Low recycling discharges with full lithium wall coatings in CDX-U


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Outline

- CDX-U lithium and fueling systems for 2005
- Recycling and particle confinement time results
  - ~30% recycling coefficient (record for magnetically confined plasmas)
- New magnetic diagnostics, equilibrium reconstructions
- Plasma confinement results
  - Up to an order of magnitude increase in confinement times
  - Exceeds ITER98P(y,1) scaling by 2 - 4×
    » Record confinement enhancement for an ohmic tokamak
- LTX status
- Where is this headed?
Three lithium, two gas fueling systems available

CDX-U: $R_0 = 34$ cm, $a = 22$ cm, $\kappa \leq 1.6$, $B_T(0) \leq 2.1$ kG, $I_p \leq 80$ kA, $\tau_{\text{disch}} < 25$ msec, $T_e(0) \sim 100$ eV, $n_e(0) < 6 \times 10^{19}$ m$^{-3}$

- Lithium tray limiter
  - 300 g of lithium in a toroidal tray
  - Half Li inventory liquid
- New electron beam lithium coating system
  - Used lithium in tray as source
- New resistively heated lithium evaporator
  - NSTX prototype
- Gas injection systems
  - Wall mounted piezo valve
  - Supersonic gas injector

⇒ Up to 1000Å of lithium coatings between discharges
⇒ 600 cm$^2$ of liquid lithium forms lower limiter
Recycling coefficient reduced to \(~0.3\) with liquid lithium tray, evaporative coatings

- \(D_\alpha\) emission at the centerstack
  - Lithium coated (solid)
  - Primary plasma contact

- \(~3\times\) reduction in \(D_\alpha\) for full-tray liquid lithium operation (2000 cm\(^2\))
- \(T_e(a)\sim28\) eV with lithium
  - \(~20\) eV without
    - \(\sim17\%\) \(D_\alpha\) emission correction
- \(N_e(a)\sim1\times10^{18}\) m\(^{-3}\) (both conditions)
  - Bare tray: deuterium prefill only
  - Liquid lithium operation required
    - \(5-8\times\) increase in gas fueling

- **Lithium reduces recycling coefficient**
  - \(R\) from \(~1\) to \(~0.3\)
    - Overestimate (background light)
- Lowest \(R\) ever obtained for a magnetically confined plasma
- Thinner coatings from resistive evaporator produced \(~5\%\) recycling reduction
- 2005 global \(R\sim0.6 - 0.7\)
Full wall coatings + partial liquid lithium tray produced very high particle pumping rates

- Effective particle confinement time $\tau_p^* = \tau_p/(1-R)$, $R$= recycling coefficient, reduced dramatically with liquid lithium limiters and wall coatings
  - $\tau_p^*$ too long to measure in the complete absence of lithium wall coatings

- Particle pumping rate in CDX-U is $1 \cdot 2 \times 10^{21}$ part/sec.
- Sufficient to pump a TFTR supershot
  - But the active wall area in CDX-U is only 0.4 m²
  - ~Two orders of magnitude less than the active wall area in TFTR during lithium wall conditioning.
- Liquid lithium also eliminated all traces of water
  - Oxygen vastly reduced
- Carbon, other impurities also reduced
Impurity ion temperature increases by 3× with lithium

- Carbon impurity level (signal magnitude) drops by over an order of magnitude
- No profile information (no radial localization)
- No Thomson scattering

Shot: 0426041431 C-IV at 4658.

No lithium
24 eV

$fwhm=0.506$ Angstrom
$T_i=23.95$ eV, $dT_i=2.08$ eV

Shot: 0428041950 C-IV at 4658.3

Hot lithium
71 eV

$fwhm=0.870$ Angstrom
$T_i=70.89$ eV, $dT_i=13.5$ eV
New magnetic diagnostics permitted reconstructions, measurement of $\tau_E$ in 2005

- Magnetic probes, compensated diamagnetic loop added
- Equilibrium and Stability Code (ESC) modified to include vessel eddy currents
  - Response function approach
  - Calibrated with “step function” coil pulses
  - Compensation for nonaxisymmetric eddy currents
Measured confinement times exceed scalings

- 61kA < $I_p$ < 78kA
- 2.1 kG
- Identical loop voltage waveforms
- $0.5 < \langle n_e \rangle < 1 \times 10^{19}$ m$^{-3}$

- Pre-lithium confinement times: 0.6 - 1.1 msec (kinetic)

- ITER98P(y,1) included START data (slightly larger “small” ST)
- Confinement in CDX improved by 6× or more with lithium wall coatings, partial liquid lithium limiter
- Exceeds scaling by 2-3×
- Largest increase in ohmic tokamak confinement ever observed
Lithium discharges exhibit long confinement times, very low loop voltage

- Reconstruction of centerstack limited plasma from ESC
- Total coating of 6500 Å of lithium had been applied during preceding 90 min.
  - 900 Å applied 1 min. before discharge
- $\tau_E$ for this discharge exceeded 9 msec
  - Not shown in scaling plot
  - Exceeds ITER98 scaling by $>4\times$
  - Corresponding global $\chi_E$ is $5m^2/sec$
- Surface voltage at current peak $<0.5V$
  - 300 J stored energy
  - $L_i \sim 0.7$
  - Very low ohmic power input: 32 kW
  - Low ohmic power a future concern
    » Lithium area 600 cm$^2$ for the discharges for which reconstructions are available
    » Loop voltage was lower with a full (2000 cm$^2$) tray (2003, 2004)
LTX will have 5 m² wall of liquid lithium

- Last shell segment coming out of the brazing furnace
- Two resistively heated lithium evaporators will provide full coverage of inner (304L) surface
- Heaters will maintain shell temperature ~300°C

- CAD view of shell in vessel
- First plasma in late CY2006
CDX-U performance has already greatly exceeded predictions for LTX

CDX-U lithium (measured, ~70 kA, 2 kG)

START data

CDX-U

LTX (orig proj) - 4 kG, 300 kA

LTX (orig proj) - 2 KG, 250 kA

- Projections from recent renewal submission (Spring 05)
  - L-mode scaling
- TSC, ASTRA projected confinement time for LTX at 3.8 kG, 250 kA was <3.1 msec (edge fueling)
- Observed confinement time for CDX-U at ~70 kA, 2.1 kG is already 2-3× higher
- Existing tokamak scalings are not good predictors for lithium tokamak performance

(M. Walsh, APS-DPP98)
Absorbing walls with core fueling may produce very long reactor confinement times

- Flat temperature profiles
  - No conduction losses
- Energy confinement time will be determined by particle confinement
- Particle confinement is always determined by the best confined species
- No temperature gradient drivers for ITG, other turbulence
  - No “profile consistency” for density profile
  - Particle transport in present machines may be driven by thermal instabilities
- Core fueled, nonrecycling lithium tokamak may have neoclassical confinement

\[
D_{\text{neo}} \approx 0.016 \frac{n_{20}}{B_p^2 \sqrt{T_{i,10}}} \sqrt{\frac{a}{R}} \quad \text{(m}^2/\text{sec)}
\]

\[\Rightarrow \tau_\text{E} \sim \tau_\text{p} \sim \frac{a^2}{D_{\text{neo}}} \quad \tau_\text{E} > 10 \text{ seconds for Component Test Facility with } a \sim 0.4 \text{ m}\]

\[\Rightarrow\text{ CTF requires only 10 MW of NBI at 45 keV}\]
  - \(T_\text{e} = T_\text{i} = 15 \text{ keV}\)
  - Driven - no alpha confinement
Lithium tokamak leads to a simple, compact Component Test Facility for reactor R&D

- PFC: 0.1-0.5 mm “creeping” lithium film in porous moly or tungsten surface
  - Required replacement rate:
    ~10 liter/hour (flow rate < 1 cm/sec) for ITER
- Small size = access for core fueling with low voltage NBI
- $R_0=1.25\text{m}, \ a=0.75\text{m}, \ A=1.66, \ \kappa =2, \ 3T, \ 11 \text{ MA}$
- At 40% $\beta$, $P_{\text{fusion}}=400 \text{ MW}$ (=ITER)
  - Plasma volume =26 m$^3$
  - 3% of ITER
  - Manageable tritium requirements for reactor development

CTF with TF, PF and blanket comparable in volume to present-day light water fission reactor pressure vessel (~100 m$^3$)
Summary

- In 2005 CDX-U simultaneously employed 600 cm$^2$ liquid lithium limiter + 1000 Å between-shots lithium wall coatings
  - Higher recycling than 2003-04 full-tray operation
  - But: new diagnostics for equilibrium, confinement

- Particle removal rates produced in CDX-U sufficient to pump a TFTR supershot

- Recyclings coefficients of ~30% are the lowest ever achieved in a magnetically confined plasma

- 6-10 × enhancement in low recycling discharge confinement times over high recycling case
  - Largest increase in ohmic tokamak confinement ever observed
  - Empirical tokamak scalings appear irrelevant to lithium tokamaks

- CDX-U now being disassembled, converted to LTX
  - 25× increase in liquid lithium surface over best-case CDX-U

- Leads to a lithium walled CTF with a porous-metal lithium-filled PFC
  - Porous metal walls with slow flow are presently under development via Phase I and Phase II SBIRs