$v_{th_i} < u < v_{th_e}$

$$\frac{d}{dx}\left(\frac{\mathrm{erf}(x)}{x}\right) \xrightarrow{x_i \gg 1} -\frac{1}{x^2}$$

$$\frac{d}{dx}\left(\frac{\mathrm{erf}(x)}{x}\right) \xrightarrow[x_e = \frac{u}{v_{th_e}} \ll 1]{} -\frac{4x}{3\sqrt{\pi}}$$

$$\frac{du}{dE} = -\frac{e^2 q_T^2 \ln\Lambda\, m_e}{4\pi\varepsilon_0^2 m_T^2}\left[\underbrace{\left(1+\frac{m_T}{m_e}\right)\frac{4}{3\sqrt{\pi}}\,u\left(\frac{m_e}{2T_e}\right)^{\frac{3}{2}}}_{\text{electron contr.}} + \underbrace{Z\left(1+\frac{m_T}{m_i}\right)\frac{1}{u^2}}_{\text{ion contr.}}\right]$$

$E_{cr} = [20 \div 30]\cdot T_e$

$k_B T$ E_{cr} E_{T_0}

1) $E_{T_0} > E_{cr}$ mostly ions ⋮ mostly electrons

2) $E_{T_0} < E_{cr}$ mostly ions ⋮ /

$\tau_{coll} \sim ms$

$$t_E \sim \left(\frac{m_i}{m_e}\right)\cdot \tau_{coll} \sim s$$

Types of heating systems:

Ohmic heating : initial phases of the discharge

Neutral Beam injection

Wave heating → ion cyclotron resonance heating
→ electron " " "

Auxiliary heating mechanisms

Heating by the fusion products

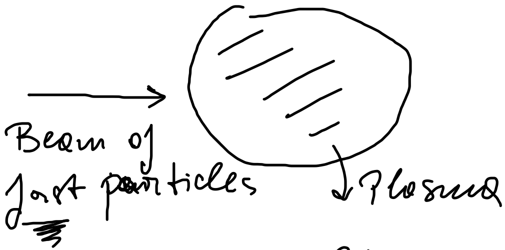
→ intrinsic heating mechanism

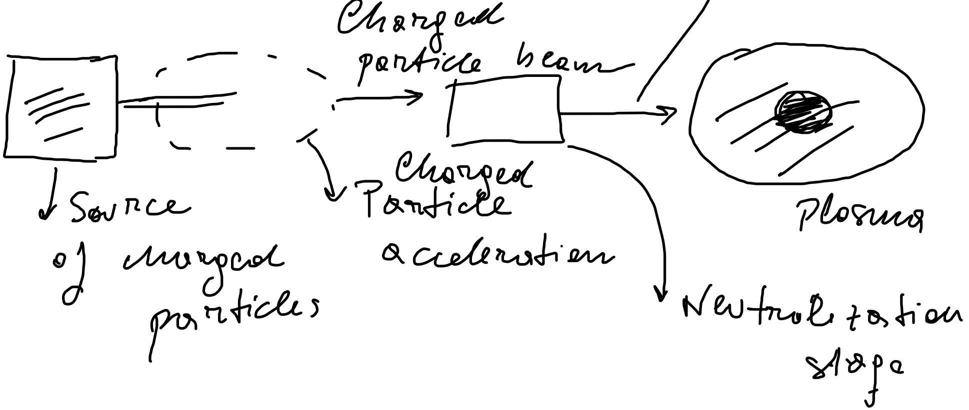
$$d + t \rightarrow \alpha + n \qquad E_n \simeq 14\ MeV \qquad E_\alpha \simeq 3.5\ MeV$$

$T \sim keV$

α ↓ confined

Neutral Beam Injection





In the plasma the neutral beam is ionized

Ionization should occur mostly in the centre

$\Rightarrow$ E_b is chosen to ionize the beam mostly in the centre

Present day machines

$E_b \lesssim 100$ keV

$R_0 = 1 \div 3$ m

$a = 0.5 \div 1$ m

$T \sim$ keV

$n \sim 10^{19} \div 10^{20}$ m^{-3}

$T \sim 5$ keV

$E_{cr} \sim 30 \cdot T_e \sim 150$ keV

$E_b < E_{cr}$

NBI mostly heats the ions in present day devices

Future devices (large) ITER

$R_0 = 6$ m

$a = 2$ m

$n > 10^{20}$ m^{-3}

$E_b \sim 1$ MeV

$T_e \sim 20$ keV

$E_{cr} \sim 500 \div 600$ keV

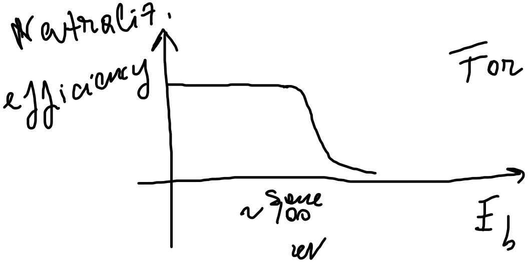
$E_b > E_{cr}$

NBI heats mostly the electrons

NBI $\left\{\begin{array}{l}\text{Moderate energies} \quad E_b \sim \text{MeV} \\ \text{High power} \quad P_b \sim \text{several MW} \\ \qquad\qquad\qquad\quad \simeq 30 \text{ MW}\end{array}\right.$

$P = I \cdot \Delta V$ $\quad \Delta V \sim \text{MV}$

$30 \text{ MW} = I \cdot \text{MV} \Rightarrow I = 30 \text{ A}$ (compared to ~nA for conventional acc.)
μA



For positive ions

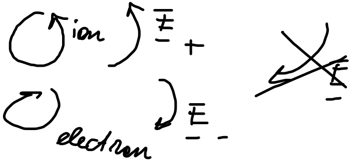
If $E_b = 1$ MeV: negative ion beam

Wave heating $\underline{B}$ $\omega_L = \frac{qB}{m}$

$$\nu_L = \frac{\omega_L}{2\pi} = \frac{qB}{2\pi m}$$

$\nu_{wave} \sim \nu_L$

$\nu_{wave} \sim \nu_L$
Polarization
Accessibility



B $q_e \sim q_i$

$$\frac{\nu_{L_e}}{\nu_{L_i}} = \frac{m_i}{m_e}$$

$B = 1$ T Hydrogen

$$\nu_L \sim \frac{1.6 \cdot 10^{-19} \quad 1}{6 \cdot 1.67 \cdot 10^{-27}} \sim 10^{-1}\ 10^{8} \sim 10^{7}\ \mathrm{Hz}$$

~ 10 MHz

Radio frequency waves

Antenna

Heat { ions
electrons

$\nu_{ce} \sim 20$ GHz

↳ microwaves

Gyrotron

Technology is more complex than antenna

"Simple" propagation in the plasma

Very effective heating system

<u>Electron heating</u>

Fusion products

$d + t \to \underline{\alpha} + n \qquad E_\alpha \simeq 3.45$ MeV

(predominantly) <u>electron heating</u>

$T_e \sim 20$ keV

$E_{cr} \sim 500 \div 600$ keV

	Present devices	next step devices
NBI	(mostly) ions	(mostly) electrons
RF waves	(mostly) ions [electrons]	same
μ waves	(mostly) electrons	same
Fusion products	(mostly) electrons	same

T_e is mostly increased
Strong need for energy equipartition
el → ions : good confinement