MFE Burning Plasmas and Innovative Confinement Concepts

Bick Hooper

LLNL

Presentation at the Snowmass Summer Workshop
July 8-19, 2002

Work performed under the auspices of the U.S. DOE by the U. of California LLNL under contract No. W-7405-Eng-48

What is an ICC?

- **Goal 2 of the Integrated Program Planning Activity states**

  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

  For this talk I will draw on features from the continuum of non-burning plasma experiments, including the "ICCs:"

  - **Advanced Tokamak**
  - **Proof-of-Principle (ICC) Experiments**
  - **Concept Exploration (ICC) Experiments**
  - **Science Experiments which bridge the gap between fusion and natural plasmas (e.g. exploring the physics of magnetic reconnection)**

Burning plasma physics within a balanced portfolio of diverse concepts is essential for development of an attractive power source

We must engender creativity and inventiveness to achieve fusion energy

PHYSICS

- Burning plasma physics will impact advanced tokamaks and many ICCs directly and through a predictive scientific and technology base
- A predictive science base requires outstanding diagnosis of the burning plasma coupled through fundamental theory and computational modeling to the ICCs, advanced tokamak, and science experiments

A BETTER REACTOR?

- Vision: A concept or innovation that works better or changes the paradigm for fusion energy
- Pursuing a portfolio of toroidal concepts will broaden parameter space — testing, expanding, and strengthening our scientific basis — introducing innovation on the path to a reactor

NEW TALENT

- Innovation, both in the ICCs and burning plasmas attracts bright, young talent
  - Needed for future strength in plasma and fusion energy
  - Needed to support a burning plasma science experiment
  - Students are particularly attracted by local, innovative experiments

Transferring science between ICCs and burning plasmas

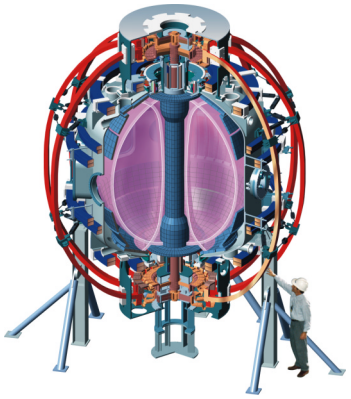
- A predictive, science base is essential to long-term progress
  - Thus, bpx should have:
    - o broad operating space and flexibility to vary parameters
    - o extensive diagnostics
    - o coupling to modeling

  We will return to these requirements later

- The overlap with burning plasma physics will differ among the ICCs, ranging from large for the PoP experiments to almost none for some of the ICCs

  It is useful to look at examples to see how this overlap varies
  - Spherical Torus, as a toroidal PoP with a development path similar to the conventional tokamak
  - Spheromak as a toroidal concept with possible alternative development paths
  - Toroidal plasmas as a unified plasma science
  - IEC-POPS as a concept with very little in common with the conventional tokamak

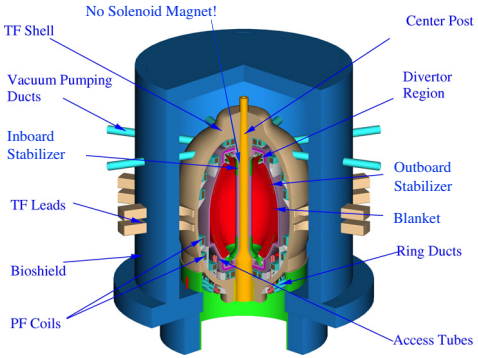
Burning Plasmas and the Spherical Torus — a PoP toroidal plasma



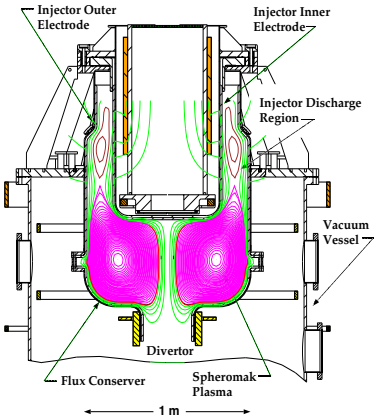
- The ST is a tokamak squeezed to the lower limit of aspect ratio, leading to
  - Strong fieldline curvature
  - Low outboard toroidal magnetic field
  - High beta, with central value ~ 1

- Strong overlap with tokamak burning physics
  - Alpha-generated pressure may impact high beta, MHD stability, and control
  - TAE modes will have similar physics
  - Energy confinement may contain substantial features of electrostatic turbulence
  - Heating, fueling, rotation, and current drive have similar technology (+ others – e.g. helicity drive?)
  - Plasma-boundary interactions will require a divertor or other means of handling high power

- Differences allow new contributions to bp tokamak physics
  - Strong diamagnetic effects, deep magnetic well
  - Large Alfvén Mach numbers, altered MHD equil., stability
  - Large ion gyroradii, strong magnetic effects on turbulence
  - Large dielectric constant ~ 100, $v_{alpha} \sim 4\ v_{Alfvén}$
  - Large mirror-ratio effects on plasma boundary physics



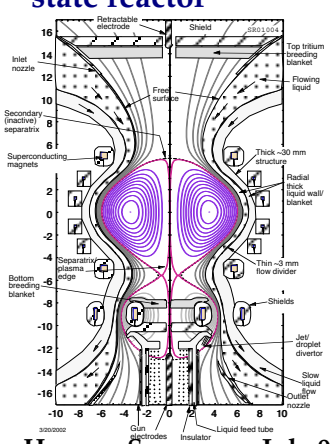
Burning Plasmas and the spheromak — a CE toroidal plasma



- The spheromak is potentially an excellent reactor, *but*
  - The physics still poorly understood — we don't know if it will work at all in the burning plasma regime
  - Several reactor visions: "*conventional*," *liquid-wall steady-state*, *liquid-wall pulsed*, and *core for magnetized target fusion* — we need new physics results to evaluate these realistically
  - Spheromak plasmas differ from tokamaks – First-principles, scientific capability will be needed to apply bp physics

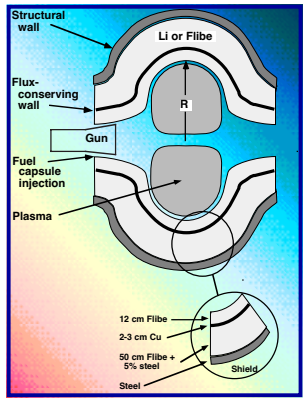
- Moderate overlap with tokamak burning physics — but extent unclear
  - MHD equilibria and stability, but at $q < 1$
  - Self-consistent pressure profiles from fusion products
  - Alpha particle drive for Alfvén and other modes
  - High-power plasma-wall interactions

Liquid-wall, steady state reactor

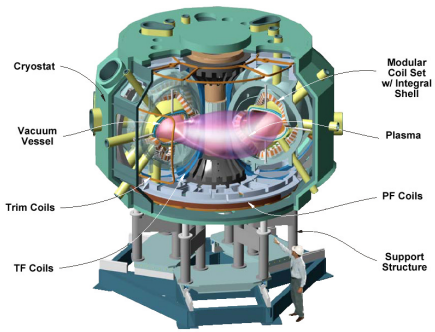


- Spheromaks operate in a very different physics regime than the tokamak, both complementing and expanding it
  - $q < 1$ — as in the RFP
  - Transport driven by magnetic turbulence, at least in present experiments
  - Singly connected volume
  - Current-drive options include electrostatic helicity injection

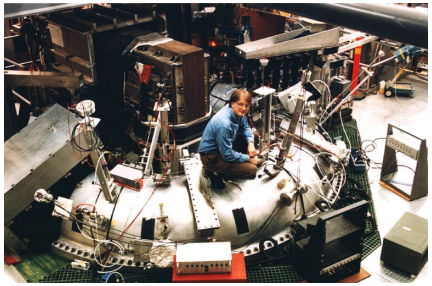
Liquid-wall, pulsed reactor



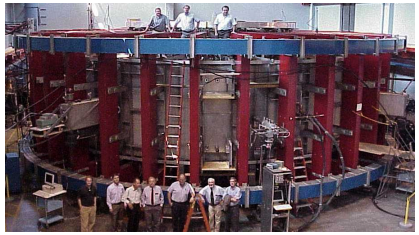
Toroidal experiments, including stellarators, RFPs, FRCs, ETs broaden the parameter space for toroidal plasmas while seeking a better reactor

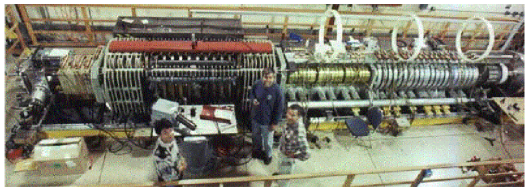


- The broad parameter space explored by the ICC toroidal plasmas will strengthen the science of toroidal plasmas, e.g. variations relative to the tokamak:
  - symmetry versus quasi-symmetry
  - safety factor and shear
  - role of plasma current
  - magnetic well
  - beta
  - size



- The physics overlaps between these devices and the bpx vary from high for the stellarator to moderate for the FRC
- These experiments explore new physics, test and extend physics from tokamaks, and offer new reactor opportunities



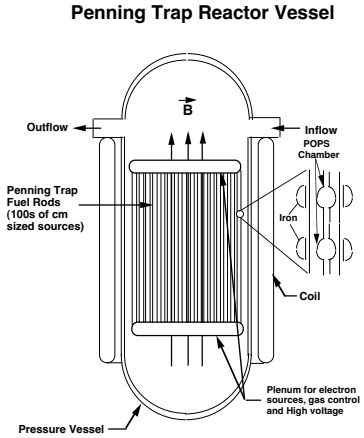


Burning Plasmas and Inertial Electrostatic Confinement (POPS) — a CE non-toroidal plasma

- The Periodically Oscillating Plasma Sphere is radically different from the tokamak, with a very different reactor vision
- An example of an attempt to shift the paradigm for fusion

- Almost no overlap with tokamak burning physics
  - No toroidal magnetic field — plasma is confined by the electrostatic potential
  - Behavior and stability of a thermal plasma in a pulsed, parabolic electrostatic well — central to the concept — have no parallel in the tokamak
  - Critical issues — e.g. electron cloud uniformity, space charge neutralization during ion collapse, impurity control, oscillation control differ significantly from magnetized fusion plasmas

- Reactor looks more like a fission assembly than a tokamak
  - There are many small "spheres" comprising the reactor ~ 10^7 in the illustrated reactor
  - Wall power (neutron) loads are comparable to a fission reactor as the coolant (doped - H_2O) absorbs the neutrons



Technology transfer will be as important as physics

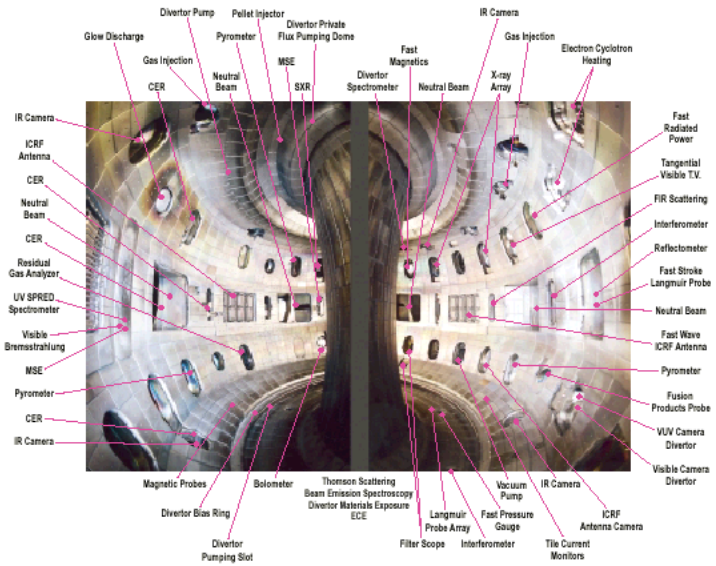
Most burning plasma technologies are applicable to one or more of the ICCs

- **Magnetic coils — Superconducting coils will be needed for most steady-state devices, although resistive coils may be acceptable if the plasma beta is high**
- **Heating and current drive technologies — Applicable to many ICCs; new current drive techniques such as helicity injection may be developed**
- **Fueling technologies — Gas puffing or pellet injection are sufficiently flexible to be adapted to most toroidal ICCs. Compact toroid injection is an advanced option**
- **Plasma facing components — Many ICCs have higher wall power loads than the tokamak, so this may be one of the most important spin-offs**
- **Remote handling — Development of and experience with remote handling will be of major utility to the ICCs**
- **Nuclear Technology — Breeder materials tests and blanket designs will be applicable to many concepts**

What do we learn from these examples?

- **The potential impact of a burning plasma experiment (bpx) on an ICC varies from large to almost zero**
- **Even in an ICC with large overlap, there are significant differences in the detailed physics — after all, the goal is to develop a better fusion reactor**
- **At the other extreme, there is a significant paradigm shift — the goal is a qualitatively different approach to fusion energy and the overlap is small**
- **Application of the results from a bpx will require development of a predictive, scientific understanding which is NOT concept specific**
- **We need to nurture a broad range of ideas — of varying maturity — which have the potential to yield a better fusion reactor**
- **We should expect the base program to evolve and mature — there will be new ideas, some concepts will progress to higher levels of development, and deeper understanding of the science will occur**

Knowledge development requires outstanding diagnostics



View of DIII-D interior, showing diagnostic locations (from DIII-D 5-year plan

- The Advanced Tokamak is our "gold standard" for diagnostics
  - As our "Performance Extension" program it has significant resources
  - Highly quantitative results – e.g. in current profiles and turbulence amplitudes – have generated major advances in our understanding
  - The AT will still be our best test bed for studying many phenomena — e.g. electron transport

- Neither the burning plasma experiment nor the ECs are likely to reach this level of diagnostic capability
  - The burning plasma experiment will operate in an intense radiation environment, making diagnostic access and operation very difficult
  - Most ECs focus on specific physics issues, but lack sufficient resources to implement such a broad set of diagnostics
  - PoPs may have a large enough array of diagnostics to complement the AT

The AT can help bridge between the bpx and the ICCs

- **Test features of burning plasma physics in detail, albeit in a limited regime**
- **Test new physics from the ICCs, including from science experiments focused on narrow physics issues**
- **Guide experiments on the bpx**
- **Strengthen the coupling of these results to theory and computational modeling, including testing the results of these calculations**

The AT can be both a path to a better tokamak reactor and a flagship for our entire fusion energy program, helping to unify burning plasmas, PoP experiments, ECs and basic science studies

Knowledge transfer requires predictive science

Predictive science — enabled by modern computations — is essential to transferring knowledge among concepts and levels of development

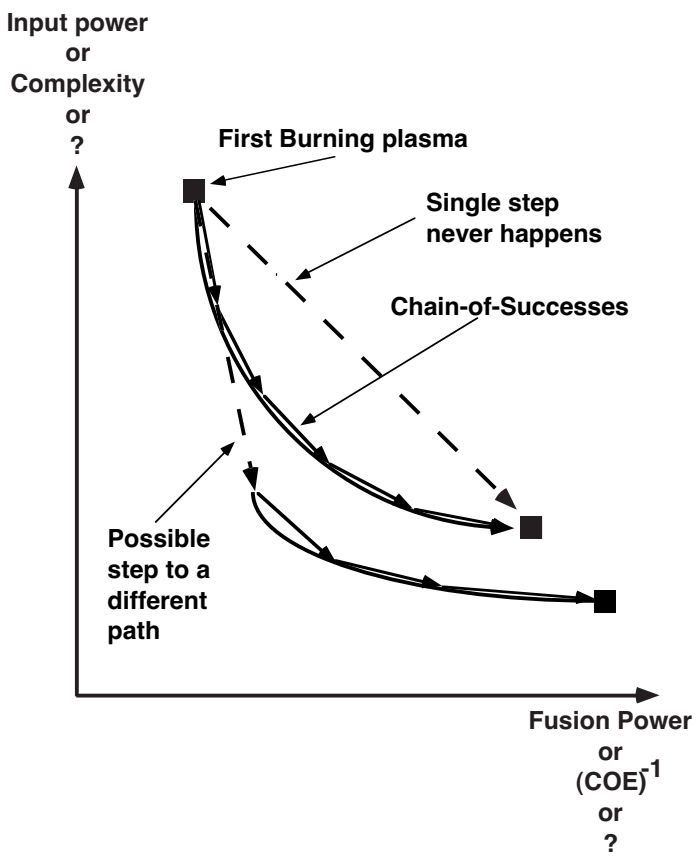
- **Even for the closest relatives of the tokamak, operation is in a different part of parameter space than the proposed burning plasma experiments**
  - **Extrapolation of bp physics results will be needed to apply them to ICCs**
  - **Unification of physics across a broad range of parameters will be needed**

- **Most phenomena of interest are complex and nonlinear — only computations can address them quantitatively**

Successful transfer of knowledge will require both the bpx and the rest of the program to be tightly coupled to a strong computational modeling effort

A Fusion Energy Reactor is a complex system

John Nuckolls has spoken of the need for a *"Chain-of-Successes"* in the development of Fusion Energy — as for any complex system



- **Fusion energy will certainly progress to useful energy this way, perhaps even with discontinuities as new innovations become possible**
- **Successful inventions can provide discontinuities in development, yielding a better end product than envisioned in the initial success**
- **Many — probably most — creative and inventive ideas won't pan out, but we need an environment that encourages them — we cannot predict the birth of the ultimate fusion power source**

Choosing the US burning-plasma experiment – the ICC perspective

The chosen burning plasma experiment must be capable of exploring a broad range of physics parameters, have good access, include a well thought-out diagnostic plan, and be supported by a strong theoretical and computational modeling effort

Given this,

- **The burning plasma experiment will couple successfully to the ICC programs, guiding their development into the bp regime**
- **It will strengthen the US fusion energy program by including the science of burning plasmas as one of our core strengths**

A unified fusion energy program will require everybody — from OFES to the bench scientist — to pull together