FIRE Overview

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for the FIRE Team

Prepared for
Uniform Assessment
Snowmass Fusion Summer Study

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http://fire.pppl.gov

Critical Issues to be Addressed by the Next Stage of Fusion Research

- **Burning Plasma Physics**
    - strong nonlinear coupling inherent in a fusion dominated plasma
    - access, explore and understand fusion dominated plasmas

- **Advanced Toroidal Physics**
    - develop and test physics needed for an attractive MFE reactor
    - couple with burning plasma physics

- **Boundary Physics and Plasma Technology** (coupled with above)
    - high particle and heat flux
    - couple core and divertor
    - fusion plasma - tritium inventory and helium pumping

- **Neutron Resistant Materials** (separate facility)
    - high fluence testing using “point” neutron source

- Superconducting Coil Technology does not have to be coupled to physics experiments - only if needed for physics objectives

- Nuclear Component Testing should wait for the correct reactor materials

The Modular Strategy for MFE

Second Phase

Scientific
Feasibility

Third Phase

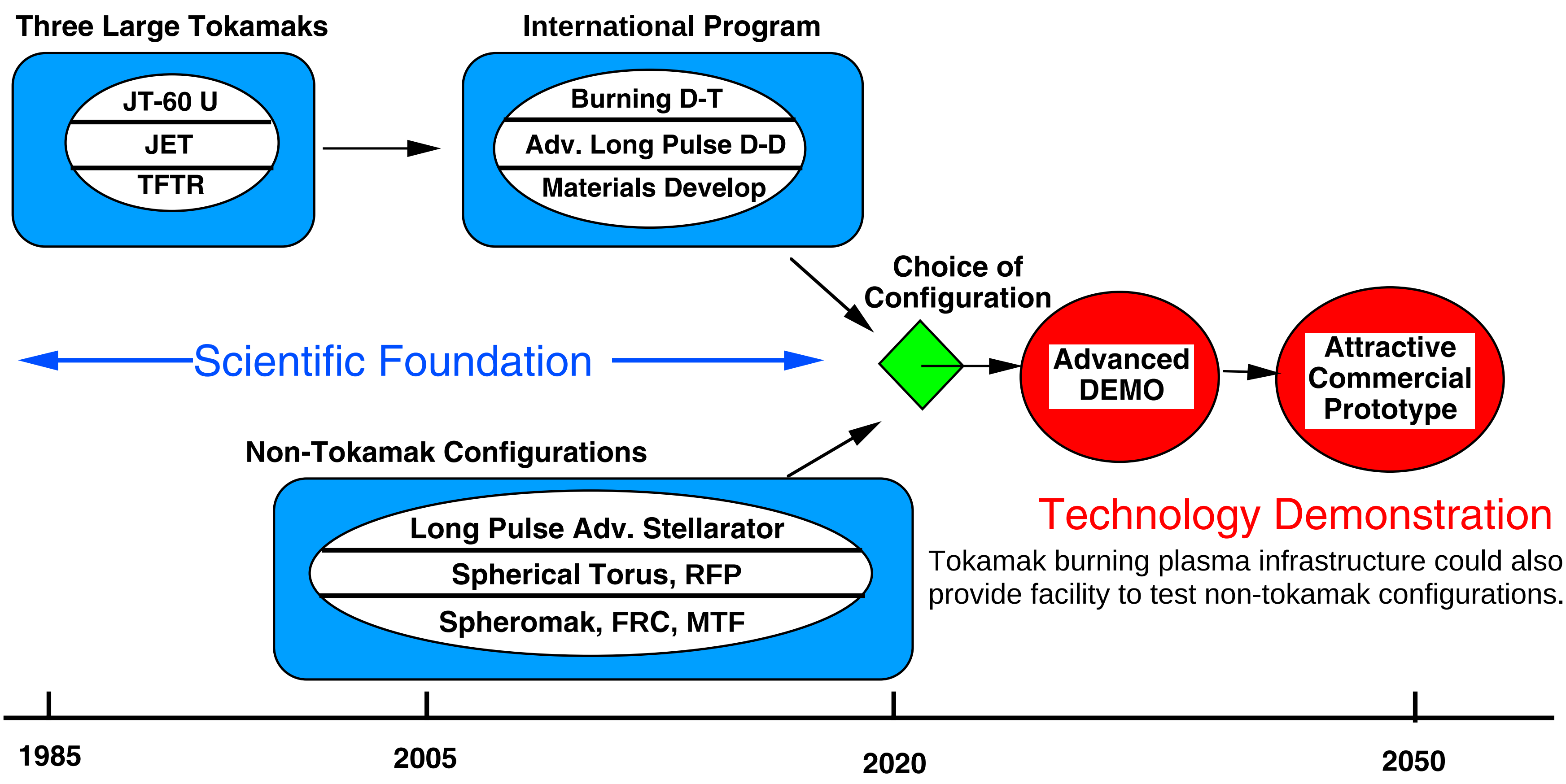
Burning Plasma
Scientific Base

Fourth Phase

Electric Power
Feasibility

Commercialization Phase

Economic
Feasibility



Three Large Tokamaks

- **JT-60 U**
- **JET**
- **TFTR**

International Program

- **Burning D-T**
- **Adv. Long Pulse D-D**
- **Materials Develop**

Scientific Foundation

Choice of Configuration

Advanced DEMO

Attractive Commercial Prototype

Non-Tokamak Configurations

- **Long Pulse Adv. Stellarator**
- **Spherical Torus, RFP**
- **Spheromak, FRC, MTF**

Technology Demonstration

Tokamak burning plasma infrastructure could also provide facility to test non-tokamak configurations.

Reduced Technical Risk

Streamlined Management Structure

Better Product/Lower Overall Cost

Increased Technical Flexibility

Faster Implementation

(the overall Modular Strategy includes IFE)

Fusion Science Objectives for a Major Next Step Burning Plasma Experiment

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.

Need to develop an integrated burning plasma simulation with good visualization output - useful for design phase, experimental phase and to provide the transfer to other configurations and “DEMO”.

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

$f_{bs} = I_{bs}/I_p$ (~ 25 % in H-Mode)	≥ 50% as target AT	up to 75% allowed
β_N	~ 2.5, no wall	~ 3.6, n = 1 wall stabilized

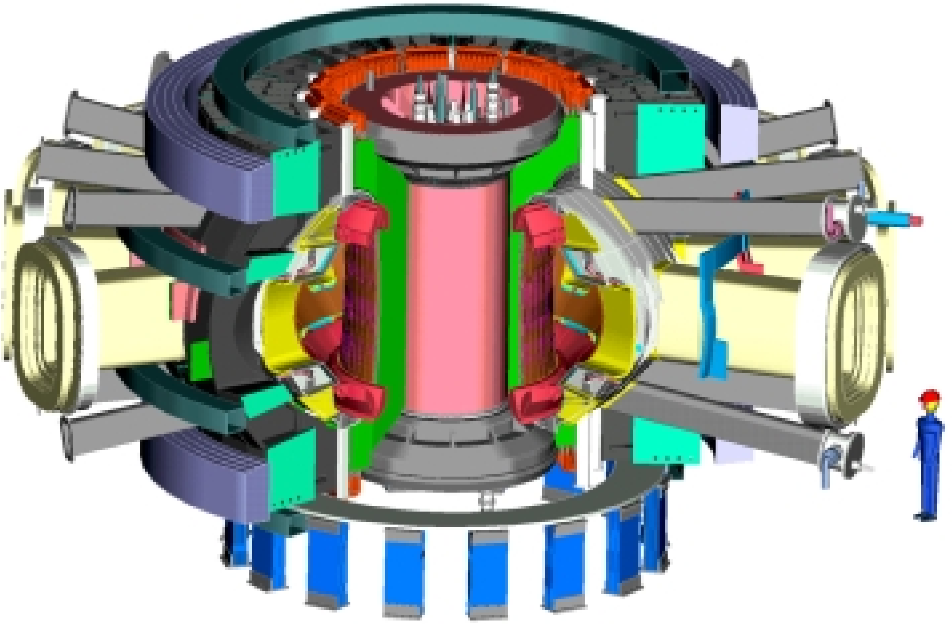
Quasi-stationary

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

Fusion Ignition Research Experiment

(FIRE)

http://fire.pppl.gov



Design Features

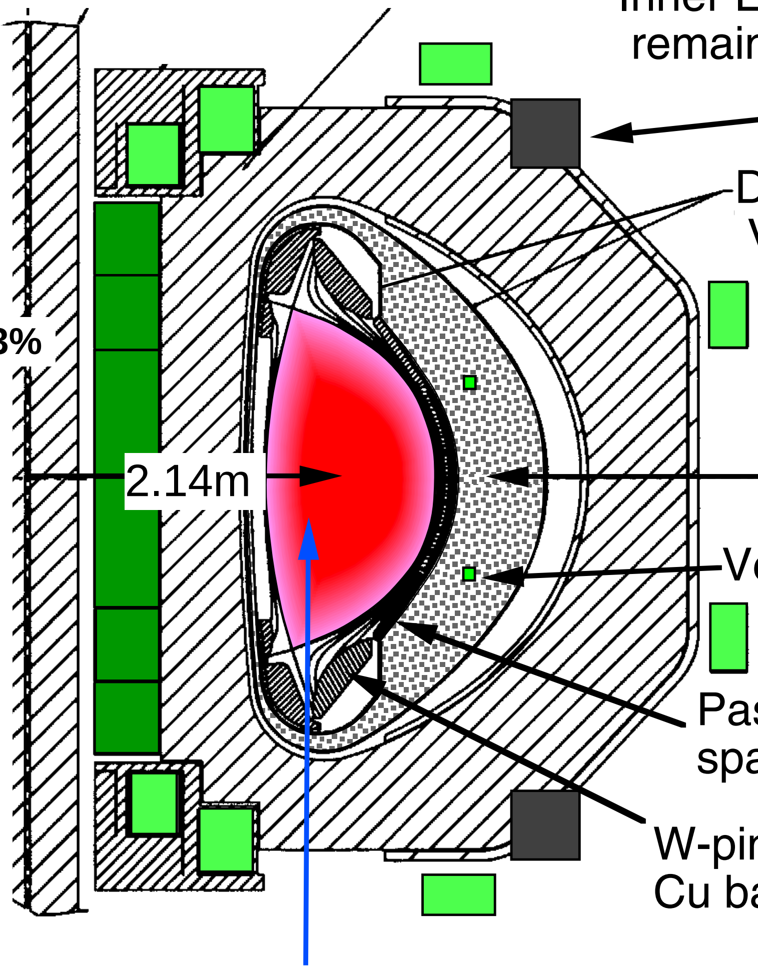
- R = 2.14 m, a = 0.595 m
- B = 10 T
- W_{mag}= 5.2 GJ
- I_p = 7.7 MA
- $P_{aux} \leq$ 20 MW
- Q ≈ 10, P_{fusion} ~ 150 MW
- Burn Time ≈ 20 s
- Tokamak Cost ≈ $375M (FY99)
- Total Project Cost ≈ $1.2B at Green Field site.

Mission:
Attain, explore, understand and optimize magnetically confined fusion-dominated plasmas.

FIRE Baseline for Snowmass Assessment

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.

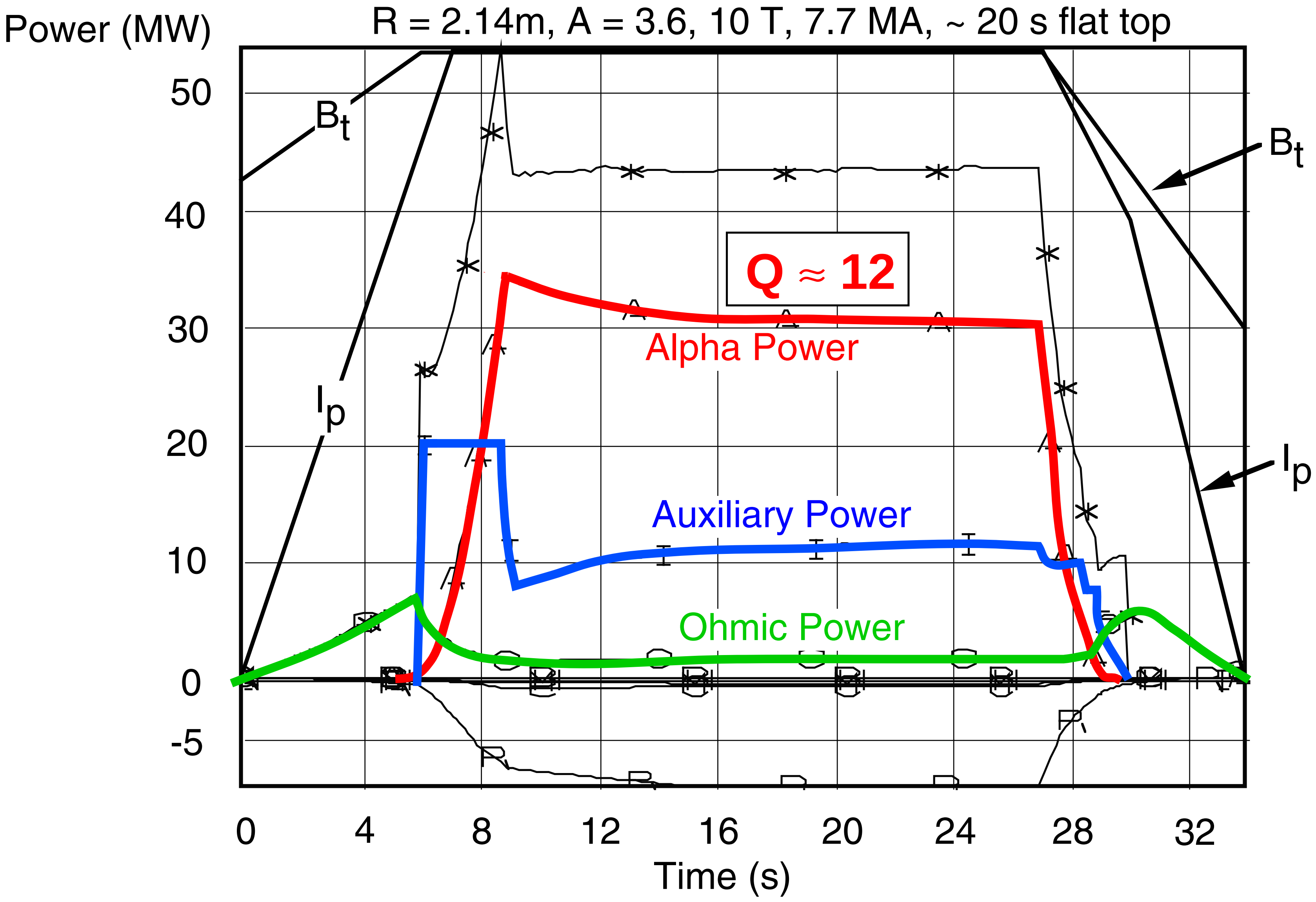
Basic Parameters and Features of FIRE

R, major radius	2.14 m
a, minor radius	0.595 m
κx, $\kappa 95$	2.0, 1.77
δx, $\delta 95$	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 2ΩT, 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, ~6 - 8 MW m-3 in plasma
Neutron wall loading	~ 2.3 MW m-2 Limits pulse length in some AT modes
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 Plasma Parameters (Elmy H-Mode, Q = 10)

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

1 1/2-D Simulation of Elmy H-Mode in FIRE (TSC)



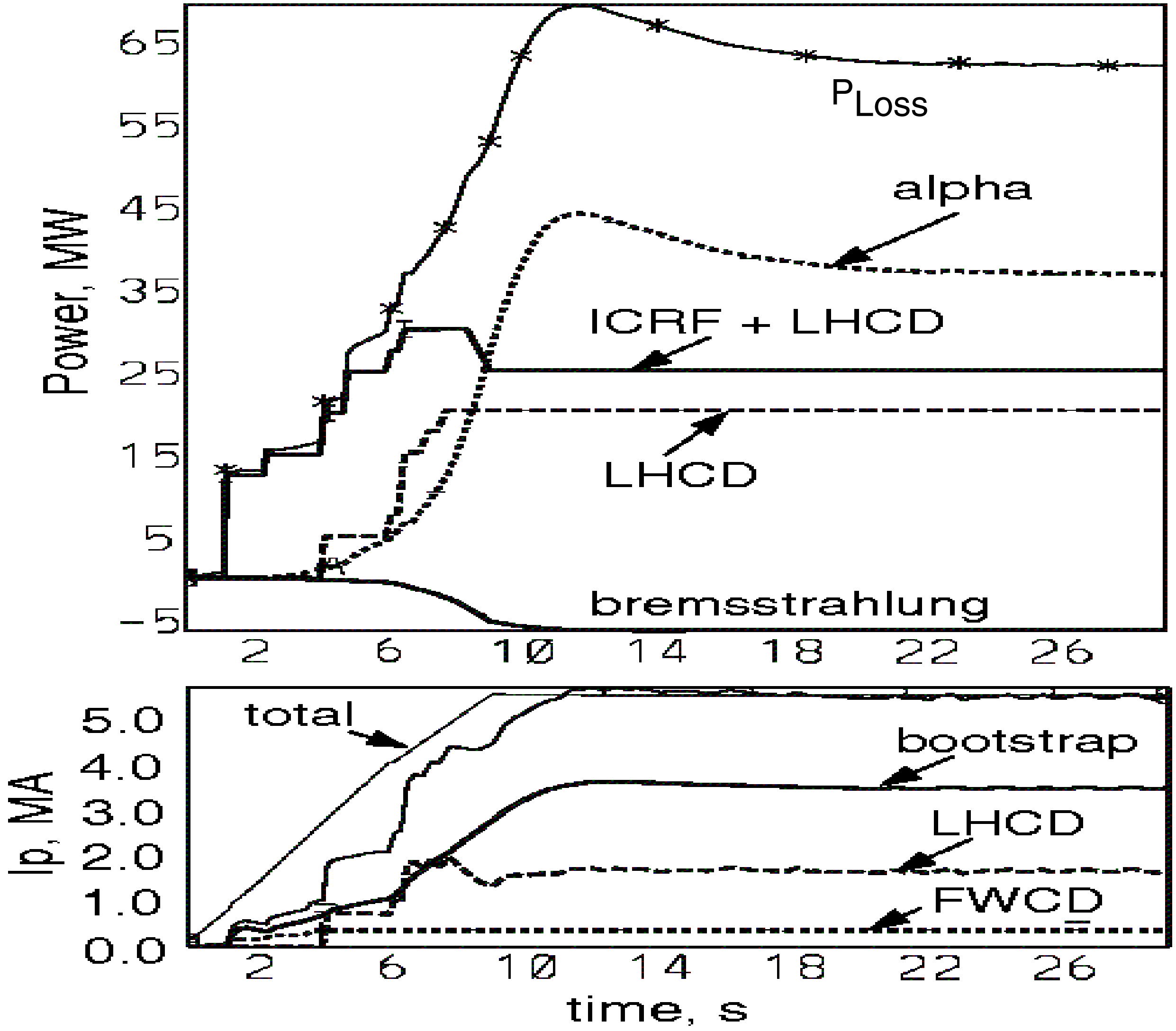
- ITER98(y,2) scaling with H(y,2) = 1.1, n(0)/<n> = 1.2, and $n/n_{GW} = 0.67$
- Burn Time ≈ 20 s ≈ 21 $\tau_E \approx 4\ \tau_{He} \approx 2\ \tau_{skin}$

Q = Pfusion/(Paux + Poh)

1 1/2 D Simulation of a Burning (Self-Drive > 50%) Plasma in FIRE

- $\chi(r)$ matching exp't data, H(y, 2) = 1.6, other models available (eg. GLF23)
- $\beta_N = 3.0$, $f_{BS} = 64\%$, reversed shear, $q_{min} \approx 2.7$ at $r/a \approx 0.8$, 3/2,5/2 NTM stable

partial wall for n= 1



60 % self-heated

64% self-current drive

TSC -C. Kessel APS-DPP