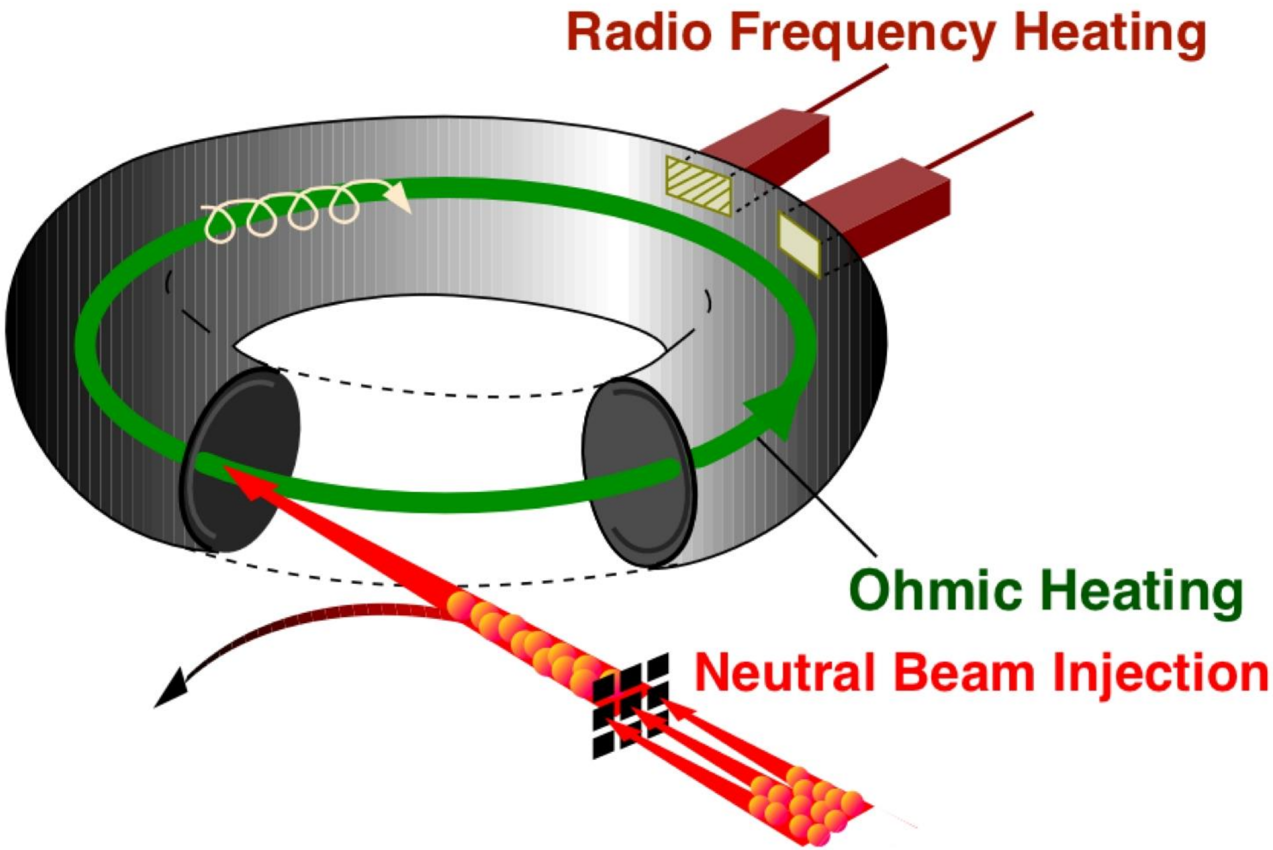
Introduction to Nuclear Fusion

Prof. Dr. Yong-Su Na

How to heat up a plasma?

Plasma Heating



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

Ohmic heating

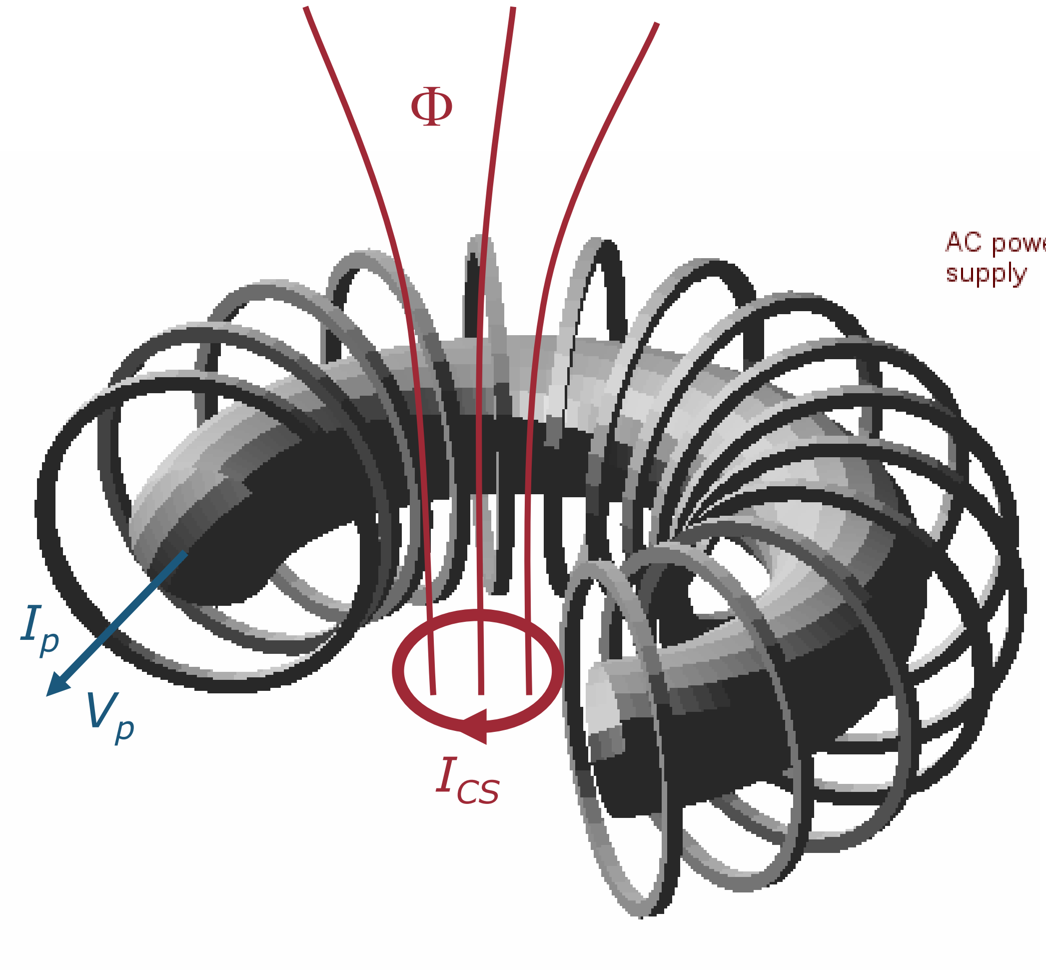
Ohmic Heating

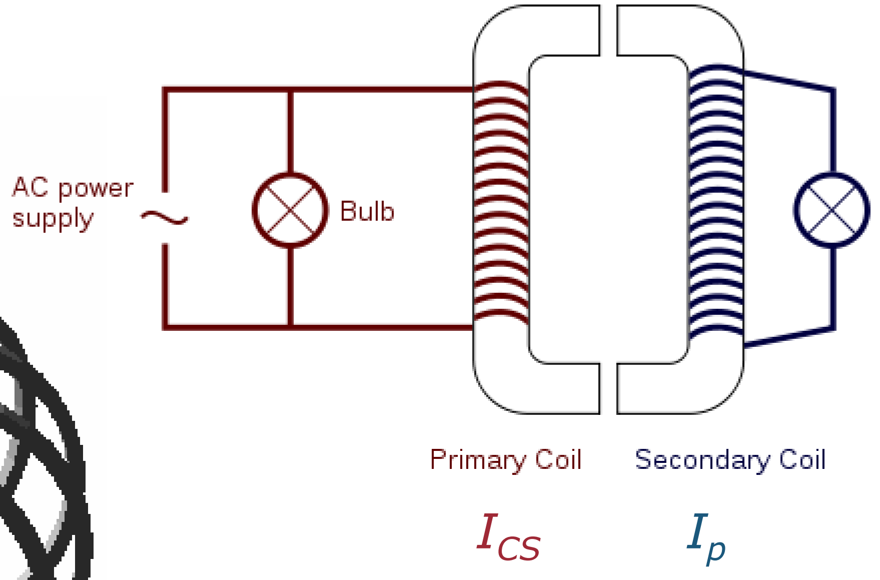
Electric blanket

Auction (Korea)

- 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





$$L_p \frac{dI_p}{dt} + I_p R_p = V_p = -\frac{d\phi}{dt}$$

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

Ohmic Heating

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

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

q_0, q_a limited by instabilities

Magnetic field limited by engineering
→ compact high-field tokamak

Ohmic Heating

$$\tau_E = \frac{W}{P_{in} - \frac{\partial W}{\partial t}} \approx \frac{W}{P_{in}} = \frac{3/2\left(n_i T_i + n_e T_e\right)}{P_{in}}$$

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

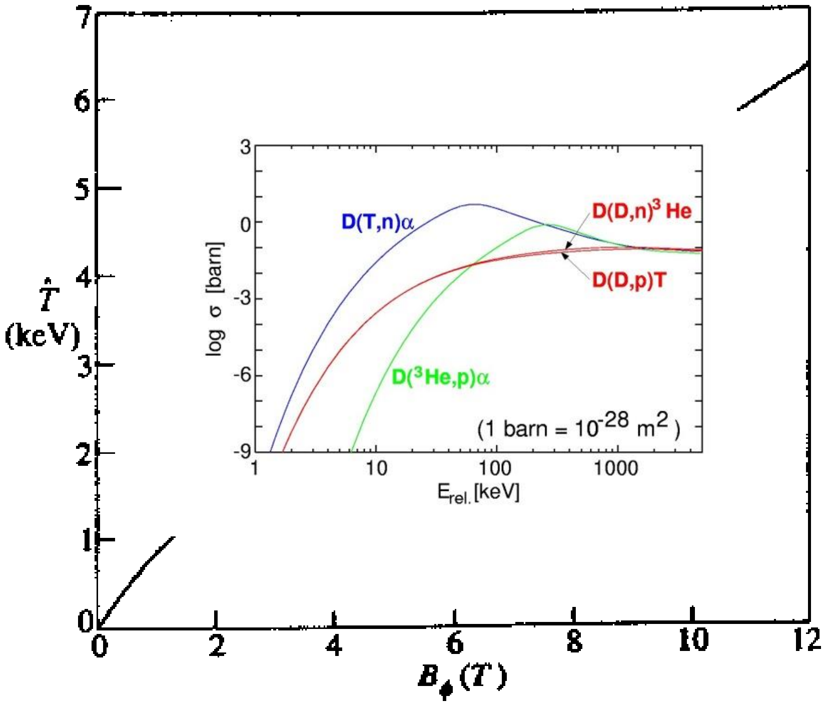
$$T = 2.7\times10^8\left(\frac{Z_{eff}\tau_E}{nq_a q_0}\right)^{\frac{2}{5}}\left(\frac{B_\phi}{R}\right)^{\frac{4}{5}}$$

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

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

Alcator scaling

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



Average temperatures above ~ 7 keV are necessary before alpha heating is large enough to achieve a significant fusion rate.

Weston M. Stacey, "Fusion Plasma Physics" WILEY-VCH (2005)

Ohmic Heating

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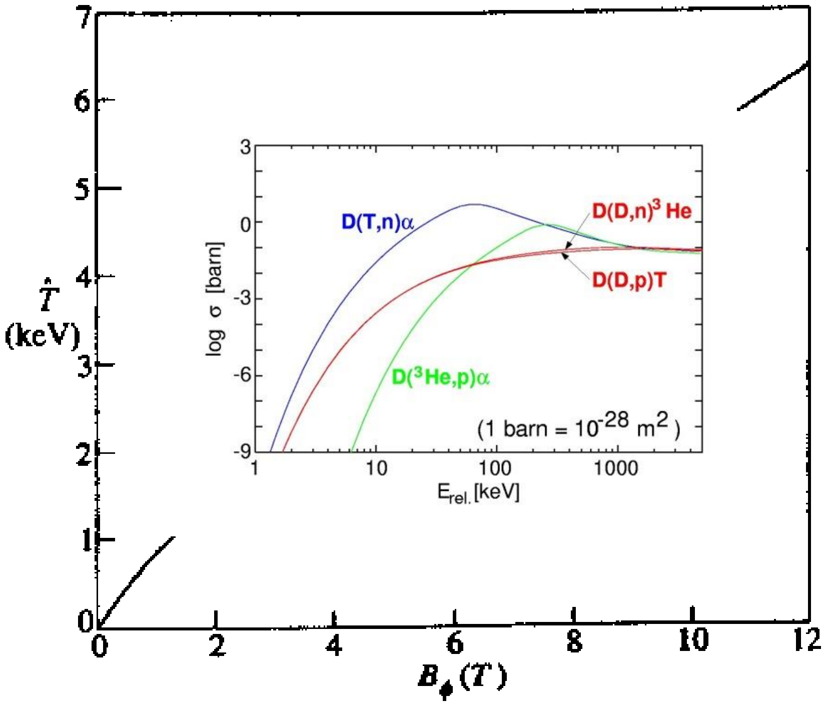


It seems unlikely that tokamaks that would lead to practical reactors can be heated to thermonuclear temperatures by Ohmic heating!

Weston M. Stacey, "Fusion Plasma Physics" WILEY-VCH (2005)

Neutral Beam Injection (NBI)

Neutral Beam Injection

WIKIPEDIA
The Free Encyclopedia

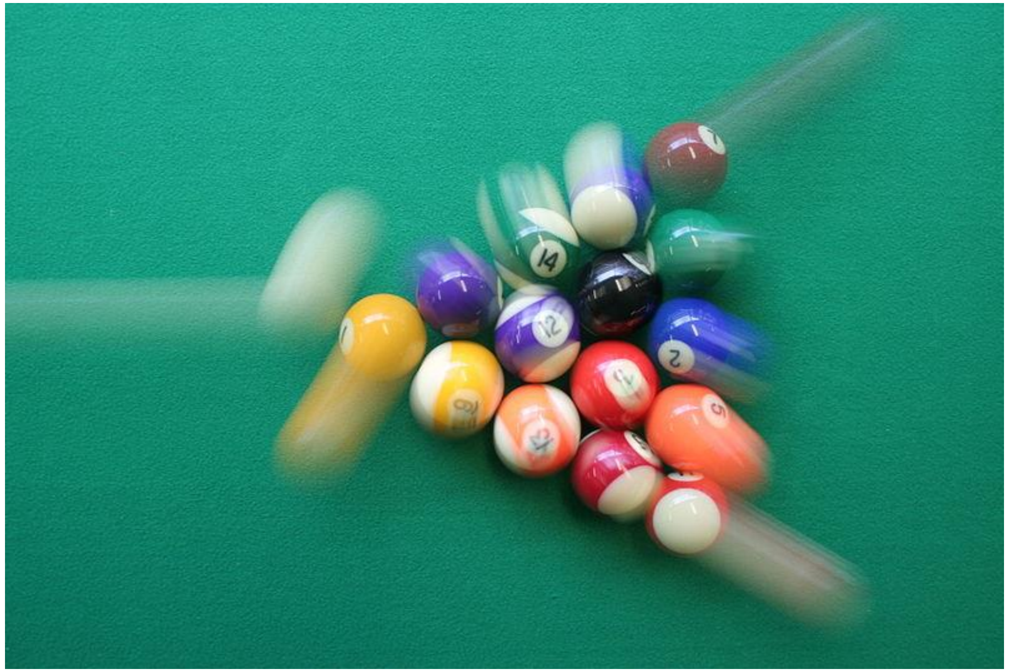
Neutral Beam Injection

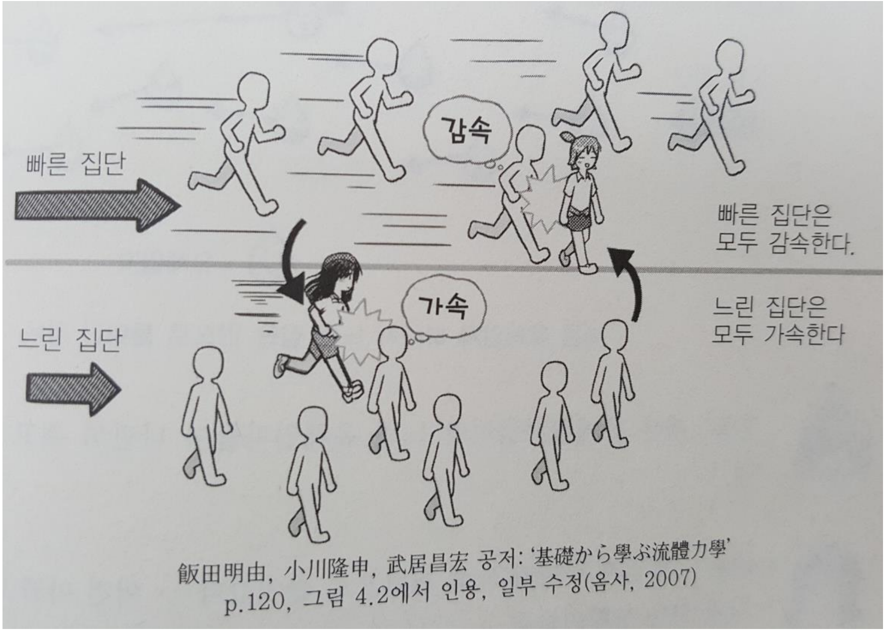
259-Car Autobahn pile-up near Braunschweig, largest in German history: (20 July 2009)

- 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.

WIKIPEDIA
The Free Encyclopedia

Neutral Beam Injection





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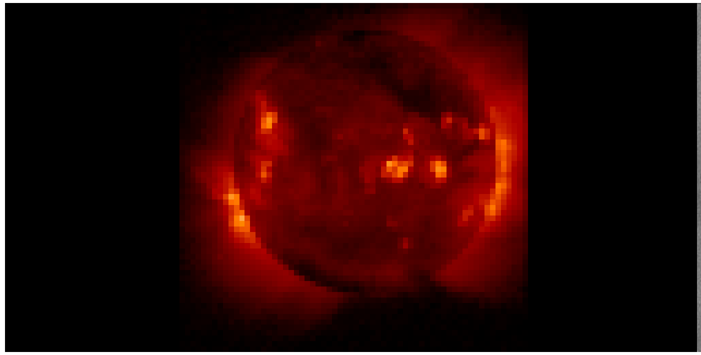
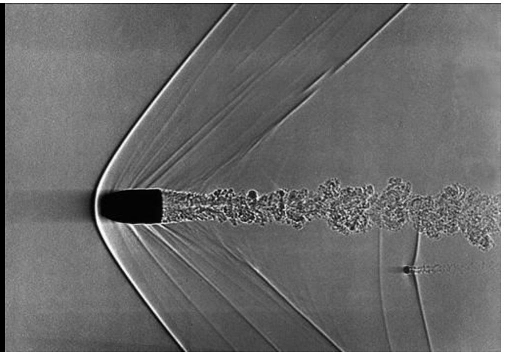
Neutral Beam Injection



Plasma



Neutral beam

NBI

Andy Warhol

- 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

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

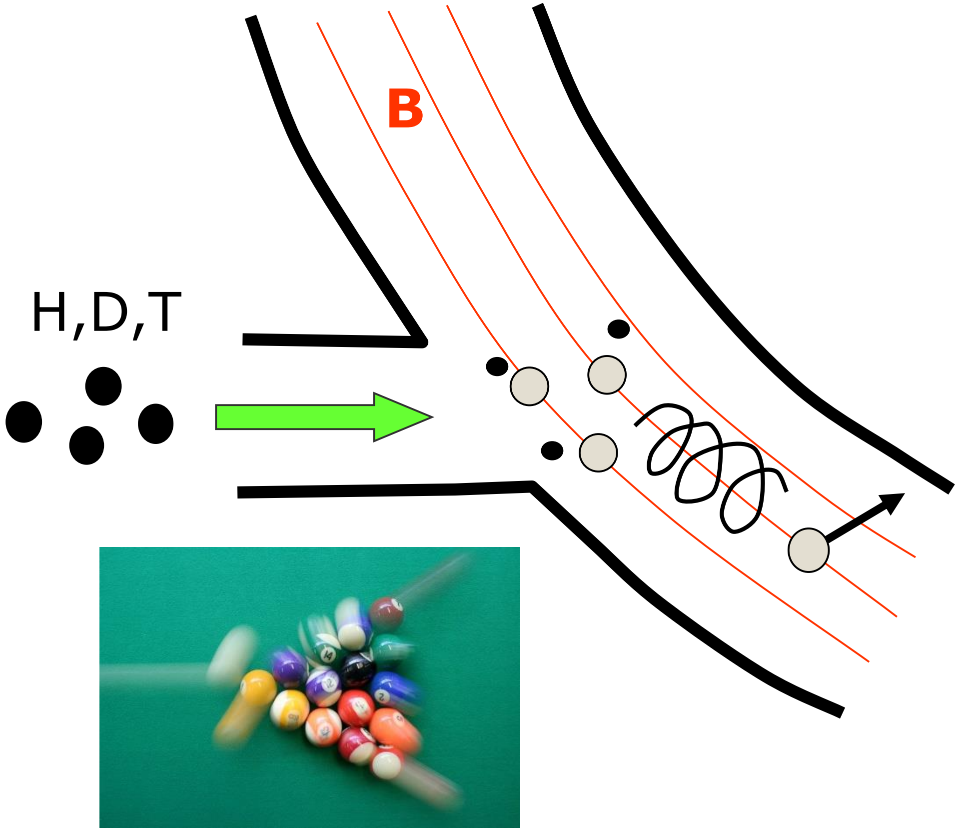
Neutral Beam Injection

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

⇓
Ionisation in the plasma

⇓
Beam particles confined

⇓
Collisional slowing down



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

Dirk Hartmann, "Plasma Heating", IPP Summer School, IPP Garching, September 20, 2001

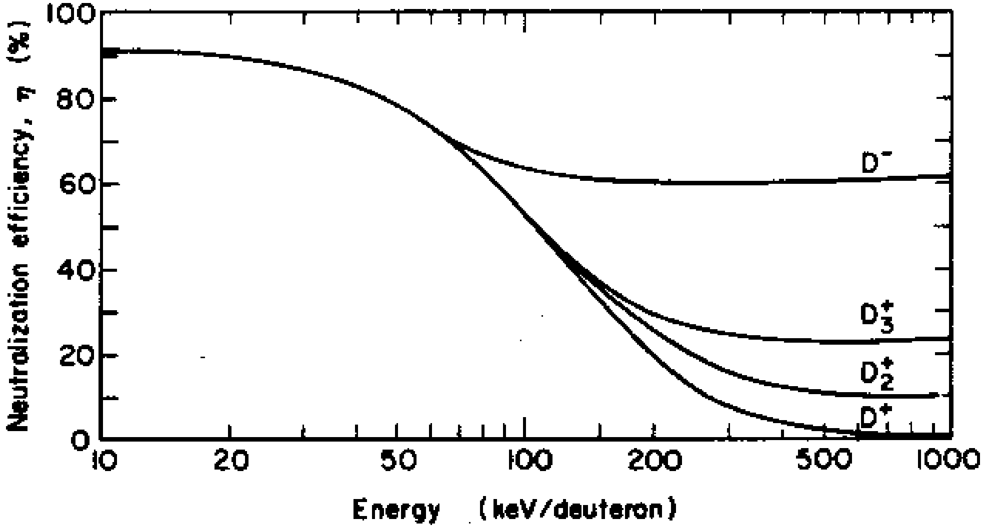
Neutral Beam Injection

- **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

- **Energy Deposition in a Plasma**

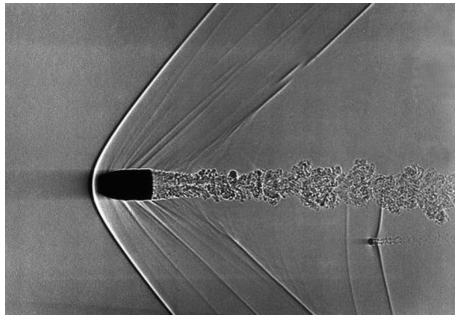
Charge exchange: $D_{fast} + D^{+} \rightarrow D^{+}_{fast} + D$

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

http://www.doopediat.com/_upload/image1/50000/53000/400/53018.jpg

Neutral Beam Injection

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- Attenuation of a beam of neutral particles in a plasma

$$\frac{dN_b(x)}{dx} = -N_b(x) n \sigma_{tot} \quad N_b(x) = N_b(0)\exp(-n\sigma_{tot} x)$$

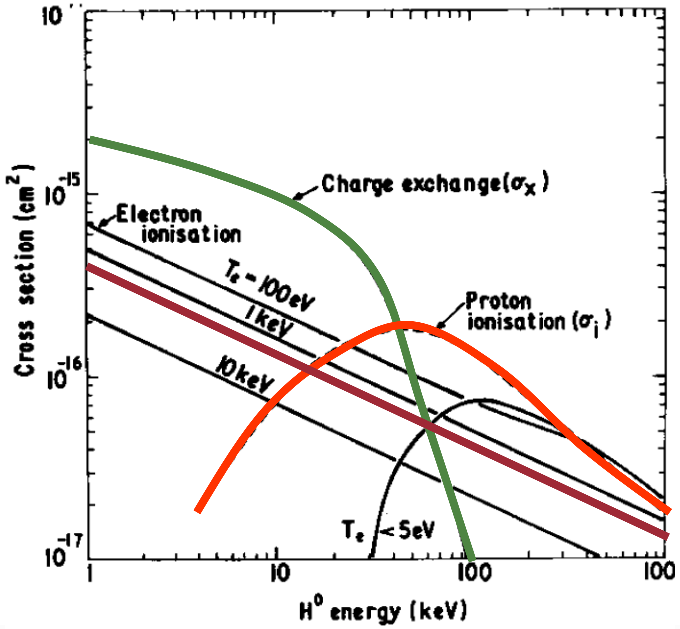
Ex. beam intensity: $I(x) = N_b(x) v_b = I_0 \cdot \exp(-x/\lambda)$

$$\lambda = \frac{1}{n\sigma_{tot}} \approx 0.4m$$

Penetration (attenuation) length

$$n = 5 \cdot 10^{20} m^{-3} \quad E_{b0} = 70 keV \quad \sigma_{tot} = 5 \times 10^{-20} m^2$$

In large reactor plasmas, beam cannot reach core!



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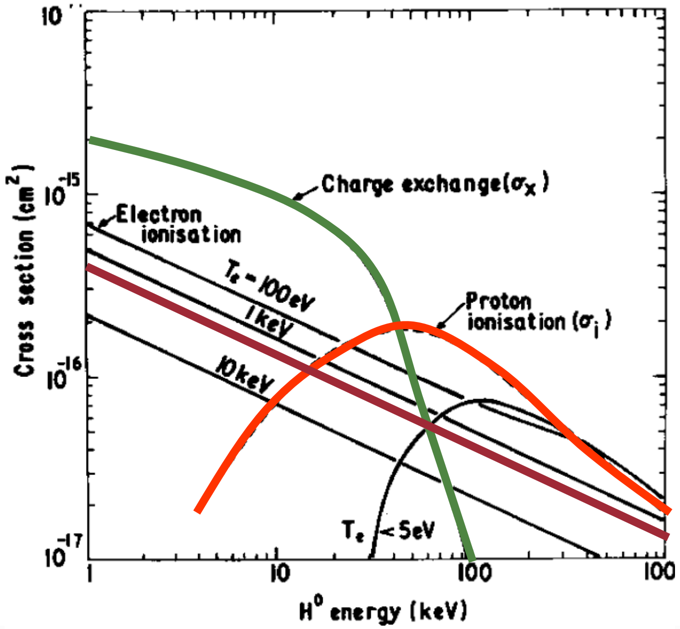
- Attenuation of a beam of neutral particles in a plasma

- General criterion for adequate penetration

$$\lambda \equiv \frac{1}{n\sigma_{tot} Z_{eff}^{\gamma}} = \frac{5.5\times10^{17} E_b(keV)}{A(amu)n(m^{-3})Z_{eff}^{\gamma}} \geq a/4$$

$$E_b \geq 4.5\times10^{-19} AnaZ_{eff}^{\gamma}$$



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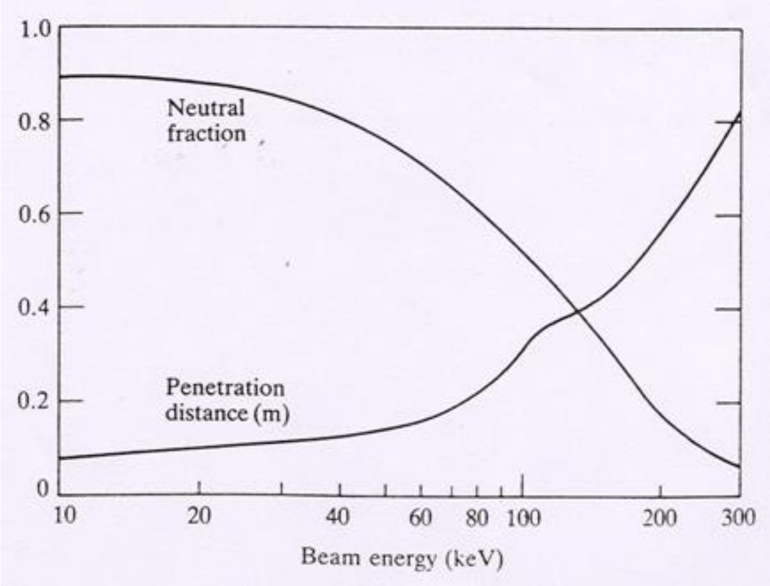

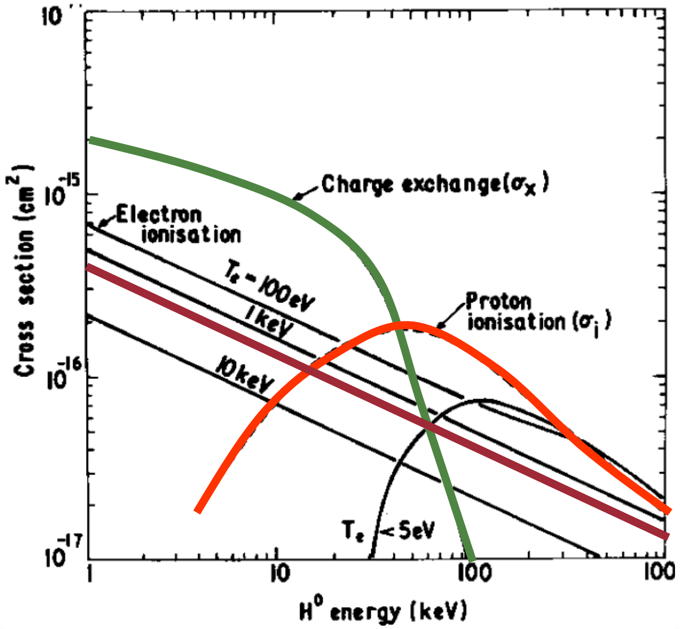

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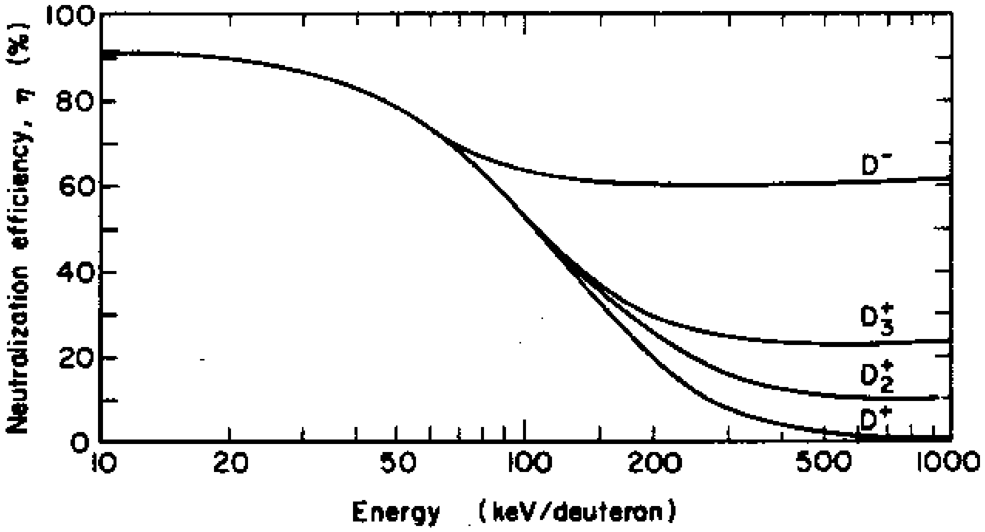

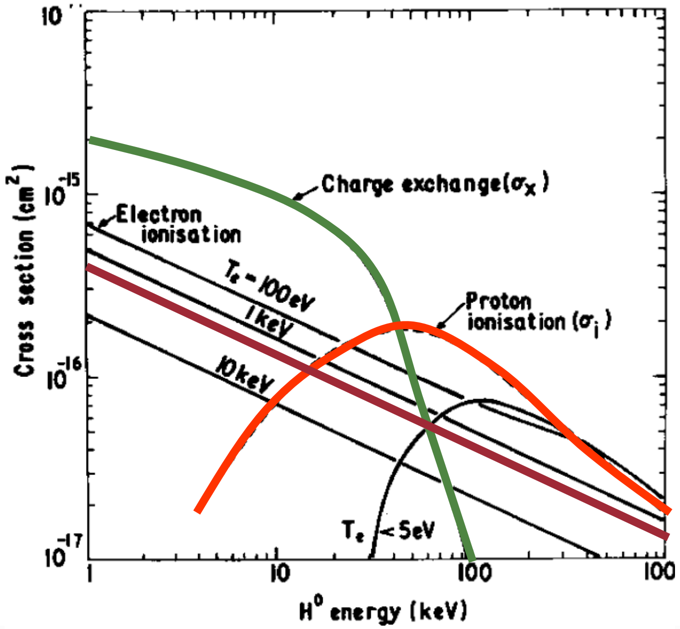

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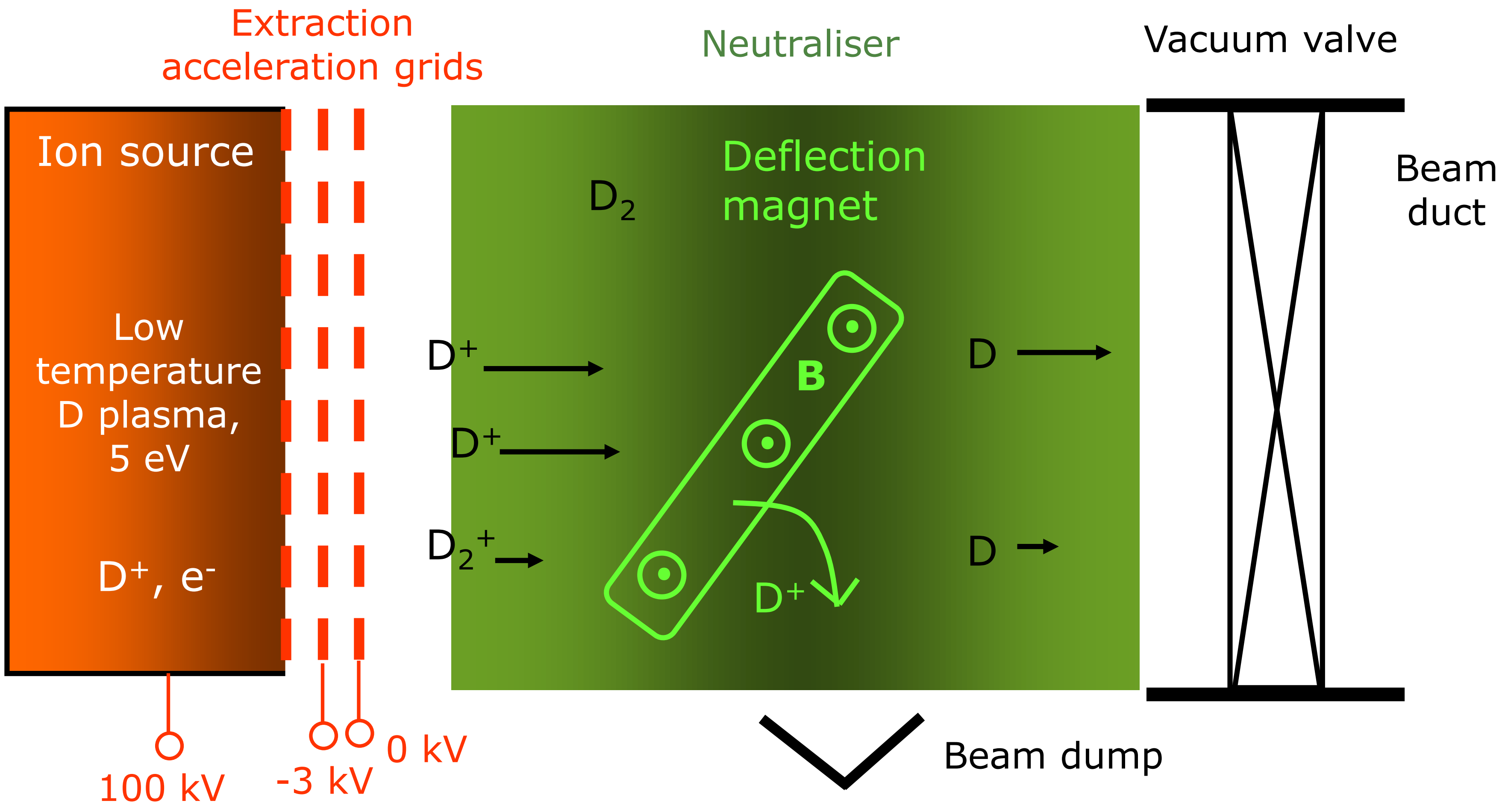
Neutral Beam Injection

- **Generation of a Neutral Fuel Beam**



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

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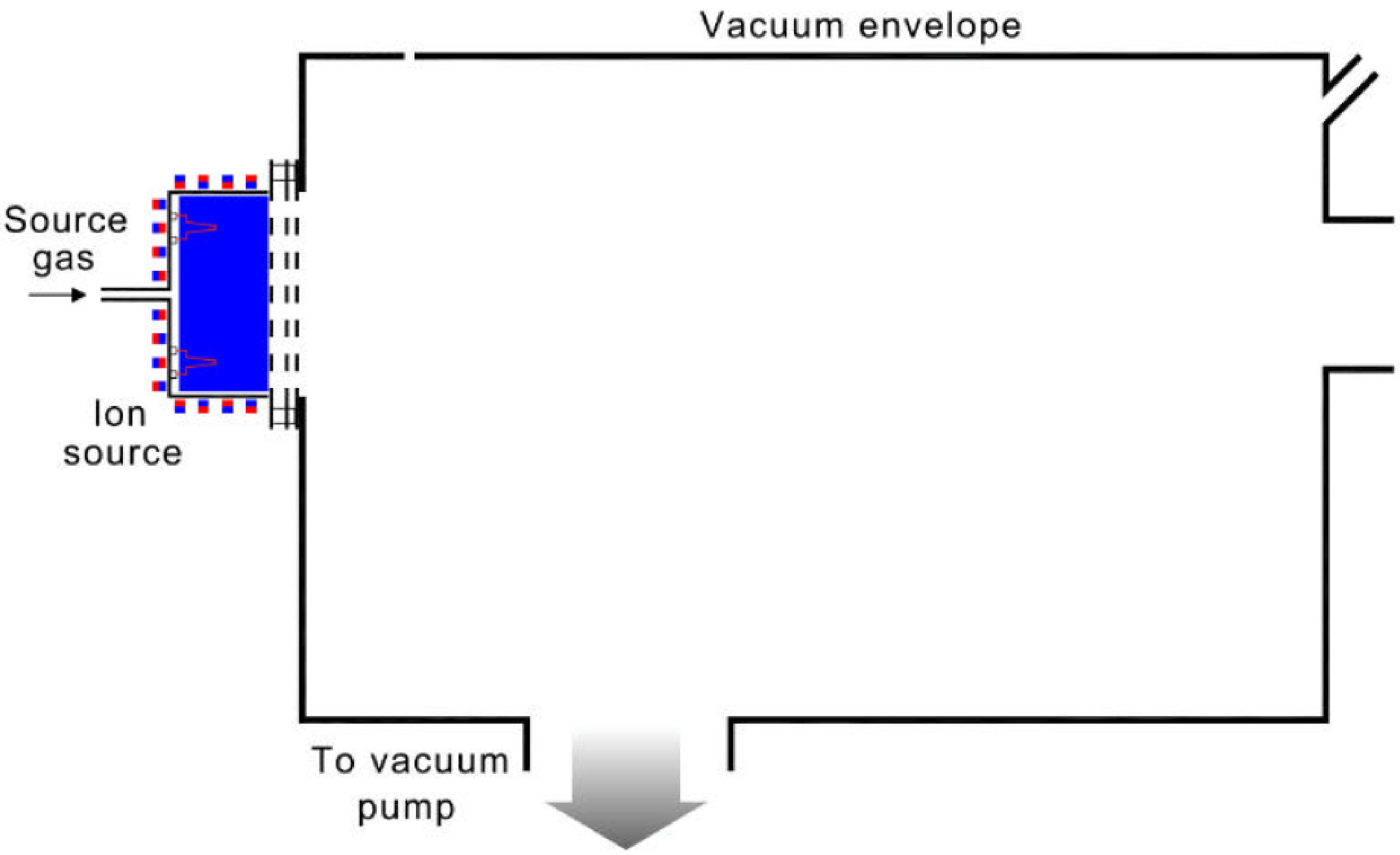
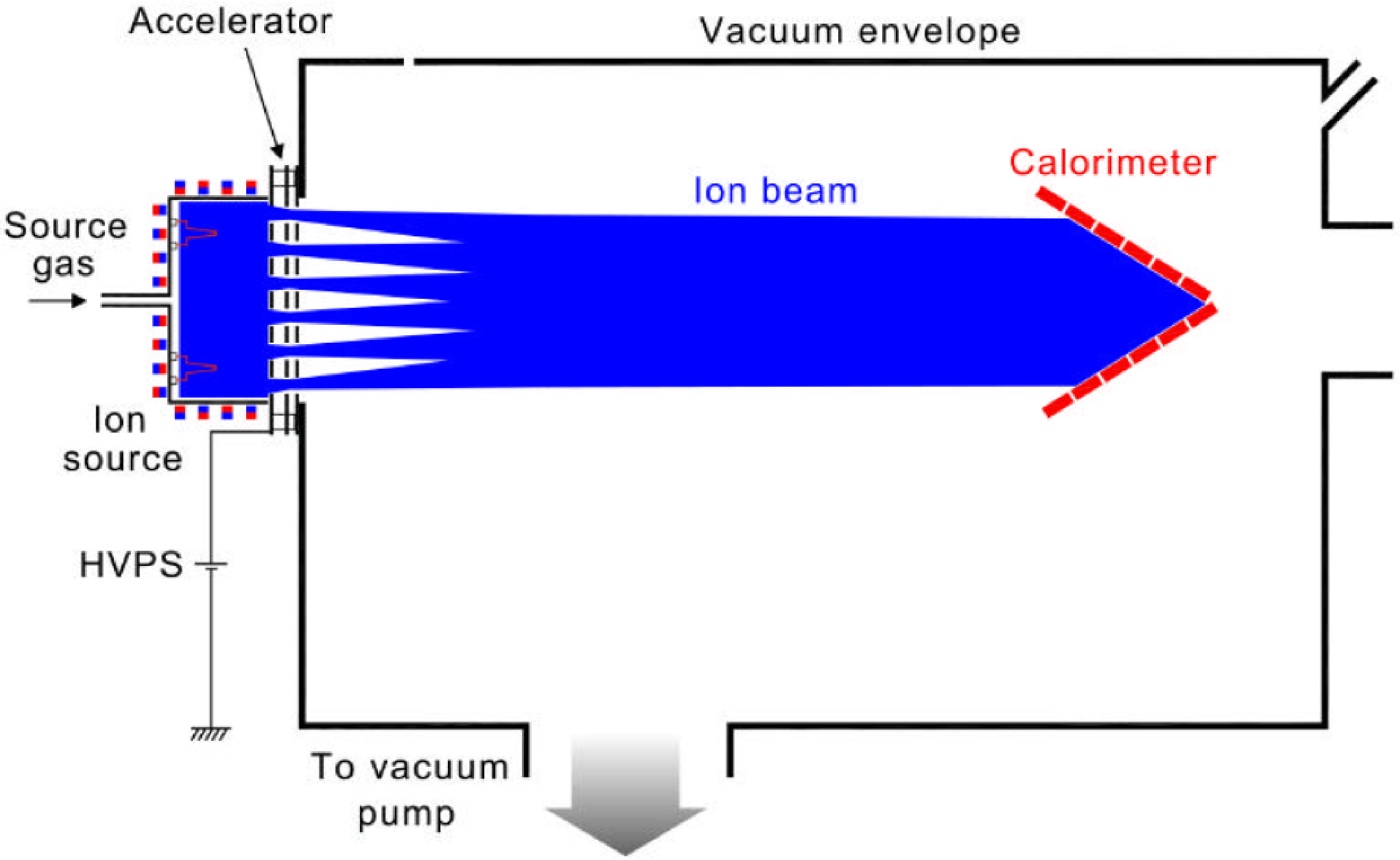
Neutral Beam Injection

- **Ion Source**



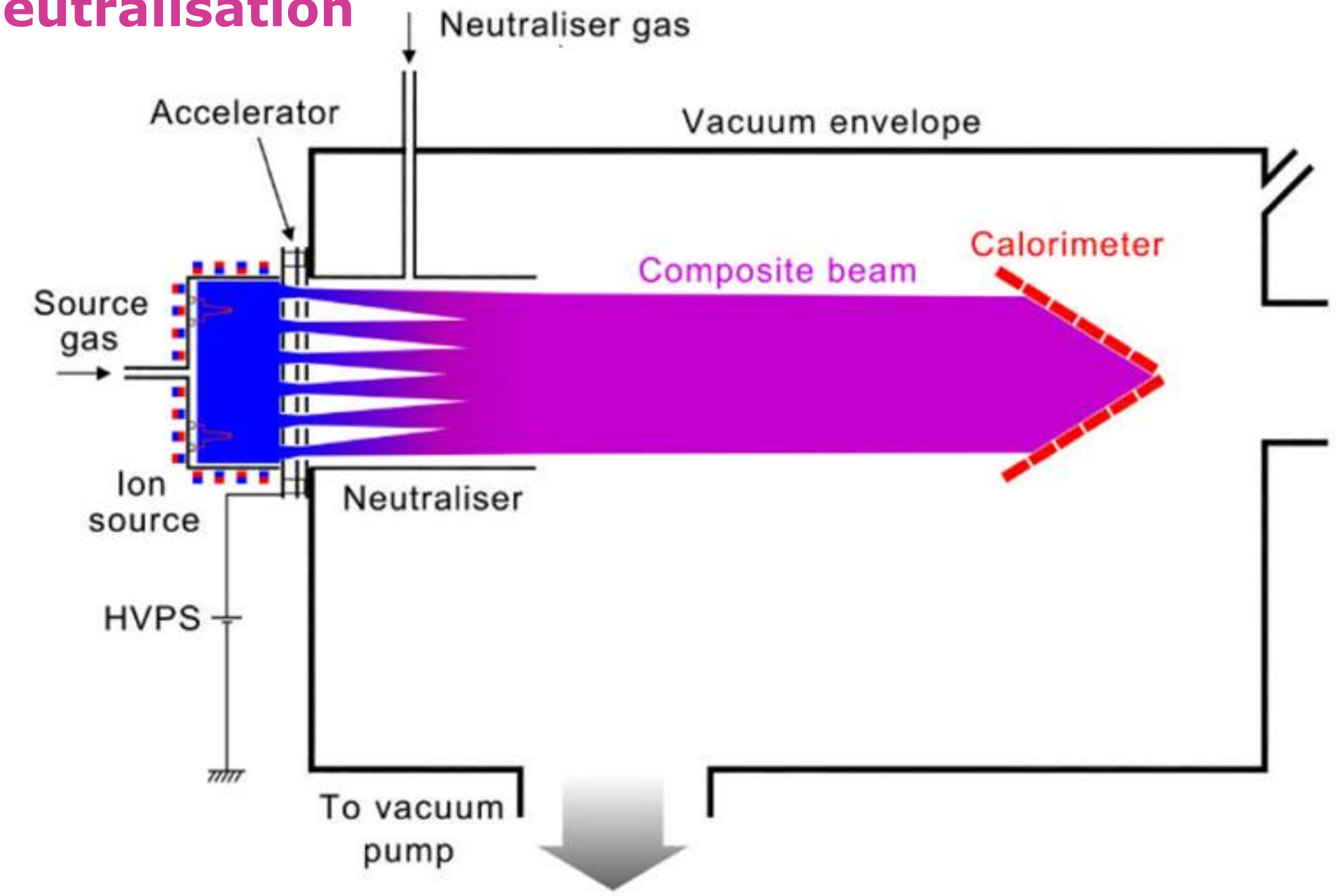
Neutral Beam Injection

- **Ion Acceleration**



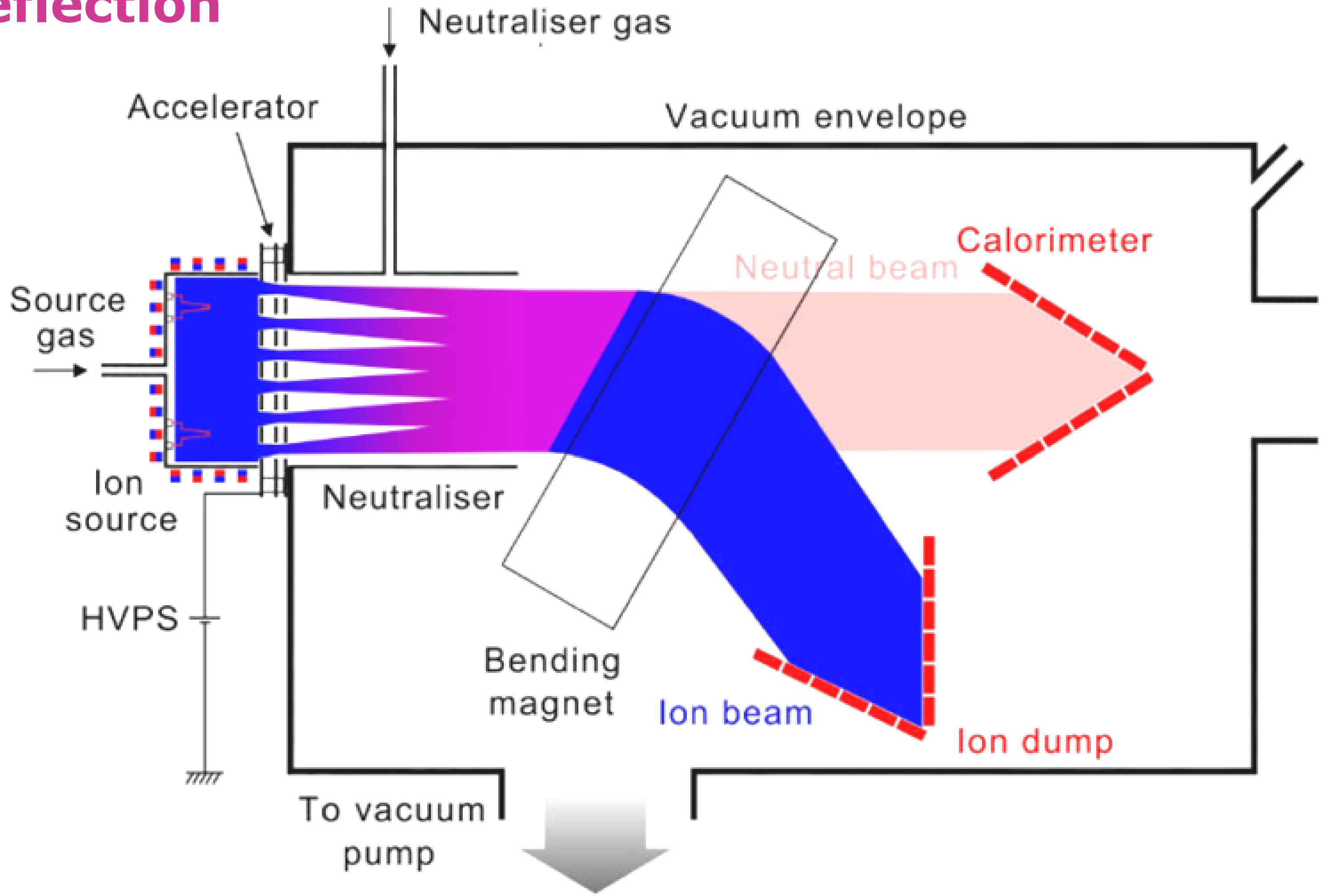
Neutral Beam Injection

- **Ion Neutralisation**



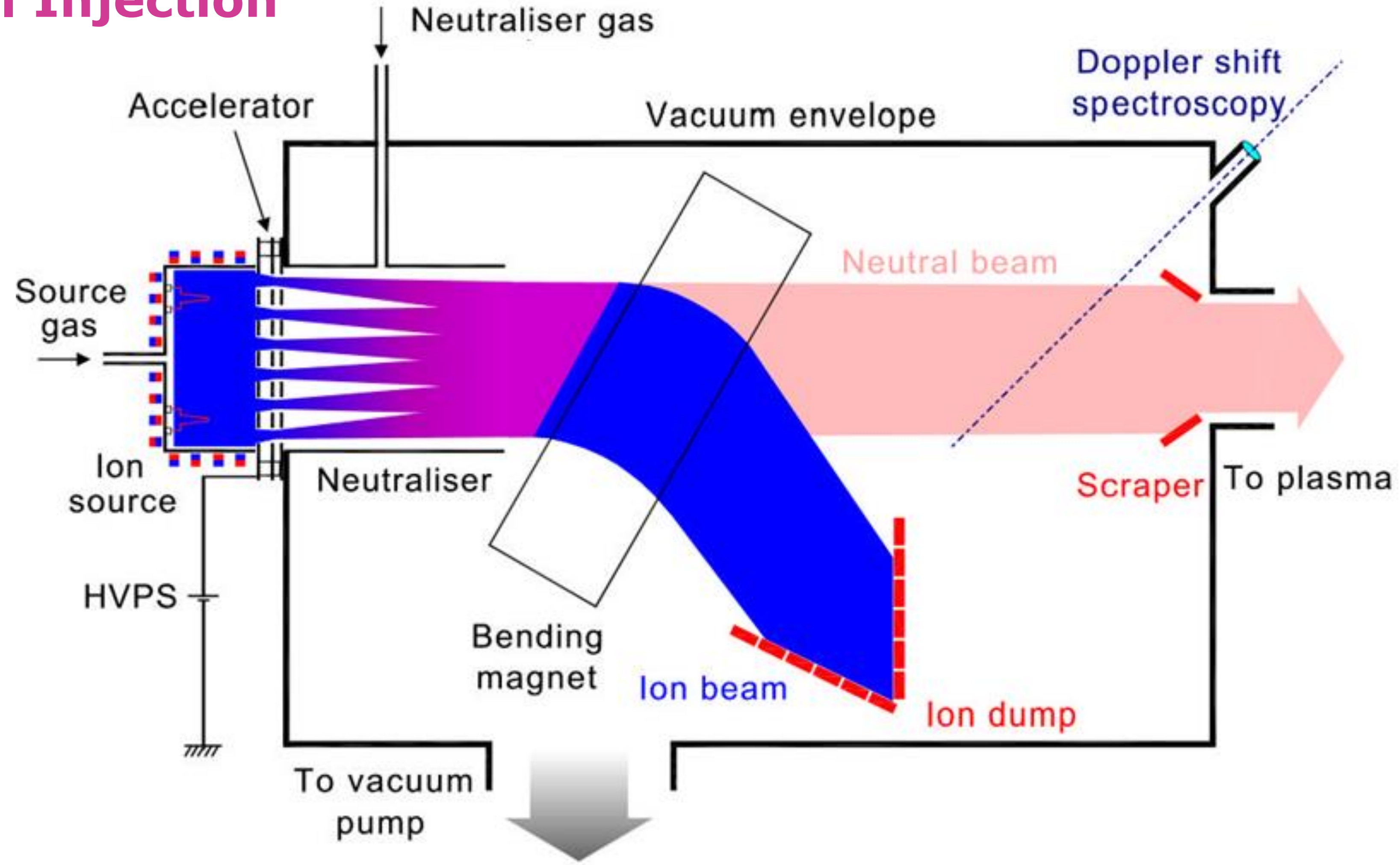
Neutral Beam Injection

- **Ion Deflection**



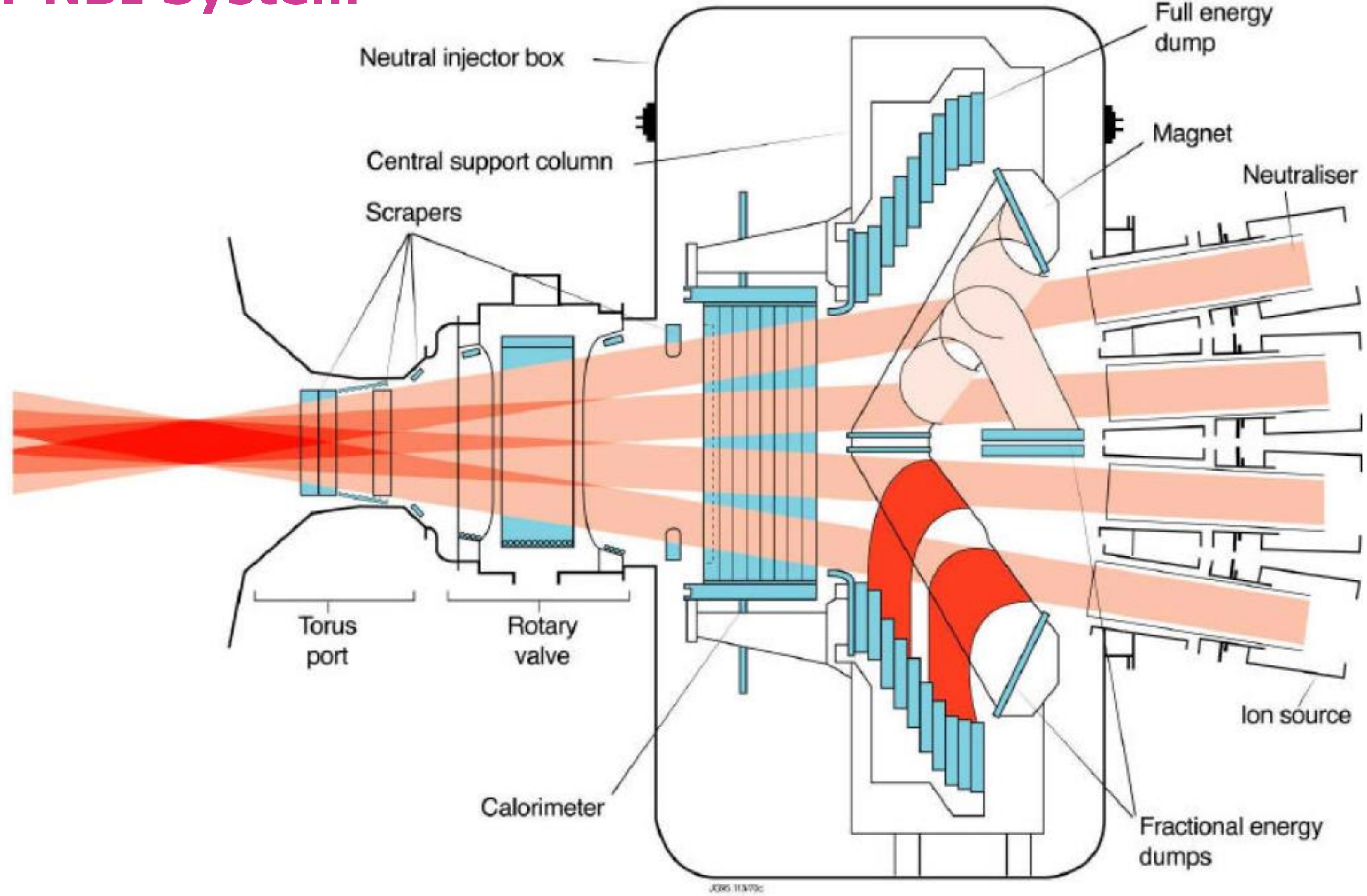
Neutral Beam Injection

• **Neutral Injection**



Neutral Beam Injection

- JET NBI System



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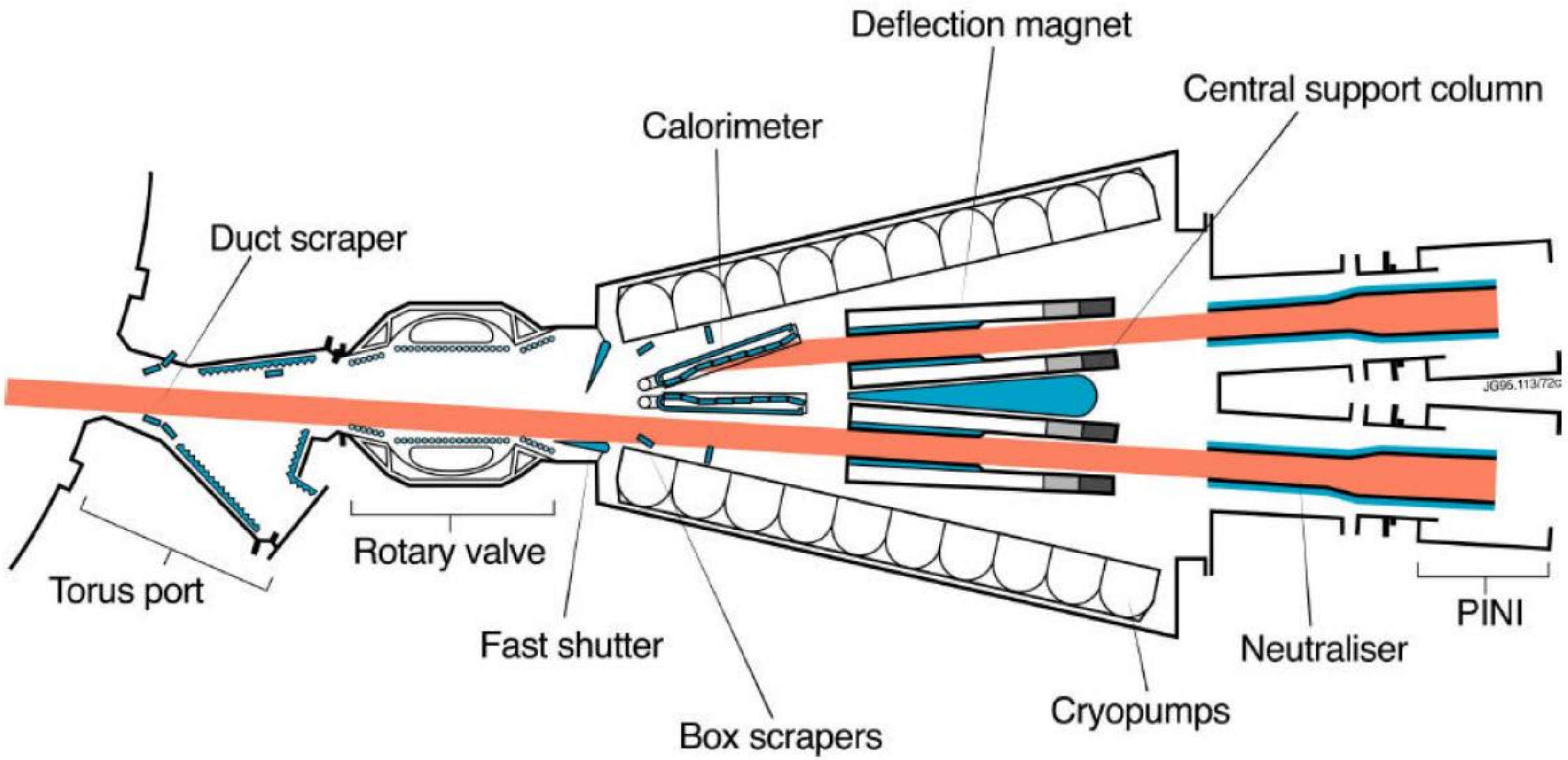


Neutral Beam Injection

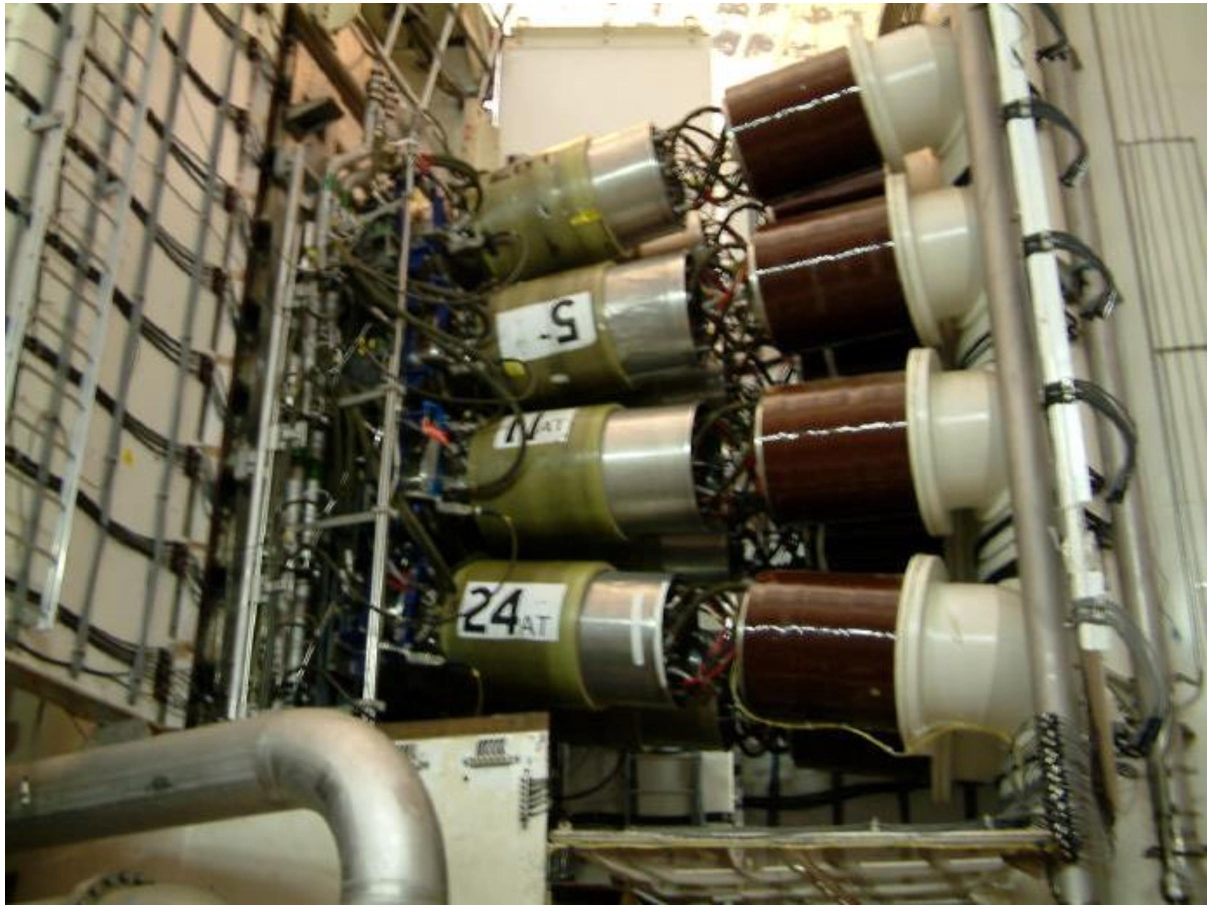
- **JET NBI System**

JET with machine and Octant 4 Neutral Injector Box

https://www.euro-fusion.org/eurofusion/europe-participates/czech-republic/

Neutral Beam Injection

- **JET NBI System**



Octant 4 Neutal Injector Box

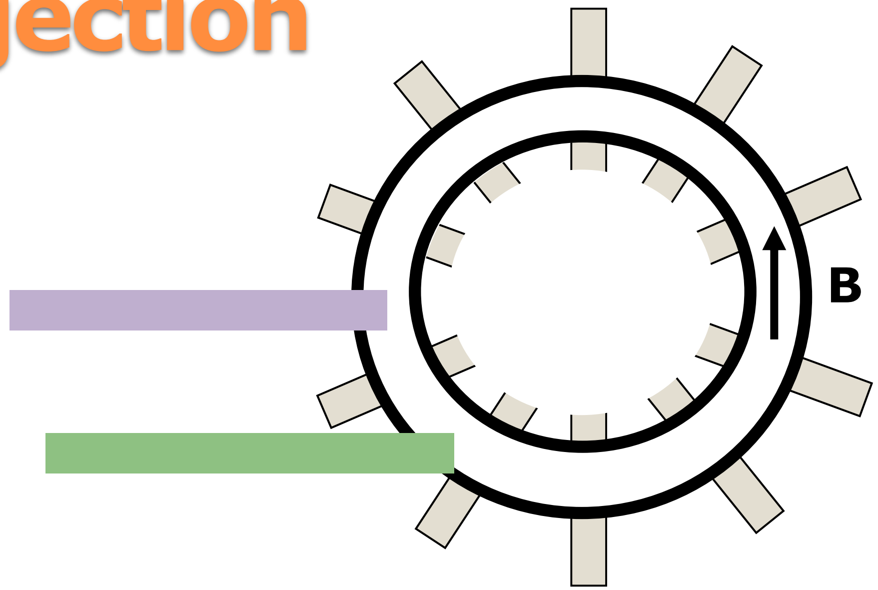
https://www.euro-fusion.org/eurofusion/europe-participates/czech-republic/

Neutral Beam Injection

- **Injection Angle**

Radial (perpendicular, normal) injection

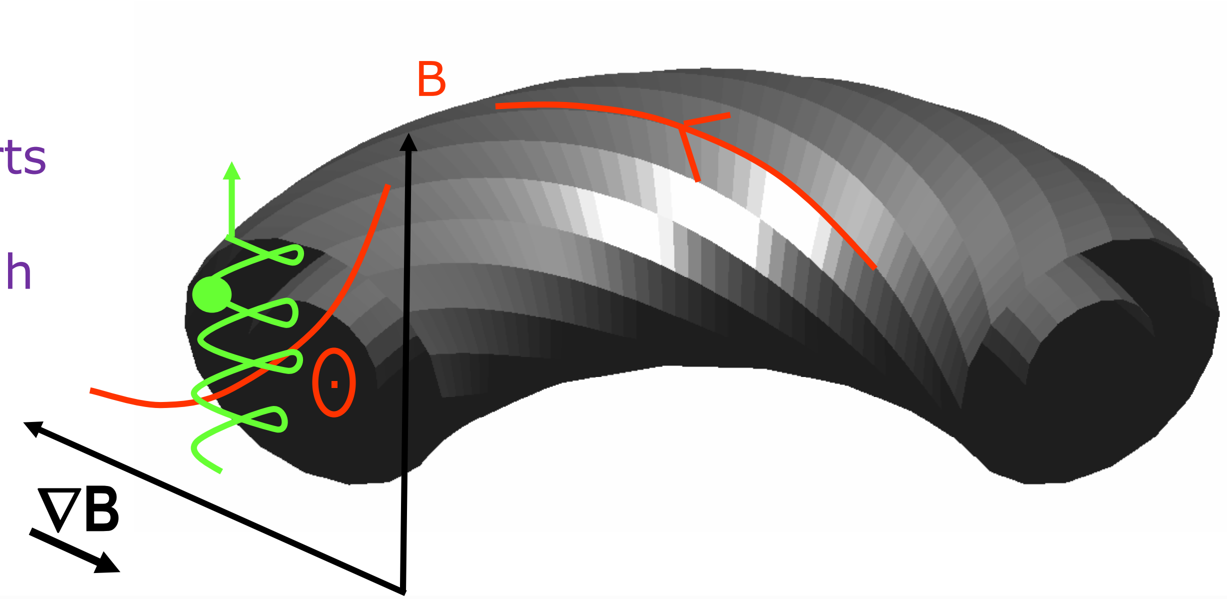
Tangential injection



Radial injection:

- standard ports
- particle loss
- shine-through

$$\mathbf{v}_{D,\nabla B} = \pm \frac{1}{2} v_{\perp} r_L \frac{\mathbf{B} \times \nabla B}{B^2}$$



Dirk Hartmann, "Plasma Heating", IPP Summer School, IPP Garching, September 20, 2001

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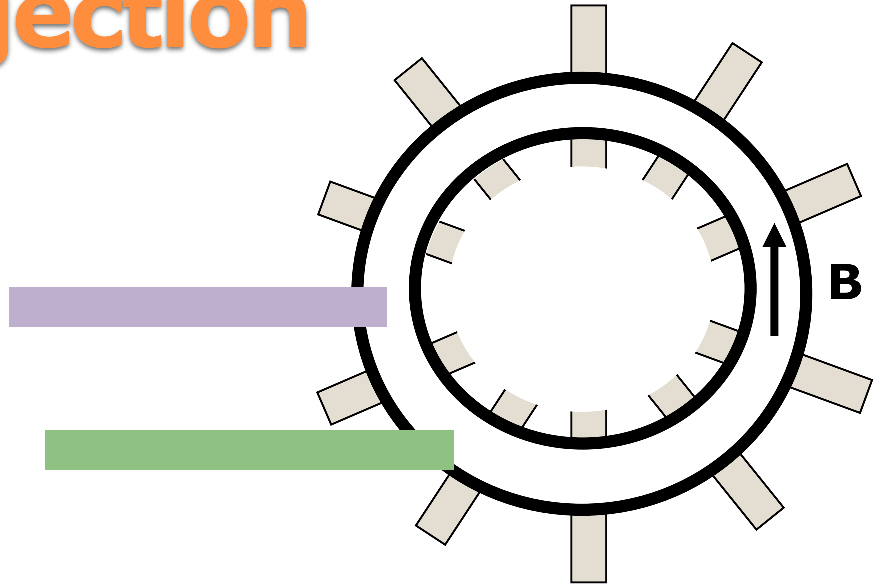

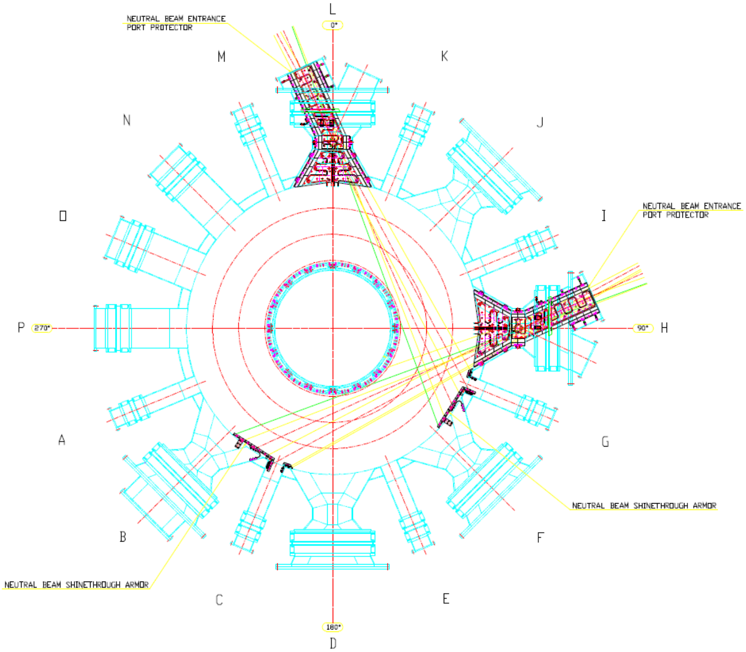

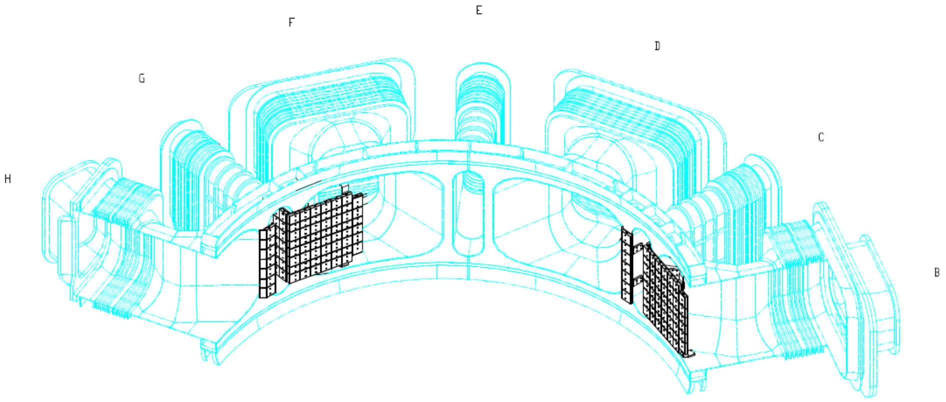

KSTAR NB shine-through armor

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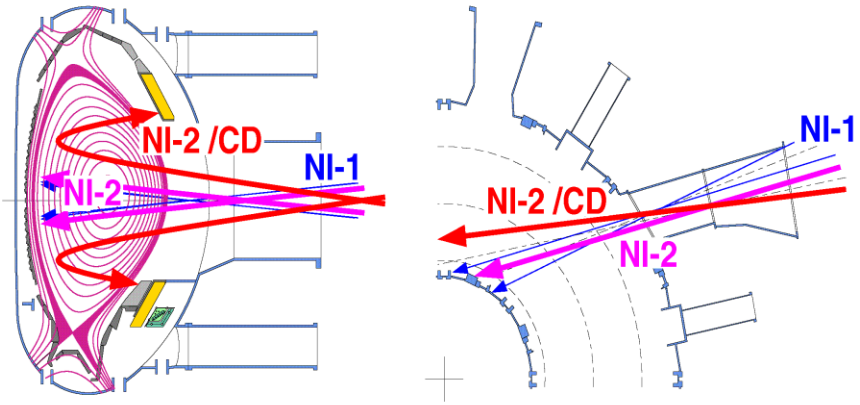
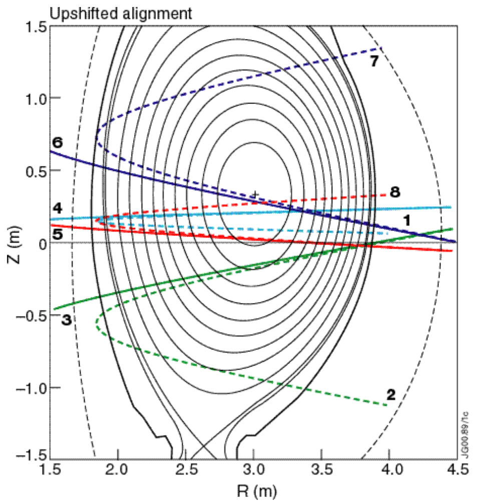
Neutral Beam Injection

ASDEX Upgrade



JET



Solid = Normal, Dashed = Tangential