HEATING TOKAMAK PLASMA WITH FAST IONS

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OUTLINE OF LECTURE 2A

- **Ohmic heating of plasmas**
- **Evolution of fast ion distribution function in energy space, ion and electron heating**
- **Drift orbits**
- **Neutral beam injection (NBI)**
- **Ion Cyclotron Resonance Heating (ICRH)**
- **Fusion products**
- **Summary**

OHMIC HEATING

- All tokamaks are heated initially by the plasma current
  Ohmic power = $I_P V = [I_P]^2 R$
  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
  - there is a maximum temperature ~ 5 keV that can be reached by Ohmic heating

- Additional heating techniques are needed to obtain 10-20 keV temperature thermal ions. Heating plasma up to this temperature range with a small density population of “fast” ions with energy $E_f \gg T_i \sim T_e$ is the most attractive and natural way

HEATING THE PLASMA WITH FAST ION POPULATION

- Fast particle population (e.g. fusion-born alpha-particles) has high energy,

$$E_f \gg T_i \sim T_e$$

  but low density,

$$n_f \ll n_e$$

- Energy content of the fast particle population may be comparable to thermal plasma energy content,

$$\beta_f = n_f E_f \sim \beta_{therm}$$

- Source of the fast ions may be isotropic in velocity space (fusion-born alpha-particles) or anisotropic (a beam of fast ions)
- The fast ions transfer their energy to thermal ions and electrons by Coulomb collisions.

FAST ION EVOLUTION IN MAXWELLIAN PLASMA-1

- **Consider evolution of fast ion distribution function, $f\left(v_x,\ v_y,\ v_z\right)$, due to the Coulomb collisions with thermal plasma species in homogeneous plasma. An axial symmetry of the distribution function is assumed during the evolution:**

$$f\left(v_x,\ v_y,\ v_z\right)=f\left(v,\ \vartheta\right);\ v=\sqrt{v_\parallel^2+v_\perp^2};\ \vartheta=\tan^{-1}\left(v_\perp/v_\parallel\right);\ v_\perp=\sqrt{v_x^2+v_y^2};\ v_\parallel=v_z$$

- **This evolution can be described by Fokker-Planck equation for fast ion distribution function $f\left(v,\ \vartheta\right)$ with initial velocity V_0**

- **Typical range of the fast ion velocities satisfies $v_i << V_0 << v_e$. Neglecting self-collisions between fast ions, Fokker-Planck equation becomes linear and it has the form**

FAST ION EVOLUTION IN MAXWELLIAN PLASMA-2

$$\frac{\partial f}{\partial t}=\frac{V_0^3}{\tau v^2}\left\{\frac{\partial}{\partial v}\left[\frac{V_0^2 a(v)}{2v}\frac{\partial f}{\partial v}+b(v)\,f\right]+\frac{c(v)}{V_0}\cdot\frac{1}{\sin\vartheta}\frac{\partial}{\partial\vartheta}\left[\sin\vartheta\frac{\partial f}{\partial\vartheta}\right]\right\}-\nu f+pF$$

where

$$a(v)=\frac{T_e}{E_0}\left\{\tilde{Z}_2+\frac{4}{3\sqrt{\pi}}\frac{m_0}{m_e}\left(\frac{v}{v_e}\right)^3\right\};\qquad b(v)=\tilde{Z}_1+\frac{4}{3\sqrt{\pi}}\frac{m_0}{m_e}\left(\frac{v}{v_e}\right)^3;\quad c(v)=Z_{eff}\frac{V_0}{2v}+\frac{2}{3\sqrt{\pi}}\frac{V_0}{v_e}=Z_{eff}\frac{V_0}{2v}\left(1+\frac{4}{3\sqrt{\pi}}\frac{v}{v_e}\right);$$

$$\tau=\frac{1}{\pi\sqrt{2}}\frac{E_0^{3/2}m_0^{1/2}}{Z_b^2e^4n_eL}$$

$$\tilde{Z}_1=\frac{m_0}{n_e}\sum_i\frac{Z_i^2n_i}{m_i};\qquad \tilde{Z}_2=\frac{m_0}{n_eT_e}\sum_i\frac{Z_i^2n_iT_i}{m_i};\qquad Z_{eff}=(1/n_e)\sum_i Z_i^2n_i;$$

L is the Coulomb logarithm, m_0 the fast ion mass, E_0, V_0 are the initial energy and velocity of fast ions and two last terms in the right-hand-side of this equation represent sink and source of the energetic ions. Source: $2\pi\int_0^\infty v^2dv\int_0^\pi F(v-v_0;\vartheta)\,d\vartheta=1$

VELOCITY SPACE DIFFUSION AND DRAG

$$\frac{\partial f}{\partial t}=\frac{V_0^3}{\tau v^2}\left\{\frac{\partial}{\partial v}\left[\frac{V_0^2 a(v)}{2v}\frac{\partial f}{\partial v}+b(v)f\right]+\frac{c(v)}{V_0}\cdot\frac{1}{\sin\vartheta}\frac{\partial}{\partial\vartheta}\left[\sin\vartheta\frac{\partial f}{\partial\vartheta}\right]\right\}-\nu f+pF$$

- Diffusion of $f(v,\ \vartheta)$ is given by two terms proportional to $a(v)$ and $c(v)$, with the pitch-angle scattering $c(v)$ usually dominating over the velocity diffusion $a(v)$
- The diffusion gives a broadening (in velocity space) of the distribution function
- The drag (also called “dynamical friction”) is represented by $b(v)$.
- The drag gives a deceleration (slowing-down) of the distribution function

CLASSICAL SCHEME OF PLASMA HEATING BY FAST IONS-1

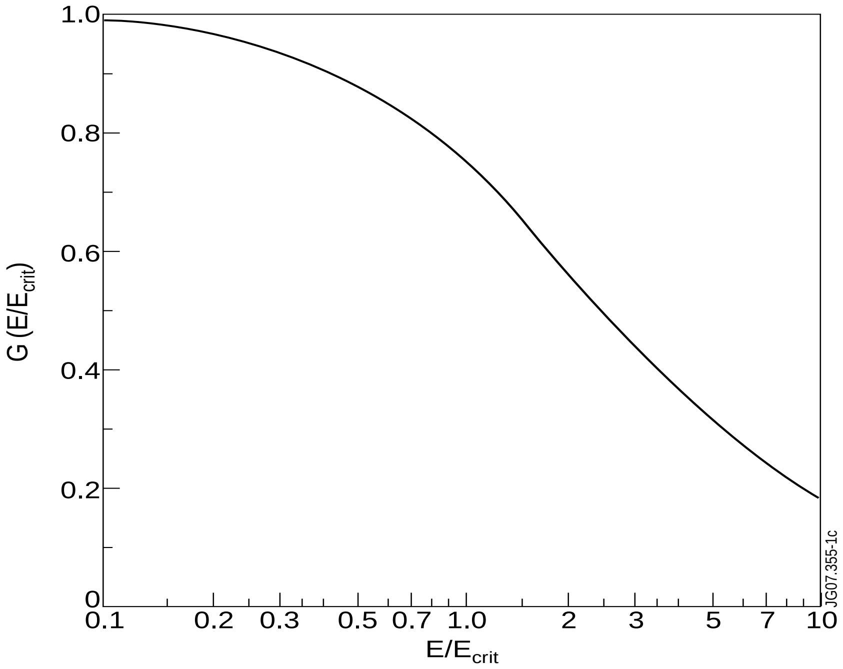
- The fast ions transfer their energy to thermal ions and electrons by Coulomb collisions. If the energy of the fast ions is less than a critical value

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

  power flows mainly to thermal ions rather than to electrons. Here, A_f, A_i are atomic masses of fast ions and thermal ions, T_e is electron temperature, n_i and n_e are ion and electron densities, and Z_i is atomic number of thermal ions.
- Above the critical energy, the drag dominates in Fokker-Planck equation
- Below the critical energy the diffusion dominates

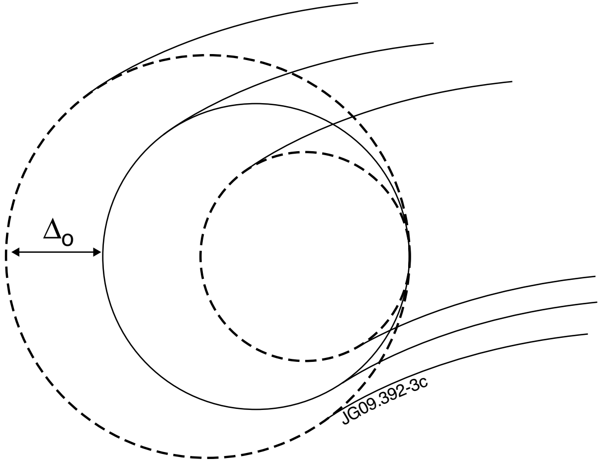
CLASSICAL SCHEME OF PLASMA HEATING BY FAST IONS-2

- 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



ION ORBITS IN A TORUS - 1

- In a straight magnetic field the ions move along helical orbits centered on a field line. The radius of the orbit is the Larmor radius
- In a torus the ion orbits are centered on drift surfaces which are displaced from the magnetic surface by value $\Delta_{Orbit} \equiv \Delta_O$



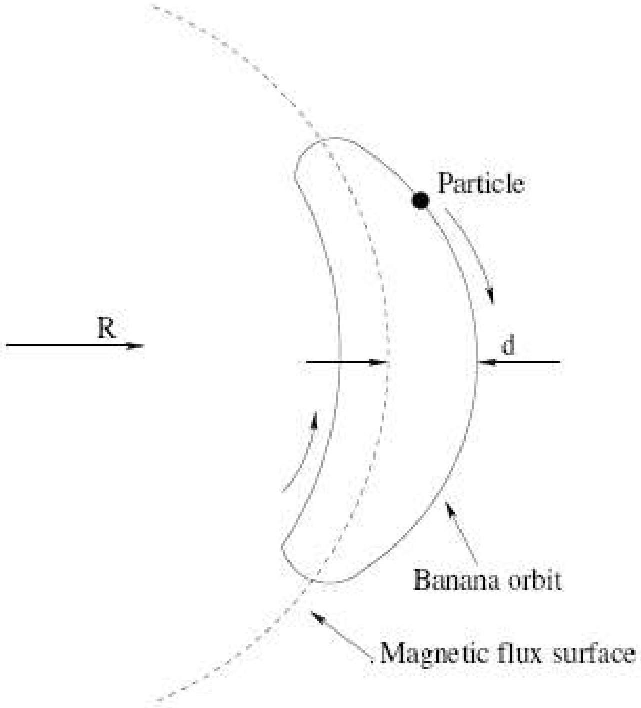
- The Larmor radius depends on B_T. The displacement Δ_O depends on B_P (and thus on current I_P) and is:

  Inwards for ions moving in the same direction as I_P

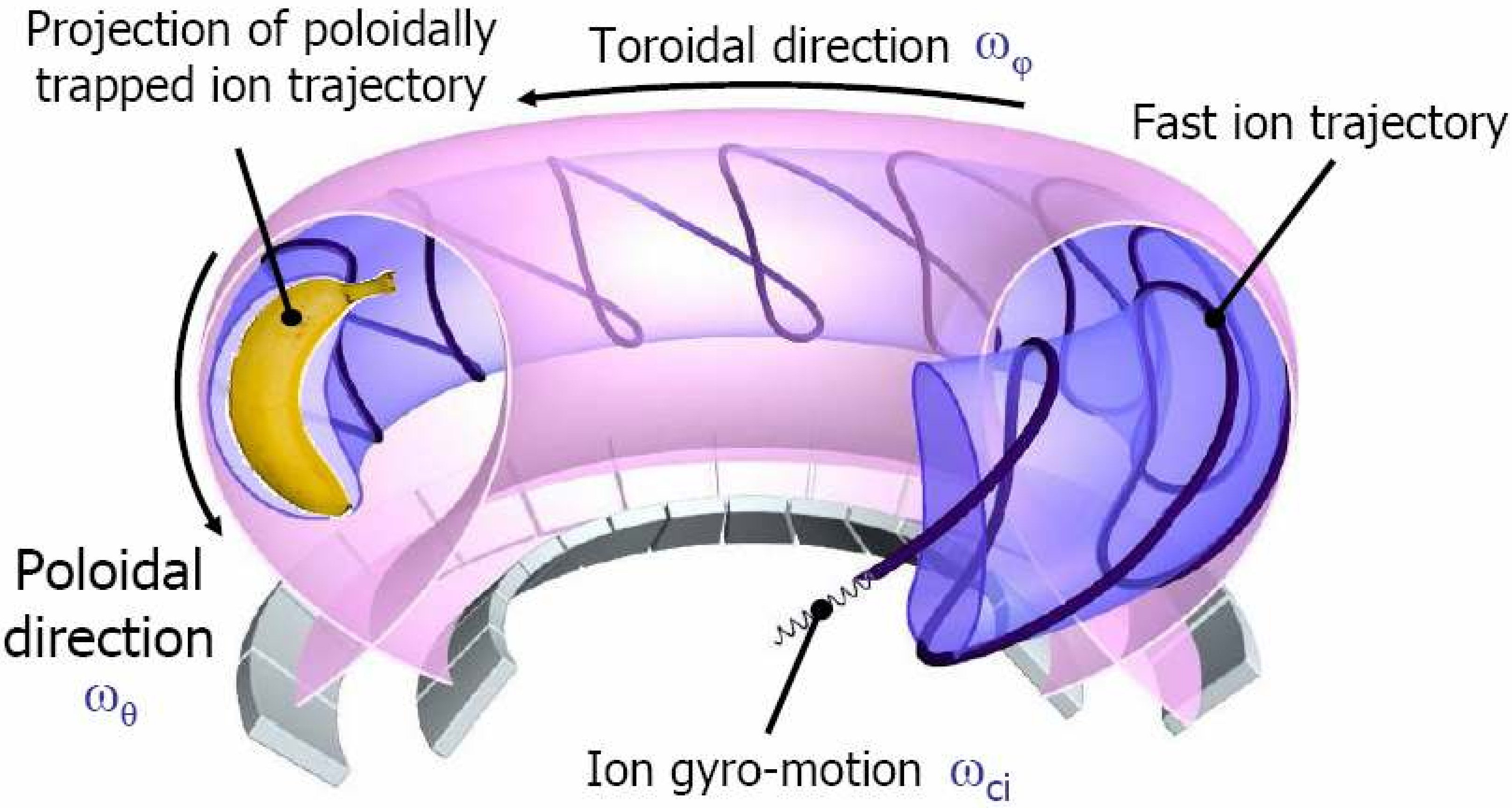
  Outwards for ions moving in the opposite direction

ION ORBITS IN A TORUS - 2

- Some ions are reflected by the strong toroidal field at the inside of the torus
- The projection of the ion orbit onto the poloidal plane looks like a “banana”



FAST PARTICLE ORBITS: TRAPPED ORBITS



NEUTRAL BEAM INJECTION - 1

- Ions from the ion source accelerate by grids to high energy
- Then they pass through the neutraliser and become neutral high energy atoms
- The neutral beam penetrates the tokamak magnetic fields. 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 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 NBI on ITER) have $E > E_{crit}$ so they heat ELECTRONS

NEUTRAL BEAM INJECTION - 2

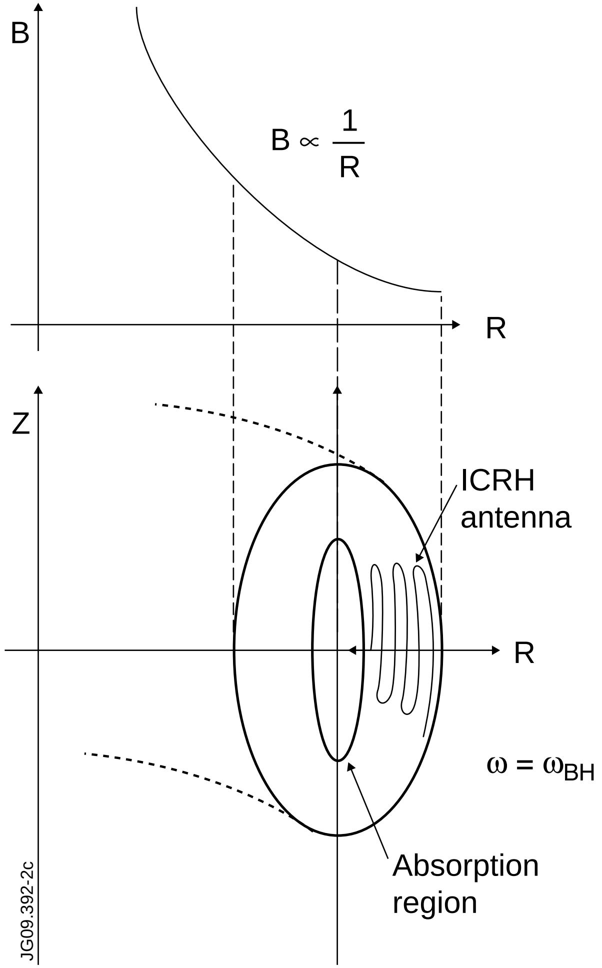
Advantages

- Efficient heating of ions
- High power capability (40 MW on TFTR, 24 MW on JET)
- Drives plasma rotation (stabilising lock modes)
- Fuelling!
- Some current drive

Disadvantages

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

ION CYCLOTRON RESONANCE HEATING - 1



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

ALPHA PARTICLE HEATING AND BURNING PLASMAS

- Burning plasmas: auxiliary heating used, but significant plasma self-heating by fusion alphas exists → plasma becomes exothermic medium

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

- However, electrons do not fuse, we need to heat ions with fusion born alpha-particles. The problem of re-directing the alpha-heating from electrons to IONS is called “alpha-channeling”

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	$3.52\cdot10^3$	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).

FAST PARTICLES IN JET

Machine	JET	JET	JET	JET	ITER
Type of fast ions	Hydrogen	He^3	He^4	Alpha	Alpha
Source	ICRH tail	ICRH tail	ICRH tail	Fusion	Fusion
Mechanism	minority	minority	3rd harmonic of NBI	DT nuclear	DT nuclear
τ_S (s)	1.0	0.9	0.4	1.0	0.8
P_f (0) (MW/m^3)	0.8	1.0	0.5	0.12	0.55
n_f (0) / n_e (0) (%)	1.0	1.5	1.5	0.44	0.85
β_f (0) (%)	2	2	3	0.7	1.2
$\langle\beta_f\rangle$ (%)	0.25	0.3	0.3	0.12	0.3
max$\lvert R\nabla\beta_f \rvert$ (%)	≈5	≈5	5	3.5	3.8

Slowing down time: τ_S ; heating power per volume at the magnetic axis: P_f (0); ratio of the on-axis fast ion density to electron density: n_f (0) / n_e (0); on-axis fast ion beta: β_f (0); volume-averaged fast ion beta: $\langle\beta_f\rangle$ (%); normalised radial gradient of fast ion beta, max$\lvert R\nabla\beta_f \rvert$. Predicted values of similar parameters are also given for alpha-particles in ITER.

SUMMARY

- Ohmic heating has maximum 5 keV temperature; heating by small population of fast ions is required to obtain 10-20 keV optimum for DT

- There is a critical energy E_{crit} at which the heating flows from fast ions to electrons and ions become equal. Fast ions with $E > E_{crit}$ heat mostly electrons, $E < E_{crit}$ - heat ions.

- Two dominant effects determine evolution of fast ions in velocity space: drag and diffusion

- Drift orbits of fast ions may be passing or trapped

- NBI and ICRH are two main techniques generating various types of fast ions

- Alpha particles mostly heat electrons