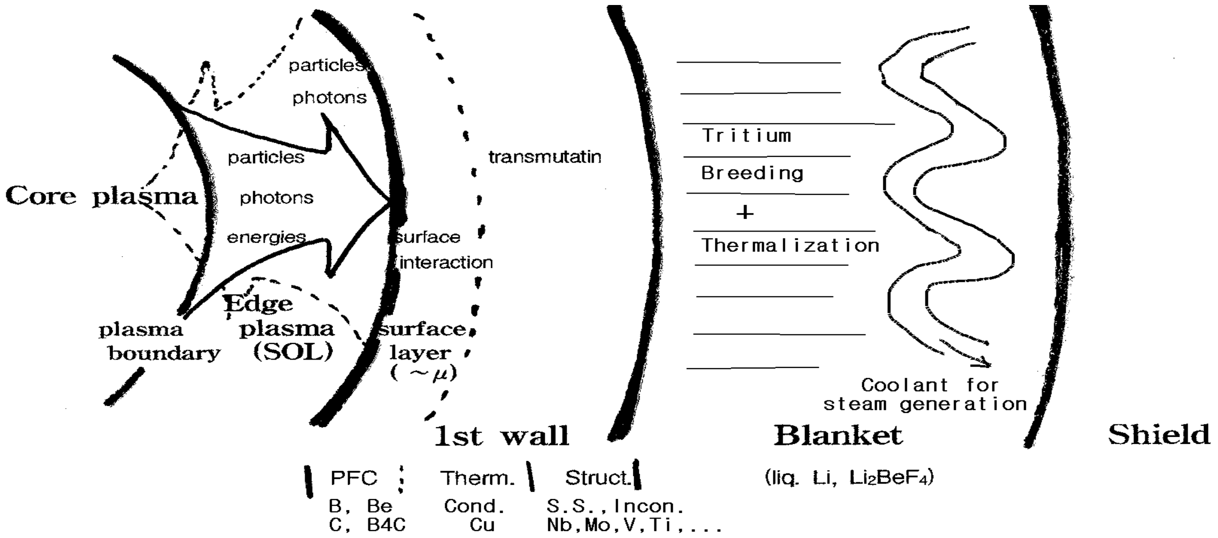
Chapter 5. Plasma-Surface Interaction

Reading assignment: Stacey *Chap. 6,* Harms *Chap. 13*



1. Fluxes to the surface

A. *Particle fluxes*

- Ions: Diffusing fuel ions (H, D, T)
  - Fusion α
  - Diffusing impurities (wall materials, residual gases in chamber, adsorbed gases in surface)
  - Energetic ions from NBI
- Electrons: Diffusing plasma electrons
  - Runaway electrons
- Neutrals: Recycling neutrals
  - NBI neutrals
- Fusion neutrons

Note)

Incident fluxes on the wall

$$\Gamma_w^{i,e} \approx \frac{\bar{n}V}{\tau_{pS}} = \frac{\bar{n}\pi a^2 L}{\tau_p 2\pi r_w L}, \qquad \Gamma_w^{imp},\ \Gamma_w^{\alpha} \ll \Gamma_w^{i,e}$$

B. *Photon fluxes*

Bremst., cyclotron, impurity radiations

C. *Energy fluxes*

Particle energies, Radiation energies, Heat conduction

→ Wall load : 1 MW/m^2 ≈ 14.1 MeV-n flux of $4.43\times10^{17} n/m^2 s$ thru wall.

2. Surface interaction phenomena

Alteration of surface (wall erosion) → impurities
Production of particle and photon fluxes

A. Reflection by backscattering

B. Adsorption and desorption

Residual cooler gases implanted inside wall
→ Release of gases

C. Physical sputtering - Erosion

Ejection of surface atom from (low-temperature) wall
as a result of collision cascade in the lattice atoms by n, i, a
when acquired energy > surface binding energy U_o(~25 *eV*)

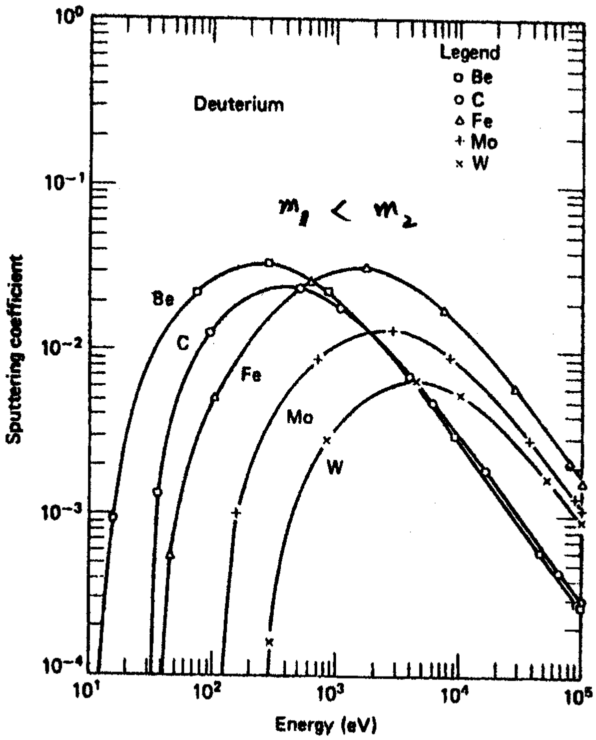
Sputtering yield : $Y \equiv$ *ejected atoms/incident particles*

Semi-theoretical value

$$Y(E)^{\uparrow} \approx \frac{20}{U_O}(Z_1Z_2)^2\frac{m_1^{\uparrow}}{m_2}\frac{E}{(E+50Z_1Z_2)^2} \quad \textit{atoms/particle} \qquad (1)$$

Y for D : Fig 6.1.1

$Y\downarrow$ as $m_2(Z_2)\uparrow$ $\Leftarrow$

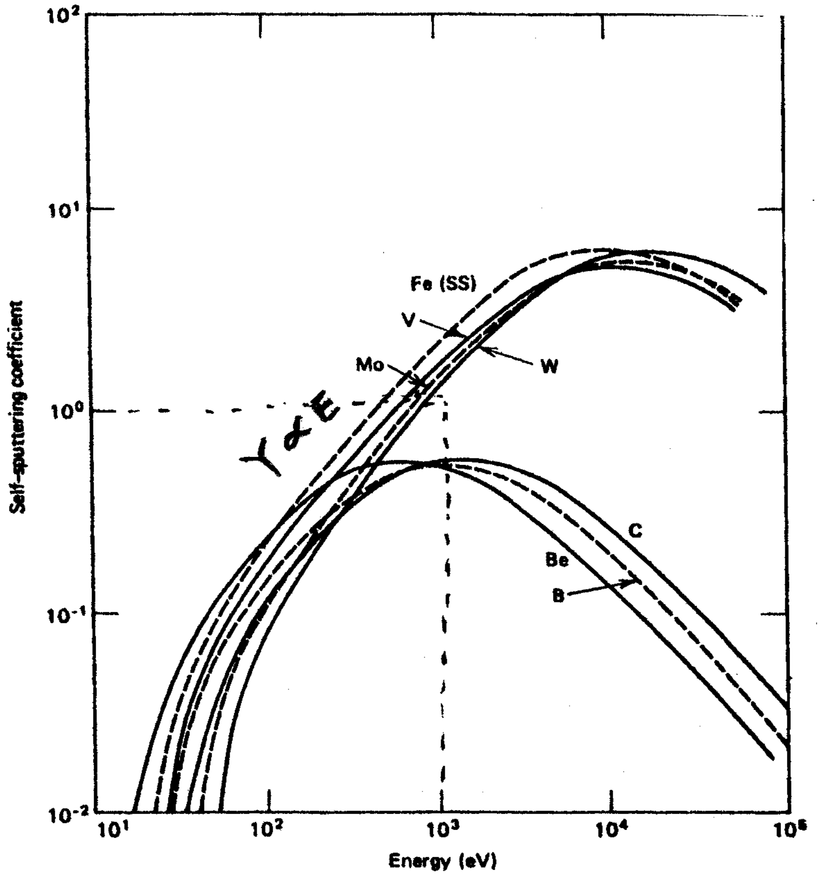


Stacey[4] Fig. 6.1.1 Physical Sputtering Yield for a Number of Materials for Deuterons

Threshold incident energy to produce sputtering

$$E_{tl} = \frac{(m_1+m_2)^2}{4m_1m_2}U_{o2} \qquad (2)$$

Self-sputtering yield for reincident ions : Fig 6.1.2



Stacey[4] Fig. **6.1.2. Self-sputtering yield for a number of materials**

For large Z_2 $\quad Y(E) \approx 10^{-3}E$

$> 1 \quad$ for $E \geq 10^3\ eV$

→ avalanche effect of impact

→ tolerable limit

Neutron sputtering:

$Y \approx 10^{-4} \sim 10^{-5}$ *atoms/ neutron*

D. Chemical sputtering

(e.g.) (H, D, T) + C

incident particle + surface atom → chemical compound + reduced U_o

$$\Rightarrow \quad Y_c(E) \geq 2Y_p(E)$$

E. Vaporization and melting

Disruptive instabilities → Thermal shock on the wall

→ spalling, cracking, melting, evaporation

Fig.6.1.3: Calculated melting zone (s.s) ↑ as energy density ↑, disrup. time ↑.

Stacey[4)]

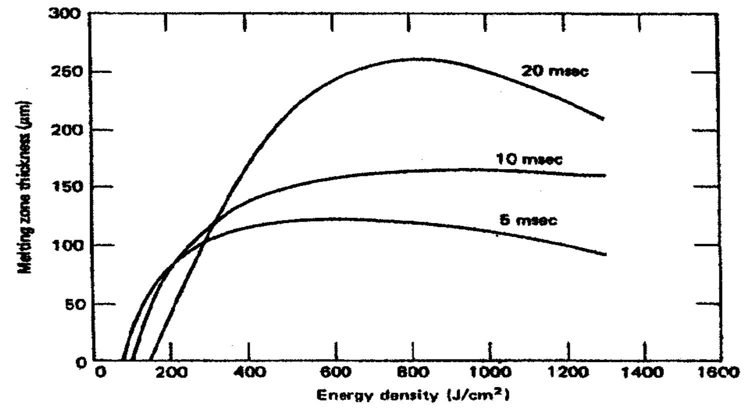
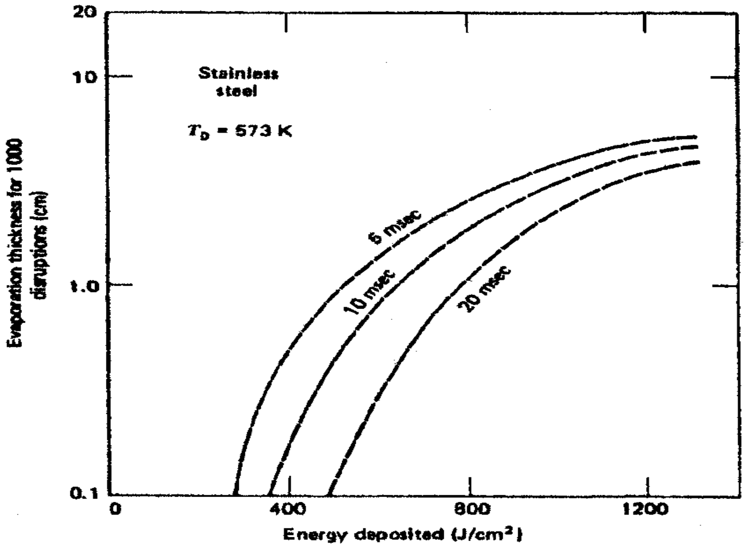


Fig.6.1.4: Evap. thickness for 1000 disrup.(s.s) as E ↑, t ↓

Stacey[4)]



F. Blistering and Flaking

Blistering: gas bubble in ~μ-thick surface layer (unsoluble, He)

Flaking: Blister rupture by lateral stress and surface layer breaking

G. Electron emission (photoelectric, thermionic, X-ray, secondary)

H. Radiation damage & Transmutation by 14.1-MeV Neutron

Knock-on collisions --> interstitial, spikes, voids, displacements, ...

n capture reactions: (n,p), (n, α) → production of p, α in 1st wall

→ swelling, radiation damage of wall, diffuse back to plasma

* **Interactions in the plasma boundary**

- NBI and recycling atoms ←(CX, I_i, I_e, R)→ Plasma ions, electrons
- Impurity atoms (ions) from 1st wall ←(I, Exc., R, Coul. collsion)→

Plasma electrons (ions) ⇒ Radiation cooling

3. Impurity radiation

= Bremss. + line radiation due to electron collision and excitation
+ radiative recombination loss

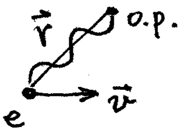
A. Bremsstrahlung (Braking radiation)

Mainly due to e-i collisions (In e-e or i-i colls., rad. fields exactly cancel)

Radiation fields (dipole approx.):

$$\boldsymbol{E} \approx \frac{e}{4\pi\varepsilon_o c^2}\frac{\boldsymbol{r}\times(\boldsymbol{r}\times\dot{\boldsymbol{v}})}{r^3} \propto \frac{1}{r},\quad r\gg 1 \qquad (3)$$

$$\boldsymbol{B} \approx \frac{\mu_o e}{4\pi c}\frac{\dot{\boldsymbol{v}}\times\boldsymbol{r}}{r^2} \propto \frac{1}{r},\quad r\gg 1 \qquad (4)$$

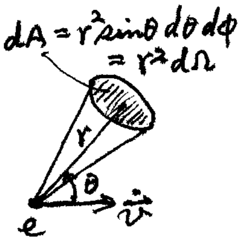


Poynting vector (instantaneous e.m. energy flux)

$$\boldsymbol{P}_{rad} = \boldsymbol{E}\times\boldsymbol{H} = \frac{e^2}{16\pi^2\varepsilon_o c^3}\frac{\boldsymbol{r}\times(\boldsymbol{r}\times\dot{\boldsymbol{v}})\times(\dot{\boldsymbol{v}}\times\boldsymbol{r})}{r^5} \qquad (5)$$

Radiative power per unit solid angle emitted from a charge

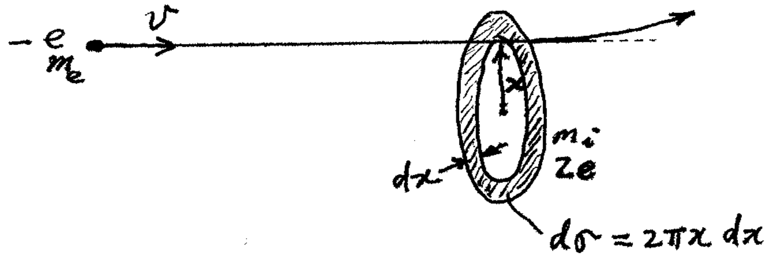
$$\frac{dW_{rad}}{d\Omega} = r^2\boldsymbol{P}_{rad}\cdot\hat{\boldsymbol{r}} = \frac{e^2}{16\pi^2\varepsilon_o c^3}|\dot{\boldsymbol{v}}|^2\sin^2\Theta \qquad (6)$$



Total power radiated by an accelerated charge

$$W_{rad} = \int_0^{2\pi} d\Phi \int_0^{\pi} d\Theta \sin\Theta\; r^2\boldsymbol{P}_{rad}\cdot\hat{\boldsymbol{r}} = \frac{1}{6\pi\varepsilon_o}\frac{e^2|\dot{\boldsymbol{v}}|^2}{c^3} \qquad (7)$$

Assume small-angle Coulomb scattering



$$\tau \approx \frac{x}{\upsilon} \ll 1 \qquad \text{otherwise continuous spectrum} \qquad (8)$$

$$F = m_e|\dot{\boldsymbol{v}}| = \frac{Ze^2}{4\pi\varepsilon_o x^2} \quad\Rightarrow\quad |\dot{\boldsymbol{v}}| \approx \frac{Ze^2}{4\pi\varepsilon_o m_e x^2} \qquad (9)$$

Power radiated from a single e-i collision

(9) in (7):

$$W_{rad} = \frac{Z^2 e^6}{96\pi^3\varepsilon_o^2 c^3 m_e^2 x^4} \qquad (7)^*$$

Number of collsions per unit volume of n_e with n_i in $d\sigma$ during τ

$$dN = n_e n_z d\sigma\,\upsilon\tau = n_e n_z 2\pi x^2 dx \qquad (10)$$

Total bremsstrahlung power density at all impact parameter x

$$P_{br} = \int_{x_{\min}}^{x_{\max}} W_{rad}\,dN = \frac{Ze^6 n_e n_Z}{48\pi^2\varepsilon_o^3 c^3 m_e^2}\int_{h/2\pi m_e v}^{\lambda_D}\frac{dx}{x^2}$$

$$= \frac{Z^2 e^6 n_e n_Z v}{24\pi\varepsilon_o^3 c^3 m_e h} = \left(\frac{e^6\sqrt{2}}{12\pi^{3/2}\varepsilon_o^3 c^3 m_e^{3/2} h}\right) Z^2 n_e n_Z T_e^{1/2} \qquad (11)$$

where $\upsilon = \sqrt{8kT_e/\pi m_e}$, $h/2\pi m_e v \rightarrow \frac{\hbar}{\triangle p}$ since $\triangle x \triangle p = \hbar$

Quantum correction: $q_f = \sqrt{\frac{3}{2}}$ = Gaunt factor by Spitzer

$$P_{br} = \left(\frac{e^6\sqrt{3}}{12(m_e\pi)^{3/2}\varepsilon_o^3 c^3 h}\right) Z^2 n_Z n_e (kT_e)^{1/2}$$

$$\approx \mathbf{4.8\times10^{-43} Z^2 n_Z n_e T_e^{1/2}(keV)} \quad MW/m^3 \qquad (12)$$

$$\approx 4.8\times10^{-43} Z_{eff} n_e^2 T_e^{1/2}(keV) \quad MW/m^3$$

B. *Power loss by line radiation* due to radiative decay after electron collision excitation

$$A_o^{+Z} + e \rightarrow (A_l^{+Z})^* \rightarrow A_o^{+Z} + \gamma + E_{Zl}$$

$$P_L = n_e \sum_z \sum_l n_z E_{Zl} X_{Zl} \quad (\, X_{Zl}\text{: elec. coll. exc. rate} \,)$$

$$\approx \mathbf{1.8\times10^{-44} Z^4 n_e n_Z T_e^{-\frac{1}{2}}}(keV) \quad MW/m^3 \qquad (13)$$

C. *Power loss by radiative recombination*

$$A_o^{+(Z+1)} + e \rightarrow A_o^{+Z} + \gamma + \underset{\text{ioniz. pot.}}{E_{Z+1}} + \underset{\text{free elect. K.E.}}{E_{elec}}$$

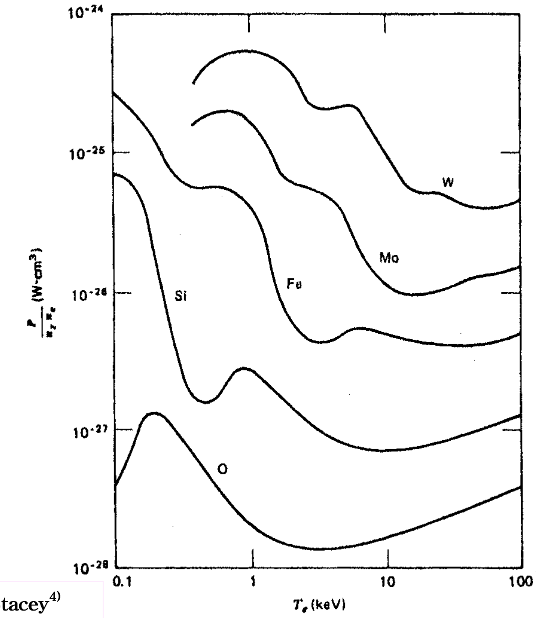
$$P_R = n_e \sum_Z n_{Z+1} \langle (E_{Z+1} + E_{elec}) \sigma_R v \rangle_{Z+1}$$

$$\approx \mathbf{4.1\times10^{-46} Z^6 n_e n_Z T_e^{-\frac{3}{2}}(keV)} \quad MW/m^3 \qquad (14)$$

D. *Normalized impurity radiative power*

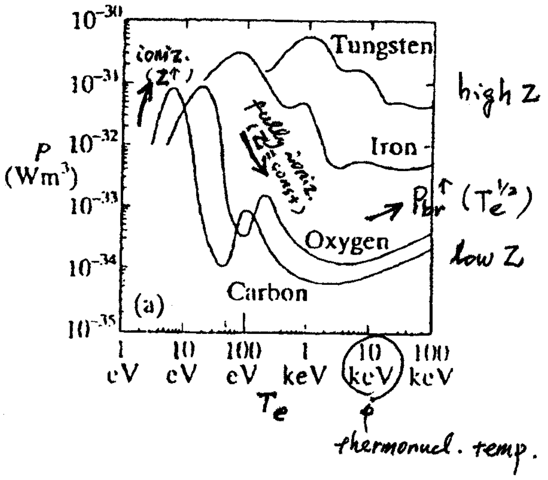
$$W_{rad}^{\uparrow} \equiv \frac{P_{imp}}{n_e n_Z} = \frac{\overset{\propto Z^2 T^{1/2}}{P_{br}} + \overset{\propto Z^4/T^{1/2}}{P_L} + \overset{\propto Z^6/T^{3/2}}{P_R}}{n_e n_Z} = f(T_e, Z^{\uparrow}) \qquad (15)$$

⇒ Fig. 6.2.2

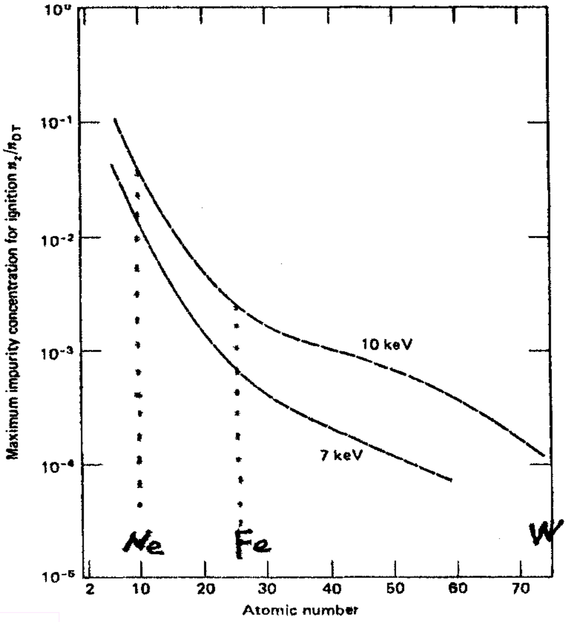


Stacey[4]

Figure 6.2.2. Impurity radiative power loss from a plasma.



E. Maximum permissible impurity concentration



Stacey[4] Fig. 6.2.3 Maximum impurity concentration for which ignition can be achieved

$$\left(\frac{n_Z}{n_{DT}}\right)^{\uparrow}_{\max} = f(Z^{\downarrow},\ T^{\uparrow})$$

At 10 keV

. Low Z (~10): $\left(\frac{n_Z}{n_{DT}}\right)_{\max} \approx 10\ \%$ Ne

. Medium Z (~26): $\left(\frac{n_Z}{n_{DT}}\right)_{\max} \approx 0.5\ \%$ Fe

. High Z (~ 74): $\left(\frac{n_Z}{n_{DT}}\right)_{\max} \approx 0.01\ \%$ W

4. Imputrity control

→ maintain $\frac{n_Z}{n_{DT}} < \left(\frac{n_Z}{n_{DT}}\right)_{\max}$

A. Wall surface control

Suppression of high-z impurity formation or impurity formation itself

Eq.(1) Fig. 6.1.1; Eq.(15) Figs. 6.2.2, 6.2.3

$$\Rightarrow \quad Y(E)^{\uparrow},\ P_{imp}^{\downarrow},\ \left(\frac{n_z}{n_{DT}}\right)_{\max}^{\uparrow} \quad \text{as } Z^{\downarrow}$$

1) Low-z wall surface

(~μm coating, < 1 cm curtain or shingle)

C,	Li,	Be,	B
high chem. sputt.	easy evap.	toxic, low m.p.	(n, α), (n.p) →He, H

$$\left(\frac{n_z}{n_{DT}}\right)_{\max} \geq 10\ \%$$

2) Wall modification

Bake-out, Discharge cleaning, Gettering, Honey comb surface

B. Plasma boundary region control

1) Gas blanket model

High density cold neutral gas refreshed continuously in boundary region

→ (particle and energy fluxes) ↓ with low energies ($< E_{t1}$)

→ wall erosion ↓ → n_Z↓ $\quad$ Eq.(2)

Expected thickness $\approx 1m$ and high P drives instabilities

⇒ impractical !

2) Vacuum model

Low particle densities in SOL by divertor and/or limiter

→ (particle, energy, impurity fluxes) ↓

a. Divertors

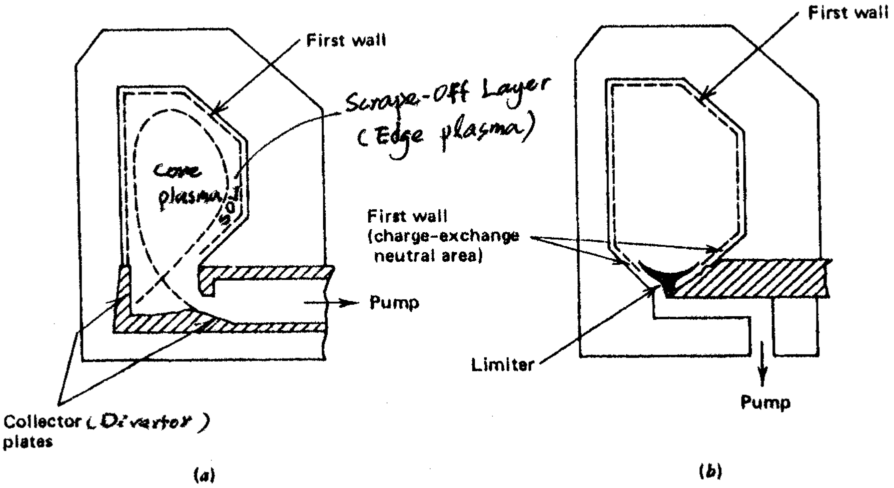
i) Principle

Bending outer magnetic fields away from plasma

→ Removing outer layer of plasma to external chamber

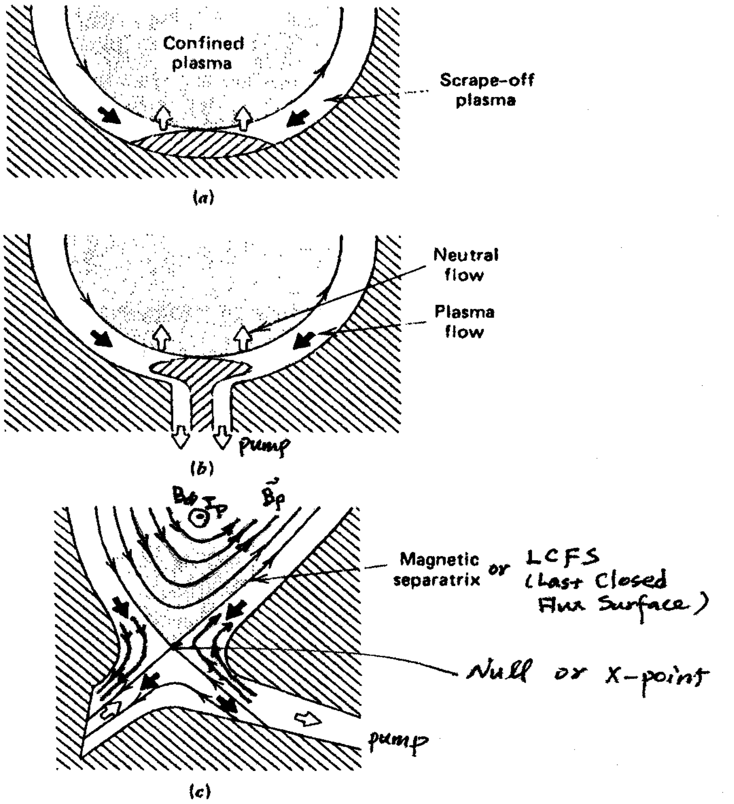
→ Cooling → Neutralizing → Pumping away

Figs. 6.3.2 & 6.3.3



Stacey[4]

Figure 6.3.2. Poloidal divertor and pumped-limiter configurations in a tokamak: (*a*) divertor; (*b*) limiter.



Stacey[4]

Figure 6.3.3. Limiter and divertor plasma flow patterns: (*a*) simple limiter; (*b*) pumped limiter; (*c*) divertor.

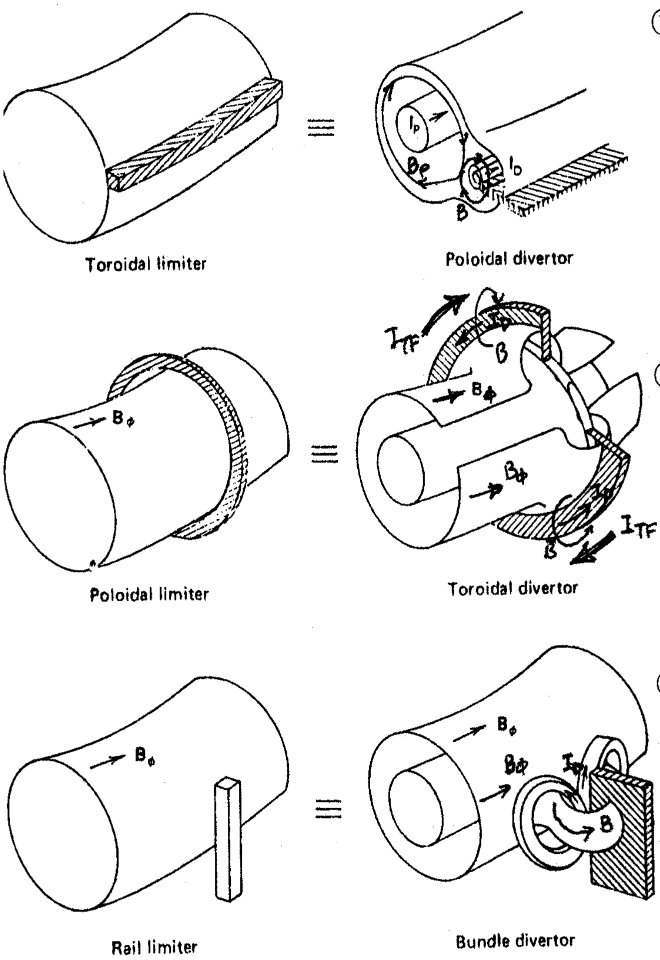
ii) Functions

① Reduction of 1st wall bombardment (Unloading)

② Reduction of impurity flow into plasma
(Shielding for impurity control)

③ Exhaust plasma particles and power and Removal of He ash

iii) Types (Stacey[4]) Fig 6.3.1)

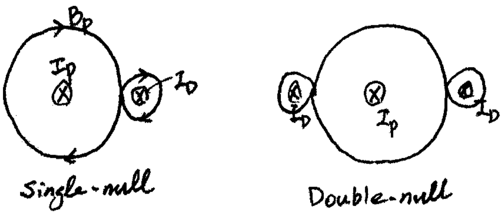


Toroidal limiter Poloidal divertor

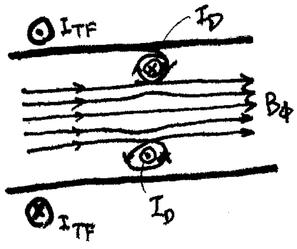
Poloidal limiter Toroidal divertor

Rail limiter Bundle divertor

① Poloidal divertor (axisymmetric)

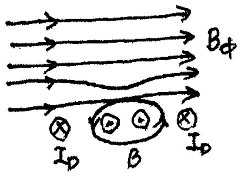


② Toroidal divertor



Non-axisymm.,
Need large Aspect ratio
Not used in tokamaks

③Bundle divertor



iv) Problems

① Complex coil systems
② High cost
③ Difficult maintenance

b. Limiters (Figs. 6.3.1 - 6.3.3)

Scrape-off plasma by solid conductor
→(refl. neutrals)→ Pumping out
Type : Toroidal, Poloidal, Rail
Problem :
High heat load and sputtering rate on limiter → impurities
→ low-Z coating of limiters (C or Be on W)

(Note) H-mode dischange (disch. with divertors and/or limiters)
→ global confine time ↑: exactly not understood

Homework Stacy 6- 2, 3, 4, 7, 9; Harms 13- 2, 3, 4, 5