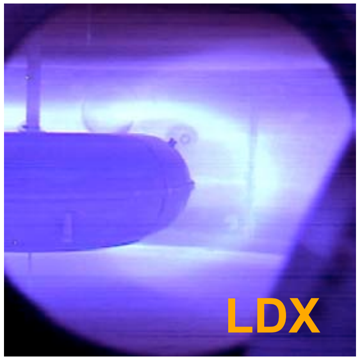
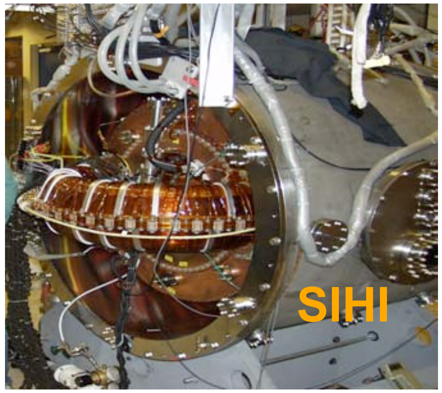
Summary of the 2007 Innovative Confinement Concepts Workshop

Simon Woodruff
WOODRUFF SCIENTIFIC, LLC, 1700 Seventh Ave, Suite 2100, Seattle, WA 98101

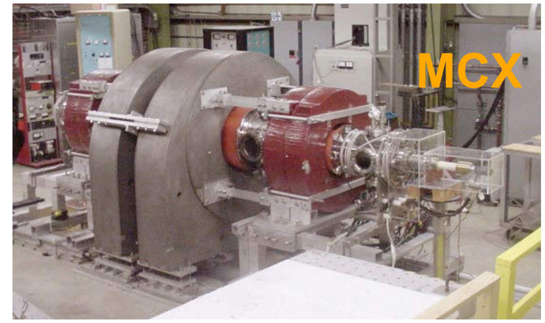
With useful comments from Adil Hassam, Brett Chapman, Sam Barish

Fusion Power Associates Annual Meeting and Symposium
Fusion Energy: Preparing for the NIF and ITER Era
December 4-5, 2007
Doubletree Hotel, Oak Ridge, Tennessee


LDX

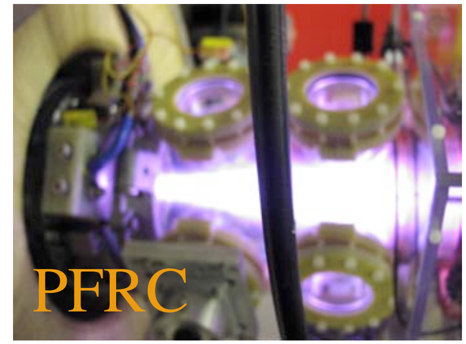

SIHI

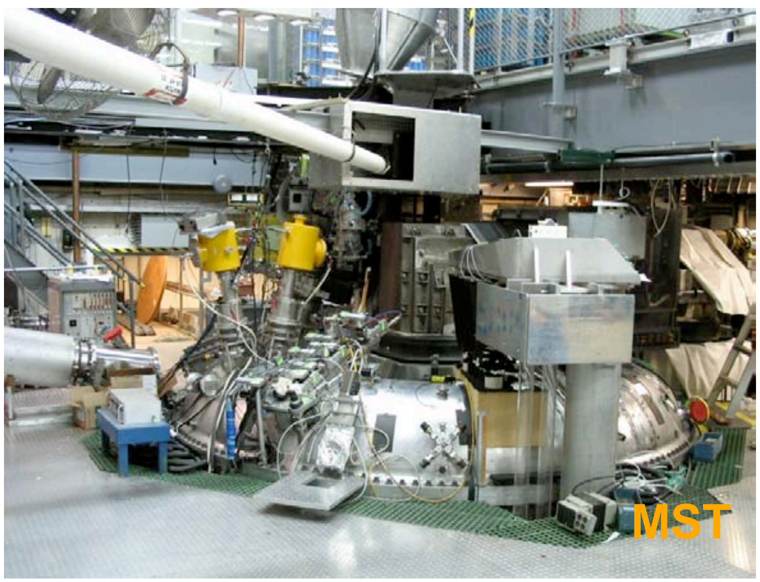

FRX-L

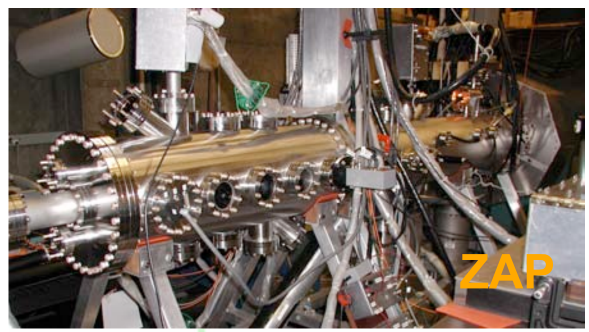

MCX


TCS

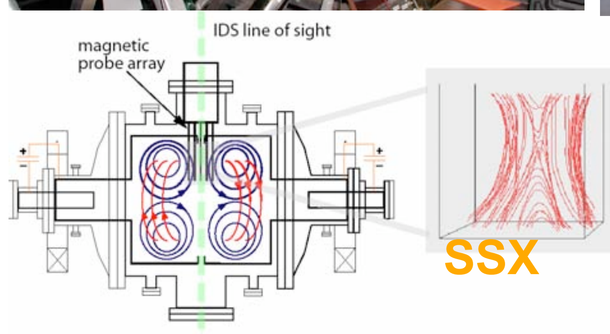

SSPX


PFRC


MST


ZAP


FRX-L


IDS line of sight
magnetic
probe array
SSX


AFRL

Outline

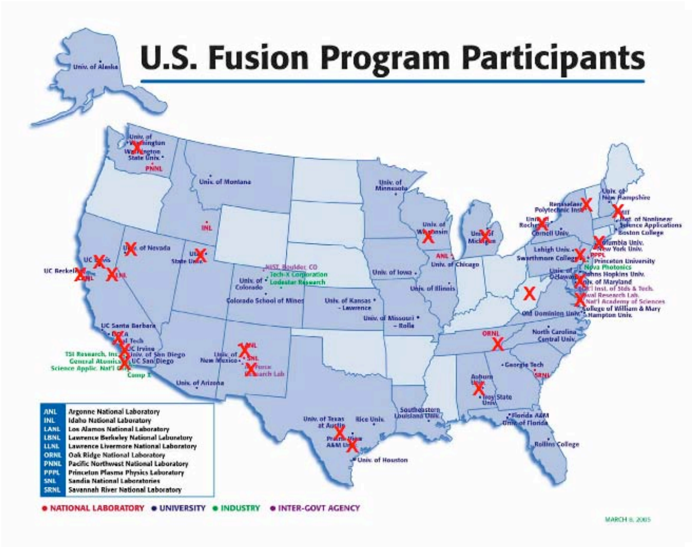
-- Meeting overview (history, purpose, talks, scope)

-- Some highlights (by concept/subject):
- --Compact tori
- --Small tokamaks
- --IFE related
- --Simulations
- --Diagnostics

-- Summary and call for papers for ICC2008

ICC Workshop 2007: evolving towards a conference for smaller fusion concepts.

Meeting took place at the University of Maryland.



In total, there were **120 contributions from ~35 separate institutions** (national labs, universities, and industry in the USA and from Europe, and Japan).

Written proceedings now published in the Journal of Fusion Energy contains ~40 papers to appear as a special edition.

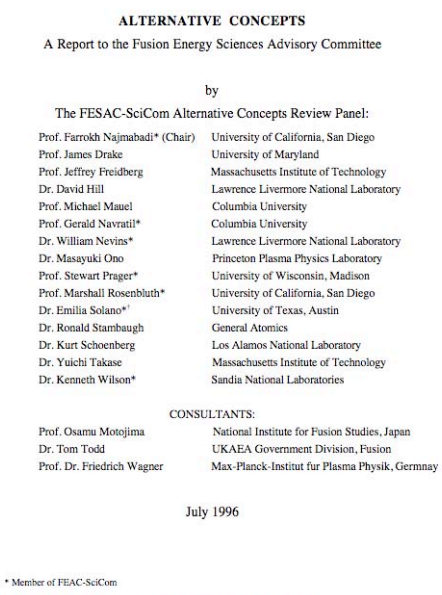
Subjects spanned a wide range of issues, from confinement studies through to completely novel ideas, and some controversial ones presented in a 'Skunkworks' session.

ICC workshops started in 1997 and have continued, taking place once every 18 months.

Typical workshop size is ~120 contributions, sometimes from abroad.

Usually the meeting is a forum for 'innovative concepts' (classed as **Basic Science**, **Concept Exploration**, or **Proof of Principal**).

ICC research is supported by 13 community planning activities in the last 15 years (e.g. FESAC, FEAC, OFES, PCAST, SEAB, IPPA), but most notably:



ALTERNATIVE CONCEPTS

A Report to the Fusion Energy Sciences Advisory Committee

by

The FESAC-SciCom Alternative Concepts Review Panel:

Prof. Farrokh Najmabadi* (Chair)	University of California, San Diego
Prof. James Drake	University of Maryland
Prof. Jeffrey Freidberg	Massachusetts Institute of Technology
Dr. David Hill	Lawrence Livermore National Laboratory
Prof. Michael Mauel	Columbia University
Prof. Gerald Navratil*	Columbia University
Dr. William Nevins*	Lawrence Livermore National Laboratory
Dr. Masayuki Ono	Princeton Plasma Physics Laboratory
Prof. Stewart Prager*	University of Wisconsin, Madison
Prof. Marshall Rosenbluth*	University of California, San Diego
Dr. Emilia Solano*†	University of Texas, Austin
Dr. Ronald Stambaugh	General Atomics
Dr. Kurt Schoenberg	Los Alamos National Laboratory
Dr. Yuichi Takase	Massachusetts Institute of Technology
Dr. Kenneth Wilson*	Sandia National Laboratories

CONSULTANTS:

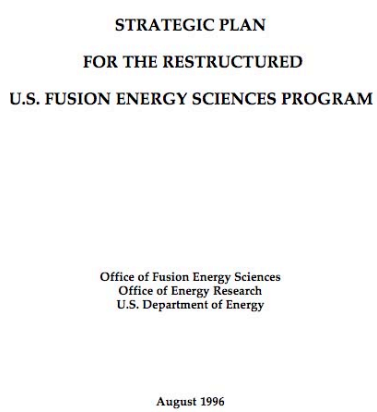
Prof. Osamu Motojima	National Institute for Fusion Studies, Japan
Dr. Tom Todd	UKAEA Government Division, Fusion
Prof. Dr. Friedrich Wagner	Max-Planck-Institut fur Plasma Physik, Germnay

July 1996

* Member of FEAC-SciCom

† Dr. Solano resigned from SciCom and this Panel before this report was completed.

FESAC 1996



STRATEGIC PLAN

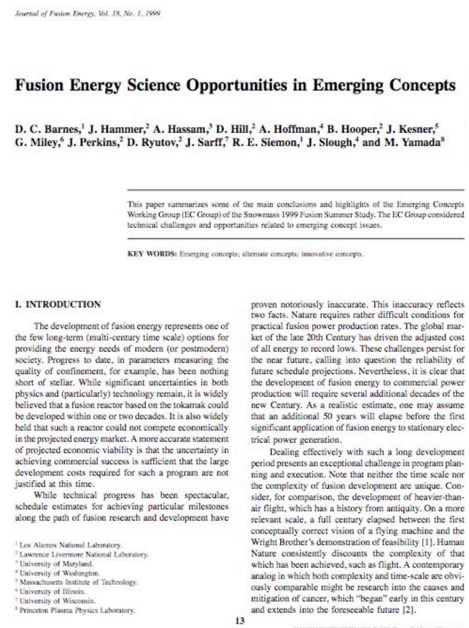
FOR THE RESTRUCTURED

U.S. FUSION ENERGY SCIENCES PROGRAM

Office of Fusion Energy Sciences
Office of Energy Research
U.S. Department of Energy

August 1996

OFES 1996



Journal of Fusion Energy, Vol. 18, No. 1, 1999

Fusion Energy Science Opportunities in Emerging Concepts

D. C. Barnes,[1] J. Hammer,[2] A. Hassam,[3] D. Hill,[2] A. Hoffman,[4] B. Hooper,[2] J. Kesner,[5] G. Miley,[6] J. Perkins,[2] D. Ryutov,[2] J. Sarff,[7] R. E. Siemon,[1] J. Slough,[4] and M. Yamada[8]

This paper summarizes some of the main conclusions and highlights of the Emerging Concepts Working Group (EC Group) of the Snowmass 1999 Fusion Summer Study. The EC Group considered technical challenges and opportunities related to emerging concept issues.

KEY WORDS: Emerging concepts; alternate concepts; innovative concepts.

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].

[1] Los Alamos National Laboratory.
[2] Lawrence Livermore National Laboratory.
[3] University of Maryland.
[4] University of Washington.
[5] Massachusetts Institute of Technology.
[6] University of Illinois.
[7] University of Wisconsin.
[8] Princeton Plasma Physics Laboratory.

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SM 1999

A Plan for the Development of Fusion Energy

Robert Goldston,[1,18] Mohamed Abdou,[2] Charles Baker,[3] Michael Campbell,[4] Vincent Chan,[4] Stephen Dean,[5] Amanda Hubbard,[6] Robert Iotti,[7] Thomas Jarboe,[8] John Lindl,[9] B. Grant Logan,[10] Kathryn McCarthy,[11] Farrokh Najmabadi,[3] Craig Olson,[12] Stewart Prager,[13] Ned Sauthoff,[14] John Sethian,[15] John Sheffield,[16] and Steven Zinkle[17]

This is the final report of a panel set up by the U.S. Department of Energy (DOE) Fusion Energy Sciences Advisory Committee (FESAC) in response to a charge letter dated September 10, 2002 from Dr. Ray Orbach, Director of the DOE's Office of Science. In that letter, Dr. Orbach asked FESAC to develop a plan with the end goal of the start of operation of a demonstration power plant in approximately 35 years. This report, submitted March 5, 2003, presents such a plan, leading to commercial application of fusion energy by mid-century. The plan is derived from the necessary features of a demonstration fusion power plant and from the time scale defined by President Bush. It identifies critical milestones, key decision points, needed major facilities and required budgets. The report also responds to a request from DOE to FESAC to describe what new or upgraded fusion facilities will "best serve our purposes" over a time frame of the next twenty years.

KEY WORDS: Fusion energy, fusion program plan.

"This [progress in fusion science] is an enormous change that is enough to change the attitudes of nations toward the investments required to bring fusion devices into practical application and power generation."
Presidential Science Advisor John Marburger.

"By the time our young children reach middle age, fusion may begin to deliver energy independence. . . and energy abundance. . . to all nations rich and poor. Fusion is a promise for the future we must not ignore. But let me be clear, our decision to join ITER in no way means a lesser role for the fusion programs we undertake here at home. It is imperative that we maintain and enhance our strong domestic research program. . . . Critical science needs to be done in the U.S., in parallel with ITER, to strengthen our competitive position in fusion technology."
Secretary of Energy, Spencer Abraham

"The results of ITER will advance the effort to produce clean, safe, renewable, and commercially-available fusion energy by the middle of this century. Commercialization of fusion has the potential to dramatically improve America's energy security while significantly reducing air pollution and emissions of greenhouse gases."
President George W. Bush

[1] (Chair), Princeton Plasma Physics Laboratory.
[2] University of California, Los Angeles.
[3] University of California, San Diego.
[4] General Atomics.
[5] Fusion Power Associates.
[6] MIT Plasma Science and Fusion Center.
[7] CH2M Hill.
[8] University of Washington.
[9] Lawrence Livermore National Laboratory.
[10] Lawrence Berkeley National Laboratory.
[11] Idaho National Engineering and Environmental Laboratory.
[12] Sandia National Laboratory, New Mexico.
[13] University of Wisconsin.
[14] Princeton Plasma Physics Laboratory.
[15] Naval Research Laboratory.
[16] ORNL, and UT Joint Institute for Energy and Environment.
[17] Oak Ridge National Laboratory.
[18] To whom correspondence should be addressed. E-mail: rgoldston@pppl.gov

EXECUTIVE SUMMARY

This report presents a plan for the deployment of a fusion demonstration power plant within 35 years,

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FESAC 2002

SM 2002 - “The ICC experiments address several programmatic and fusion energy science objectives by:

1. Working within a broad range of plasma and fusion energy sciences, including **cross fertilization** with other fields of plasma science;

2. Seeking concepts and innovations that work better or **change the paradigm** for fusion energy;

3. Broadening the physics of toroidal magnetic confinement by **operating in parameter regimes inaccessible by the tokamak**;

4. Strengthening university plasma science and technology programs, **engaging faculty** by providing opportunities to contribute to plasma and fusion science **with small-to-medium size experiments**; and

5. **Attracting bright, young talent** with the vision of unlimited energy for mankind while providing the opportunity to participate in experiments they can “get their hands around.

Workshop committee comprised of experts from many institutions (some more active than others).

John Barnard	Lawrence Livermore National Laboratory
Bruno Bauer	University of Nevada, Reno
Brett Chapman	University of Wisconsin
Darren Garnier	Columbia University
Jean-Luc Gauvreau	University of California, Los Angeles
Rob Goldston	Princeton Plasma Physics Laboratory
Jeff Harris	Australian National University
Adil Hassam	University of Maryland
Bick Hooper	Lawrence Livermore National Laboratory
Tom Jarboe	University of Washington
Stephen Knowlton	Auburn University
Harry Mclean	Lawrence Livermore National Laboratory
Brian A. Nelson	University of Washington
Paul Parks	General Atomics
Thomas Pedersen	Columbia University
John Perkins	Lawrence Livermore National Laboratory
Carl Sovinec	University of Wisconsin
Ed Synakowski	Lawrence Livermore National Laboratory
Francis Thio	U.S. Department of Energy
Simon Woodruff	Woodruff Scientific, LLC
James W. Van Dam	University of Texas, Austin
Glen Wurden	Los Alamos National Laboratory
Mike Zarnstorff	Princeton Plasma Physics Laboratory

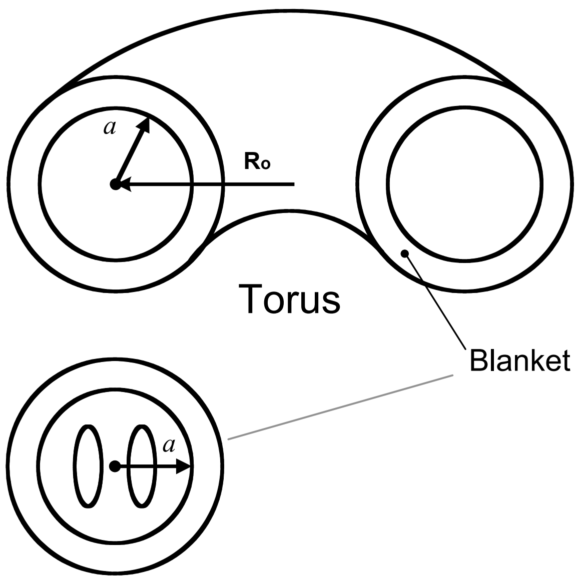
During the last 10 years, a range of experimental configurations have been discussed at the ICC workshop: still evolving.

Toroidal high B	Toroidal low B	Toroidal no applied B	Linear	Non magnetic
HBT-EP Resistive-wall stab. Tokamak trans. phys. Divertor innovation Pegasus LTX HSX CTH QPS	**Reversed field pinch** (MST) **Dipole** LDX	**Spheromak** (SSPX, HIT-SI, SSX, CalTech) **FRC** (TCS-U, Odd-parity RMF, SSX, PHD, PFRC, Theory) Magneto-Bern. Exp. **Magneto-Inertial Fusion** (FRX-L, Solid liner, theory, stand-off driver) Accelerated FRC CT Accel Inverse Z-pinch	**Mirror** Mary. Centr. Exp. **Flow Pinch** (ZAP)	**IEC** **Fast ignition**
$7M	**$7M**	**~$10M**	**~$3M**	**~$?.M**

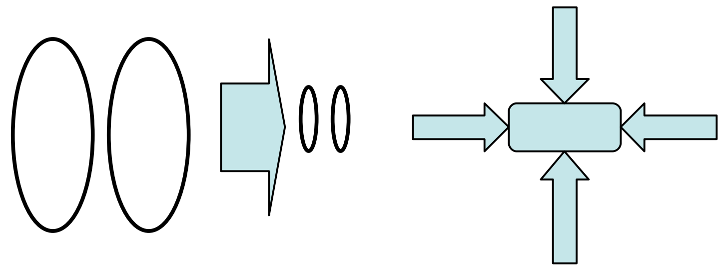
Broadly, ICCs seek to reduce *size* and *complexity* of the fusion system.

Doubly:
structure
links plasma

Simply:
nothing
links plasma



Or **inertial**:



Magnetized plasma/solid

(Overlap with HEDP)

Can magnetic systems operate with lower applied toroidal field?

Can magnetic fields improve inertial systems?

ICC2007 Workshop organized into 5 oral sessions and a skunkworks, with ~6 talks per session + parallel poster sessions + OFES input.

High Beta Magnetic Confinement: RFP, LDX, Pegasus, ZaP & MCX	***Chair: Darren Garnier***
Inertial Fusion Energy Research	***Chair: John Perkins***
Simply Connected and/or Current Drive Solutions: Spheromaks, Stellarators and Others	***Chair: Bick Hooper***
Theory and Computation	***Chair: James Van Dam***
High-Beta and Simply Connected: FRC	***Chair: Alan Hoffman***

Compact Tori: High temperatures in devices with good surface conditioning.

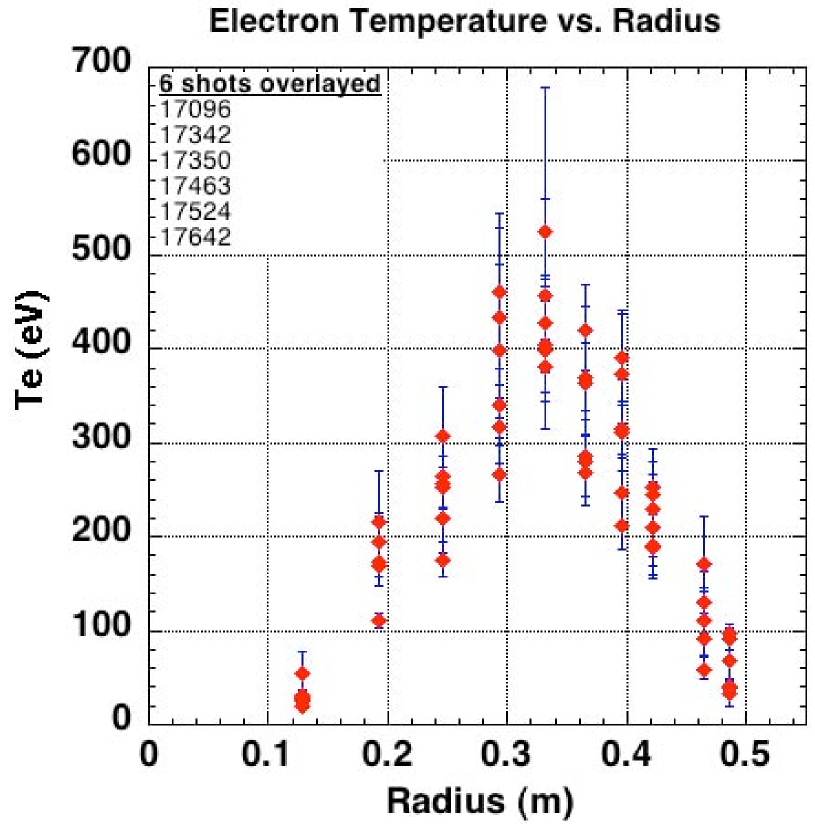
Obtained 500eV in the LLNL SSPX Spheromak experiment, benchmarked with 3D MHD simulations to show toroidal mode evolution.

Obtained higher confinement mode in TCS-U FRC after upgrading vacuum system.

FRX-L - obtaining high density operations ready for FRC compression with AFRL Shiva-Star cap bank (first shot for March).

PFRC demonstrating odd-parity rotating magnetic field sustainment.

A new record for spheromaks: SSPX attains 500eV



Kind permission of H. McLean

Tokamaks: Attainment of High Normalized Current by J(r) Manipulation in the Pegasus Toroidal Experiment

The Pegasus Toroidal Experiment is an ST designed with the purpose of studying pressure and current limits at very low aspect ratio.

At A<1.2, kink stability is expected for values of I_p/I_{tf} up to 3 (I_N up to 18 MA/m-T). At this level, stable values of Troyon beta in excess of 70% are predicted.

[1] G. Gartska *et al* to appear Journal of Fusion Energy Special Edition (2007)

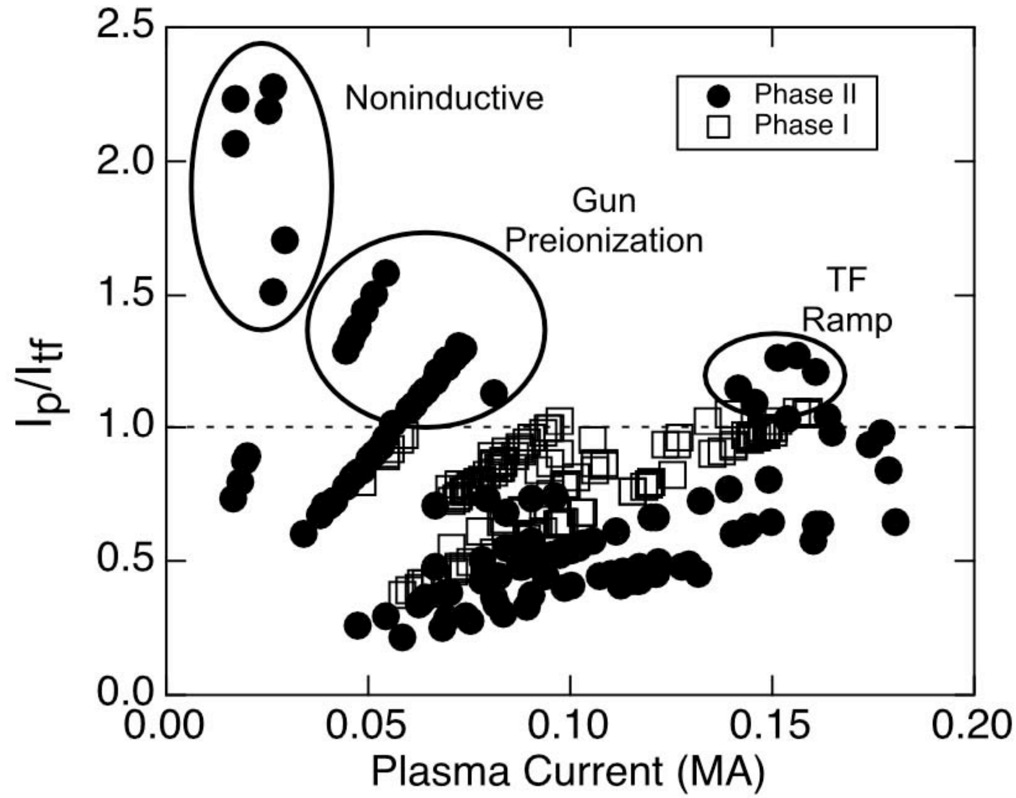


Figure 4.

See also, e.g.:

Bogatu, Ioan N.Hyper-Velocity Dusty Plasma Jets for Disruption Mitigation

Ryutov, Dmitri D.A ‘snow-flake’ divertor as a possible approach to reducing divertor heat loads in tokamaks

IFE: Magneto-Inertial Approach to Direct-Drive Laser Fusion - Gotchev *et al*

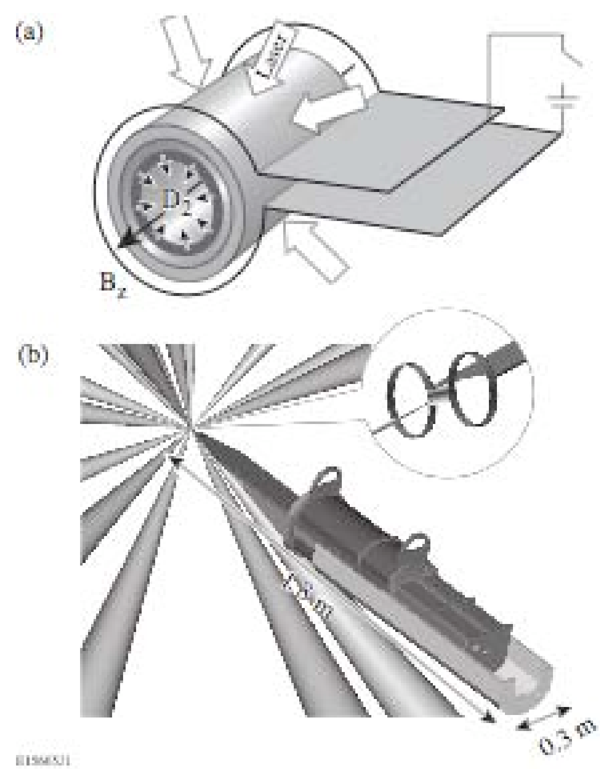
Magneto-Inertial Approach to Direct-Drive Laser Fusion

O. V. Gotchev,[1,2] N. W. Jang,[1,2] J. P. Knauer,[1] M. D. Barbero,[1] and R. Betti[1,2]
[1]Laboratory for Laser Energetics, University of Rochester, 250 East River Road, Rochester, New York 14623
[2]Fusion Science Center for Extreme States of Matter and Fast Ignition Physics, University of Rochester, 250 East River Road, Rochester, NY 14623

C. K. Li and R. D. Petrasso
Plasma Science and Fusion Center, Massachusetts Institute of Technology, MA 02139

Keywords: inertial confinement, high-beta plasmas, magnetic insulation

A magneto-inertial fusion (MIF) approach to inertial confinement fusion (ICF), based on laser-driven magnetic-flux compression (LDFC) is described. This approach benefits from both the high-energy-density characteristic to ICF and the thermal insulation of the fuel by magnetic fields, typical of MFE. The reduction in thermal-conduction losses in the hot spot of an imploding target that has trapped and amplified a pre-seeded magnetic flux leads to increased hot-spot temperatures at lower implosion velocities than required in conventional ICF. This can lead to ignition designs with larger energy gains. This work describes the main concept and the use of a compact magnetic-pulse system to seed a macroscopic magnetic field into cylindrical DD-filled targets, which are radially driven with the OMEGA laser. The compression of the internal magnetic flux is measured with proton deflectometry. Magnetohydrodynamic simulations predict compression of a 0.1-MG seed field to multi-megagauss values, at which levels the radial electron thermal conduction in the hot spot is significantly inhibited. Initial benchmark experiments are described.



See also, e.g.

Dunne, Mike A European path to Fast Ignition Fusion Energy

Erlandson, Alvin C .New Concepts for Reducing Costs and Improving Efficiency of Solid-State Laser Drivers for Inertial Fusion Energy

Sethian, John D Laser Fusion Energy and the Fusion Test Facility Naval Research Laboratory

Simulation: PPPL, U. Wisconsin and U. Washington pushing MHD code development - aiming for predictive capability.

FRC Theory and Modeling
PI: Belova, Davidson,
H. Ji, M. Yamada (PPPL)

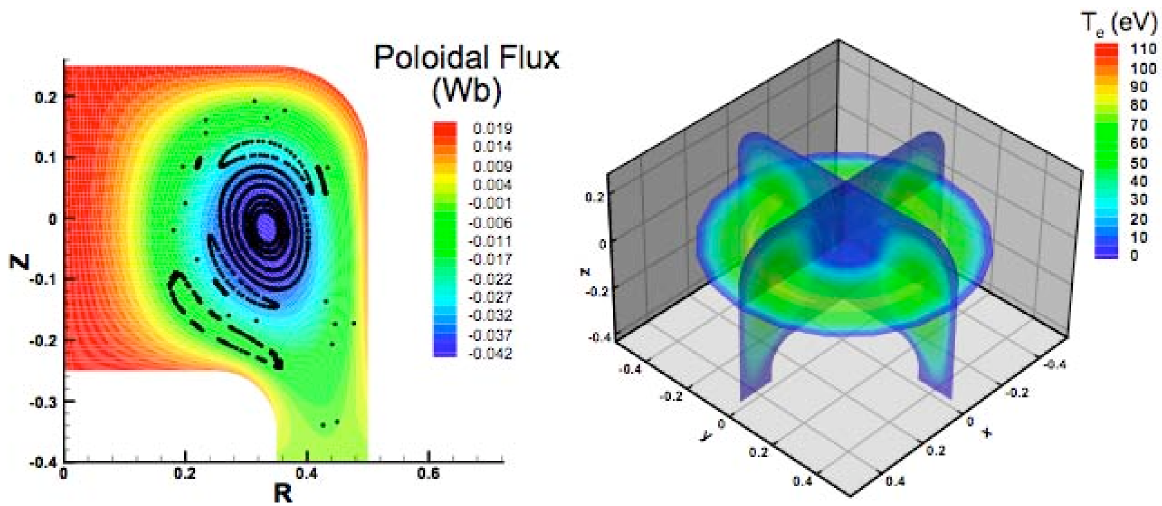
Develop and apply state-of-the-art numerical simulations to provide an improved understanding of FRC formation / stability properties.

NIMROD Team
U.Wisc - PI: Sovinec

3D resistive MHD simulations with the NIMROD code address fundamental physics in many ICC and tokamak expts.

PSI Center - U. Washington PIs: Jarboe, Milroy

In concert with experiments refine present computational tools with sufficient physics.

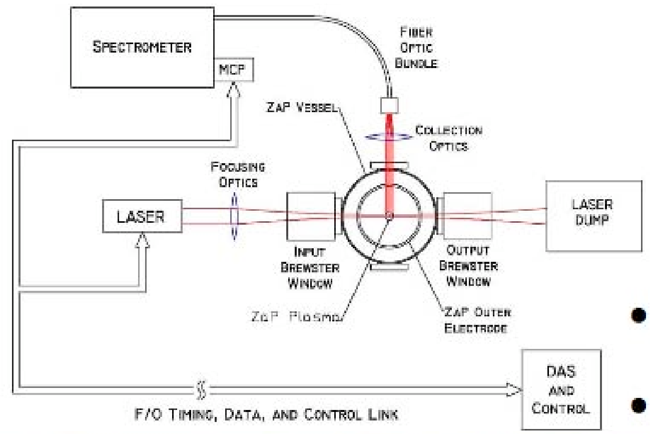


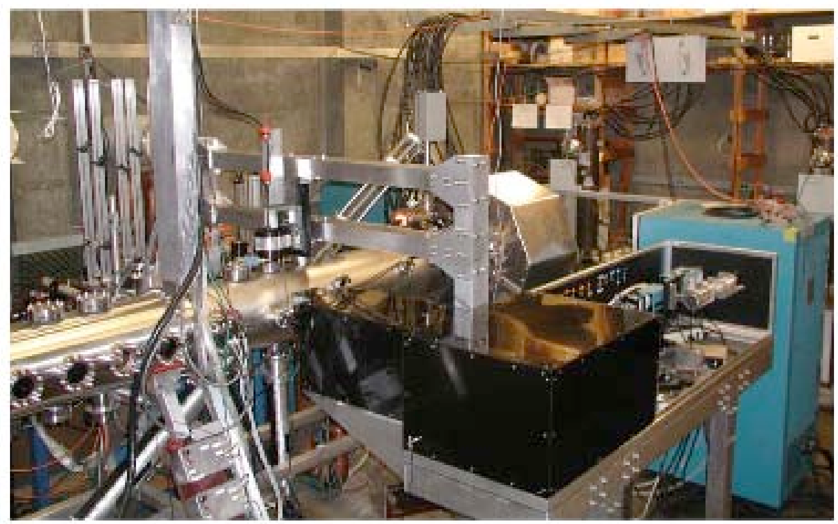
Sovinec

Diagnostics: Temperature Measurements on the ZaP Experiment - *Golingo* (UW)

The Plasma Characteristics are measured with an Array of Diagnostics

- Plasma density
  - A two chord heterodyne quadrature interferometer
  - A holographic interferometer
- Plasma velocity
  - A 0.5 m spectrometer which views 20 parallel chords through the plasma (ICCD)
  - A 1.0 m spectrometer with a 16 channel PMT at the exit slit (IDS)
- Shape and position of the emission from the plasma
  - An Imacon fast-framing camera
  - A 16 chord photodiode array and two 32 chord photodiode arrays
- Magnetic fields and current location
  - An axial array of surface magnetic probes
  - Four azimuthal arrays of surface magnetic probes
  - Zeeman splitting measurements
- Other diagnostics are used to verify these measurements
  - A 0.5 m spectrometer with a CCD and PMT
  - A bolometer and filter scopes
  - Gridded energy analyzer
  - Langmuir/Mach probe





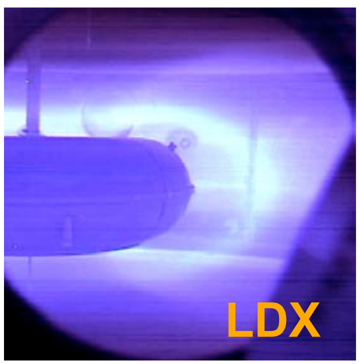
See also e.g.:
Teodorescu, Catalin Measurements of plasma isorotation on MCX University of Maryland

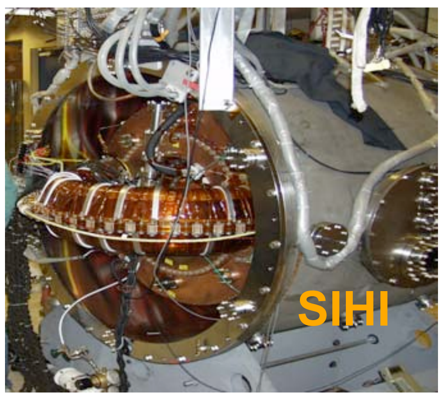
Summary

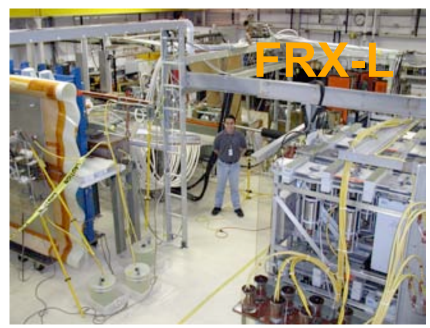
ICC 2007 was well attended - 120 contributions from 35 institutions in the USA and abroad.

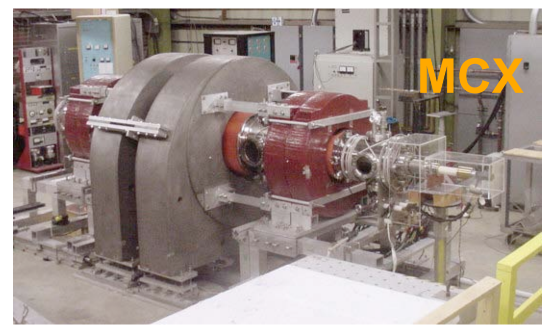
Scientific program moving towards a conference with published proceedings in JOFE.

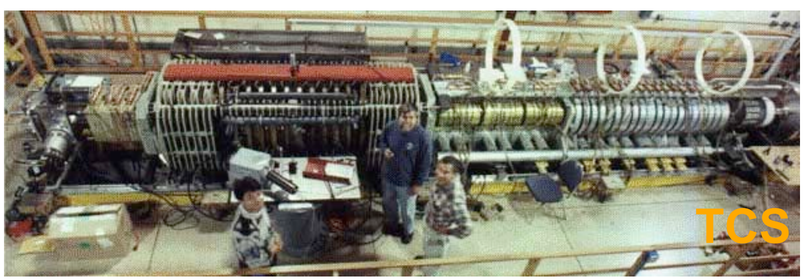
ICCs continue to explore important critical physics issues, employing advanced simulations, novel diagnostics and innovative approaches to technical problems.

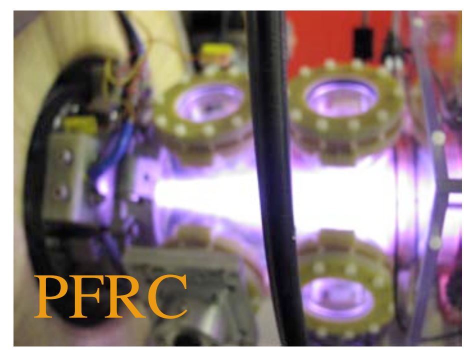










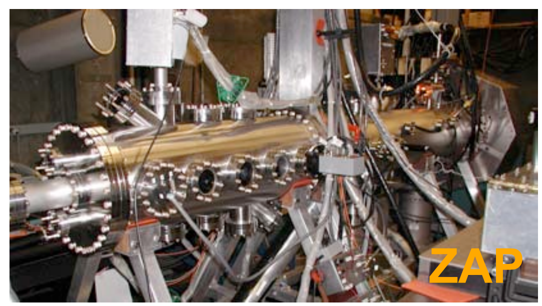


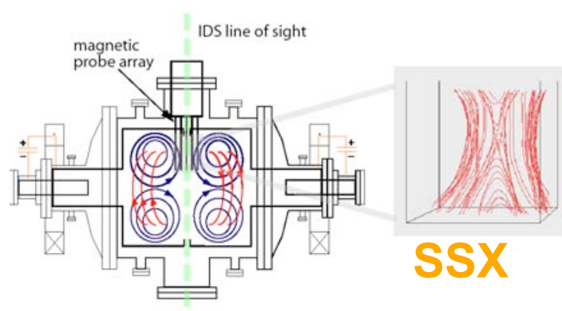
Call for papers for ICC 2008

The Innovative Confinement Concepts Workshop (ICC2008) will take place June 24 to 27, 2008 in Reno, Nevada.

Abstract submission, registration, and hotel reservations can be handled through the website:

http://iccworkshops.org/icc2008/





Extra material

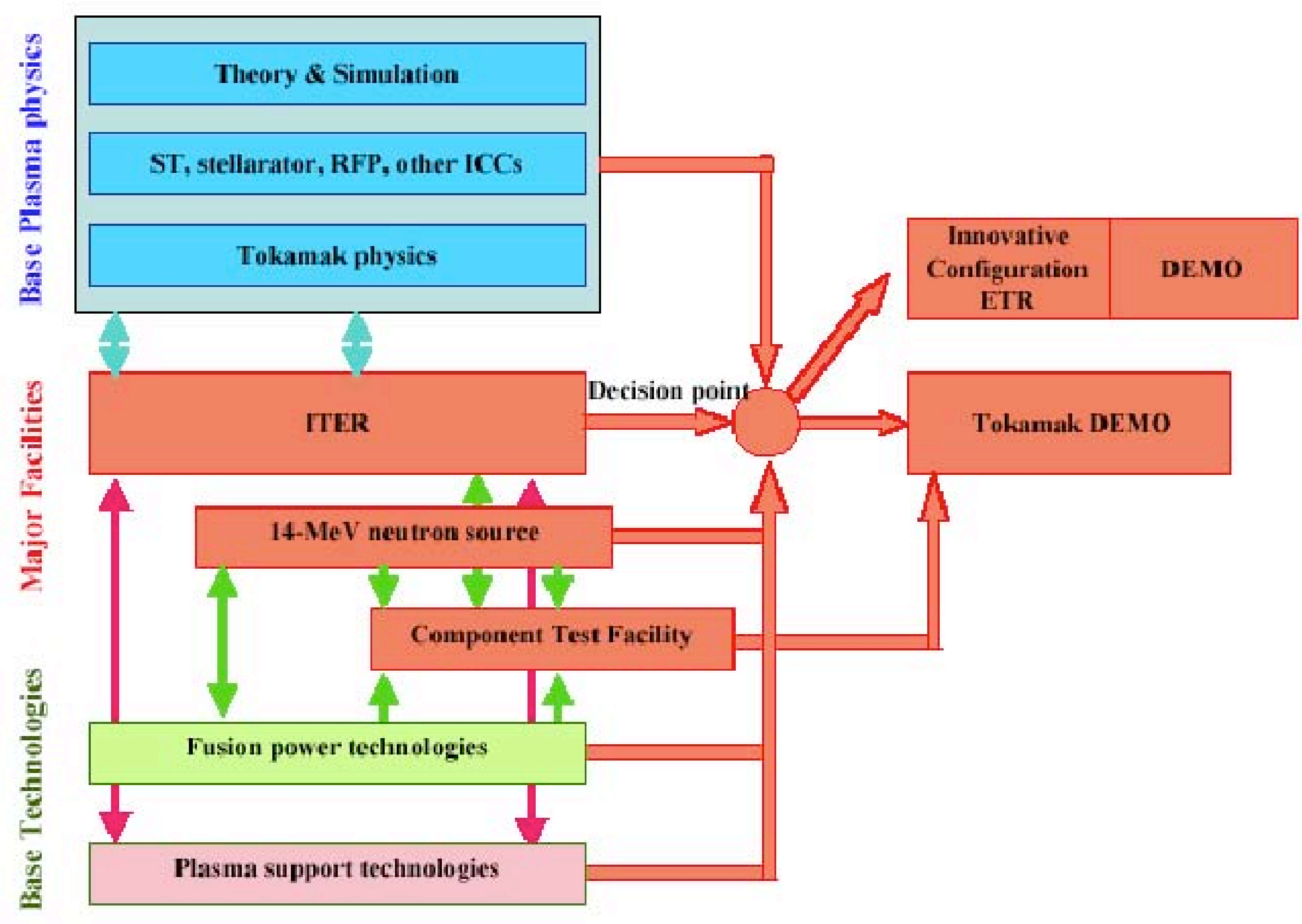
Innovative Confinement Concepts

- **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).
- Small-scale experiments (<1-2M/year) deliver **value** science.

SM 1999

_ Reduce or eliminate applied toroidal field
_ 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 puters) to obtain an idea of the range of possible futures.
_ Utilize high or __ __ (plasma pressure relative to magnetic pressure), to allow for possible advanced fuel cycle
_ Operate at intermediate density (between magnetic fusion and inertial fusion)

e.g. SM 2002 and IPPA - “The ICC experiments address several programmatic and fusion energy science objectives



e.g. SM 2002 and IPPA 1999

Words relating to the ICCs:

The Innovative Confinement Concepts are a core part of the US base Fusion Energy Sciences Program, along with the Advanced Tokamak (AT) program and the theory and computational modeling program.

The ICC program responds to Goal 2 of the Integrated Program Planning Activity: Resolve outstanding scientific issues and establish reduced-cost paths to more attractive fusion energy systems by investigating a broad range of innovative magnetic confinement configurations.

Skunkworks: opportunity to think quite outside the box, and so some talks are quite controversial.

The subject is novel ideas for fusion reactors -- physics and/or technology -- and not reporting on existing alternate concept research.

Novel ideas include significant new twists on old ideas, combinations of ideas that together offer a qualitative advantage, or completely new concepts and new opportunities created by technology advances, e.g. fast ignition in ICF.

Some suggested constraints on skunkworks: (a) conservation of energy and momentum (b) 2nd law of thermodynamics (c) no low temperature fusion unless you can demonstrate either unambiguous results or plausible barrier penetration schemes!

ICC Workshop Purpose

This workshop is for presentation of results and ideas about concepts that might make large steps towards practical fusion power, complementing the important feasibility steps of the International Tokamak Experimental Reactor (ITER), and the National (laser) Ignition Facility (NIF).

The ICC experiments also complement the mainline concepts in the advancement of plasma science. These experiments test the general validity of plasma physics and technology in wider parameter regimes, develop new fusion plasma physics, and cross-fertilize with other fields of plasma science.