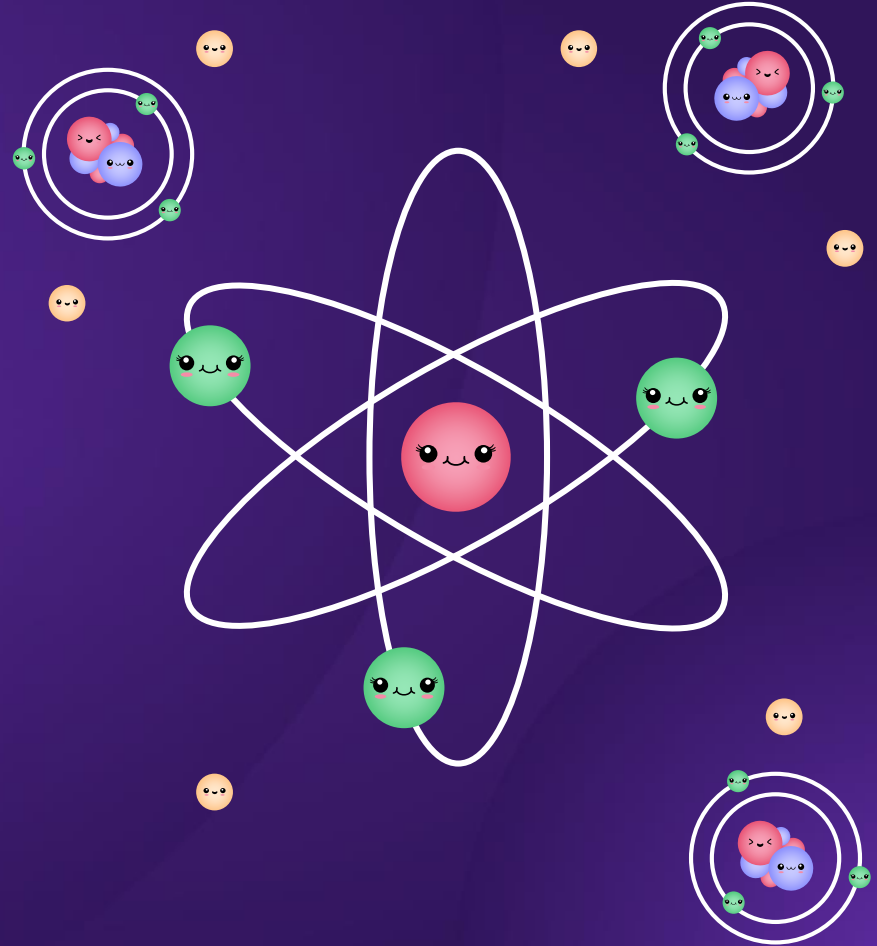
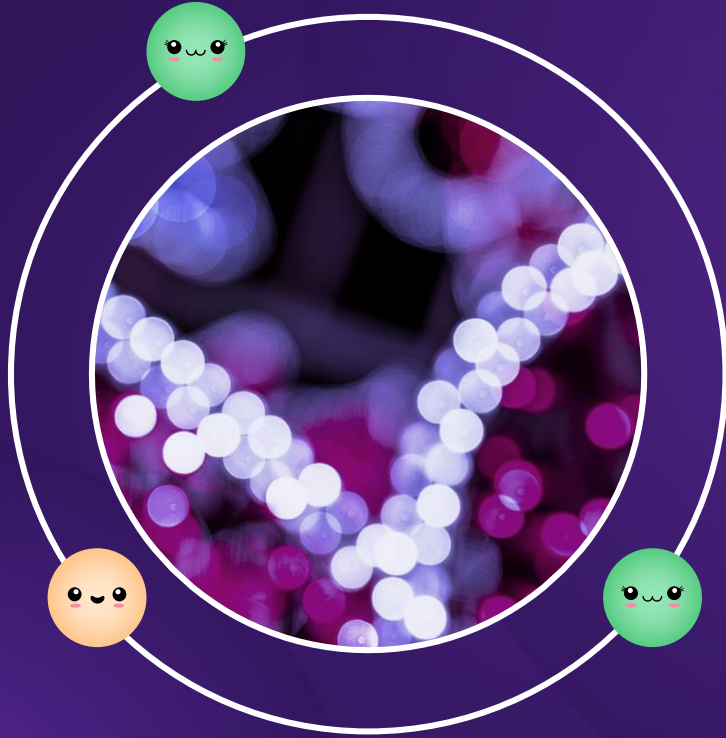


Fusion

Chow Ka Chun
Cheng Wai Yuen

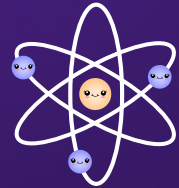




Introduction of Fusion

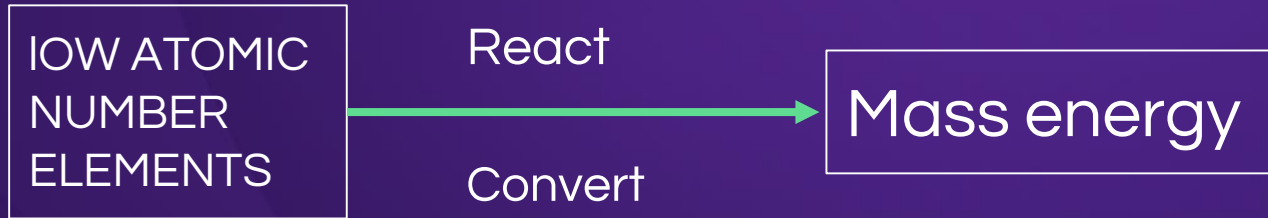
1.1 Basics of Fusion

1.2 Feasibility of Fusion

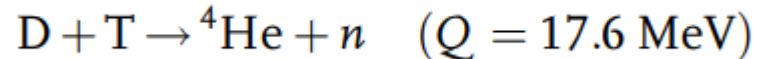


1.1 Basics of Fusion

- An inexhaustible source of energy for the future
- Mechanism: Under proper conditions,

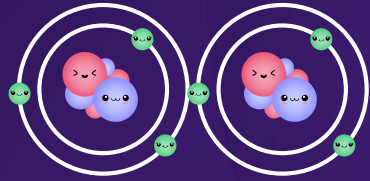


- E.g.



1.1 Basics of Fusion

- Prerequisite:



1

> Repulsive Coulomb force

2

Short-range attractive
nuclear force →

High
temperature

The fusion reaction rate per unit volume can be written

$$R(\text{fusions}/\text{m}^3) = n_1 n_2 \langle \sigma v \rangle_{12}$$

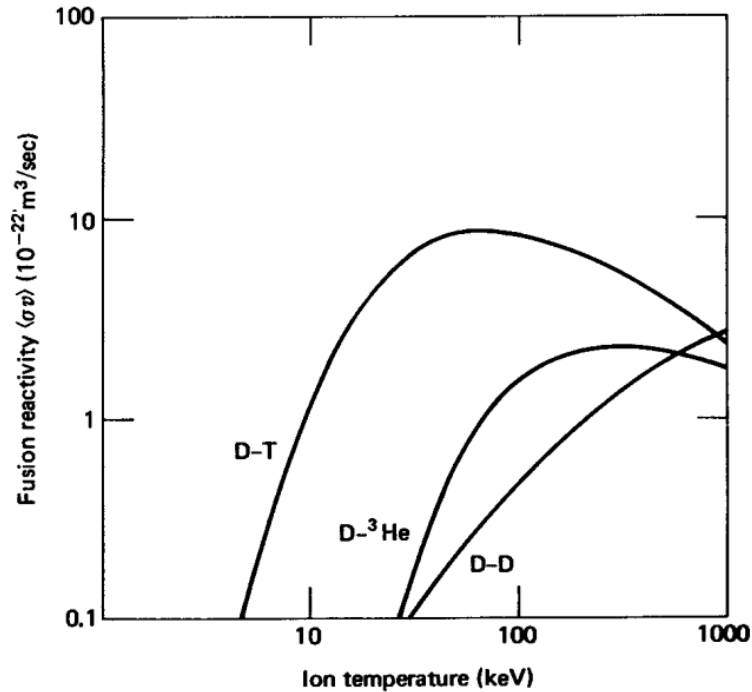


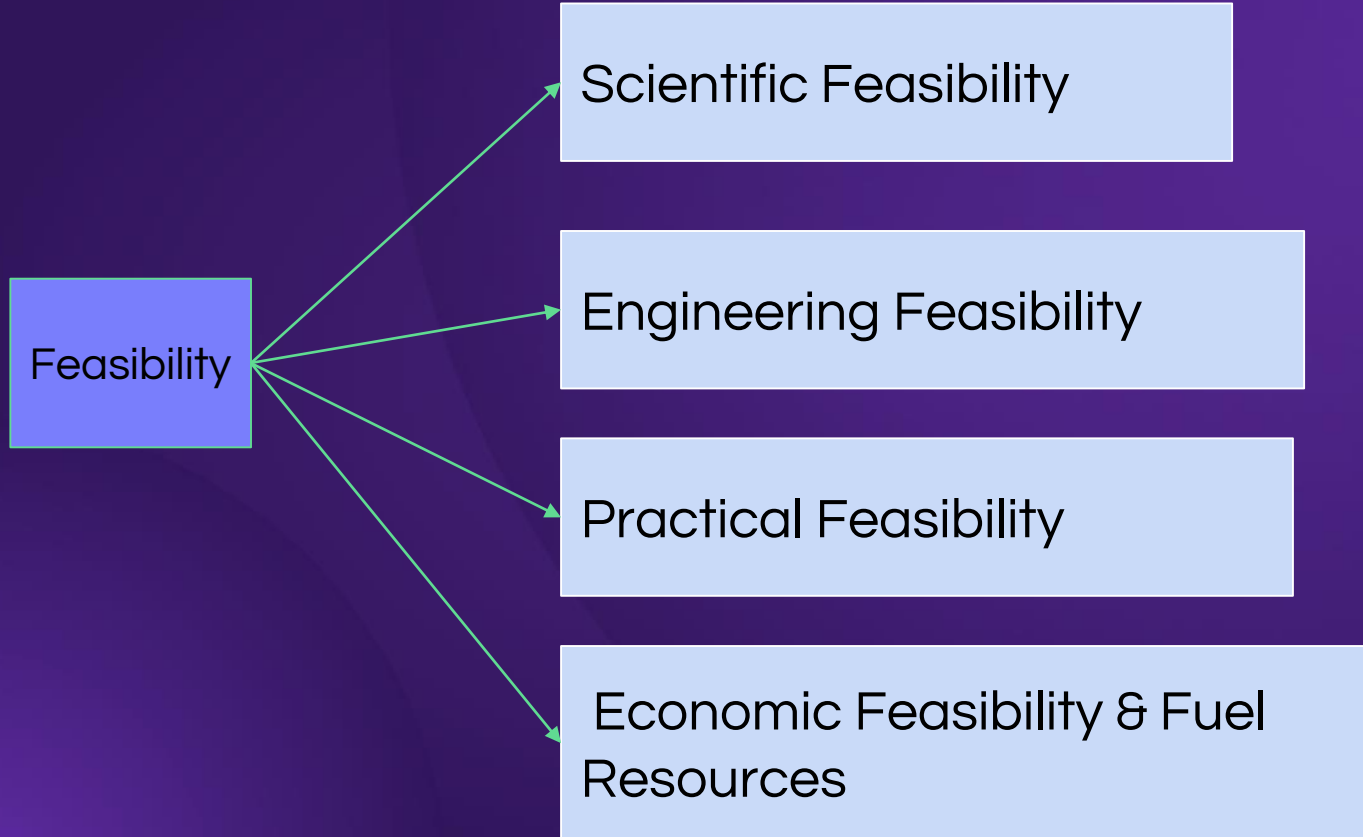
Figure 1.1 Fusion reactivity.

- D-T fusion reactivity is much greater than other fusion reactants



necessary conditions is the principal goal

1.2 Feasibility of Fusion



1.2 Scientific Feasibility

- $\therefore$ thermonuclear temperatures $\rightarrow$ sufficient positive energy

$$Q_p = \frac{\text{fusion power}}{\text{external heating power}}$$

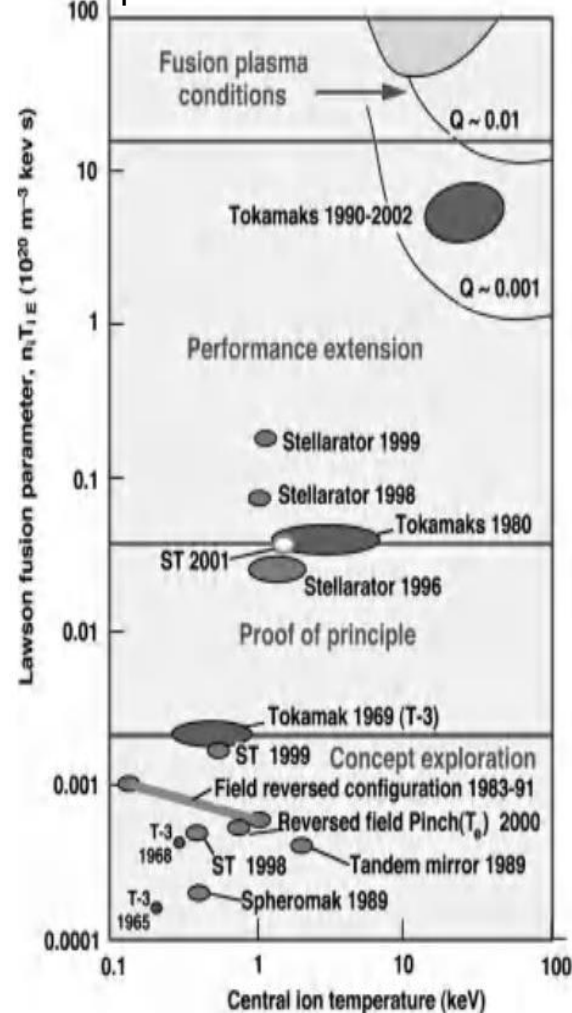
- Using plasma power amplification factor as the measurement
 $\rightarrow Q_p > 1 = \text{breakeven}$
 $\rightarrow Q_p = \infty: \text{ignition}$
- $\therefore$ practical definition = Q_p large enough (probably > 10) that net electrical power can be economically produced

The plasma power balance can be written as

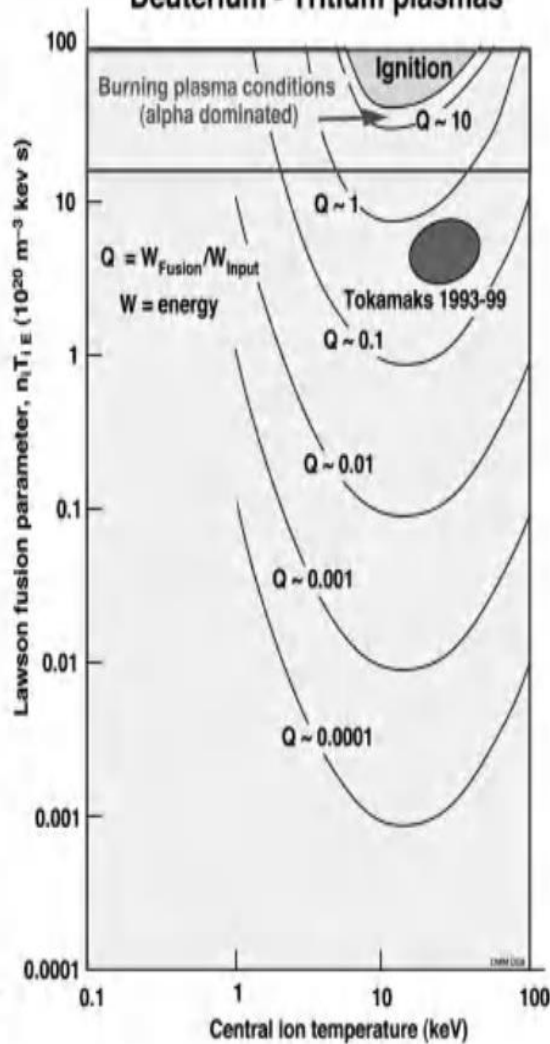
$$\text{fusion heating} + \text{external heating} \geq \text{radiation loss} + \text{transport loss}$$
$$\frac{1}{4} n^2 \langle \sigma v \rangle_{fus} U_\alpha \left(1 + \frac{5}{Q_p} \right) \geq f_z n^2 L_z + \frac{3nT}{\tau_E}$$

Deuterium plasmas

$$nTtE = ptE$$



Deuterium - Tritium plasmas



- The triple product $nTtE = ptE$
High plasma pressure & long plasma energy confinement time $\rightarrow$ power balance at high Q_p (all required achieving)

- Magnitude of the confining magnetic field pressure MHD

$$\beta \equiv \frac{\text{plasma pressure}}{\text{magnetic pressure}} = \frac{nkT}{B^2/2\mu_0}$$

Achieving plasma pressure

Sufficiently large values of β
(practical scientific feasibility)

1.2 Engineering Feasibility

Required technologies

```
graph LR; A[Required technologies] --> B[Plasma support technologies (heat & confine the plasma)]; A --> C[Nuclear technologies (power reactor)];
```

Plasma support technologies (heat & confine the plasma)

- Systems included: vacuum, magnet, plasma heating, fueling etc
- Survive in the high particle & heat fluxes
→ITER & future fusion reactors
- R&D programme to carry out ITER

Nuclear technologies (power reactor)

- To breed tritium required for D-T plasma operation
- Heat removal & power conversion

1.2 Practical Feasibility

- Sustainable modes of operation is the key
→E.g. For continuous/ quasi-continuous operation

Preferable

Short-pulse operation with long down-times between pulses

Compared to

- Non-inductive current-drive techniques
→conventional tokamak confinement concept (plused)
- Stellarator

Practical
feasibility
issue
exists

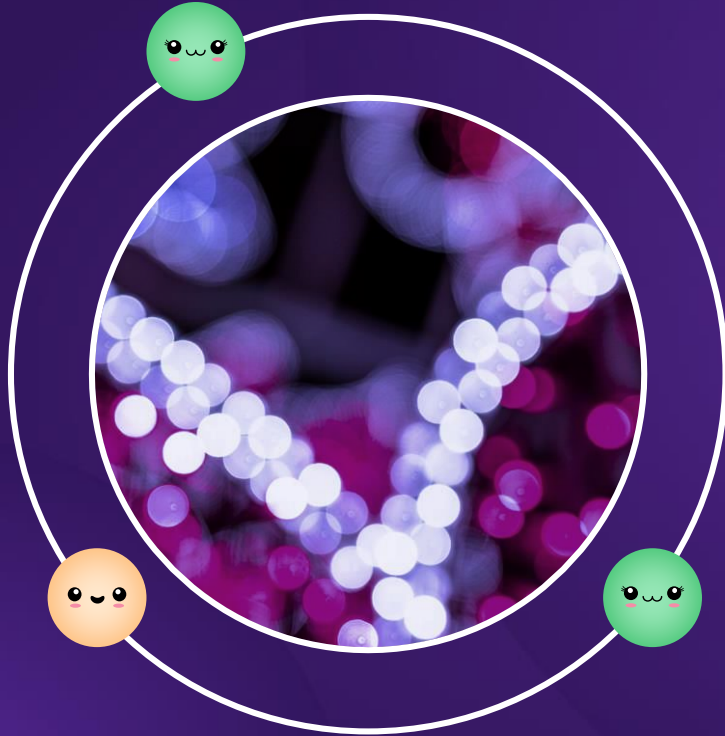
1.2 Economic Feasibility & Fuel Resources

Today's situation

- Cost estimate of fusion electricity is expensive
→neglected: cost of preventing carbon emission, energy potential of uranium
- Mainly Fossil fuels

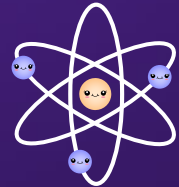
For future consideration

- World's estimated electricity usage in 2050 → fossil fuels gone
- Lithium (fusion) would last more than 6000 years



Confinement Concepts

- 2.1 Magnetic Confinement
- 2.2 Tokamaks
- 2.3 Stellarator
- 2.4 Spherical Torus
- 2.5 Reversed-Field Pinch



2.1 Magnetic Confinement

Closed Toroidal Confinement Systems

- Within a **confinement chamber** by the proper choice of position and currents in a set of **magnetic coils**
- Poloidal field produces by a toroidal current flowing in the **plasma** or by **external coils**

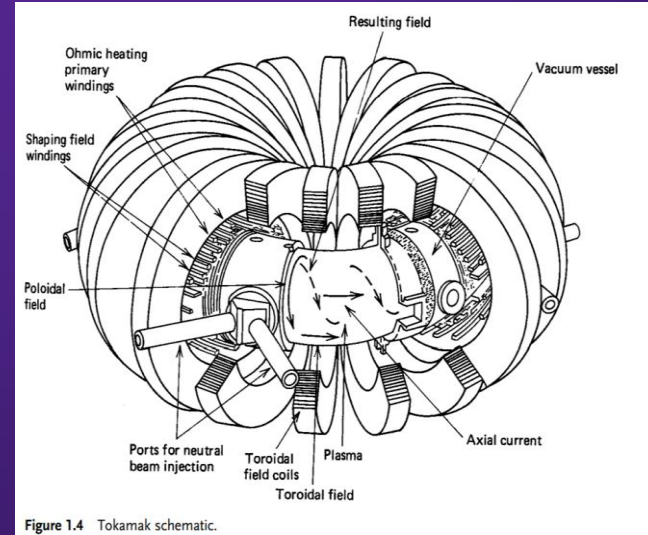
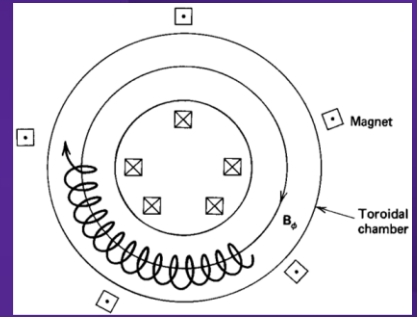


Figure 1.4 Tokamak schematic.

Open Toroidal Confinement Systems

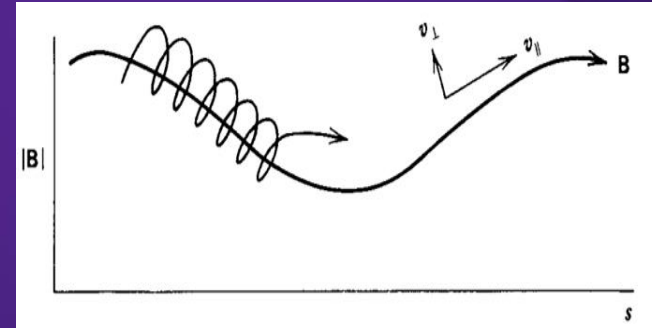
Magnetic
Confinement

2.1 Magnetic Confinement

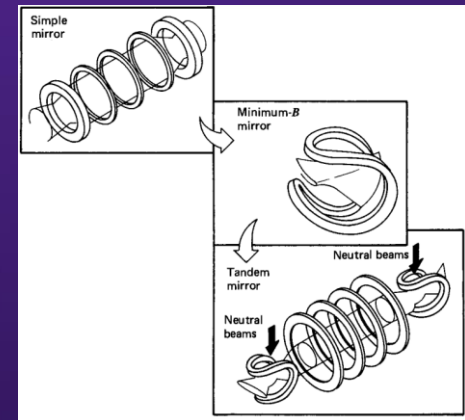
Magnetic Confinement

Open Toroidal Confinement Systems

- ✓ confine a plasma within a fixed confinement chamber, by trapping the charged particles in a magnetic well
- When particles $>$ values of $\mu \rightarrow$ RHS vanishes $\rightarrow$ reflects & travels back along the field line $\rightarrow \uparrow$ magnetic field strength $\rightarrow >$ RHS vanishes again (**simple mirror**)



Closed Toroidal Confinement Systems



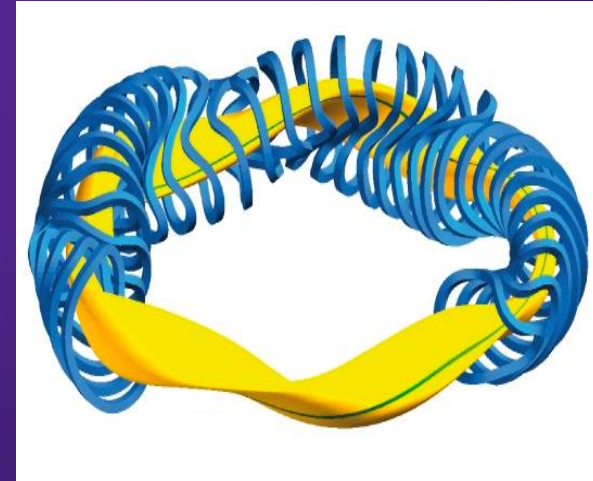
2.2 Tokamaks

- closed toroidal confinement concepts
- The toroidal field can be represented as

$$B_{\phi}(r, \theta) = \frac{B_{\phi}^0}{(1 + r/R_0)\cos \theta} \equiv \frac{B_{\phi}^0}{1 + \varepsilon \cos \theta}$$

2.3 Stellarator

- toroidal confinement devices
- pairs of helical conductors
- net toroidal field nulled (require toroidal field coils)
- potential advantages
 - 1. no inherent limitation to the length of operation
 - 2. Disruptive termination of the discharge



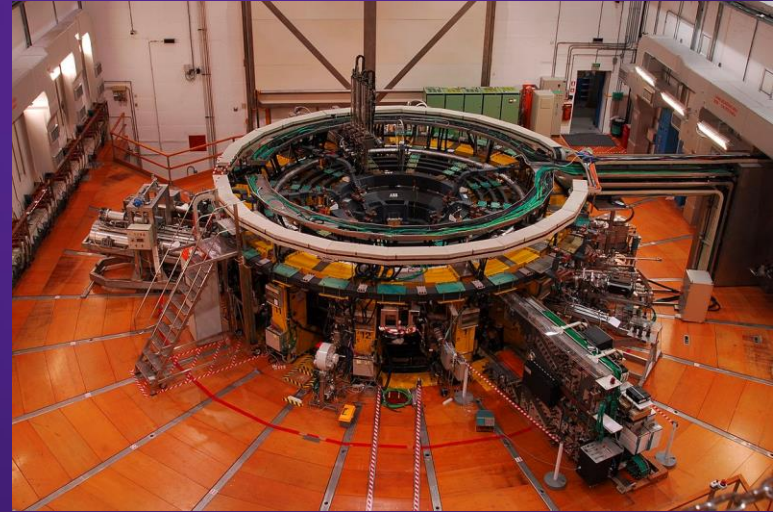
2.4 Spherical Torus

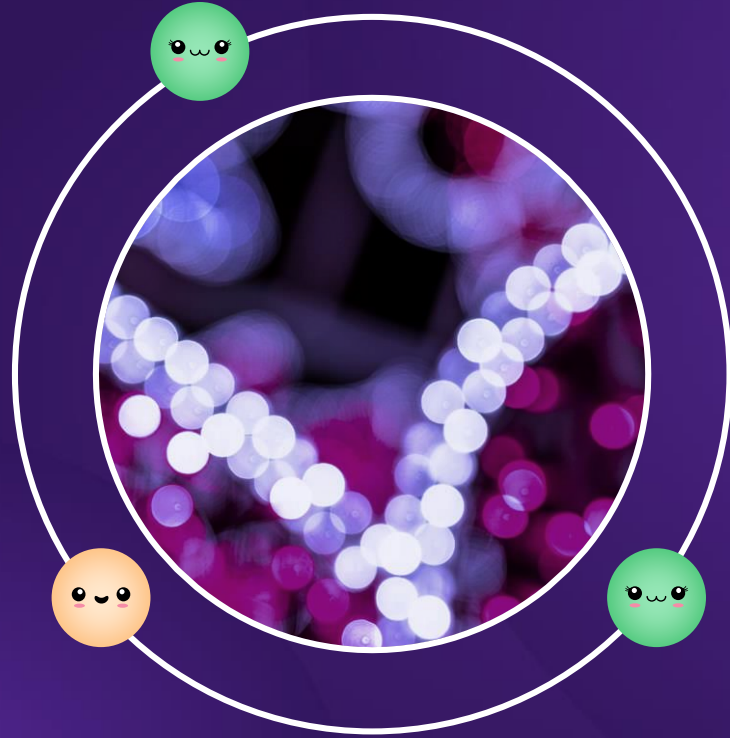
- minimum size central region tokamak
- lower magnetic field strength to confined plasma pressure



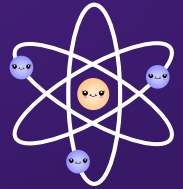
2.5 Reversed-Field Pinch

- toroidal field produced by external coils
- direction of the toroidal field is reverse
- ohmic heating may be possible





Fusion Reactors



3 Fusion Reactors (Future application)

1. Plasma physics and fusion technology limits
2. Physical characteristics of future fusion reactors and neutron sources
3. Discussion on the considerations of tokamak

3 Plasma Physics & Engineering Constraints

- Confinement

$$\tau_E = H_H \tau_E^{IPB98(\gamma,2)} \quad \tau_E^{IPB98(\gamma,2)} = 0.0562 I^{0.93} B^{0.15} P^{-0.69} \bar{n}_{e20}^{0.41} \times M^{0.19} R^{1.97} A^{-0.58} \kappa^{0.78},$$

→magnetic field and plasma size → threshold power

- Density Limit

→require achieving high particle density →high power density

$$\bar{n}_{e20} \leq \frac{I_p(MA)}{\pi a^2}$$

→constraint:

→plasma current

→plasma size

→fusion power

3 Plasma Physics & Engineering Constraints

- Kink Stability Limit

→related to the requirement of where δ is the plasma triangularity

→limitation on the allowable combination of B, I, R and a

$$q_{95} = \frac{5a^2 B}{RI} \left(\frac{1 + \kappa^2(1 + 2\delta^2 - 1.2\delta^3)}{2} \right) \frac{\left(1.17 - \frac{0.65}{A} \right)}{\left(1 - \frac{1}{A^2} \right)^2} \geq 3.$$

3 Plasma Facing Component Heat Fluxes

- Fatigue Limit

- subjected to cyclic loading → fail after a mean number of cycles
- NS(e) which depends on the material & cyclic strain (e)

$$q''_{fat} = \frac{2\kappa(1-\nu)}{f_{pfc}\alpha} \frac{\epsilon_{\max}(N_D)}{t_c} - \frac{1}{2} q''' t_c$$

- Heat Flux Limit

- limit on three maximum allowable heat fluxes $q''_{\max} = \max\{q''_{th}, q''_T, q''_{fat}\}$
- high power density tokamaks may be thwarted by heat flux

limits

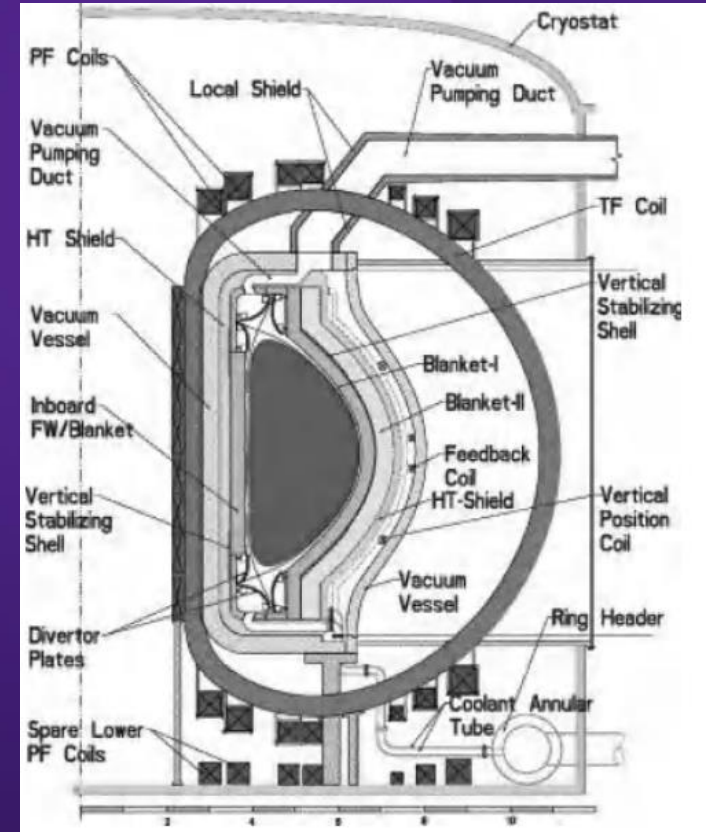
3 Future Tokamak Reactors

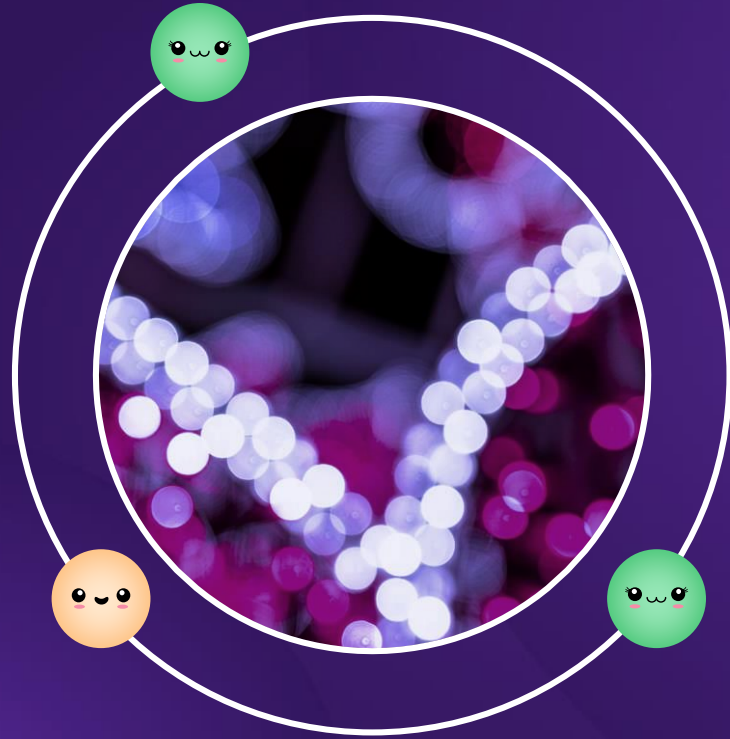
- ARIES-I
→designed on relatively modest extension of ITER database
- High Field ARIES-I
→Improvements with extended the toroidal field strength at the coil from 16 to 19T
- Reverse Shear
→take advantage of anticipated physics avances → operation at higher β_N with improved plasma confinement

	First stability		Reverse-shear	
	ARIES-I	High-field: ARIES-I	ARIES-RS	ARIES-AT
Major radius (m)	8.0	6.75	5.5	5.2
Plasma aspect ratio	4.5	4.5	4.0	4.0
Plasma elongation, κ	1.8	1.8	1.9	2.1
β (%) (β_n)	2 (2.9)	2 (3.0)	5 (4.8)	9.2 (5.4)
Peak field at the coil (T)	16	19	16	11.5
On-axis field (T)	9.0	11	8	5.8
Neutron wail load (MW/m ²)	1.5	2.5	4	3.3
ITER89-P multiplier	1.7	1.9	2.3	2.0
Plasma current (MA)	12.6	10	11.3	13
Bootstrap current fraction	0.57	0.57	0.88	0.91
Current-driver power (MW)	237	202	80	35
Recirculating power fraction	0.29	0.28	0.17	0.14
Thermal efficiency	0.46	0.49	0.46	0.59
Cost of electricity (¢/kWh)	10	8.2	7.5	5

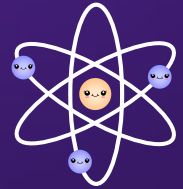
3 Future Tokamak Reactors

- ARIES-AT
→ design for an advance tokamak power reactor
- The volume inside of the fusion reactor pressure vessel
 1. considerably larger than Pressurized water Reactor (PWR)
 2. Comparable to the volume within the pressure vessel enclosing the reactor system for the gas-cooled 'next generation nuclear plant' (NGNP)





Inertial confinement fusion



Introduction

1. Make use of laser to heat up and compress the source

Introduction

High enough to fulfil Lawson criterion

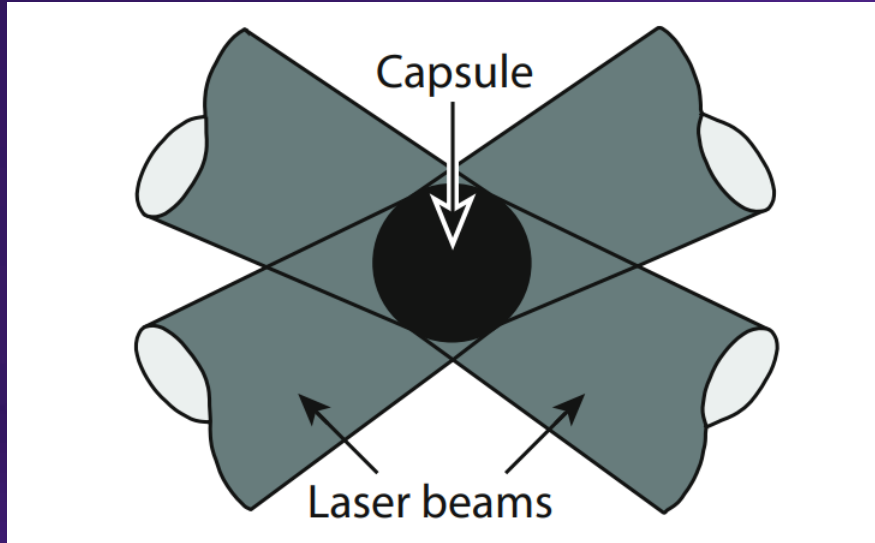
What is Lawson criterion?

the parameter of energy balance in plasma

Lawson criterion

$$n\tau_E = \frac{n_{DT} R}{4c_s} = \frac{\rho R \cdot N_A}{4c_s M_{DT}}.$$

Direct drive

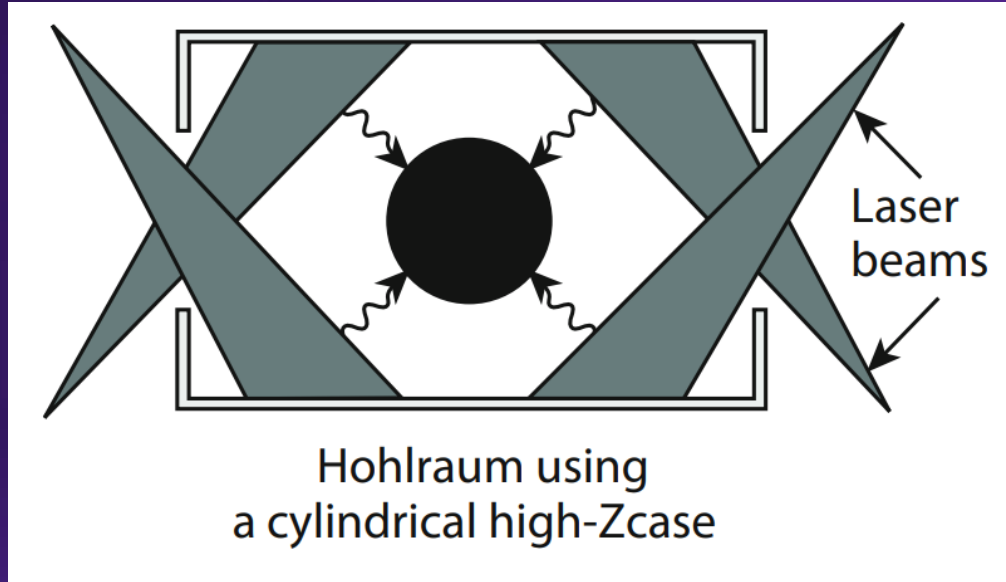


1. Directly impinge laser on the capsule

limitation

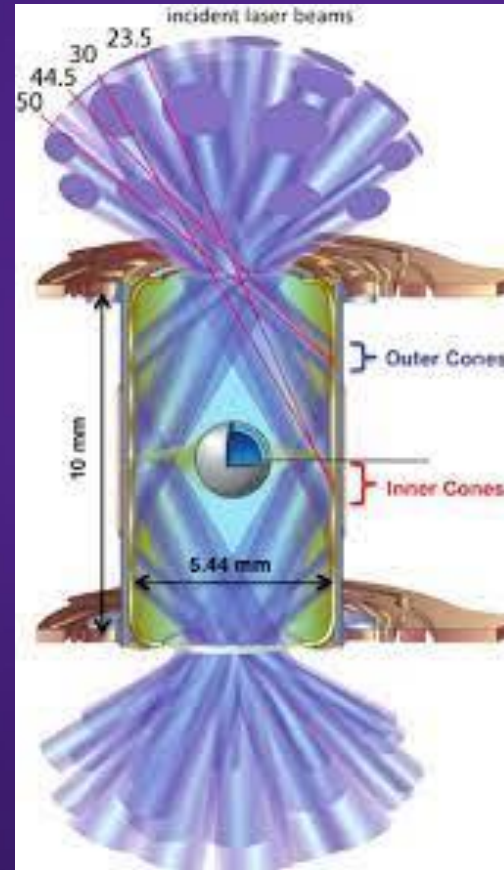
1. Problem of critical density
2. difficulty in getting the laser light to penetrate at electron densities higher than the critical density

Indirect drive



Laser impinge on the 'hohlraum' to emit X-ray

Hohlraum



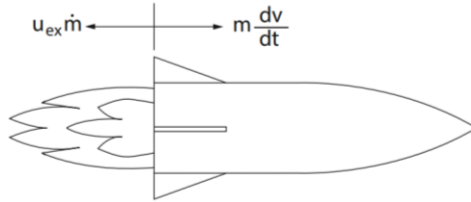
imposion

$$m \frac{dv}{dt} = u_{ex} \dot{m} = -u_{ex} \frac{dm}{dt}, \quad (10.36)$$

and thus $-u_{ex} dm/m = dv$, so that

$$v(t) = u_{ex} \ln \left(\frac{m(0)}{m(t)} \right). \quad (10.37)$$

Fig. 10.13 Rocket momentum balance



The rocket equation

Hydrodynamic Instabilities

form a limit on the ability for an imploding ICF target to retain its spherical symmetry

limit the maximum achievable compression of the target

Hydrodynamic Instabilities

Rayleigh-Taylor instability

Kelvin-Helmholtz instability

Richtmeyer-Meshkov instability

1. End