NSTX LTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

Up Against the Wall: Liquid Lithium for the Chamber Technology Challenge in Fusion Energy

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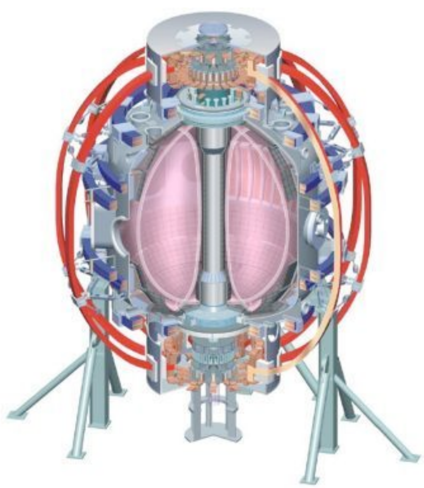
April 28, 2009



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Outline

- “First Wall” Problem and Liquid Metal Solution
- Spherical Torus Magnetic Confinement Concept
- Liquid Lithium Handling for “Free Surface” Studies
- High Heat Load Experiments with Electron Beams
- Plasma Fueling with Supersonic Gas Injection
- Lithium Coatings on Plasma Facing Components
- Future Plans and Challenges

Liquid Metals Provide Possible Solution for "First Wall" Problem in Fusion Reactors

- Liquid metals can simultaneously provide:
  - Elimination of erosion concerns
    - Wall is continuously renewed
  - Absence of neutron damage
  - Substantial reduction in activated waste
  - Compatibility with high heat loads
    - Potential for handling power densities exceeding 25 MW/m^2

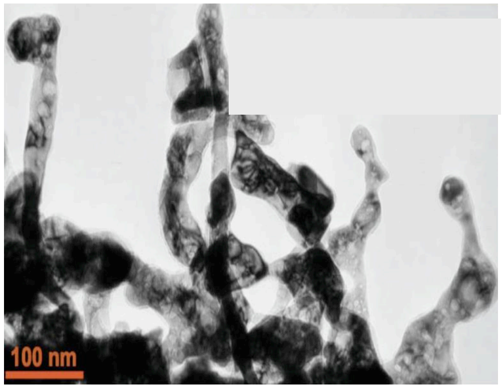
Present Solid Materials Problematic

- **Tungsten is only candidate for fusion reactors**
  - **Tests involving long-term exposure to plasma reveals surface damage**

Example: NAGDIS-II: pure He plasma

N. Ohno et al., in IAEA-TM, Vienna, 2006

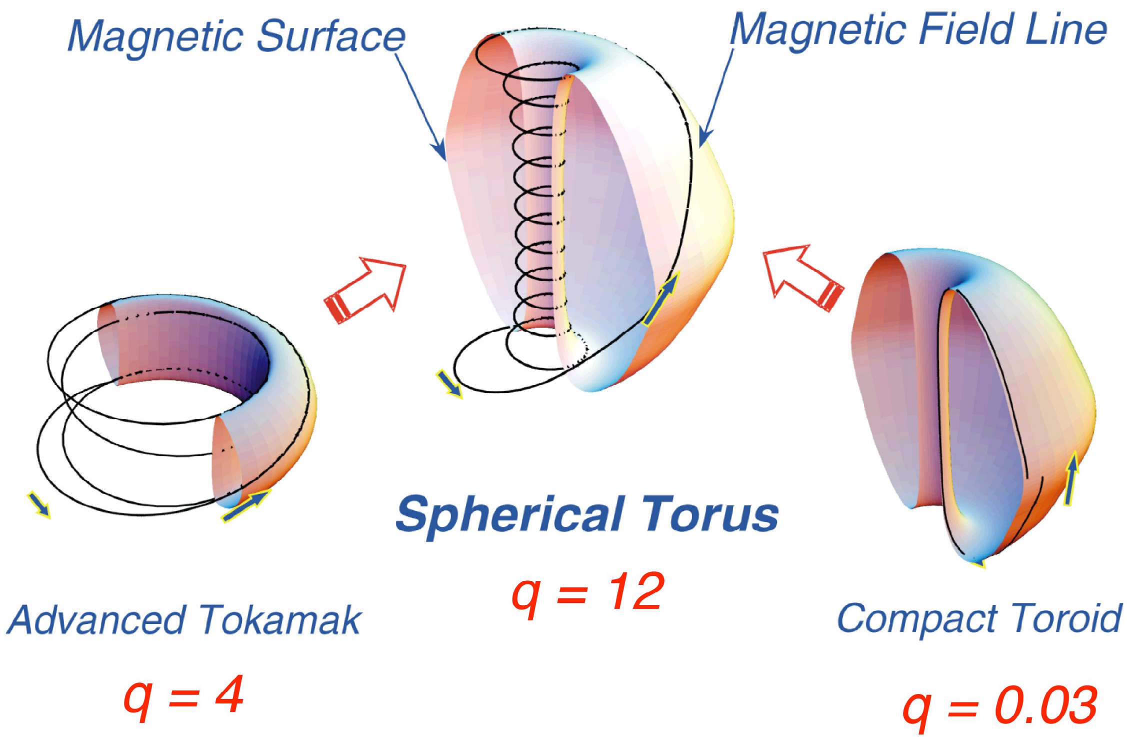
- **Bombardment with $3.5x10^{27}$ He^{+}/m^{2} at E_{ion} = 11 eV for t = 36,000 s**



100 nm (VPS W on C) (TEM)

• Structures appear on scale of tens of nm and reflect swelling due to "nanobubbles"

Research on Plasma-Facing Components Focused on Spherical Torus Devices at PPPL

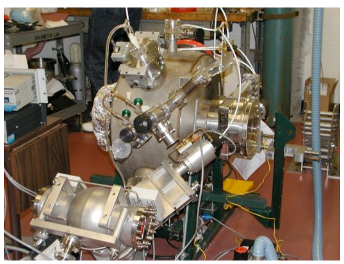


- **Spherical Torus represents "intermediate" confinement scheme**
  - **Tokamak: toroidal current dominates**
  - **Compact toroid: poloidal current dominates**
- **Greater field line length on inboard "high field" side improves confinement and stability**
  - **Reduces toroidal field required for more efficient magnetic confinement**

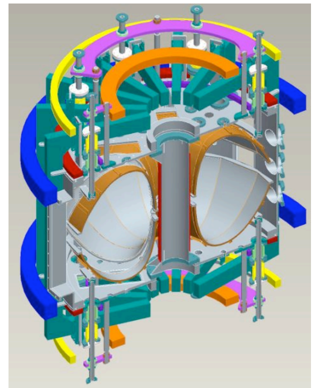
Lithium Tokamak Experiment and National Spherical Torus Experiment used to develop PFC's for future machines

LTX lithium handling facility

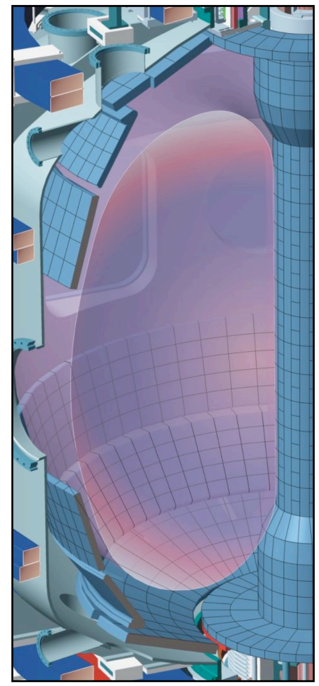
LTX PFC test facility



Purdue surface analysis facilities

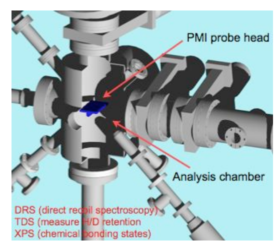


LTX
- Fully-nonrecycling liquid lithium PFC's
- Profile control with core fueling



NSTX
- High performance plasma with lithium PFC's
- High power divertor using liquid lithium

NSTX materials analysis probe

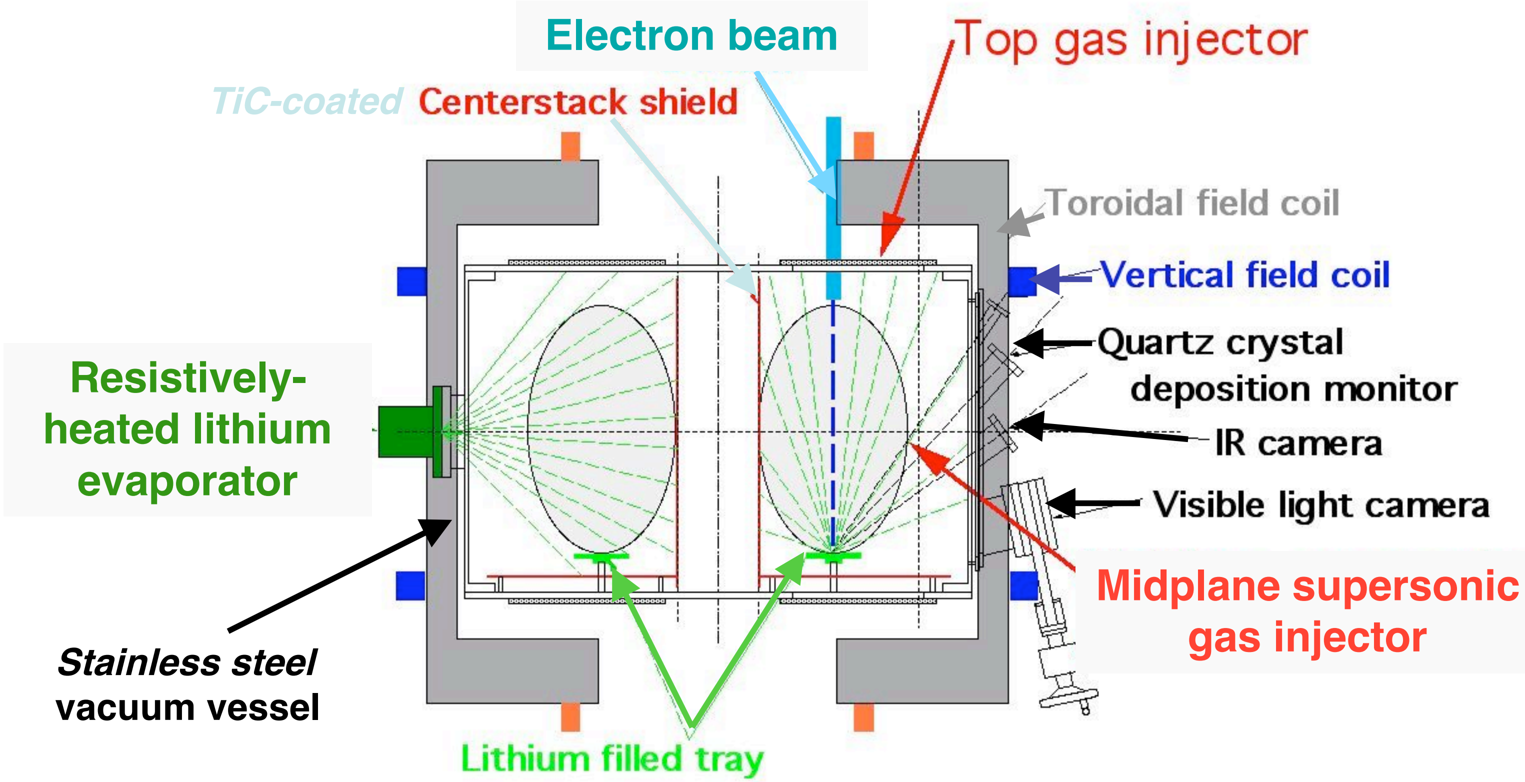


Retention of hydrogenic species and impurities

Next Step ST's

Initial "free-surface" liquid lithium experiments performed on Current Drive Experiment-Upgrade

R_0=34 cm, a = 22 cm, $I_P \leq 80$ kA, $B_T(0) \leq 2.1$ kG, $T_e(0) \sim 100$ eV, $n_e(0) < 6 \times 10^{19}$ m^{-3}



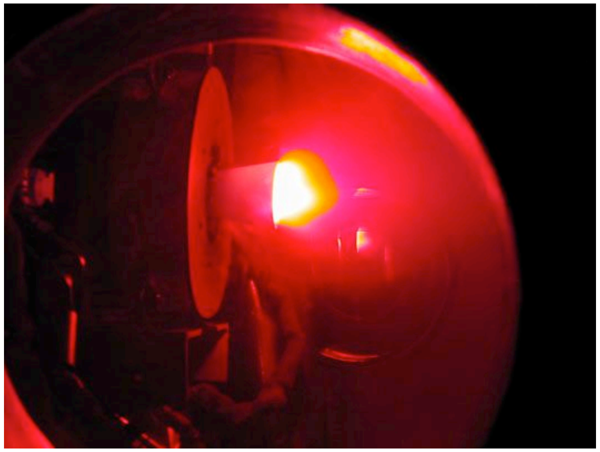
Fully toroidal tray: R_0= 34 cm, width = 10 cm, 6 mm deep

Stainless steel “tray” installed on Current Drive Experiment-Upgrade (CDX-U) to hold lithium

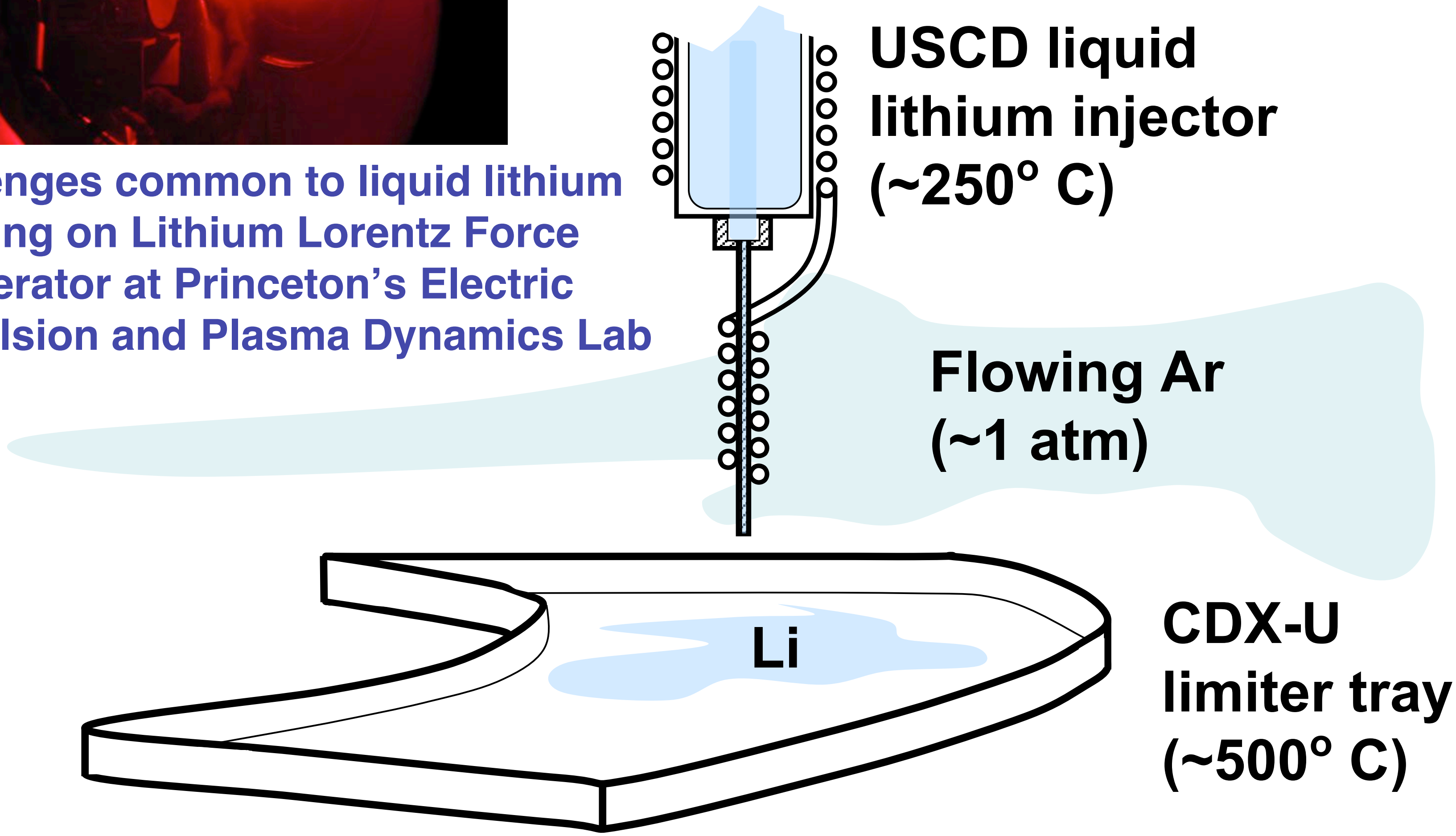
- 34 cm major radius, 10 cm wide, 0.64 cm deep
- Fabricated in two halves with a toroidal electrical break
- Heaters beneath for temperature control up to 500°C

- Heat/lithium shield between tray and lower vacuum flange
- Heat shield on center stack

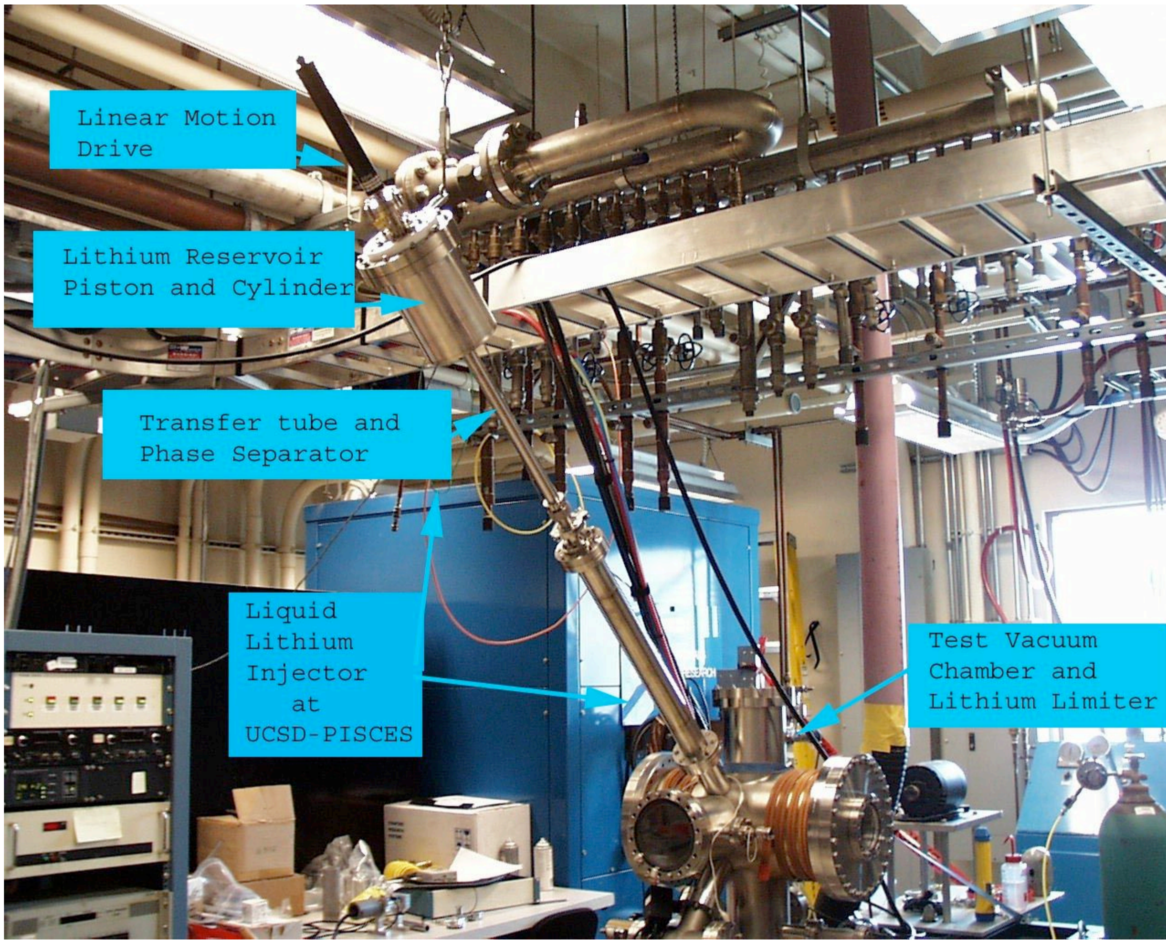
University of California at San Diego (UCSD) asked to develop liquid lithium loading system required to fill "tray"



- Challenges common to liquid lithium handling on Lithium Lorentz Force Accelerator at Princeton's Electric Propulsion and Plasma Dynamics Lab



Complex arrangement of heated reservoir and transfer tube needed to keep lithium liquid during loading



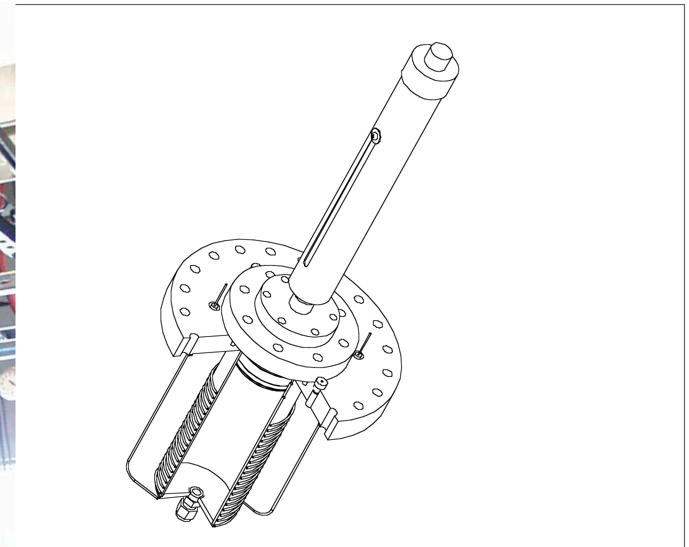
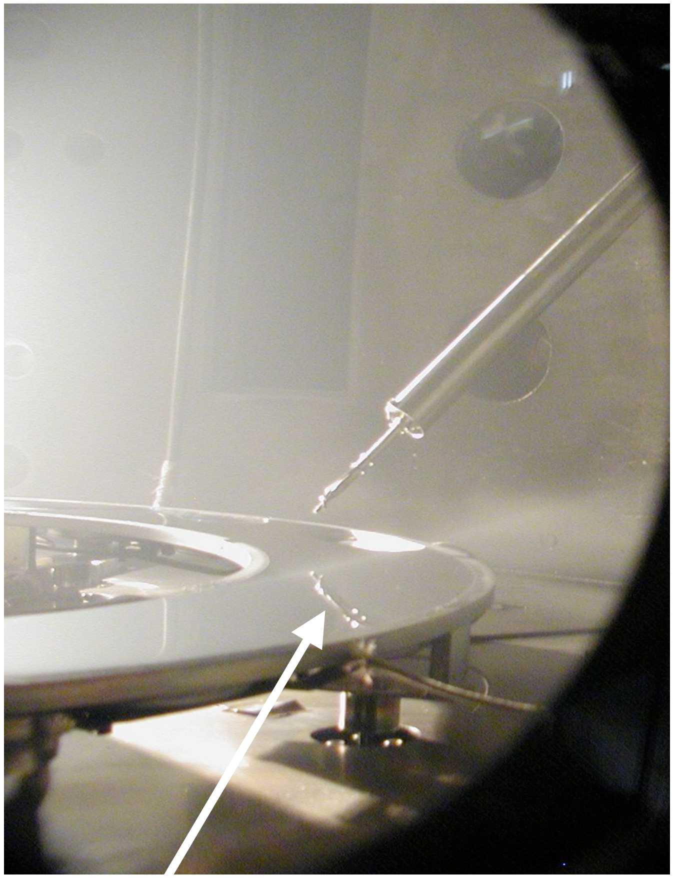
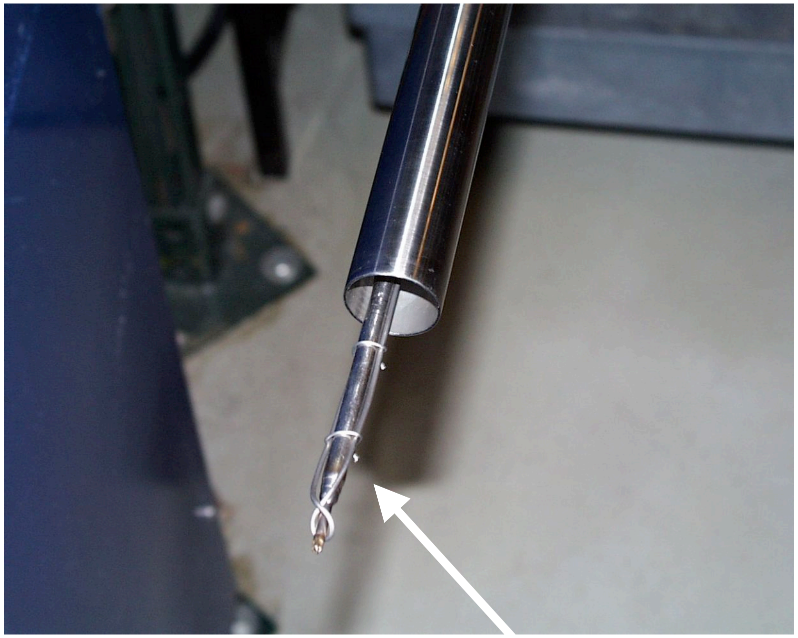


Diagram showing heated liquid lithium reservoir with motion drive and piston

Loader successful in transferring liquid lithium to heated "tray" inside CDX-U vacuum chamber

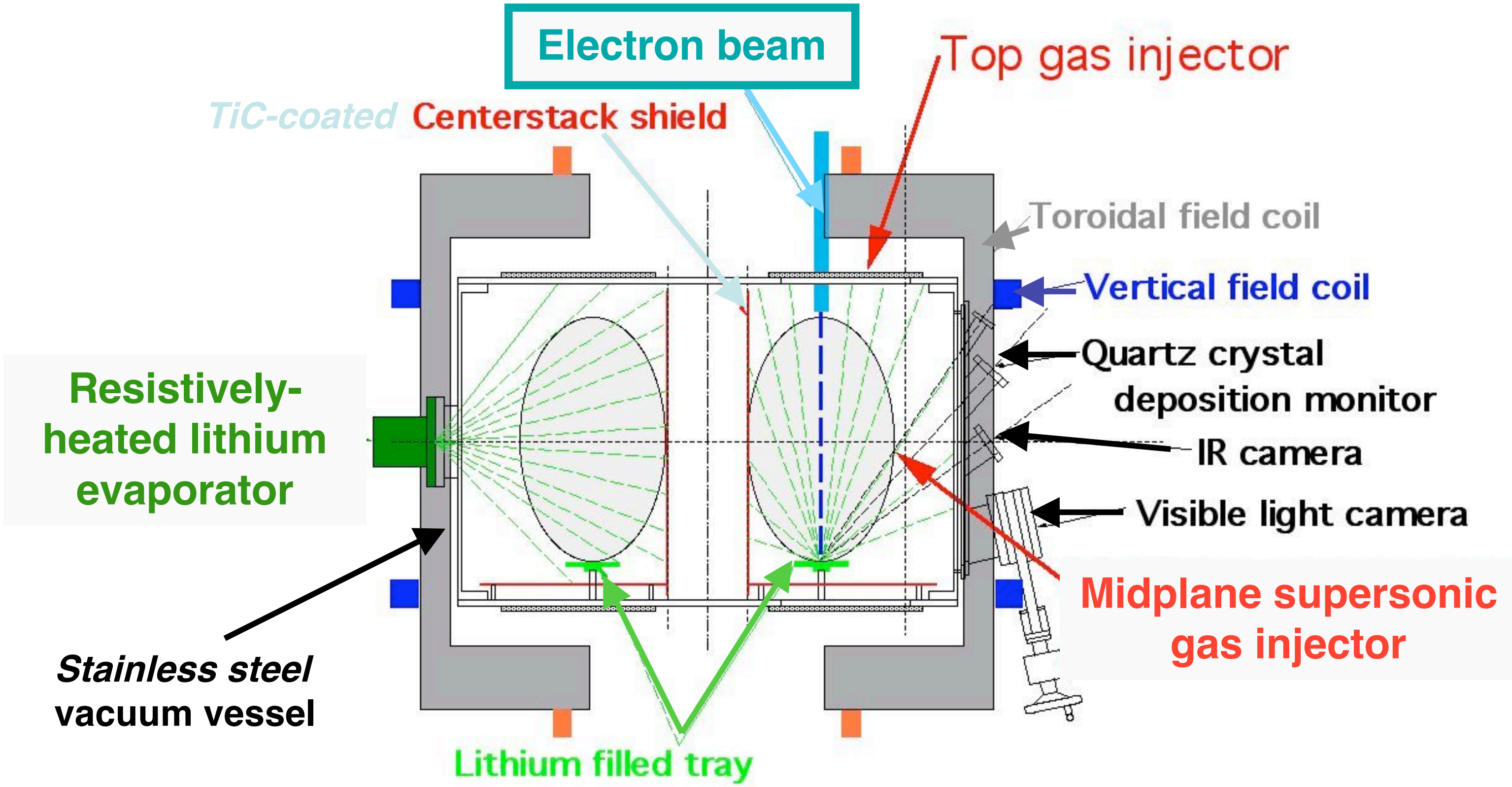


- Tip of loader reflected on surface of liquid lithium covering tray



- Closeup of loader end showing heater extending to tip

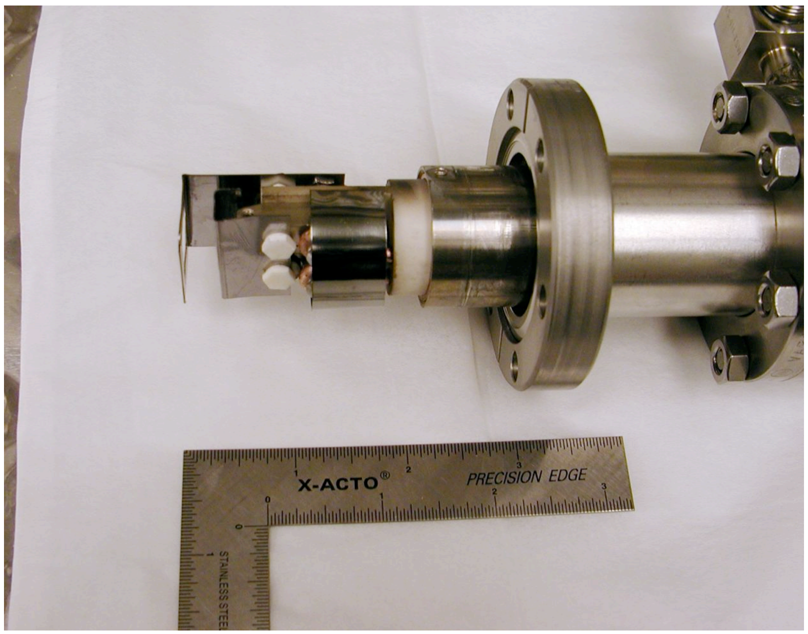
Electron beam installed initially for as method to create lithium-coated PFC's



Fully toroidal tray: R_0= 34 cm, width = 10 cm, 6 mm deep

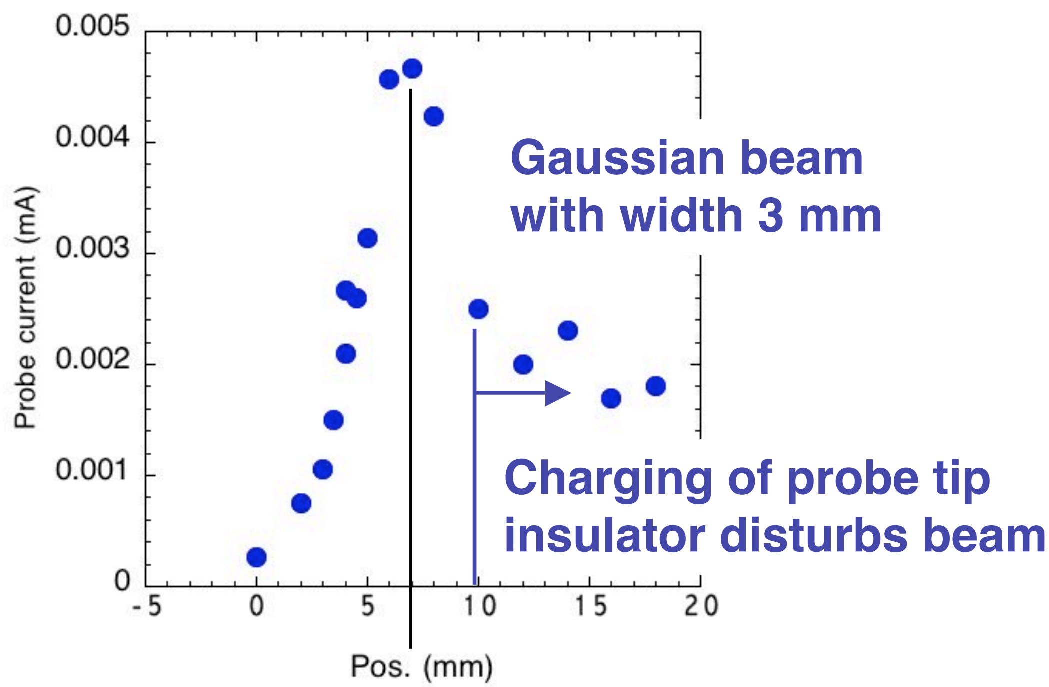
- "Tray" only provides "partial" liquid lithium PFC
- Resistively-heated evaporator and electron beam heating lithium in tray provide greater PFC coverage

Commercial electron beam (e-beam) used to provide intense local heating of lithium

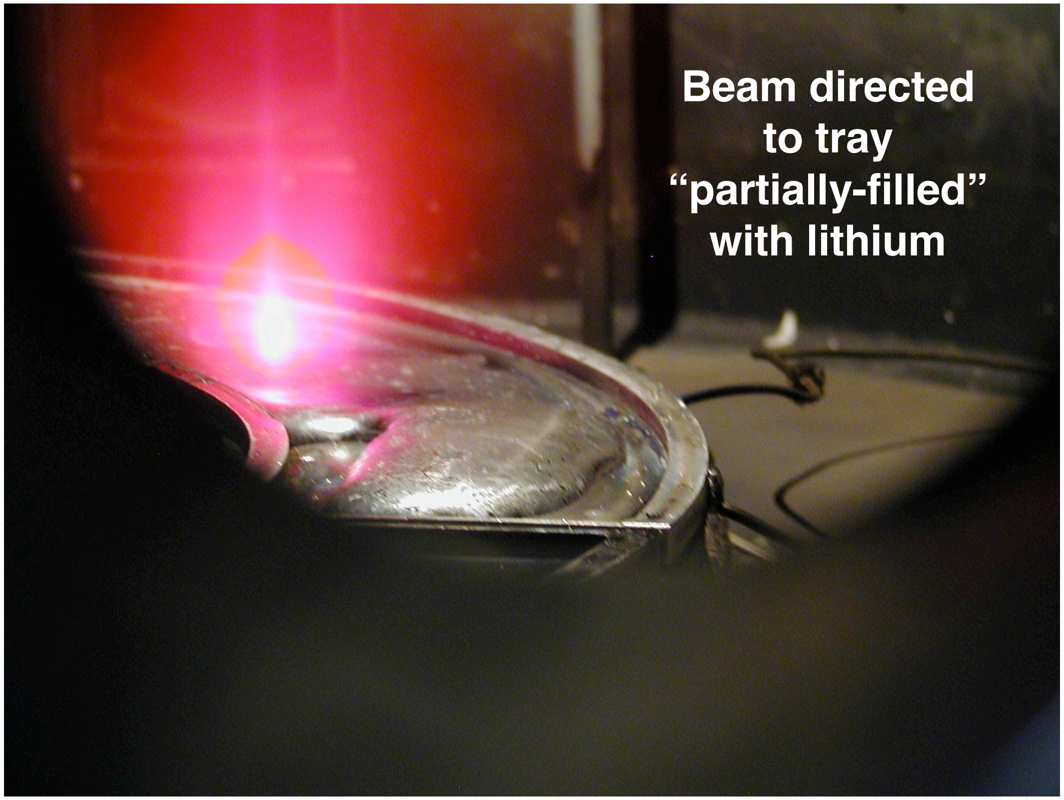


Modified commercial electron beam head

Measured electron beam profile

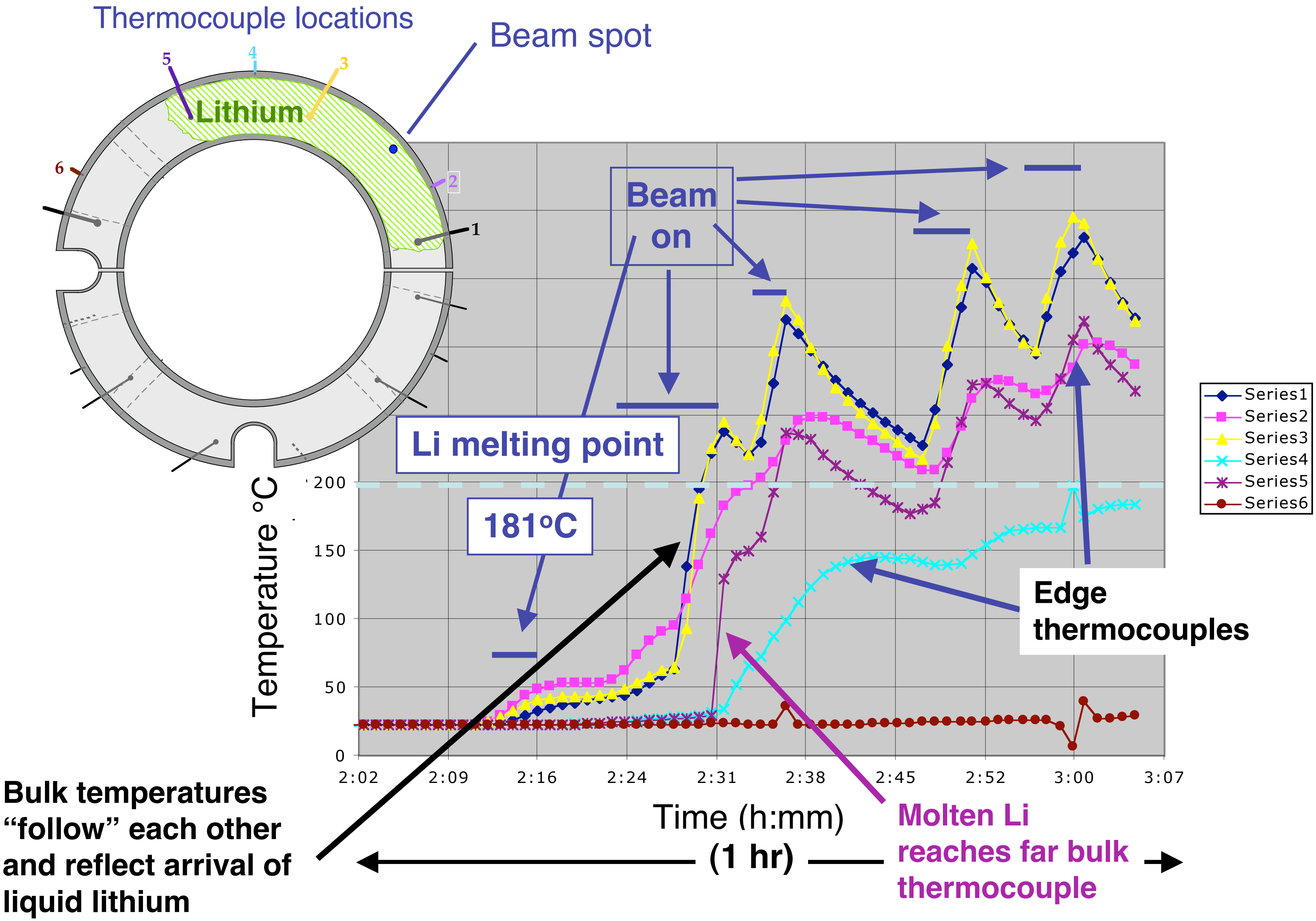


Tokamak poloidal field coils used to provide vertical "guide" field to direct e-beam to lithium



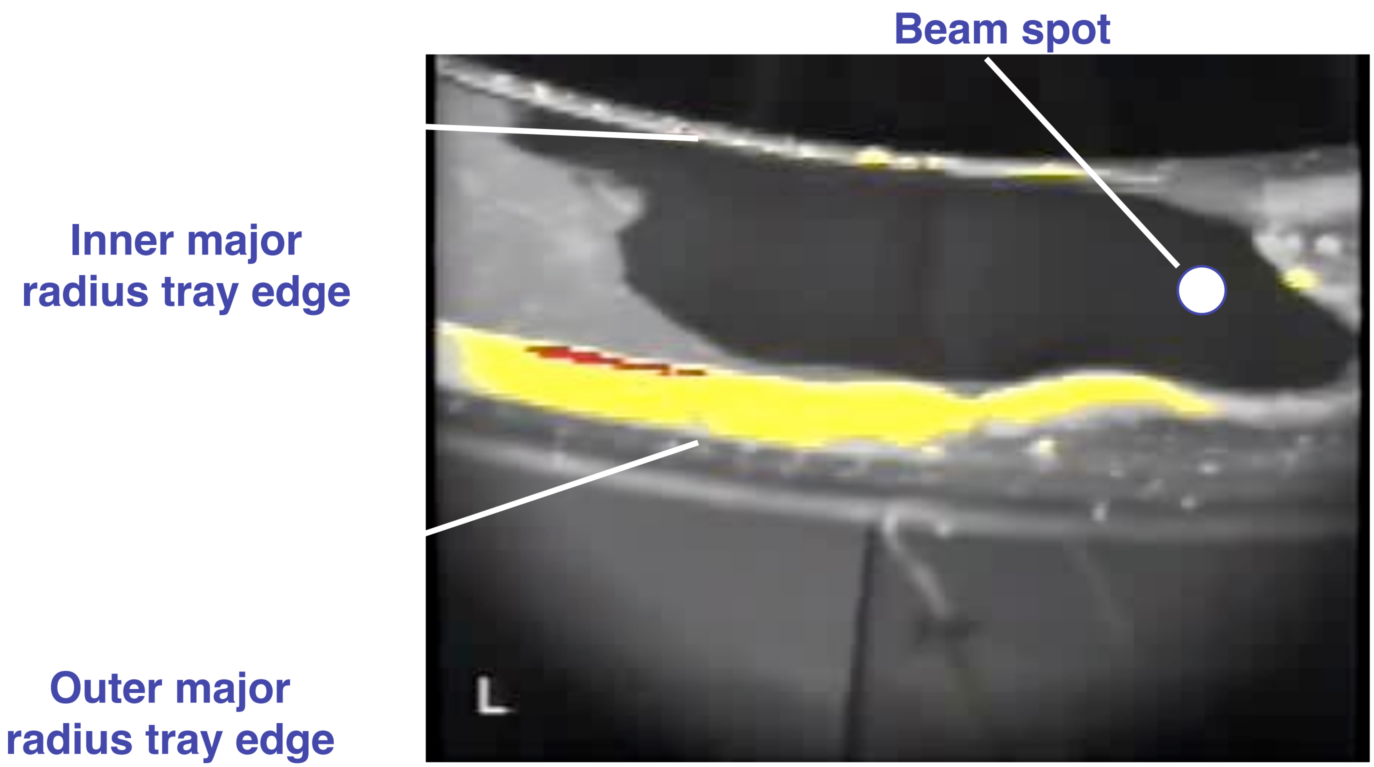
- **100 nm lithium wall coatings at maximum evaporation rate of 600 mg/minute**
  - **CDX-U magnetic fields guide 4 kV, 0.3 - 0.4 A beam for 300 - 400 seconds**
  - **Lithium area in tray ~600 cm^2 >> beam spot for power density up to 60 MW/m^2**

All lithium liquefied before evaporation occurs



Localized heat deposition affects surface tension and "Marangoni effect" can induce lithium flows

IR Camera Image



- Yellow denotes +55°C, red denotes +110°C
- Area under beam should go to 1400°C in 0.1 sec with conduction only
  - No "hot spot" appears however
  - Shows ability of lithium to dissipate high beam power densities

Marangoni convection can lead to high fluid velocities and efficient heat transfer

Dependence of surface tension on temperature imposes boundary condition:

Derivative of surface tension

Viscosity $$\nu \vec{V}_n{}' \Big|_{surface} = \frac{d\sigma(T)}{dT} \nabla_s T$$

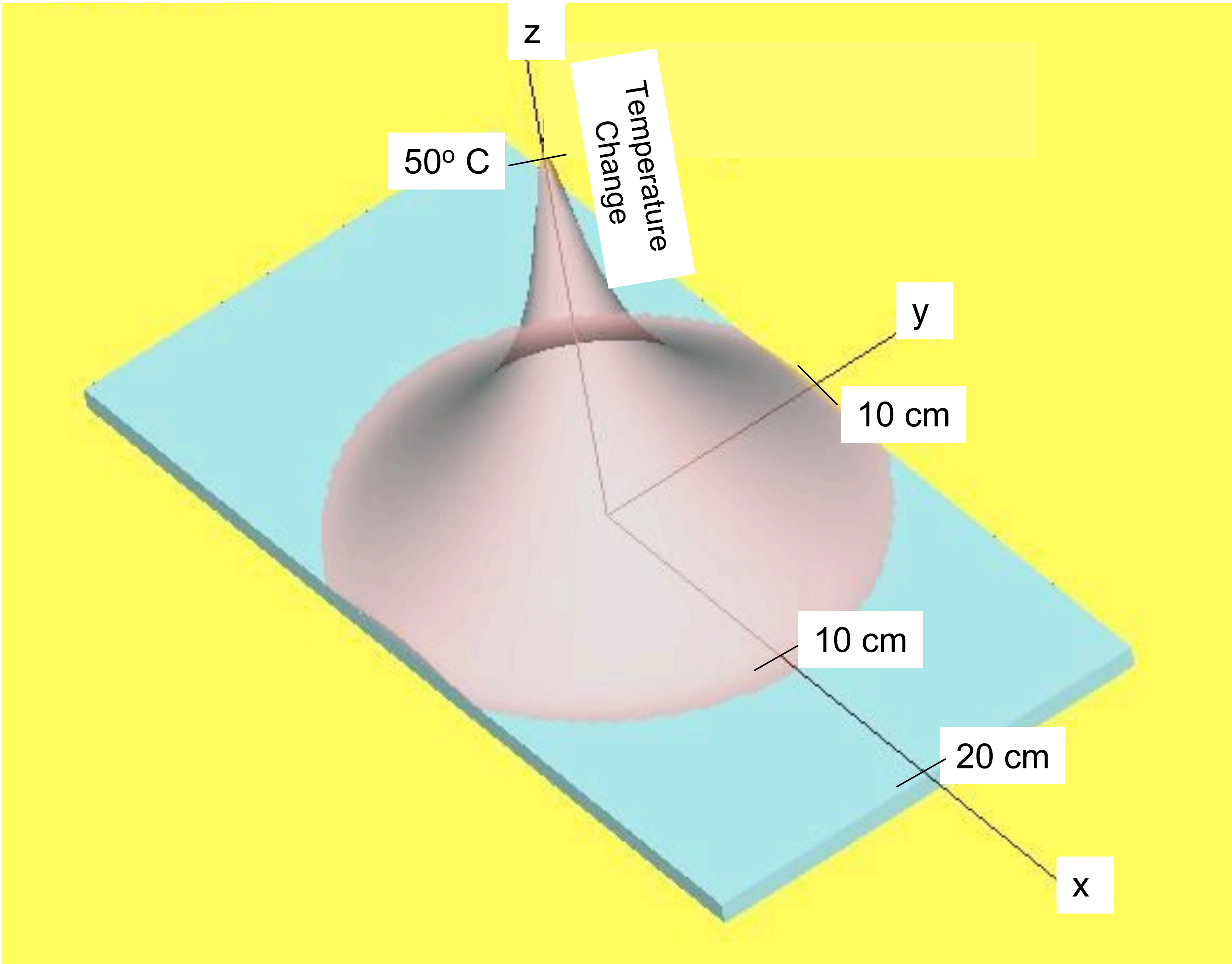
Derivative of fluid velocity normal to surface

Solve for fluid velocity in terms of viscous boundary layer d:

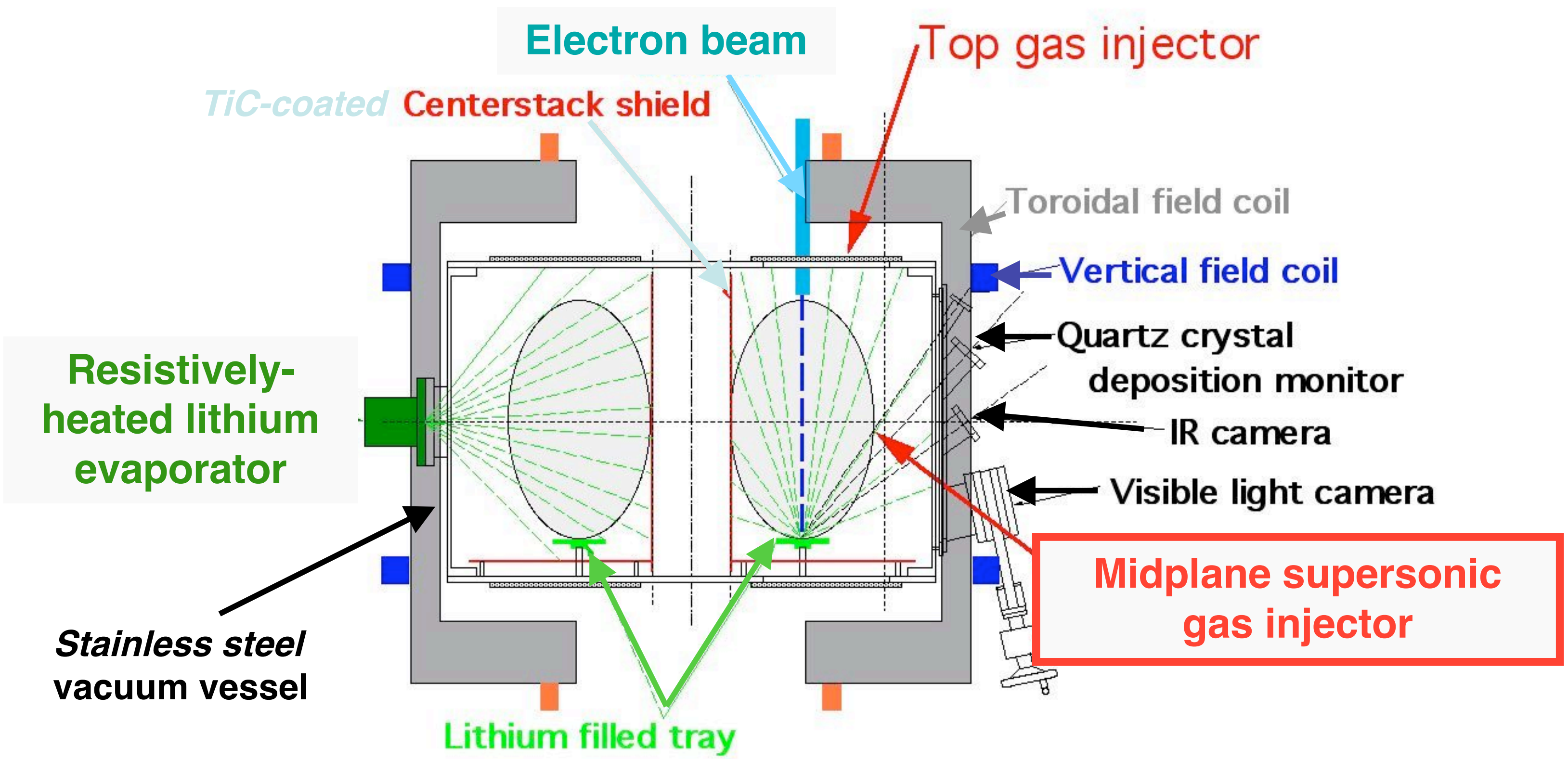
$$\vec{V} = \frac{1}{\nu} \frac{d\sigma(T)}{dT} \nabla_s T d$$

- **Using values for lithium leads to velocity of 10 m/s**
- **Leads to efficient heat transfer from e-beam spot**

Calculations show modest temperature rise over broad area instead of highly localized heating



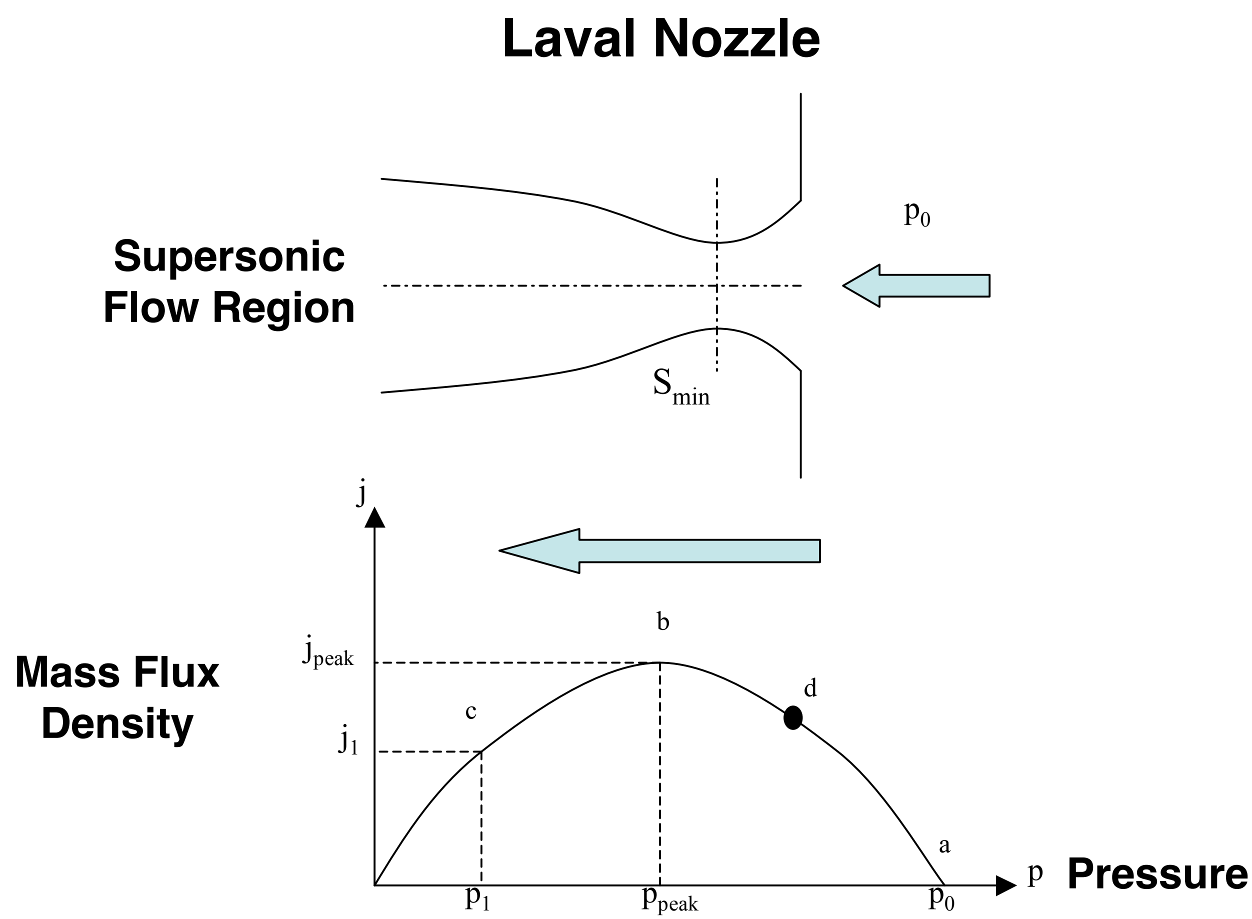
Ability of lithium PFC to "pump" hydrogen "working gas" required new fueling methods



Fully toroidal tray: R_0= 34 cm, width = 10 cm, 6 mm deep

- **"Top" gas injector consists of simple tube attached to vacuum chamber**
  - Distance from plasma limits fueling efficiency
  - Separation of gas valve from end of tube leads to slow time response

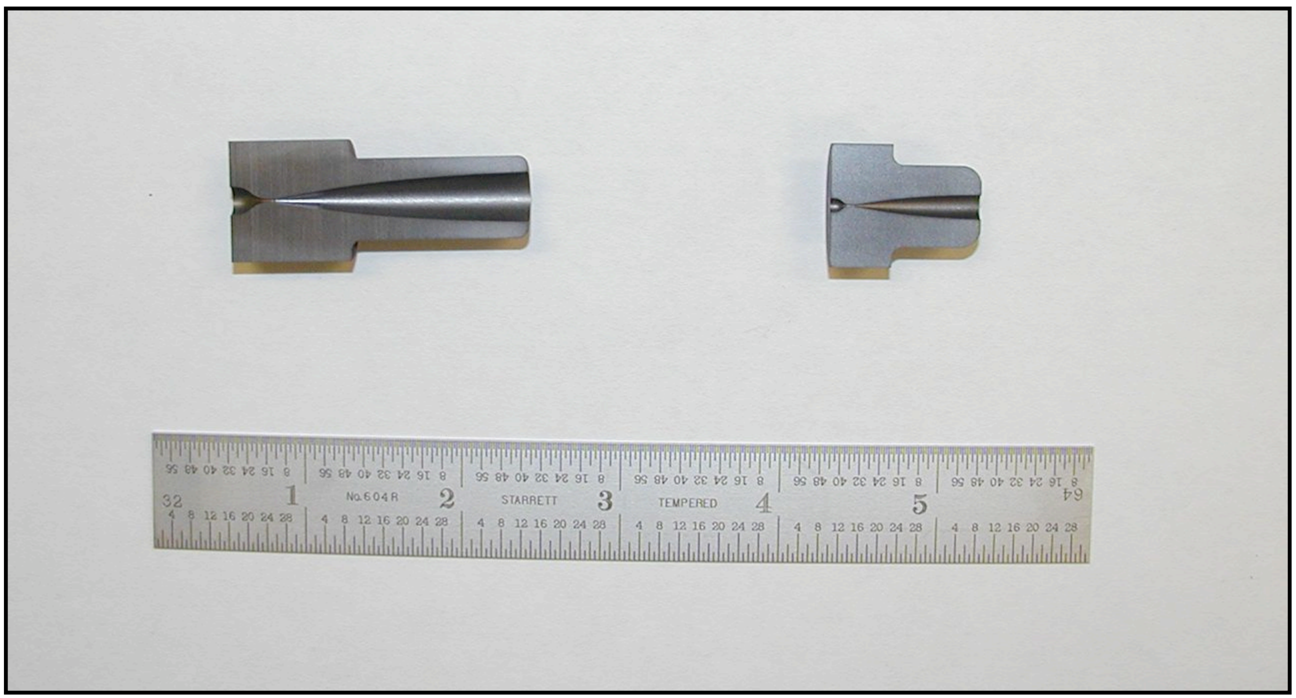
Supersonic gas injector (SGI) implemented to improve fueling



- **Principle well-established for large nozzles in aerospace applications**
  - **Situation not clear for small-scale nozzles needed for plasma fueling**

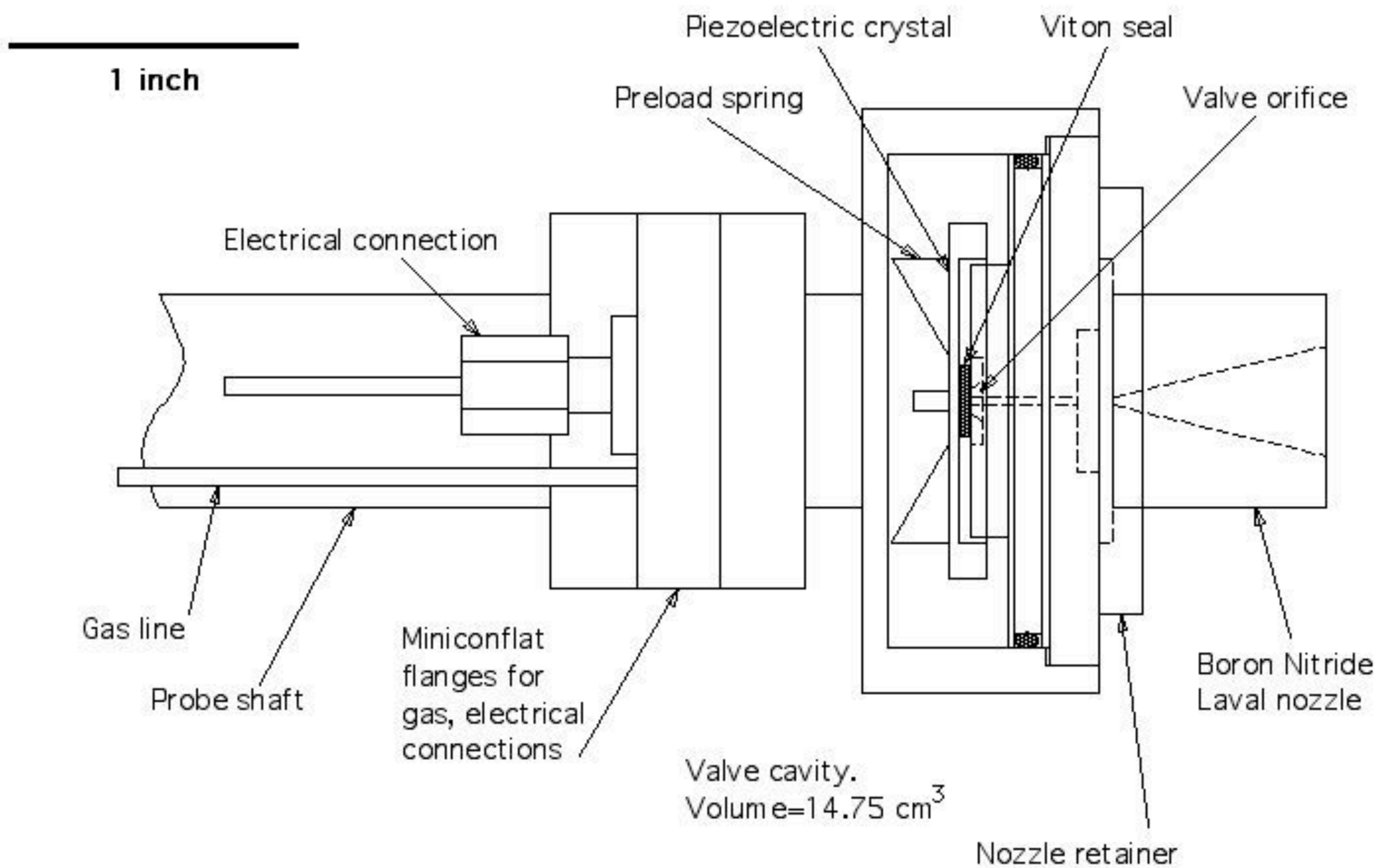
First attempt involved only scaling down design for Mach 8 nozzles

- **Original design included 0.6 inch throat diameter [Ph. D. Thesis Princeton University Department of Mechanical and Aerospace Engineering, 1997]**
- **New graphite nozzles built with 0.02 and 0.01 inch throat diameters**



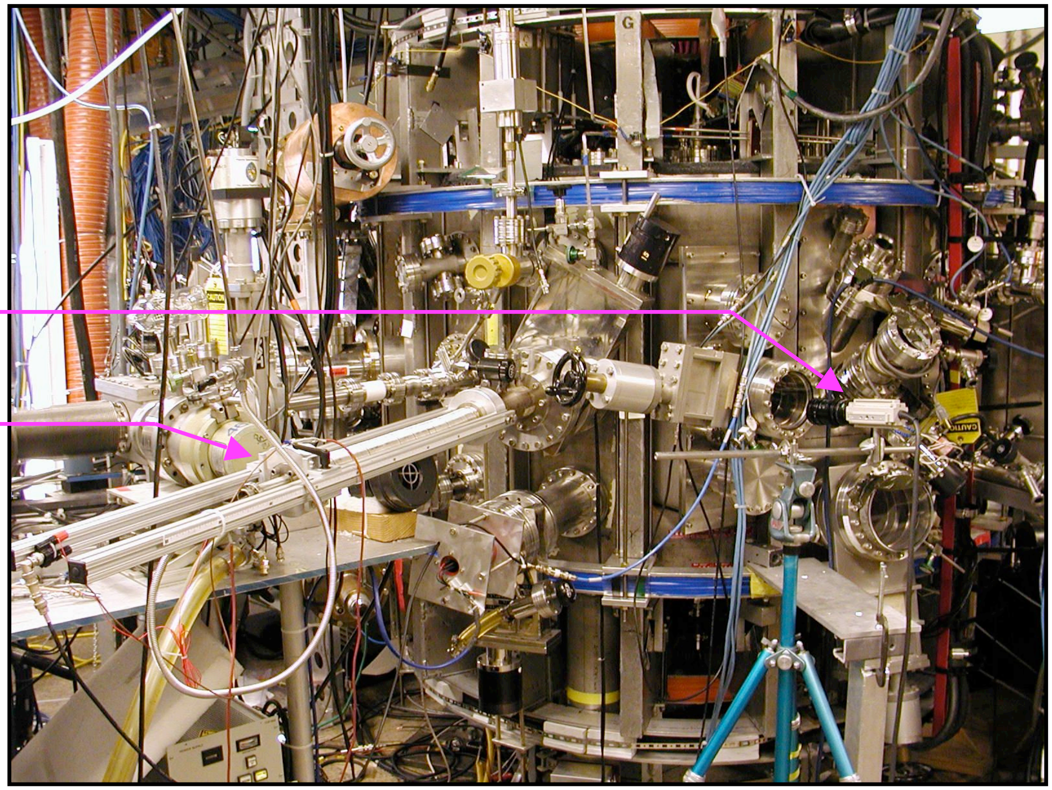
Close coupling of valve to nozzle permits fast time response

Assembly drawing - modified PV-10 piezoelectric valve with mount and Laval nozzle

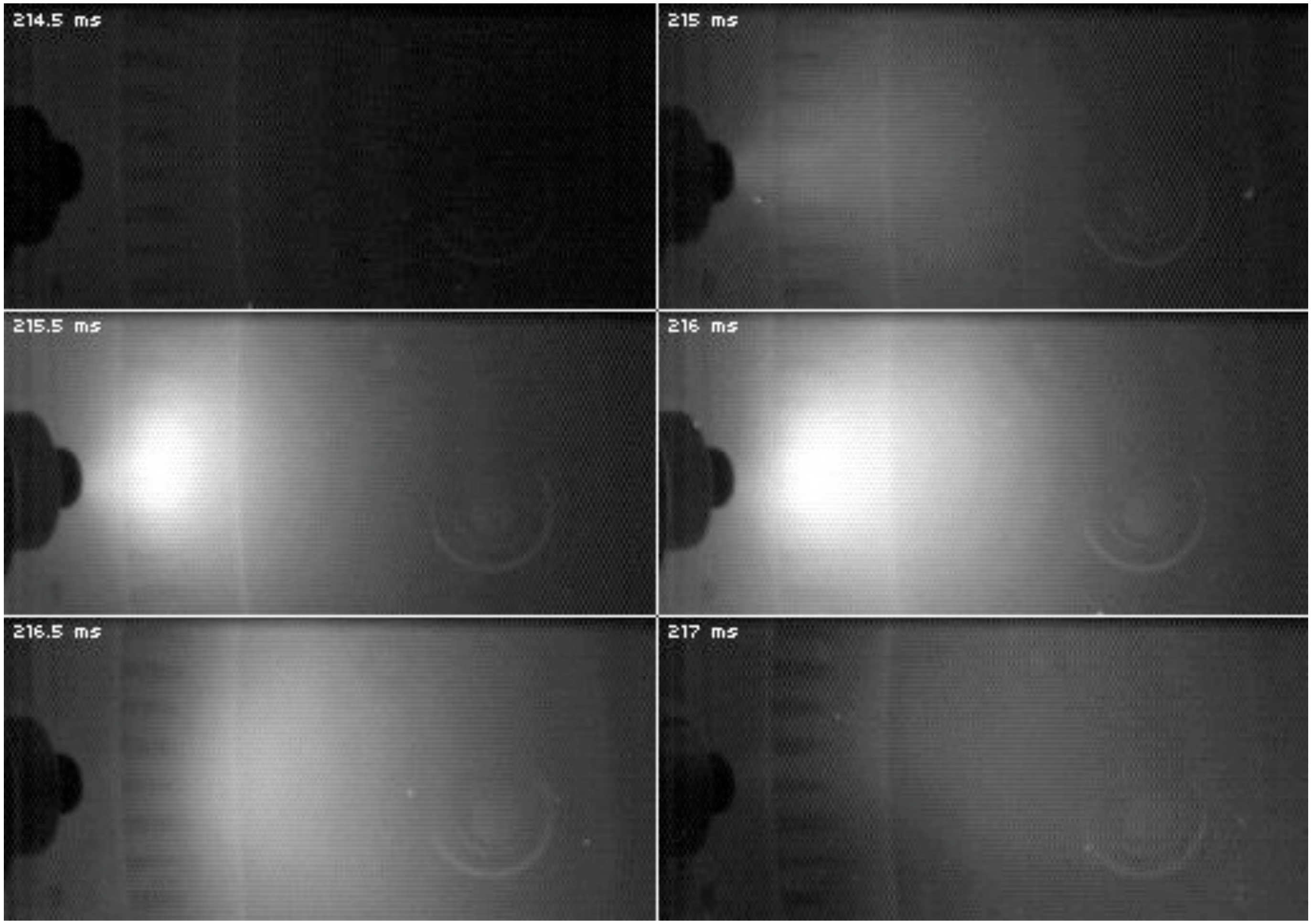


SGI installed on CDX-U with position adjustment capability

- **SGI mounted radially**
- **Fast visible camera installed with tangential view**
  - **Used to image gas plume from SGI**



Gas injection from SGI imaged



Lithium PFC's expected to reduce recycling

- "Conventional" PFC
  - Hydrogenic "working gas" not retained in PFC
  - Influx of gas back into plasma becomes major fueling source ("high recycling")
  - Results in long effective particle confinement time
- Lithium PFC
  - High chemical reactivity with hydrogen isotopes means "working gas" is trapped in PFC
  - PFC is no longer major fueling source ("low recycling")
  - Results in short effective particle confinement time

Density measurements during SGI fueling used to determine effect of lithium PFC's on recycling

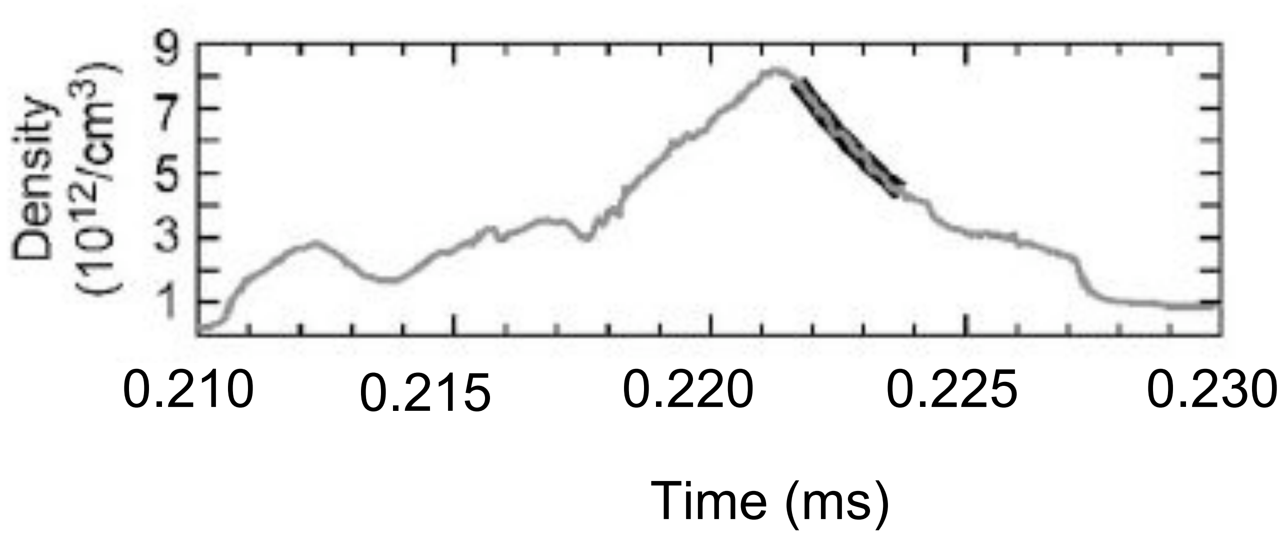
- **Define "effective" particle confinement time as function of recycling coefficient R**
  - **High recycling means high effective particle confinement time**

$$\tau_p^* = \frac{\tau_p}{1 - R}$$

- **Time behavior of density then gives indication of R**
  - **Finite decay when SGI terminates means low recycling**
    - **PFC does not provide significant fueling**

$$N_e = N_e(0)\exp\left(-\frac{t}{\tau_p^*}\right)$$

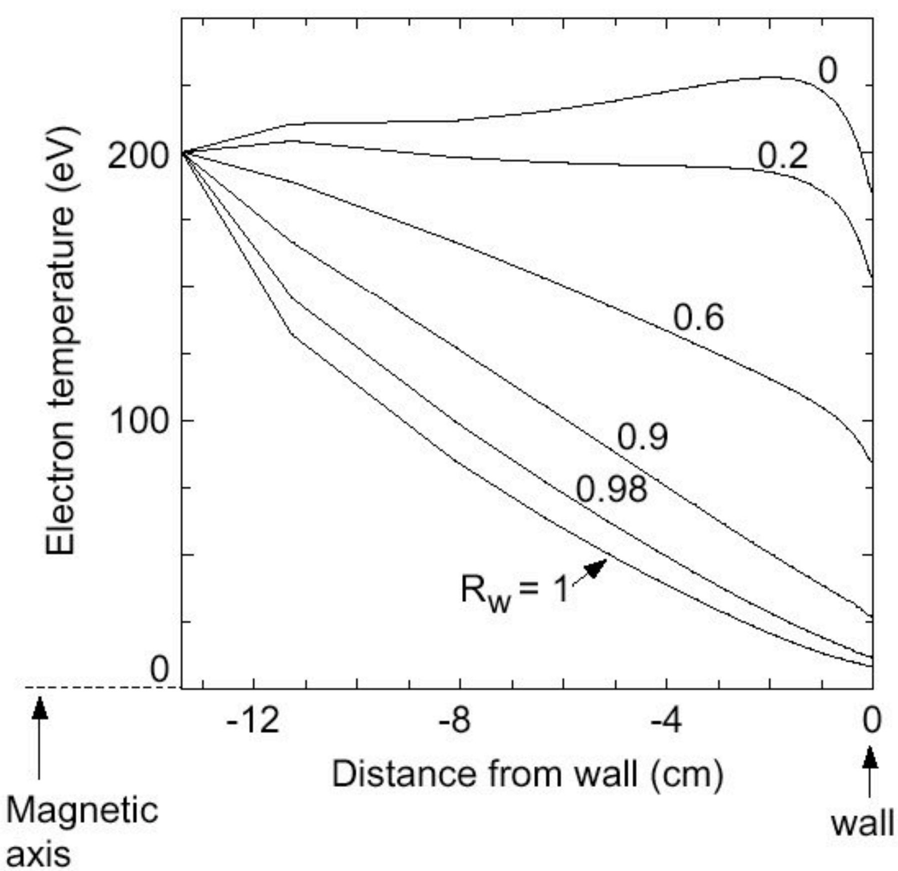
Measurements in plasmas with lithium PFC's indicate lowered recycling



- **Gas puff ends at 220 ms**
  - **Decay indicates dependence of density on external fueling**

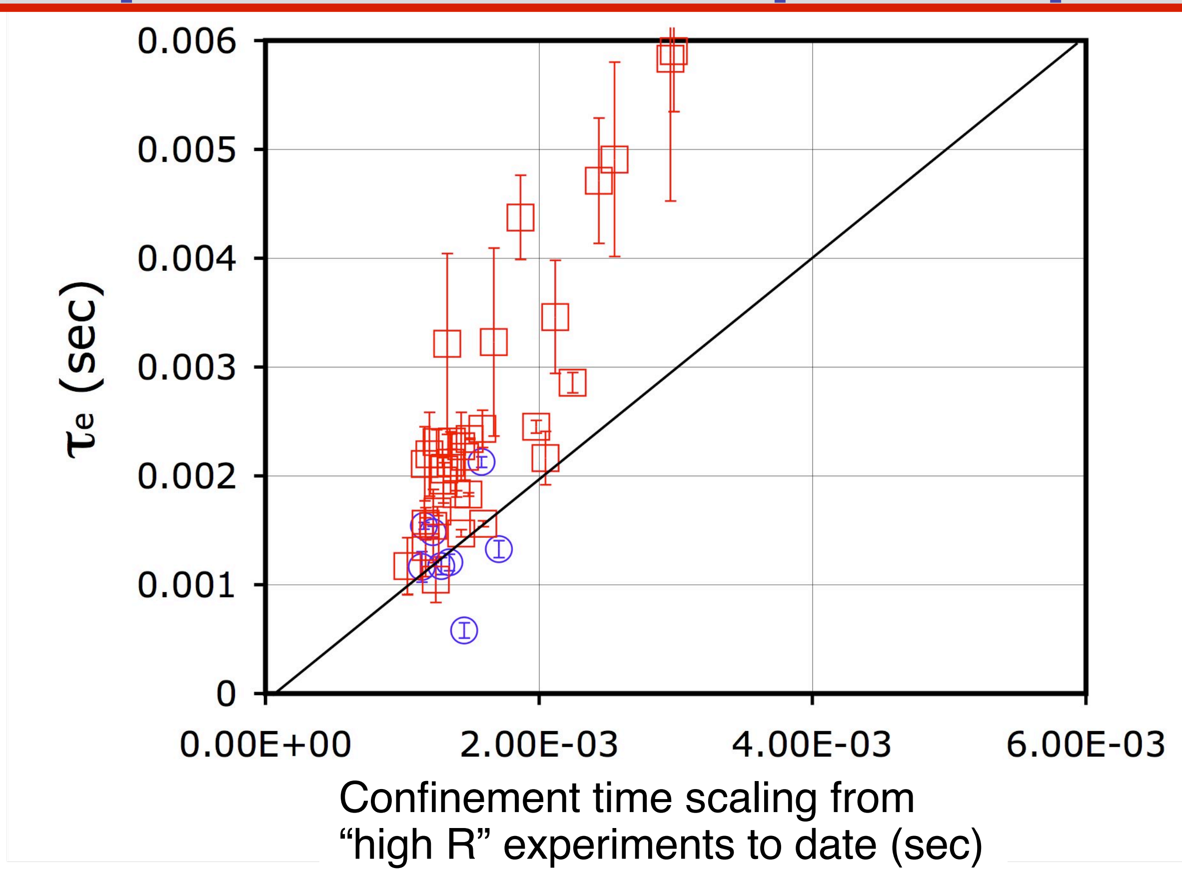
Salient prediction of low R is reduced transport due to "flattened" electron temperature profile

- **Low R means suppression of cold gas flow back into plasma**
  - **Temperature gradients reduced across plasma**
    - **Lowered internal ∇T_e drive for turbulence-driven electron transport**



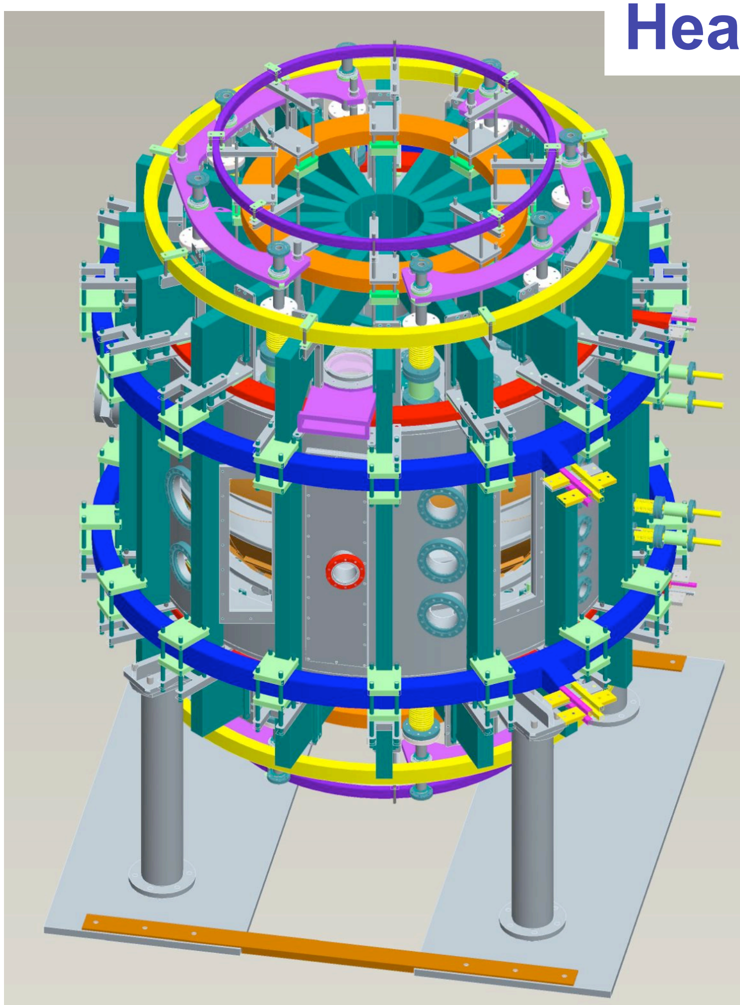
Demonstrated as R is varied in transport modeling from Lawrence Livermore National Laboratory

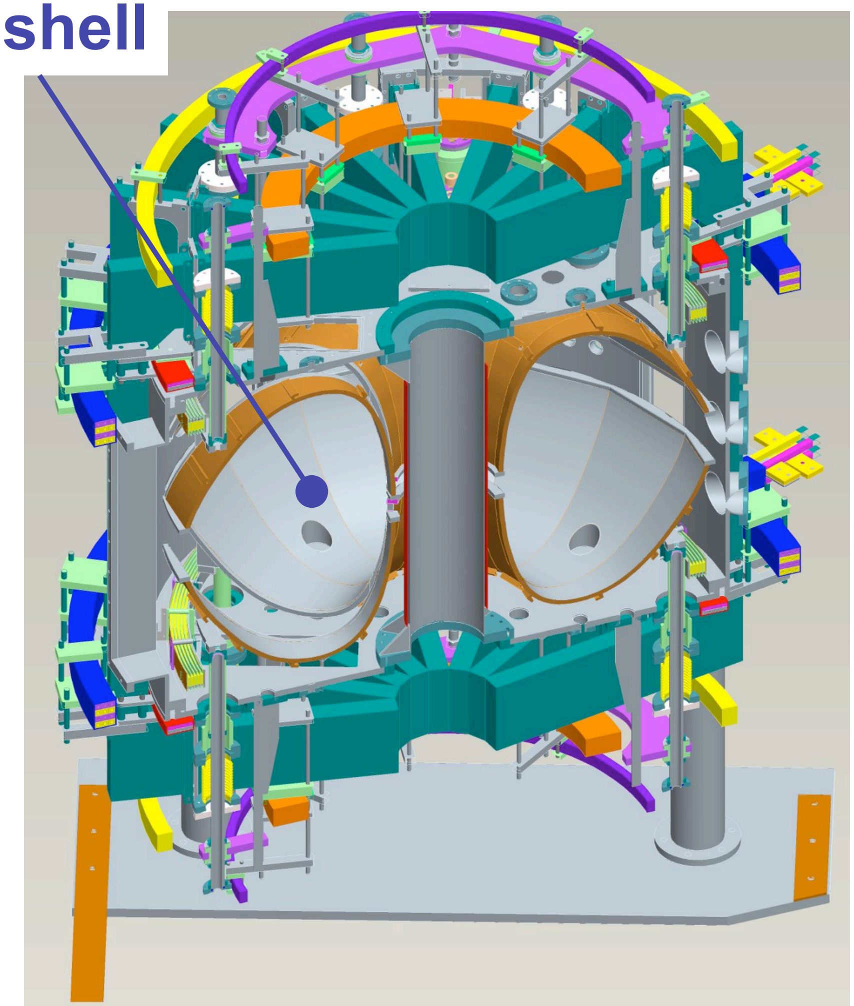
Results from CDX-U with "partial" lithium PFC's exceed predictions from past experiments



- **Lithium PFC's improved confinement in CDX-U by 6 times or more**
  - **Exceeds scaling by factor of 2-3**
    - **Largest increase in ohmic tokamak confinement ever observed**

CDX-U performance motivated upgrade to LTX with lithium "shell" that nearly encloses plasma





Lithium Tokamak Experiment (LTX)

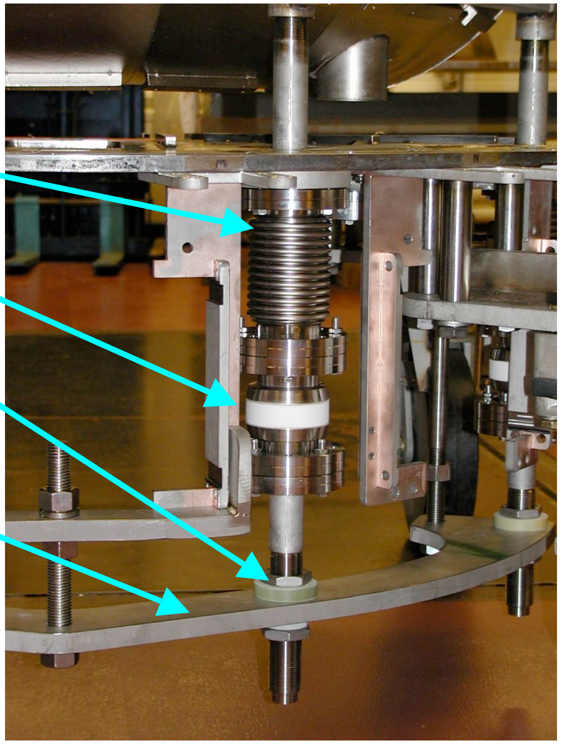
Requirements for thermal and mechanical isolation create engineering challenges

Bellows

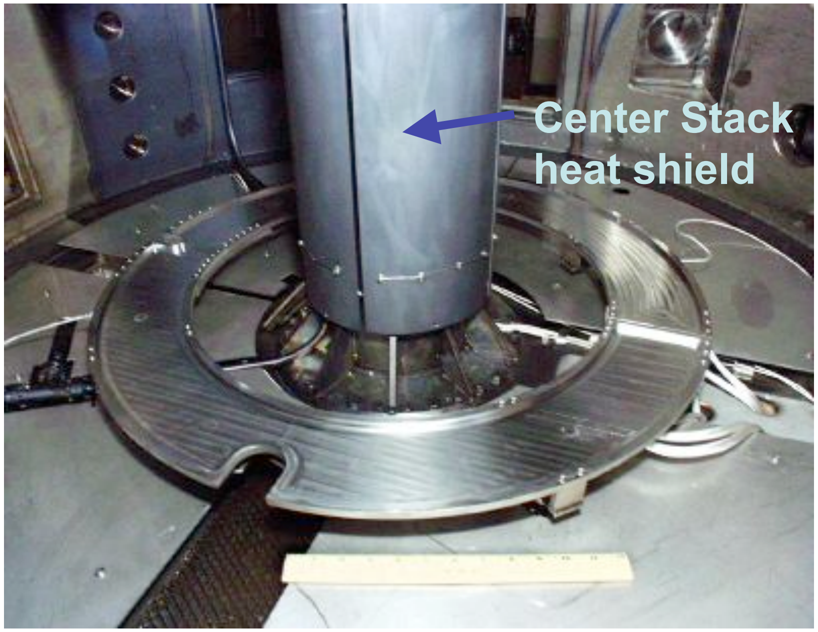
Ceramic break

G10 bushing

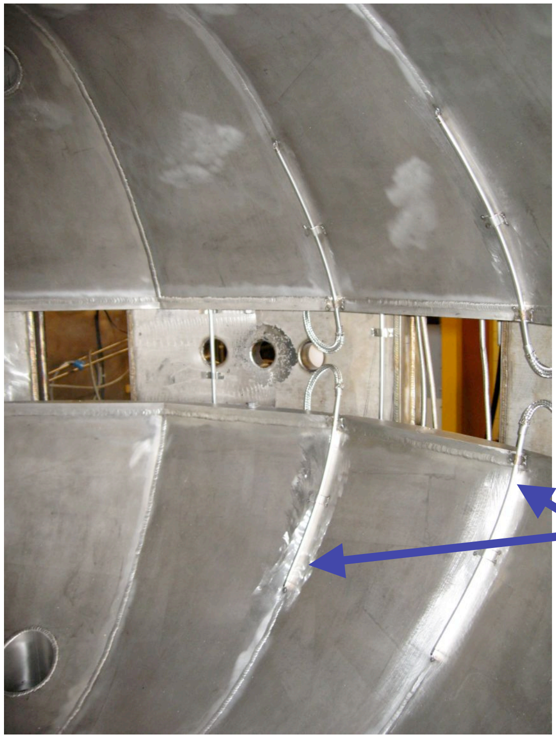
External mechanical support structure



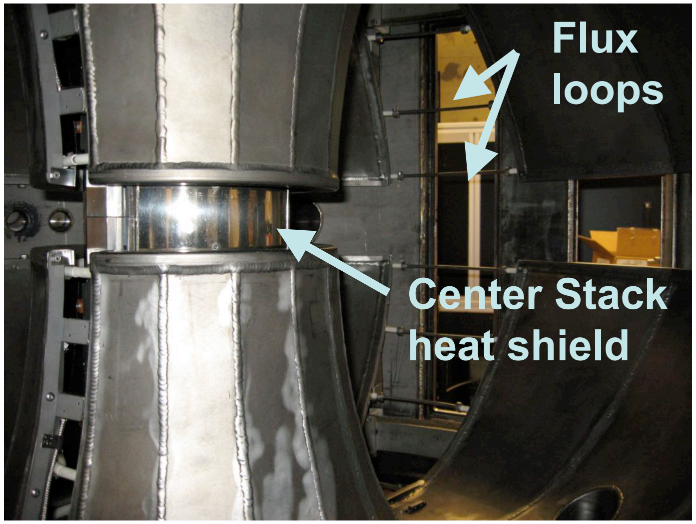
Heaters keep LTX shell above lithium melting point to provide liquid lithium PFC



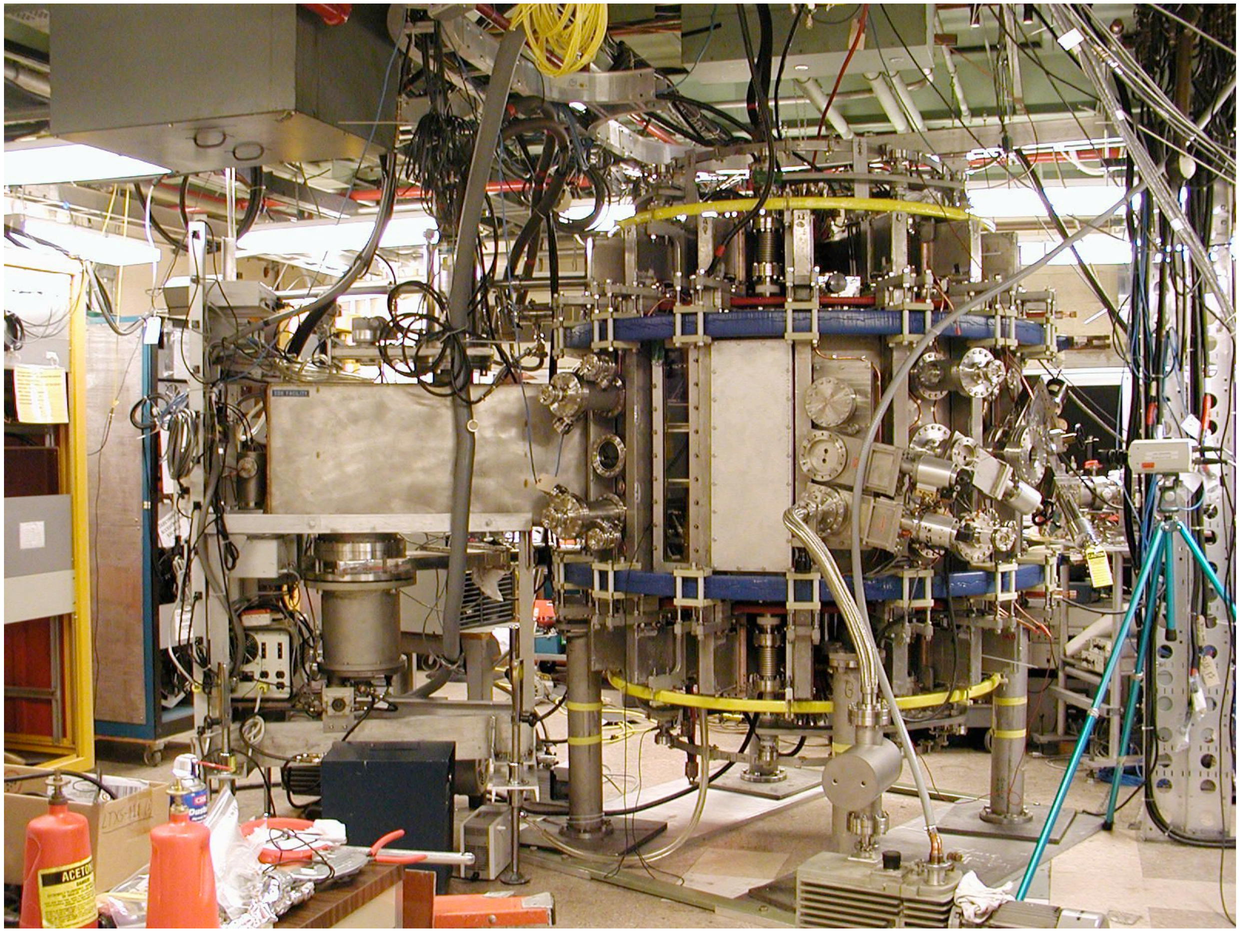
LTX shell replaces CDX-U tray



Protective tubes for magnetic field pickup ("Mirnov") coils



LTX complete and experiments beginning



- **First plasma achieved on 3 October 2008**
- **Diagnostics being installed**

Size and complexity of NSTX requires more measured approach to lithium PFC's

Device Parameters

R = 85 cm

a = 65 cm

κ = 1.7 - 2.7

δ = 0.3 - 0.8

B_T = 5.5 kG

τ_{TF} (3.5 kG)~ 3 sec
~ 6 τ_{skin}

I_p = 1.5 MA

V_p = 14 m^3

E_p ~ 430 kJ

P_{NBI} = 7.4 MW

P_{HHFW} = 6 MW

350°C bakeout

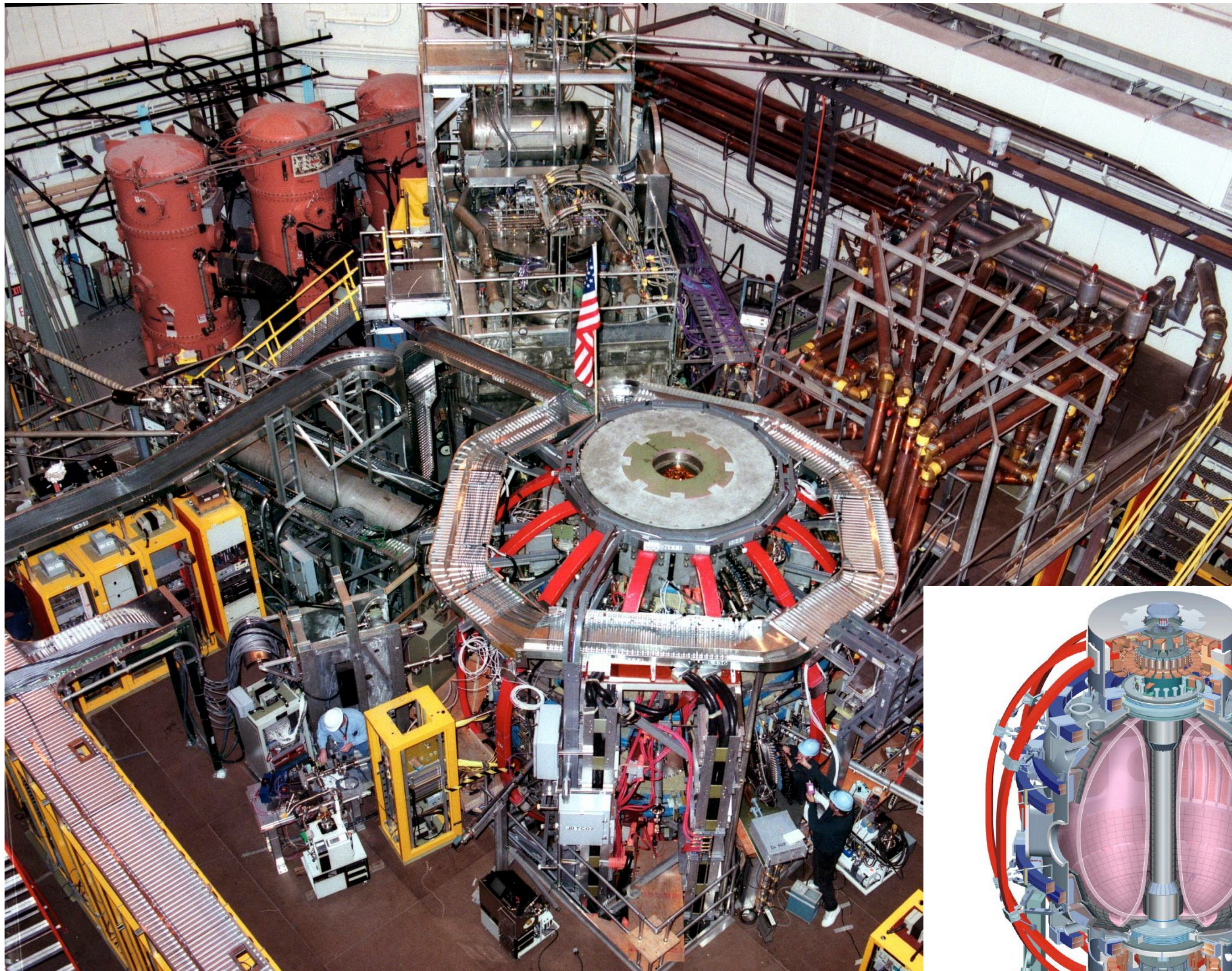
Passive Plates

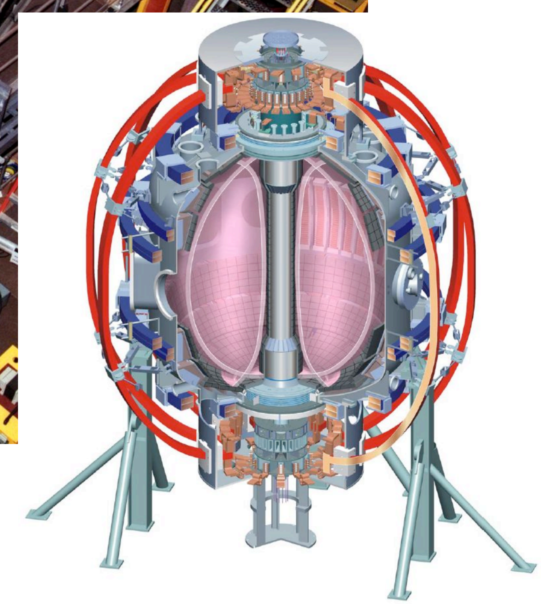
RWM Coils

I_{CHI} ~ 400 kA

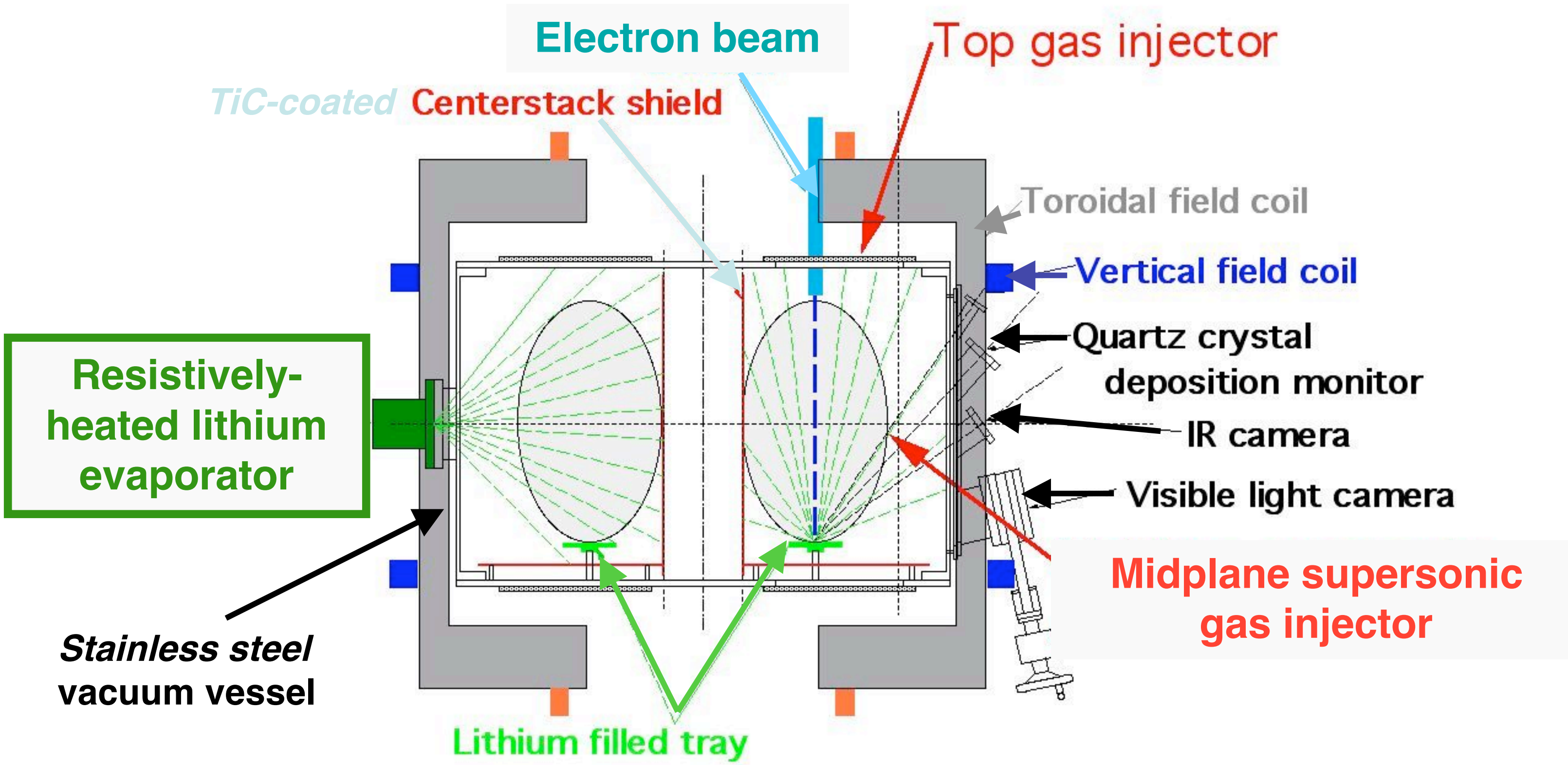
60 cm dia. ports

Wide tang. access





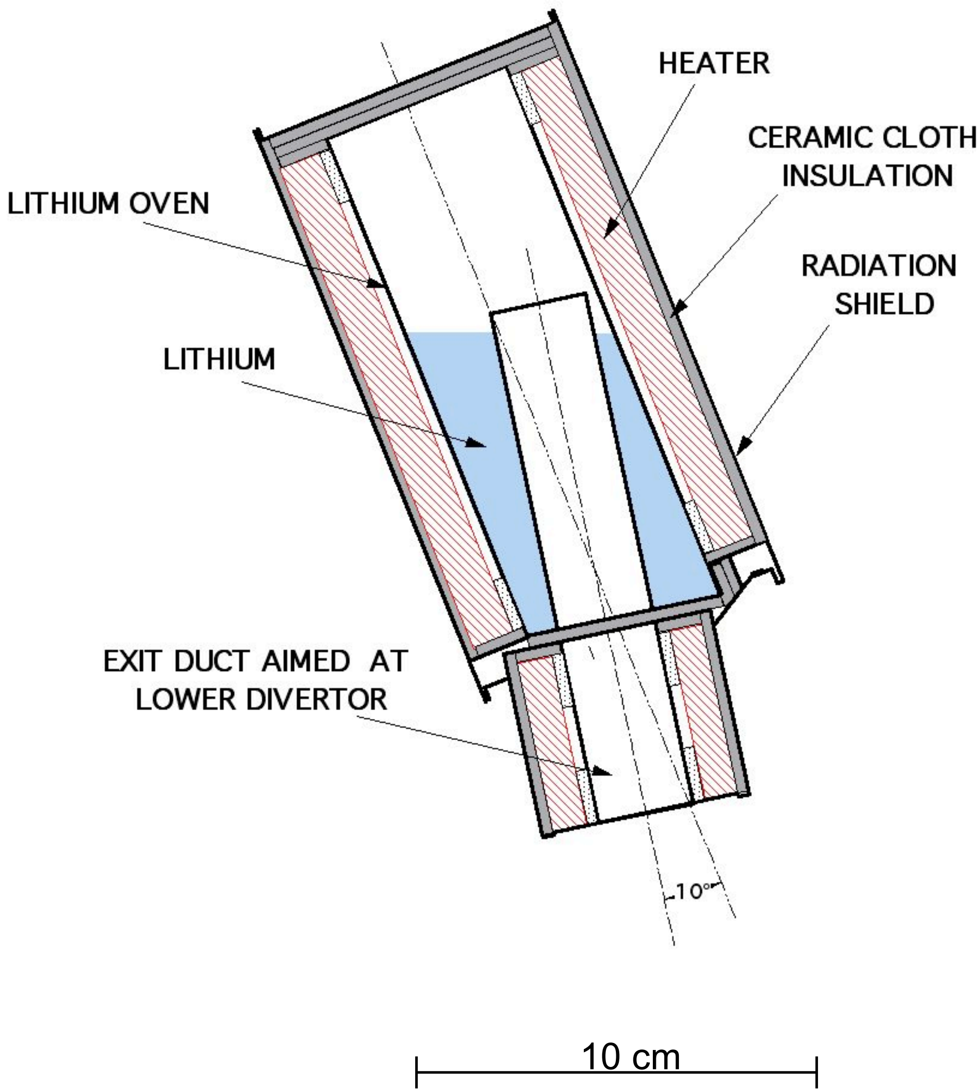
Lithium PFC research in NSTX begun with coatings prior to liquid surface implementation



Fully toroidal tray: R_0= 34 cm, width = 10 cm, 6 mm deep

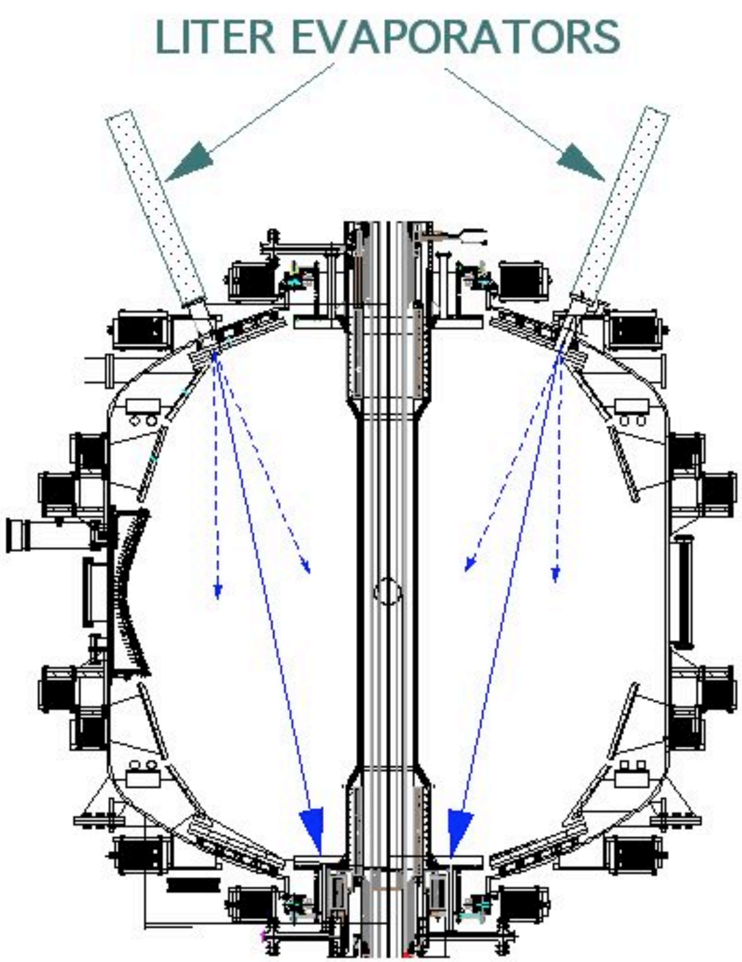
- **Use evaporator similar to type developed on CDX-U**

NSTX LIThium EvaporatoR (LITER) consists of heated reservoir inside stainless steel oven

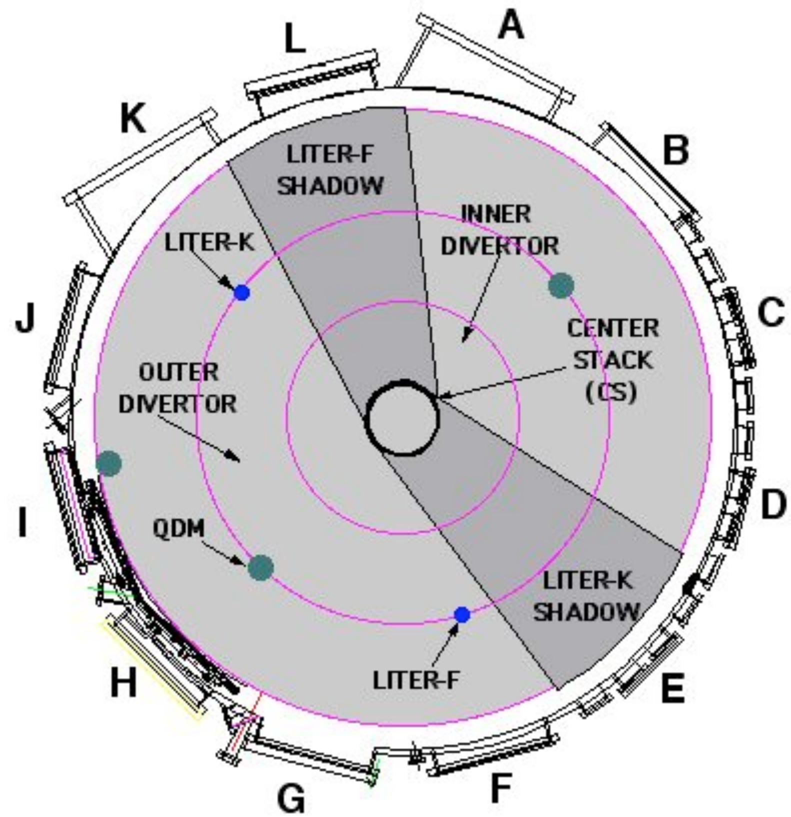


- Capacity: 90 g Li
- Oven Temp: 600-680°C
- Rate: 1mg/min - 80mg/min

Two LITERs oriented for coating NSTX divertor region with lithium

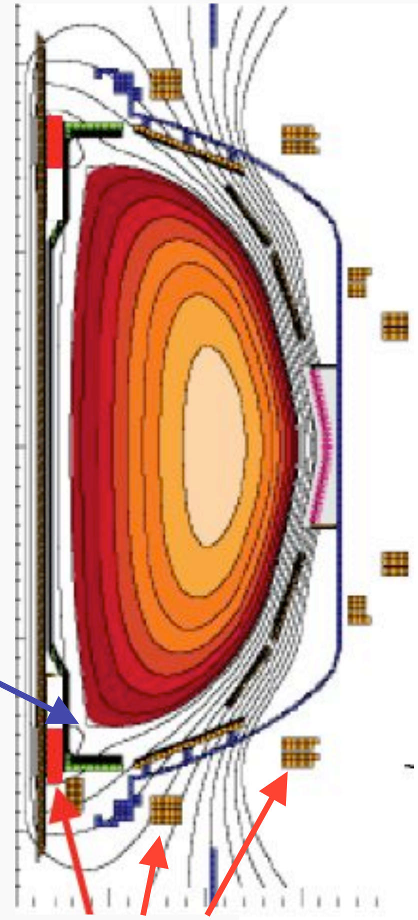


• LITER central aiming axis to graphite divertor and gaussian angle at 1/e (dashed)



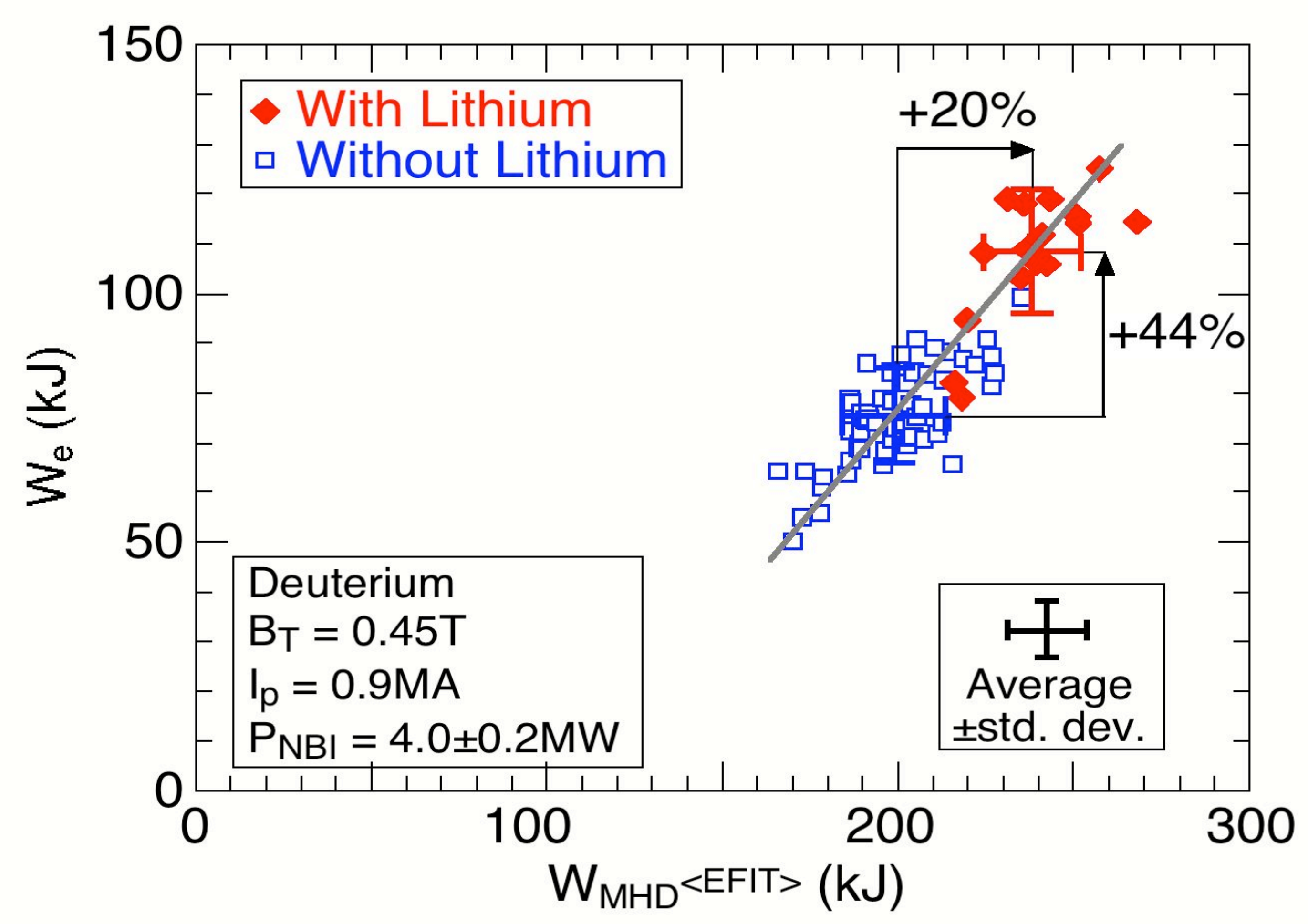
• Toroidal locations of LITER and Quartz Deposition Monitors (QDM)

High recycling observed in NSTX divertor region



- Divertor region
- Poloidal field coils

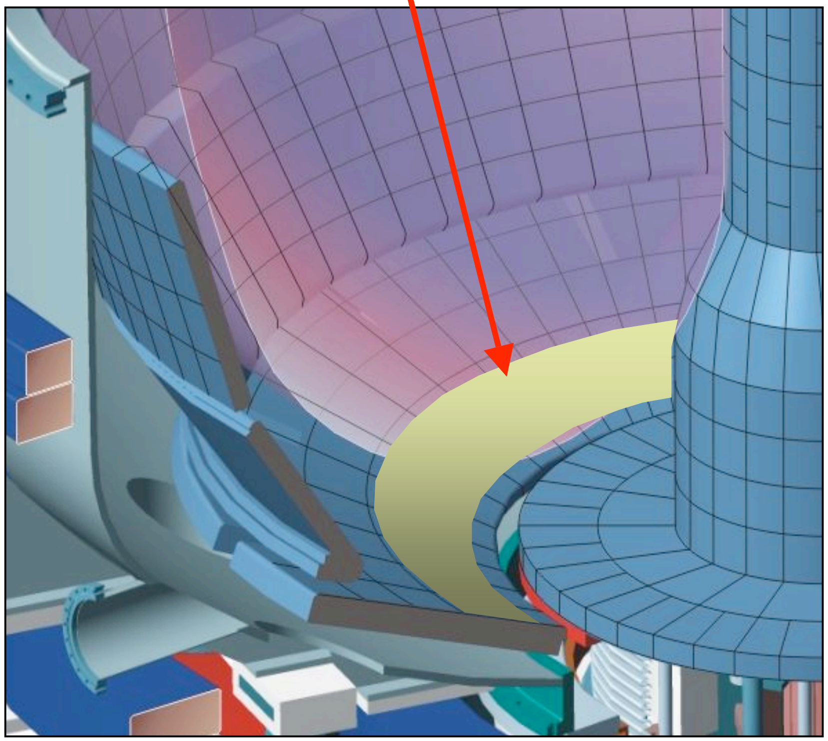
Lithium coatings improve plasma performance in NSTX



- **Increase in total stored energy primarily attributable to rise in electron stored energy**

Next step is to replace section of divertor region with fully-toroidal liquid lithium surface

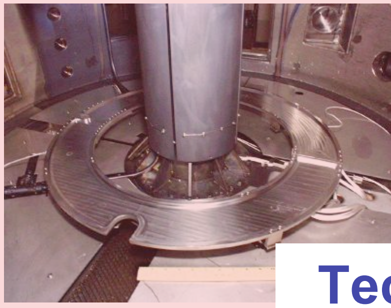
Liquid Lithium Divertor (LLD) to be installed on lower divertor in 2009



LLD sections being fabricated at Sandia National Laboratories

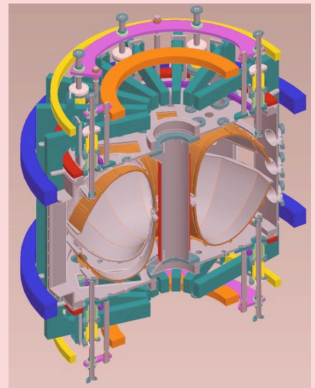
- Lithium in porous molybdenum surface to be kept liquid by heated copper substrate
- Objective is to determine if liquid lithium can sustain deuterium pumping beyond capability of solid lithium coatings

Lithium research at PPPL includes complementary technology and ST concept improvement missions



CDX-U
• Free-surface liquid lithium

Technology Development Mission

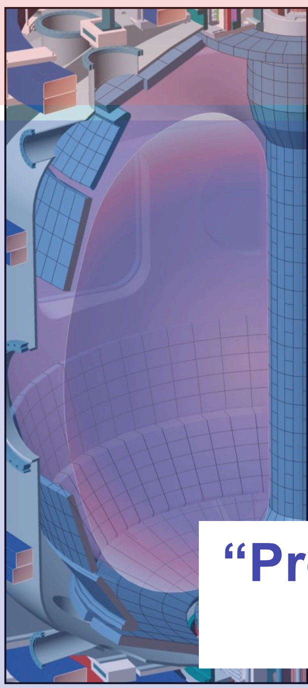


LTX
• Static liquid lithium on shell

LTX-U
• Flowing liquid lithium PFC

Physics of tokamaks with lithium walls

Next Step ST's



NSTX Liquid Lithium Divertor for Power Handling
• Electron beam testing needed to evaluate concepts

NSTX Plasma Improvement Tools
• Lithium evaporator
• Lithium powder dropper
• (Boronization)
• (Cryopumping)

Lithium-carbon chemistry

ST-specific physics understanding

Basic materials science

"Proof of Principle" Mission

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*Work supported in part by US DOE Contracts DE-AC02-76CH03073

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*Work supported in part by US DOE Contracts DE-AC02-76CH03073, DE-AC04-94AL85000, DE-AC52-07NA27344, and DE-AC05-00OR22725