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Simulations of Spheromak Formation and Sustainment from Multi-pulse Helicity Injection

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Young Faculty Award 2014
Alternate Fusion Concepts

Abstract

The spheromak is a particular type of self-organized plasma configuration with toroidal and poloidal magnetic flux generated mainly by currents within the plasma. Spheromaks contain magnetic fields that are in principle closed (i.e. do not intercept the chamber walls in which they are produced) and have the interesting property of being simply connected. This means that no materials such as magnetic coils or vacuum vessel walls link the magnetic torus, unlike other configurations such as the tokamak, the stellarator, or the reversed field pinch. This topological simplicity makes the spheromak an attractive concept to confine fusion-grade plasmas: the confinement vessel would be significantly simpler and cheaper to build than that of the tokamak, and would allow for implementation of simpler liquid metal walls for heat extraction and protection of vessel walls from damage.

The present DARPA Young Faculty Award concentrates on using established plasma numerical codes to model the effects of coaxial helicity injection profiles (CHI) on spheromak magnetic field structure and evolution, and on how self-organization and magnetic reconnection can be controlled externally to improve confinement. Magnetic helicity, which is a measure of magnetic field twistedness and linkage, is approximately conserved during spheromak formation or during magnetic reconnection events. In particular, experimental evidence of quantization of helicity during CHI pulses will be investigated numerically. The ultimate goal in terms of spheromak physics is to maximize the amount of helicity injected by controlling the CHI gun current, while minimizing the losses by reducing the number of times the CHI source needs to be pulsed, and thus reduce the number of reconnection events that lead to losses.

Background


NASA-NOAA

Energy and security

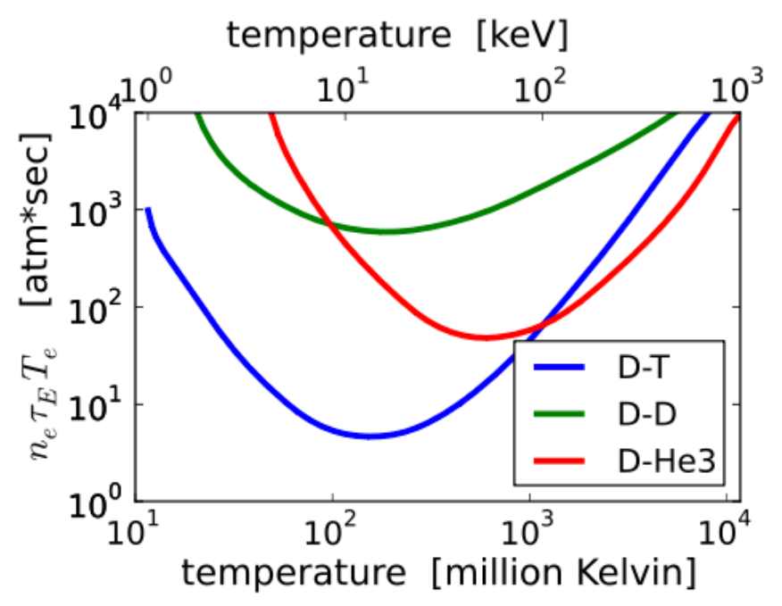
- The demand for energy will continue to accelerate throughout the world.
  - More than $1600 billion was invested in 2013 to provide consumers with energy[1].
  - The cumulative expenditure in energy by the year 2035 will be $48 trillion[1]
- The wealth and health of a nation are often measured through[2]:
  - The extent and accessibility of its energy reserves
  - The capability of its energy distribution infrastructure
  - The efficiency by which it leverages energy into economic output.
- Disruption of above capabilities can make a nation disproportionally vulnerable[3].
- Nuclear energy is expected to provide up to 30% of the world's electricity demand, but if done with fission, this also increases proliferation risks[4].

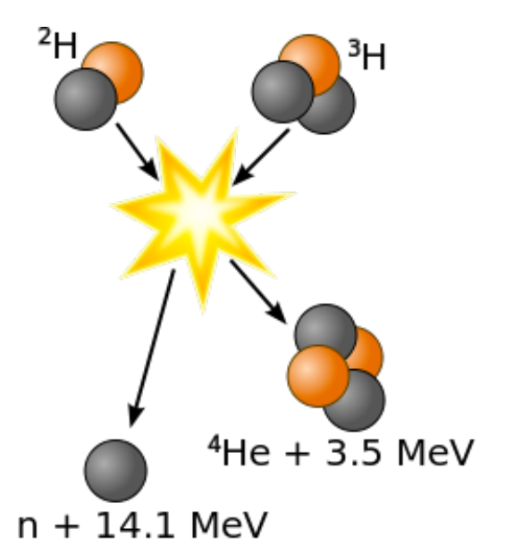
Electric Energy Sources[4]

	2007		2100	
Combustion	1482 GWe-yr/yr	69.2%	4800 GWe-yr/yr	40%
Nuclear	296 GWe-yr/yr	13.8%	3600 GWe-yr/yr	30%
Hydro	342 GWe-yr/yr	15.9%	700 GWe-yr/yr	6%
Other Renewables	26 GWe-yr/yr	1.2%	2900 GWe-yr/yr	24%
Total	2046 GWe-yr/yr	100%	12,000 GWe-yr/yr	100%

Fusion Energy

- Fusion energy offers many advantages over other sources:
  - Abundant fuel everywhere on Earth;
  - No air pollution and not dependant on seasonal variations;
  - No risk of a runaway reaction.
  - No high-level nuclear waste, and proliferation resistance.
- Magnetic fusion plants would present low proliferation risk compared to fission
  - Clandestine production of nuclear weapons materials using fusion research facilities can be considered a highly implausible scenario[5].
- D-T reaction is easiest to achieve, but challenging to maintain sufficient particles hot enough, for long enough (i.e., the Lawson criterion: $n_E \tau_E T_E > 3\times10^{21}$ keV s/m^3), to get net energy gain.





Alternate Fusion Concepts

- The best performing magnetic fusion concept to date is the tokomak.
  - Has achieved close to energy breakeven (Q =1), but machine is large and engineering is very challenging.
  - Vessel is a toroid with 18 external coils to apply pressure on the plasma.
- ITER: the first experiment to demonstrate sustained Q > 1, will use 23,000 tons of steel, with over 400 tons of superconductors.
  - Initially priced at US $5 billion, it is now estimated to cost more than $20 billion, and will be years behind schedule.

Spheromaks

- Spheromaks are self-organized and force free magnetic confinement configurations.
- Topologically simpler and more compact than tokamaks.
- Reactor studies using spheromaks anticipate an order of magnitude reduction in mass with respect to tokamaks.
- Spheromaks would not require superconducting coils, and would be much easier to extract fusion power while minimizing neutron damage and engineering complexity.

Force free in MHD implies $J \times B = 0$

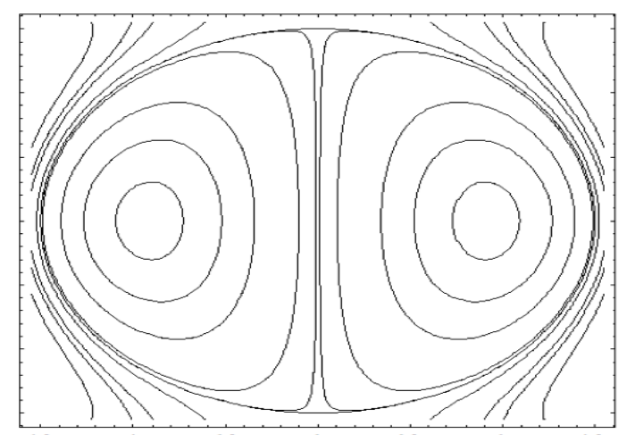
(i.e. plasma currents are field-aligned)

Using Ampere's Law: $\nabla \times B = \mu_o J$

Obtain

$$\boxed{\nabla \times B = \lambda B}$$

where λ is an eignevalue.


Magnetic flux contours from J x B = 0

Helicity Injection

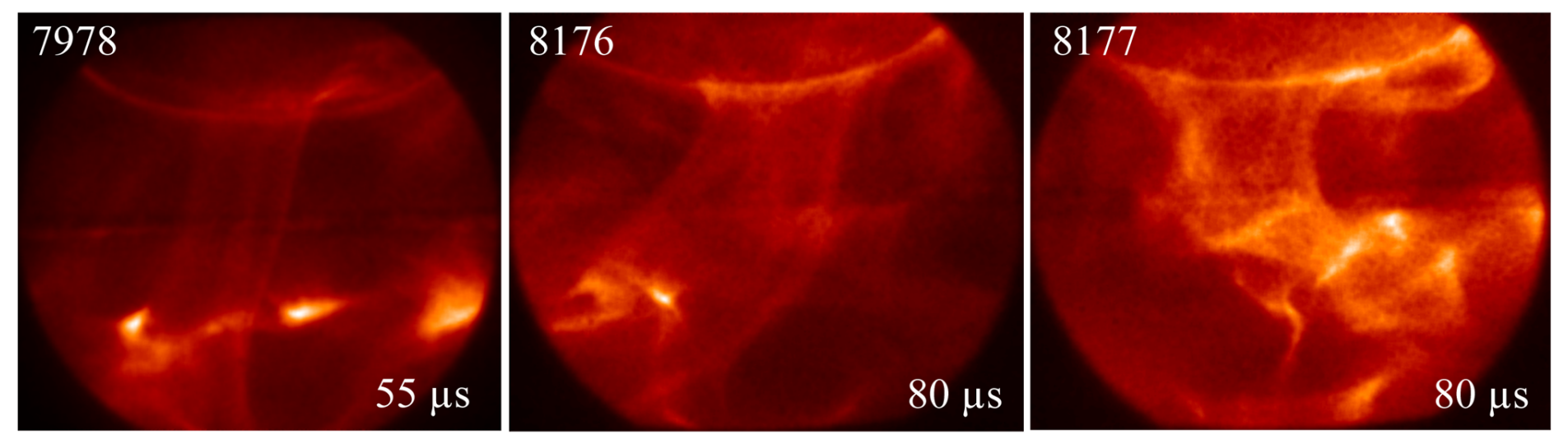
- Even though magnetic flux contours are symmetric, magnetic fields are inherently asymmetric ,i.e., helical.
- Higher helicity translates to better heating (higher currents along B) and confinement (stronger B in closed flux surfaces).
- For a driven spheromak, with gun voltage V_g and gun flux Ψ_g , the helicity, *K*, rate equation for a driven spheromak is

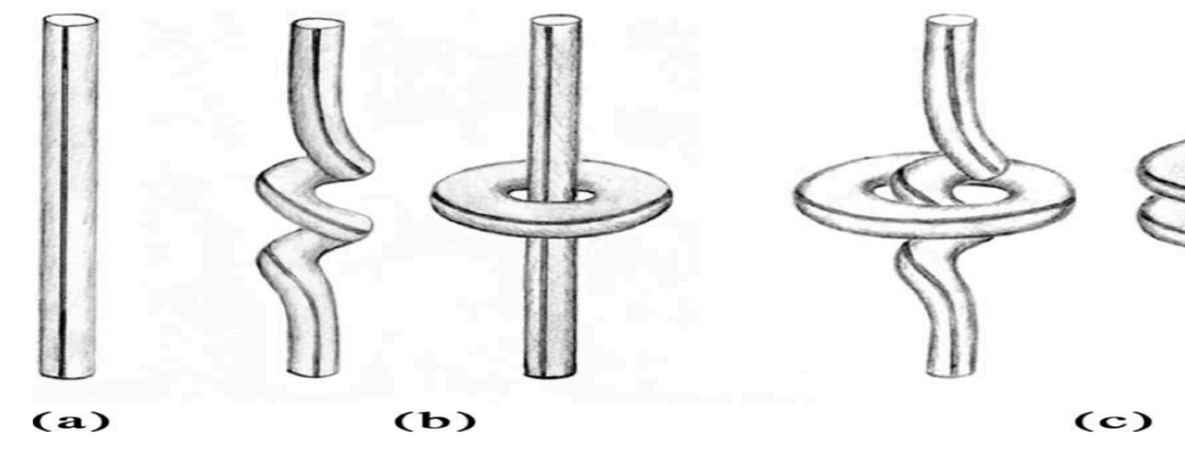
$$\frac{dK}{dt} = 2V_g\Psi_g - 2\int \eta \mathrm{J}\cdot\mathrm{B}\, d^3r$$

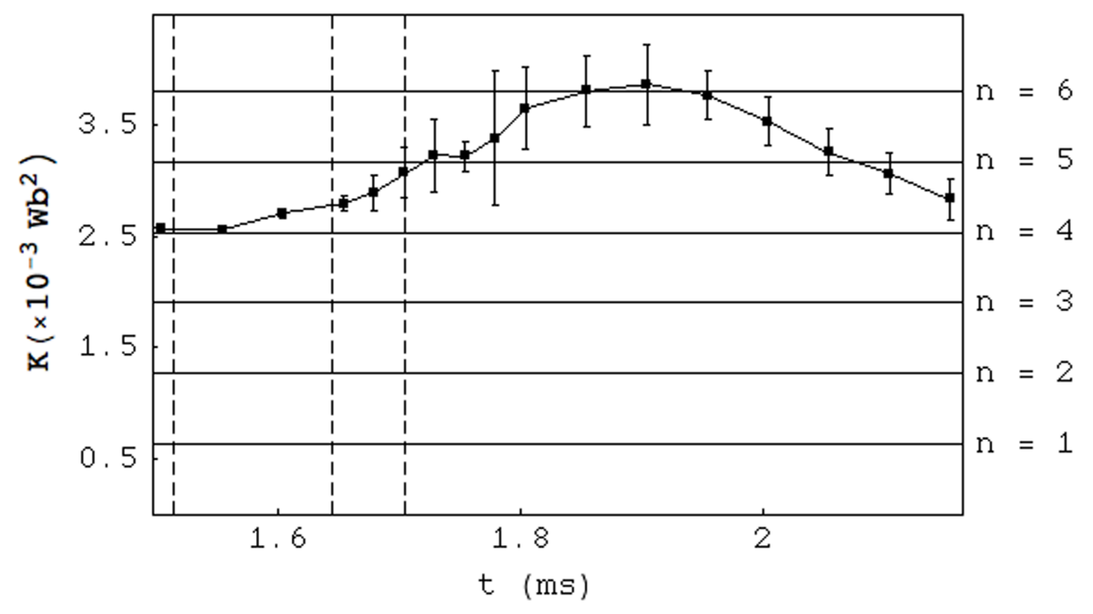
- Experiments at the Sustained Spheromak Physics Experiment[7] (SSPX) showed a large kink in the plasma column is responsible for the initial spheromak formation[8].
- Experiments also showed indications that helicity is quantized[8].

$$\boxed{K_n = 2n\Phi^2}$$

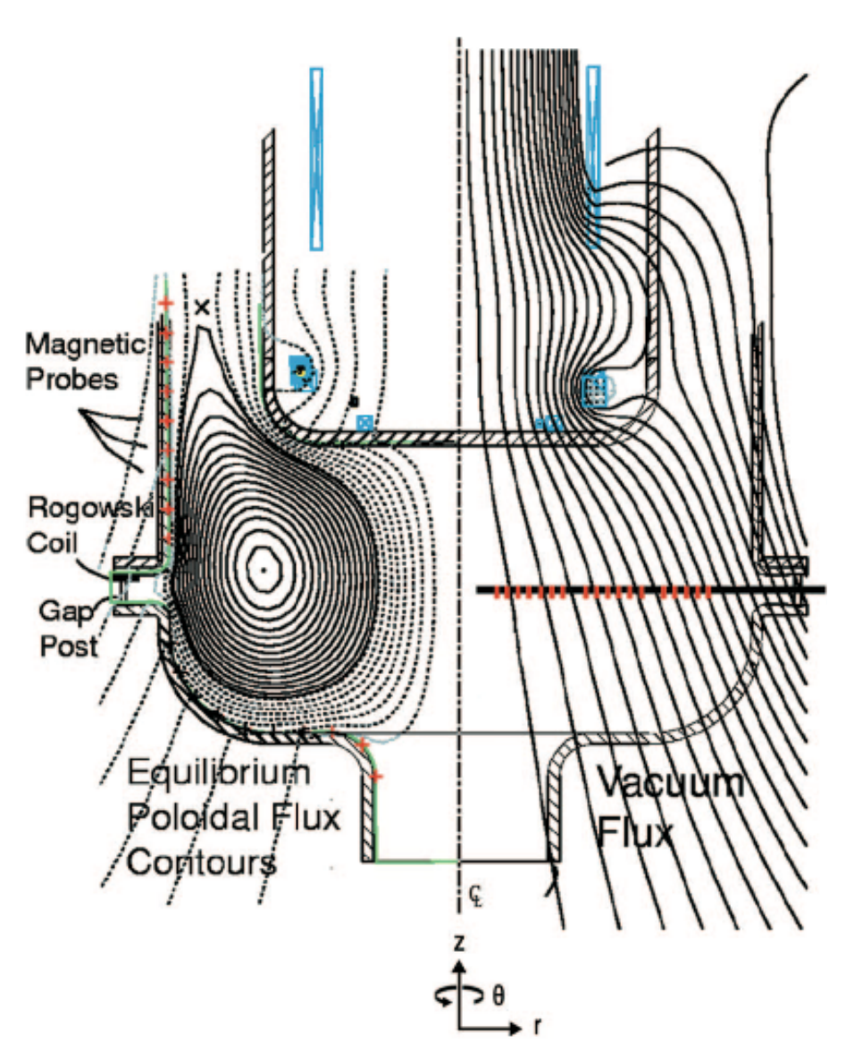
- Where Φ is the flux through the column, and *n* is the number of linked rings (model below).





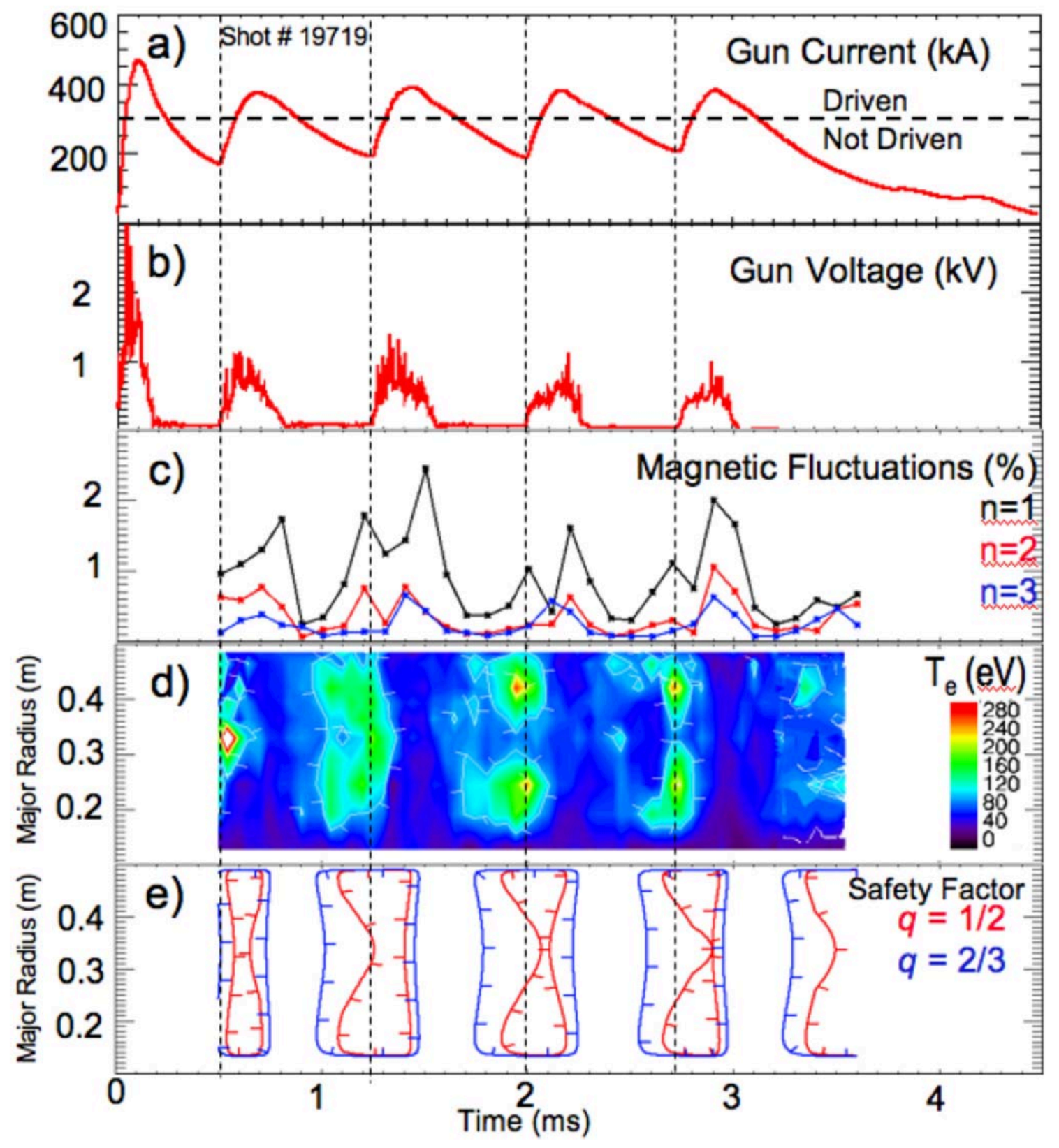


- Helicity evolution in SSPX during multi-pluse operation, from Ref. 8



The Challenge for Spheromaks

- Multi-pulse current injection[9] was found to be an effective way to sustain the spheromak in SSPX



- However, most confined energy was lost at each pulse (likely through magnetic reconnection).
- The SSPX helicity injection rate was limited by hardware (number of capacitors, switches, line inductance, etc.)

Numerical Simulations

- NIMROD[10], a resistive MHD code was used to simulate SSPX with great success.
- The simulation takes *n, T*, **V**, **B**, and **J** to be functions of all three spatial dimensions and time.

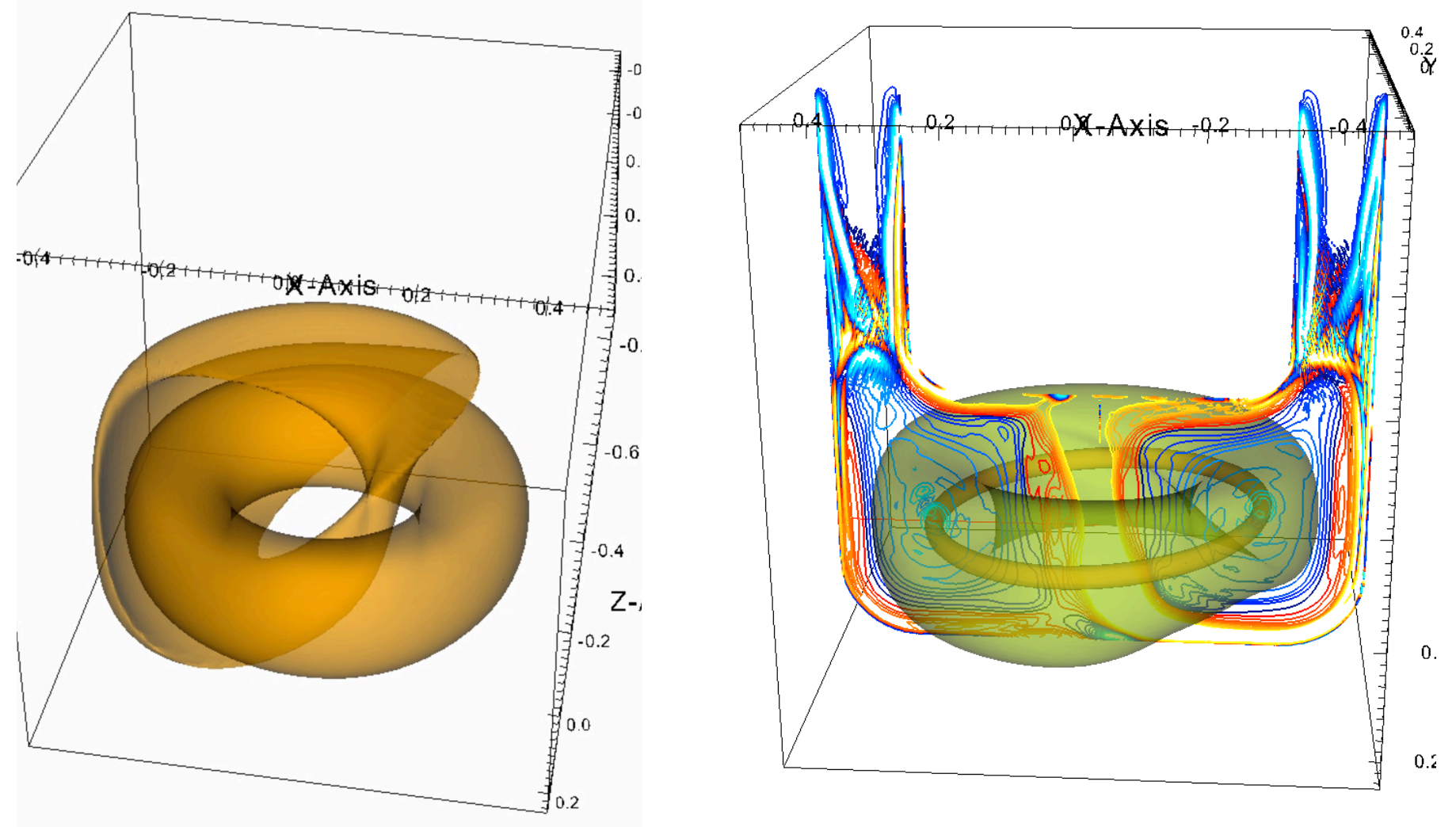
$$\text{(1)}\qquad \frac{\partial n}{\partial t} + \nabla\cdot(n\mathbf{V}) = \nabla\cdot D\nabla n,$$

$$\text{(2)}\qquad \rho\left(\frac{\partial \mathbf{V}}{\partial t} + \mathbf{V}\cdot\nabla\mathbf{V}\right) = \mathbf{J}\times\mathbf{B} - \nabla p + \nabla\cdot\rho\nu\nabla\mathbf{V},$$

$$\text{(3)}\qquad \frac{nk_B}{\gamma-1}\left(\frac{\partial T}{\partial t} + \mathbf{V}\cdot\nabla T\right) = -\frac{p}{2}\nabla\cdot\mathbf{V} + \nabla\cdot nk_B[\chi_\parallel\hat{\mathbf{b}}\hat{\mathbf{b}} + \chi_\perp(\mathbf{I}-\hat{\mathbf{b}}\hat{\mathbf{b}})]\cdot\nabla T + \frac{\eta\mathbf{J}^2}{2},$$

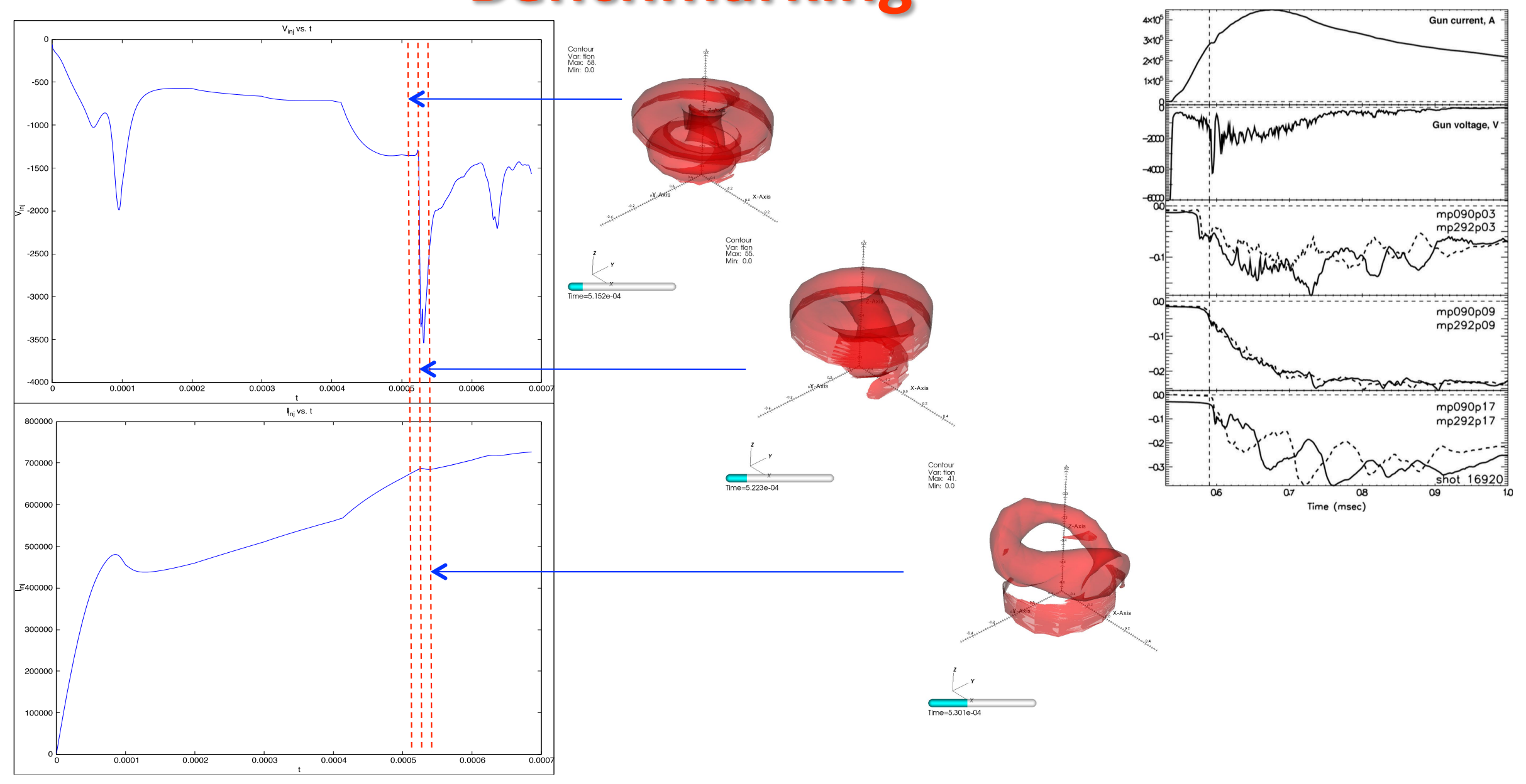
$$\text{(4)}\qquad \frac{\partial \mathbf{B}}{\partial t} = \nabla\times(\mathbf{V}\times\mathbf{B} - \eta\mathbf{J}),$$

$$\text{(5)}\qquad \mu_0\mathbf{J} = \nabla\times\mathbf{B},$$



- NIMROD captured important physics of spheromak formation and sustainment, but does not include kinetic effects.
- The same gun circuitry used for SSPX was programmed into NIMROD, but different current profiles not explored.

Benchmarking



New Paradigm in Spheromak Reactors

- A paradigm shift will be explored here in searching for helicity injection profiles that can increase helicity and sustain temperature for longer.

Key Insights / Innovation

- Simulations will allow helicity injection into spheromaks at much higher rates than previous simulations or experiments.
- Simpler flux conserver than previous experiments.
- Higher helicity content per pulse than previous knowledge.
- More efficient coaxial helicity injection for magnetic energy buildup
- More time to allow stability and healing of magnetic surfaces , and thus higher plasma temperature and lower energy losses.

Scientific / Technical Impact

- Advance numerical simulations with resistive MHD and kinetic effects necessary to study fusion plasmas.
- Understand the physics of self-organization and reconnection in magnetized plasmas with high helicity content without the need to invoke turbulence.
- Relevance to astrophysics: astrophysical jets are conjectured to contain high helicity and plasma flows at their source.

Potential Applications

- Compact, transportable and deployable fusion reactors.
- Fusion energy reactors at least 1 order of magnitude smaller and less massive than tokamaks; much lower engineering complexity, higher reliability, lower cost.
- Energy security: proliferation resistance, fuel abundance, manageable (cost effective) nuclear waste.

The Team

- P.I. Carlos Romero-Talamás, Assistant Professor of Mechanical Engineering at UMBC.
- Dr. John O'Bryan, expert on flux rope merging simulations with NIMROD, has joined as a postdoctoral scholar the research efforts under direction of Prof. Romero-Talamás.
- Woodruff Scientific, with extensive experience on spheromak simulations and experiments, will work closely with Dr. O'Bryan and Prof. Romero-Talamás on developing NIMROD and running simulations at NERSC supercomputers.

Acknowledgements

Work performed under DARPA grant N66001-14-1-4044.

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