Overview of plasma-wall interactions in the SSPX spheromak experiment

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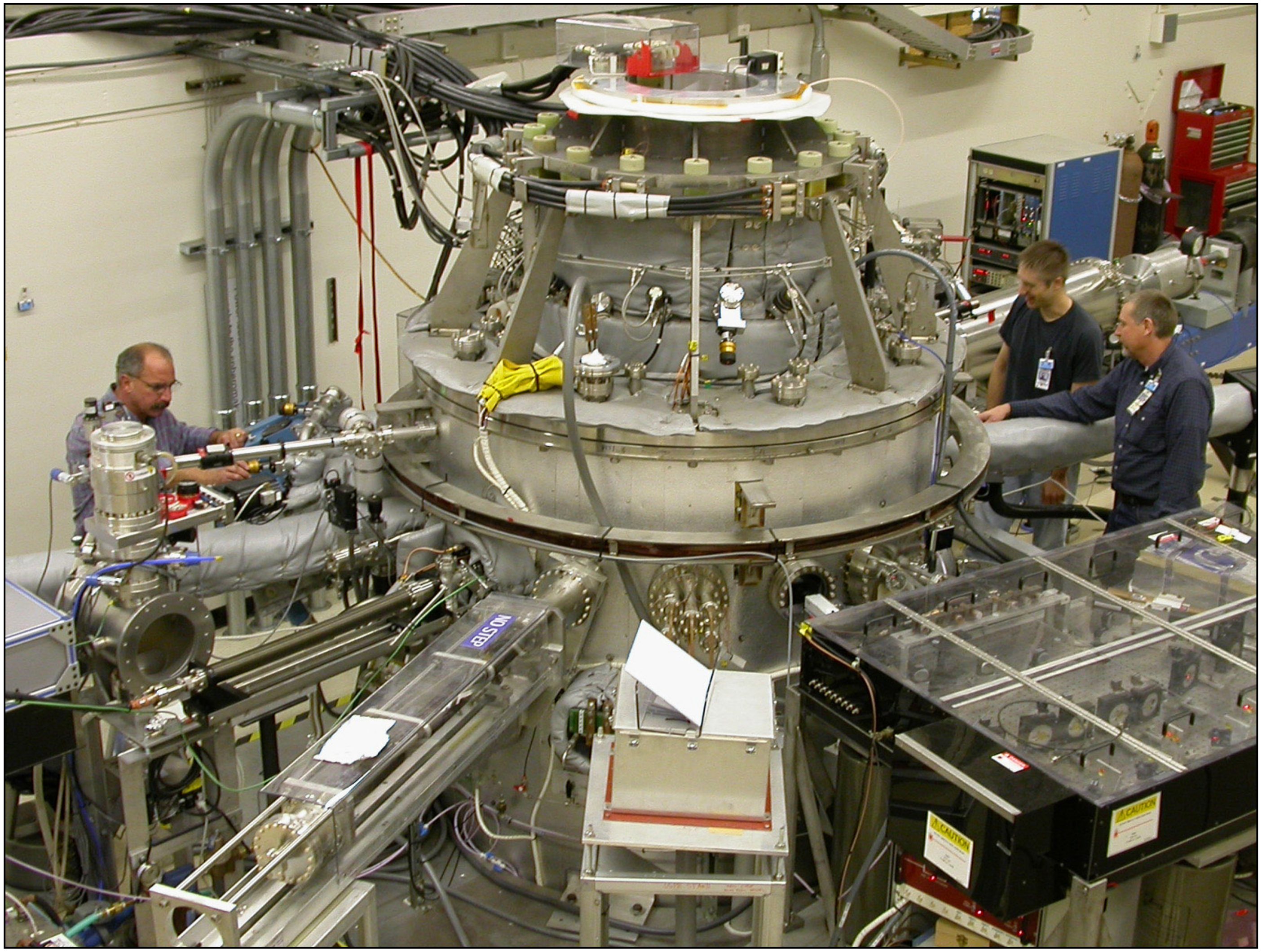
Outline of this talk

- **Overview of the spheromak concept and purpose of the Sustained Spheromak Physics eXperiment**
- **Impurity control**
- **Power Balance**
- **Density control**
- **Future directions**

Workshop Agenda

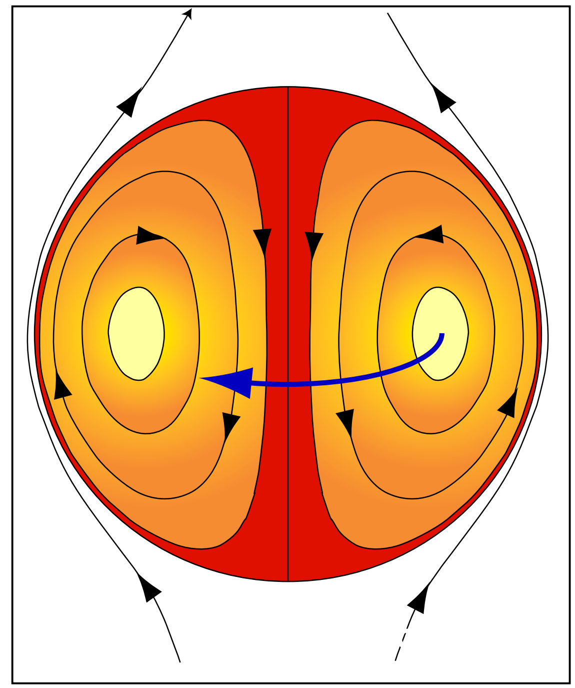
The SSPX Spheromak began operating at LLNL in 1999



The SSPX spheromak

The Spheromak is a "self-organized" plasma configuration

- **A low-aspect ratio (R/a » 1) toroidal plasma with**
  - — **toroidal magnetic field on axis**
  - — **poloidal magnetic field on edge**
  - — **force-free currents parallel to fields**
    ($\nabla P = j \times B \approx 0$) $\Rightarrow$ $\nabla \times B = \lambda B$ $\lambda = j/B$



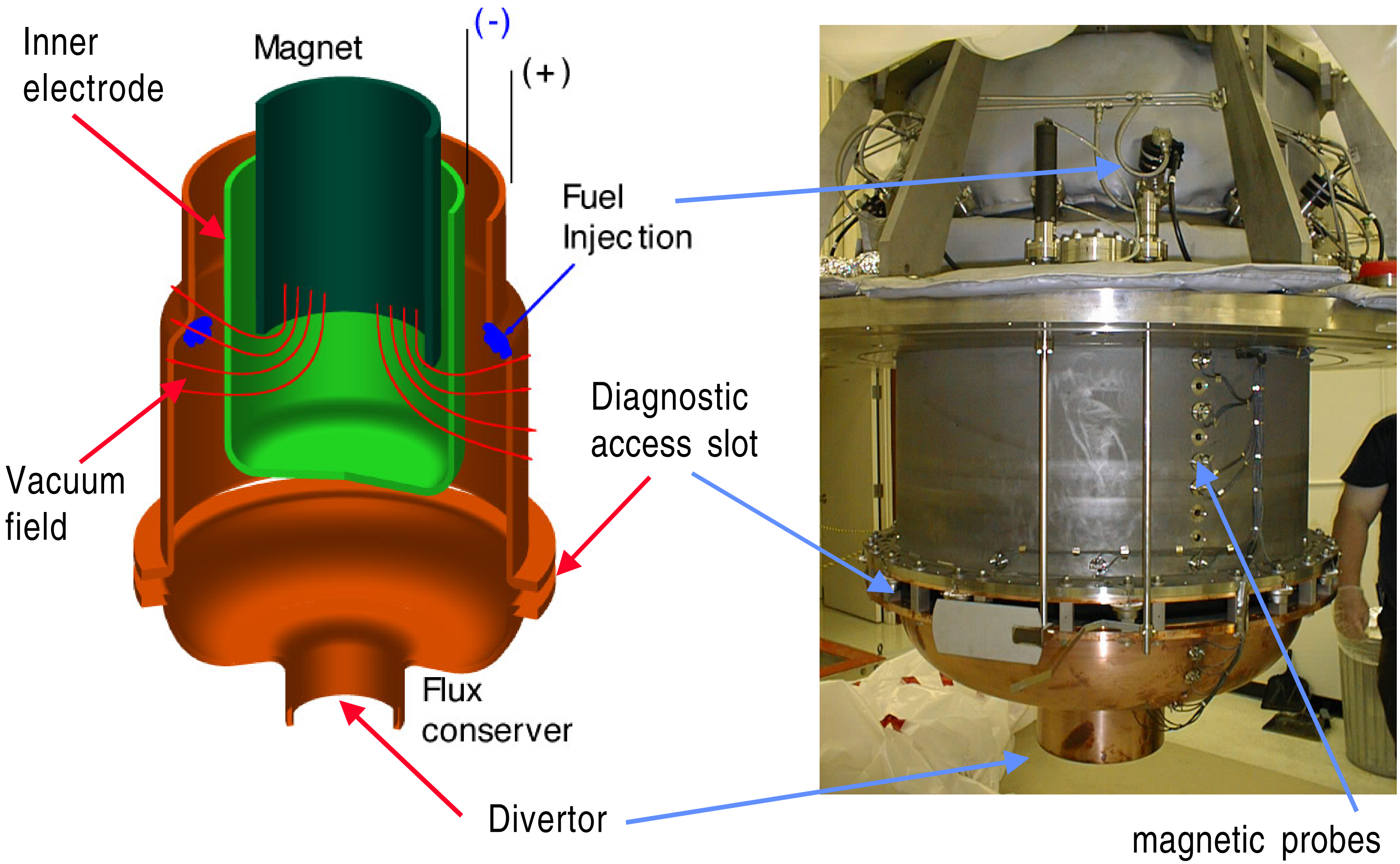
- **Internal confining magnetic fields result from plasma currents in a self–consistent manner:**

  more efficient to generate fields in hot plasmas

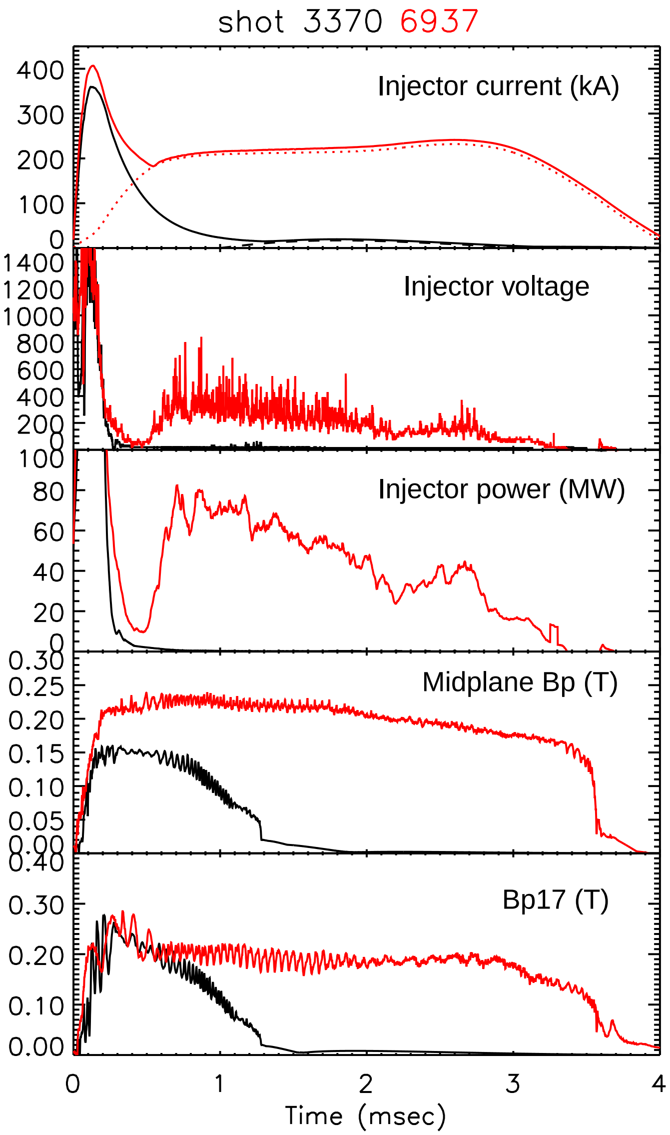
- **Magnetic fluctuations maintain configuration near that with minimum internal field energy: a Taylor "relaxed state".**

Self-generated magnetic fields point to potential for an attractive fusion reactor concept.

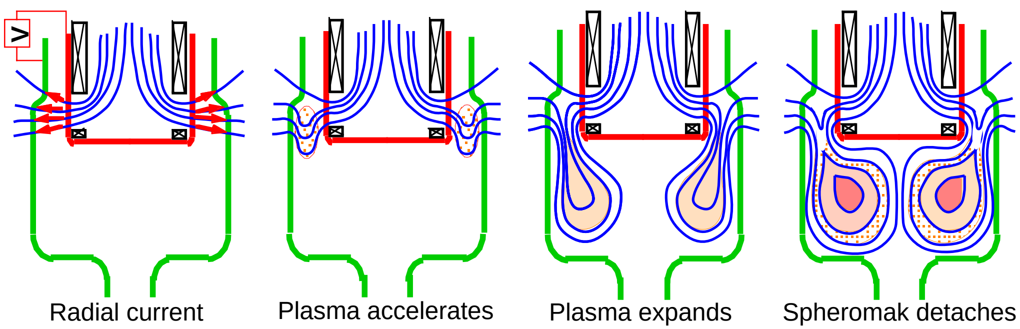
We use DC coaxial injection to form spheromak plasmas in SSPX



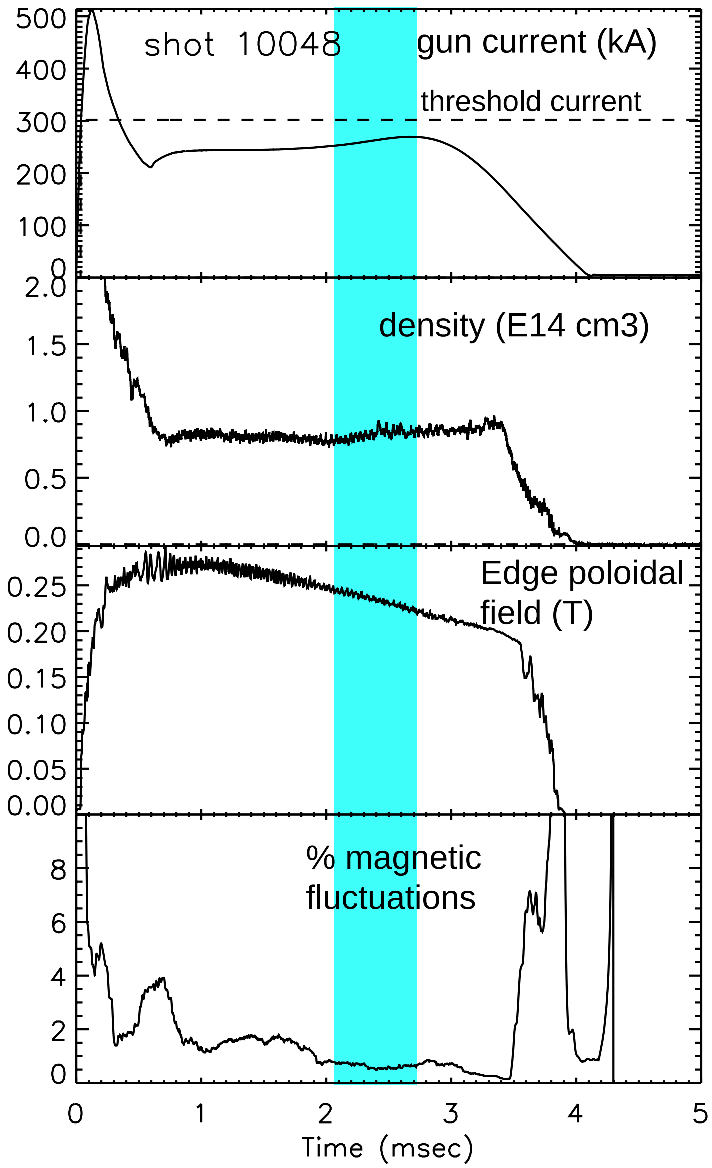
Standard formation and sustainment operation

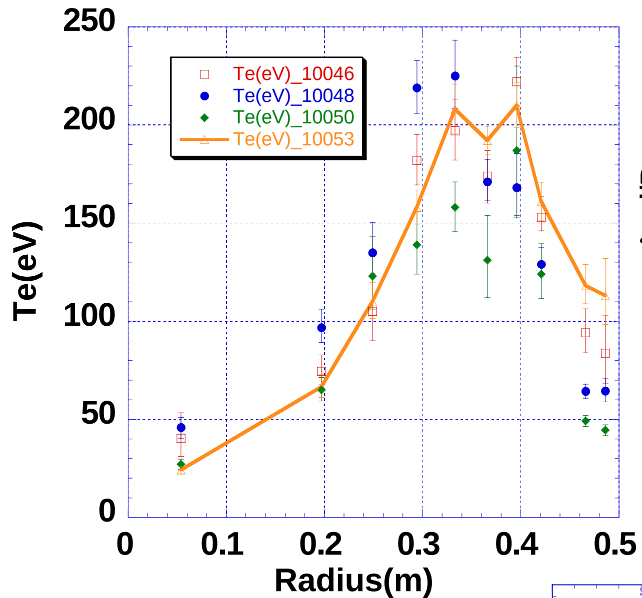


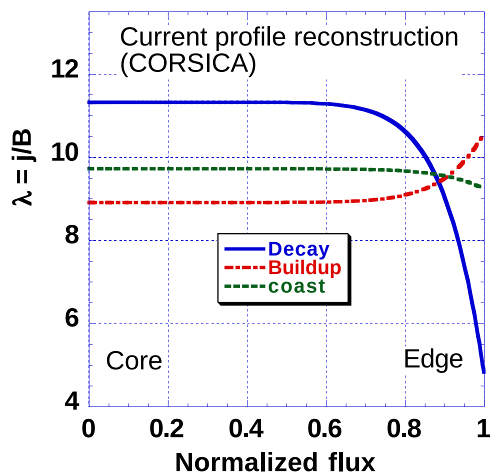
- High current pulse forms spheromak (peak current well above threshold).
- Plasma is sustained with lower current from a second bank – current must remain above threshold.
- Peak edge poloidal magnetic field (and hence toroidal plasma current) is proportional to peak current.
- Threshold current depends on vacuum magnetic field geometry.

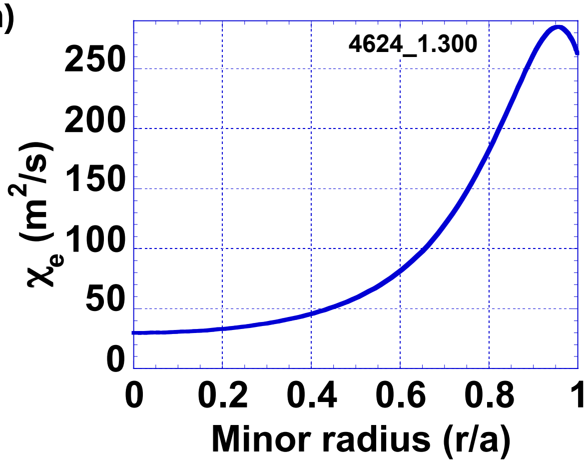


Fluctuation levels have been reduced by controlling the injection current





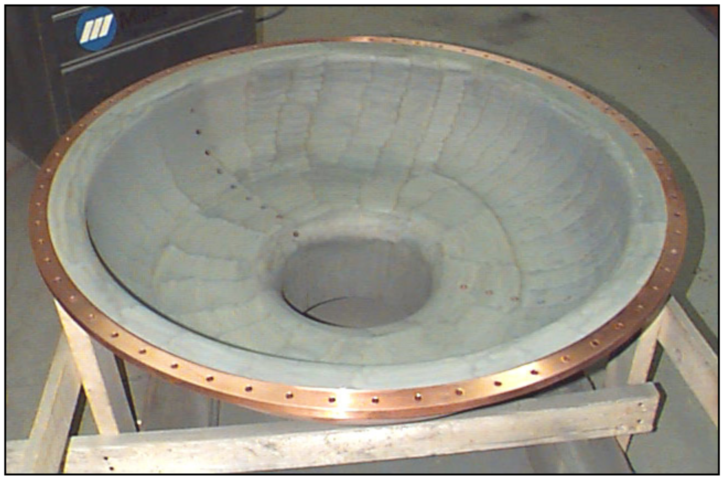


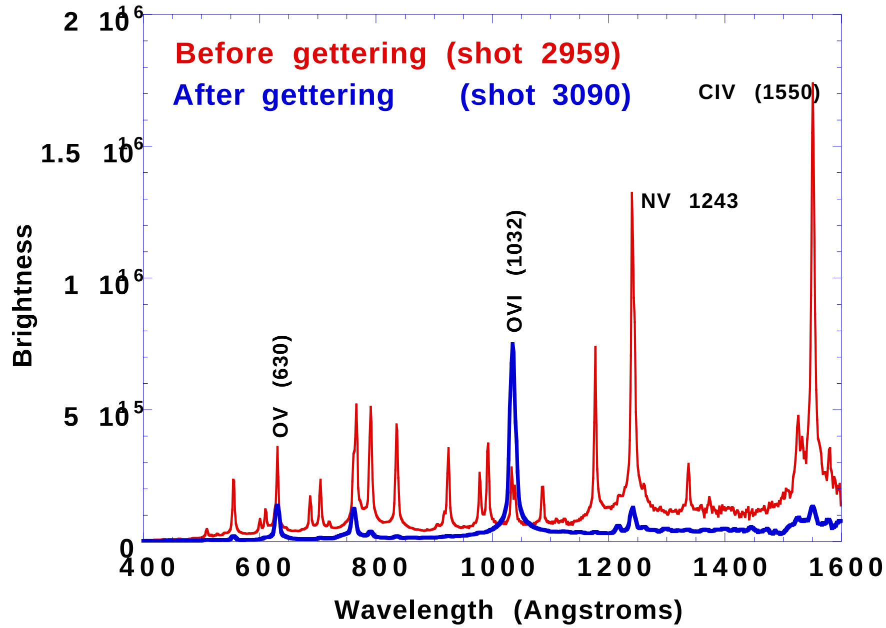


Lower drive current reduces edge current density and suppresses low-order modes.

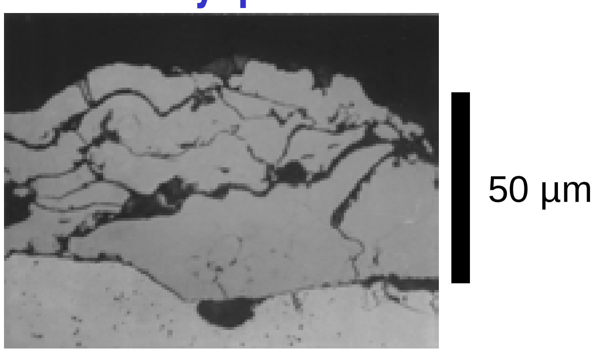
Proper wall-conditioning is required to obtain plasmas with low Z_{eff}

Plasma-sprayed W coatings





Relatively porous surface



D. Buchenauer, SNL

- **Impurity radiation lowers T_e and maximum B field.**
- **Conditioning Processes:**
  - — **high temperature bake (165 C)**
  - — **hydrogen glow discharge cleaning**
  - — **titanium gettering (every 4 shots)**
  - — **helium plasma operation (12 shots)**

Boronization using Carborane ($C_2B_{10}H_{12}$): Nontoxic, Non-explosive, and Inexpensive

- Does not require special handling equipment
  - No special vacuum equipment, filters, etc.
  - Non-gaseous
- Nontoxic, non-explosive and simple hardware = inexpensive

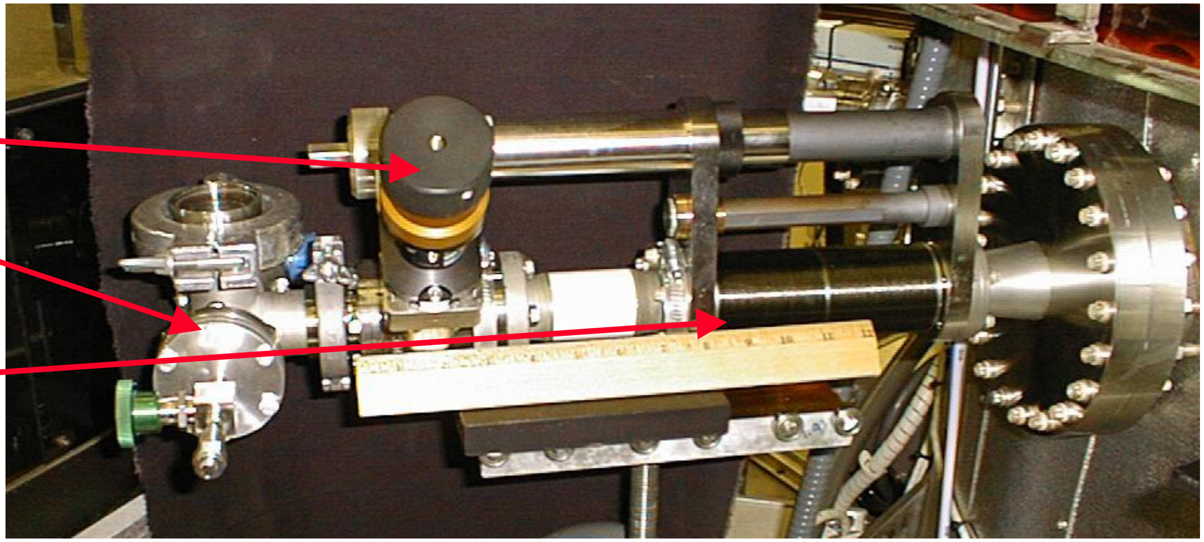
- Boronization procedure:
  - He GDC and vessel baked to ~150C
  - GDC total pressure ~75 mTorr (90%helium 10% Carborane)
  - Vapor pressure rises x10 with each 10 C rise in carborane temp
  - Deposition rate ~40 nm/hr
  - Current density ~ 6 μamps/cm^2

Chamber Isolation Valve

Carborane Chamber

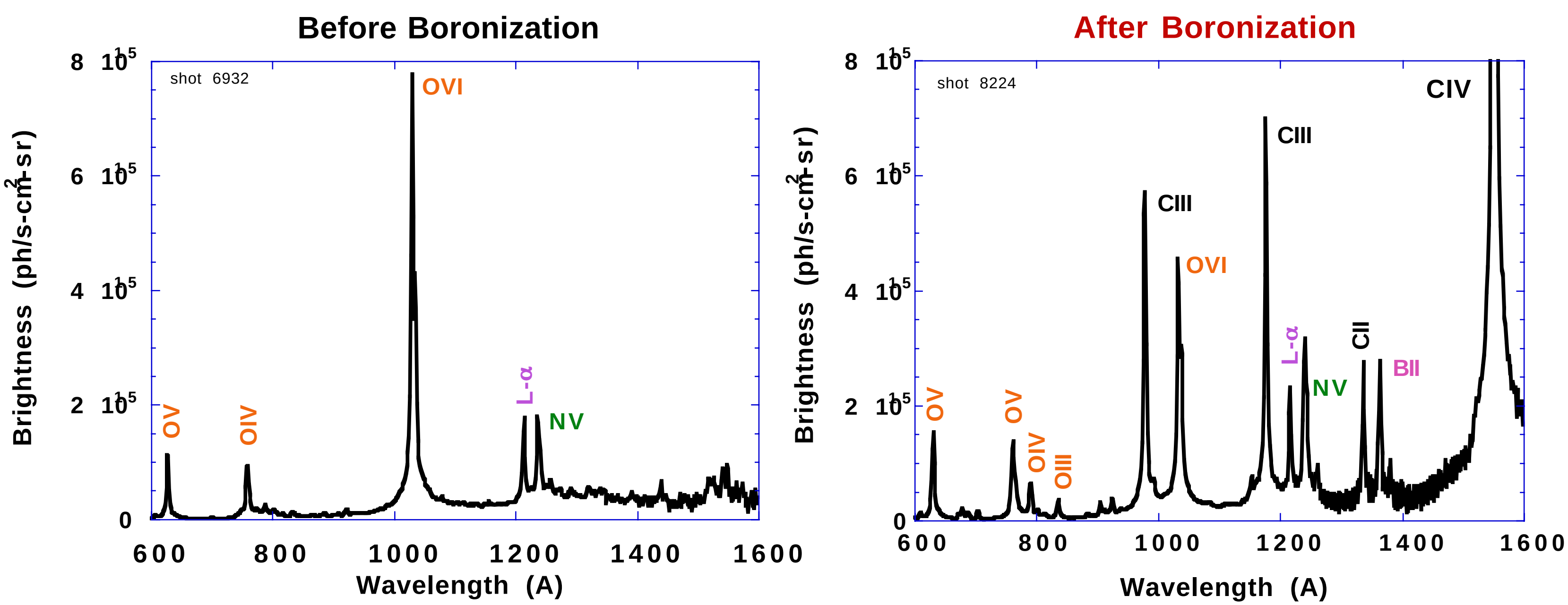
Delivery tube (0.5”OD) insertion bellows

Heater tapes not shown

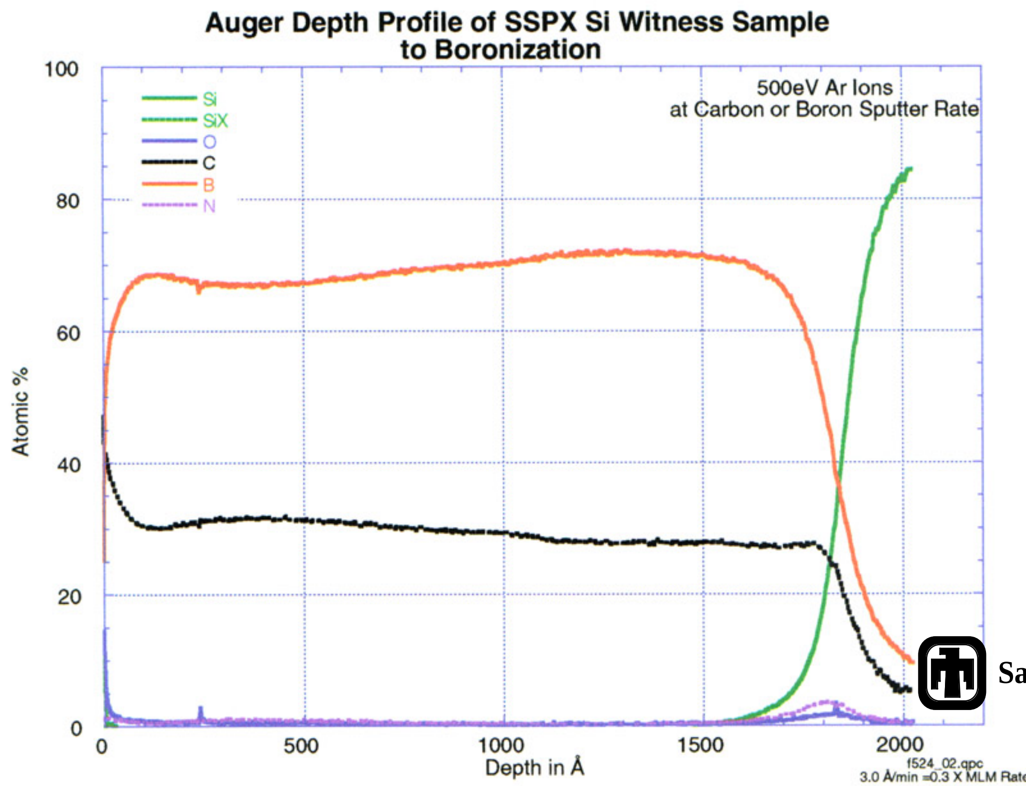


Increased Impurity Radiation Observed after Boronization with Carborane

- Deposition layer ~180 nm thick contains boron and carbon in a 70:30 ratio
- Increased carbon content with elevated electron density
- Oxygen concentration essentially unchanged
- After ~150 discharges:
  - Boron line radiation dropped to pre-boronization level
  - Carbon radiation dropped ~x40; yet x20 higher than before boronization



170nm boron–carbon film produced during 4hr helium GDC during 165 C bake



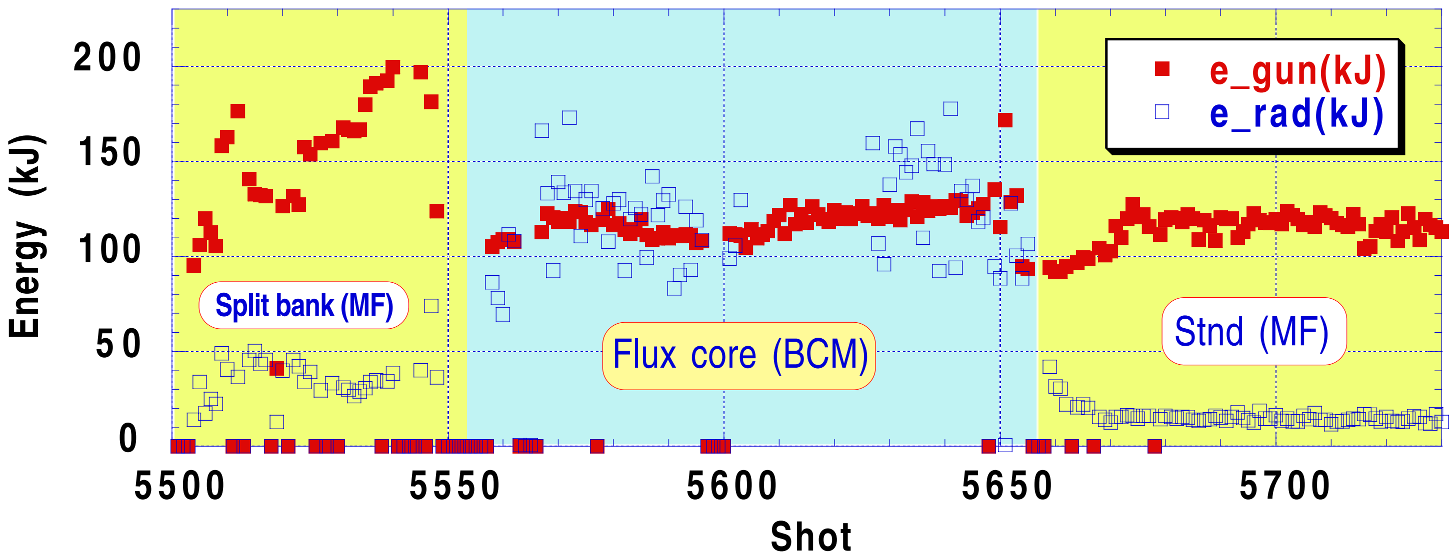
Depth calibration based on boron sputtering

Dean Buchenauer

Sandia National Laboratories

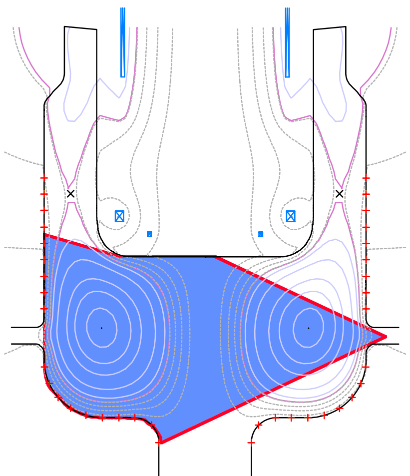
- Coupons located in diagnostic slot at flux conserver radius.
- Thin (50A) layer with B:C=1.9:1 may be reflect shutdown conditions.
- Boron lines observed for about 100 discharges, carbon remains longer.

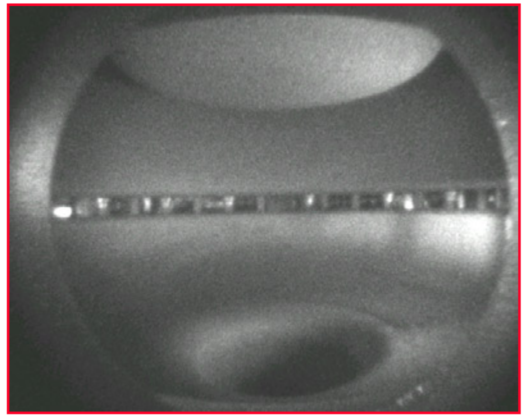
In clean plasmas, charge exchange and impurity radiation are a small fraction of input power

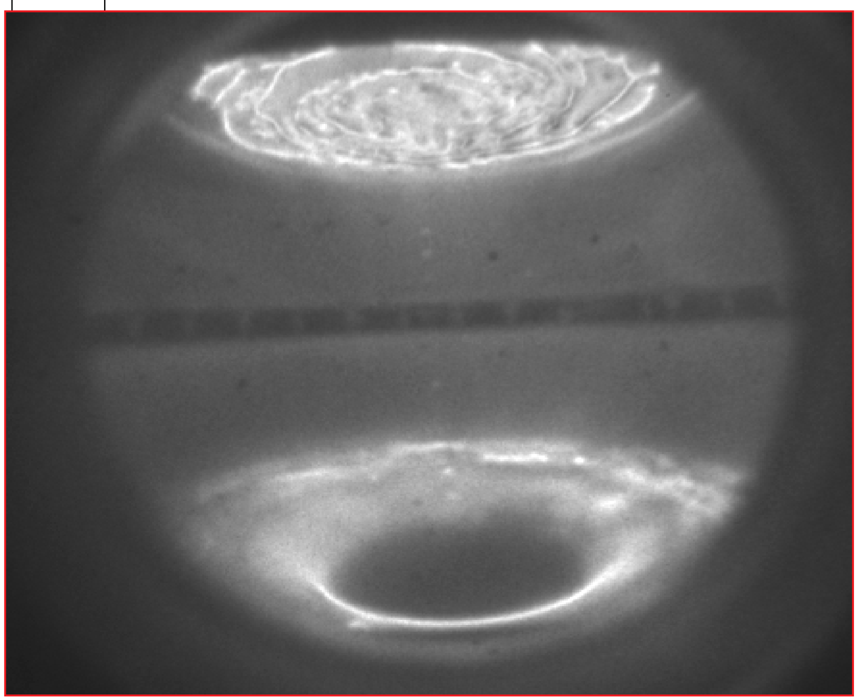


- Bolometer close to the plasma at the midplane provides integrated radiation and CX energy losses.
- Impurity radiation dominated by OVI (carbon is fully stripped).
- $P_{rad} \approx 15\%$ of P_{input} for clean plasmas.
- Melting of divertor plate in Flux core configuration produced almost 100% radiation loss!

High speed imaging shows complex plasma-surface interactions



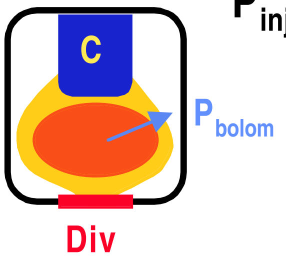




Images courtesy of C. Romero-Talamas (Caltech)

- 4μsec exposure time in visible light midway through discharge
- Bright spots on bottom of inner electrode points to possible filamentation on open field lines.
- Interaction with lower flux conserver shows both limiter and electrode characteristics.

Power balance measurements show that most of the power goes to the divertor (discharge anode)

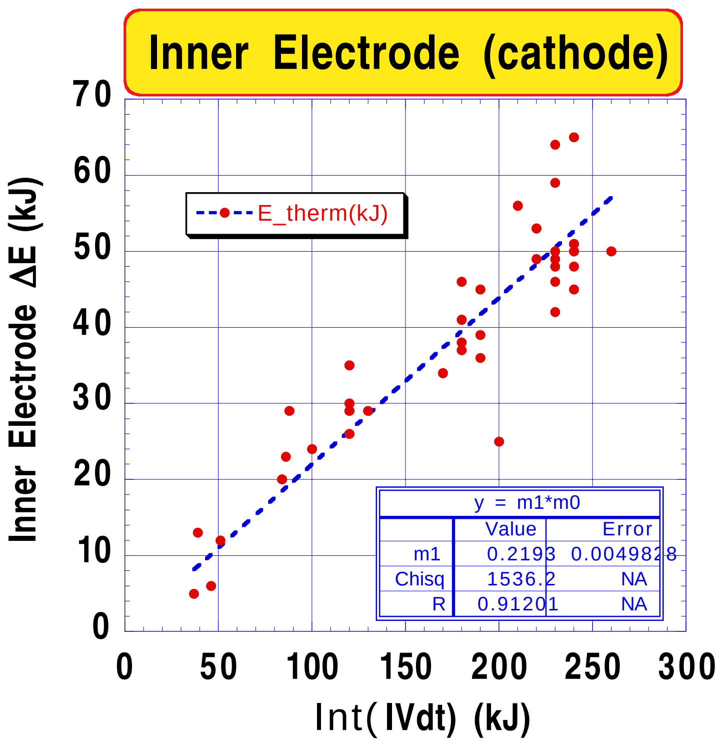


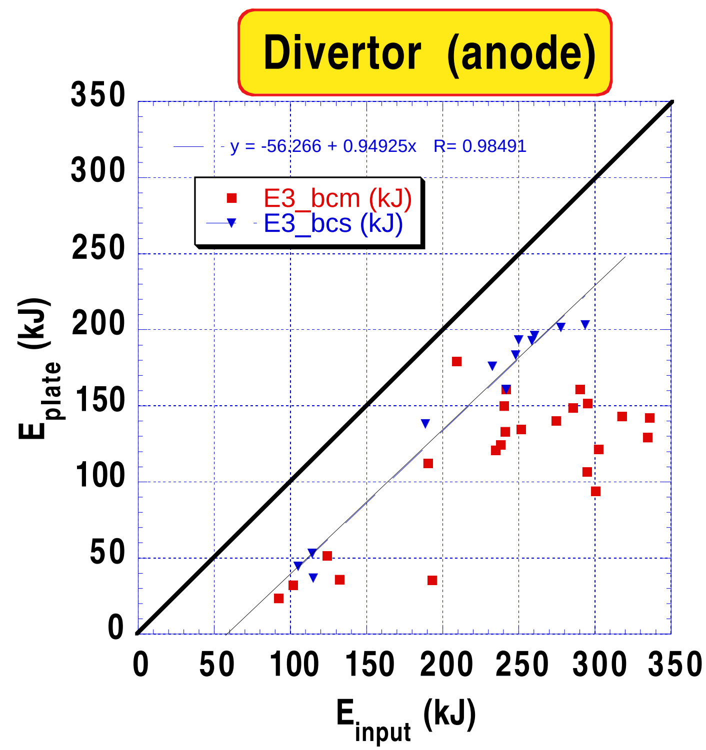
$$P_{inj} = I_g V_g = P_{cx} + P_{rad} + P_{cath} + P_{anode} + \dot{W}_B + \dot{W}_{nkT}$$

$$= P_{bolom} + P_{inr\text{-}elec} + P_{div} + \dot{W}_B + \dot{W}_{nkT}$$

$$1.0 = 0.15 + 0.2 + 0.7 + 0 \text{ (stationary)}$$

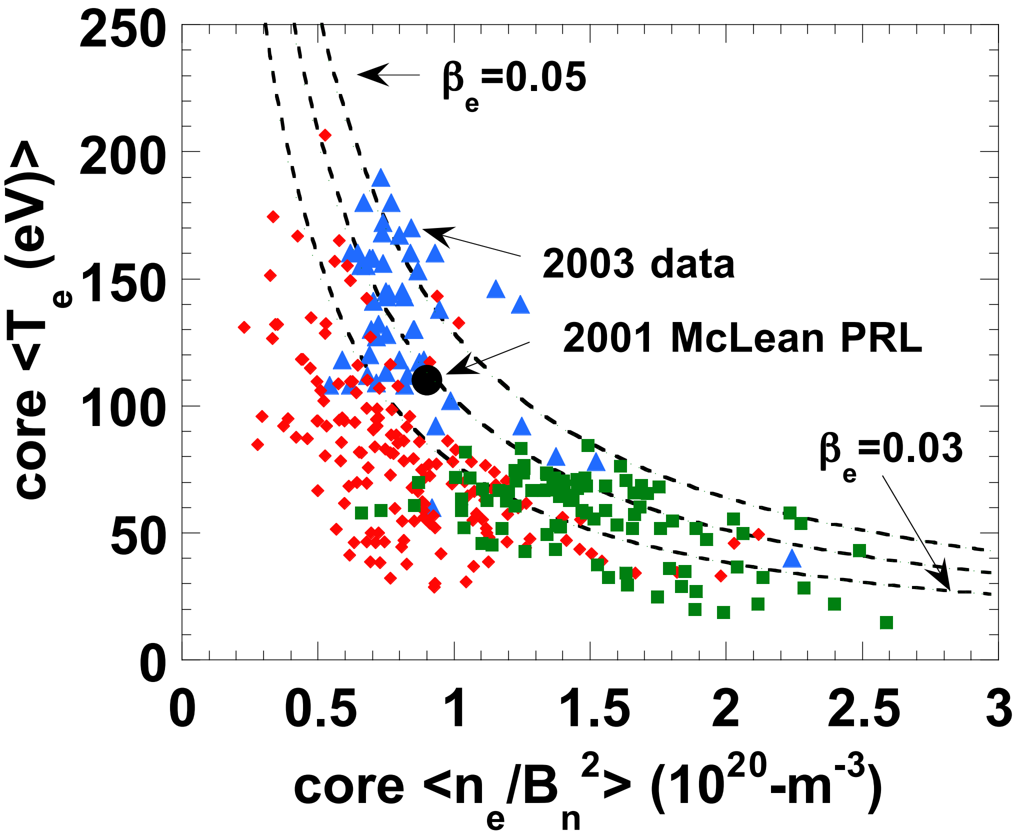
High level power balance



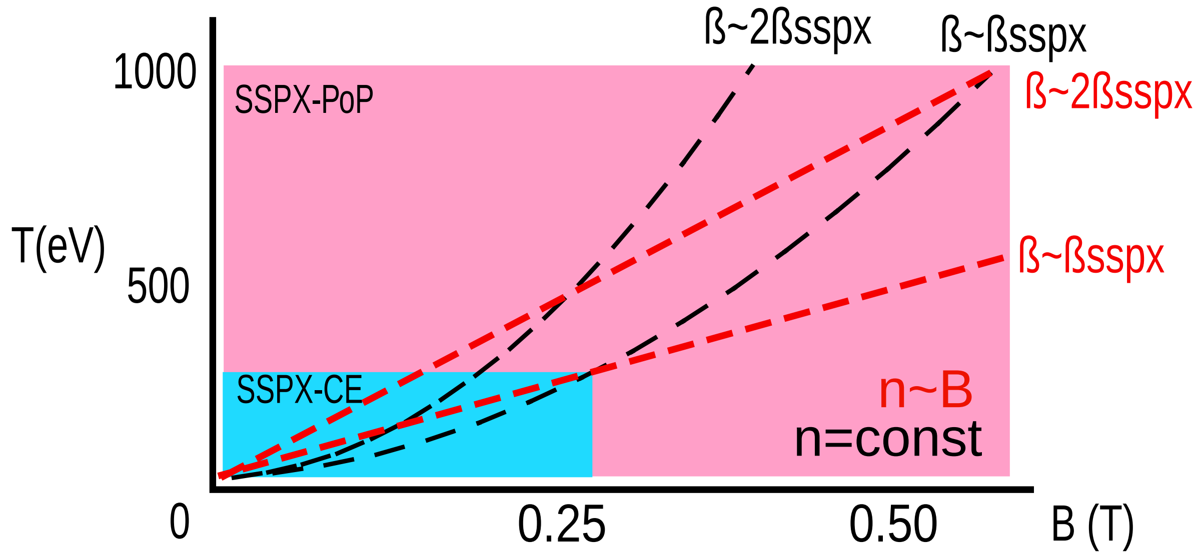


Temperature measurements point to importance of density control

- Core T_e measured in sustained plasmas.
- Upper limit observed for $\beta = 2\mu_0 nkT/B^2$.
- Higher fields or lower density should $\uparrow T_e$.
- In the spheromak, higher fields are obtained by higher plasma current.
- So far, I_{tor} and $B_{sphere} \propto I_{gun}$.



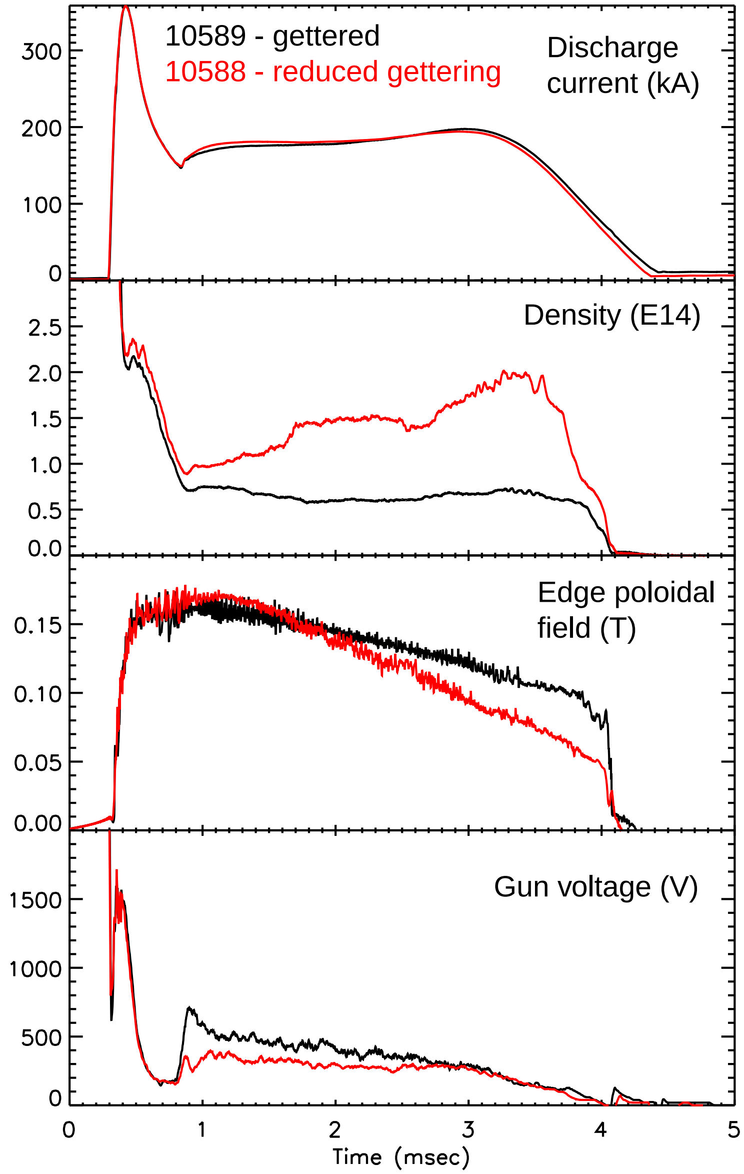
Extrapolation to next-step spheromaks point to the importance of density control



B=k*Igun	0.36	0.75	Ig (MA)
Helicity balance	0.254	0.38	Ig (MA)

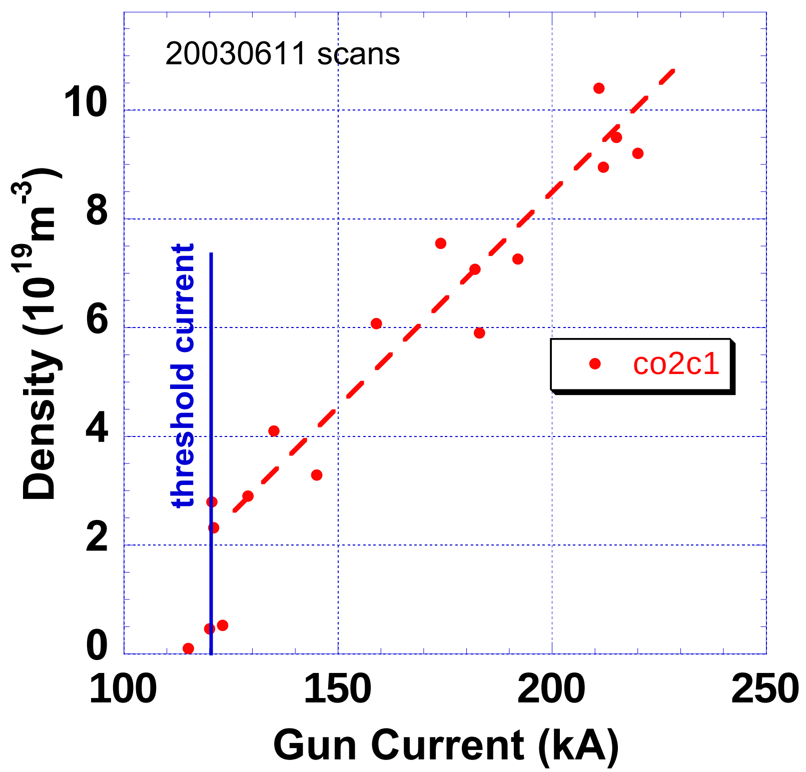
- **Target 1 keV spheromak plasma. What are the device requirements?**
- **Transport scaling sets device size (minor radius).**
- **Beta limit and density scaling determine field and toroidal current.**
- **Field generation efficiency (B_p/I_{gun}) sets bank and injector requirements.**

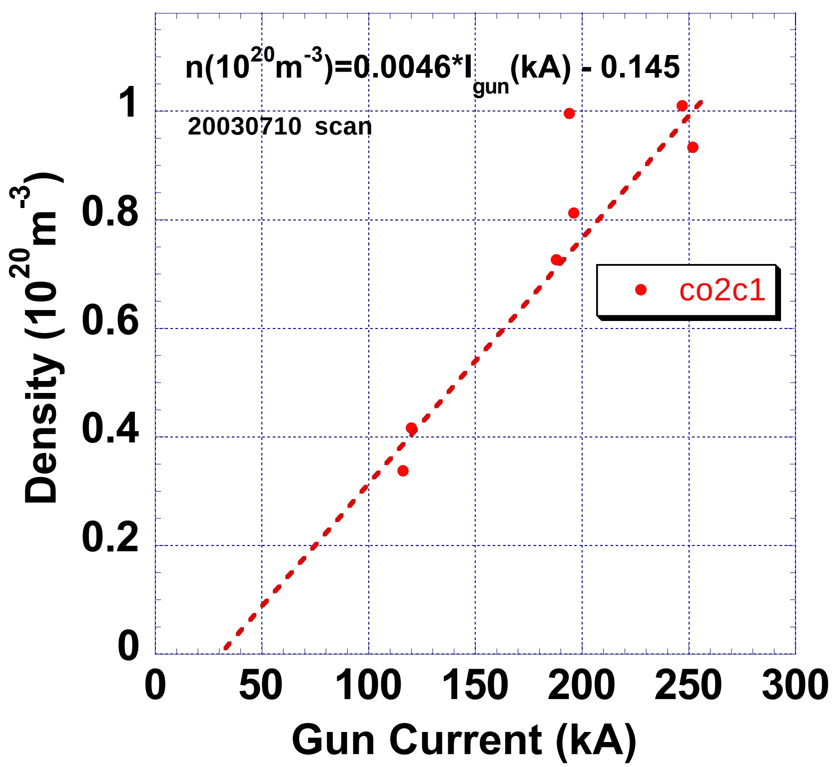
Spheromak density is sustained by recycling



- **Initial density corresponds to full ionization of gas puff @ -250μsec.**
- **Density decay time (~350μsec) represents ion loss to walls-much shorter than magnetic field decay time.**
- **Steady-state density depends on wall conditioning and gun current, not initial gas puff.**
- **Gettering in main chamber only, not in coaxial source region.**
- **Effectiveness of gettering reduced after 3 – 4 discharges.**

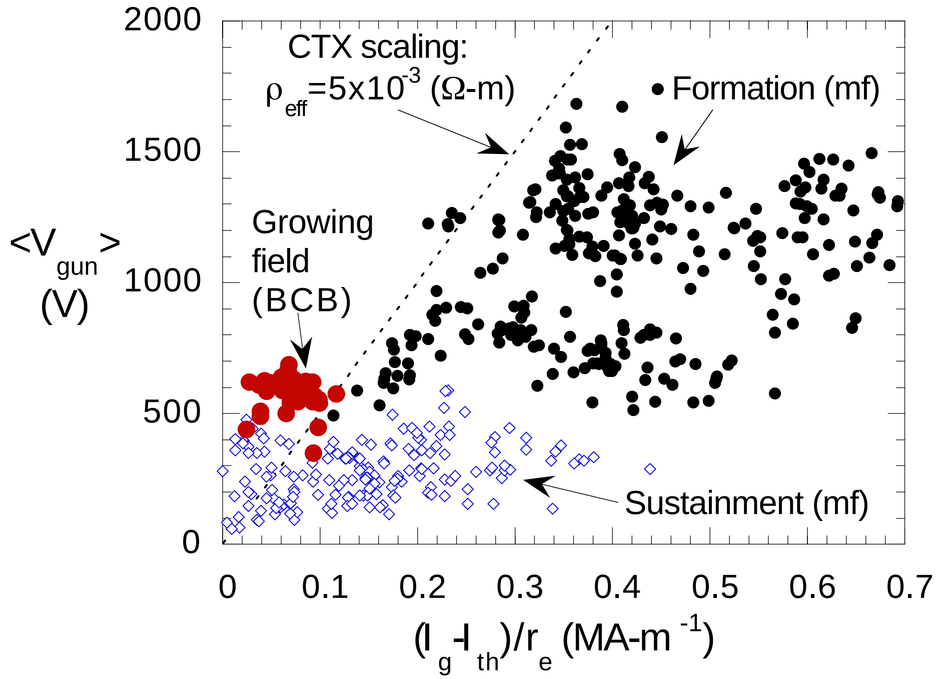
Discharge current determines density



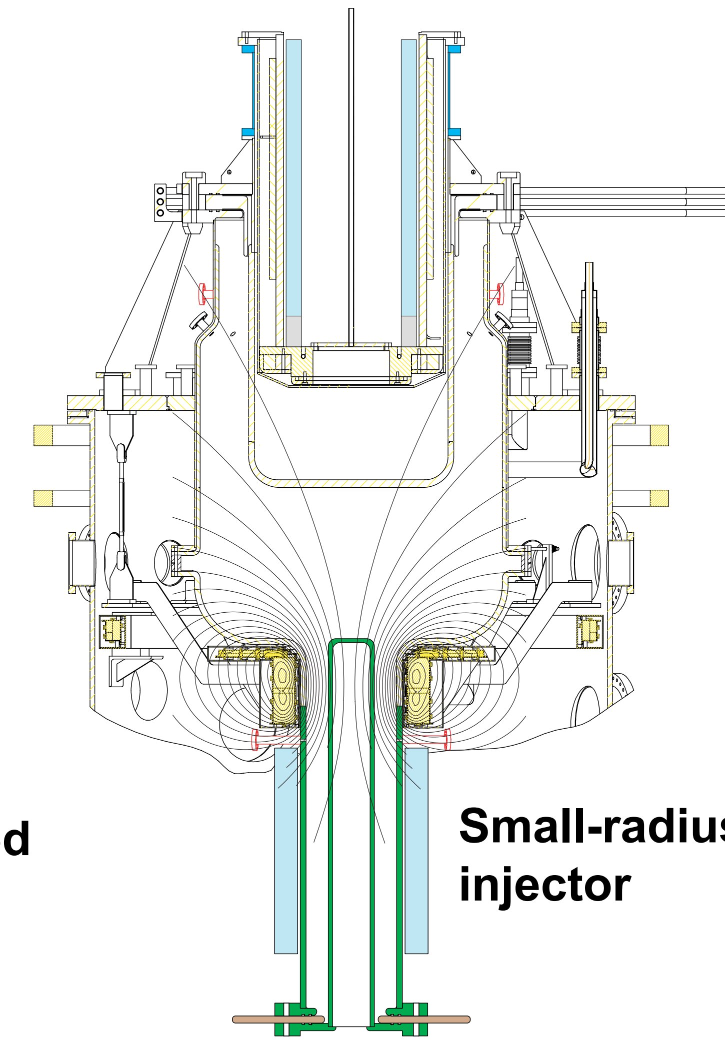


- **Current scan at fixed flux explores effect of sustainment threshold.**
- **Current scan at fixed $\lambda=I_{gun}/\phi_{gun}$ explores scaling at optimal current.**

Small radius gun should increase inductive voltage and increase the spheromak magnetic fields.



- **Smaller gun increases discharge voltage and coaxial magnetic field**
- **Factor of two voltage increase expected**
  - **$V \sim L \sim \log(R_o/R_i)$**
  - **L_{new} / L_{old} = .30 / .17**
  - **Higher helicity input rate $\sim V_{gun}\psi_{gun}$**



Small-radius injector

Summary

- Spheromak potentially offers attractive reactor concept for magnetic fusion energy

- We are producing driven spheromaks with low-amplitude fluctuations and peaked temperature and pressure profiles
  - Power balance shows low radiation losses
  - $T_{e0} \geq 200$eV
  - Wall conditioning key to obtaining best performance

- Magnetic field generation and density control are important aspects to showing favorable scaling to next step devices
  - Attractive reactor concept depends on efficient field generation
  - Optimal density avoids beta limits and gives high T_e.

- A new coaxial injector will be installed to increase the magnetic field.

Workshop Agenda