Alternative Configurations

Simon Woodruff
Woodruff Scientific, Inc

Presented to the Science Undergraduate 2021 Introduction to Fusion Energy and Plasma Physics Course e Laboratory Internship (SULI)

Outline

1. Background
2. Fusion Taxonomy
3. Path to Market for Fusion
4. Fusion Costing
5. Fusion Enterprises
6. Discussion
7. Summary

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1. **Background**
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Background 2003 - 2007

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An Overview of Tokamak Alternatives in the US Fusion Program with the Aim of Fostering Concept Innovation

S. Woodruff[1]

The US fusion program has operated for just over 50 years, during which time the tokamak has emerged as the most promising vehicle for a burning plasma experiment. However, many other concepts have been built and investigated as alternatives (and possible improvements) to the tokamak, perhaps to make energy from fusion an economic reality sooner. This Paper is an overview of the conventional alternatives to the tokamak and a set of those that are not so conventional with the aim of fostering concept innovation. Usually the devices are grouped into magnetic, inertial, electrostatic, or other categories, with subcategories. Here, the groupings of conventional- and non-conventional-alternatives are used too. The conventional alternatives are those devices that have been adopted as serious alternatives, and for which many references are immediately available (e.g. rfp, mirror, stellarator, spheromak, laser ICF, etc). The non-conventional alternatives comprise approaches that are not being currently investigated or are worth consideration. In this grouping lie ideas like impact fusion, muon catalyzed fusion, and many historical ones (like the Elmo Bumpy Torus). Several examples of the physics of non-conventional alternatives are presented in summary form as examples of skunkworks in the hope that others will take up the challenge of concept innovation.

KEY WORDS: Fusion; history; alternates; tokamak; skunkwork; innovation; innovative confinement concepts.

INTRODUCTION

The talk on which this paper is based was presented at the 2004 Innovative Confinement Concept Workshop [1] and was motivated by a need to interest younger scientists in presenting novel ideas at the 'Skunkworks' session. The Skunkworks usually occurs towards the end of the conference, and is an opportunity to present concept innovations. For the last 3 years, only senior scientists were presenting, and it occurred that younger scientists were perhaps neither too familiar with the ideas that had gone before, nor perhaps were they too aware of methods of concept innovation. This paper is therefore written with the aim of bringing many of the previous concepts to light and in the hope that younger scientists will take up the challenge of concept innovation and contribute at ensuing skunkworks.

Previous concepts have been surveyed by a number of authors. Dolan's 1982 compilation is perhaps the most thorough, giving overview and detail of both magnetic and inertial approaches [2]. A recent book by Braams and Stott covers the history of most of the magnetic configurations in both the US and abroad [3]. Teller compiled descriptions of the main alternatives to the tokamak [4], Lindl reviewed the status of indirect laser IFE [5] in addition to which, there are several textbooks and papers that review the alternatives [6–9]. At the recent 2002 Snowmass meeting (and previous Snowmass meeting in 1999), a large number of alternatives were discussed and talks/papers were presented [10], and the progress in the so-called Innovative

[1] Department of Nuclear Engineering, Etcheverry Hall, UC Berkeley, Berkeley, CA 96701, USA.

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BRIEF COMMUNICATION

Path to Market for Compact Modular Fusion Power Cores

Simon Woodruff · Jennifer K. Baerny · Nathan Mattor · Don Stoulil · Ronald Miller · Theodore Marston

Abstract The benefits of an energy source whose reactants are plentiful and whose products are benign is hard to measure, but at no time in history has this energy source been more needed. Nuclear fusion continues to promise to be this energy source. However, the path to market for fusion systems is still regularly a matter for long-term (20 + year) plans. This white paper is intended to stimulate discussion of faster commercialization paths, distilling guidance from investors, utilities, and the wider energy research community (including from ARPA-E). There is great interest in a small modular fusion system that can be developed quickly and inexpensively. A simple model shows how compact modular fusion can produce a low cost development path by optimizing traditional systems that burn deuterium and tritium, operating not only at high magnetic field strength, but also by omitting some components that allow for the core to become more compact and easier to maintain. The dominant hurdles to the development of low cost, practical fusion systems are discussed, primarily in terms of the constraints placed on the cost of development stages in the private sector. The main finding presented here is that the bridge from DOE Office of Science to the energy market can come at the Proof of Principle development stage, providing the concept is sufficiently compact and inexpensive that its development allows for a normal technology commercialization path.

Keywords Commercial fusion systems · Compact fusion power cores · Spheromak · Compact torus · Deuterium-tritium fusion

S. Woodruff (✉) · J. K. Baerny · N. Mattor · D. Stoulil
Woodruff Scientific Inc., 4501 Shilshole Ave NW, Seattle, WA 98107, USA
e-mail: simon@woodruffscientific.com

J. K. Baerny
e-mail: jennifer@woodruffscientific.com

N. Mattor
e-mail: nathan@woodruffscientific.com

D. Stoulil
e-mail: don@woodruffscientific.com

R. Miller
Decysive Systems LLC, 813 Calle David, Santa Fe, NM 87506, USA
e-mail: rmiller@grappawireless.com

T. Marston
Marston Consulting, 1921 Waverley St., Palo Alto, CA 94301, USA
e-mail: ted.marston@gmail.com

Introduction

While the day of fusion systems designed for net power production is dawning, follow-on devices are being proposed that require large capital outlays which inhibits both their development and commercial deployment. The Department of Energy (DOE) Office of Science supports fundamental research which could potentially lead to the future deployment of commercial systems, and while this research is comprehensive, it is also primarily directed at the most developed and usually the largest systems. DOE Office of Science programs will therefore have an inherent time-line that is longer than industry typically tolerates, and a preference towards systems carrying the lowest scientific risk. Within the commercial sector, time-lines for demonstrating critical milestones are short and resources scarce, requiring a very different approach in the design of commercial systems.

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Summary of US Fusion Program Planning Documents Relating to Innovative Confinement Concepts (1992–2005)

S. Woodruff[1,2]

During the 1990's approximately 15 planning documents were produced by community consensus and by panels of experts. These documents lead to the restructuring of the Office of Fusion Energy (OFE). The OFE adopted joint goals of science and performance and opened a solicitation for Innovative Confinement Concept (ICC) experiments. This paper summarizes the documents that appeared during this time that relate to the ICCs.

KEY WORDS: Innovative Confinement Concepts (ICC); FESAC; OFES; OTA; PCAST.

INTRODUCTION

The role of fusion concepts that are proposed as alternatives (or significant modifications) to the tokamak has been quite consistent during the last 15 years. The main method for setting the course of the fusion program is for the director of the Office of Science to solicit advice from the Fusion Energy Sciences Advisory Committee (FESAC) and act on those findings. Sometimes, Congress sees fit to ask the Office of Technology Assessment (OTA) for advice on how it should set budgets. Somewhat less commonly, the President may ask an advisory committee to help define the direction, and so the Presidents Committee of Advisors on Science and Technology (PCAST) may meet (similarly, the Secretary of Energy Advisory Board (SEAB) can meet). The Office of Fusion Energy Sciences (OFES) may react directly to the conference reports produced by Congress and the Senate. Further, there may be community-wide activities that help define the consensus, such as the Snowmass meetings. This paper summarizes the main statements made in these planning documents relating to tokamak alternatives, finding a consistent approach.

Tokamak alternatives consist of a diverse set of devices [1], and are referred to variously as Alternates, or Innovative Confinement Concepts (ICCs), or Emerging Concepts (ECs). The terminology has evolved over the years too—Alternates are generally viewed as the widest set of concept that are not large aspect-ratio tokamaks, ICCs are generally promising concepts that are at a low level of development, with EC sometimes as a synonym for ICC. This paper is a summary of the planning documents in relation to both Alternates and ICCs within the US fusion program.

The text is structured as follows. Section 'History' outlines the history of the fusion program from the 1990's through to the present day. Section 'Present Day Context' contains a brief discussion of the present day context of ICC research. Section 'Summary' contains a summary of the main points.

HISTORY

During the period 1992–2005, 13 separate documents were produced that summarize the motivation and context for ICC research, found in Table 1. Prior to 1992, the magnetic fusion energy budget had been in decline (from a peak of ~$800M/year in 1983

[1] Department of Aeronautics and Astronautics, University of Washington, Seattle, WA, 98195, USA.
[2] To whom correspondence should be addressed. E-mail: woodruff@aa.washington.edu

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ORIGINAL PAPER

Technical Survey of Simply Connected Compact Tori (CTs): Spheromaks, FRCs and Compression Schemes

S. Woodruff

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Abstract A possible means for reducing core complexity and size could lie with research into simply connected compact tori. Much progress has been made in the last 20 years, and now tokamak-like confinement is being reported, with work focusing on understanding beta-limits, transport and novel means of generating magnetic fields both in sustained and pulsed scenarios. Compact torus research is maturing, with many experiments integrated into a national program to resolve well defined critical physics issues. This article summarizes the work from the last 20 years both as a historical overview and an outline of the present status.

Keywords Innovative confinement concepts · Technical survey

Introduction

In order to make fusion energy a viable economic alternative, significant improvements in concept design need to occur. Broadly, these improvements must reduce the cost of the presently envisaged reactor cores by simplifying the overall engineering, and by providing a more efficient means for accessing fusion conditions. Various panels of experts have met during the last 15 years to stress this point and to ensure that concept innovation remains a central component to the national program (for a summary see [1]). *Simply connected* means that there is no material linking the center of the device, making the first wall either a cylinder or a sphere. Omitting material from the center of the machine immediately reduces the cost of the core, and sometimes removes the need for remote handling. There are several magnetic concepts that fall into this category with varying degrees of maturity, they are the Spheromak, Field Reversed Configuration, Flow-Through Pinch, Mirror and Centrifugal Mirror. Further there are concept innovations in each area—it is possible to compress simply connected concepts too. Here we limit the scope of this technical survey to compact tori, and outline the Spheromak, FRC and means for their compression. In each section, the history and issues are discussed, and physics principles of each concept is given, finally, a summary of the reactor visions that have appeared in literature during the last 20 years is presented.

The first section of the 'Technical Survey' has appeared in the special edition of the Journal of Fusion Energy, summarizing the history of planning documents produced in the US fusion program over the last 15 years relating to concept innovation [1]. This article is the final section of the Innovative Confinement Concepts Roadmap, which became the 'Technical Survey' of ICCs, after the APS meeting in 2005 [2]. The scope of the work was reduced after community input to entail only simply-connected concepts. The work has been presented in various guises, for example, at the Global Climate and Energy Project meeting in Princeton [3] and at the Fusion Power Associates annual meeting on Capitol Hill, Washington DC [4].

This article is structured as follows. In the section titled 'Concept Development', the staged approach to fusion energy development in the US program is presented. Then in the section titled 'Simply Connected Compact Tori', all of the major devices are discussed, broken into subsections on 'Spheromaks', 'Field Reversed Configurations (FRCs)' and 'Adiabatic Compression'. There follows a brief

S. Woodruff (✉)
Woodruff Scientific, LLC, 301 Minor Avenue North #429, Seattle, WA 98109, USA
e-mail: simon@woodruffscientific.com

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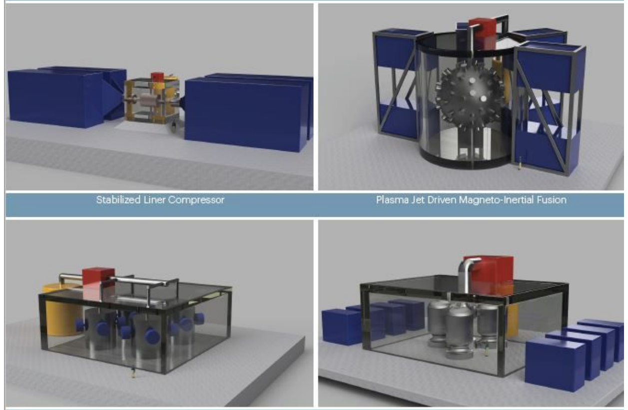

Conceptual Cost Study for a Fusion Power Plant Based on Four Technologies from the DOE ARPA-E ALPHA Program

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Woodruff Scientific, Inc.
Decysive Systems

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[1] Department of Nuclear Engineering, Etcheverry Hall, UC Berkeley, Berkeley, CA 96701, USA.

Historical review: how to make sense of it?

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Table 1. List of US fusion devices, type date and institution.

Concept Name	Acronym	Location	Type	Operate	Reference
Mirrors					
Table Top		LLNL	Classical mirror	1950s	[4,7]
Toy Top		LLNL	Classical mirror	1950s	[4,7]
Alice		LLNL		1960s	[3]
Baseball		LLNL	Min-B		[2,4]
Multiple Mirrors			Multiple	1977	[2]
Two 'X' Two 'B'	2XIIB	LLNL	Mirror		[2,4]
Tandem Mirror		UW	Tandem		[3,7]
Tandem Mirror Experiment	TMX, TMX-U	LLNL	Tandem	1979	1979 [2,7]
Rotating Mirror			Rotating	1980	[2]
Mirror Fusion Test Facility-B	MFTF-B	LLNL	Tandem Mirror	1983	[2,7]
	TARA	MIT	Tandem	1984	[3]
Phaadrus-B		Uwisc	Tandem	1987	[3]
Mabneto-Bernoulli Experiment		Utexas	Rotating	2003	[11]
Mirror Confinement Experiment	MCX	UMO	Rotating	1999· · ·>	[11]
Elmo Bumpy Torus					
Elmo Bumpy Torus	EBT	ORNL	Torodial geometry	Early 1980's	[2,3]
	EBS	ORNL	Linear geometry		[2]
Field Reversed Configurations					
	ASTRON	LLNL	Electron beam	1973	[2,3]
Relativistic Electron Coil Experiment	RECE	Cornel	Electron beam		[3]
	FRX-B	LANL	Frc	1979	[2]
	TRX, TRX-1,2	STI (Uwash)	Frc	1980–1986	[11]
Large S Experiment	LSX	(Uwash)	Frc	1986–1991	[11]
Large Sourece Modification	FRX-C/LSM	Lanl	Frc		[2]
	HBQM	Uwashington	Frc	∼1990	[3]
	CSS	Uwashington	Frc	∼1990	[3]
Translation Confinement and Sustainment	TCS	Uwashington	Frc	1999· · ·>	[8,11]
	Firex	Cornell	Frc		[11]
	FRX-L	LANL	Frc	2003· · ·>	[11]
	PHD	Uwashington	Frc	2004· · ·>	[11]
International Ring Devices and Cusps					
Octopole		San Diego	Octupole	1965	[3]
Quadrupole		San Diego	Quadrupole	1968	[3]
Quadrupole		ORNL	Quadrupole	1968	[3]
Spherator	Spherator	PPPL		1968	[3]
	SP-3	PPPL		1969	[3]
	LSP	PPPL		1970–1971	[3]
Superconducting levitron	SCL	LLNL	dipole	1971	[3]
	FM-1	PPPL	Multipole	1971–1976	[3]
Toroidal Magnetic Cusp	TORMAC		Toroidal Magnetic Cusp	1978	[2]
Levitated Octupole		UW	Octupole	1970's	[3]
Quadrupole		LANL			[3]
SurMAC	SURMAC	UCLA	Dodecapole	1981	
	CTX	Columbia		1999	[8]
Levitated Dipole Experiment	LDX	MIT	Dipole	1999· · ·>	[11]
Toroidal Pinches (and rfps)					
Perhapsatron S-4		LANL	teroidal pinch	1958	[3]
Gamma		LLNL	teroidal pinch	1958	[3]
(Scyllac Linear Experiment)	(SLX)	LANL			[3]
Scyllac full torus	SFT	LANL			
	Scyllac	LANL			
	ZT-1	LANL	rfp	1970–1974	[3]
	ZTH	LANL	rfp		
Z-Theta Pinch	ZT-40M	LANL	rfp	1981	[3]
Ohmically Heated Toroidal Experiment	OHTE	GA	rfp	1981–1988	[2,3]
Madison Symmetric Torus	MST	UW	rfp	1985· · ·>	[11]

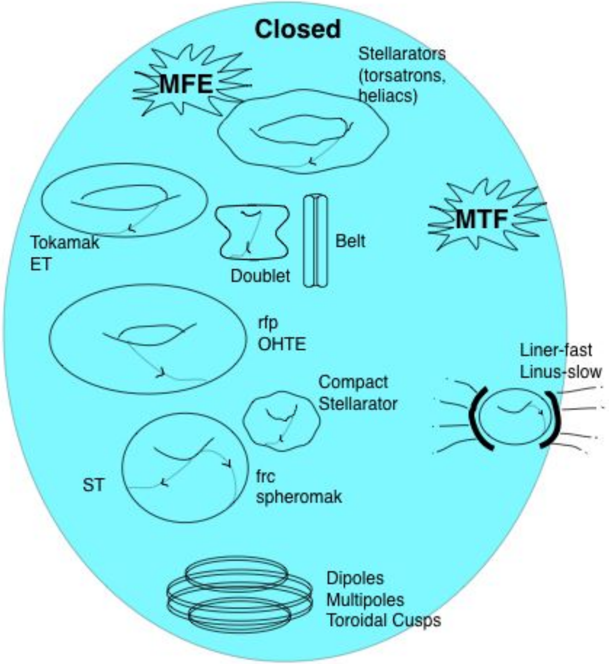
Table 1. *(Continued)*

Concept Name	Acronym	Location	Type	Operate	Reference
Tokamak variants					
Medusa		Uwisc	ST	mid 1990s	
Helicity Injected Torus	HIT and HITII	Uwash	ST	1994· · ·>	[11]
Electric tokamak	ET	UCLA	ET		[11]
National Spherical Torus Experiment	NSTX	PPPL	ST	1999· · ·>	[8,11]
Pegasus		Uwisc	ST	1999· · ·>	[11]
Stellarators					
Early Stellarators A · · ·> C		Princeton		1950s–1960s	[3]
Hybritron		LLNL		1960s?	
Proto-Cleo		UW	Classical	1970s	[2]
Interchangable Module Stellarator	IMS	UW	Modular	1978	[8,3]
Advanced Toroidal Facility	ATF	ORNL		1980s	[8]
Compact Auburn Torsation	CAT	Auburn	Torsatron	1990s	[8]
Helically Symmetric Experiment	HSX	UW	Stellar	1996· · ·>	[8]
National Compact Stellarator Experiment	NCSX	PPPL	Compact	2006?	[11]
Spheromaks					
Beta-II	Beta-II	LLNL	Coaxial Gun-driven	1980s	[8]
Compact Torus Experiment	CTX	LANL	Coaxial Gun-driven	1980s	[8]
Spheromak 1	S1	PPPL	Inductive	1980s	[8]
Proto-Spheromak	PS	UMO	Conical Theta-Pinch		[8]
Barkeley Compact Torus Experiment	BCTX	UCB	Coaxial Gun-driven	1990s	[8]
Swarthmore Spheromak Experiment	SSX	Swarthmore	Coaxial Gun-driven	1999· · ·>	[8]
Bellan Spheromak	Bellan	Caltech	Planar Gun-Driven	1999· · ·>	[8]
Sustained Spheromak Physics Experiment	SSPX	LLNL	Coaxial Gun-driven	1999· · ·>	[8]
Steady Inductive Helicity Injection expt.	SIHI	Uwashington	Inductive	2003· · ·>	[11]
Z-pinches and linear theta pinches					
Dense plasma focus				1965–1970	[2]
Fast Linear Pinch	FLP	LANL			
Scylla		LANL	Linear theta pinch		[3]
Imploding liners				1980	[2]
Hard-core pinches					[2]
LASL Fast Linear		LANL		1980	[2]
Flow-though Z-pinch	ZAP	Uwash	Z-pinch	1995· · ·>	[11]
Z	Z	SNL		1997	[11]
IEC					
Farnsworth Fusor				1950s	
Hirsch IEC				1967–1968	
(See NY Academy od Science report from 1975 for work in early 1970s)		Uillinois	IEC	1973	
		PennState	IEC	1974	
Various IEC devices		Uwisc	IEC	1990s	[11]
Various devices		Uillinois	IEC	1990s	[11]
Various Devices		Daimler	IEC	1990s· · ·>	[11]
Penning experiment – Ions	PFX-I	LANL	IEC	1994–2002	[11]
Periodically Oscillating Potential Sphere	POPS	LANL	IEC	2000· · ·>	[11]
Laser IFE					
Cyclops		LLNL		1976	[5]
Argus		LLNL		1978	[5]
Shiva		LLNL		1979	[5]
Nike		NRL			[5]
Novette		LBNL		1983	[5]
Nova		LBNL		1985	[5]
Omega		Rochester		1996	[5]
National Ignition Facility	NIF	LLNL		1997	[5]

Table 1. *(Continued)*

Concept Name	Acronym	Location	Type	Operate	Reference
Ion/Electron Accelerators					
Aurora		Harry Diamond		1972	[2]
Proto II		SNL		1977	[2]
Scaled Final Focus Experiment					[8]
Beam Combining Experiment				1996	[8]
Particle Beam Fusion Accelerator	PBFA	SNL		1980	[8]
Single Beam Linac Experiment		LBNL		1980–1986	[8]
Multiple Beam Experiment	MBE-4	LBNL		1985–1991	[8]
High Current Experiment	HCX	LBNL		2002	[8]
Channel Focussing experiments		LBNL		2004?	[8]
STS-500	STS-500	LLNL		2004?	[8]

Conceptual taxonomy of fusion approaches



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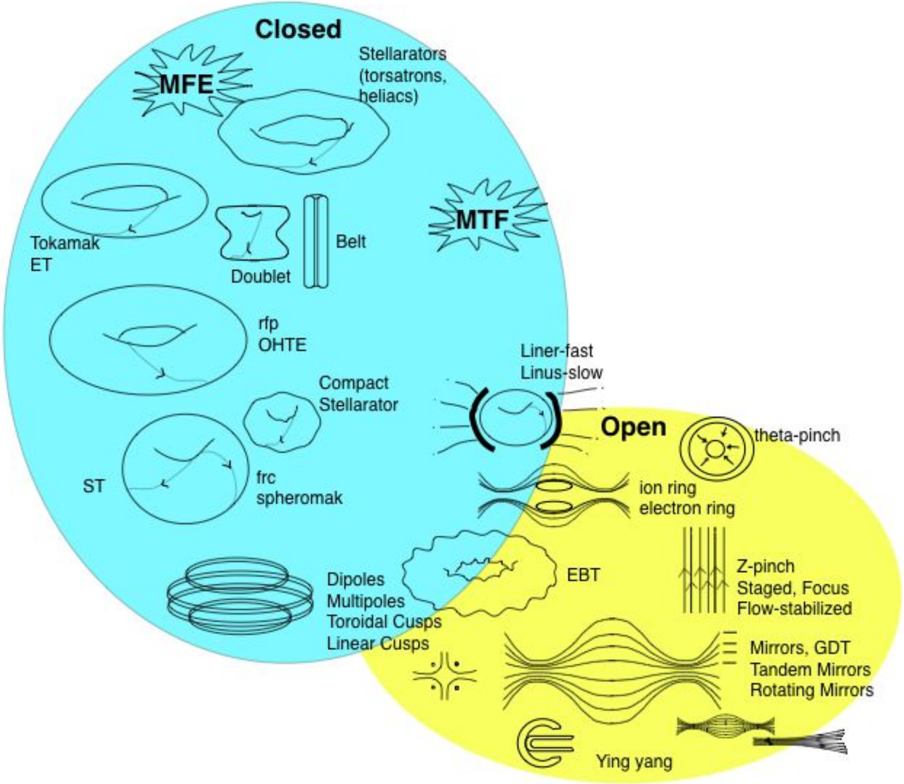

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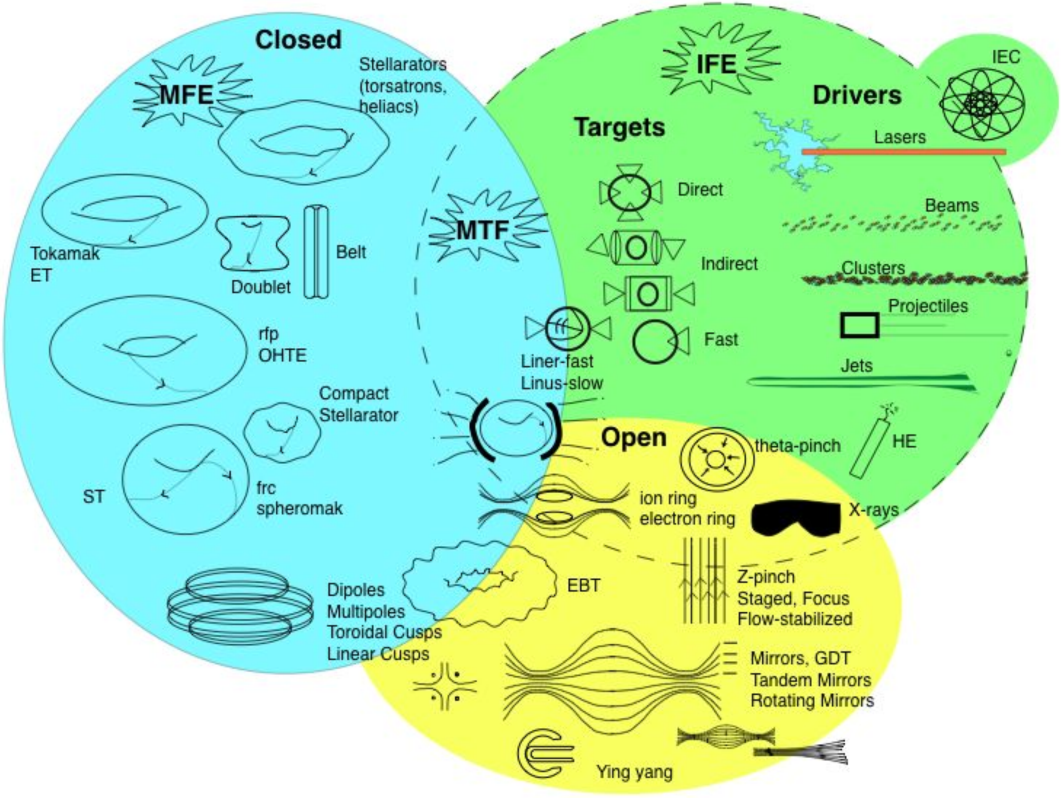

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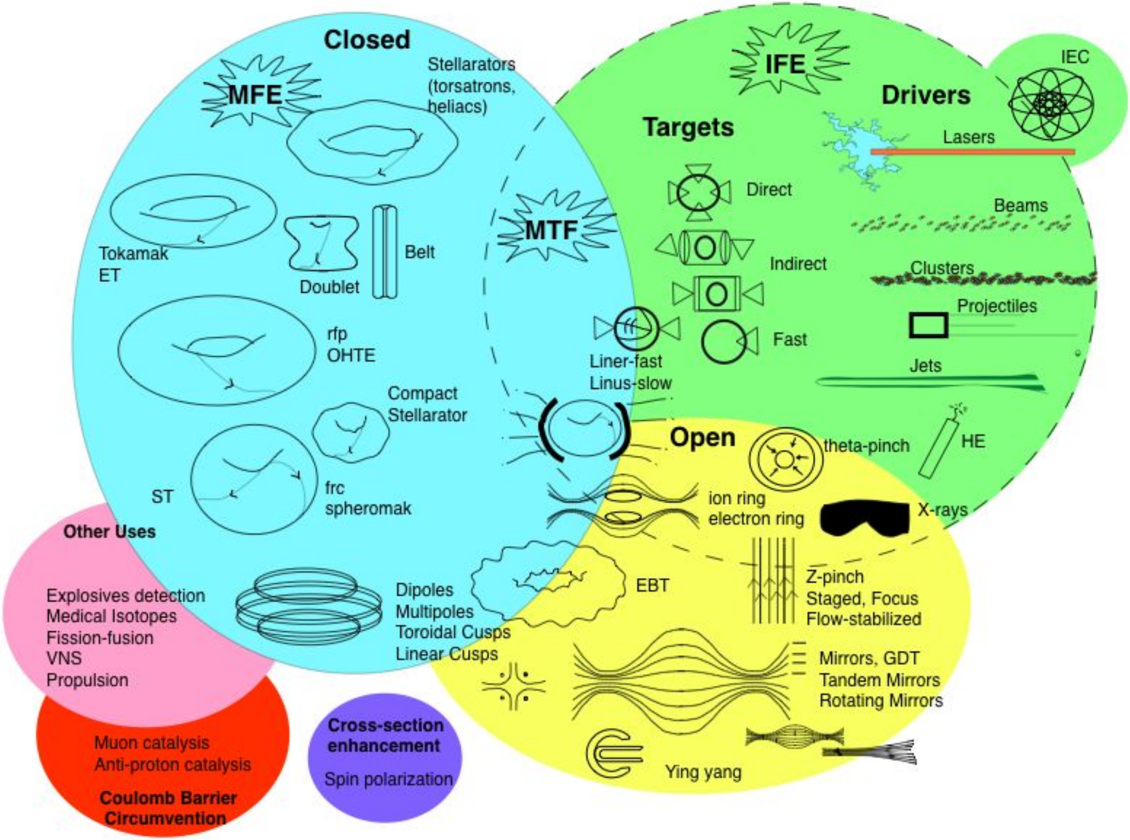

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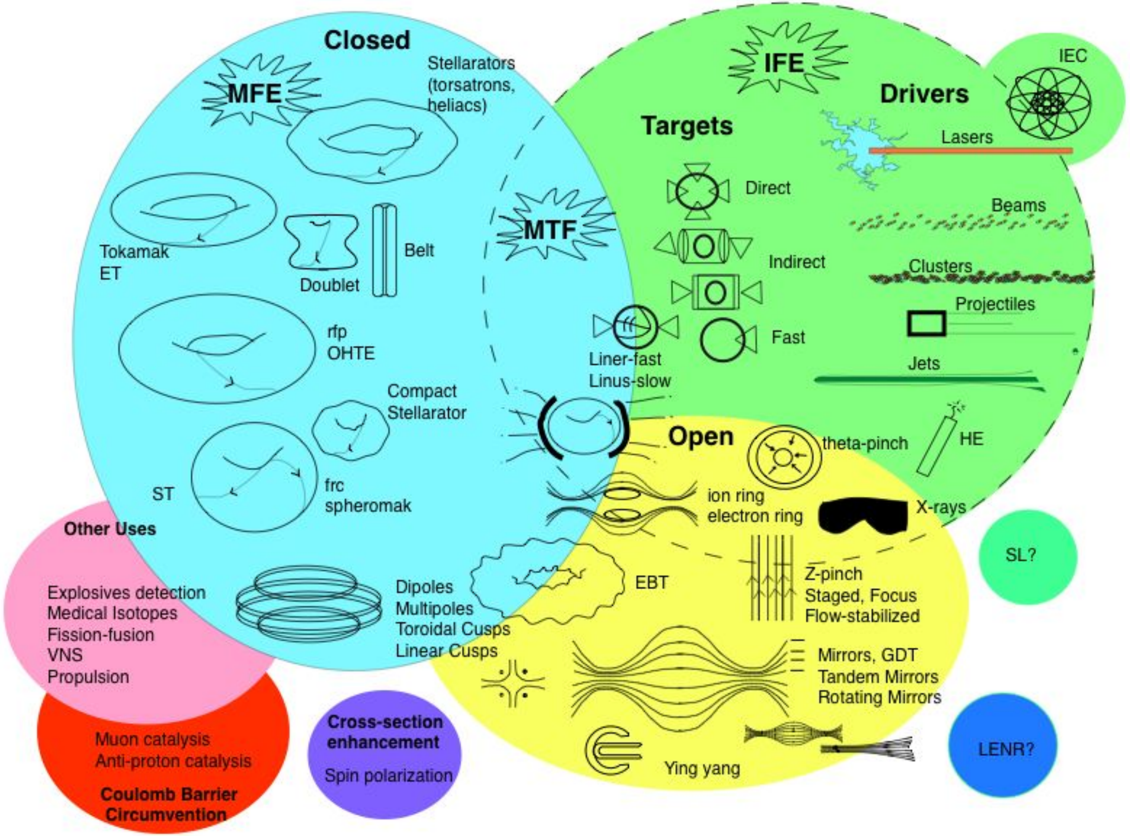

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S. Woodruff (✉) · J. K. Baerny · N. Mattor · D. Stoulil
Woodruff Scientific Inc., 4501 Shilshole Ave NW, Seattle, WA 98107, USA
e-mail: simon@woodruffscientific.com

J. K. Baerny
e-mail: jennifer@woodruffscientific.com

N. Mattor
e-mail: nathan@woodruffscientific.com

D. Stoulil
e-mail: don@woodruffscientific.com

R. Miller
Decysive Systems LLC, 813 Calle David, Santa Fe, NM 87506, USA
e-mail: rmiller@grappawireless.com

T. Marston
Marston Consulting, 1921 Waverley St., Palo Alto, CA 94301, USA
e-mail: ted.marston@gmail.com

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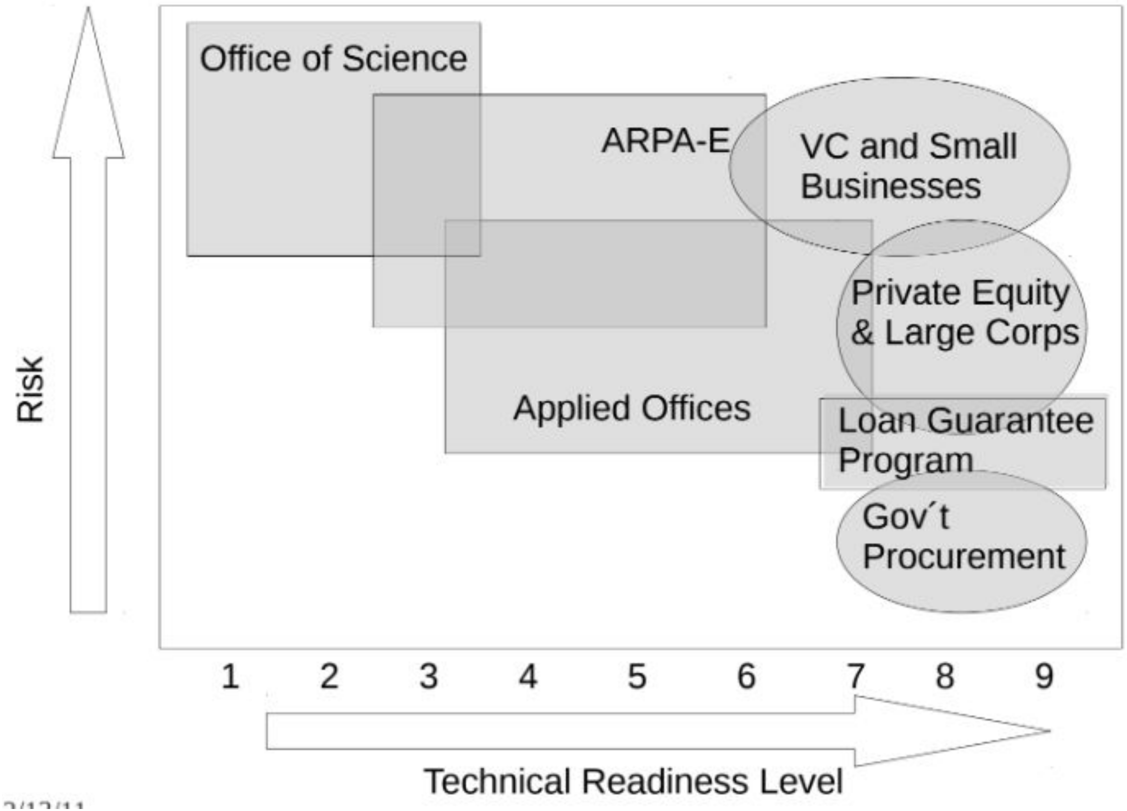
Why innovate? Path to market is constrained by available $



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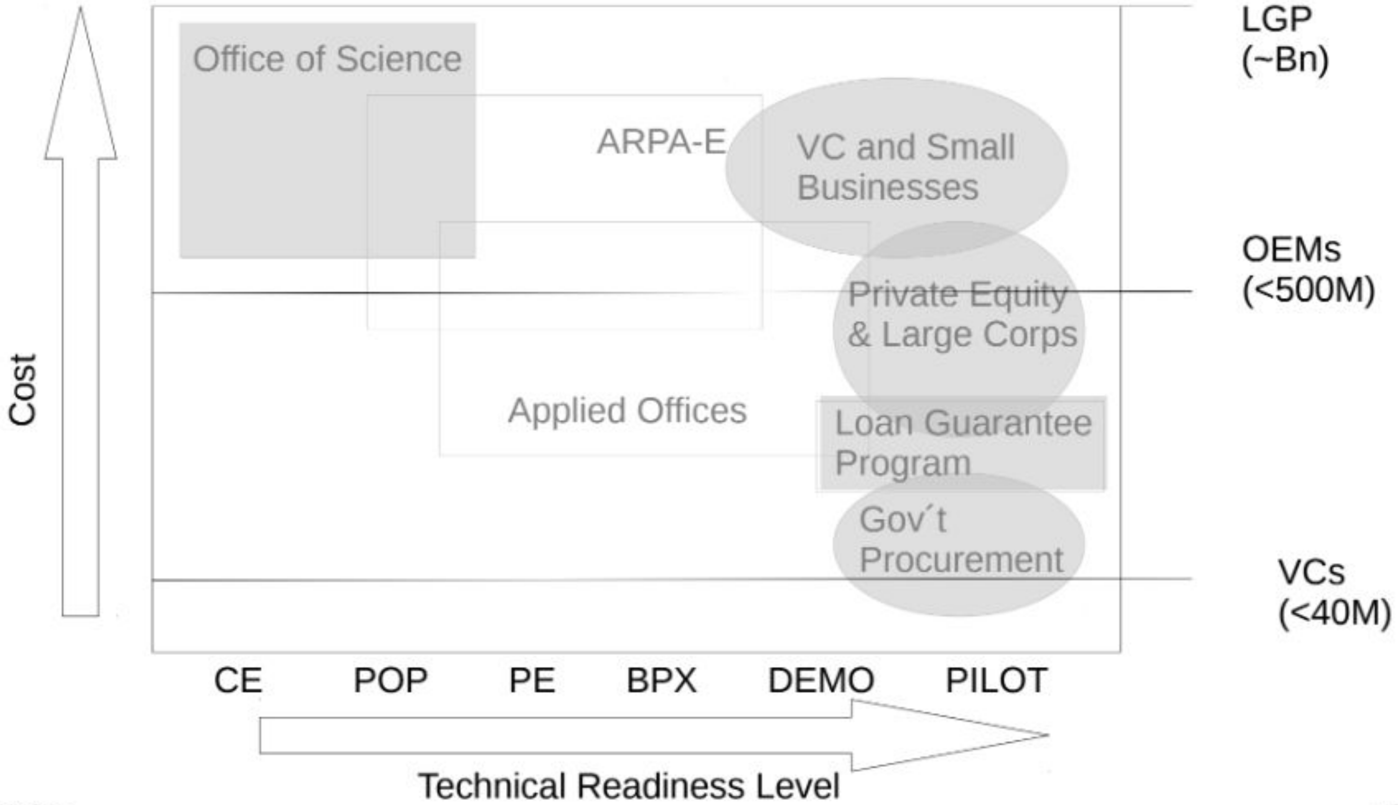

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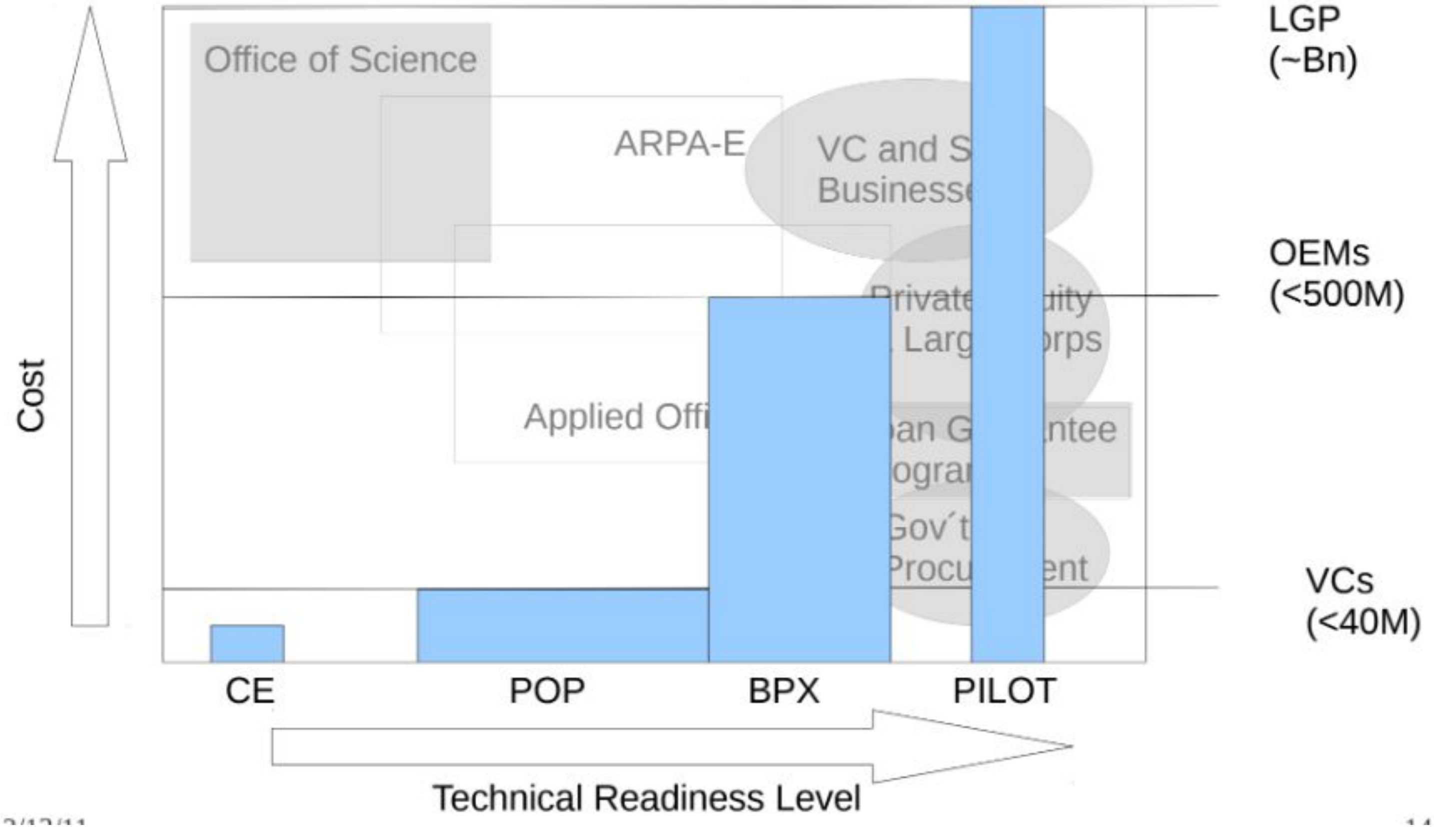
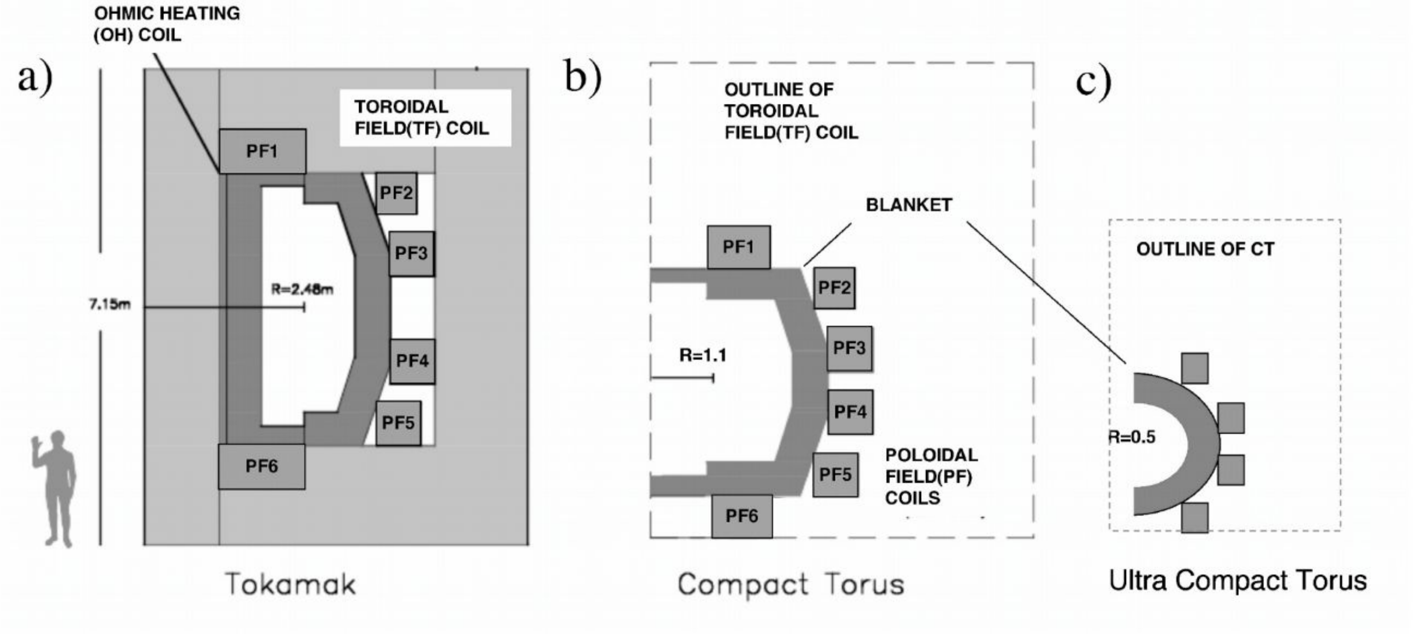


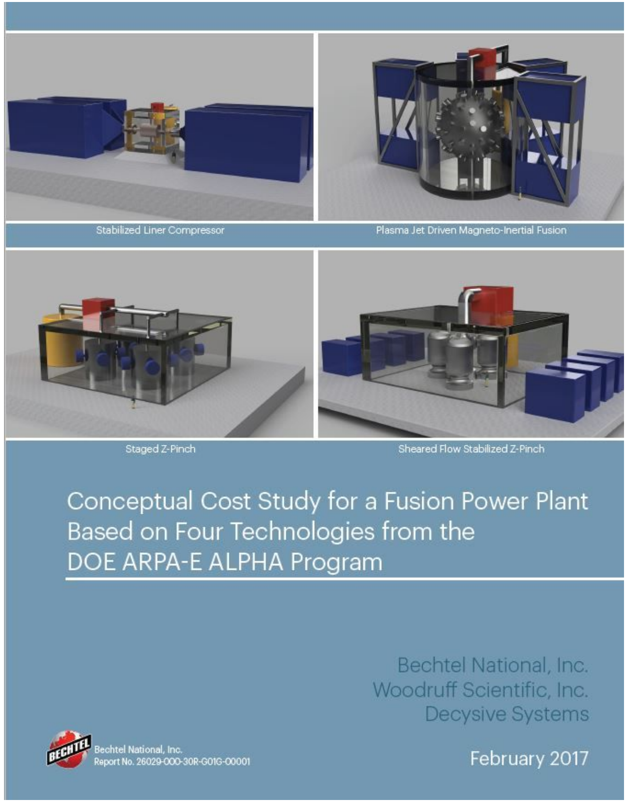
What might fit in a standard commercialization path?



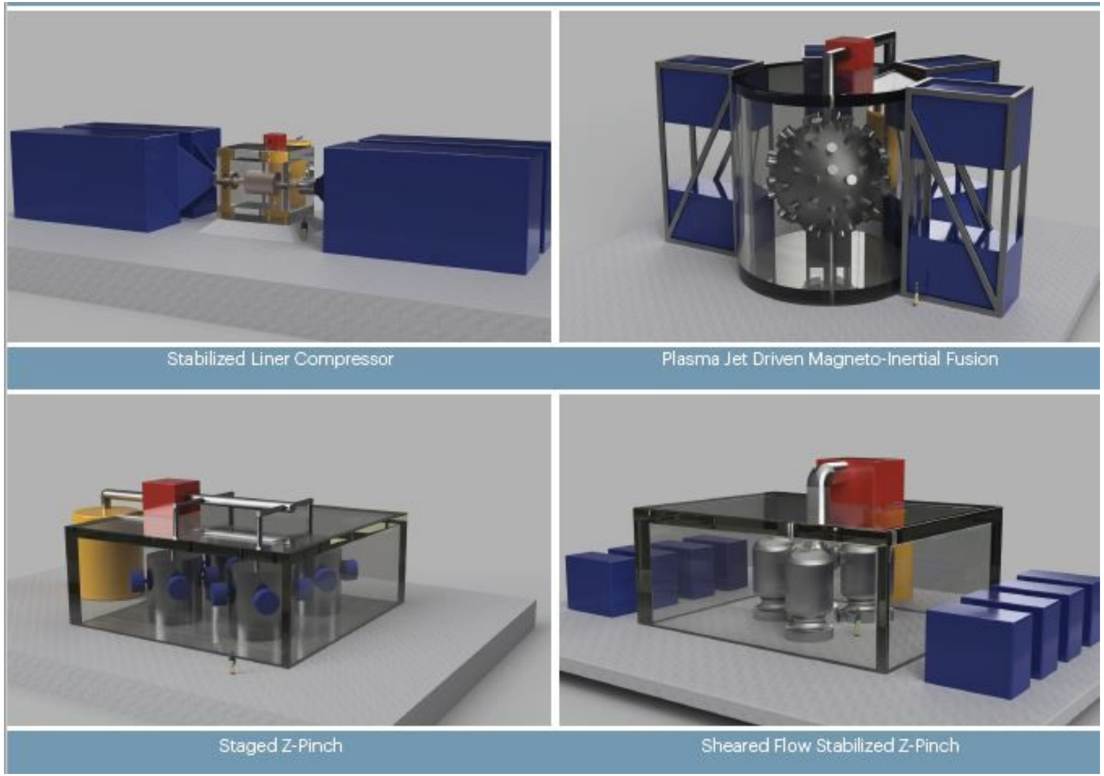
Power:	~GWe	~GWe	<100MWe
Cost:	~3Bn	~1.5Bn	100M

Outline

1. Background
2. Fusion Taxonomy
3. Path to Market for Fusion
4. **Fusion Costing**
5. Fusion Enterprises
6. Discussion
7. Summary



ARPA-E is interested in knowing the cost of fusion systems



In 2017 ARPA-E supported the first fusion costing study for 4 concepts in the ALPHA program.

Work was carried out by Bechtel, Woodruff Scientific and Decysive Systems.

Considered only the Total Capital Costs of the main systems, not the cost of electricity.

Concepts were the Stabilized Liner Compressor, Plasma Jet MIF, the Flow Through Z-pinch and the Staged Z-pinch.

In 2021 the costing is being applied to many more concepts

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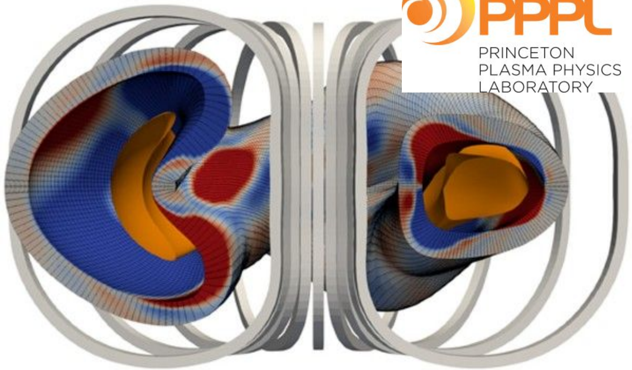
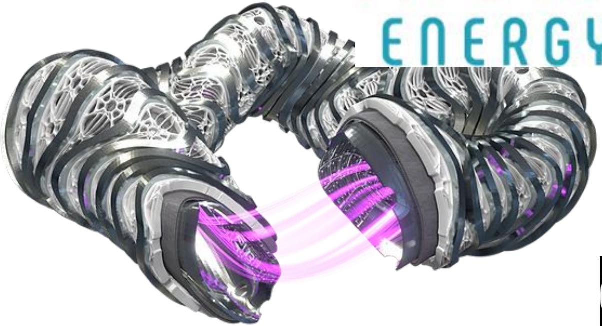
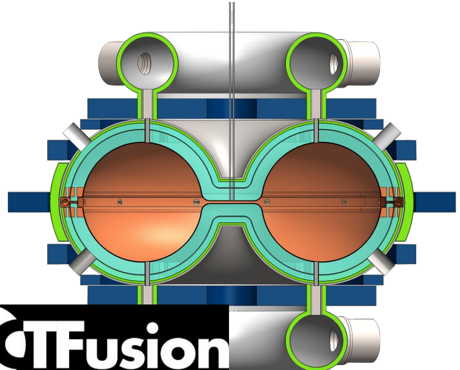
PPPL
PRINCETON PLASMA PHYSICS LABORATORY



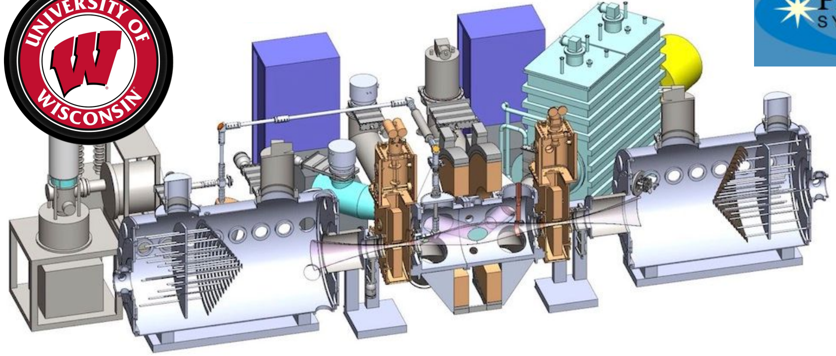
TYPE ONE ENERGY



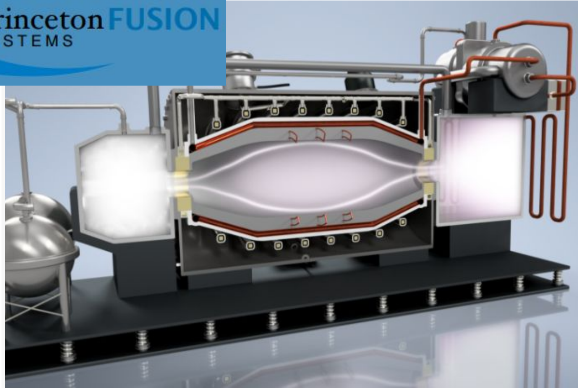


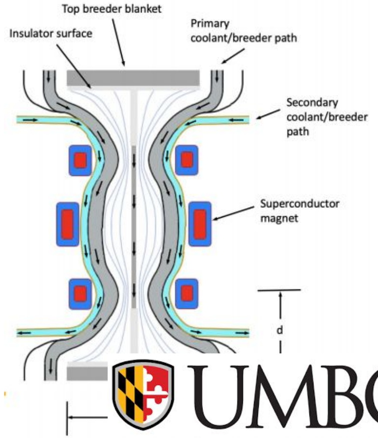
CTFusion

UNIVERSITY OF WISCONSIN



Princeton FUSION SYSTEMS





UMBC

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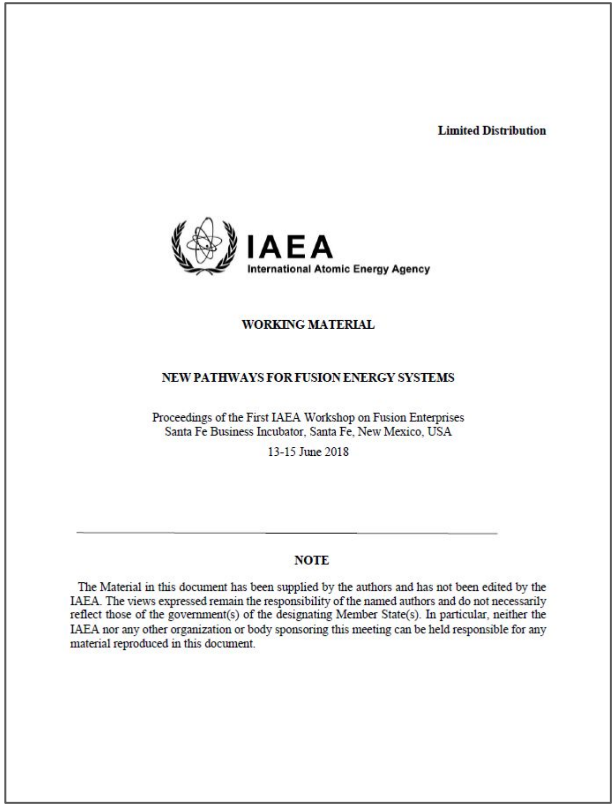

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IAEA
International Atomic Energy Agency

WORKING MATERIAL

NEW PATHWAYS FOR FUSION ENERGY SYSTEMS

Proceedings of the First IAEA Workshop on Fusion Enterprises
Santa Fe Business Incubator, Santa Fe, New Mexico, USA
13-15 June 2018

NOTE

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Picking up on Path to Market, IAEA workshop series focus on commercialization

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Market

Commercialization paths to market

Reactor design for systems with market potential

Externalities

Fusion energy generators and enabling technologies

Fusion generator technologies: MFE

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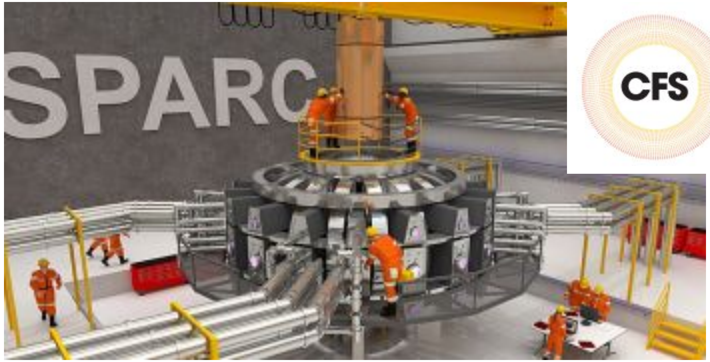
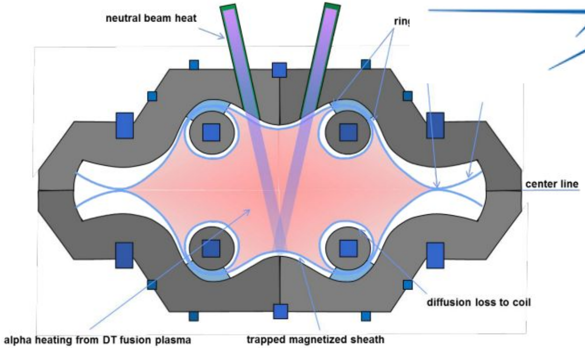
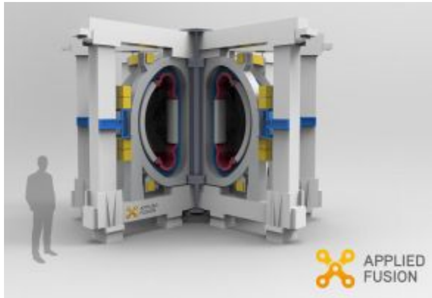
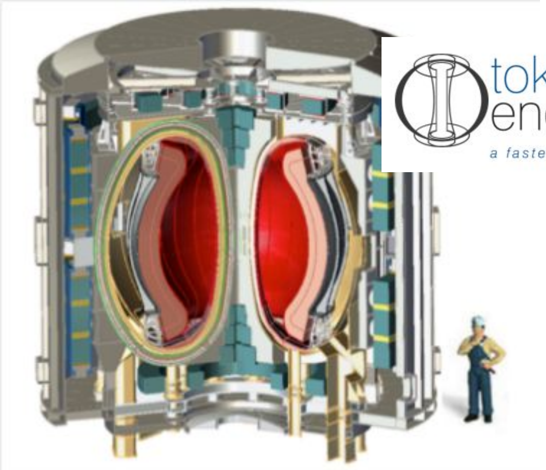


CFS

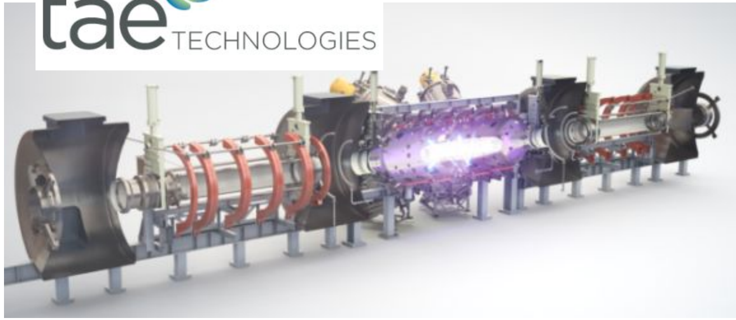




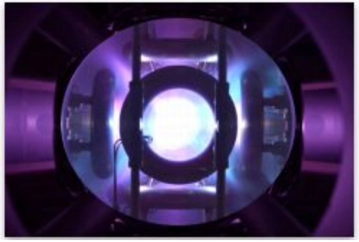


tokamak energy
a faster way to fusion

tae TECHNOLOGIES



EMC2®



Fusion Generator Technologies: MIF

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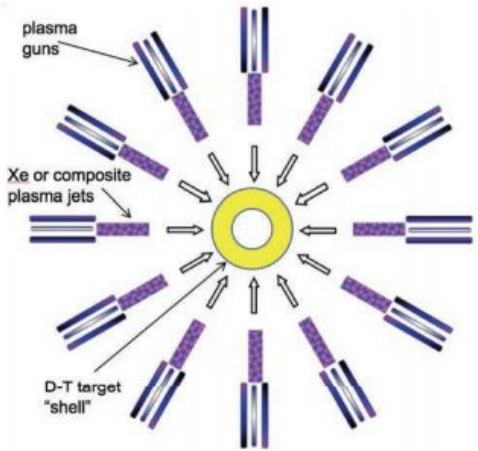
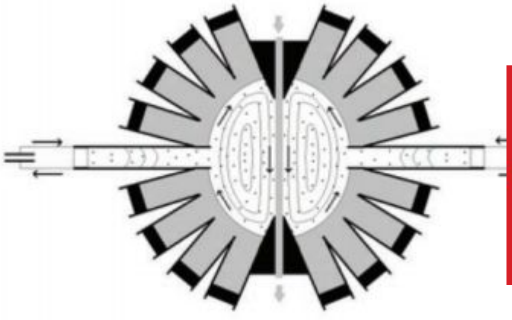
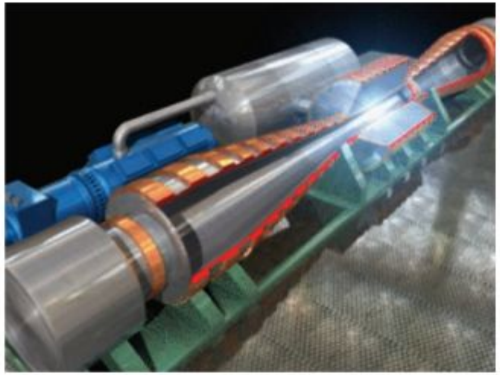


Merging hypersonic plasma jets
(HyperJet Fusion)



Coaxial helicity injection to form a
spherical tokamak (General Fusion)

generalfusion



Helion Energy

Merged field-reversed
configuration (FRC)
(Helion Energy)

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Discussion

- Fusion is still not yet commercial, but efforts are now being made to make it so.
- Concept innovation is still desired, which means that focusing on ‘discovery driven science’ is of critical importance.
- Working on the mainline devices is also important - everything from ITER to CFS to TAE, etc is exciting.

Summary

- Background consists of 20 years of innovation
- Fusion alternatives can be presented as a taxonomy
- Commercialization of fusion requires us to think small
- Compactness is desired by ARPA-E programs
- IAEA now switched on to fusion enterprises - another workshop coming up in Oxford 2022.

→ VERY exciting time to be involved in fusion!

References

Dropbox link for the main texts discussed here.

IAEA Fusion Enterprises Workshop

Email me for more information if you want secondary texts also:
simon@woodruffscientific.com