Compact Torus Panel

FRC and Spheromak

Status report

Theme 5 Workshop

PPPL, March 16-20, 2009

Bick Hooper

Fusion Energy Program, LLNL

My work performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under contracts W7405-ENG-48 and DE-AC52-07NA27344.

The CT Panel Report builds on the TAP report with the goal:

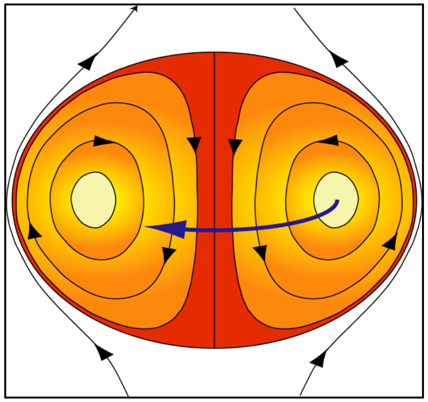
> Define research thrusts to develop the physics of the FRC and spheromak needed to produce fusion-quality plasmas in the ITER era

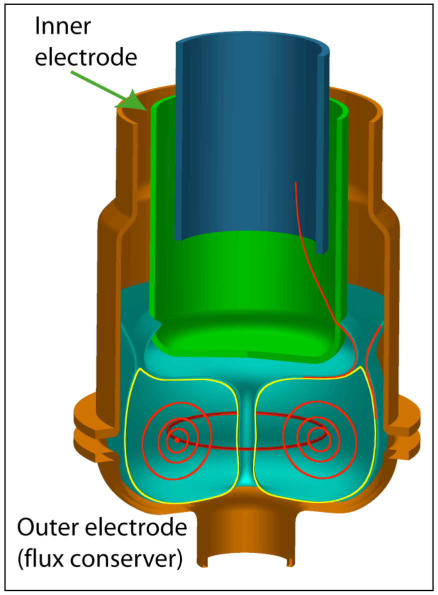
Progress is reported in three talks representing the panel:

- Fusion opportunities for CTs (Simon Woodruff)
- FRC issues, needs, and gaps (Richard Milroy)
- Spheromak issues, needs, and gaps (Bick Hooper)
  Draft thrusts for the FRC and spheromak

SPHEROMAK ISSUES, NEEDS, AND GAPS

Spheromak — concept and status





- Toroidal equilibrium in simply-connected flux conserver
- $q < 1$
- Generated by helicity injection, induction, and other techniques

<u>Achievements</u>

- Flux-conserver radius = 0.5 m
- $B > 1$ T, $I_T > 1$ MA, $\psi_{Pol} = 75$ mWb
- $T_e = 500$ eV in *slowly-decaying* plasmas
  Electron thermal conductivity ~ L-mode
  $\chi_e = 1\text{-}10\ m^2/s$ (core)
- $\beta_{peak,electron} = 5 – 20\%$
- Spheromak sustained by helicity injection (electrostatic and inductive)
- Resistive MHD simulations agree well with many experimental results
- Several small experiments are studying formation and sustainment

ISSUES — unchanged from the TAP report

Tier 1

- ***Sustainment and Confinement*:**
  Achieve efficient, time-averaged current drive simultaneously with good confinement
- ***Formation*:**
  Develop an efficient formation technique to generate fusion-relevant spheromak magnetic fields

Tier 2

- ***Transport*:**
  Determine underlying transport mechanisms and confinement scaling in low-collisionality spheromak plasmas
- **Beta limits**
  Understand beta-limiting mechanisms
- ***Particle Balance and Density Control*:**
  Understand particle balance and control of plasma density and impurities

Tier 3

- **Fast Particles**
  Understand effects of fast particles on current drive, stability, and confinement
- **Resistive wall modes**
  Demonstrate resistive-wall mode control
- **Technology**
  Develop technology for long-pulse operation

SPHEROMAK RESEARCH NEEDS (1)

Sustainment and Confinement

Use experiments and simulations to investigate sustainment methods that reduce or avoid magnetic relaxation over at least part of a discharge cycle

- **Helicity current drive that is consistent with good confinement – *Possibilities*:**
  - **Operation in which fluctuations drop rapidly enough with plasma temperature that energy is well confined – e.g. using $n_{toroidal} >> 1$ modes to drive the dynamo**
  - **Good confinement (coaxial) regions of poloidal flux to minimize energy losses**
  - **Pulsed injection of helicity into outer flux surfaces, e.g. merging small spheromaks with the primary one**
  - **Non-axisymmetric approaches to helicity drive**
  - **Application of alternating field current drive (OFCD)**
  - **Auxiliary heating to minimize helicity losses in the spheromak**

- **Neutral beams or rf current drive to sustain the spheromak**

- **Separate plasma current drive (“refluxing”) in time from a coasting (slowly decaying), confinement/burn phase**

- **Develop pulsed spheromak fusion**

Improved computations, including two-fluid and other effects, can guide experiments

SPHEROMAK RESEARCH NEEDS (2)

Formation

Improve energy efficiency of building the magnetic field from the present 5-20%

Increase amplification of the spheromak bias flux from the factor of 6-10 found in experiments to the factor of 50 required to minimize losses on open field lines

- Improve coupling efficiency between the power supply and plasma
- Optimize confinement and electron temperature, and minimize dissipation during buildup
- Evaluate effects of a decrease in open field-line volume after formation by extracting applied, bias flux and injected current
- Determine the efficiency of alternate methods of formation, e.g. using fast injection
- Use simulations to model formation, e.g. sensitivity to geometry, and to guide experiments

SPHEROMAK RESEARCH NEEDS (3)

Transport

Understand the electron transport mechanism for the low $\chi_{E,e}$ observed in slowly-decaying spheromaks

Measure and understand ion transport mechanism(s) in spheromaks

- **New experiments will be required, including:**
  - **Plasma heating to separate transport from ohmic heating limits**
  - **Rotation control to explore effects on confinement**
- **Diagnostic capability will need to be expanded, including**
  - **Ion temperature diagnostics for the interior plasma**
  - **Fluctuation measurements, including a means to differentiate between electrostatic and electromagnetic modes**
- **Computational support is needed to develop an understanding of transport mechanisms in a high-β, low-q plasma**

SPHEROMAK RESEARCH NEEDS (4)

Beta Limits

Determine the mechanism that limited the peak $\beta_{electron}$ in SSPX to 5-10%

- Possible mechanisms include ohmic heating limits and pressure-driven modes

– Auxiliary heating will be required to differentiate between these mechanisms and to study their behavior

Understand the pressure-driven mode that limited the peak beta in CTX to 20% and was occasionally seen in SSPX

- Diagnostic capabilities capabilities to measure pressure and density profiles, mode onset, etc.

- Support by computations and simulations will be a critical component of a program to resolve this issue

SPHEROMAK RESEARCH NEEDS (5)

Particle Balance and Density Control

Understand the physics of particle and density balance in spheromaks

- **Measurements of particle fluxes to and from the helicity injector and flux-conserver walls need to be measured**
  - **Fueling experiments, including gas-puffing in the helicity injector and edge plasma, laser blow-off measurements, etc.**
  - **Extensive density diagnostics, including edge Thomson scattering to understand particle physics**
  - **Computational modeling to understand and guide experiments**

- **A dedicated facility may be needed to understand the physics of the edge plasma and divertor**

SPHEROMAK RESEARCH NEEDS (6)

Fast Particles

Fast particles will result from neutral-beam injection for heating, current drive, and current-profile control

- The physics of coupling to and exciting plasma modes in a high-β, low-q plasma is undeveloped and an important extension from the physics in q > 1 plasmas

Resistive-wall modes

Resistive wall modes (n=1/m=1 tilt and shift) will become important as the spheromak pulse length is extended

Locked modes may impact the plasma confinement and other spheromak parameters

- Control of resistive-wall modes can build on results from the tokamak and RFP

Technology

Long-pulse, spheromak operation will require development of technology for helicity injection, heat-handling in the divertor and on the flux conserver walls, etc.

- Development of necessary technologies should begin during the ITER era

SPHEROMAK GAPS (1)

Sustainment and confinement

- **There is presently no moderate-sized experiment with ultra high vacuum capability, long-pulse capability, and comprehensive diagnostics**
- **Existing simulation capabilities are challenged by calculations at high Lundquist number, e.g. for evaluating stability including two-fluid and kinetic kinetic effects. *Needed is increasing access to computing facilities*.**
  - **This could be resolved if the FSP is directed and funded to create a general plasma simulation tool instead of a tokamak-specific tool.**

Formation

- **Although many new formation techniques can be studied in small experiments, a facility is needed with the size and capabilities of that required for sustainment research**
- **Computational needs can be addressed by the capabilities needed for sustainment**

SPHEROMAK GAPS (2)

Transport and beta limits

- **A facility with more capability than SSPX will be needed, including density (~ 10^{20} m^{-3}) and temperature (~ 1 keV), and enough power to burn through impurities.**
  - **Excellent vacuum conditioning (glow, bake, getter), refractory first wall coatings, and programmable flux and current.**
  - **A comprehensive diagnostic set, including Thomson scattering, ion-temperature diagnostics, polarimetry, interferometry, spectroscopy, measurements to quantify magnetic surface quality**
- **Neutral beams, and perhaps rf heating, will be pivotal to understanding transport and beta limits.**
- **Computational and simulation support will be required**

Particle Balance and Density Control

- **Either a dedicated facility or upgrades to the above facility will be needed**
- **The divertor needs to be carefully designed and diagnosed**
- **Computational and simulation support will be required**

SPHEROMAK GAPS (3)

Fast Particles

- A means of forming energetic particles and diagnosing their effects does not exist for spheromaks

Particle Balance and Density Control

- Either a dedicated facility or upgrades to the facility used for transport, etc. research will be needed

- The divertor needs to be carefully designed and diagnosed

Resistive Wall Modes

- No present facility is capable of addressing resistive wall physics in spheromaks

- Incorporating thin-shell and external vacuum models is a tractable numerical approach for resistive wall studies, and simulation of feedback stabilization needs appropriate time-dependent sources. Damping for rotational stabilization may require sound-wave damping or other kinetic effects.

Technology

- New facilities will be required. It is premature to define them at this time.

Common Spheromak and FRC Needs:

Diagnostics and Theory/Computation

Research Thrusts

Contributions to fusion/plasma science

- **Extend MHD and other science to:**
  - **Low q, $0.2 < q < 1$**
  - **Ultra low aspect ratio, < 2**
  - **High beta $0.1 < \beta < 1$**
  - **Kinetically-dominated plasmas**
  - **Effect of sheared flow on stability and confinement**
- **Plasma self-organization and magnetic relaxation**
  - **Connects to space and astrophysical plasmas**
- **Non-inductive start-up and sustainment of plasmas using helicity injection**
- **Translatable plasmas including**
  - **Separating formation from burning**
  - **CT fueling**

CT DIAGNOSTIC NEEDS

Diagnostic capabilities on the CTs have been significantly limited by low budgets

Examples include:

- **Thomson scattering has been missing from recent FRCs and many spheromaks**
- **Ion temperature measurements have been limited to the edge using Doppler-broadening spectroscopy of low-ionization impurities**
- **Internal magnetic field measurements have been limited to wall probes except in low-temperature plasmas**
- **Fluctuation measurements are limited to wall probe arrays**

Progress in CT research requires better diagnostics and support for their operation and interpretation

CT THEORY AND MODELING NEEDS

Theory and modeling have contributed to progress in understanding FRCs and spheromaks, but expansion of this effort would contribute significantly to future scientific progress

- **FRCs have been supported by hybrid kinetic-MHD codes (e.g. HYM)**
  - **Extension of codes to include more physics, faster numerics, etc., will pay important dividends in understanding stability at large *s***
- **Spheromaks have benefited significantly from resistive MHD simulations (e.g. NIMROD and others)**
  - **Continued development with two-fluid physics, kinetic components, improved boundary conditions, etc. are needed to understand spheromak physics and to guide experiments**

See the White Paper by Carl Sovinec for a discussion of theory and code development for spheromaks and RFPs. Many of the general conclusions also apply to the FRC

CT Research Thrusts (1)

Research Thrust: Determine the scientific feasibility of magnetic fusion in a toroidal magnetic configuration within a simply-connected geometry and no toroidal-field coils or transformer

Four Sub-thrusts are proposed:

The first two Research Sub-Thrusts for CTs focus on the Tier 1 issues for the FRC and spheromak.

- **Satisfactory resolution of these issues will enable a broader attack on the physics issues**
- **This will position the CTs to propose Proof-of-Principle level experiments to lead community-wide research.**

The second two Research Sub-Thrusts address integrated research in physics for the ITER era.

CT Research Thrusts (2)

Extend the stable regime of the FRC to large *s*

Sub-Thrust 1: **Study FRC stability for a wide range of the ratio of plasma radius to the Larmor radius:**

- **Closely coupled experiments and theory/simulations addressing stability at large *s*.**
- **Research on existing experiments will contribute important understanding**
- **At least one new experiment or significant-upgrade of an existing experiment to operate in the high-*s* regime**
  - **A means of forming and sustaining the FRC, with neutral beams to inject energetic ions, and appropriate conducting walls.**
  - **Significant diagnostic capability, providing data for detailed comparison with simulations**
  - **Existing simulation codes contain a good physics basis, but require extending it and improving numerical capability to allow a reasonable computer time.**

CT Research Thrusts (3)

Understand how to form and sustain a spheromak in a way that is compatible with good confinement

Sub-Thrust 2: Spheromak formation and sustainment compatible with good confinement:

A multicomponent thrust including

- **Small experiments to test new, potentially transformative ideas**
- **A new experiment, at least the size and capability of SSPX, to test new concepts in a high-quality, well diagnosed environment.**
- **Simulations to explore new concepts, to understand how they would be implemented in a larger experiment, and to interpret experiments**

CT Research Thrusts (4)

Achieve the ITER-era goal for FRCs — a sustained or long-pulsed plasma at kilovolt temperatures, with favorable confinement scaling

Sub-Thrust 3: Understand the integrated impacts of FRC physics in the fusion-plasma, high-beta regime using NBI or RF, addressing transport, current drive, fast particles, heating and other important physics:

An integrated physics thrust, including

- **A flagship facility to develop an understanding of FRC physics at a level at least sufficient to meet the ITER-era goal**
- **Sufficient understanding to assess plausible scenarios for advanced-fuel reactor concepts**

The research can make a fundamental contribution to overall fusion research by investigating:

- **The effectiveness of high energy ions for stabilizing global MHD modes in toroidally confined plasmas**
- **The efficiency of current drive methods**
- **The effects of natural divertors on plasma confinement and stability**

CT Research Thrusts (5)

Achieve the ITER-era goal for spheromaks — a sustained or long-pulsed plasma at kilovolt temperatures, with favorable confinement scaling

Sub-Thrust 4: Understand the integrated impacts of spheromak physics in the fusion-plasma regime, including transport, beta limits, and particle balance and density control:

- **An integrated physics thrust**
- **A flagship facility to develop an understanding of spheromak physics at a level at least sufficient to meet the ITER-era goal**
- **The facility will require:**
  - **A high-quality vacuum environment**
  - **Neutral-beam and/or rf for heating, current drive and profile control**
  - **An extensive set of diagnostics**
- **Small experiments to explore specific physics issues and technology improvements to improve physics understanding and performance**
- **Extensive theory and computational support**
  - **Ideally integrated into a fusion-program wide FSP effort**
  - **Provide an understanding of fusion/plasma physics in a parameter regime with $q < 1$**