Sustainment Physics of a Self-Organized Spheromak Torus Imbedded in an Open Magnetic Field

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Presented in honor of

The Legacy of Richard F. Post

Fusion Power Associates Annual Meeting

Livermore, CA

December 3-4, 2008

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.

LLNL-PRES-409231

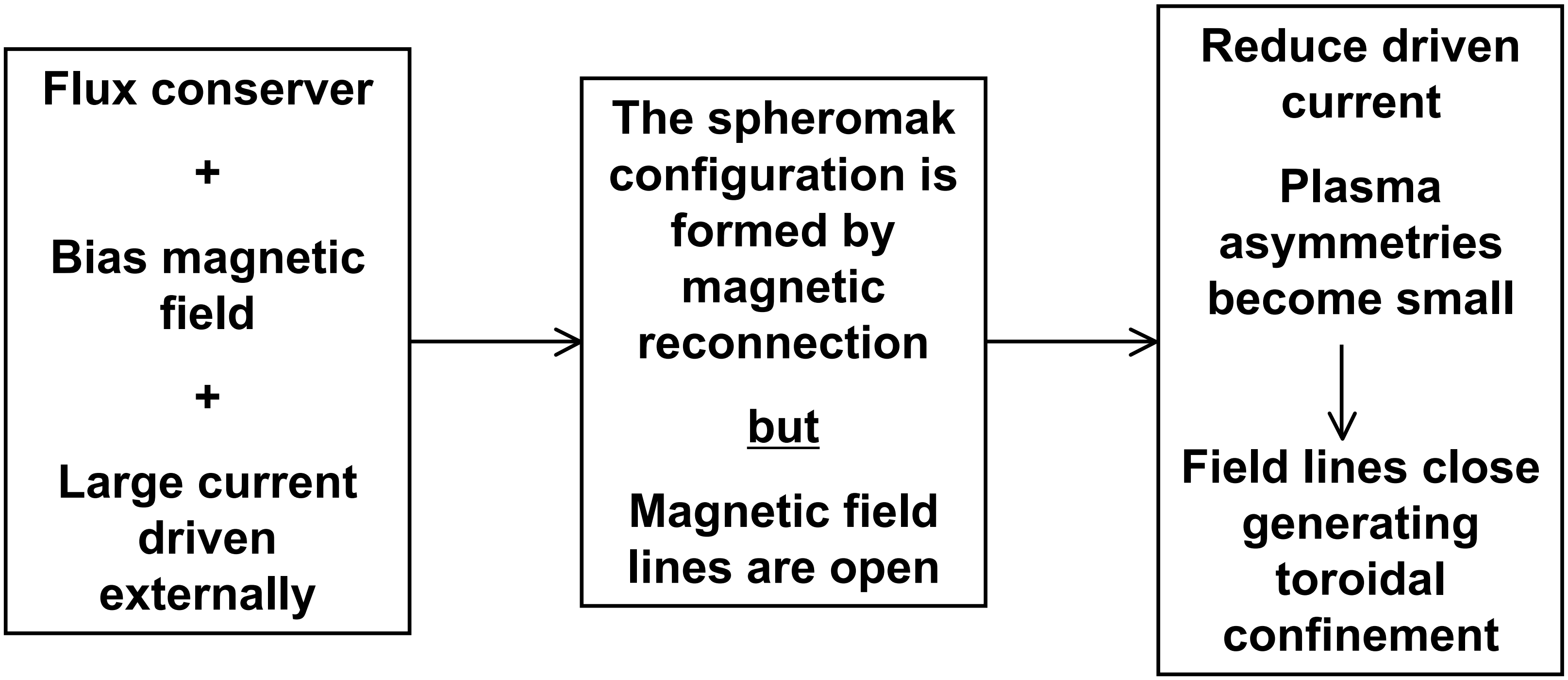
The spheromak

The spheromak is a toroidal magnetic confinement configuration formed from an open magnetic field lines when:

- **Currents in the plasma are sufficiently high to generate large magnetic field larger than the bias field**
- **Conducting wall boundary conditions around the plasma shape the configuration, yielding a "mode" with the spheromak geometry**
- **Axisymmetry is broken, allowing a transition from the initial field geometry to the spheromak "mode" (Cowlings theorem)**

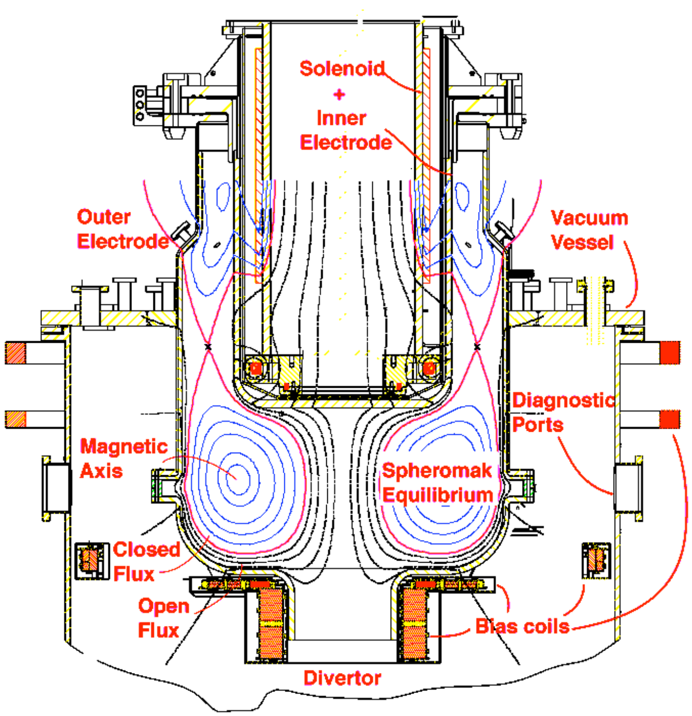
We describe formation and buildup of the plasma and consider options for sustainment or long-pulse operation with good magnetic confinement

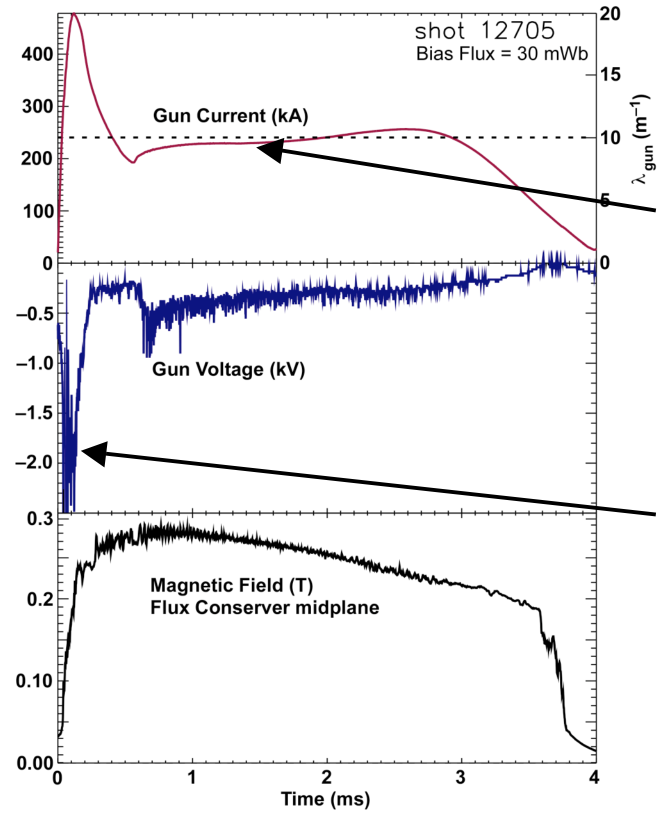
Spheromak formation and magnetic field line closure



The issue: How do we use this confinement geometry for fusion energy generation?

SSPX — spheromak formation by helicity injection



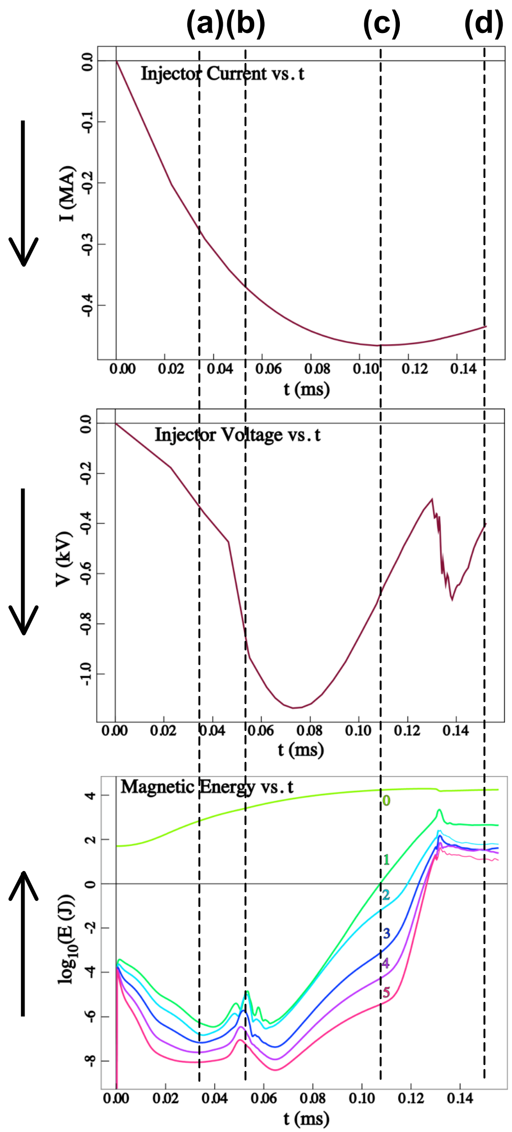


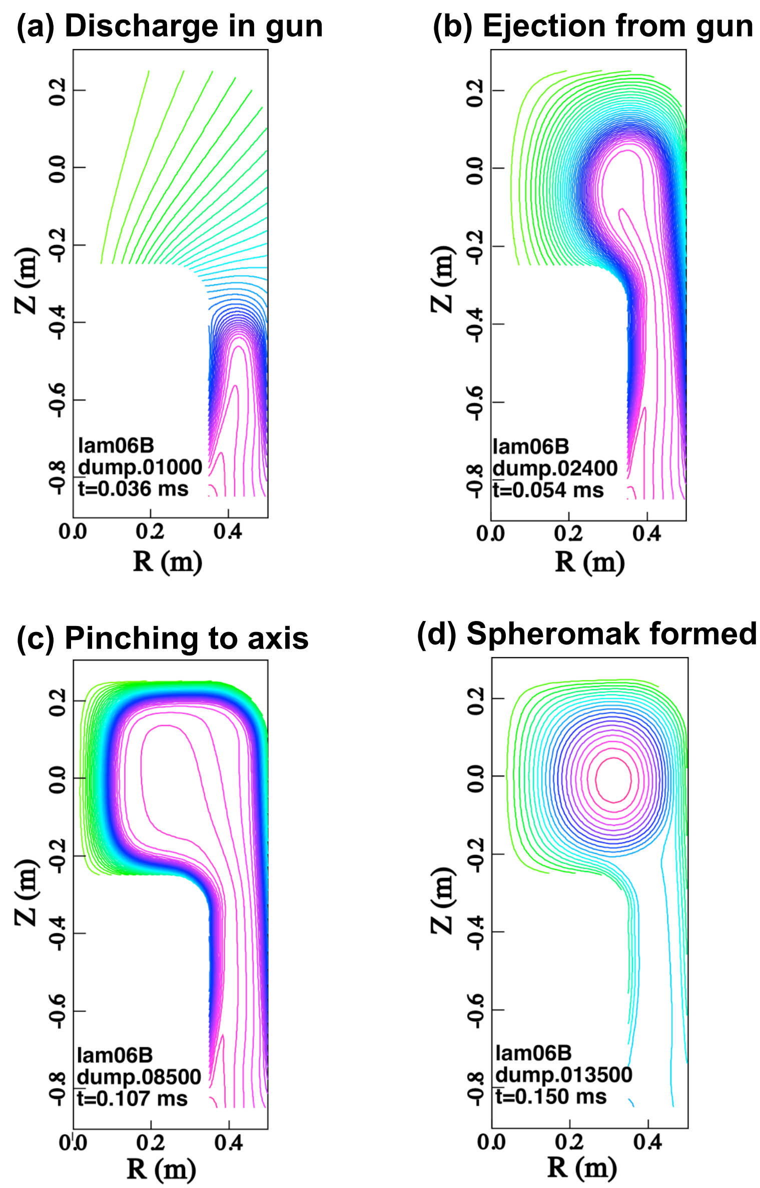
Current drops below threshold for reconnection — good confinement in slowly-decaying spheromak

Strong cathode voltage spikes — reconnection events

Helicity – a measure of linked magnetic fluxes – is injected using a bias poloidal field and a toroidal field from injected poloidal current

MHD simulations help clarify the physics

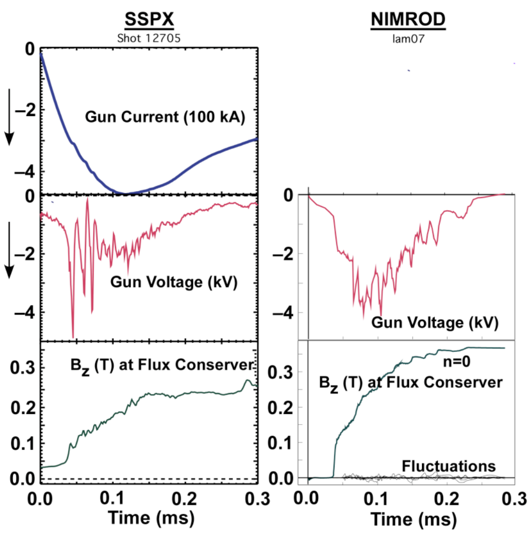




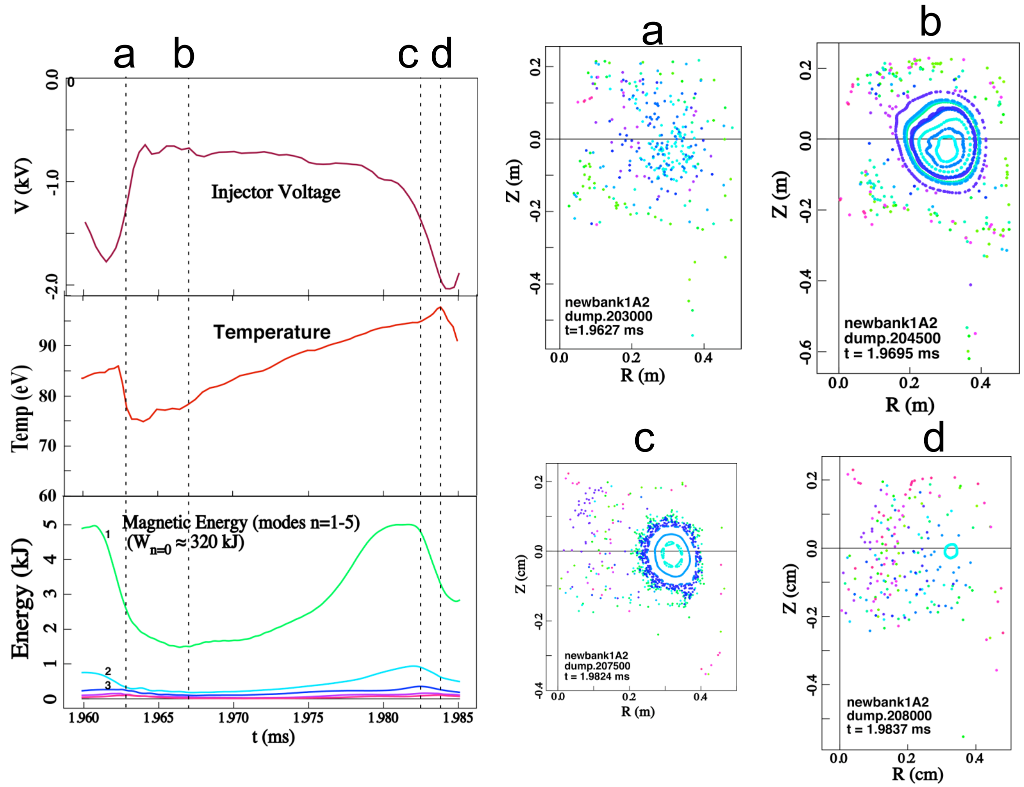
Simulations using the NIMROD code. Ref.: E. B. Hooper, et al., Phys. Plasmas **15**, 032502 (2008).

SSPX Flux conserver (L/R = 0.5m/0.5m) – Exp. and Simulation
Formation and effect of reconnection on field lines

Voltage spiking during formation

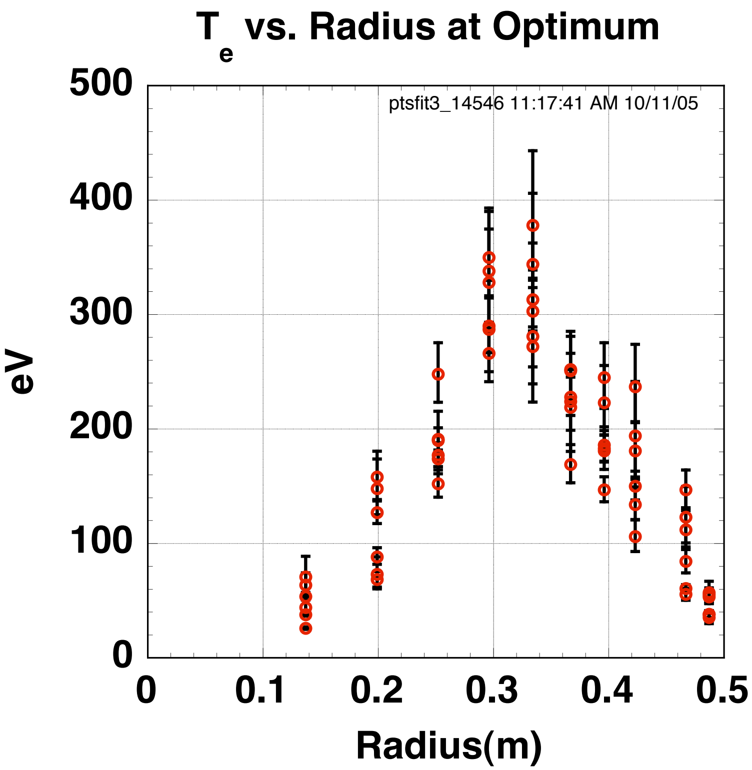


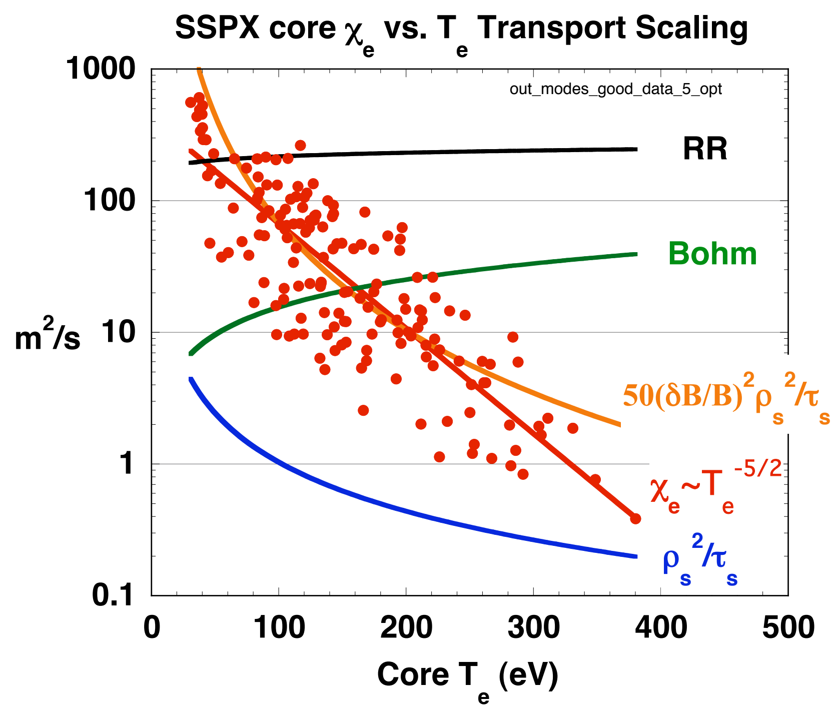
Reconnection breaks up flux surfaces



Ref.: E. B. Hooper, et al., Phys. Plasmas **12**, 092503 (2005). The field line behavior was measured on FACT: M. Nagata, et al., Phys. Rev. Letters 71, 4342 (1993).

Slowly-decaying plasmas — T_e is as high as 500 eV and χ_e(core) is between 1-10 m^2/s





The spheromak has good confinement when the flux surfaces are good!

Ref.: H. S. McLean, et al., Phys. Plasmas 13, 056105 (2006).

The issue for fusion energy is thus:

Accessing good confinement confinement while sustaining the plasma long enough for net energy production

In experiments and theory/simulations to date:

- **During helicity injection, the magnetic field lines are open**
- **Energy losses to the walls are large and "outrun" helicity transport into the spheromak core**

Theory refs.: A. H. Boozer, Phys. Fluids B **5**, 2271 (1993); R. W. Moses, Phys. Plasmas **8**, 4839 (2001); T. K. Fowler and R. Gatto, Plasma Phys. Control. Fusion **49**, 2007 (2007).

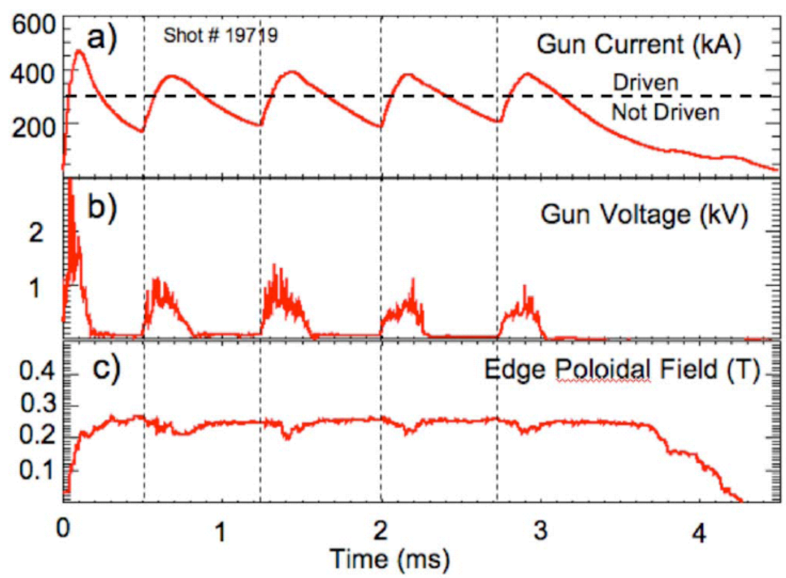
Paths towards fusion power

There are several possible paths forward:

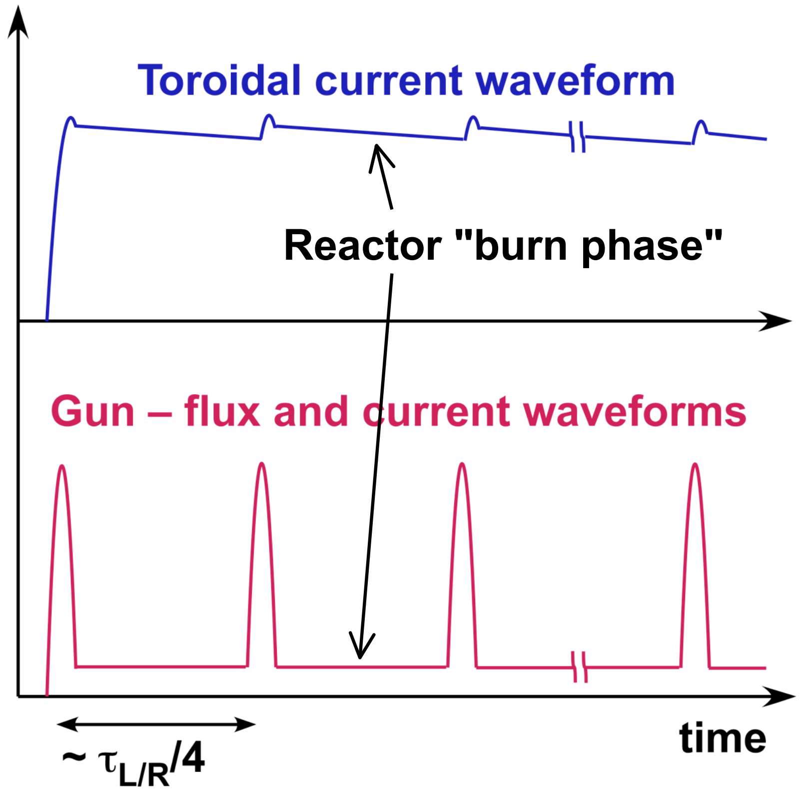
- **Invention:**
  - **High frequency turbulence may allow confinement which is sufficiently good for T_e to be large during helicity injection**
- **Separate the helicity injection and confinement by a process which opens field lines only locally**
- **Separating field building and confinement/burn in time by pulsing or periodically rebuilding the field**
- **Current drive by neutral beams or rf**

Waveforms for pulsed ("refluxed") spheromak

SSPX



"Reactor"

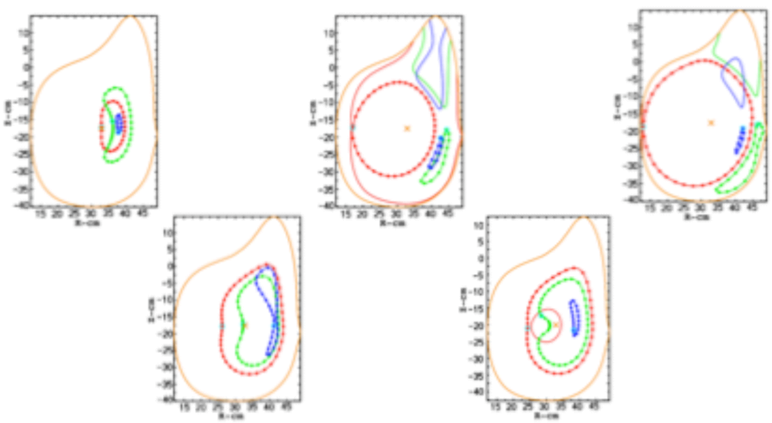


Fundamental issue: Efficiency of rebuilding must be high to allow the generation of net energy

Ref.: B. Hudson, Phys. Plasmas **15**, 056112 (2008); E. B. Hooper, et al., Bull. Am. Phys. Soc. **51**, 79 (2006).

Current drive by neutral beams — Preliminary studies are interesting

Orbit and current drive studies in SSPX show confined orbits for fast ions injected at angles close to the average magnetic field line direction



Calculations for a reactor by Fowler show good net power efficiency

- **The Cordey model was applied to a simple spheromak reactor model**
- **A net power efficiency appears possible, yielding possible reactors:**

Q	a(m)	P_{fusion} (MW)	P_{beam} (MW)	I(MA)	B(T)
10	2.1-3.4	1200-1400	120-140	74	4.3-7.1
20	3.3-5.4	3000-3400	150-170	74	2.7-5.4

MHD calculations suggest that the resulting configuration may be stable

The results are promising but preliminary and further study of auxiliary current drive is warranted

Ref.: R. Jayakumar, et al., UCRL-TR-235704 (2007); T. K. Fowler, et al., J. Fusion Energy, published on line (2008).

Summary

Spheromak physics — extended by experiments and simulations

- **We now have a good enough understanding of the physics to consider realistic reactor scenarios**

Experiments, theory, and simulations to date have not found a path to simultaneous sustainment (by helicity injection) and good energy confinement

But:

There are interesting reactor concepts, including

- **Refluxing –– time separation of current drive and confinement/burn phases**
- **Auxiliary current drive, e.g. by neutral beams**

Resources for spheromak research have been small, and there is still considerable room for invention