Exploring Burning Plasma Physics in the Laboratory

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for the FIRE Study Team

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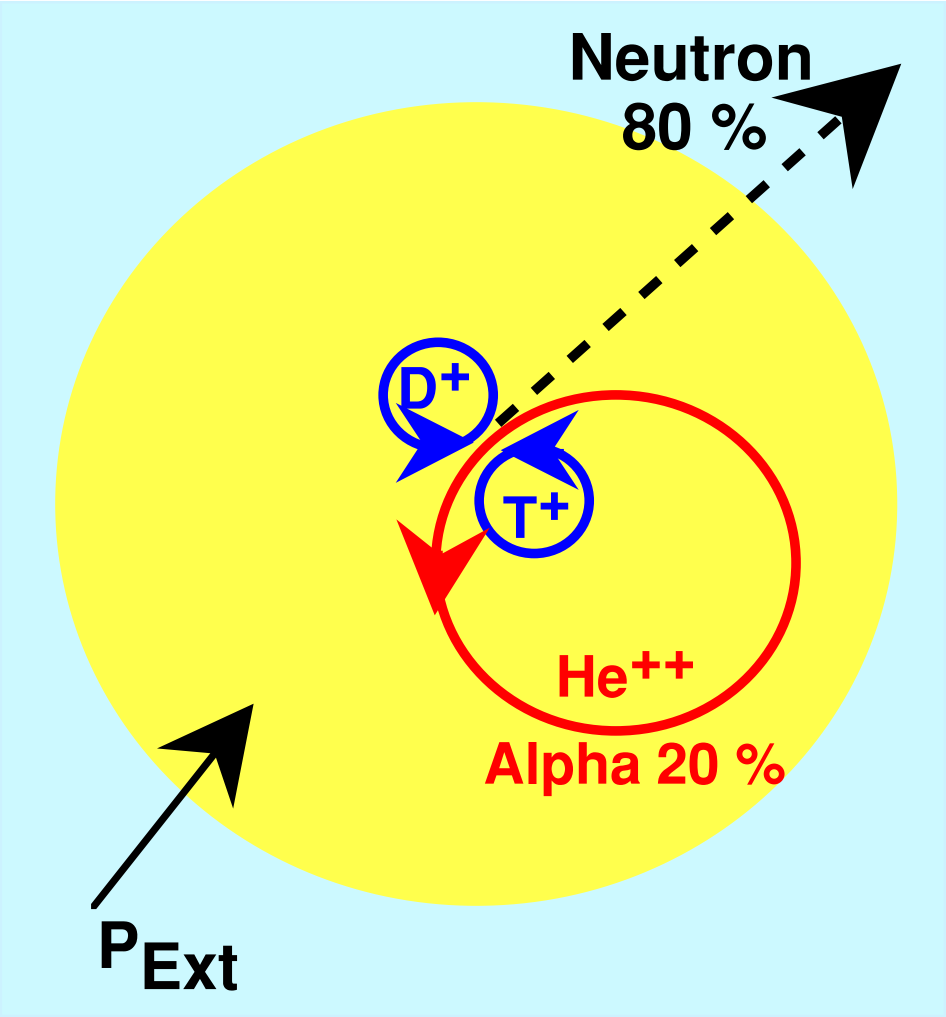
http://fire.pppl.gov

Self-Heating is Critical for a D-T Fusion Reactor



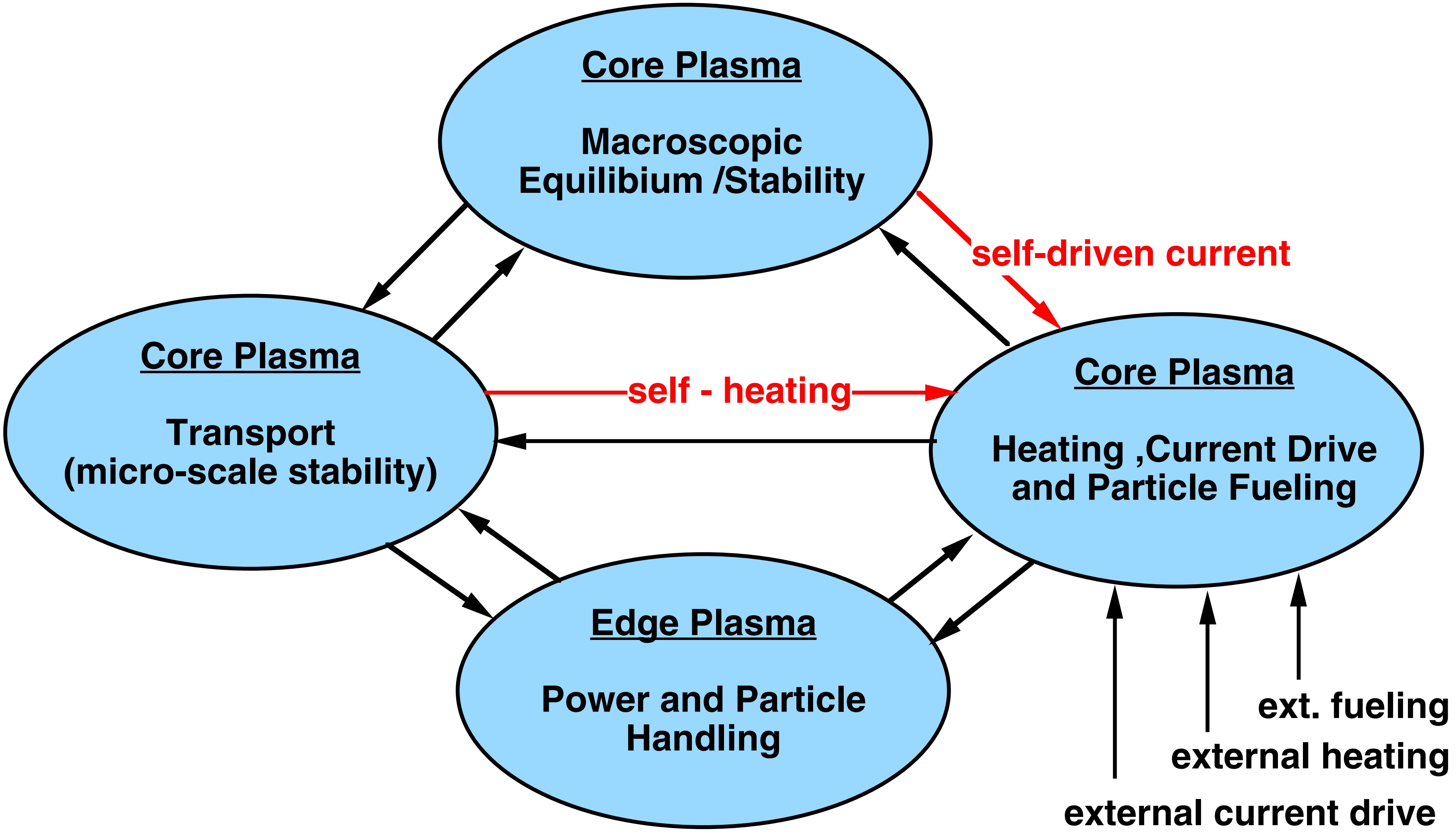
Alpha Physics Issues

- Alpha confinement
- Alpha Energy to Plasma
  - from alphas
  - to plasma electrons
- Burn Control
- Alpha Ash Removal
- Alpha Driven Instabilities

$$Q = \frac{P_{Fusion}}{P_{Ext}}, \quad f_{\alpha} = \frac{P_{alpha}}{P_{Heat}} = \frac{Q}{Q + 5}$$

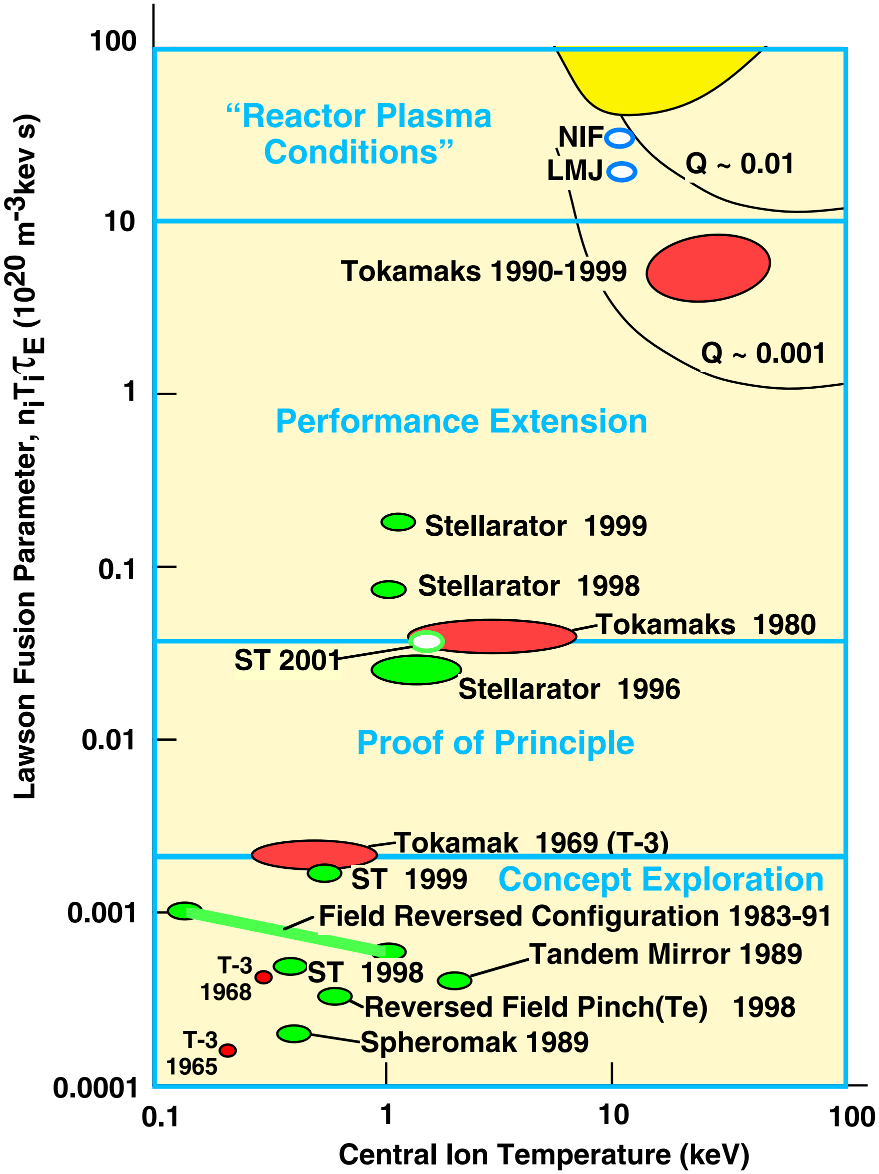
The alpha particle, which has 20% of the fusion reaction energy, remains trapped in the plasma and heats the plasma.

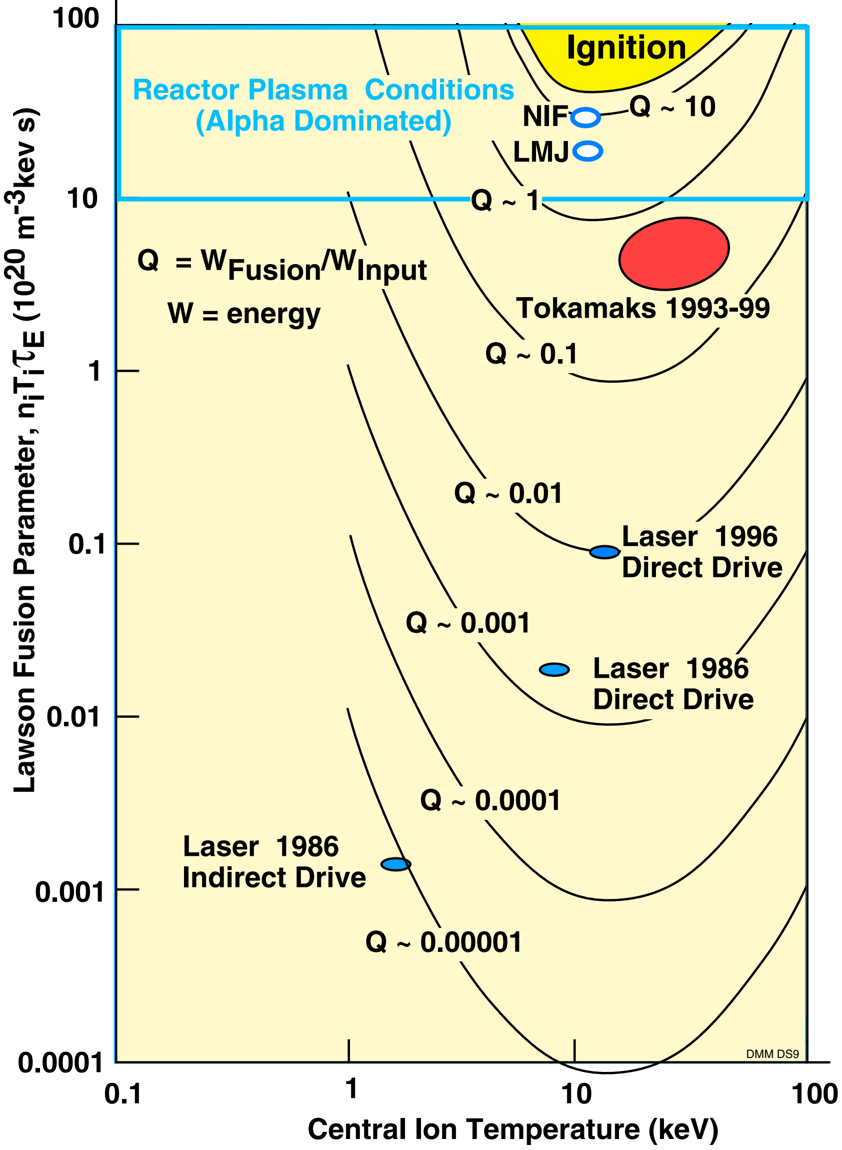
Fusion Plasmas are Complex Non-Linear Dynamic Systems



Can a fusion dominated plasma be attained and controlled in the laboratory?

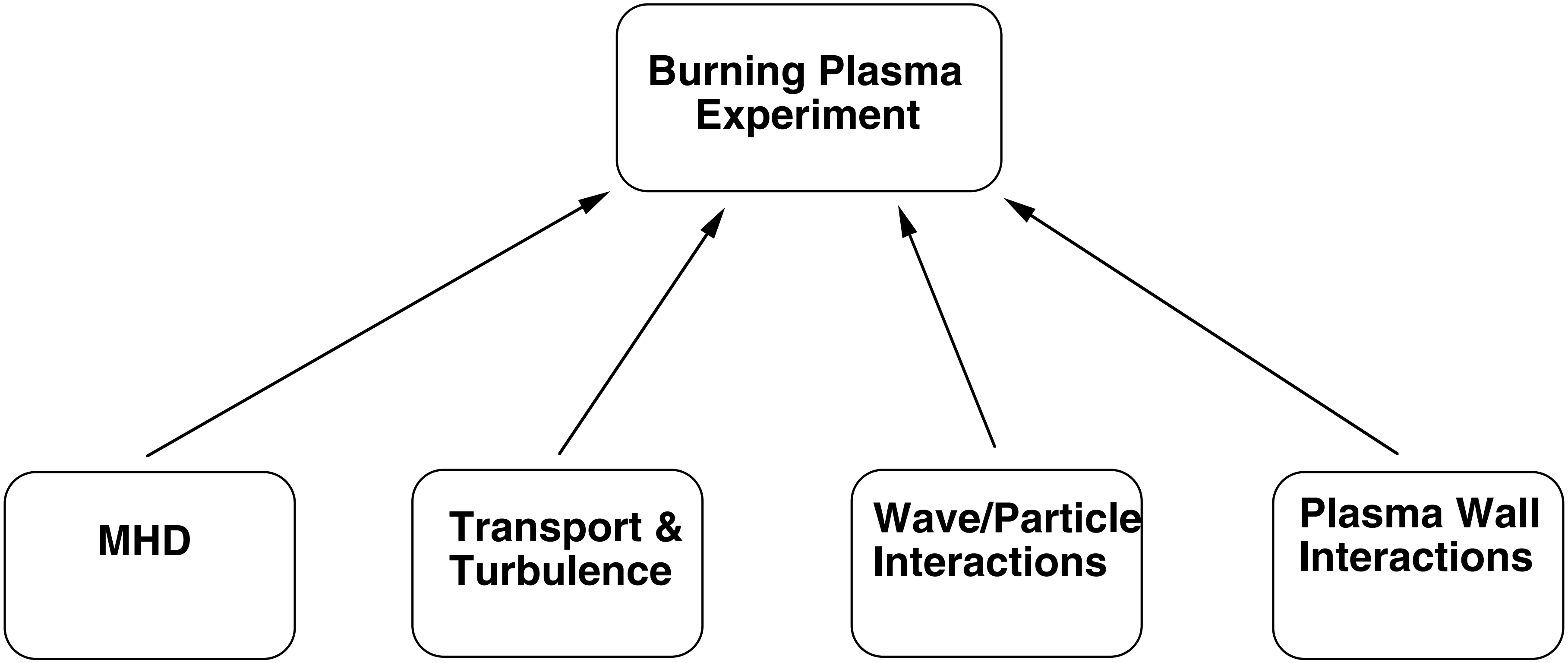
The Tokamak is Technically Ready to Address Self-Heating Physics


Deuterium Plasmas


Deuterium - Tritium Plasmas

The tokamak is sufficiently advanced to permit the design, construction and initiation of a next step burning plasma experiment within the next decade that could address the fusion plasma and self-heating issues for magnetic fusion.

Major Advances & Discoveries of 90's Lay Foundation for Next Step Burning Plasma Experiments



Burning Plasma Experiment

MHD

- q-profile control and measurement
- steady-state, bootstrap equilibria
- active mode control of kink & tearing

Transport & Turbulence

- shear-flow turbulence suppression
- gyro-kinetic theory based models
- extensive data-base models on transport using dimensionless scaling

Wave/Particle Interactions

- alpha heating in DT found to be classical for Q ≤ 1
- "standard model" of Alfvén Eigenmodes
- LHCD & ECCD used for near SS & mode control

Plasma Wall Interactions

- detached divertor demonstrated
- large scale models developed
- high heat-flux metallic technology developed

Advanced Burning Plasma Exp't Requirements

Burning Plasma Physics

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

Advanced Toroidal Physics

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

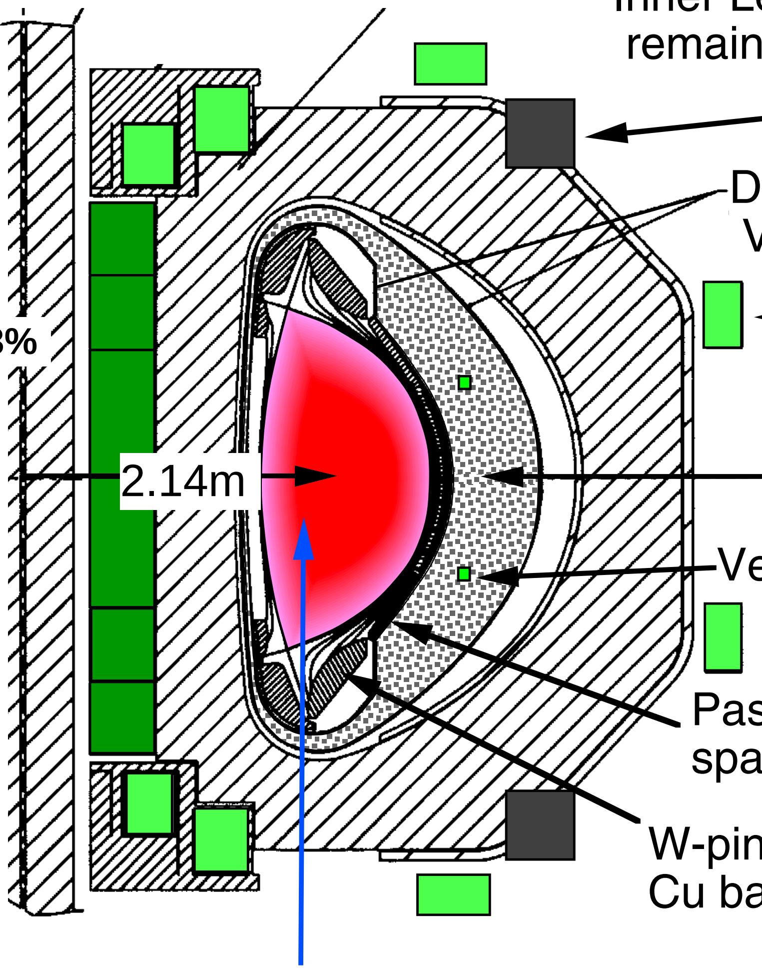
Quasi-stationary

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

A Compact High Field Tokamak has Advantages for BP Expt's

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

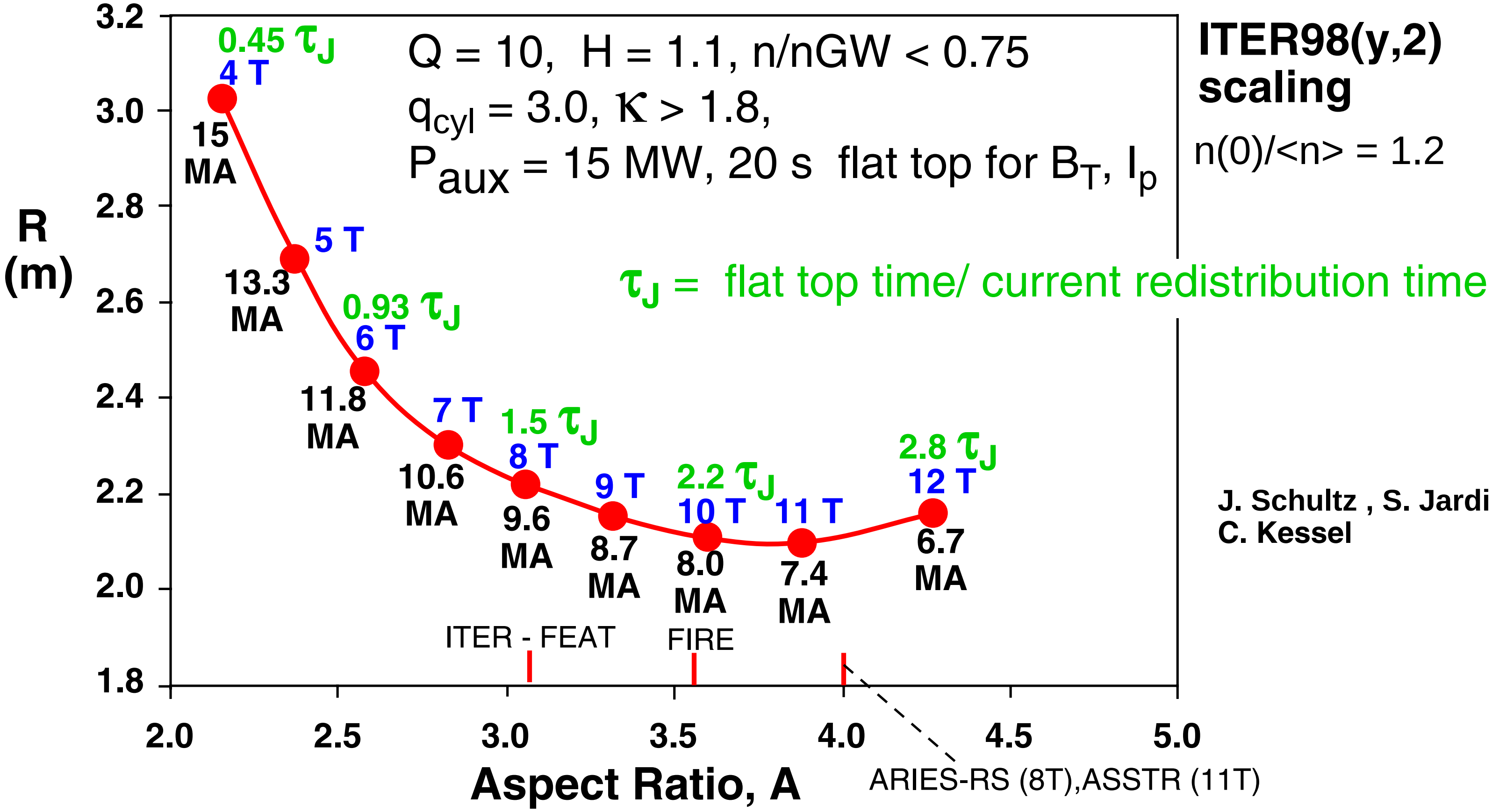
Direct and Guided Inside Pellet Injection

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

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.



$Q = 10$, $H = 1.1$, $n/n_{GW} < 0.75$

$q_{cyl} = 3.0$, $\kappa > 1.8$,

$P_{aux} = 15$ MW, 20 s flat top for B_T, I_p

τ_J = flat top time/ current redistribution time

ITER98(y,2) scaling

$n(0)/\langle n \rangle = 1.2$

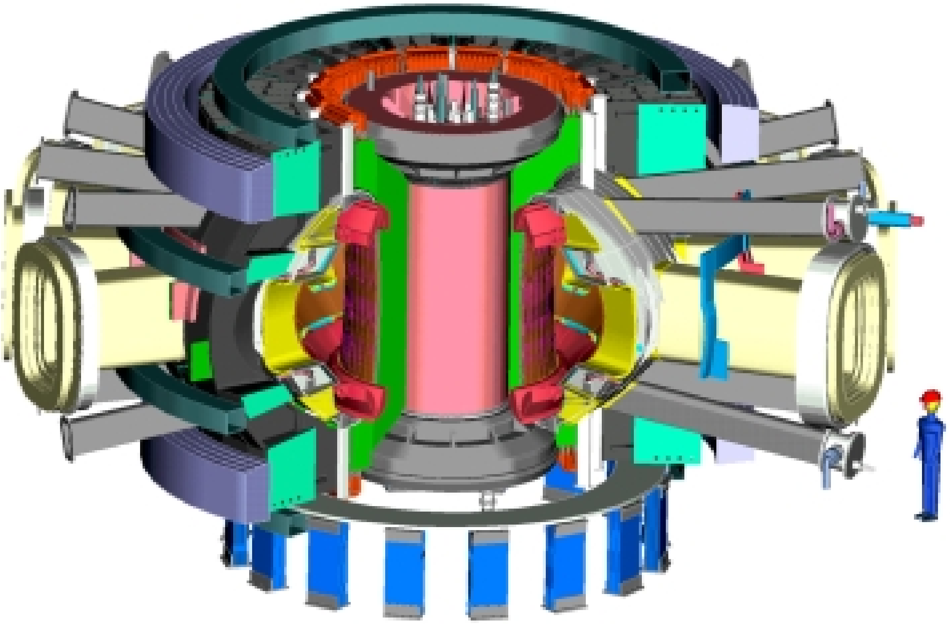
J. Schultz , S. Jardin
C. Kessel

What is the optimum for advanced steady-state modes?

Fusion **I**gnition **R**esearch **E**xperiment

(FIRE)

http://fire.pppl.gov



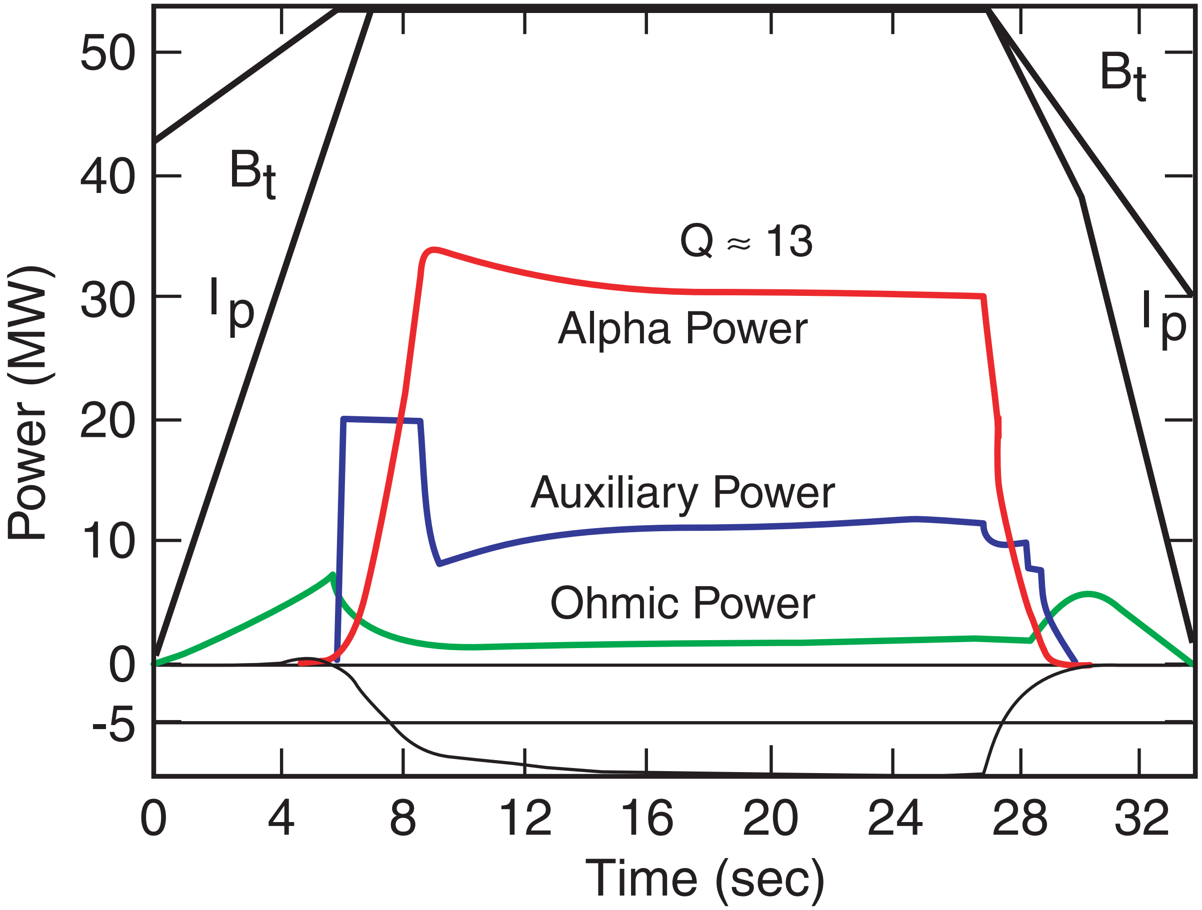
Design Features

- 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.

U.S. Based, part International Modular Strategy

Simulation of Burning Plasma in FIRE



B = 10 T

I_p = 7.7 MA

R = 2.14 m

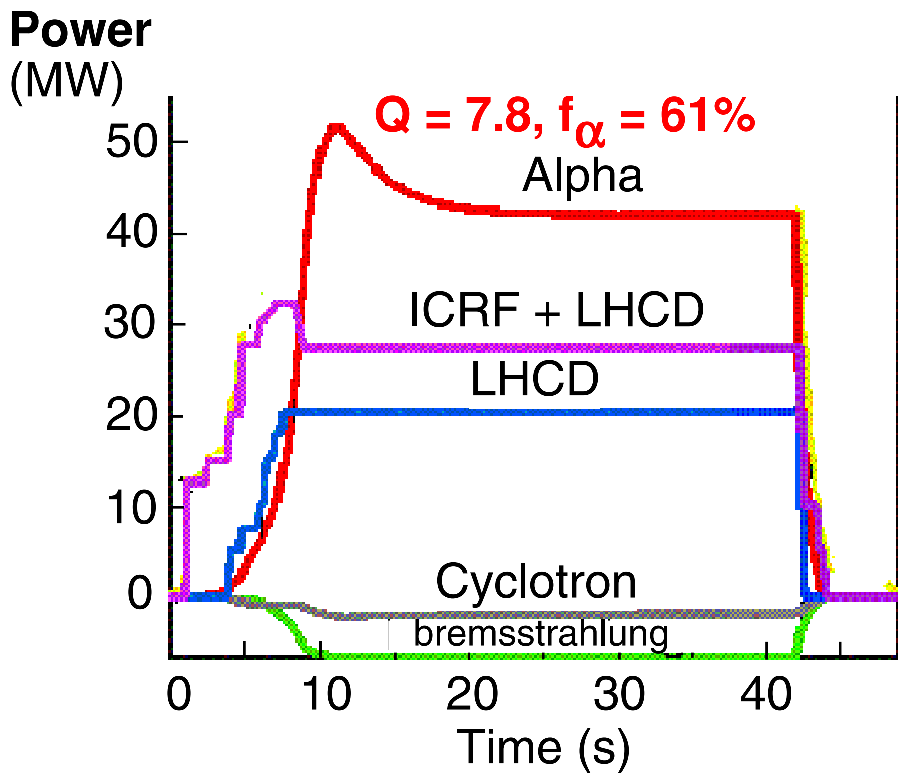
A = 3.6

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

Q = Pfusion/(Paux + Poh)

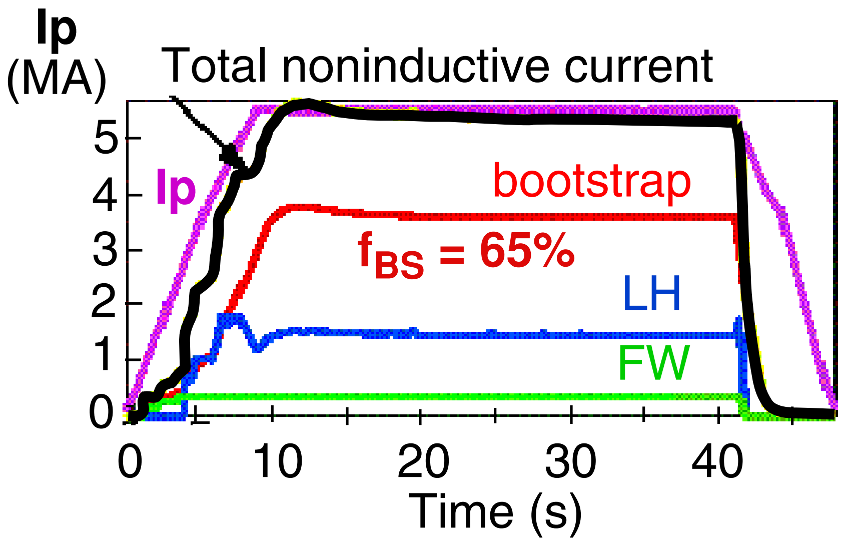
Advanced Burning Plasma Physics could be Explored in FIRE

Self-Heating Dominant



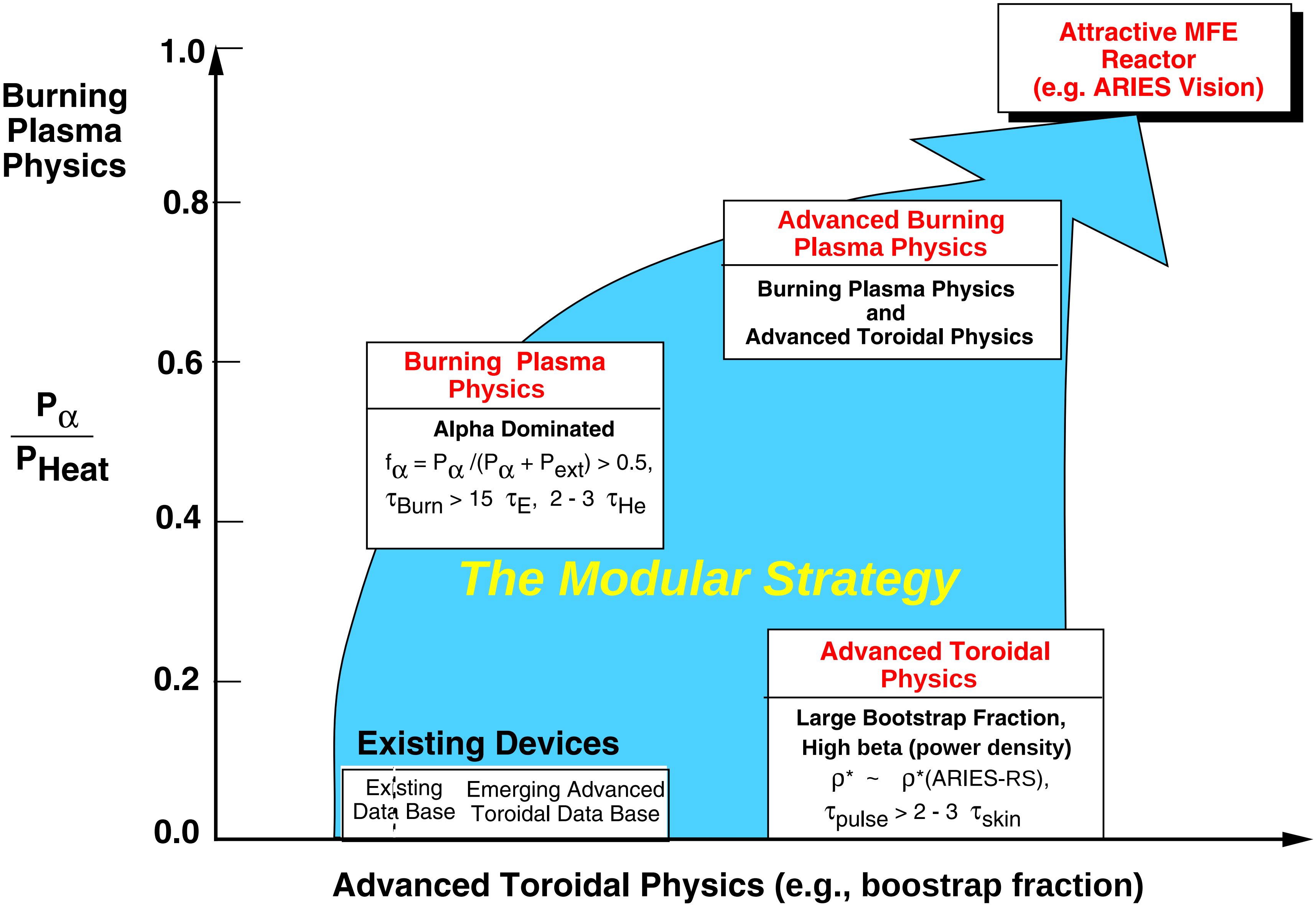
Self-Current Drive Dominant

Fully Non-Inductive for > 1 τ_{CR}



Tokamak simulation code results for H(y, 2) = 1.6, $\beta_N = 3.5$, would require RW mode stabilization. $q(0) = 2.9$, $q_{min} = 2.2$ @ r/a = 0.8, 8.5 T, 5.5 MA

Success with FIRE would Address the Critical Burning Plasma Science Issues for an Attractive MFE Reactor



Attractive MFE Reactor
(e.g. ARIES Vision)

Advanced Burning Plasma Physics

Burning Plasma Physics
and
Advanced Toroidal Physics

Burning Plasma Physics

Alpha Dominated

$f_\alpha = P_\alpha/(P_\alpha + P_{ext}) > 0.5$,

$\tau_{Burn} > 15\ \tau_E$, $2 - 3\ \tau_{He}$

Advanced Toroidal Physics

Large Bootstrap Fraction,
High beta (power density)
$\rho^* \sim \rho^*$(ARIES-RS),
$\tau_{pulse} > 2 - 3\ \tau_{skin}$

Existing Devices

Existing Data Base	Emerging Advanced Toroidal Data Base

Attain a burning plasma with confidence using “todays” physics, but allow the flexibility to explore tomorrow’s advanced physics.