Physics Basis for Advanced and Conventional Operating Modes in FIRE

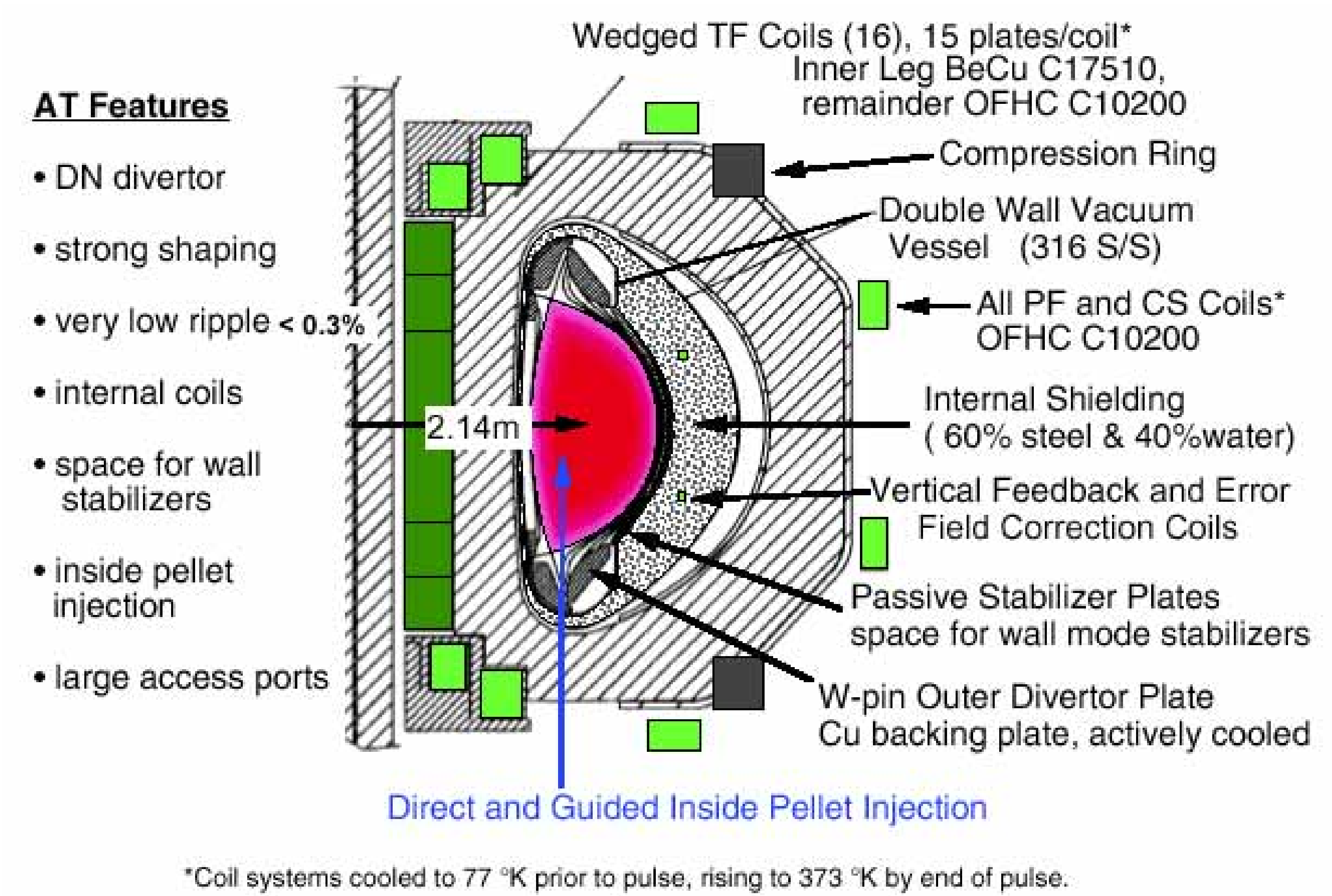
C. Kessel, D. Meade, and FIRE Team
Princeton Plasma Physics Laboratory

APS--Division of Plasma Physics
Orlando, 11/11-15/2002

Objectives of FIRE

- Develop the experimental/theoretical basis for burning plasma physics
  - Q ≈ 10 ELMy H-mode for $\tau_{burn} > 2 \times \tau_{cr}$
  - Q > 5 Advanced Tokamak for $\tau_{burn} > 1\text{-}5 \times \tau_{cr}$
- Adopt as many features as possible of projected Power Plant designs
- Only address technological issues required for successful device operation
  - Fueling, pumping, power handling, plasma control, neutronics, materials, remote handling, and safety
- Utilize the compact high-field Cu coil approach <u>to keep the device cost at ≈ \$1 B</u>

Fusion Ignition Research Experiment



Vertical Stability for FIRE with κ_x=2.0

- Design passive structures to slow vertical instability for feedback control and provide a stability factor fs > 1.2
- Passive stabilizers are 1.5 cm thick Cu, toroidally continuous on outboard and inboard sides
- For most unstable plasmas (full elongation and low pressure βp=0.1), over the range 0.7 < li(3) < 1.1, the stability factor is 1.3 < fs < 1.13 and growth time is 43 < τg(ms) < 19
- Utilize internal control coils for feedback on the plasma vertical position, located just outside the inner VV, with second coil installed for redundancy
- Control simulations indicate that for random disturbances with ΔZrms = 1 cm, and step disturbances with ΔZ = 2 cm, the peak power is 7-14 MVA, with I(peak) = 65-90 kA-turns and V(peak) = 50-75 V/turn

FIRE Utilizes High Triangularity δ_x=0.7

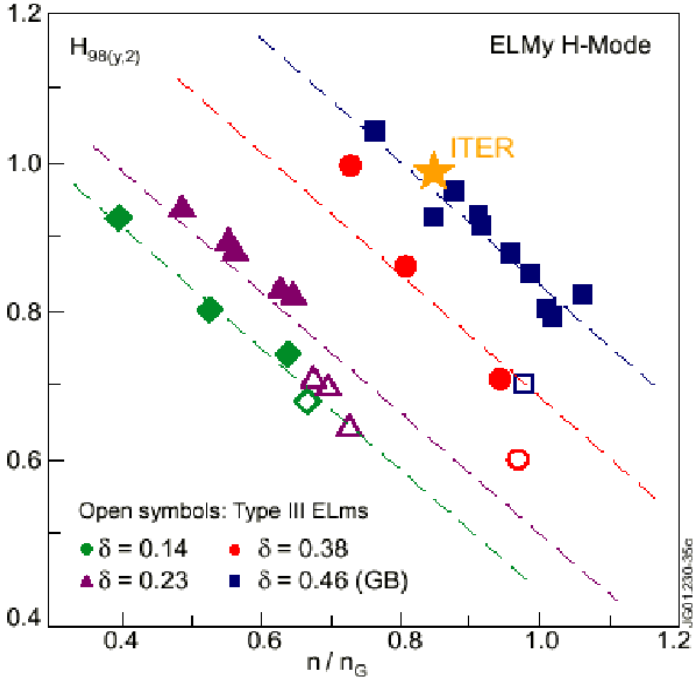


Figure 2.2-2 Confinement Enhancement Factor Relative to the ITERH-98(y,2) Scaling as a Function of n/n_G in JET[5]

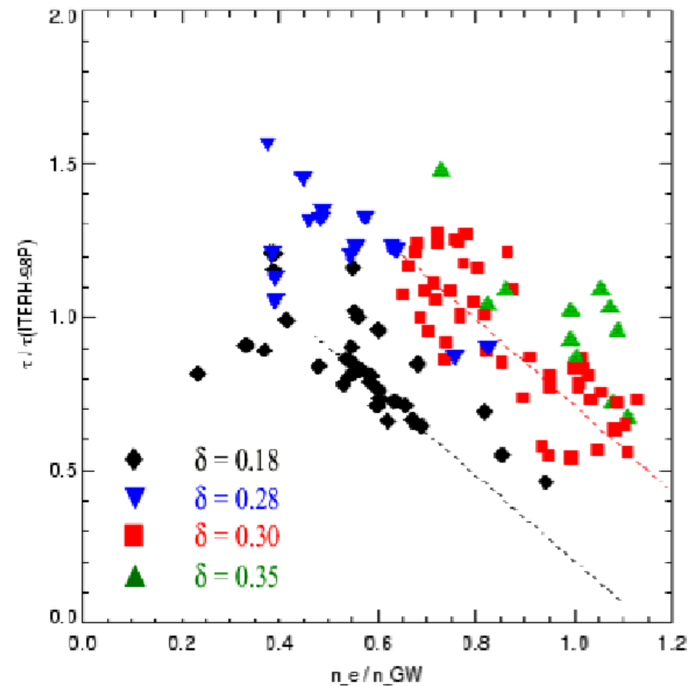


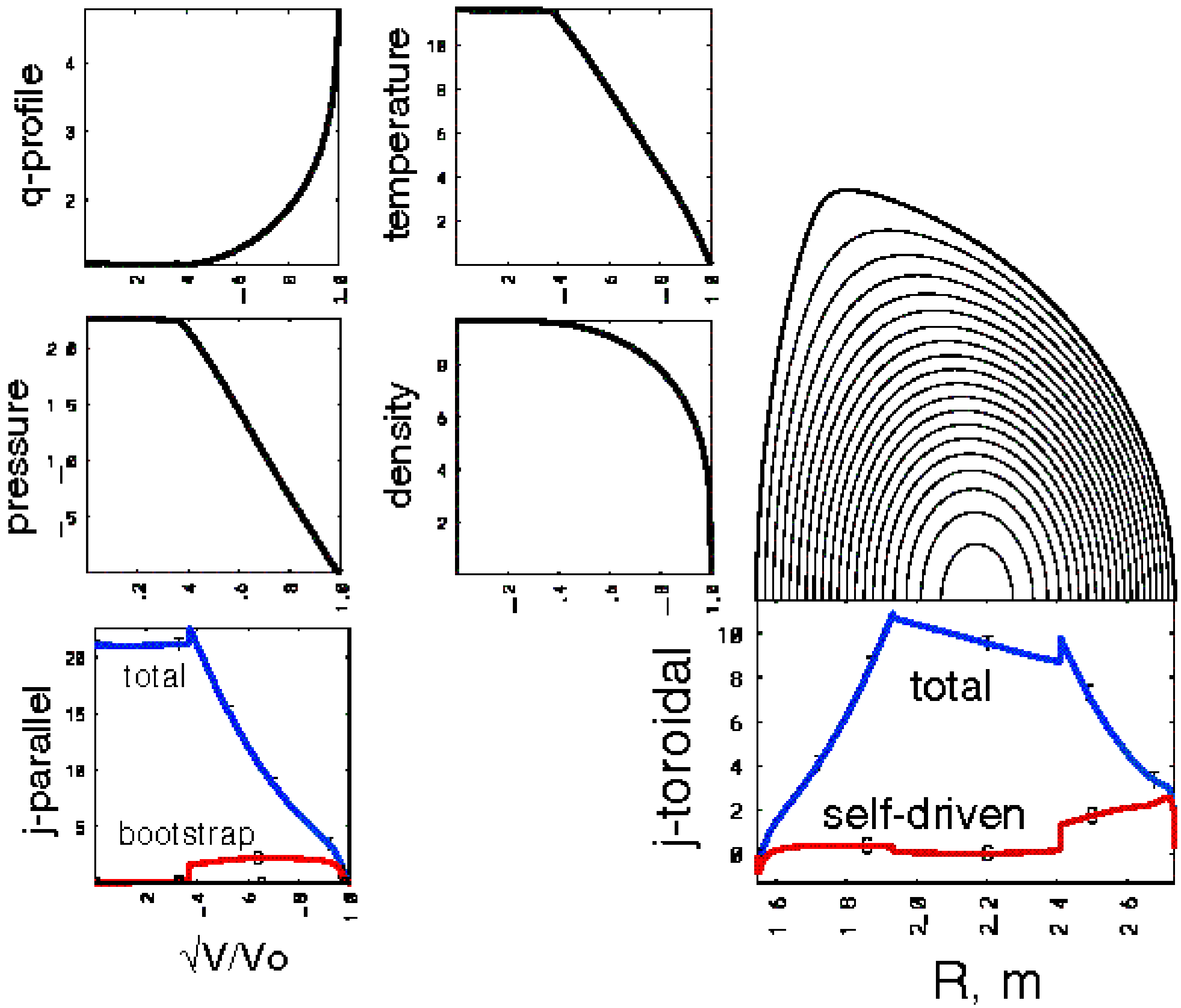
Figure 2.2-3 Confinement Enhancement Factor Relative to the ITERH-98P(y) Scaling as a Function of n/n_G in ASDEX Upgrade[6]

High δ benefits:

Energy confinement, Higher n/nGr, Higher pedestal pressure, MHD stability, Access to non-Type I ELM regimes

Ideal MHD for FIRE Reference Discharge

Self-consistent ohmic/bootstrap equilibria



Sawtooth is unstable at FIRE's βp, fast alphas likely to stabilize, $\tau_{stab} >> \tau_E$ and low li lead to weak affect, according to Porcelli prediction

n=1 External kink

$\beta N \approx 3.5$

n=∞ ballooning

$\beta N \approx 3.0$

Stabilization of NTMs with LHCD on FIRE

Make Δ′ more negative

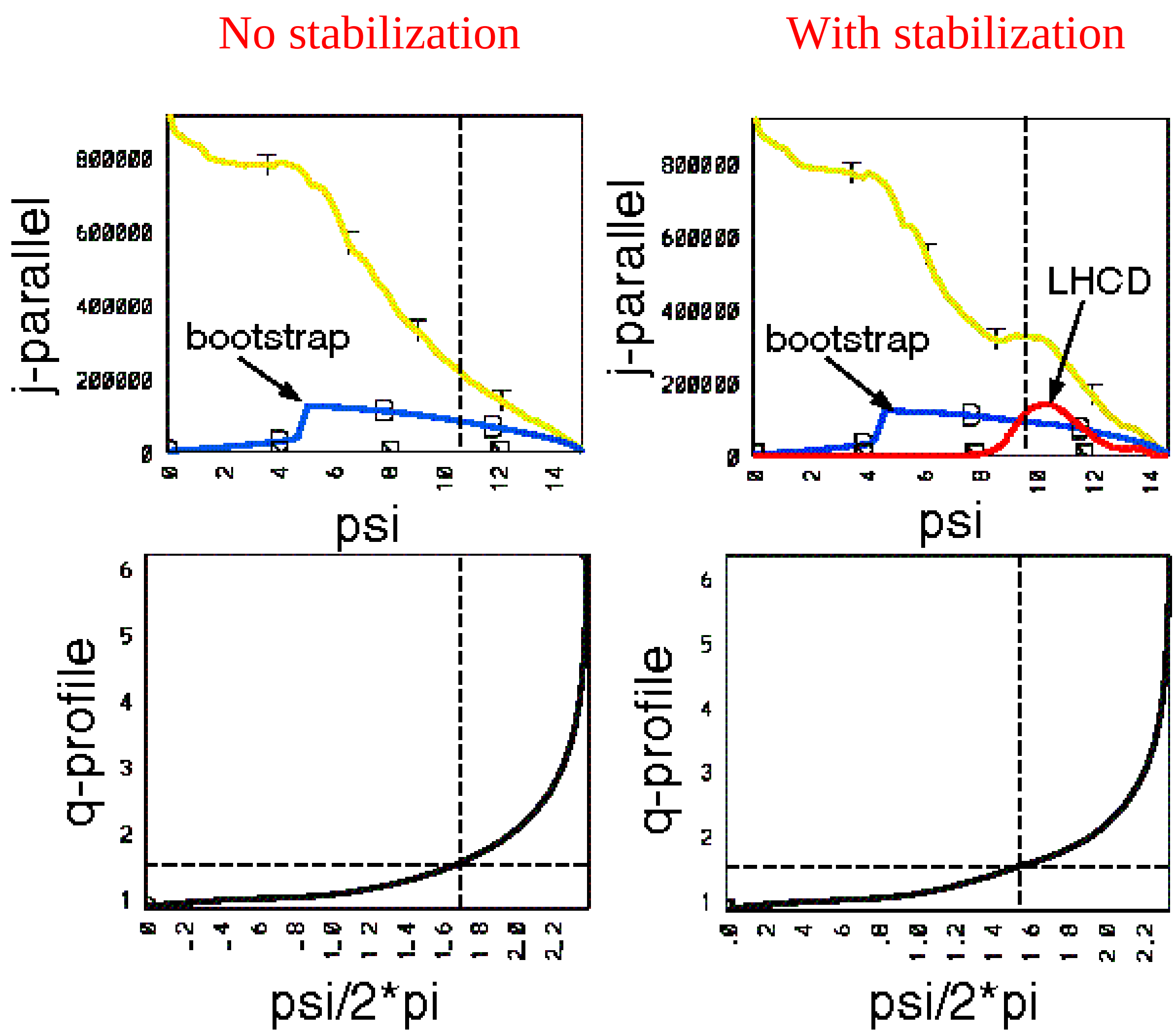
12.5 MW of LHCD injected

(3,2) surface targeted

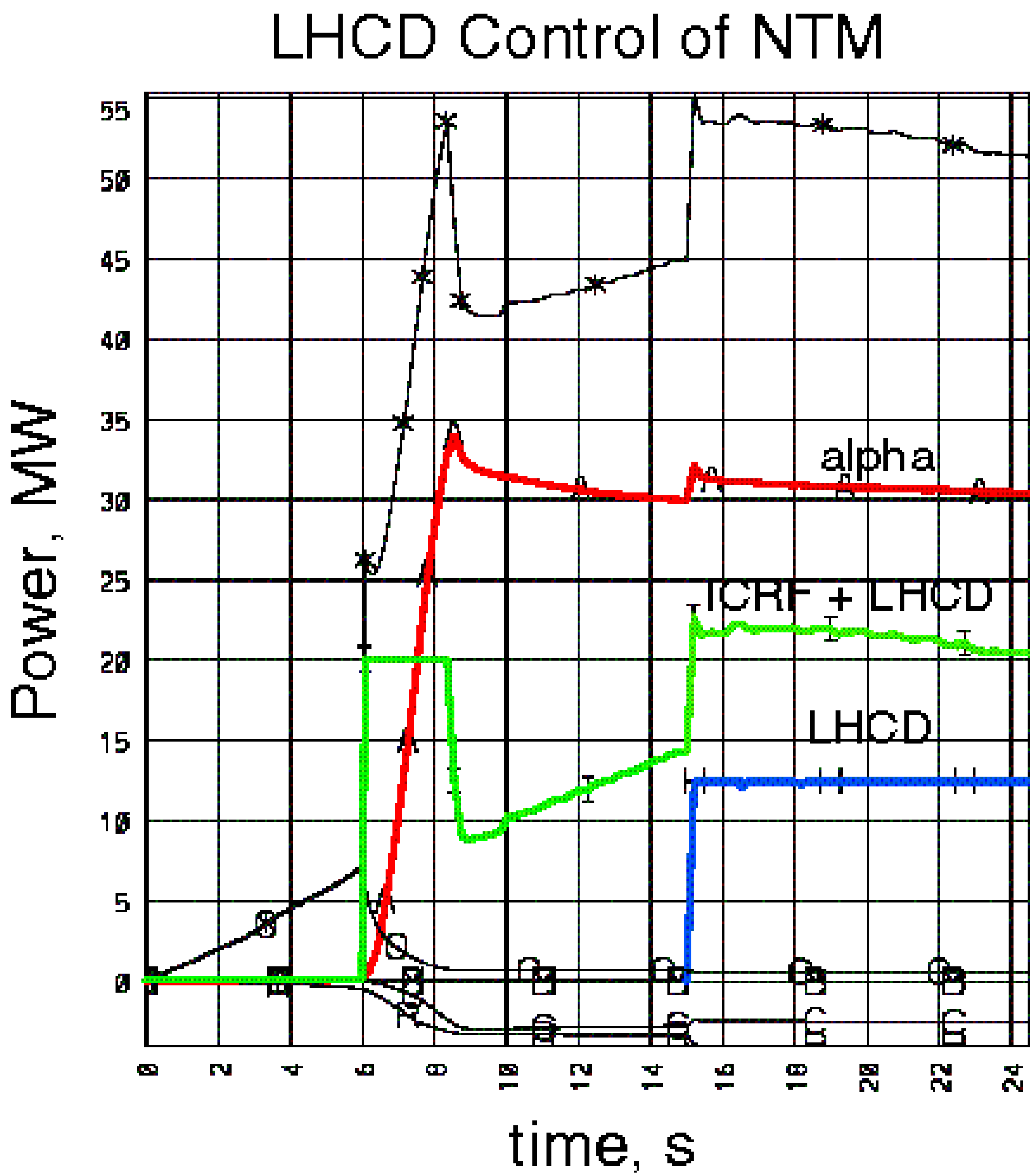
I(LH)=0.65 MA

Pursuing PEST3 resistive analysis

Compass-D shown NTM stabilization with LHCD



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

Impurities in FIRE

- Reference assumption for impurities is 3% Be, giving Zeff ≈ 1.4
- First wall consists of Be coated Cu tiles, divertor is tungsten
- Extrapolation of multi-machine database suggests that FIRE's high density would lead to lower Be content ~ 0.5% (Matthews, J. Nuc. Mater. 1997, and ITER Physics Basis, Nuc. Fus. 1999)

$$Z_{eff} = 1 + (4.5 - 5.5)\frac{P_{rad} Z^{0.19}}{S^{1.03} n_e^{1.95}}$$

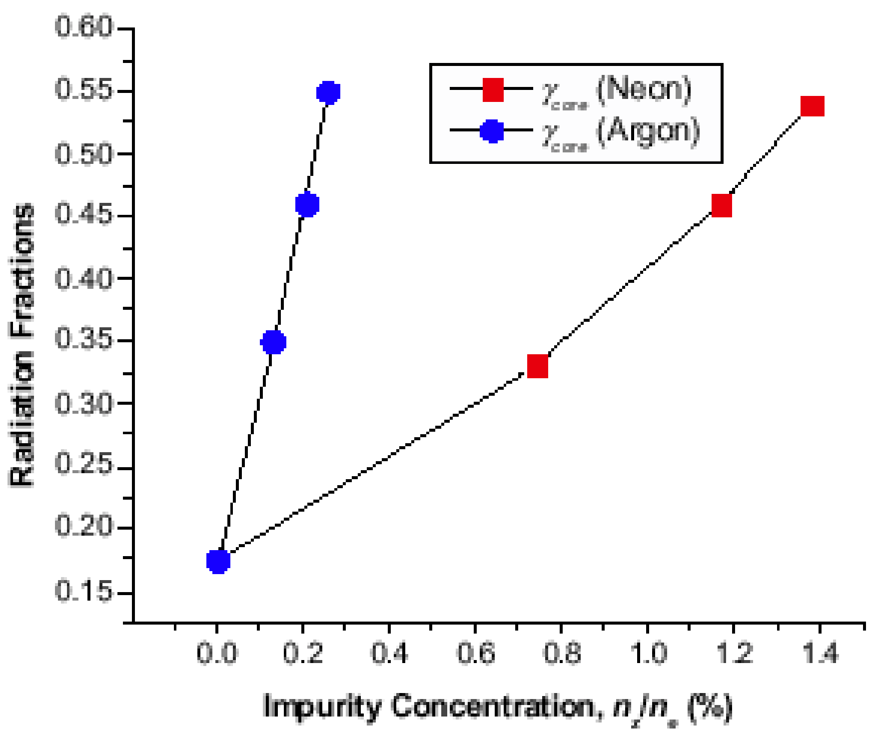
- Higher Z inert gases can be used to enhance the radiation and relieve the divertor heat load

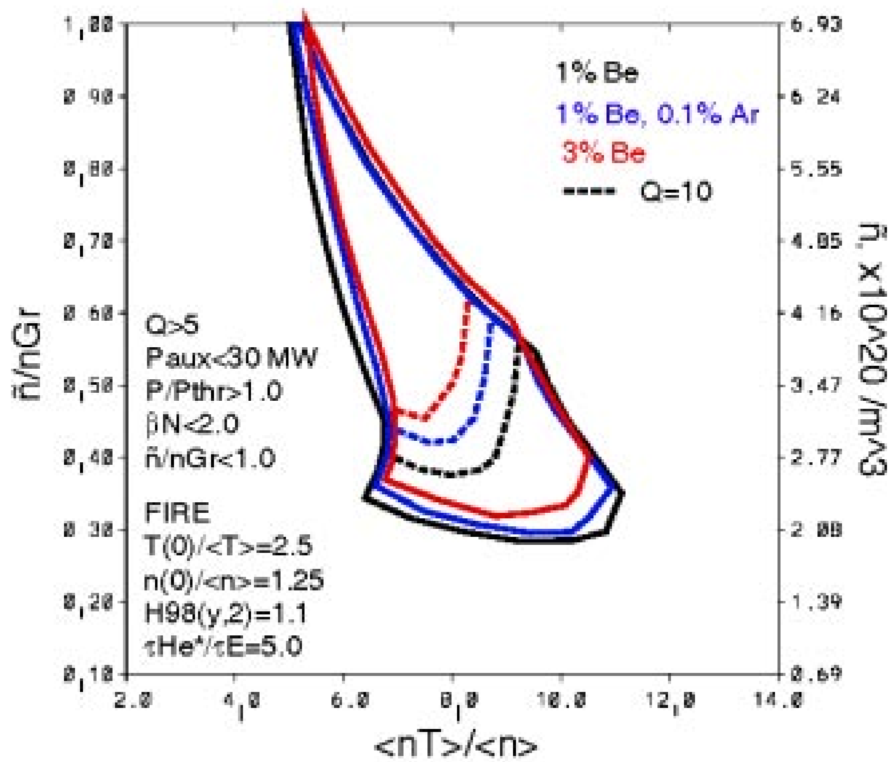
Preliminary Impurity Analysis

J. Mandrekas, GTWHIST

Results below assumes 3% Be fixed intrinsic impurity,
and adds Ne or Ar

Argon appears to be a good candidate for enhanced radiation with lower Be content (say 1-2%)





Impurity Variations

n/nGr = 0.7, <T> = 6.5 keV, H(y,2) = 1.1, n(0)/<n> = 1.2, T(0)/<T>=2.5

	3% Be	2% Be, 0.1% Ar	1% Be, 0.1% Ar	1% Be, 0.2% Ar
P_{aux}, MW	9.55	12.7	10.4	16.6
f_{rad}	0.27	0.45	0.42	0.60
Q	15.6	12.5	16.6	10.3
P_{loss}/P_{LH}	1.24	1.27	1.33	1.33
Z_{eff}	1.40	1.60	1.48	1.79

P_{fusion} = 150-185 MW, P_{LH} = 26.3 MW

$$P_{loss} = P_{alpha} + P_{aux} + P_{ohm} - P_{brem} - P_{cyc} - P_{line}/3$$

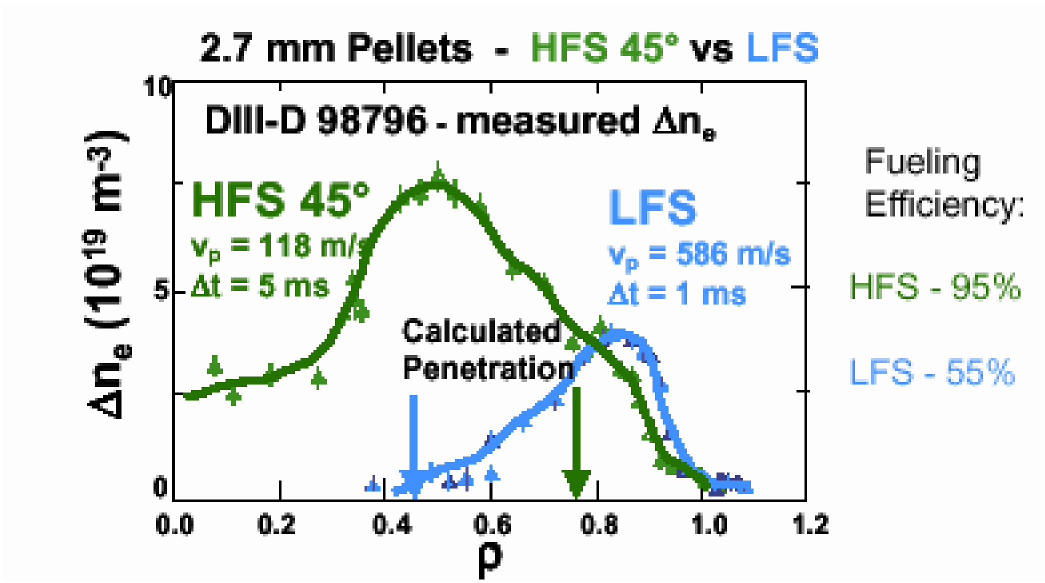
HFS Pellet Launch and Density Peaking ---> Needs Strong Pumping

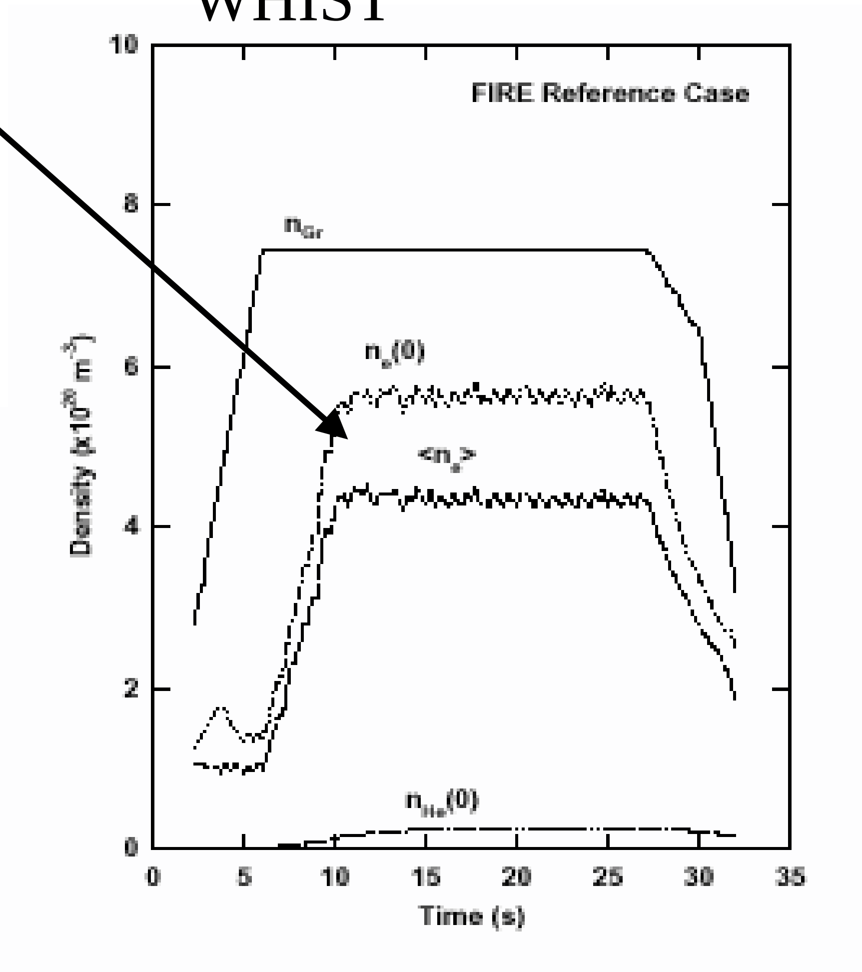
FIRE reference discharge with uniform pellet deposition, achieves n(0)/<n> ≈ 1.25

P. T. Lang, J. Nuc. Mater., 2001, on ASDEX and JET

L. R. Baylor, Phys. Plasmas, 2000, on DIII-D

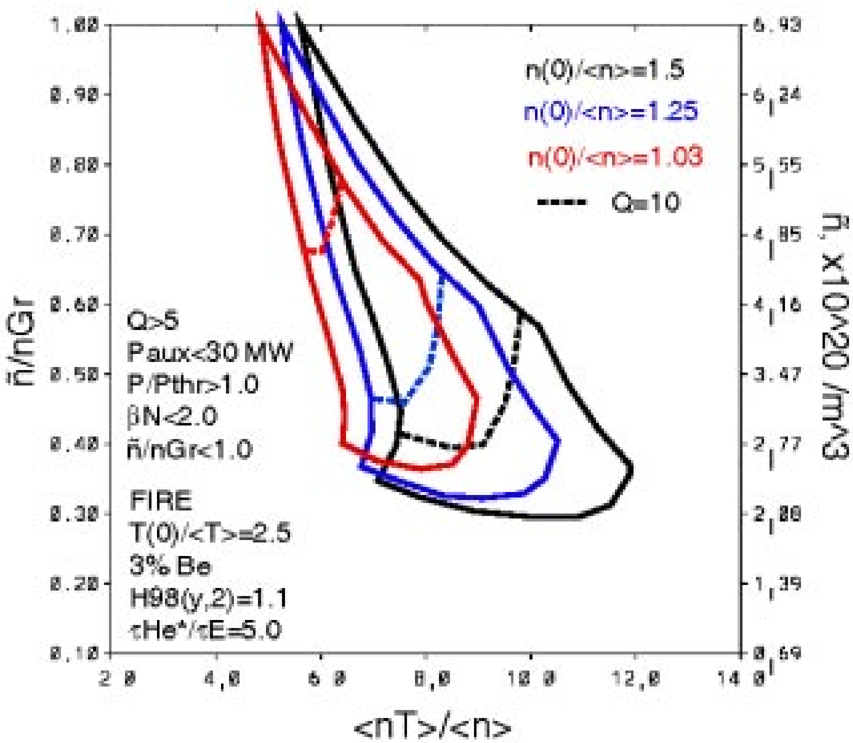
Simulation by W. Houlberg, ORNL, WHIST



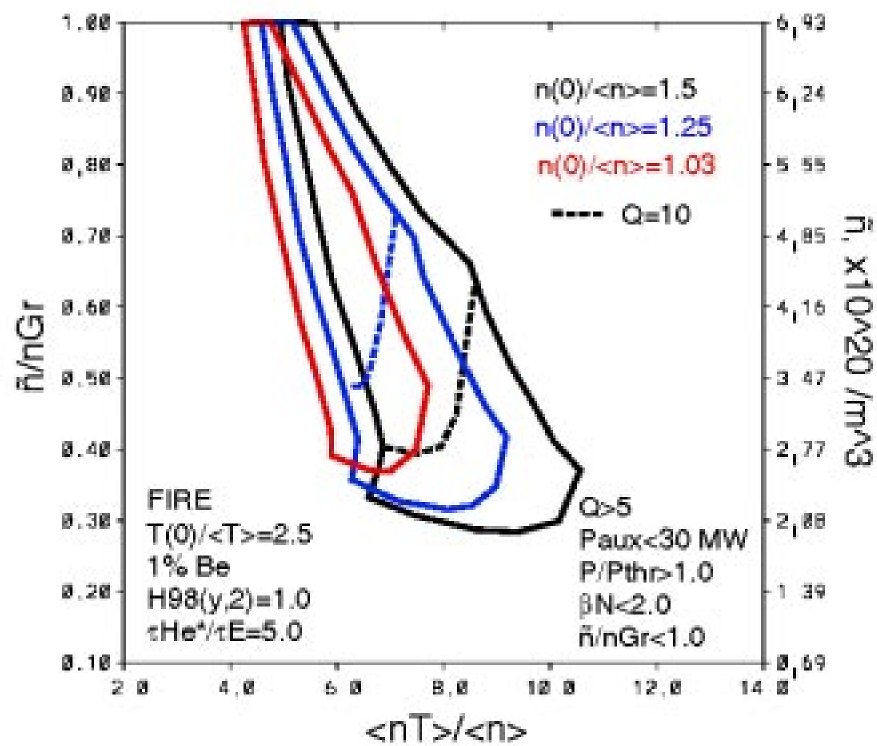


POPCONs for FIRE, Density Peaking

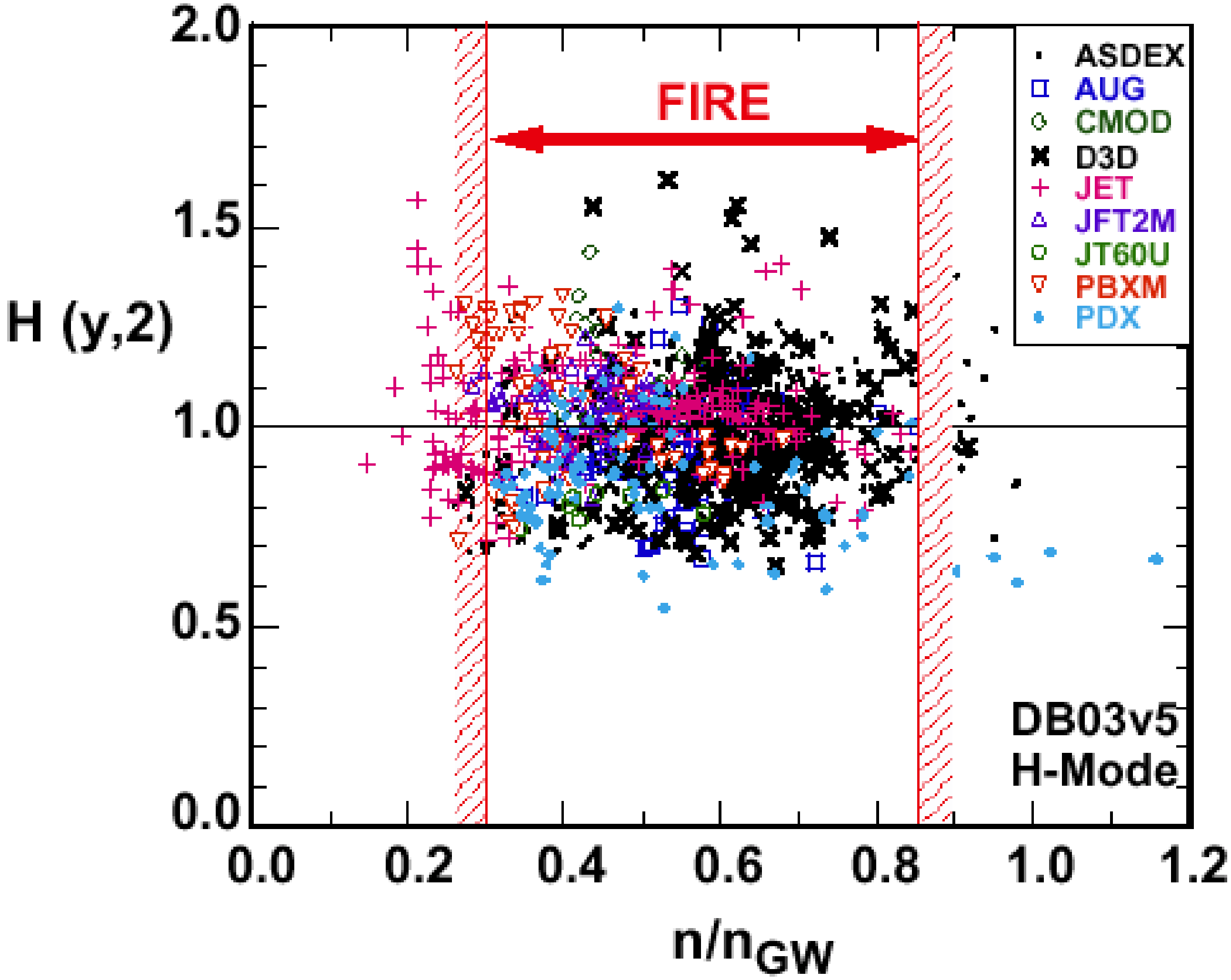
3% Be and H98(y,2)=1.1



1% Be and H98(y,2)=1.0



FIRE Can Access Most of the Existing H-mode Database



IPB(y,2) scaling constructs a line through database

τE = H(y,2) × f(Ip,Bt,n,R,κ,ε,P)

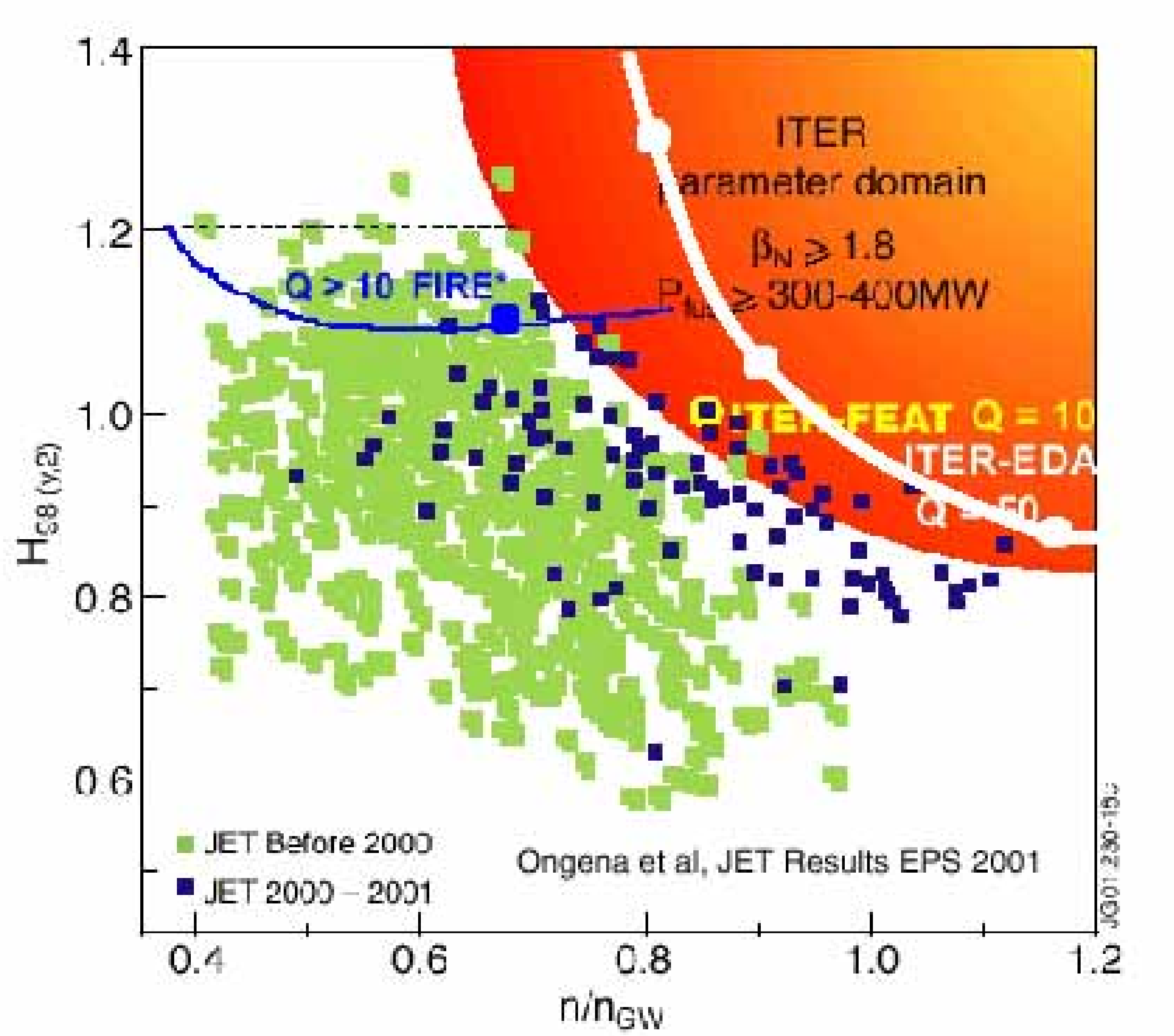
What is the impact of……

δ

n/nGr

n(0)/<n>

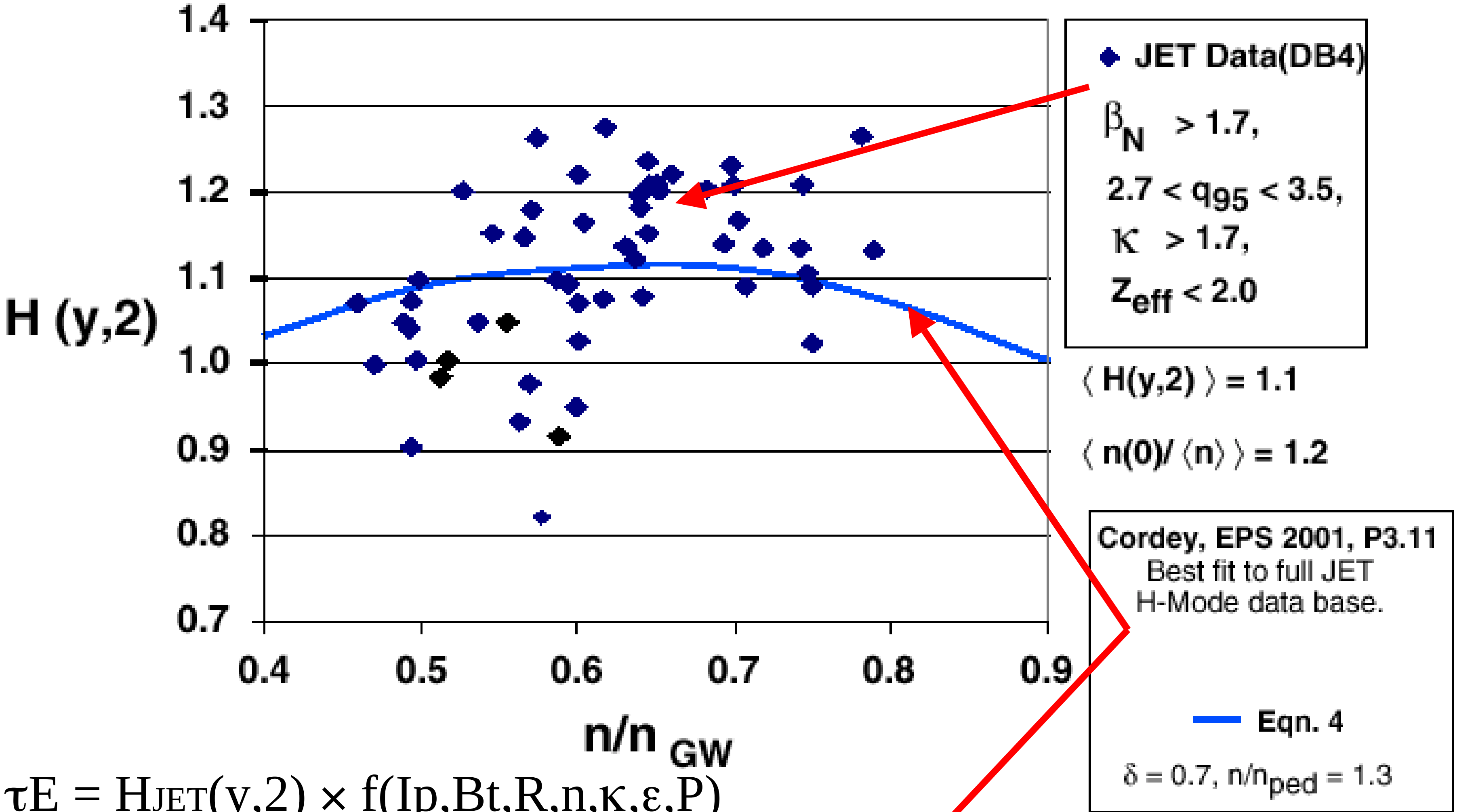
Density and Global Energy Confinement From JET Database



FIRE's Q=10 operating points have n/nGr values below onset of degradation in confinement

Access to higher n/nGr values with H ≥ 1 would enhance FIRE's operating space

In JET ELMing H-modes H(y,2) Varies With n/nGr



$\tau E = H_{JET}(y,2) \times f(Ip,Bt,R,n,\kappa,\varepsilon,P)$

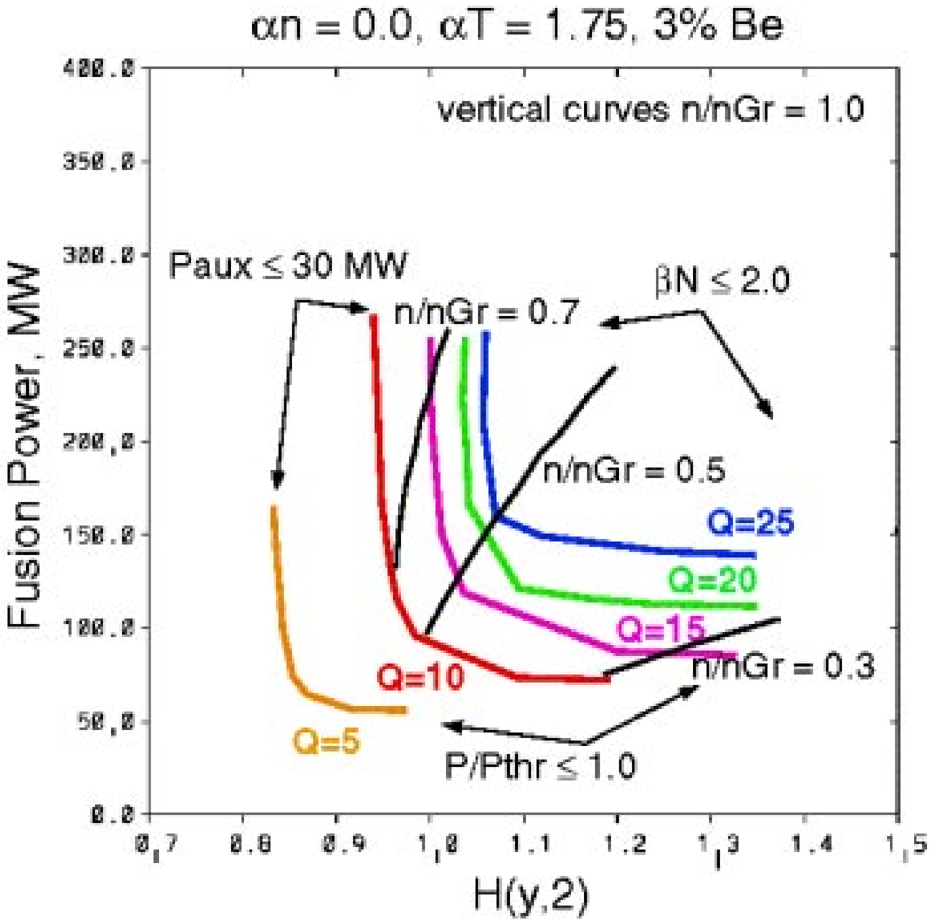
$H_{JET}(y,2) = 0.71 + 0.33\delta - 1.58(n/nGr-0.63)^2 + 0.58(n/n_{ped}-1)$

P_{fusion} vs H(y,2) Operating Space

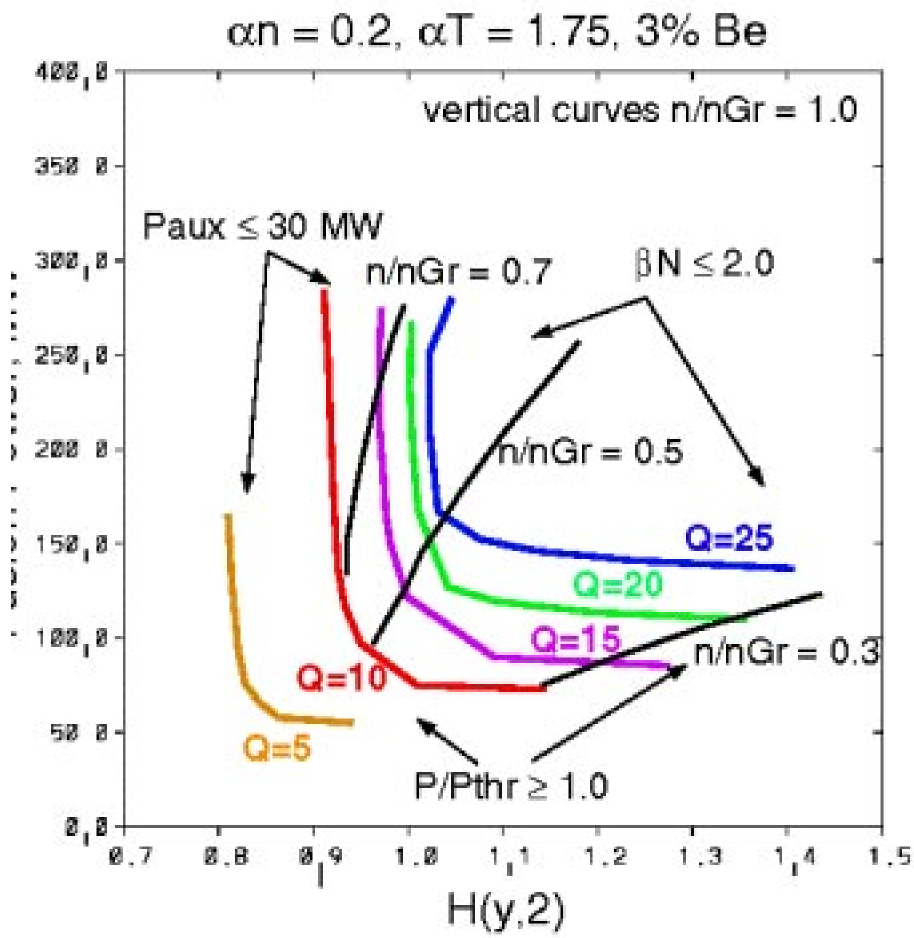
Improvements in H(y,2) rapidly access higher Q operation

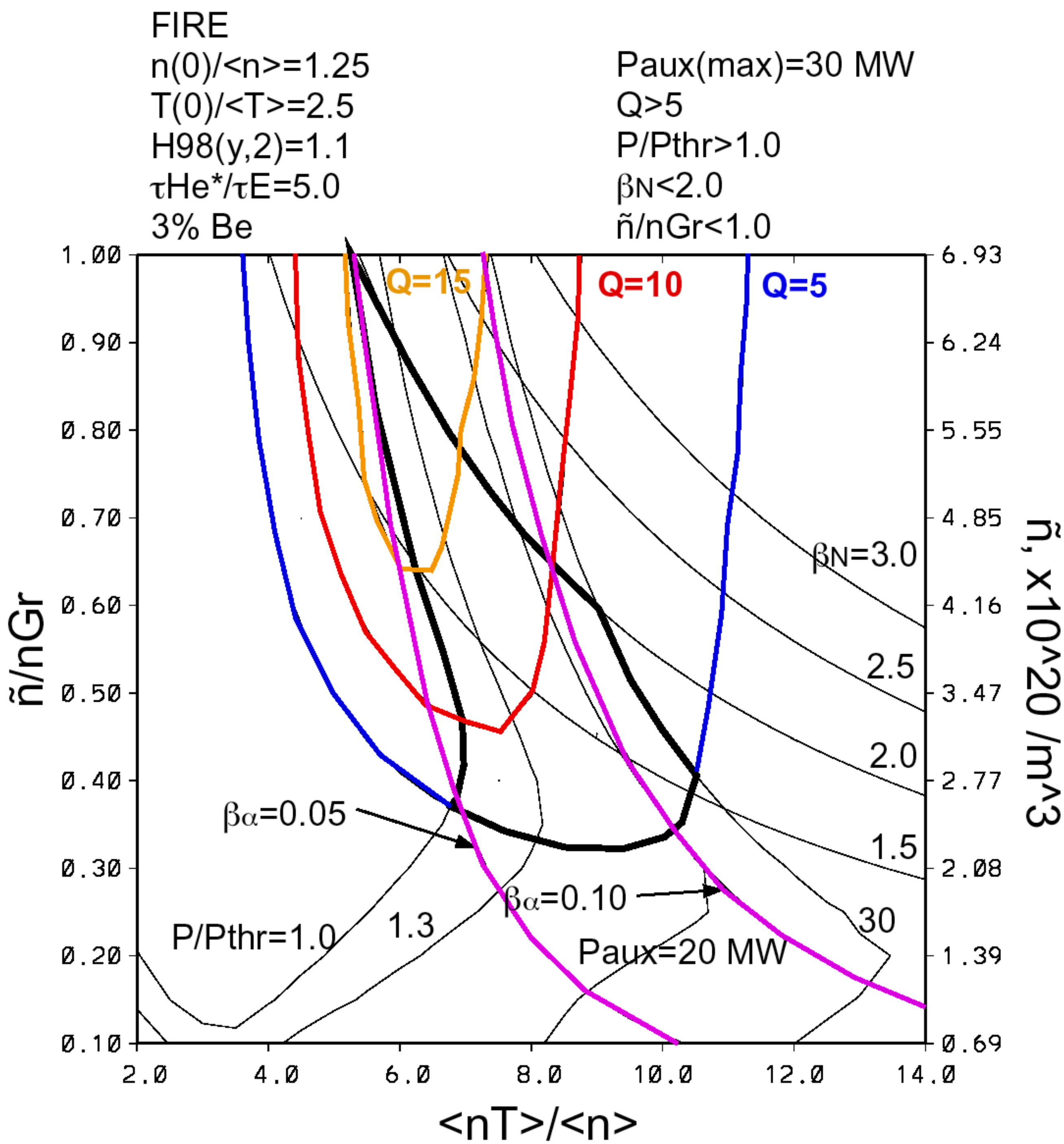
Operating space is to the right of the colored curves for given Q

n(0)/<n> = 1.0



n(0)/<n> = 1.2




FIRE
n(0)/<n>=1.25
T(0)/<T>=2.5
H98(y,2)=1.1
τHe*/τE=5.0
3% Be
Paux(max)=30 MW
Q>5
P/Pthr>1.0
βN<2.0
ñ/nGr<1.0
Q=15
Q=10
Q=5
βN=3.0
2.5
2.0
1.5
βα=0.05
βα=0.10
30
P/Pthr=1.0
1.3
Paux=20 MW
ñ/nGr
ñ, x10^20 /m^3
<nT>/<n>
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
6.93
6.24
5.55
4.85
4.16
3.47
2.77
2.08
1.39
0.69
2.0
4.0
6.0
8.0
10.0
12.0
14.0

Threshold for L-H Transition and H-mode Operation --- Type I ELM or ??

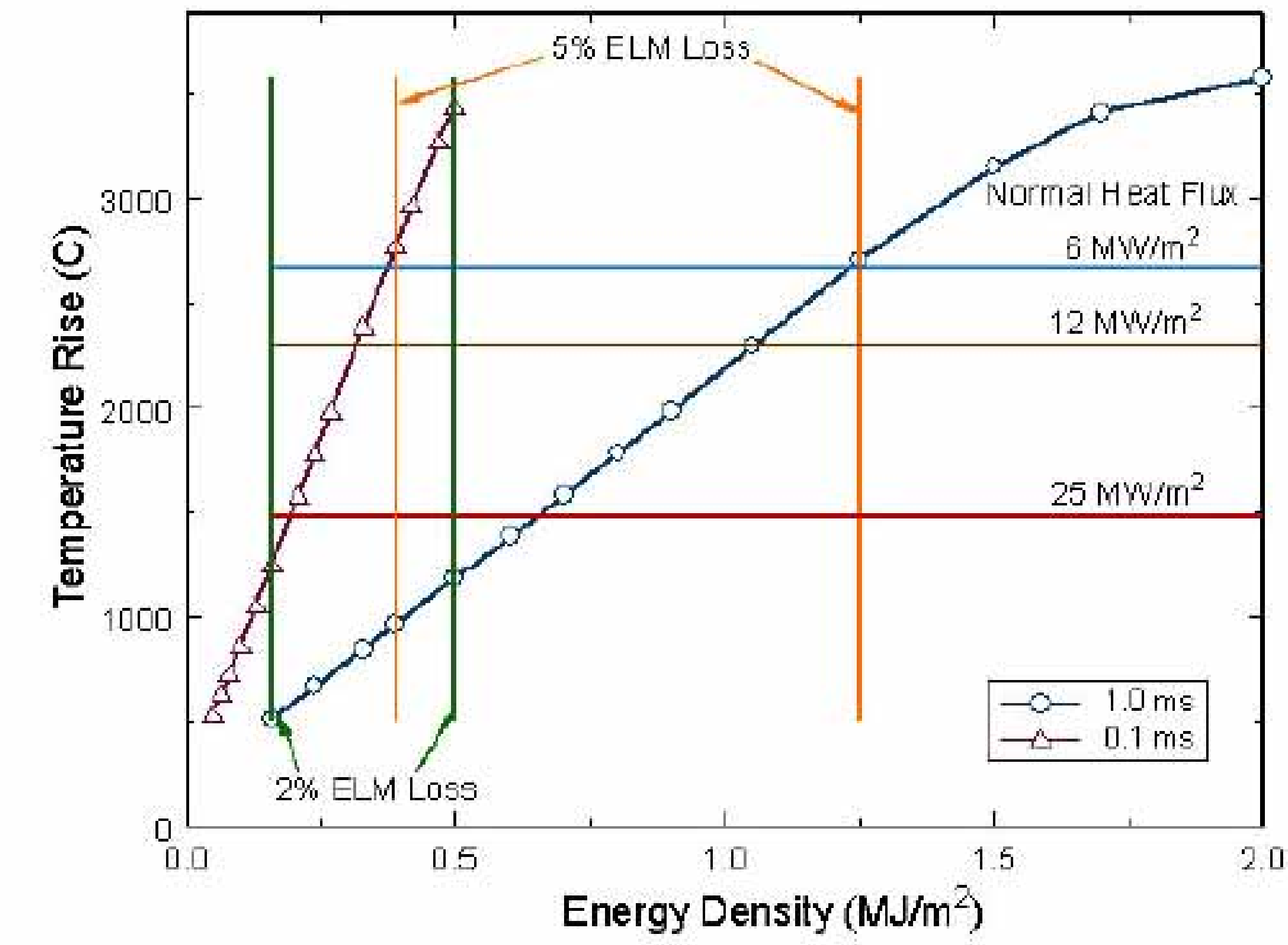
- Recent DIII-D experiments show that DN plasmas have similar Pthr as SN, when plasma shape (triangularity) is controlled (Carlstrom, APS, 2001)
- In flattop P(loss)/Pthr, δ, ne, Tped, ... determine type of ELMs and quality of confinement
  - EDA H-mode on C-Mod
  - Type II or grassy ELMs on DIII-D and JT-60U
  - Type II ELMs at high density on ASDEX-U
  - QDB regime on DIII-D
- Need smaller ΔWELM for divertor lifetime, requiring higher fELM, but with good confinement

Estimates indicate that some partial detachment $q \leq 12$ MW/m2, spreading of ELM heat flux by 2-4, and $\Delta W_{ELM} < 3\%$ of Wth to avoid melting

ELM Operating Space

M. Ulrickson

Fraction of stored energy in ELM ----> Energy Density
Time over which ELM occurs -----> Temp Rise of Tungsten
Avoid material erosion by keeping temp rise low



FIRE Uses ICRF Heating for Its Reference Discharge

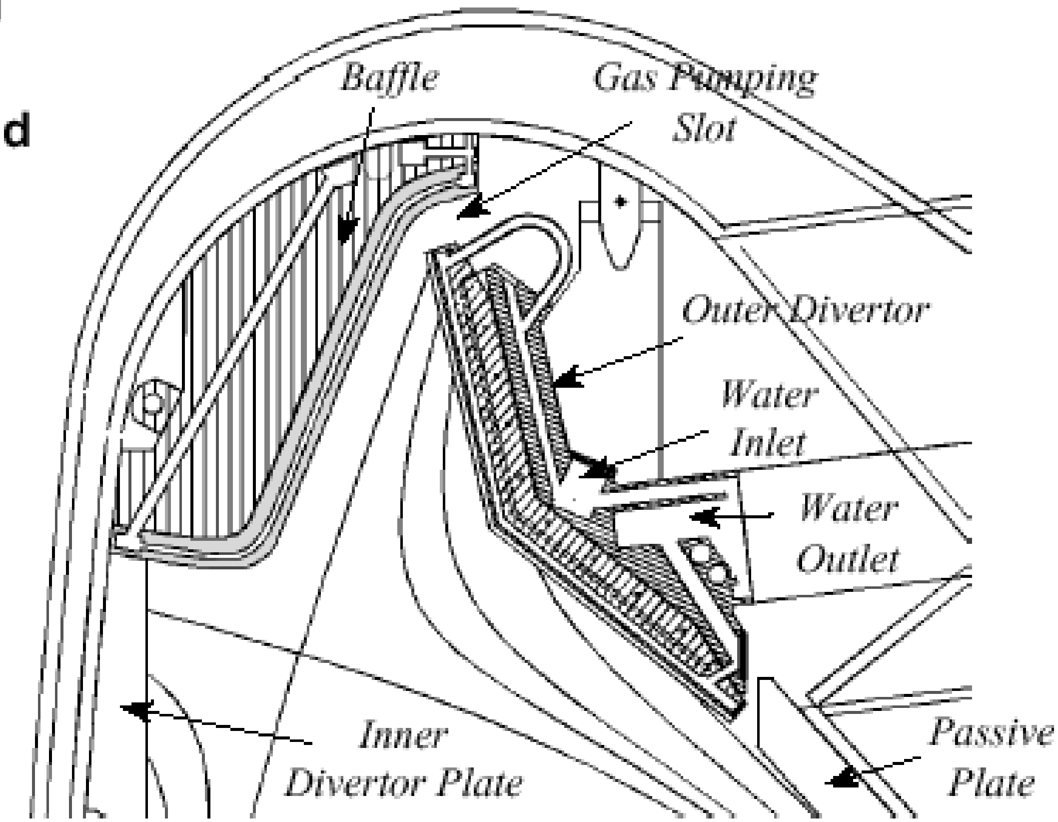
- ICRF ion heating
  - 80-120 MHz
  - 2 strap antennas
  - 4 ports (2 additional reserved)
  - 20 MW installed (10 MW additional reserved)
  - He3 minority and 2T heating
  - Frequency range allows heating at a/2 on HFS and LFS (C-Mod ITB)
- Full wave analysis
  - SPRUCE in TRANSP
  - Using n(He3)/ne = 2%
  - $n_{20}(0) = 5.3$, $\langle n_{20} \rangle = 4.4$
  - $P_{ICRF} = 11.5$ MW, $\omega = 100$ MHz
  - $T_{He3}(0) = 10.2$ keV
  - $P_{abs}(He3) = 60\%$
  - $P_{abs}(T) = 10\%$
  - $P_{abs}(D) = 2\%$
  - $P_{abs}(elec) = 26\%$

Antenna design --->D. Swain, ORNL

FIRE's Divertor Must Handle Attached(25 MW/m2) and Detached(5 MW/m2) Operation

D. Dreimeyer, M. Ulrickson

- Build on design/fabrication approaches developed during ITER-EDA
- W-brush armor for divertor and plasma-sprayed Be for first wall tiles
- Cu-alloy finger elements for high heat flux outer target
- Swirl tape or helical wire inserts for CHF enhancement
- Dome-like construction for lower heat flux baffle
- Passively-cooled W-Cu tiles for low heat flux inner target
- Modular units for remote maintenance during operation



Preliminary FIRE fueling system parameters

Fisher, et al., ORNL

Parameter	Gas Fueling System	Pellet Fueling System	Remarks
Design fueling rate	200 torr-l/s for 20 s	200 torr-l/s for 20 s	Torus pumping capacity is 200 torr-l/s
Operational fuel rate	100-175 torr-l/s	100-25 torr-l/s	Isotopic fueling
Normal fuel isotope	D (95-99%) T,H (5-1%)	T (40-99 %) D(60-1%)	D-rich in edge, T-rich in core
Impurity fuel rate	25 torr-l/s	TBD (prefer gas for impurity injection)	25 torr-l/s reduces DT fuel rate due to fixed pumping capacity
Impurity species	Ne, Ar, N_2, other?	TBD	TBD
Rapid shutdown system	Massive gas puff ~10^6 torr-liter/s	"killer" pellet or liquid D jet	For disruption/VDE mitigation
Pellet sizes (cyl. diameter)	N/A	3, 4, 4 mm	3 mm for density rampup, 4 mm for flat-top

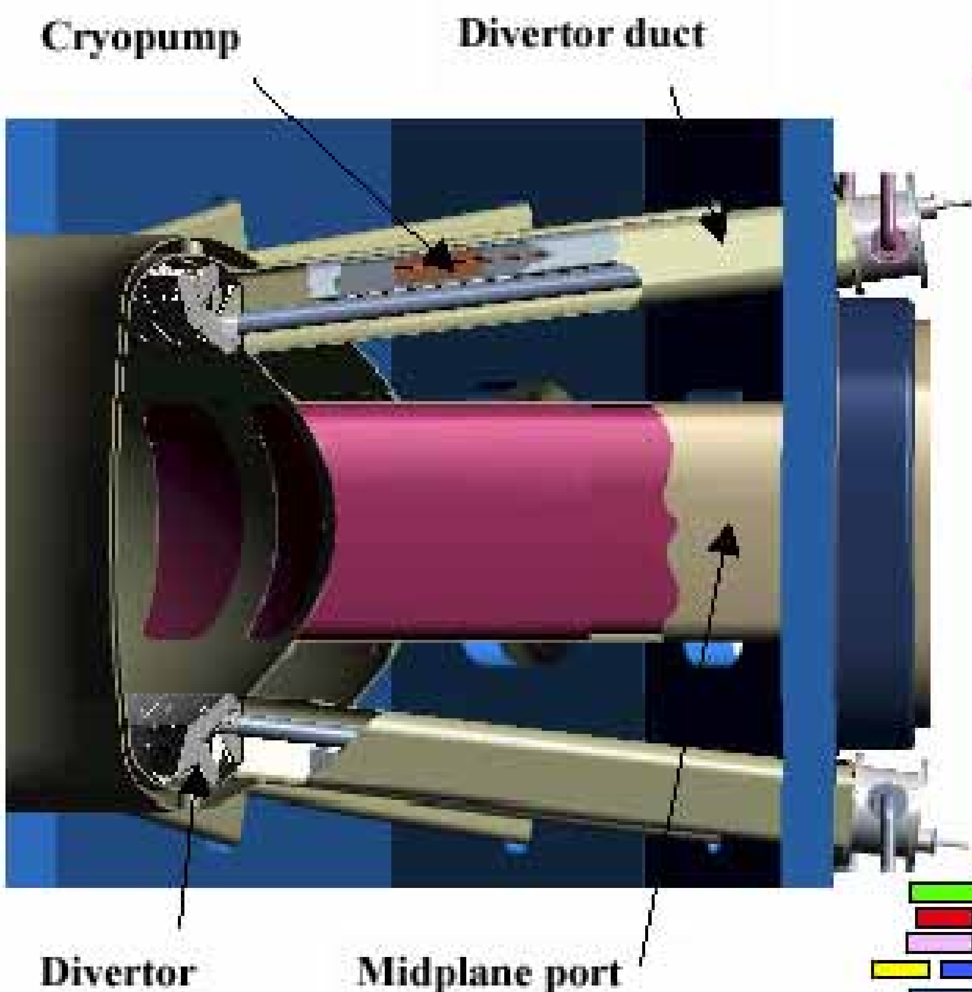
FIRE Vacuum Vessel Pumping

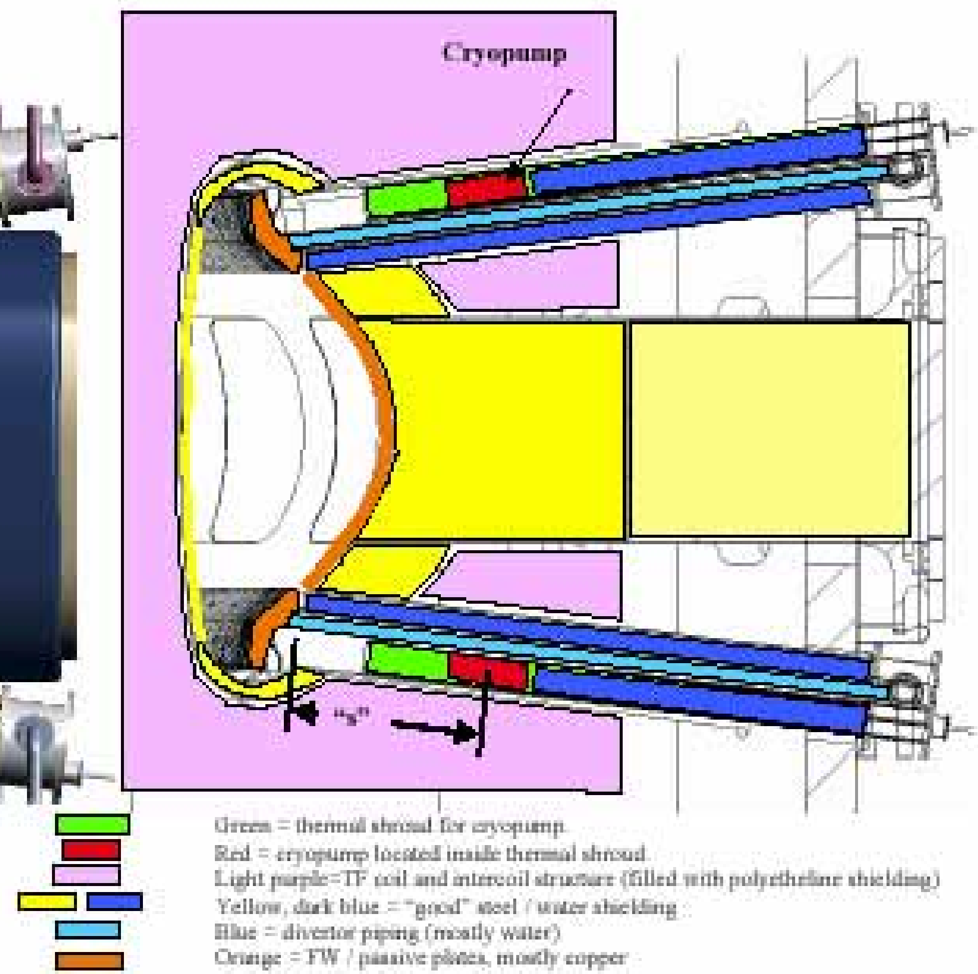
Fisher, et al., ORNL

- Current baseline is cryopumps: 16 total with 8 each top and bottom, close coupled to torus, no interface valve (i.e. regenerate to torus):
  - Cryocondensation/diffusion pumps backed by turbo/drag pumps
  - Designed to pump in both the free-molecular and viscous flow regimes
  - Water is pumped on the ID of the 160 mm diameter by 1 meter long, 30 K entrance duct which connects the divertor to the cryocondensation pump
  - Other impurity gases are pumped on a 0.5 m long 15K shield
  - Hydrogen is pumped by cryocondensation by a liquid helium cooled in-duct pump
  - The 2 torr-l/s helium gas produced by the D-T fusion reaction is compressed by viscous drag in the entrance duct by a factor of up to 100
  - The compressed helium gas is pumped by a turbo/drag pump located outside the biological shield through the divertor duct
  - cryogenic cooling requirement for the 16 pumps at a pumping rate of 200 torr-l/s and the nuclear heating loading (estimated at 0.03 watt/cm^3 at the proposed cryopump location) is 3 watts per pump. The liquid helium cooling rate required during a shot is 200 l/h for the 16 pumps.

In-Duct Cryopumping System for FIRE

Fisher, et al., ORNL



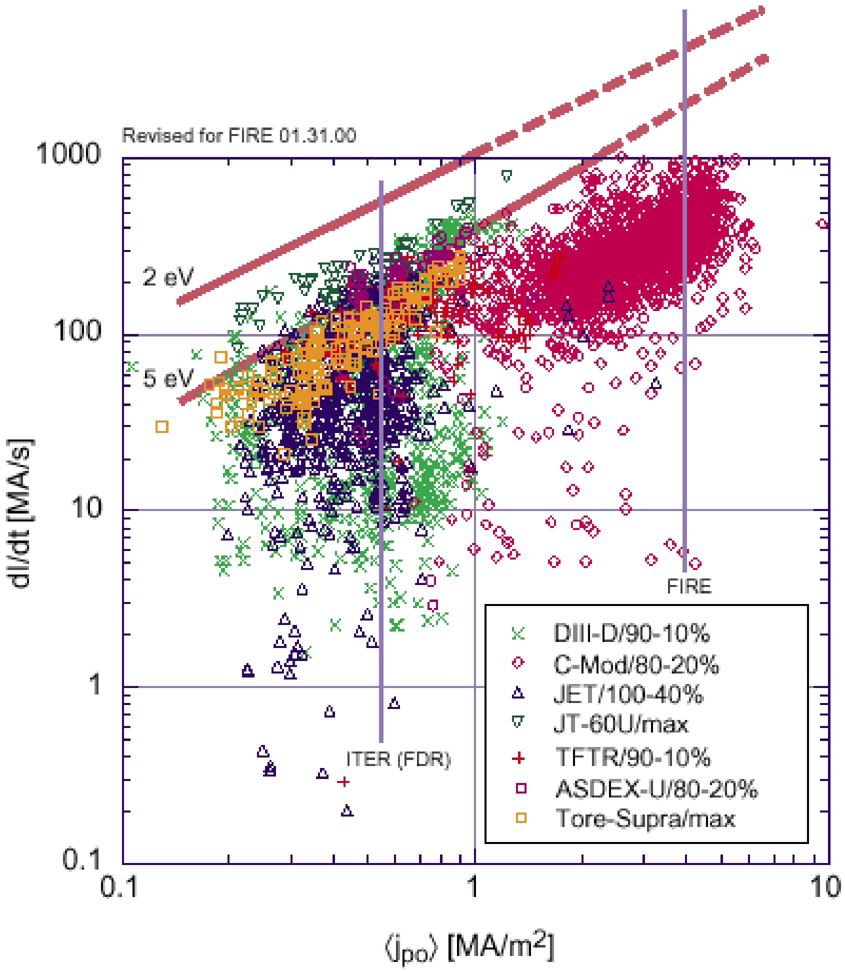


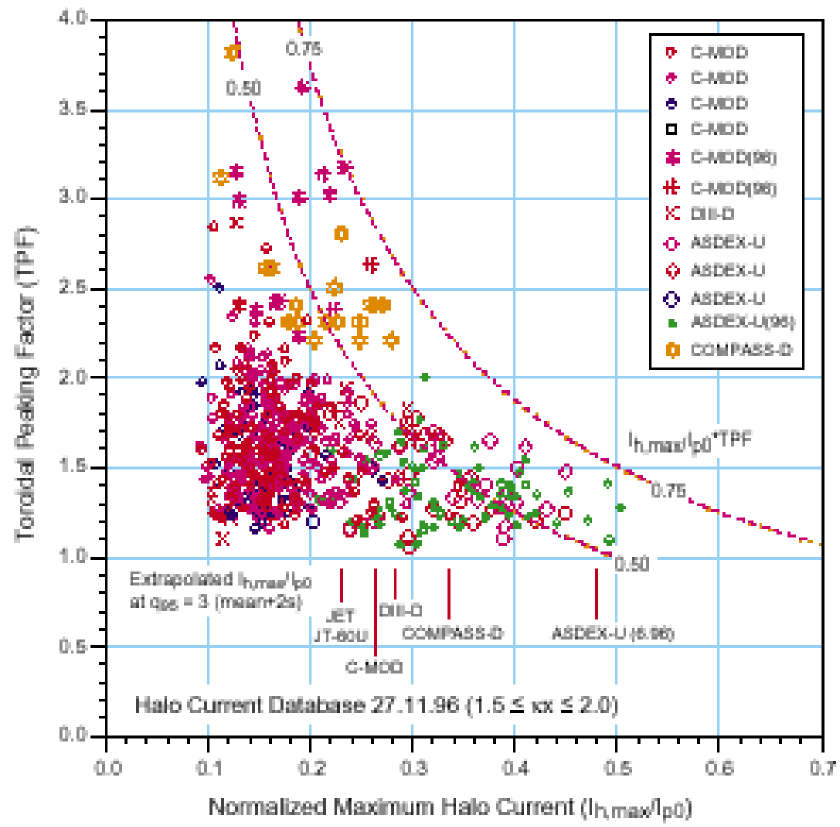
FIRE Disruption Specification

dIp/dt(absolute max) = 3 MA/ms, dIp/dt(typical max) = 1 MA/ms

I(halo)/Ip × TPF = 0.75 (abs. max), 0.5 (typ. max), I(halo)/Ip = 0.4

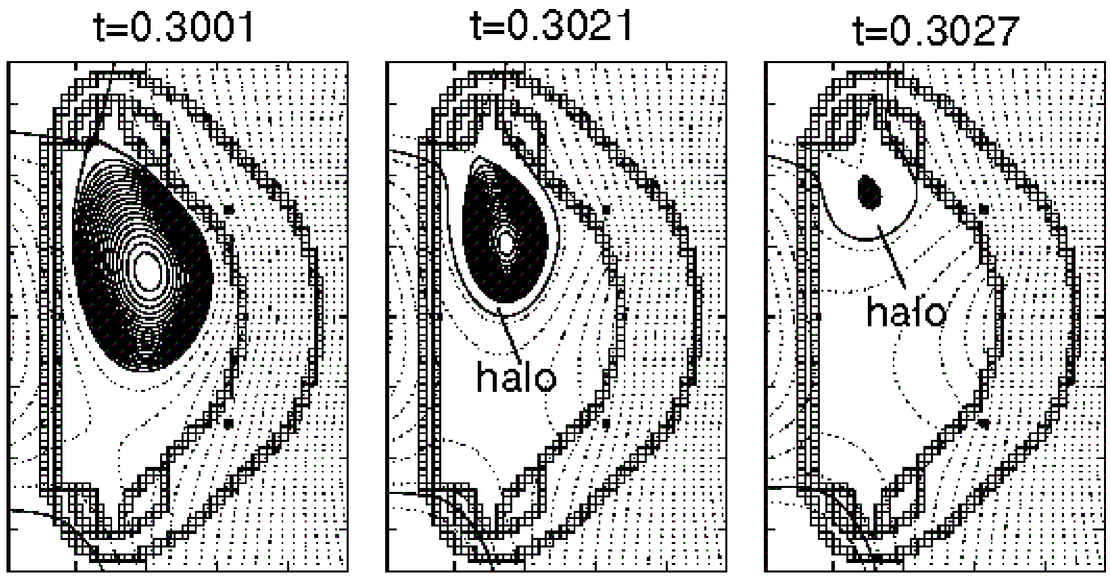
J. Wesley, GA

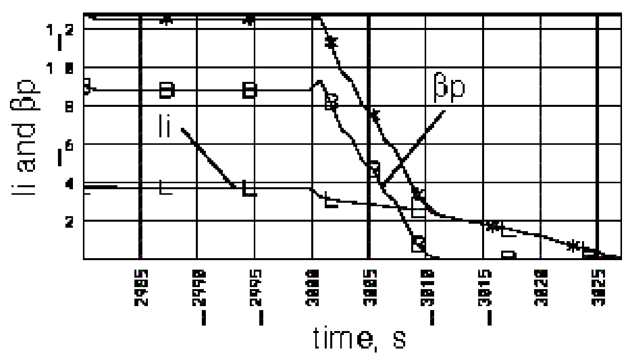


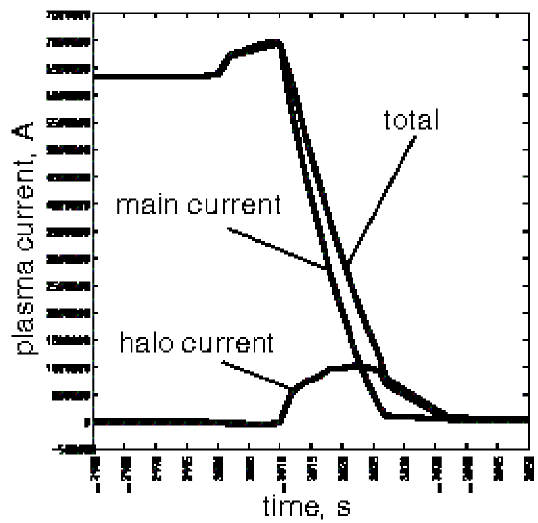


FIRE Disruption Analysis

VDE Simulation with 3 MA/ms Current Quench, TSC Simulation Used to Drive 3D Structure Models ----> M. Ulrickson/B. Nelson



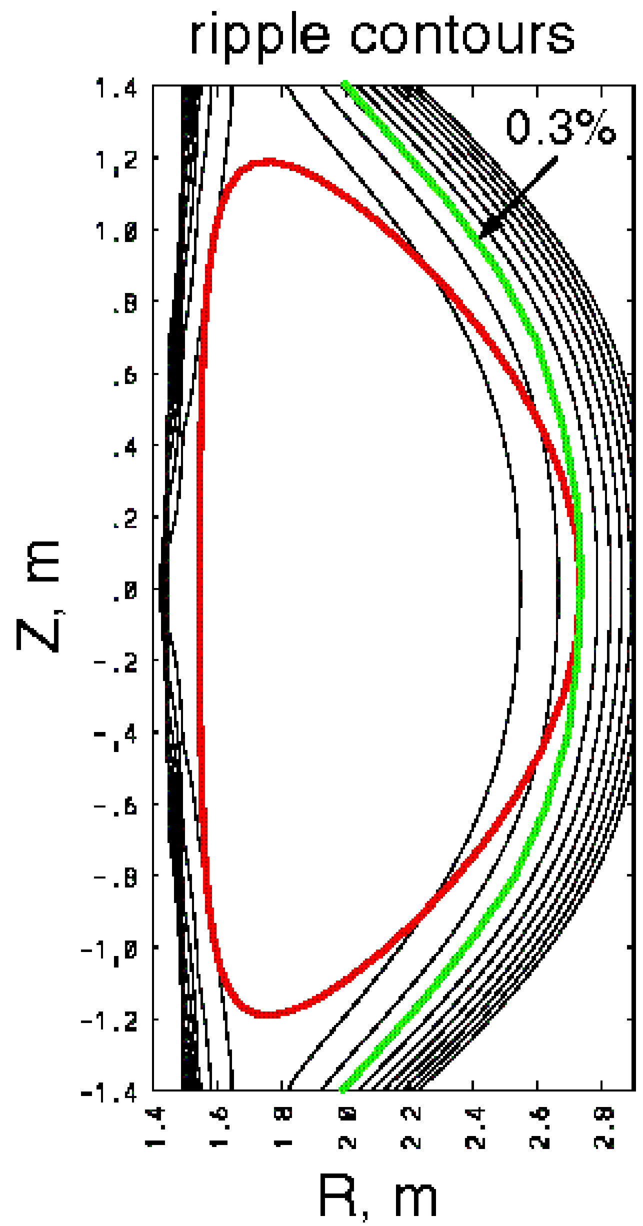




Limitations for FIRE's Flattop Time

- TF coil heating
  - For B_T = 10 T, t(flattop) = 20 s
  - For B_T = 8.5 T t(flattop) = 30 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/stress (rarely limiting, except..)
  - For low li Advanced Tokamak modes, Ip < 5.5 MA to allow t(flattop) = 20-35 s, due to divertor coil heating and stress limits

TF Ripple and Alpha Particle Losses



<u>TF ripple very low in FIRE</u>

δ(max) = 0.3% (outboard midplane)

Alpha particle collisionless + collisional losses = 0.3% for reference ELMy H-mode

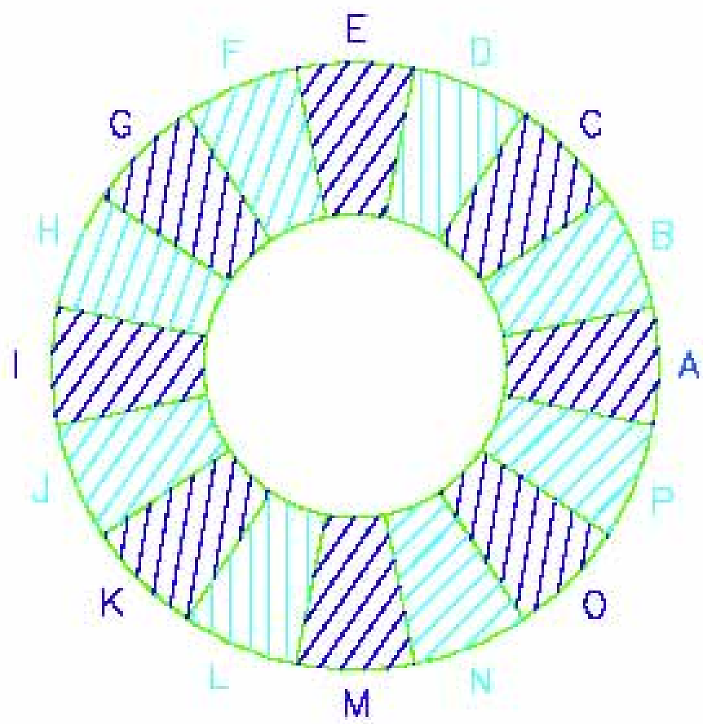
For AT plasmas alpha losses range from 2-8% depending on Ip and Bt

----> are Fe inserts required for AT operation??? ----> JFT-2M Fe plates

FIRE Port/Diagnostics Layout

FIRE Diagnostics:

Outer Upper Port Assignments



A: Divertor IR TV,
IR TV,
Penning Gauge
B: Divertor Pump/Water
C: Multichord Visible Spectrometer,
Bolometer Array
D: Divertor Pump/Water
E: Divertor IR TV,
IR TV,
Thermocouple Wiring
F: Divertor Pump/Water
G: ASDEX Gauges,
Divertor UV Spectrometer
H: Divertor Pump/Water
I: Rotation CXRS,
Divertor IR TV,
Divertor TV
J: Divertor Pump/Water
K: Bolometer Array,
Separatrix Interferometer
L: Divertor Pump/Water
M: Divertor IR TV,
Divertor TV,
Thermocouple Wiring
N: Divertor Pump/Water
O: Divertor Filterscope,
ASDEX Gauges
P: Divertor Pump/Water

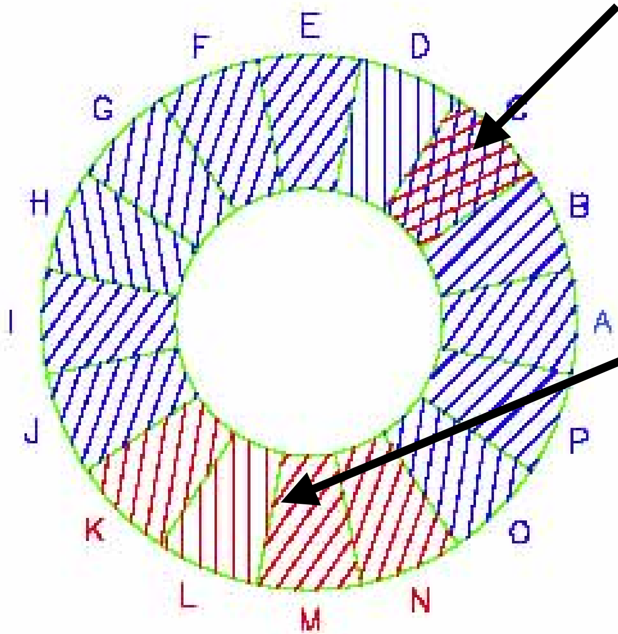
Divertors every other port

K.M.Young 23 Jan. 02 19th IEEE/NPSS Symp. On Fus. Engg.

PPPL Princeton Plasma Physics Laboratory

FIRE Port/Diagnostics Layout

FIRE Diagnostics:
Radial Port Assignments



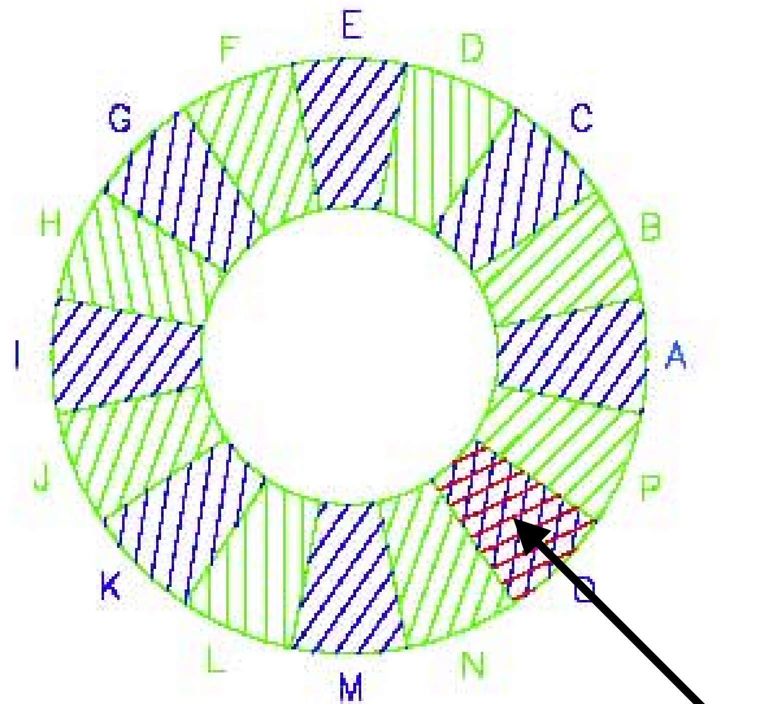
Blue: Diagnostics Components
Orange: Diagnostics-provided Services
Red: Auxiliary Systems
Green: Services

A: MSE (2),
CXRS (2),
Beam Emission Spectroscopy,
Lost-α System
B: Diagnostic Neutral Beam
C: Pump Duct,
Pellet Injector,
Ion Gauges,
RGA
D: Visible Survey Spectrometer,
Visible Filterscopes,
Visible Bremsstrahlung,
UV Survey Spectrometer
E: X-ray Crystal Spectrometer,
X-ray PHA,
Hard X-ray Detector
TVTS Dump
F: TVTS Detection
Plasma TV,
IR TV,
MM-wave Receiver
G: Neutron Camera,
Neutron Fluctuation Detectors
Bolometer Array
H: ECE Systems,
Reflectometers,
MM-wave Collective Scattering Source and Receiver,
Magnetics Wiring

I: TVTS Detection,
Plasma TV,
IRTV
Soft X-ray Array
J: TVTS Laser,
Pellet Charge Exchange,
Li-Pellet Injector,
Hard X-ray Detector
Synchrotron Rad. Detector
K: ICRF Launcher
L: ICRF Launcher
M: ICRF Launcher
N: ICRF Launcher
O: FIR Interferometer/ Polarimeter,
Plasma TV,
IR TV,
Bolometer Array
P: MSE (1),
CXRS (1),
α-CHERS

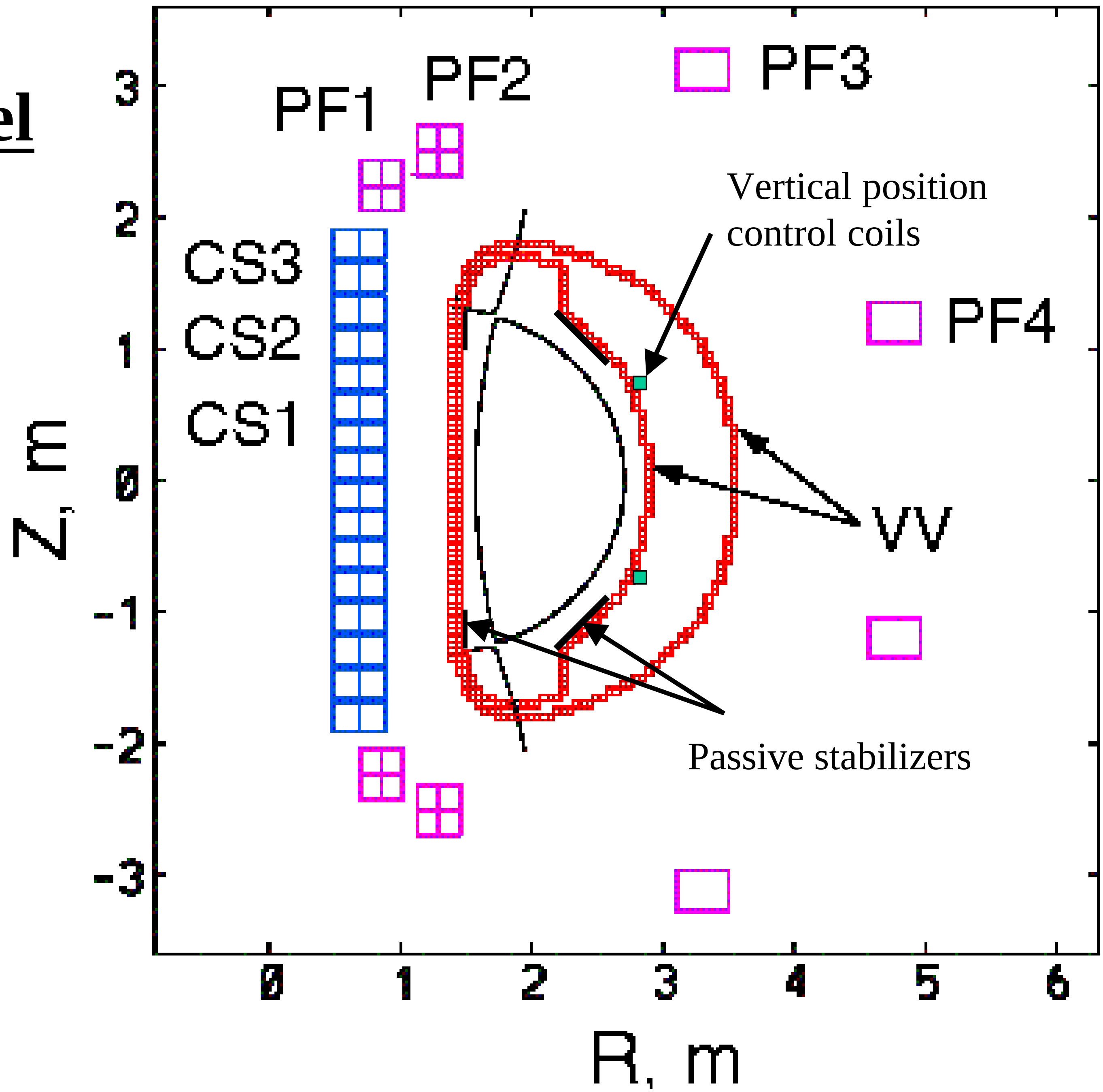
FIRE Port/Diagnostics Layout

FIRE Diagnostics:
Outer Lower Port Assignments



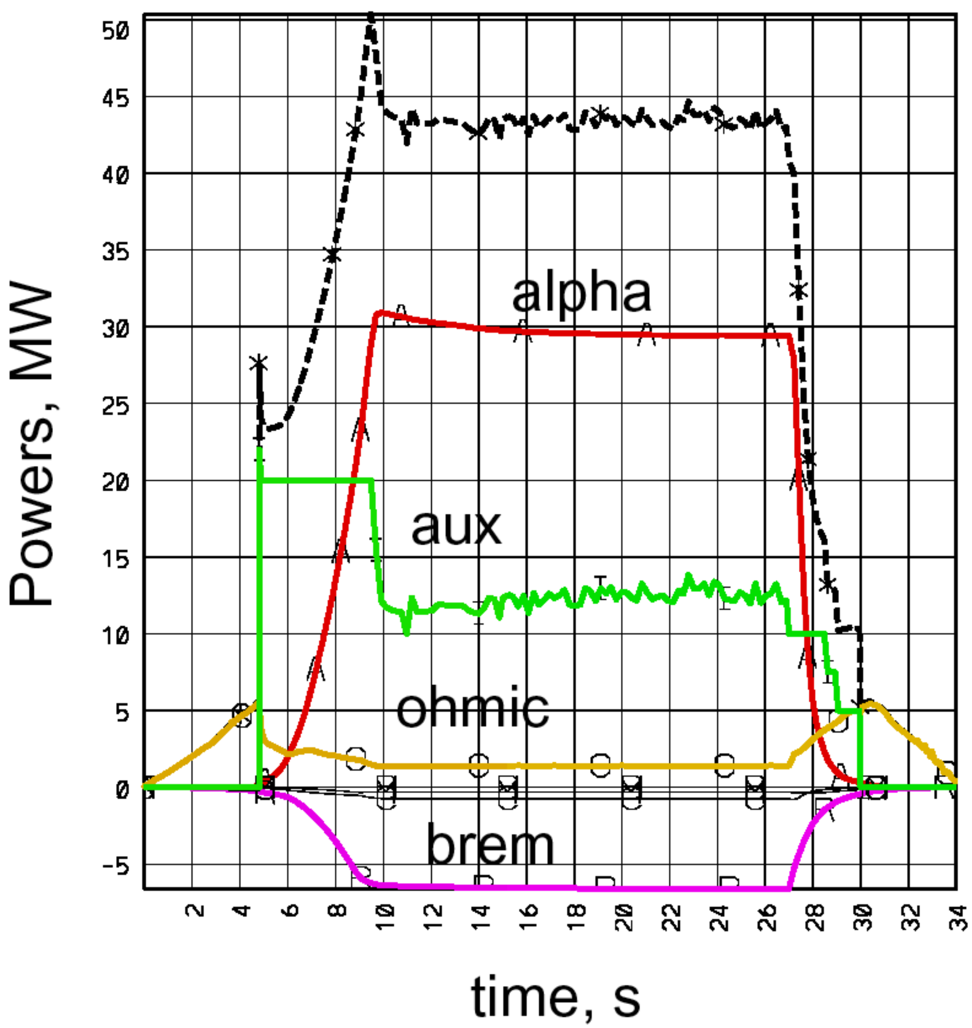
A: Divertor IR TV,
IR TV,
Penning Gauge
B: Divertor Pump/Water
C: Multichord Visible Spectrometer,
Bolometer Array
D: Divertor Pump/Water
E: Divertor IR TV,
IR TV,
Thermocouple Wiring
F: Divertor Pump/Water
G: ASDEX Gauges,
Divertor UV Spectrometer
H: Divertor Pump/Water
I: Rotation CXRS,
Divertor IR TV,
Divertor TV
J: Divertor Pump/Water
K: X-point Thomson Scattering,
Bolometer Array
L: Divertor Pump/Water
M: Divertor IR TV,
Divertor TV,
Thermocouple Wiring
N: Divertor Pump/Water
O: Divertor Filterscope,
ASDEX Gauges,
Inside-Launch Pellet
P: Divertor Pump/Water

TSC Model



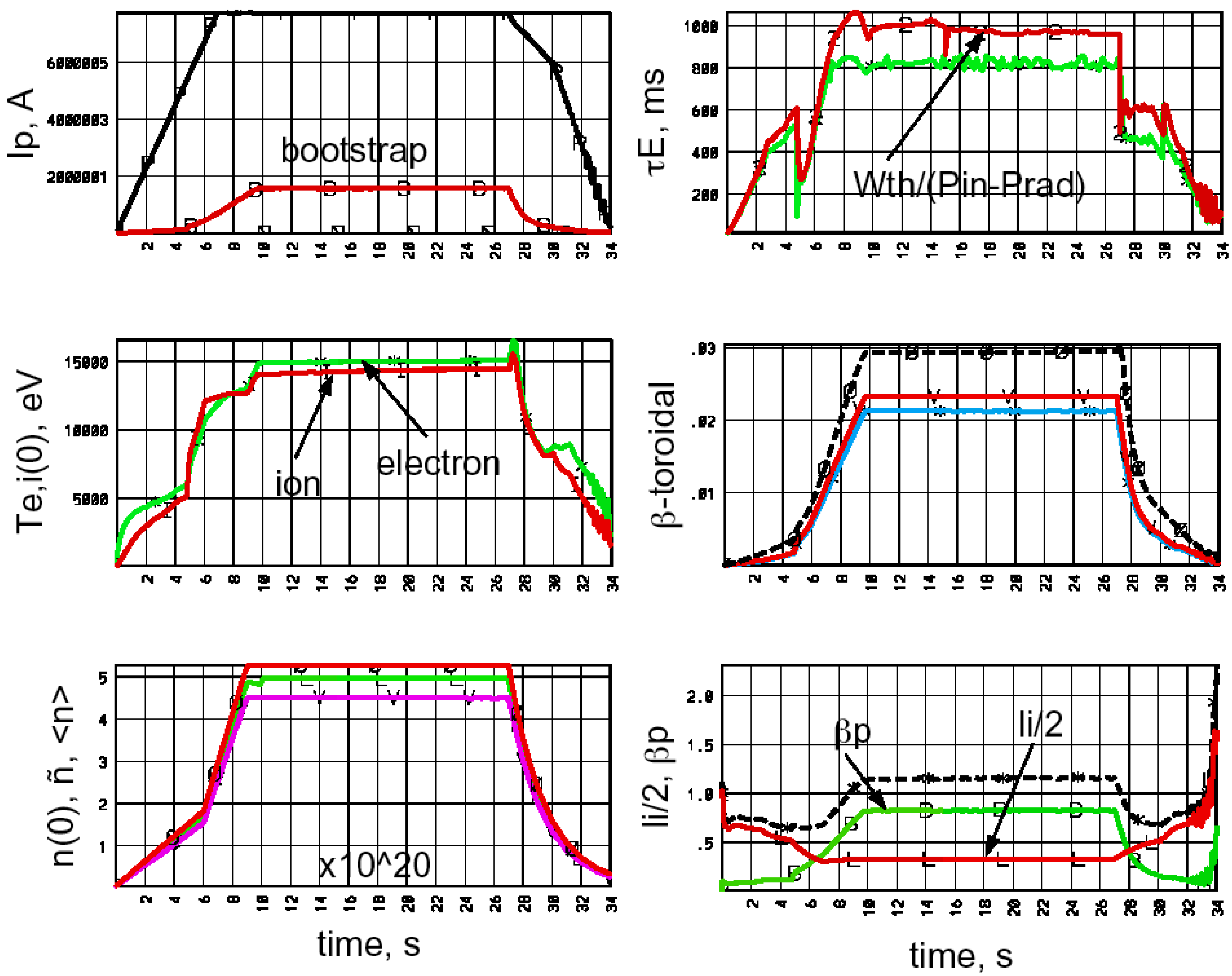
PF1
PF2
PF3
PF4
CS3
CS2
CS1
Vertical position control coils
VV
Passive stabilizers
3
2
1
0
-1
-2
-3
Z, m
0
1
2
3
4
5
6
R, m

TSC 1.5D Simulation of FIRE Reference Discharge

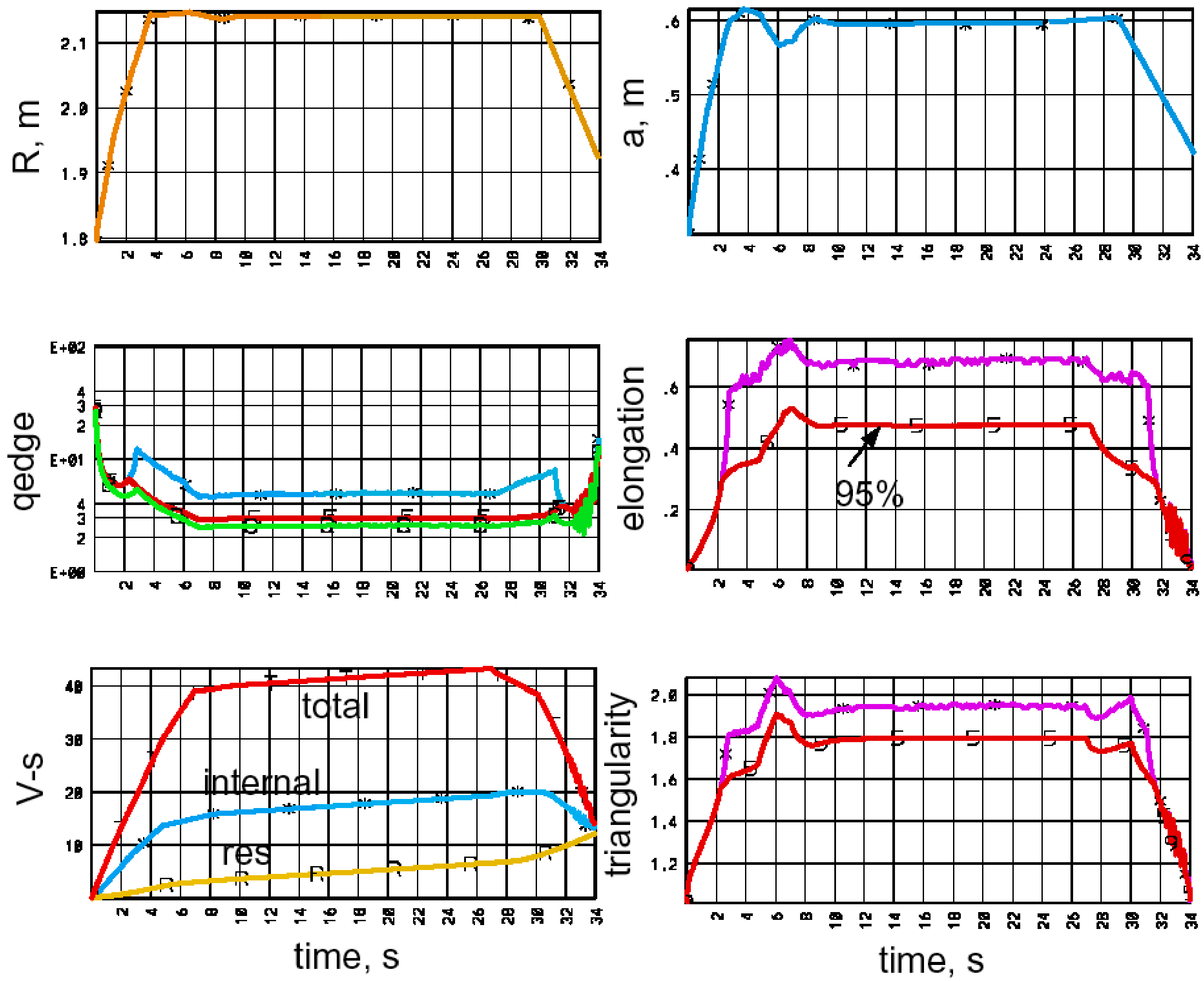


Ip = 7.7 MA	Te, i(0) = 15.0 keV
Bt = 10 T	Tped = 4.5 keV
q95 = 3.05	$\Delta\psi$(ramp) = 39 Vs
li = 0.65	$\Delta\psi$(burn) = 4.2 Vs
r(saw) = 0.2 m	fbs = 0.20
βN = 1.8	P(aux) = 13.0 MW
βp = 0.8	P(alpha) = 30 MW
n/nGr = 0.72	P(brem) = 6.6 MW
n(0)/<n> = 1.18	P(ohmic) = 1.5 MW
$n_{20}(0)$ = 5.3	P(loss) = 37 MW
Zeff = 1.38	P(L-H) = 26 MW
Wth = 35.5 MJ	τHe*/τE = 5

TSC 1.5D Simulation of FIRE Reference Discharge

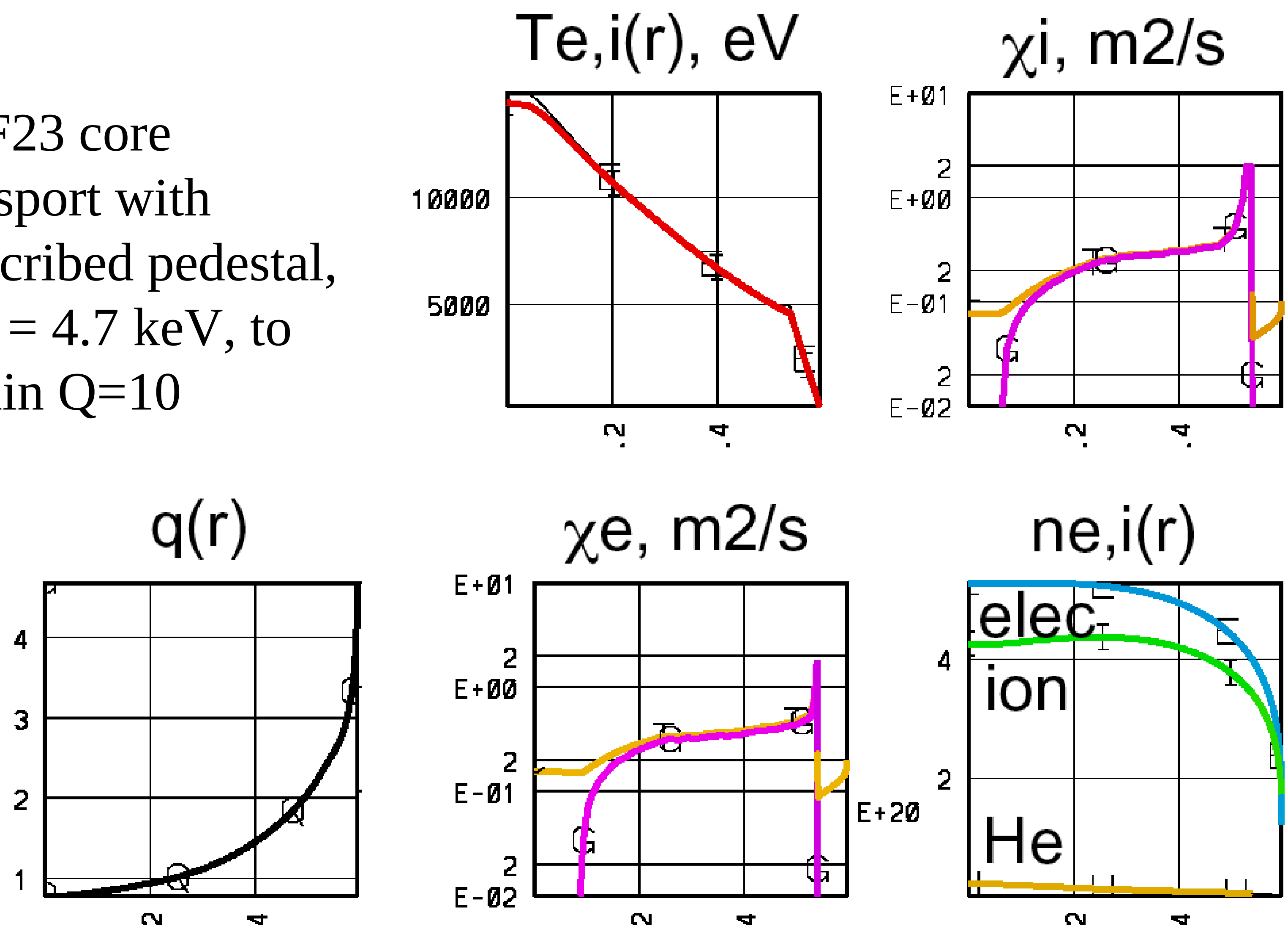


TSC 1.5D Simulation of FIRE Reference Discharge

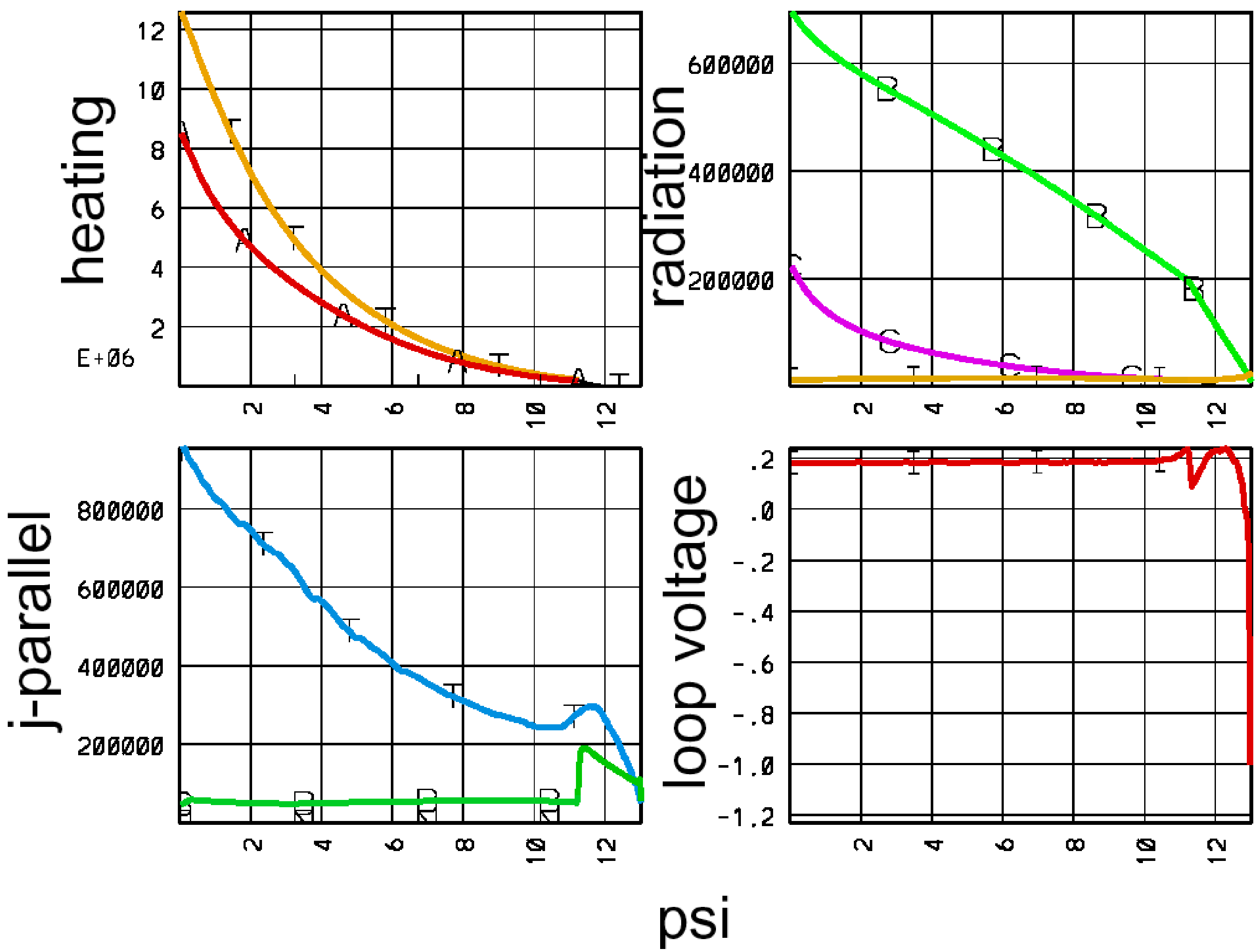


TSC 1.5D Simulation of FIRE Reference Discharge

GLF23 core transport with prescribed pedestal, T_{ped} = 4.7 keV, to obtain Q=10



TSC 1.5D Simulation of FIRE Reference Discharge



Limitations for FIRE's AT Operating Space

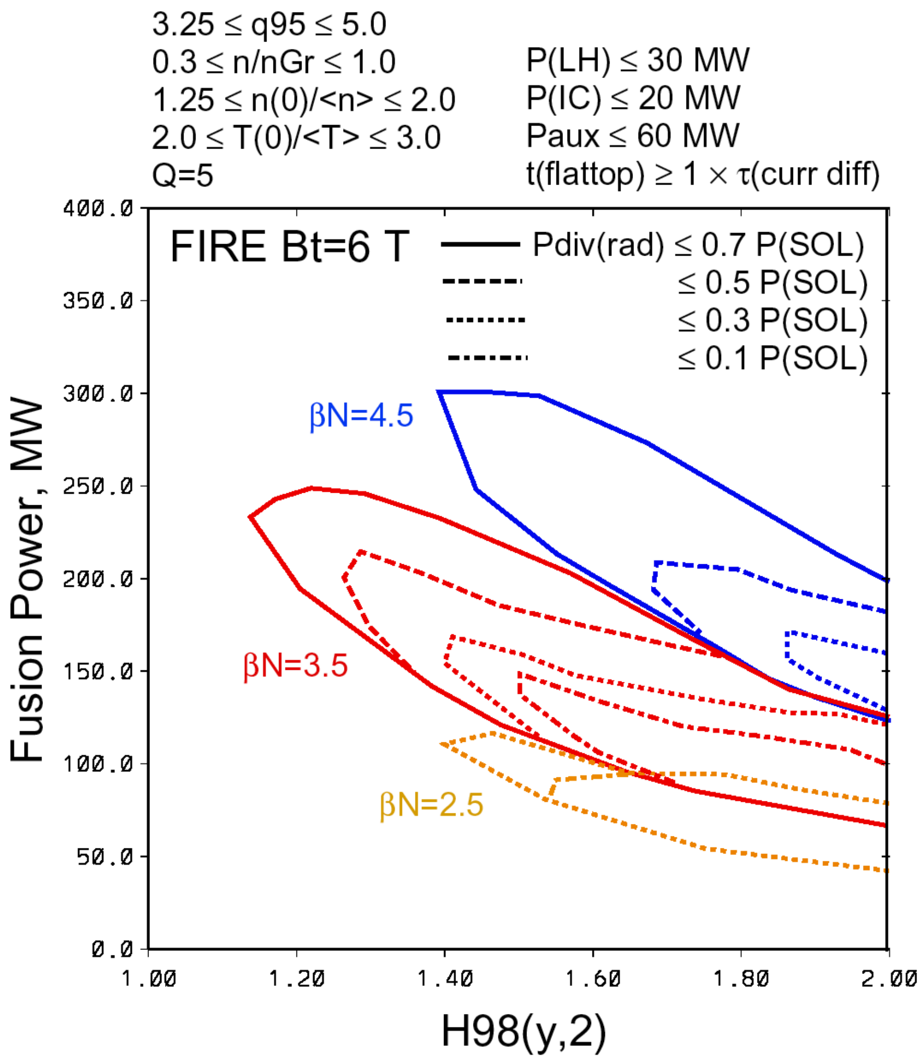
- TF Coil Heating: Bt=10 T for 20s, Bt=8.5 T for 30 s
- Nuclear Heating in VV: (200 MW) × (20s) = 4000 MW-s
- Nuclear and Surface Heat Load on FW: < 1.0 MW/m2 with peaking factor of 2
- Particle Heat Load to Divertor: P(SOL)-Pdiv(rad) < 28 MW
- Radiative Heat Load to Divertor and Baffle Surfaces: < 8 MW/m2
- Divertor Coil Heating for low li Plasmas for Longest Pulses: Ip < 5.5 MA
- Installed Auxiliary/CD Power

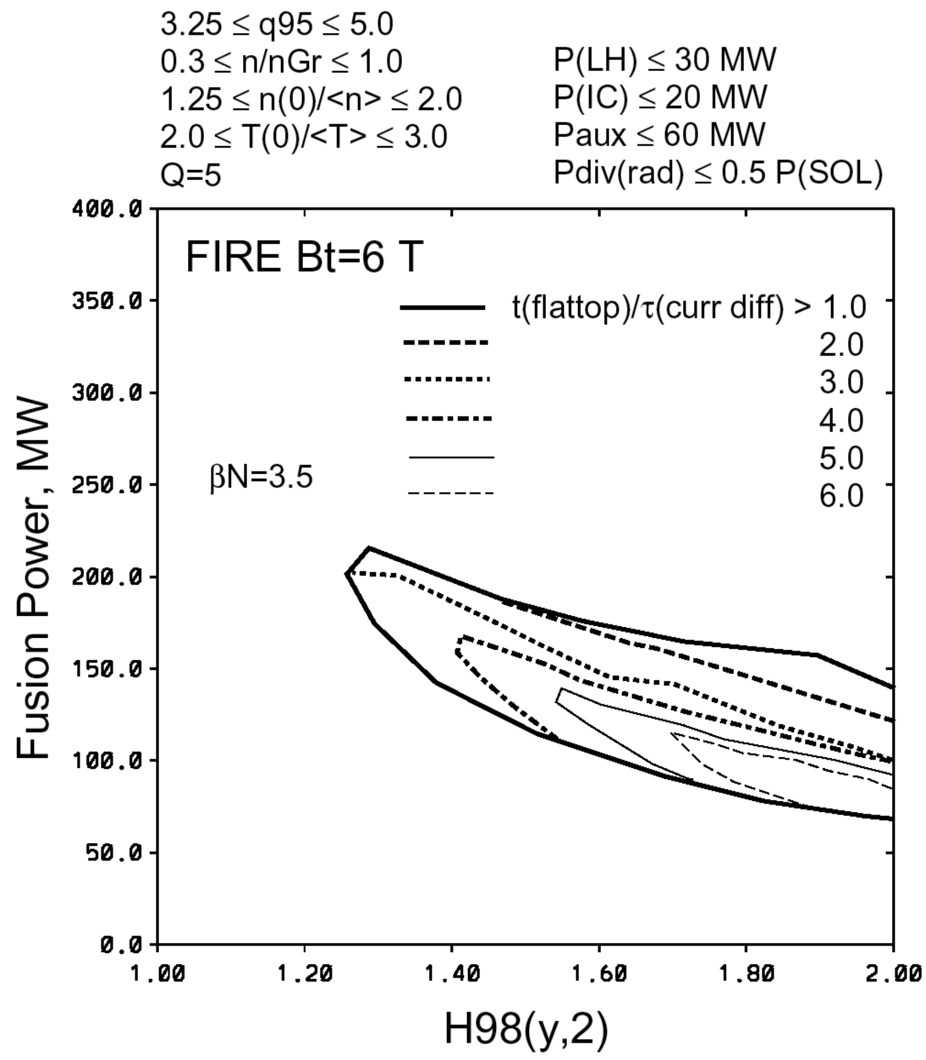
0D Operating Space Analysis for FIRE AT

- 0D calculations
- Using FIRE 1.5D AT scenario
  - ICRF/FW, 30 MW
  - LHCD, 30 MW
- Using CD efficiencies
  - η(FW)=0.20 A/W-m2
  - η(LH)=0.20 A/W-m2
- P(FW) and P(LH) determined at r/a=0 and r/a=0.75
- I(FW)=0.3 MA
- I(LH)=Ip(1-fbs)
- Scanning Bt, q95, n(0)/<n>, T(0)/<T>, n/nGr, βN, fBe, fAr

- Q=5
- Constraints:
- τ(flattop)/τ(CR) determined by VV nuclear heat or TF coil
- P(LH) and P(FW) $\leq$ max installed powers
- P(LH)+P(FW) $\leq$ Paux
- Ip < 5.5 MA, divertor coil heating for low li plasmas
- P(first wall) < 1.0 MW/m2 with peaking of 2.0
- P(SOL)-Pdiv(rad) < 28 MW
- Pdiv(rad) < 8 MW/m2

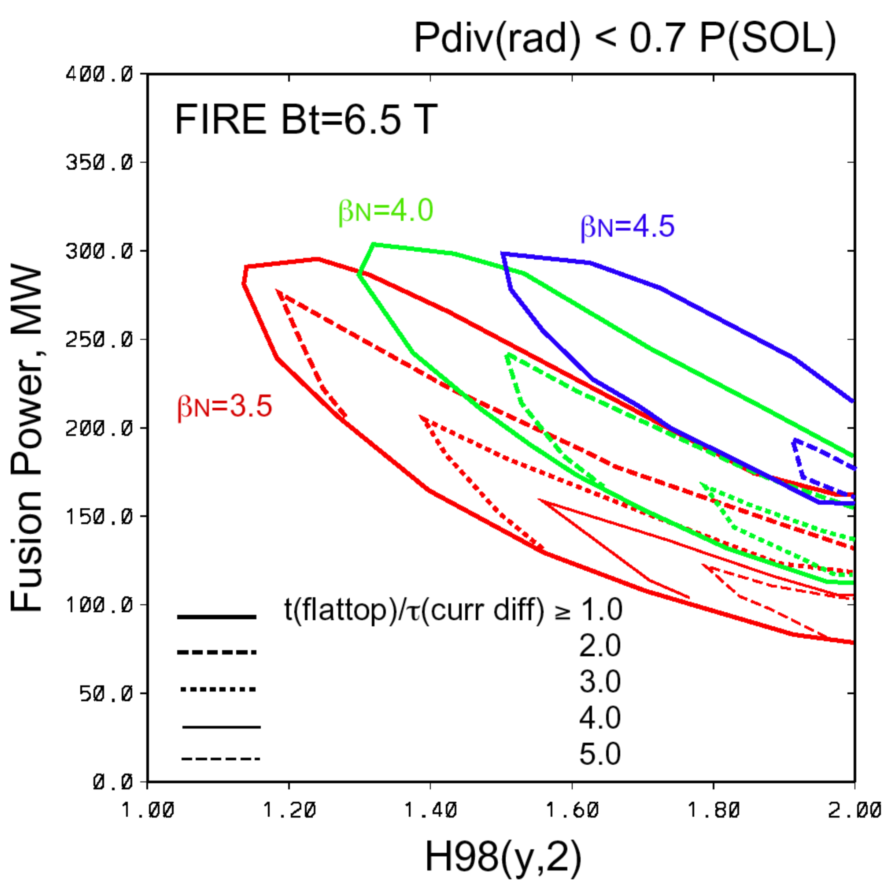
FIRE's AT Operating Space

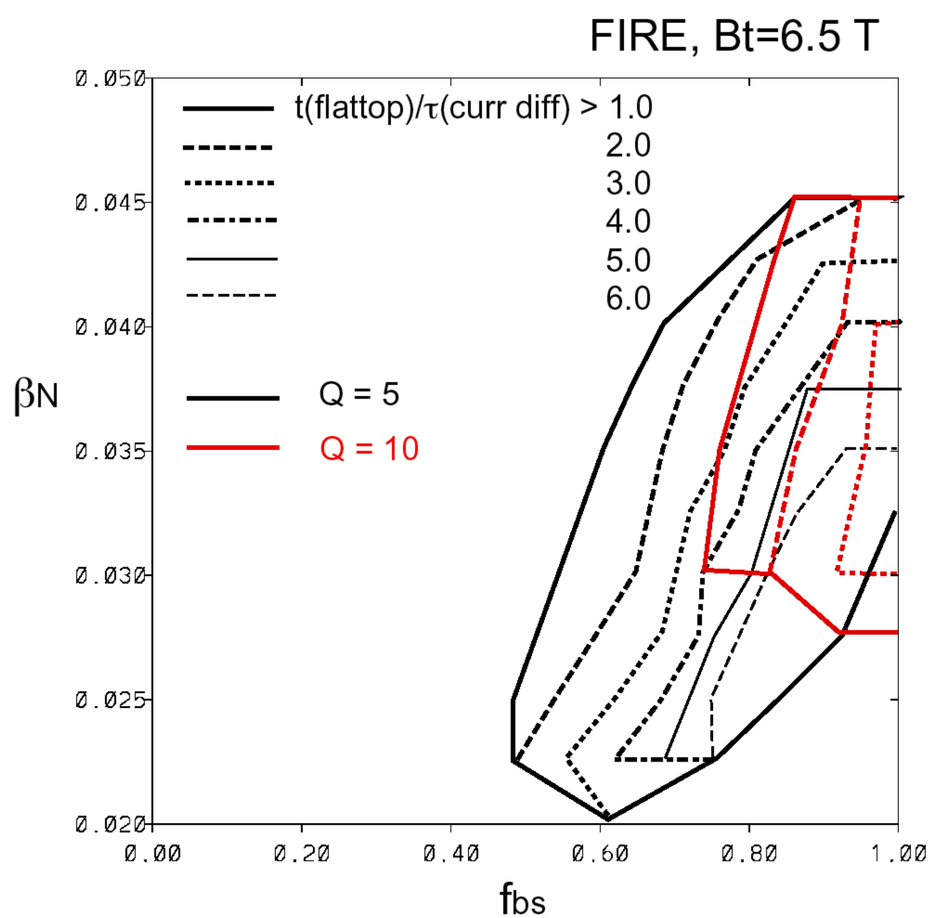




FIRE's AT Operating Space

Accessible to higher t_{flat}/τ_j decreases at higher βN, higher Bt, and higher Q





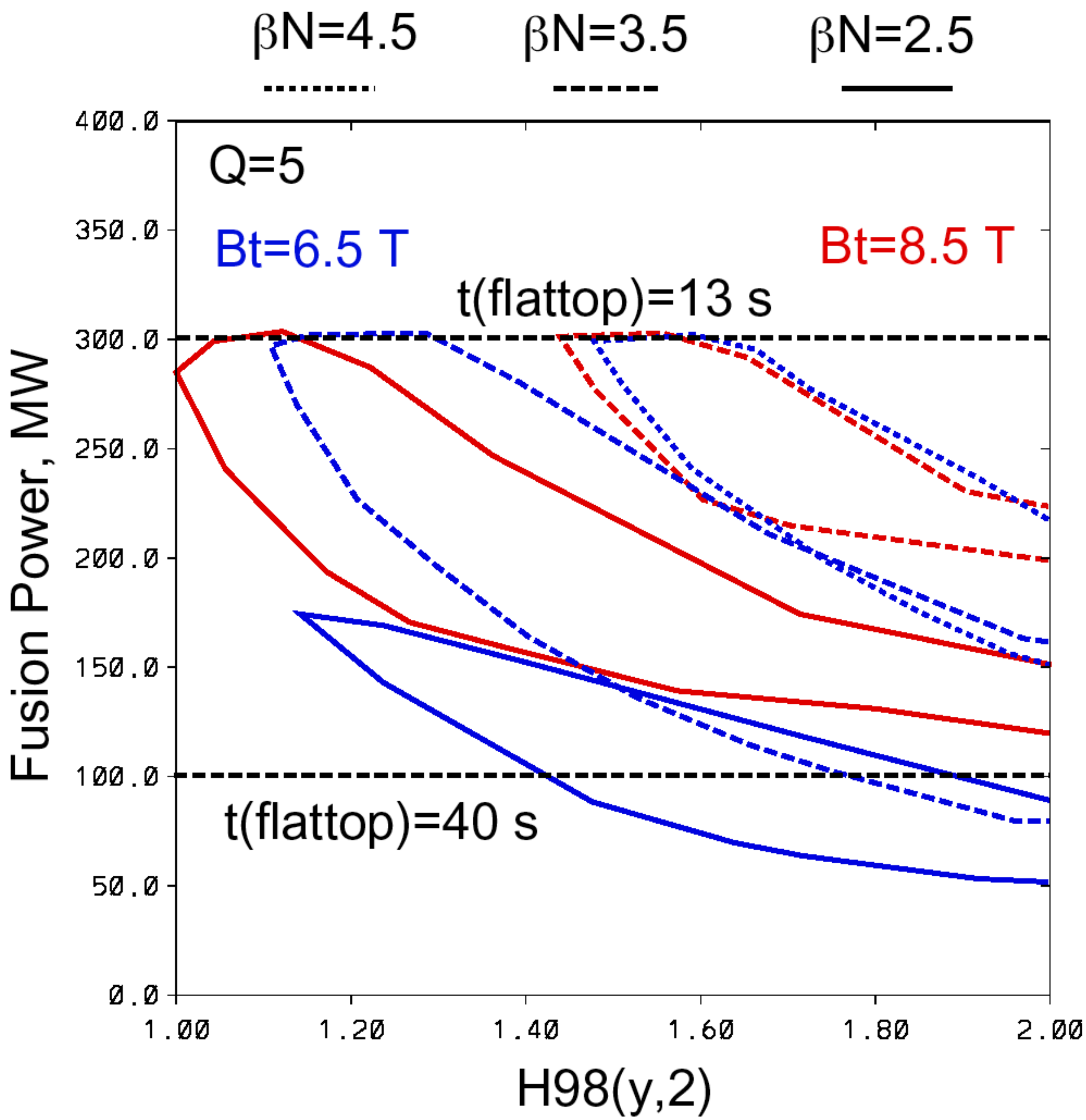
FIRE’s AT Operating Space

Operating space allowing up to 100% of P(SOL) to be radiated in divertor

6.5T allows access to wide βN range

Resulting fusion power limits the accessible flattop time

All solutions satisfy FW and divertor power handling

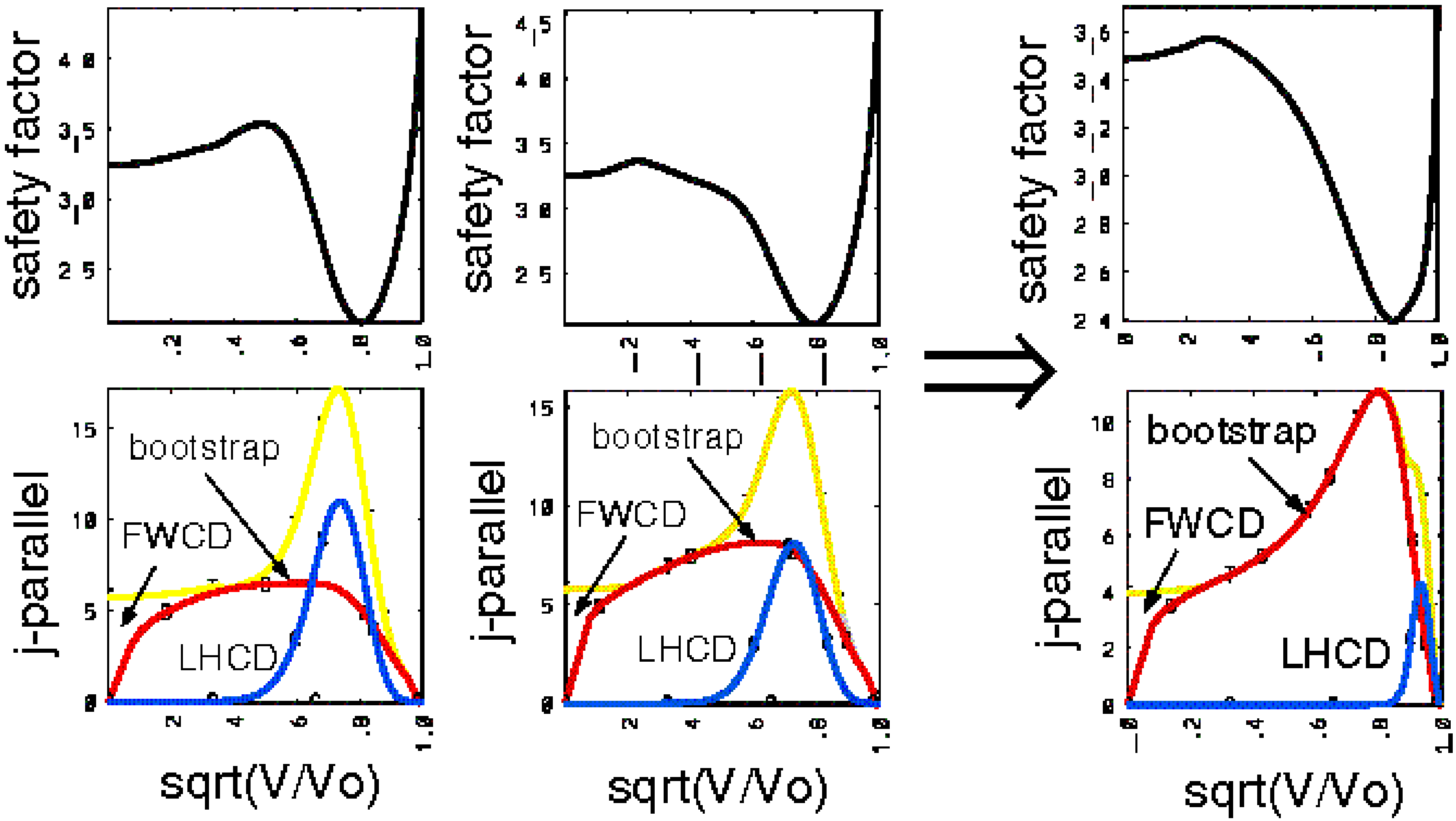


FIRE's Advanced Tokamak Plasmas are Prototypes Leading to ARIES-AT

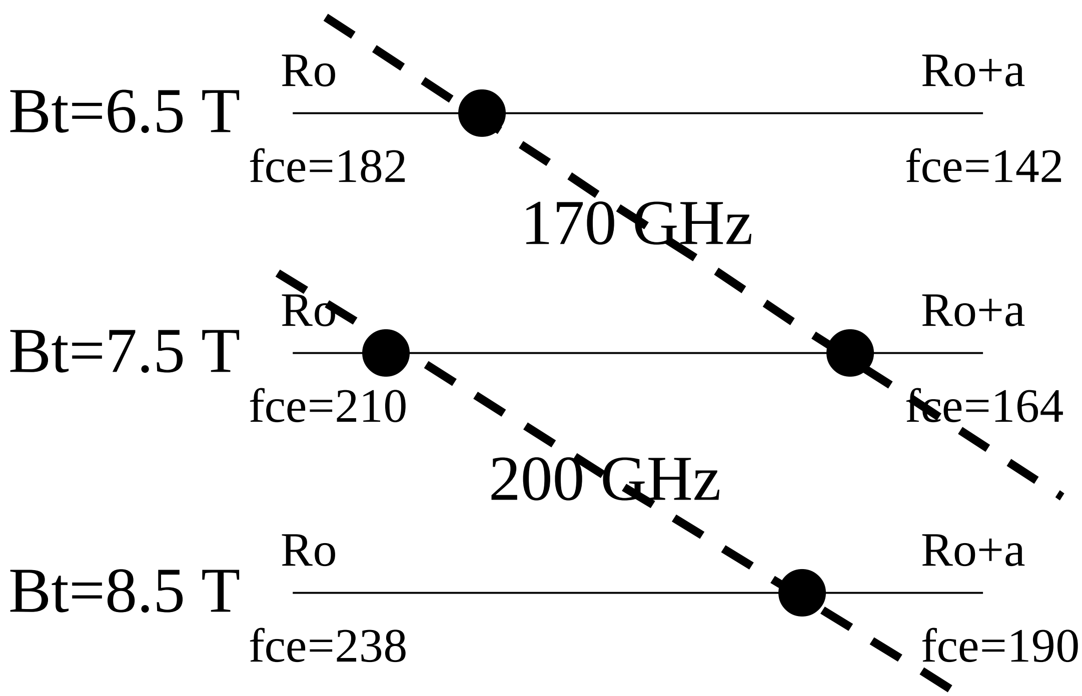
No wall stabilization, β_N=2.5, f_{BS}=50%

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

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



Neo-Classical Tearing Modes at Lower Bt for FIRE AT Modes



Target Bt=6-7 T for NTM control, to utlilize 170 GHz from ITER R&D

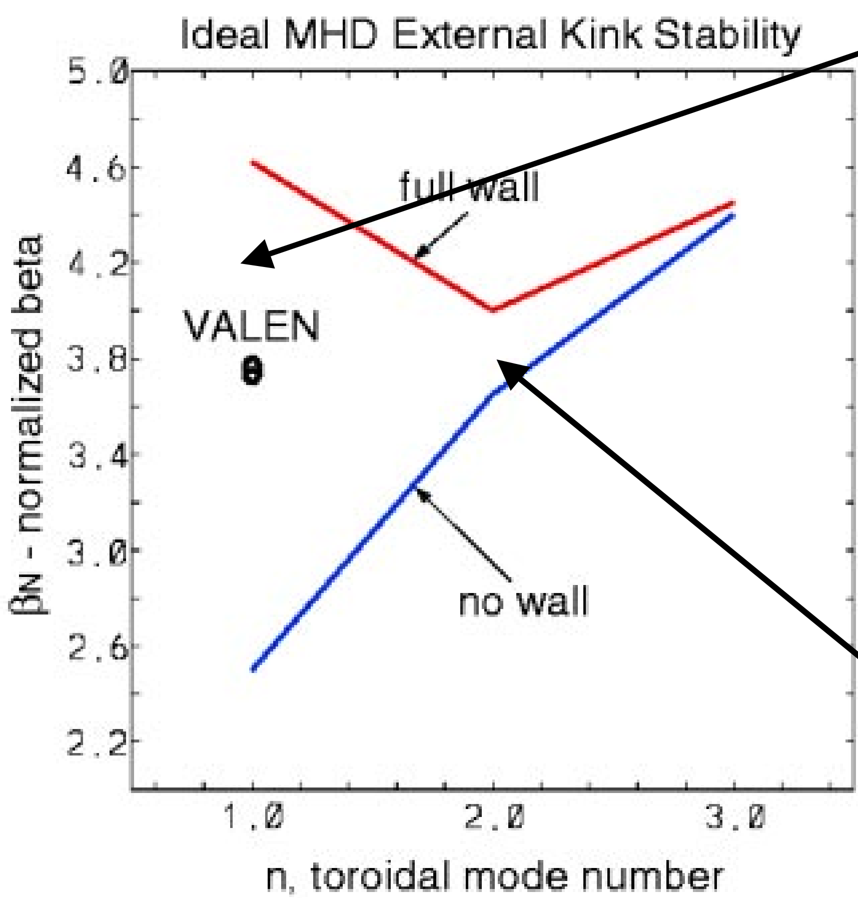
Must remain on LFS for resonance

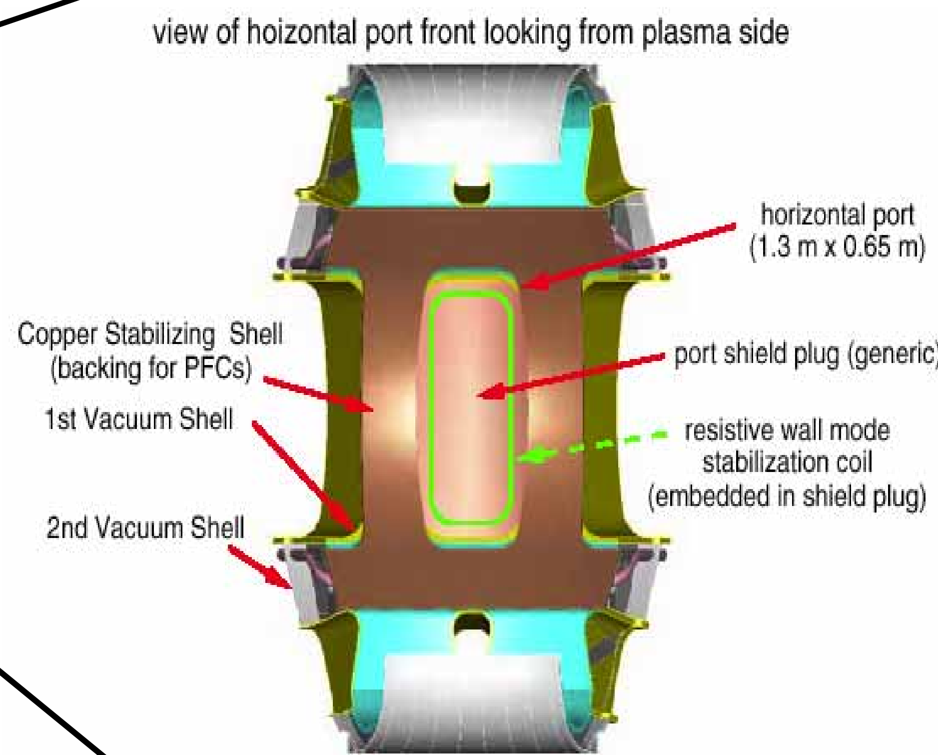
ECCD efficiency, can local βe be high enough to avoid trapping boundary??

Can we rely on ECH only to suppress NTM's and avoid CD efficiency issues?

Stabilization of n=1 RWM is a High Priority on FIRE

Feedback stabilization analysis with VALEN shows strong improvement in β, taking advantage of DIII-D experience, most recent analysis indicates βN(n=1) can reach 4.2





What is impact of n=2??

ICRF/FW Viable for FIRE On-Axis CD

Calculations assume same ICRF heating system frequency range, approximately 40% of power absorbed on ions, can provide required AT on-axis current of 0.26-0.4 MA with 20 MW (2 strap antennas)

PICES (ORNL) and CURRAY(UCSD) analysis

ω = 115 MHz

n|| = 2.0

n(0) = 5x10^20 /m3

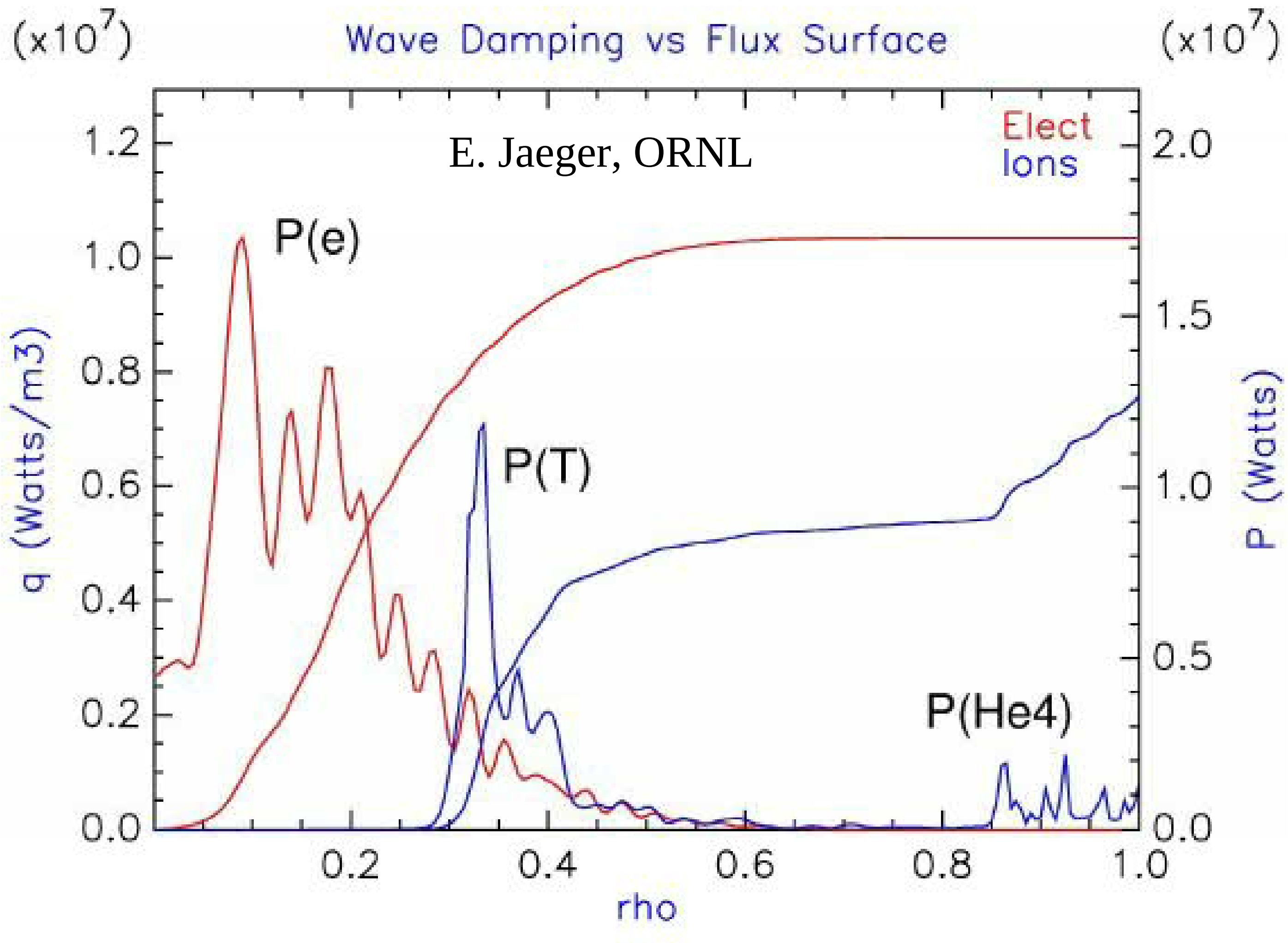
T(0) = 14 keV

40% power in good part of spectrum (2 strap)

----> 0.02 A/W

CD efficiency with 4 strap antennas??

Operating at lower frequency to avoid ion resonances??



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

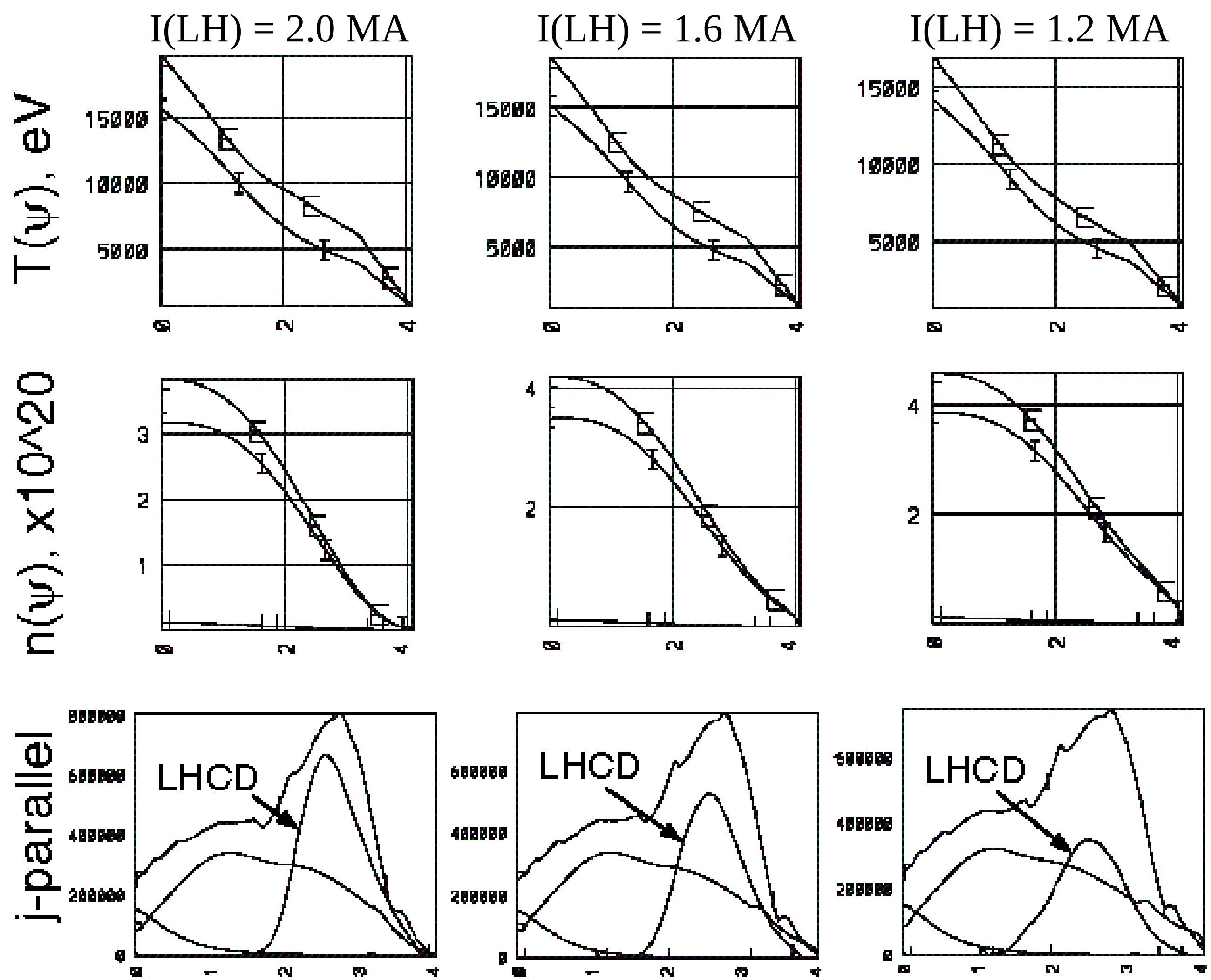
Deepest penetration

T(ψ) an n||

Avoid mode conversion

Maximum A/W

T(ψ)/n(ψ)



Benchmarks for LHCD Between LSC and ACCOME (Bonoli)

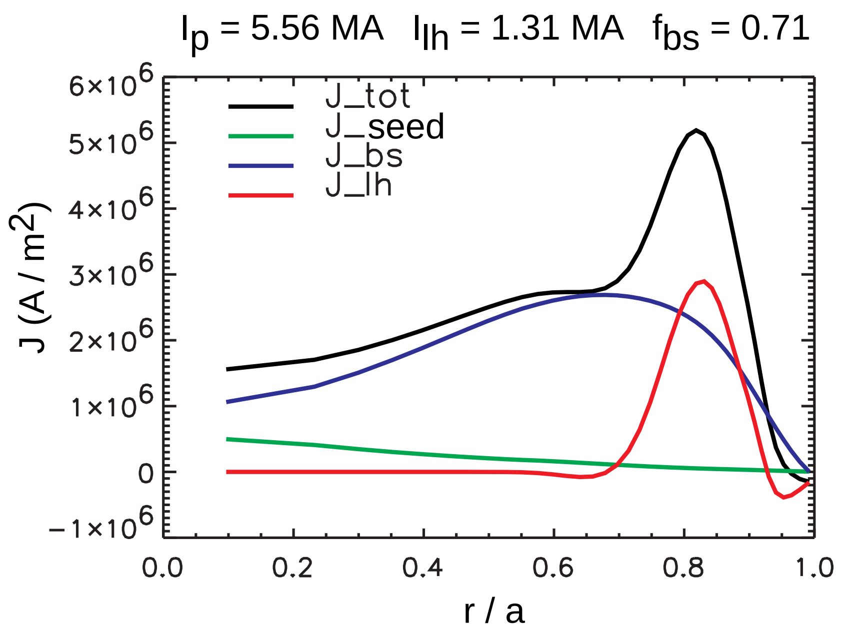
Trapped electron effects reduce CD efficiency

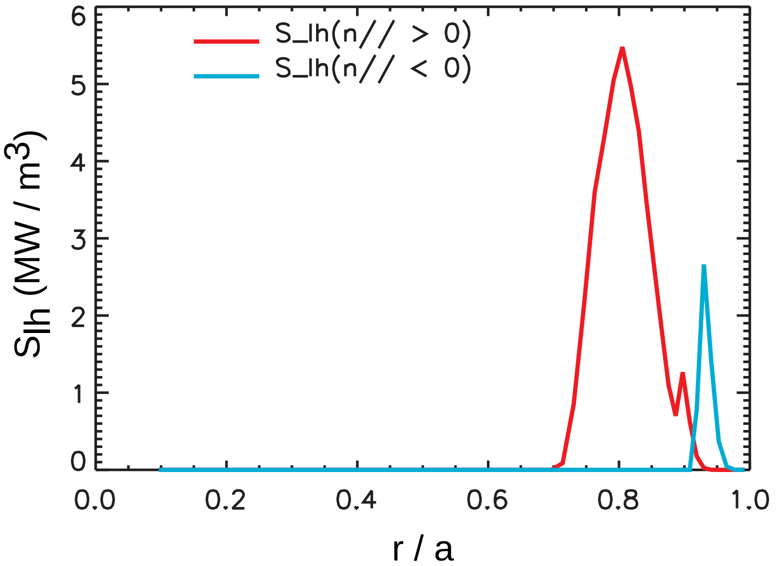
Reverse power/current reduces forward CD

Recent modeling with CQL and ACCOME/LH19 will improve CD efficiency, but right now……..

Bt=8.5T ----> 0.25 A/W-m2
Bt=6.5T ----> 0.16 A/W-m2

<u>**FIRE has increased the LH power from 20 to 30 MW**</u>

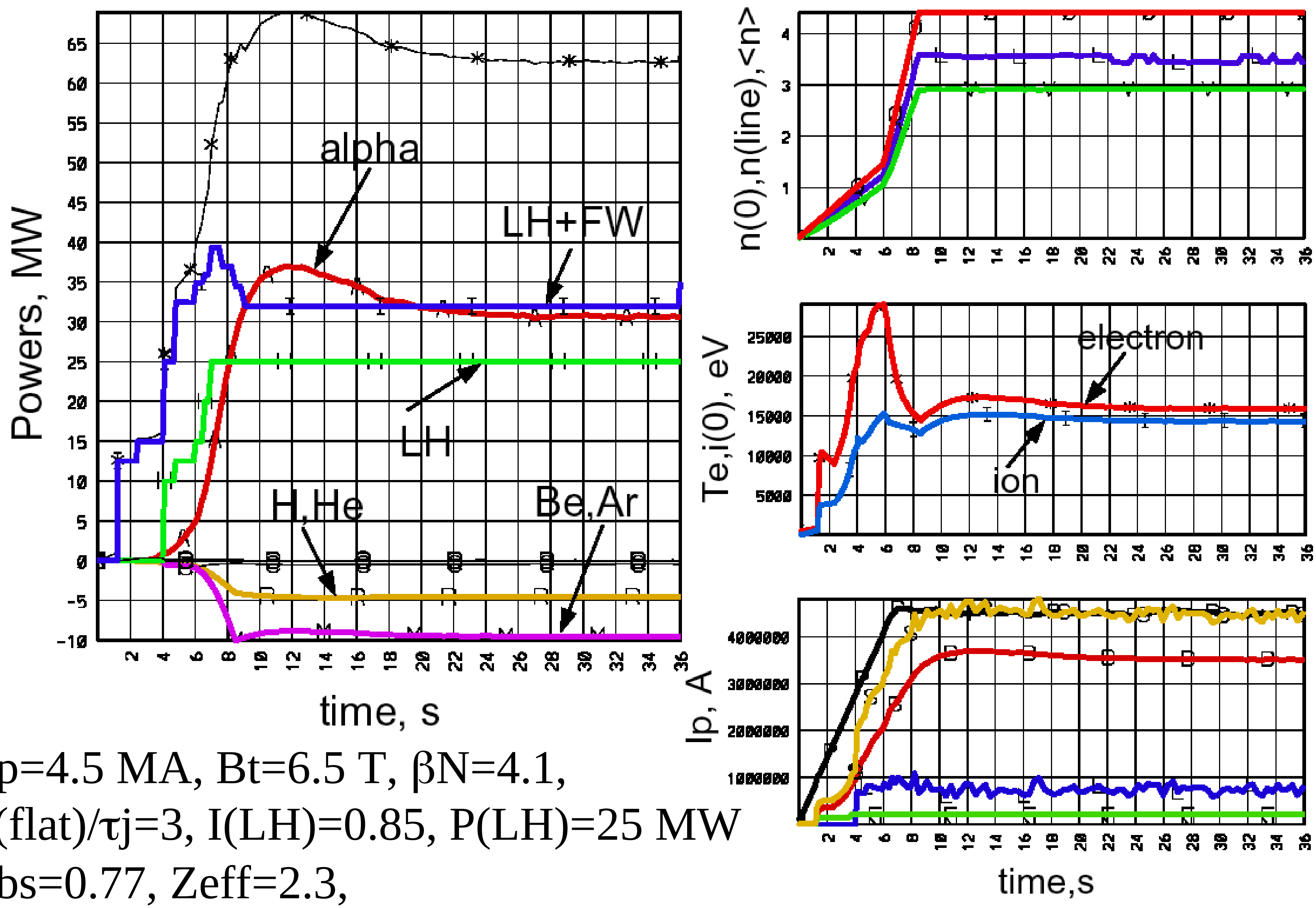




TSC-LSC Simulation of Burning AT Plasma in FIRE

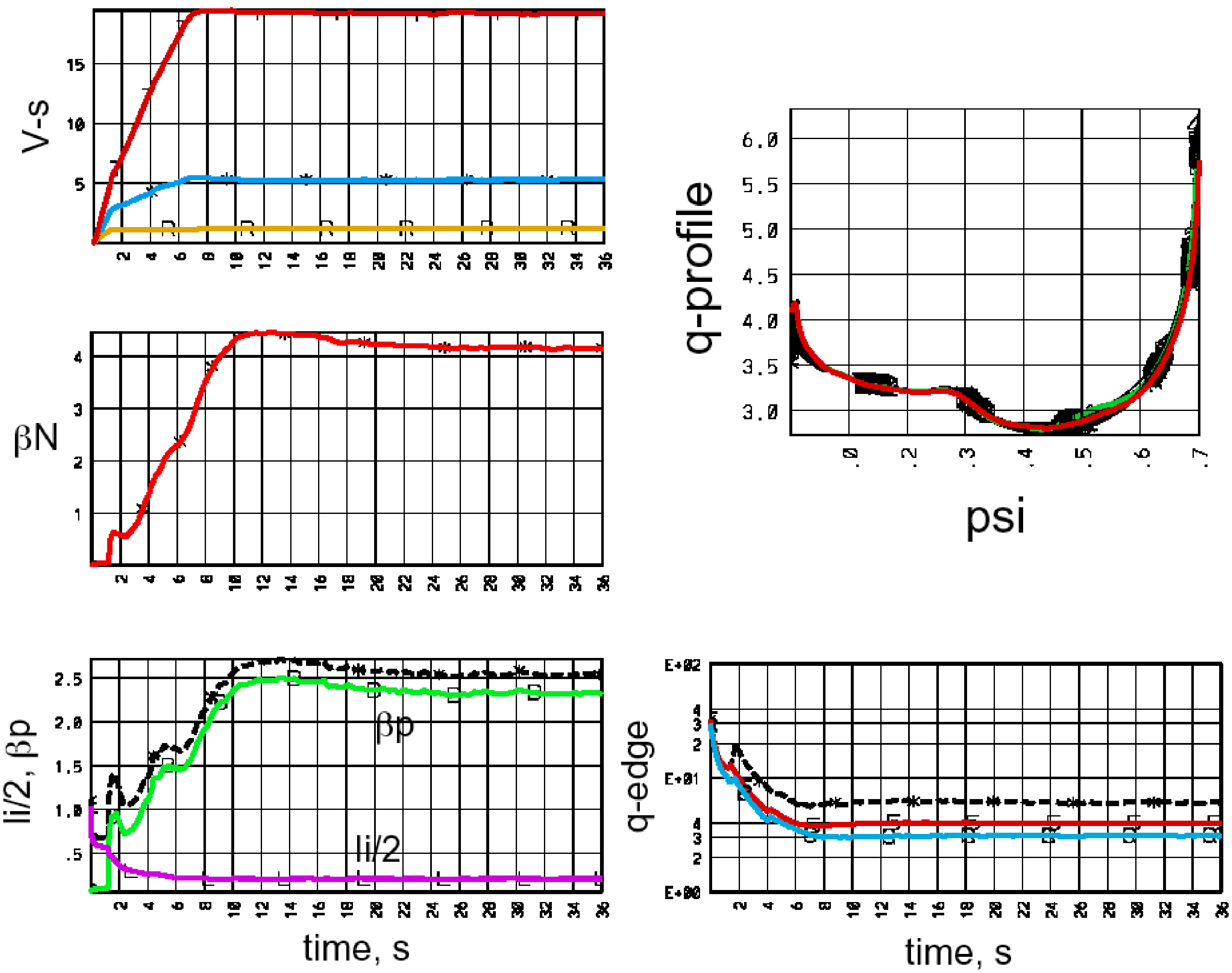
- Bt=6.5 T, Ip=4.5 MA
- q(0) =4.0, q(min) = 2.75, q(95) = 4.0, li = 0.42
- β = 4.7 %, βN = 4.1, βp = 2.35
- n/nGr = 0.85, n(0)/<n> = 1.47
- n(0) = 4.4x10^20, n(line) = 3.5, n(vol) = 3.0
- Wth = 34.5 MJ
- τE = 0.7 s, H98(y,2) = 1.7
- Ti(0) = 14 keV, Te(0) = 16 keV
- Δψ(total) = 19 V-s,
- Pα = 30 MW
- P(LH) = 25 MW
- P(ICRF/FW) = 7 MW
  - Up to 20 MW ICRF used in rampup
- P(rad) = 15 MW
- Zeff = 2.3
- Q = 5
- I(bs) = 3.5 MA, I(LH) = 0.80 MA, I(FW) = 0.20 MA
- **t(flattop)/τj=3.2**

TSC-LSC Simulation of Q=5 Burning AT Plasma

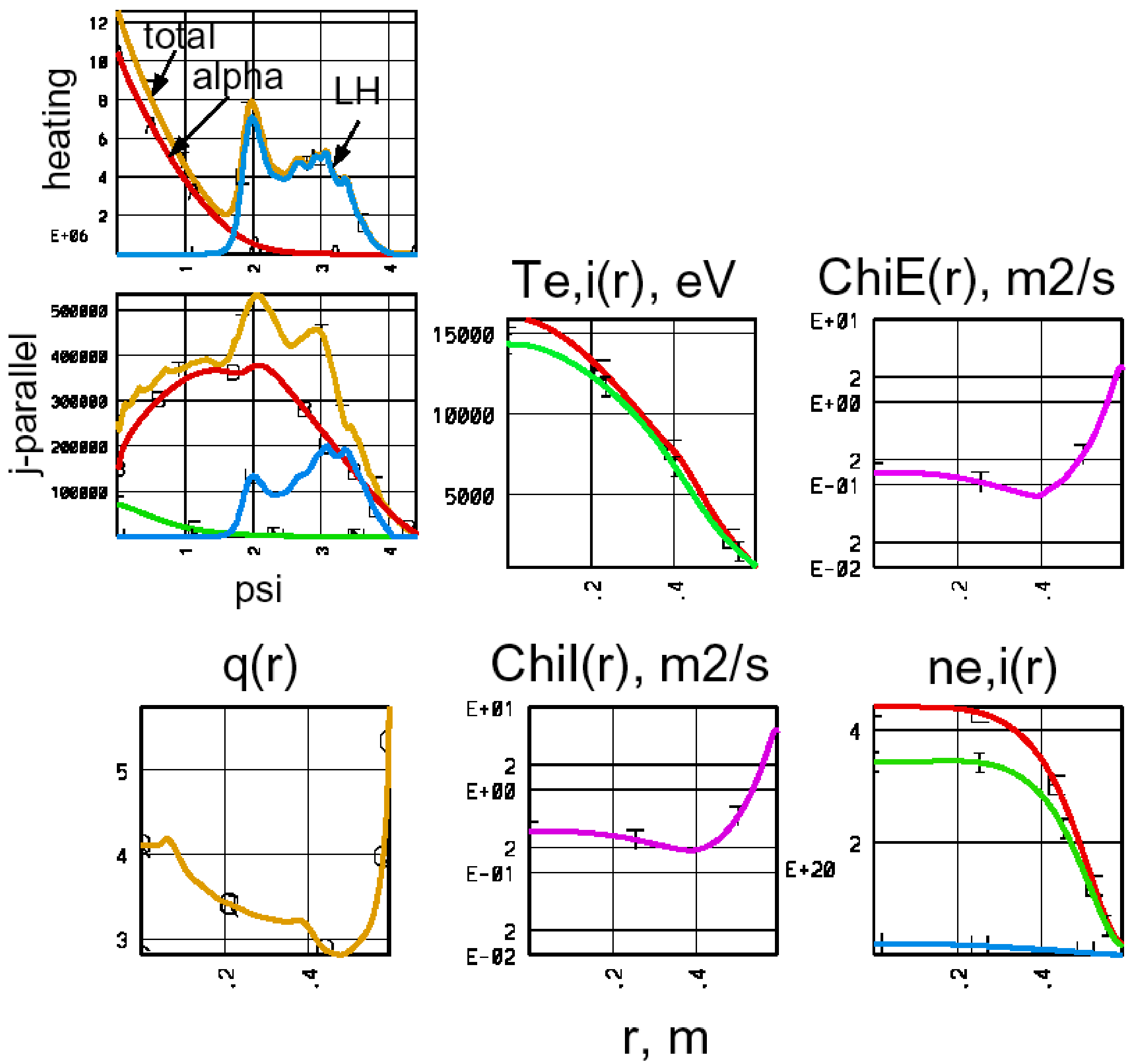


Ip=4.5 MA, Bt=6.5 T, βN=4.1,
t(flat)/τj=3, I(LH)=0.85, P(LH)=25 MW
fbs=0.77, Zeff=2.3,

TSC-LSC Simulation of Q=5 AT Burning Plasma



TSC-LSC Simulation of Q=5 AT Burning Plasma



Conclusions

- Work continues to define the integrated physics and engineering basis for FIRE's successful operation
- The compact copper TF and PF coil tokamak design can provide a significant operating space for the study of burning plasma physics
  - Access various Q values within engineering and physics constraints
  - Time scales greater than the current diffusion time
  - Inductive operation for ELMy H-mode and non-inductive operation for Advanced Tokamak mode
- **FIRE can provide the plasma physics basis for extrapolation to fusion power devices**