Fundamentals of Plasma Physics - Fusion plasma (IV)

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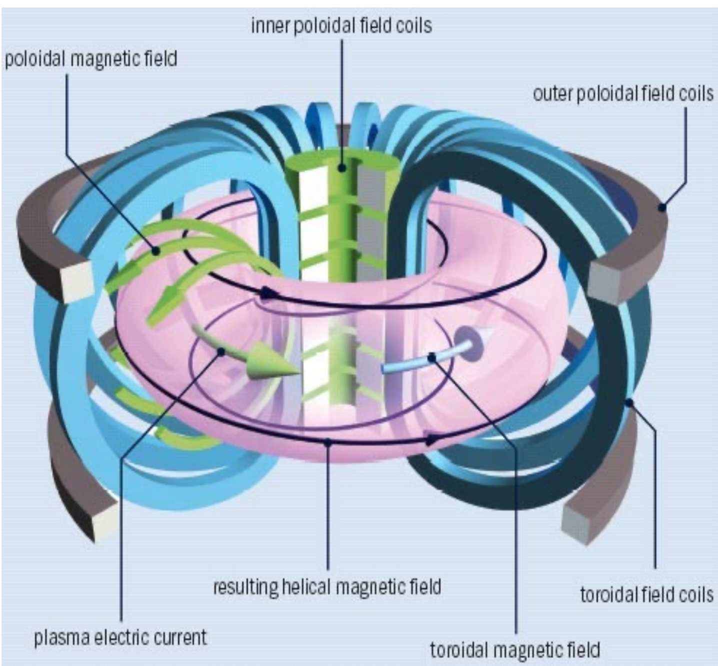
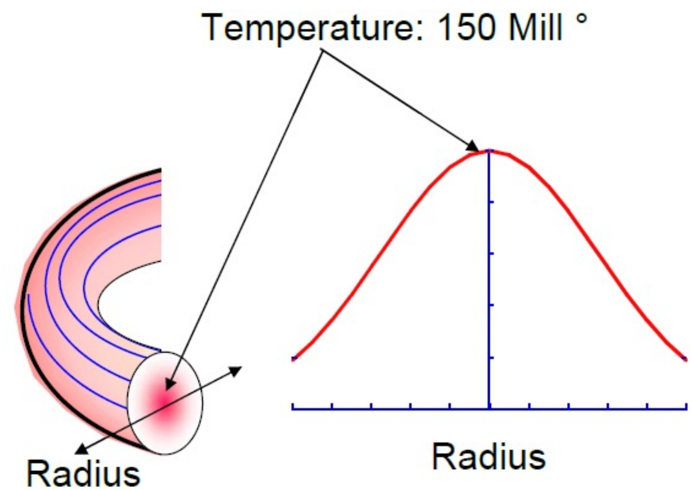
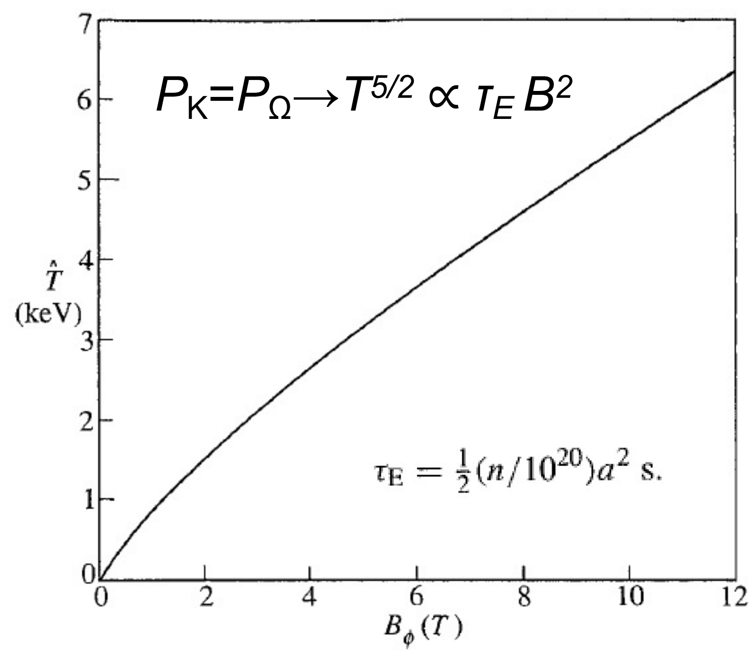
2023. 12

How to build a fusion device?

- What shape is the device probably?
- What size should the device be?
- How to operate the device for fusion
  - How to heat plasma?



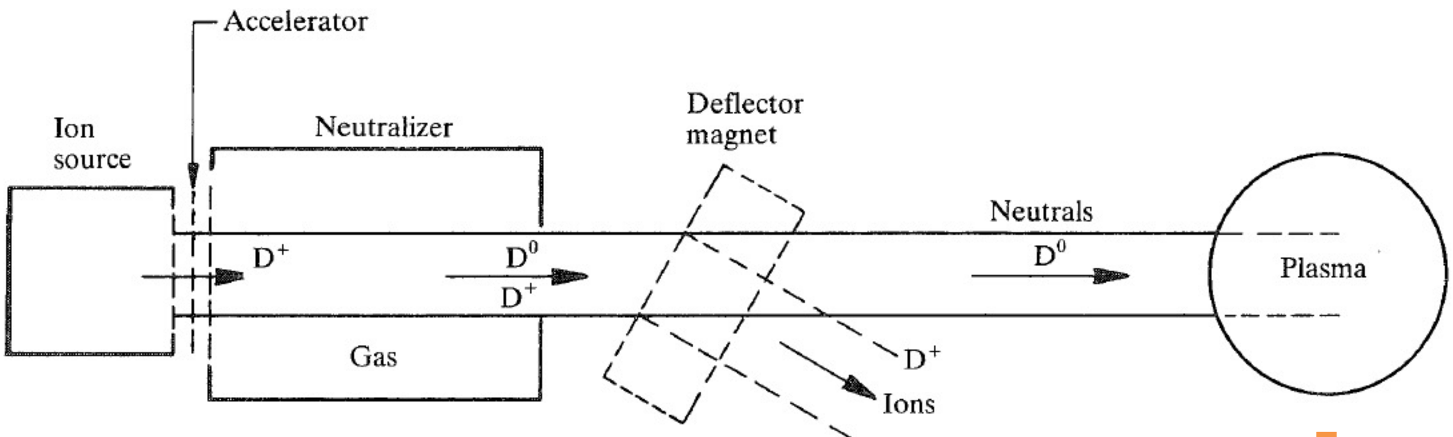




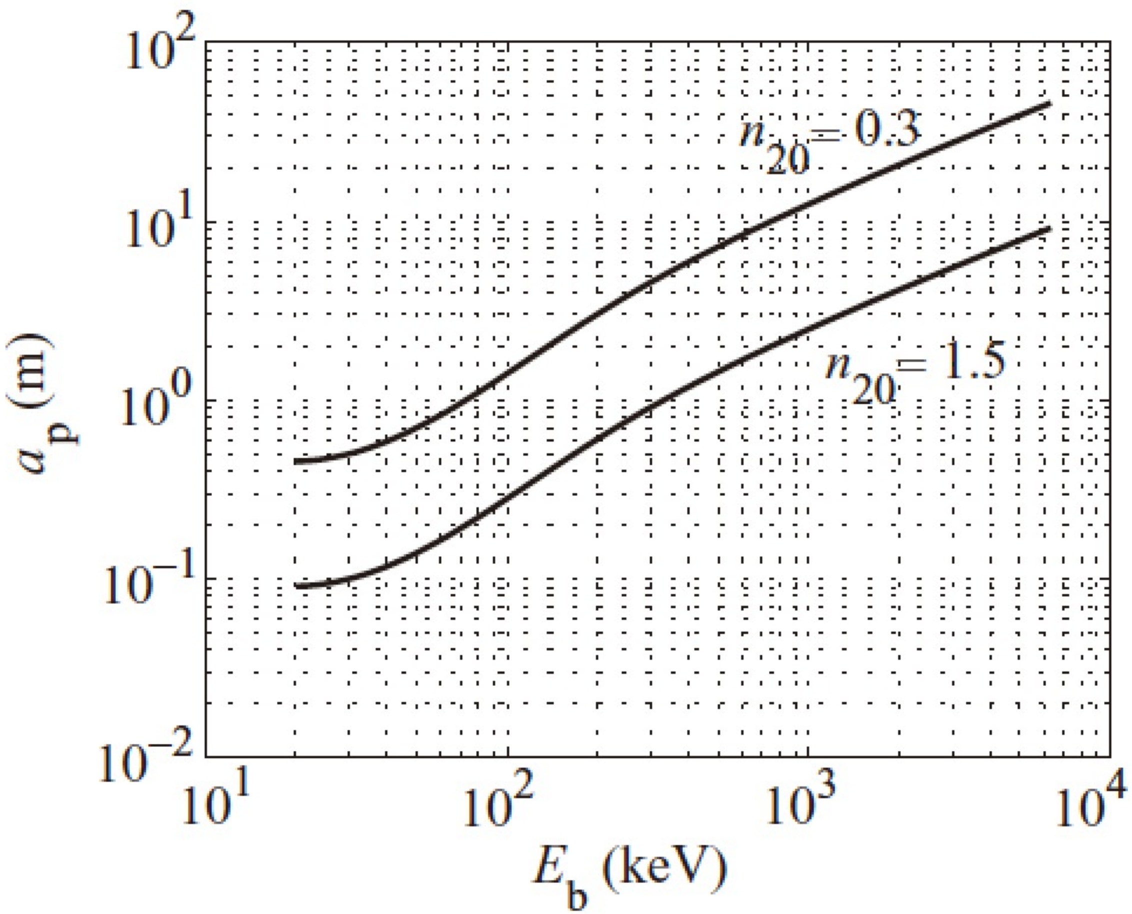
- So how to heat the plasma from 3keV to Ignition?
- Or how to heat the plasma in the stellarator?

Auxiliary Heating

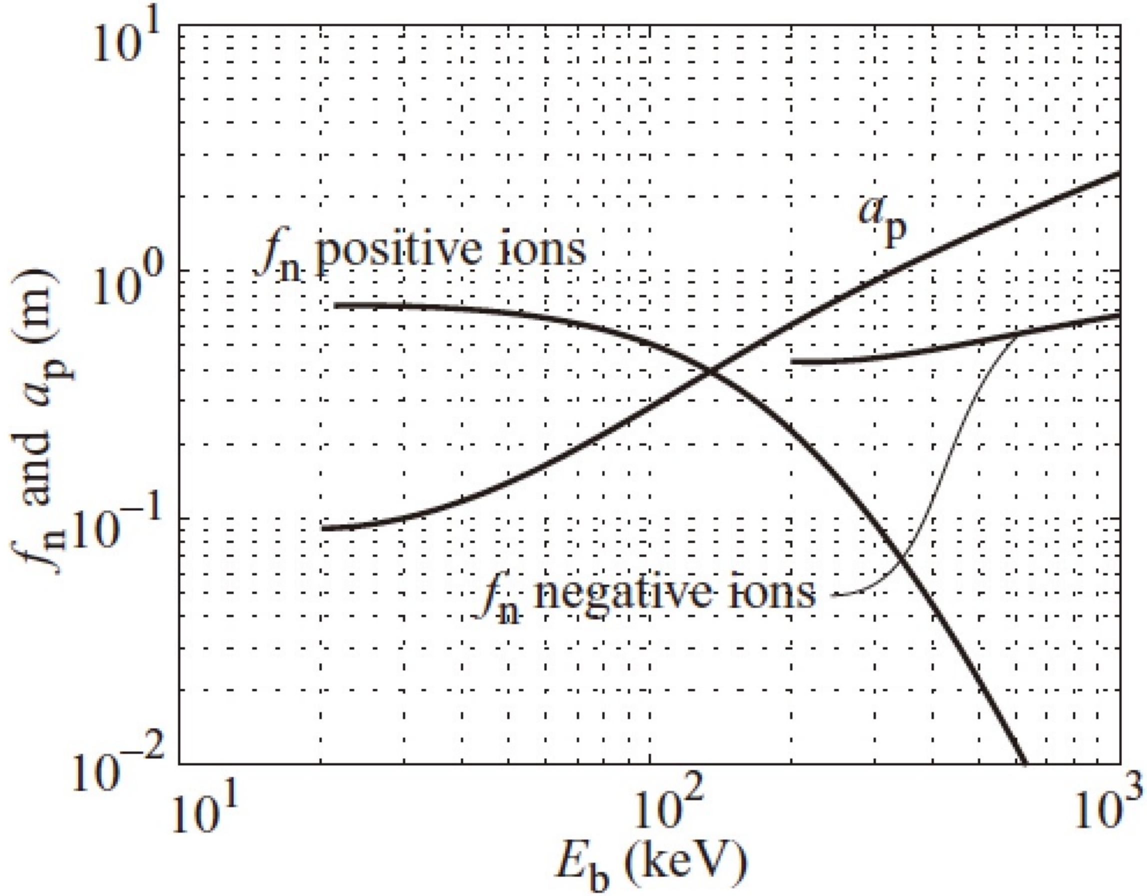
- NBI



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	$H_b + e \rightarrow H_b^+ + 2e.$



Beam penetration depths for a typical JET discharge with $n20 = 0.3$, $a = 1$, and a simple reactor with $n20 = 1.5$, $a = 2$ (Wesson, J. (2004). *Tokamaks*, third edition. Oxford: Clarendon Press).



Neutralization fraction vs. beam energy for positive and negative ion beams. Also plotted is the penetration depth for *n*20 = 1.5. (Wesson, J. (2004). *Tokamaks*, third edition. Oxford: Clarendon Press).

rf heating

?

作业：　简述微波炉加热的原理

Collisional case: AC Ohmic heating

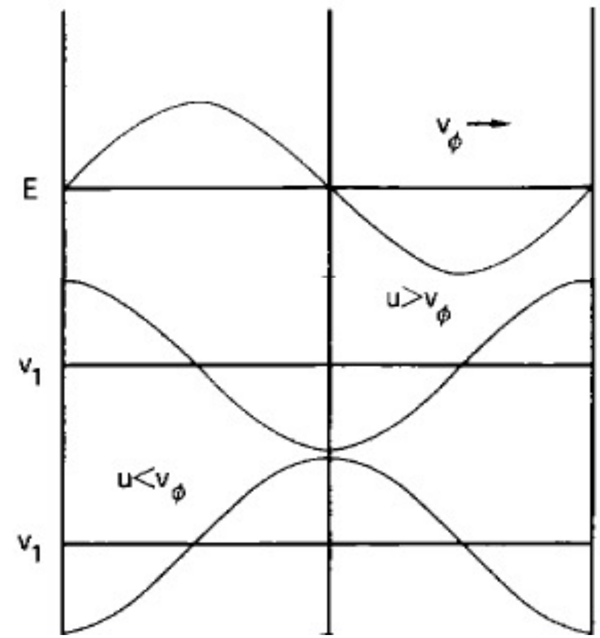
- $P = \boldsymbol{E} \cdot j \sim q\boldsymbol{E} \cdot u$

$$-\mathrm{i}\omega m_{\mathrm{e}}\boldsymbol{u} = -e\boldsymbol{E}$$

- Collisionless $P = q\boldsymbol{E} \cdot u$

is a pure imaginary

$\langle P \rangle_t = 0$



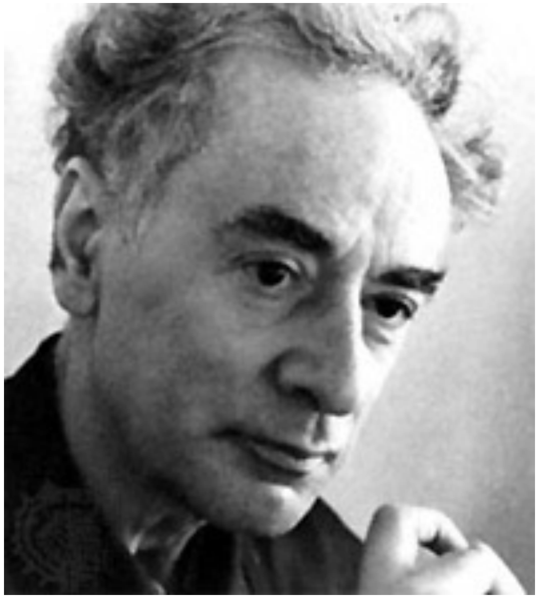
- Collisional

$$-\mathrm{i}\omega m_{\mathrm{e}}\boldsymbol{u} = -e\boldsymbol{E} - m_{\mathrm{e}}\nu\boldsymbol{u} \qquad \boldsymbol{u} = \frac{e}{m(\nu - \mathrm{i}\omega)}\boldsymbol{E}$$

$\langle P \rangle_t \neq 0$

Landau Damping（朗道阻尼）

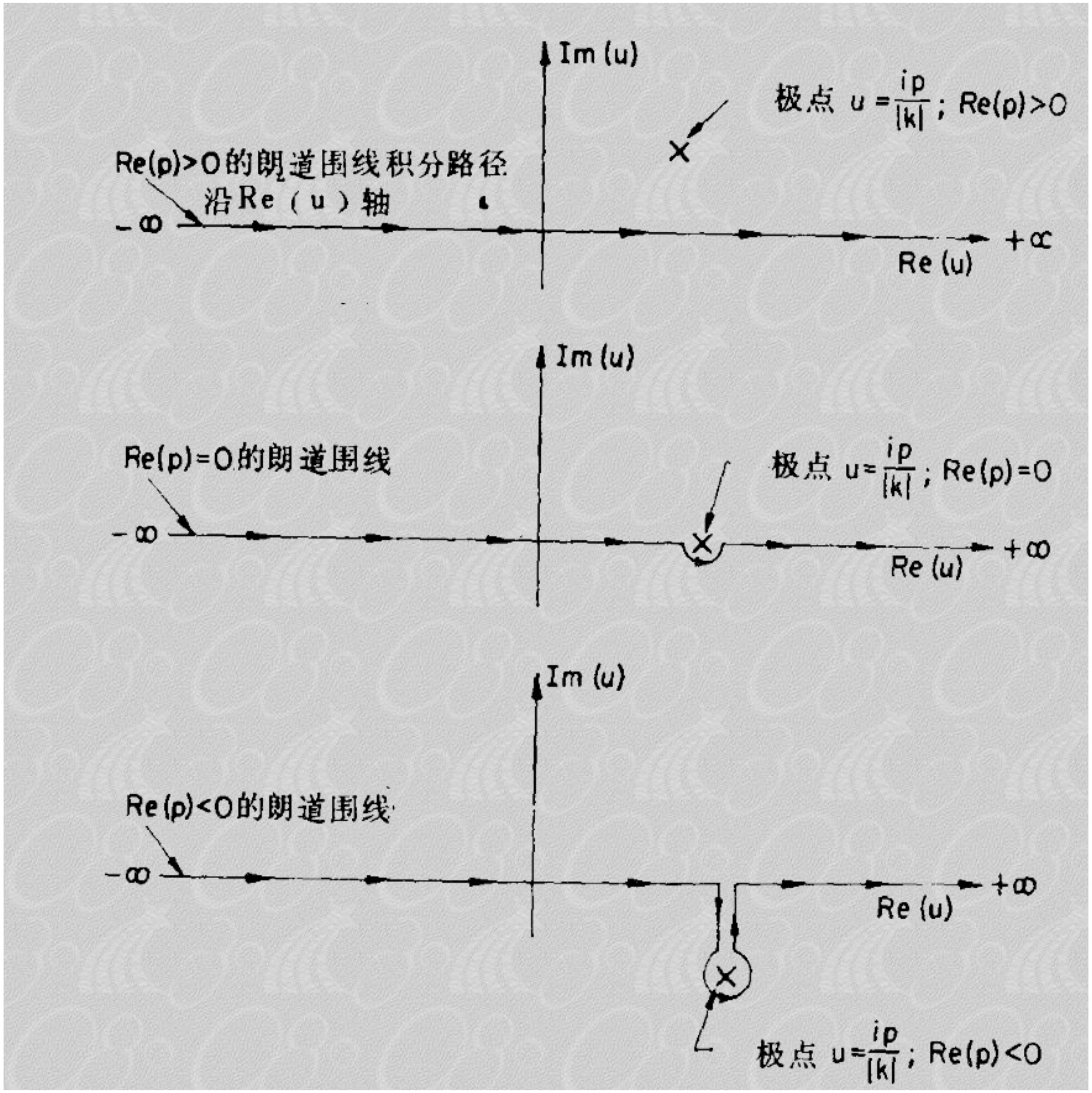
- An electrostatic wave $\boldsymbol{E}=E_x\exp(\mathrm{i}kx-\mathrm{i}\omega t)$ will be damped in a plasma in collisionless case
- the most outstanding achievement in plasma physics
- theoretically derived in 1946 by Landau, experimentally verified in 1966.



L. Landau
Nobel Prize for Physics 1962

$$1=-\frac{\omega_{\mathrm{pe}}^2}{k^2}\int_{-\infty}^{\infty}\mathrm{d}v\,\frac{\partial\hat{f}_0/\partial v}{(v-\omega/k)}.$$

$$\mathrm{Im}\left(\frac{\omega}{\omega_{\mathrm{pe}}}\right)=-0.22\sqrt{\pi}\left(\frac{\omega_{\mathrm{pe}}}{kv_{\mathrm{th}}}\right)^2\exp\left(\frac{-1}{2k^2\lambda_{\mathrm{D}}^2}\right)$$



Im (u)
极点 $u=\frac{ip}{|k|}$; Re(p)>0
Re(p)>0的朗道围线积分路径沿Re(u)轴
$-\infty$
$+\infty$
Re (u)
Im (u)
Re(p)=0的朗道围线
极点 $u=\frac{ip}{|k|}$; Re(p)=0
$-\infty$
$+\infty$
Re (u)
Im (u)
Re(p)<0的朗道围线
$-\infty$
$+\infty$
Re (u)
极点 $u=\frac{ip}{|k|}$; Re(p)<0

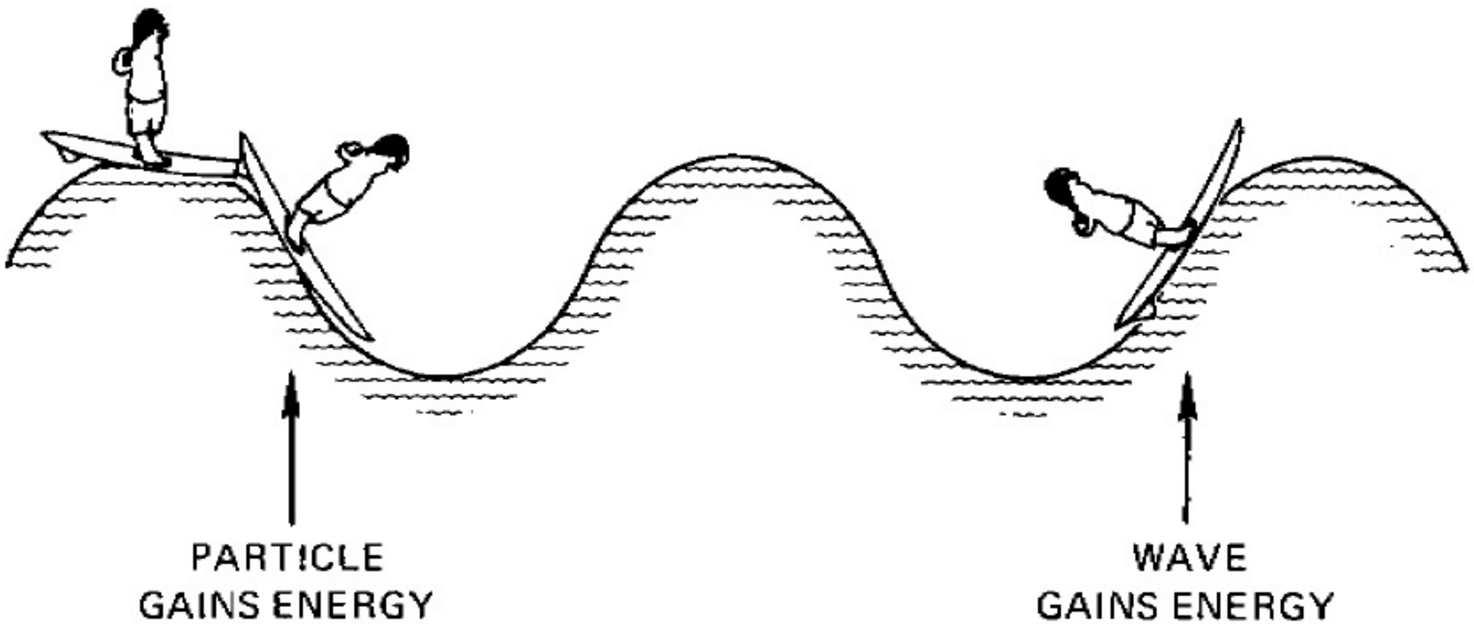
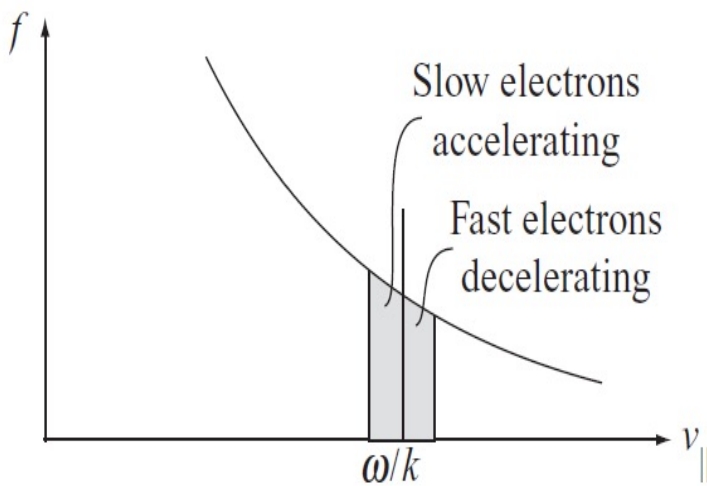


FIGURE 7-17 Customary physical picture of Landau damping.



- FF Chen 1974

Consider particle motion in an electrostatic wave

$$\mathbf{E} = E_1(z,t)\mathbf{e}_z = E_\parallel \cos(k_\parallel z - \omega t)\mathbf{e}_z$$

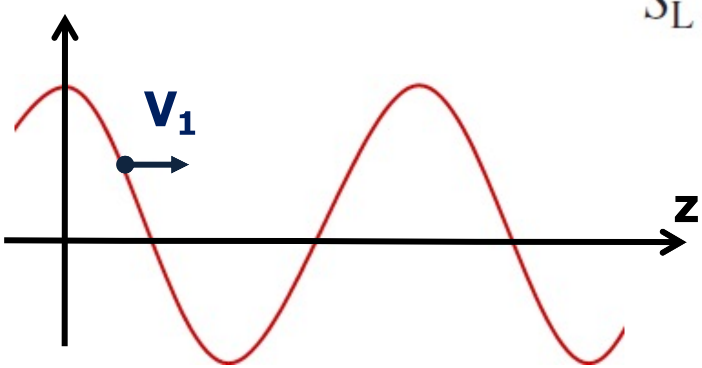
$$\frac{\mathrm{d}v}{\mathrm{d}t} = -\frac{e}{m_e} E_\parallel \cos(\omega t - k_\parallel z) \qquad v(0) = v_\parallel,$$

$$\frac{\mathrm{d}z}{\mathrm{d}t} = v \qquad z(0) = z_i.$$

$$\frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{m_e v^2}{2}\right) = -e\,\mathbf{v}\cdot\mathbf{E} \qquad \frac{\mathrm{d}\overline{W}}{\mathrm{d}t} = \frac{k_\parallel}{2\pi}\int_0^{2\pi/k_\parallel} \frac{\mathrm{d}W}{\mathrm{d}t}\mathrm{d}z_i$$

$$S_L(t) = -\frac{e^2 E_\parallel^2 n_0}{2m_e k_\parallel}\int_{-\infty}^{\infty}\left(\frac{\omega \sin\overline{\omega}t}{\overline{\omega}} - \sin\overline{\omega}t\right)\frac{\partial f_\parallel}{\partial v_\parallel}\mathrm{d}v_\parallel$$

$$= -\frac{\pi e^2 E_\parallel^2 n_0 \omega}{2m_e k_\parallel^2}\left(\frac{\partial f_\parallel}{\partial v_\parallel}\right)_{\omega/k_\parallel}$$



$$\boxed{\overline{\omega} = \omega - k_\parallel v_\parallel}$$

It is Landau damping!

Optional homework: derive the Landau damping from the picture of wave-particle energy tranfer

A similar but different collisionless mechanism：Cyclotron Damping（回旋阻尼阻尼）in perpendicular direction

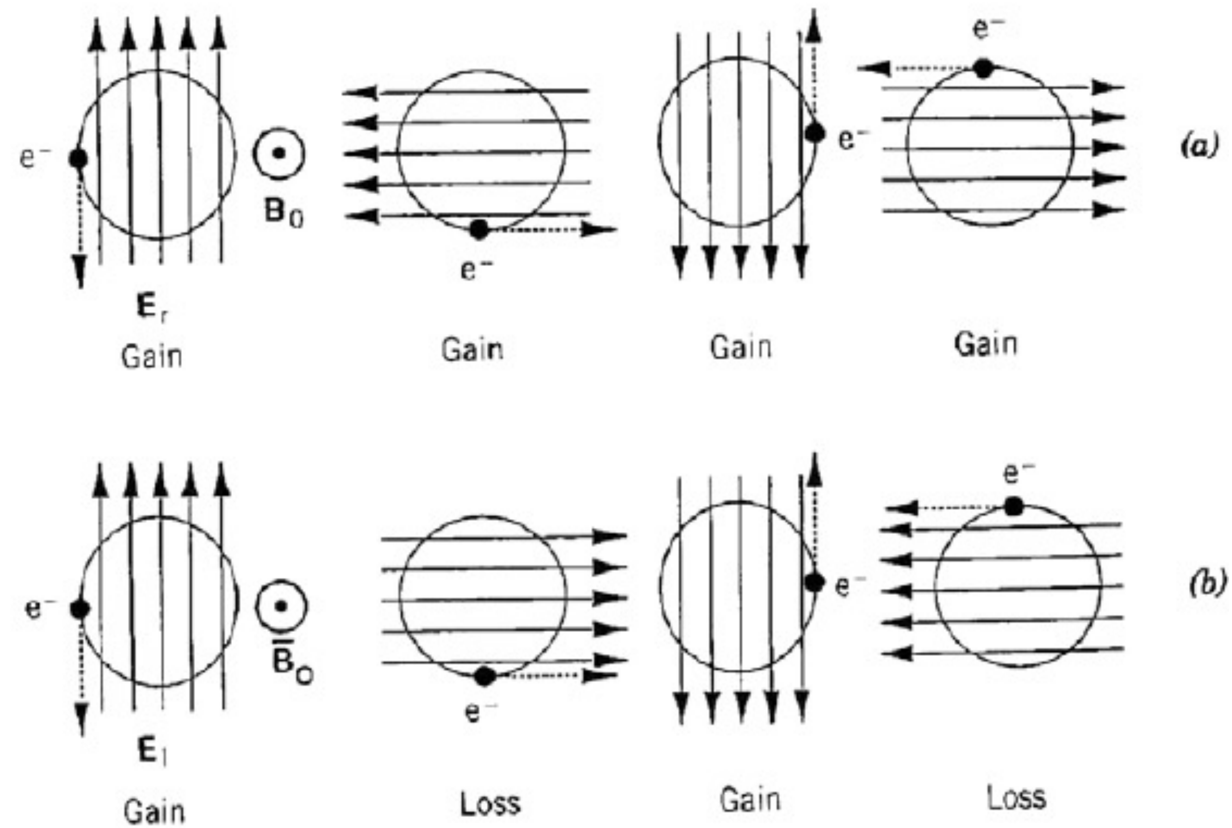
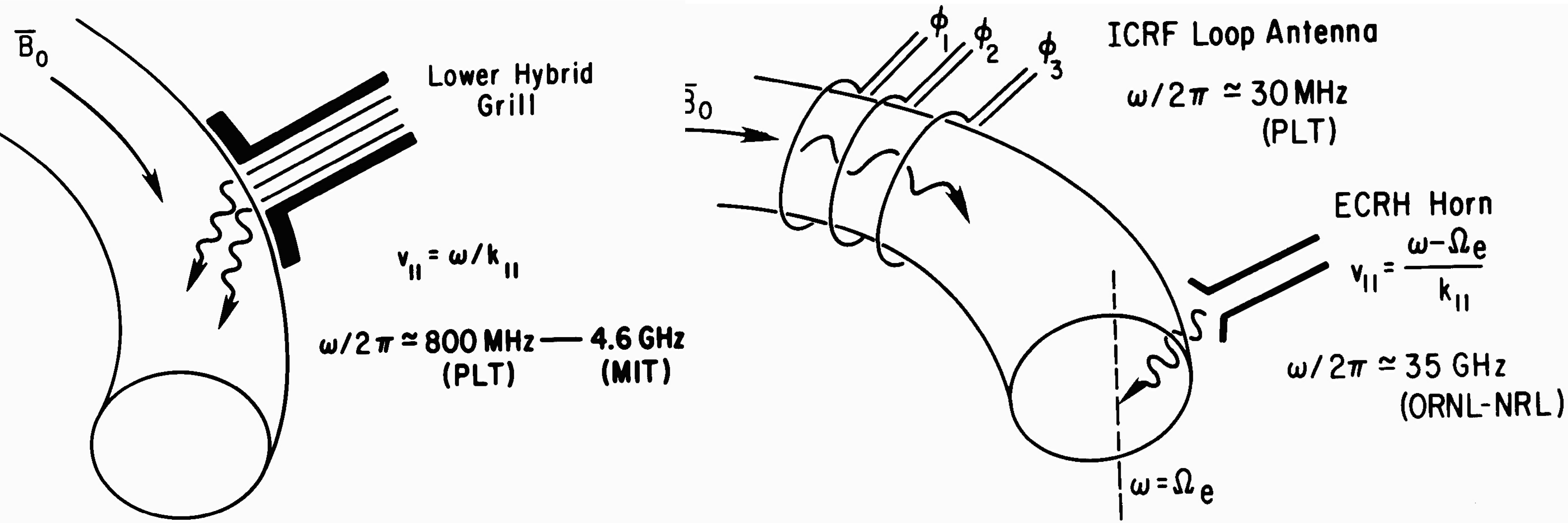
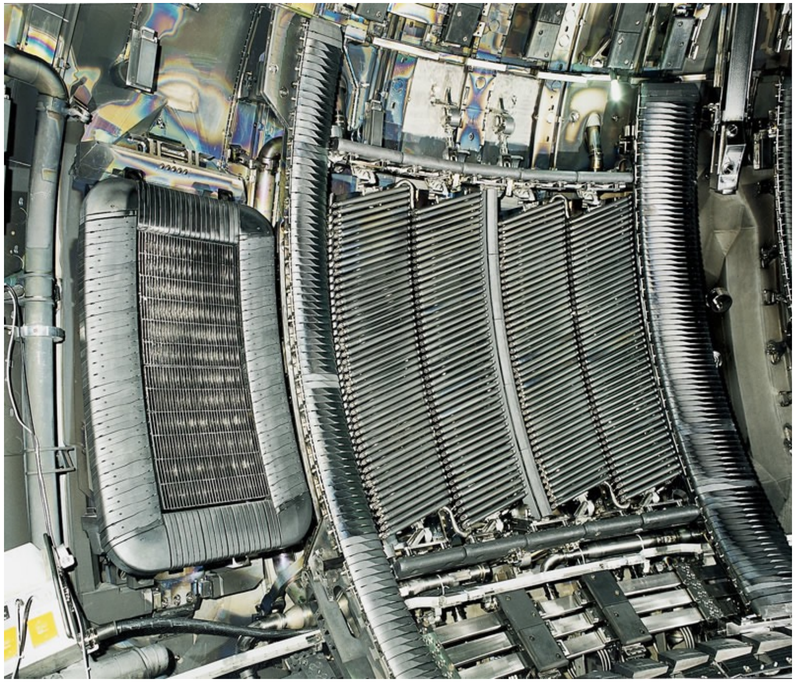


Fig. 1. Mechanism of electron cyclotron heating

- Main methods of rf heating in tokamaks

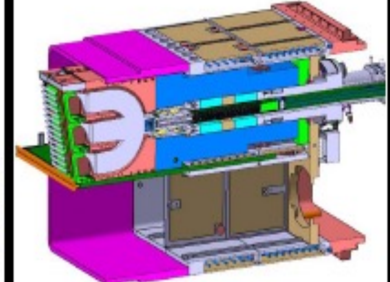
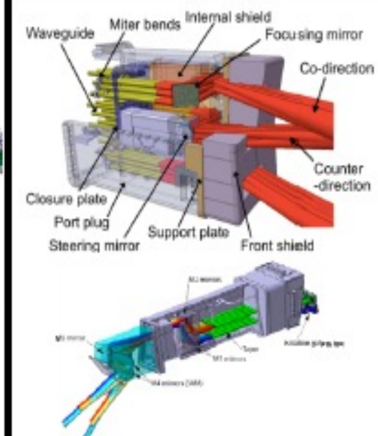
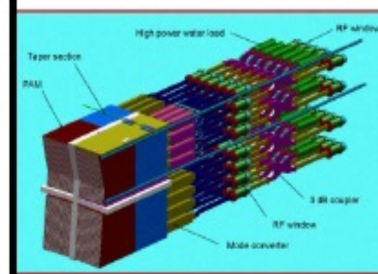


- Quite complex physics in rf-plasma physics… …
(for example the effect of nonuniformity of plasma and magnetic field)



JET

ITER Heating & Current Drive Systems

NB	IC	EC	LH
Neutral Beam - 1 MeV	Ion Cyclotron 40-55MHz	Electron Cyclotron 170GHz	Lower Hybrid ~5 GHz
			
33MW* +16.5MW#	20MW* +20MW#	20MW* +20MW#	0MW* +40MW#
Bulk current drive limited modulation	Sawtooth control modulation < 1 kHz	NTM/sawtooth control modulation up to 5 kHz	Off-axis bulk current drive

*Baseline Power
#Possible Upgrade

P_{aux} for Q=10 nominal scenario: 50MW

130 MW (max installed)
(110 MW simultaneous)

IC H&CD	32.2
EC H&CD	77.5
NB H&CD	96.0
Heating and CD, subtotal	205.7

~5$/W

How to build a fusion device？

- **What shape is the device probably?**
- **What size should the device be?**
- **How to operate the device for fusion energy?**
  - **How to heat plasma?**
  - **Other operations?**