Comments on Innovative Confinement Concepts
and
Burning Plasma Science

E. B. Hooper

Lawrence Livermore National Laboratory

Workshop on Burning Plasma Science
Exploring the Fusion Science Frontier

Austin, Texas
December 11-13, 2000

Work performed under the auspices of
the U.S. DOE by the U. of California LLNL
under contract No. W-7405-Eng-48

Fusion/Plasma Science Concepts

- **A wide variety of concepts contribute to fusion/plasma science and are potential fusion energy sources**

Toroidal Magnetic Configurations

Stellarator
Compact Stellarator
Tokamak
Advanced Tokamak
Spherical Torus

RFP
Spheromak
FRC
  Ion Ring FRC

Levitated Dipole

Open Magnetic Configurations

Tandem Mirror
Gas Dynamic Trap

Centrifugally Confined Plasma

Flow-Through Z-Pinch

High Density Pulsed

Inertial Fusion
  Laser Driven
  Heavy Ion Driven
  Fast Ignitor

Magnetized Target Fusion

Inertial Electrostatic Confinement

Penning Trap (magnetized)
Spherically Convergent Ion Flow
Periodically Oscillating Plasma Sphere

Other

Muon Catalysis
Cross-Section Enhanced

- **I will comment on the concepts in blue; black (italics) will not be discussed**
- **The viability of each concept will *not* be considered here — success will be assumed**

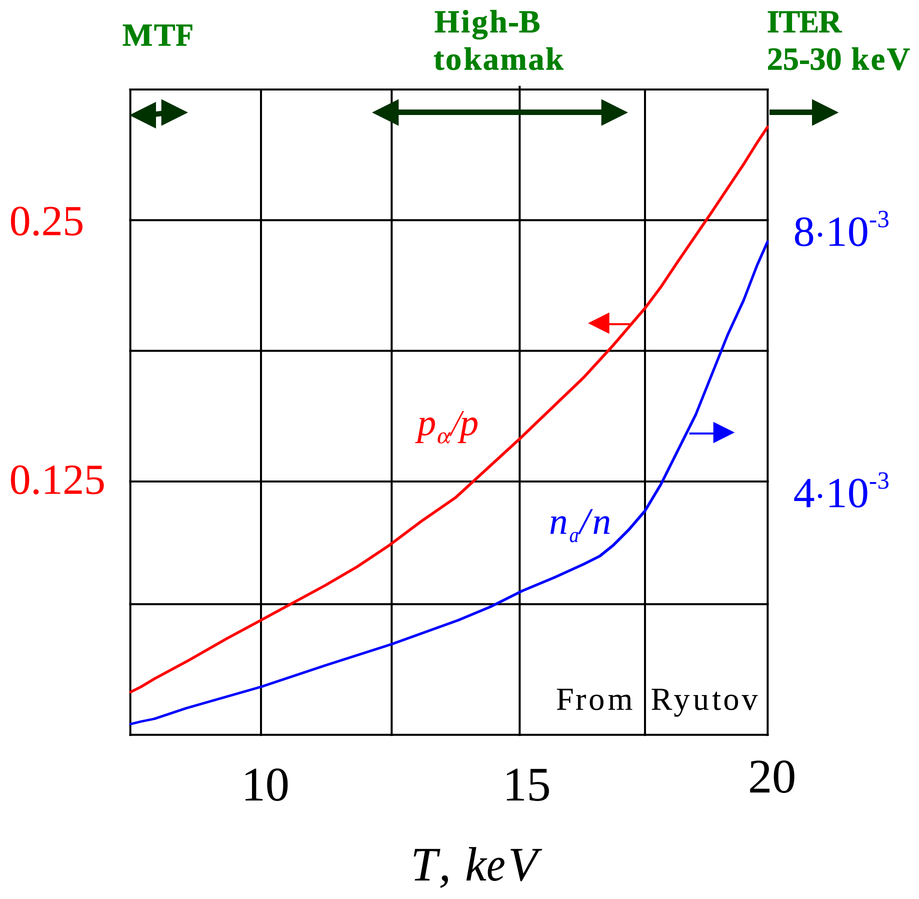
What is a burning plasma in each ICC?

CONCEPT		SELF HEATED?	CW OR PULSED?	COMMENTS
RFP	Self-Organized Plasmas (toroidal)	Y	CW	CW current drive mechanism needed
Spheromak		Y	CW/P	Pulsed plasma could translate to burn chamber
FRC		Y	CW/P	“Ideal” config ($\beta\sim1$) if physics allows. Pulsed plasma could translate to burn chamber
Ion Ring FRC		N?	CW	Ion ring stabilizes FRC, but low gain reactor
Levitated Dipole		Y	CW	Stable at high beta Probably aneutronic fuel
Tandem Mirror		Y	CW	Thermal ions: potentially confined. Alphas: mirror confined
Gas Dynamic Trap		Y	CW	Collisional plasma: $\lambda << L$ L large for good axial confinement

Centrifugally Confined Plasma	Y	CW	Supersonic rotation confines ions axially Alphas are mirror confined
Flow-Through Z-Pinch	N	P	$I_{pinch} > 1$ MA $L < v_{drift,\alpha}\tau_{s,\alpha}$ (energy lost axially)
Magnetized Target Fusion	N	P	Compression heats to burn temp.; alphas not needed for burn – $\tau_{s,\alpha} \sim \tau_{dwell} \approx \tau_{burn}$ Plasma may be FRC, spheromak, Z-pinch, etc.
Inertial Electrostatic Confinement	N	CW	Direct conversion recovers alpha energy

Magnitude of alpha effects — sensitivity to T_e

- **Balancing fusion generation of energetic alphas against drag on electrons — shows strong sensitivity of alpha pressure and density on temperature**



From Ryutov

- **Low electron-temperature concepts (MTF, mirrors) have normalized alpha pressures and densities more than an order of magnitude less than ITER**
- **Even in High-B tokamaks these ratios are several times less than in ITER**
- **As a result, the physics of the alphas may qualitatively differ in ITER, High-B tokamaks, and low T_e alternates**

Issue: Collective alpha-driven instabilities and associated alpha transport

RFP Spheromak	Instabilities may differ from tokamaks: $B_T \sim B_p$, $q<1$, small bananas, coupling to resistive MHD modes
FRC	$B_T = 0$ will affect instabilities
Levitated Dipole	Closed fieldlines with no rotational transform or shear will change mode characteristics from tokamak. Reactor designs for D-^{3}He have T_e=75 keV – thus likely high pressure of reaction products
Tandem Mirror	Alphas may couple strongly to Alfvén waves in axially-uniform central cell. Possible loss-cone mode; “bouncing” alphas may drive drift or ballooning instabilities
Gas Dynamic Trap	Collisional plasma may damp instabilities; low density of alphas weakens drive
Centrifugally Confined Plasma	
Flow-Through Z-Pinch	
Magnetized Target Fusion	Instabilities and transport of alphas less important than in tokamaks; in some configurations (e.g. MAGO) prompt alpha losses from drifts make instability transport moot
Inertial Electrostatic Confinement	Could degrade focus or reduce efficiency of direct conversion Any instabilities very different from those in magnetic confinement — Could broaden ion focus or degrade efficiency of direct recovery

Issue: Transport physics relevant to reactor

RFP Spheromak	Banana width small. Magnetic field fluctuations may generate alpha transport, e.g. due to random walk of banana turning point. Alphas may increase magnetic fluctuations and lower energy confinement of thermal plasma. Radial thermal barriers, if any, may differ from tokamaks
FRC	Possible current drive by selective loss of alphas
Levitated Dipole	Classical confinement possible; convective cells may transport particles Reaction products may affect pressure distribution, driving strong convection
Tandem Mirror	Axial confinement (central cell) likely more important than radial
Gas Dynamic Trap	Axial confinement may be more important than radial, but mirror ratio >> 1.
Centrifugally Confined Plasma	
Flow-Through Z-Pinch	Needs axial pressure equilibrium (e.g. with pressure in expansion tank); otherwise expansion at sound speed yields small $n\tau$. No closed drift surfaces for alphas
Magnetized Target Fusion	Convective cells or other mixing of high-A liner material may constrain performance
Inertial Electrostatic Confinement	N/A

Issue: Stability (Non-ideal MHD, resistivity, etc.)

RFP **Spheromak**	Alphas and heating profile in q<1 plasma may excite resistive kink, tearing, or interchange modes. High shear in RFP may be stabilizing. Alphas may effect j•B/B2 profile and thus stability
FRC	Alpha FLR effects may be stabilizing
Levitated Dipole	
Tandem Mirror	
Gas Dynamic Trap	Probably not an issue in collisional plasma
Centrifugally Confined Plasma	Stability to Rayleigh-Taylor and Kelvin-Helmholtz is crucial to CCP
Flow-Through Z-Pinch	Possible disruptive instabilities (e.g. sausage, kink) sensitive to velocity, pressure profiles
Magnetized Target Fusion	Probably not an issue
Inertial Electrostatic Confinement	Not applicable

Issue: Plasma Control

RFP **Spheromak**	Resistive wall mode control similar to tokamak; burn control probably similar. Control of $j \bullet B/B^2$ profile may be required. Dynamo may be affected by alphas and heating. Low bootstrap current. No disruptions?
FRC	Alpha pressure gradient drives confining diamagnetic current No disruptions
Levitated Dipole	No disruptions No parallel current drive
Tandem Mirror	Potential barrier height allows control of confinement No disruptions
Gas Dynamic Trap	No ash accumulation No disruptions
Centrifugally Confined Plasma	No disruptions Large recycling power required to maintain rotation
Flow-Through Z-Pinch	
Magnetized Target Fusion	No disruptions, but wall interactions could be a problem
Inertial Electrostatic Confinement	Driven system; control not a major issue No disruptions

Issue: Boundary Physics

RFP Spheromak	High edge currents and close-fitting wall may exacerbate plasma/wall interactions. Power and particle handling techniques not worked out
FRC	“Natural” divertor along external fieldlines
Levitated Dipole	Perhaps like a limited tokamak. Ring bombardment must be small
Tandem Mirror	Linear geometry minimizes boundary issues
Gas Dynamic Trap	Linear geometry minimizes boundary issues
Centrifugally Confined Plasma	Linear geometry minimizes boundary issues
Flow-Through Z-Pinch	Linear geometry minimizes boundary issues. Need for velocity shear may have consequences for boundary. End structures may be a limit (bombardment by fast alphas) unless axial pressure gradient controls losses.
Magnetized Target Fusion	Mixing of wall material with plasma is a critical issue, but alphas have little effect on it
Inertial Electrostatic Confinement	Wall interactions very different from toroidal-magnetized concepts

Summary of issues: Relevance of tokamak burning plasma experiment to ICCs

- Development of theory, technology, diagnostics will benefit all concepts
- Relevance of specific issues in the tokamak to each ICC is summarized:
  1 = Highly relevant, 2 = Somewhat relevant, 3 = Little relevance, blank = unexplored
- Ratings are subjective; quantitative analysis needed for many issues

ICC	Collective alpha instab.	Transport physics	Stability	Plasma control	Boundary physics
RFP	2	2	2	2	2
Spheromak	2	2	2	2	2
FRC	2	3	3	2	2
Levitated Dipole	3	2	3	2	2
Tandem Mirror	2	3	3	3	3
Gas Dynamic Trap	2	3	3	3	3
Centrifugally confined		3	3	3	3
Flow-through Pinch		3	3	3	3
Magnetized Target Fusion	3	3	3	3	3
Inertial Electrostatic Confinement	3	3	3	3	3

Further Comments

- ST burning plasma is likely more relevant to the spheromak and RFP than is a compact (advanced?) high-B tokamak
  - Plasma profiles more like spheromak (low aspect ratio)
  - Plasma currents generate appreciable toroidal field
  - High edge currents
  - Possibility of operation in q<1 regime

- At Snowmass we defined Emerging Concepts for the continuing exploration and expansion of alternate approaches to fusion energy. A healthy program will continue to explore ideas at the frontier while working on the more mature approaches.
  - Some ECs have little in common with the tokamak other than a dream of fusion energy . Electrostatic Confinement is perhaps the extreme example of this
  - As new ideas emerge, their relationship to knowledge developed by a Burning Plasma Experiment will need to be evaluated
  - We must not get trapped into the mindset of the early 90s: focus only on the lead concept. The fusion energy program must maintain a set of diverse, scientifically rich experiments to provide opportunities for minimum cost energy production.

- In the end we have to recognize that resources are at the heart of our discussions: What is the right balance for limited dollars and people to undertakings ranging from burning plasmas to emerging concepts?