PART I

MAGNETIC NUCLEAR FUSION: WHERE WE ARE AND WHAT IS THE NEXT STEP

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Outline

- Introduction to fusion and magnetic fusion
- Plasma heating with fast ions
- NBI and ICRH
- The step from ion heating to electron heating
- Burning plasma as exothermal medium
- Summary

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NUCLEAR FUSION OF HYDROGEN ISOTOPES D&T

- **Nuclear fusion reaction D+T = He + n +17.6 MeV of hydrogen isotopes deuterium (D) and tritium (T) is the “easiest” to access:**

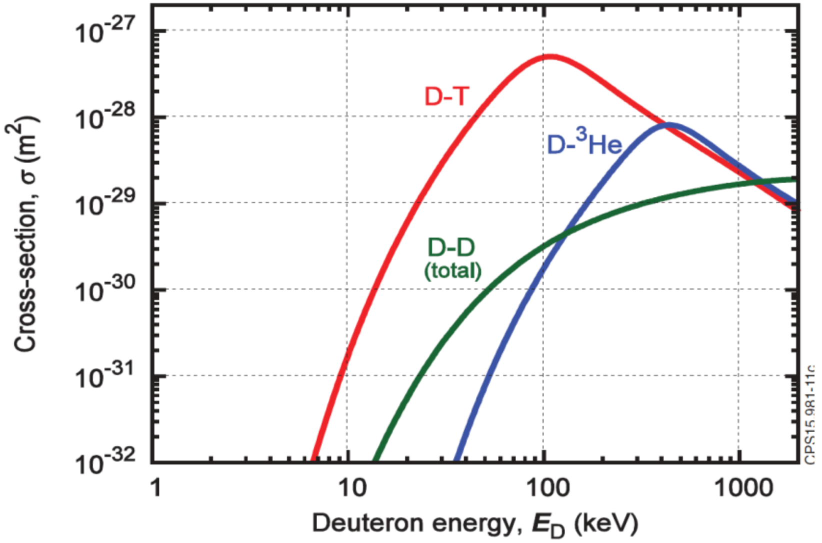


Figure 1. Cross-sections for fusion reactions D–D, D–^{3}He, and D–T as functions of the deuteron projectile energy.

- **Fusion power production: use alpha-particles (20% of fusion energy) for self-sustained heating of the plasma; use neutrons (80% of energy) for breeding new tritium and generating steam/ power.**

ENVIRONMENTAL ADVANTAGES OF FUSION

- Deuterium is naturally abundant (0.015% of all water), Tritium must be obtained from lithium, $^6Li + n = T + {}^4He$. Raw materials are water & lithium.

- To generate 1GW for 1 year (equivalent to a large industrial city):

  COAL: 2.5 Mtonnes – produces 6 Mtonnes CO_2;
  FISSION: 150 tonnes U – produces several tonnes of fission waste;
  FUSION: 1 tonne Li + 5 Mlitres water.

- Fusion gives no “greenhouse” gasses.

- Fusion reactor structure will become activated but will decay to a safe level in < 100 years. Tritium is radioactive: half-life is 13 years.

- No plutonium or long-lived (thousands of years) active waste from fuel cycle.

METHODS OF FUSION PLASMA CONFINEMENT

Gravity (Sun and stars) – works well but dimensions are too large;

Inertial (H-bomb, lasers or beams) – needs pressure 10^{12} atm for very short times 10^{-11} s. Did it work?

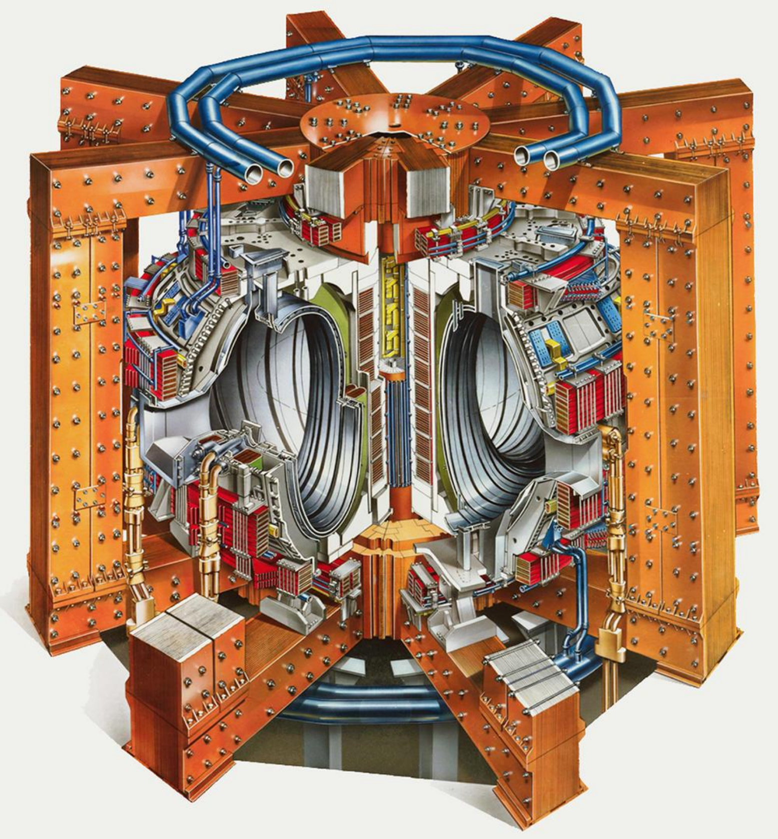
Largest H-bomb tested delivered energy of 2.4×10^{17} Joules = 58.6 Mt of TNT = 10 times the combined power of all the conventional explosives used in World War II, (*https://military-history.fandom.com/wiki/Tsar_Bomba*)

97% of the explosion power was provided by fusion, almost no waste

It was very cheap, ~ 60 cents per 1 kT of TNT in the prices of 1950th (E. Fermi)

Magnetic –(tokamak, stellarators, mirror etc.) – needs few atms x few seconds, plasma is confined by magnetic field B. Work is in progress.

MAGNETIC FUSION: TOKAMAK JET (JOINT EUROPEAN TORUS)



$V \approx 100\ m^3$; $R=3\ m$; $a=1\ m$; $B_{max} = 4\ T$; $I_{max} = 7\ MA$; $P_{FUS} \approx 16\ MW$

ACHIEVING SELF-SUSTAINED MAGNETIC FUSION

- Three key parameters for deuterium-tritium (D-T) fusion to occur in plasma:

  $T_i \approx$ 7-20 keV to overcome Coulomb force between D and T;
  Long enough energy confinement time τ_E = Plasma energy/ Heat loss;
  Fuel density n_D and n_T must be high enough;

- The “ignition” Wesson triple-product criterion for self-sustaining fusion:

$$n\,T\,\tau_E > 5 \times 10^{21}\ \mathrm{m}^{-3}\ \mathrm{keV\ s}\ (\approx 10\ \mathrm{atm\ s}) \qquad (*)$$

Parabolic n, T profiles and peak values were used for (*) [1].
For easier understanding what (*) means for *magnetic* fusion machines, we multiply and divide (*) by B^2 and represent the ignition criterion in the form:

$$\beta\,\tau_E\,B^2 > 4\ \mathrm{T}^2\ \mathrm{s}, \quad \text{where } \beta = P_{plasma}/P_{magnetic} = 4\mu_0\,(nT)/B^2$$

[1] J. Wesson, Tokamaks, Oxford Uni. Press, 4th Edition, p.11 (2011).

THREE WAYS OF ACHIEVING IGNITION IN MAGNETIC FUSION

$$\beta\,\tau_E\,B^2 > 4\ T^2\,s$$

- First way: Increasing τ_E

  This implies a *larger size* fusion reactor. From the balance of plasma energy $W = n \cdot T \cdot V$ for a *steady-state* ignited plasma with volume V and alpha-heating $P_\alpha = 0.2\ P_{FUSION}$, we obtain:

  $$dW/dt = -W/\tau_E + P_\alpha = 0$$

  $$\rightarrow P_\alpha = W/\tau_E = n\,T\,(V/\tau_E)$$

  For generating 1 GW power at typical values B= 5T, β = 5%, we need plasma volume $V \approx 1000\ m^3$ for ignition;

  Present day large volume machine JET had $V \approx 100\ m^3$ → all experiments were done with *sub-critical* volumes;

  Next step burning plasma project ITER will have $V \approx 800\ m^3$.

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THREE WAYS OF ACHIEVING IGNITION IN MAGNETIC FUSION

$$\beta\, \tau_E\, B^2 > 4\ T^2\ s$$

- Second way: Increasing B

Technologically challenging to obtain B > 5 T.
The engineering constraints on the *coil structural integrity* become severe as the magnetic pressure generated is $B^2/2\mu_0 \approx 1\ kg/cm^2$ for B =0.5 T, but it becomes ≈ 400 kg/cm^2 for B =10 T.

Present-day: Alcator C-MOD (US) with magnetic fields up to 8.1 T [2].
They achieved a world record for plasma pressure in magnetic confinement reaching 2.05 atmospheres.

Several next step machines were considered along this avenue, e.g., IGNITOR (Italy) and FIRE (US).

[2] M. Greenwald et al., Physics of Plasmas 21, 110501 (2014).

THREE WAYS OF ACHIEVING IGNITION IN MAGNETIC FUSION

$$\beta\, \tau_E\, B^2 > 4\ T^2\ s$$

- **Third way: Increasing β**

β is *limited by MHD instabilities* at a level of few % in tokamaks with conventional aspect ratio, e.g. $a/R \approx 0.3$. In contrast to increasing τ_E or B, the increase in β is not a technological problem.

Spherical tokamaks with $a/R \approx 1$, START [3] and then – NSTX, achieved volume averaged $<\beta> \geq 30\%$!

Present day: MAST-Upgrade (UK) and NSTX-Upgrade (US).
Next step project: STEP (UK).

The use of *high-temperature superconductors* may increase B in STs significantly thus combining the two avenues of B and β increase in STs.

[3] M. Gryaznevich et al., Phys. Rev. Lett. 80 (1998) 3972

HEATING THE PLASMA WITH FAST IONS:

WHERE WE ARE NOW

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S.E.Sharapov, Schekochihin Seminar, Oxford University, 28 January 2025

OHMIC HEATING

- Tokamaks are heated initially by the plasma current

$$\text{Ohmic power} = I_P\, V = [I_P]^2\, R$$

$$\text{Plasma resistivity } R \sim [T_e]^{-3/2}$$

- As the plasma gets hotter:
  - its resistivity gets smaller – the ohmic power falls
  - the energy losses increase - τ_E gets smaller
  -

- Additional heating techniques are needed to obtain 7-20 keV temperature thermal ions. Heating plasma up to this temperature range with a low density population of fast ions from auxiliary heating systems is one of the most attractive ways

CLASSICAL SCHEME OF PLASMA HEATING BY FAST IONS-1

- **Fast ion (E_{Hot} >> T_e, T_i) population is used of low density, n_{Hot} << n_e**
- **Energy content may be comparable to thermal plasma, $\beta_H = n_{Hot}\, E_{Hot} \sim \beta_{therm}$**
- **The fast ions transfer their energy to thermal ions and electrons by Coulomb collisions. If the energy of the fast ions is less than a critical value**

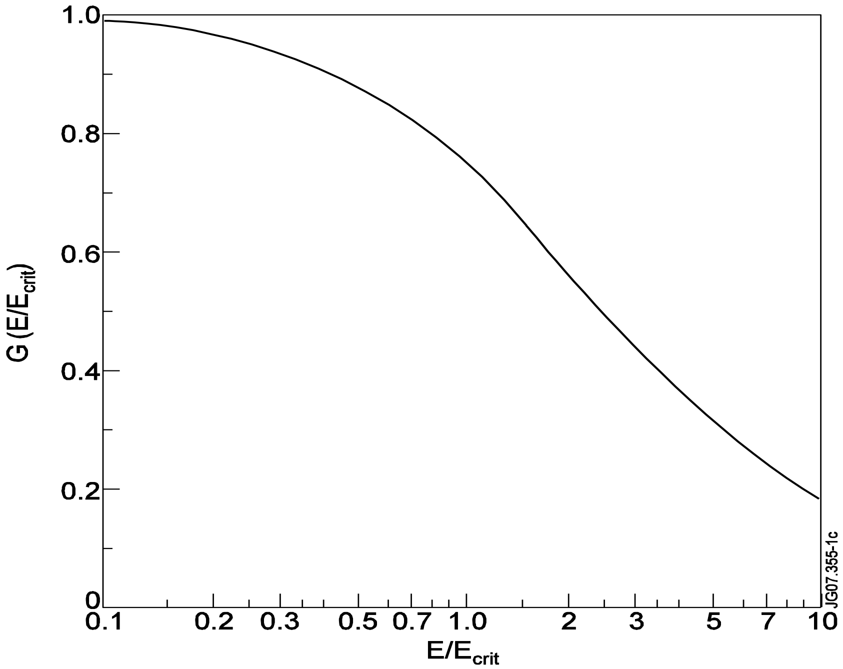
$$E_{crit} = 14.8 A_f T_e \left(\sum_i n_i Z_i^2 / n_e A_i \right)^{2/3},$$

power flows mainly to thermal ions rather than to electrons. Here, A_f, A_i are atomic masses of fast and thermal ions, Z_i is atomic number of thermal ions.

- **For hydrogen beam and plasma we have $E_{crit}=15T_e$**

CLASSICAL SCHEME OF PLASMA HEATING BY FAST IONS-2

- **The amount of energy going from ions with initial energy E into plasma ions is given by Stix formula $G_i = \frac{E_{crit}}{E}\int_0^{E/E_{crit}} \frac{dy}{1+y^{3/2}}$, and $G_i\left(E/E_{crit}\right)$ is illustrated below**



FAST PARTICLES IN JET DT DISCHARGE WITH 16 MW FUSION

	E, keV	E_{crit}/T_e	E/E_{crit} for T_e=14 keV	$G_i/G_e = G_i/(1-G_i)$
Fusion alpha-particles	$3.52 \cdot 10^3$	33	7.62	0.3
Deuterium NBI	140	16.5	0.61	5.67
Tritium NBI	160	25	0.46	9
ICRH-accelerated hydrogen	≈500	8.25	4.33	0.54

Main types of energetic ions in JET D-T plasma (D:T=50:50, JET pulse #42976).

AUXILIARY HEATING ON JET: NEUTRAL BEAM INJECTION - 1

- Positive ions from ion source accelerate by grids to energy of up to ≈150 keV
- Then they pass through the neutraliser and become neutral high energy atoms
- The neutral beam penetrates the tokamak plasma then. The penetration of the beam depends on the NBI energy, mass and on the plasma density
- Within plasma neutrals are ionized by collisions with thermal ions & electrons
- These NBI-produced fast ions are trapped by the tokamak magnetic fields
- NBI systems on JET, JT-60U, TFTR, DIII-D have $E \leq E_{crit}$ so they heat IONS
- NBI systems on MAST & NSTX, (and future Negative NBI of ≈1 MeV on ITER) have $E > E_{crit}$ so they heat ELECTRONS

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NEUTRAL BEAM INJECTION - 2

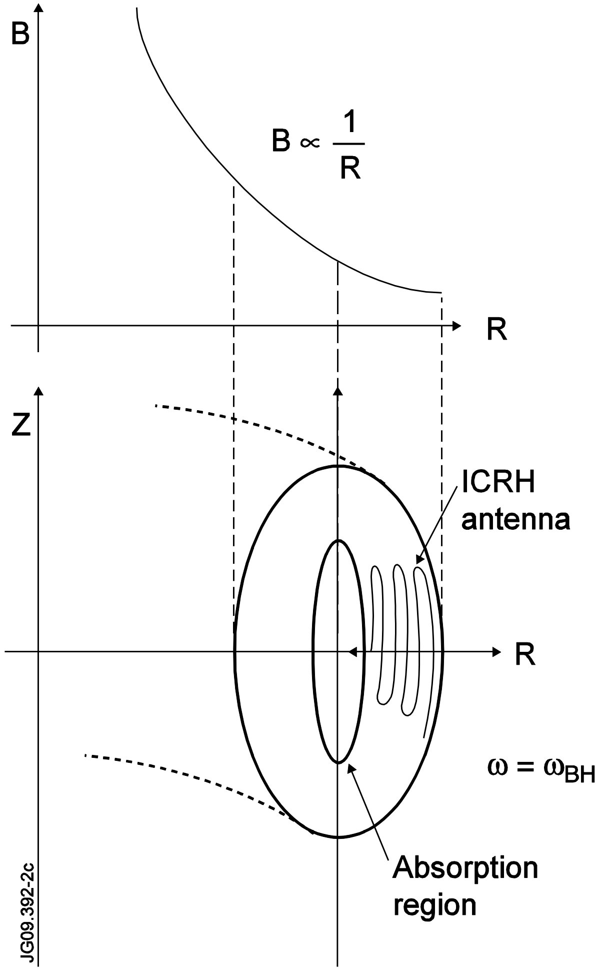
Advantages

- Efficient heating of ions
- High power capability (40 MW on TFTR, 32 MW on JET)
- Drives plasma rotation (stabilising lock modes)
- Fuelling!
- Some current drive

Disadvantages

- Need MeV energy beams for penetrating in a reactor of ITER size → Negative ion source for NBI is needed
- Heating not well localised
- Large aperture

AUXILIARY HEATING: ION CYCLOTRON RESONANCE HEATING



ION CYCLOTRON RESONANCE HEATING - 2

Advantages

- Localised heating
- Hydrogen minority ICRH creates H minority with $E > E_{crit}$ - it heats ELECTRONS
- However, heating of IONS is also possible (e.g. ^{3}He minority in DT plasma)
- Some current drive

Disadvantages

- Antenna inside the vessel
- Low power capability
- Plasma coupling may be a problem in, e.g. H-mode with ELMs affecting plasma edge

HEATING THE PLASMA WITH FUSION ALPHA-PARTICLES

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ALPHA PARTICLE HEATING AND BURNING PLASMAS

- Alphas born at 3.5 MeV have $E \gg E_{crit}$ → they heat ELECTRONS

- The step from present-day experiments on Large machines (JET, JT-60U, TFTR, DIII-D) to future burning plasma experiments (ITER, STEP, DEMO etc.) means a transition from

NBI →ion heating → FUSION

To

α's + NNBI +ECRH → electron heating → ion heating →FUSION

- The additional electron intermediatory may be a difficult one. Say, we know how fast ions interact with ITG. However, we may have a larger problem of whether/ how they will interact with ETG (or some other electron turbulence), even before ITG becomes important.

Example: Electron Heating in Shaped Plasmas. Important for ITER as α-particles will heat mostly electrons

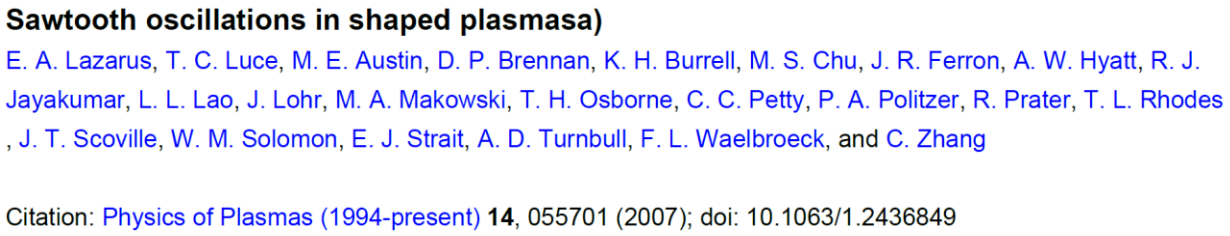
INSTITUTE OF PHYSICS PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION

Plasma Phys. Control. Fusion **48** (2006) L65–L72 doi:10.1088/0741-3335/48/8/L01

LETTER TO THE EDITOR

A comparison of sawtooth oscillations in bean and oval shaped plasmas

E A Lazarus[1], F L Waelbroeck[2], T C Luce[3], M E Austin[2], K H Burrell[3], J R Ferron[3], A W Hyatt[3], T H Osborne[3], M S Chu[3], D P Brennan[4], P Gohil[3], R J Groebner[3], C L Hsieh[3], R J Jayakumar[5], L L Lao[3], J Lohr[3], M A Makowski[5], C C Petty[3], P A Politzer[3], R Prater[3], T L Rhodes[6], J T Scoville[3], E J Strait[3], A D Turnbull[3], M R Wade[3], G Wang[6], H Reimerdes[7] and C Zhang[8]



Sawtooth oscillations in shaped plasmasa)

E. A. Lazarus, T. C. Luce, M. E. Austin, D. P. Brennan, K. H. Burrell, M. S. Chu, J. R. Ferron, A. W. Hyatt, R. J. Jayakumar, L. L. Lao, J. Lohr, M. A. Makowski, T. H. Osborne, C. C. Petty, P. A. Politzer, R. Prater, T. L. Rhodes, J. T. Scoville, W. M. Solomon, E. J. Strait, A. D. Turnbull, F. L. Waelbroeck, and C. Zhang

Citation: Physics of Plasmas (1994-present) **14**, 055701 (2007); doi: 10.1063/1.2436849

RESISTIVE INTERCHANGE DEPENDS ON PLASMA CROSS-SECTION

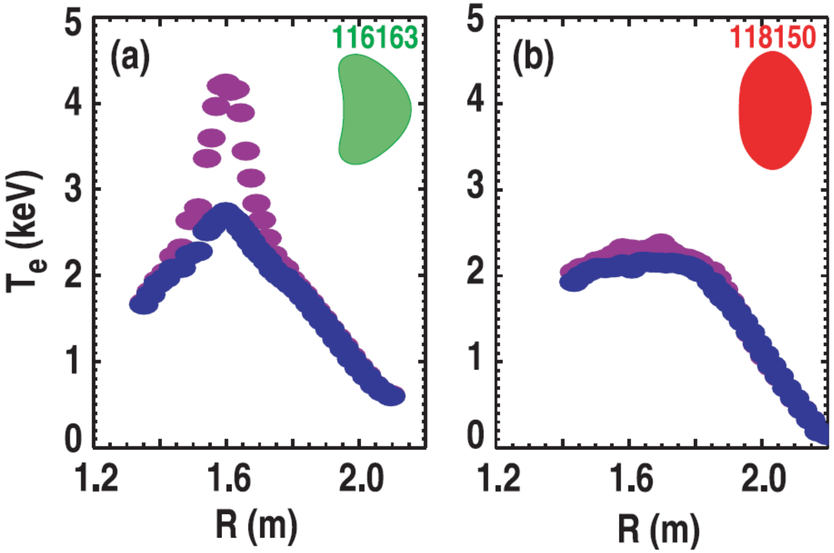


Figure 5. Response to 10 ms pulse of central ECH in middle of sawtooth ramp. The lower profiles (blue) are 1 ms before ECH and the upper profiles (violet) are 10 ms later; (*a*) bean shape with deposition centred at $\rho \approx 0.02$ and (*b*) the oval shape with deposition centred at $\rho \approx 0.06$. Note that even before the ECH there is already a substantial difference in the central ∇T_e.

Which scenario will be relevant for ITER?

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ALPHA-PARTICLE HEATING OF DEUTERIUM-TRITIUM PLASMA:

- Burning plasmas: auxiliary heating used for some control, but plasma self-heating by fusion alphas dominates → plasma becomes exothermic medium

- The leading-order alpha-particle heating effects may be identified in accordance with $Q=P_{FUS}/P_{IN}$,

$Q \approx 1$ – at the threshold (JET had $Q \approx 0.6$ in record fusion power plasma in 1997)
$Q \approx 5$ – alpha-particle effects on heating, turbulence, and on Alfvén instabilities
$Q \approx 10$ (ITER target) – nonlinear coupling between alphas, MHD stability, bootstrap current, turbulent transport, interaction plasma-boundary
$Q \geq 20$ – burn control and transient ignition phenomena
$Q \rightarrow \infty$ - ignition (the fusion DT plasma becomes entirely self-heated through the fusion-born α-particles).

The transport properties of α-particles are of crucial importance for plasma heating profile, the plasma dilution due to the 'helium ash' accumulation, and the power loading upon the first wall.

SUMMARY

- Fusion of D&T isotopes is a very attractive, but difficult (!!!) option for energy production on our planet
- Three main avenues derived for the ignition in magnetic fusion: i) the large plasma volume avenue, ii) the high B avenue, and iii) the high β avenue
- Depending on the energy, fast ions deliver most of their energy to electrons or ions of thermal plasma.
- Auxiliary heating systems with fast ions on JET: i) neutral beam injection (NBI) that herats IONS, and ion cyclotron resonance heating (ICRH) that heats ELERCTRONS in H-minority scenario, or IONS in the He3 minority case.
- Alpha-particles heat electrons. Negative NBI with energy 1 MeV as well as ECRH will heat electrons too, so the next-step burning plasmas will have dominant electron heating and could significantly differ from present-day experiments.
- Many other issues will arise in burning plasma that becomes exothermic medium.