Alternative pathways to fusion energy
(focus on Department of Energy Innovative Confinement Concepts)

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1. Motivation: cutting edge plasma science and a paradigm shift for fusion.

2. Innovative confinement concepts:
   a) Doubly connected
   b) Simply connected closed
   c) Simply connected open
   d) Theory support

3. Culture of innovation
1. Motivation: cutting edge plasma science and a paradigm shift for fusion.

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3. Culturing innovation
Innovative Confinement Concepts

• **Cutting-edge** plasma science across the nation.

• Experiments offer to fundamentally **change the paradigm** of Fusion Energy Sciences.

• Experiments aim to **operate in new plasma regimes**.

• Premier method to **train the next generation** of plasma researchers (more than 100 students/year).

• The US program **leads the world** in concept innovation.

• Small-scale experiments (<1-2M/year) deliver **value** science.
Can we fundamentally change the paradigm? Yes! Think: complexity, scale and new physics.

- To first order, the total weight of the fusion core is a measure of its cost.
- ‘Simply connected’ may be a virtue.

**Total cost**
- Direct cost 65%
- Indirect cost 25%
- Contingency 10%

**Direct cost**
- Reactor 50-60%
- Conventional plant 35-30%
- Structures 15-10%

**Reactor Cost**
- Coils 30%
- Shield 10%
- Blanket 10%
- Heat Transfer 15%
- Auxiliary power 15%
- Other components 20%

**Diagram**
- Doubly: structure links plasma
- Simply: nothing links plasma

**Symbols**
- CT
- R0
- Blanket
- Torus
- Coils
- Shield
- Blanket
- Heat Transfer
Fusion development path is staged to address scientific and performance metrics.

<table>
<thead>
<tr>
<th>Qualitative Metrics (advancement requires a science-based prediction that the next-level metrics can be met)</th>
<th>Target Quantitative Metrics for MFE*</th>
<th>Target Budget ($M/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept Definition</td>
<td>$\tau &gt; \tau_A$</td>
<td>0.3</td>
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<tr>
<td>- Defines a CE experiment that addresses uncertain physics or tech issues of the concept</td>
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<td>- At a minimum, theory indicates that the CE experiment will be grossly stable</td>
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<td>- A fusion application is defined</td>
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| Concept Exploration | $T = 0.4 \text{ keV}$  
$\eta_T = 10^{17} \text{ s/m}^3$ | < 3.0 |
| - 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 |
| Proof of Principle | $T = 2 \text{ keV}$  
$\eta_T = 10^{19} \text{ s/m}^3$ | < 15.0 |
| - 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 |
ICC experiments are often divided into several different categories.

<table>
<thead>
<tr>
<th>“Doubly connected”</th>
<th>“Simply connected”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tokamak / stellarator</td>
<td>Non-tokamak / stellarator</td>
</tr>
<tr>
<td>Pegasus LTX HSX CTH QPS</td>
<td>Spheromak</td>
</tr>
<tr>
<td>$7M</td>
<td>$7M</td>
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<tr>
<td></td>
<td></td>
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<tr>
<td>$9M</td>
<td>$4M</td>
</tr>
</tbody>
</table>
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The Reversed Field Pinch toroidal plasma configuration.

**Madison Symmetric Torus (UW)**

$R=1.5$ m, $a=0.5$ m, $I_p \leq 0.55$ MA

**Potential Advantages as Fusion Power Core:**
- compact, high beta configuration
- low magnetic field requirement
- single-piece maintenance

**Tokamak-like Confinement (Transiently)**
Levitated Dipole Experiment

Space observations, nonlinear numerical simulations, and basic laboratory experiments show high-beta, good confinement, and rapid adiabatic convection of plasma is possible in dipole-confined plasma.

Can we produce well-confined, high-beta plasma with a levitated dipole and understand large-scale adiabatic convection that maintains energy confinement while allowing rapid removal of impurities and fusion products?

FY06-07 Campaign
- **Complete testing of levitation systems.**
  Complete installation (in progress) and tests of new launcher-catcher system and levitation control systems.
- **Initiate investigation of confinement and stability of plasma confined by levitated dipole and heated with higher-power ECRH.**
  Investigate quasi-steady-state plasmas produced by multiple-frequency ECRH. Study higher-density thermalized plasmas.
- **Funding reduction (-8%):** will eliminate support for two graduate students.

FY08 Campaign
- **Expanded diagnostics for detailed physics observations,** and allow increased run time of LDX experimental facility.
- **Investigate the unique capability of a dipole for high plasma beta, high energy confinement,** and adiabatic convective flows.
- **Answer critical questions to evaluate the potential for attractive dipole fusion with advanced (non D-T) fuels.**

Research Staff: 2 scientists (Drs. Garnier and Hansen),
4 graduate students, PI's (Kesner & Mauel)
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Sustained Spheromak Physics Experiment.

Investigates magnetic field generation and confinement in high temperature spheromaks.

- Low magnetic fluctuations with low edge $\lambda \rightarrow$ no low-order rational surfaces
- $T_e = 350$ eV

Potential Advantages as Fusion Power Core:
- compact, low aspect ratio
- no linked coils – no coils along geometric axis
- easy to disassemble and maintain
HIT-SI is making progress towards its goal of inductively sustaining a closed-flux, high-β, spheromaks.

Novel current drive scheme being explored to form spheromaks more efficiently.

Flux conserver shaped to obtain high beta spheromaks.

Modeling

Goal

$I_p = 5 \ I_{inj}$

Taylor State, $I_p = 1.5 \ I_{inj}$
Achieved:
• Dynamical measurement of 3D magnetic geometry in merging experiments.
• Measurement of bi-directional jets with 1.33 m ion Doppler spectrometer.

Plans:
• Continued study of doublet FRC, flux-core dipole-trapped spheromak, and other novel CT configurations
• Comparison of IDS flow measurements with 3D simulation (HYM, NIMROD, MH4D, etc)
• Merged spheromaks in oblate flux conserver (tilt stable)
The TCS Field Reversed Configuration (FRC)

Potential Advantages as Fusion Power Core:
- Very high $\langle \beta \rangle = 1 - x_s^2/2$ \hspace{1cm} $x_s \equiv r_s/r_c$
- Simple linear geometry: $B_e = B_o/(1-x_s^2)$
- Natural divertor: unrestricted flow out ends.

U. Washington TCS Experiment
(Translation, Confinement, Sustainment)
\[ r_c = 0.42, \quad \ell_s = 2.5 \text{ m} \]

True steady-state operation with rotating magnetic field (RMF) current drive
Greatly enhanced stability
PPPL calculations point way to complete stability

High temperatures produced by fast formation should be achievable with slow, reactor relevant formation in new improved vacuum system
A UW / PPPL collaboration using RMF & TNBI could result in fusion breakthrough
Princeton FRC Experiment: FY2006

Program: test theoretical predictions that odd-parity RMF can form, confine, heat, and stabilize FRC plasma

FY06 accomplishments
Plasma formation at sub-mT fill pressures
Added capabilities: Hall effect probe, diamagnetic loops, 170 GHz interferometer, 2 divertors
Characterization of internal flux conservers
New method to measure RMF penetration
Operation of components at full design parameters:
  \( B_v \) to 400 G; RMF power to 10 kW;
  Pulse length 5 ms; 1% duty factor
  \( B_{RMF} \) to 15 G; Density to \( 10^{13} \, \text{cm}^{-3} \)

*Phys. Rev. Lett.* on ion heating theory
PhD produced: A. Landsman
Graduate students: N. Ferraro, D. Fong, D. Lundberg, A Roach
Undergraduate: D. Olivan
Collaborators: A. Glasser (LANL), E. Scime (WVU), G. Zaslavsky (CIMS)

Plasma well separated from Pyrex vessel

Goal: Research aimed at the development of a clean, compact, steady-state, reliable, and practical fusion reactor.

- Operation at 100 kW RF power
- Superconducting components to extend pulse length
The plasma beta ranges from 0.8 to 1
The heart of the device fits on a modest table-top
The plasma density is high ~$10^{19} \text{ cm}^{-3}$
The current density can be 1000 MA/m$^2$
The magnetic field confining the plasma is 500 Tesla !
The auxiliary heating power level is ~ 1000 Gigawatts !

Potential Advantages as Fusion Power Core:
- Pulsed, high pressure. Gets around sustainment issues.
- Simple geometry
- Hybrid of inertial and magnetic confinement
Pulsed High Density (PHD) Fusion Experiment

Potential advantages as a fusion core

- Minimum B field at highest plasma pressure (β~1)
- Simple linear system – reactor wall is steel pipe
- Variable output power ~ 10-100 MW not multi-GW
- Burn chamber well separated from plasmoid formation/heating.
- Direct electric power conversion with expansion of fusion heated plasmoid (Brayton cycle - η > 90%)
- Low mass system directly applicable to space propulsion
- Key physics and scaling have been demonstrated
  - Developmental cost order of magnitude less - POP experiment ~ 1 M$ / year

Energy required to achieve fusion conditions is transferred to FRC plasmoid from array of axially sequenced coils.

Current experiment to create initial FRC plasmoid for fusion breakeven experiment
Diffuse pinch experiment studies wall-plasma interactions & confinement

Initially flux-compression experiments planned. Follow-on experiments to use plasma pinch.

1. Self-organization observed numerically
2. Potential for fusion reported at IAEA
   Siemon et al., Nuc. Fusion 45, 1148 (2005)
3. Experimental design presented at APS
   Siemon et al., Makhin et al., 47th APS-DPP (2005)

Predictions of wall plasma are sensitive to assumptions about energy transport near the surface... Which are right?
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ZAP Z-pinch produces a stable column by providing a shear in the velocity.

To generate a Z-pinch configuration with an embedded axial flow the ZaP experiment couples a coaxial accelerator with a pinch assembly region.

Potential Advantages as Fusion Power Core:
- linear system
- no coils
- natural exhaust.

Mission: Create a supersonic rotating plasma to augment magnetic confinement by centrifugal force and stabilize flute modes with velocity shear.

Potential Advantages as Fusion Power Core:
- High beta
- Simple linear geometry
- Natural divertor: unrestricted flow out ends.

Achievements
- **Supersonic Rotation**: $\text{ExB}$ rotation up to Mach 2.5, $T_i \sim 40$ eV
- **“HR-mode”**: High rotation mode discovered, x2 better confinement
- V’ Shear measured: exceeds theoretical criterion (multi-chord spectrometer)

Plans
- **Confinement scalings**: parametric scans, optimize and hold HR mode
- **Plasma jet injection**: off-axis momentum input (with HyperV Corp.)
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**FRC Theory and Modeling**  
**PI:** E. Belova, R. Davidson, H. Ji, M. Yamada (PPPL)

**Objective**
Develop and apply state-of-the-art numerical simulations to provide an improved understanding of FRC formation and stability properties; validate the theoretical models, and improve agreement between theory and existing experimental results; provide theoretical support and guidance for FRC experiments.

**Program Accomplishments FY2005-FY2006:**
- A study of the effects of the energetic beam ions on FRC stability properties for different FRC and beam parameters has been performed. A new stability regime has been discovered for oblate FRCs with a close-fitting conducting shell and energetic beam ion stabilization.

- A series of two-dimensional and three-dimensional high-resolution simulations of counter-helicity spheromak merging and FRC formation have been performed using the two-fluid version of the HYM code. New signatures of Hall reconnection have been identified which are specific to the counter-helicity magnetic field geometry and have been shown to be related to the generation of a quadrupole magnetic field in Hall-MHD reconnection.

- Performed MHD and hybrid simulations to study the effects of resistive relaxation, profile consistency, and self-organization in FRCs.

- Performed three-dimensional simulation studies of the MRX spheromak merging and FRC formation experiments, including MHD stability study and detailed comparison with experimental results.
Goals and accomplishments of Plasma Science and Innovation Center (PSI-Center)

- In concert with experiments refine present computational tools with sufficient physics, boundary conditions, and geometry to be calibrated with experiments and achieve improved predictive capabilities.

- Areas of refinement of NIMROD and MH4D:
  - Two fluid / Hall physics
  - Kinetic and FLR effects
  - Reconnection, relaxation physics
  - Transport, atomic physics, and radiation
  - Boundary conditions and geometry

- Initial experiments to test and calibrate codes: FRX-L, MBX, SSPX, SSX, HIT-SI, PHD, TCS, ZaP, Caltech experiments, and MST.
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   d) Theory in support of ICCs

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Annual ICC conference:
This year, the Innovative Confinement Concept workshop hosted by the University of Texas, Austin entailed 115 contributed papers, 37 oral presentations on most of the ICC concepts in the US (plus one from Italy, one from Russia), organized into six sessions --> Special edition of JoFE.

Fusion Skunkworks: new ideas, including patents.

New Proposals, e.g.:
SPIRIT - Ji et al PPPL
Flux-Core ST - Hsu et al LANL

Collaborations with new NSF Centers (e.g. CMSO @ UW)
Then, thinking internationally for a moment…

GDT, Novosibirsk, Russia

Gamma 10, Tsukub, Japan

Mirror based systems investigated in the US on smaller scale presently, but in the 1980’s they were the main alternative to the tokamak.

Presently researched in Russia and Japan, although expertise still in the USA: small level of effort around the country.

Other non tokamak concepts being researched in Italy, Germany.
Summary

- ICC experiments add strength and robustness to the fusion program through scientific portfolio diversity.
- They explore pathways to improve confinement, stability and reactor configurations.
- Exploits physics and engineering advantages offered by geometric and topological variations, higher densities, higher B fields, rotation, flow shear, electric fields, pulsed modes, etc.
- This diversity combined with the excellence of research makes the U.S. program the world leader in innovative concepts.