = 8 T, use 2D resonance, requires ≤ 120 MHz
- FWCD for Bt = 6.5-10 T
  - 115 MHz at Bt = 10 T
  - 109 MHz at Bt = 9.5 T
  - 98 MHz at Bt = 8.5 T
  - 86 MHz at Bt = 7.5 T
  - 75 MHz at Bt = 6.5 T
- ITB formation and control (C-Mod)
  - HFS heating at half-radius, 84-120 MHz for Bt = 7-10 T using 2T
  - LFS heating at half-radius, 80-90 MHz for Bt = 9.5-10 T using 2T
  - LFS heating at half-radius, 86-120 MHz for Bt = 6.5-9 T using 2D
- Be is primary impurity and its 2nd resonance is between 2D and 2T

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

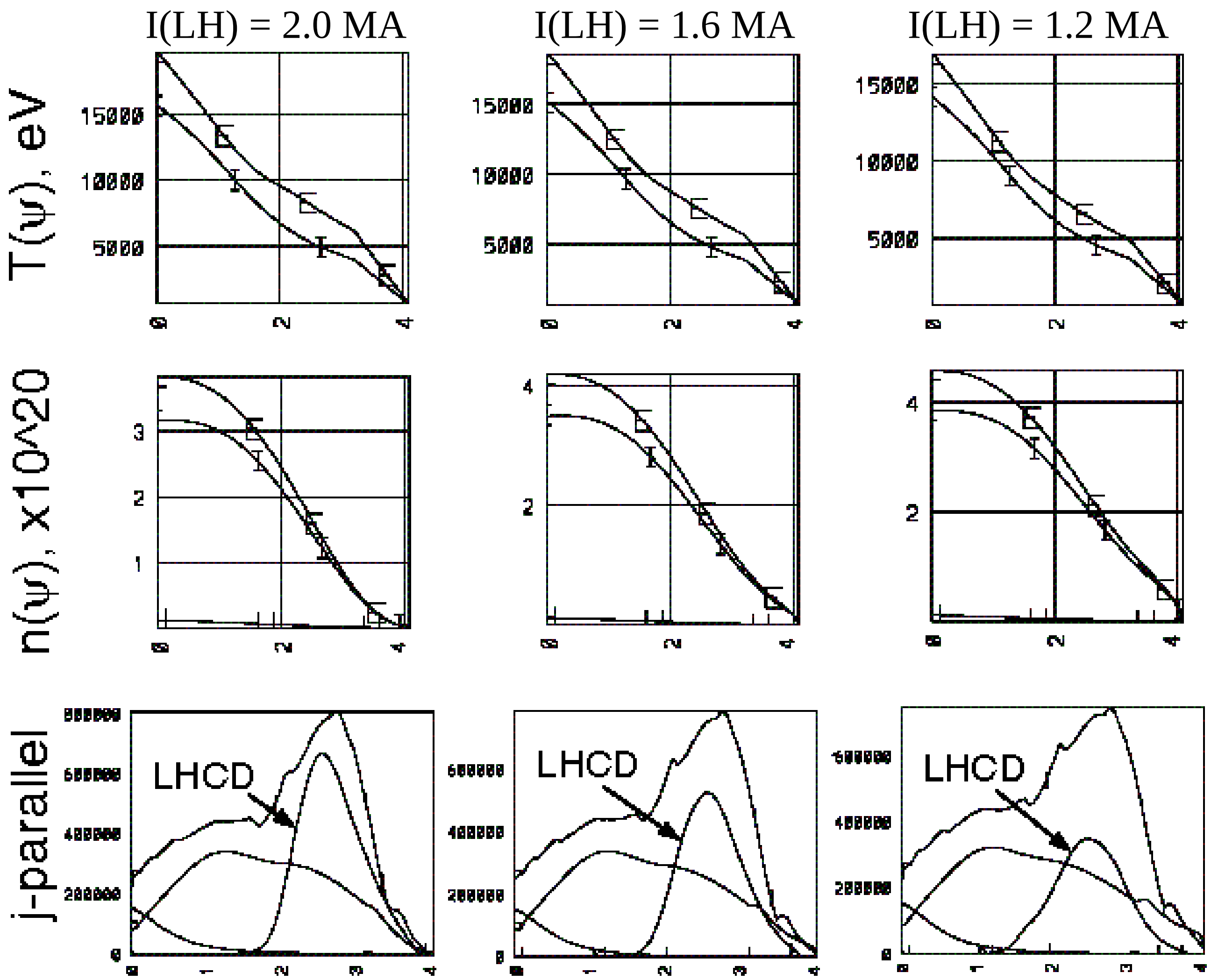
Deepest penetration

T(ψ) an n||

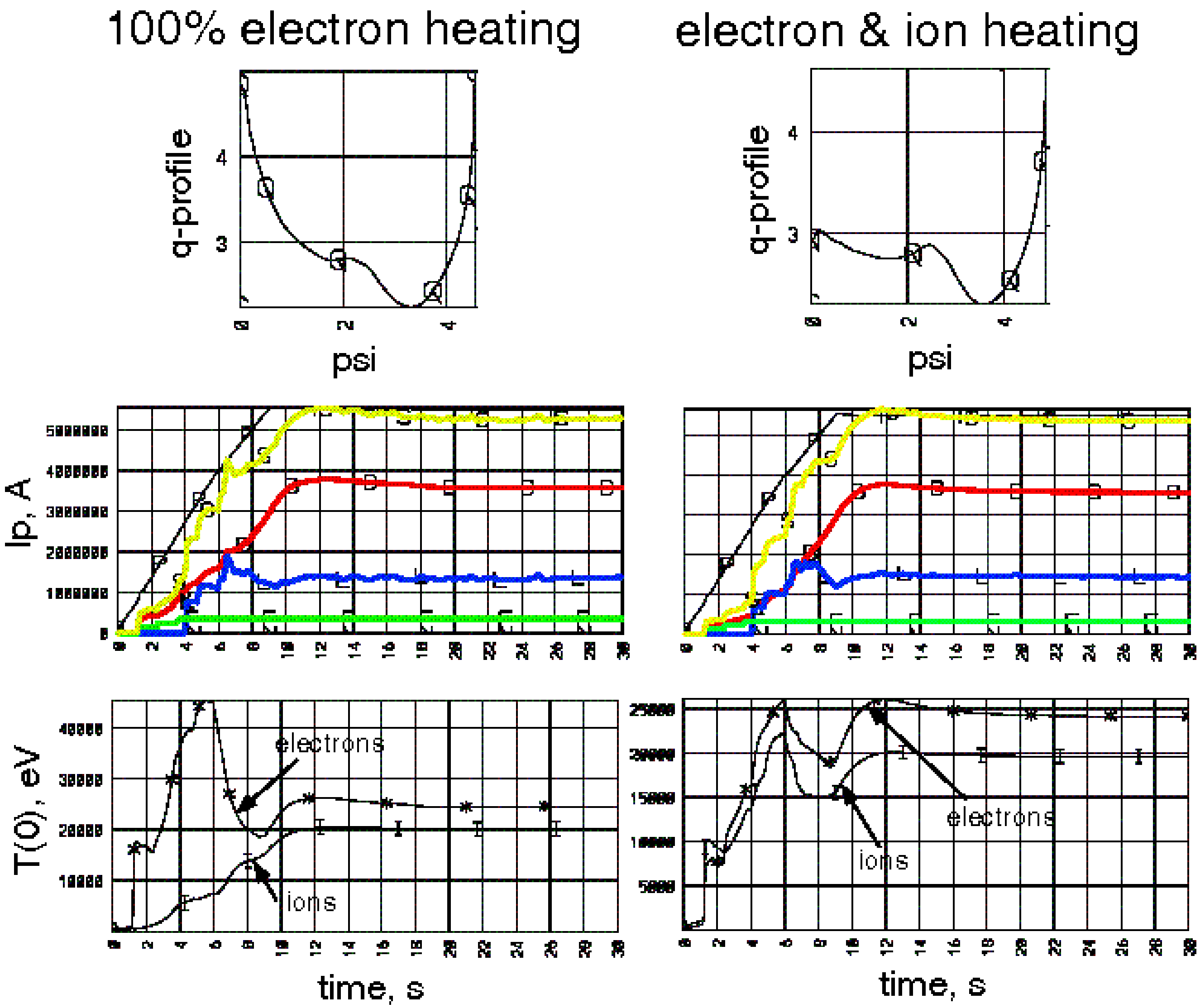
Avoid mode conversion

Maximum A/W

T(ψ)/n(ψ)



Electron and Ion Heating Split Can Strongly Influence AT Scenarios



100% electron heating

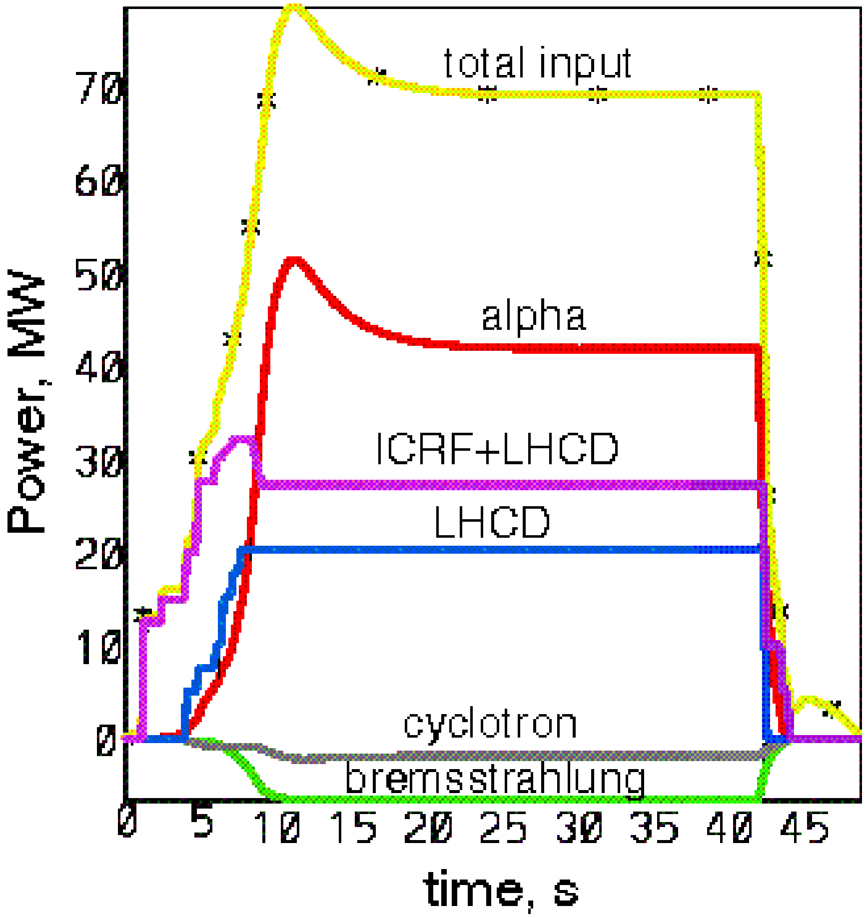
electron & ion heating

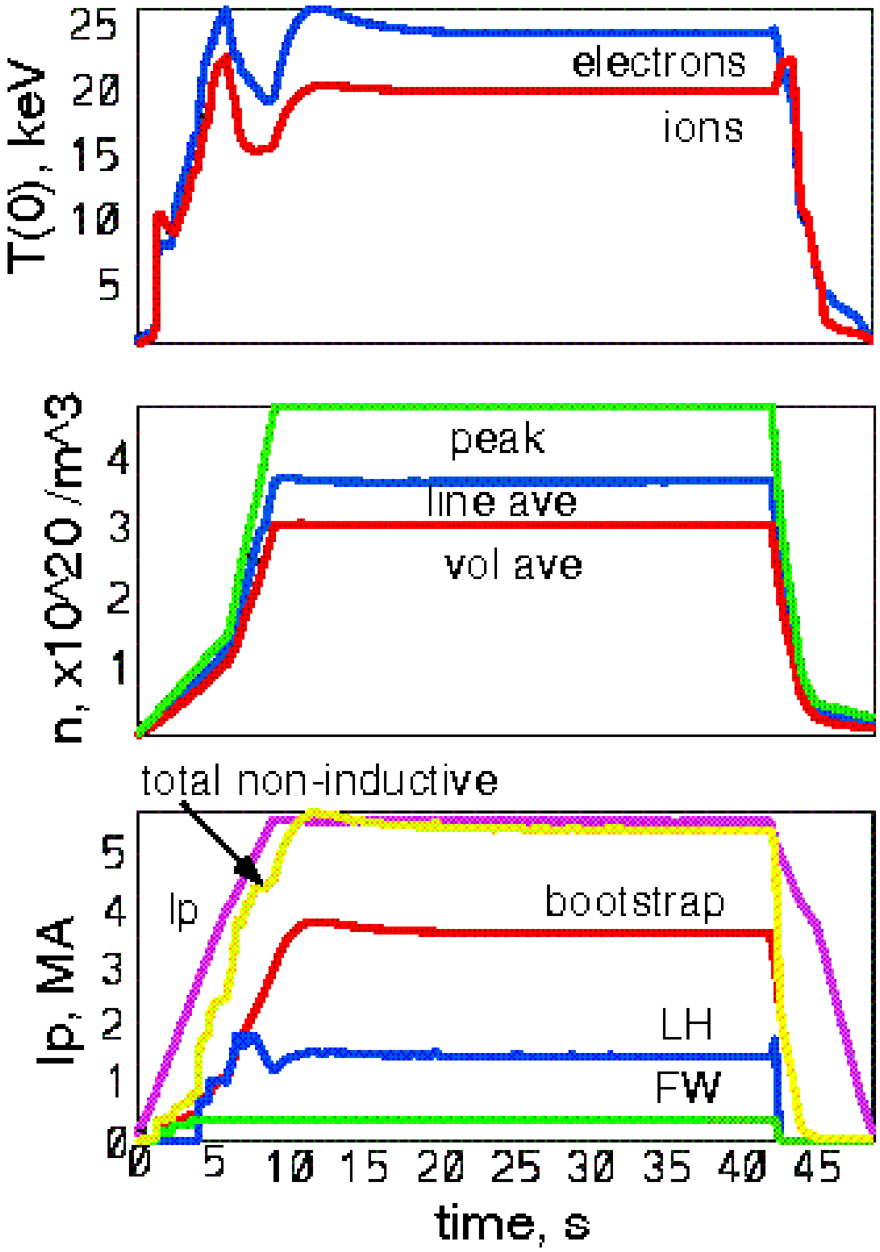
TSC-LSC Simulation of Burning AT Plasma in FIRE

- 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

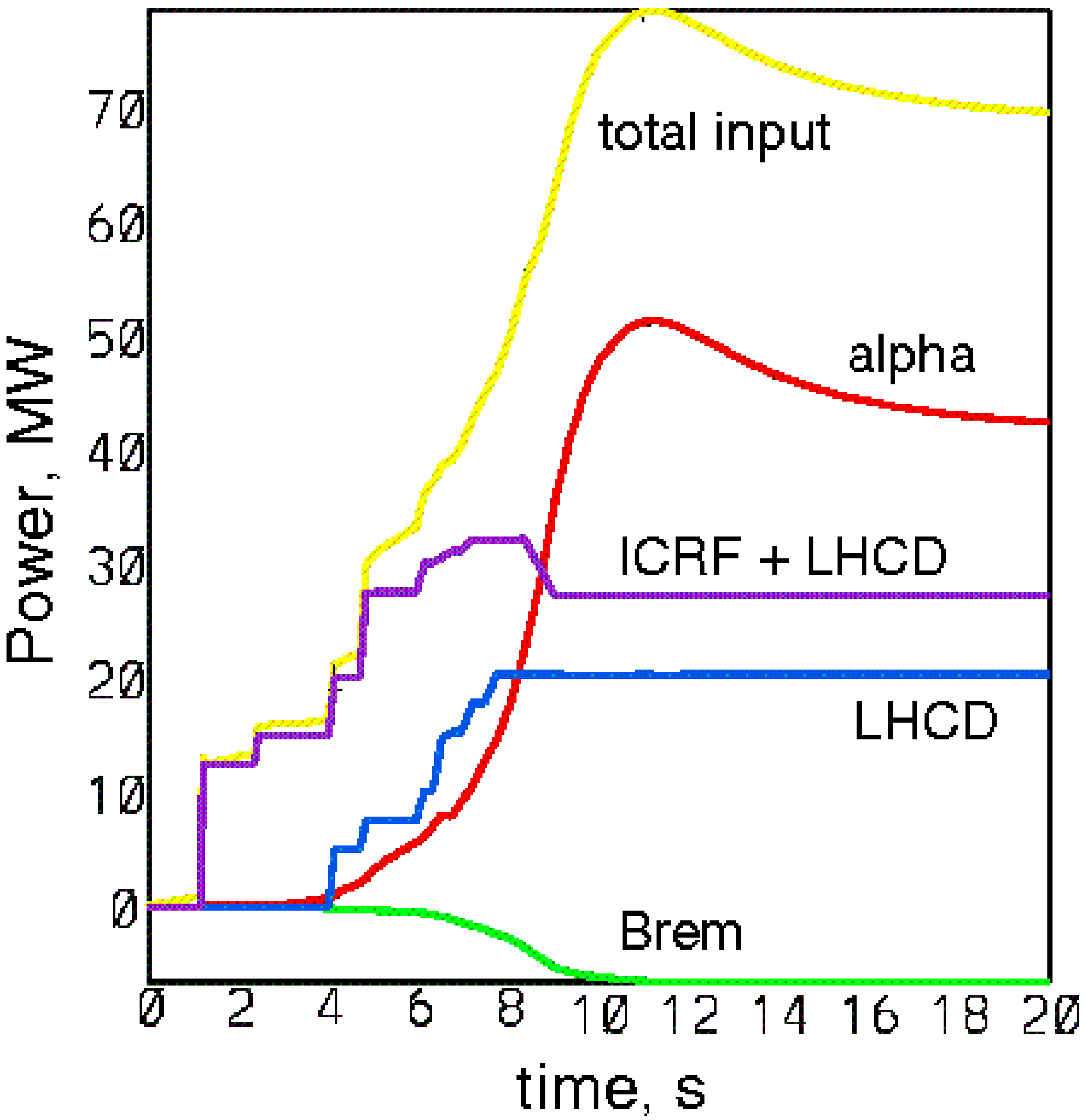
TSC-LSC Simulation of Q=7.8 Burning AT Plasma

t(flattop) = 32 s

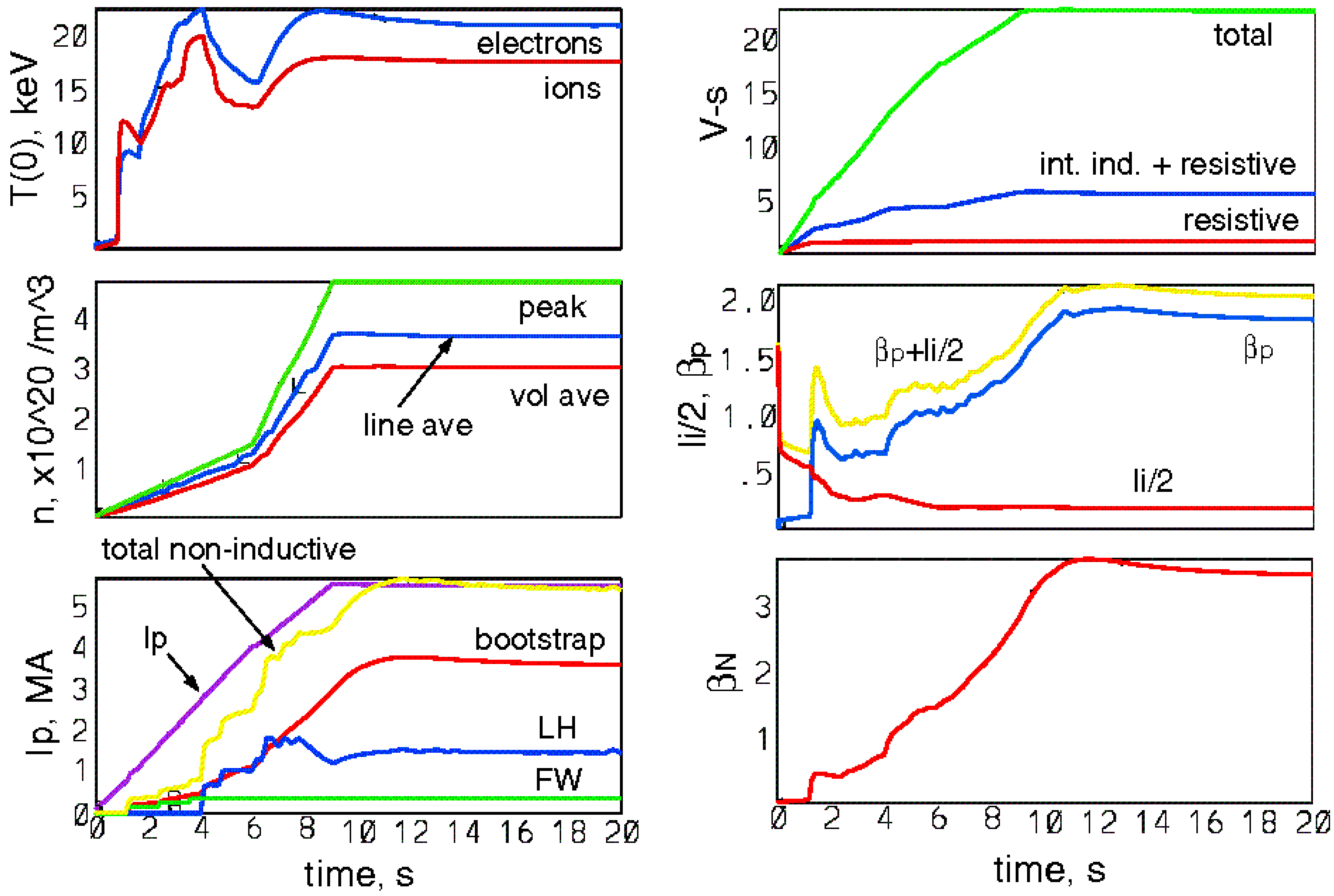




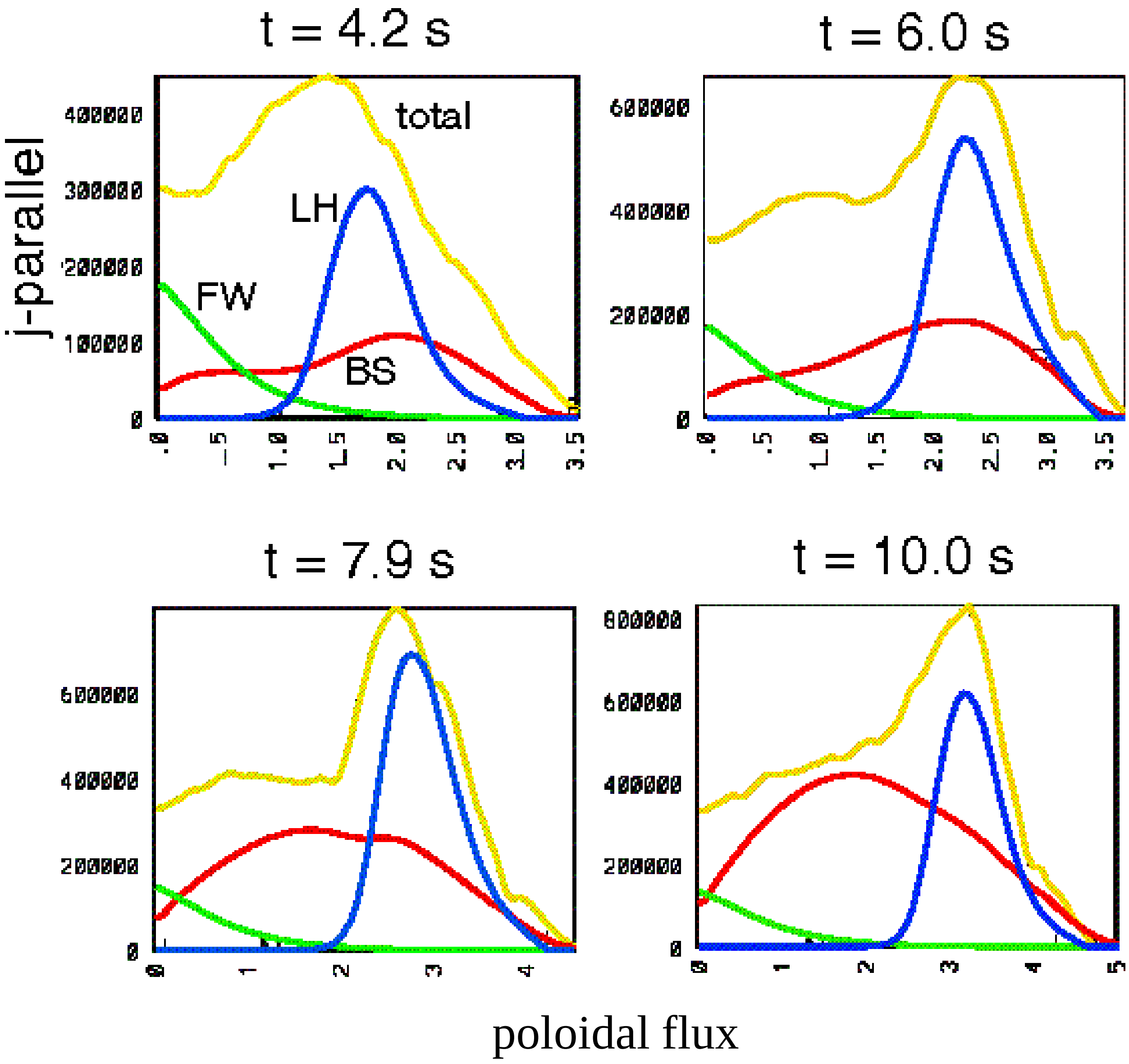
TSC-LSC Simulation of Q=7.8 Burning AT Plasma



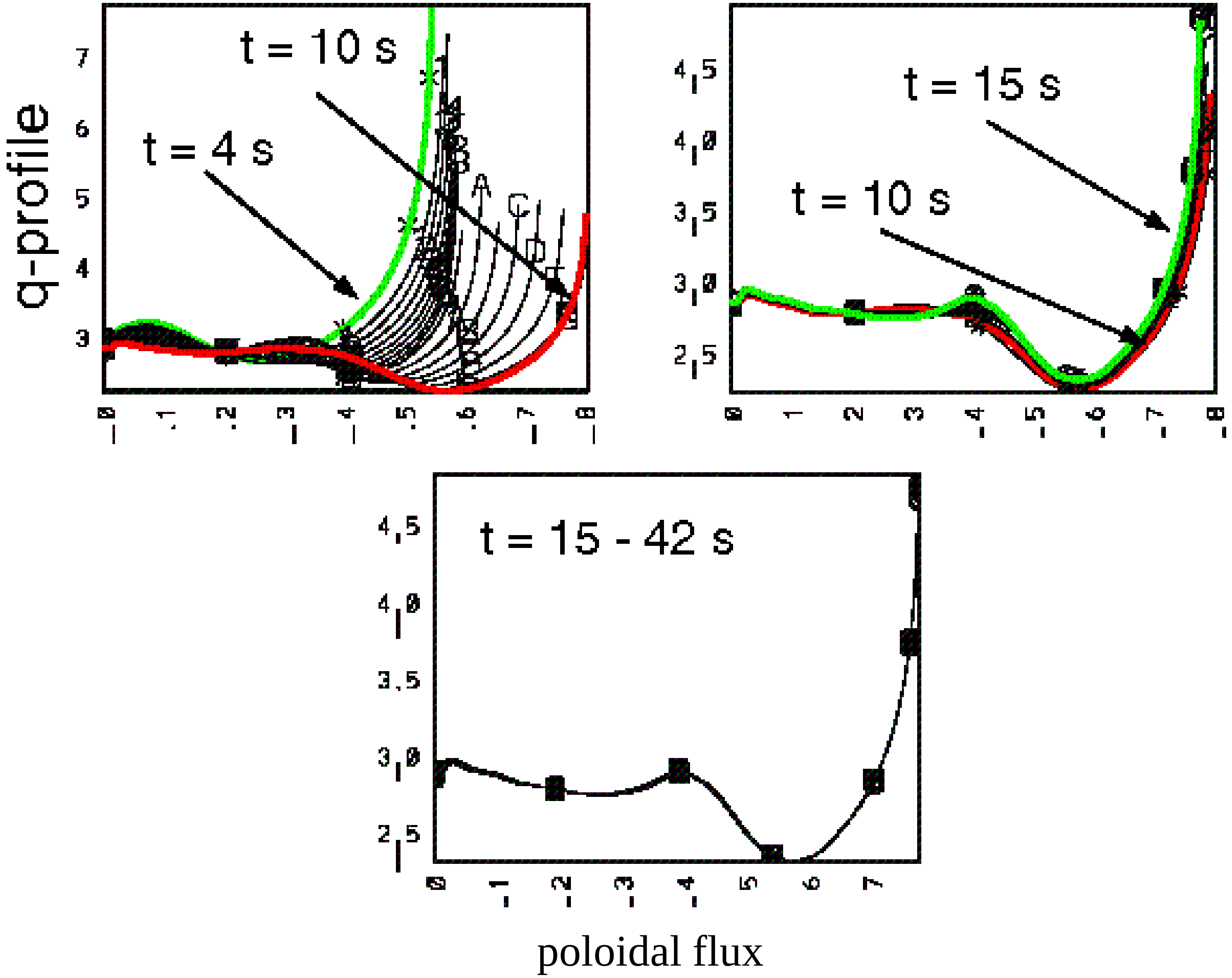
TSC-LSC Simulation of Q=7.8 Burning AT Plasma



TSC-LSC Simulation of Q=7.8 Burning AT Plasma

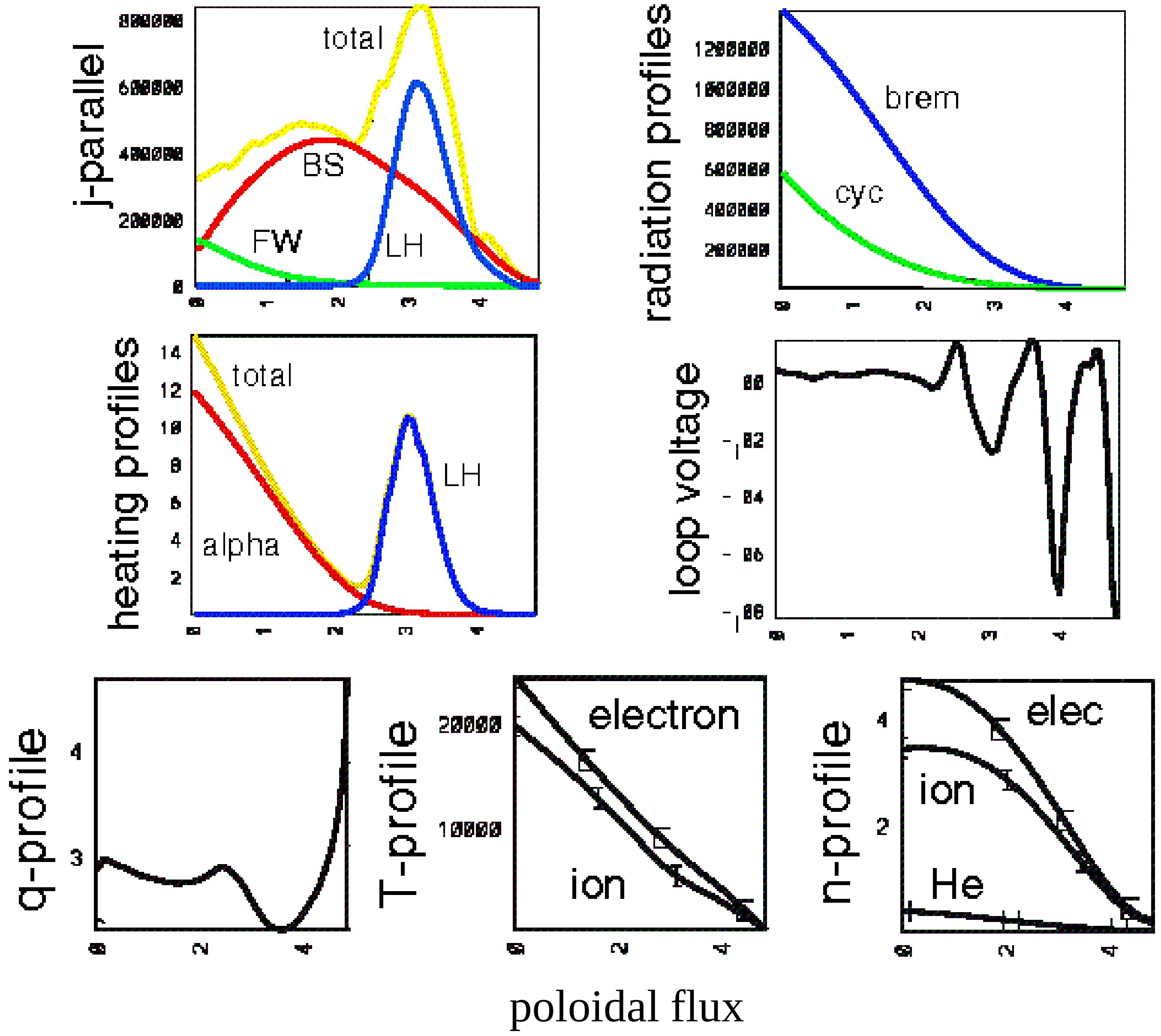


TSC-LSC Simulation of Q=7.8 Burning AT Plasma



TSC-LSC Simulation of Q=7.8 Burning AT Plasma

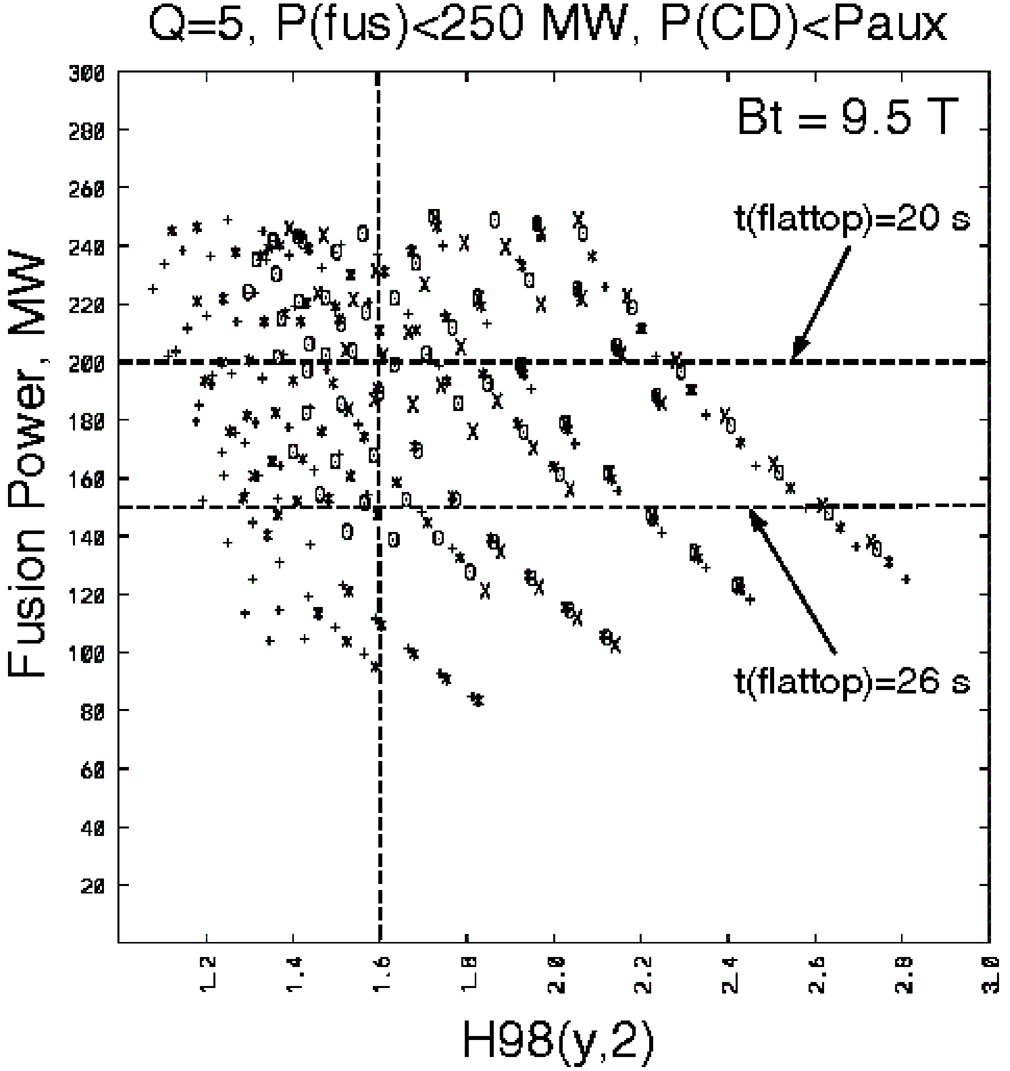
Flattop profiles



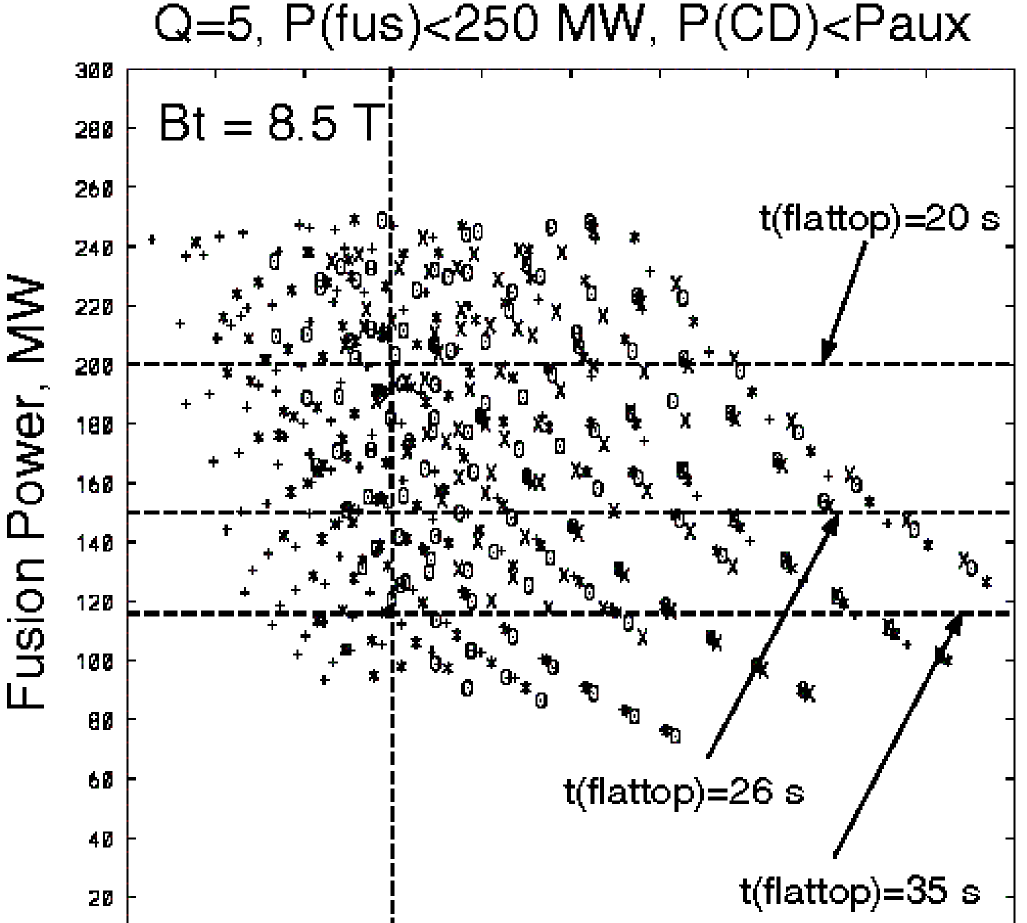
FIRE Flattop Time and AT Capability

- Present FIRE Design
  - Nuclear heating in VV, nuclear heating plus surface heating in FW tiles, and TF coil heating can limit flattop time
  - At P(fus)=200 MW, t(flattop)=20 s, due to VV nuclear heating which coincides with TF coil flattop at 10 T
- With conservative assumptions, FW tile heating appears not to limit flattop time for t(flattop) < 50 s
- Based on this, we can scale the flattop time with P(fus)
  - P(fus)=200 MW, t(flattop)=20s, Bt=6.5-9.5 T
  - P(fus)=150 MW, t(flattop)=26s, Bt=6.5-9.5T
  - P(fus)=115 MW, t(flattop)=35s, Bt=6.5-8.5T
  - P(fus)=82 MW, t(flattop)=49s, Bt=6.5-7.5T
- As P(fus) is reduced AT plasmas require higher H98 to maintain Q

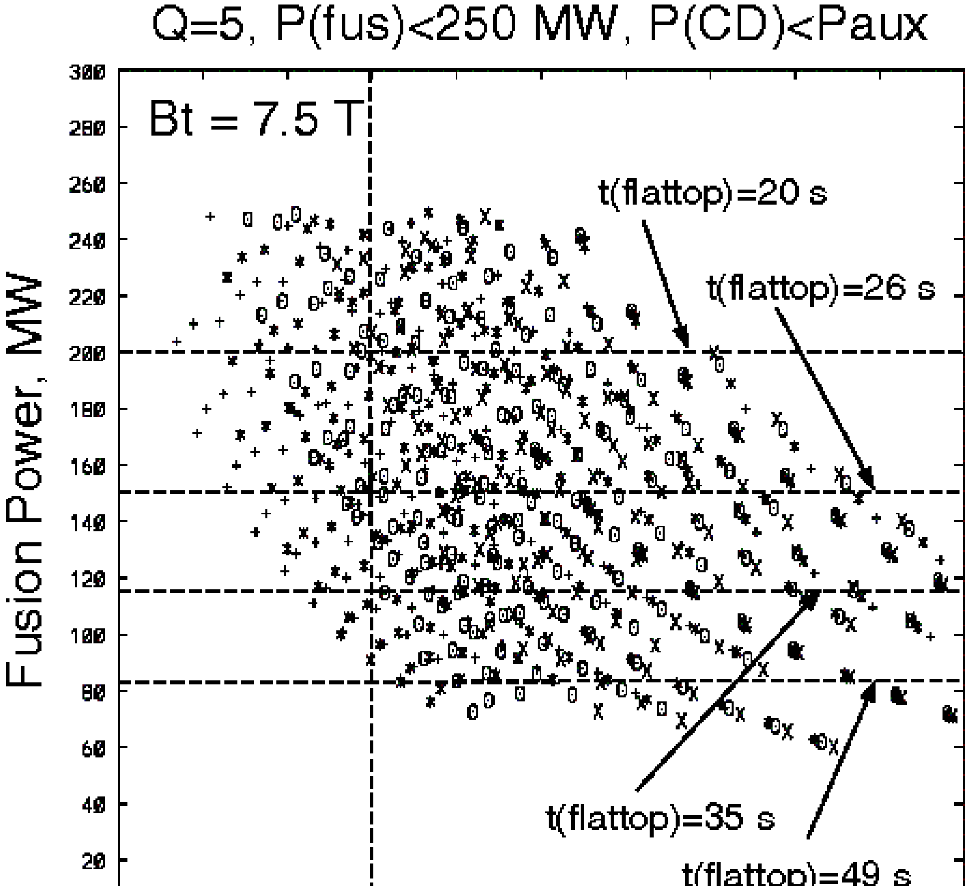
Bt = 9.5 T, AT Plasmas Within Fusion Power/Flattop Time Constraint



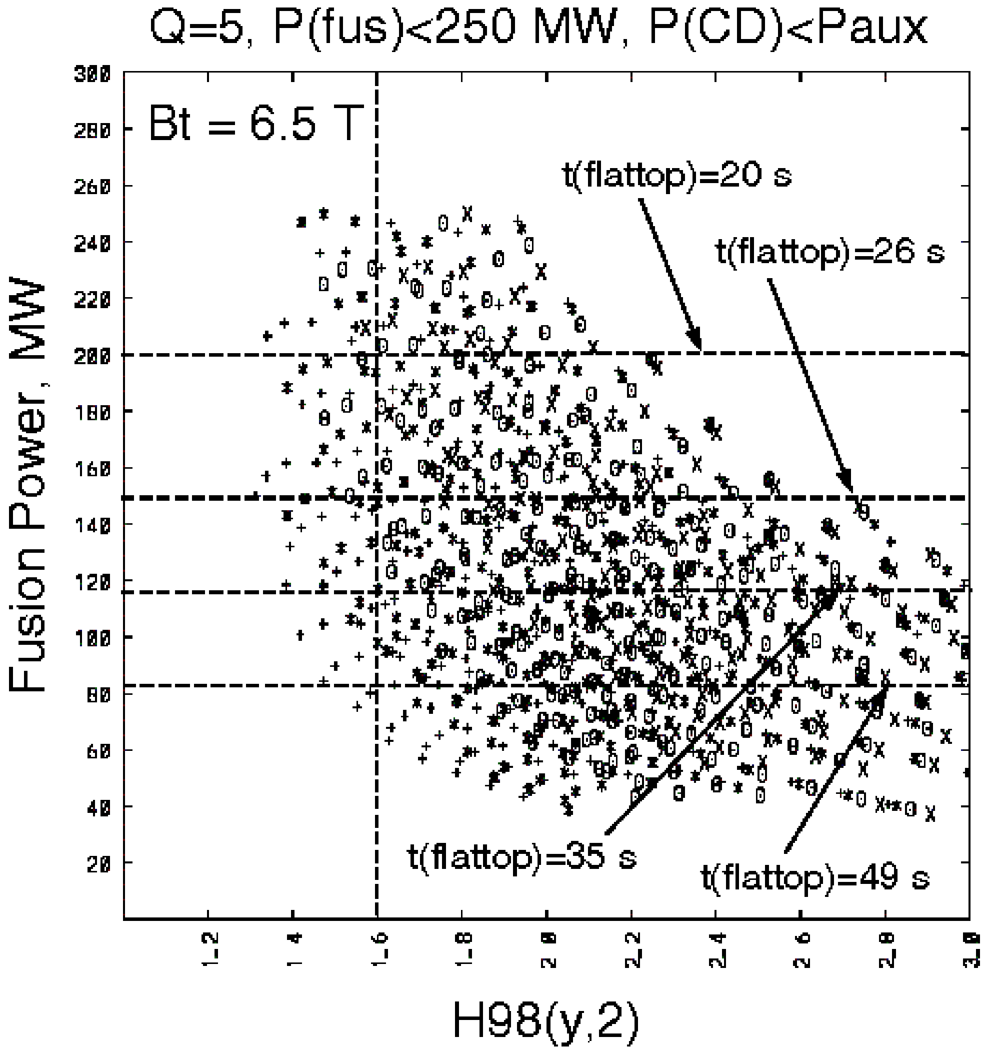
Bt = 8.5 T, AT Plasmas Within Fusion Power/Flattop Time Constraint



Bt = 7.5 T, AT Plasmas Within Fusion Power/Flattop Time Constraint



Bt = 6.5 T, AT Plasmas Within Fusion Power/Flattop Time Constraint



Minimum H98 Cases in Q=5 Database

Fusion Power/Flattop Time Constraint

n(0)/<n> P(fus)< 200 MW	Bt (T)	q95	Ip (MA)	HH(y,2)	n/nGr	fbs	Pcd(MW)	βN
2.00	9.5	3.5	6.38	1.18	0.45	0.46	33.4	2.0
2.00	8.5	3.5	5.70	1.13	0.75	0.58	34.9	2.5
2.00	7.5	3.3	5.34	1.19	0.95	0.66	31.7	3.0
1.75	9.5	4.1	5.44	1.20	0.85	0.60	37.8	2.5
1.75	8.5	3.3	6.05	1.23	0.55	0.48	38.9	2.5
1.75	7.5	3.1	5.68	1.27	0.65	0.54	35.8	3.0
1.50	9.5	4.3	5.20	1.40	0.65	0.54	33.0	2.5
1.50	8.5	3.9	5.12	1.41	0.75	0.59	33.2	3.0
1.50 P(fus)< 150 MW	7.5	3.5	5.03	1.42	0.85	0.61	34.0	3.5
2.00	9.5	4.1	5.44	1.25	0.55	0.54	25.3	2.0
1.75	9.5	4.7	4.75	1.34	0.95	0.68	25.2	2.5
1.50 P(fus)< 115 MW	9.5	4.7	4.75	1.53	0.65	0.59	24.6	2.5
2.00	8.5	4.3	4.64	1.33	0.95	0.71	20.0	2.5
1.75	8.5	4.3	4.64	1.43	0.75	0.63	22.5	2.5
1.50 P(fus)< 82 MW	8.5	4.5	4.44	1.70	0.55	0.56	19.3	2.5
2.00	7.5	4.7	3.75	2.20	0.45	0.93	1.4	3.0
1.75	7.5	4.7	3.75	1.74	0.95	0.82	8.9	3.0
1.50	7.5	4.7	3.75	1.84	0.85	0.71	14.3	3.0

FIRE Physics/AT Future Work

- Examine IFS/PPPL and MMM transport models
- Add particle transport to reference discharge with pellet fueling
- Update AT scenarios to FIRE* parameters
- Apply GLF23 and particle transport to AT scenarios
- Insert ICRF/FW module into TSC
- Provide FIRE* reference parameters and files for Snowmass
- Provide updated AT scenario parameters and files for Snowmass
- Work with various Snowmass subgroups to provide needed data
- Update vertical stability and control
- Examine PF scenario equilibria
- Startup calculation
- ???