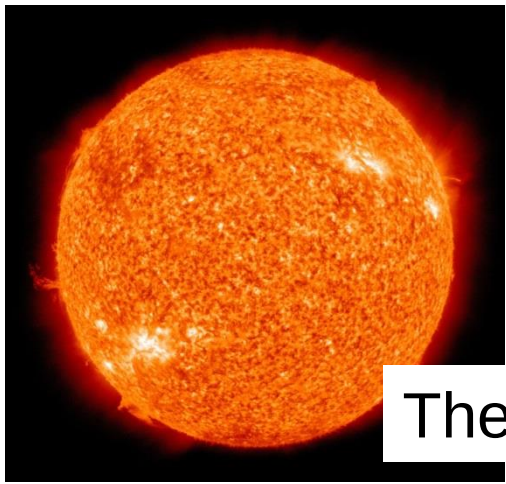
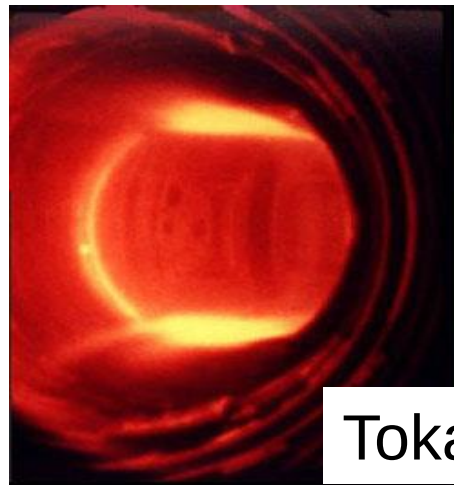




The Sun



Tokamak

Magnetic Confinement Fusion and Tokamaks

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2017 CNS Conference
Niagara Falls, June 4-7, 2017



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)

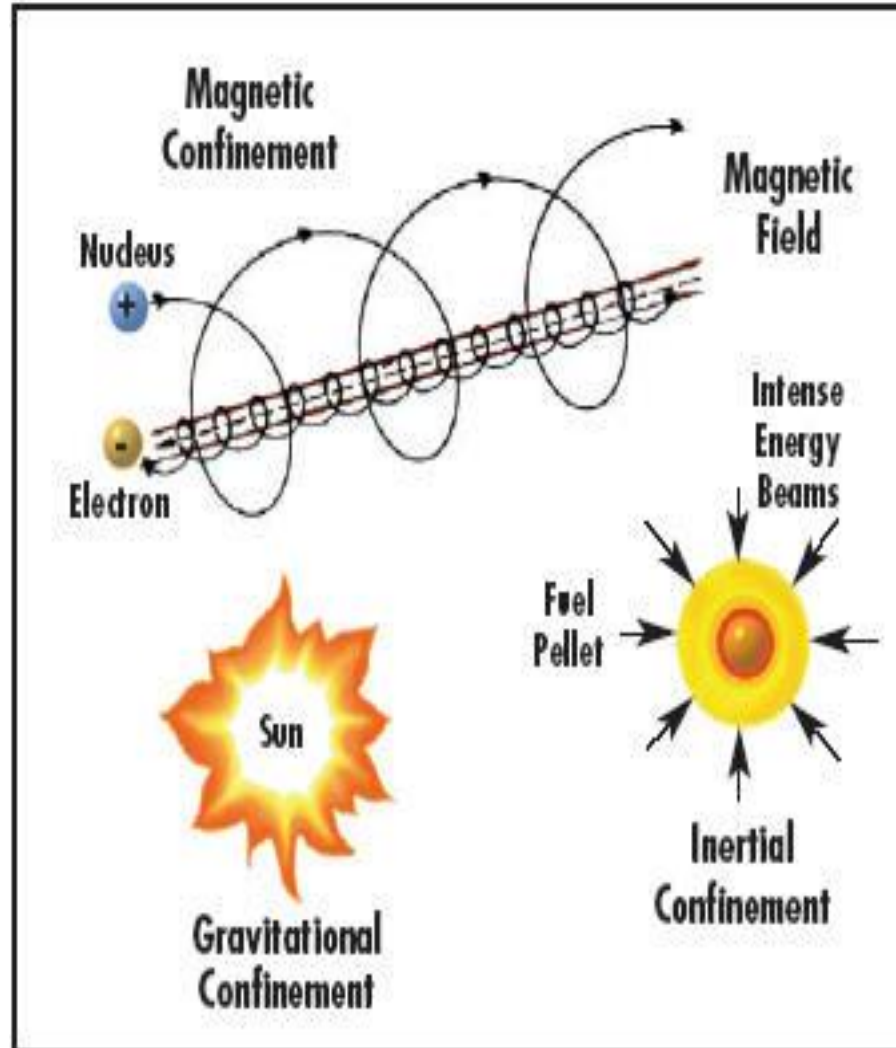
$$Q = \frac{\text{fusion power}}{\text{input power}} \gg 1$$

Types of confinement schemes

Inertial

Magnetic field

Gravitation (sun)

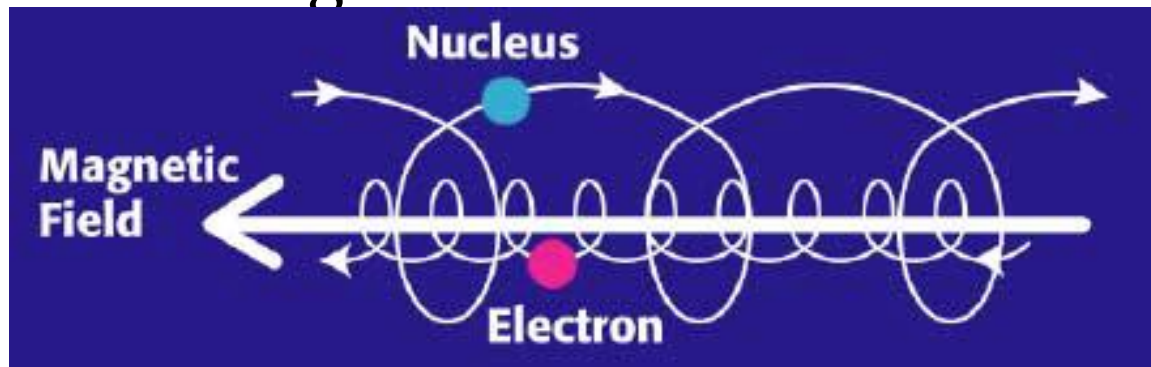


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Magnetic Fusion

- 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)

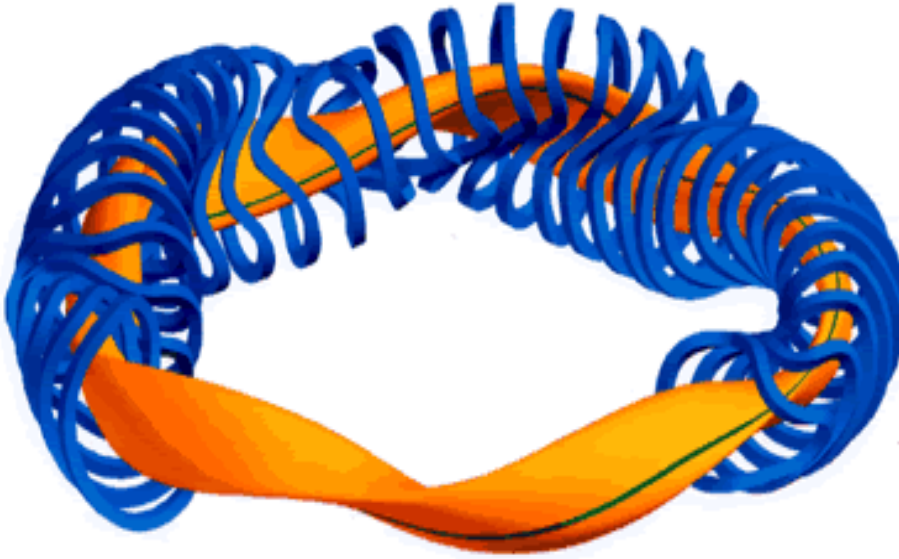


- Closed magnetic field lines are preferred (toroidal devices)

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

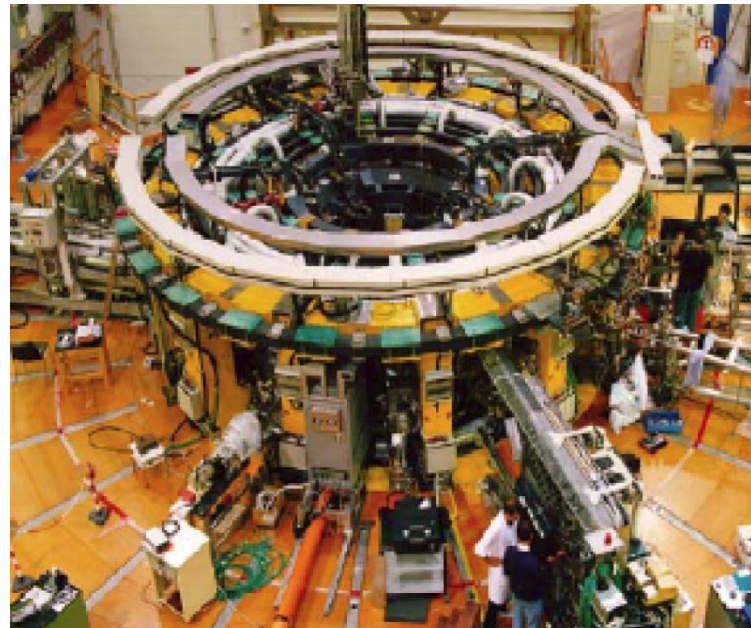
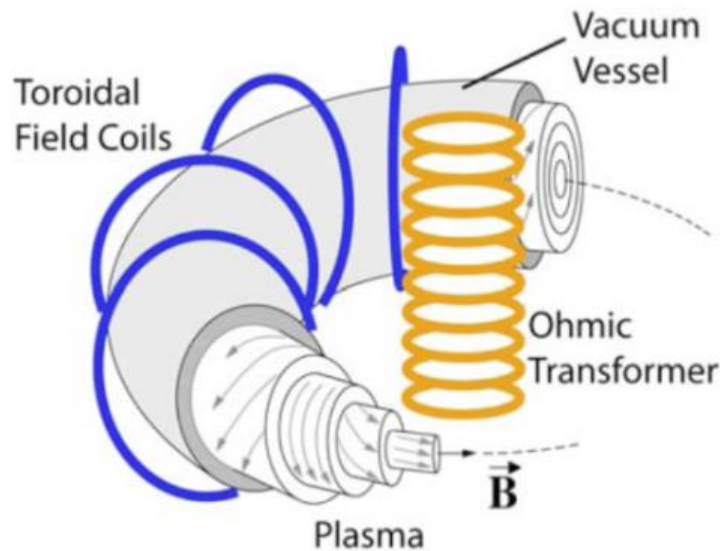
Stellarator



sophisticatedly
shaped
superconducting
coils create the
necessary
magnetic
configurations

- Wendelstein 7-X, Greifswald, Germany
 - Largest stellarator built.
 - First hydrogen plasma in Wendelstein 7-X on February 3, 2016.

Reversed Field Pinch



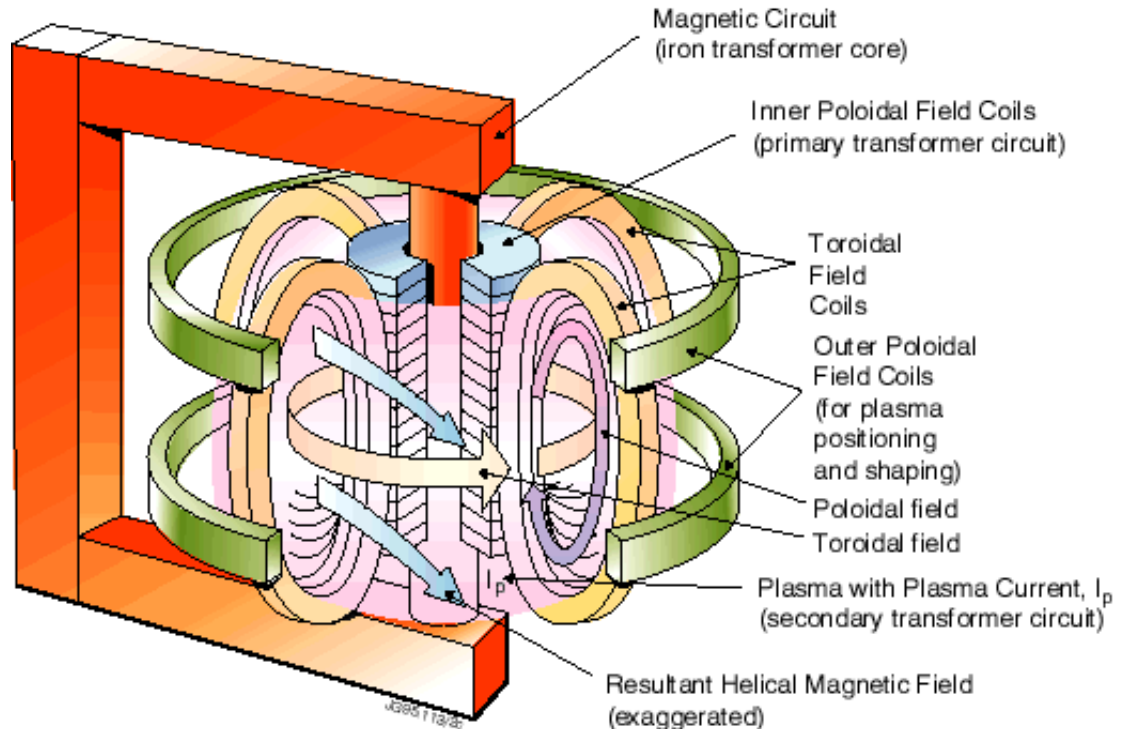
- RFX, Padova, Italy - largest RFP
- MST, Madison, USA
- KTX, Hefei, China – Newest RFP built

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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)
 - $R/a=2.96\text{m}/1.25\text{m}$, $B=3.45\text{T}$, $I=7\text{ MA}$
- JT-60U, Japan
 - $R/a=3.45\text{m}/1.2\text{m}$, $B=4.4\text{T}$, $I=5\text{ MA}$
- 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 α particles (plus additional heating)
- Tritium breeding
- High bootstrap 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

$a = 2.0 \text{ m}$

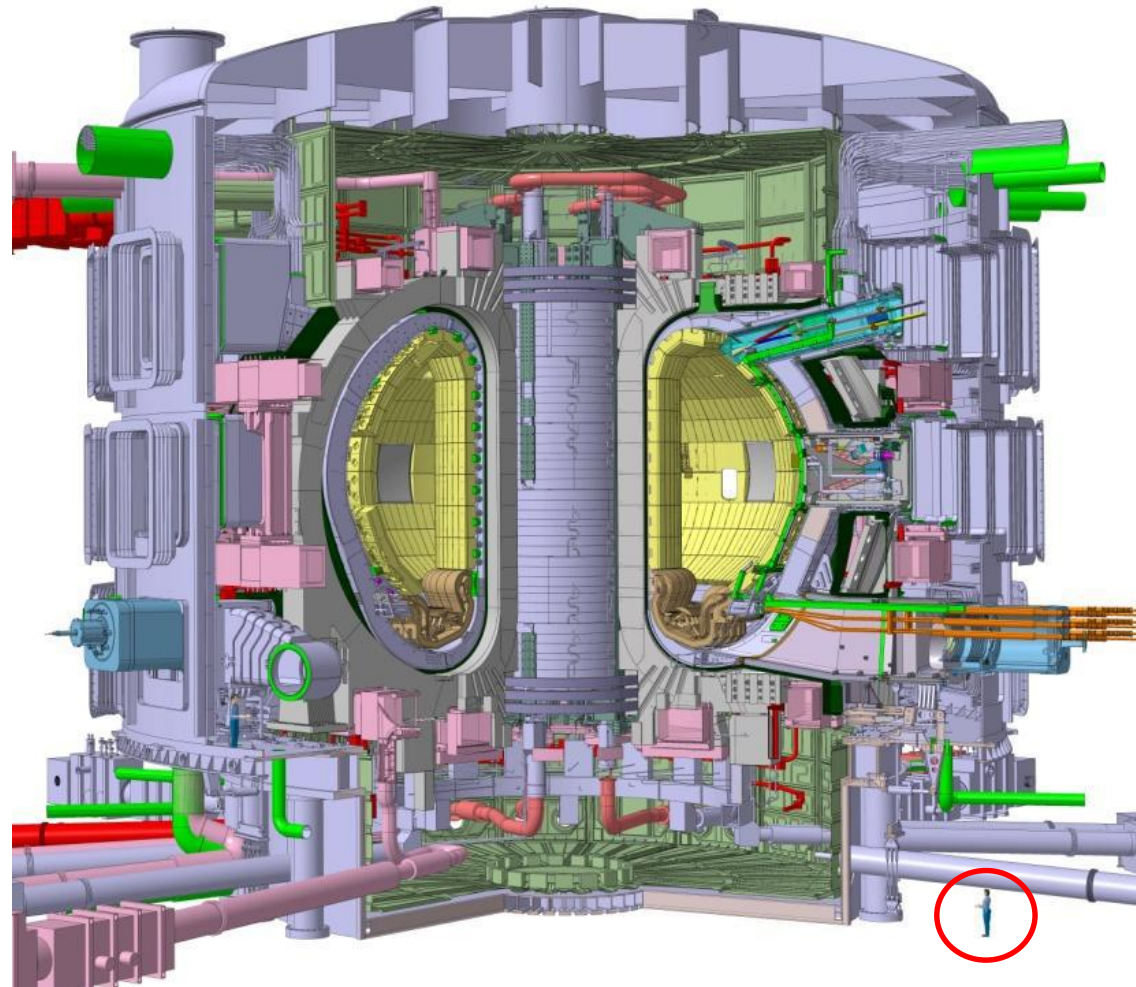
$R = 6.2 \text{ m}$

$Q = 10$

Power:

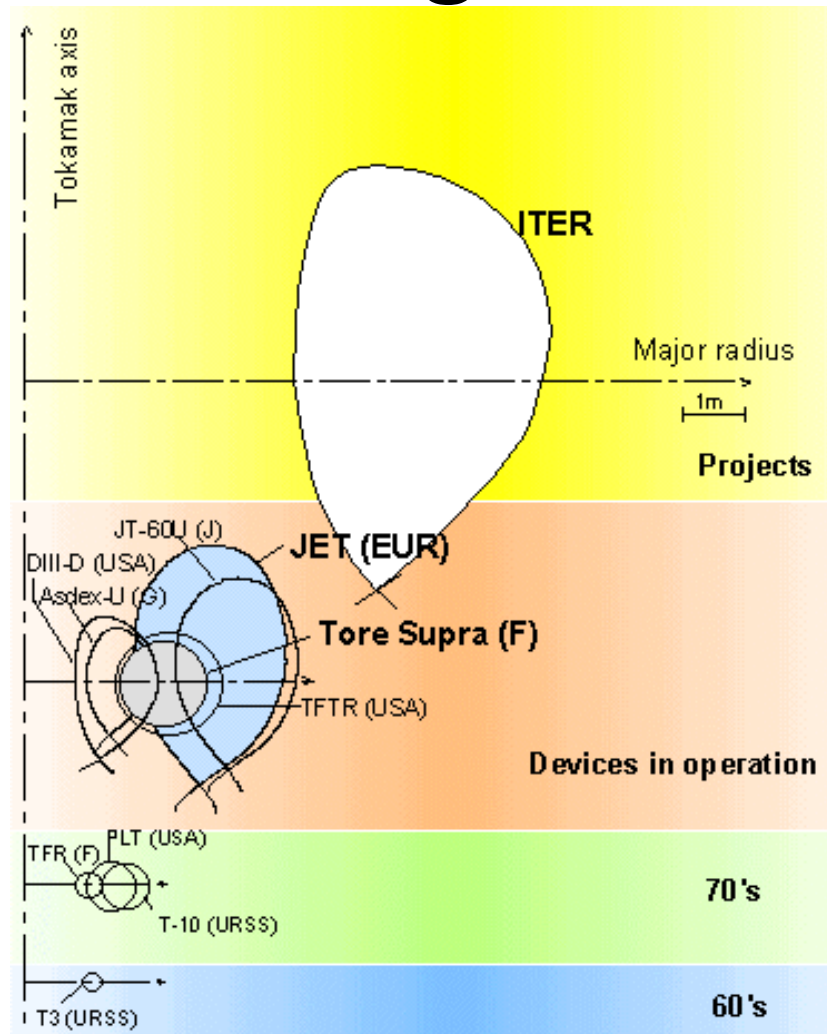
500 MW fusion

73 MW heating

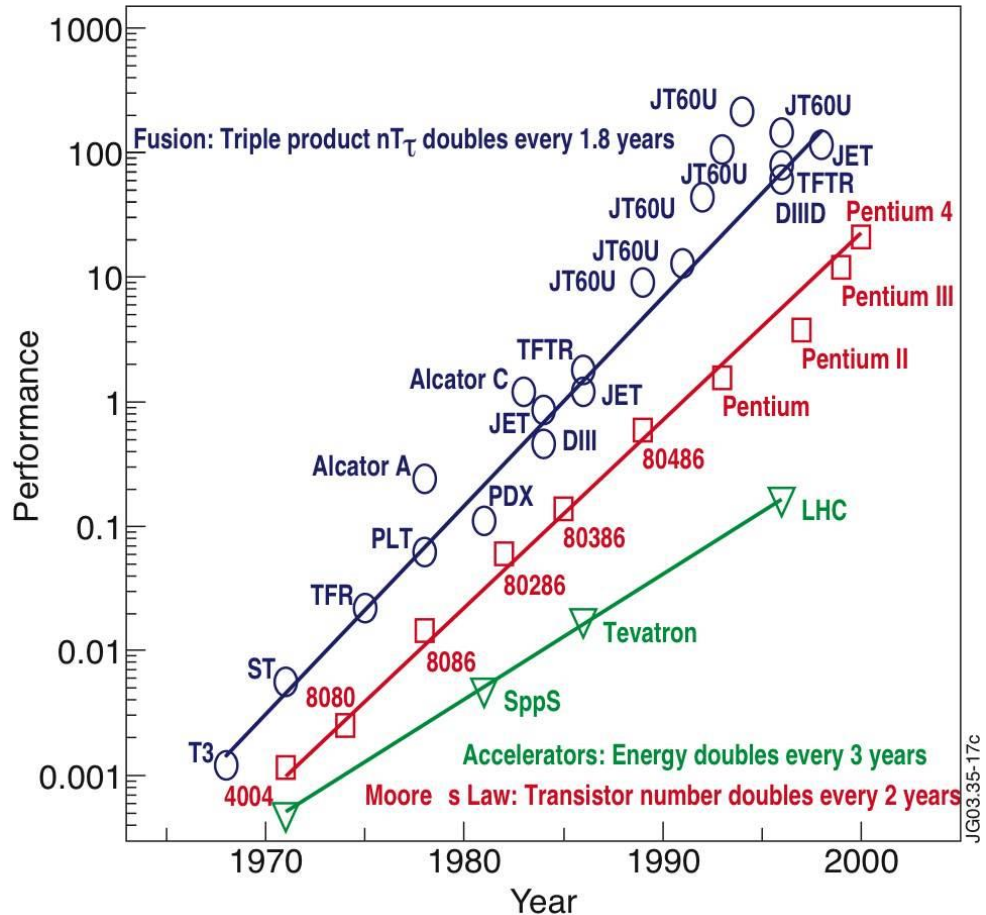
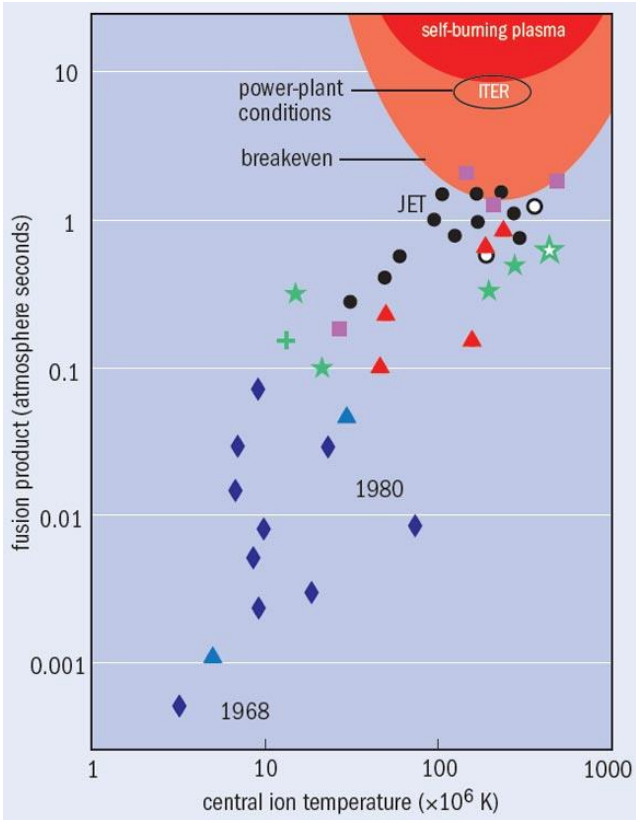


Human size

Progress



Fast progress vs. Moore's Law



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



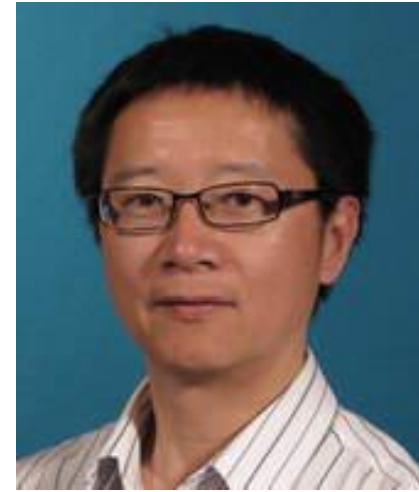
M. Bradley
(expt.)



A. Hirose
(theory, expt.)



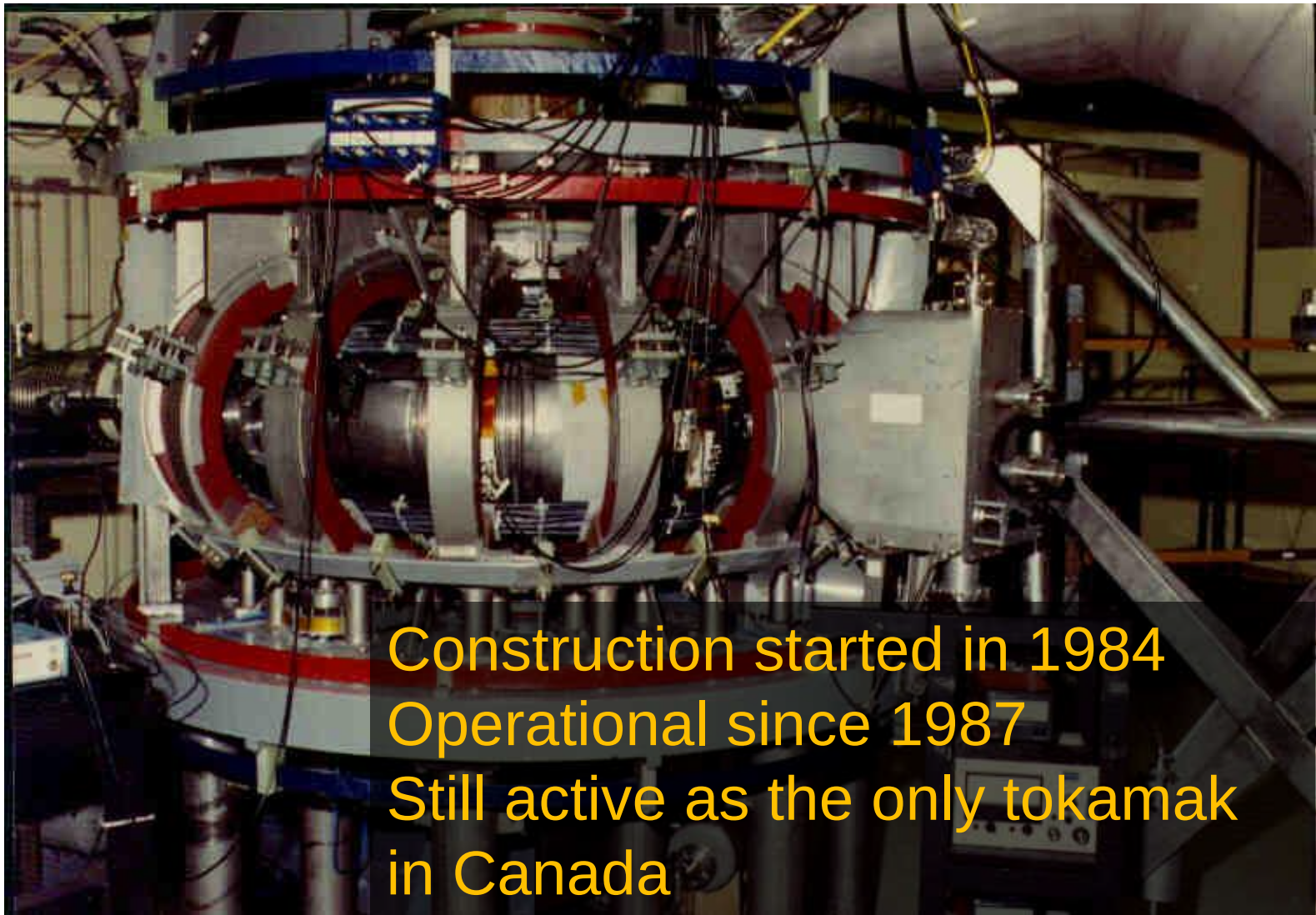
A. Smolyakov
(Theory)



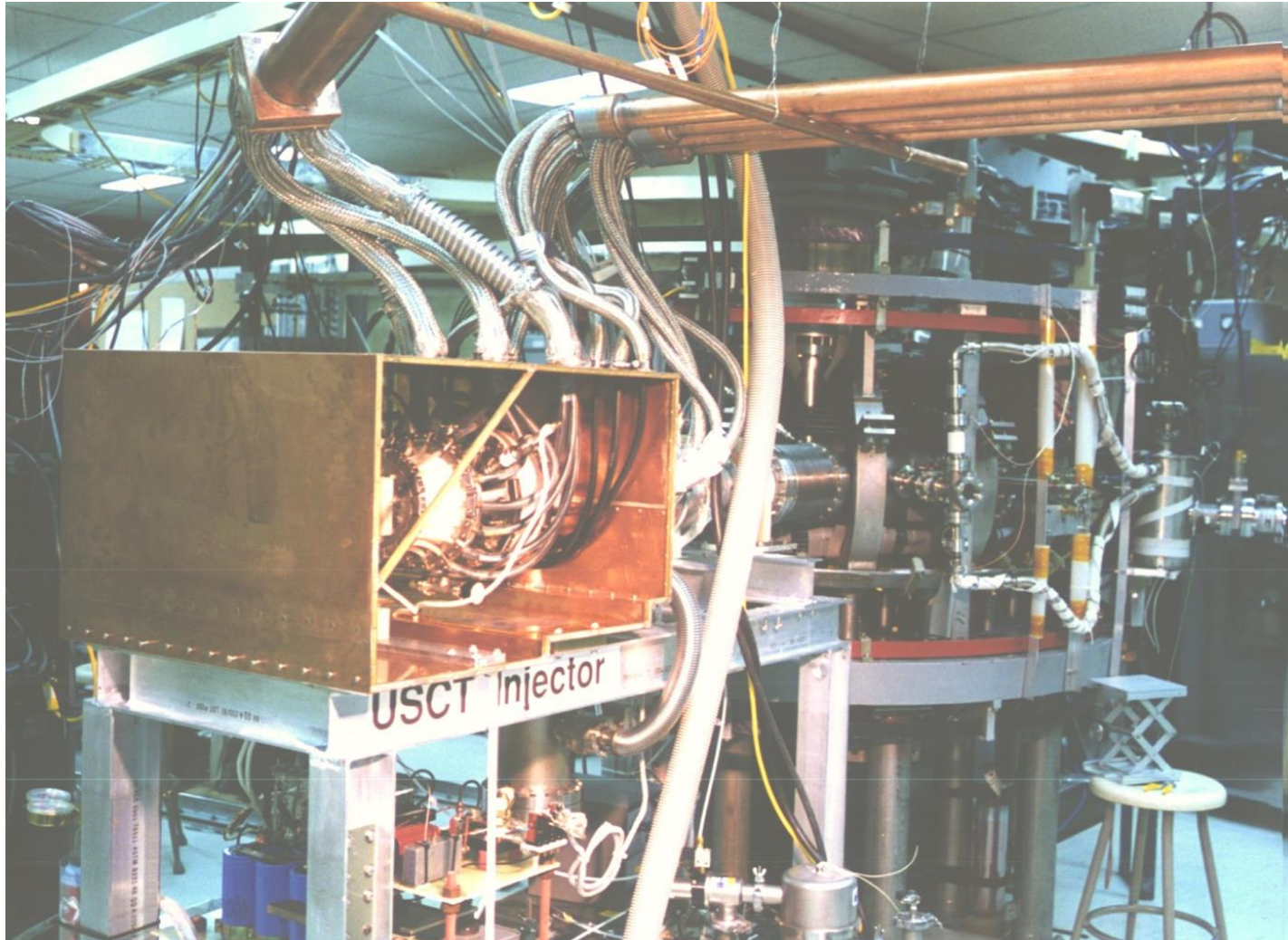
C. Xiao
(expt.)

A new faculty member in Plasma Physics
is being recruited

STOR-M Tokamak



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

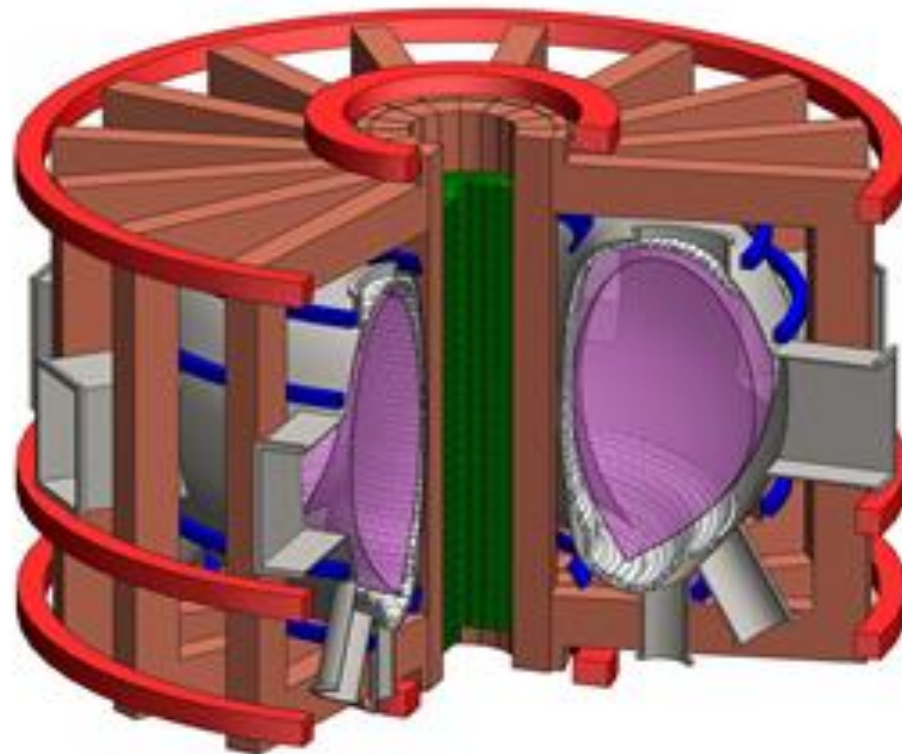


- **High toroidal field** up to **3T**, **LN2** cooled copper magnet
- Plasma major radius 0.4 - **0.6m**, $R/a = 1.6 - 1.8$
- Moderate elongation ($k \sim 2.5$) and triangularity ($d \sim 0.3$), DND
- Plasma current up to 2MA
- Pulse duration 1-10 sec
- **2MW NBI** + EBW/ECRH **heating**; Li conditioning
- **Possibility of DT ops**
- ***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



Scale

1m

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

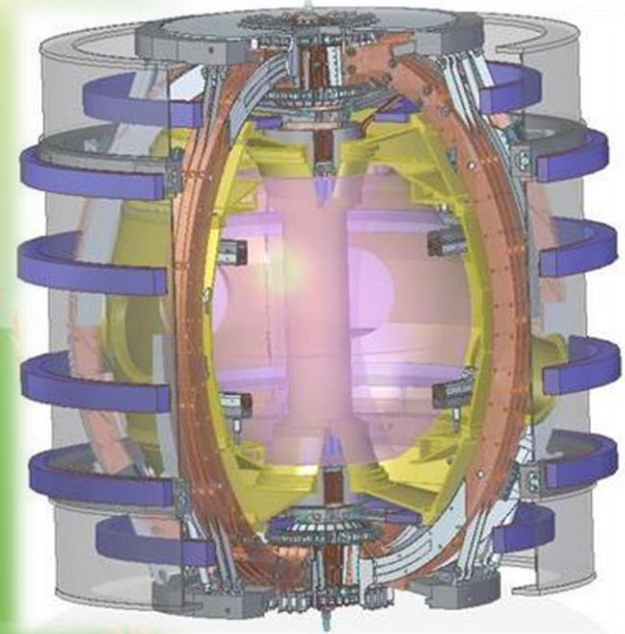
2017
Industrial
Research
Chair

2019
Network of
Centres of
Excellence

2018
Canada
Excellence
Research
Chair

2019
Canada First
Excellence
Research
Fund

Infrastructure



Partnerships

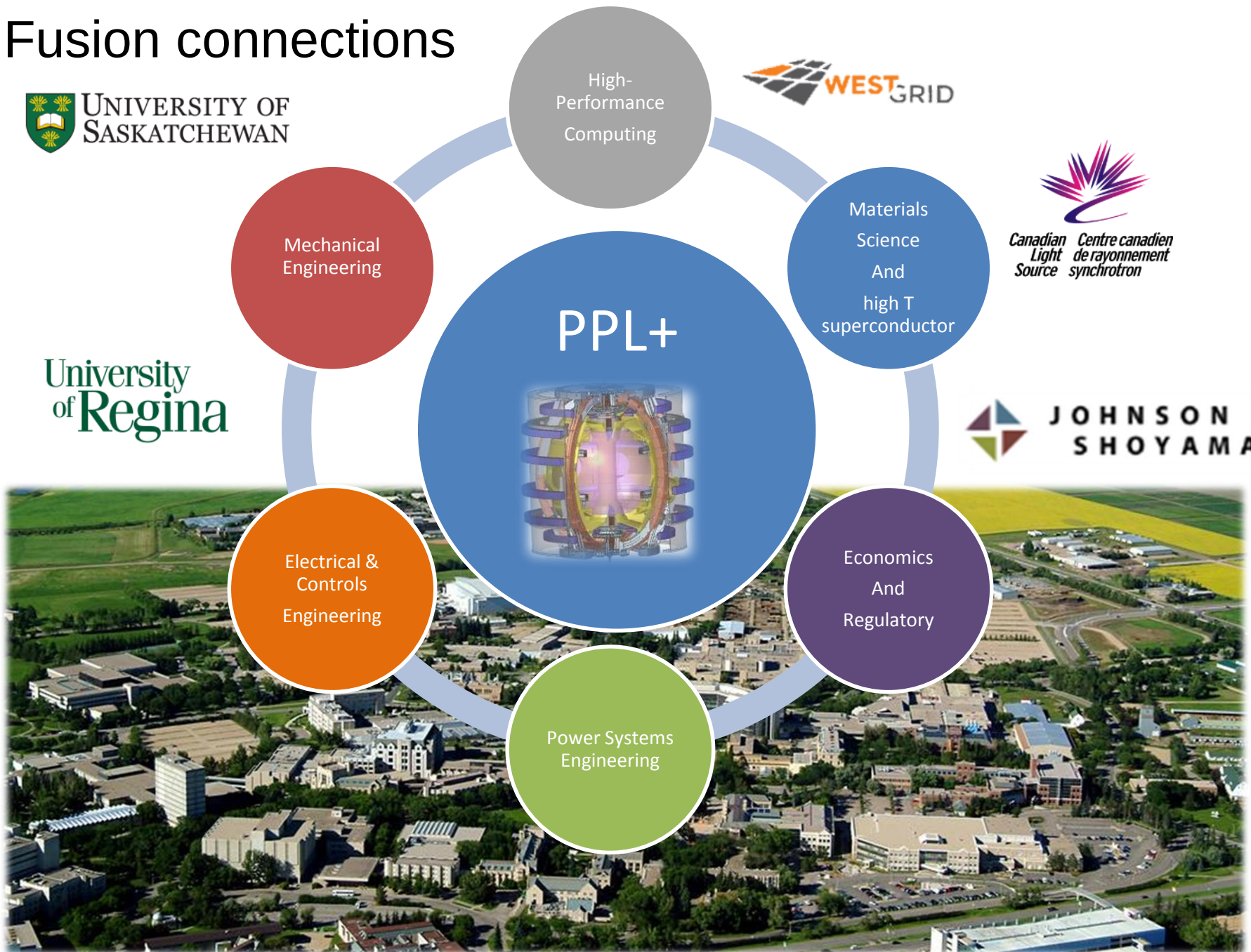
generalfusion



Fusion connections



University
of Regina

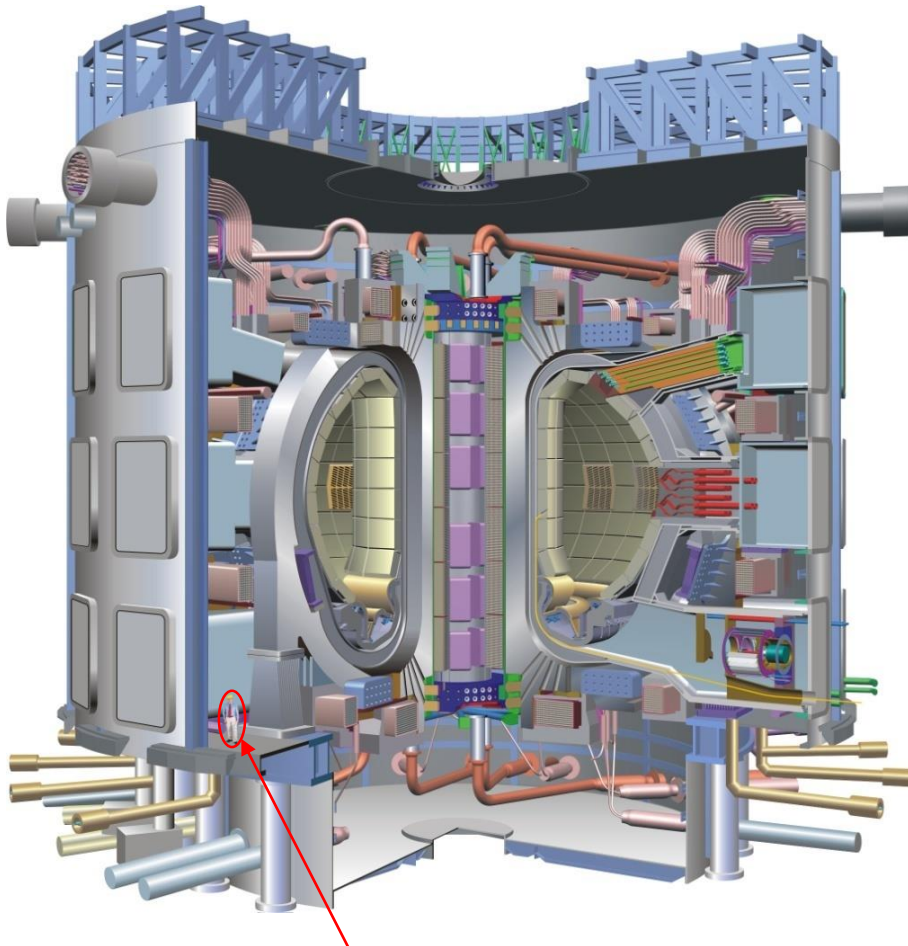


Summary

- 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)



Human size

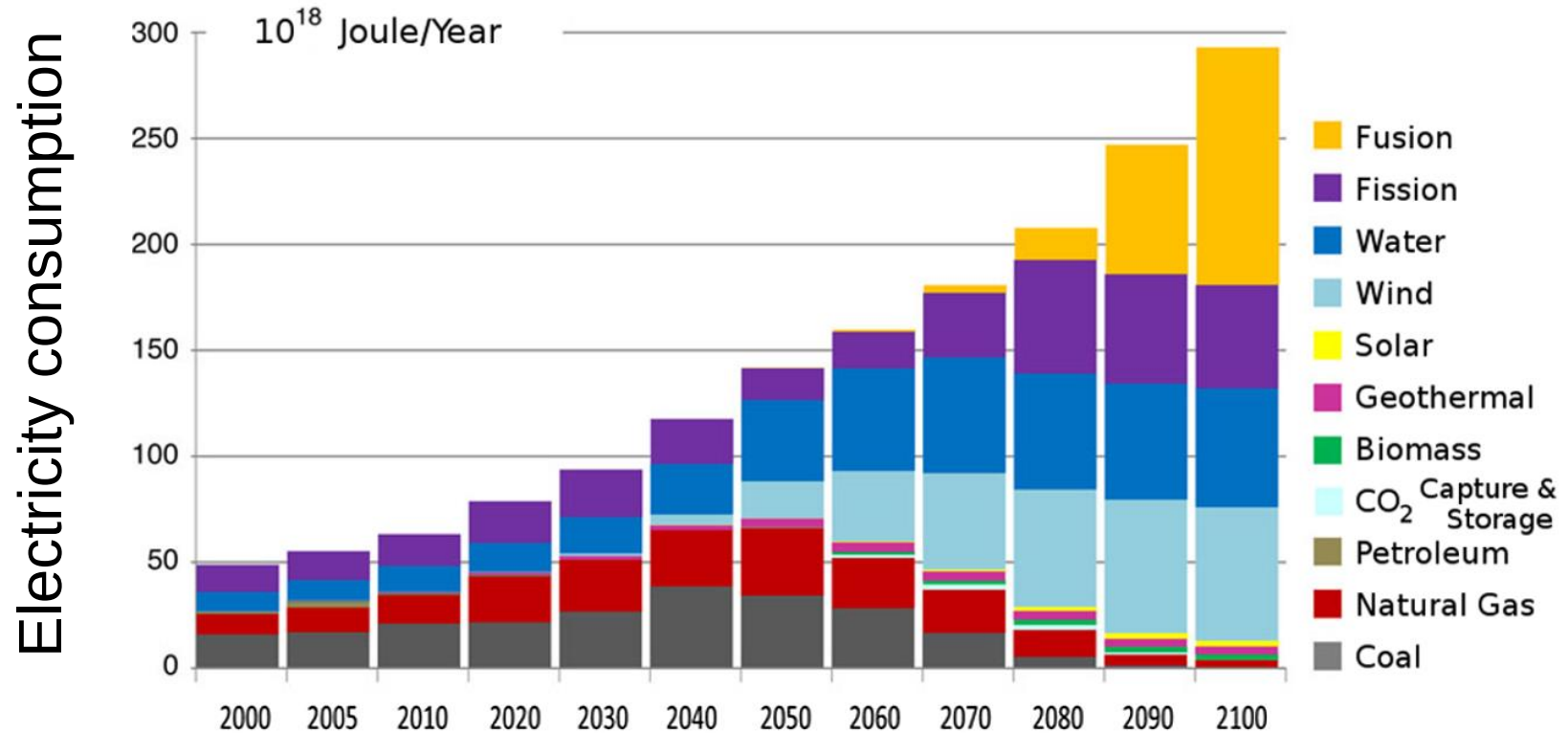
ITER Parameters

Plasma Major Radius	6.2	m
Plasma Minor Radius	2.0	m
Plasma Volume	840	m ³
Plasma Current	15.0	MA
Toroidal Field on Axis	5.3	T
Fusion Power	500	MW
Burn Flat Top	>400	s
Power Amplification	>10	

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