Overview of Spheromak Formation Experiments in SSPX

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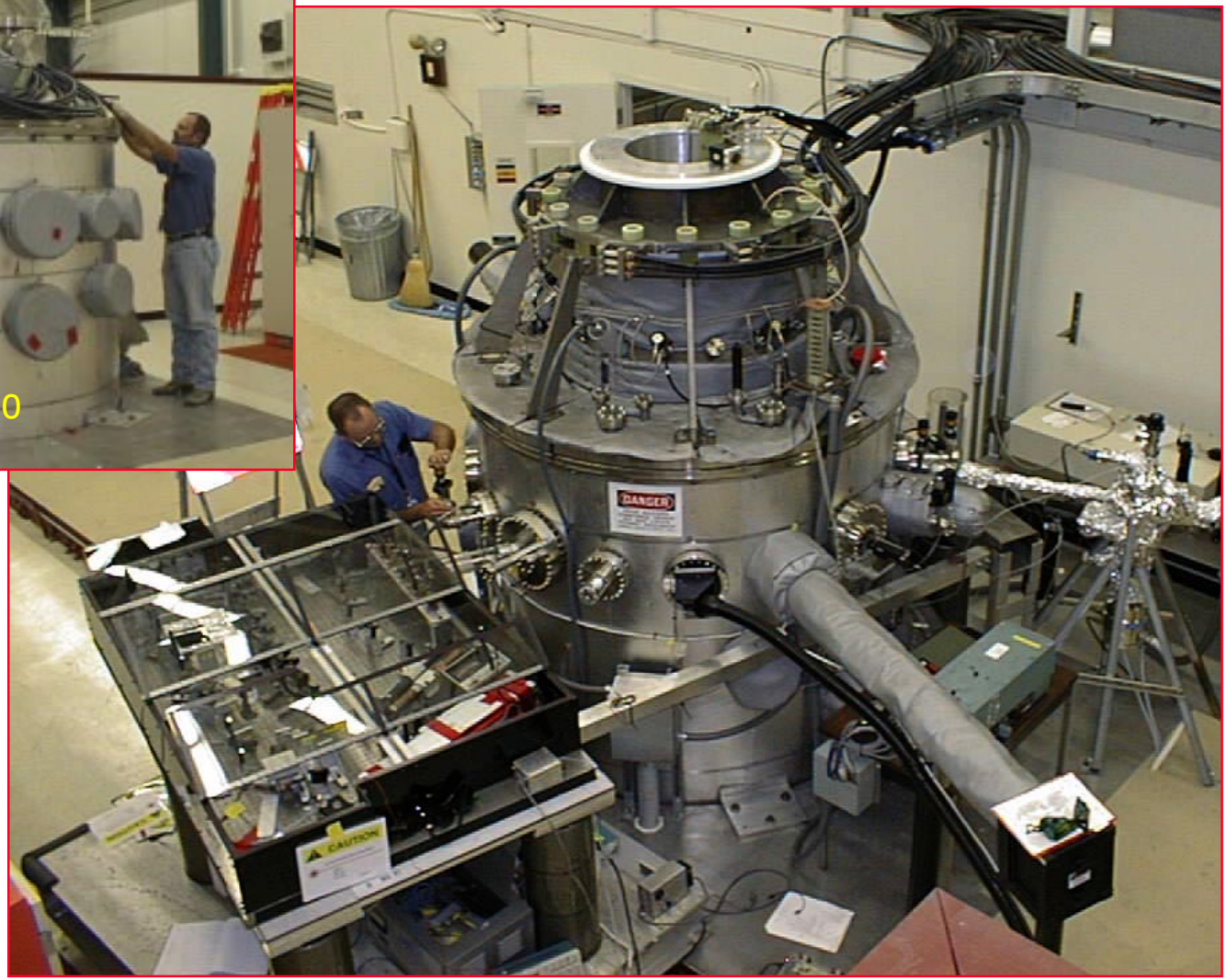
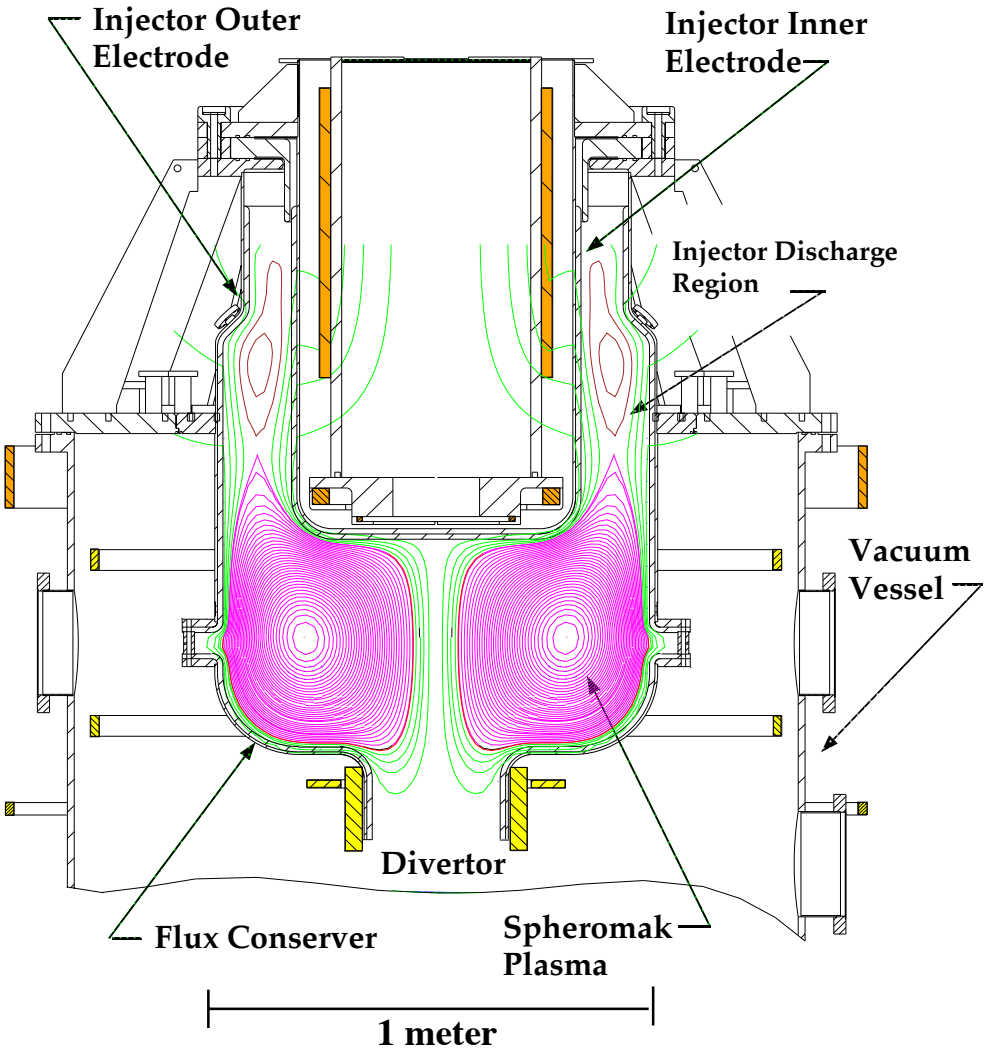
- Sustained Spheromak Physics eXperiment

SSPX is operating routinely now

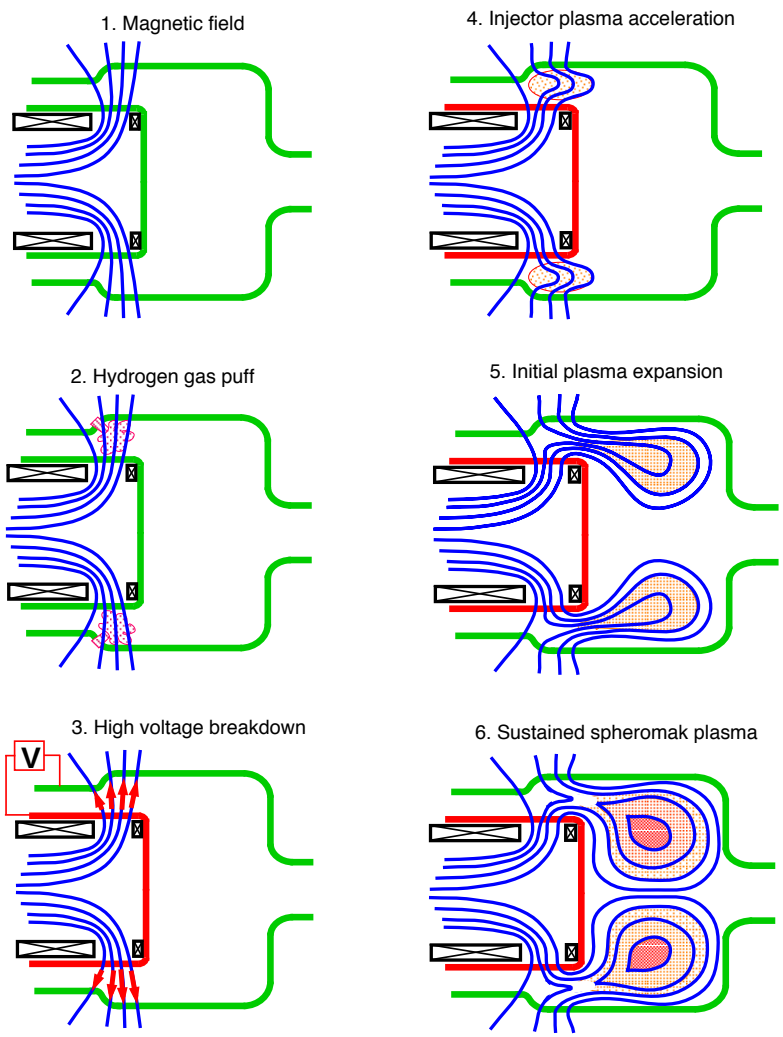


The SSPX Spheromak: sustainment + flexible geometry



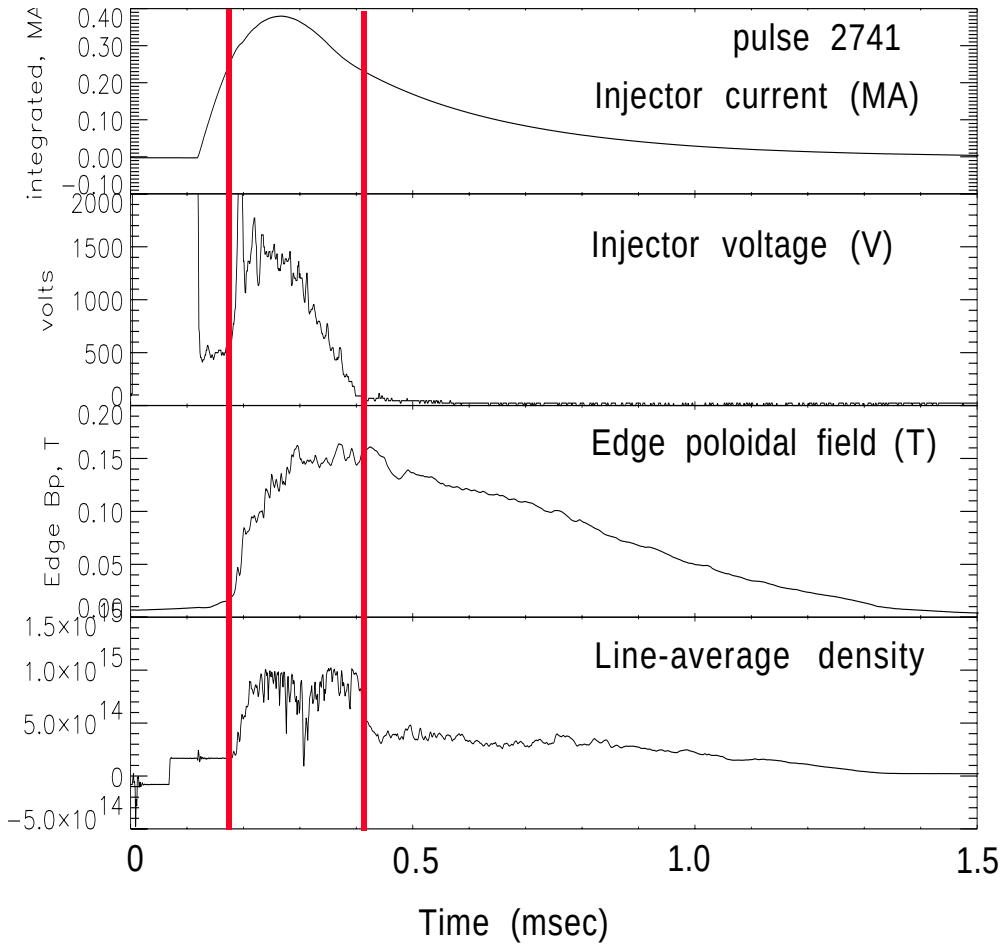
- Conformal solid copper flux conserver minimizes dissipation.
- Improved injector and magnetic configuration (bias coils).
- Tungsten coating to reduce sputtering.
- Plasma minor radius of 0.23m.
- 450kA peak injector current, up to 300kA sustaining current (2msec).
- Expected peak $I_{tor} \cong 1.2$ MA (0.5MA to date), with $B_{tor} \leq 2$ T.

SSPX plasma is formed using Coaxial Injection



- Coaxial electrodes with radial DC magnetic field, B_{radial} , across the gap.
- Gas puff and HV between electrodes causes breakdown
- Current down central electrode produces toroidal field,
- $J_r \times B_{tor}$ force pushes plasma down injector and into flux conserver if sufficient pressure to bend radial field lines.
- Reconnection at throat leaves toroidal spheromak plasma inside flux conserver with poloidal and toroidal fields and currents.

Typical SSPX discharge with formation bank.



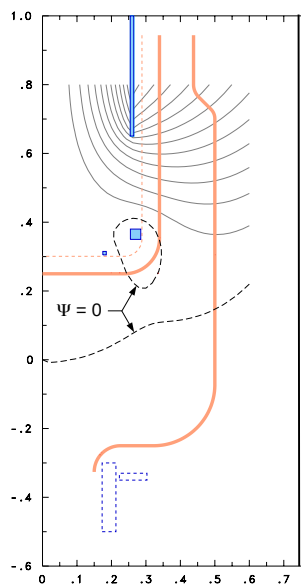
- Poloidal field builds until bank voltage drops.
- Density during decay is about $3\times10^{14}cm^{-3}$ for this pulse with Ti gettering.
- Power balance between ohmic input and radiation loss sets a minimum J/n for burn-through.
- Best estimate suggests that we need to lower density about factor of four. See poster by McLean

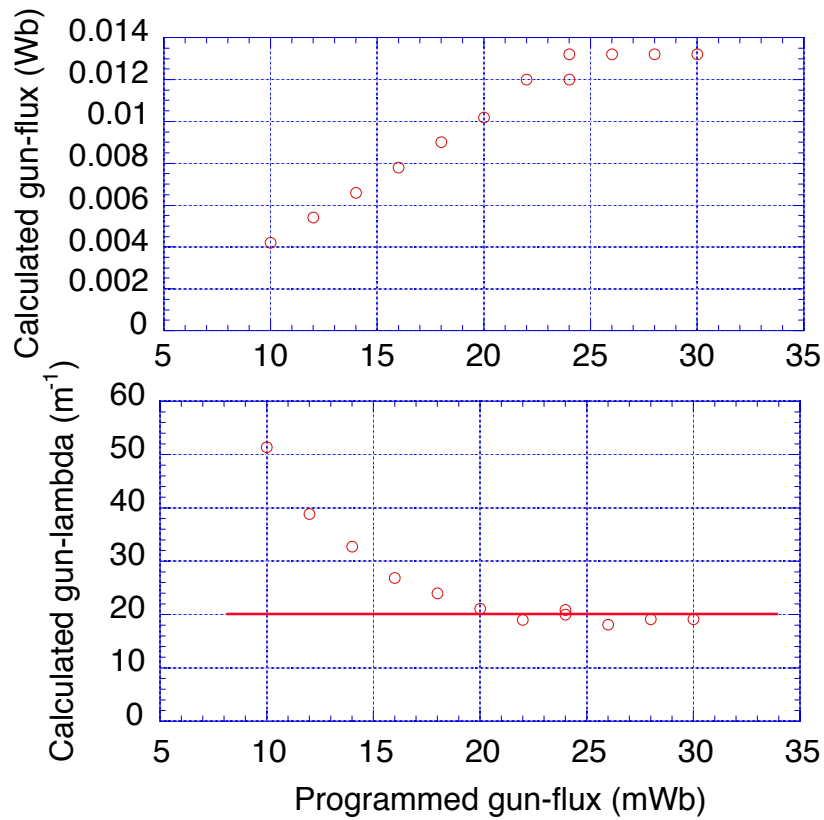
Spheromak Formation Threshold Agrees with Predictions if not Overdriven

• Ejection thresholds can then be calculated from:

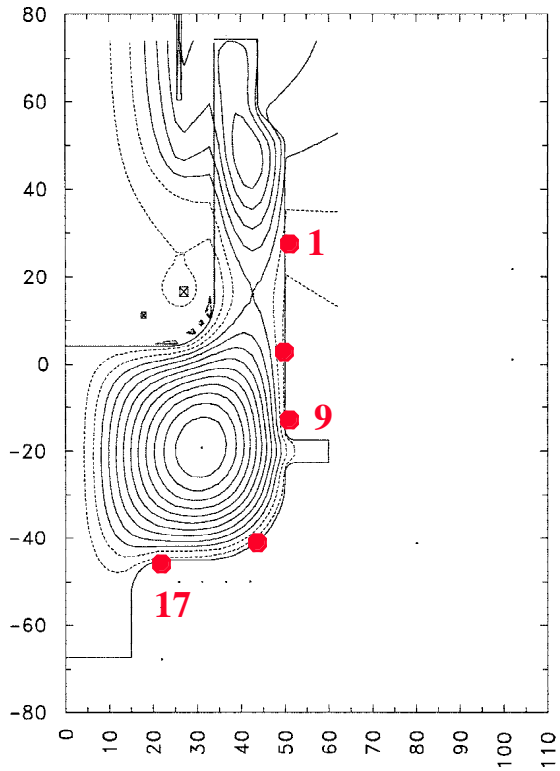
$$\lambda_{crit} = \frac{\mu_0 I_{inj}}{\psi_{inj}} = \mu_0 \frac{I_{thresh}}{2\pi \int_{0.42}^{0.5} r B_p(r) dr}$$

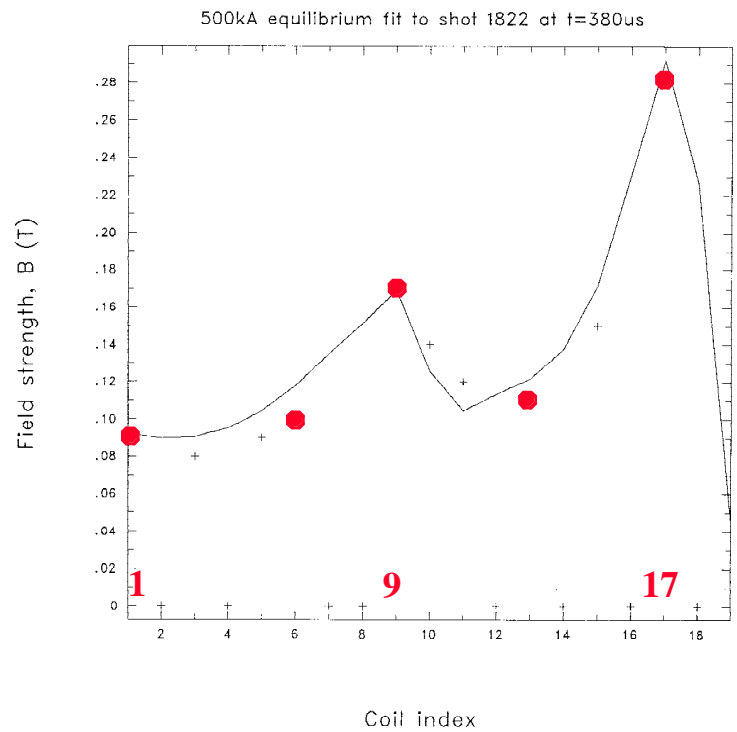
where the I_{thresh} is determined at the time of steep rise of V_{inj}.





CORSICA models magnetic probe data to obtain spheromak parameters

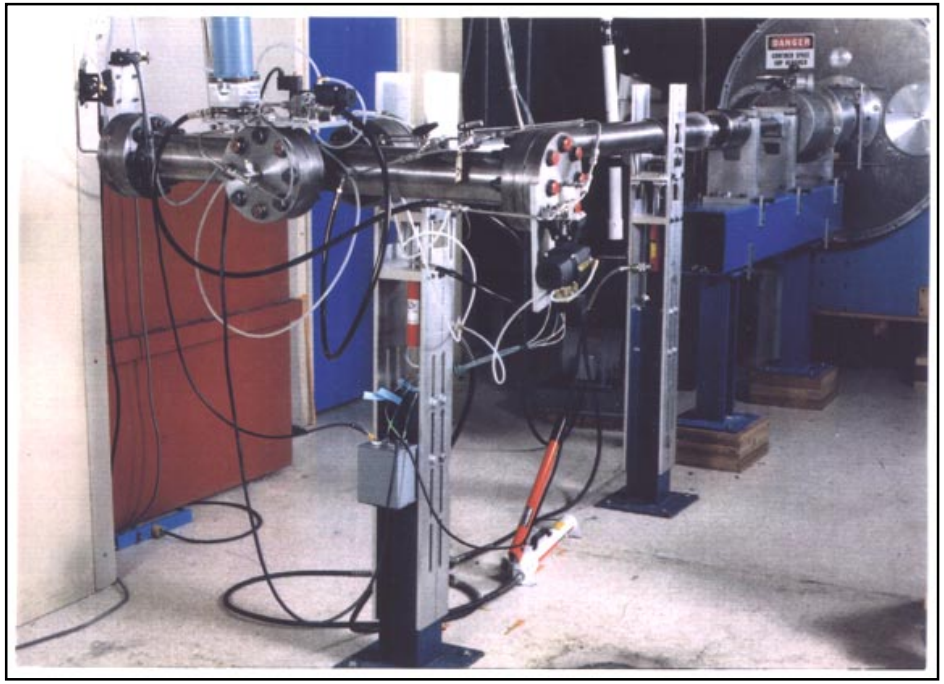


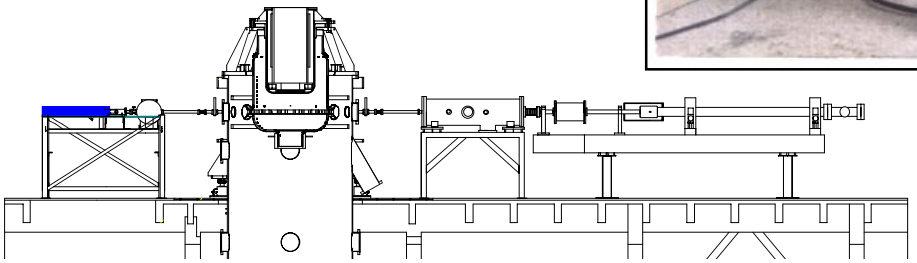


- **During buildup to 500kA, λ=j/B constant on closed field lines and about twice that on the open field lines connecting the electrodes.**
- **Internal measurements needed to nail down current profile.**

Transient Internal Probe provides B_T profiles

- Collaboration with U. Washington (grad student on site)
- Measure Faraday rotation of laser light in a high speed bullet as it transits plasma tangent to magnetic axis in 250μsec.
- $B_T(r)$ gives internal data needed to reconstruct current profile.
- Can also record magnetic fluctuations



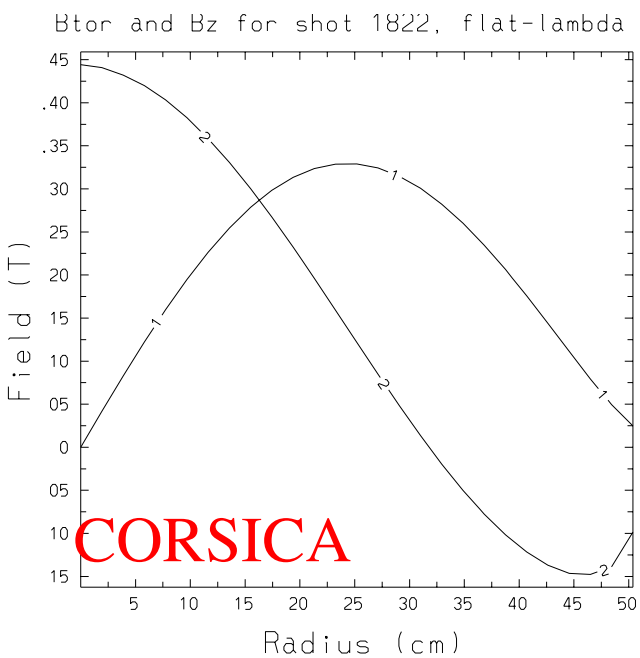


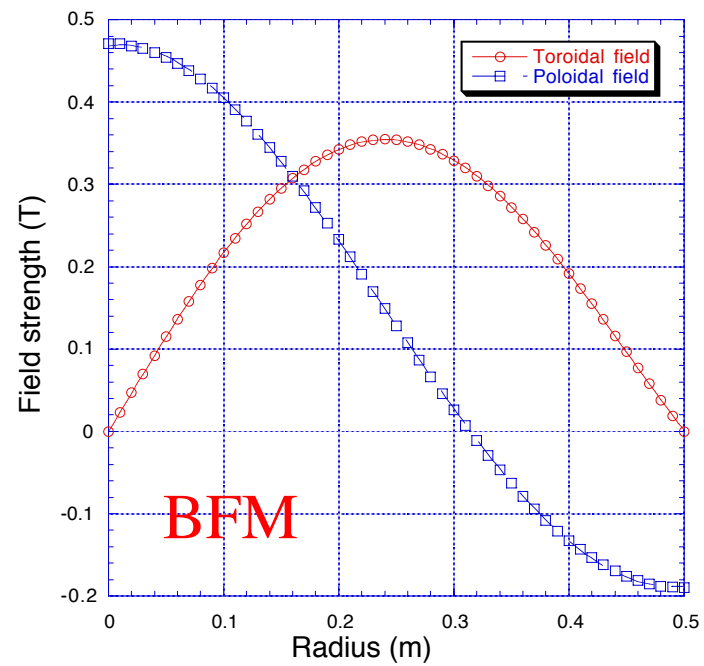
see poster by Holcomb

During decay phase, fields match Taylor relaxed state

The Bessel function model is a good model for the relaxed state, describing the field configurations with a single constant: λ - defined by the geometry of the configuration.

$$\vec{B}_0 = B_0[J_0(\lambda r)\hat{z} + J_1(\lambda r)\hat{\theta}]$$

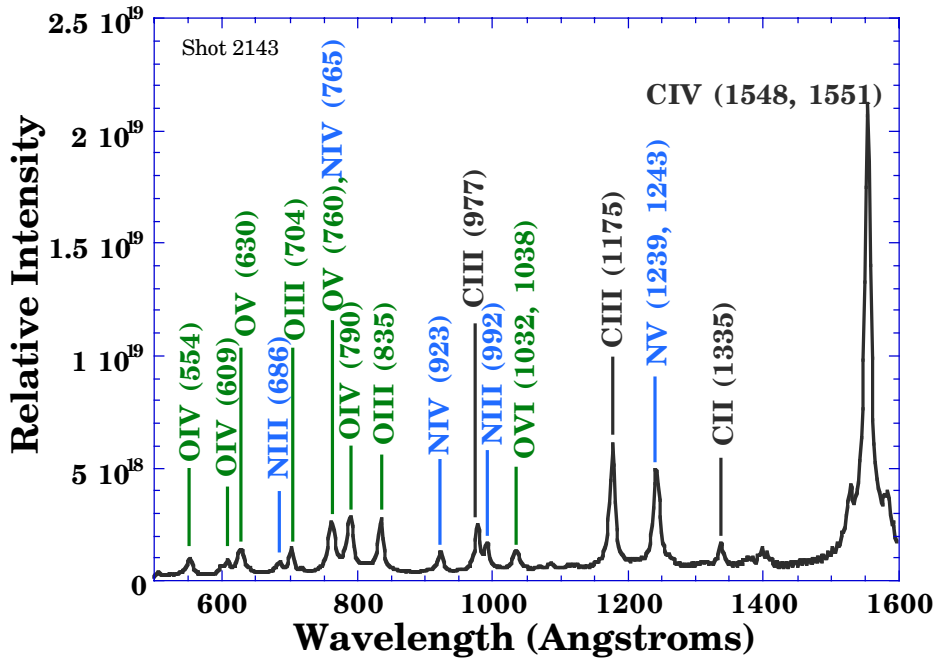




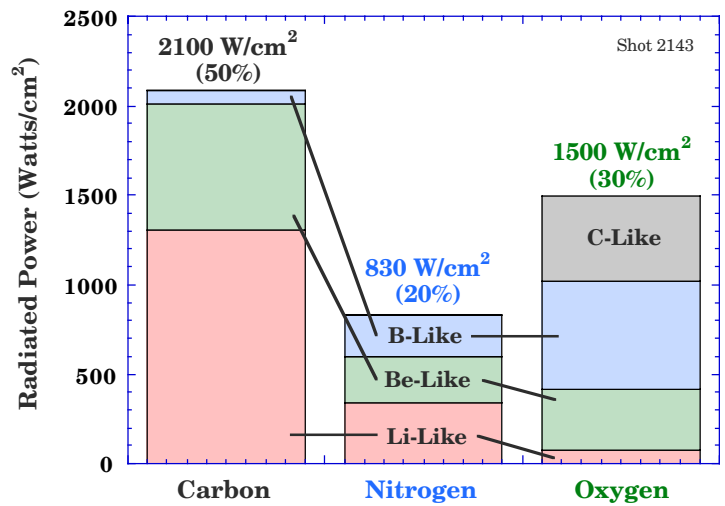
During decay, the spheromak quickly reaches a relaxed state. For shot 1822 at t=475μs, the plasma fields fit well to a CORSICA equilibrium with a flat λ-profile. The form of the internal field gives good agreement with the BFM (above), also determined for a current of ~300kA. Minor differences can be seen in he edge poloidal field.

VUV Spectra show Carbon is main radiator

Emission spectrum from SPRED



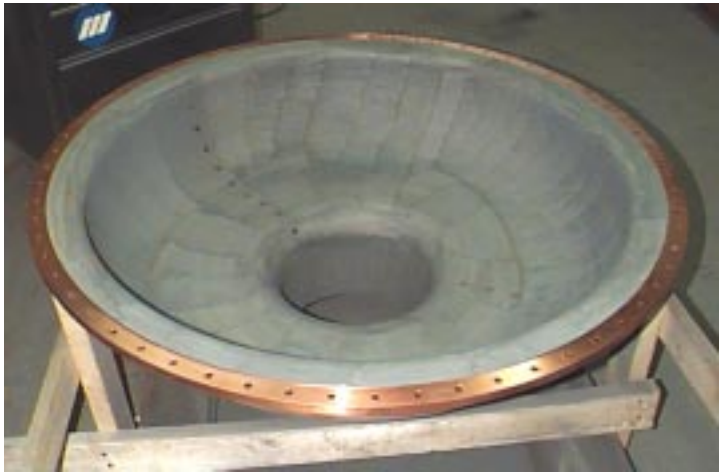
Calculated impurity emissivity



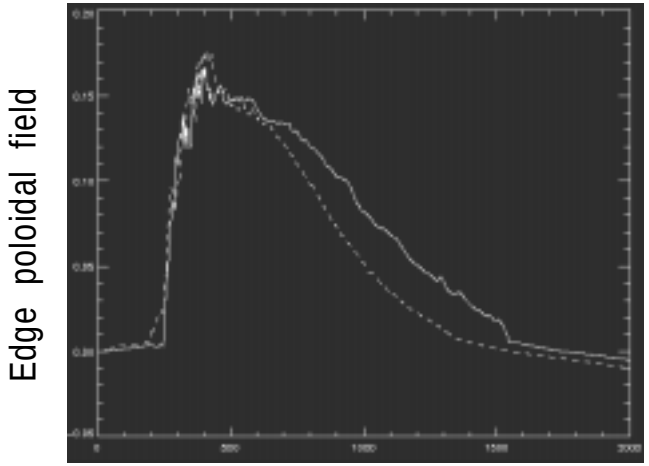
- Impurity content should be reduced by improved GDC, Ti gettering, and possibly the removal of some of the tungsten coating on the flux conserver.

Longer decay times observed with improved wall conditioning (Titanium gettering)

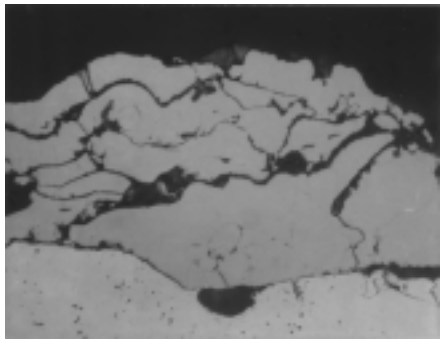
Plasma-sprayed W coating on FC



Field decays more slowly

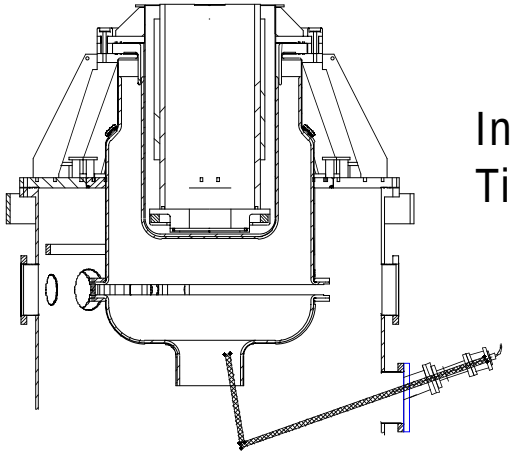


Surface porosity may be an issue



50 μm

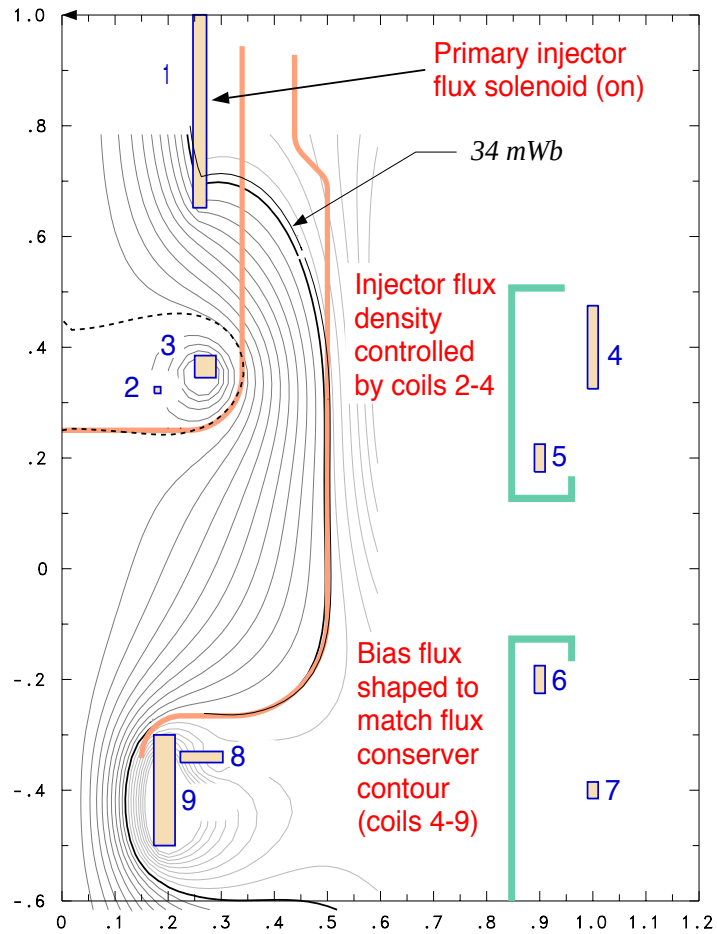
D. Buchenauer, SNL



Insertable Ti getter

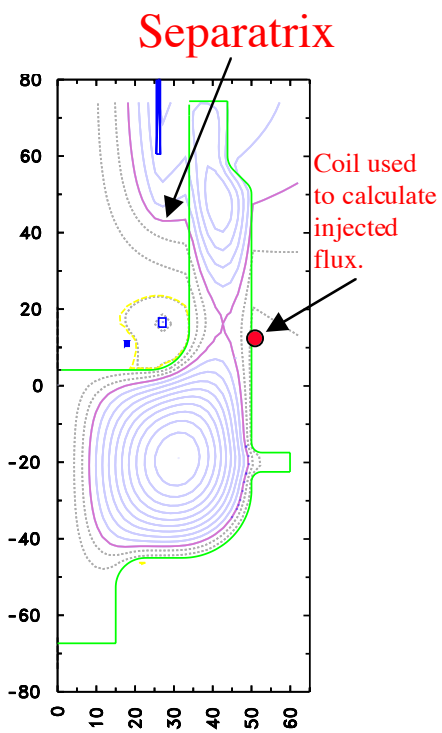
Bias coils will modify the formation process and should also allow more efficient injection

- With bias coils, vacuum field lines pass through flux conserver
  - field errors minimized
  - reduced losses in the injector
  - utilizes larger fraction of initial flux, which increases drive efficiency
  - threshold set by kink stability of central column
- Bias coils have been built and will be installed this summer
  - Two internal coil assemblies
  - Two external coil assemblies
  - Power supplies installed



Preliminary experiments with a partial flux core yield better spheromak plasmas

Standard Flux



$$\psi_{inj} = 2\pi \int_{0.42}^{0.5} r B_{@mouth}(r)\,dr \approx \frac{\psi_{gun}}{2}$$

- Gain in efficiency due to increase in flux drawn from gun:

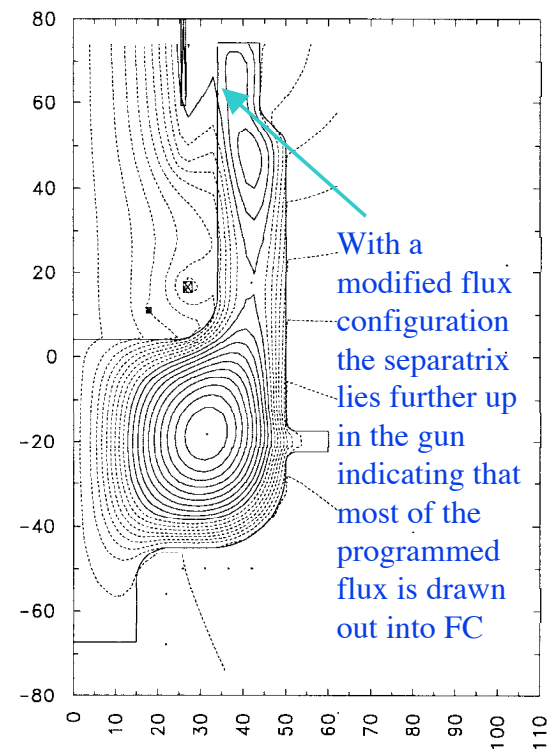
$$\varepsilon = \frac{\lambda_S}{\lambda_{inj}} = \frac{\lambda_S \psi_{inj}}{\mu_0 I_{inj}}$$

- Drawing more flux into FC leads to higher 'helicity injection' rate:

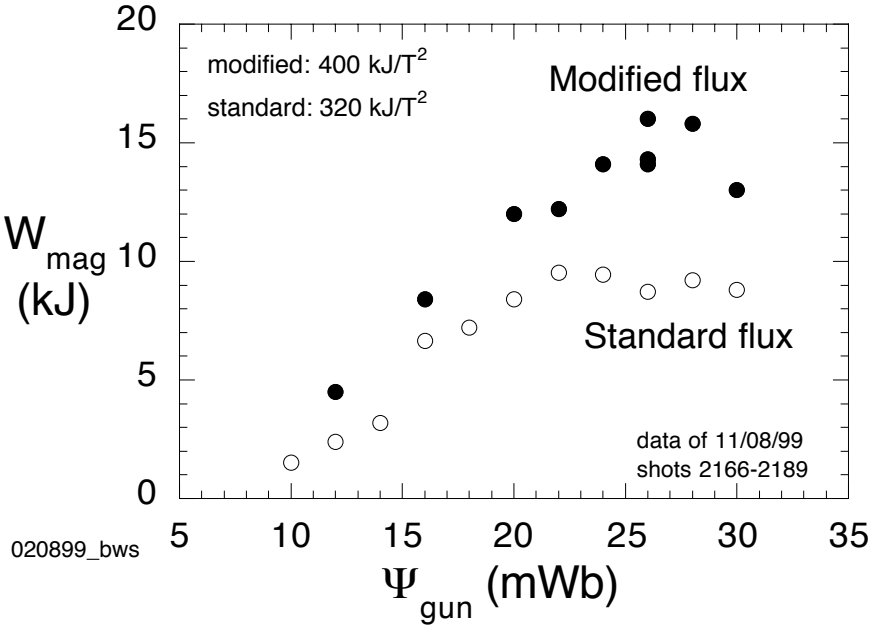
$$K = 2V_{inj}\psi_{inj}$$

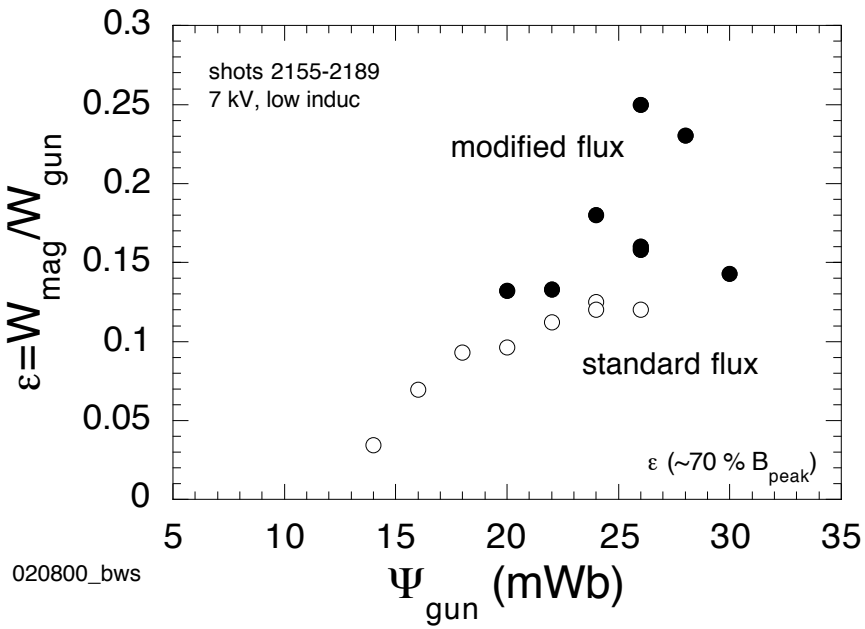
- Longest field-decay times found for this mode of operation: ~twice those obtained for standard flux-config.; indicates higher temperatures.

Modified Flux



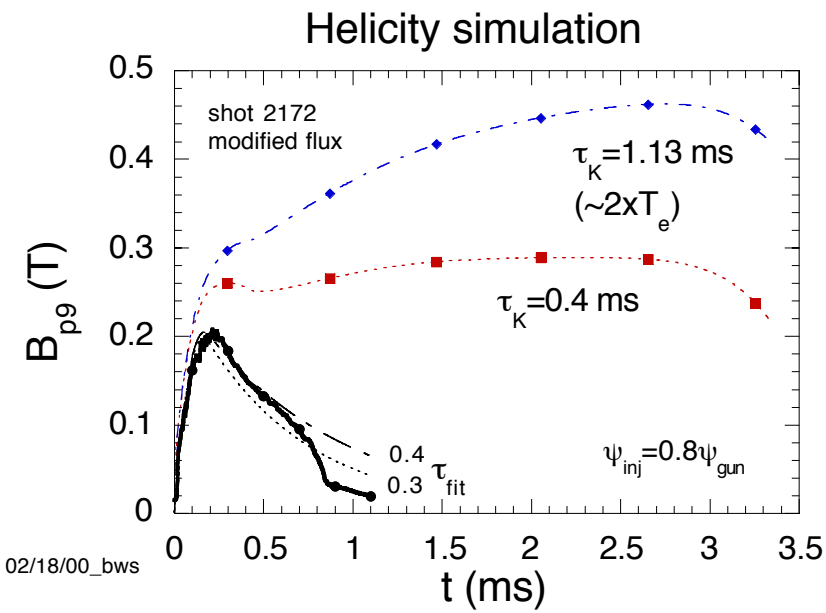
Coaxial injection is more efficient for partial flux core

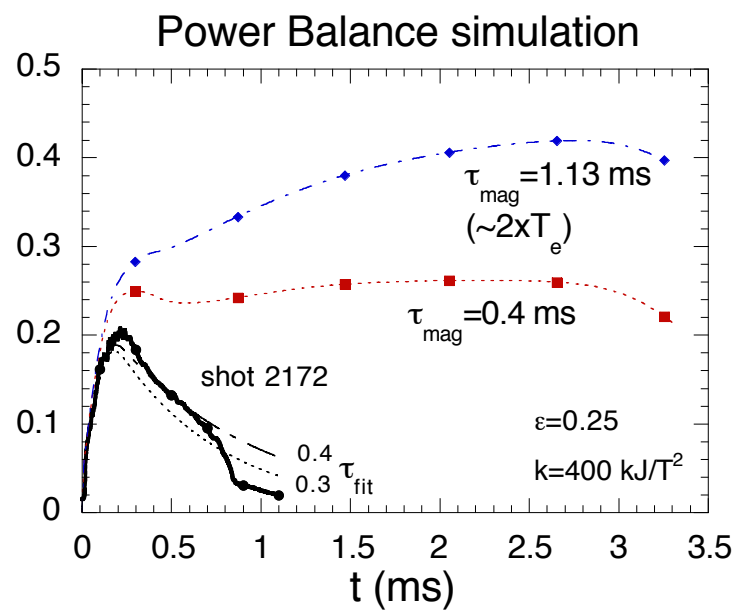




- Stored energy calculated by CORSICA using external magnetics data.
- Partial flux core configuration is improved, but still leaves more than half of flux in the injector region.

Helicity balance or energy balance give similar results for extrapolation to operation with sustainment bank





$$\frac{\partial K}{\partial t} = \frac{-K}{\tau_K} + 2V_g\psi_g$$

$$\frac{\partial W}{\partial t} = \frac{-W}{t_W} + \varepsilon I_{inj} V_{inj}$$

- Data from partial flux core operation
- Results sensitive to estimated decay times (T_e) for helicity (or magnetic energy) see poster by Stallard

SSPX Facility Supports a National Spheromak Program

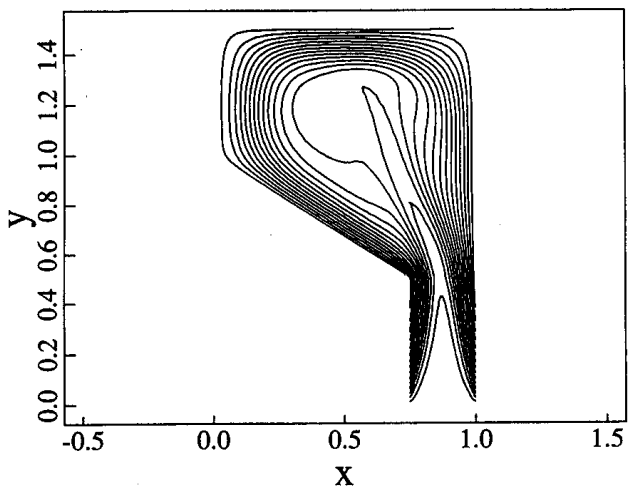
- Direct Funding to university groups supports students and scientists:
  - UC Davis and University of Washington for diagnostic development
  - UC Berkeley for reactor studies and power balance measurements

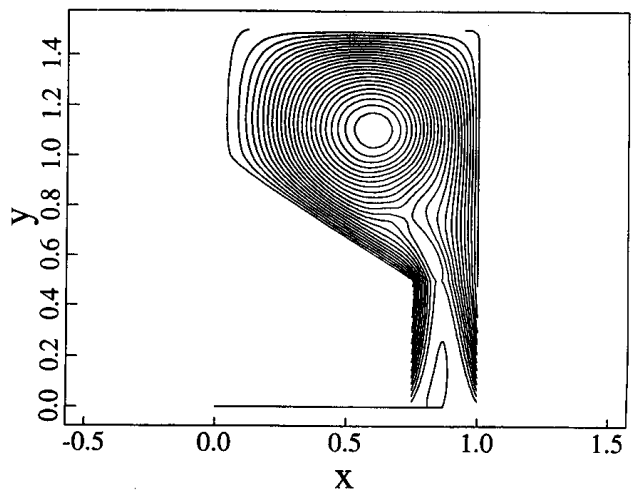
- Other Labs and Universities also participate in the SSPX program
  - Wisconsin with spectroscopy and Thomson procurement from GA
  - LANL with diagnostics and particle balance studies ($200k in FY00)
  - SNL with wall conditioning and surface physics (~0.5FTE)
  - NIMROD consortium (SAIC, LANL, Wisc., GA, etc.) does 3-d MHD
  - Himeji Institute of Technology (Japan) with ion Doppler measurements

- Remote Site capability will facilitate off-site collaborations
  - Other groups can participate effectively in experiments with little travel.
  - Improved capability from the VTL community proposals on Info. Tech.

Theory support is an important program element

- Realistic prediction of the formation and sustainment of the spheromak requires 3-d, time-dependent, nonlinear resistive MHD simulations
- We are using the NIMROD code (Sovinec, et al., LANL, and Schnack, SAIC).





- General theory support on injection physics
  - Threshold and formation physics, fluctuation analysis (e.g. USPR)
  - Operation simulation and reconstruction (CORSICA)
  - UEDGE simulation of injector and edge plasma

see poster by B.I. Cohen

Summary

- The SSPX spheromak is operating reliably
  - Reproducible discharges over full range of injector design parameters
  - Formation threshold consistent with coaxial injector geometry
  - T_e is low: improving wall conditioning to reduce recycling and impurity content, and adding bias coils to increase injection efficiency
  - Buildup limited by pulse length; very close to having sustainment bank
  - Steadily improving diagnostic suite: SPRED, CO2, USPR, PTS, and TIP
- The SSPX facility at LLNL provides national capability for studying spheromak physics and testing new configurations