FIRE

An Opportunity to Test and Extend Confinement Understanding

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for the FIRE Team

Presented to
Plasma Physics Group
Lehigh University

August 24, 2001

http://fire.pppl.gov

Recent Events

Energy Authorization Bill (HR 4) passed by the House on August 1, 2001 directs DOE to submit a plan for a U.S. Burning Plasma Experiment to Congress by July 2001.

FESAC Endorses Recommendations of Burning Plasma Panel on August 2.

National Research Council is preparing a proposal to review burning plasma physics as required by HR 4 and recommended by FESAC.

Preparations are beginning for a Snowmass Summer Study 2002 that will emphasize burning plasmas.

Panel Recommendation Fully Endorsed by FESAC August 2, 2001

3. *The US Fusion Energy Sciences Program should establish a proactive US plan on burning plasma experiments and should not assume a default position of waiting to see what the international community may or may not do regarding the construction of a burning plasma experiment. If the opportunity for international collaboration occurs, the US should be ready to act and take advantage of it, but should not be dependent upon it. The US should implement a plan as follows to proceed towards construction of a burning plasma experiment:*

- Hold a "Snowmass" workshop in the summer, 2002 for the critical scientific and technological examination of proposed burning plasma experimental designs and to provide crucial community input and endorsement to the planning activities undertaken by FESAC. Specifically, the workshop should determine which of the specific burning plasma options are technically viable, but should not select among them. The workshop would further confirm that a critical mass of fusion scientists believe that *the time to proceed is now* and not some undefined time in the future.

- Carry out a uniform technical assessment led by the NSO program of each of the burning plasma experimental options for input into the Snowmass summer study.

- Request the Director of the Office of Energy Sciences to charge FESAC with the mission of forming an "action" panel in Spring, 2002 to select among the technically viable burning plasma experimental options. The selected option should be communicated to the Director of the Office of Science by January, 2003.

- Initiate a review by a National Research Council panel in Spring, 2002, with the goal of determining the desirability as well as the scientific and technological credibility of the burning plasma experiment design by Fall, 2003. This is consistent with a submission of a report by DOE to congress no later than July, 2004.

- Initiate an outreach effort coordinated by FESAC (or an ad-hoc body) to establish an appreciation and support for a burning plasma experiment from science and energy policy makers, the broader scientific community, environmentalists and the general public. This effort should begin now.

Fusion Science Objectives for a Major Next Step Magnetic Fusion Science Experiment

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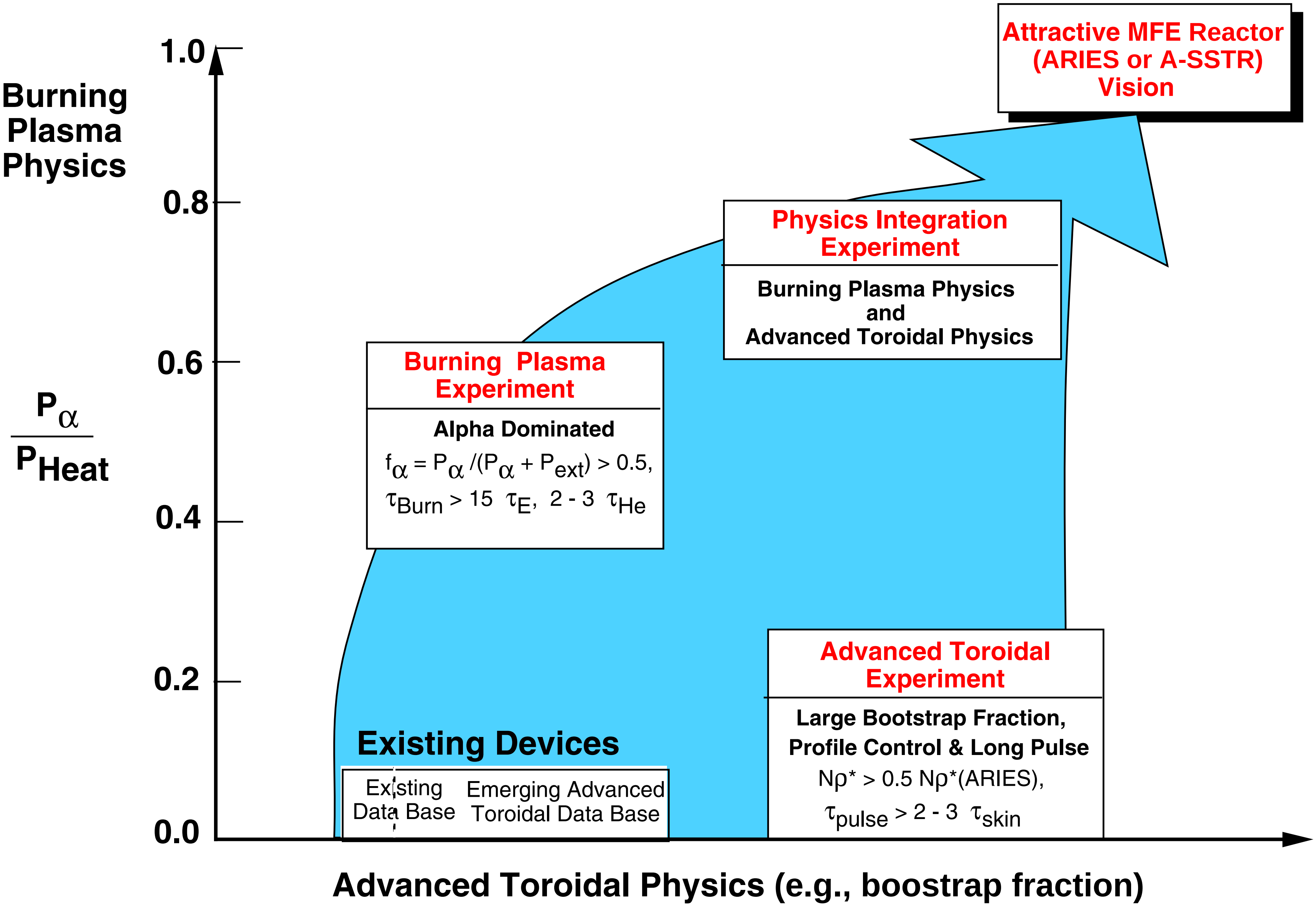
Explore and understand the strong non-linear coupling that is fundamental to fusion-dominated plasma behavior (self-organization)

  - Energy and particle transport (extend confinement predictability)
  - Macroscopic stability (β-limit, wall stabilization, NTMs)
  - Wave-particle interactions (fast alpha particle driven effects)
  - Plasma boundary (density limit, power and particle flow)

- Test/Develop techniques to control and optimize fusion-dominated plasmas.
- Sustain fusion-dominated plasmas - high-power-density exhaust of plasma particles and energy, alpha ash exhaust, study effects of profile evolution due to alpha heating on macro stability, transport barriers and energetic particle modes.
- Explore and understand various advanced operating modes and configurations in fusion-dominated plasmas to provide generic knowledge for fusion and non-fusion plasma science, and to provide a foundation for attractive fusion applications.

Stepping Stones for Resolving the Critical Fusion Plasma Science Issues for an Attractive MFE Reactor



Attractive MFE Reactor (ARIES or A-SSTR) Vision

Physics Integration Experiment

Burning Plasma Physics and Advanced Toroidal Physics

Burning Plasma Experiment

Alpha Dominated

$f_\alpha = P_\alpha/(P_\alpha + P_{ext}) > 0.5$, $\tau_{Burn} > 15\ \tau_E$, $2 - 3\ \tau_{He}$

Advanced Toroidal Experiment

Large Bootstrap Fraction, Profile Control & Long Pulse

$N\rho^* > 0.5\ N\rho^*$(ARIES), $\tau_{pulse} > 2 - 3\ \tau_{skin}$

Existing Devices

Existing Data Base	Emerging Advanced Toroidal Data Base

The Modular or Multi-Machine Strategy.

Advanced Burning Plasma Exp't Requirements

Burning Plasma Physics

Q	≥ 5, ~ 10 as target,	ignition not precluded
$f_\alpha = P_\alpha/P_{heat}$	≥ 50%, ~ 66% as target,	up to 83% at Q = 25
TAE/EPM	stable at nominal point,	able to access unstable

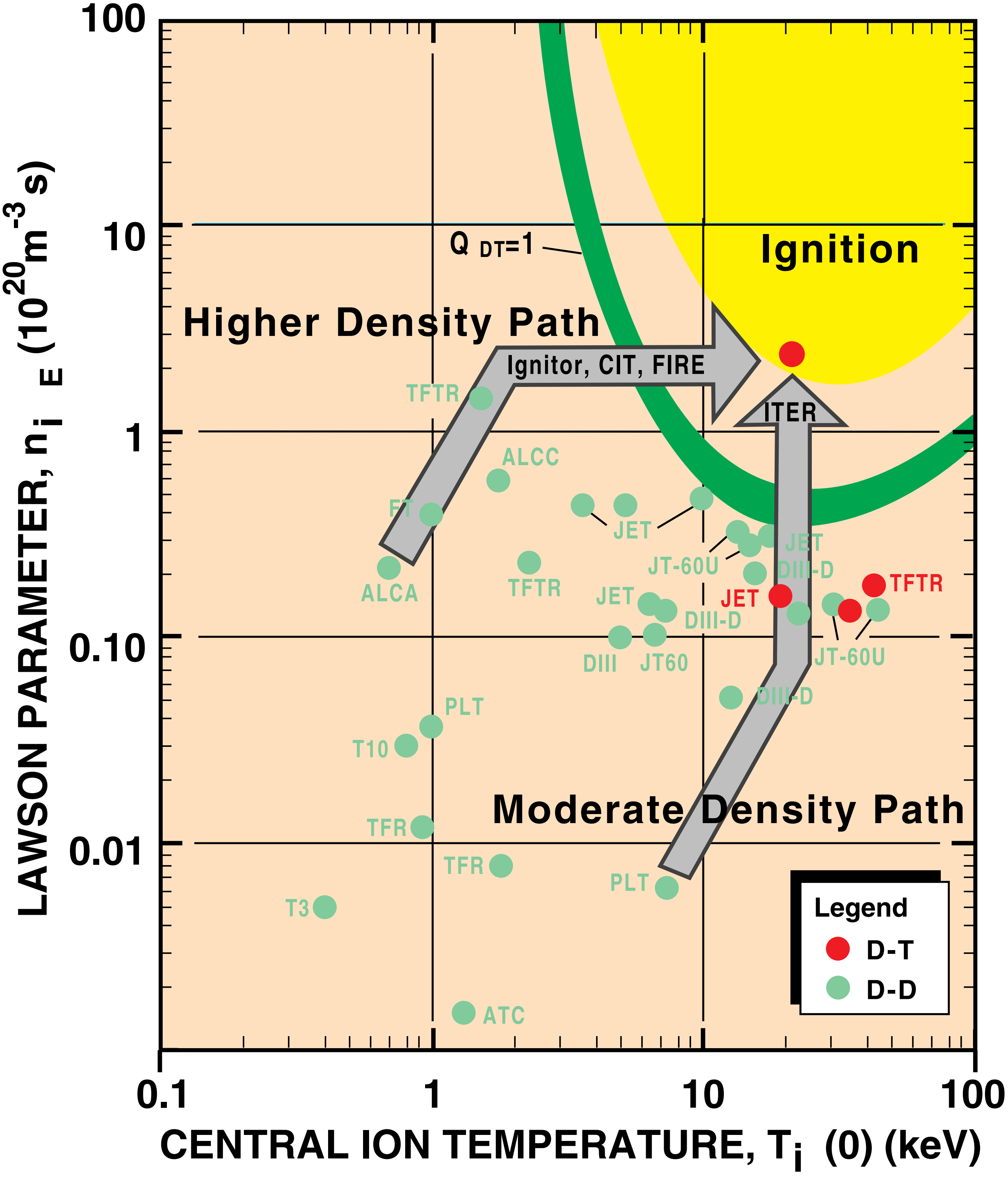
Advanced Toroidal Physics

$f_{bs} = I_{bs}/I_p$	≥ 50%	up to 75%
β_N	~ 2.5, no wall	~ 3.6, n = 1 wall stabilized

Quasi-stationary

Pressure profile evolution and burn control	> 10 τ_E
Alpha ash accumulation/pumping	> several τ_{He}
Plasma current profile evolution	1 to 3 τ_{skin}
Divertor pumping and heat removal	several τ_{pump}, $\tau_{heat\ transfer}$

Magnetic Fusion Pathways to Ignition

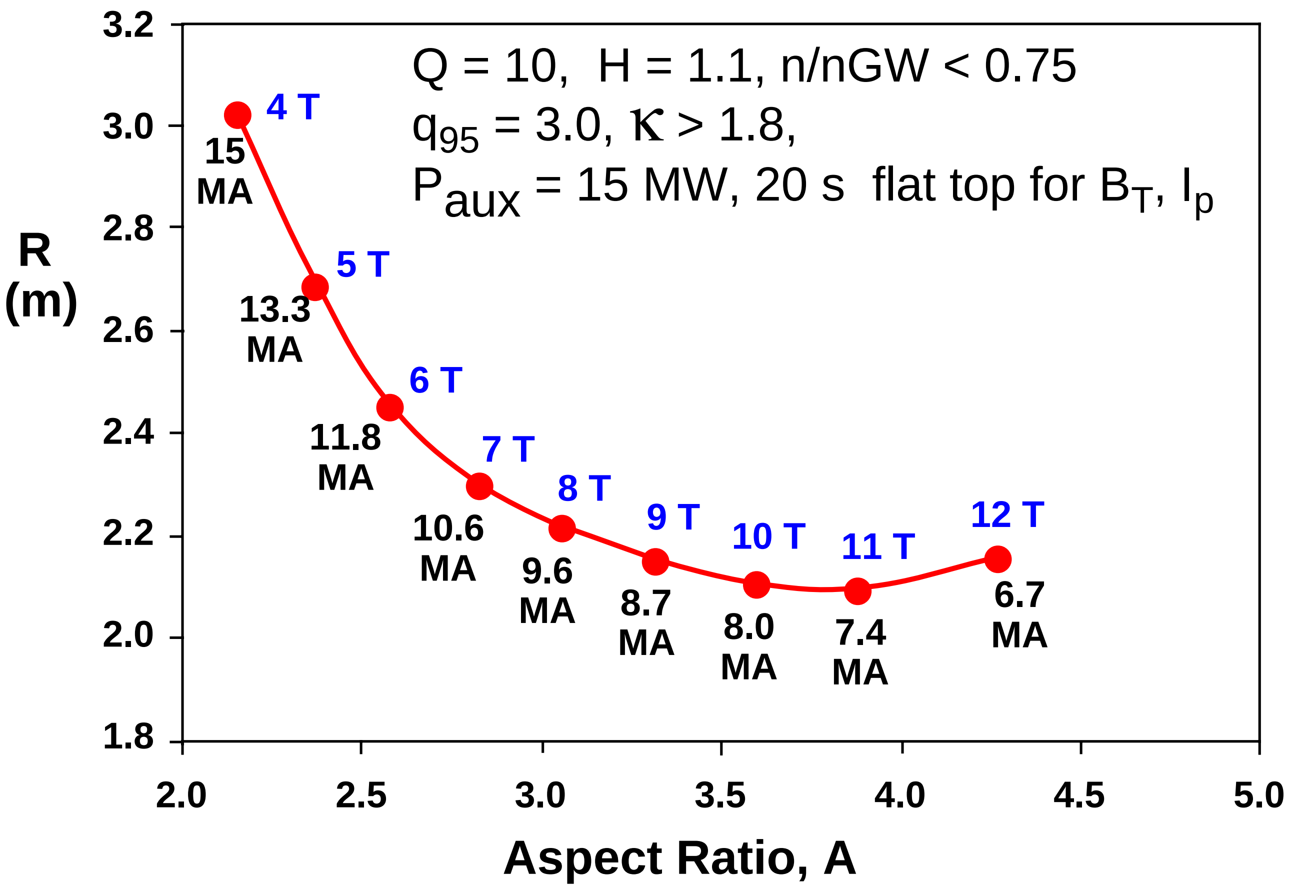


#97GR041.ntau-98 FIRE

Optimization of a Burning Plasma Experiment

- Consider an inductively driven tokamak with copper alloy TF and PF coils precooled to LN temperature that warm up adiabatically during the pulse.

- Seek minimum R while varying A and space allocation for TF/PF coils for a specified plasma performance - Q and pulse length with physics and eng. limits.

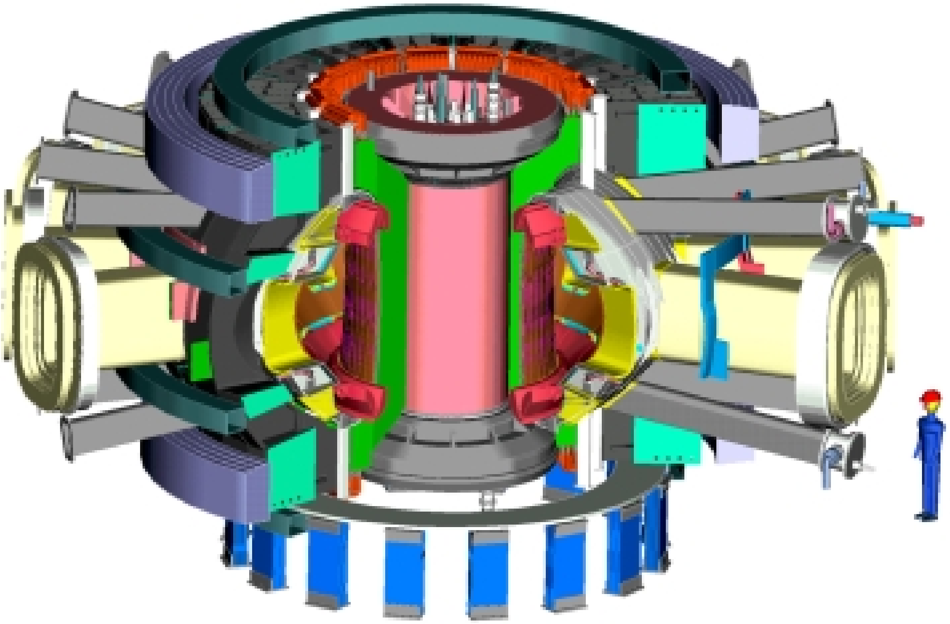


S. Jardin and
C. Kessel

Fusion Ignition Research Experiment

(FIRE*)

http://fire.pppl.gov



Design Features

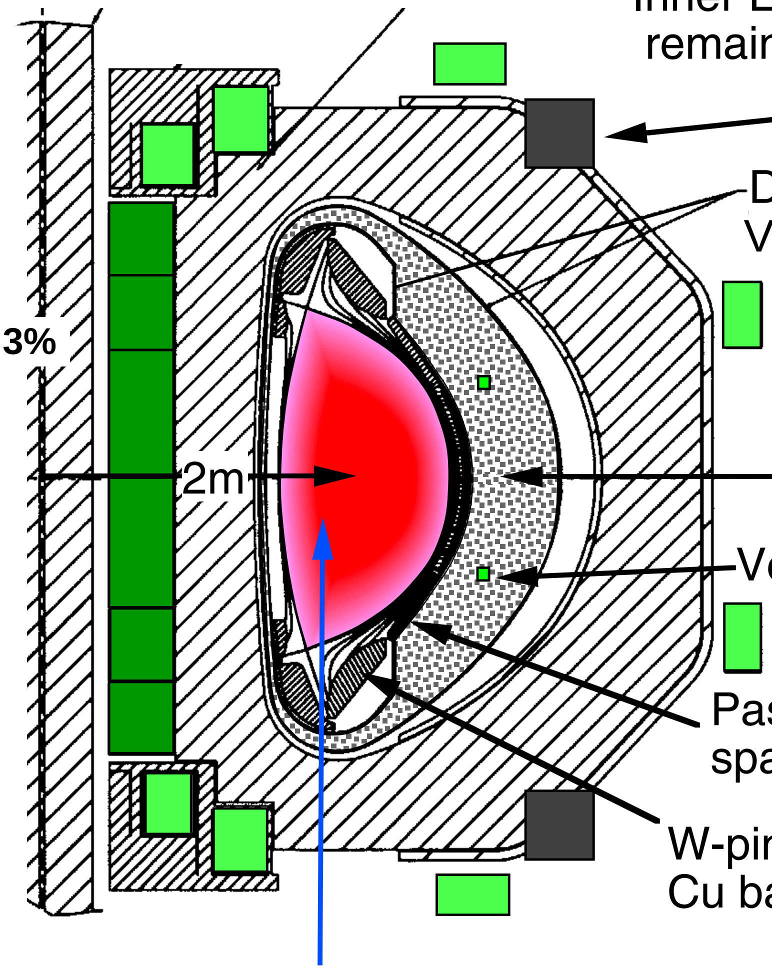
- R = 2.14 m, a = 0.595 m
- B = 10 T
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA
- $P_{aux} \leq$ 20 MW
- Q ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s
- Tokamak Cost ≈ $375M (FY99)
- Total Project Cost ≈ $1.2B at Green Field site.

Attain, explore, understand and optimize fusion-dominated plasmas that will provide knowledge for attractive MFE systems.

FIRE Incorporates Advanced Tokamak Innovations

AT Features

- DN divertor
- strong shaping
- very low ripple **< 0.3%**
- internal coils
- space for wall stabilizers



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

Compression Ring

Double Wall Vacuum
Vessel(316 S/S), Be First Wall

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.

Basic Parameters and Features of FIRE*

R, major radius	2.14 m
a, minor radius	0.595 m
κx, κ95	2.0, 1.77
δx, δ95	0.7, 0.55(AT) - 0.4(OH)
q95, safety factor at 95% flux surface	>3
Bt, toroidal magnetic field	10 T with 16 coils, 0.3% ripple @ Outer MP
Toroidal magnet energy	5.8 GJ
Ip, plasma current	7.7 MA
Magnetic field flat top, burn time	28 s at 10 T in dd, 20s @ Pdt ~ 150 MW)
Pulse repetition time	~3hr @ full field and full pulse length
ICRF heating power, maximum	20 MW, 100MHz for $2\Omega_T$, 4 mid-plane ports
Neutral beam heating	Upgrade for edge rotation, CD - 120 keV PNBI?
Lower Hybrid Current Drive	Upgrade for AT-CD phase, ~20 MW, 5.6 GHz
Plasma fueling	Pellet injection (≥2.5km/s vertical launch inside mag axis, guided slower speed pellets)
First wall materials	Be tiles, no carbon
First wall cooling	Conduction cooled to water cooled Cu plates
Divertor configuration	Double null, fixed X point, detached mode
Divertor plate	W rods on Cu backing plate (ITER R&D)
Divertor plate cooling	Inner plate-conduction, outer plate/baffle- water
Fusion Power/ Fusion Power Density	150 - 200 MW, ~10 MW m-3 in plasma
Neutron wall loading	~ 3 MW m-2
Lifetime Fusion Production	5 TJ (BPX had 6.5 TJ)
Total pulses at full field/power	3,000 (same as BPX), 30,000 at 2/3 Bt and Ip
Tritium site inventory	Goal < 30 g, Category 3, Low Hazard Nuclear Facility

FIRE* Parameters

R_plasma/ a_plasma	2.14 / 0.595
A	3.6
κa	1.81
δ95	0.4
<ne>, 10^20 /m^3	4.55
Paux (MW)	14.5
Pheat (MW) = Ploss	34
Bt(T) / Ip(MA)	10 / 7.7
Ion Mass	2.5
H(y,2)-ITER98	1.11
H-ITER 89P	2.61
alpha_n / alpha_T	0.2 / 1.0
li(3)	0.8
τaup*(He)/τauE	5
Cbs	0.7
f_bs	0.27
ν*	0.058
1/ρ*(uses To)	352
β (thermal only), %	2.24
q95	3.05
<n>l/greenwald	0.70
P_fusion (MW)	150.7
Pheat/P(L->H)	1.29
Q_DT*= Pfusion/Paux	10.39
Q_DT =Pf/(Pext + Poh)	10.01
fraction_alpha heating	0.67
τauE	1.04
ni(0)τ_ETi(0)	52.27
skin time	12.23
W(MJ), thermal / W alpha (MJ)	35.3 / 2.3
beta_alpha, %	0.15
Rgradbeta_alpha	0.04
v_alpha/v_alfven	2.01
beta_total, %	2.38
beta_N	1.84
eps*betap	0.20
<T>n / To	6.47 / 11.04
Zeff	1.41
Be concentration,%	3.00
Ar concentration, %	0.00
He concentration, %	2.30
Ploss/2πRx/ndiv (MW/m)	1.48

Transport Issues/Benefits from a Major Next Step Tokamak Experiment

- Predicting confinement and performance is a central issue for a next step experiment that challenges our understanding and predictive capability.

- Methods Available

  1. 0-D Statistical based models (eg ITER scalings for H-Mode)
     dimensionless variables ala wind tunnel
     projections from individual points(Barabaschi) or similar points(DM)

  2. 1 1/2-D (WHIST, TSC)
     profiles and time evolution

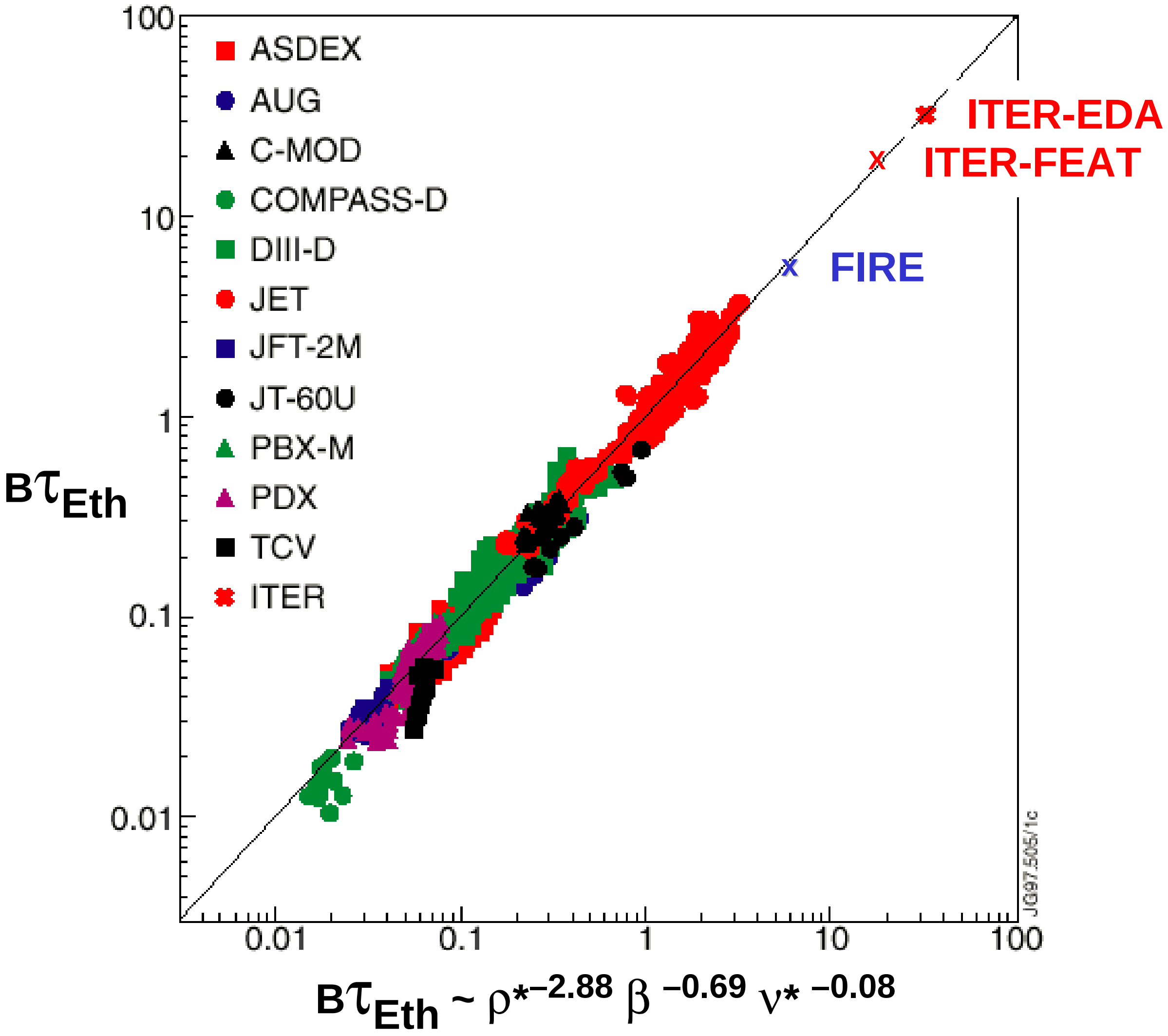
  3. “First Principles” based core transport models
     - gyrokinetic/gyrofluid
     - multi-mode model
  4. Edge Pedestal and density limit models
- What experimental capabilities or features in a next step experiment are needed to better resolve and understand transport issues?

FIRE is a Modest Extrapolation in Plasma Confinement

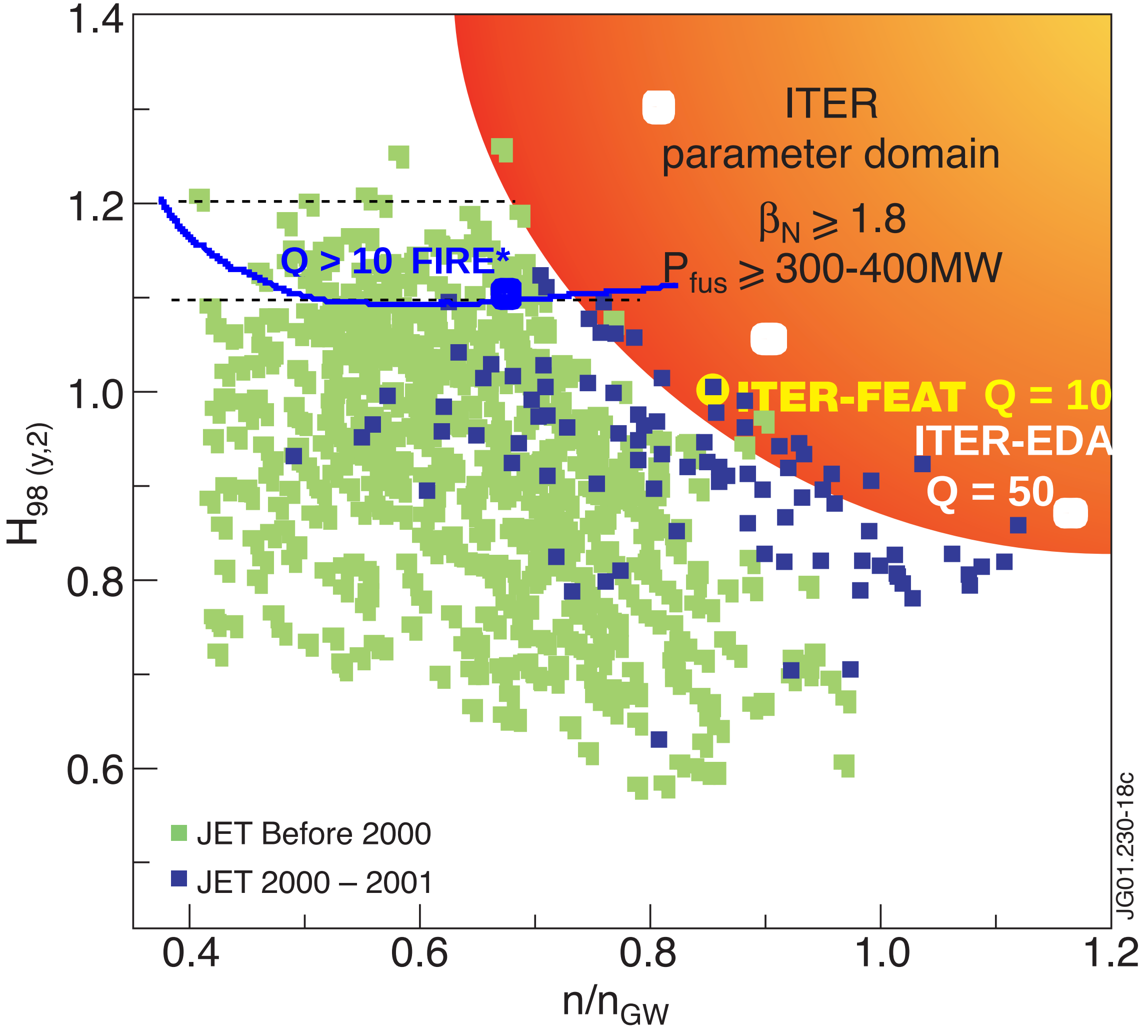
Dimensionless Parameters
$\omega_c \tau$ $\rho^* = \rho / a$ $\nu^* = \nu_c / \nu_b$ β

Similarity Parameter
$B R^{5/4}$

Kadomtsev, 1975

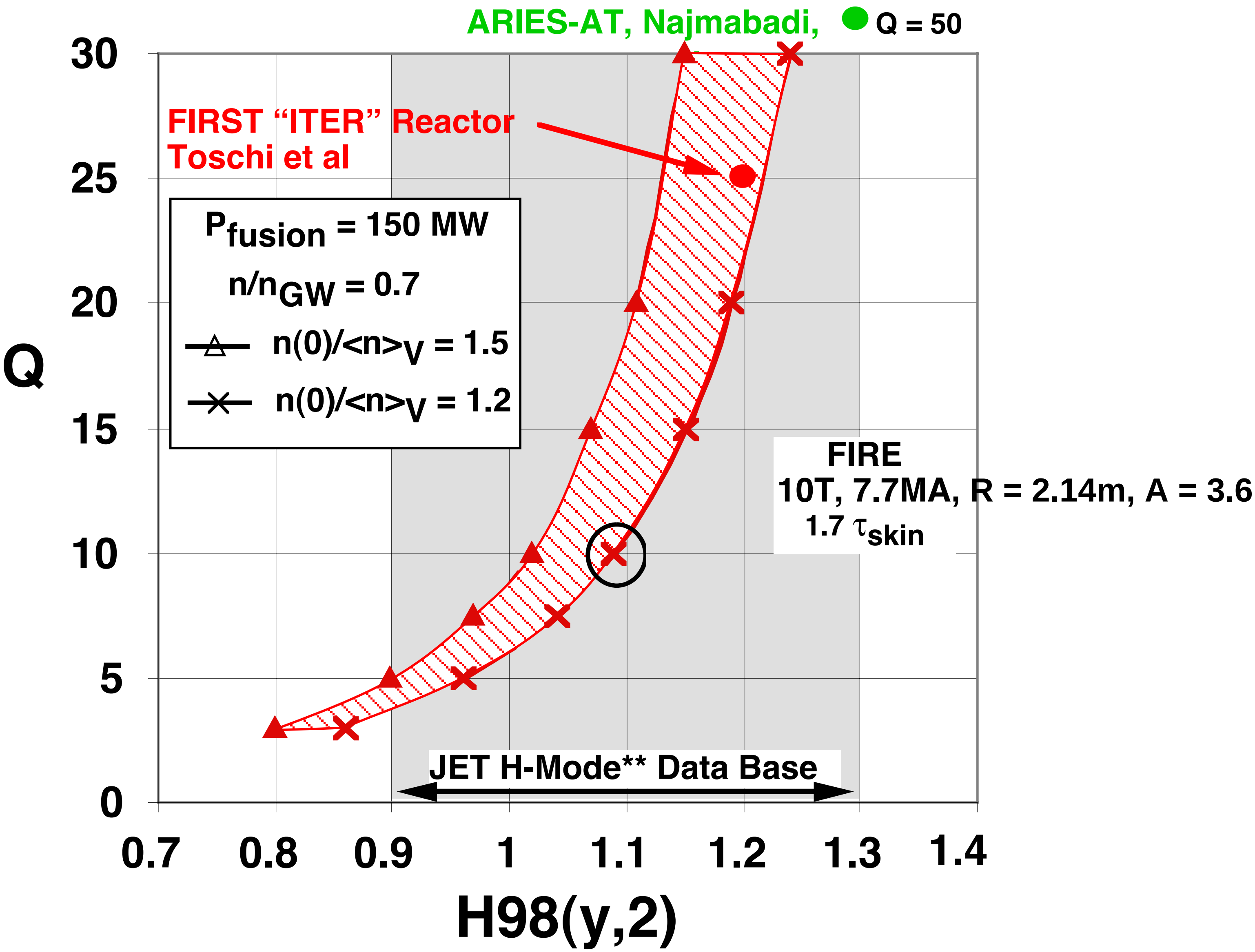


Comparison Operating Ranges of ITER-EDA, ITER-FEAT and FIRE with JET H-Mode Data



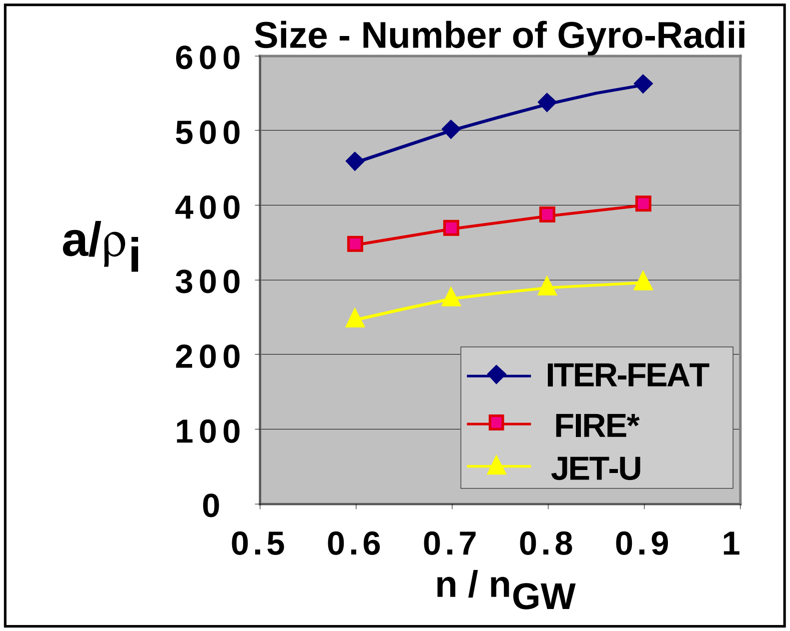
- Extension of JET parameter domain leading to simultaneous realization of $H_{98(y,2)} = 1$, $n/n_{GW} > 0.9$ and $\beta_N \geqslant 1.8$ using different approaches and
- In addition Plasma purity as required for ITER: Zeff ~ 1.5
- For quasi-stationary phases of several seconds
- **Consolidation of ITER Q = 10 Reference scenario**
- **Data Base for FIRE* Q > 10 is as strong as ITER. Note and ITER-EDA added - DMM**

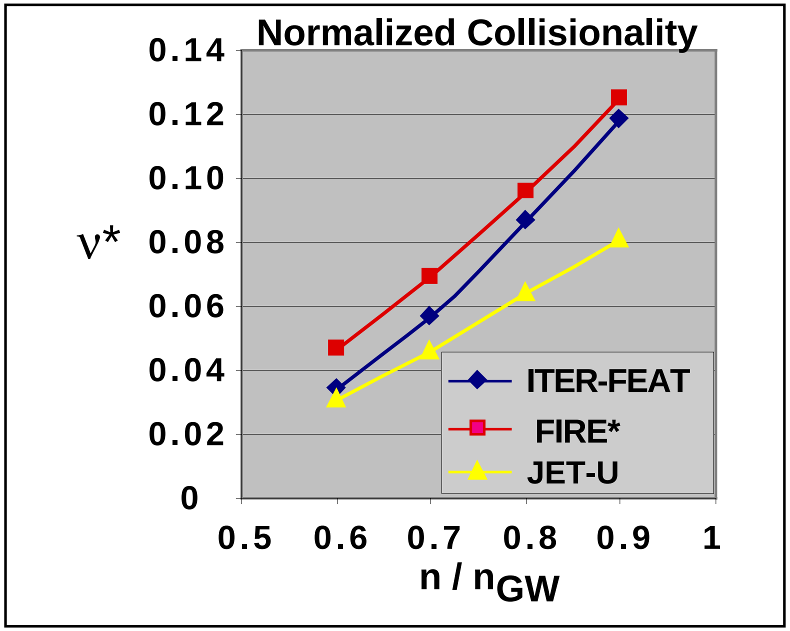
Projections to FIRE Compared to Envisioned Reactors

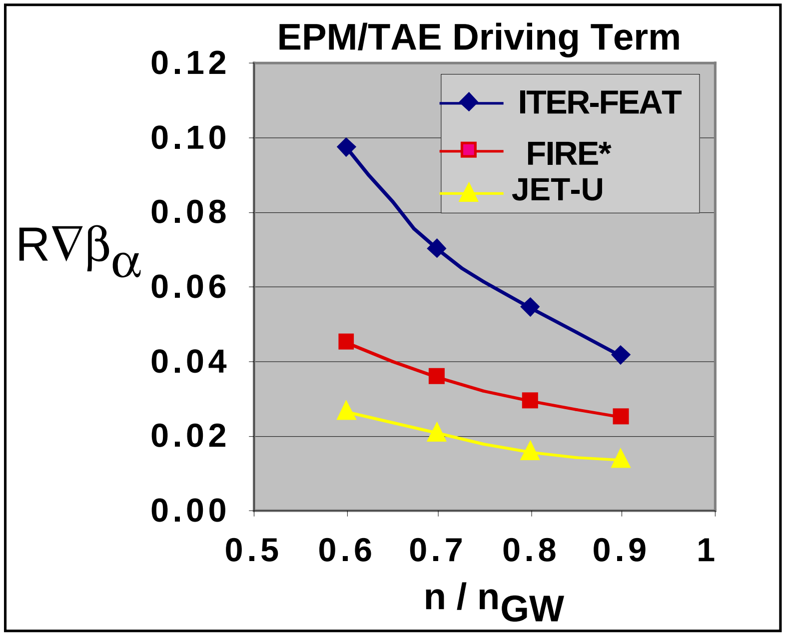


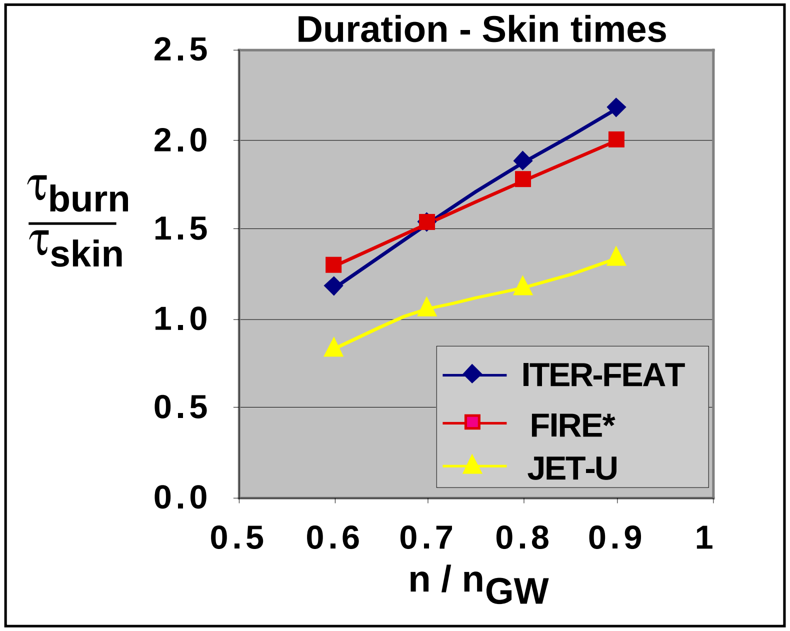
Parameters for H-Modes in Potential Next Step D-T Plasmas

ITER-FEAT (15 MA): Q = 10, H = 0.95, FIRE*(7.7 MA): Q = 10, H = 1.03, JET-U (6 MA): Q = 0.64, H = 1.1


Size - Number of Gyro-Radii


Normalized Collisionality

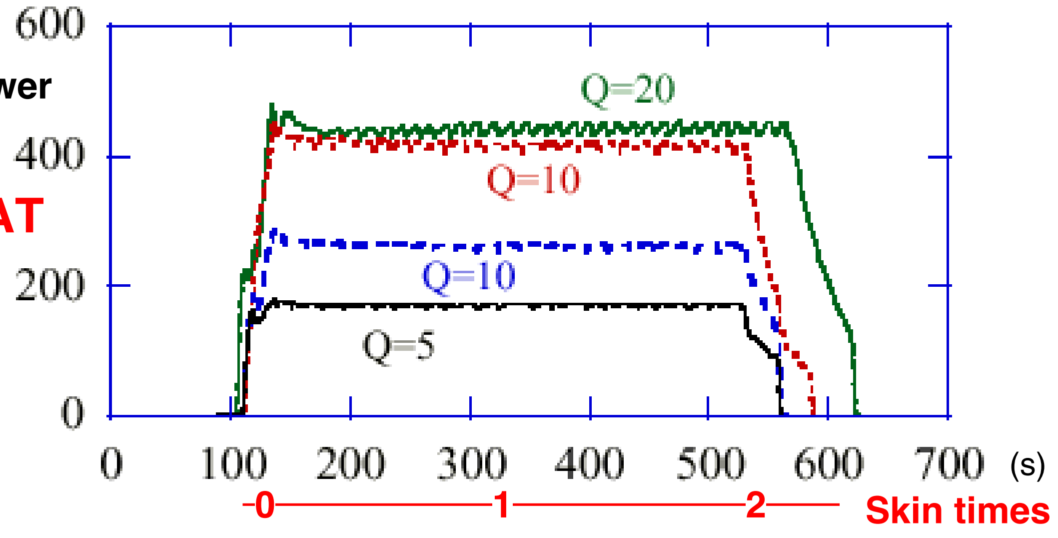

EPM/TAE Driving Term


Duration - Skin times

Normalized Burn Time (Plasma Skin Time)

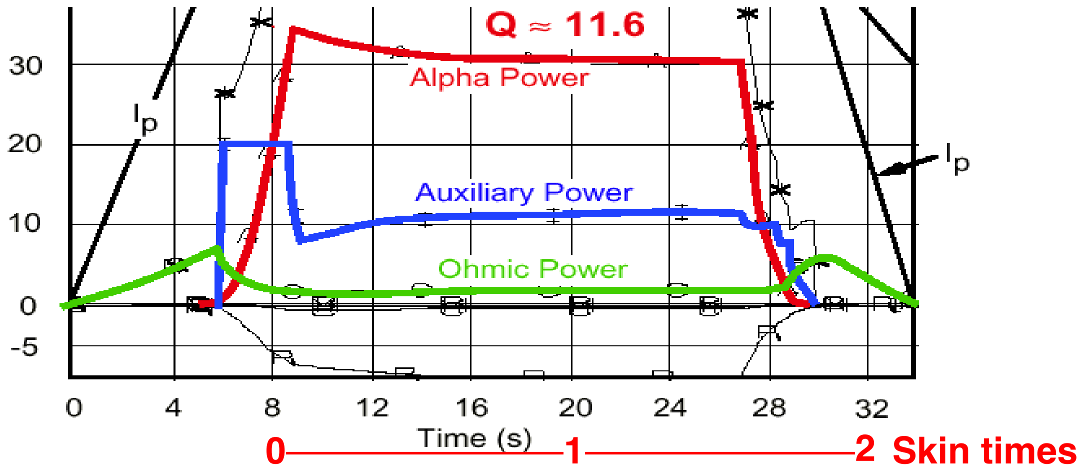
Fusion Power (MW)

ITER-FEAT



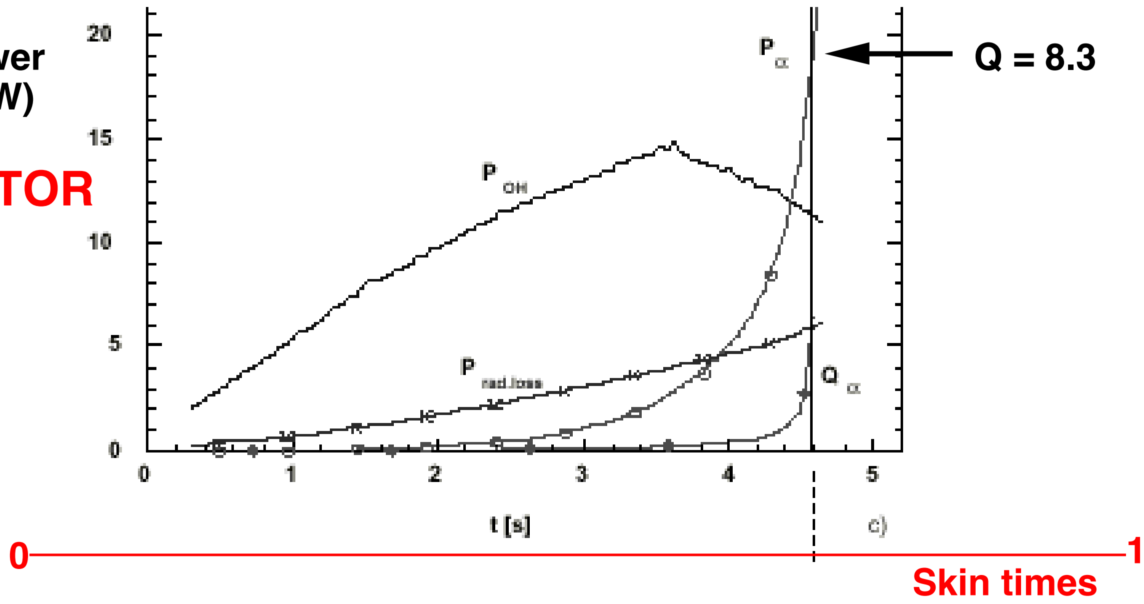
Power (MW)

FIRE*

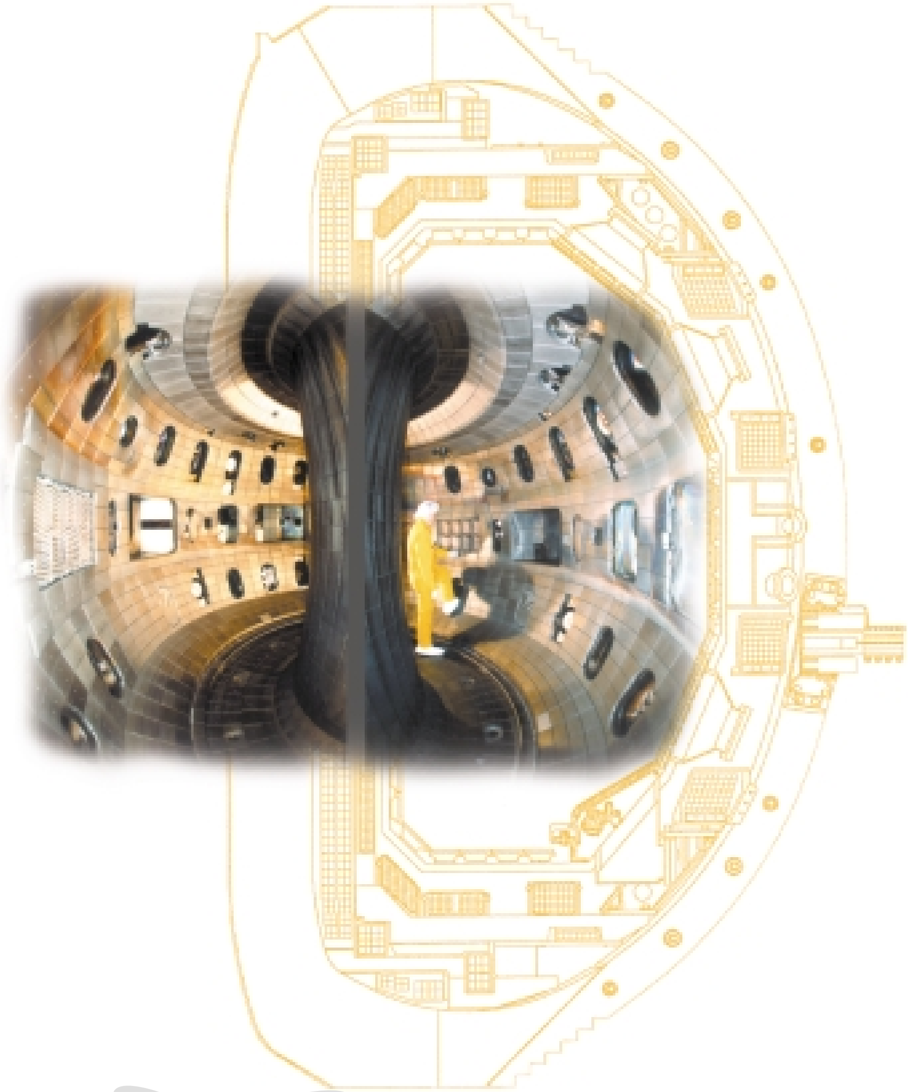


Power (MW)

IGNITOR



Waveforms from talks presented at UFA BPS Workshop 2



Burning Plasma Projections Using The GLF23 Transport Model

by
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* Lehigh University

Acknowledgements:
C. Kessel, D. Meade, G. Hammett

Presented at
Burning Plasma Workshop II

May 1, 2001

DIII-D
NATIONAL FUSION FACILITY

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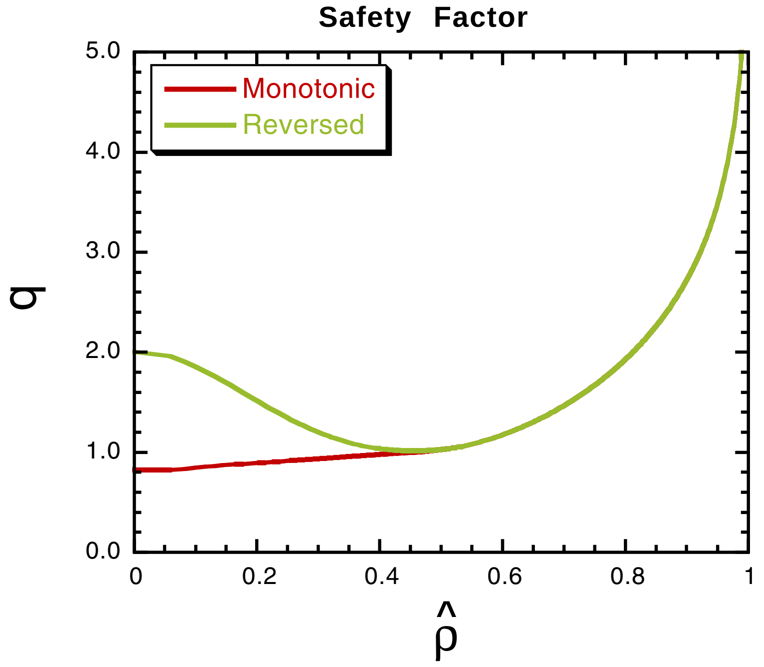
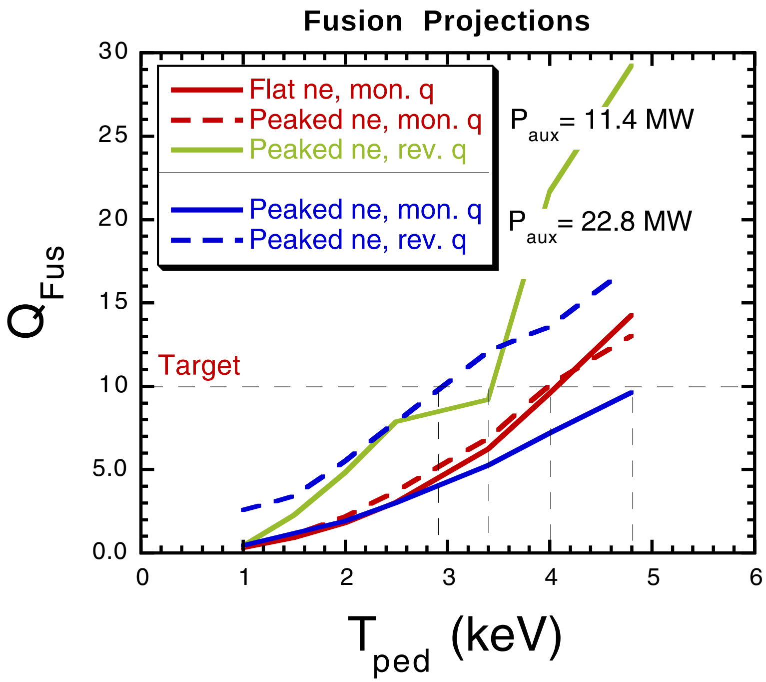
University

Fusion Projections for FIRE

- ***Temperature profiles predicted for monotonic and reversed q-profiles while computing the effects of ExB shear and alpha-stabilization***
  - $n_{ped} = 3.6\times10^{20}\ m^{-3}$, $n_{e0}/n_{ped} = 1.5$
  - ***ExB shear effects small since no toroidal rotation except for peaked density, reversed shear case where ITB develops***
  - ***Alpha heating computed using TRANSP reaction rates***





Pedestal Temperature Requirements for Q=10

GLF 23 Studies by Kinsey, Waltz and Staebler

Device	Flat ne◆	Peaked ne*	Peaked ne w/ reversed q
IGNITOR❖	5.1	5.0	5.1
FIRE	4.1	4.0	3.4
ITER-FEAT✦	5.8	5.6	5.4

◆ flat density cases have monotonic safety factor profile

* $n_{eo} / n_{ped} = 1.5$ with n_{ped} held fixed from flat density case

❖ 10 MW auxiliary heating

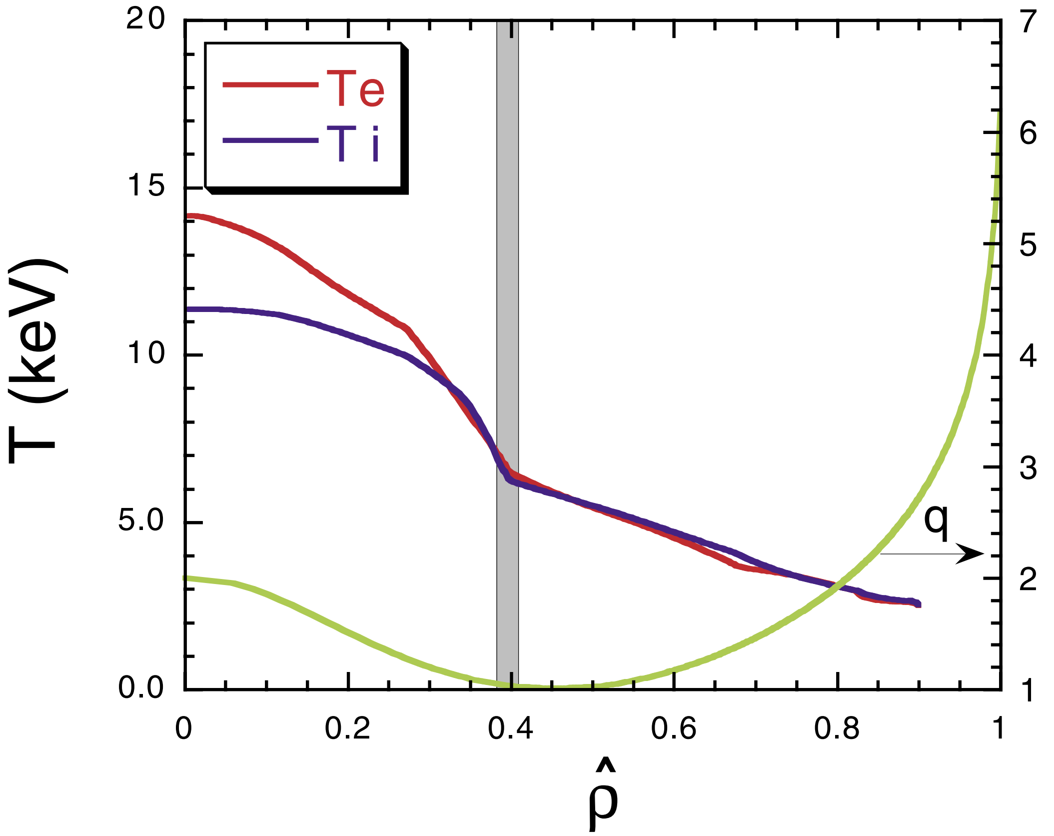
11.4 MW auxiliary heating

✦ 50 MW auxiliary heating

FIRE has the strongest shaping and low n/nGW which projects to high pedestal temperature.

GLF23 Predicts an ITB In FIRE as a Result of Alpha-stabilization of the ITG Mode

- Barrier only forms if some density peaking is present
- Diamagnetic component of ExB shear helps after ITB is formed

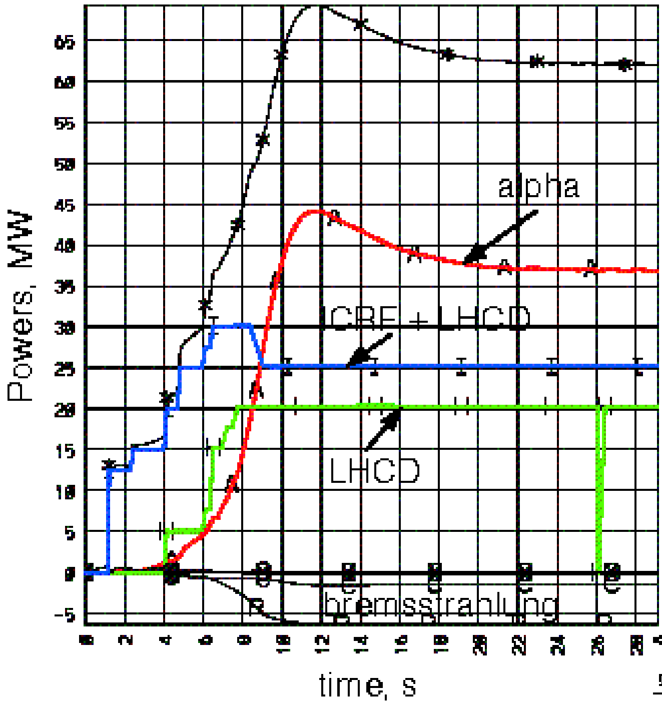


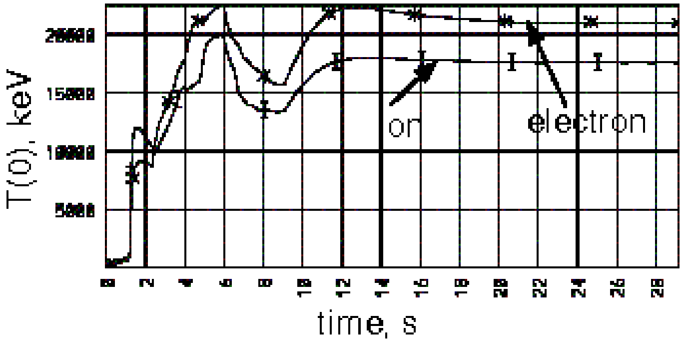
Kinsey, Waltz and Staebler
UFA BPS Workshop 2

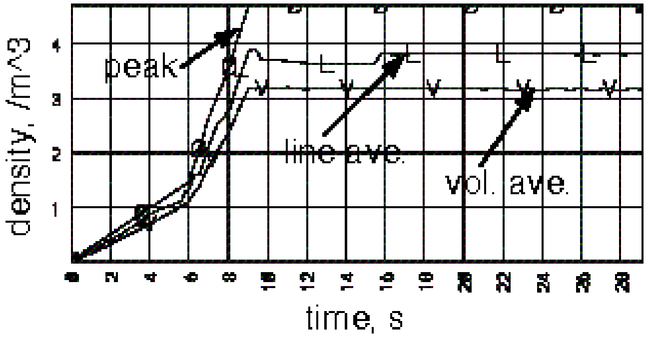
JEK - BP2001

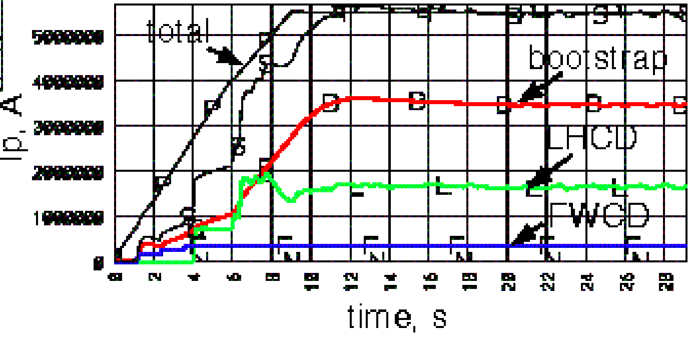
Dynamic Burning AT Simulations with TSC-LSC for FIRE

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 (64%),
I_{FW}=0.35 MA









H(y,2)=1.6

Confinement Status and Needs Regarding FIRE

- Present confinement understanding provides a reasonable estimate of burning plasma performance. However, the desire to reduce size (cost) drives one to reduce the margin.

- A combined experimental, theoretical and simulation initiative with the goal of improving the predictions for a Next Step Experiment, such as FIRE, would serve to highlight and focus effort on this area. The VBPX.

- What capabilities are needed in a Next Step Experiment to help resolve the confinement issues critical to understanding and predicting the performance of a fusion plasma? How does one characterize the plasma boundary in terms of dimensionless or dimensional parameters

- Fusion reactors of the future would benefit from improvements such as $H \approx 1.2$, modest peaking and $n \approx n_{GW}$ as well as advanced tokamak features. The NSO should be able to explore these areas.

- The effort in preparation for the Snowmass Summer Study 2002 will energize the effort on confinement issues.