Fusion Energy Science Opportunities in Emerging Concepts

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I. Introduction

The development of fusion energy represents one of the few long-term (multi-century time scale) options for providing the energy needs of modern (or postmodern) society. Progress to date, in parameters measuring the quality of confinement, for example, has been nothing short of stellar. While significant uncertainties in both physics and (particularly) technology remain, it is widely believed that a fusion reactor based on the tokamak could be developed within one or two decades. It is also widely held that such a reactor could not compete economically in the projected energy market. A more accurate statement of projected economic viability is that the uncertainty in achieving commercial success is sufficient that the large development costs required for such a program are not justified at this time.

While technical progress has been spectacular, schedule estimates for achieving particular milestones along the path of fusion research and development have proven notoriously inaccurate. This inaccuracy reflects two facts. Nature requires rather difficult conditions for practical fusion power production rates. The global market of the late 20th Century has driven the adjusted cost of all energy to record lows. These challenges persist for the near future, calling into question the reliability of future schedule projections. Nevertheless, it is clear that the development of fusion energy to commercial power production will require several additional decades of the new Century. As a realistic estimate, one may assume that an additional 50 years will elapse before the first significant application of fusion energy to stationary electrical power generation.

Dealing effectively with such a long development period presents an exceptional challenge in program planning and execution. Note that neither the time scale nor the complexity of fusion development are unique. Consider, for comparison, the development of heavier-than-air flight, which has a history from antiquity. On a more relevant scale, a full century elapsed between the first conceptually correct vision of a flying machine and the Wright Brother's demonstration of feasibility.[1] Human Nature consistently discounts the complexity of that which has been achieved, such as flight. A contemporary analog in which both complexity and time-scale are obviously comparable might be research into the causes and mitigation of cancer, which "began" early in this century and extends into the foreseeable future.[2]

Five decades into the coming Century is a very long time in terms of science and technology. One need only contrast today's technical world with that of 50 years ago, and add to the accounting the accelerating rate of advance in many technically supporting areas (*e.g.* computers) to obtain an idea of the range of possible futures. Given the unpredictability of the period over which fusion energy development will continue, it seems that an essential element of the present and near-future program should be a broad, phased investigation of alternative approaches. We have adopted the imperfect descriptor of "Emerging Concepts" for these investigations.

The need for an Emerging Concepts component arises from two sources. First, the best strategy for dealing with uncertainty is to provide a range of optional approaches at all times, so that those which can benefit most from changing technology or market factors may advance at the earliest time. Secondly, the only known effective means of dealing with long-term technical problems is to advance the science base supporting their solution (consider aerodynamics in the case of flight or molecular biology in the case of cancer research), and science advances most rapidly when it finds principles which apply across a large range of situations (or configurations).

II. Process and Scope

The Emerging Concepts Working Group (EC Group) of the Snowmass 1999 Fusion Summer Study considered technical challenges and opportunities related to Emerging Concept issues. This report summarizes the findings of the EC Group. There are four Subgroups of the EC Group, namely:

Table 1: Emerging Concepts Subgroups

Subgroup	Charter
Physics Issues	**Physics issues for Emerging Concepts**
Reactor Issues	**Long-term physics and technology vision for Emerging Concepts as fusion reactor systems**
Next Step Issues	**Next development steps for Emerging Concepts and metrics for these developments**
Technical Opportunities	**Opportunities for Emerging Concepts to contribute to an area outside of fusion or provide a breakout path toward fusion**

These Proceedings contain individual, detailed reports from each of these Subgroups. Our purpose here is to summarize some of the main conclusions and highlights of these findings.

Let us first define our scope. In recent years, the fusion program has laudably placed a great emphasis on innovation and begun an Innovative Confinement Concepts (ICC) program. We strongly endorse innovation at all levels of the program, but believe that in addition to large portions of the ICC program which are studying close variants of the tokamak (Spherical Torus and Compact Stellarator), the program needs a continuous, vigorous supply of genuinely alternative concepts. These are concepts which make a qualitative change in the geometry or plasma state from that found in a tokamak. Some examples of these qualitative changes are:

- Reduce or eliminate applied toroidal field B_T
- Reduce level and number of external controls
- Reduce energy for high-gain inertial fusion ignition or reduce auxiliary heating
- Utilize more favorable spherical or linear geometry
- Utilize high or ∞ β (plasma pressure relative to magnetic pressure), to allow for possible advanced fuel cycle
- Operate at intermediate density (between magnetic fusion and inertial fusion)

There are numerous examples of plasma confinement concepts which fit these general guidelines. Table 2 shows those that were examined in some detail by the EC Group. For each concept, the name, a reference citation, and a brief description are given. Also shown in Table 2 are recent innovations in either physics (theoretical of experimental) or

Table 2: New and exciting features of Emerging Concepts.

CONCEPT	DESCRIPTION	NEW FEATURE(S)
Reversed Field Pinch (RFP)[3]	**Low B_T, self-organized, moderate β, relative of tokamak**	**Five-fold increase in energy confinement by profile control**
Spheromak[4]	**Compact torus; no B_T**	**Operating modes to minimize turbulence, modern wall conditioning.**
Field Reversed Configuration (FRC)[5]	**Zero B_T everywhere; very high β; strong kinetic stabilization**	**Stability at R/ρ_i=4, evidence of self-organization, rotating magnetic field current drive.**
Ion Ring[6]	**Large ion orbit version of FRC**	**Potential stabilizing element for FRC.**
Magnetized Target Fusion (MTF)[7]	**Combines magnetic insulation with inertial compression by relatively massive, slow liner**	**Dramatic advance in liner technology. Variety of suitable plasma targets with sufficient confinement.**
Dipole[8]	**Levitated internal ring, poloidal B only**	**Simple magnetic field geometry. Theoretically shown to support high β with MHD and drift wave stability.**
Centrifugal[9]	**Mirror B geometry with large rotation driven by applied E**	**Theoretical simulation of stability with flow shear indicates strong potential well formation.**
Mirror/Gas Dynamic Trap[10]	**B mirror with electrostatic plugging in collisionless or collisional regime**	**Novosibirsk GDT indicates β =30%, classical behavior of sloshing ions and classical electrons at T_e=150 eV.**
Electrostatic[11]	**Ions confined and spherically focussed by large E**	**Pulsating electrostatic trap (POPS) eliminates ion collisional isotropization.**
Flow Pinch[12]	**Z-pinch stabilized by strong axial flow**	**Sheared flow stabilization.**
ast Ignitor[13]	**High density inertial pre compression followed by petawatt ignition pulse**	**Petawatt laser technology.**
Other[14]	**See notes and discussion**	

technology which have stimulated interest in each concept. Space does not allow a detailed description of each of these concepts. The interested reader who wishes to learn more details about any given concept should examine the cited references.

III. Physics Subgroup Summary

The range of physics contained in the study of the Emerging Concepts of Table 2 is enormous. In addition to concept-specific issues, the Physics Subgroup identified several cross-cutting physics issues. These are:

- The role of convective cells in particle and energy transport
- Kinetic effects on macroscopic stability
- Effects of sheared flow on macroscopic stability
- Physics of large or dominant electric fields in fusion plasmas
- Confinement physics at high or ultra-high β
- Role of helicity conservation in current drive and related self-organization phenomena

Development of the physics base required for cost-effective continuing tokamak development would be greatly facilitated by an improved understanding of any or all of these areas. As one of many examples which may be given, current numerical studies of micro-turbulence driven transport are adding electromagnetic and kinetic effects. These effects (along with sheared flow and self-organization) are known to be important in the much easier diagnosed macrostability of the FRC.

IV. Reactor Subgroup Summary

Emerging Concepts offer unique reactor features, which may lead to a qualitative improvement in cost and maintainability, with associated increased attractiveness to the customer. Table 3 shows some of these unique features grouped by concept:

Table 3: Reactor features of Emerging Concepts.

Concept	Motivation
RFP	Low external field; no disruptions
Spheromak, FRC	Simple geometry; small size; open axial divertor
MTF, Flow Pinch	Low development cost; compatible with liquid walls
Levitated Dipole, Centrifugally confined	High β, classical confinement; no current drive
Mirrors	Low physics risk; linear geometry
Electrostatic, IEC, POPS	Small unit size; low-cost development; high mass power density; alternate applications
Fast Ignitor	High gain; low recirculating power

Again, many examples of reactor advantages associated with Emerging Concepts could be given. As on such, there appears at first examination to be a greater accessibility for incorporating liquid walls into many such reactors. This follows from the linear, open geometry of several of the concepts, including FRC, MTF, Flow Pinch, and Mirrors.

V. Next Step Subgroup Summary

Each Emerging Concept that was reviewed stated its goals and requirements for a next step. There was also a considerable discussion of the program environment which would favor the appropriate and timely development of such concepts. The following are the major conclusions:

1) The existing levels of concept development should be modified to be more compatible with Emerging Concepts, which are currently all below the Performance Enhancement stage. Specific recommendations are summarized in Table 4. There should be quantitative metrics applied at each stage, as shown in the table. There should be an additional development level added below Concept Exploration; this is denoted Concept Development in the table. There should be no lower limit for budget, and while there should be no absolute upper limit, a budget greater than twice the guidance shown in the Table would require extraordinary justification.
2) Support of Emerging Concepts should continue as a matter of policy for the foreseeable future. Past efforts at down-selection have caused unnecessary delays in the development of many of Emerging Concepts, and such policy decisions are incompatible with the present, science-oriented program. The present level of support of around 5% is insufficient, and this figure should be increased substantially as appropriate technical opportunities arise.

VI. Technical Opportunities Subgroup Summary

Emerging Concepts present opportunities for a range of applications not so easily accessible for mainline concepts. This is because they are compact and have more flexible geometry. Table 5 shows some of the possible applications which may be addressed sequentially as fusion parameters advance. It is worth noting that at least one Emerging Concept, the gridded Inertial Electrostatic Confinement device, has already been commercialized.[15]

VII. Conclusions

Emerging Concepts enrich and strengthen the fusion program by providing diverse:

- Unique opportunities for fusion science physics and technology development
- Possibilities of much improved to breakthrough fusion products
- Great potential for non-energy applications of fusion science (already commercialized fusion source)

Emerging Concepts are required for healthy multi-decade fusion program to feed higher stages of development and support mainline research through transfer of plasma science. Emerging Concept research is justified in its own right by constant progress in fusion metrics ($nT\tau_E$, sustainment, mass power density, …) at reasonable cost.

Table 4: Program development phases appropriate to Emerging Concepts

	Qualitative Metrics (advancement requires a science-based prediction that the next-level metrics can be met)	**Target Quantitative Metrics for MFE***	**Target Budget ($M/yr)**
Concept Definition	• Defines a CE experiment that addresses uncertain issues of the concept • At a minimum, theory indicates that the CE experiment will be grossly stable • A fusion application is defined	$\tau > \tau_A$	0.3
Concept Exploration	• Obtains sufficient theoretical, computational, & experimental knowledge & understanding of the science to confidently describe the current CE experiment and predict the next PoP experiment • Gross stability is demonstrated • A competitive fusion reactor is supported by the physics & technology	T = 0.4 keV $n\tau = 10^{17}$ s/m^3	3.0
Proof of Principle	• Establishes most of the experimental & theoretical physics bases and validity for fusion application • Can confidently describe and predict the performance extension experiment • An improved fusion reactor is supported by the physics & technology	T = 2 keV $n\tau = 10^{19}$ s/m^3	15.0

Table 5: Non-electric-power applications of Emerging Concepts.

----------------------------- present applications ------------------------------
• Fusion neutron activation analysis, non-destructive testing and inspection • Plasma and technology, e.g, plasma thrusters, plasma processing, chemical waste processing • Scientific studies, e.g. solar and magnetosphere physics
----------------- near term applications under development----------------
• Neutron tomography • Medical isotopes & radiation therapy • Neutron source for driven fission reactors (improved safety), materials testing, nuclear waste transmutation
----------------------future applications under study-------------------------
• High- power fusion space propulsion units • Small electrical fusion power units with advanced fuels and direct conversion

Fusion needs a continuous, peer-reviewed, emerging concept program, supported as a matter of policy at some percentage of the national budget. Elements of this program should be:

- An incubator for fledgling, new ideas, encouraged by some combination of:
  + Summer institute
  + Scientific empowerment of all researchers to encourage broad and open study
  + Application of theoretical and computational resources
  + Involvement of academia and quality new students
- Periodic (annual), significant open competition for new starts and renewals
- Well-defined metrics and periodic peer reviews for ongoing Concept-Exploration projects
- Well-defined metrics and clear mechanism for "graduation" to the Proof-of-Principle level

References:

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14. Other concepts were discussed during our proceedings. These include: Tandem FRC/Ion ring reactor, J. Hammer; Pycnonuclear fusion -- S. Ichimaru; Propagating Burn Z-Pinch -- F. Winterberg; Linear/Toroidal confinement system -- A. Sen; Self-generated magnetic field system -- T. Dolan.
15. Information is available at http://www.fusionstar.de/.