Visualization of experimental and numerical data at the Sustained Spheromak Physics Experiment

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Outline of This Presentation

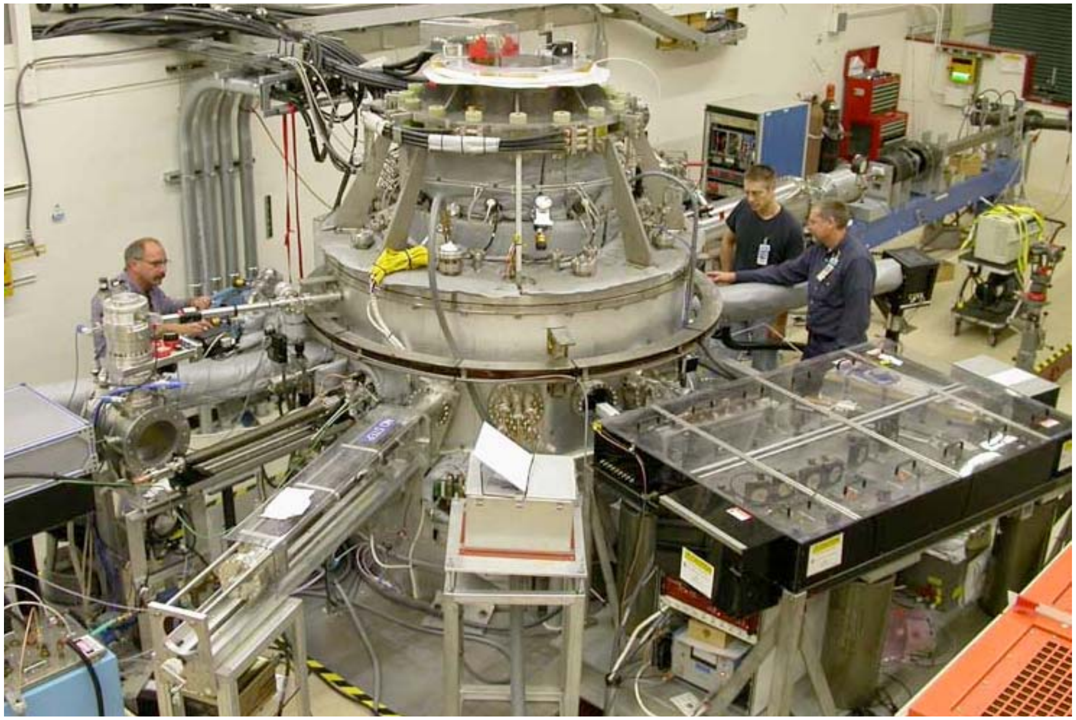
- The Sustained Spheromak Physics Experiment
- Imaging and magnetic diagnostics.
- Numerical MHD simulations of SSPX, and spheromak formation hypotheses.
- The search for reconnection and flux ropes.

Sustained Spheromak Physics Experiment (SSPX)

- The research program has focused on two important areas:
  - Magnetic field generation by coaxial helicity injection with associated internal helicity.
  - The effect of magnetic fluctuations on energy confinement in the driven spheromak.
- Basic plasma science is an integral part of the SSPX program.

- SSPX has been operating at the Lawrence Livermore National Laboratory since 1999.

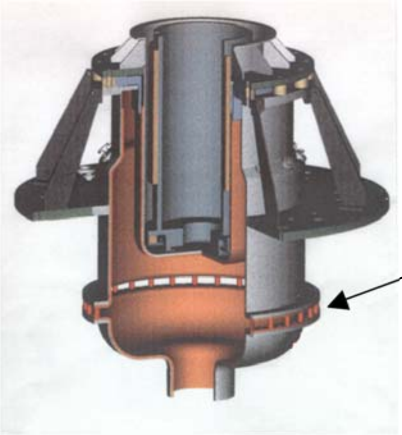
Typical SSPX parameters	
Flux conserver size: Radius × Height (m)	**0.5 ×0.5**
Radius of magnetic axis	**0.31 m**
Minor radius	**0.17 m**
Peak discharge current	**550 kA**
Toroidal current	**600 kA**
Peak toroidal field	**0.6 T**
Edge poloidal field	**0.35 T**
Plasma duration	**11 ms**
Plasma density	**7×10^{19} m^{-3}**
Peak Te	**350 eV**

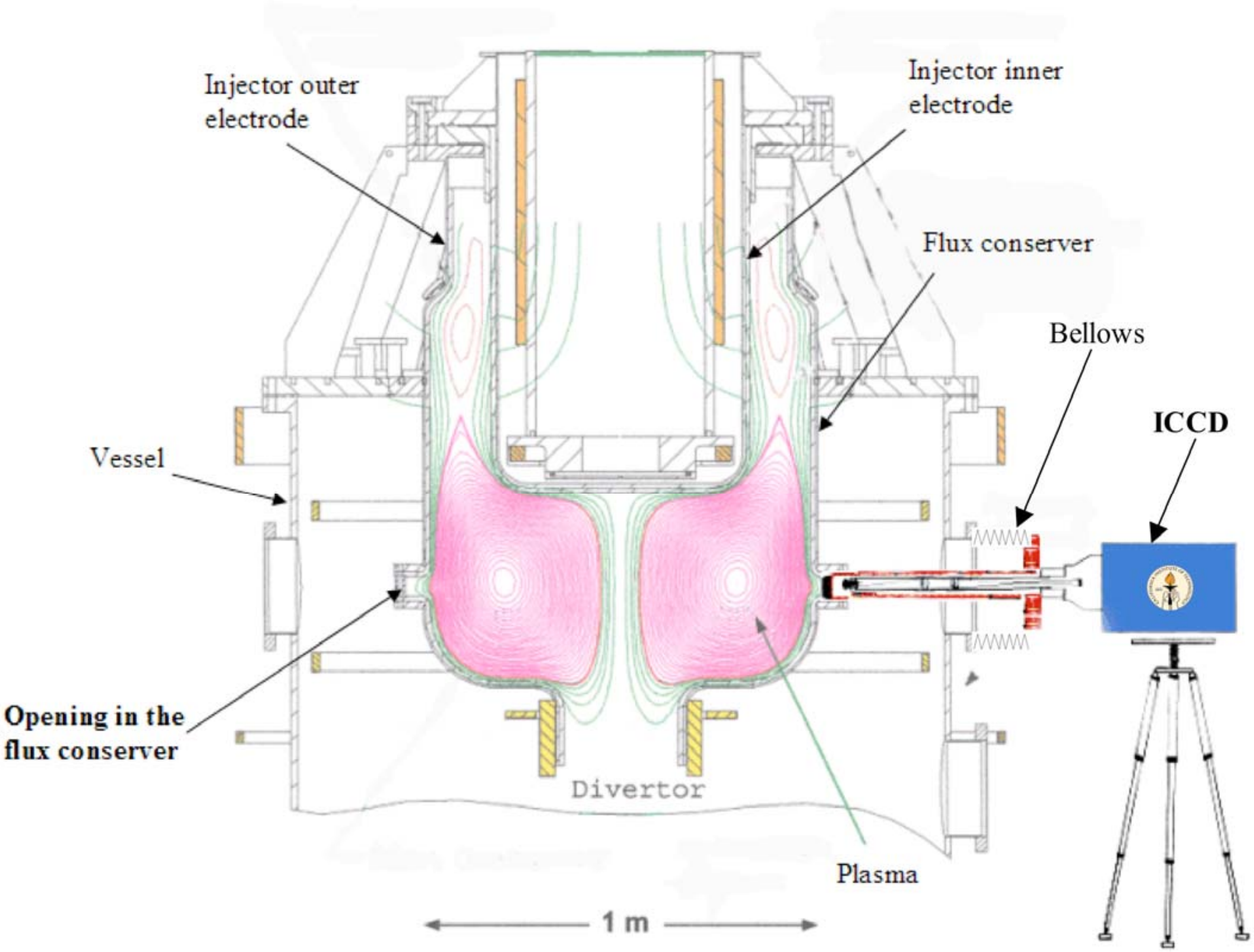


The SSPX facility at Livermore showing the vacuum vessel and major external diagnostics. Not shown: magnet supplies, capacitor banks, and control systems.

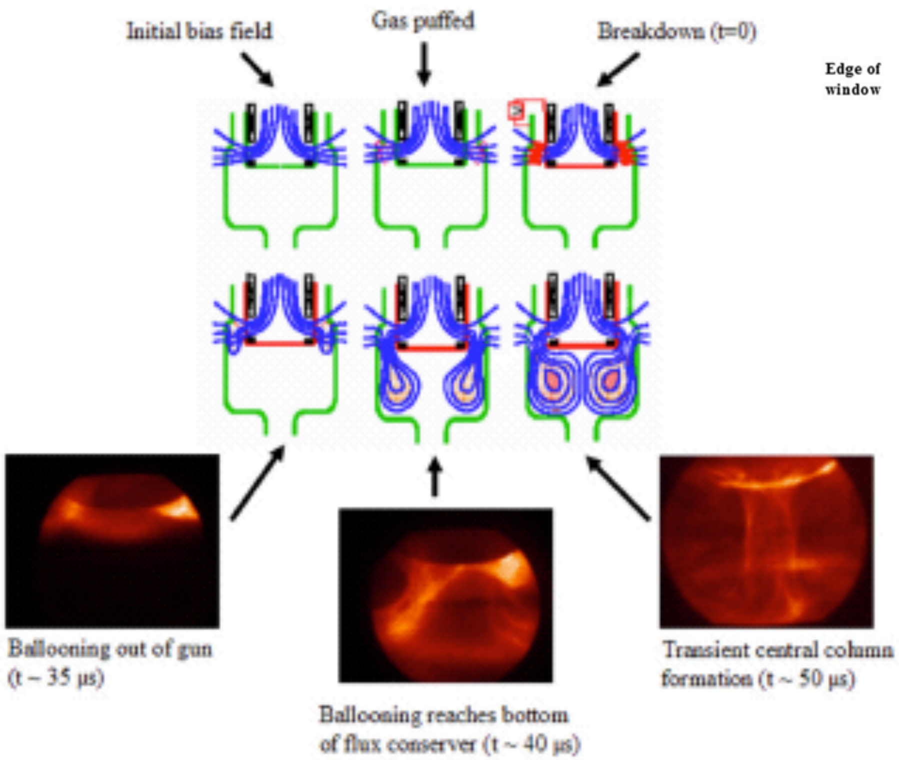
High-speed imaging diagnostic

The SSPX chamber has an opening in the flux conserver and several viewports for instrumentation and measurements

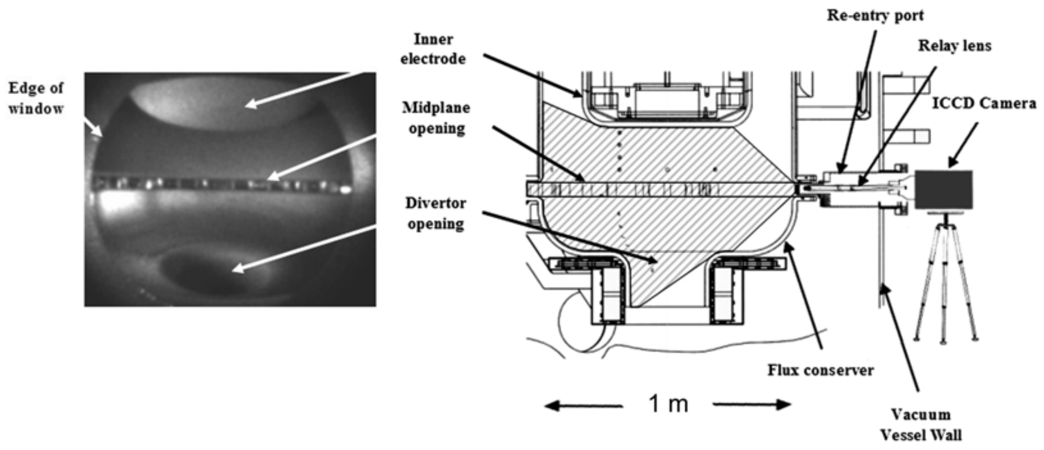


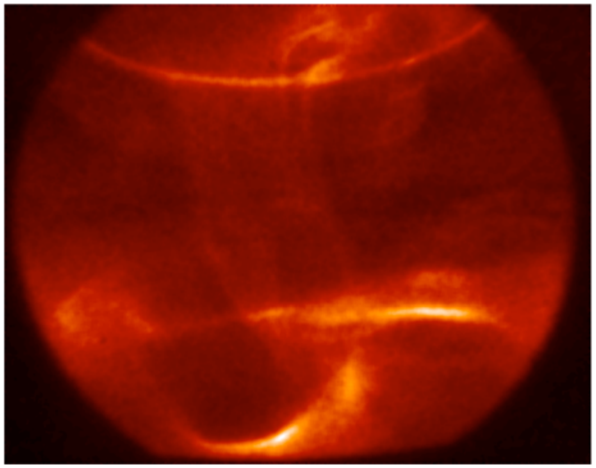


Early Formation Sequence Seen With the Caltech High-speed Camera



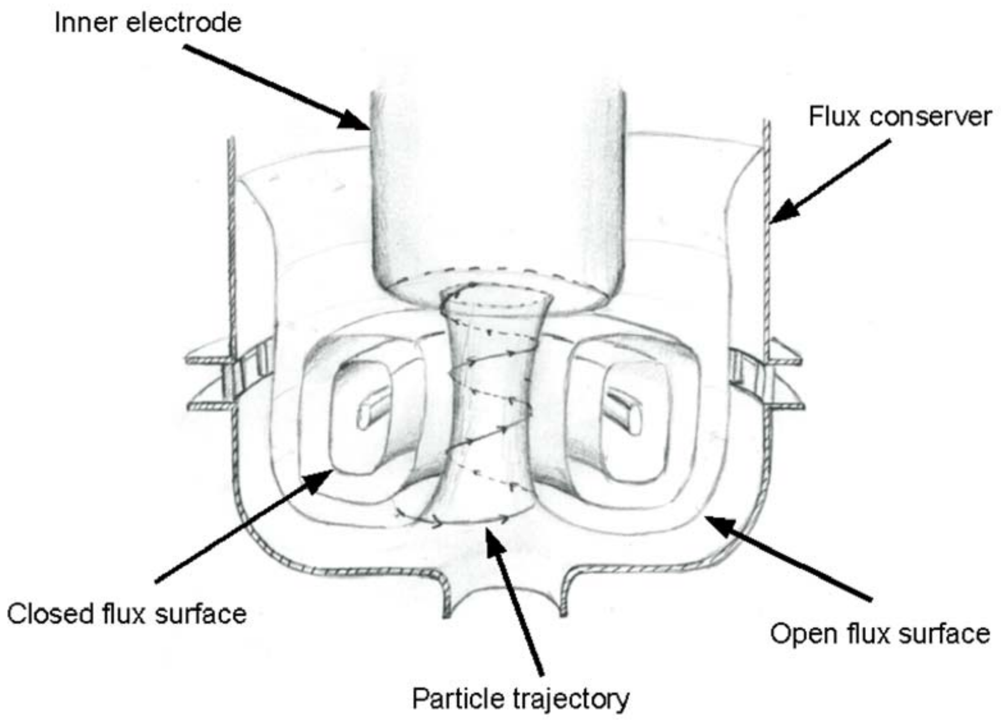
Early formation sequence





Shortly after the column is formed, it kinks

Spheromak with open and closed surfaces



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

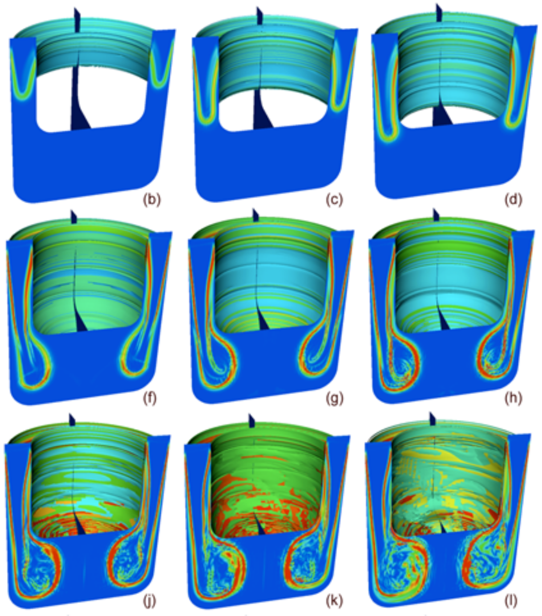
- Helicity injection and flux amplification processes still poorly understood.
- Reconnection is essential, but not sure when and where it happens.
- Both SSPX and NIMROD achieve closed (toroidally averaged) surfaces, but mechanisms appear to be different.

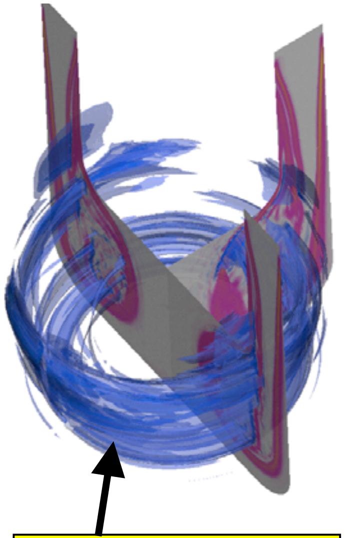
Formation Hypotheses

Magnetic Reconnection and Helicity Injection

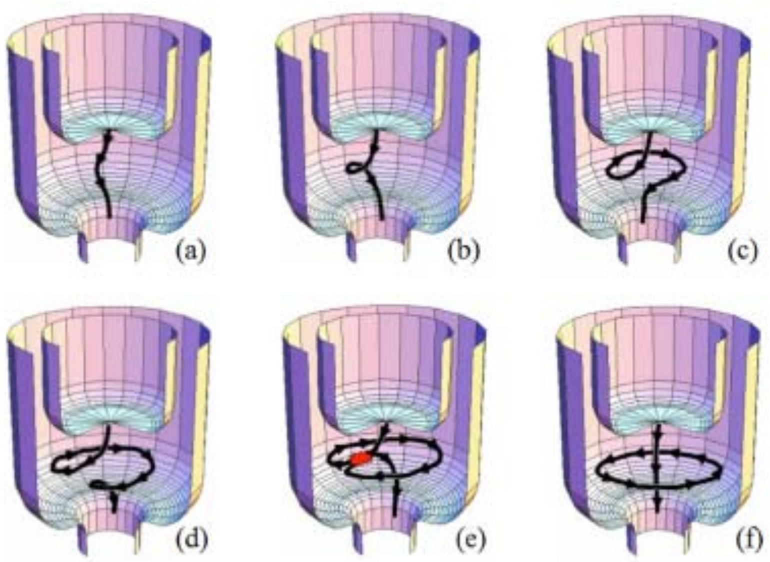
- Flux amplification involves reconnection, but the mechanism that leads to flux amplification in SSPX is still unknown.
- Two models proposed:
  1. NIMROD predicts negative current sheets near the X-point of the mean-field spheromak, with chaotic behavior prior to relaxation for spheromak formation.
  2. The transient column bends and forms two loops that then reconnect to form linked flux.

NIMROD also shows the transient column formation.





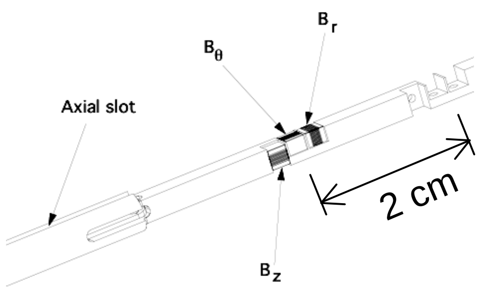
NIMROD: λ ($\mu_o J_{||}/B$) reversal (in 3D) and chaos prior to Taylor relaxation



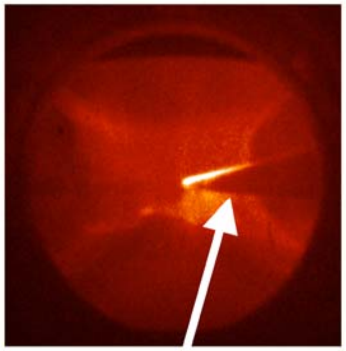
Two-turn reconnection (in a localized region) to form linked flux

Insertable probes to study magnetic evolution

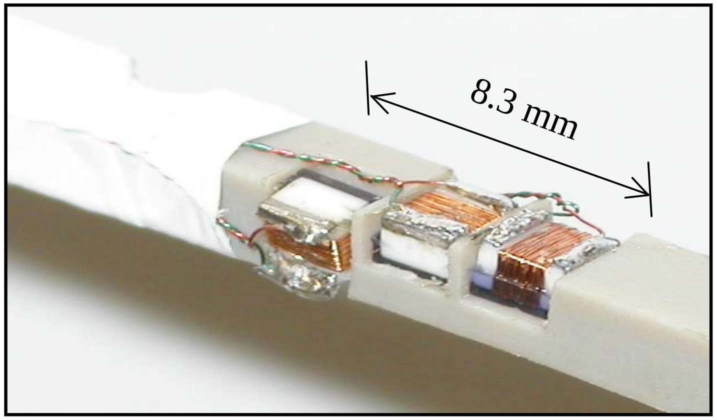
Measures (B_r , B_θ ,B_z) along the entire machine radius.
Array of 24 clusters every 2 cm.



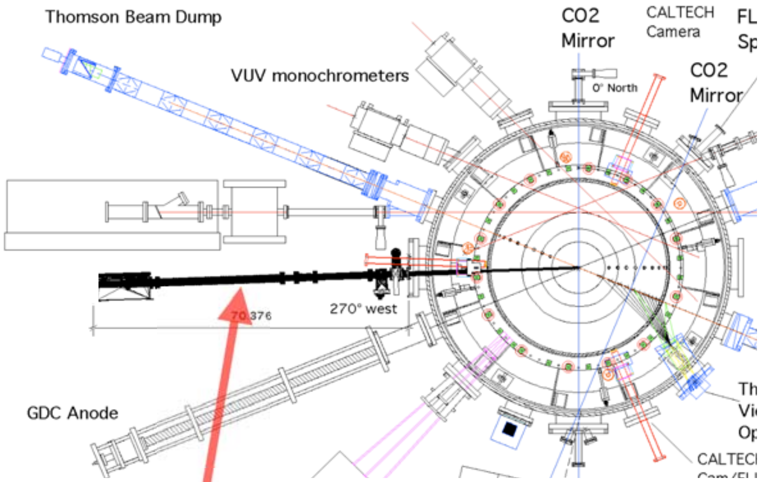
72 chip inductors arranged in 24 clusters

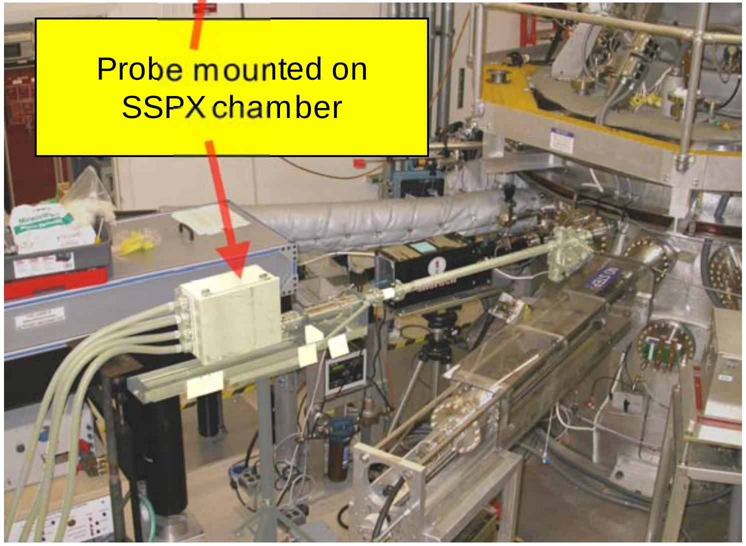


Measuring B field inside plasma column



Chip inductors
Number of turns: 50
Inductance: ~ 5 μH

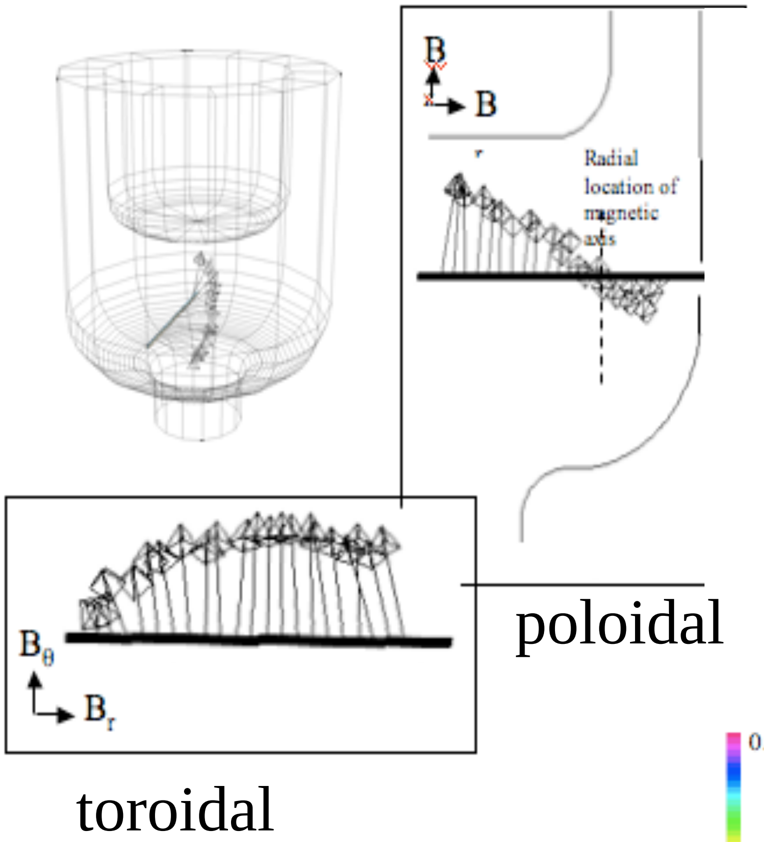


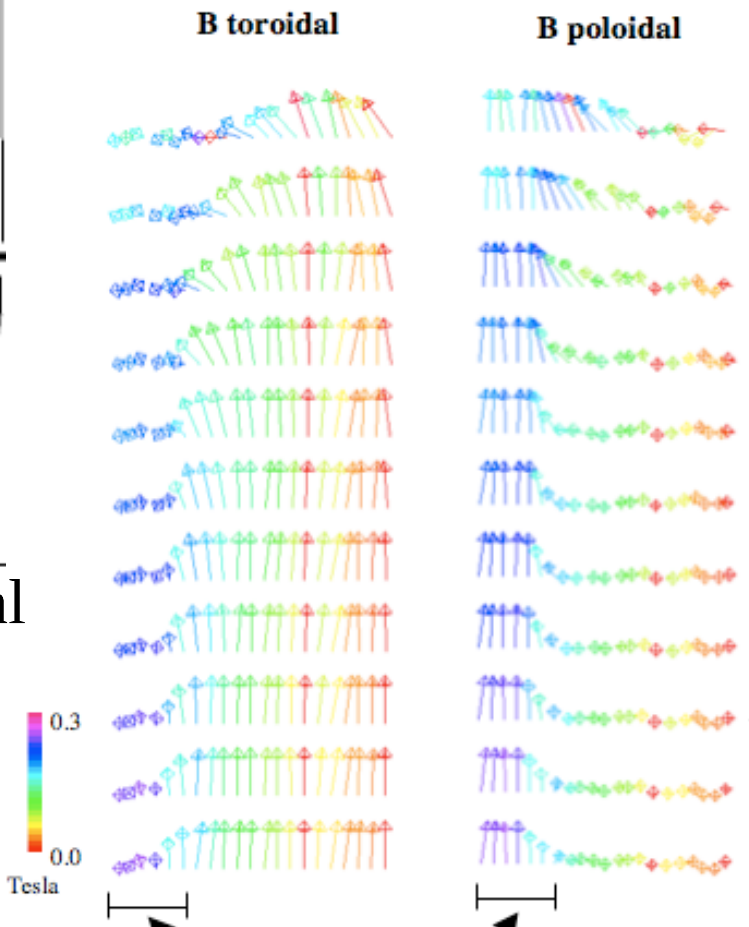


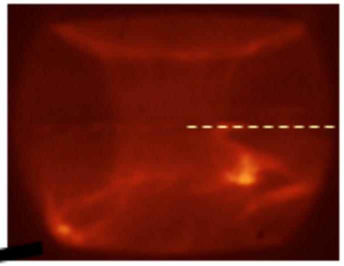
Probe mounted on SSPX chamber

Probe can be retracted without perturbing vacuum

Magnetic Measurements

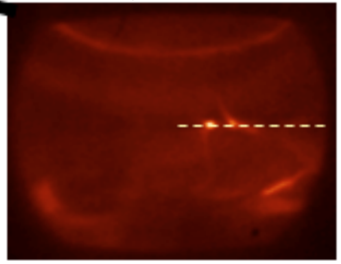






55 µs

60 µs



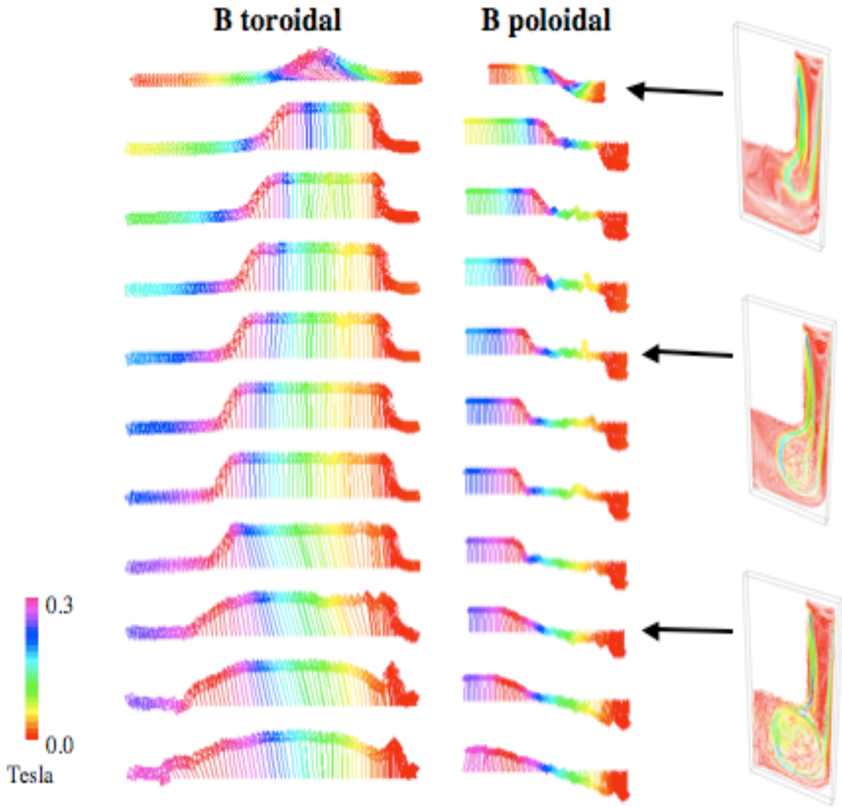
A hollow current profile is measured before kinking

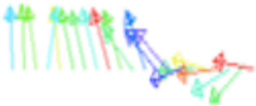
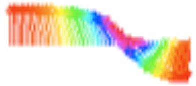
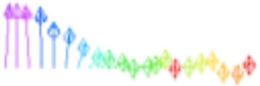
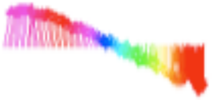
Hollow current profile

Shot 15261

Comparison Between NIMROD and SSPX

NIMROD Magnetic Signal

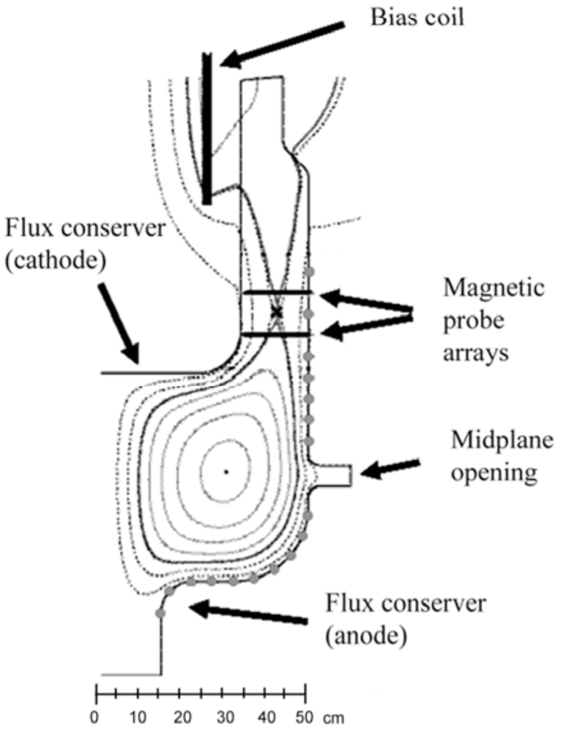


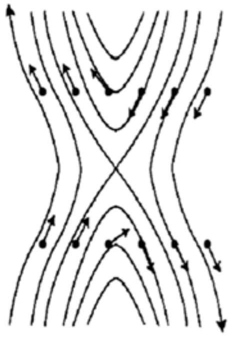
	SSPX poloidal	NIMROD poloidal
Plasma first reaches the probe after breakdown. $t_{hel} = 0\ \mu s$		
Hollow central column. Magnetic signals are still similar, but in SSPX the central column is thinner. $t_{hel} = 11.0\ \mu s$		
NIMROD has reversed poloidal field (necessary for equilibrium), but not SSPX $t_{hel} = 15.6\ \mu s$		

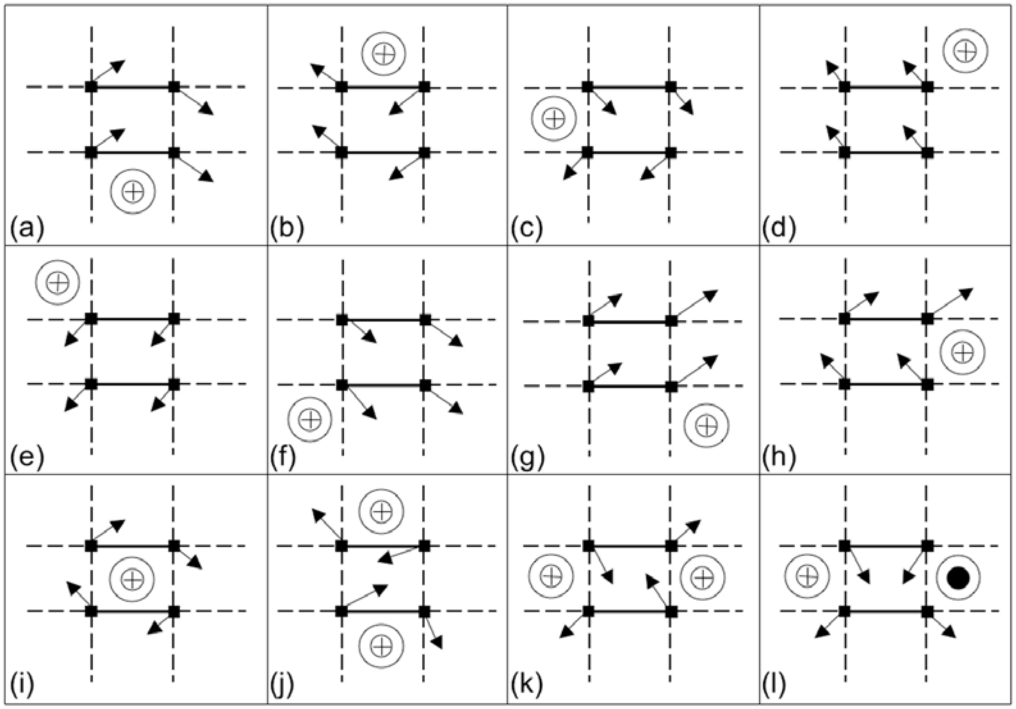
Numerical simulations reproduce closely the ejection of plasma out of the gun. However, NIMROD shows poloidal flux inside the bubble tenths of microseconds before what is observed in the experiment

Magnetic Reconnection is essential for formation

- Magnetic reconnection required to form closed flux surfaces.
- Challenging to find X-points and O-points in short time-scales and varying spatial scales.

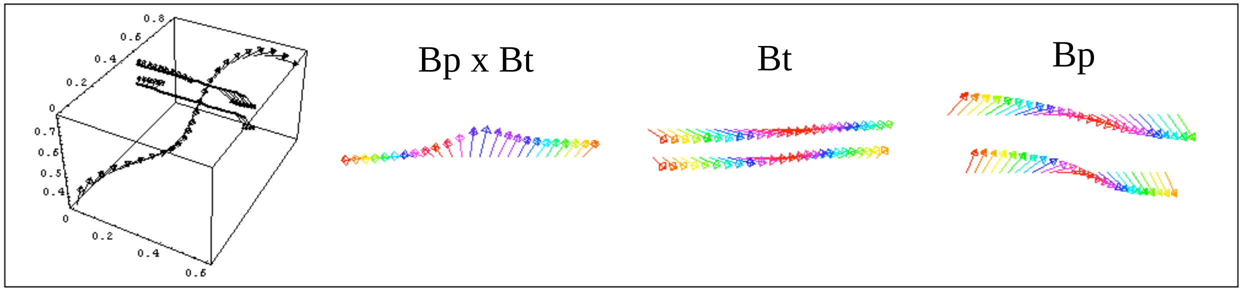




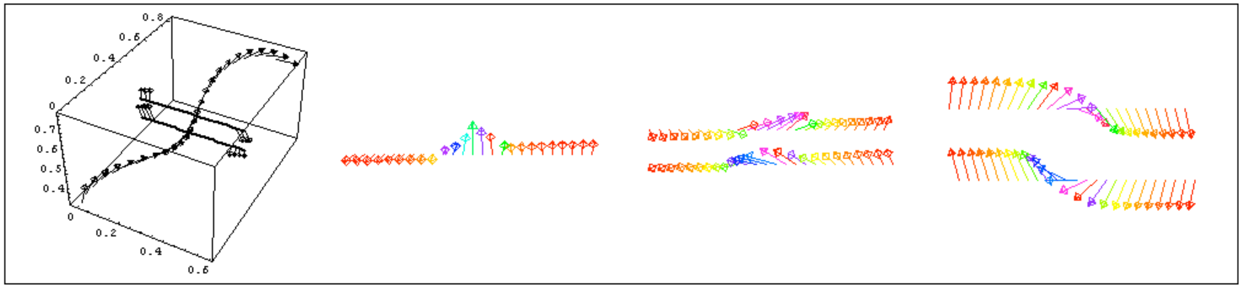


Flux rope simulator

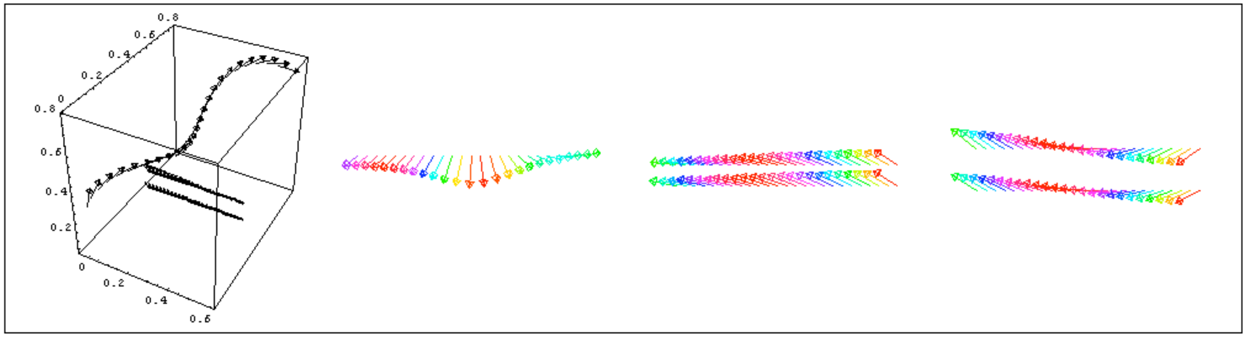
- A code was created to simulate current-carrying flux ropes with with finite diameter and arbitrary shapes.
- The simulations are used to learn how signals from ropes are like as they fly past one or multiple probe arrays



t_1
Flux rope below probes



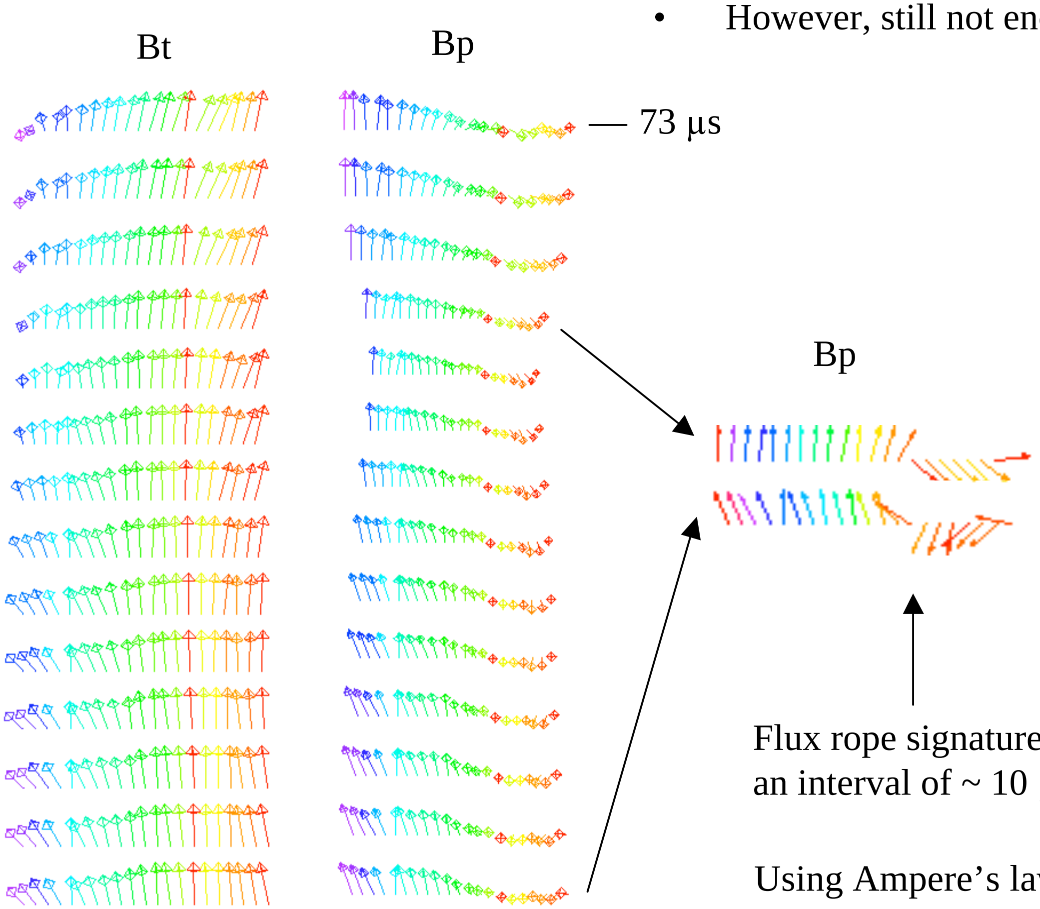
t_2
Flux rope between probes



t_3
Flux rope above probes

Flux ropes in SSPX

- Flux ropes are inferred for short periods of time using the insertable probe.
- However, still not enough to follow the entire kink process.



Magnetic signals for shot 15261. Vector data separated every microsecond.

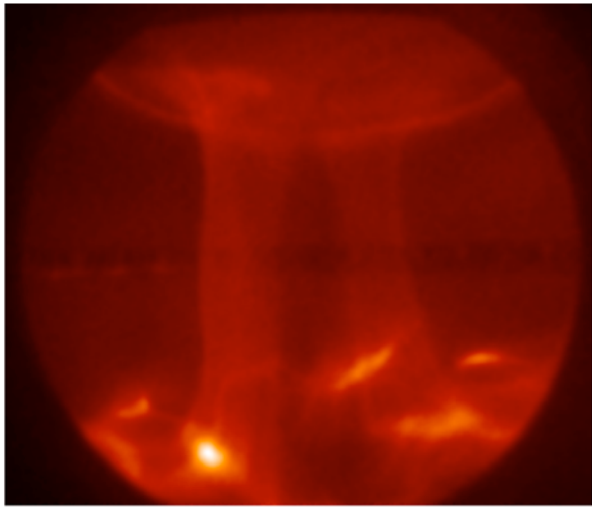
Flux rope signature in an interval of ~ 10 µs

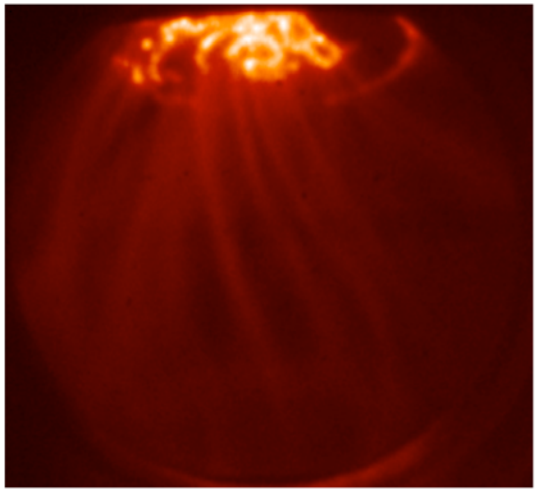
Using Ampere’s law, a single flux rope would carry ~ 50 kA.

If a structure that passes by the probe within this interval is approx. constant, then a single probe array works as a double probe.

Discussion

- Number of reconnection events during formation, together with helicity accounting in the formation column, will help elucidate spheromak formation.
- Algorithms to search for reconnection (X-points) and flux ropes (O-points) are being developed.
  - Solutions are non-unique for limited number of probes.
  - Multiple ropes and highly kinked structures pose even greater challenge.

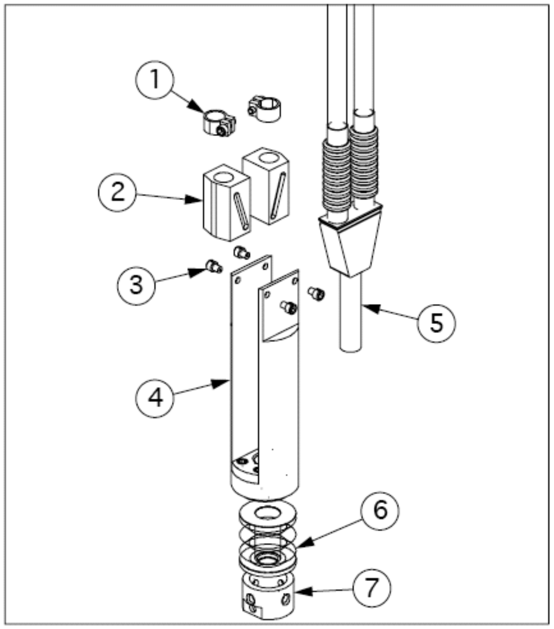




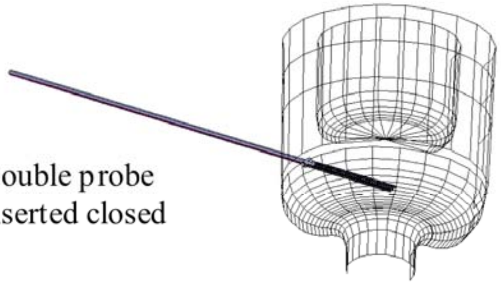
(decay stage)

Future work

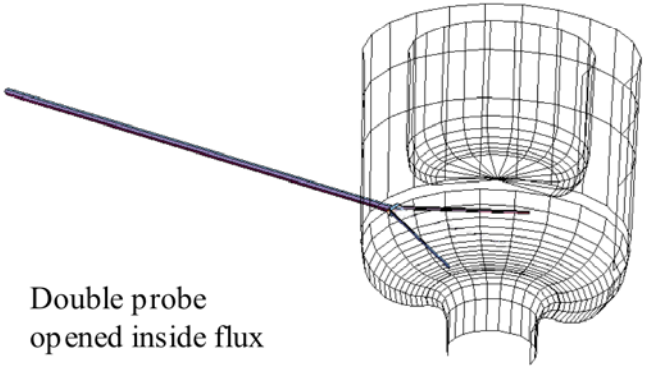
- Build a double-array probe that is movable inside the volume.
  - Search for X-points and O-points with automated software (challenge: to make the search ‘fast’).
  - Probe will further constraint the reconstruction of kinks in the column.



Probe mechanism must withstand ‘harsh’ plasma conditions.



Double probe inserted closed



Double probe opened inside flux conserver