Advanced Tokamak Scenarios for the Fusion Ignition Research Experiment

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FIRE is Pursuing Burning Advanced Tokamak Plasmas

- High potential benefits of Advanced Tokamak operation make AT research mandatory on any Burning Plasma Experiment (Snowmass 1999)
- ARIES Power Plant studies show that AT plasmas provide
  - High β **---->** high fusion power density
  - Large bootstrap (self-driven) current and good alignment **---->** low recirculating power
  - Good plasma confinement consistent with high β and high bootstrap current **---->** high fusion gain Q
  - This combination drives down the machine size and the cost of electricity (COE)
- FIRE must demonstrate that these plasmas can be established and maintained in a stationary state

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 ≥ 1-2 current diffusion times
  - Study and resolve both standard (H-mode) and advanced tokamak (AT) burning physics issues
  - Keep the device cost at ≈ $1 B

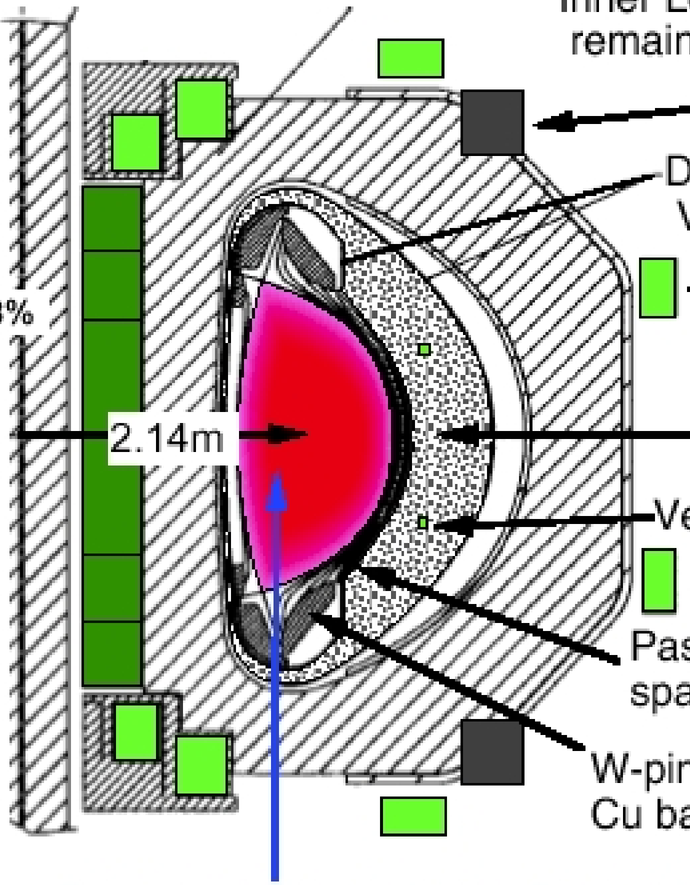
Limitations for FIRE’s Flattop Time

- TF coil heating
  - For B_T = 10 T, t(flattop) = 20 s
  - For B_T = 8.5 T t(flattop) = 35 s
- Nuclear heating of Vacuum Vessel (stress limit)
  - For P_{fusion} = 200 MW, t(flattop) = 20 s
- Nuclear and Surface heat load on FW tiles (temp limit)
  - For 120% radiated power assumption, not limiting until t(flattop) > 50 s
- PF coil heating (rarely limiting, except..)
  - For low li Advanced Tokamak modes, Ip < 5 MA to allow t(flattop) = 20-35 s, due to divertor coil heating and stress limits

Fusion Ignition Research Experiment

AT Features

- DN divertor
- strong shaping
- very low ripple < 0.3%
- internal coils
- space for wall stabilizers
- inside pellet injection
- large access ports



Wedged TF Coils (16), 15 plates/coil*
Inner Leg BeCu C17510,
remainder OFHC C10200

Compression Ring

Double Wall Vacuum
Vessel (316 S/S)

All PF and CS Coils*
OFHC C10200

Internal Shielding
(60% steel & 40%water)

Vertical Feedback and Error
Field Correction Coils

Passive Stabilizer Plates
space for wall mode stabilizers

W-pin Outer Divertor Plate
Cu backing plate, actively cooled

Direct and Guided Inside Pellet Injection

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

FIRE's Advanced Tokamak Development is a Sequence of Improvements

Increase β

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

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

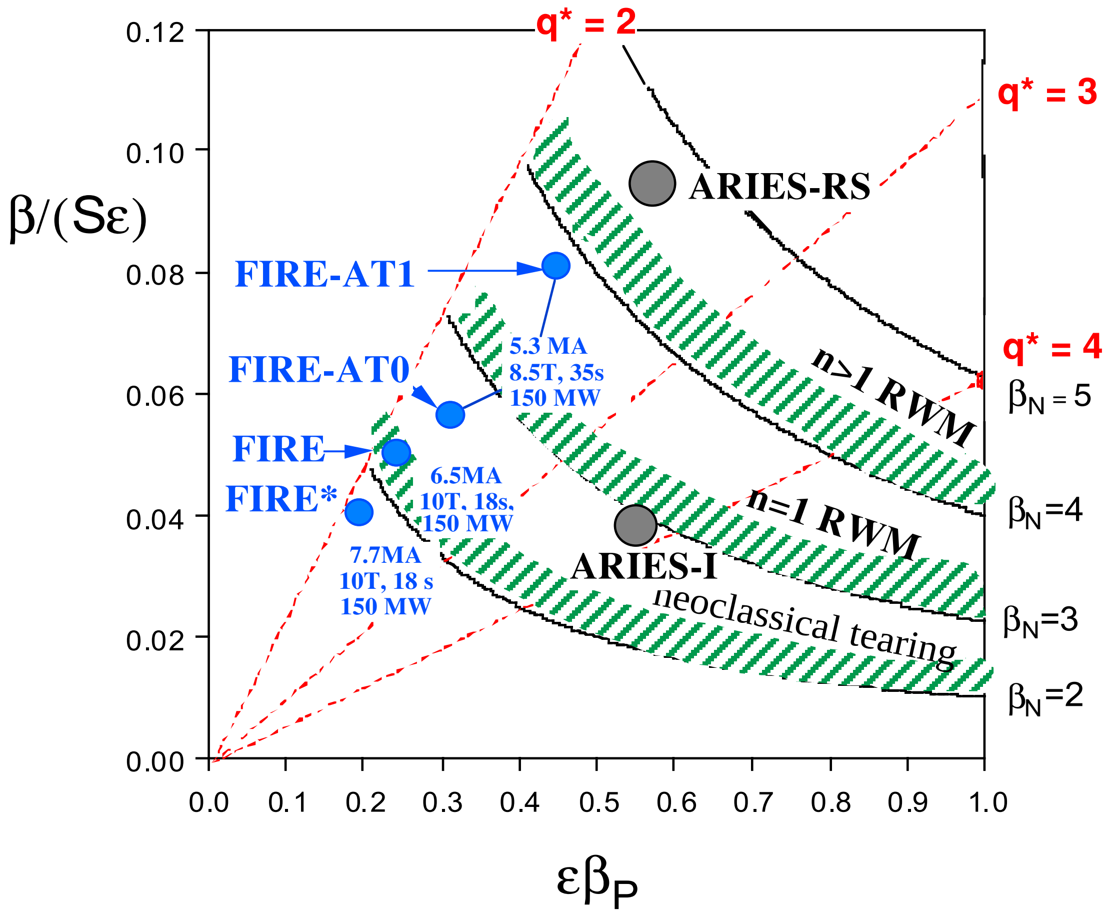
- Increase β
- Current drive
- Control of n and T profiles

Extend pulse lengths

More sophisticated control

Optimize plasma edge/SOL/divertor

Attractive AT plasmas have been identified by ARIES Power Plant studies



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 that are consistent with bootstrap and CD

FIRE Has Adopted the AT Features Identified by ARIES Studies

- High toroidal field
- Double null
- Strong shaping
  - $\kappa = 2.0$, $\delta = 0.7$
- Internal vertical position control coils
- Cu wall stabilizers for vertical and kink instabilities
- Very low ripple (0.3%)
- ICRF/FW on-axis CD
- LH off-axis CD
- LHCD stabilization of NTMs
- Tungsten divertor targets
- Feedback coil stabilization of RWMs
- Burn times exceeding current diffusion times
- Pumped divertor/pellet fueling/impurity control to optimize plasma edge

Systems Analysis Shows That H98 > 1.2 for Q=5

Generate large database of solutions to power balance

$\beta_N = 2.0\text{-}5.0$

$q_{95} = 3.1\text{-}4.7$

$n(0)/\langle n\rangle = 1.25\text{-}2.0$

$n/n_{Gr} = 0.3\text{-}0.95$

$B_t = 6.5\text{-}9.5$ T

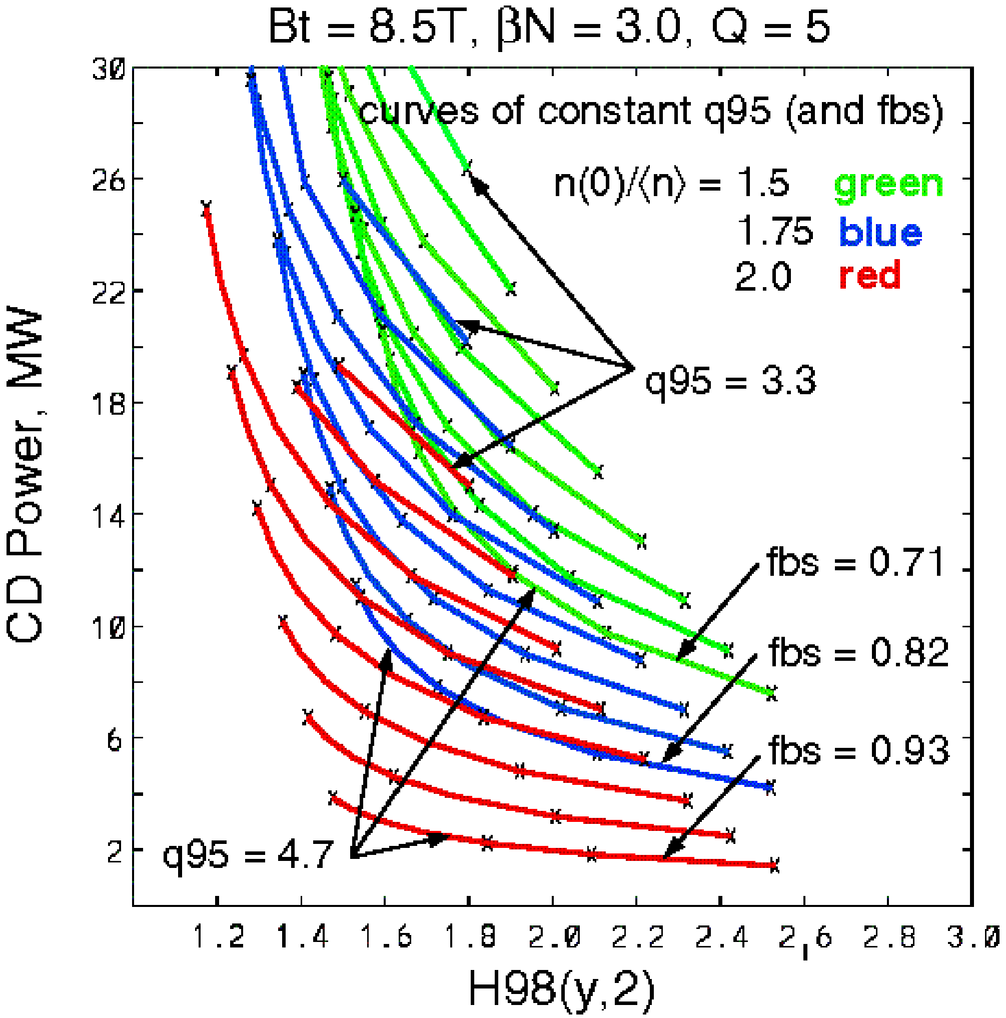
$Q = 5\text{-}10$

Apply screens to database to find trends and viable operating points

$P_{CD} < P_{AUX}$

$P_{CD} < 35$ MW

$P_{fusion} < 250$ MW



FIRE Can Access a Large AT Operating Space within Physics and Eng. Constraints

$B_t = 7.5\text{-}9.5$ T

$q_{95} = 3.1\text{-}4.7$

$n(0)/\langle n\rangle = 1.25\text{-}2.0$

$n/n_{Gr} = 0.3\text{-}1.0$

$\beta_N = 2.0\text{-}5.0$

$P_{CD} < 30$ MW

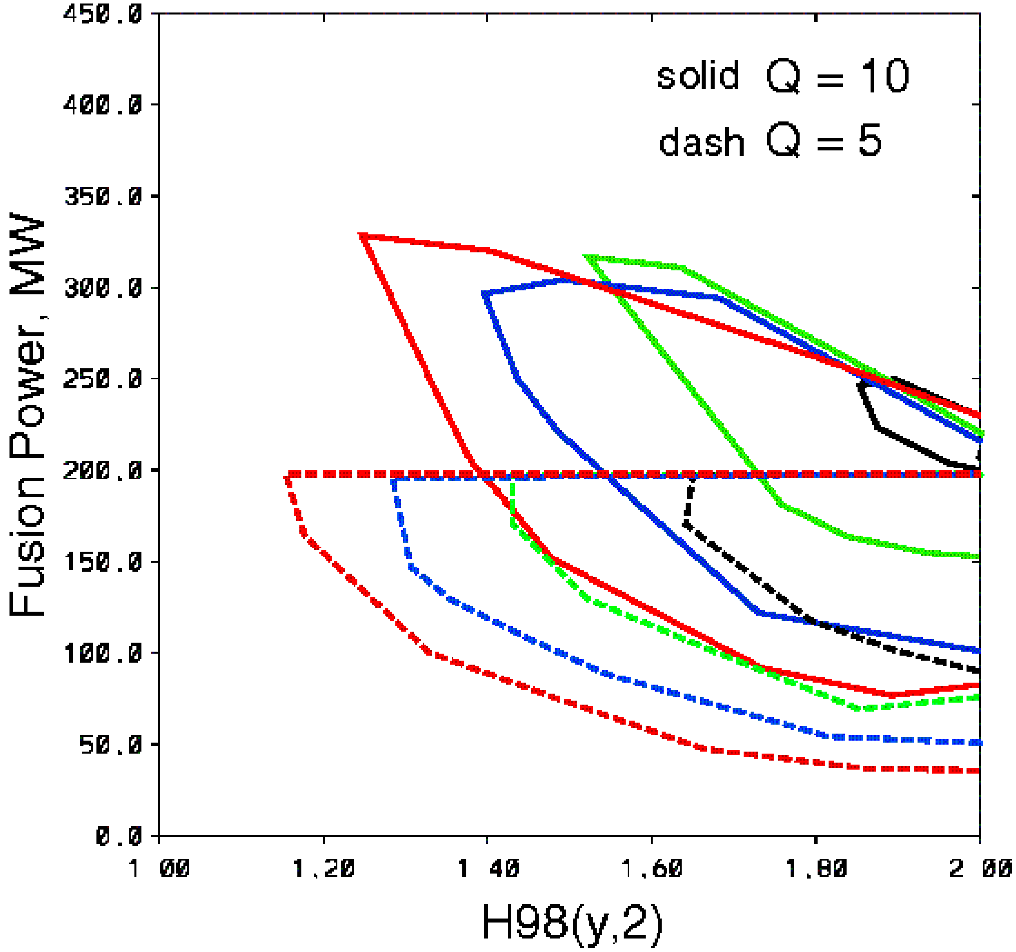
$P_{AUX} < 40$ MW

t(flattop) ≥ 1× τ(current relax)

$\tau_E = H_{98}(y,2) \times f(I_p,R,\varepsilon,B_t,n_{20},\kappa,P)$

$H_{98}(y,2) = 1$, standard ELMy H-mode

$n(0)/\langle n\rangle$ = 2.00 red
1.75 blue
1.50 green
1.25 black



High $n(0)/\langle n\rangle$, high n/n_{Gr}, and high f_{BS} give lowest H98

Systems Analysis Show Critical Requirements for Burning AT Plasmas

- Burning AT plasmas must simultaneously meet
  - Plasma power balance (a given Q)
  - $P_{CD} \leq P_{aux}$
  - Can't operate at very low density to make CD efficiency higher
- Density profile peaking
  - Pellet fueling
  - Internal transport barrier (ITB) in particle channel
  - Very broad density profiles require high H98 and P_{CD}
- Ability to approach or exceed Greenwald density limit
  - Requires high bootstrap fraction
  - High n/n_{Gr} reduces required H98 and increases required P_{CD}
- IPB98(y,2) global energy confinement scaling penalizes higher β
  - Individual experiments do not support this trend
  - Predictions for H98 factors may be pessimistic

Stabilization of NTMs with LHCD on FIRE

Make Δ′ more negative

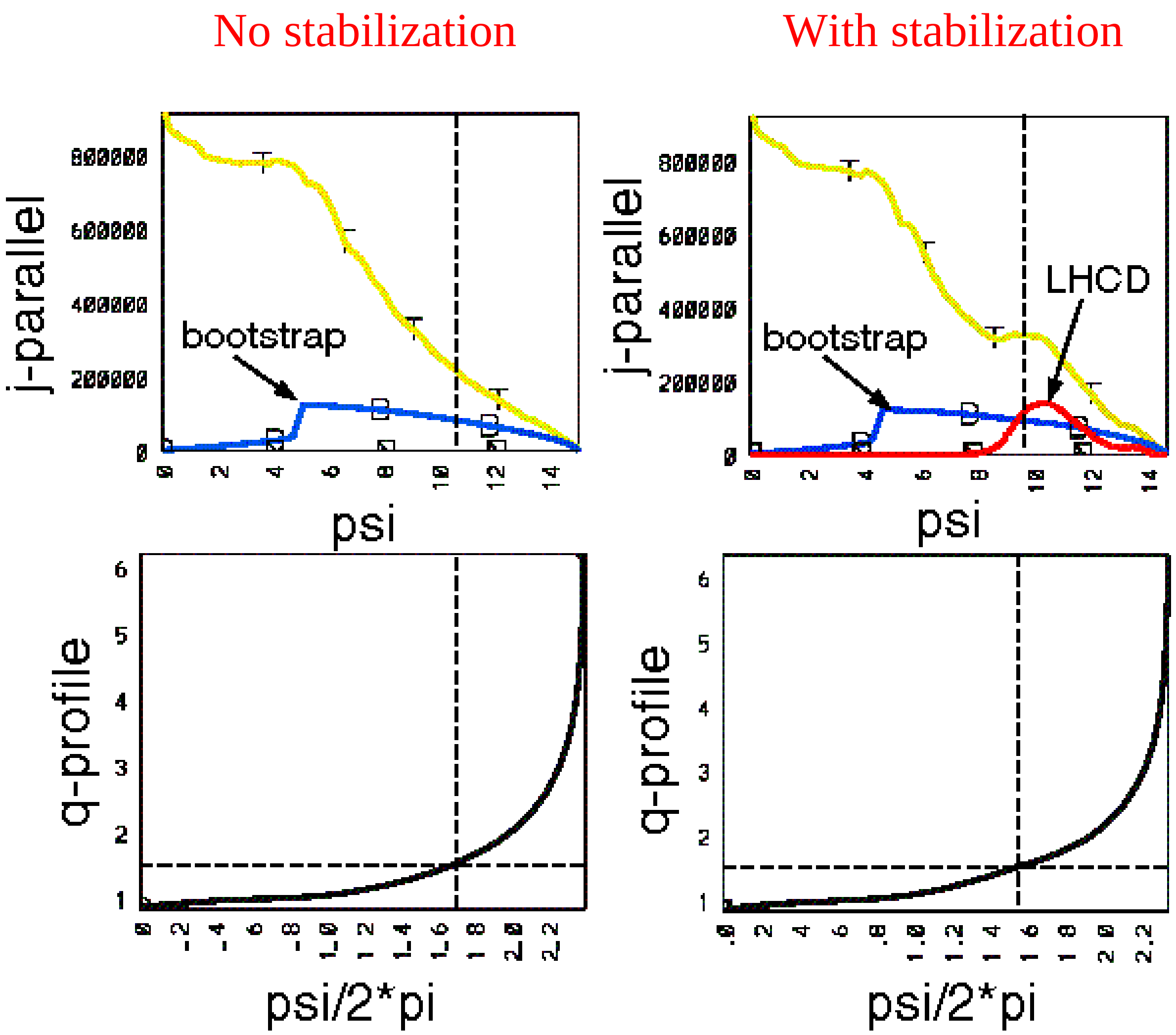
12.5 MW of LHCD injected

(3,2) surface targeted

I(LH)=0.65 MA

Pursuing PEST3 resistive analysis

Compass-D shown NTM stabilization with LHCD


No stabilization

With stabilization

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 = 5.4 MA

Bt = 8.5 T

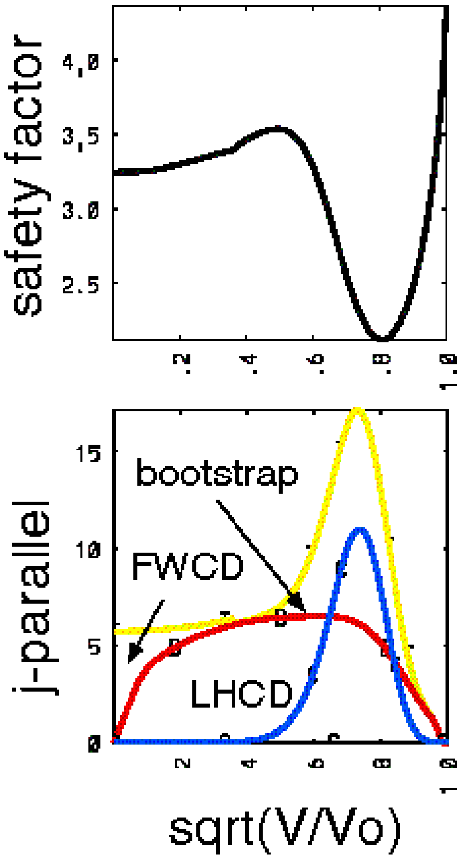
No wall stabilization

$\beta_N = 2.5$

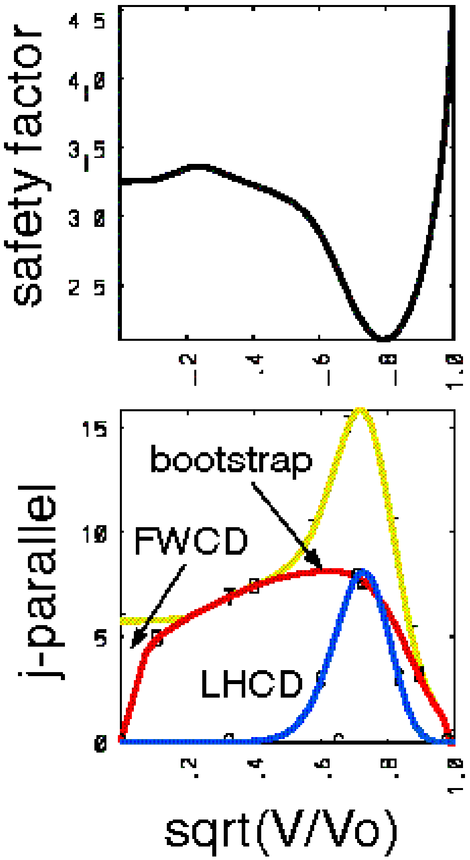
n=1 RWM stabilized

$\beta_N = 3.65$

$\beta_N = 2.5$, $f_{bs} < 0.55$,
I(LH)=2.1 MA,
I(FW)=0.25 MA

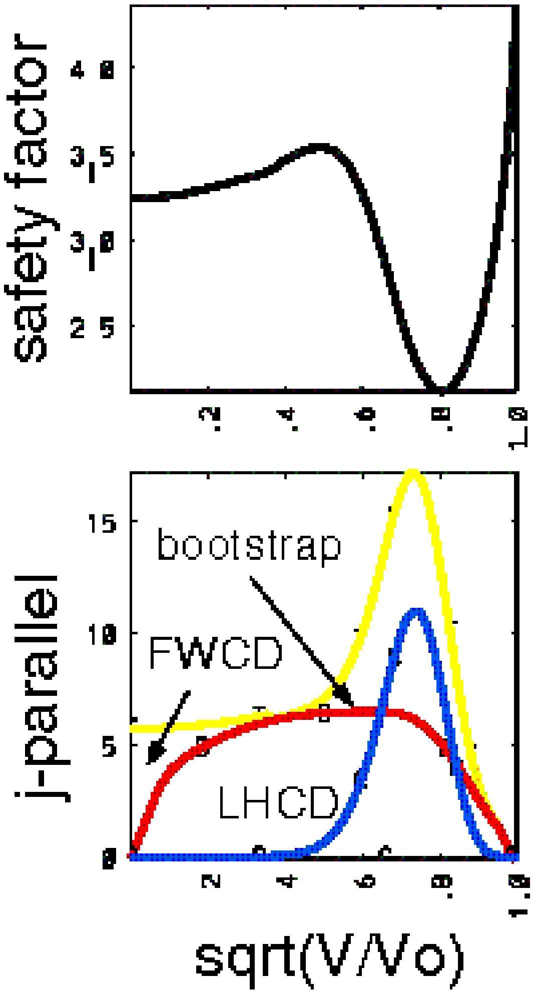


$\beta_N = 3.65$, $f_{bs} < 0.75$,
I(LH)=1.5MA,
I(FW)=0.2 MA

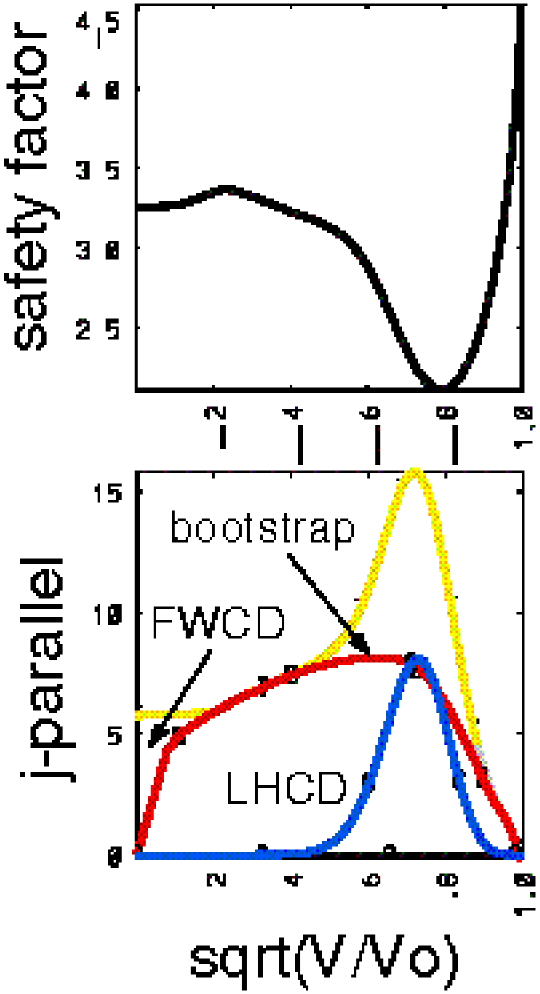


FIRE’s Advanced Tokamak Plasmas are Prototypes Leading to ARIES-AT

No wall stabilization,
β_N=2.5, f_{BS}=50%

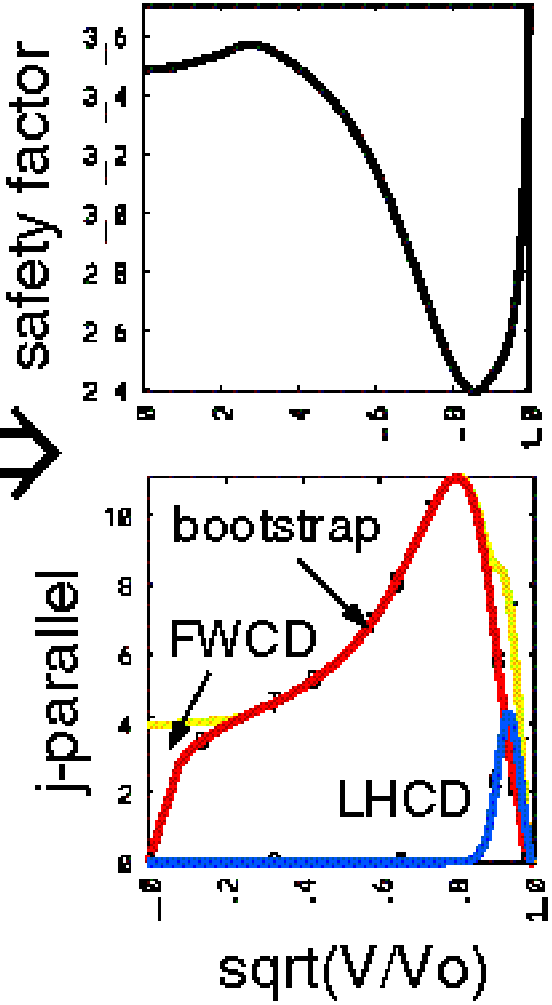


n=1 RWM stabilized,
β_N=3.7, f_{BS}=70%



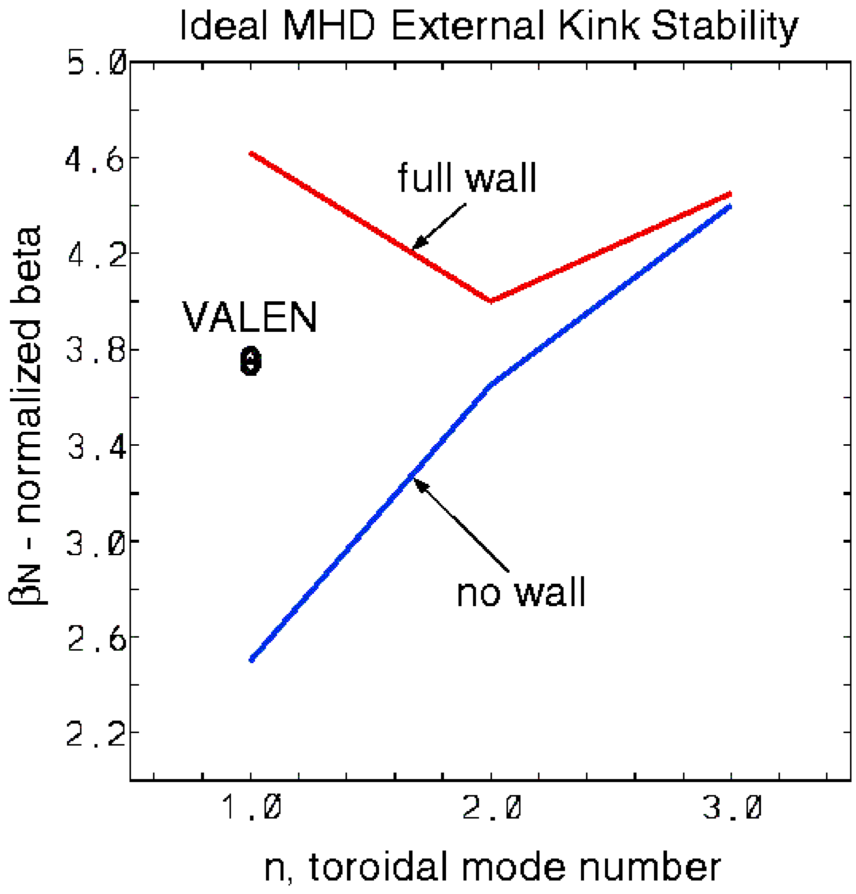
⇒

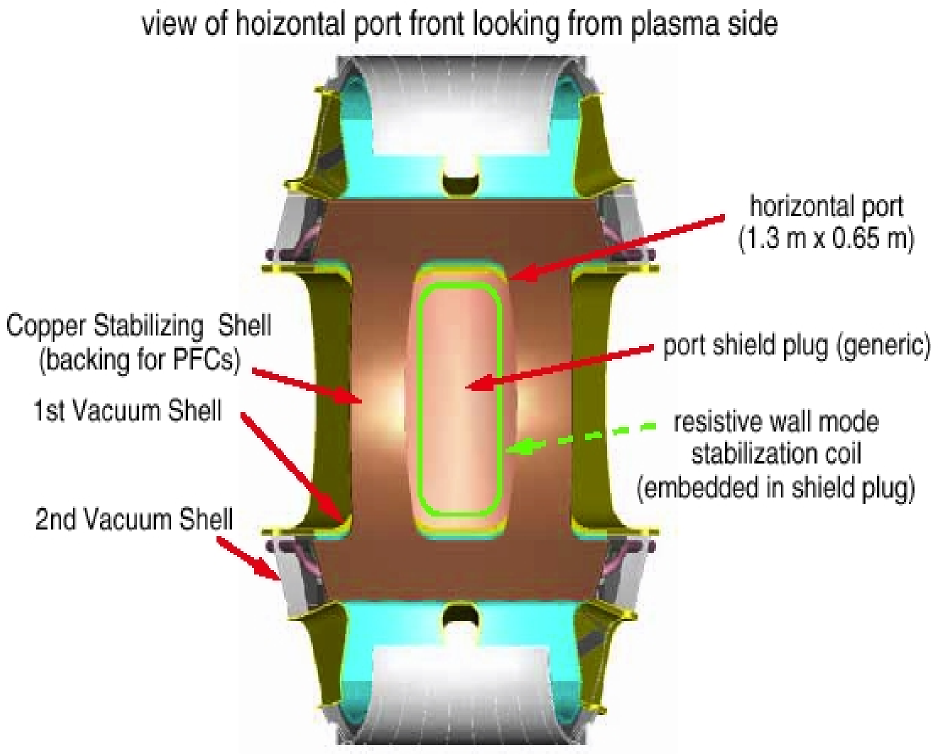
n≤4 RWM stablized,
β_N=5.4, f_{BS}=90%



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

ICRF/FW(ORNL)

With existing ICRF heating system

P(ICRF)=20 MW

ω=80-120 MHz

2 strap antennas

n(0)=5x10^20 /m^3

T(0)=14 keV

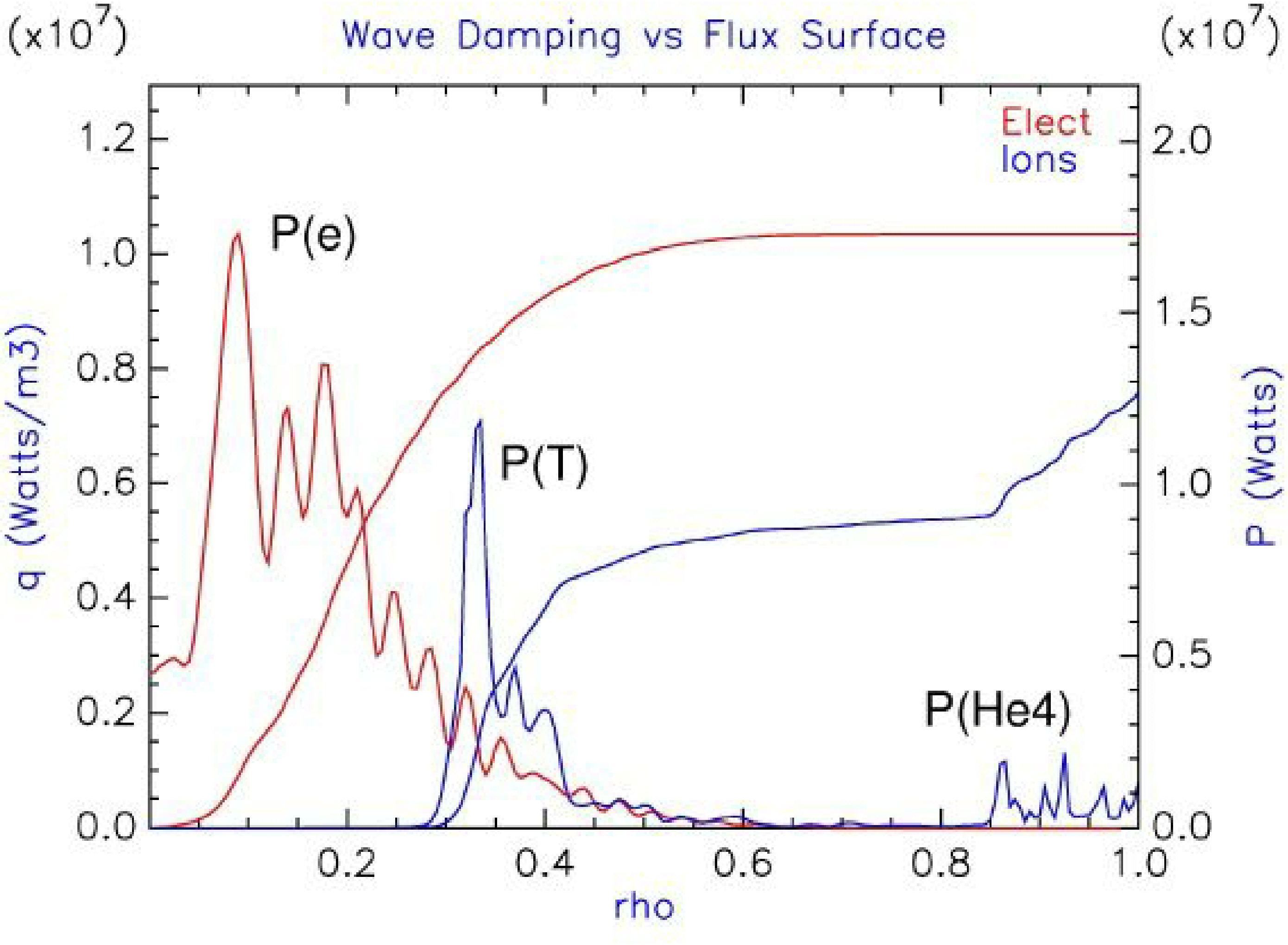
--> 40% power into good part of spectrum

--> 40% power absorbed on ions

--> 0.02 A/W

--> maximum I(FW)=0.4 MA

ICRF Heating system can provide on-axis current required, <u>with more efficient on-axis CD as an upgrade</u>



LHCD Viable for FIRE Off-Axis CD

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

<u>TSC-LSC analysis, PPPL</u>

ω = 4.6 GHz

n|| = 2.0, Δn|| = 0.3

n(0) = 4.5x10^20 /m3

T(0) = 22 keV

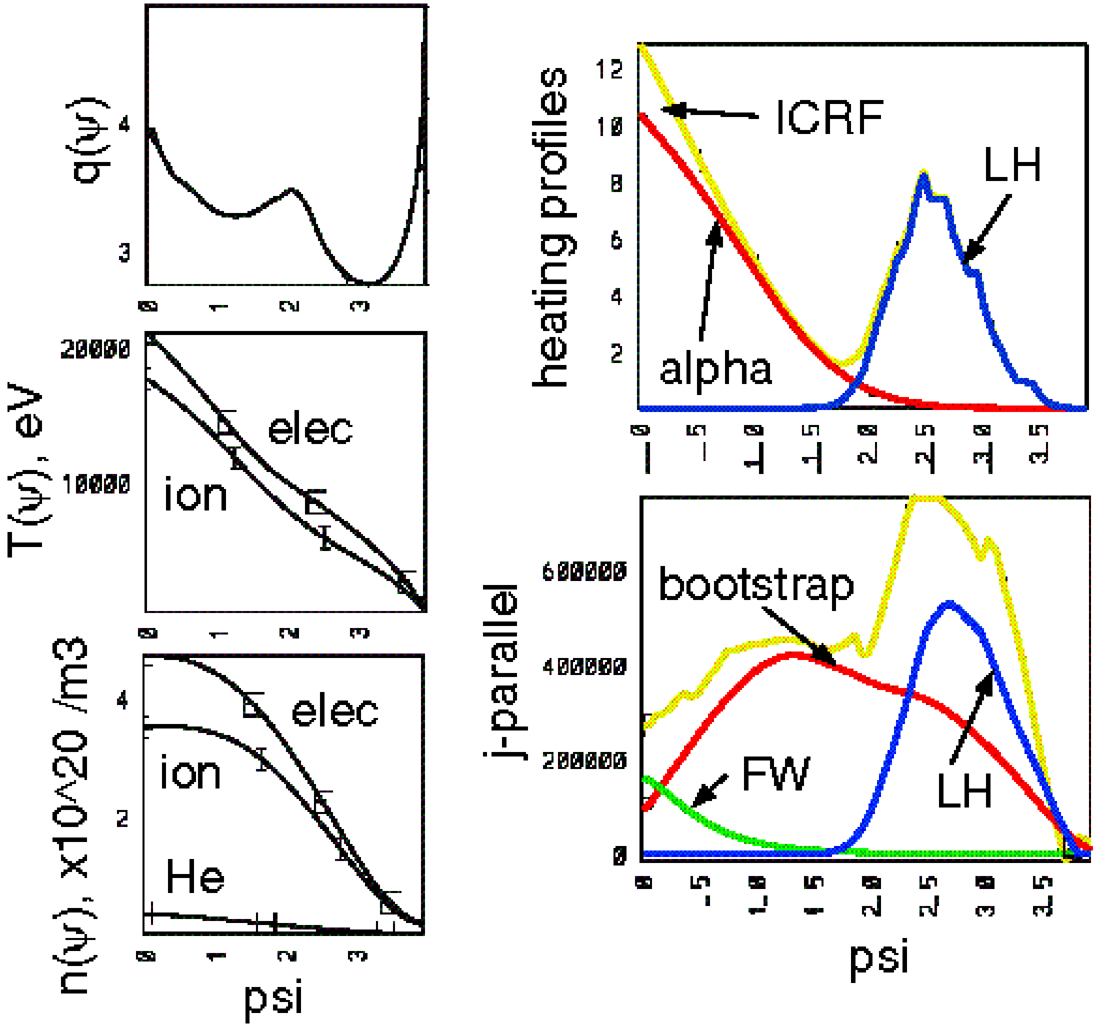
n(0)/<n> = 1.5

Bt = 8.5 T

----> 0.085 A/W

Alpha particle absorption needs to be determined

All rays launched from outboard midplane



Quasi-Stationary AT Burning Plasmas are the Primary Focus for FIRE

- 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 1-3 x τ_{jdiff} (20-50 s)
- Q = 5-10
- H98(y,2) > 1.0

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

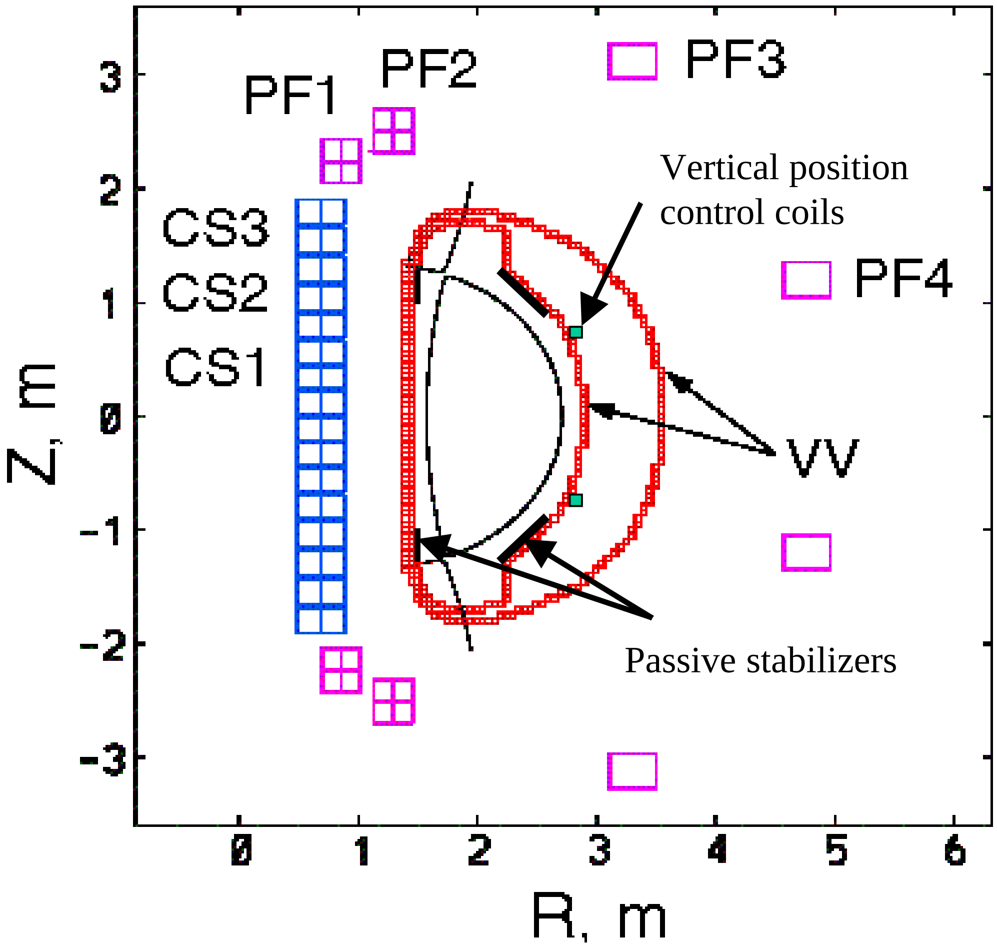
TSC-LSC Simulation Demonstrates Quasi-Stationary Burning AT Plasma in FIRE

Quasi-stationary AT plasmas

- Ip ramped up with both inductive and non-inductive CD
- Flattop sustained by 100% non-inductive CD
- t(flattop) > 1× τ(current relax)
- Q = 5-10

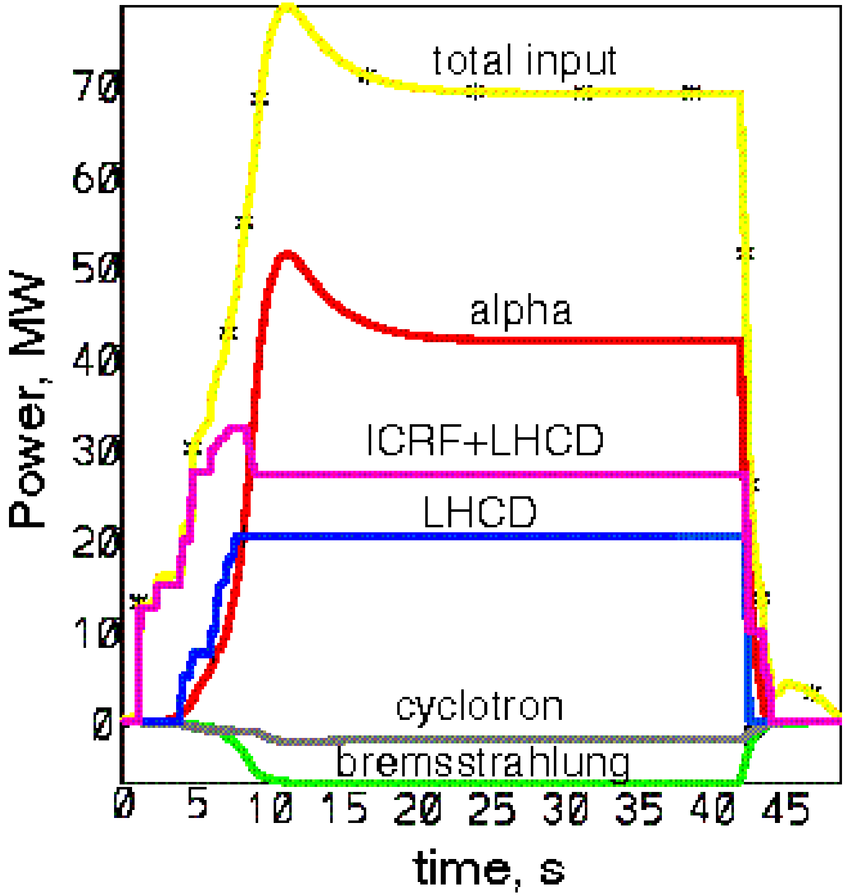
Transient AT plasmas with dominantly inductive current

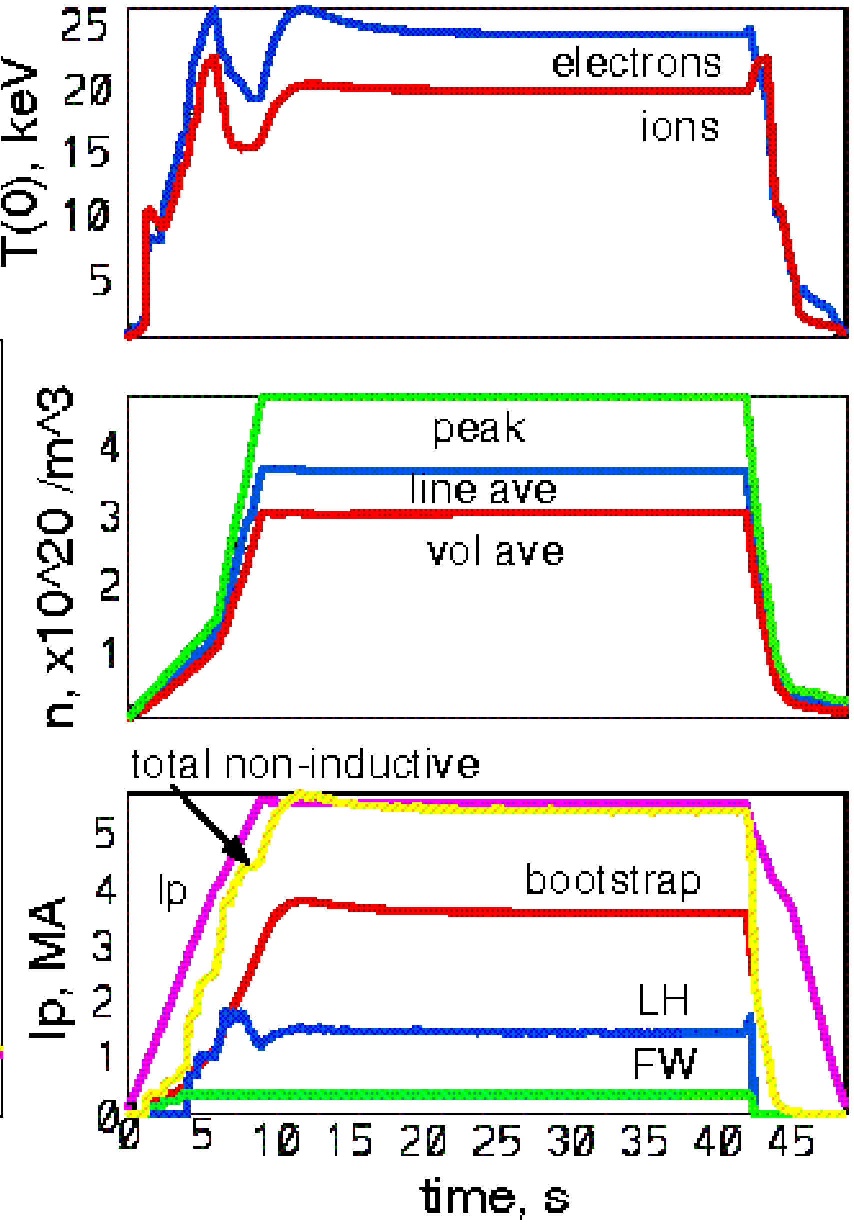
Long pulse DD (nonburning) 100% non-inductive at reduced Ip and Bt



TSC-LSC Simulation of Q=7.8 Burning AT Plasma

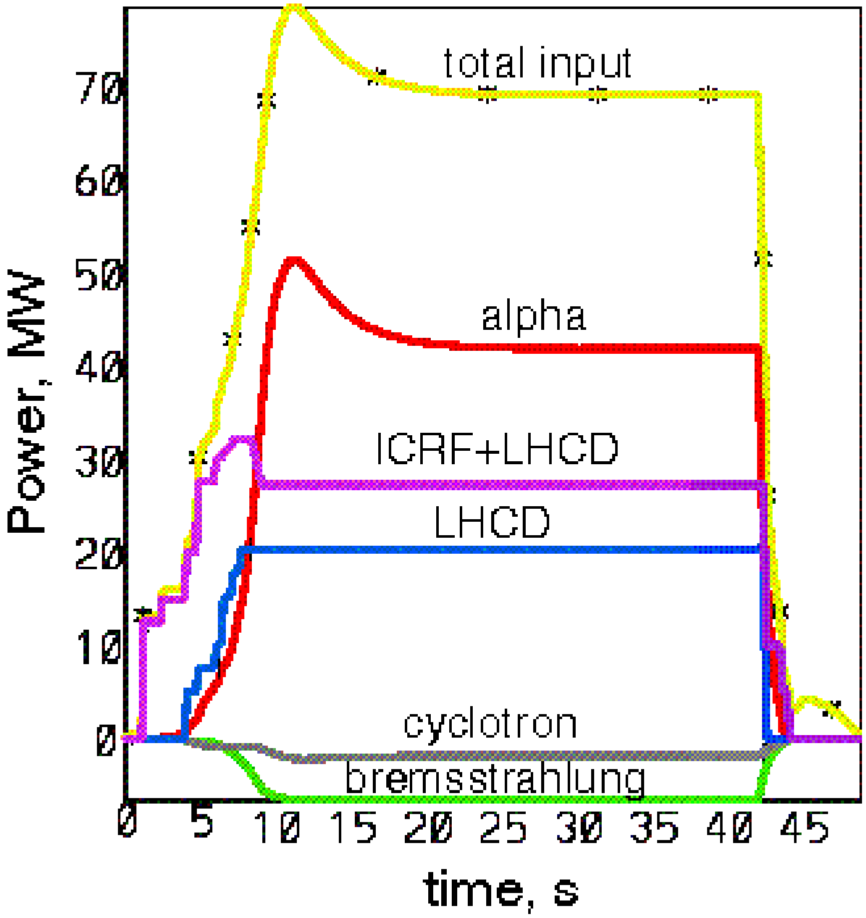
I_p=5.4 MA, B_t=8.5T, β_N=3.5, β=4.4%, n/n_{Gr}=0.5, $n(0)/\langle n \rangle$=1.6, $n_{20}(0)$=4.7, $T_i(0)$=20 keV, $T_e(0)$=24 keV, I_{LH}=1.5 MA, I_{FW}=0.35 MA, I_{BS}=3.6 MA, τ_E=0.6 s, H98=1.6

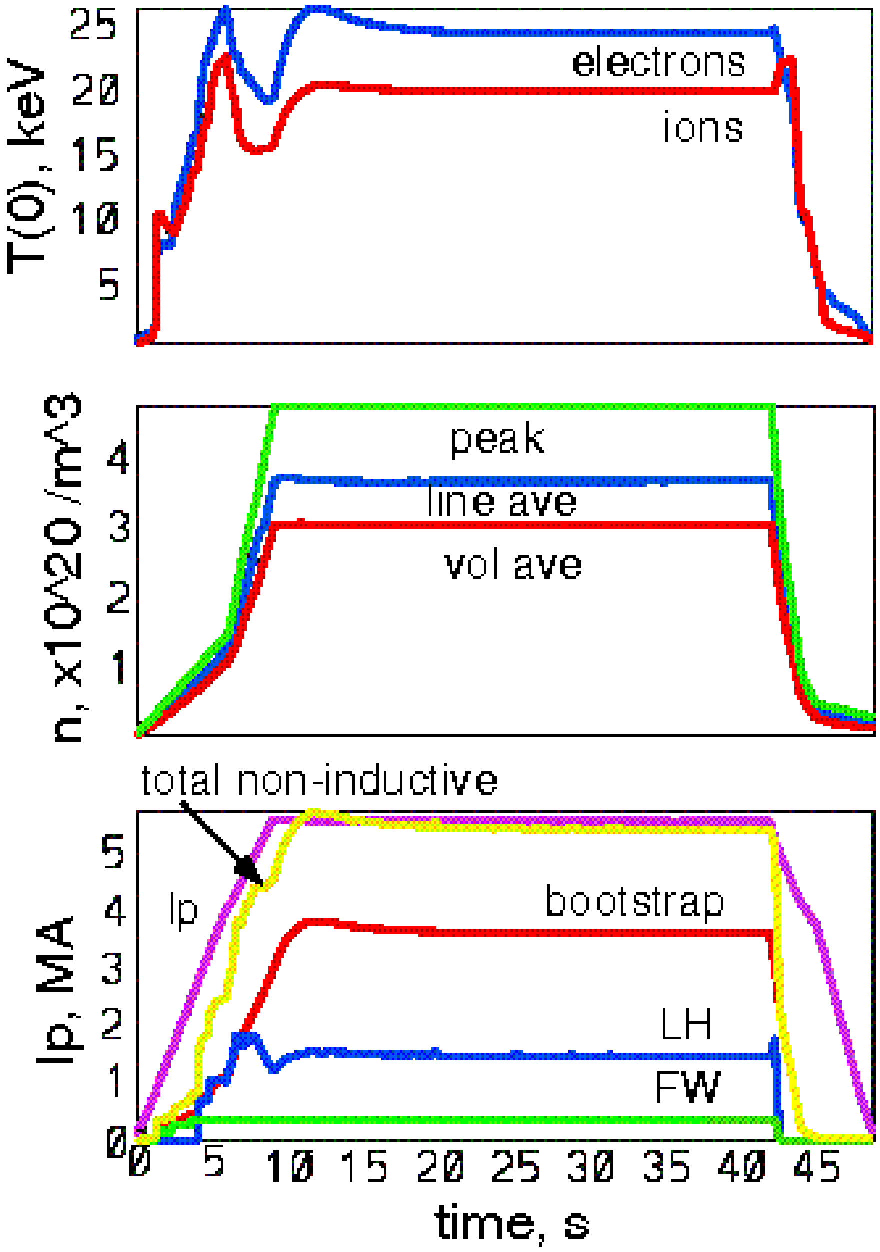




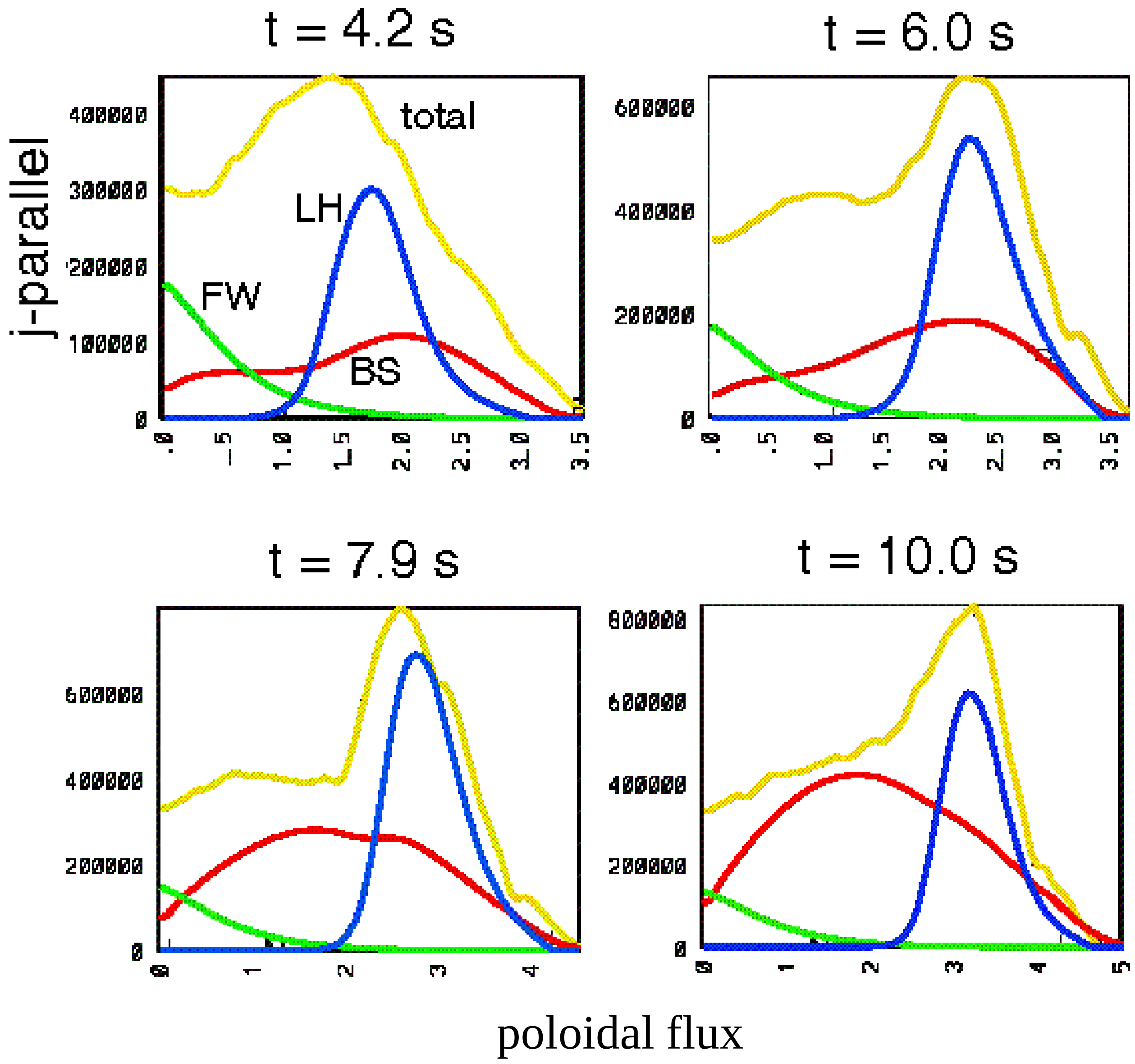
TSC-LSC Simulation of Q=7.8 Burning AT Plasma

t(flattop) = 32 s





TSC-LSC Simulation of Q=7.8 Burning AT Plasma



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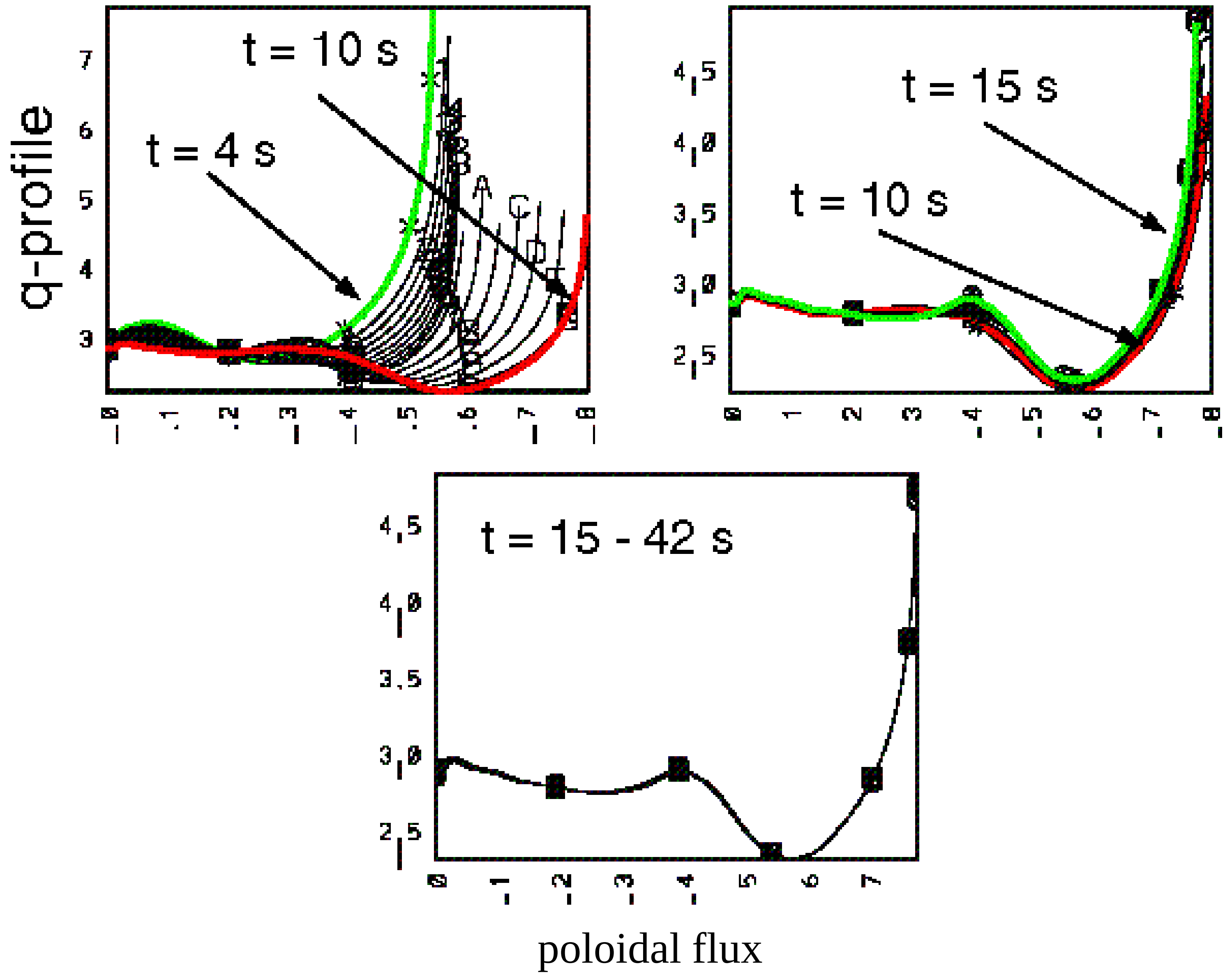

Burning AT Plasma Issues

- Ripple losses are larger due to high q, low Ip and low B_T
- Alfven eigenmodes are expected to be more severe
- Higher order NTMs
  - (5,2) and (3,1) surfaces
- RWM stabilization
  - n=1 feedback
  - Then what for n>1 RWM's
- Plasma edge conditions
  - L-mode or H-mode
  - Radiation characteristics
  - Impurities
- Core T,n profile control
  - Density peaking for bootstrap current
  - Internal transport barrier formation
- Plasma rotation
  - Is rotation needed with feedback for RWM stability
  - Sheared rotation for turbulence suppression
- Experimental progress on AT plasmas is critical
  - ASDEX-U, C-Mod, DIII-D, JET, JT-60U

FIRE Can Access a Large Operating Space for Advanced Tokamak Plasmas

- 0D analysis indicates an operating space for H98 > 1.2-1.4 for Q=5-10 within physics and engineering constraints
- Stable equilibria consistent with RFCD capability have been found with $\beta_N \geq 2.5$ and $f_{bs} \geq 0.5$ requiring no kink stabilization, and $\beta_N \geq 3.5$ and $f_{bs} \geq 0.75$ with n=1 RWM stabilization
- ICRF/FW and LHCD analysis indicate these are viable CD sources
- TSC/LSC analysis show that quasi-stationary burning plasmas can be established and maintained for current diffusion time scales
- Several critical issues exist for burning AT plasmas