Fusion

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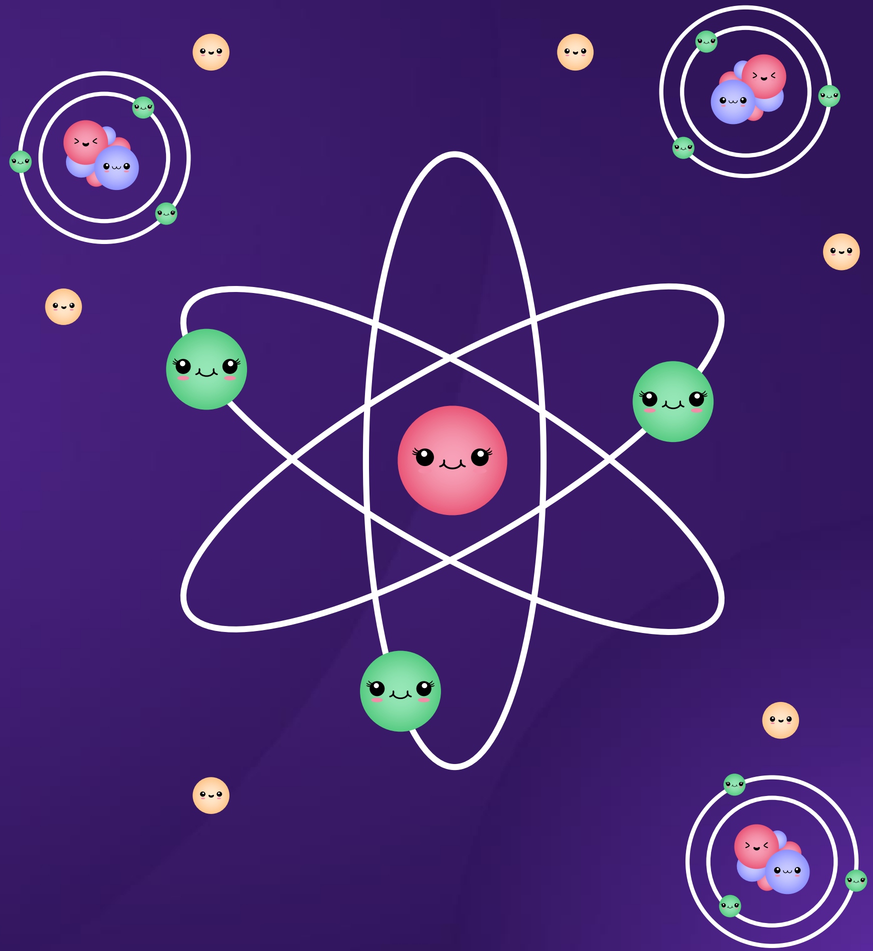
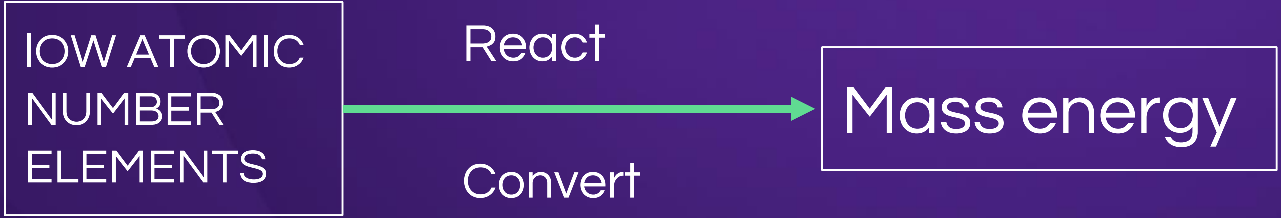


Introduction of Fusion

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,

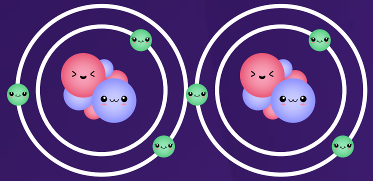


- E.g.

$$D + T \rightarrow {}^{4}He + n \quad (Q = 17.6\ MeV)$$

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

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

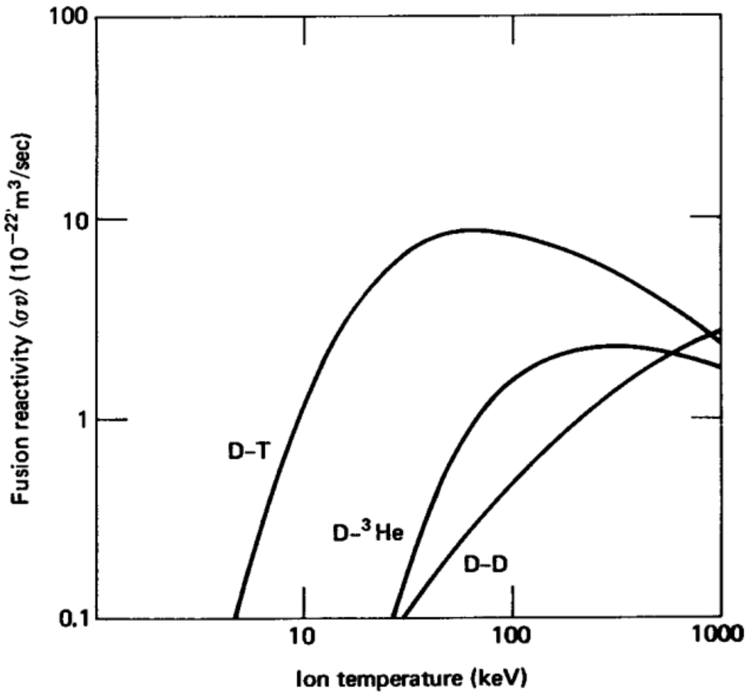
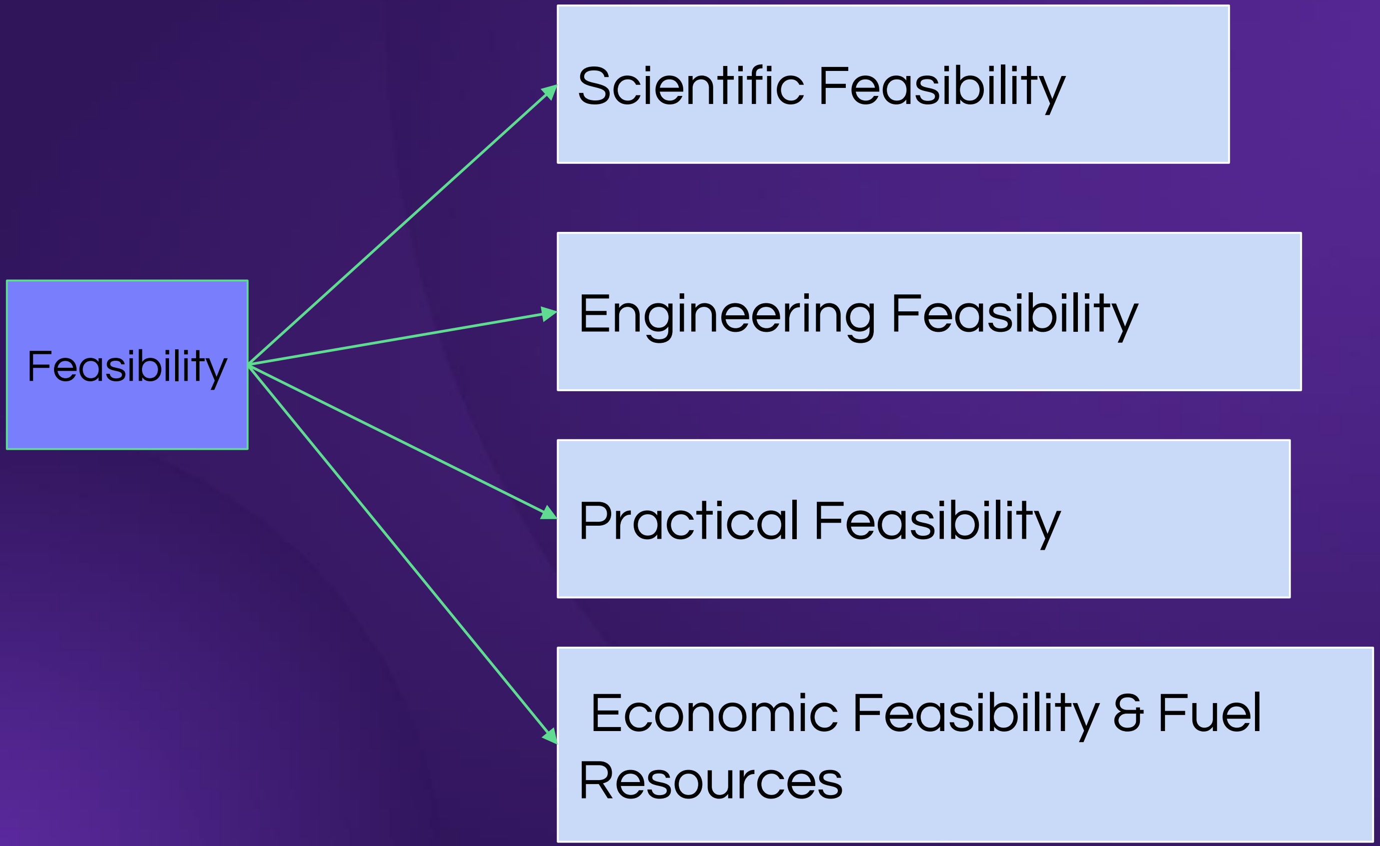


Figure 1.1 Fusion reactivity.

- 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

- ∵thermonuclear temperatures → sufficient positive energy

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

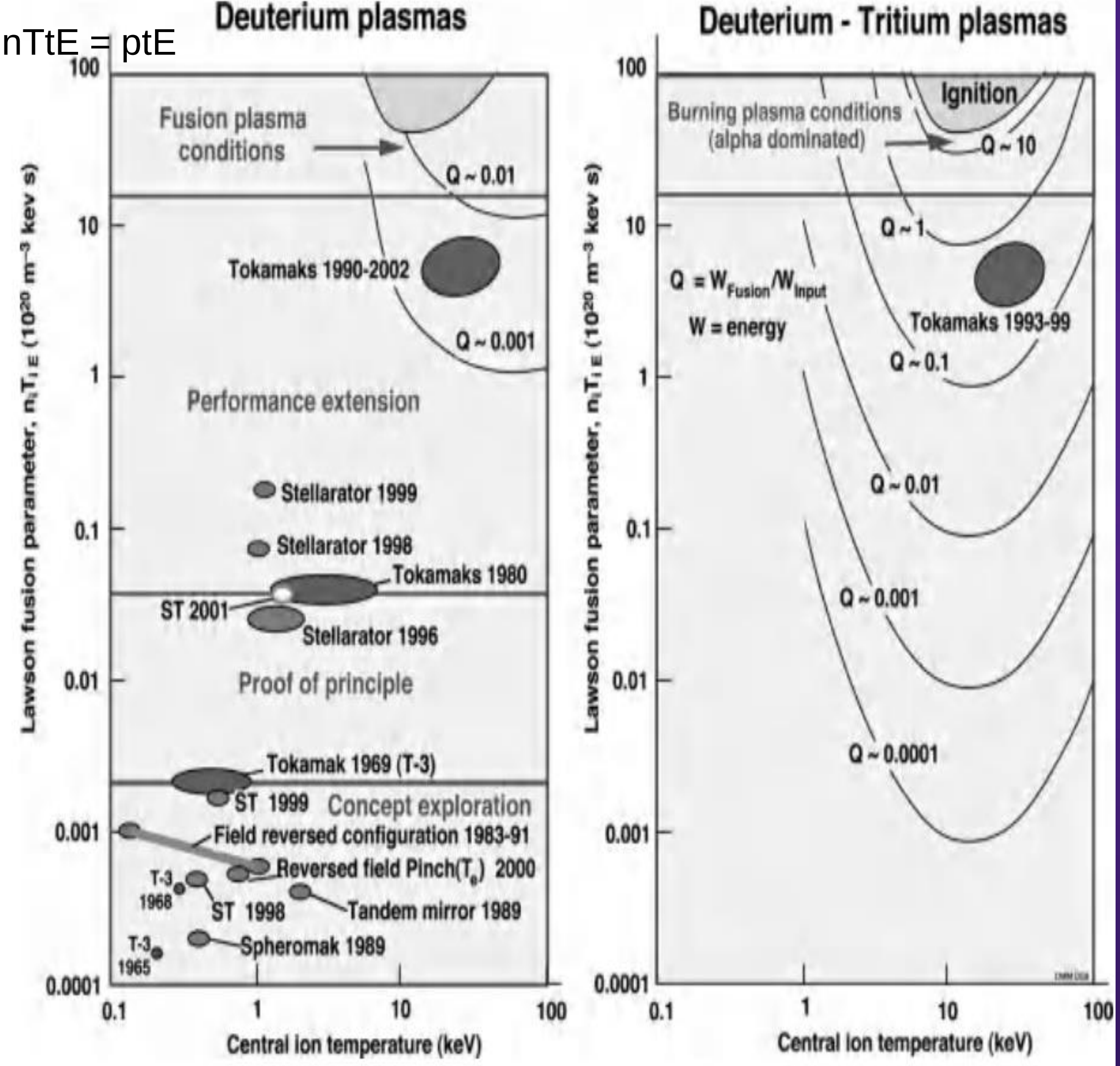
- Using plasma power amplification factor as the measurement
  - →Qp > 1 = breakeven
  - →Qp =∞: ignition
- ∴practical definition= Qp large enough(probably >10) that net electrical power can be economically produced

The plasma power balance can be written as

$$\textit{fusion heating} + \textit{external heating} \geq \textit{radiation loss} + \textit{transport loss}$$

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

nTtE = ptE



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

- Magnitude of the confining magnetic field pressure MHD

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

⬇

Achieving plasma pressure

⬇

Sufficiently large values of β (practical scientific feasibility)

1.2 Engineering Feasibility

Required technologies

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

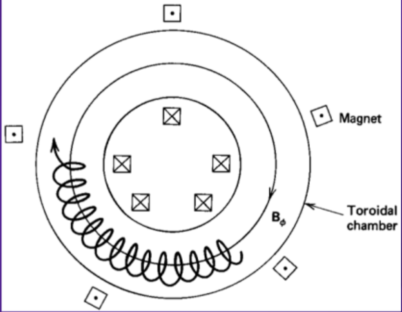
2.1 Magnetic Confinement

Magnetic Confinement

Closed Toroidal Confinement Systems

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

Open Toroidal Confinement Systems



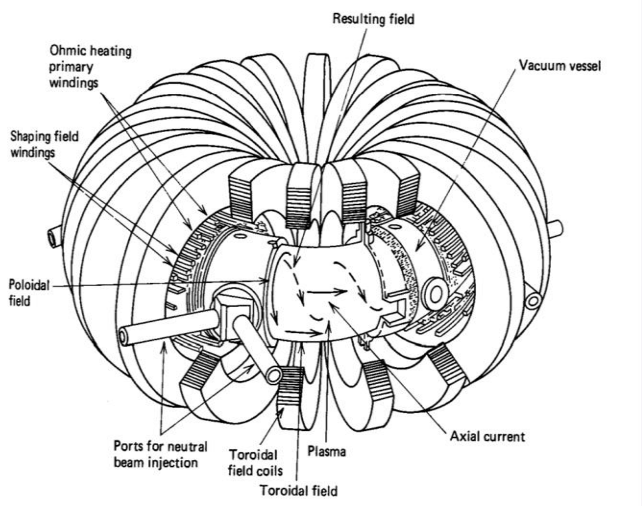


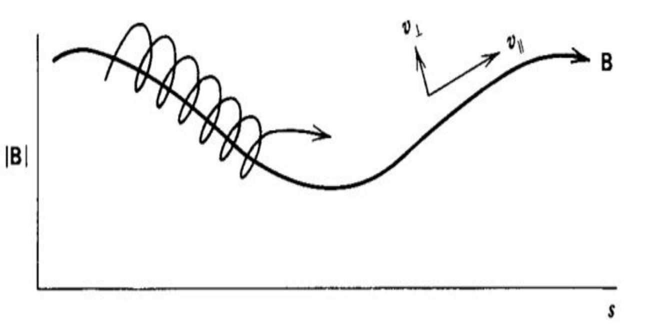
Figure 1.4 Tokamak schematic.

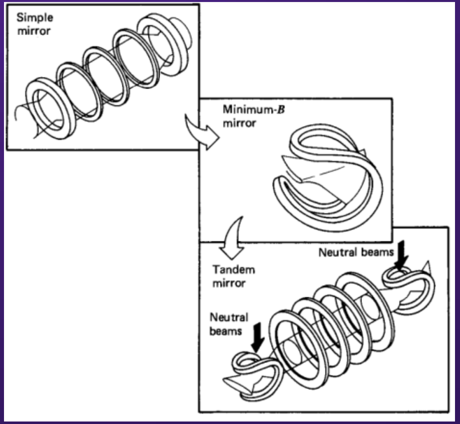
2.1 Magnetic Confinement

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 μ →RHS vanishes → reflects & travels back along the field line→ ↑ magnetic field strength → >RHS vanishes again (simple mirror)





Closed Toroidal Confinement Systems

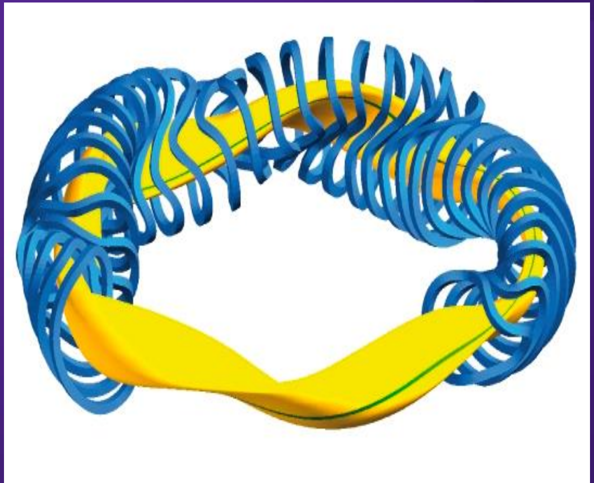
2.2 Tokamaks

- 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



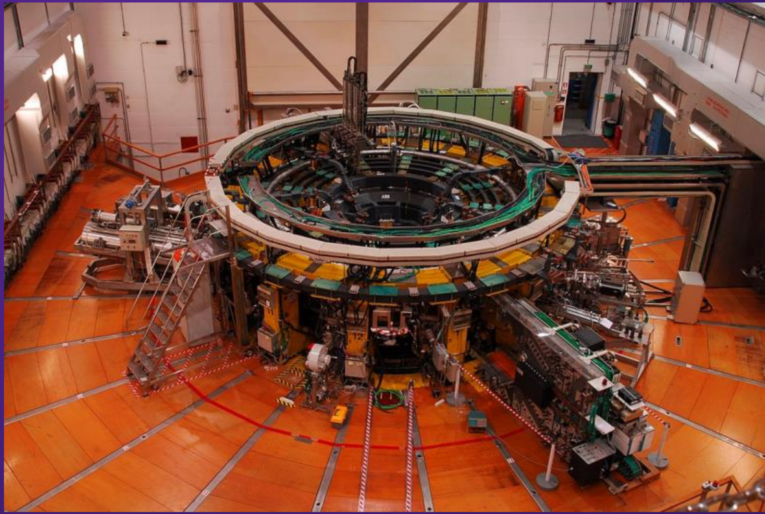
2.4 Spherical Torus

- 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 characterics of future fusion reactors and neutron sources
3. Discussion on the considerations of tokamak

3 PLasma Physics & Engineering Constraints

- Confinement

$$\tau_E = H_H \tau_E^{IPB98(y,2)}$$

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

→magnetic field and plasma size → threshold power

- Density Limit

→require achieving high particle density →high power density

→constraint:

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

→plasma current

→plasma size

→fusion power

3 PLasma Physics & Engineering Constraints

- Beta Limit

  →The MHD stability limit on the plasma pressure

$$\beta_c \equiv \frac{\langle n_e T_e + n_i T_i + p_\alpha \rangle}{\frac{B^2}{2\mu_0}} \leq \beta_N \frac{I(MA)}{aB} = const \times l_i \frac{I}{aB}$$

  →To achieve high values of βN, I and B→high plasma power density plasma size for a given fusion power level

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 Physics & Engineering Constraints

- Startup Inductive Volt-seconds
  →requirement consists of a component
  1. induce the plasma current in the absence of resistive losses
  2. Overcome resistive losses during startup

  $$(\Delta\Phi)_{ind} = IL_p \quad (\Delta\Phi)_{res} = C_{Ejima}\mu_0 RI$$

  →plasma discharge maintenance after startup determines by a trade-off
  1. Length of the burn pulse
  2. Achievable bootstrap current
  3. Amount of power required for non-inductive current drive
  4. Overall design of the coil systems

3 Plasma Facing Component Heat Fluxes

- Stress Limits

  pc= coolant pressure

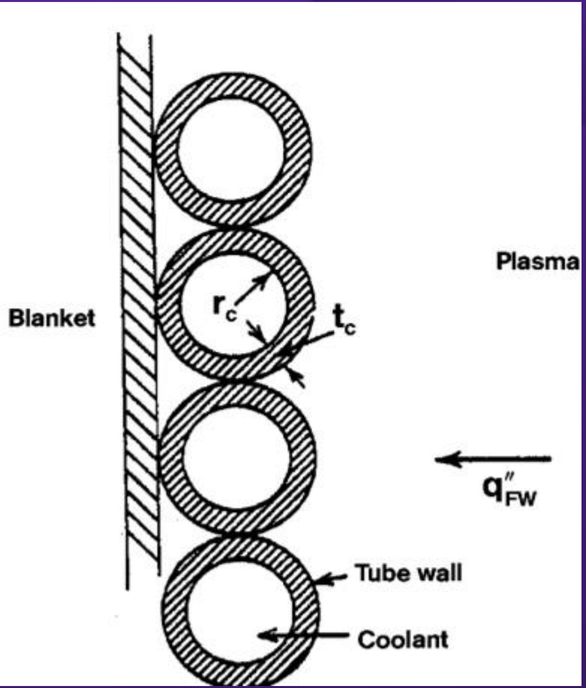
  rc= coolant tube radius

  tc= coolant tube thickness

  pdis ′ B2 q=2m0= disruption pressure

$$\sigma_{th} = \frac{\alpha E\left(f_{pfc} q'' t_c + \frac{1}{2} q''' t_c^2\right)}{2\kappa(1-\nu)}$$

$$\sigma_{th} + \sigma_p \leq 3S_m$$



A stress limit on the maximum allowable Heat flux to the plasma facing component q00 stress

3 Plasma Facing Component Heat Fluxes

- Temperature Limit
  →surface temperature constrained to below Tmax

$$T_s = T_c + f_{pfc} q''_T \left(\frac{t_c}{\kappa} + \frac{1}{h} \right) + \frac{q''' t_c^2}{2\kappa} \leq T_s^{\max}$$

Tc= coolant temperature
h=surfac heat transfer 'film' coefficient
qT=Maximum allowable heat flux

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)

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

- Heat Flux Limit
  →limit on three maximum allowable heat flu $q''_{max} = \max\left\{q''_{th}, q''_{T}, q''_{fat}\right\}$
  →high power density tokamaks may be thwarted by heat flux

limits

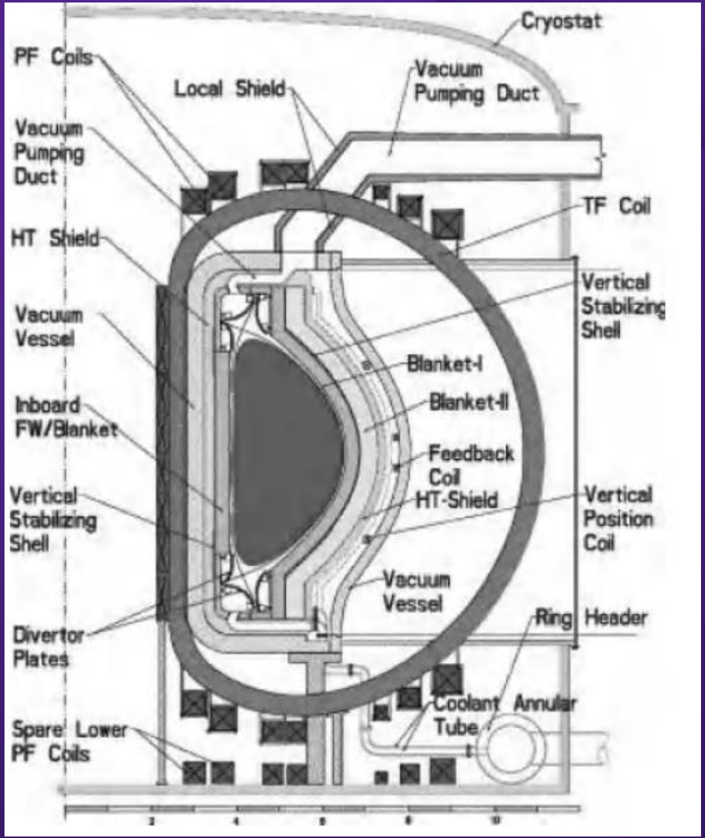
3 Future Tokamak Reactors

- 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 βN 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

4.1 Introduction
4.2 Direct and indirect drive
4.3 Laser interact with matter

4.1 Introduction

What laser light do

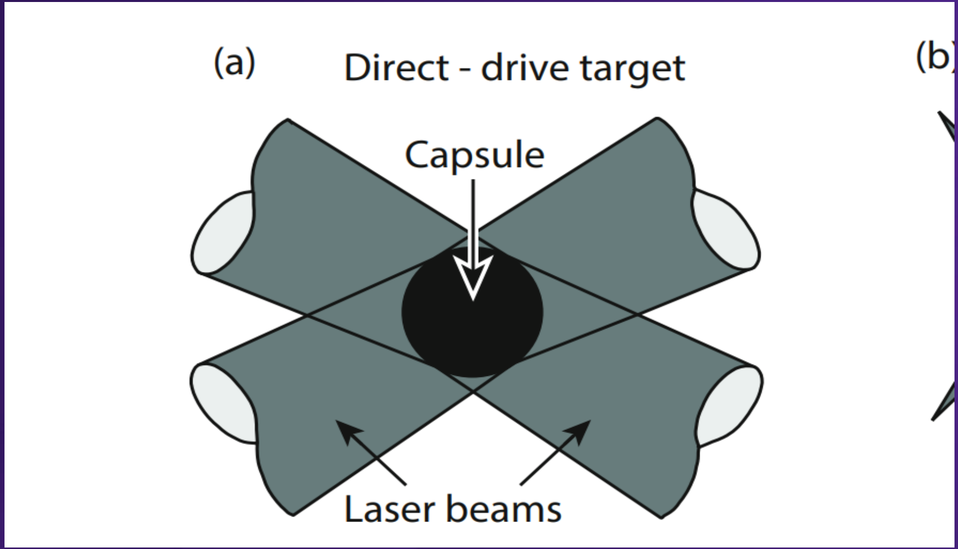
1. compress the D-T gas
2. heat up the mixture

4.1 Compression

$$Y = Y_0 f_B m_f^{compressed}$$

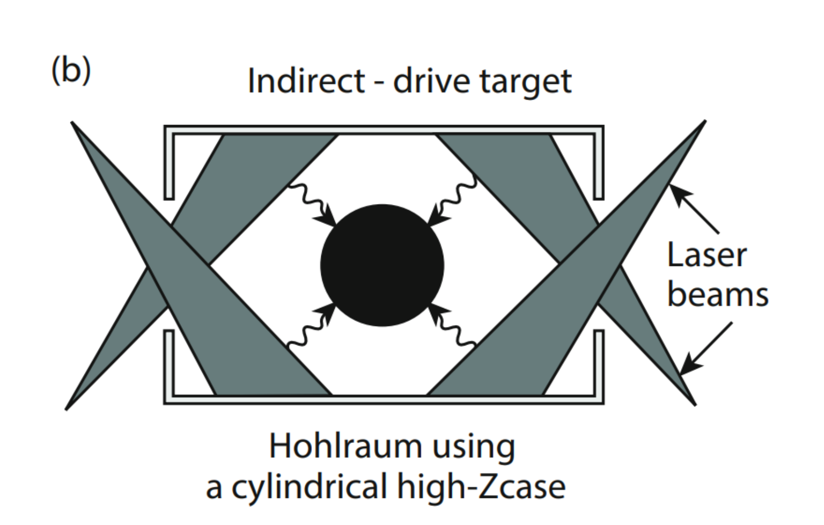
1. Have practical need
2. Less energy is needed

4.2 Direct drive



ablation of the material on the outside of the target capsule causes compression of the capsule

4.2 Indrect drive



laser energy impinges on the inside of the ‘hohlraum’
Material of ‘hohlraum’ typically is high-Z material such as gold or uranium and X-rays are emitted.

interaction of laser and matter

5.1 inverse bremsstrahlung

4.3.1 inverse bremsstrahlung

process by which light is absorbed in collisional plasma

$$-\ln(\alpha_T) = 2\int_0^L \kappa_{ib}\,dx = 2\frac{\nu_{ei}(n_{crit})}{c}L\int_0^1 \frac{u^2du}{\sqrt{1-u}} = \frac{32}{15}\frac{\nu_{ei}(n_{crit})}{c}L. \tag{10.7}$$

Thus the total reflected energy fraction is $\alpha_{abs} = 1 - \alpha_T$ and thus the absorbed fraction is

$$\alpha_{abs} = 1 - \exp\left(-\frac{32}{15}\frac{\nu_{ei}(n_{crit})}{c}L\right). \tag{10.8}$$

5.2 resonance absorption

1. process by which light is absorbed at the critcal density

$$\Phi(\tau) = \frac{4\left(\tau K_{\frac{1}{3}}\left(\frac{2\tau^3}{3}\right)\right)^{3/2}}{\sqrt{3\pi}\sqrt{K_{\frac{2}{3}}\left(\frac{2\tau^3}{3}\right)}}. \qquad (10.12)$$

Here K is the modified Bessel function (these functions of order $1/3$ and $2/3$ are also known as Airy functions). The absorbed energy fraction is

$$f_{abs} = \Phi(\tau)^2/2, \qquad (10.13)$$

with

$$\tau \equiv (L\omega_L/c)^{1/3}\sin\theta. \qquad (10.14)$$

5.3 Nonlinear Effects

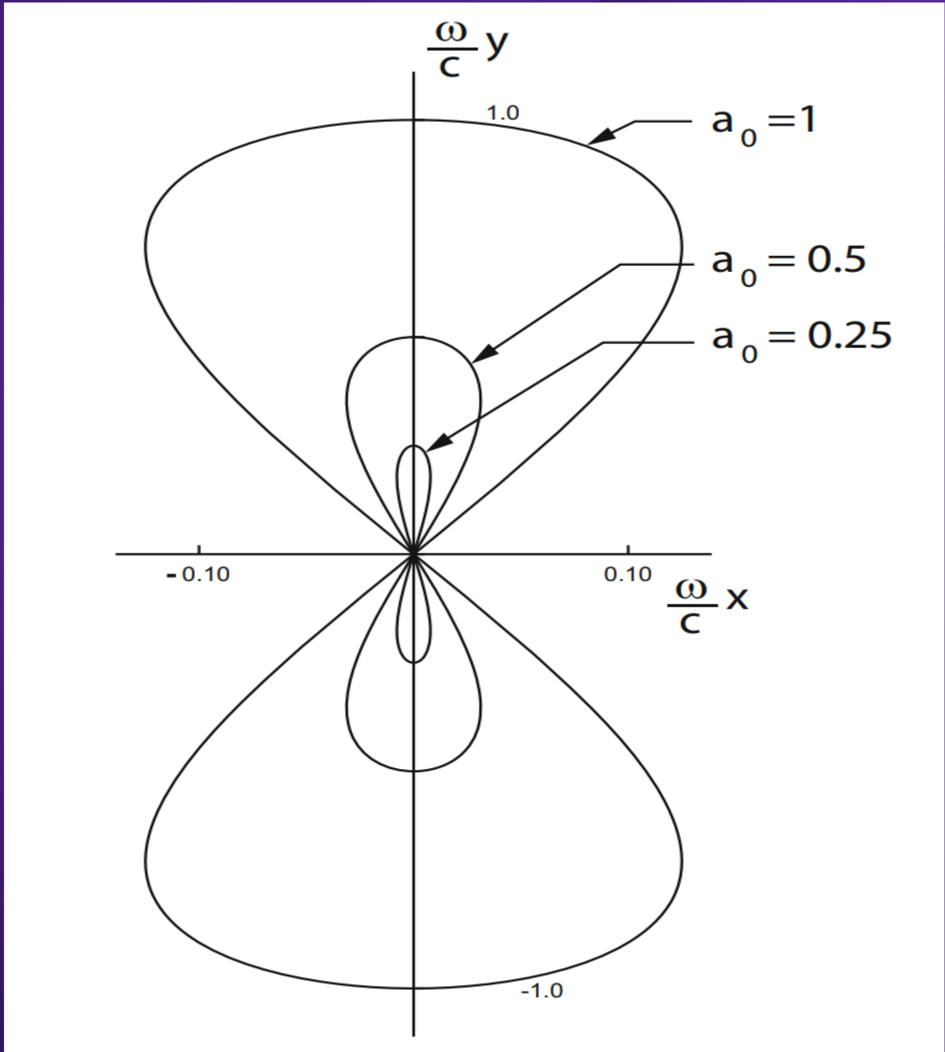
$$\mathbf{E} = E_0 \hat{y} e^{i(kx-\omega t)}, \qquad \mathbf{B} = \frac{1}{c}\hat{x} \times \mathbf{E}.$$

$$y(t) = -\frac{q_e E_0}{m\omega^2}\cos\omega t = -a_0 \frac{c}{\omega}\cos\omega t,$$

$$x(t) = -\frac{q_e^2 E_0^2}{8 m_e^2 c}\sin 2\omega t = -\frac{a_0^2}{8}\frac{c}{\omega}\sin 2\omega t.$$

5.3 Nonlinear Effects

The motion of Electrons in High-Amplitude Electromagnetic Field would be nonlinear



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