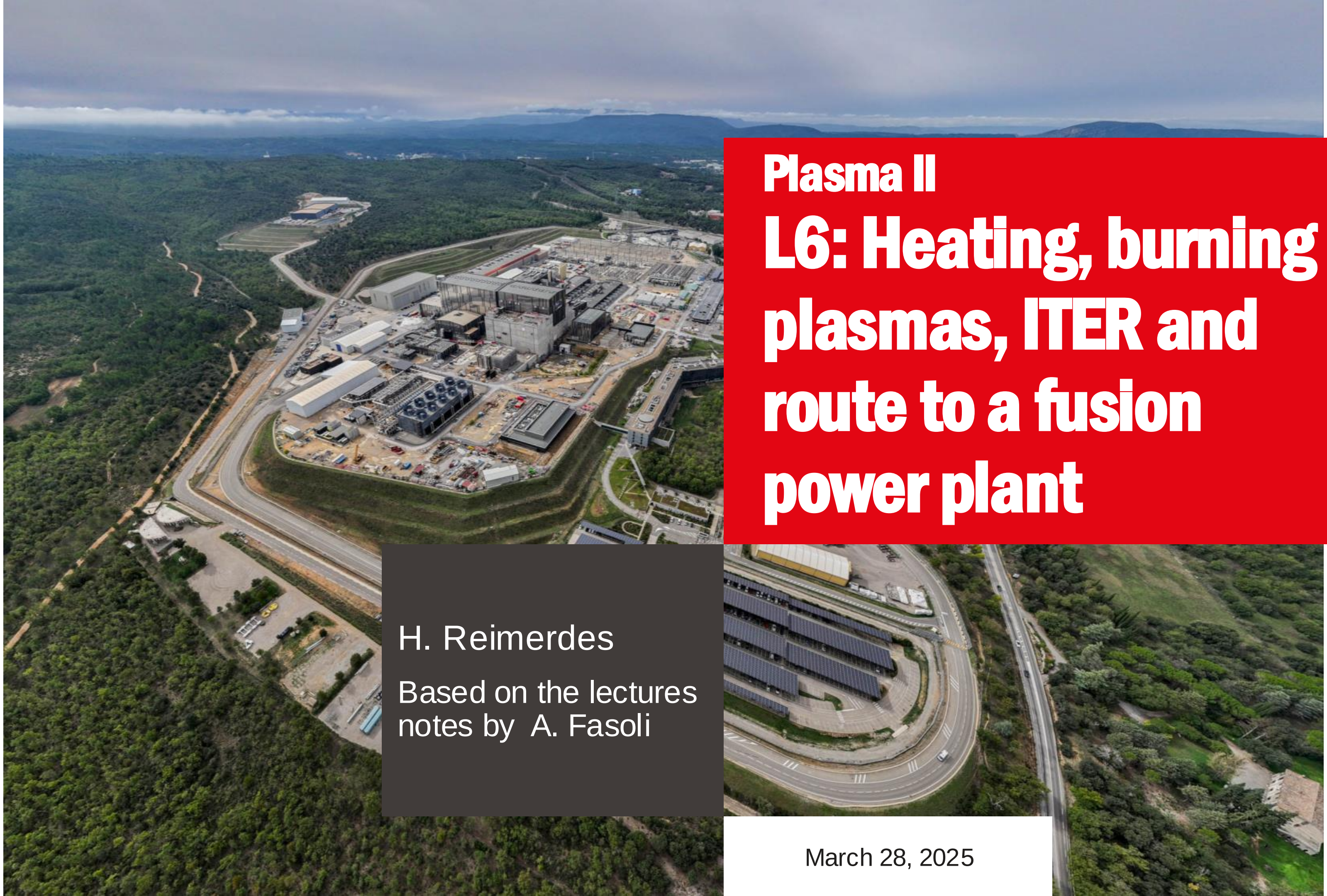
EPFL



Plasma II
L6: Heating, burning plasmas, ITER and route to a fusion power plant

H. Reimerdes

Based on the lectures notes by A. Fasoli

March 28, 2025

Swiss Plasma Center

Outline

1. Plasma heating
   - Need for (auxiliary) heating
   - Neutral beam heating
   - Heating by waves
2. ITER as the first burning plasma
   - Alpha-particle heating
3. Towards a fusion power plant
   - Tritium self-sufficiency

Material

- See also EPFL MOOC “Plasma physics: Applications” #7f,g,hi,j
  - https://learning.edx.org/course/course-v1:EPFLx+PlasmaApplicationX+1T_2018/home
- Freidberg, *Plasma Physics and Fusion Energy*, Ch. 15

Minimum heating power

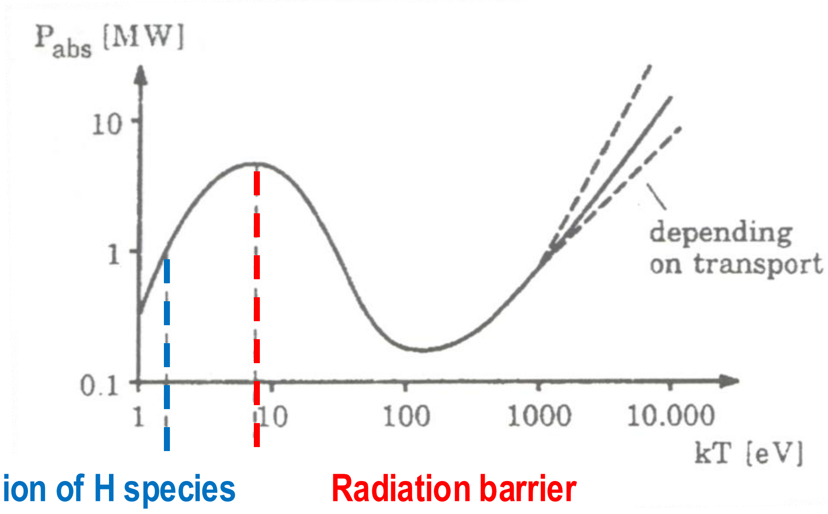
- Ionisation of plasma species (hydrogen isotopes)
  - Ex.: Mid-size tokamak (R=2m, A=4)

Energy needed to ionise gas?

- *Radiation barrier* or *impurity burn-through:* line emission from incompletely ionised impurities is maximum for T<100 eV (~10eV for light impurities like C, O)

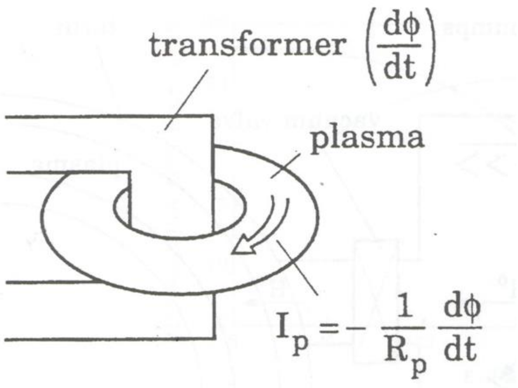
Minimum heating power

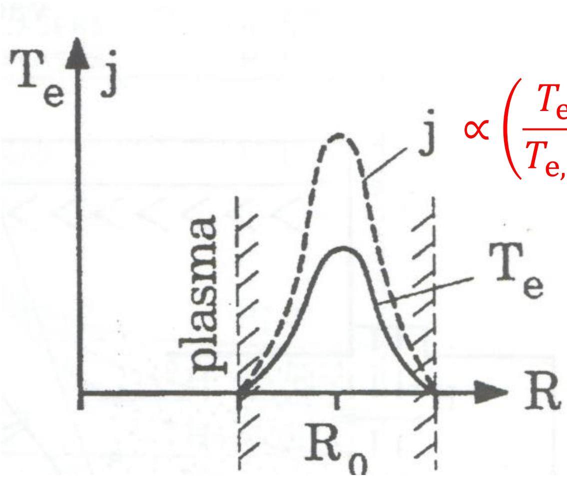
- Ionisation of plasma species (hydrogen isotopes)
- *Radiation barrier* or *impurity burn-through:* line emission from incompletely ionised impurities is maximum for T<100 eV (~10eV for light impurities like C, O)
  - Ex.: Mid-size tokamak (R=2m, A=4)
    - P_{heat} ~ 1MW to fully ionize
    - P_{heat} ~ 5MW to overcome radiation barrier



Ohmic heating intrinsic to the tokamak concept

- Ohmic current $\bar{j} = \frac{\bar{E}}{\eta} = \frac{V_{\text{loop}}/(2\pi R)\hat{e}_\phi}{\eta}$ with $\eta = \frac{\sqrt{2}}{\pi^{3/2}} \frac{m_e^{1/2} Z\, e^2 \ln\Lambda}{12\, \varepsilon_0^2 T_e^{3/2}}$



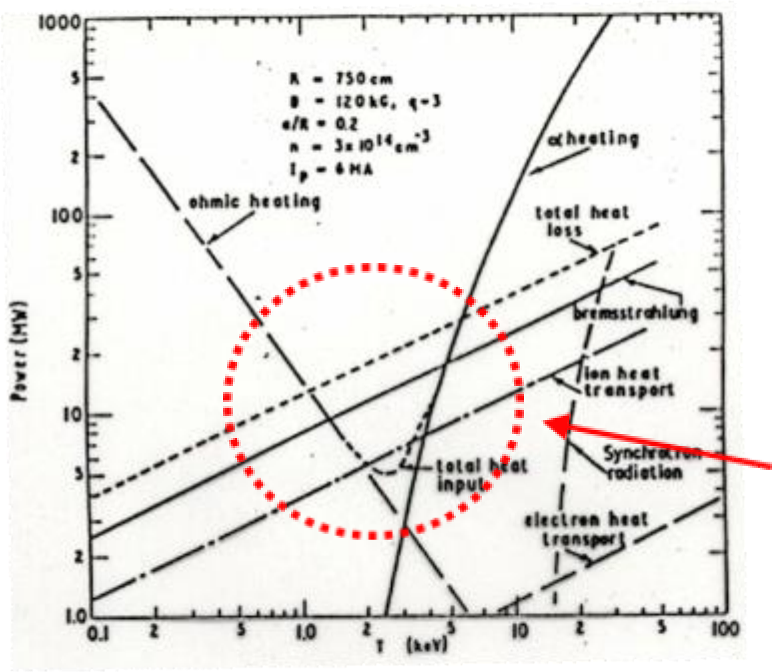


$\propto \left(\frac{T_e}{T_{e,0}}\right)^{3/2}$

- ➢ Ohmic current density peaks on axis
- ➢ Ohmic heating $P_{\text{Ohm}} = \int \bar{j}\bar{E}\, dV = \int \eta j^2\, dV$ less effective at higher T_e

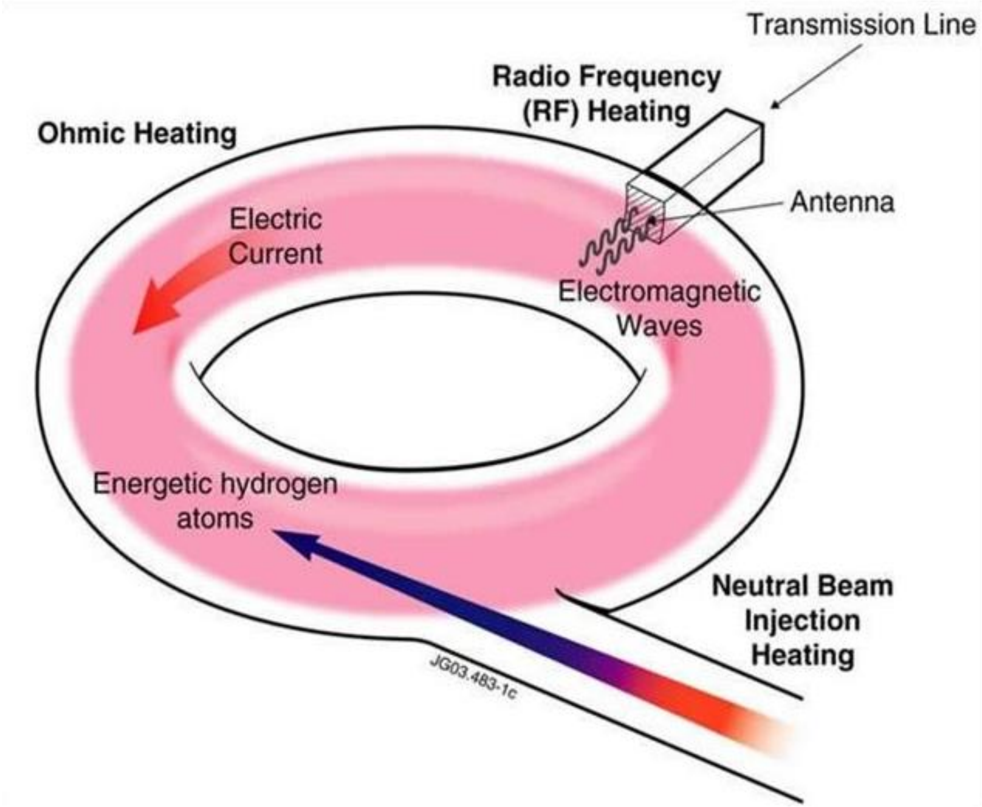
Ohmic heating not sufficient to heat the plasma to the required temperature (>10keV)

- Ohmic heating only sufficient to heat a typical fusion plasma up to 1keV



➢ Need to fill in 'gap' between ohmic heating and α-heating (T>5-7keV)

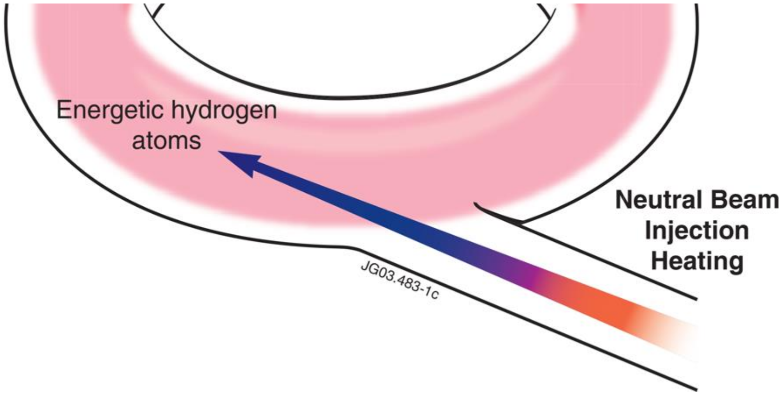
Additional plasma heating



Outline – Plasma heating

- Need for (auxiliary) heating
- **Neutral beam heating**
- Heating by waves
  - Reminder of EM waves in plasma
  - Ion Cyclotron
  - Electron Cyclotron

Basic idea of Neutral Beam Injection (NBI) heating

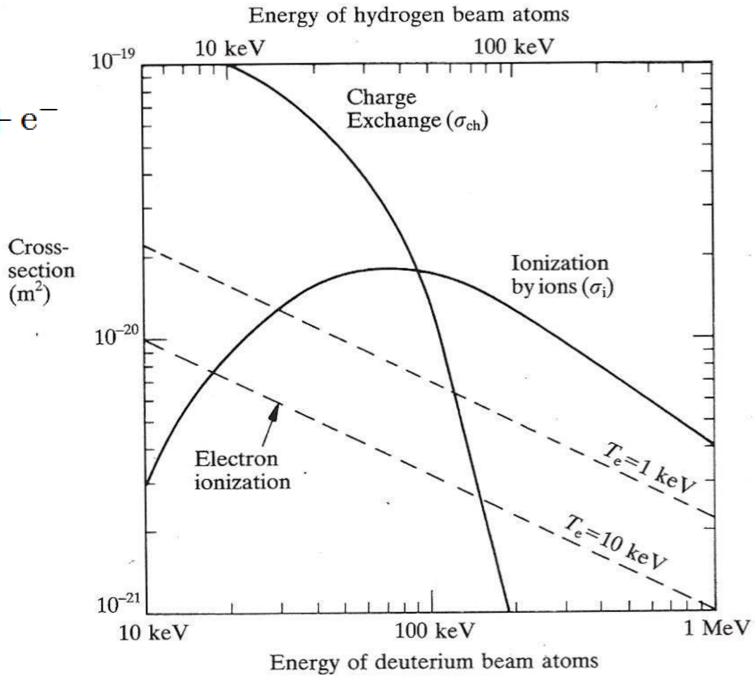


- Energetic deuterium and tritium ions could be injected into plasma, to give energy to ‘colder’ plasma particles
  - But *B*-field prevents penetration of energetic ions!

➢ **Idea:** use **neutral particles** at high energy to get into the plasma, where they ionise and heat the bulk plasma via Coulomb collisions

Physical processes occurring during beam penetration in plasma, leading to ionisation

Charge exchange:	$H_b + H_p^+$	$\rightarrow$	$H_b^+ + H_p$
Ionization by ions:	$H_b + H_p^+$	$\rightarrow$	$H_b^+ + H_p^+ + e^-$
Ionization by electrons:	$H_b + e^-$	$\rightarrow$	$H_b^+ + 2e^-$



[Source: J. Wesson, Tokamaks, 2nd edition, Clarendon Press -Oxford]

Evolution of beam intensity

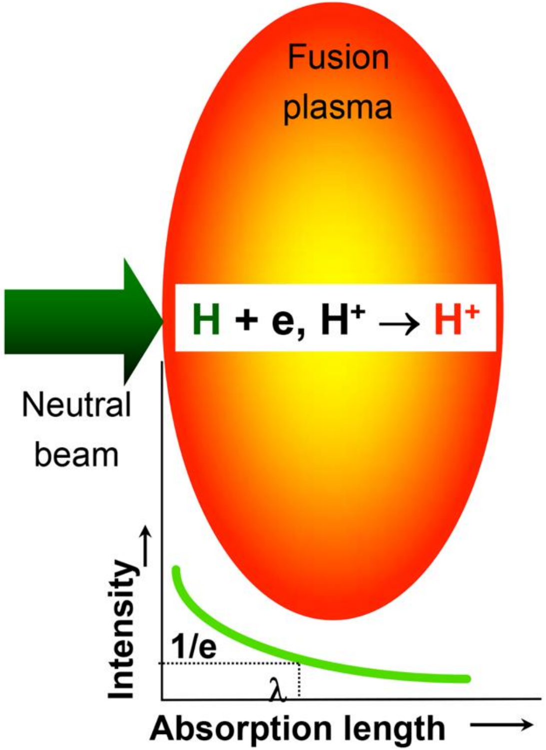
- Neutral particle flux

$$\frac{dI_b}{dx} = -n_p\left(\sigma_{ch} + \sigma_i + \frac{\langle\sigma_e v_e\rangle}{v_b}\right) I_b$$

- Decay length

$$\lambda_b = \frac{1}{n_p\left(\sigma_{ch} + \sigma_i + \frac{\langle\sigma_e v_e\rangle}{v_b}\right)}$$

  - **Too short**: power absorbed at the edge
  - **Too long**: Beam damages wall after passing the plasma (shine-through)



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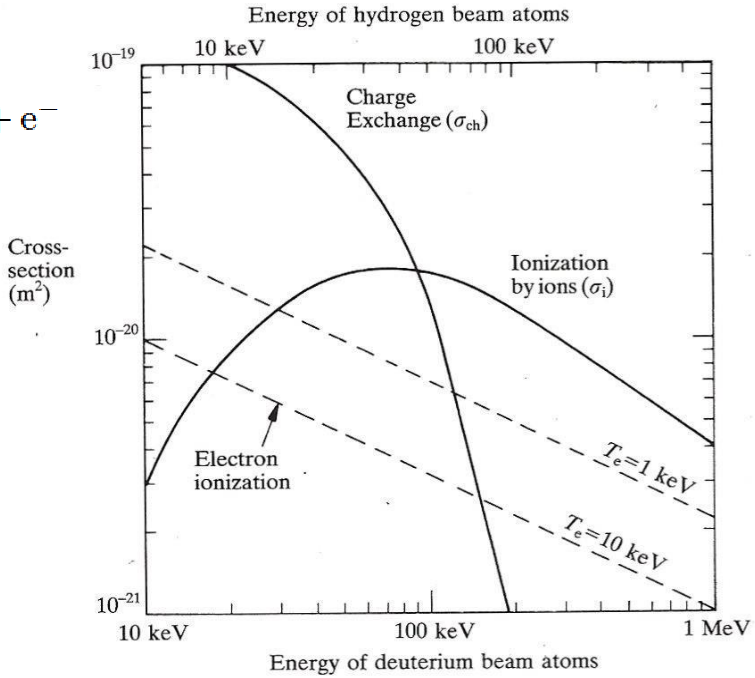
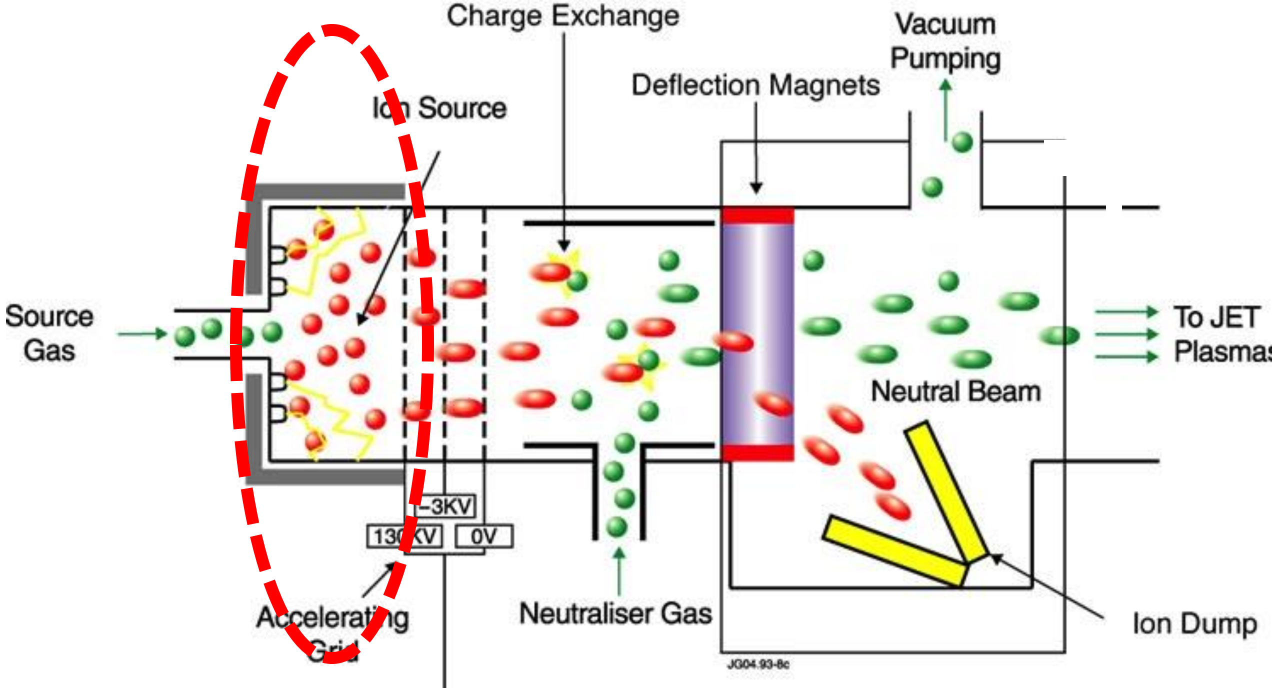


- ➢ For a large plasma (>1m) we need large beam energies (>300keV)

[Source: J. Wesson, Tokamaks, 2nd edition, Clarendon Press -Oxford]

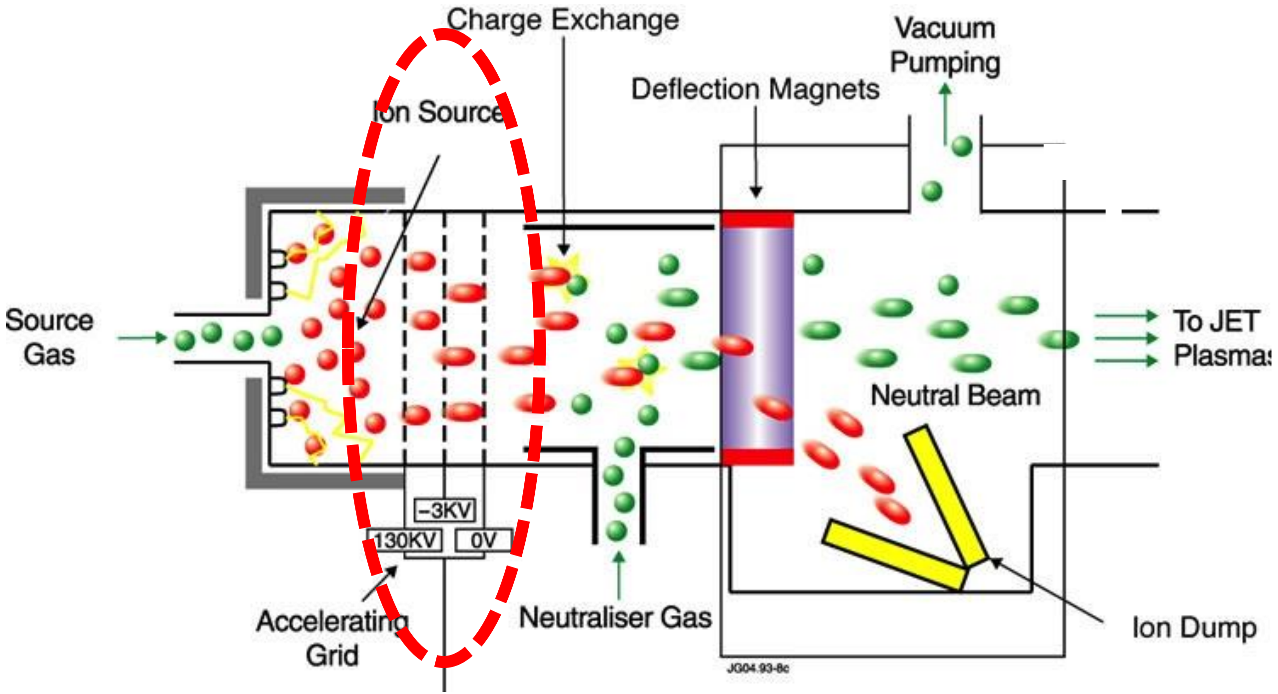
Neutral Beam Injector – Ion source

- Ex.: NB injector in JET



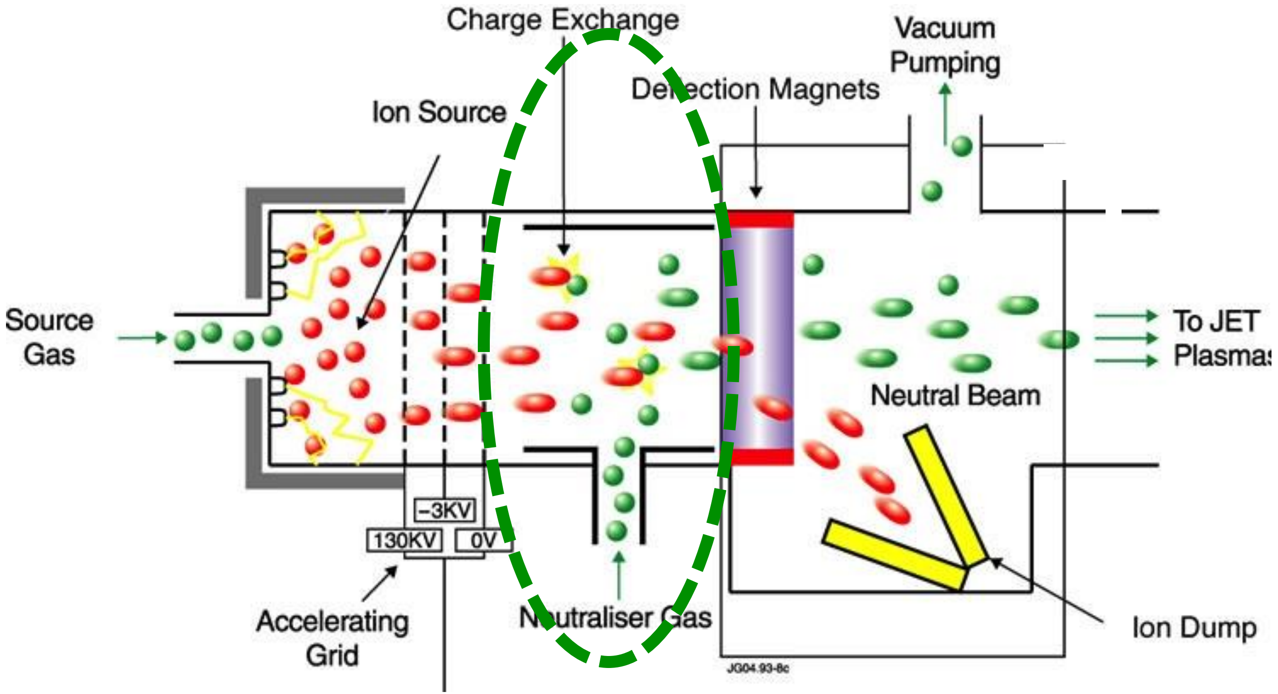
Neutral Beam Injector – Acceleration grid

- Ex.: NB injector in JET



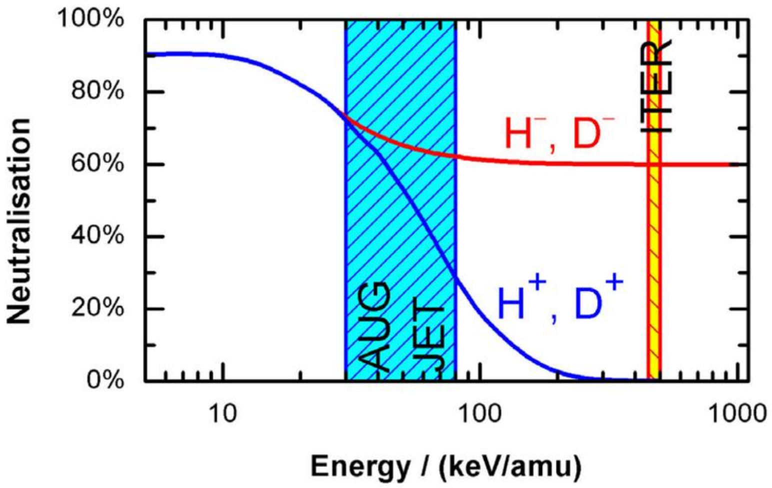
Neutral Beam Injector – **Neutraliser**

- Ex.: NB injector in JET



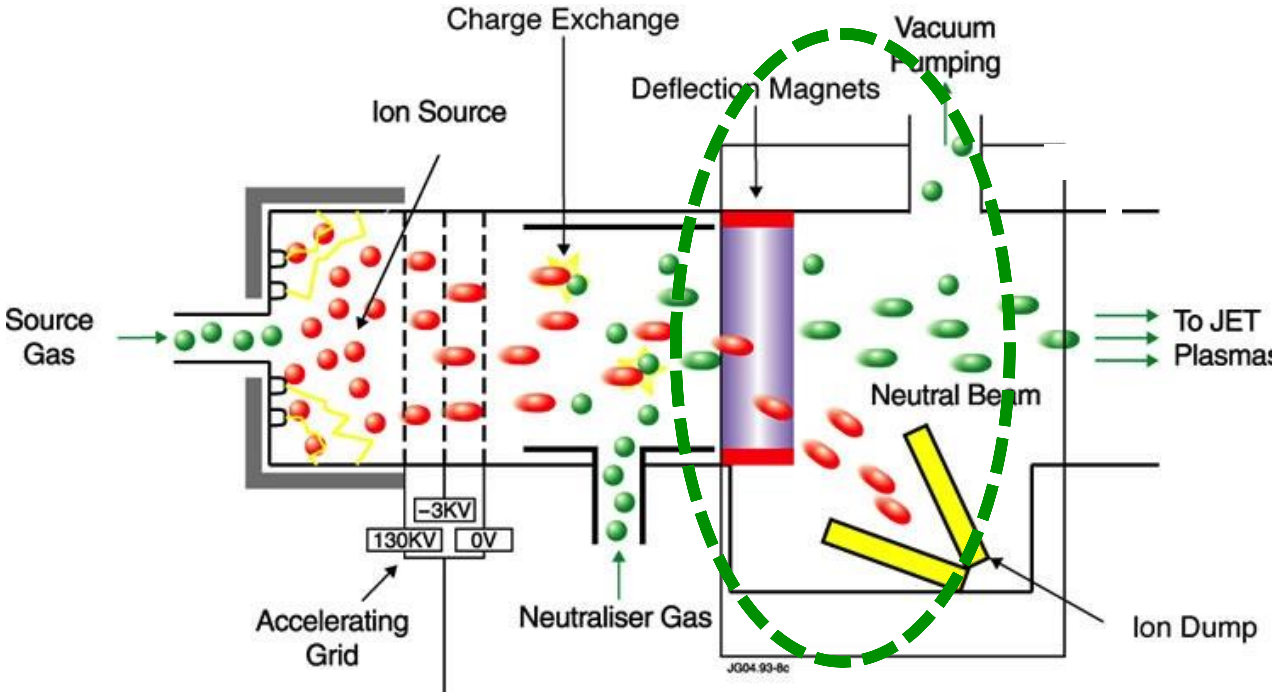
NBI: neutralisation efficiency

- Neutralisation efficiency for **positive ions** decreases for high ion energies
- ➢ For large, dense plasmas (→ ITER) we need **negative ion** beams



Neutral Beam Injector – Deflector

- Ex.: NB injector in JET



Which species will be heated by the fast beam ions?

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- Fast ions thermalise through **Coulomb** collisions

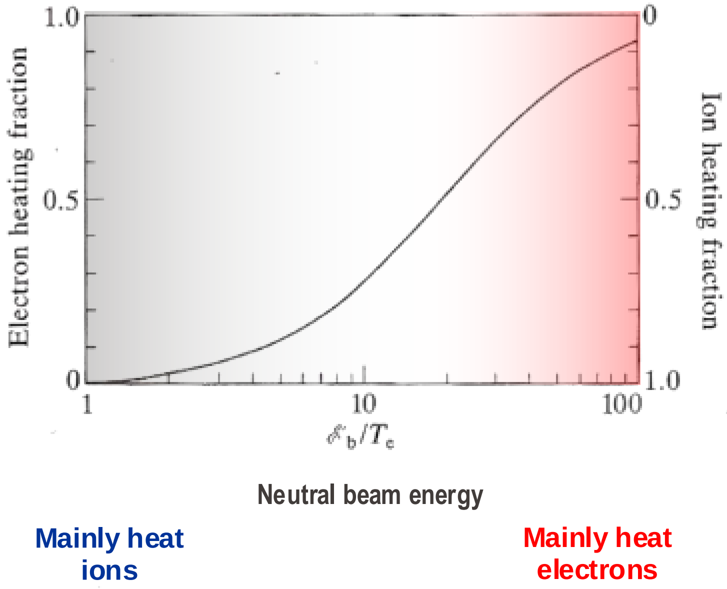
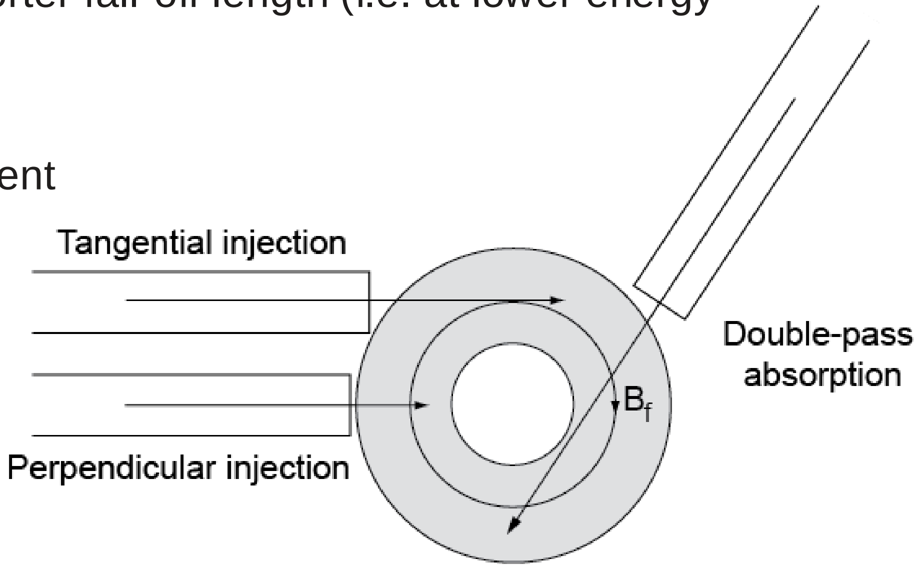


Fig. 5.4.1 Electron and ion heating by deuterium beam ions with energy $\mathscr{E}_b$ as fractions of the total heating plotted against $\mathscr{E}_b/T_e$ for a deuterium plasma.

Neutral Beam Injector – Injection geometry

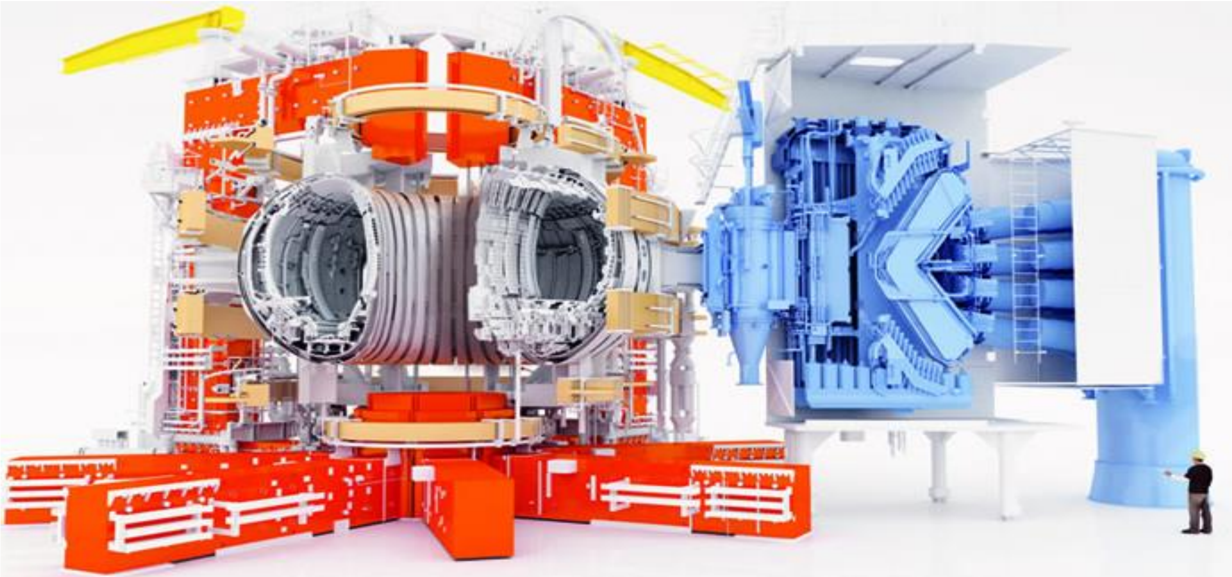
- Perpendicular injection
  - allows for easiest access
  - central absorption requires shorter fall-off length (i.e. at lower energy or large devices)
- Tangential injection
  - Maximises beam ion confinement
  - Maximises current drive
- Double-pass absorption
  - When shine-through is a problem (i.e. at high beam energy or small devices)



[Figure adapted from J. Freidberg, PP & FE, Fig. 15.2]

Example of present NBI system: JET

- Up to 34MW of radial and tangential injection
  - 2x8 injectors: 80keV (H^+) or 130keV (D^+)



Summary – NBI heating

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Advantages

- Simple beam-plasma interaction
- Driving current non-inductively
- Central fuelling

Disadvantages

- Power deposition not localised
- Large opening in chamber
  - Loss of surface for T-breeding (see part 3)
- Low electrical efficiency
  - Low neutralisation efficiencies at large energies required for large plasmas

Heating by electro-magnetic waves

- Absorption and propagation depends on relation of wave frequency to plasma frequencies (i.e. plasma density) and cyclotron frequencies (i.e. magnetic field)
- Distinguish propagation parallel ($\bar{k} \parallel \bar{B}$) and perpendicular ($\bar{k} \perp \bar{B}$) to the magnetic field

Phase velocity

- Resonances
  - Phase velocity $\bar{v}_p$ → 0
  - Infinite refractive index
  - Absorption of power possible
- Cut-off
  - Phase velocity $\bar{v}_p$ → infinity
  - Zero refractive index
  - Wave decays & power is reflected

Reminder: Waves in plasmas

- Key frequencies

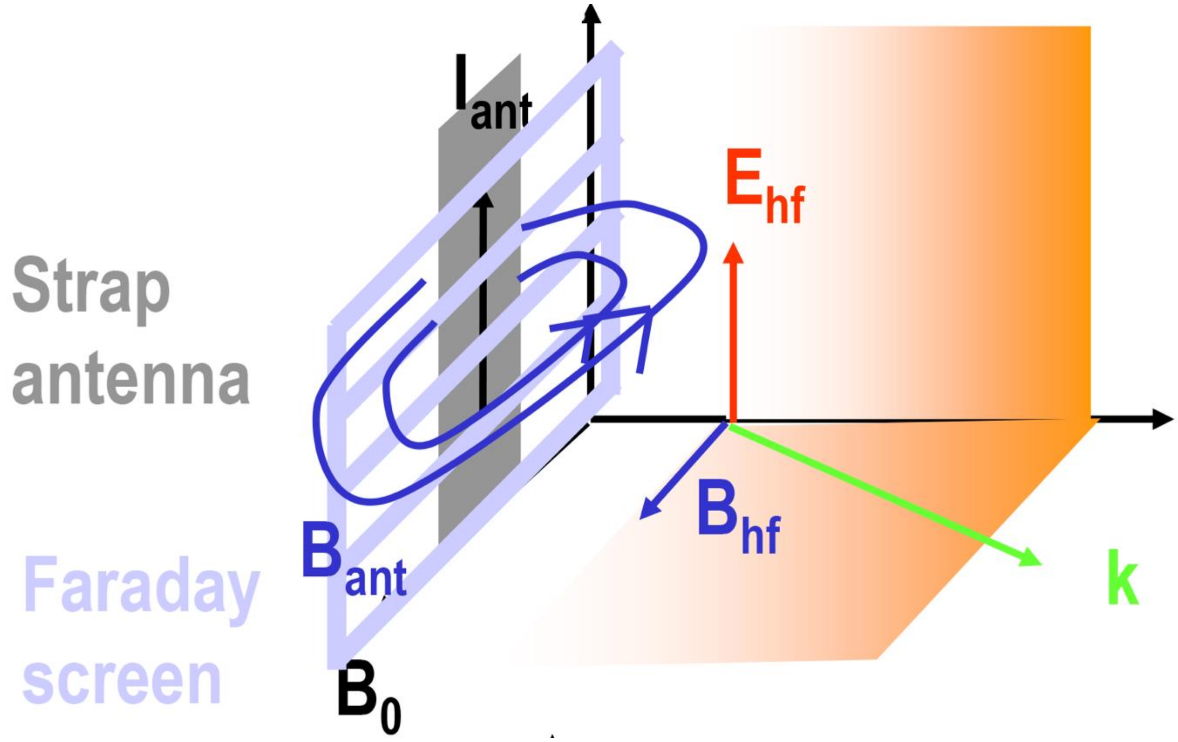
Ion cyclotron resonance heating (ICRH)

- Absorption at the ion cyclotron frequency (fundamental or 2nd harmonic)

$$f = f_{\mathrm{ci}} \sim 15 B_{[T]} [MHz] \text{ for } H^+$$

- 30-100 MHZ → meter waves
- Various schemes for wave absorption
  - Harmonic heating: 2nd harmonic of main ion species, e.g. $\omega = 2\Omega_{\mathrm{c,D}|T}$
    - 1st harmonic has wrong polarisation for absorption
    - Requires high temperature for absorption
  - Minority heating: 1st harmonic of a minority ion, e.g. $\omega = \Omega_{\mathrm{c},H} > \Omega_{\mathrm{c,D}}$ (for hydrogen in deuterium)
    - Minority species heated to high temperatures

ICRH – Antenna excitation of fast wave



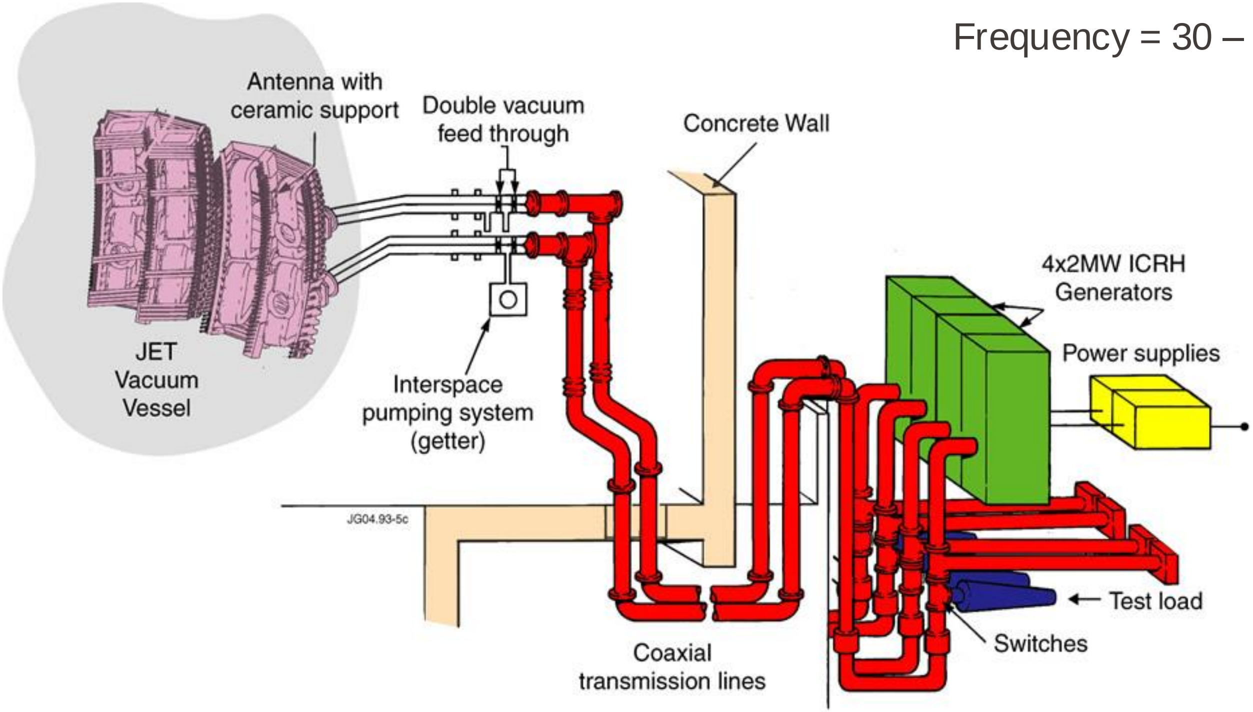
Example of present ICRH system – JET

‘ITER like’ four strap antennas with 8MW/m^2

‘Old’ two-strap antennas with 1.8MW/m^2

Example of present ICRH system – JET

Frequency = 30 – 55 MHz



Summary – ICRH heating

Advantages

- Accessible and cost effective source & component technology
- Directly heats ions
- Good coupling efficiency

Disadvantages

- Complex wave physics
- Strong E-fields at antenna can damage surfaces and produce impurities
- Difficulty in matching the load
- Large surface use in chamber

Electron cyclotron heating (& current drive)

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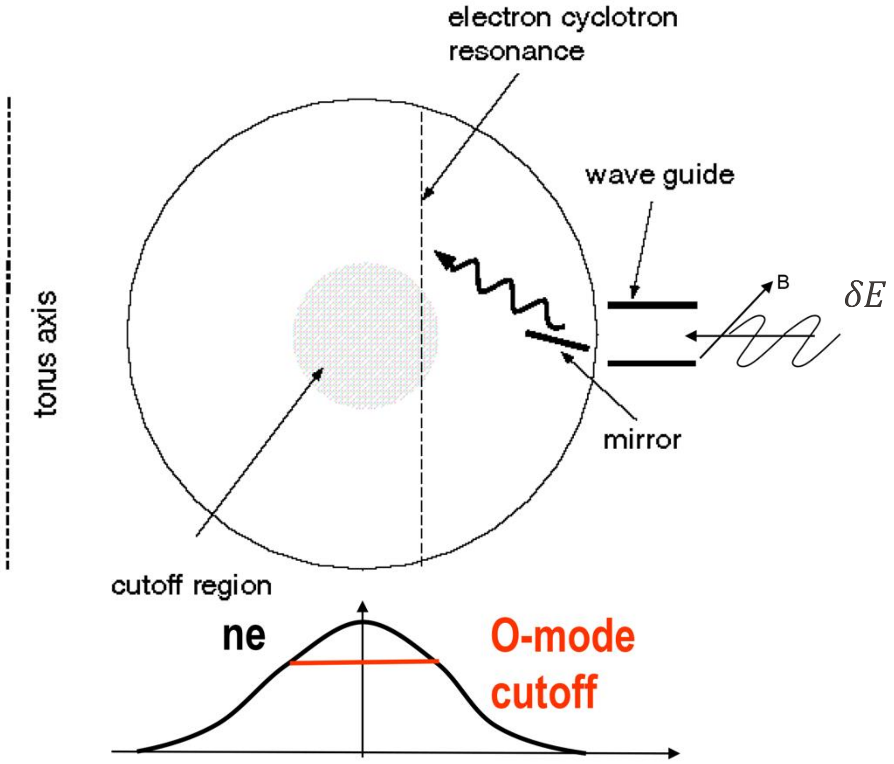
- Absorption at the electron cyclotron frequency (fundamental or higher harmonics)

$$f = f_{\mathrm{ce}} \sim 28 B_{[T]} [GHz]$$

- 30-170 GHz → Millimeter waves
- Generated by gyrotrons
- Wave propagation in high density plasmas limited by cut-off frequency
- Distinguish schemes ordinary $\delta\bar{E} \parallel \bar{B}_0$ (O-mode) and extraordinary $\delta\bar{E} \perp \bar{B}_0$ (X-mode) wave polarization
  - Differ in absorption and propagation

ECRH – O-mode ($\delta\bar{E} \parallel \bar{B}_0$)



- Launch wave with $f_{\mathrm{wave}} \sim f_{\mathrm{ce}}(R_0)$ for central heating

- Issue of accessibility: reach resonance while avoiding cut-off

ECRH – X-mode ($\delta\bar{E} \perp \bar{B}_0$)

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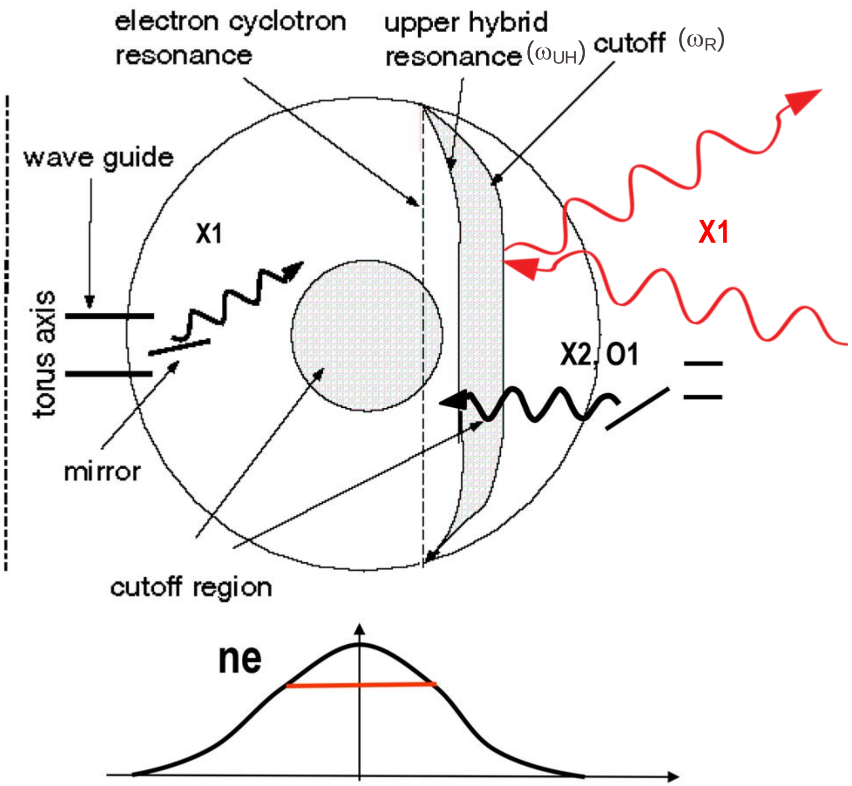
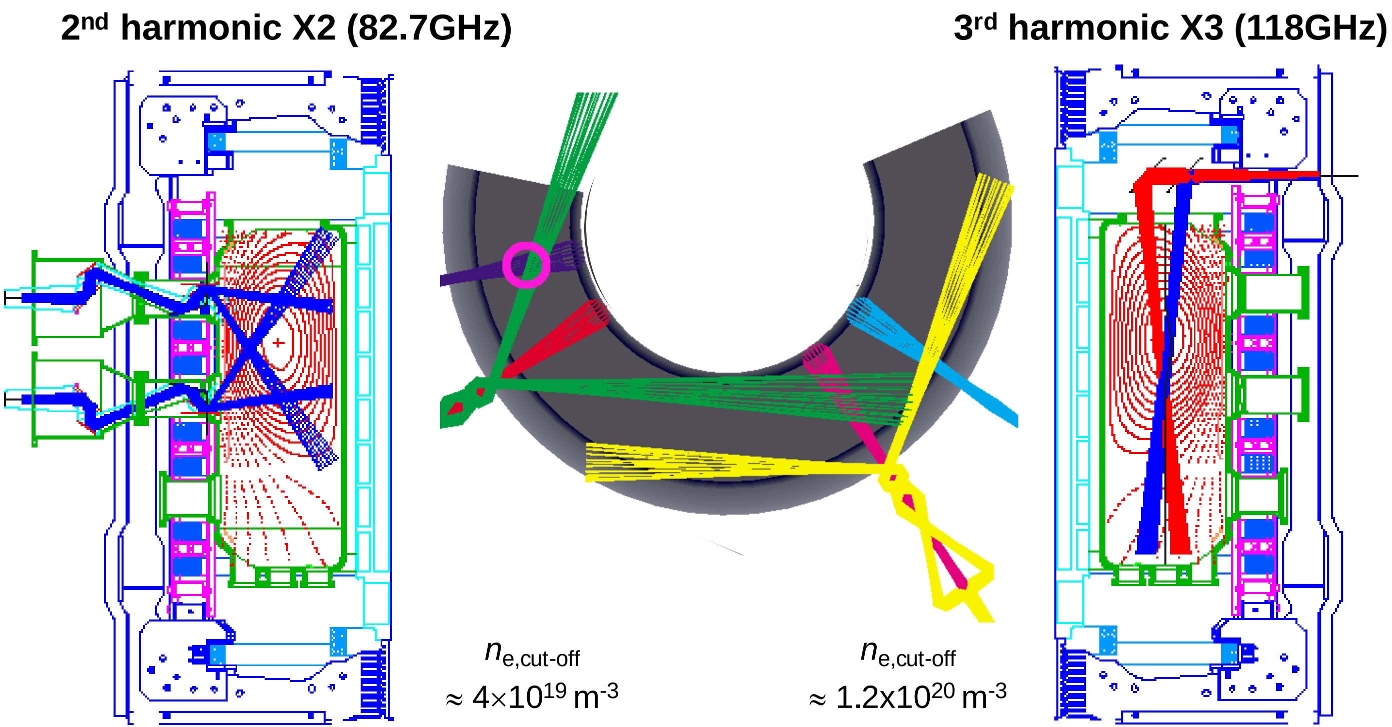


- Launch wave with $f_{\text{wave}} \sim f_{\text{ce}}(R_0)$ for central heating
  - LFS launch encounters cut-off first!

➢ Use 2nd harmonic
$$f_{\text{wave}} \sim 2 f_{\text{ce}}(R_0)$$

- Issue of accessibility: reach resonance while avoiding cut-off

Example of present ECRH system - TCV



6 × 0.5MW, 2s
Side launch ECH, ECCD

3 × 0.5MW, 2s
Top launch ECH

Summary – EC heating (& current drive)

Advantages

- Quasi-optical propagation
- No need for in-vessel antennas
- High flexibility, allowing localised heating and current drive and control of instabilities
- High electrical efficiency

Disadvantages

- Density cut-offs
- Electron heating only
- Ongoing R&D to improve reliability of high frequency, high power sources

Heating by waves - summary

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	ICRH	LH	ECRH
Heated species	(Energetic-) Ions or electrons	Electrons & ions	Electrons
Frequencies	30-100MHz (meter waves)	1-3 GHz (decimetre waves)	30-170GHz (millimetre waves)
Issues	• Requires fast ion population • High E-fields at antenna can damage surface and generate impurities	• Generates fast electrons • Distance between wave guide and plasma must be small	• Plasma density (cut-off restricts access
Advantage	• Can directly heats ions	• 'Cheap' • High current drive efficiency	• Localised absorption

Outline

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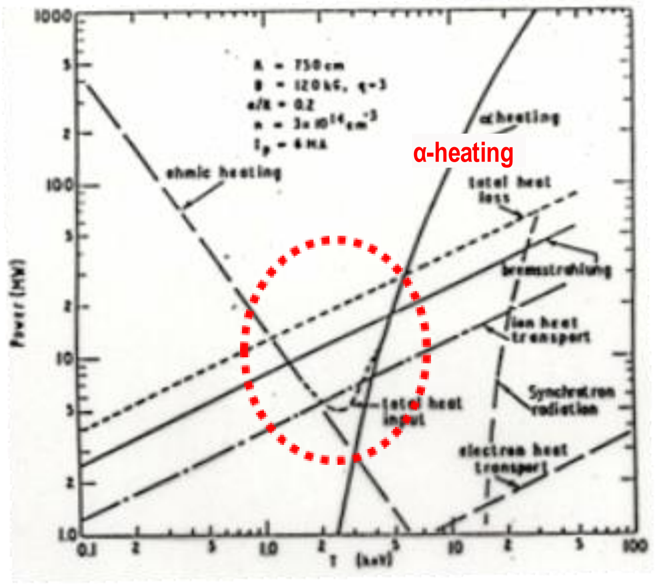
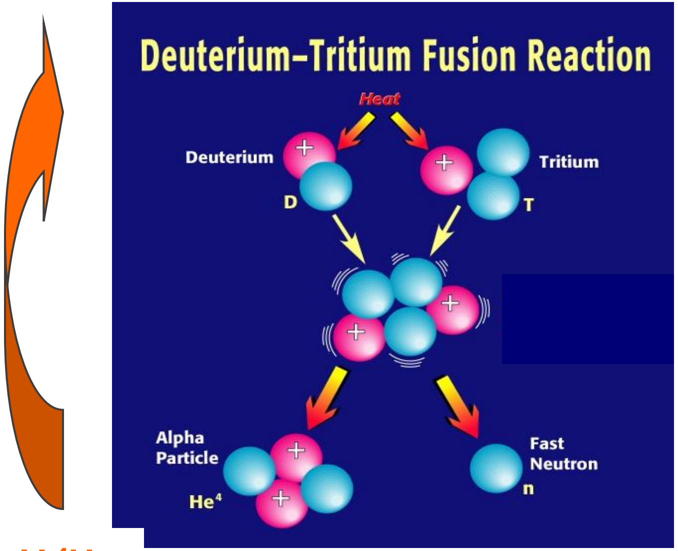
1. Plasma heating
   - Need for (auxiliary) heating
   - Neutral beam heating
   - Heating by waves
2. **ITER as the first burning plasma**
   - Alpha-particle heating
3. Towards a fusion power plant
   - Tritium self-sufficiency



α-particle heating

- Integral part of fusion energy based on D-T reaction
  - Pass energy to D-T plasma through collisions before leaving the plasma
  - Reminder (L5): Neo-classical step size $\delta_{BAN} \approx \delta_{\mathrm{DRIFT}} \approx q\rho_{\mathrm{L}}/\sqrt{\varepsilon}$ with

$$\rho_{\mathrm{L}} = \frac{\sqrt{2m_{\mathrm{i}}k_{\mathrm{B}}T_{\mathrm{i}}}}{qB}$$



3.5 MeV ^{4}He for plasma self-heating

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α-particle heating

- Integral part of fusion energy based on D-T reaction
  - Pass energy to D-T plasma through collisions before leaving the plasma
  - Reminder (L5): Neo-classical step size $\delta_{BAN} \approx \delta_{\mathrm{DRIFT}} \approx q\rho_{\mathrm{L}}/\sqrt{\varepsilon}$ with

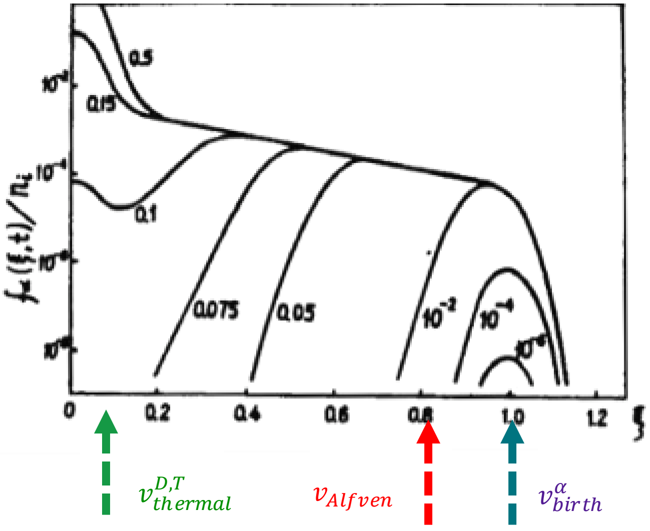
$$\rho_{\mathrm{L}} = \frac{\sqrt{2m_{\mathrm{i}}k_{\mathrm{B}}T_{\mathrm{i}}}}{qB}$$

  - Fast alpha-particles may resonate with Alfvén waves

$$v_{\mathrm{Alfvén}} = \frac{B}{\sqrt{\mu_0 n_i m_i}}$$

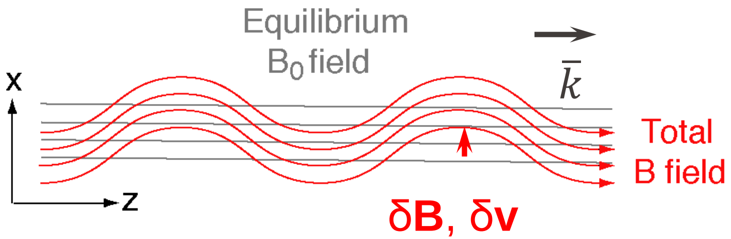
Typical velocities in a tokamak

B=4T; *T*=10keV; *n*=10^{20}m^{-3}

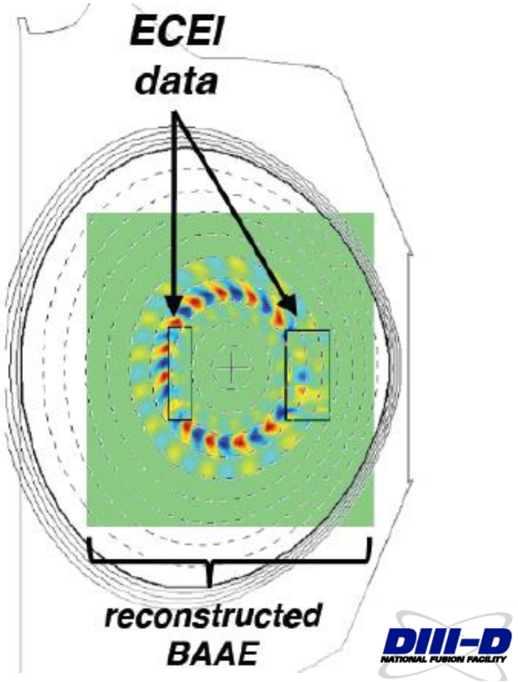


Fast ions and Alfvén waves

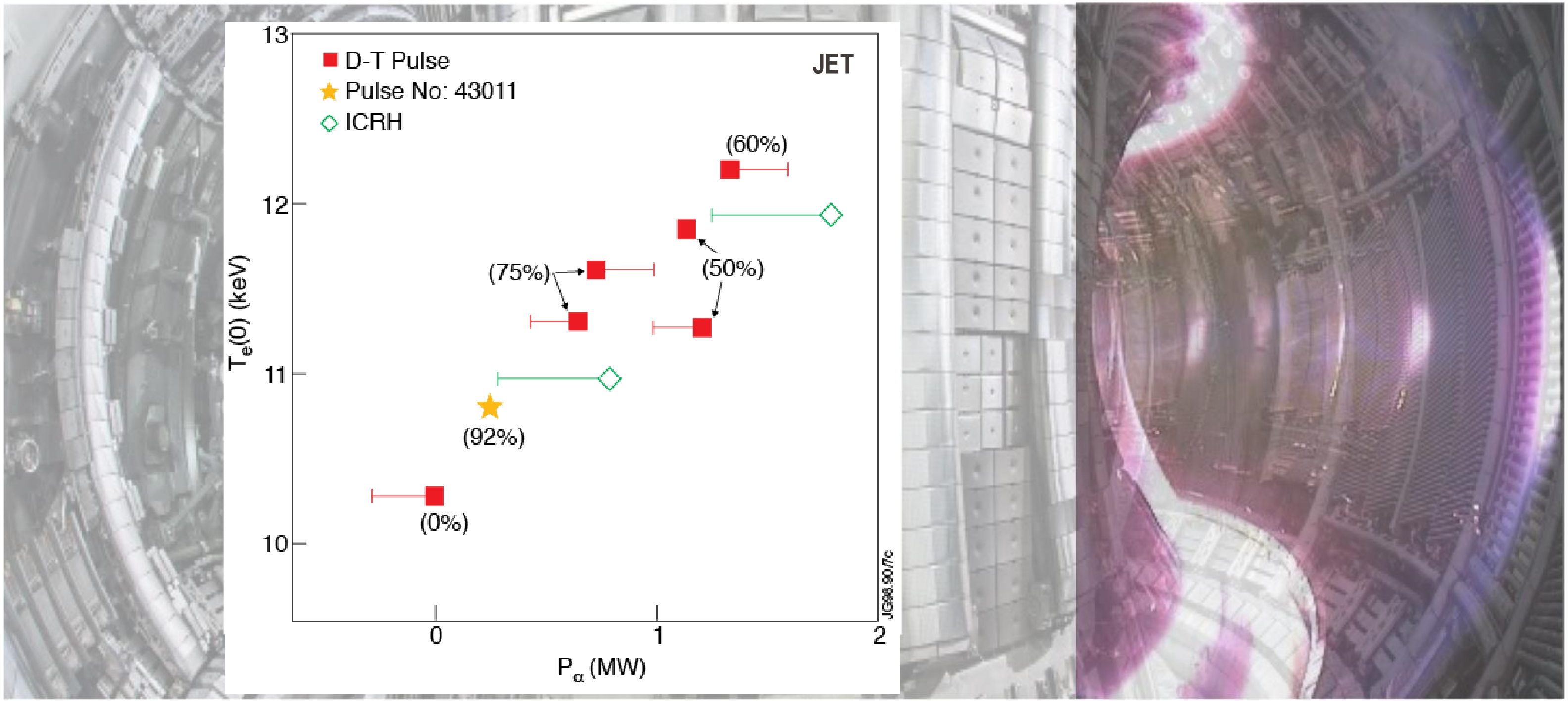
- *B*-field and plasma frozen together → field lines are strings with tension and inertia → Alfvén wave propagation



- Slowing down α's (but also fast ions generated by additional heating) can resonate with Alfvén waves



Electron heating by fusion α's studied in JET D-T plasmas



[JET Team, Nucl. Fusion (1999)]

Definition of a burning plasma (see L1)

- Energy balance

$$dW_{\mathrm{th}}/dt = P_{\alpha} + P_{\mathrm{ext}} - W_{\mathrm{th}}/\tau_{\mathrm{E}}$$

α-heating *ext. heating* *losses*

- Fusion energy gain: $Q = P_{\mathrm{fusion}}/P_{\mathrm{ext}} = 5\,P_{\alpha}/P_{\mathrm{ext}}$
- **α-heating fraction:** $f_{\alpha} = P_{\alpha}/(P_{\alpha} + P_{\mathrm{ext}}) = Q/(Q + 5)$

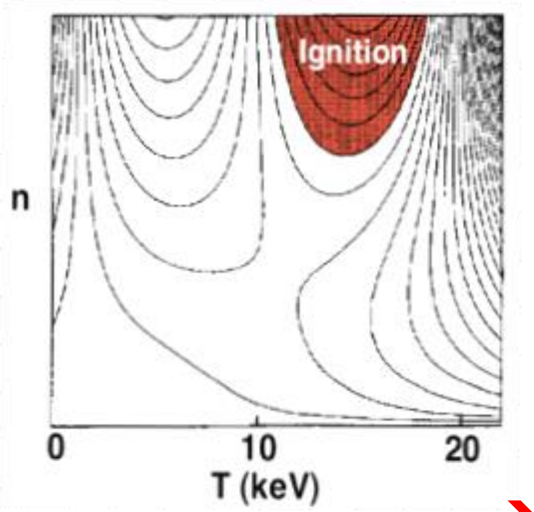
***Q* = 1**	**f_α=17%**	**➔ *breakeven***
***Q* = 5**	**f_α=50%**	
***Q* = 10**	**f_α=67%**	
***Q* = ∞**	**f_α=100%**	**➔ *ignition***

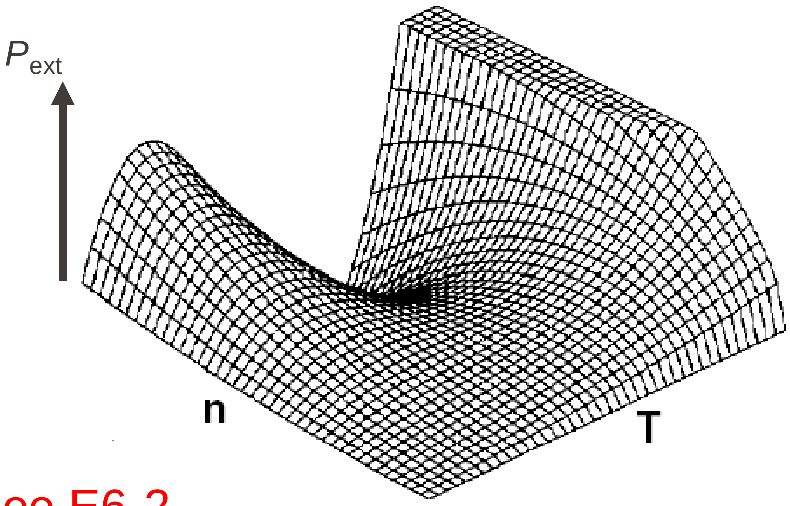
$f_{\alpha} > 0.5$ → *burning plasma*

Burn stability

- A (limited) thermal runaway can occur, when ext. heating for steady-state

$$P_{\text{ext}} = \underbrace{3n_\text{e}TV/\tau_\text{E}}_{P_\text{loss}} - \underbrace{\tfrac{1}{4}n_\text{e}^2\langle\sigma_{\text{D-T}}v\rangle E_{\text{fusion}}V}_{P_\alpha} < 0$$





➔ See E6-2

ITER parameters

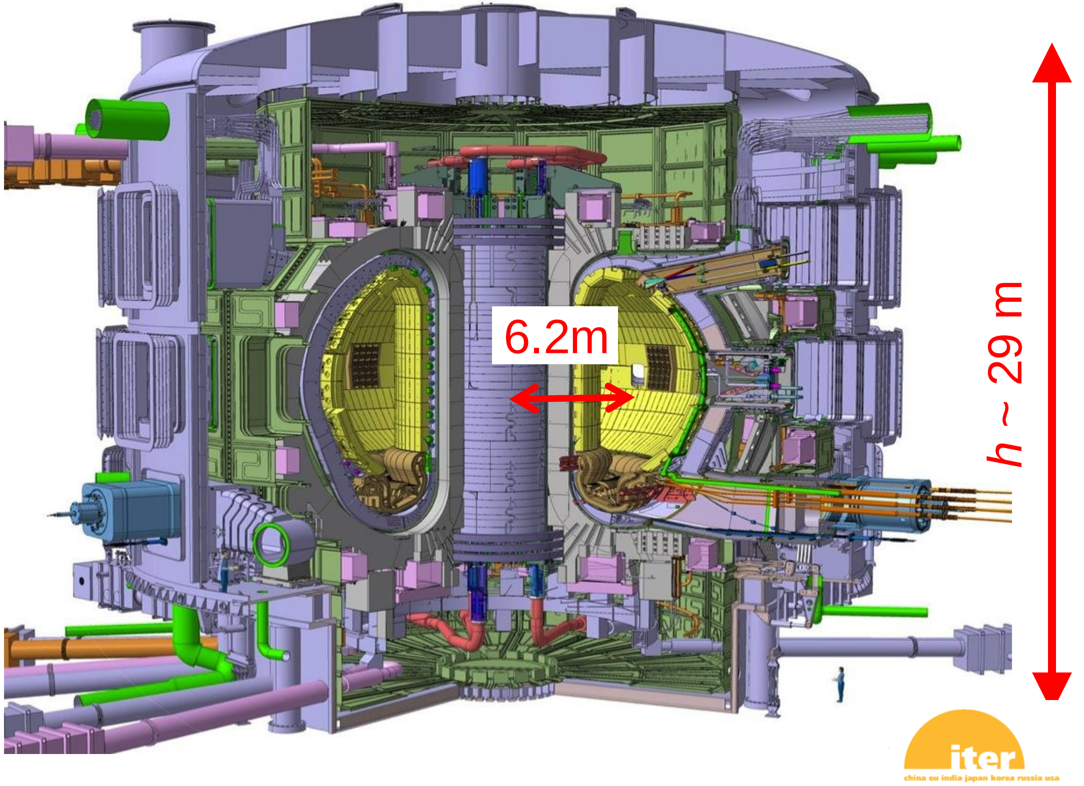
- Major radius
  - $R_0 = 6.2$ m
- Plasma current
  - $I_P \leq 17$ MA
- Magnetic field
  - $B_0 \leq 5.3$ T
- External heating
  - $P_{ext} \approx 50$ MW

⇩

- Costs
  - 10-15 billion €

⇩

- Fusion power
  - $P_{fus} = 500$ MW for 500s



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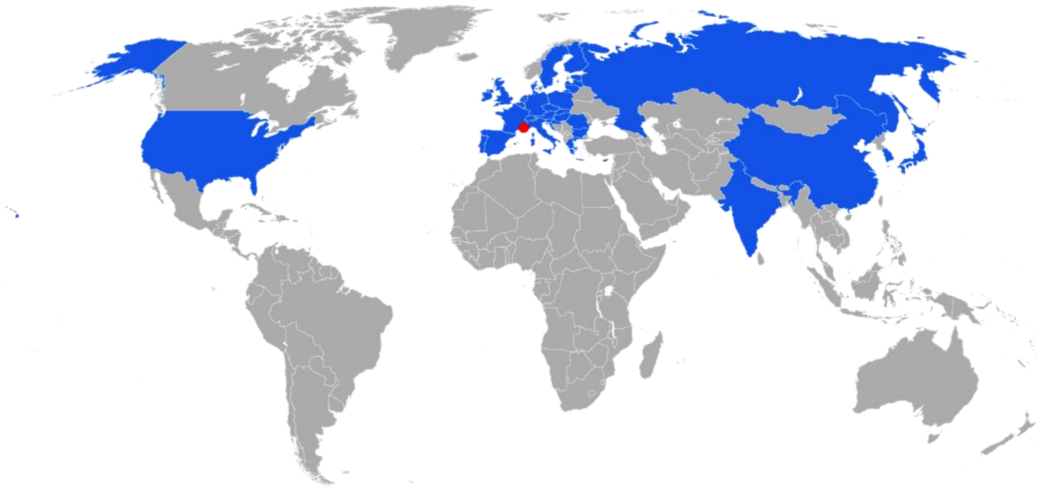
ITER project

- **Mission**: *Demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes*
  - Currently being build in Cadarache, France
  - Major international collaboration in fusion energy research involving Europe, China, India, Japan, Russia, South Korea and USA



iter
china eu india japan korea russia usa

ITER design goals

Physics

- Produce a significant fusion power amplification factor ($Q \geq 10$) in long-pulse operation
- Aim to achieve steady-state operation of a tokamak ($Q = 5$) and retain the possibility of exploring ‘controlled ignition’ ($Q \geq 30$)

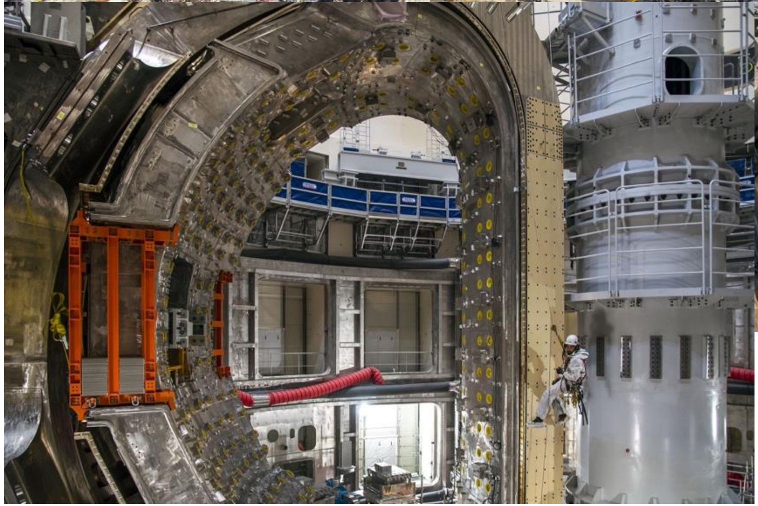
Technology

- Demonstrate integrated operation of technologies for a fusion power plant
- Test components required for a fusion power plant
- Test concepts for a tritium breeding module

ITER construction site

March, 2019 [www.iter.org]

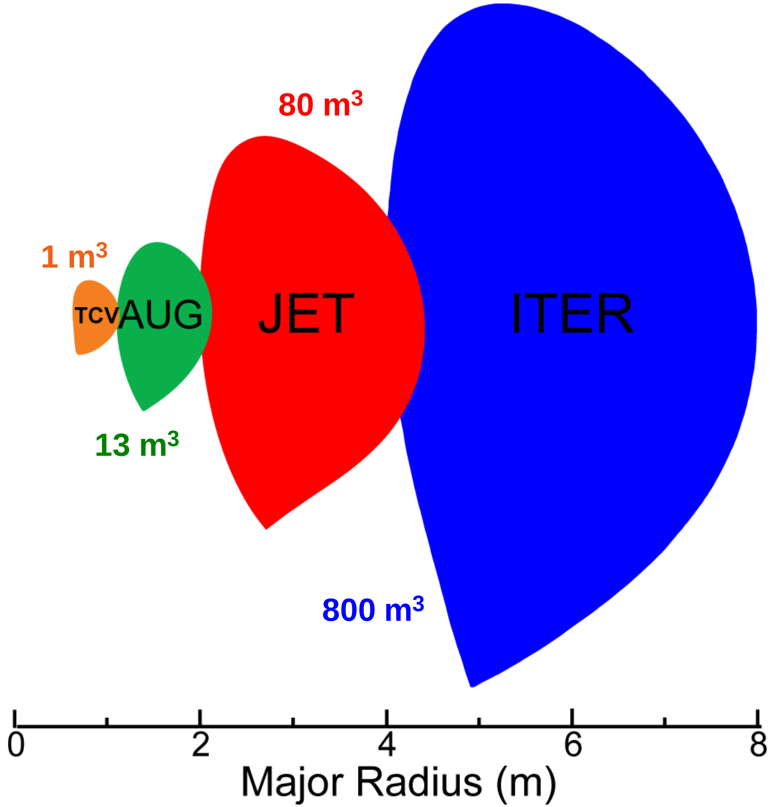
Dec. 2021 [www.iter.org]



June 2022 [www.iter.org]

EU 'step ladder' approach towards ITER

- TCV (EPFL)
  - R = 0.9m
  - B_T = 1.4T
- ASDEX-Upgrade (IPP, Garching, Germany)
  - R = 1.6m
  - $B_T \leq$ 3.9T
- JET (CCFE, Culham, UK)
  - R=3.0m
  - $B_T \leq$ 4T
- ITER
  - R=6.2m
  - $B_T \leq$ 5.3T



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Beyond ITER - DEMO

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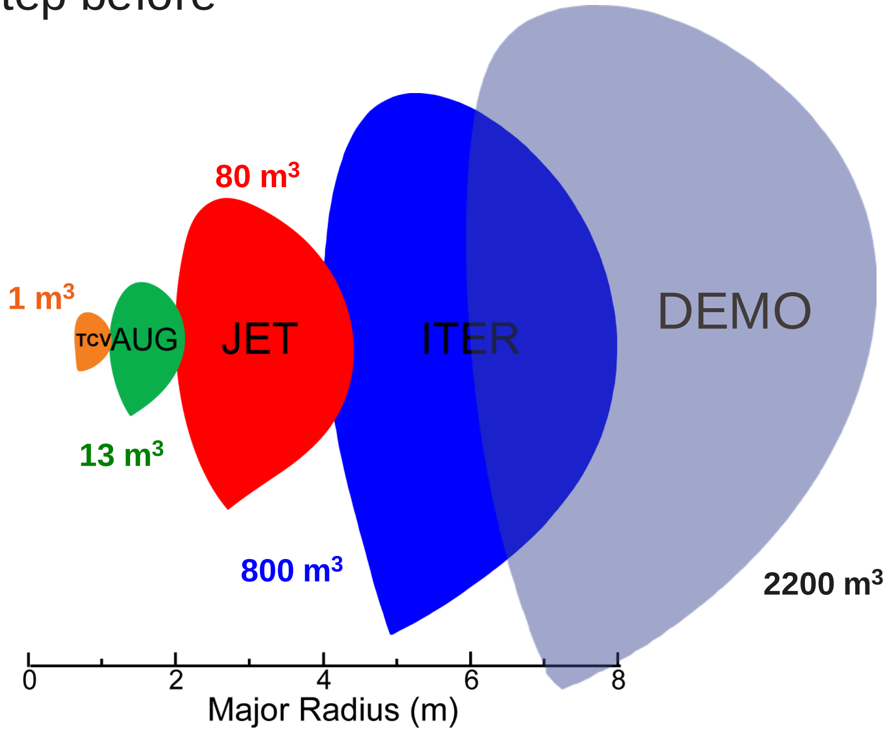
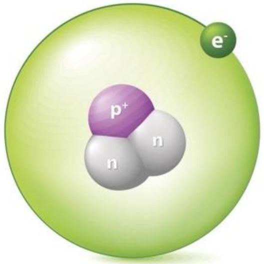
- First fusion power plant - last step before commercial deployment
  - ***Q* ≥ 30**
  - **P_{fusion} ~ 2GW**
  - **$P_{electric}$ ~ 500MW**

➢Requires
  - *R* = 8.8m
  - B_T = 5.8T



Tritium – general properties

- Half life time: 12.3 years
- Decay mode
  - β decay: T → ^{3}He + e + $\bar{\nu}_e$ + 18.6 keV



Tritium consumption

- Tritium – natural inventory

~3.6 kg produced mostly by impact of cosmogenic neutrons on N

^{14}N + n → ^{12}C + T

^{14}N + n → 3 ^{4}He + T

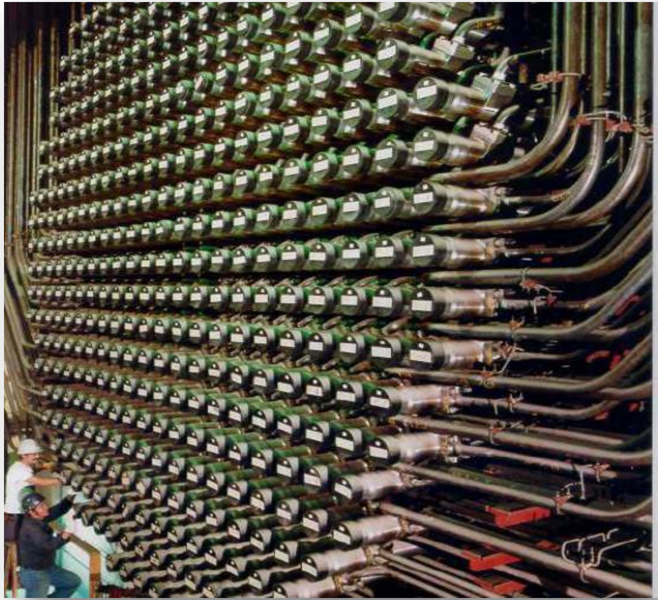
Tritium – anthropogenic inventory

- T is generated in heavy water fission reactors (PHWR), predominantly of CANDU type (CANadian Deuterium natural Uranium reactor)
  - 2015: 31 operating CANDU reactors (+16 Indian derivatives)

- Total T production ~0.3kg/(GWe*year)

➢ Total recovery of 1.5kg/year

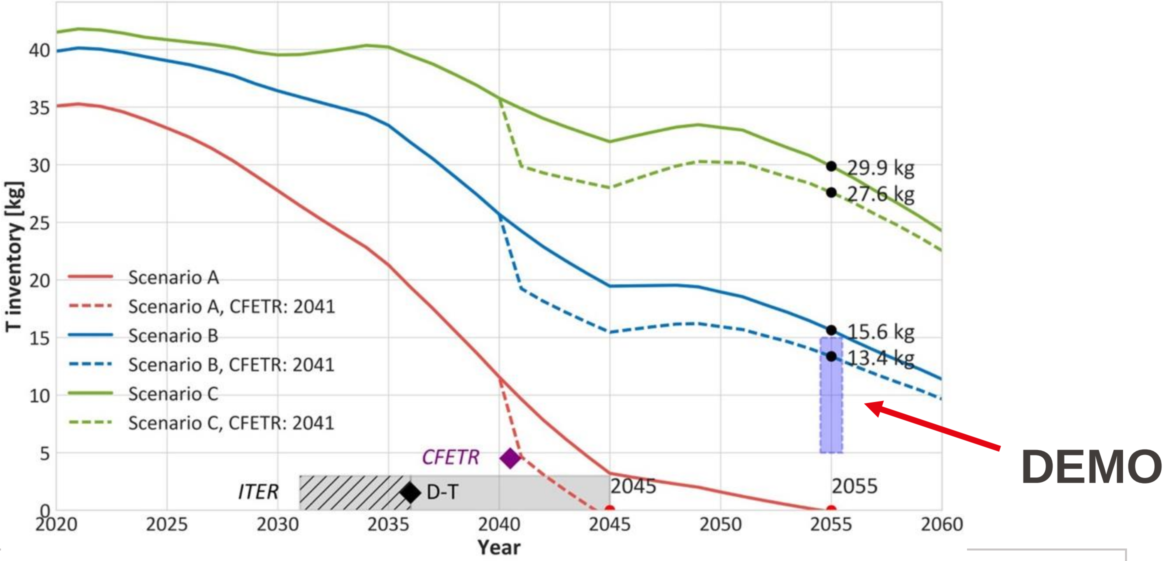
➢ Presently 27kg at hands in Darlington (Canada) recover facility



CANDU Pressurized Heavy Water Reactor

Availability of tritium for the start-up inventory of a DEMO reactor not guaranteed

Projection of tritium inventory in Canada, Romania and Korea



Scenarios differ in refurbishment plans and assumed operational life of CANDU reactors
Source: M. Kovari, et al., Nucl. Fusion (2017)

Tritium breeding blanket

- Fusion reactor must be T self sufficient (see L1)

$$Li^6 + n \rightarrow T + He^4 + 4.8\ \text{MeV}$$

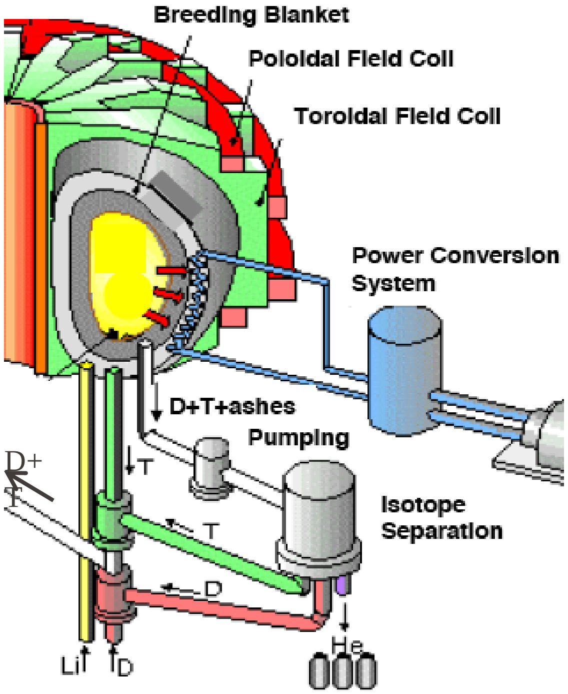
- Tritium breeding ratio

$$\mathbf{TBR} = \frac{\textbf{tritium bred}}{\textbf{tritium burnt}}$$

- **TBR** >1 to compensate losses, which implies the use of n-multiplier
- Reactions (see L1)

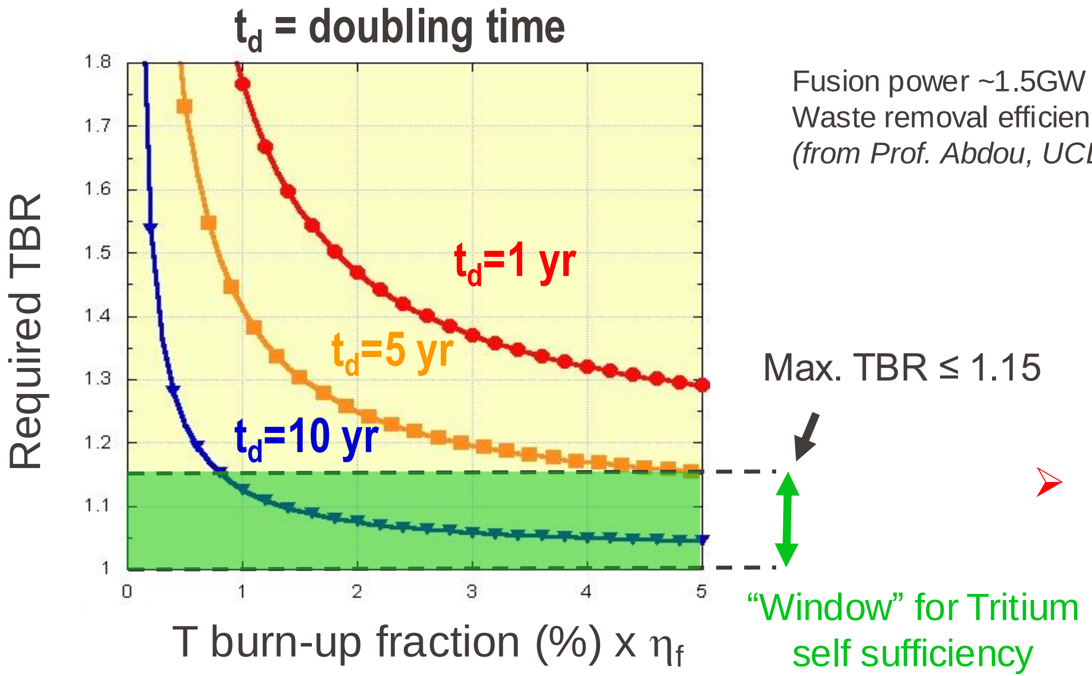
$$\begin{aligned} n + {}^9\text{Be} + 3\ \text{MeV} &\rightarrow 2\alpha + n' + n'', \\ n + \text{Pb} + 10\ \text{MeV} &\rightarrow \text{Pb} + n' + n''. \end{aligned}$$

- Options
  - Be in Li pebbles
  - Pb in the form of LiPb coolant



Impact of T fuel cycle parameters on fusion development

- Required TBR for T self-sufficiency depends on burn-up fraction, fuelling efficiency and fusion reactor doubling time



Fusion power ~1.5GW
Waste removal efficiency ~0.9
(from Prof. Abdou, UCLA)

- Significant R&D needed to stay in window

Recap of 2. and 3.

- Burning plasma
  - Fast ions (alpha particles) must be sufficiently well confined
  - Loss of actuators for control and increased degree of self-organisation
  - Extend parameter regime beyond current experiments
- Tritium fuel cycle of a fusion reactor
  - T inventory critical for safety and deployment (initial and subsequent reactors)
  - Economics would benefit from further R&D
    - Plasma physics: fuelling efficiency η_f, burnup fraction f_B
    - Engineering: Tritium breeding ratio TBR, processing time t_p