EXCITING OPPORTUNITIES
TO ADVANCE FUSION ENERGY
IN MAGNETIC CONFINEMENT CONCEPTS

PRESENTED BY

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FOR THE

MAGNETIC FUSION CONCEPT WORKING GROUP

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Special Thanks To:

MFCWG Convenors

— Herb Berk

— Ray Fonck

— Jim Drake

— Martin Greenwald

— Dave Hill

— Brad Rice

— John Sarff

— Bob Taylor

— Mike Zarnstorff

BREAKOUT GROUP LEADERS

Transport in magnetic confinement concepts

– Martin Greenwald, John Sarff

MHD stability in magnetic confinement concepts

– Ted Strait, Chris Hegna

Plasma boundary and particle control

– Bruce Lipschultz, Tom Rognlien

Achieving steady-state operation in MFE devices

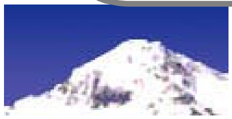
– Hutch Neilson, Ed Synakowski

Burning plasmas in magnetic confinement concepts

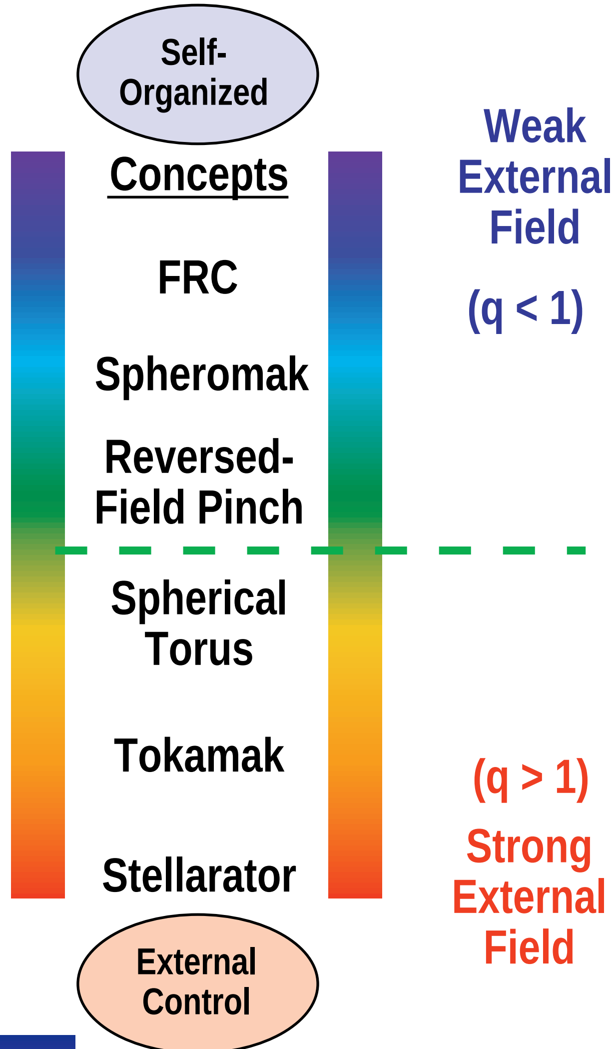
— Raffi Nazikian, Wayne Houlberg

MFE concept integration & performance measures

— Mike Zarnstorff, Stan Luckhardt

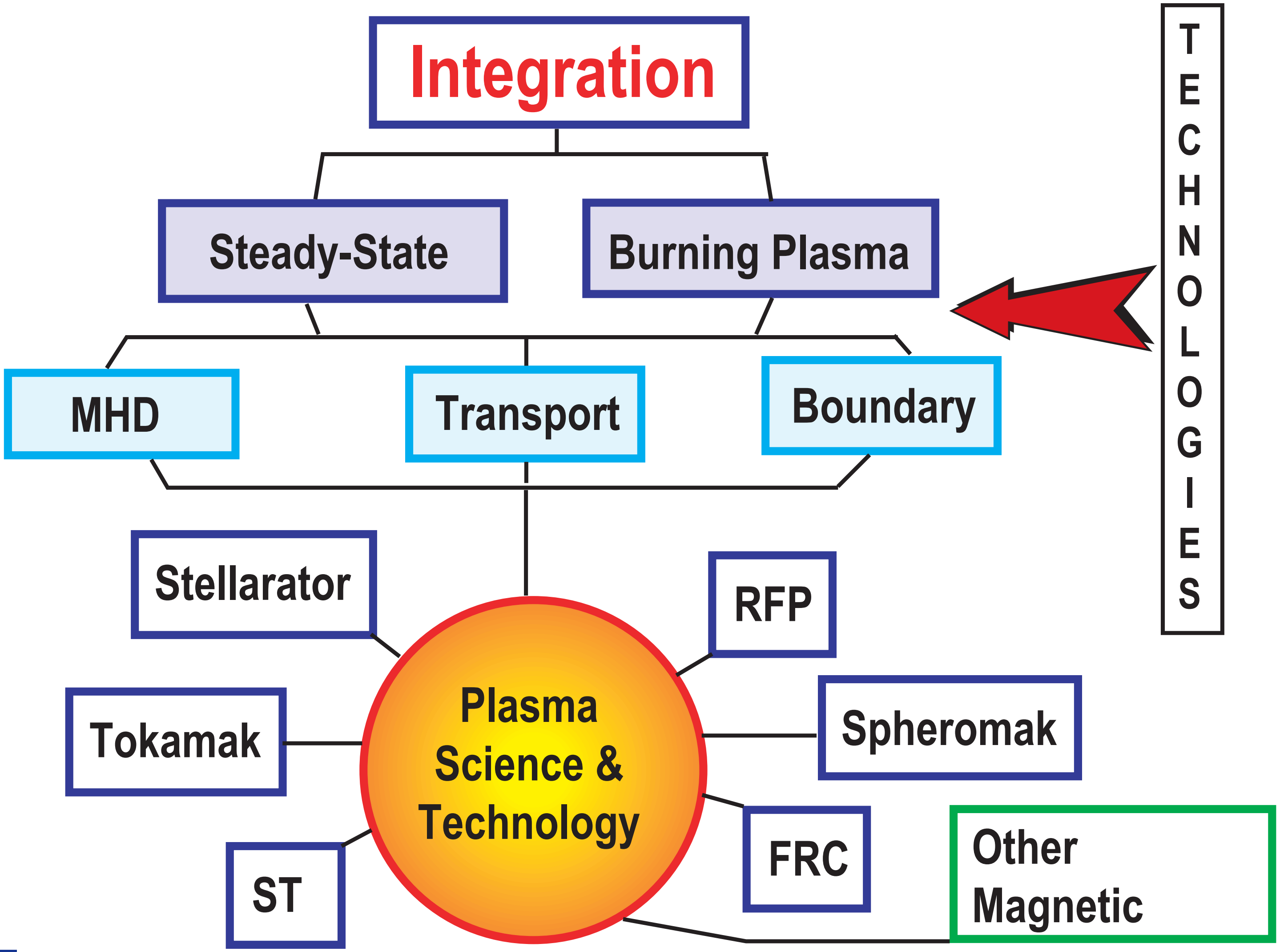


Complementarity of MFE Research Portfolio Targets Critical Issues



- **Classify by degree of external magnetic control vs ability of plasma to organize itself**
- **Strong degree of complementarity and commonality in concepts**
  - Study of one enhances ability to develop others

Elements of a Scientific Roadmap for MFE



EC: D. Barnes

The Goals of MFE Research

Determine the optimum magnetic configuration(s) for attractive fusion energy production, by ...

- Using a spectrum of magnetic configurations ranging from externally-controlled to self organized, to ...
  - **Understand the scientific foundations of MFE (equilibrium and stability, transport, boundary, plasma control), and to..**
  - **Integrate these elements to optimize a steady-state, high-performance magnetic fusion plasma**

Be prepared to move forward with the next stage of MFE development

- **Burning Plasma (JET-Upgrade, FIRE, Ignitor)**
- **Steady State (KSTAR, ...)**
- **Integrated test of sustained burning plasma (ITER-RC)**

  Participate in the ITER-RC if EU or Japan decide to construct

MFE Goals (cont.)

- **Provide fertile environment for new ideas and innovation in MFE**
  - New confinement concepts, improvements/hybrids of existing concepts
  - Cross-fertilization of ideas and research across concepts

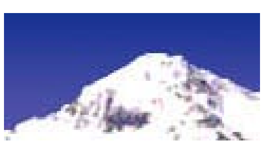
Two over-arching themes have emerged from the MFCWG discussions

Across Magnetic Concepts and Across Scientific Disciplines

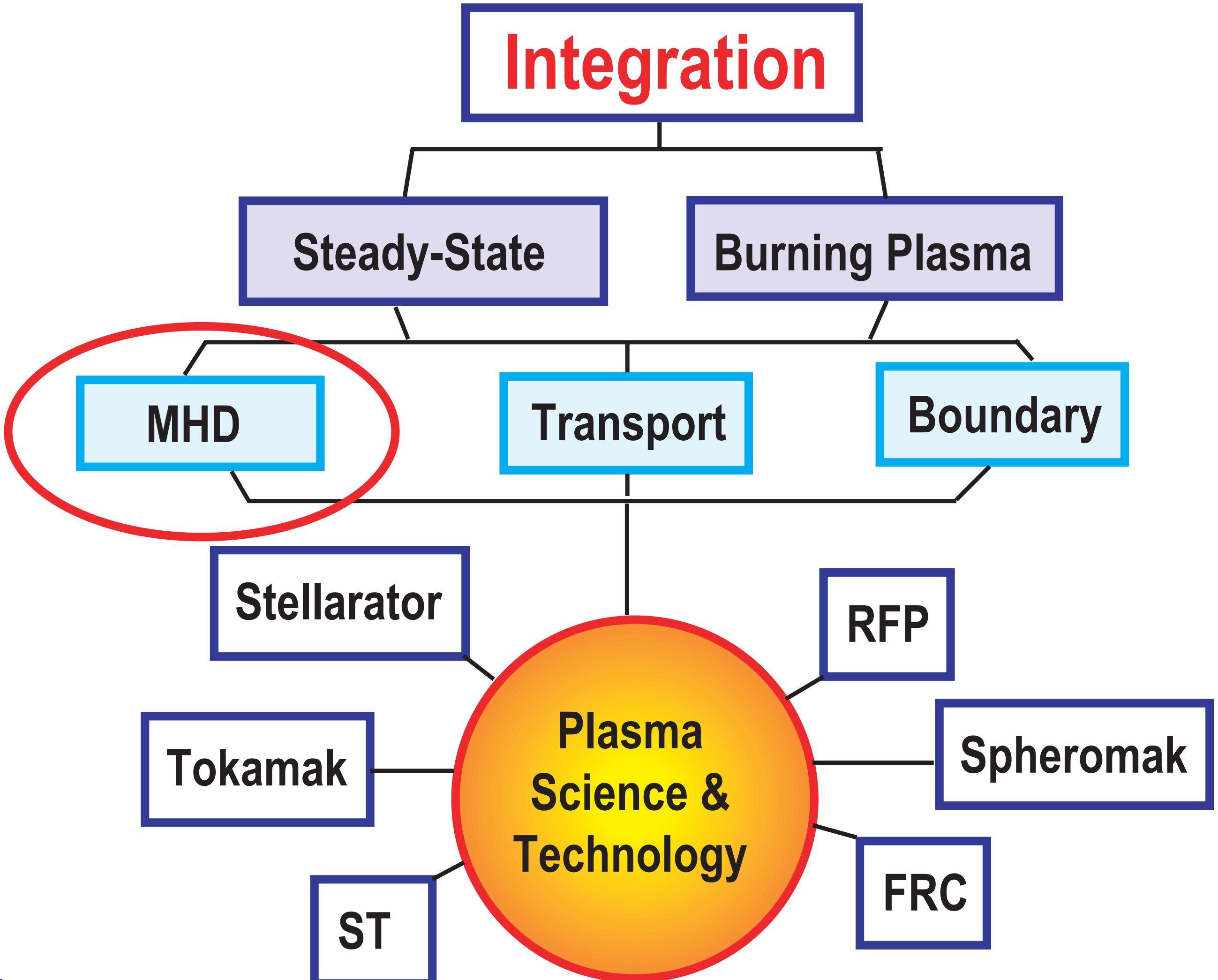
- **Physics Understanding and Predictive Capability to Develop the Scientific Basis for Fusion Energy**
  - Allows (fosters) commonality across concepts and levels of development
  - Transferability of physics learned from one magnetic concept to another
  - Rapid development of concepts (possibly skipping a level)
  - Opportunity to reduce the cost of fusion energy development
    Optimal design of experiments/facilities— rapid development
- **Development and employment of plasma control tools**
  - Scientific Understanding
  - Performance optimization
  - Innovative technological and scientific solutions
    $\Rightarrow$ Partnership between technology & physics

Elements required for physics understanding and predictive capability

- Innovative, comprehensive diagnostic measurements are essential
- Operational time for detailed scientific investigation
- Strong coupling between theory, modeling, and experiment
- Inclusion of more complete plasma physics and detailed geometric effects into modeling codes using advanced computational tools
- Control tools for detailed physics investigation
- Program emphasis: strong focus on science



MHD Stability in the MFE Roadmap



Improving plasma stability: Issues & Opportunities

- **Critical issue: Fusion performance improves with beta, but …..**
  MHD instabilities often limit performance at high beta.
  - Ideal Kink/Ballooning Modes (limits are well understood)
  - Tearing Modes (including Neoclassical)
  - Resistive Wall Modes

  A possible consequence of violating stability boundaries is a disruption

- **Opportunity: Configuration innovation extends stability boundaries**
  - 2D and 3D discharge shaping, helical coils
    (2-D): C-MOD, DIII-D, NSTX, MAST, … (3D): NCSX
  - Profile modifications at low aspect ratio MAST, NSTX, Pegasus
  - Suppression of instabilities by negative magnetic shear LHD, NCSX, Reversed-Shear Tokamaks
  - Flowing liquid lithium wall New concept, needs further evaluation

Improving plasma stability - Opportunities

- **Avoidance of instabilities:**
  - Optimization of pressure and current profiles Many Devices
  - Active feedback control of profiles (ASDEX-U, C-MOD, DIII-D, JET, JT-60U, MST)
  - Rotational stabilization
    Very high natural rotation (ST, Spheromak, FRC),or driven rotation (ET)
- **Active control of MHD modes**
  - Feedback stabilization by localized RF current drive
    ASDEX-U, COMPASS-D (now); DIII-D (2000)
  - Feedback stabilization by external coils DIII-D, HBT-EP (1999-2003); need concept exploration for RFP.
- **Disruption Mitigation**
  - neutral point operation (JT-60U), solid or gas injection (C-MOD, JT-60U, ASDEX, DIII-D); liquid jet

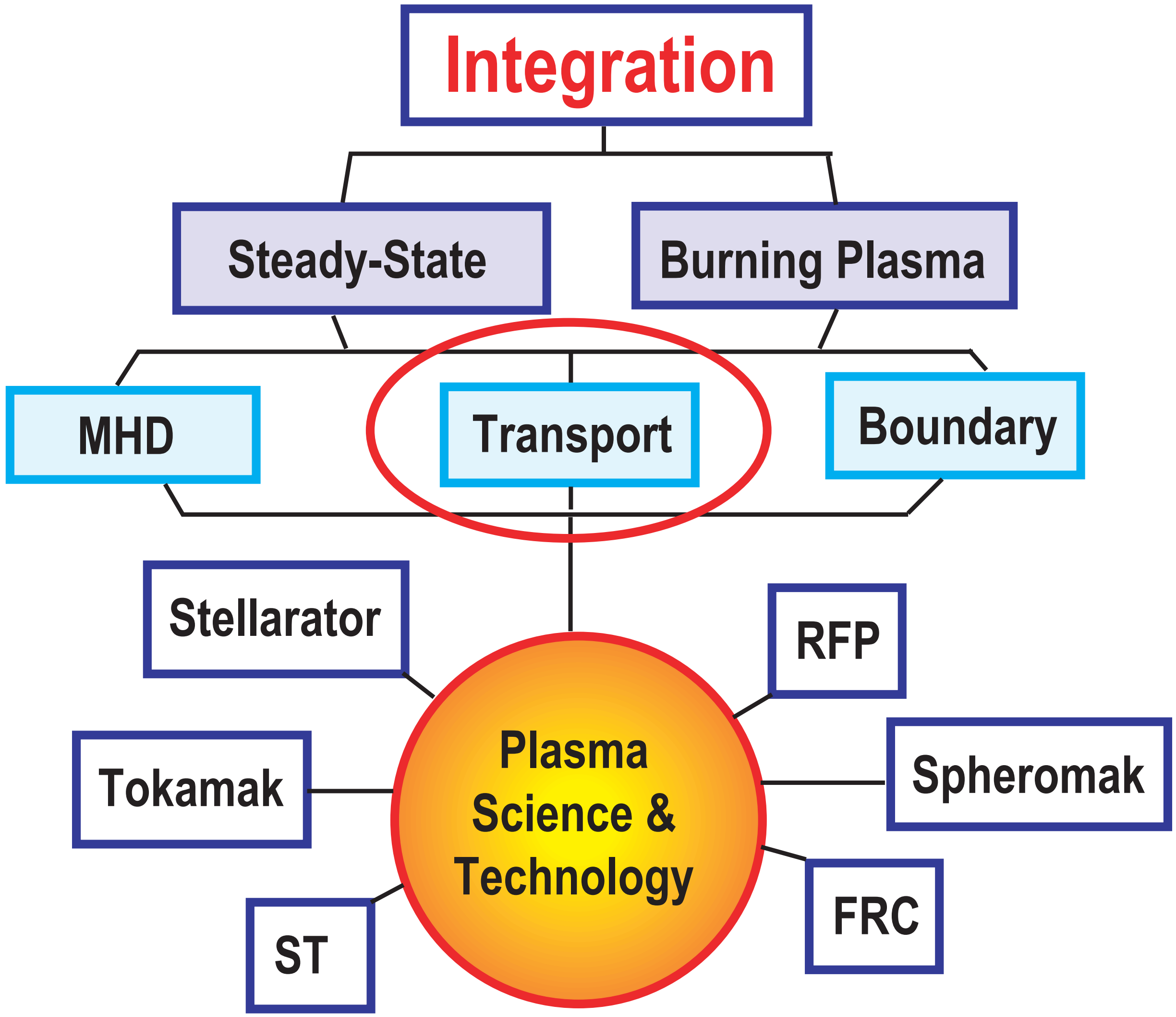
Beyond Standard MHD

- **Critical issue: Ideal and resistive MHD has had much quantitative success, but ... Standard ideal and resistive MHD is not sufficient to describe some magnetic configurations and observed phenomena.**
- **Opportunity: Develop and apply analytic theory and predictive codes with:**
  - Flow, flow shear (equilibrium, relaxation, stability: RWM, ...)
  - Neoclassical effects (resistive stability: NTM, ...)
  - 2-fluid physics (equilibrium and stability)
  - Finite Larmor radius (ideal and resistive stability)
  - Kinetic effects (energetic particle instabilities: TAE, ...)
  - 3D magnetic field structure (islands, stochasticity)

➽ **Linear and nonlinear, 2-D and 3-D analytic theory and fluid-based codes are an opportunity to include these additional physics effects for all configurations.**

➽ **Need to support both analytic theory and large scale code development, and encourage coupling of theory/ numerics/experiment.**

Transport in the MFE Roadmap



Transport Issues

1. Need for science based predictive capability for transport including density limits.
   - Empiricism useful but can only take us so far
   - Special requirements
     - Particle and impurity transport
     - Electron thermal transport
     - Neo-classical transport
     - Dynamics

Why is solving this essential?

- Confidence in design
  - Reduce uncertainty and costs for “next stage” for all concepts at any stage of development.
  - Ability to transfer physics experience between concepts
- Enable rapid innovation of new or improved concepts
- Turbulent transport as physics “grand challenge”

Transport Opportunities

Develop physics based predictive capability

- Improve experimental/theory/computation cooperation and comparison
- Key additional physics in turbulence simulations
  - Electromagnetics, electron, and impurity dynamics
  - General geometry
  - Flows
  - edge/core coupling
- Extend diagnostic coverage of turbulence (core and edge)
  - Measure key quantities $\tilde{n}, \tilde{\varphi}, \tilde{T}, \tilde{B}$ over a wide range of spatial scales
  - Employ new ways of measuring and analyzing turbulence (imaging, cross phase measurements, synthetic diagnostics from simulations, …)
  - Pursue innovation
- Marshal additional resources
  - Machine run time and port space
  - Turbulence and transport studies in new facilities (from basic plasma to burning plasma experiments)
  - Exploit next generation computing capabilities
  - Pursue interconcept studies

Need to Control Turbulence & Transport

This implies control of density, temperature, current and flow profiles

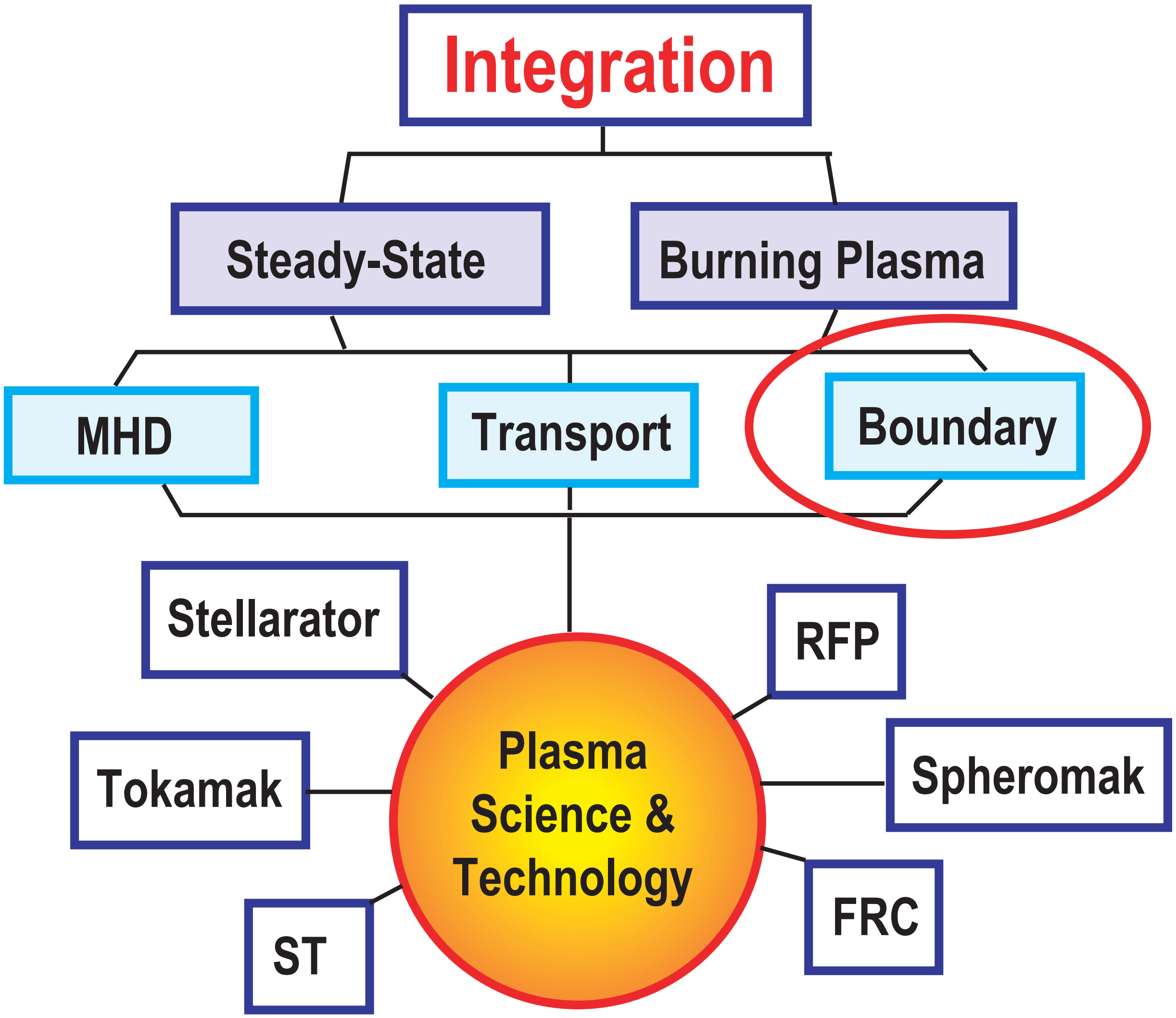
Why essential?

- Improve performance (eg. β, τ, , etc.)
- Control pressure and current profiles consistent with MHD stability
- Optimize profiles for bootstrap current – steady state (relax current drive requirements)
- Formation and dynamic control of bifurcations and transport barriers

Opportunities

- Deploy and test tools
  - Flow control, particularly RF drive
  - Current drive
  - Density control/fueling
  - Power deposition
- Profile diagnostics (eg V_θ)
- Demonstrate integrated high β, enhanced confinement, steady state operation
- Integrate theoretical modeling in control design

Boundary Plasma in the MFE Roadmap



Plasma Boundary: We have a solution for a conventional Tokamak

- **We have a reasonable scientific basis for a conventional long-pulse tokamak divertor solution at high density (collisional edge, detached)**
  - Low T_e recombining plasma leads to low heat and particle fluxes at wall
  - Adequate ash control, compatible with ELMing H-mode confinement
  - Appropriate for future tokamaks (e.g. to high density ITER-RC)
  - We have concerns about *simultaneously* handling disruptions/ELMs and tritium inventory which shorten divertor lifetime

- **The challenge is to find self-consistent operating modes for other configurations ...**

There are common boundary control ISSUES & OPPORTUNITIES that must be addressed to move MFE concepts forward

1. **Extend boundary control techniques to lower-collisionality plasmas and other magnetic geometries**

- Poloidal Divertor at low density for current drive (AT, ST, Spheromak)
- Non-axisymmetric magnetic geometries (Stellarator, RFP)
- Radiative Mantle (all)
- Kinetic effects, drifts (all); large mirror ratio (ST and LDX)

2. **Develop control of impurity sources & transport to maximize boundary radiation and core cleanliness**

- Flow control techniques, e.g. induced SOL ion flow, neutral flow valve (Tokamaks, ST)
- Better impurity source and transport characterization (all)
- Biasing, helicity injection, RF launchers (Tokamaks, ST, Spheromak, Mirrors)

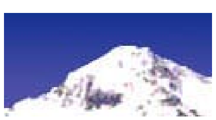
Boundary ISSUES & OPPORTUNITIES (cont)

3. Develop reactor-relevant materials (e.g. low T retention and radiation effects) compatible with clean core plasmas

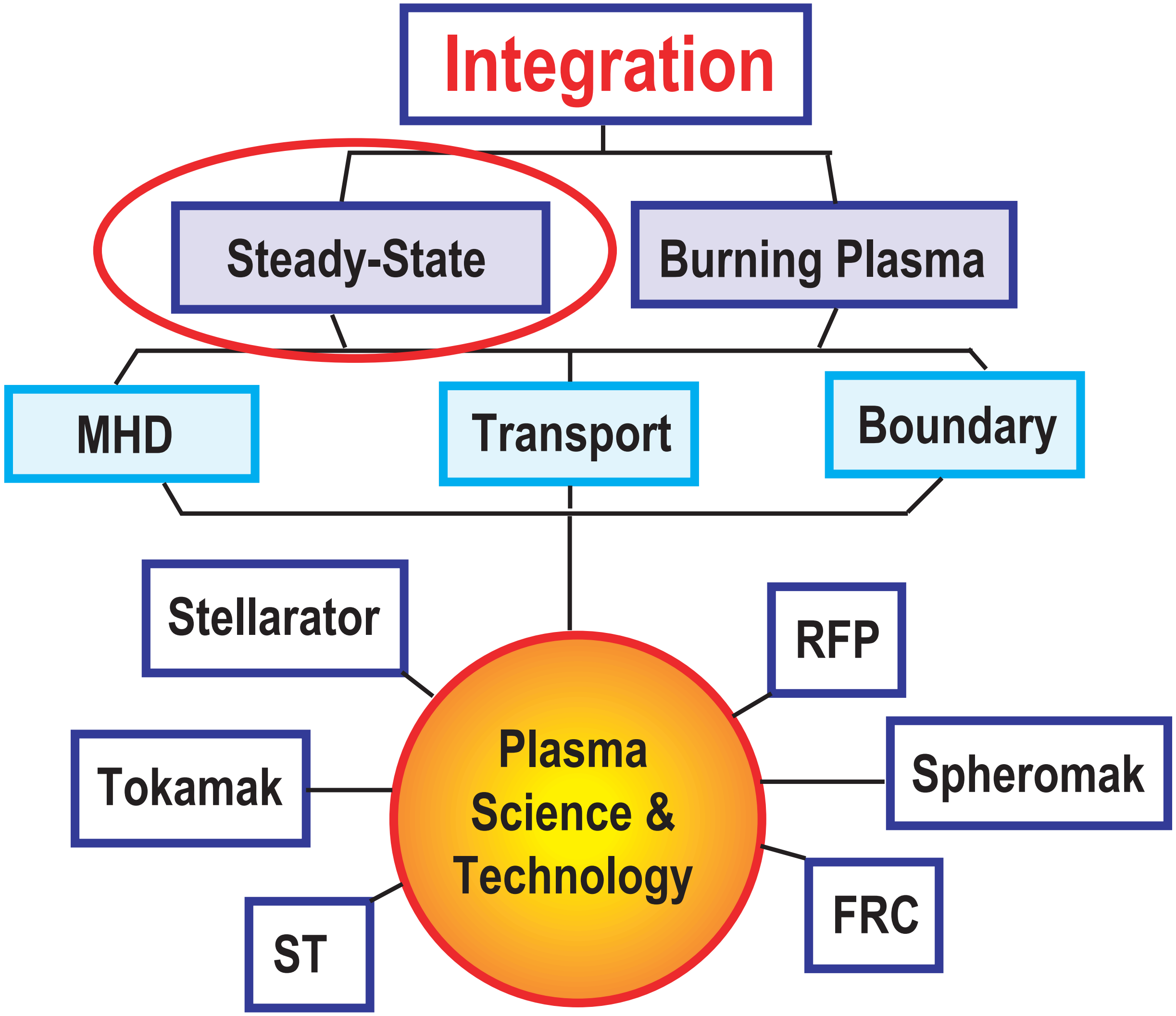
- Solid Low-Z, e.g. Be (JET, move away from graphite)
- Solid High-Z (Mo in C-Mod)
- Liquid Surfaces, e.g. Li, FLIBE, etc.(no MFE devices yet, Li Divertor CDX-U)
- Disruption mitigation, e.g. He puff, solid pellets (several)

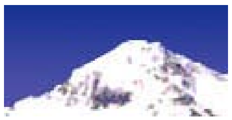
4. Develop physics understanding of core-edge coupling

- Diagnosis and modeling of transport in presence of open field lines, particularly J, n_o, and flow in edge (RFP, Tokamaks, Stellarator, ST)
- Deep core fueling, wall conditioning, materials effect on core (particularly important in emerging concepts and steady-state devices)
- Control heat and particle flux transients, e.g. ELMs (all)



Steady State Issues in the MFE Roadmap





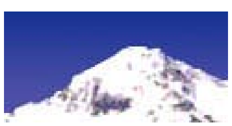
Achieving Steady State MFE Plasmas

Two Key Issues (currently limiting progress toward Steady State MFE):

- **Plasma Control**
  to achieve and sustain a high-performance plasma configuration.

- **Power and Particle Handling**
  compatible with a high-performance plasma configuration.

- These issues are serious-- **complementary approaches are needed for a successful resolution**



Key Plasma Control Opportunities

Current profile control to prevent profile evolution to unstable configuration.

- **Near term- complementary approaches:**
  - **NBI+ EC+bootstrap in AT (DIII-D, next 3 years).**
  - **ICRF+LH+bootstrap in AT (C-Mod, 2002-08)**
- **Longer term: NSTX (2001+), KSTAR (2004+), etc.**

Helical fields and 3D shaping for disruption suppression.

- **Stellarator PoP program (proposed). Complementary approaches:**
  - **High-bootstrap AT-like approach: NCSX QA, high β PoP experiment.**
  - **Low- bootstrap approach (CE-level test): QOS experiment.**

MHD mode control for steady-state, high-beta scenarios.

- **Control NTM with EC, RWM with feedback coils in AT. (DIII–D, next 3 yrs)**
- **Test No-wall $\Rightarrow$ Wall performance gains in ST (NSTX)**
- **Stabilize kinks with resistive shell in RFP. (CE devices)**

Key Plasma Control Opportunities, cont'd.

Current drive for startup and sustainment

- CHI+HHFW+NBI+bootstrap in ST (NSTX next 3-4 years).
- CHI in Spheromak (SSPX, next 3 years)
- OFCD in RFP (theory opportunity now; test in MST, next ~5 years)
- Rotating fields in FRC (U. Wash).

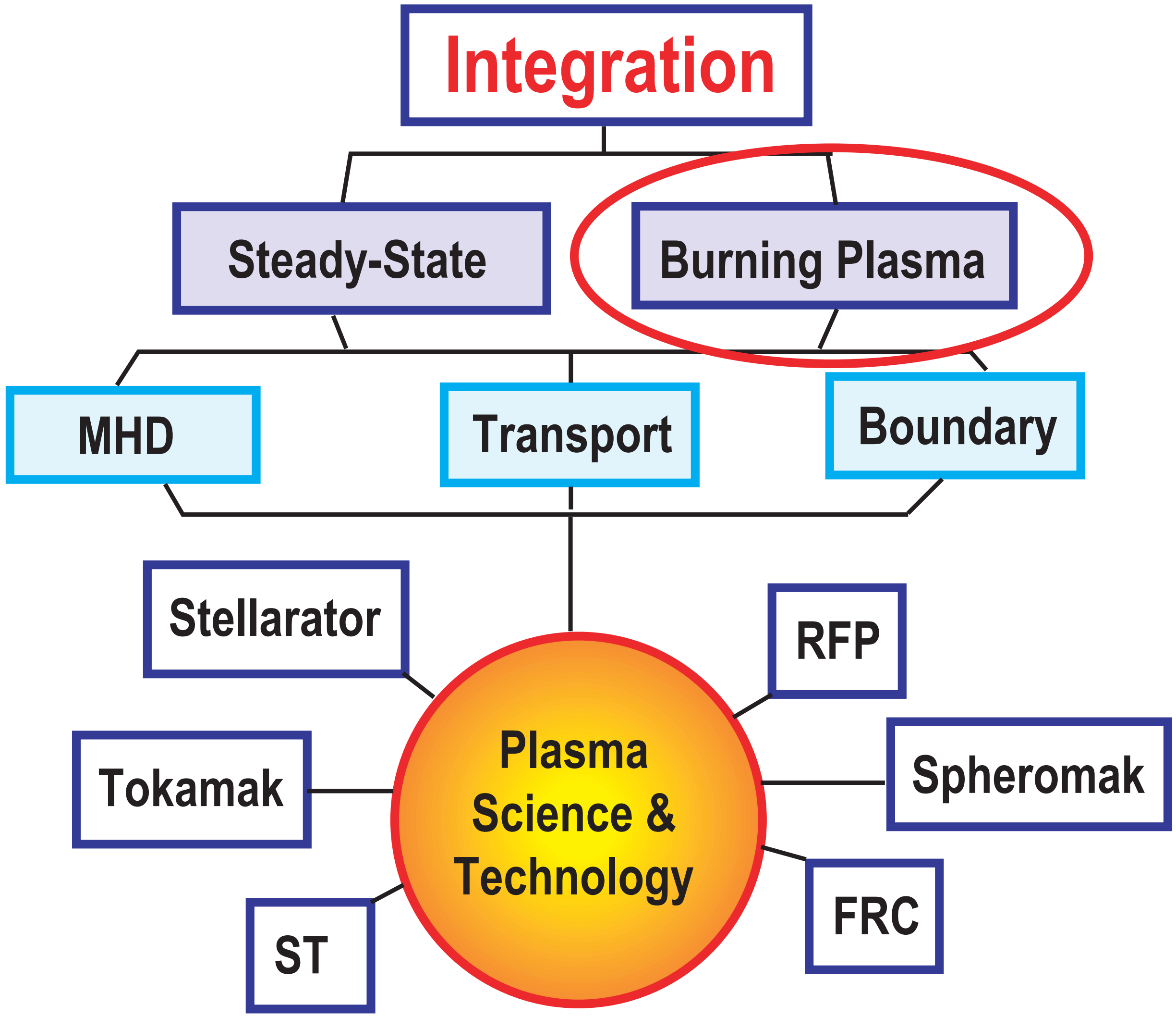
Local turbulence and transport control

$\Rightarrow$ control pressure, bootstrap profiles; stability margins

- RF-driven flow shear most likely tool, e.g. MC-IBW in C-Mod (now).

More ideas exist; scientific and technological innovations are urgently needed

Burning Plasma in the MFE Roadmap



Why a Burning Plasma?

- The excitement of a magnetically-confined burning plasma experiment stems from the prospect of investigating and integrating frontier physics in the areas of energetic particles, transport, stability, and plasma control, in a relevant fusion energy regime. This is fundamental to the development of fusion energy.

- Scientific understanding from a burning plasma experiment will benefit related confinement concepts, and technologies developed for and tested in such a facility will benefit nearly all approaches to magnetic fusion energy.

Frontier Physics to Investigate and Integrate in a Self-Heated Plasma

- **Energetic Particles**
  - Collective alpha-driven instabilities and associated alpha transport.
- **Transport**
  - Transport physics at dimensionless parameters relevant to a reactor regime $(L/r_i)^*$: scaling of microtubulence, effects on transport barriers…
- **Stability**
  - Non-ideal MHD effects at high L/r_i: resistive tearing modes, resistive wall modes, particle kinetic effects…
- **Plasma Control**
  - Wide range of time-scales: feedback control, burn dynamics, current profile evolution
- **Boundary Physics**
  - Power and particle handling, coupling to core

$^*L/r_i$ is the system size divided by the Larmor radius.

Scientific Transferability

A well-diagnosed, flexible burning plasma experiment will address a broad range of scientific issues and enable development and validation of theoretical understanding applicable in varying degrees to other magnetic concepts

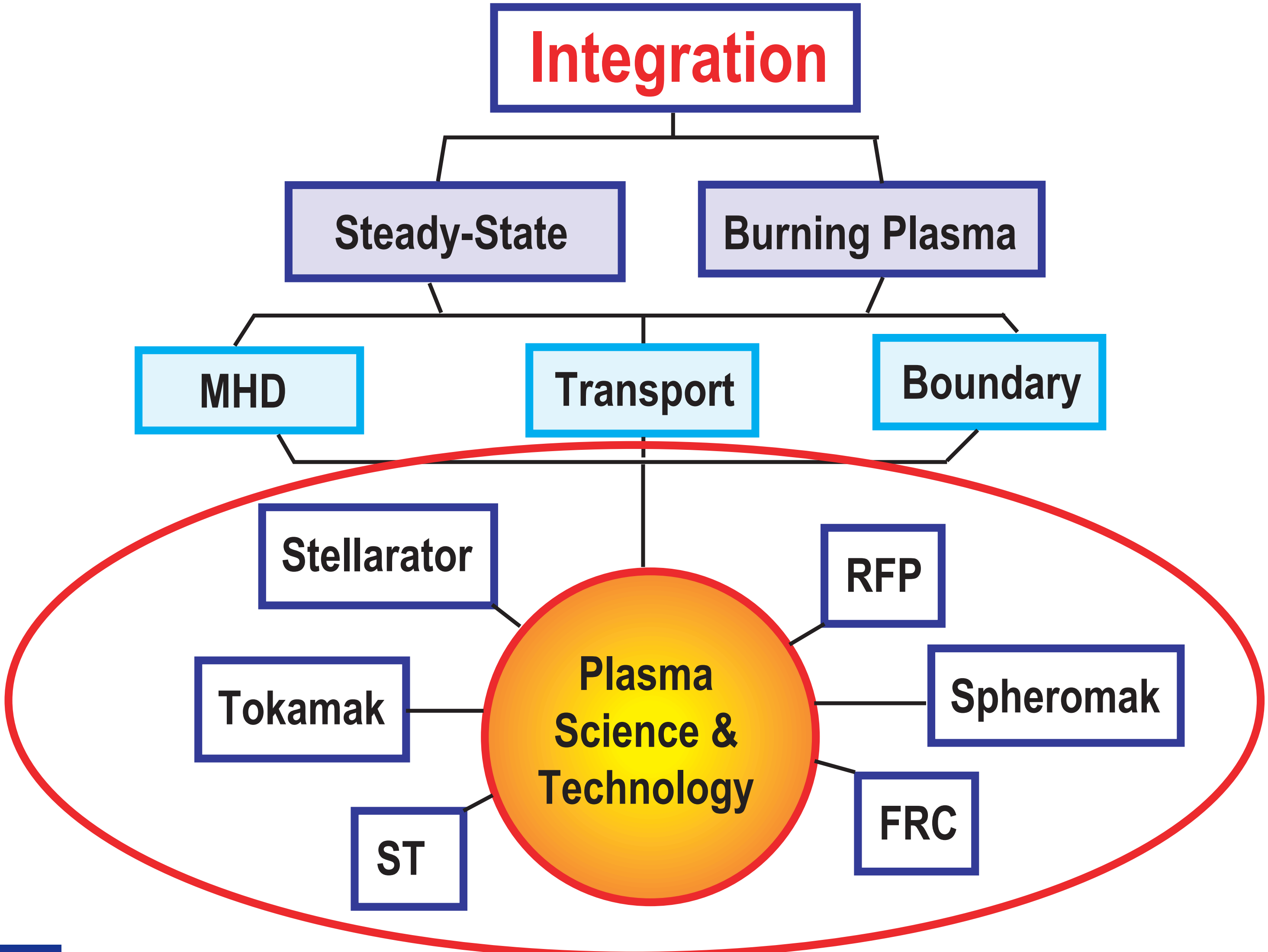
- Energetic particle density gradient driven instabilities
- Transport and burn control techniques
- Boundary Physics, power and particle handling issues

Burning Plasma Opportunities

- The tokamak is technically ready for a high gain burning plasma experiment

- The US has exciting opportunities to explore BP physics by:
  - Pursuing burning plasma physics through collaboration on potential international facilities (JET Upgrade, IGNITOR and ITER-RC)
  - By seeking a partnership position, if the ITER construction proceeds
  - Continued design/studies of moderate cost burning plasma experiments (e.g., FIRE) capable of exploring advanced regimes
  - Exploiting the capability of existing and upgraded tokamaks to explore and develop advanced operating regimes suitable for burning plasma experiments.

Magnetic concepts in the MFE Roadmap



The Magnetic Concept Portfolio

High B_T, q>1 Concepts (development status)

- Conventional tokamak (PE)
- Advanced tokamak (PE)
- Electric Tokamak (CE)
- Stellarator (PE)
- Compact stellarator (PoP proposed)
- Spherical Torus (PoP)

FED	Fusion Energy Development
PE	Performance Extension
PoP	Proof of Principle
CE	Concept Exploration

Challenge: Optimize stable, steady-state, high-performance plasma using 2D and 3D shaping, MHD stability control, and profile control.

Low B_T, q<1 Concepts

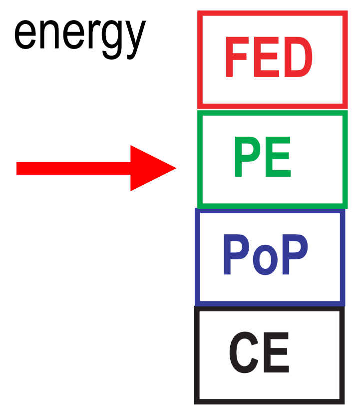
- Reversed Field Pinch (CE; PoP proposed)
- Spheromak (CE)
- Field-Reversed Configuration (CE)

Challenge: Demonstrate adequate confinement for fusion energy and explore techniques to improve confinement and extend pulse duration.

Conventional Pulsed Tokamak (presently at PE)

- **<u>Prospective Fusion Energy Benefits</u>**
  - Provides testbed for developing technology and generic fusion energy science
  - Demonstrated stability and confinement
  - Mature experimental database, performance nearest goal of fusion energy

- **<u>Issues</u>**
  - Must avoid and mitigate disruptions and ELMS at operating β to reduce forces and heat load
  - Large size and cost
  - Pulsed operation: cyclic heat and stress loads, requires energy storage



Advanced Tokamak (AT) (presently at PE)

- **Prospective Fusion Energy Benefits**
  - Steady state via high bootstrap current fraction
    $\Rightarrow$ reduced cyclic stress
  - High performance at lower I_P
    $\Rightarrow$ reduced capital costs, reduced disruption loads
  - Builds on extensive tokamak database & understanding

- **Issues**
  - Need to develop profile control & feedback stabilization to sustain equilibrium, stabilize MHD modes
  - Must avoid/mitigate disruptions and ELMs at high β
  - Compatibility with edge particle and power handling strategies

FED

PE

PoP

CE

Spherical Torus (ST) (presently at PoP)

- **Prospective Fusion Energy Benefits**
  - Reduced B, high β $\Rightarrow$ reduced capital costs, simpler maintenance
  - Steady state via high bootstrap current fraction
  - Predicted intrinsic turbulence stabilization
  - May provide near-term neutron source
- **Issues**
  - Need to develop non-inductive current ramp-up & sustainment
  - Center column resistive losses & radiation effects
  - Need to develop profile control & feedback stabilization to sustain equilibrium, stabilize wall modes
  - High divertor heat loads
  - Must avoid/mitigate disruptions

FED

PE

PoP

CE

Compact Stellarator (CS) (proposed for PoP)

- **Prospective Fusion Energy Benefits**
  - MHD stability, improved disruption stability and very low disruption loads, very low recirculating power by 3D magnetic field shaping
  - Reduced development costs by combining stellarator & tokamak characteristics & advantages at aspect ratio ~ 3 - 4

- **Issues**
  - Demonstrate β-limit, low disruption loads & adequate confinement at low aspect ratio
  - Compatibility with power and particle handling scheme
  - Non-planar, more costly coils. Adequate coil-plasma spacing for reactors

FED

PE

PoP

CE

Reversed Field Pinch (RFP) (proposed for PoP)

- **Prospective Fusion Energy Benefits**
  - Reduced capital costs due to low B on coils, high engineering β
  - Do not need superconducting coils

- **Issues**
  - Must reduce magnetic turbulence
  - Must develop method to efficiently sustain all the current (no significant bootstrap current)
  - Need to stabilize kink/resistive wall modes
  - Must develop reactor relevant power & particle handling

FED

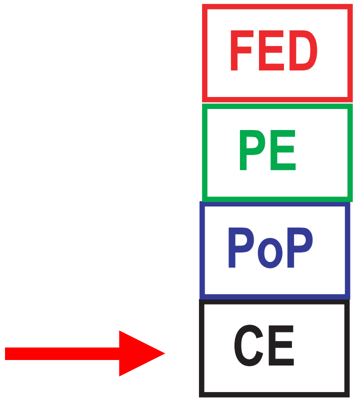
PE

PoP

CE

Spheromak (presently at CE)

- **Prospective Fusion Energy Benefits**
  - Very simple compact geometry
    $\Rightarrow$ reduced development capital costs
  - Possible sustainment by helicity injection
- **Issues**
  - Helicity injection may produce excessive magnetic turbulence
    $\Rightarrow$ plasma transport
  - Need to stabilize kink/resistive wall modes
  - Need to develop adequate power and particle handling, impurity control



MFE Provides a Path to an Optimized Energy Source

- The portfolio of magnetic configurations provides an opportunity to pursue a broad range of important scientific issues for Fusion Energy
- The development of physics understanding with predictive capability leads to rapid progress in the science base for Fusion energy and rapid progress in the individual magnetic configurations
- A burning plasma experiment offers the prospect of investigating and integrating frontier physics in the areas of energetic particles, transport, stability, and plasma control in a relevant fusion energy regime.
- Scientific understanding and innovation are key features of the magnetic fusion energy program. Together these are leading to attractive configurations for the production of fusion energy.