Magnetic Confinement Fusion and Tokamaks

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Outline

• Fusion Requirements and Approaches
• Magnetic Confinement Fusion
• How Does a Tokamak Work?
• Progress and Outlook
• Fusion Research at UofS
• Role of UofS in Fusion 2030
• Summary
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Fusion Difficulties

• In order to bring the D and T close enough to make the fusion reaction happen, the repulsive Coulomb force \(1/r^2\) between the positively charged D and T has to be overcome.

• Fuels can be heated to high temperatures (hundreds of millions degrees) in a tokamak.

• High temperature fuel (plasma) must be confined.
Requirements and Challenges

• The fuel density must be high enough to generate necessary power in the reactor → \( n \sim 10^{21} \text{ m}^{-3} \)

• The confinement time must be long so the fuels fuse before getting lost → \( \tau \sim 1 \text{ second} \)

• Fusion triple product (Lawson’s Criterion)

\[
 nT\tau \sim 10^{22} \text{ m}^{-3} \cdot \text{keV} \cdot \text{sec}
\]

• Q-value (measure of economy)

\[
 Q = \frac{\text{fusion power}}{\text{input power}} \gg 1
\]
Types of confinement schemes

Inertial

Magnetic field

Gravitation (sun)
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Magnetic Fusion

• A charged particle makes gyro-motion around the magnetic field lines
  – Cross-field motion is restricted
  – Motion along the field lines is still free (end-loss)

• Closed magnetic field lines are preferred (toroidal devices)
Types of MCF Devices

• Magnetic field can be applied externally or induced, partially or wholly, by current flowing in the plasma.
  – Fully applied by external coils → Stellarators (Wendelstein7-X, Germany)
  – Fully induced by current in plasma → Reversed Field Pinch (RFX, Italy)
  – Applied partially by external coils and partially by the plasma current → Tokamak, currently the most promising configuration for MCF reactor
Stellarator

• Wendelstein 7-X, Greifswald, Germany
  – Largest stellarator built.
  – First hydrogen plasma in Wendelstein 7-X on February 3, 2016.
Reversed Field Pinch

- RFX, Padova, Italy - largest RFP
- MST, Madison, USA
- KTX, Hefei, China – Newest RFP built
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Tokamak

- Bend solenoid to form closed magnetic field lines
- A transformer drives plasma current
  - Heating
  - Help create helical field lines, a stable field configuration
- Vertical field for equilibrium and shaping

Tokamak: abbreviation of Russian words for toroidal magnetic chamber
Largest Tokamaks

• **JET**, UK (European Union)
  – $R/a=2.96m/1.25m$, $B=3.45T$, $I=7$ MA

• **JT-60U**, Japan
  – $R/a=3.45m/1.2m$, $B=4.4T$, $I=5$ MA

• **International Thermonuclear Experimental Reactor (ITER)**
  – >$20b$ project
  – 7 major partners (EU, USA, Russia, China, India, Korea, Japan)
  – Demonstrate self-burning tokamak reactor.
Steady State Tokamak Operation

• Superconducting toroidal coils
• Microwave/neutral beam heating for ignition
• Self-sustained heating by $\alpha$ particles (plus additional heating)
• Tritium breeding
• High boost strap current (plus current drive)
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International Thermonuclear Experimental Reactor (ITER)

• Will be the largest tokamak in the world
• International collaboration with 7 partners
  – China, EU, India, Japan, Korea, Russia, USA
  – Canada is not part of it
• Cadarache, southern France
• Start operation in about 8 years
• Demonstrate net power gain $Q \geq 10$
ITER Project

\[ a = 2.0 \text{ m} \]
\[ R = 6.2 \text{ m} \]
\[ Q = 10 \]

Power:
- 500 MW fusion
- 73 MW heating
Progress
Fast progress vs. Moore’s Law

![Graph showing fusion power plant conditions and central ion temperature comparison with Moore's Law.](image)
Demo - a step after ITER

• Demo will be a real test reactor between ITER and commercial reactors to address many known and unknown issues
  – First wall material
  – Materials for structures and coils that withstand the heat load and neutron bombardment
  – Tritium breeding and handling
  – Central fuelling
  – and more ...
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Plasma Physics Lab (PPL) at the University of Saskatchewan

• Nearly 60 years history of plasma and fusion research
• Operates the STOR-M tokamak, currently the only tokamak device in Canada
• A member of the IAEA Coordinated Research Projects - Research Using Small Tokamaks
History

• Established by Dr. Skarsgard in late 50s
• First Canadian tokamak STOR-1M (early 80s)
• STOR-M (built in 1987, still active)
• Compact torus injector added (90s)
• Plasma processing (90s)
• Plasma focus (2013, just started)
• Both theoretical and experimental work
Professors with PPL

• Plasma Physicists in PPL

M. Bradley (expt.)  A. Hirose (theory, expt.)  A. Smolyakov (Theory)  C. Xiao (expt.)

A new faculty member in Plasma Physics is being recruited
STOR-M Tokamak

Construction started in 1984
Operational since 1987
Still active as the only tokamak in Canada
Compact Torus Injector for Fuelling Studies
STOR-M Research Topics

• Anomalous transport
• Improved confinement
  – By electrode biasing, current pulse, CT injection
• AC operation
• CT injection (fueling)
• Stability studies (by Resonant magnetic perturbation)
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Plan A: Transfer ST-40 from Tokamak Energy, UK to UofS

• a prototype machine with full of new ideas
  – High temperature superconducting coils
  – High magnetic field.
  – First plasma just achieve recently

• Negotiable for transfer to UofS
  – Have started discussions since Aug. 2015.

~$25M capital cost, $2.5M/yr operation
• High toroidal field up to \(3\text{T, LN2}\) cooled copper magnet
• Plasma major radius \(0.4 - 0.6\text{m, } R/a = 1.6 - 1.8\)
• Moderate elongation \(k \sim 2.5\) and triangularity \(d \sim 0.3\), DND
• Plasma current up to 2MA
• Pulse duration 1-10 sec
• 2MW NBI + EBW/ECRH heating; Li conditioning
• Possibility of DT ops
• \textit{m/c plasma formation}
Plan B: STOR-U Tokamak

- Designed at UofS PPL
  - simplified tokamak design: removal of central solenoid and replacement with coaxial helicity injection will be addressed
  - Quasi-steady state operation: AC operation will be considered
  - innovative technology development
- Larger and higher parameters than the previous Canadian TdeV tokamak
  ~$100M to built, $20M/yr operation
STOR-U Tokamak
Conceptual Design

R = 80 cm  \( a = 36 \) cm
Aspect ratio = \( R/a = 2.2 \)
Elongation \( k = 1.6 \sim 1.8 \)
Magnetic field = 1.5 T
Plasma current = 1 MA
3 MW NBI
\( n_e = (1 \sim 5) \times 10^{13} \) cm\(^{-3}\)
\( T_e = 700 \sim 1,700 \) eV
\( T_i = 600 \sim 3,500 \) eV
Discharge 300 ms long
Confinement time = 35\sim 50 \) ms
A potential path for U of S

Research Leadership

2016
CREATE EOI:
Plasma Science for Fusion
Energy, Materials,
Medicine
(U of A, U of S)

2017
Industrial
Research Chair

2019
Network of
Centres of
Excellence

2018
Canada
Excellence
Research Chair

2019
Canada First
Excellence
Research Fund

Infrastructure

Partnerships

general fusion
Summary

• Tokamak is a front-runner among the magnetic fusion configurations
• Significant progresses have been made
• ITER is an important milestone in fusion research
• Fusion is a long-term and strategically important research for energy securities
• UofS can play a major role in Fusion 2030 in Canada
Thank you!
International Thermonuclear Experimental Reactor (ITER)

ITER Parameters

- Plasma Major Radius: 6.2 m
- Plasma Minor Radius: 2.0 m
- Plasma Volume: 840 m³
- Plasma Current: 15.0 MA
- Toroidal Field on Axis: 5.3 T
- Fusion Power: 500 MW
- Burn Flat Top: >400 s
- Power Amplification: >10

Human size
ST-40 budget

• ST-40 construction budget and timeline
  – $25M setup: transport, PS, cooling facility, diagnostics, heating system
  – Timeline: approximately 4 years

• ST-40 annual operating budget $2.5M:
  – Personnel 5 PDF/RA, 5 PhD (RA), 2 Res. Eng. 3, Technologists, Students, supporting staff (Total $1M/yr)
  – Equipment maintenance, consumables, repairs, facility keep-up (Total $1.5M/yr)
When Will We Get a Fusion Reactor?

When? – When we really need it