Achieving an Ohmically Heated Plasma for Fusion Energy

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We describe three frontier contexts for “achieving an ohmically heated plasma for fusion energy”

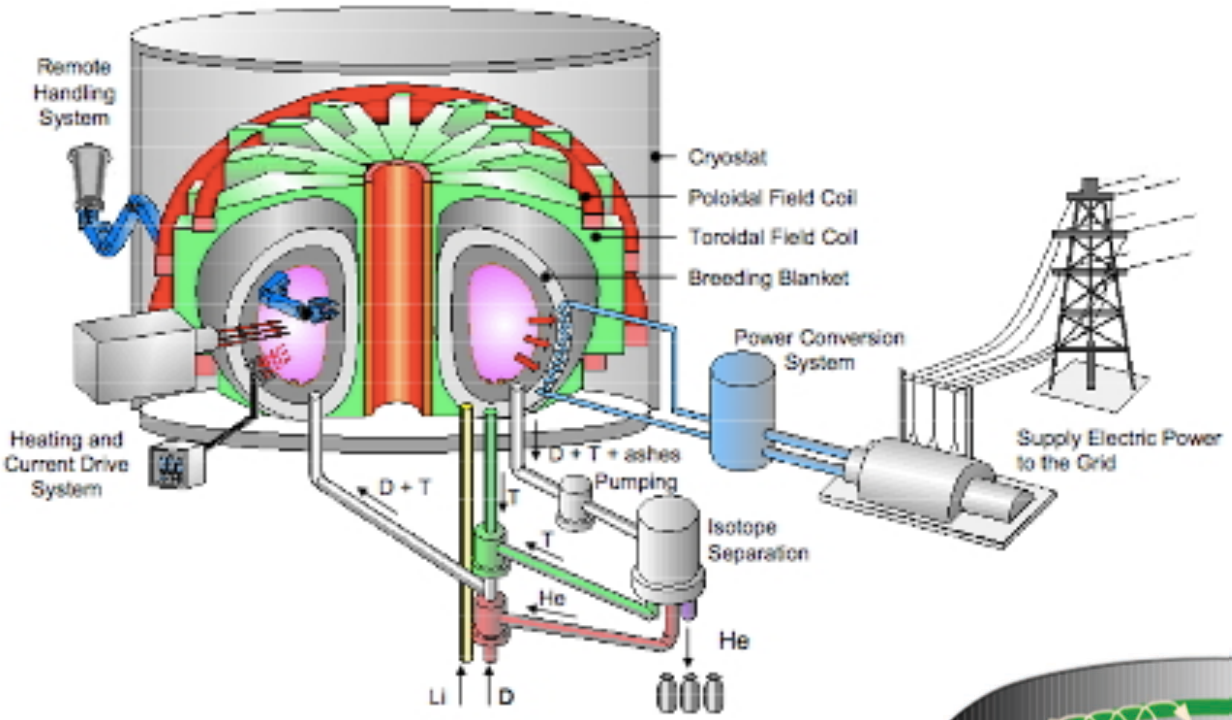
1. Heating a fusion plasma to burning conditions without radio-frequency or neutral beam power sources

2. Advancing the predictive understanding for magnetic confinement of hot plasmas

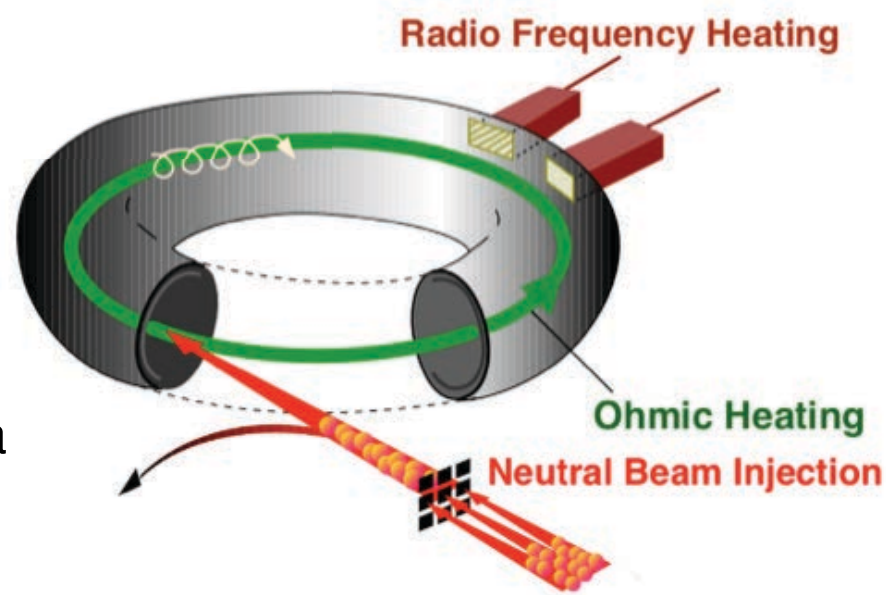
3. Advancing the physics and multi-scale modeling of self-organized plasmas for both basic plasma science and fusion

These contexts are closely associated with elements of the “exploratory magnetic confinement” portfolio and are part of a more general frontier for multi-configuration magnetic confinement research

Magnetic confinement of a hot plasma in a toroidal configuration for fusion energy



3 ways to heat
a toroidal plasma



There are three ways to heat a toroidal plasma to burning plasma conditions

- Neutral beam injection
  - Dominant source for all present-day tokamak experiments
  - Very challenging for a fusion reactor plasma, requiring 1-2 MeV neutrals and large holes in the wall and blanket
- RF injection
  - Preferred choice in almost all reactor design studies
  - The boundary conditions for ion cyclotron and lower-hyrbid antennas are very different than for the majority of the plasma-material interface that must accommodate large heat, particle, and neutron fluxes
  - A reactor must achieve low maintenance and high reliability for high availability
- Ohmic dissipation of plasma current
  - Induction is the standard method for forming a tokamak plasma, incl. ITER
  - A segmented wall/blanket is invisible to a low frequency inductive electric field, allowing the first-wall to be entirely covered by suitable materials
  - Ohmic heating is small in a tokamak, since $I_p \sim q^{-1}$ (where $q = rB_T / RB_P > 1$)
  - Ohmic heating is large in a reversed-field pinch or spheromak, since $q(r) < 1$

ARIES-AT represents an economically attractive tokamak fusion reactor and a target for the advanced tokamak program

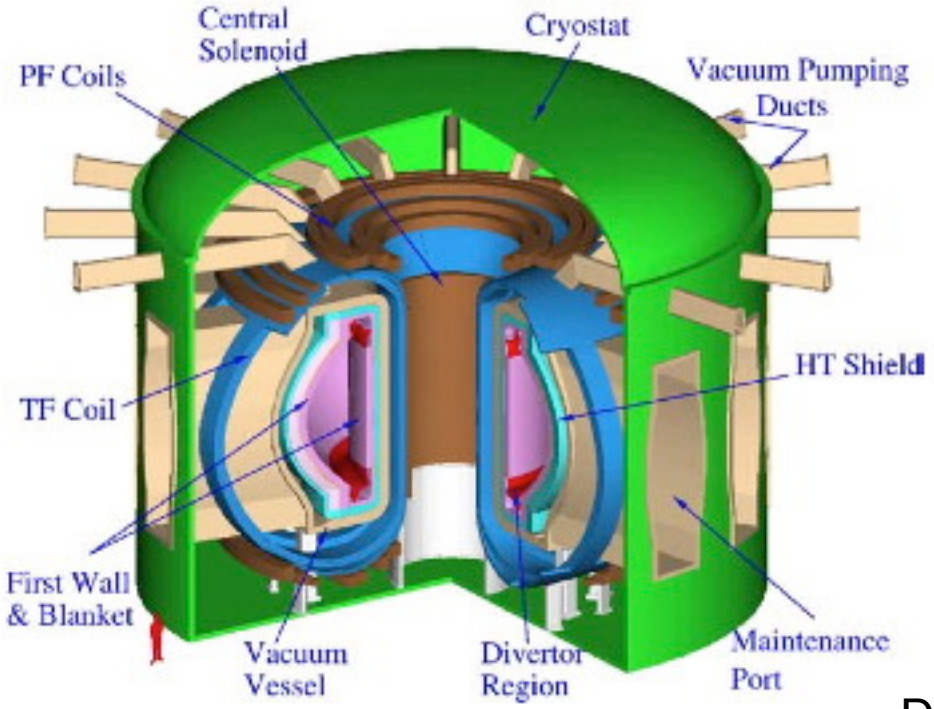


Fig. 1. The ARIES-AT fusion power core.

Najmabadi et al, FED 80, 2006

Key features:

- P_f = 1.7 GW
- P_n/A = 3.3 MW/m^2
- Q = 49
- Steady-state (91% bootstrap)
- Lower-hybrid and fast-wave for $J(r)$ control

Design has 6 distinct rf current drive systems

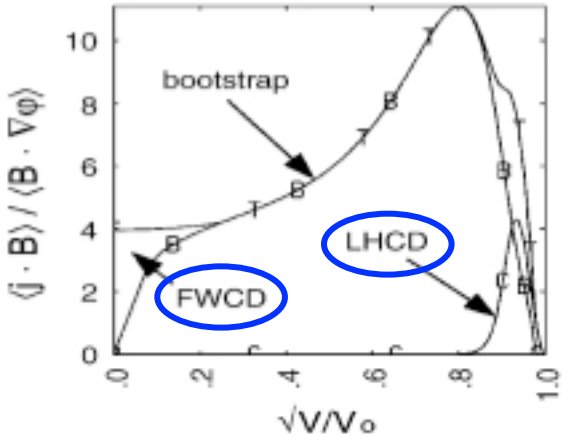
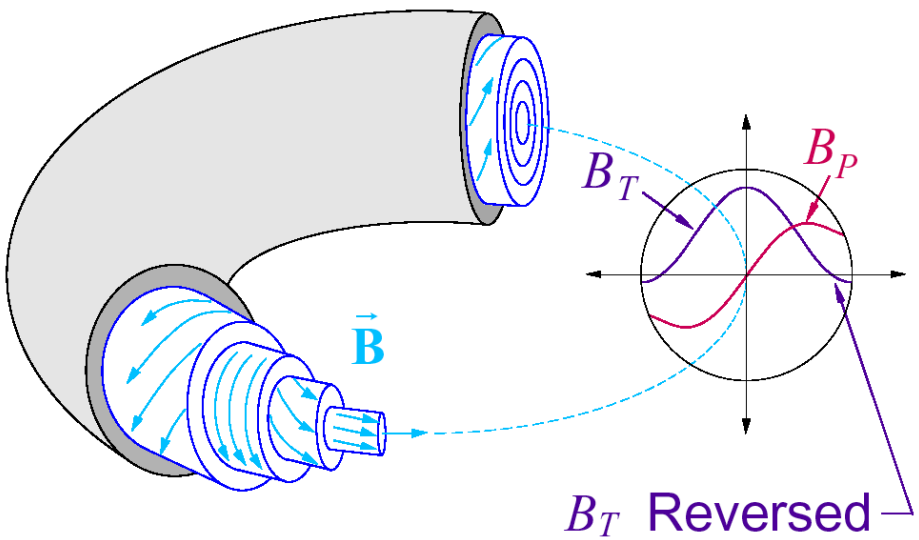


Table 3
The ARIES-AT current-drive system

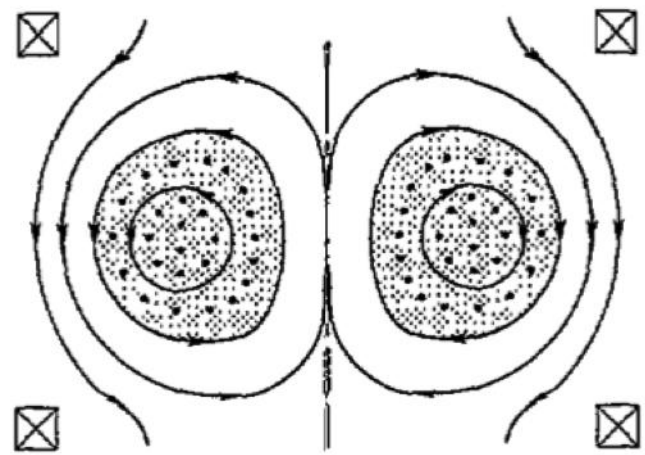
System	Frequency	$N_{\parallel}$	Power (MW)	Driven current (MA)
ICRF fast wave	96 MHz	2	4.7	0.15
Lower hybrid	3.6 GHz	1.65	3.1	0.15
	3.6 GHz	2.0	4.4	0.2
	3.6 GHz	2.5	8.2	0.3
	3.6 GHz	3.5	8.9	0.2
	2.5 GHz	5.0	12.4	0.15

The reversed field pinch and spheromak configurations are magnetized by large, field-aligned plasma current

Reversed Field Pinch

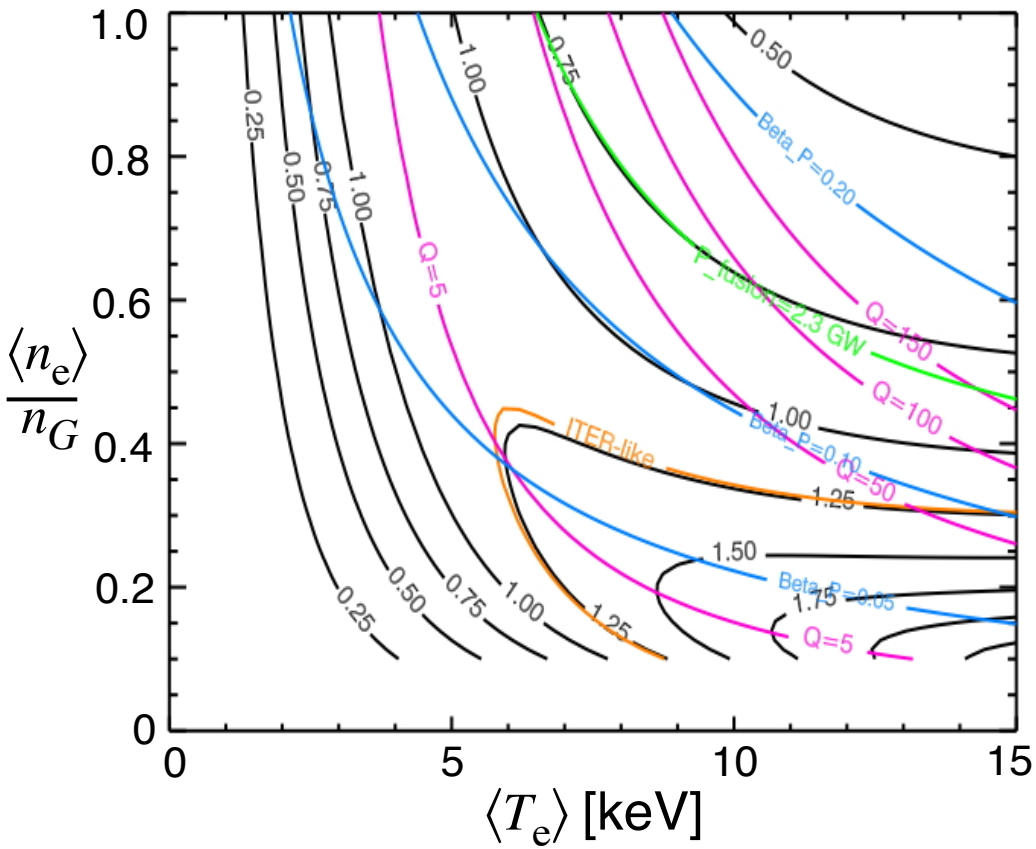


Spheromak



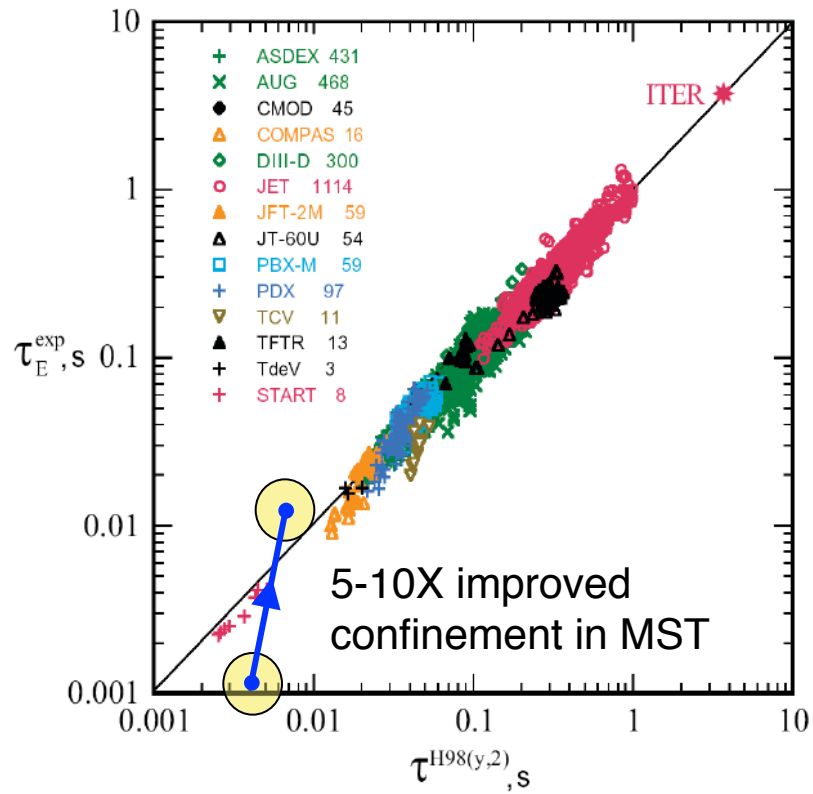
Ohmic ignition and high fusion gain are possible for an RFP plasma if the energy confinement is tokamak-like

Ohmic Ignition Power Balance
(P_n/A = 5 MW/m^2 for P_f = 2.3 GHz)



I_p = 30 MA, $\langle B \rangle$ = 5.6 T, B_{coil} ~ 3 T, P_Ω = 70 MW
(see white paper for other parameters)

Tokamak-like confinement in present-day RFP experiments



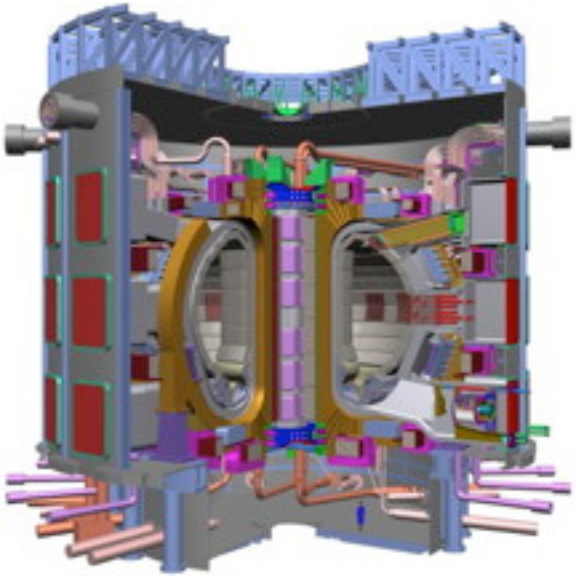
Key questions:
– Transport mechanism(s)?
– Scaling?

Frontier Context 2:

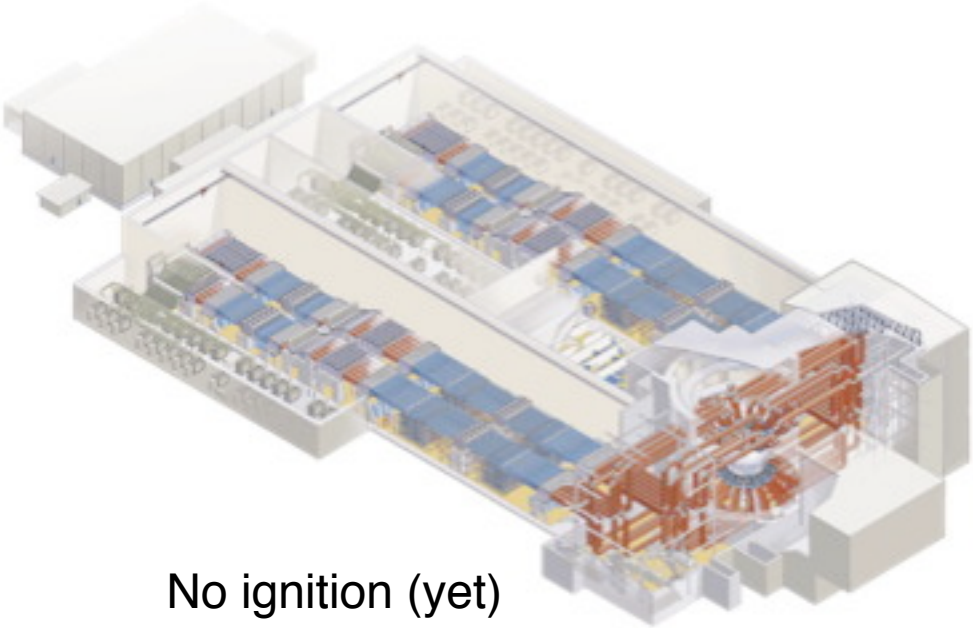
Advancing the predictive understanding for magnetic confinement of hot plasmas

Arguably the highest priority issue for fusion energy is convincing the world its science foundations are predictive

- Predictive science can help resolve key concerns for future fusion research:
  - Cost and complexity imply extrapolation beyond an established experimental basis for any particular development path appears unavoidable
  - The large gap between present-day experiments and a GW reactor that operates for millions of seconds implies the challenges are not fully articulated
  - Tradeoffs in physics, methodologies, and technologies are necessary



$$ → $$$, schedule t.b.d.



No ignition (yet)

The named toroidal magnetic configurations (tokamak, stellarator, etc.) are really one grand experiment

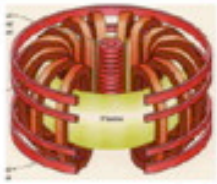
- “Predictive” implies understanding the plasma’s behavior when changing key variables
- Experimentally it is impractical to adjust the major variables of toroidal confinement in a single laboratory setting
- The frontier for predictive fusion science should embrace multiple configurations as close cousins, not just view them as competitors for fusion
- In this context, “ohmic heating to ignition” is synonymous with understanding the behavior of an axisymmetric toroidal configuration that has a large plasma current

The continuum of magnetic configurations is most often cast to emphasize tradeoffs in their differences

Stellarator

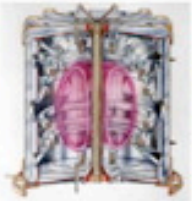
3D coils,
no current drive

Tokamak



Nested sets of planar
coils, some current drive

Spherical Torus



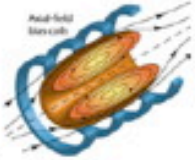
Smaller OH
transformer

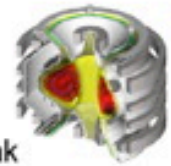
Reversed-field
pinch

Reduced
TF coils

Compact Torus

Field-reversed configuration

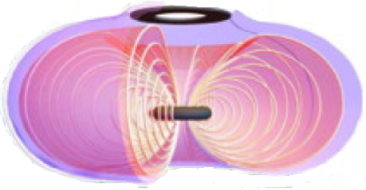




No TF coils

Spheromak

Levitated Dipole



Steady-state "current-free" plasma
configuration maintained by external coils

Increasing role of plasma currents in
providing confining magnetic fields

Self-organized plasma configuration with
internal currents maintaining the fields

Simply-connected plasma chambers

Steady-state with internal coil
(no plasma current or TF)

Can the breadth of magnetic configurations be captured in a few model equations, and even predict new optimizations?

- To be predictive, we must develop plasma models and test their experimental validity versus the major variables that define magnetic configurations
- This challenge is cross-cutting for plasma science: equilibrium and stability, nonlinear self-organization, turbulence and transport, wave-particle interactions, plasma-material interface

Example: Extended MHD

Ohm's law: $$\mathbf{E} = -\mathbf{V}\times\mathbf{B} + \frac{1}{ne}\mathbf{J}\times\mathbf{B} - \frac{1}{ne}\nabla p_e + \eta\mathbf{J} + \frac{m_e}{ne^2}\frac{\partial\mathbf{J}}{\partial t}$$

Momentum: $$nm_i\frac{d\mathbf{V}}{dt} = \mathbf{J}\times\mathbf{B} - \nabla p - \nabla\cdot\Pi_{gyro} - \nabla\cdot\nu nm_i\mathbf{W}$$

one model
↓
multiple configurations

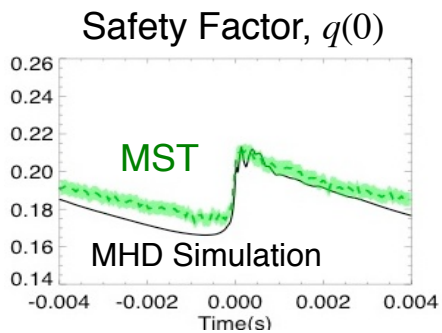
Example: Gyrokinetics for strongly magnetized plasmas …

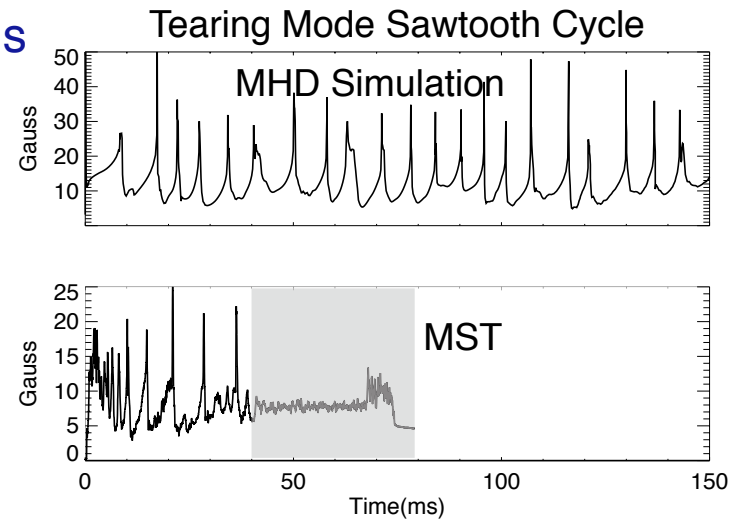
Excellent opportunities for validation of important physics models and codes using the RFP plasma

- Nonlinear, visco-resistive MHD is ripe for rigorous validation

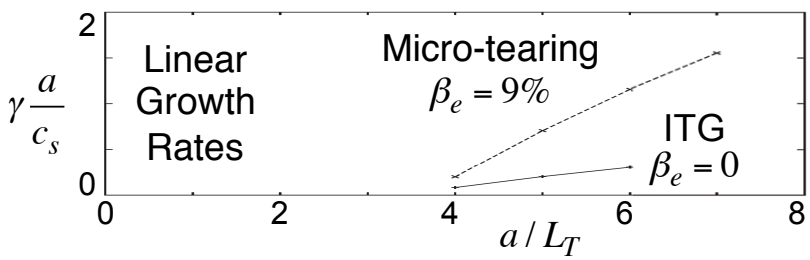
MST's advanced diagnostic set provides crucial data

Control tools yield several distinct operating regimes

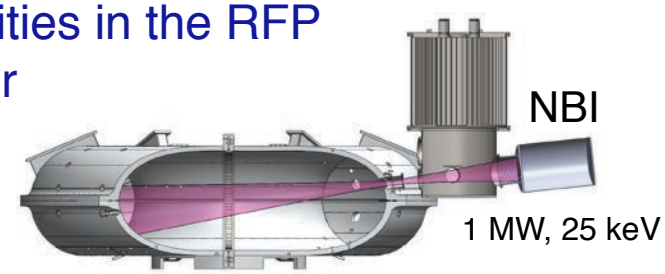


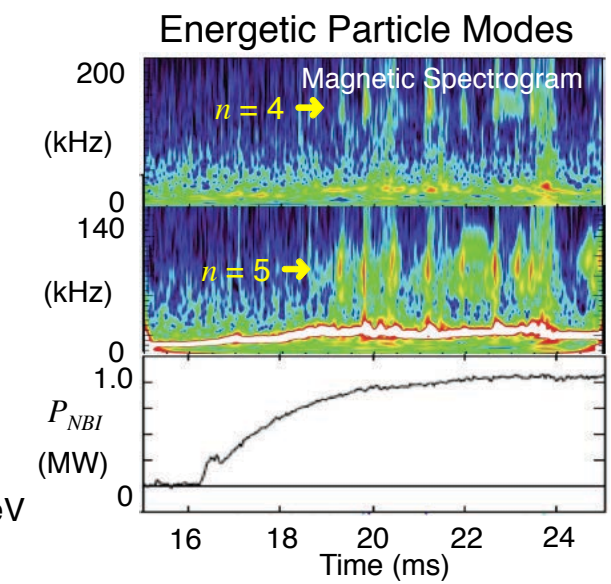


- Investigation of high-k instabilities challenges established gyrokinetic theory and modeling



- Beam-driven instabilities in the RFP stretch the parameter space for critical reactor physics





Frontier Context 3:

Advancing the physics and multi-scale modeling of self-organized plasmas for both basic and applied science

Nonlinear self-organization creates the possibility for a steady-state plasma current using ac induction

- The basic science and astrophysical context for the self-organization of RFP and spheromak plasmas is discussed by M. Nornberg and other papers on reconnection and dynamo
- Here we emphasize a fusion-relevant application

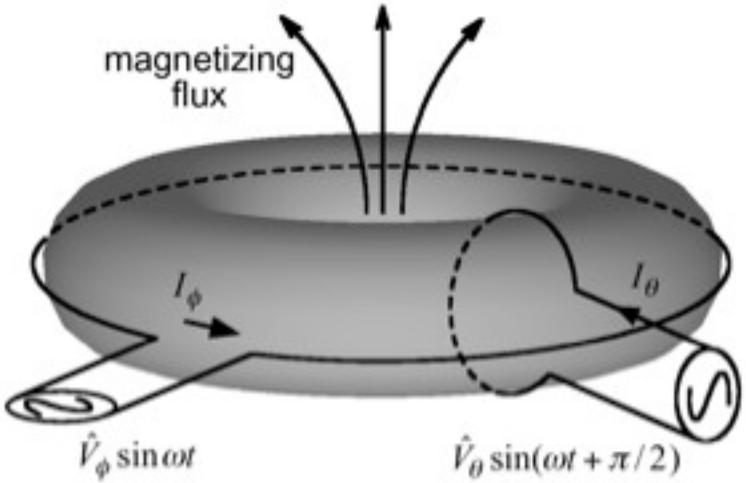
Oscillating Field Current Drive

$$\frac{\partial K}{\partial t} = 2V_\phi \Phi - 2\int \mathbf{E}\cdot\mathbf{B}dV \qquad (K = \int \mathbf{A}\cdot\mathbf{B}dV)$$

apply oscillating V_ϕ & Φ :

$$V_\phi = \hat{V}_\phi \sin\omega t \quad \& \quad \Phi = \frac{\hat{V}_\theta}{\omega}\sin\omega t + \Phi_{dc}$$

$$\langle 2V_\phi \Phi \rangle = \frac{\hat{V}_\phi \hat{V}_\theta}{2\omega}\sin\delta \qquad \delta = \mathrm{Phase}[V_\theta, V_\phi]$$



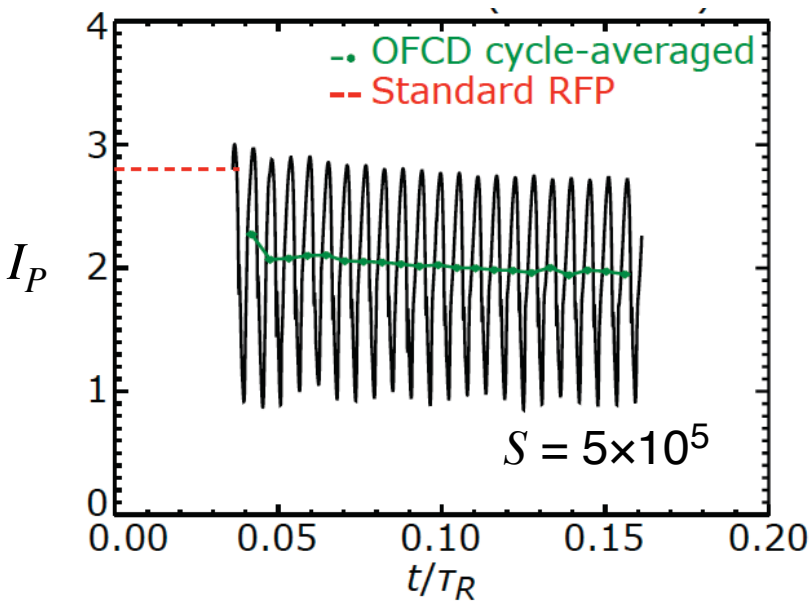
Physics basis is promising

- OFCD modulation replaces steady induction:

$$E + \langle \tilde{v} \times \tilde{B} \rangle = \eta J \quad \Rightarrow \quad \langle \hat{v} \times \hat{B} \rangle + \langle \tilde{v} \times \tilde{B} \rangle = \eta J$$

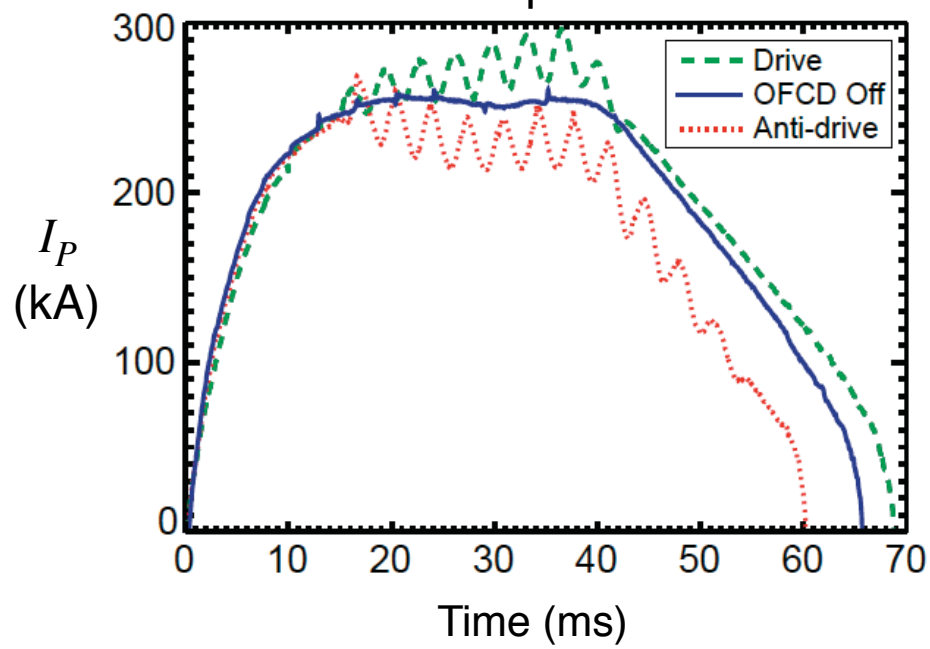
(steady induction) (OFCD)

Nonlinear MHD Computation



Ebrahimi et al

MST Experiment



McCollam et al

The stage is set for rapid progress toward predictive fusion science

- An emphasis on “verification and validation” helps provide a focal point in defining the spectrum of required program elements in experiment, theory, and modeling

- Experiments that span configuration space are essential to maximize predictive capability, and they must be well diagnosed to support validation

- Modeling must be:
  - Built capable for adjusting major variables, e.g., avoid ordering for an assumed large toroidal field
  - Multi-scale and global to address boundary conditions, inhomogeniety, and feedback between small and large scales
  - Supported by computational resources that allow both development and iterative refinements associated with verification and validation