The Spherical Tokamak as a Compact Fusion Reactor Concept

R. Kaita
Princeton Plasma Physics Laboratory

ENN Symposium on Compact Fusion Technologies
April 19 – 20, 2018

*This work supported by US DOE Contract DE-AC02-09CH11466
Outline

• Tokamaks in Magnetic Confinement Fusion
• Attractive Spherical Torus Characteristics
• Technical Advantages of Spherical Torus
• New Regimes for Spherical Torus Plasmas
• Summary and Conclusions
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- **Tokamaks in Magnetic Confinement Fusion**
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"Scientific breakeven" achieved – approximately – with D-T fusion two decades ago in JET and TFTR

- Major Radius = 2.52 m
- Minor Radius = 0.87 m
- Plasma Current = 2.7 MA
- Neutral Beam Power = 39.5 MW
- Stored Energy = 6.9 MJ
- Generated Fusion Power = 10.7 MW
ITER addresses important issues for fusion power plants but is *not* fusion power plant “prototype”

- Produce 500 MW of fusion power
- *Demonstrate integrated operation of technologies for fusion power plant*
- Achieve D-T plasma sustained through internal heating
- Test tritium breeding
- *Demonstrate safety characteristics of fusion device*

**ITER:**
- $R = 6.2\,\text{m}$
- $a = 2.0\,\text{m}$

**TFTR:**
- $R = 2.52\,\text{m}$
- $a = 0.87\,\text{m}$
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Plasma stability is determined by plasma currents and by normalized pressure $\beta$

$$\frac{2nT}{B^2 / 2}_0$$

Fusion power density must be maximized

$$p_{fus} = E_{fus} n_d n_t \left\langle v_{fus} \right\rangle \sim n^2 T^2 \sim B^4$$

Higher $\beta$ makes more fusion at given B
Spherical torus – ST – configuration enables plasmas with good confinement and stability

- “Outboard” field line shows large “pitch” due to stronger poloidal field relative to toroidal field
- “Inboard” field line exhibits smaller “pitch” due to stronger toroidal field relative to poloidal field
- Greater length on “good curvature” side where field line bulges toward plasma” side improves confinement and stability
Neutral Heating Beam

NSTX-U

Neutral Heating Beam

Major Radius = 0.94 m
Aspect Ratio (R/a) ≥ 1.5
Plasma Current = 2 MA
Neutral Beam + RF Power = 19 MW
NSTX and MAST data indicate confinement improvement with lower collisionality

\[ v_e^* \sim n_e / T_e^2 \]

ST scaling: \( \tau_{E, \text{th}} \propto v_e^* \beta^{-0.0} \)

ITER 98y,2: \( \tau_{E, \text{th}} \propto v_e^* \beta^{-0.9} \)

Continued favorable confinement trends could lead to more compact ST reactors

Normalized electron collisionality \( v_e^* \propto n_e / T_e^2 \)
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Conductor on Round Core Cables (CORC): High winding pack current density at high magnetic field

\[ J_{WP} \sim 70 \text{MA/m}^2 \text{ at } 19\text{T} \]

7 kA CORC (4.2K, 19 T) cable

Base cable: 50 layers of YBCO tapes with 38 \( \mu \text{m} \) substrate

(Van Der Laan, HTS4Fusion, 2015)
A = 2 ST pilot plant concepts with REBCO high-temperature superconductors being developed

Cryostat volume
~ 1/3 of ITER

\[ B_T = 4T \]
\[ I_p = 12.5\text{MA} \]
\[ \kappa = 2.5, \ \delta = 0.55 \]
\[ \beta_N = 4.2, \ \beta_T = 9\% \]
\[ H_{98} = 1.75 \]
\[ f_{\text{NI}} = 100\%, \ f_{\text{BS}} = 0.76 \]
\[ B_{T-\text{max}} = 17.5T \]

Vertical maintenance

\[ P_{\text{fusion}} = 520 \text{ MW} \]
\[ P_{\text{NBI}} = 50 \text{ MW} \]
\[ E_{\text{NBI}} = 0.5 \text{ MeV} \]
\[ Q_{\text{DT}} = 10.4 \]
\[ Q_{\text{eng}} = 1.35 \]
\[ P_{\text{net}} = 73 \text{ MW} \]
\[ \langle W_n \rangle = 1.3 \text{ MW/m}^2 \]
Separate ST center stack makes vertical maintenance schemes possible

Oak Ridge National Laboratory design for Fusion Nuclear Science Facility - FNSF
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Lithium plasma-facing components offer attractive alternative to high recycling, high-Z wall tokamaks

• Hot edge plasmas for enhanced performance
  – $T(a) \sim T(0)$ mean $\nabla T \sim 0$ so conduction losses are suppressed
• Low Z core impurities
  – Plasmas are able to withstand lithium influx
• Liquid lithium tolerant of high energy edge
  – No surface damage and low sputtering
• Broad scrape-off layer
  – Mitigates divertor power loading issues
Lithium Tokamak Experiment – LTX – ST used to demonstrate effects of low recycling lithium walls

- Tokamak with low aspect ratio
  - $R_0 = 40$ cm, $a = 26$ cm, $\kappa = 1.6$, $\delta = 0.2$
  - $B_{\text{tor}}$ up to 1.7 kG
  - $I_p$ up to 100 kA
- Limiter discharges
  - Surrounded by high-Z conformal conducting shell
  - High-Z wall-limited on high field side
  - No carbon plasma-facing components (PFCs)
- Ohmic plasma heating only
  - Maximum discharge length ~ 50 ms
- Operated in hydrogen
  - Fueled with midplane gas puffer on high field side
Lithium coats LTX conducting shell with four segments that conform to 80% of plasma surface.

Heated shells consist of four segments.

LTX experimental area
Flat electron temperature profiles – $\nabla T \sim 0$ – achieved in LTX Ohmic plasmas with lithium walls

- Electron temperature, density, and pressure profiles during fueling
- First observation of fully isothermal confined plasmas
- Electron temperature, density, and pressure profiles after fueling

Gas puffing cools edge

No edge cooling: $T_e(a) \sim T_e(0)$
Neutral beam fueling experiments on LTX upgrade – LTX-β – expected to achieve hot ion regime

- Simulations performed with ASTRA-ESC with transport model for “pumping” boundary conditions
- Shows achievement of core $T_i > T_e$ with 90 kW deposited in plasma
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Spherical tori or tokamaks include features that are attractive for compact fusion reactors

- Shows potential for increased MHD stability and maximum toroidal $\beta$ compared to large aspect ratio tokamaks
- Strong nearly inverse dependence of energy confinement on collisionality presents favorable trend for reactors
- Magnet designs with normal conductors or high temperature superconductors are economically attractive
- Cylindrical geometry enables modular concepts that simplify component maintenance
- Flat temperature profiles in discharges with high edge temperatures achieved with low-recycling walls suggest efficient use of plasma volume
Solution may require power plant complexes with multiple fusion reactors

“Core” of each unit designed to be “replaceable” like fission reactor fuel assemblies but without cost and complexity of long-term hazardous waste storage

Demountable reactor components

Removable fuel assemblies
References

Test lithium surfaces under “reactor” conditions on Magnum-PSI Linear Plasma Device in Netherlands

G. De Temmerman et al., Fusion Engineering and Design 88 (2013) 483–487

- \( \Gamma_{D^+} \approx 10^{24} \text{ m}^{-2}\text{s}^{-1} \) at normal incidence to target
- \( T_e \approx 3 \text{ eV}, n_e \approx 8 \times 10^{20} \text{ m}^{-3} \)
- 7 s pulses, \( B = 0.25 \text{ T} \) at target
- Evaporative Li coatings applied in-vacuum
Lithium surface persists for unexpectedly long time under plasma bombardment

- Lithium coatings persist for 3-4 seconds under intense plasma bombardment and temperatures as high as 900°C
- Estimates based on binary collision approximation for erosion indicate coating lifetimes of less than 0.5s
- Redeposition fractions of over 99% required to explain results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Discharge time</td>
<td>8x 5s (40s total)</td>
</tr>
<tr>
<td>Typical (T_e, N_e)</td>
<td>1eV, 1.4e20 m(^{-3})</td>
</tr>
<tr>
<td>Gross Li yield (TRIM est.)</td>
<td>0.52 mg m(^{-2})</td>
</tr>
<tr>
<td>Total deposited (max Net)</td>
<td>0.05 mg m(^{-2})</td>
</tr>
<tr>
<td>Redeposition (if max Net)</td>
<td>0.9 27</td>
</tr>
</tbody>
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Interpretation begins with density functional theory – DFT – calculations to simulate deuterium diffusion.
Use DFT to determine Li and D diffusivities from structural and dynamical properties of system

- Absence of suitable classical potential to describe interactions between liquid Li and H isotopes requires Kohn-Sham DFT-MD
- Simulations used Vienna *Ab Initio* Simulation Package (VASP)
  - 4 x 4 x 4 bcc cell as initial geometry for liquid lithium
    - 128 atoms with two atoms in each cubic unit cell
  - 3 x 3 x 3 “rock salt” (RS) cell as initial geometry for lithium deuteride
    - 216 atoms with eight atoms in each RS unit cell
- Simulations performed to obtain dependence of D diffusivity on different temperature (T) and ratio (β) of D to Li atoms
  - β = 0.25, 0.50, .75, and 1.00
  - T = 470, 570, 686, 793, 943, and 1143 K

M. Chen et al., Nucl. Fusion 56 (2016) 016020
Depictions of liquid lithium samples with different concentrations of D to Li atoms at various temperatures

• Li atoms depicted in green and D atoms depicted in red after 20 ps
• Cases a – d show solid-like features: ordered structures
• Cases e – f show liquid-like features: no ordered structures
KSDFT–MD provides “first principles” insights into behavior of D in Li with flux and temperature

- Liquids characterized by high diffusion of D
  - Consistent with erosion rates from earlier low deuterium flux data
  - Predicted by simulations for increasing ratio of Li to D

- Solids characterized by low diffusion of D
  - Consistent with erosion rates from high deuterium flux data from Magnum PSI
  - Predicted by simulations for equal Li and D
  - Corresponds to formation of solid LiD
  - D diffusion rises only as melting point of LiD is reached at 965°K or 1000/T_{melt} = 1.04
Use modeled diffusivities to get Li:D concentration dependence on plasma and surface conditions

- Solve 1-D equation with diffusion coefficient $\alpha(x,t)$
  $$\frac{d\beta(x, t)}{dt} = \frac{d}{dx} \left[ \alpha(x, t) \frac{d\beta(x, t)}{dx} \right]$$

- D assumed implanted uniformly in top 5 nm of material
  Surface D/Li concentration after D fluence of $10^{23}$ m$^{-2}$

T Abrams et al., Nucl. Fusion 56 (2016) 016022

D bombards surface faster than Li can absorb it
Deuterium concentration on lithium surface affects sputtering by various mechanisms

- D absorption reduces Li sputtering in two ways:
  - Preferential sputtering: less atoms available to sputter
  - Chemistry: surface binding energy – assumed equal to heat of sublimation – is higher for LiD (2.26 eV) vs. Li (1.67 eV)
- D atoms can adsorb on Li surface in several different sites
  - Motivates two different models of a Li/LiD surface

![Diagram of Adsorption Sites](image)
Modeling requires inclusion of “adatoms” that lie on surface of target material.

Near-surface Plasma

- Ionization
- Adatom formation
- Adatom evaporation/sublimation
- Charge exchange
- Recombination

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Realistic lithium erosion model includes dependence on both lithium temperature and D concentration in lithium.

\[
\Gamma_{\text{Li}}(T, \beta, \Gamma_{\text{D}^+}) = \Gamma_{\text{D}^+} + f(\beta) \left[ \frac{Y_{\text{coll}}}{3} + \frac{Y_{\text{ad}}}{1 + A \cdot \exp\left(\frac{E_{\text{eff}}}{kT}\right)} \right]
\]

- **Total Li erosion** (m\(^2\) s\(^{-1}\))
- **\(D/\text{Li mixed-material reduction factor}\)**
- **Langmuir Law**
- **Evaporation**
- **D ion flux**
- **Collisional sputtering**
- **Thermally-enhanced sputtering** (adatom-evaporation model)

\[
+ \frac{p_v(T, \beta) - p_a(T)}{\sqrt{2\pi m_{\text{Li}} kT}},
\]

_\(\beta\) - Parameter related to D/Li ratio

_\(\Gamma_{\text{D}^+}\) - D ion flux

_\(Y_{\text{coll}}\) - Collisional yield

_\(Y_{\text{ad}}\) - Adatom yield

_\(k\) - Boltzmann constant

_\(T\) - Temperature

_\(E_{\text{eff}}\) - Effective energy barrier
Calculations show mixed material dependence of erosion yield

Mixed-material Li/LiD erosion yield vs. temperature

- Calculations assume $Y_{ad}$ – constant adatom yield – and $Y_{coll}$ – collisional sputtering yield – are both reduced by $f(\beta)$
Lithium yields from 20 eV D bombardment of thick Li coatings consistent with $\beta$-dependent predictions

- Adatom mixed-material model captures quantitative evolution of Li erosion rate with temperature

- Error band reflects range distance between homogenous and partial D monolayer surface models