Fusion Reactor Technology I
(459.760, 3 Credits)

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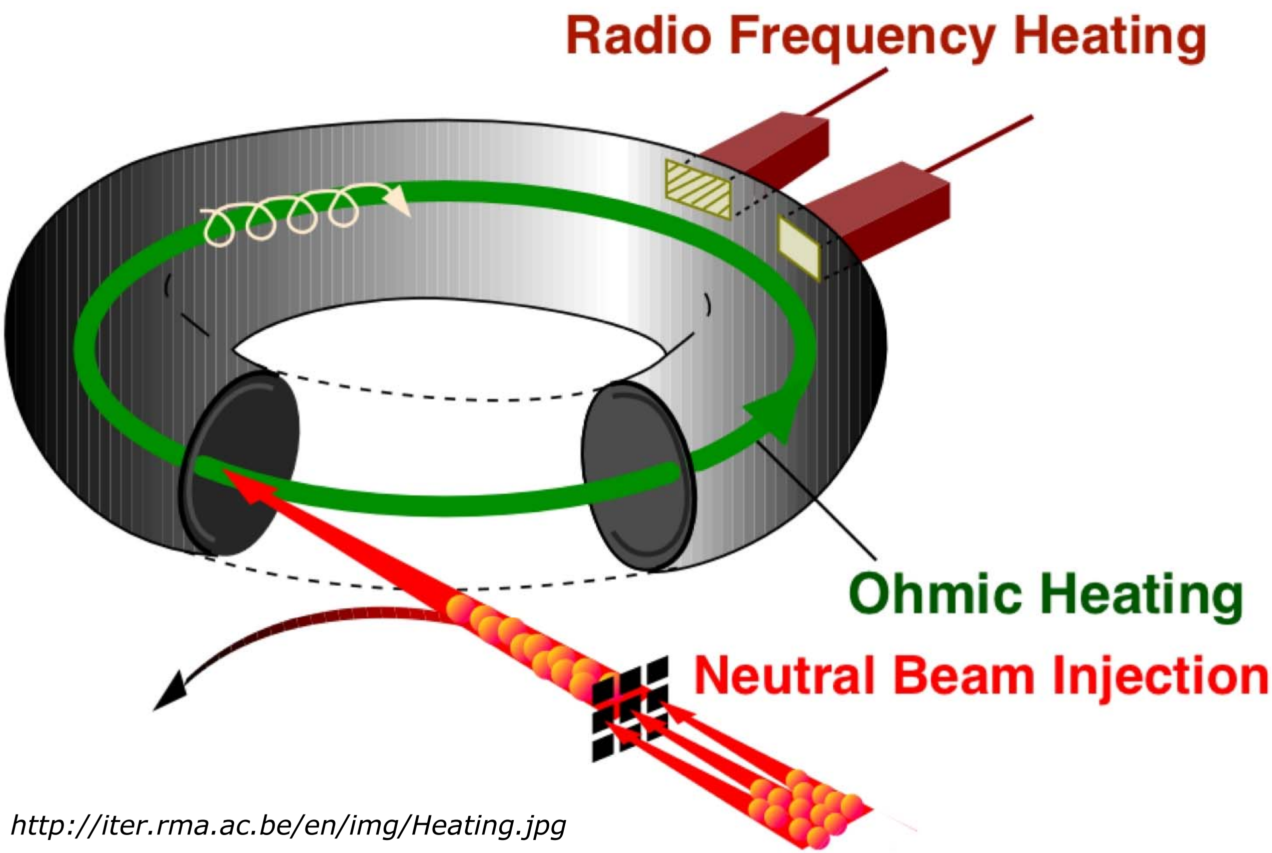
Heating and Current Drive



http://iter.rma.ac.be/en/img/Heating.jpg

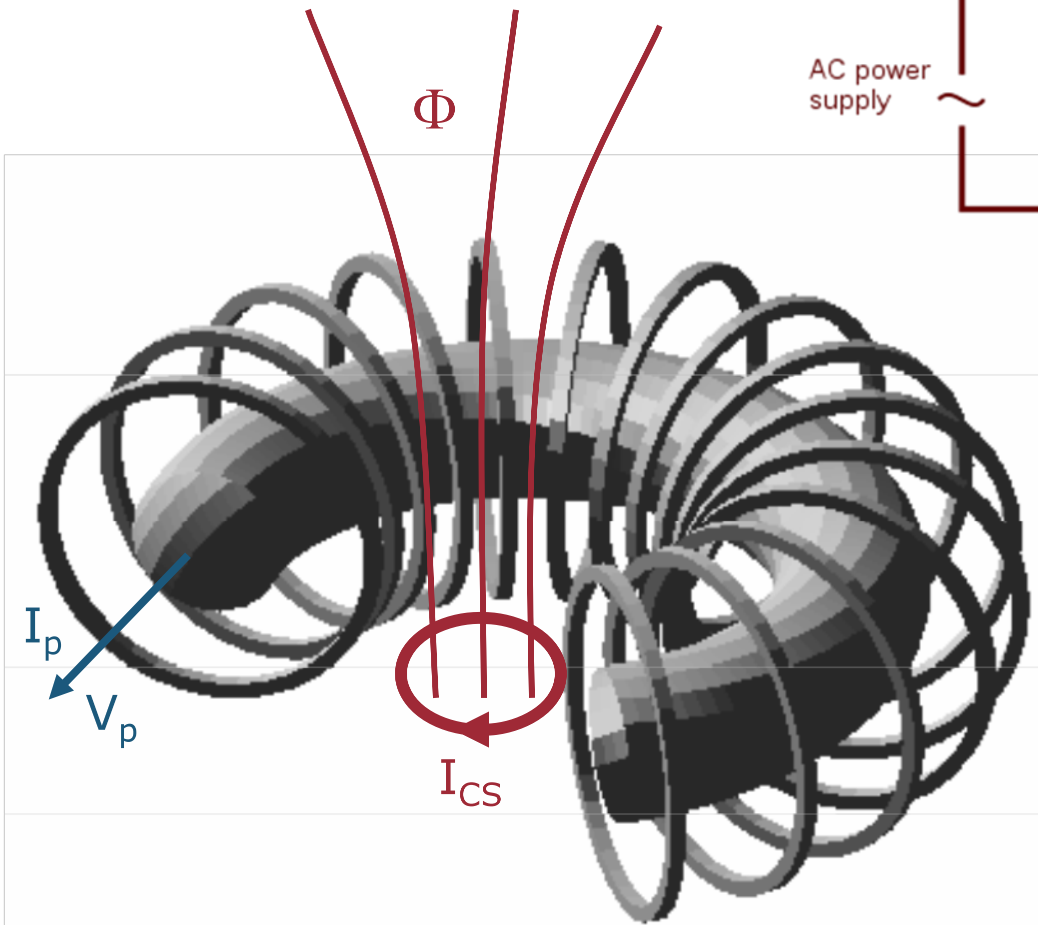
Ohmic Heating

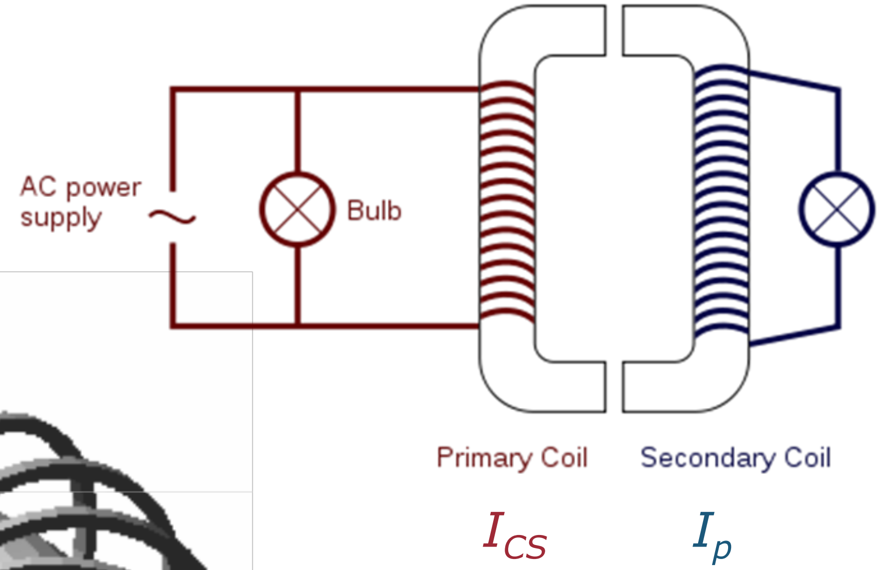
SAMIK

Electric blanket

- Intrinsic primary heating in tokamaks due to Joulian dissipation generated by currents through resistive plasma: thermalisation of kinetic energies of energetic electrons (accelerated by applied **E**) via Coulomb collision with plasma ions
- Primary heating due to lower cost than other auxiliary heatings

Ohmic Heating





$$L_p \dot{I}_p + I_p R_p = V_p = -\dot{\phi}$$

http://en.wikibooks.org/w/index.php?title=File:Transformer.svg&filetimestamp=20070330220406

Ohmic Heating

$$L_p \dot{I}_p + I_p R_p = V_p = -\dot{\phi}$$

- Total change in magnetic flux needed to induce a final current

$$\Delta\phi_{ind} = \int_0^{t_f} \dot{\phi} dt = L_p I_p^f \approx \mu_0 R_0 \left[\ln\left(\frac{8R_0}{a\sqrt{k}} \right) + \frac{l_i}{2} - 2 \right] I_p^f$$

$$l_i \approx \ln[1.65 + 0.89(q_{95} - 1)]$$ internal inductance

- Additional magnetic flux needed to overcome resistive losses during start up

$$\Delta\phi_{res} = C_E \mu_0 R_0 I_p^f, \quad C_E \approx 0.4$$ Ejima coefficient

- Further change in magnetic flux needed to maintain I_p after start up

$$\Delta\phi_{burn} = \int_0^t I_p^f R_p dt'$$

- Technological limit to the maximum value of B_{OH}

$$\Delta\phi \approx \pi r_v^2 \Delta B_{OH}$$ Tokamak is inherently a pulsed device.

Ohmic Heating

- **Ohmic heating density**

$$P_\Omega = \mathbf{j}\cdot\mathbf{E} = \eta\left\langle j^2\right\rangle \quad [W/m^2]$$

$$\eta_n = \frac{\eta_s}{\left(1-\left(\frac{r}{R}\right)^{\frac{1}{2}}\right)^2}$$

: Neoclassical resistivity

η_s: Spitzer resistivity

$$Z_{eff} = \frac{\sum_s n_s Z_s^2}{n_e}, \quad n_e = \sum_s n_s Z_s$$

Z_s: charge number for the s-type ion

$$\eta \approx 8\times10^{-8} Z_{eff} / T_e^{\frac{3}{2}} \quad (r = a/2,\ R/a = 3)$$

$$j(r) = j_0(1-(r/a)^2)^v$$

$$\left\langle j^2\right\rangle = j_0^2/(2v+1)$$

$$B_\theta(r) = \frac{\mu_0 a^2 j_0}{2(v+1)r}\left[1-\left(1-\frac{r^2}{a^2}\right)^{v+1}\right]$$

Ampère's law

$$q_a = aB_\phi / RB_\theta, \quad q_a/q_0 = v+1, \quad j_0 = 2B_\phi / Rq_0\mu_0$$

$$\left\langle j^2\right\rangle = 2\left(\frac{B_\phi}{\mu_0 R}\right)^2 \frac{1}{q_0\left(q_a - \frac{1}{2}q_0\right)}$$

Ohmic Heating

$$P_\Omega = \eta\left\langle j^2 \right\rangle = 1.0\times 10^5 \left(\frac{Z_{eff}}{T^{3/2}}\right)\left[\frac{1}{q_o(q_a - q_o/2)}\right]\left(\frac{B_\phi}{R}\right)^2$$

- Z_{eff} limited by radiation losses
- High T required for enough fusion reactions

q_a limited by instabilities

Magnetic field limited by engineering
→ compact high-field tokamak

$$q_a = \frac{aB_\phi}{RB_\theta} = \frac{aB_\phi}{R\frac{\mu_0 I_p}{2\pi a}} = \frac{aB_\phi}{R\frac{\mu_0\langle j\rangle \pi a^2}{2\pi a}} = \frac{2B_\phi}{\mu_0\langle j\rangle R} > 2$$

$$\langle j\rangle < \frac{B_\phi}{\mu_0 R}$$

Ohmic Heating

$$P_\Omega = \eta\left\langle j^2\right\rangle = 1.0\times10^5\left(\frac{Z_{eff}}{T^{3/2}}\right)\left[\frac{1}{q_o(q_a - q_o/2)}\right]\left(\frac{B_\phi}{R}\right)^2$$

$$= 3nT/\tau_E = P_L$$

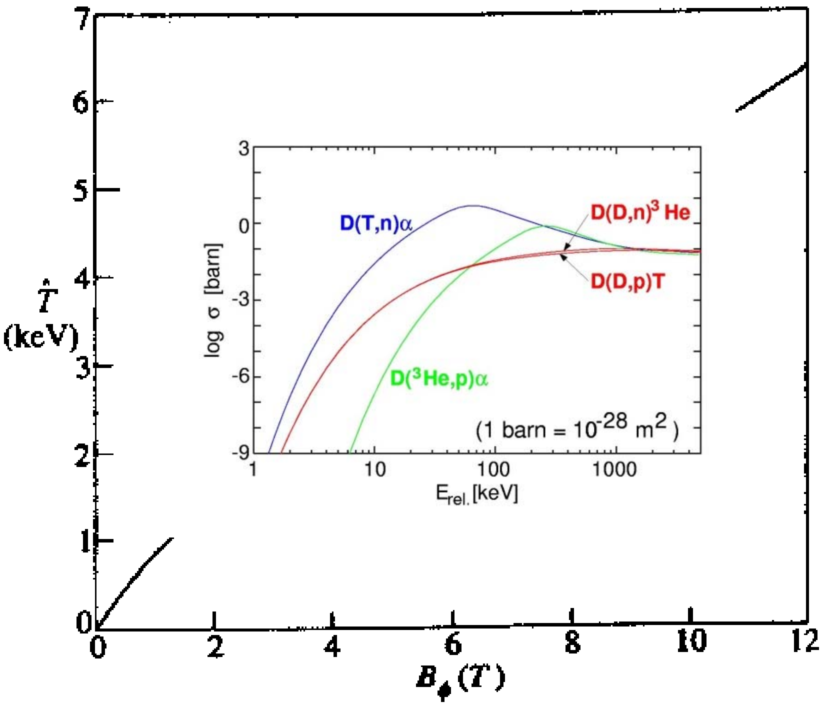
$$T = 2.7\times10^8\left(\frac{Z_{eff}\,\tau_E}{n q_a q_0}\right)^{\frac{2}{5}}\left(\frac{B_\phi}{R}\right)^{\frac{4}{5}}$$

$$Z_{eff} = 1.5 \qquad q_a q_o = 1.5$$

$$\tau_E = (n/10^{20})a^2/2$$

Alcator scaling

$$T = 0.87 B_\phi^{\frac{4}{5}}$$



It seems unlikely that tokamaks that would lead to practical reactors can be heated to thermonuclear temperatures by Ohmic heating!

Neutral Beam Injection

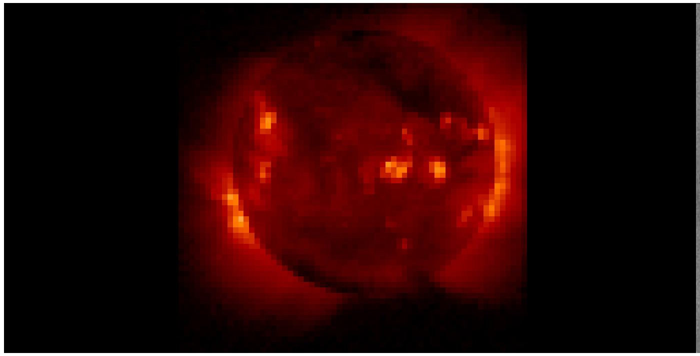
259-Car Autobahn pile-up near Braunschweig, largest in German history: (20 July 2009)

- More than 300 ambulances, fire engines and police cars rushed to the scene to tend to the 66 people injured in the crash.
- The crash was blamed on cars aquaplaning on puddles and a low sun hindering drivers.

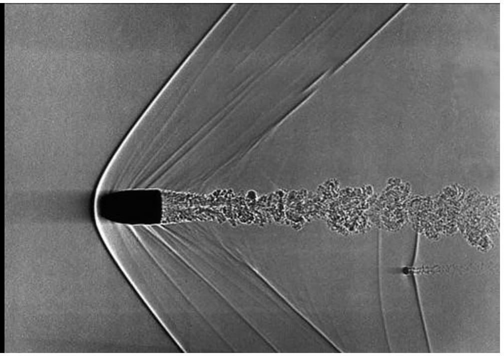
Neutral Beam Injection

259-Car Autobahn pile-up near Braunschweig, largest in German history: (20 July 2009)

Neutral Beam Injection



Plasma



Neutral beam

NBI

Andy Warhol

http://www.nasa.gov/mission_pages/galex/20070815/f.html

- Supplemental heating by energy transfer of neutral beam to the plasma through collisions

- Requirements
- Enough energy for deep penetration
- Enough power for desired heating
- Enough repetition rate and pulse length > τ_E
- Allowable impurity contamination

Neutral Beam Injection

Injection of a beam of neutral fuel atoms (H, D, T) at high energies (E_b > 50 keV)*

⇓

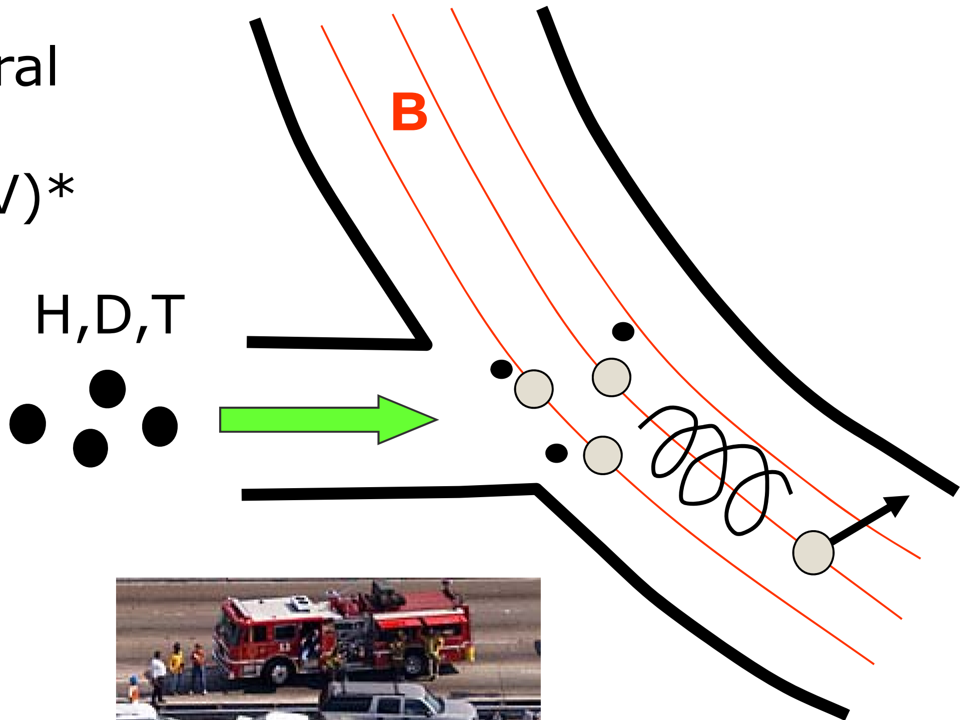
Ionisation in the plasma

⇓

Beam particles confined

⇓

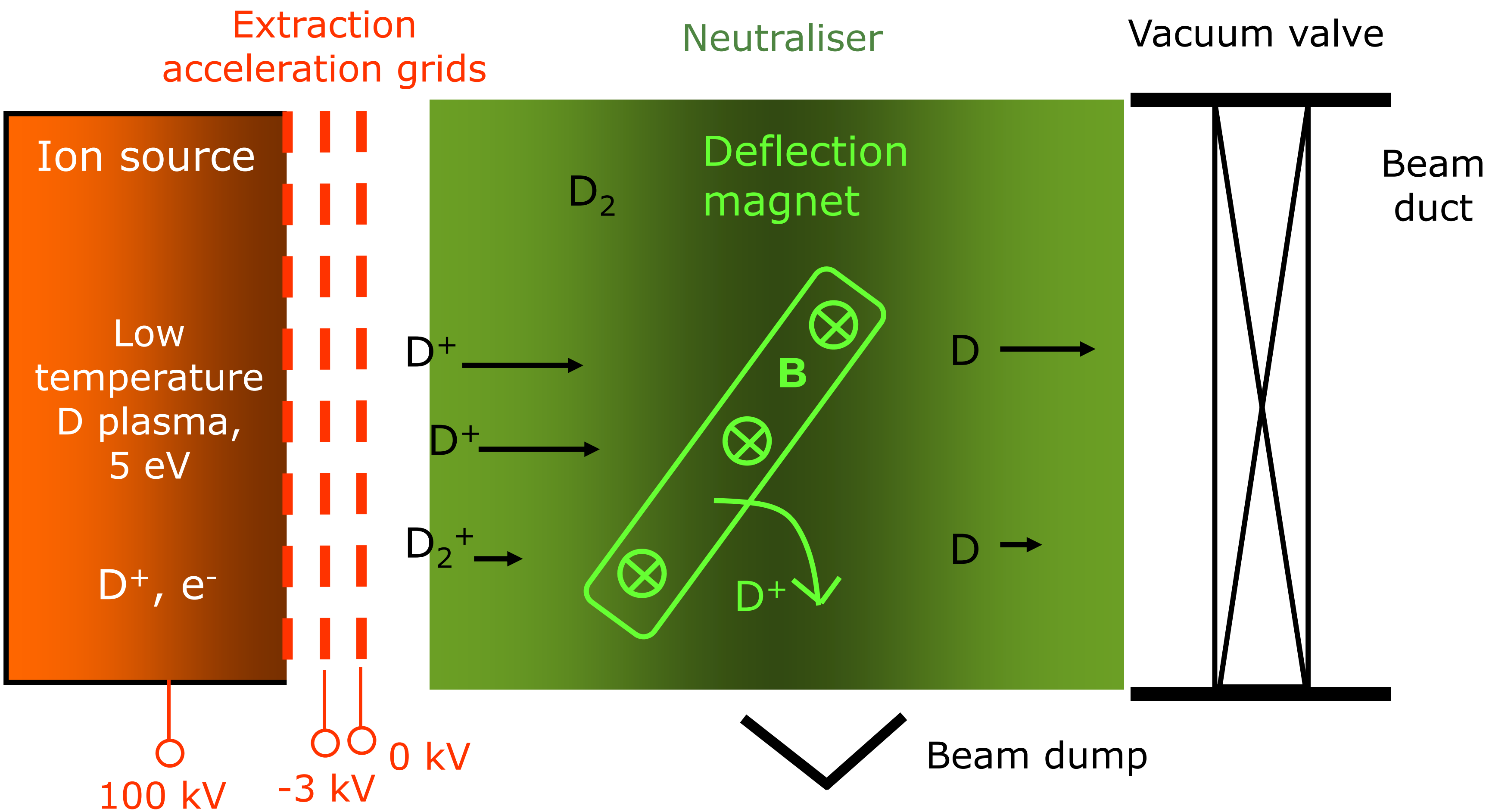
Collisional slowing down



* E_b = 120 keV and 1 MeV for KSTAR and ITER, respectively

Neutral Beam Injection

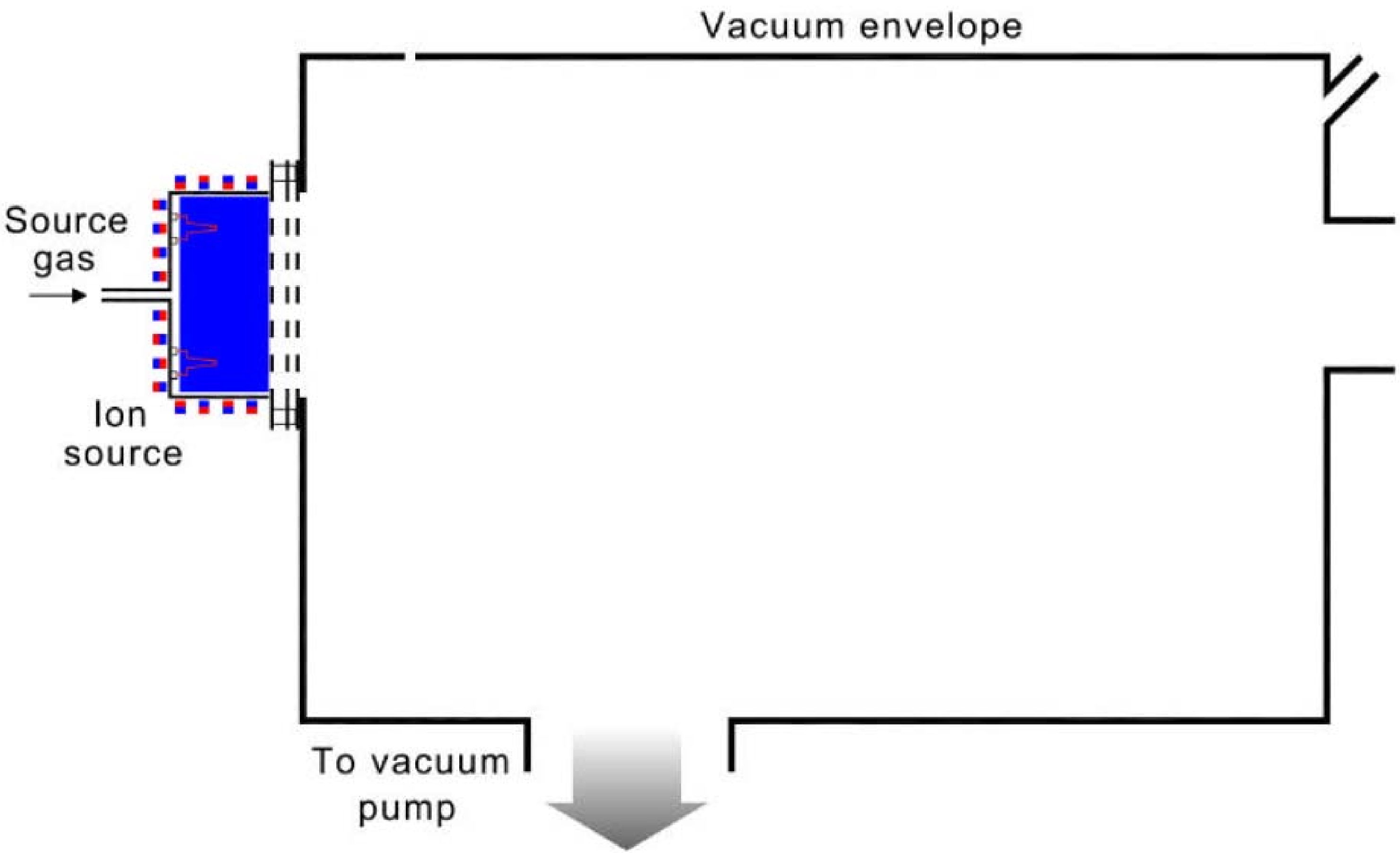
- **Generation of a Neutral Fuel Beam**



Ex) W7-AS: V=50 kV, I=25 A, power deposited in plasma: 0.4 MW

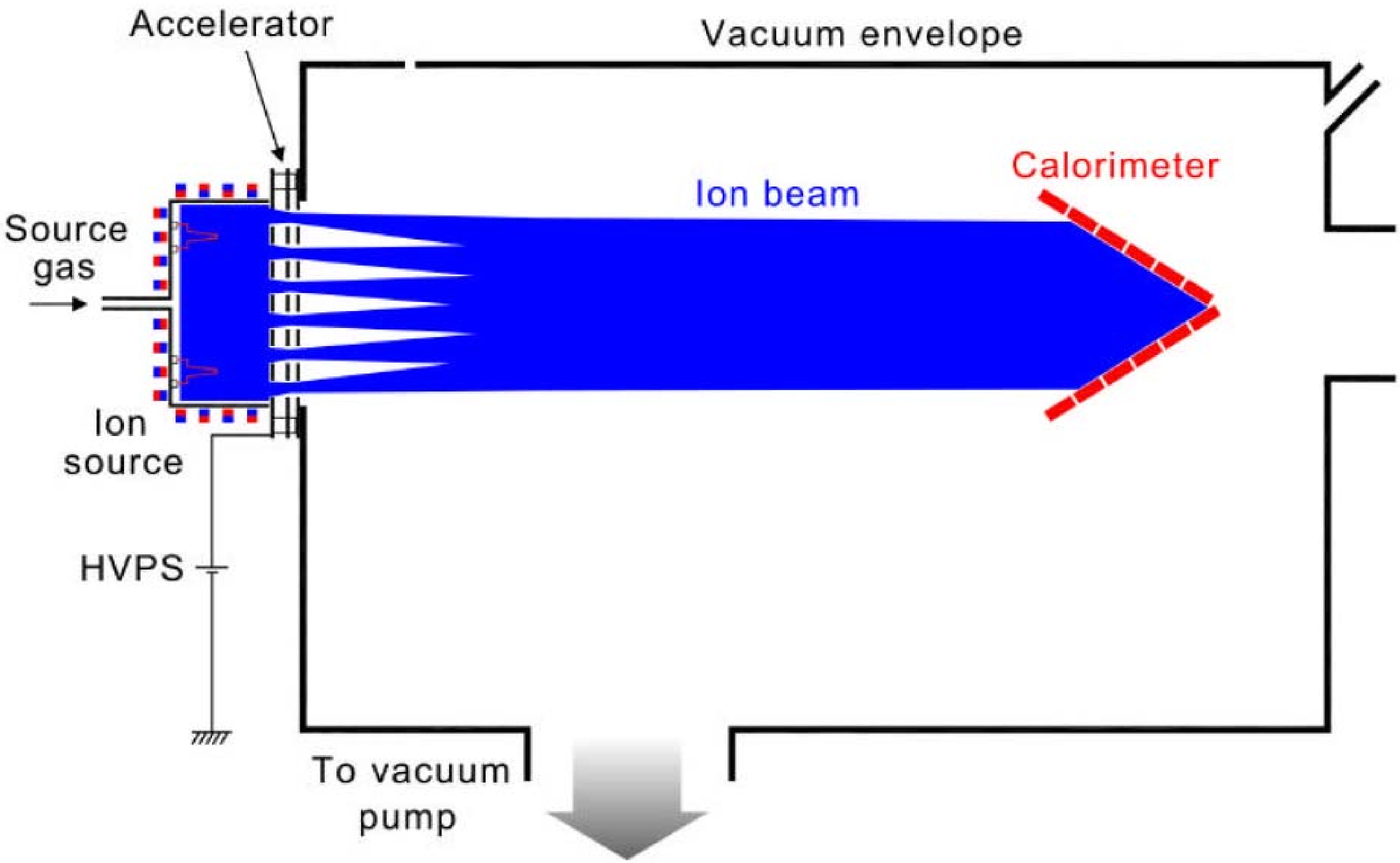
Neutral Beam Injection

- **Ion Source**



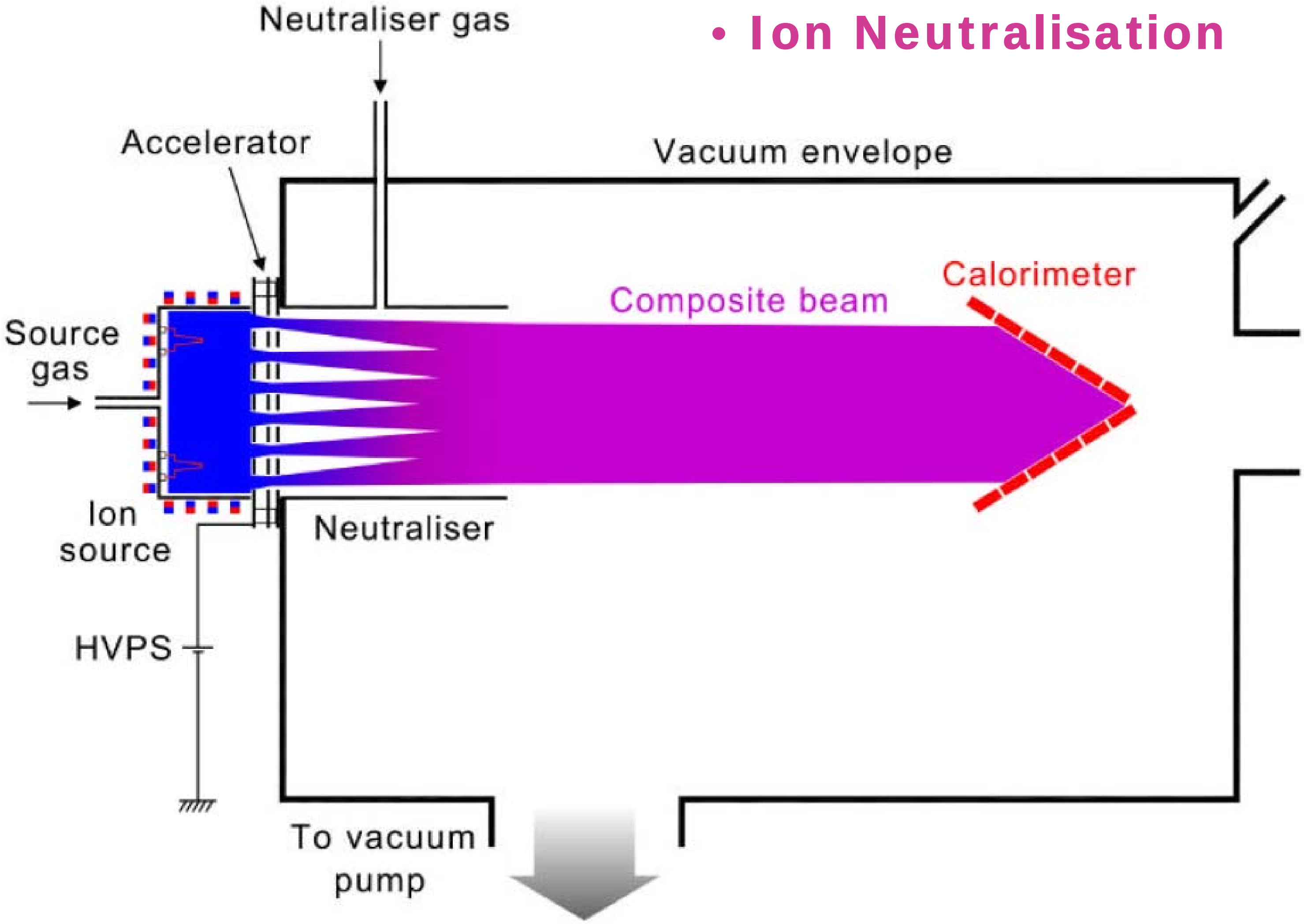
Neutral Beam Injection

- **Ion Acceleration**

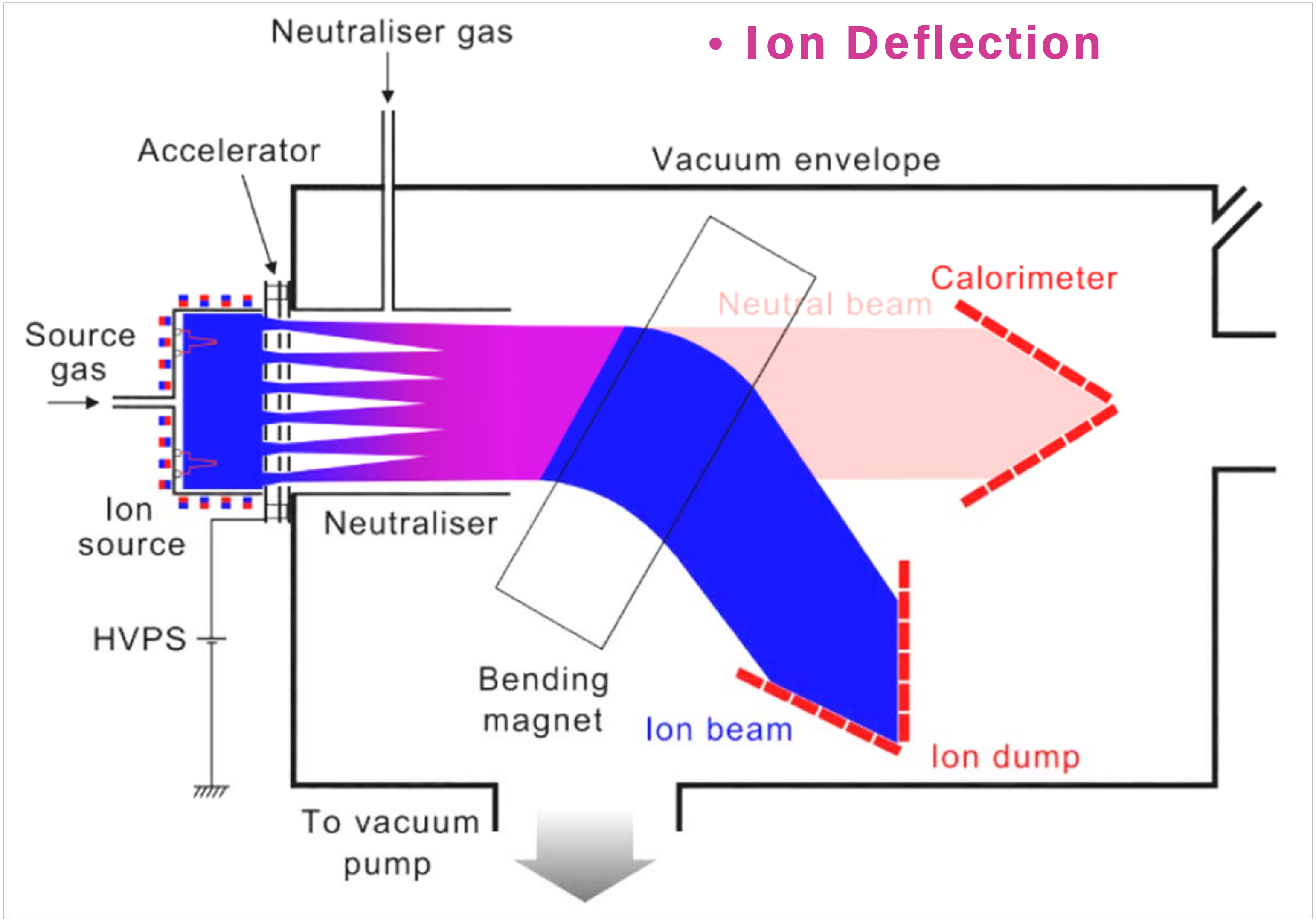


Neutral Beam Injection

- **Ion Neutralisation**

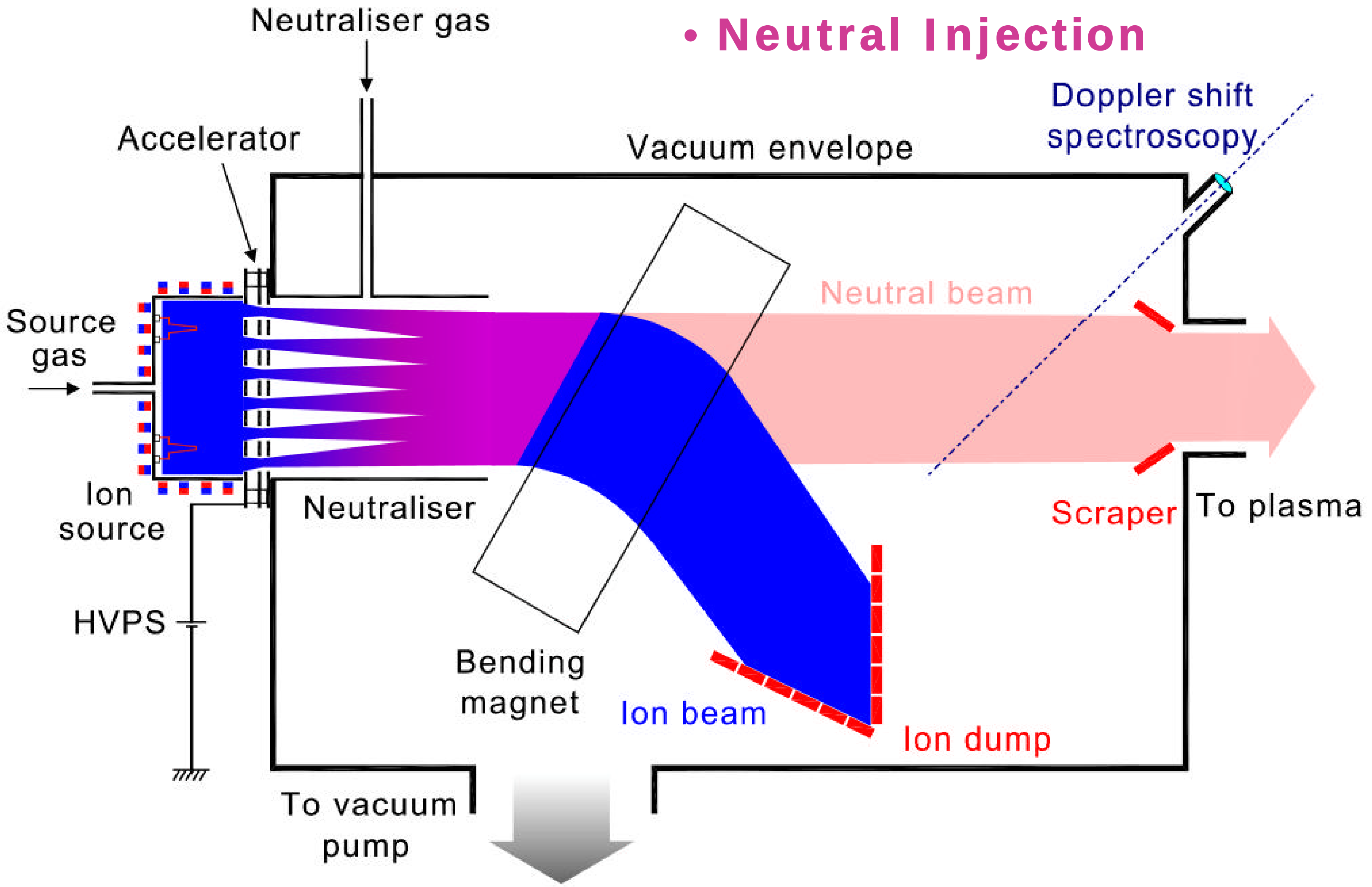


Neutral Beam Injection



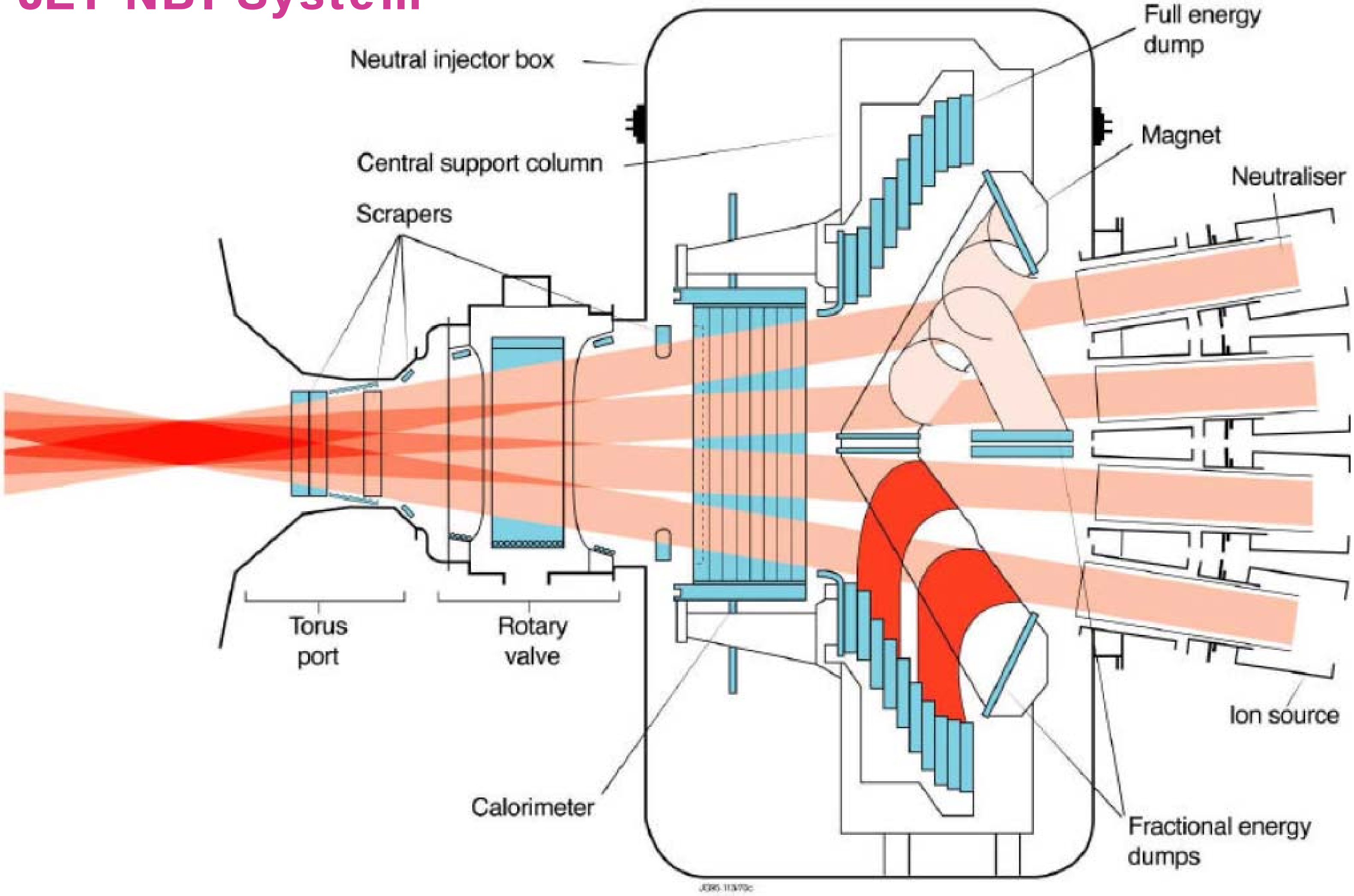
Neutral Beam Injection

- **Neutral Injection**



Neutral Beam Injection

- **JET NBI System**



Neutral Beam Injection

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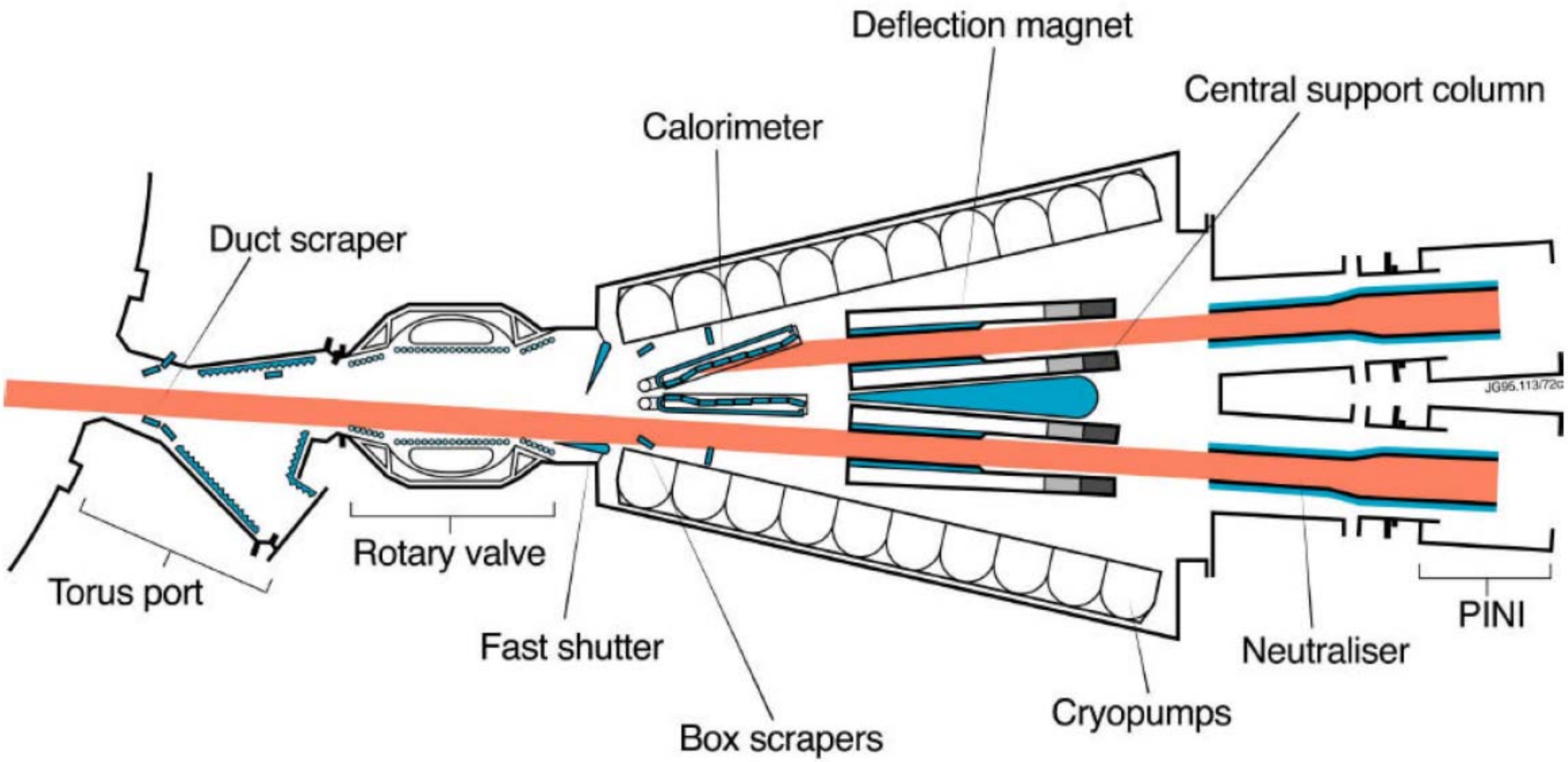
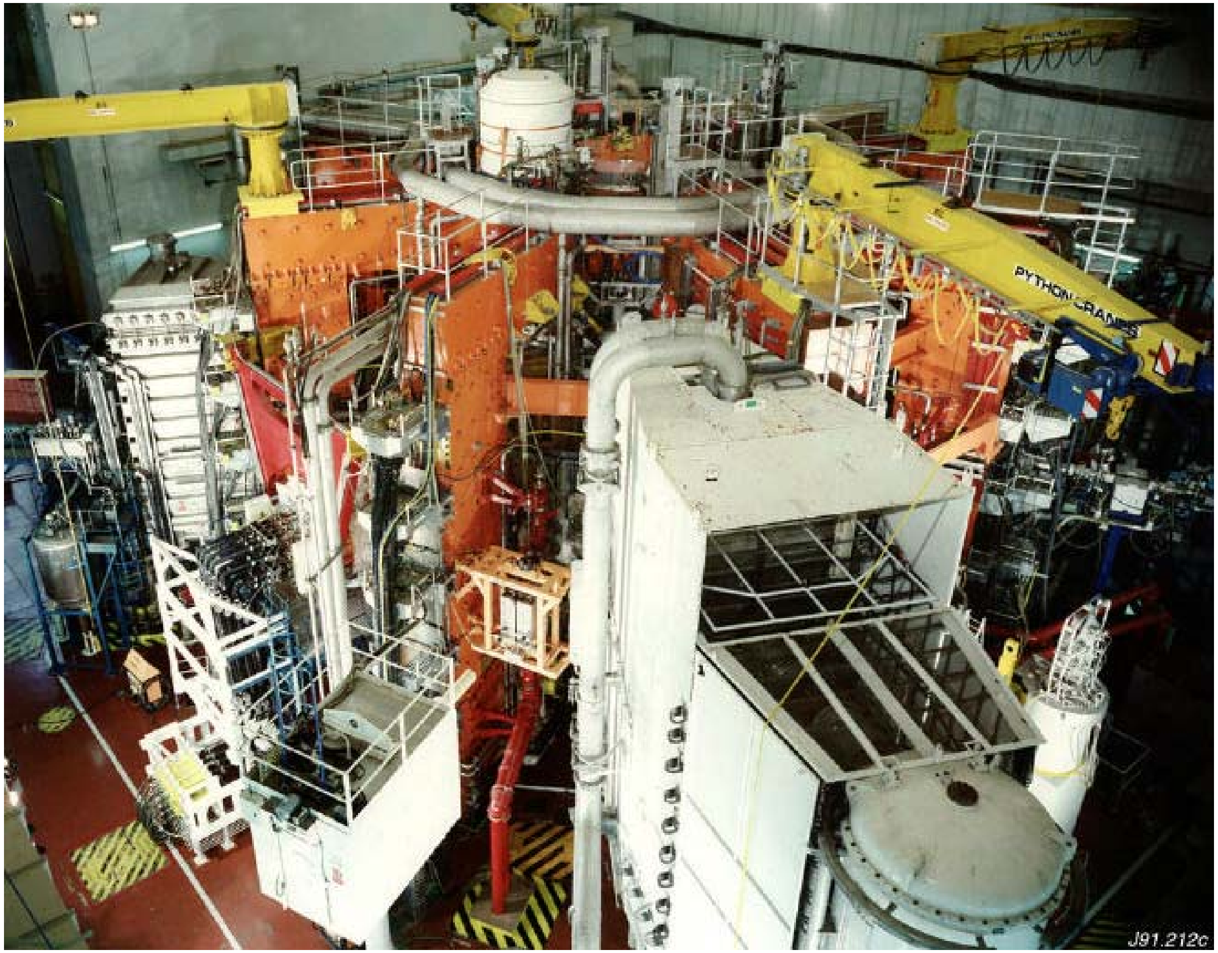


Neutral Beam Injection

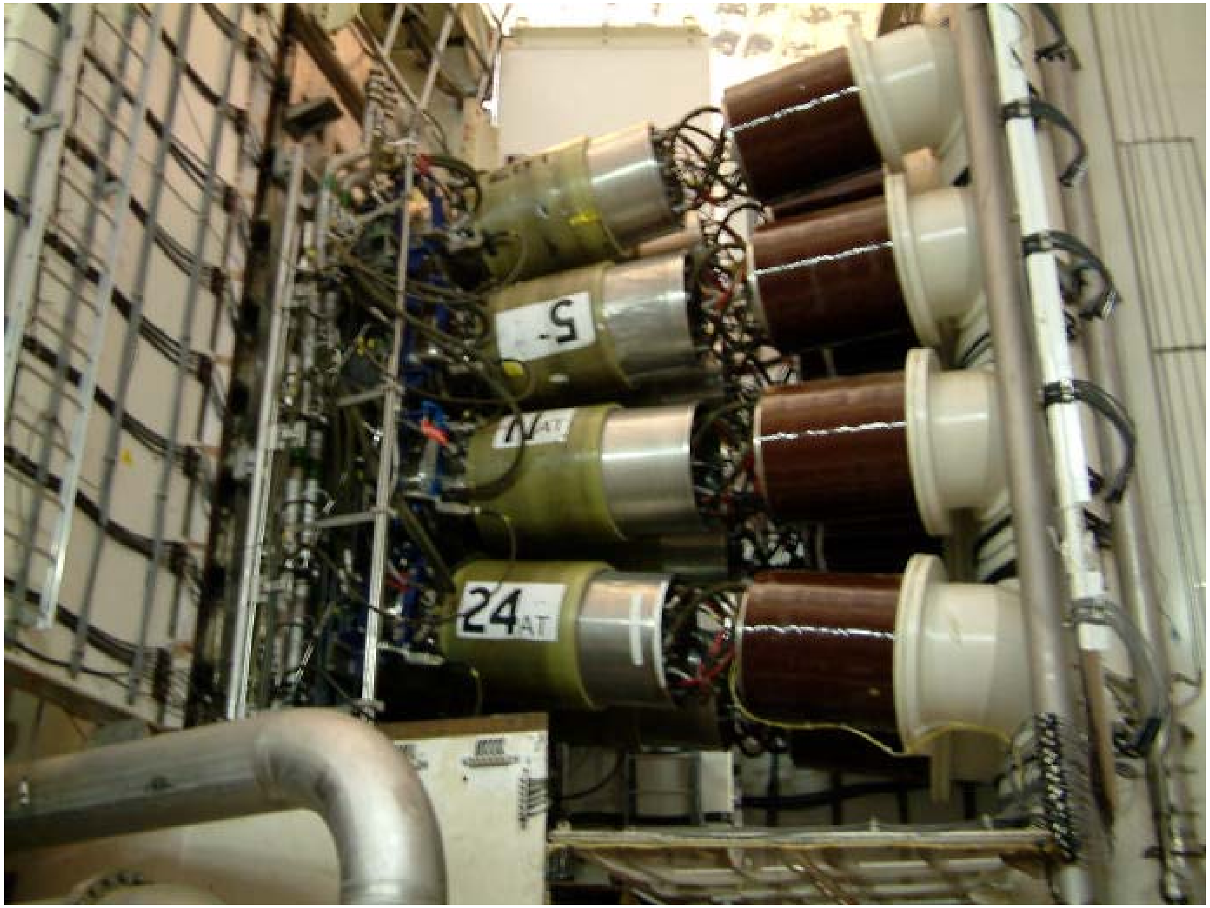
- JET NBI System



JET with machine and Octant 4 Neutral Injector Box

Neutral Beam Injection

- **JET NBI System**



Octant 4 Neutal Injector Box

Neutral Beam Injection

- **Ion source**

- Requirements

- Large-area uniform quiescent flux of high-current ions
- Large atomic ion fraction (D^+, D^-) > 75 % → adequate penetration
- Low ion temperature (<< 1 eV) to minimize irreducible divergence of extracted ion beams due to random thermal motion of ions

Neutral Beam Injection

- **Ion source**

- Ion generation
- Positive ion generation by electric discharge

$$D_2 + e \rightarrow D^+ + D + e + e$$

$$D_2 + e \rightarrow D_2^+ + e + e$$

$$D_2 + D_2^+ \rightarrow D_3^+ + D$$

- Negative ion generation

$D + e \rightarrow D^- + h\nu$ Radiative attachment in high density gas ($E_{binding}$ = 0.75 eV)

$D_2^* + e \rightarrow D^- + D$ Dissociative electron attachment by electric discharge (~eV)

$D^+ + cathode\ surface\ (+Cs) \rightarrow D^-$

$D^0 + cathode\ surface\ (+Cs) \rightarrow D^-$

Surface production by electric discharge (~100 eV range)

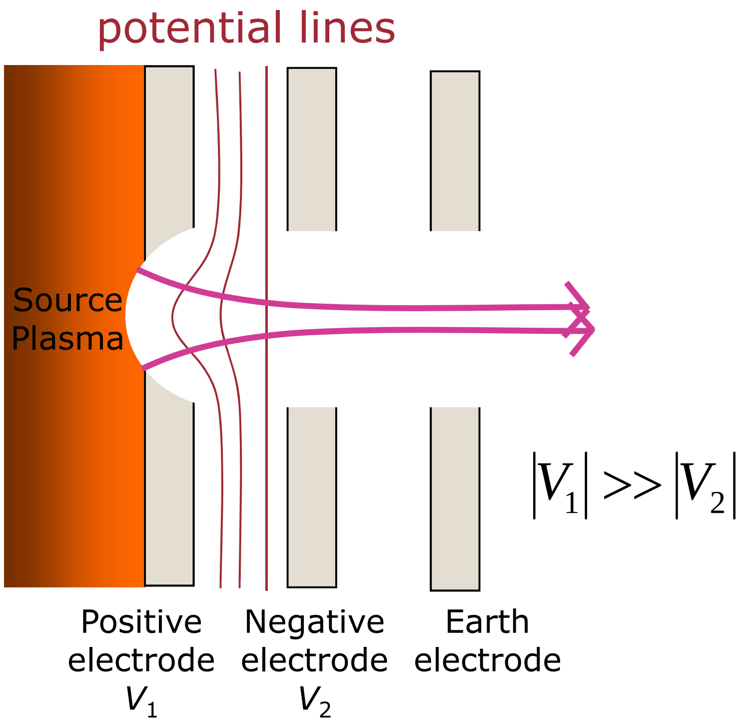
$D^+ + M^0 \rightarrow D^0 + M^+$

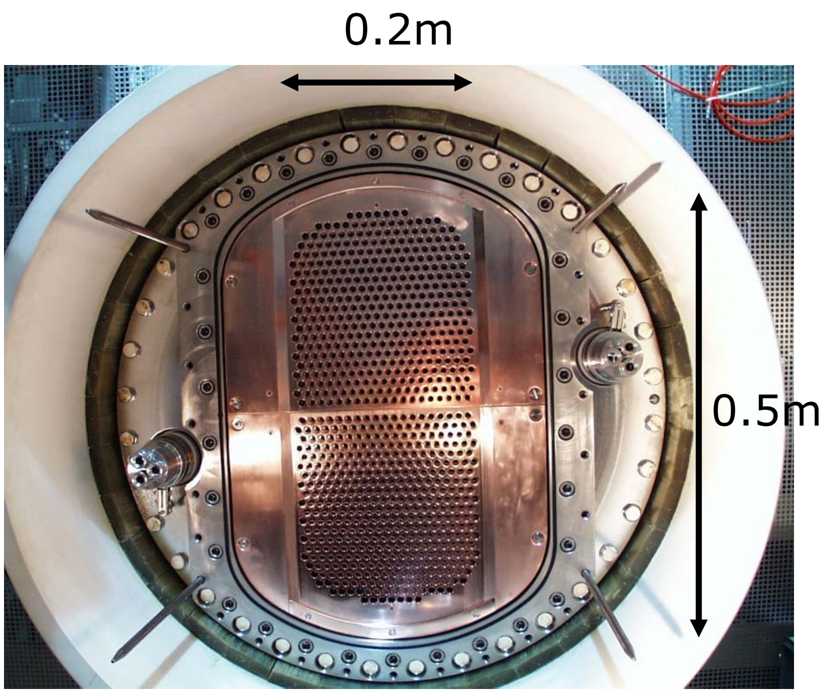
$D^0 + M^0 \rightarrow D^- + M^+$

Electron attachment (Double electron capture)
M: alkali or alkali-earth metal vapor (Cs, Rb, Na, Sr, Mg)

Neutral Beam Injection

- **Beam Forming System: Extraction and steering**
  - 3-lens system



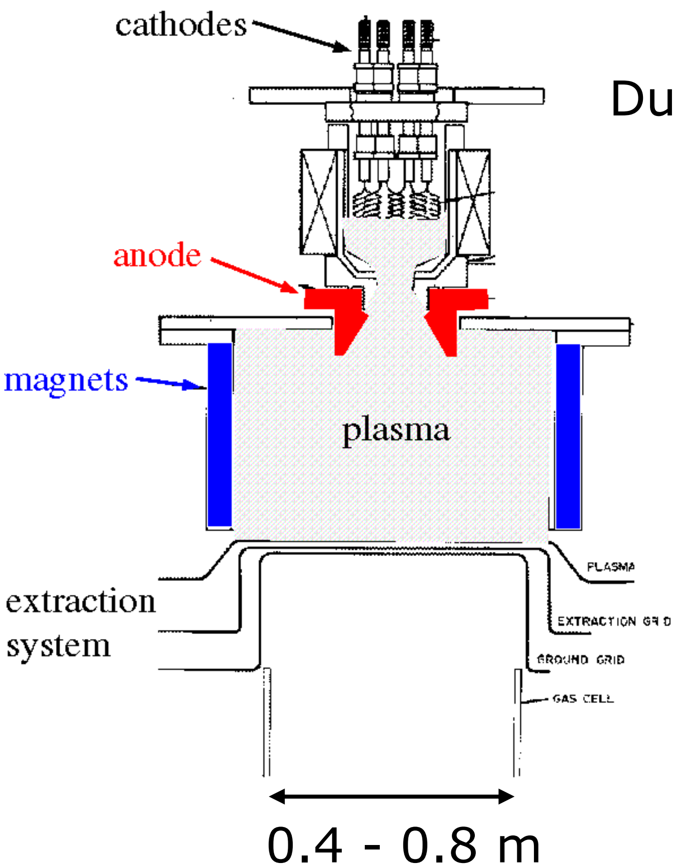


Grid system at ASDEX Upgrade

- Ion extraction + acceleration + minimum beam divergence (≤ 1°)

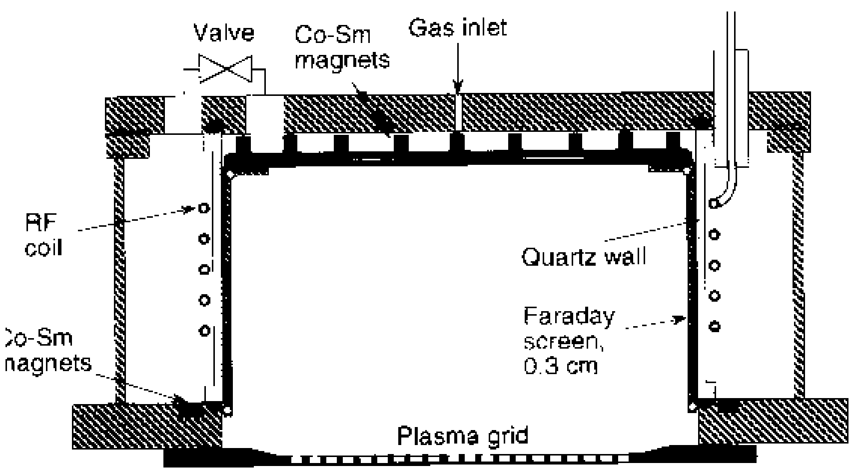
Neutral Beam Injection

- Ion sources



Duopigatron

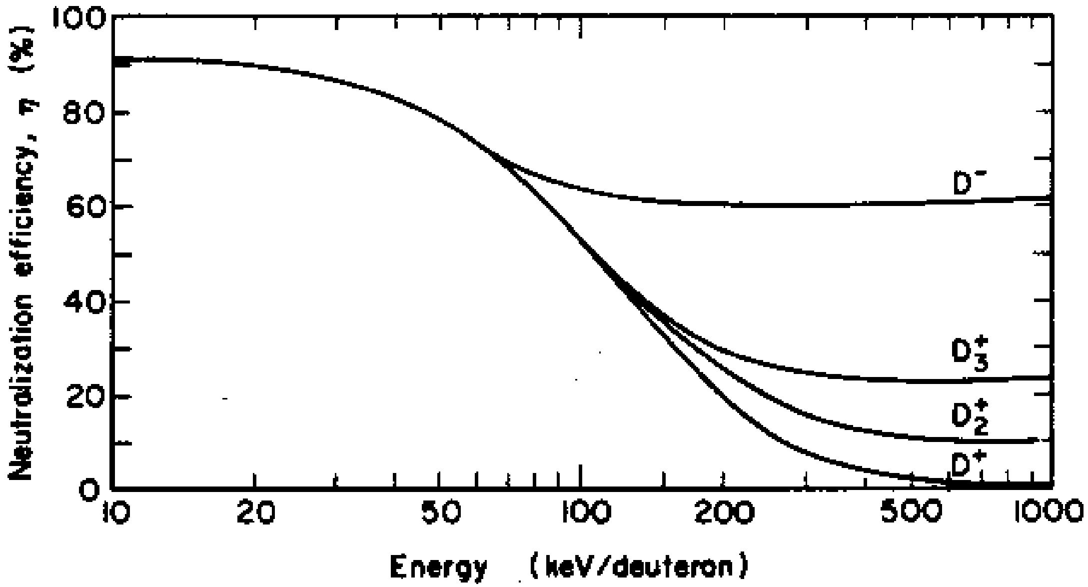
RF Source



Cathodes difficult to replace, finite life time

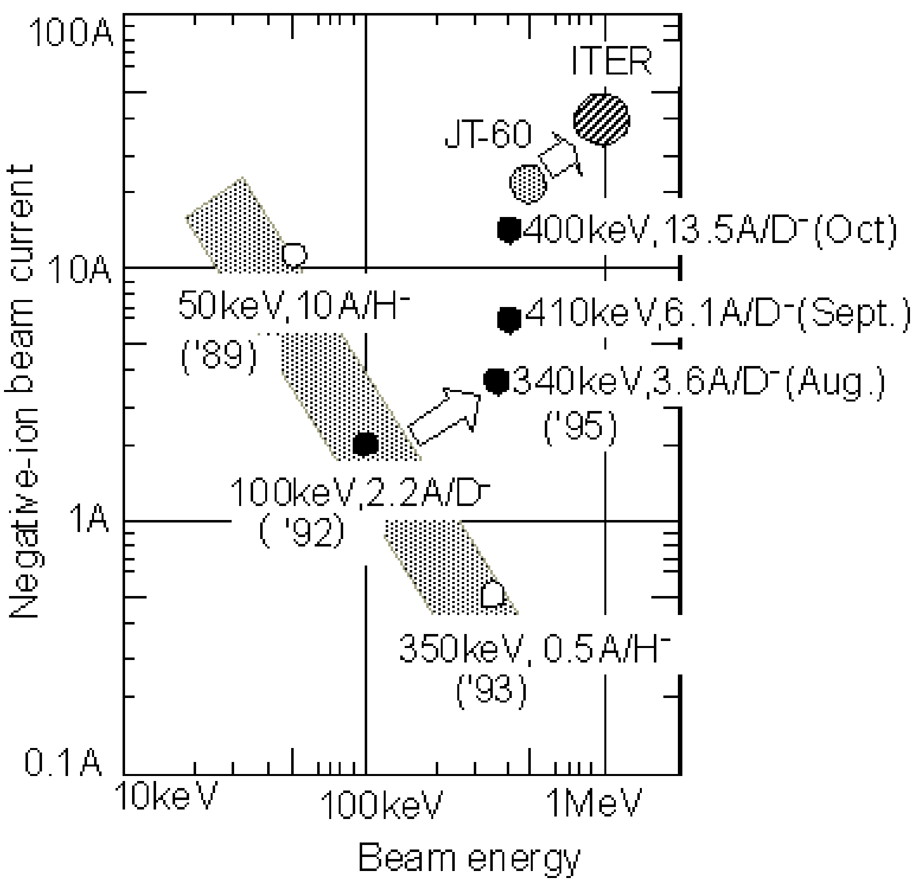
Neutral Beam Injection

- **Neutraliser**
  - Charge exchange: $$\underbrace{D^+}_{fast} + \underbrace{D_2}_{gas} \rightarrow \underbrace{D}_{fast} + \underbrace{D_2^+}_{slow}$$
  - Re-ionisation: $$\underbrace{D}_{fast} + \underbrace{D_2}_{gas} \rightarrow \underbrace{D^+}_{fast} + \underbrace{D_2}_{gas} + e^-$$
  - Efficiency: (outgoing NB power)/(entering ion beam power)



Neutral Beam Injection

- Negative ion beam development in JT-60U



Neutral Beam Injection

- **Ion Beam Dump and Vacuum Pumps**
  - Beam dump
  - Deflect by analyzing magnet
  - Minimize reionisation losses
  - Prevent local power dump at undesirable place (~kW/m^2)
  - Possible application to direct energy conversion

  - Pumping
  - Minimise reioninsaton losses
  - Prevent cold neutral particles from flowing into reactor plasma
  - Liquid He cryopumps (~10^6 l/s for ~MW system)

Neutral Beam Injection

- **Energy Deposition in a Plasma**

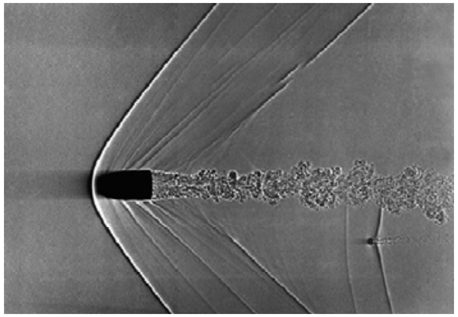
Charge exchange: $D_{fast} + D^{+} \rightarrow D^{+}_{fast} + D$

Ion collision: $D_{fast} + D^{+} \rightarrow D^{+}_{fast} + D^{+} + e$

Electron collision: $D_{fast} + e \rightarrow D^{+}_{fast} + e + e$

Attenuation of a beam of neutral particles in a plasma

n: density
σ: cross section



beam energy

NBI

Andy Warhol

http://www.nasa.gov/mission_pages/galex/20070815/f.html

Neutral Beam Injection

- **Energy Deposition in a Plasma**

Charge exchange: $D_{fast} + D^+ \rightarrow D^+_{fast} + D$

Ion collision: $D_{fast} + D^+ \rightarrow D^+_{fast} + D^+ + e$

Electron collision: $D_{fast} + e \rightarrow D^+_{fast} + e + e$

Attenuation of a beam of neutral particles in a plasma

$$\frac{dN_b(x)}{dx} = -N_b(x)n(x)\sigma_{tot}$$

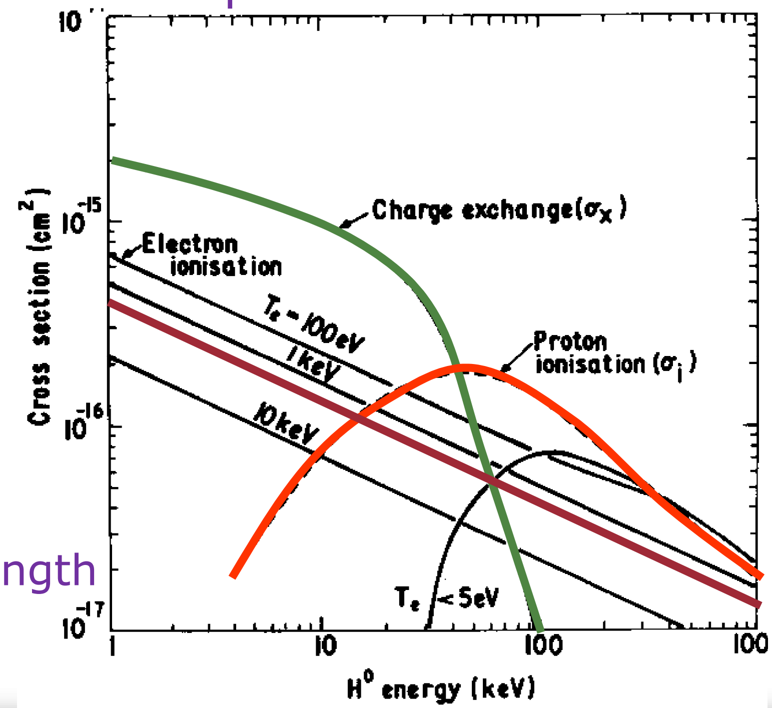
Ex. beam intensity: $I(x) = N_b(x)v_b$

$$= I_0 \cdot \exp(-x/\lambda)$$

$E_{b0} = 70keV$ $\quad \sigma_{tot} = 5\cdot 10^{-20} m^2$

$n = 5\cdot 10^{20} m^{-3}$ $\quad \lambda = \dfrac{1}{n\sigma_{tot}} \approx 0.4m$

Penetration (attenuation) length



In large reactor plasmas, beam cannot reach core!

Neutral Beam Injection

- **Energy Deposition in a Plasma**

Charge exchange: $D_{fast} + D^{+} \rightarrow D^{+}_{fast} + D$

Ion collision: $D_{fast} + D^{+} \rightarrow D^{+}_{fast} + D^{+} + e$

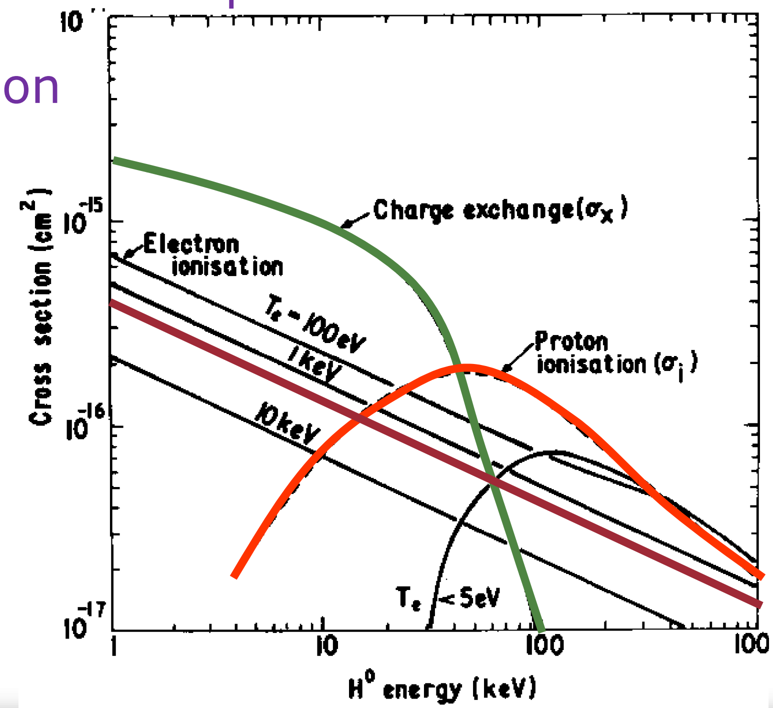
Electron collision: $D_{fast} + e \rightarrow D^{+}_{fast} + e + e$

Attenuation of a beam of neutral particles in a plasma

General criterion for adequate penetration

$$\lambda \equiv \frac{1}{n\sigma_{tot} Z_{eff}^{\gamma}} = \frac{5.5\times 10^{17} E_b(keV)}{A(amu)n(m^{-3})Z_{eff}^{\gamma}} \geq a/4$$

$$E_b \geq 4.5\times 10^{-19} AnaZ_{eff}^{\gamma}$$



Neutral Beam Injection

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Charge exchange: $D_{fast} + D^{+} \rightarrow D^{+}_{fast} + D$

Ion collision: $D_{fast} + D^{+} \rightarrow D^{+}_{fast} + D^{+} + e$

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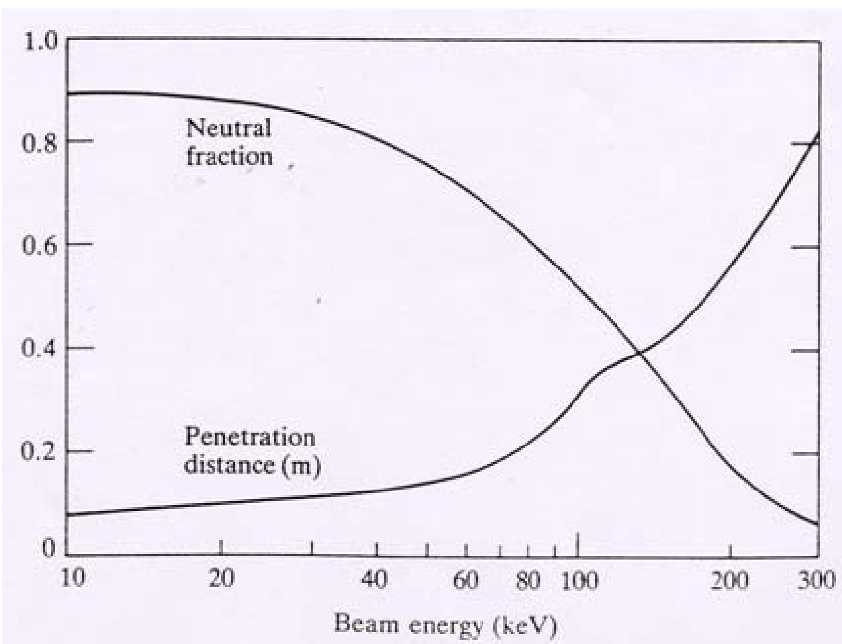
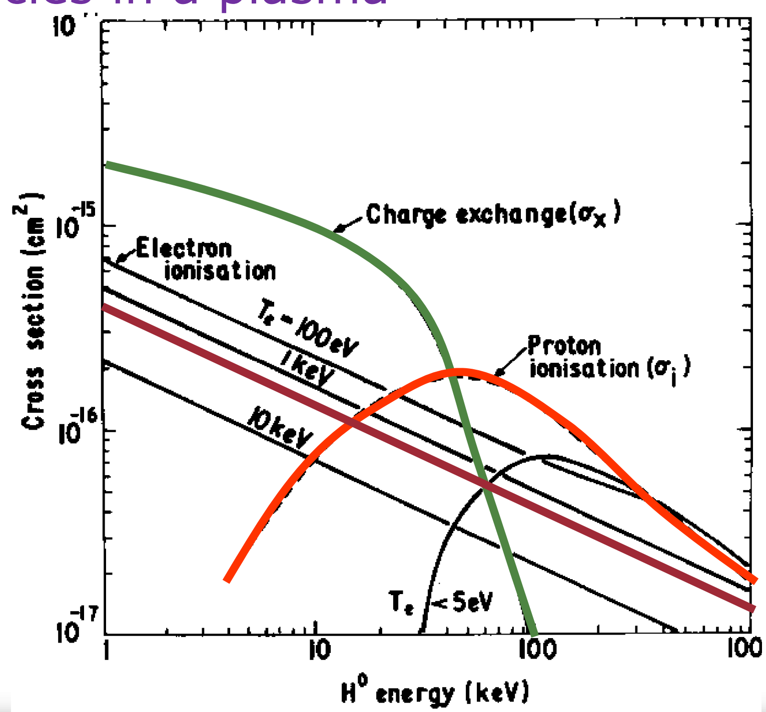
Attenuation of a beam of neutral particles in a plasma





Neutral Beam Injection

- **Slowing down**

$$-\frac{d\xi_b}{dt} = P = P_e + P_i \qquad \xi_b = \frac{1}{2} m_b v_b^2$$

$$= \frac{2^{\frac{1}{2}} n_e Z_b^2 e^4 m_e^{\frac{1}{2}} \ln\Lambda}{6\pi^{\frac{3}{2}} \varepsilon_0^2 A_b} \left(\frac{\xi_b}{T_e^{\frac{3}{2}}} + \frac{C}{\xi_b^{\frac{1}{2}}} \right), \quad C = 3\pi^{\frac{1}{2}} Z^2 A_b^{\frac{3}{2}} / 4 m_e^{\frac{1}{2}} m_i \approx 81$$

$$P = 1.71 \times 10^{-18} \frac{n_e \xi_b}{A_b \hat{T}_e^{3/2}} \left(1 + \left(\frac{\xi_c}{\xi_b} \right)^{3/2} \right) \quad [\mathrm{keVs^{-1}}]$$

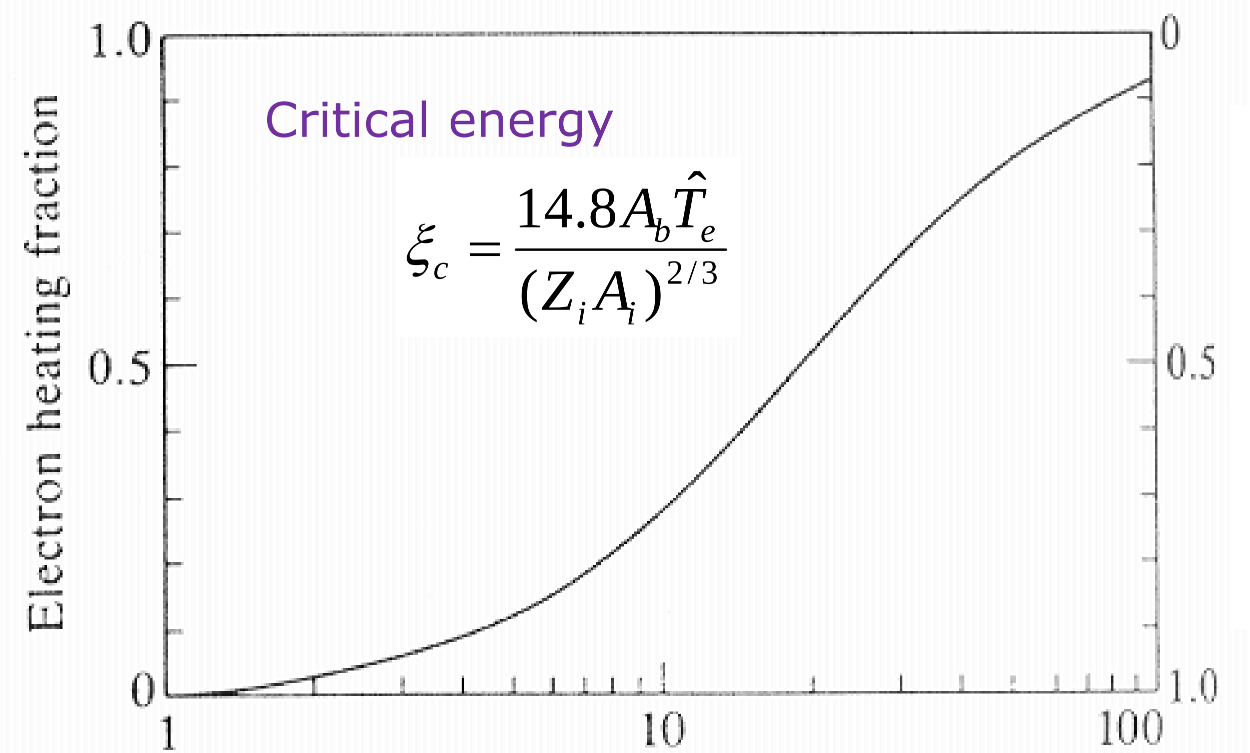
- Critical energy: The electron and ion heating rates are equal

$$\xi_c = \frac{14.8 A_b \hat{T}_e}{(Z_i A_i)^{2/3}}$$

Neutral Beam Injection

- **Slowing down**

$$P = 1.71\times10^{-18}\frac{n_e\xi_b}{A_b\hat{T}_e^{3/2}}\left(1+\left(\frac{\xi_c}{\xi_b}\right)^{3/2}\right) \quad [\mathrm{keVs^{-1}}]$$



$$\xi_c = \frac{14.8 A_b \hat{T}_e}{(Z_i A_i)^{2/3}}$$

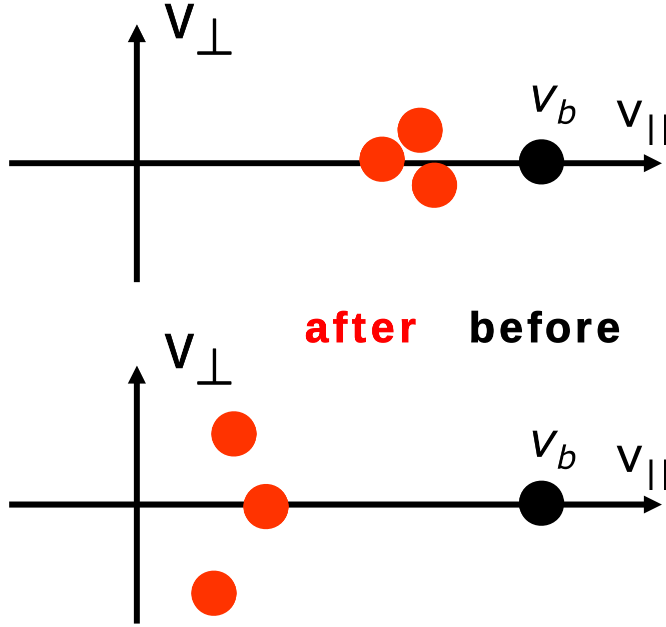
$$\xi_b / \hat{T}_e$$

Neutral Beam Injection

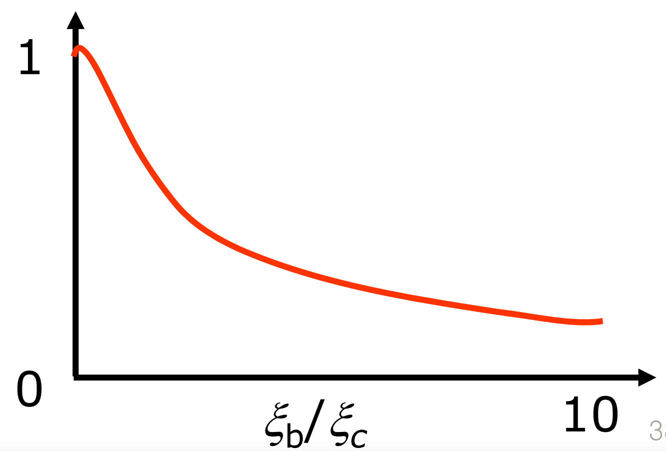
- **Slowing down**

1. $\xi_b > \xi_c$: Slowing down on electrons
   no scatter

2. $\xi_b < \xi_c$: Slowing down on ions
   scattering of beams



Fraction of initial beam energy going to ions

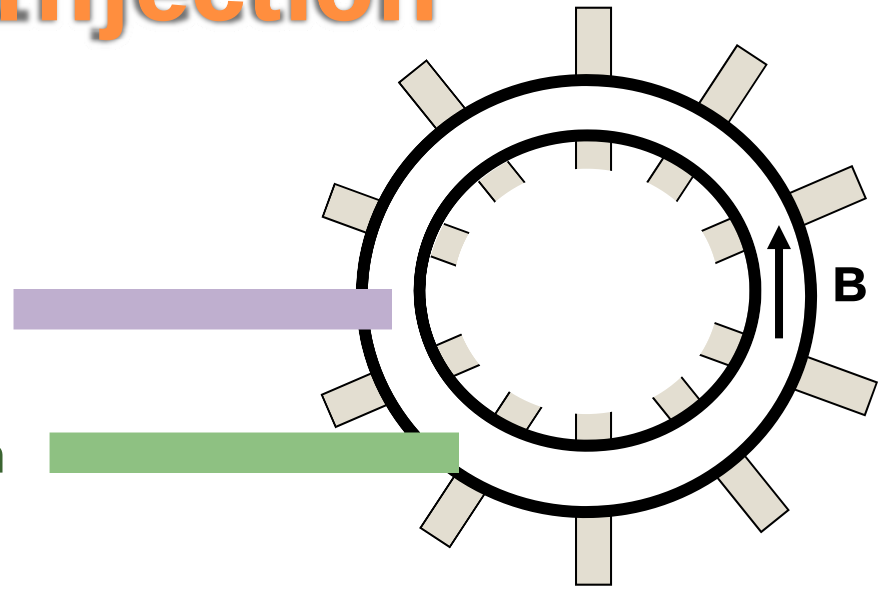


Neutral Beam Injection

- **Injection Angle**

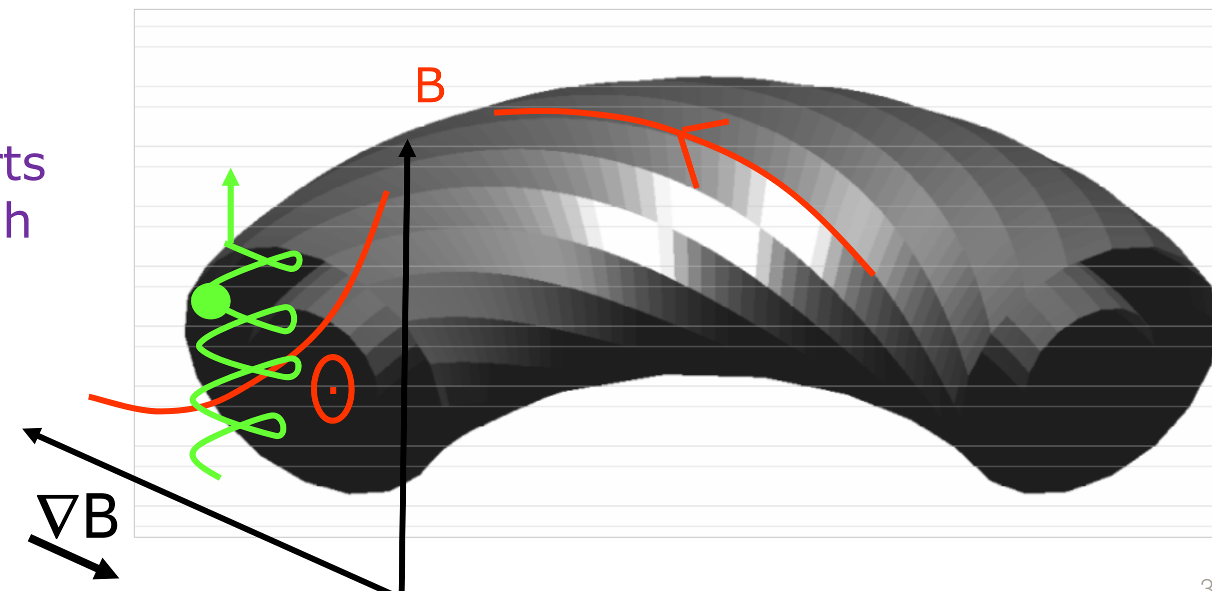
Radial (perpendicular, normal) injection

Tangential injection



Radial injection:

- standard ports
- shine-through
- particle loss

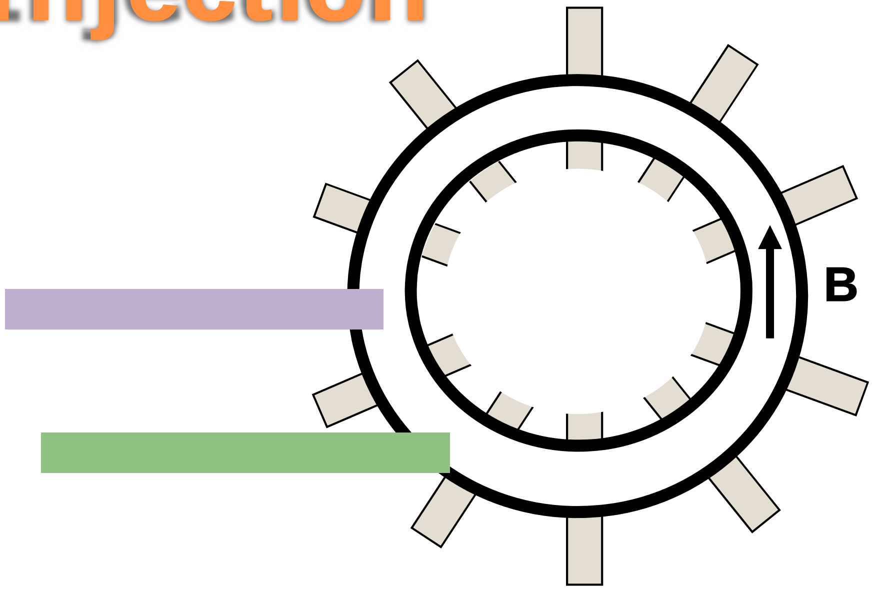


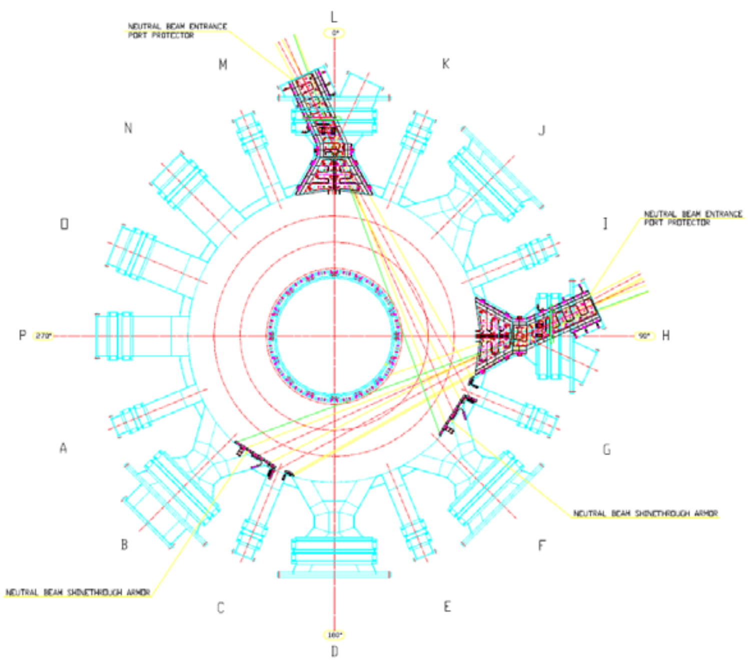
Neutral Beam Injection

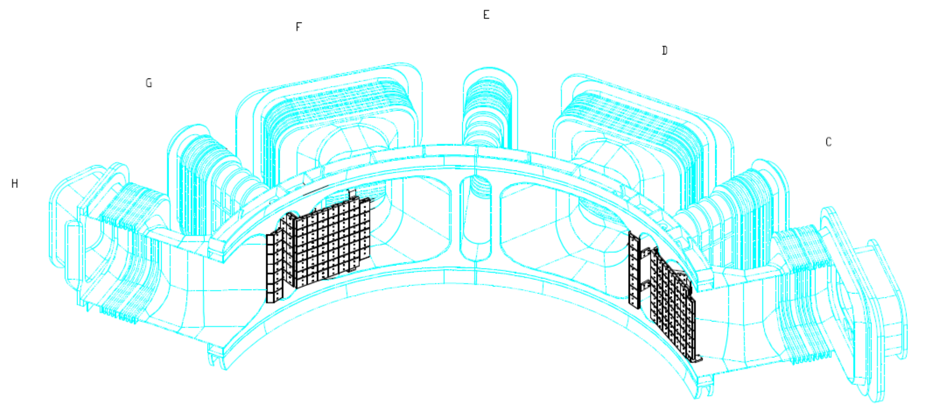
- **Injection Angle**

Radial (perpendicular, normal) injection

Tangential injection



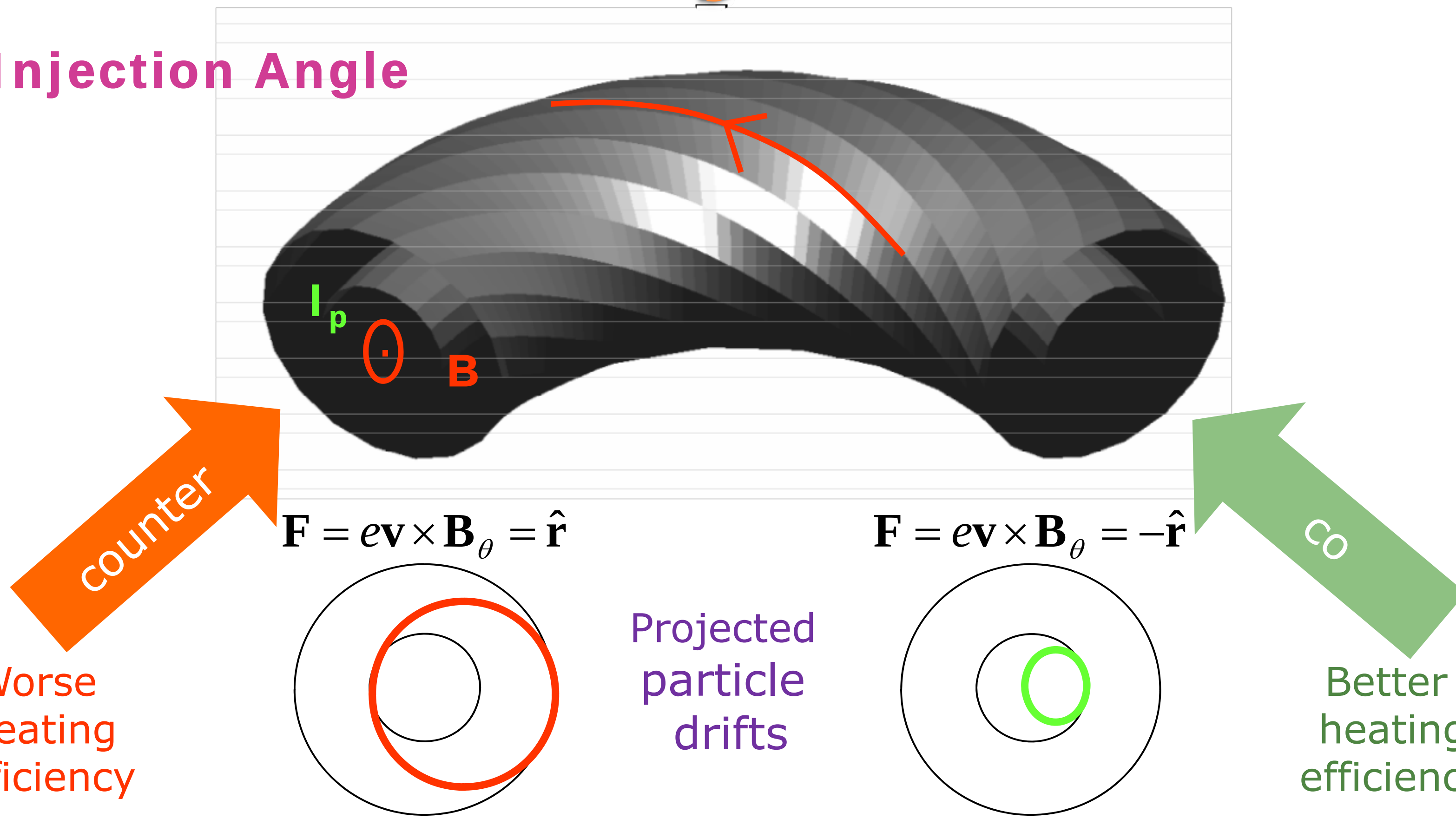




KSTAR NB shine-through armor

Neutral Beam Injection

- **Injection Angle**



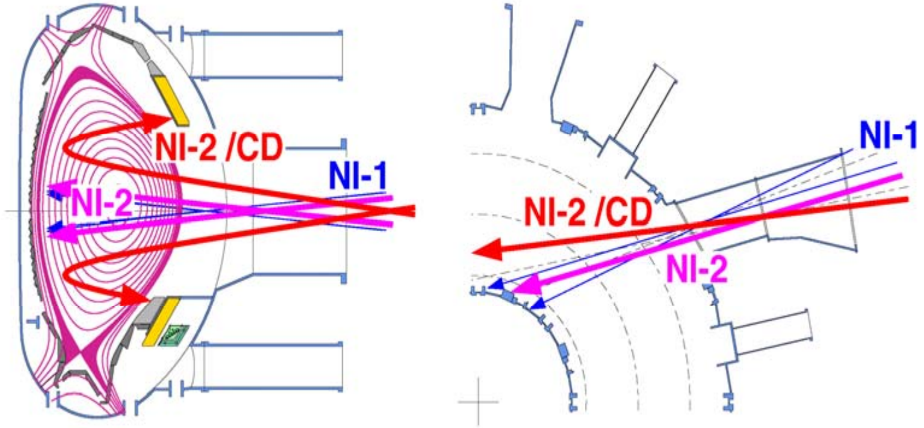
inward shift → bad drift orbits
→ energetic ion loss to wall/limiters

outward shift of orbit center

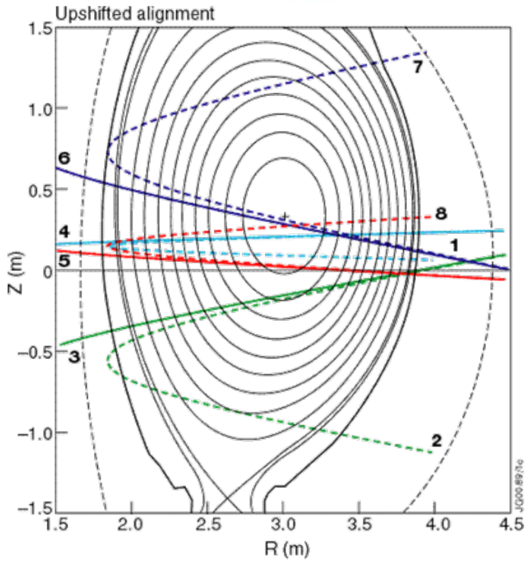
- At low magnetic fields heating efficiency depends on NBI direction.
- Best injection angle for maximum penetration and minimum orbital excursion = 10-20° off perpendicular in co-injection direction

Neutral Beam Injection

- ASDEX Upgrade



- JET



Solid = Normal, Dashed = Tangential