LA-UR-99-2070

Self-organized plasmas

Briefing for the
SEAB Task Force on Fusion Energy
Princeton Plasma Physics Laboratory
April 30, 1999

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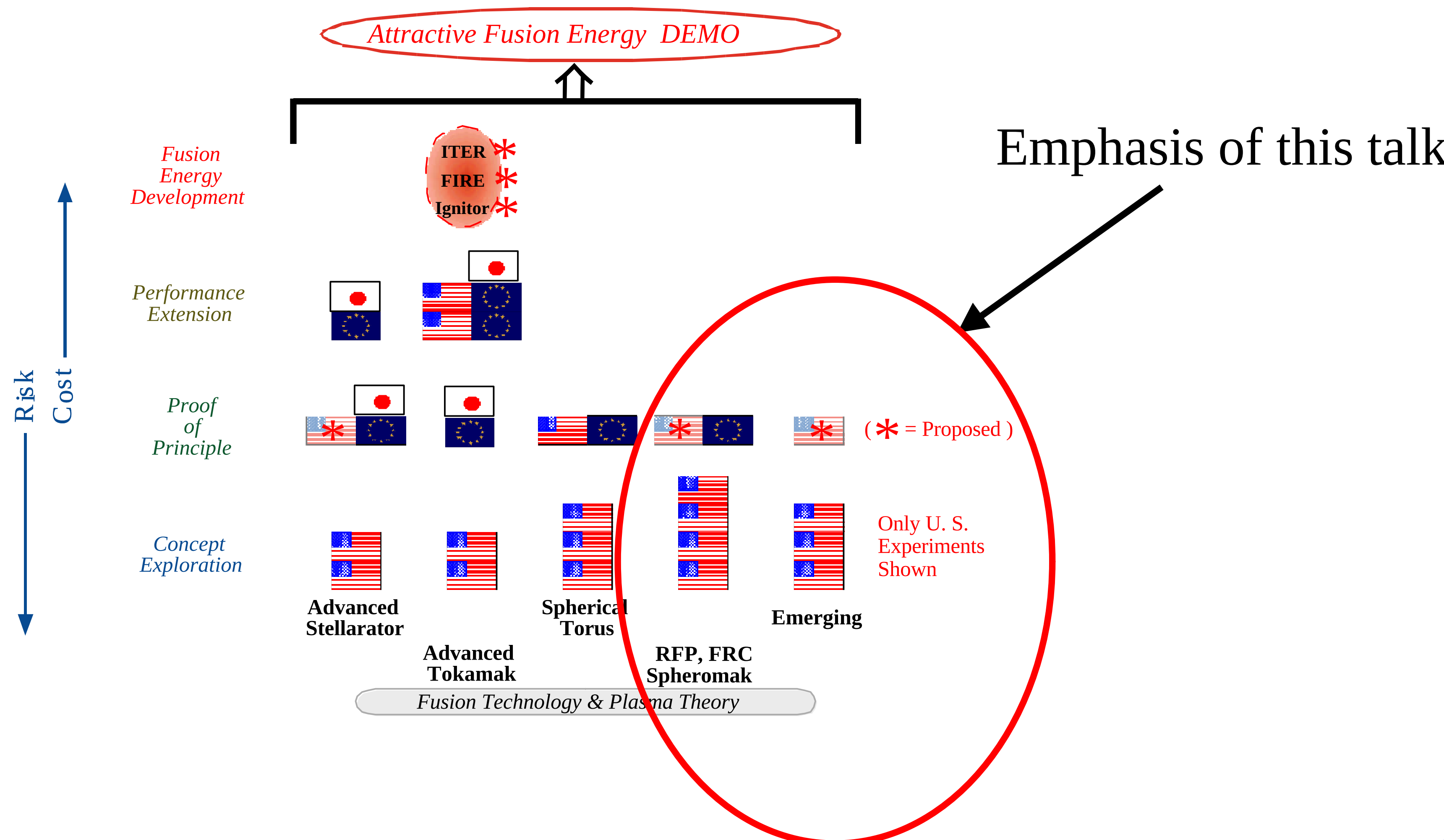
Abstract

Self-Organized Plasmas

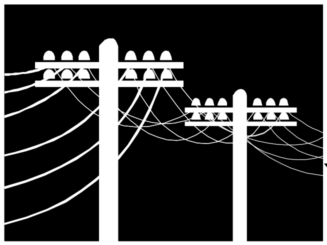
In the quest for fusion energy, sometimes Mother Nature helps. Certain plasma configurations exhibit properties known as "self-organization" where the plasma alters externally applied magnetic field in a way that improves the confinement properties needed for fusion. Examples in this talk include the reversed field pinch, the spheromak, the field-reversed configuration, and magnetized target fusion.

Exploring the less familiar

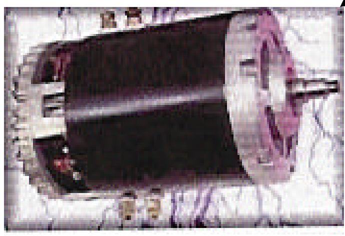


Few equations; many applications

Electricity



Motors



Cell phones

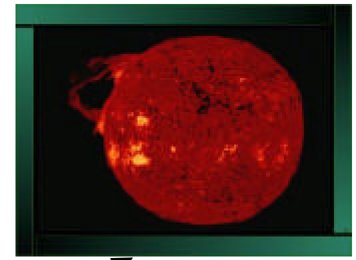
Computers

Maxwell + Boltzmann

$$\nabla \times B = j + \partial E / \partial t$$
$$\nabla \bullet B = 0$$
$$\nabla \times E = -\partial B / \partial t$$
$$\nabla \bullet E = q(n_i - n_e)$$

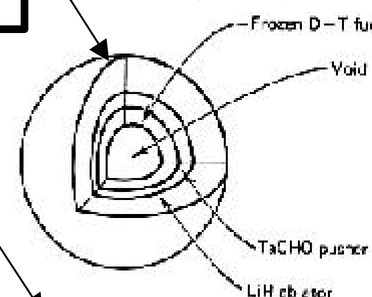
<u>MHD Approximation</u>

$$\partial n / \partial t = -\nabla \bullet (n\mathbf{u})$$
$$mnD(\mathbf{u}) / Dt = j \times B - \nabla p$$
$$3nD(kT) / Dt = P_{heat} + \nabla \bullet q - Rad$$

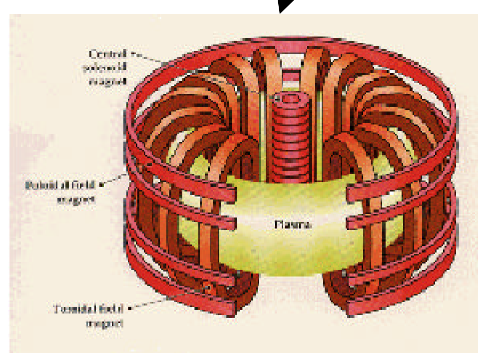


Astrophysics

ICF (B=0)



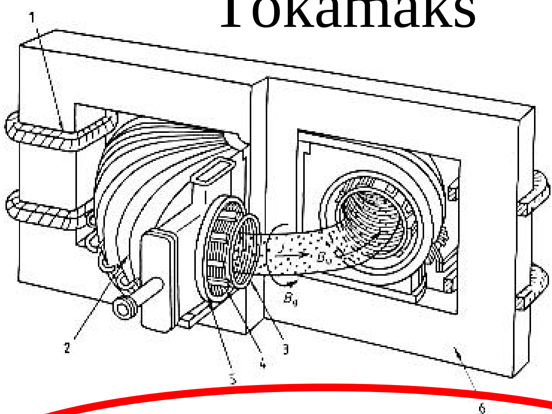
Magnetic fusion



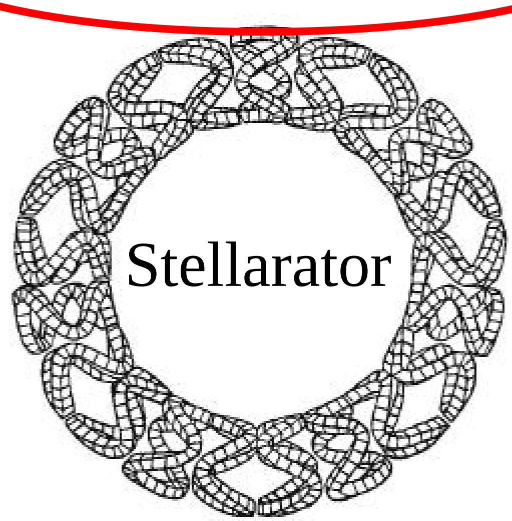
Plasma processing

Holding a plasma in a torus (donut shape) requires: $j \times B = \nabla p$

Tokamaks

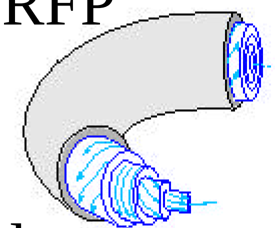


Externally controlled

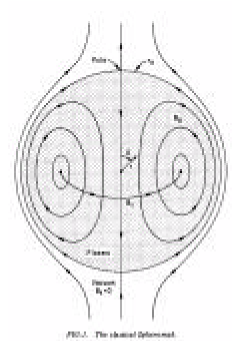


Spherical Torus

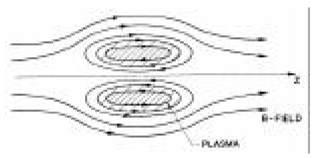
RFP



Spheromak



FRC

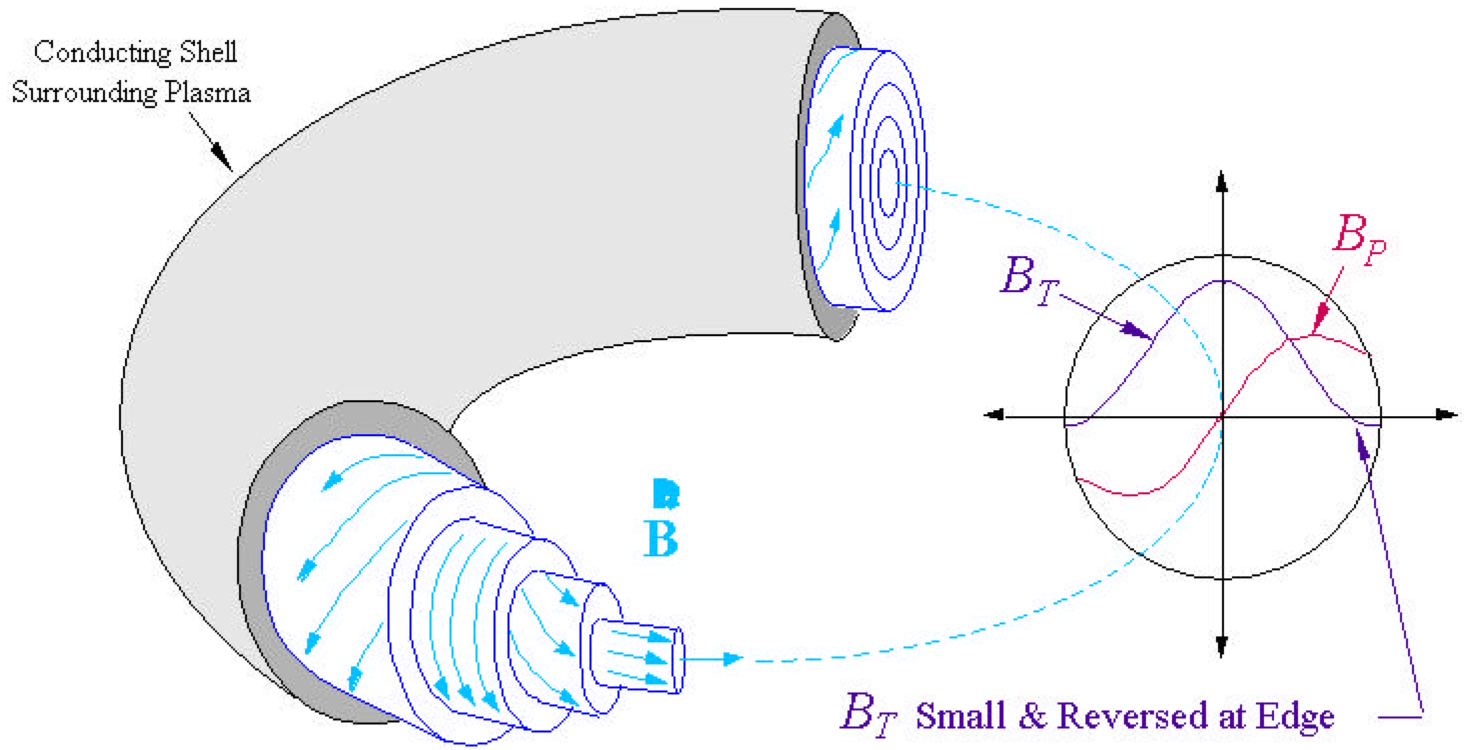


Self organized

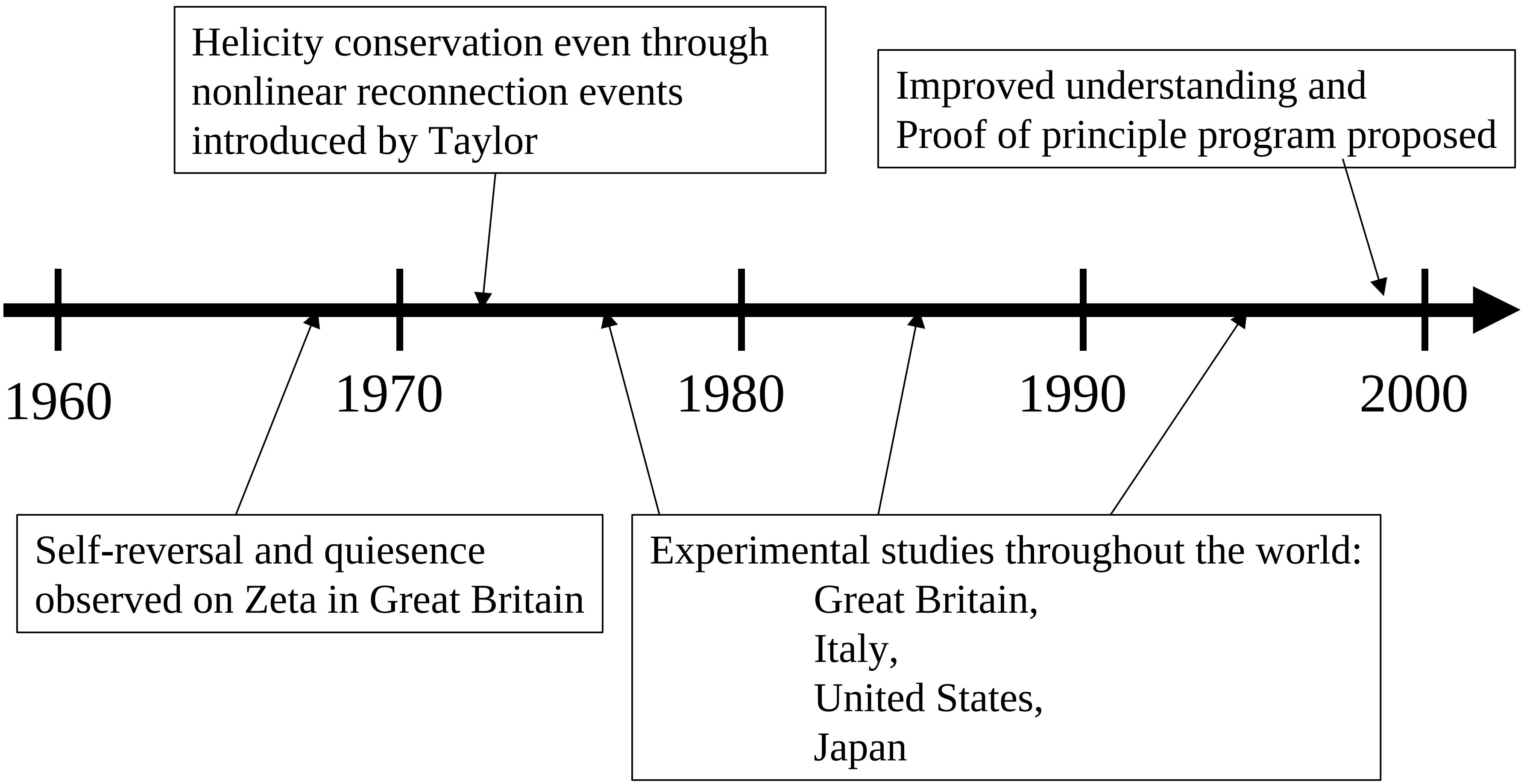
In each case one investigates thermal diffusivity χ because $\tau_E = (\text{size})^2/\ \chi$

Reversed Field Pinch: a self-organized plasma

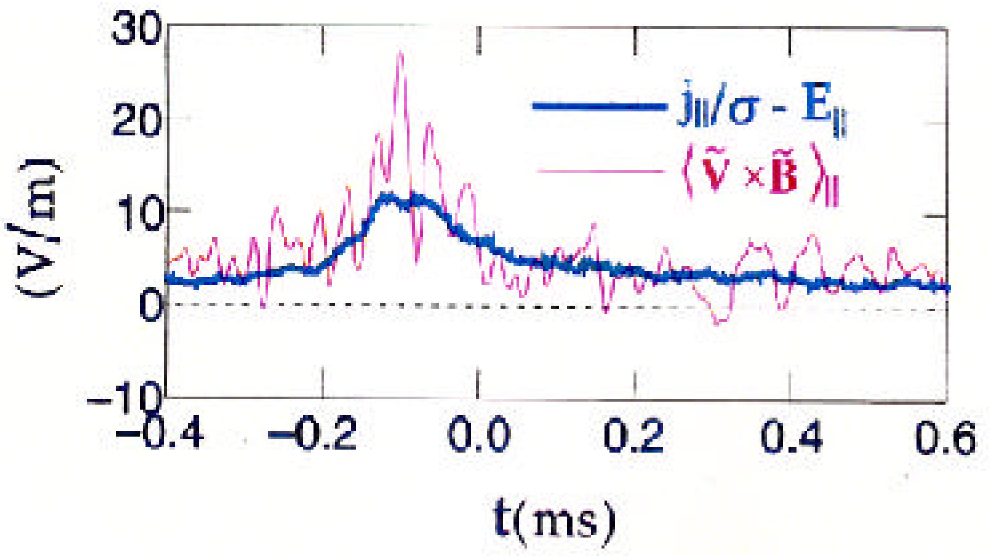
Small toroidal B reduces cost of magnet system



RFP discovered experimentally; theory by J. B. Taylor



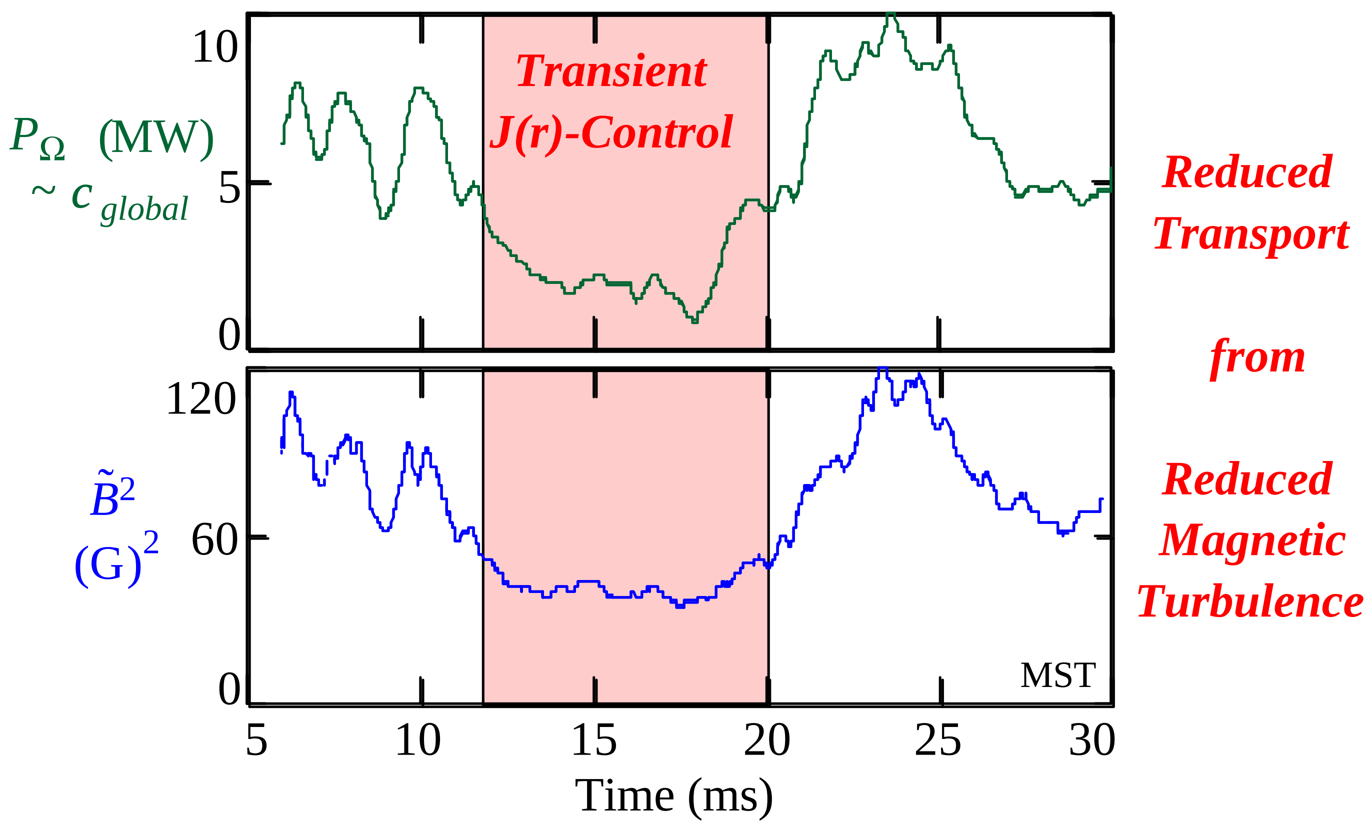
Magnetic fluctuations drive poloidal current



Parallel Ohm's Law: $E_{||} + \langle \tilde{v} \times \tilde{B} \rangle_{||} = j_{||}/\sigma$

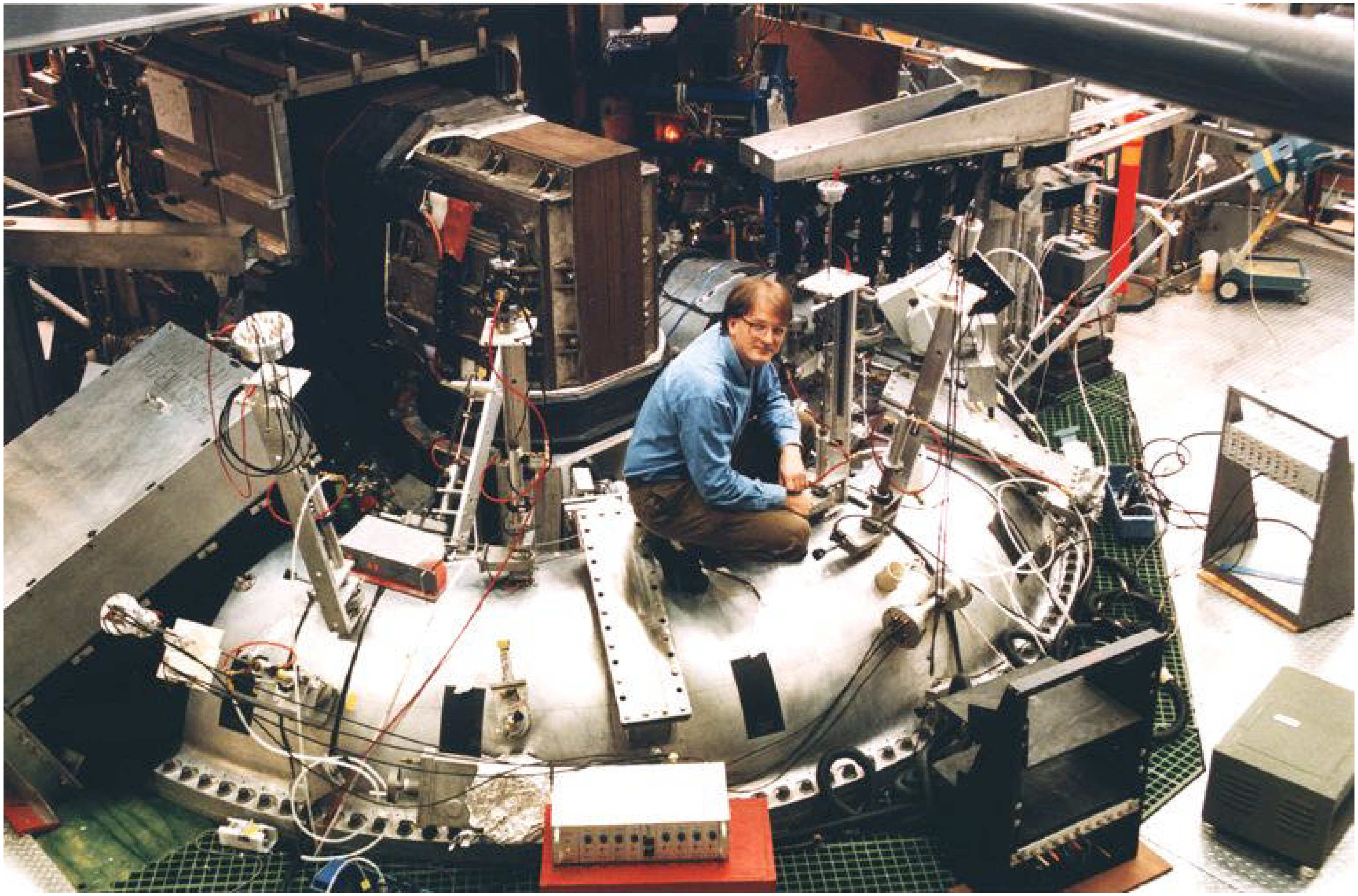
the dynamo term

Current profile control reduces dynamo-driven turbulence



This major new insight gives strong justification for a Proof-of-Principle test of the Reversed Field Pinch

Scientific progress leads to Proof-of-Principle



Understanding and improving transport is most critical RFP issue

Spheromak: logical extension of RFP to unity aspect ratio (nothing on the axis)

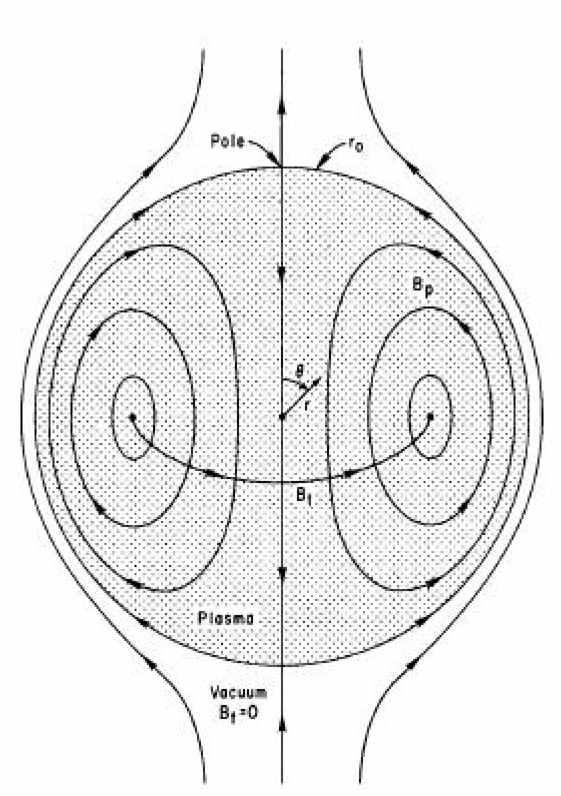


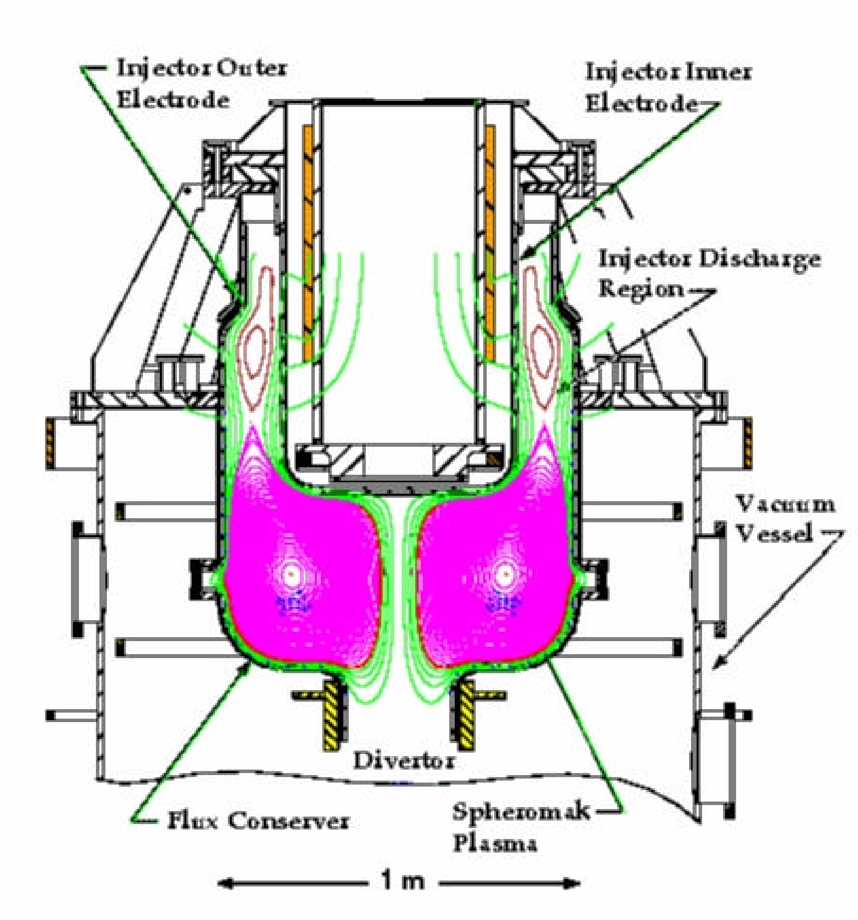
FIG.1. The classical Spheromak.

IAEA 1978: Furth, Rosenbluth *et. al.*

- Based on helicity (Taylor states) like the RFP
- First wall becomes essentially spherical
- Engineering simplicity: No material object links plasma

New experiment to address sustainment

An example of exploratory research



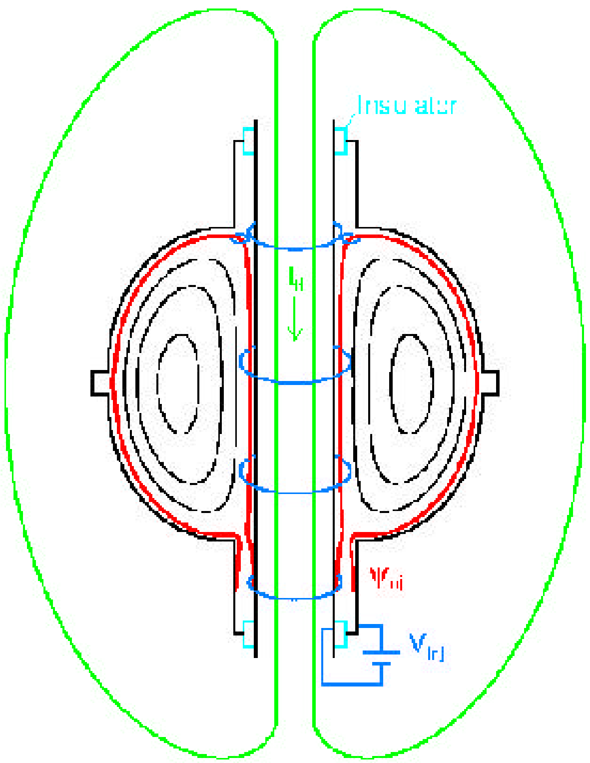
SSPX experiment at LLNL

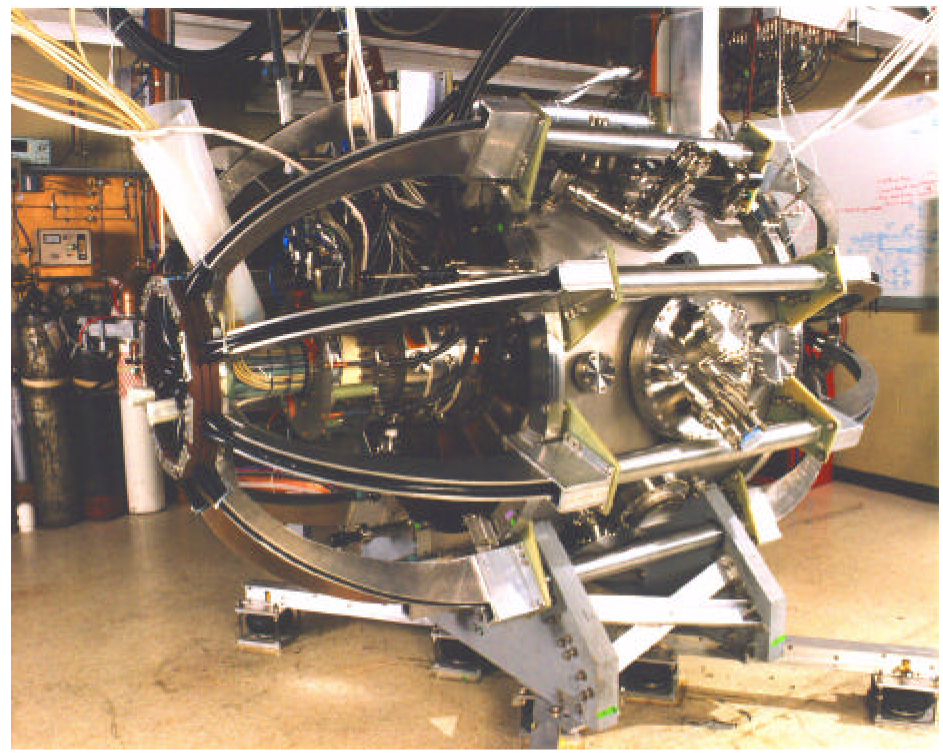
Features
- reduced field errors
- controlled helicity injection
- divertor and wall conditioning
- advanced diagnostics
- computed equilibria

Issues to investigate
- sustainment
- core energy confinement

Principle of helicity allows current drive

Exploratory experiment
U. Washington HIT experiment





Helicity injection to be tested on NSTX experiment at Princeton has potential for highly efficient current drive and may ease engineering requirements of the spherical torus central post.

SPHEROMAKS

by **Paul M Bellan** *(California Institute of Technology)*

Note

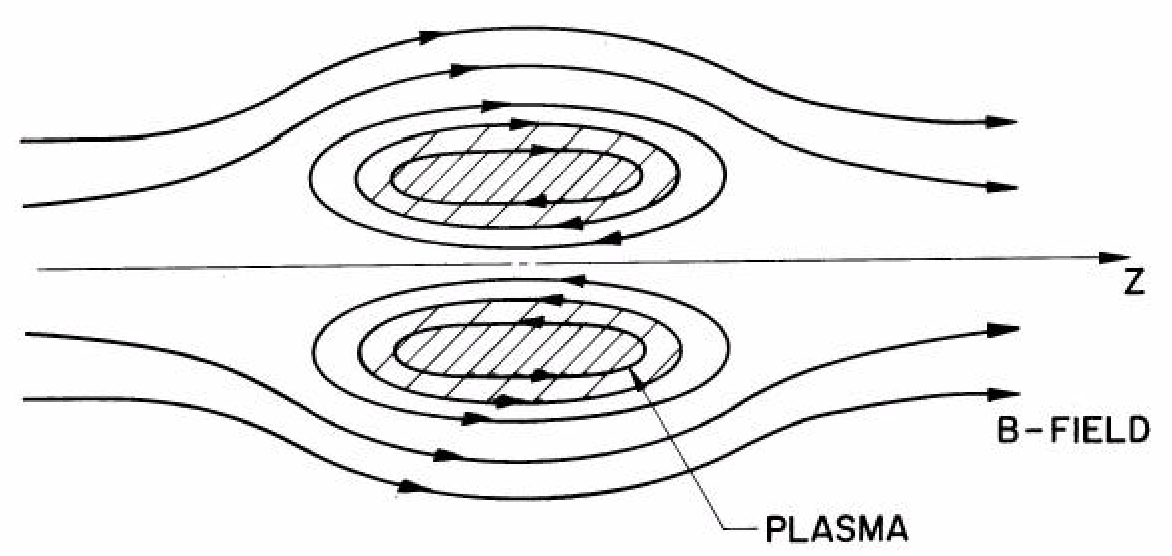
Spheromaks are easily formed, self-organized magnetized plasma configurations that have intrigued plasma physicists for over two decades. Sometimes called magnetic vortices, magnetic smoke rings, or plasmoids, spheromaks first attracted attention as a possible controlled thermonuclear plasma confinement scheme, but are now known to have many other applications.

This book begins with a review of the basic concepts of magnetohydrodynamics and toroidal magnetic configurations, then provides a detailed exposition of the 3D topological concepts underlying spheromak physics, namely magnetic helicity, Taylor relaxation, force-free equilibria, and tilt stability. It then examines spheromak formation techniques, driven and isolated configurations, dynamo concepts, practical experimental issues, diagnostics, and a number of applications. The book concludes by showing how spheromak ideas are closely related to the physics of solar prominences and interplanetary magnetic clouds.

Contents:

Imperial College Press, London (1999)

Field Reversed Configuration: high-β self-organized plasma



- $\langle\beta\rangle$ = 50-100%
- Power ~ $\beta^2 B^4$
- compact torus like spheromak

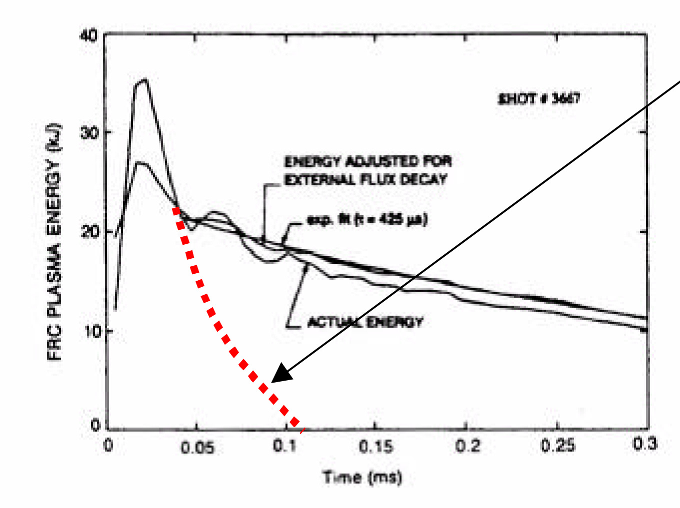
Major issue: stability

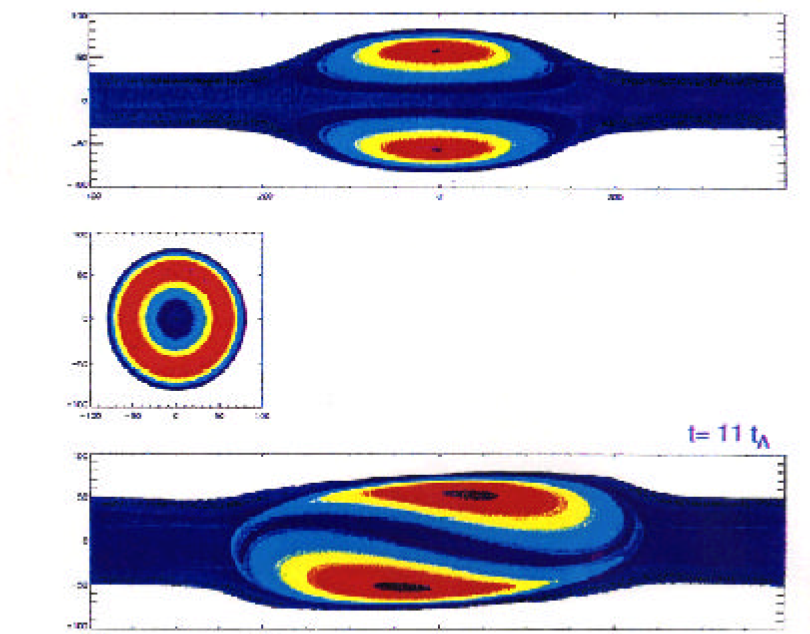
Theory of FRC behavior is incomplete

Experiments show slow decay

MHD theory predicts fast decay

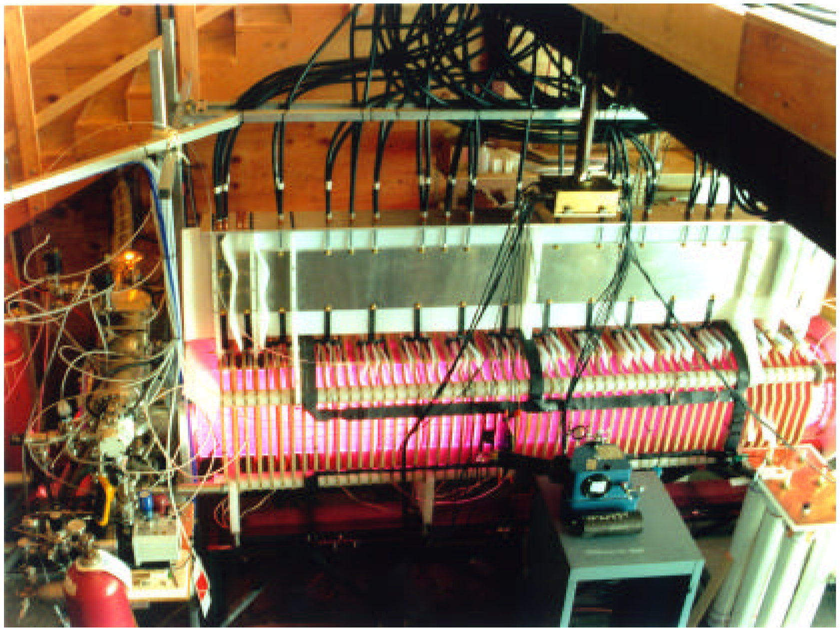
Hoffman and Slough, Nuc. Fus. **33**, 27(1993)





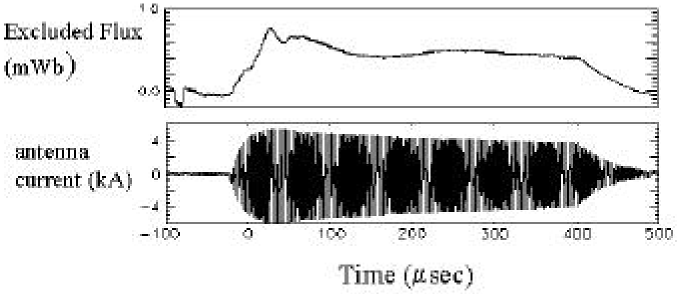
More complete theory will include kinetic effects and sheared flow

FRC sustained with current drive

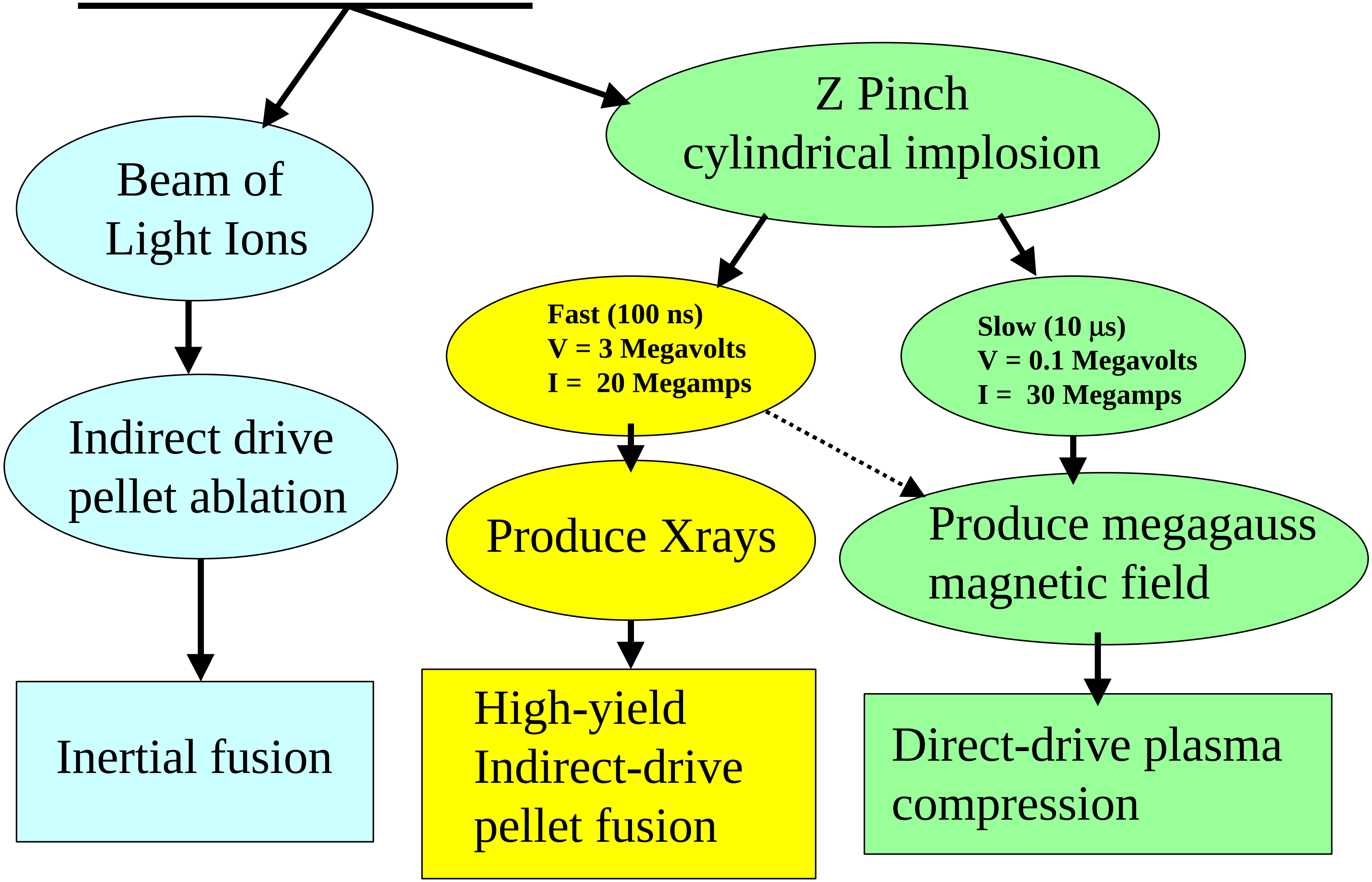


New Exploratory experiment

U. Washington rotating-magnetic-field current drive

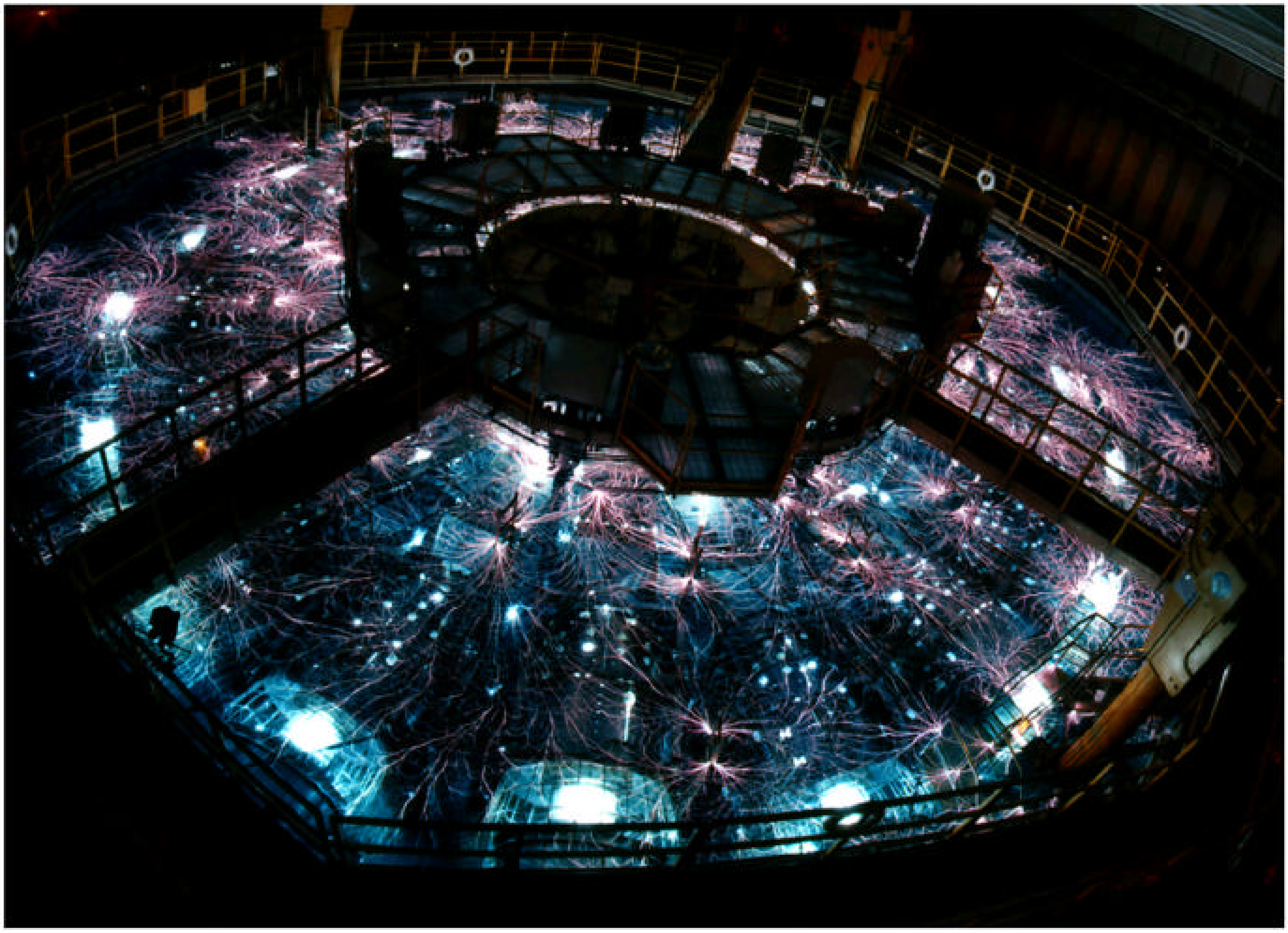


Pulsed power: *an enabling technology for fusion*



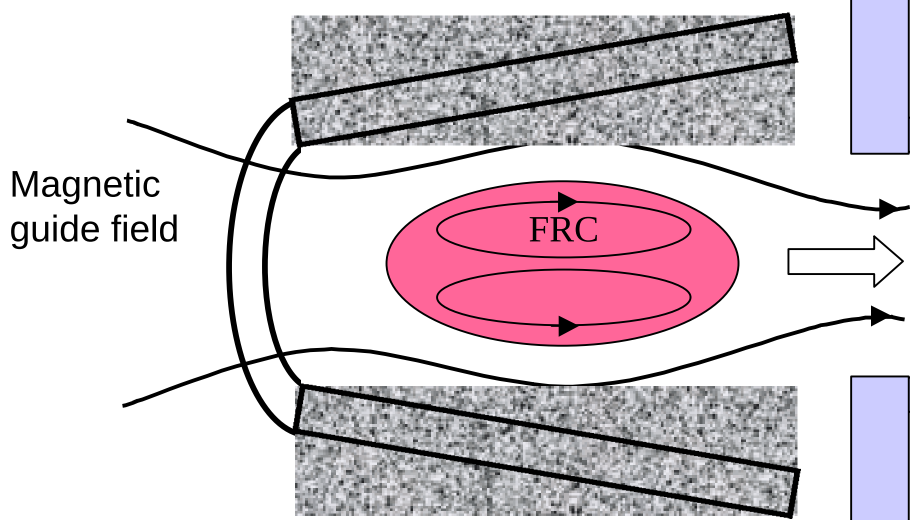
Z machine at SNL

state-of-the-art pulsed power

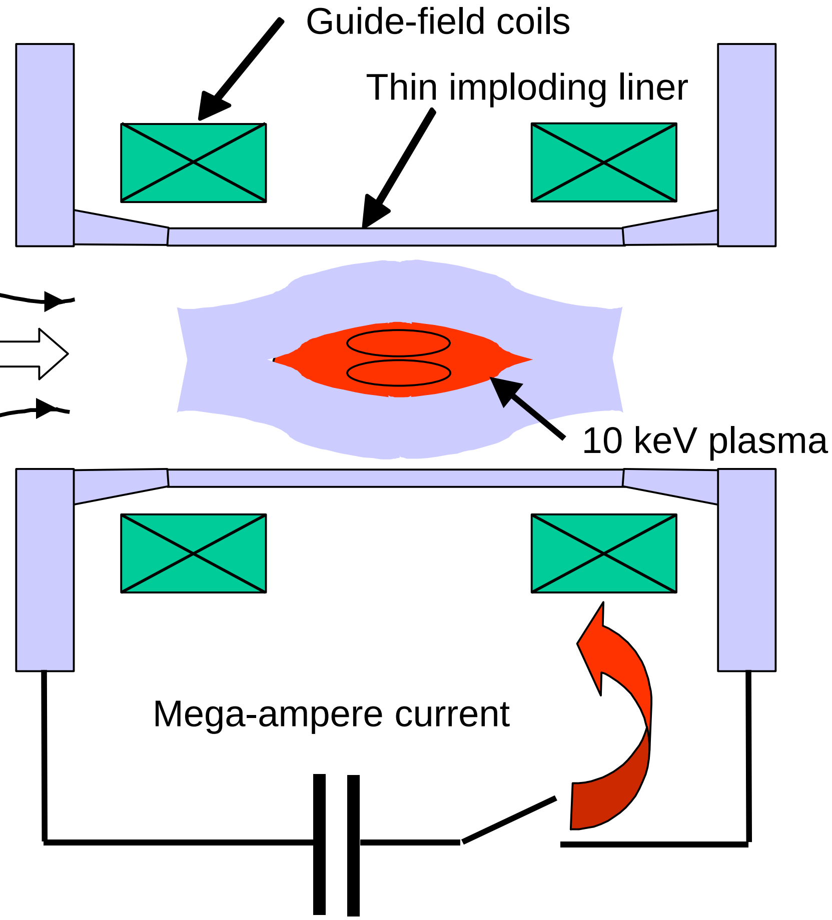


Elements of MTF

Plasma preheater and injector



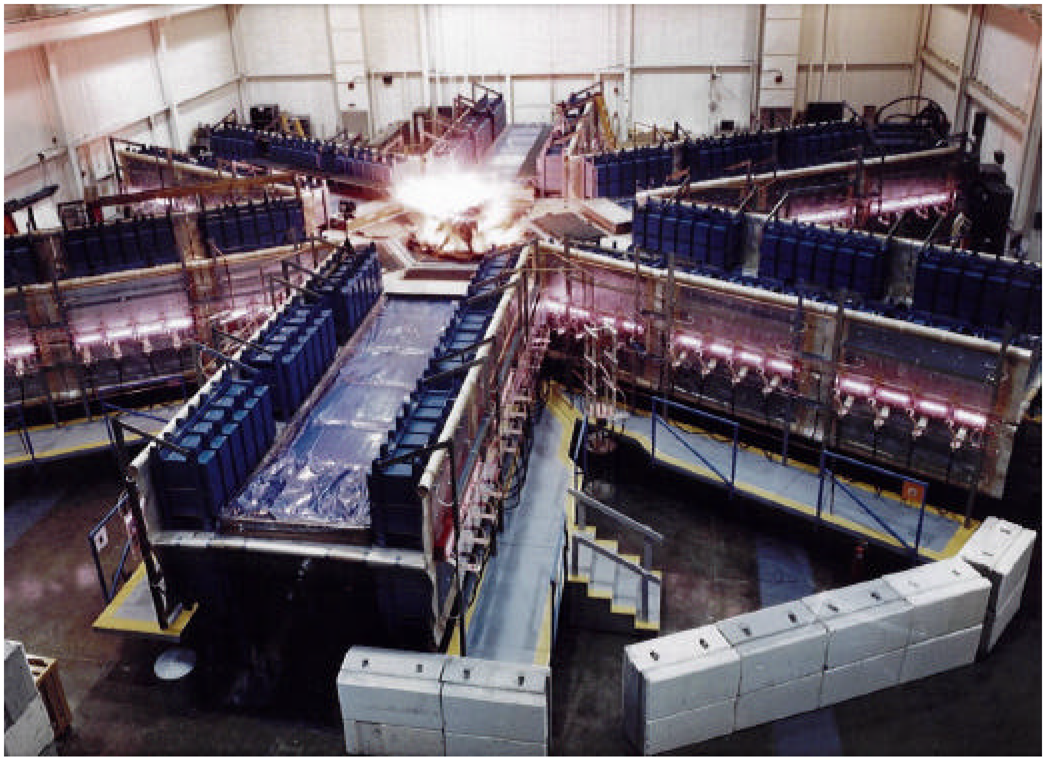
Liner implosion system



Typical parameters:

	Initial	Final
n	10^{17} cm^{-3}	10^{20} cm^{-3}
T	300 eV	10 keV
B	100 kG	10 MG

MTF Proof-of-Principle experiment

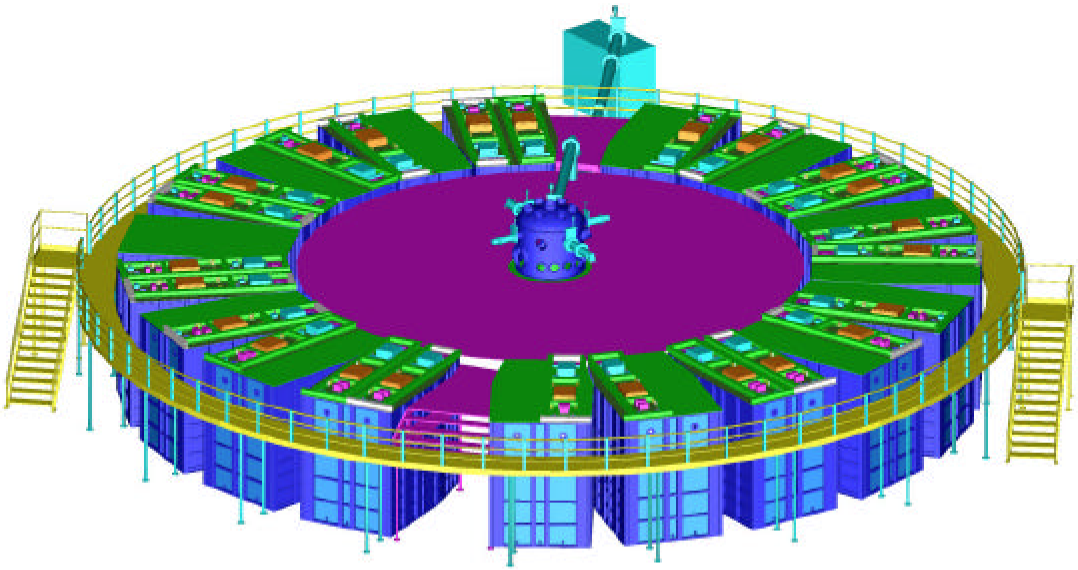


AFRL "Shiva Star" facility to drive PoP liner

- Peer reviewed and judged ready for PoP status in July 1998.
- Extends scientific study of self-organized plasma to high-field high-density regime
- Expect DT-equivalent fusion energy gain 1-10%

Magnetized Target Fusion

Potential for low-cost development path



Los Alamos ATLAS facility operational in 2001

- After PoP, performance enhancement ($Q_{equiv} \sim 1$) could be tested on $50M-ATLAS facility

As with IFE, major issue is kopeck problem: cost to manufacture components destroyed on each pulse compared with small revenue generated per pulse of fusion energy.

Summary

- Mother nature helps solve the quest for fusion by giving us "self-organized plasmas."
- More generally, fusion R&D is dynamic - new ideas and refinements in thinking are happening all the time.
- Diverse portfolio results in valuable cross-fertilization of ideas.
- By research on qualitatively different fusion approaches with different technologies, ranging from super-conducting magnets to high-power lasers, we ensure success for fusion even if a particular avenue encounters difficulty.
- Roadmap is an ongoing R&D <u>process</u> with new ideas at exploratory level to be repeatedly encouraged for the foreseeable future.