Plasma Heating

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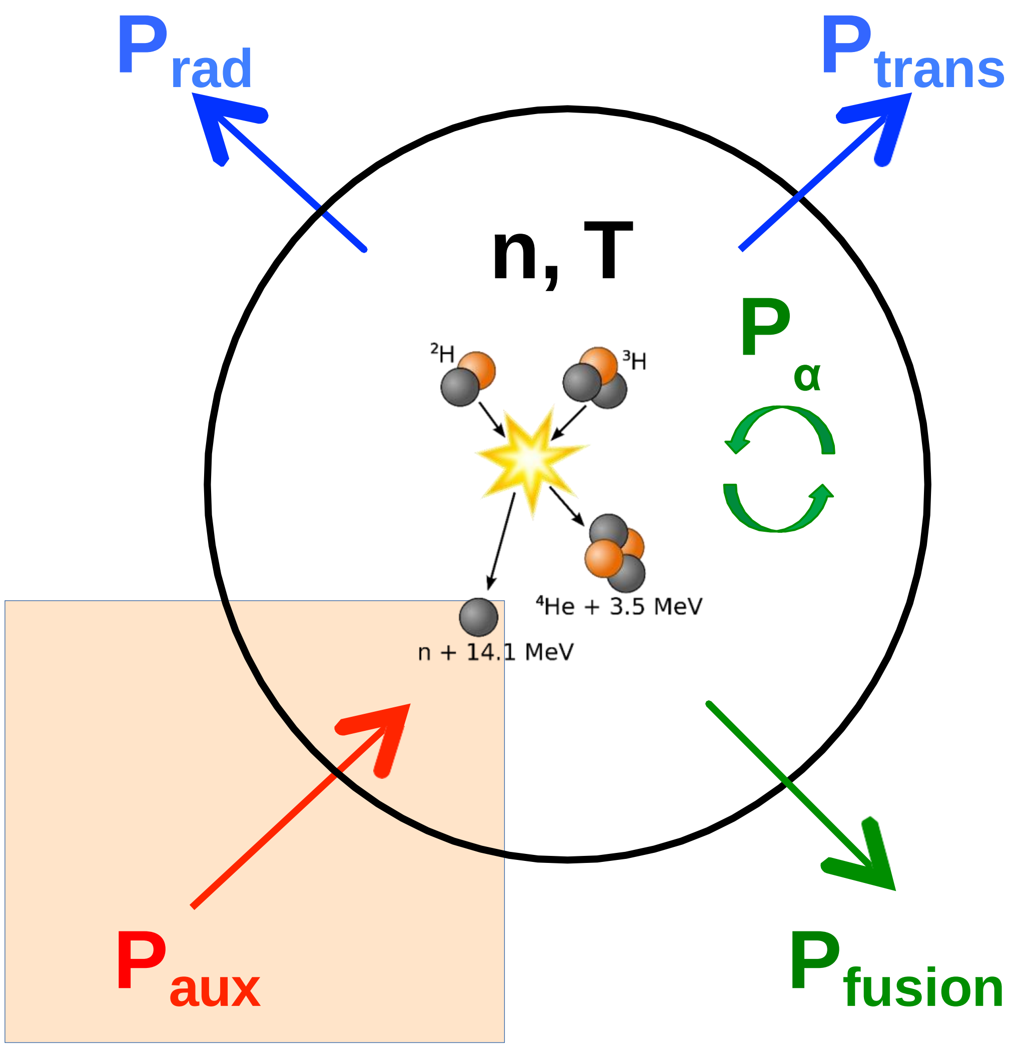
Outline

- **Minimum temperature and power for ignition**
- **Physics and technology of plasma heating systems in fusion-relevant devices**
  - **Ohmic heating**
  - **Neutral beam heating**
  - **Radio frequency heating**
- **Advantages and limitations**
- **Application and specifications of heating systems in existing devices and ITER**

Heating to ignition

Plasma heating provides initial heating to reach break-even and ignition



- Internal heating via fusion α's (> 1 MeV) ⟹ beyond ignition sole heat source
- (Fusion output power in neutrons)

- Up to self-sustained burn, auxiliary heating required to offset radiative and transport losses ⇒ P_{aux} fraction of P_{fusion}

Minimum temperature obtained from power balance of ideal ignition $S_\alpha = S_B$

- **Alpha heating**

$$S_\alpha = \frac{1}{4} E_\alpha n^2 \langle \sigma v \rangle \qquad \Rightarrow \quad p = 2nT$$

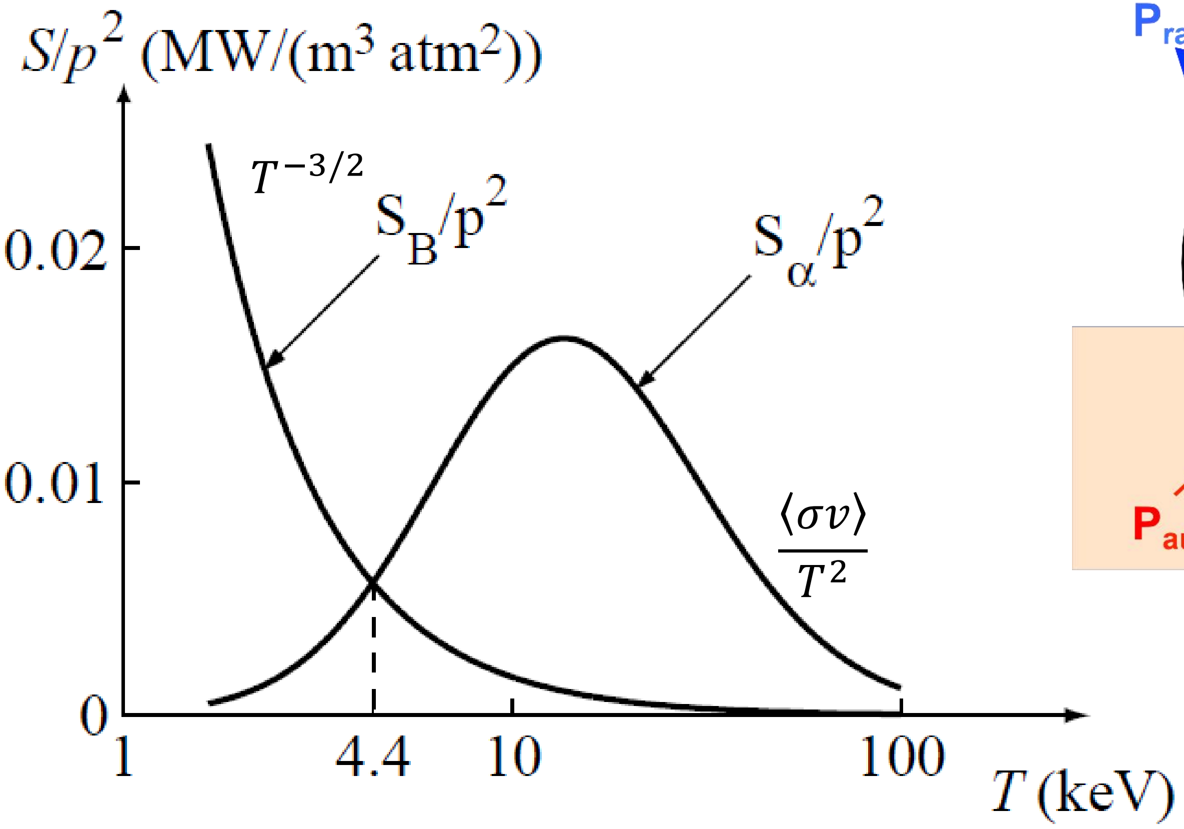
$$= \frac{1}{16} E_\alpha p^2 \frac{\langle \sigma v \rangle}{T^2}$$

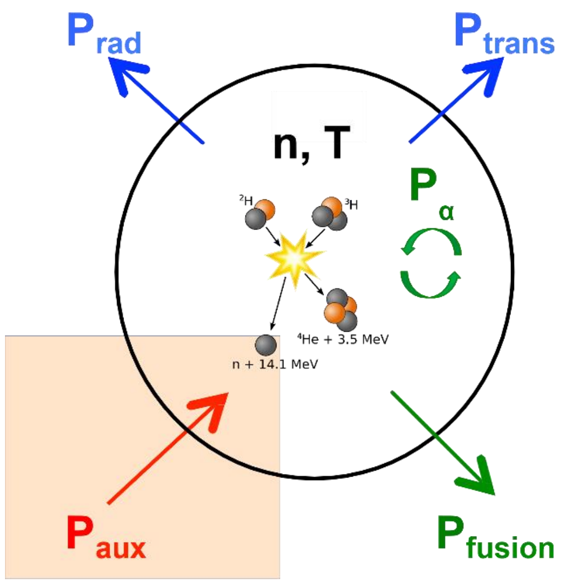
$$S_\alpha = S_B \quad \Rightarrow \quad \frac{\langle \sigma v \rangle}{T_k^{1/2}} = \frac{4C_B}{E_\alpha}$$

- **Radiation loss**
  => Bremmstrahlung

$$S_B = C_B Z_{eff} n^2 T^{1/2} = \frac{1}{4} C_B Z_{eff} \frac{p^2}{T^{3/2}}$$

Minimum temperature obtained from power balance of ideal ignition $S_\alpha = S_B$



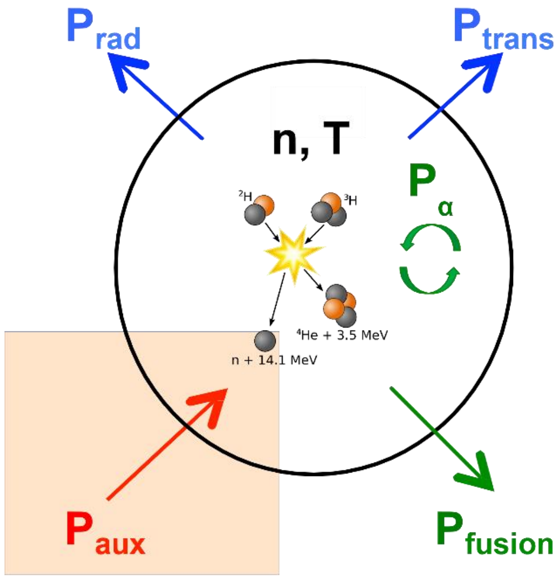


$T \geq 4.4$ keV for D-T

Minimum power obtained from thermal stability

0-D power balance

$$\frac{3}{2}\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{E_\alpha}{16} p^2 \frac{\langle \sigma v \rangle}{T^2} + S_h - \frac{C_B}{4} \frac{p^2}{T^{3/2}} - \frac{3}{2}\frac{p}{\tau_E}$$



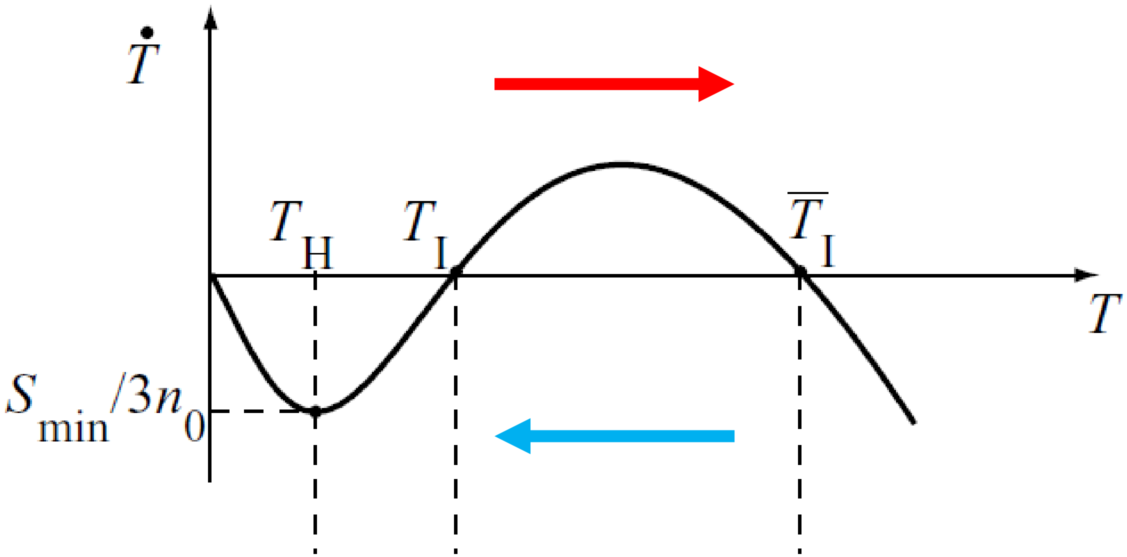
Assuming $n = n_0 \Rightarrow constant$

$p = 2n_0 T$

$$3n_0 \frac{\mathrm{d}T}{\mathrm{d}t} = \frac{E_\alpha}{4} n_0^2 \langle \sigma v \rangle + S_h - C_B n_0^2 T^{\frac{1}{2}} - \frac{3n_0 T}{\tau_E}$$

Minimum power obtained from thermal stability S_{min}/S_α = 0.25 for constant τ_E

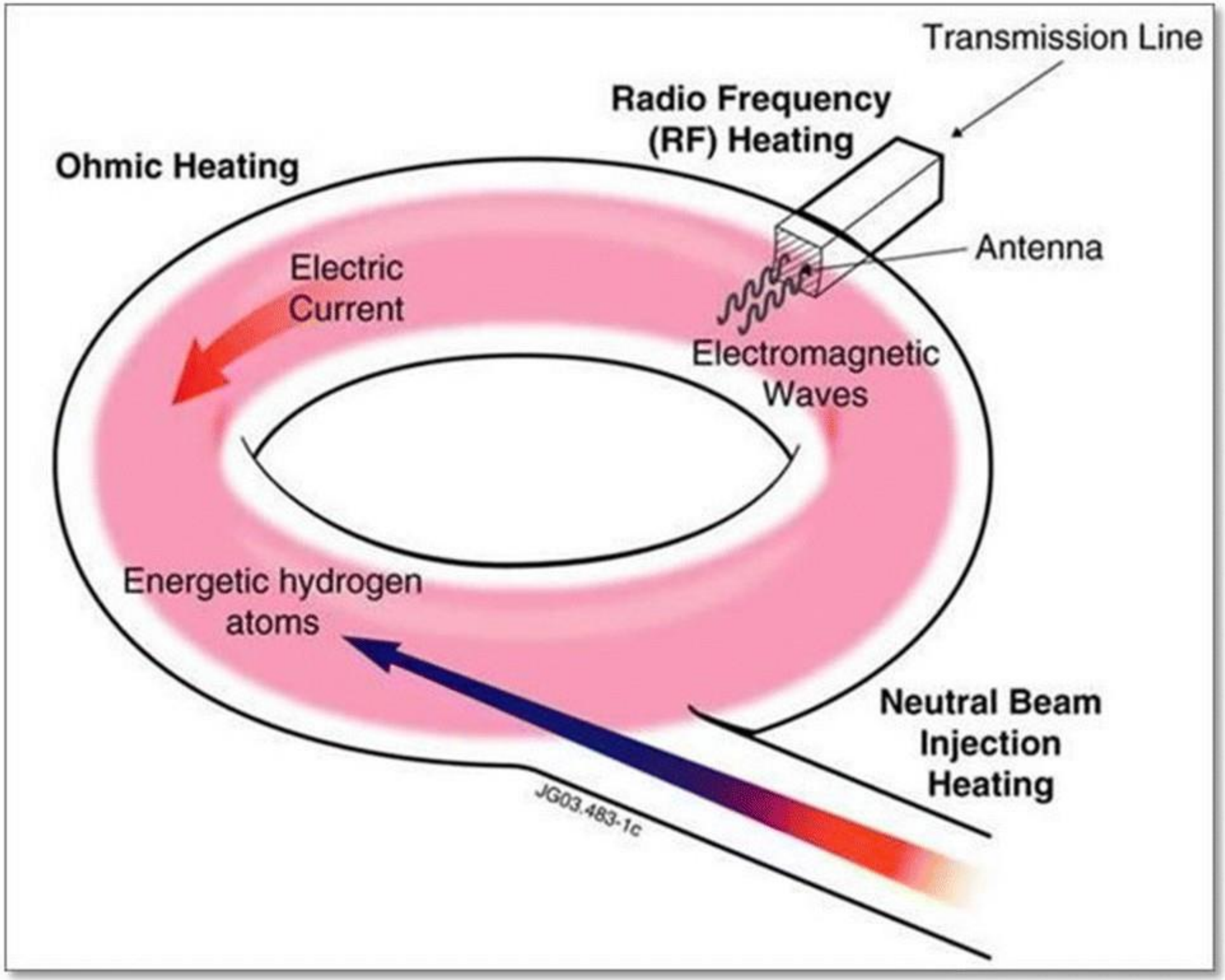
$$3n_0 \frac{\mathbf{d}\boldsymbol{T}}{\mathbf{d}\boldsymbol{t}} = \frac{E_\alpha}{4} n_0^2 \langle \sigma v \rangle + S_h - C_B n_0^2 \boldsymbol{T}^{\frac{1}{2}} - \frac{3n_0 \boldsymbol{T}}{\tau_E} \Rightarrow \; \dot{\boldsymbol{T}} \to \boldsymbol{f}(\boldsymbol{T})$$



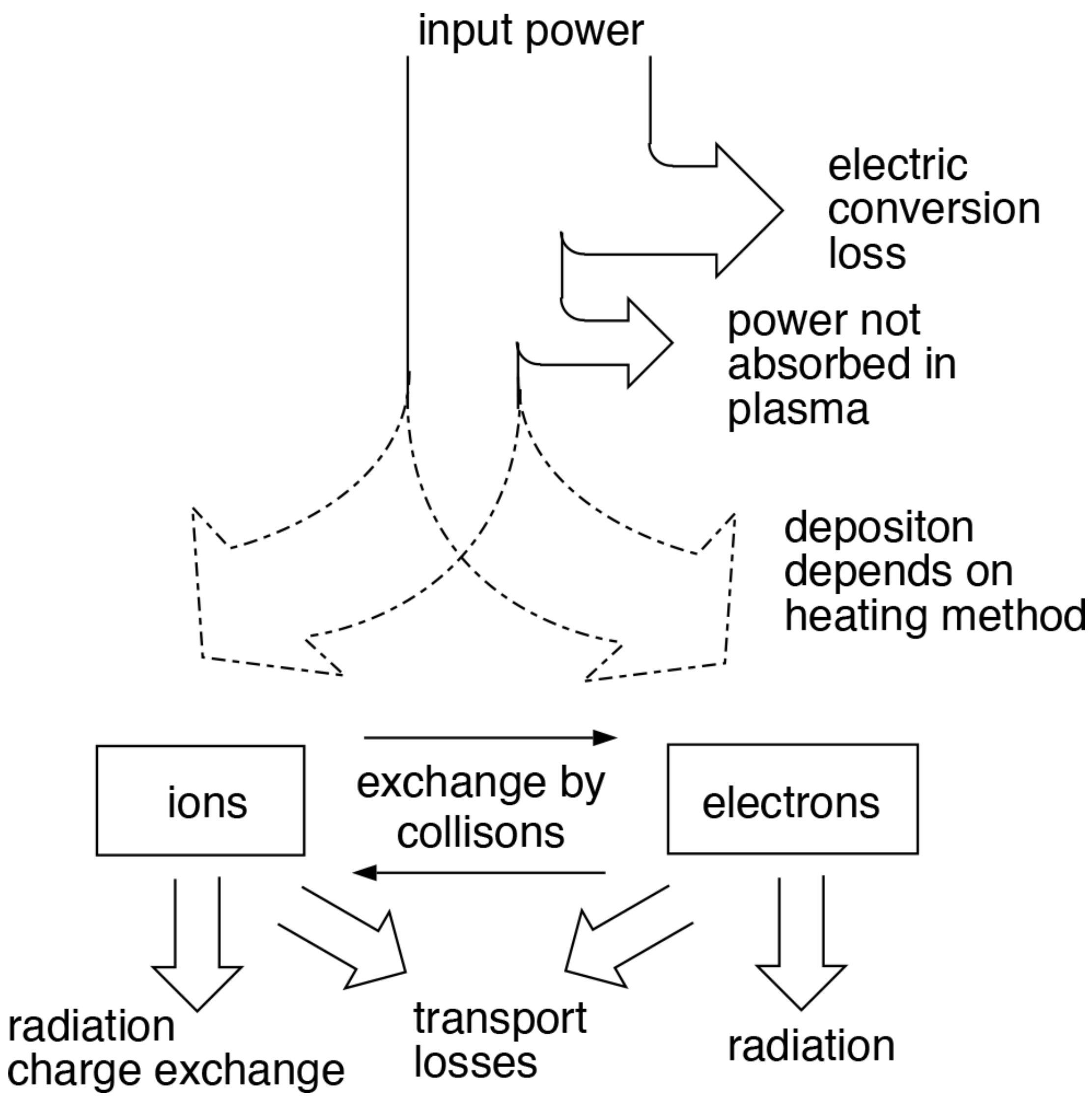
- **Thermally unstable at T_I, stable at $\overline{T}_I$**
- **S_{min} required for positive dT/dt (temperature increase)**
- **S_{min} until T_I then jumps to $\overline{T}_I$ (alpha heating)**

Tokamak heating methods

The primary heating schemes are ohmic heating, neutral beam heating, and radio frequency heating



Depending on the heating method, auxiliary power is either deposited on ions or electrons



- **Some of the total input power is lost via electric conversion or may not be absorbed by plasma**
  - E.g., beam shine-through
- **Coupling between ions and electrons making $T_e \approx T_i$**

Heating leads to an increase of the kinetic energy of plasma ions and electrons

Scheme	Absorbing particles	Limitations
Ohmic heating	Electrons	Temperature < 2 keV
Neutral beam injection	Ions (electrons)	MeV beam energies needed for large plasmas and high densities
Ion cyclotron resonance	Ions	Coupling efficiency, transients
Electron cyclotron resonance	Electrons	Cut-off densities, localized power
Lower hybrid	Electrons	Mainly for current drive
α-particle heating	Electrons	20% of total fusion power

Example: W7-X plans to use combination of ECRH, NBI and ICRH

Three heating systems developed and will be operated:

- **ECRH: main heating system and already capable for steady-state (over 30 minutes). A total power of up to 15 MW planned (now 7.5MW)**
- **NBI: not (yet) steady-state. Total NBI heating power will be 7 MW using H-atoms (D: 10 MW)**
- **ICRH: planned for next campaign with goals:**
  - Direct ion heating in high-n where ECRH fails
  - Creation of fast ions which allow study of optimized fast-particle confinement

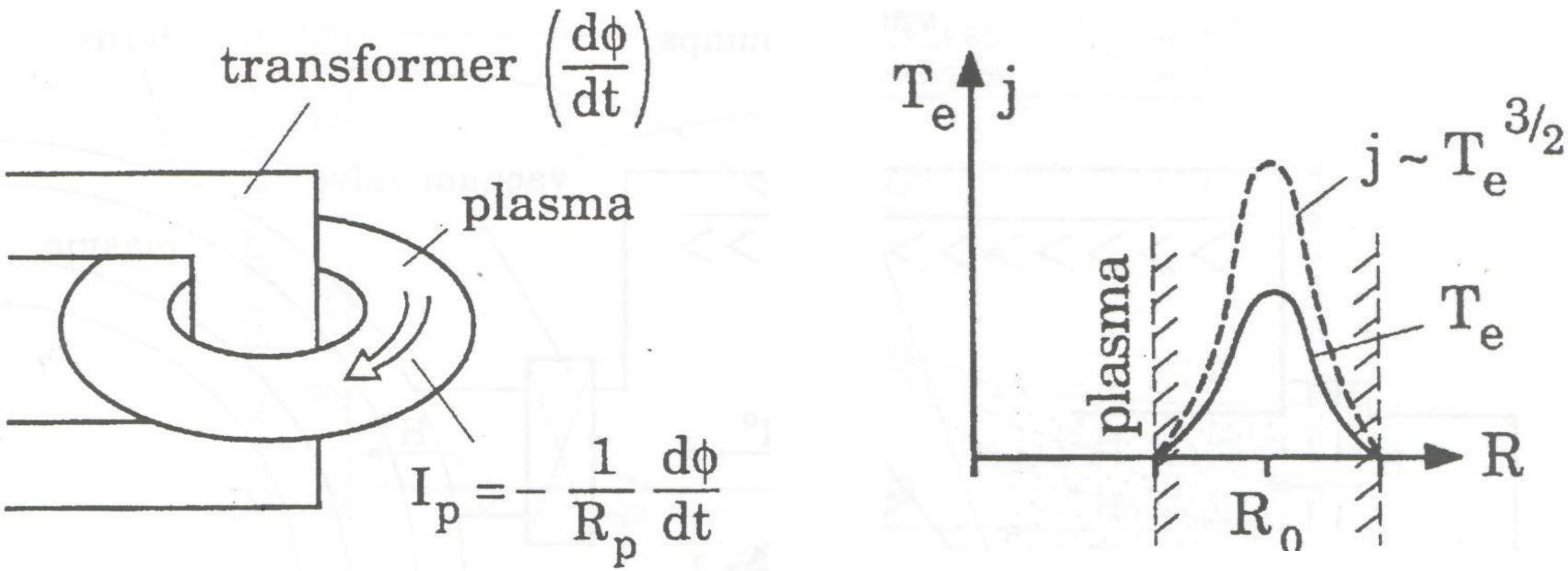
No plasma current → no Ohmic heating!

Additional considerations of applied heating scheme(s)

- **Neutral beam heating is also a particle source (D vs T)**
- **Minority heating schemes can lead to high energies in minority particles and departure from Maxwellian energy distribution**
  - Hydrogen and helium
  - Attempt not to make minority species too non-Maxwellian to allow energy transfer to main plasma
- **Heating is often coupled to non-induction current drive for extending pulse duration and manipulation of safety factor profile (performance)**
  - Neutral beam, lower hybrid, electron cyclotron heating

Ohmic Heating

Ohmic heating is established by driving an e⁻ current in a plasma and subsequent collisions between e⁻ and ions



- **Local power density:** $P_{ohmic} = \eta_{\|} j^2$
- **Total ohmic power given by total plasma current and loop voltage U_l (resistance R_p):** $P_{ohmic} = U_l I_p = R_P I_P^2$
- **Scheme can not be used in stellarators**

Ohmic heating is limited by Spitzer (electric) resistivity and plasma stability

$\eta_{Spitzer} \sim T^{-3/2}$ due to collisionality $\nu \sim \mathrm{v}^{-3}$

$q_{edge} \sim \frac{B_0}{R_0 I_M} \geq 2$ due to MHD kink instability

- **Power balance:** $P_{\Omega} = P_{\kappa}$

$$\eta_{\parallel} j^2 = \frac{3nT}{\tau_E} \Rightarrow \boldsymbol{T \sim I_m}$$

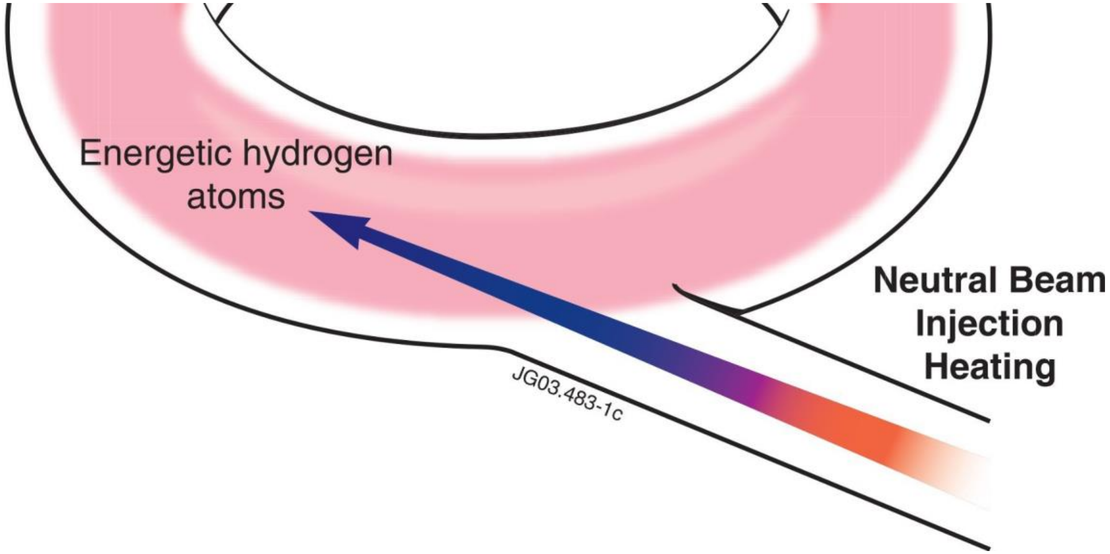
Linear scaling instead of expected $\boldsymbol{T \sim I_m^2}$

- **For $\boldsymbol{\tau_E \approx 1\ s}$ $\boldsymbol{B_0 \approx 5\ T}$, maximum $\mathbf{T \approx 3\ keV}$**
  $\Longrightarrow$ **too low for ignition**

- **Theoretically possible with higher $\boldsymbol{B_0}$**

Neutral Beam Heating

Fast (50k – 1 MeV) hydrogen neutrals are injected as beams transferring their energy to the plasma

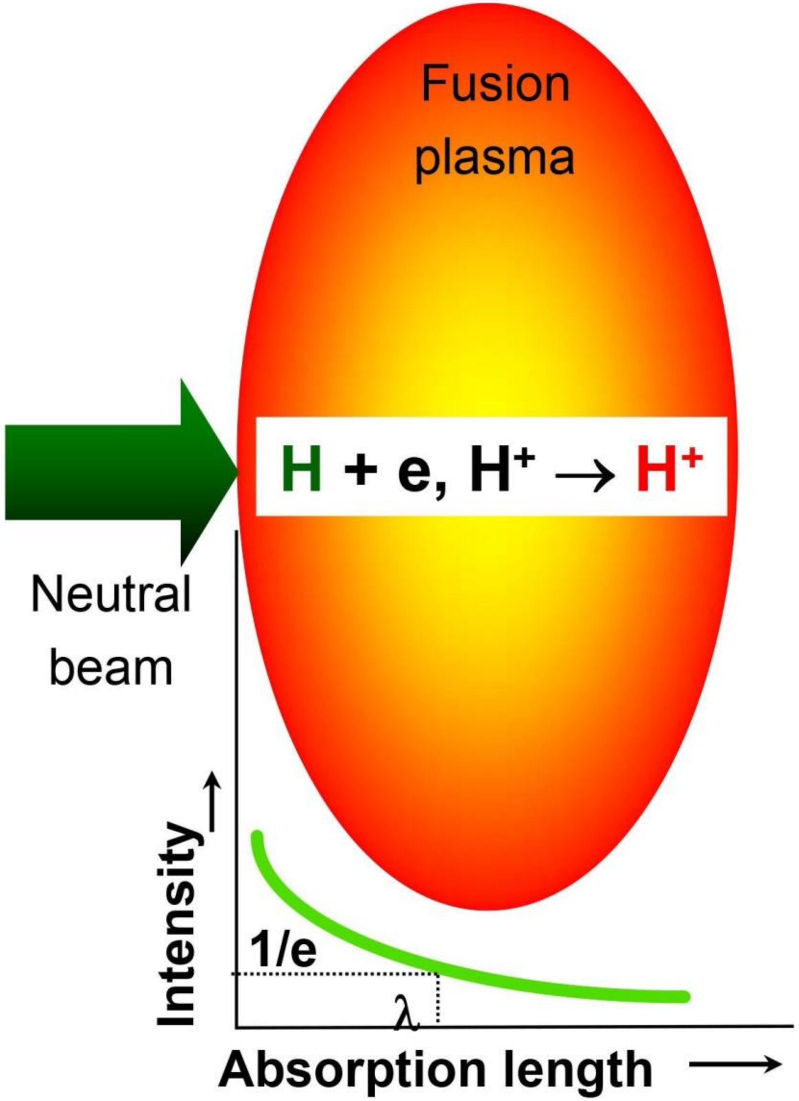


- **Neutral particles are suitable because they not affected by electromagnetic fields**

- **Heating is achieved by collisions with plasma electrons and ions (charge-exchange) generating fast ions**

- $H_f^0 + e^- \rightarrow H_f^+ + 2e^- \ (T_{plasma} < 1\ \mathrm{keV})$
- $H_f^0 + H^+ \rightarrow H_f^+ + H^0 \ (E_b < 90\ \mathrm{keV})$
- $H_f^0 + H^+ \rightarrow H_f^+ + H^+ + e^- \ (E_b > 90\ \mathrm{keV})$

A neutral beam penetrating a plasma is attenuated along the beam line



$$\mathbf{I_{beam}(x) = I_{beam,0}\, exp[-x/\lambda]}$$

with $\boldsymbol{\lambda = \frac{1}{n\sigma_\Sigma}}$

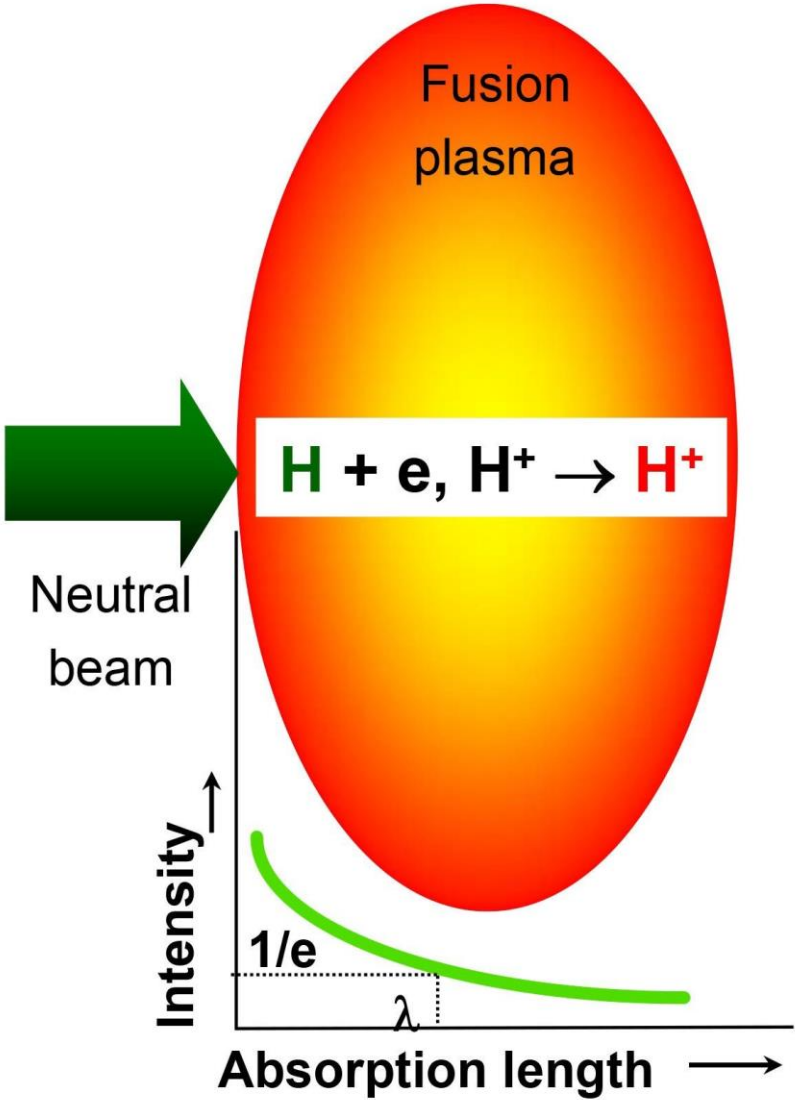
and $\boldsymbol{\sigma_\Sigma = \sum \langle \sigma_i v \rangle / v_{beam}}$

σ_Σ = total cross section

$\langle \sigma_i v \rangle$ = rate coefficients

v_{beam} = beam velocity

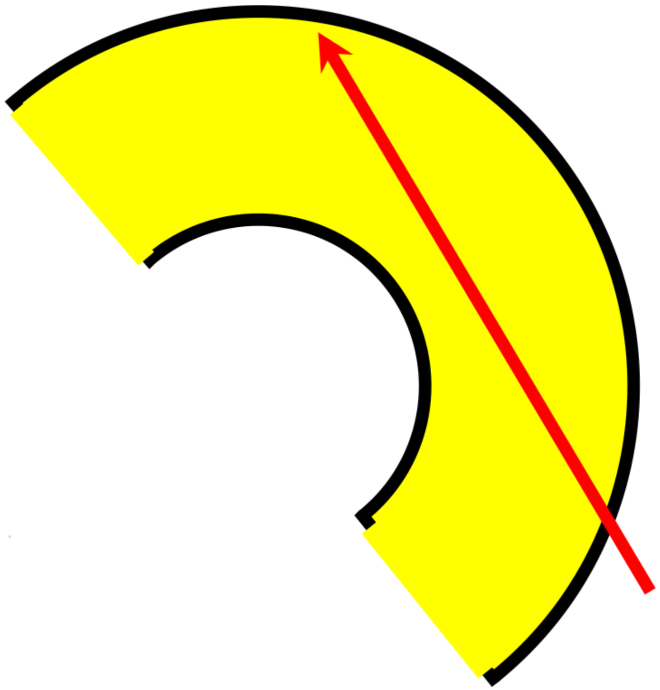
The beam penetration depth determines the power deposition profile



$$\lambda \approx \frac{E_{beam}[keV]\ /A[amu]}{18n_e[10^{19}m^{-3}]}$$

- **100 keV D beam and** $n \approx 5x10^{19}m^{-3} \Rightarrow \lambda = 0.5\ m$
- **Beam energy determines transfer to electrons and ions**
  - Critical energy; for pure-D plasma 18.5 T_e
- **Beam shine-through and prompt ion losses to wall**

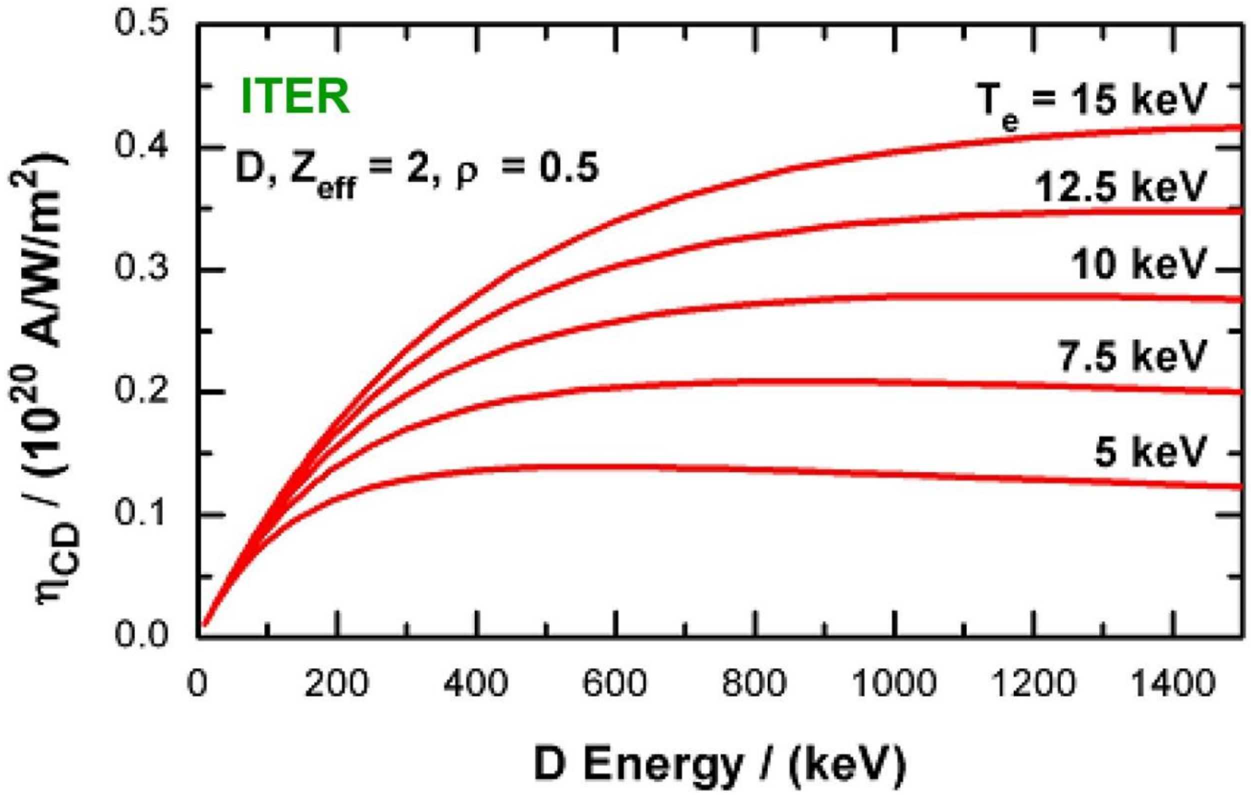
Tangential neutral beams are also used to control the current profile



- **Tangential beams increase beam-plasma interaction length**
- **Flow of fast ions in beam direction**
- **Counter current due to electrons colliding with impurities**

$$I_{NBCD} = I_{NB} + I_{counter} = I_{NB}\left(1 - G\,\frac{Z_{beam}}{Z_{eff,plasma}}\right)$$

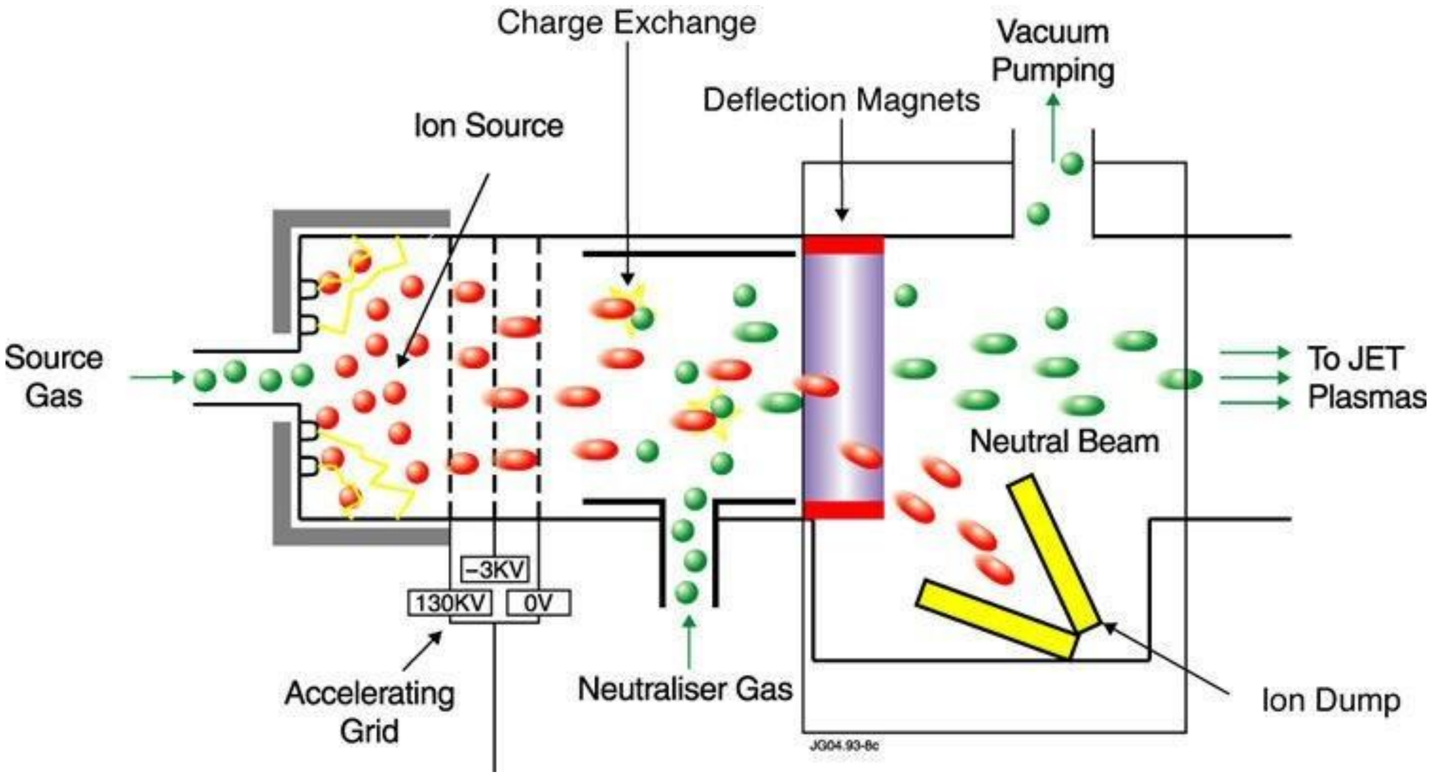
Neutral beams can drive currents, in ITER of up to 2 MA



$$\eta_{CD} = \frac{I_{NBCD} n_e R_{major}}{P_{dep}}$$

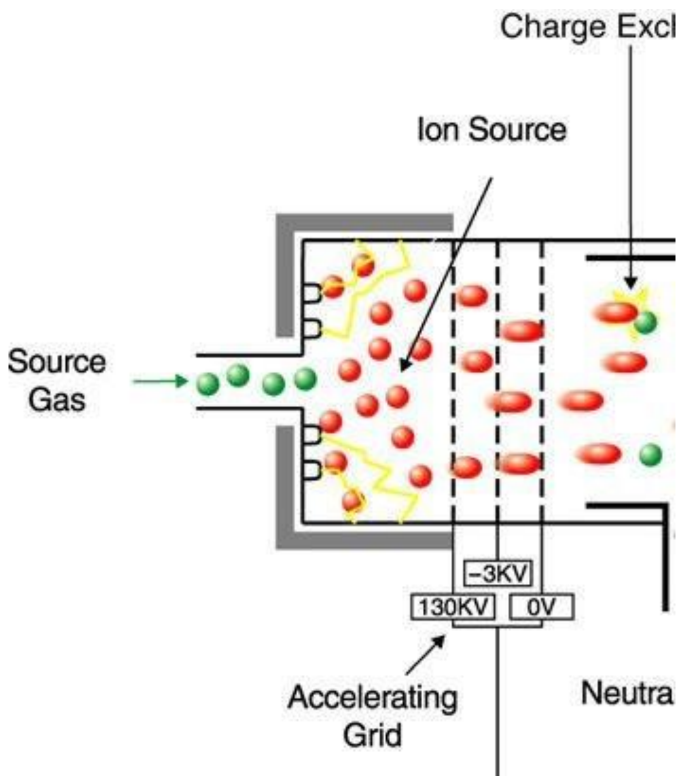
- **Current drive efficiency saturates at high beam energies, but increases with plasma temperature**

High neutral energies and beam power can be extracted from tandem ion-source/neutralizer systems



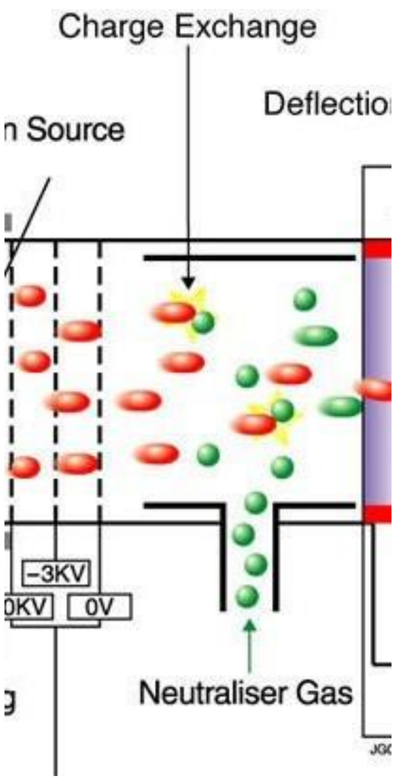
- **Generation of beam ⇒ ion source + accelerator system**
- **Neutralization of beam ions ⇒ collision with (H) gas**
- **Transport of neutral beam ⇒ ion + gas removal**

Extraction of hydrogen ions from a uniform plasma source and acceleration to high energies



- Required power: several MV → positive and negative ions
- Beam energies: tens of keV
- Beam current: tens of A
- Beam cross-section: 100s of cm²
- Beam is typically subdivided into many beamlets to avoid ion optics aberration

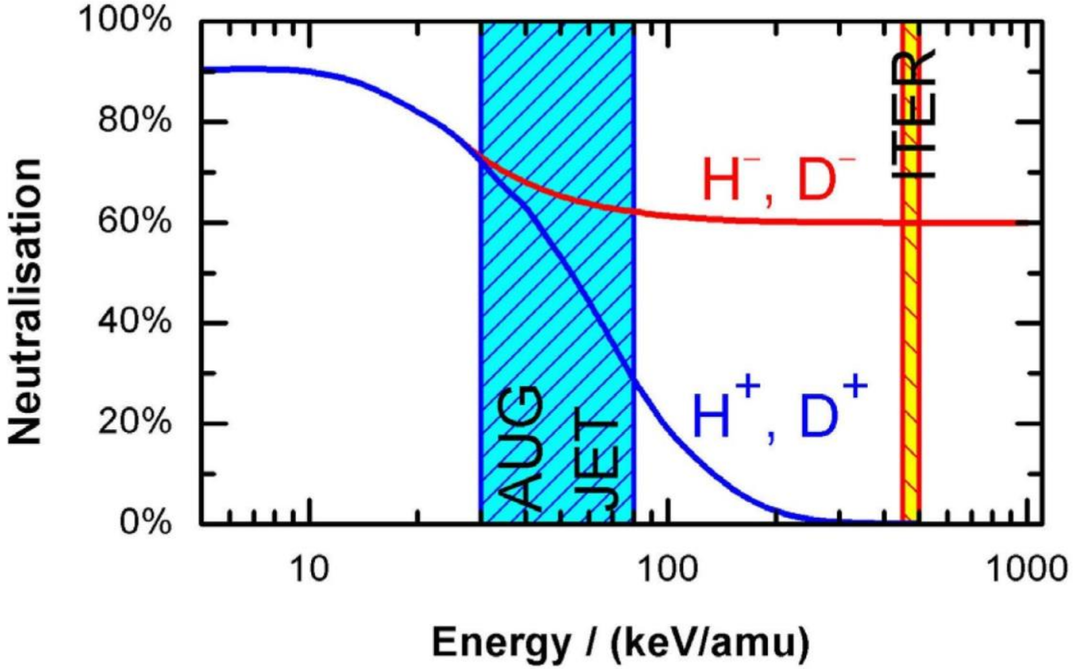
Fast ions are neutralized due to charge-exchange collisions with cold hydrogen molecules



- **Neutralization efficiency is limited:**
  - Plasma generation inside accelerator
  - Dependence of neutralization cross-section on energy
- **Positive and negative ions**
  - Negative ions have a higher neutralization efficiency at high energy

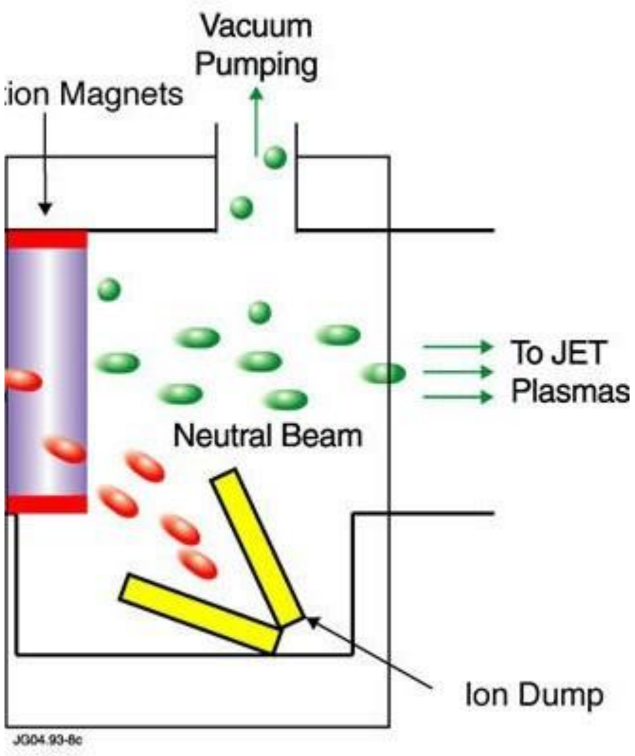
ITER's neutral beam system is based on negative ions because of the high beam energy required

- **Positive ions (AUG and JET)**
  - Low neutralization efficiency for energies > 100 keV/amu
  - Production of molecular ions (H_2^+, H_3^+)
  - High current densities



- **Negative ions (ITER)**
  - High neutralization efficiency
  - Co-extracted electrons
  - Low current densities

After neutralization, residual fast ions are removed by a magnetic or electrical filter system



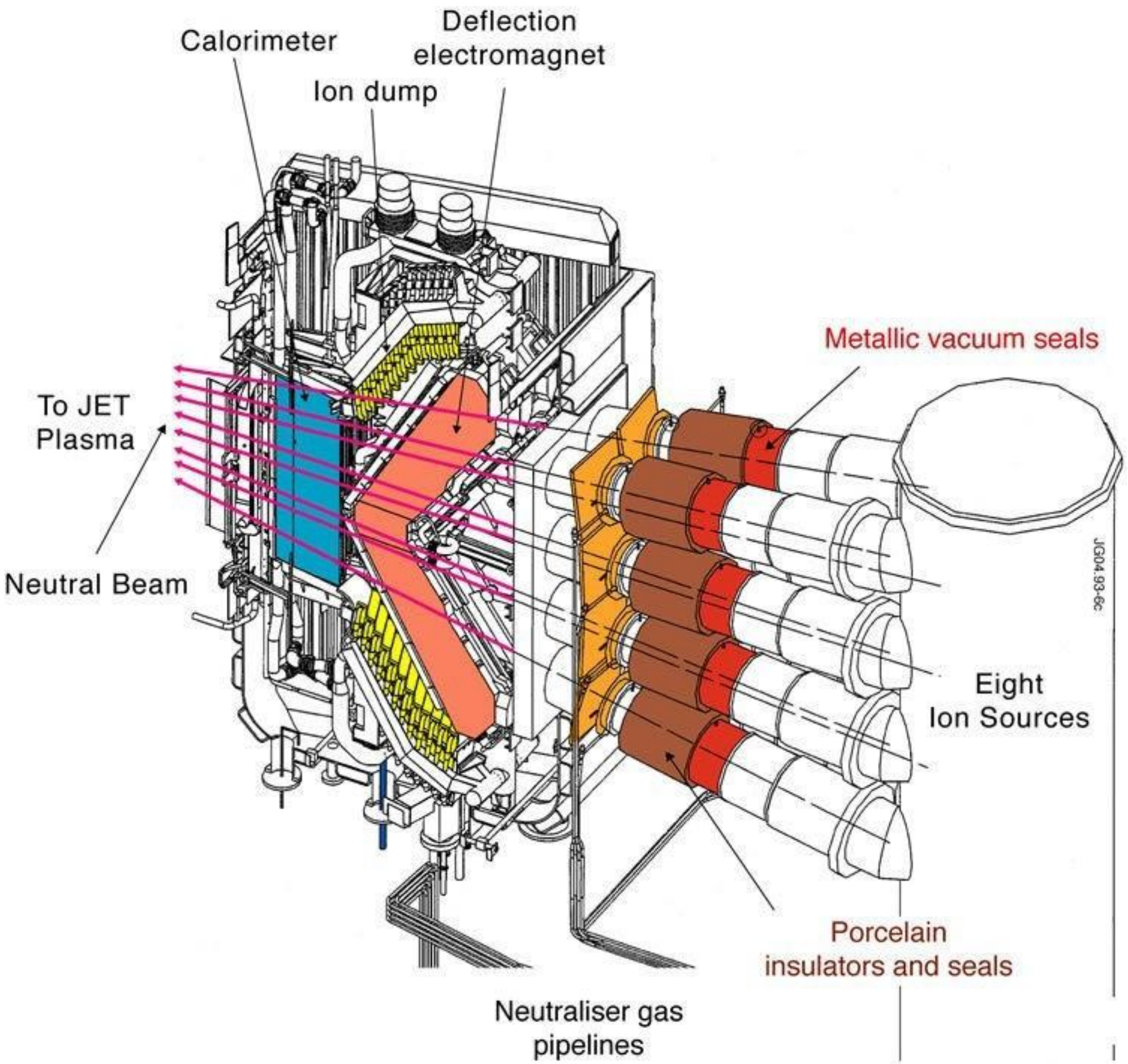
- **Deflection of residual fast ions to a water-cooled surface (ion dump)**
- **May represent up to 30% of the total beam power**
- **Other losses mainly in transmission on beamlet apertures, lesser so at source and by re-ionization**

\+ Neutralization efficiency!

Present neutral beam systems include both positive and negative beam sources

Fusion device	AUG		W7-X*	JET	LHD	JT-60U		ITER
Beam species	H^+/D^+	H^+/D^+	H^+/D^+	H^+/D^+	H^-	H^+/D^+	H^-/D^-	H^-/D^-
Type of source	Arc	RF	RF	Arc	Arc	Arc	Arc	RF
Extraction area (cm^2)	390		390	300	1150	128	1660	2000
Max. energy (keV)	55/60	72/93	55/60 (72/100)	80/130	180	75/95	360/380	1000
Injected power per source (MW)	1.6/2.5	1.4/2.5	1.4/2.5	1.5/1.4	3.75	0.9/1.4	3.3/2.7	16.7
Sources per beamline	4		1 (4)	8	2	2	2	1
Number of beamlines	1+1		2	3	3	14	1	2
Total power (MW)	12/20		2.8/5 (11.2/20)	36/32	15	27/40	13.2/10.8	33
Pulse duration (s)	4/8	4/8	10	10	10	5	10	3600
Max. current density (mA/cm^2)	250/200	160/160	250/200	160/160	35	270/210	13/9	24/20

JET has a 2 x 8-positive ion neutral beam injector system capable of injecting up to 32 MW



- **Two neutral beam boxes**
- **Each PINI produces about 2 MW**
- **Radial and tangential neutral beams**

PINI = positive ion neutral injector

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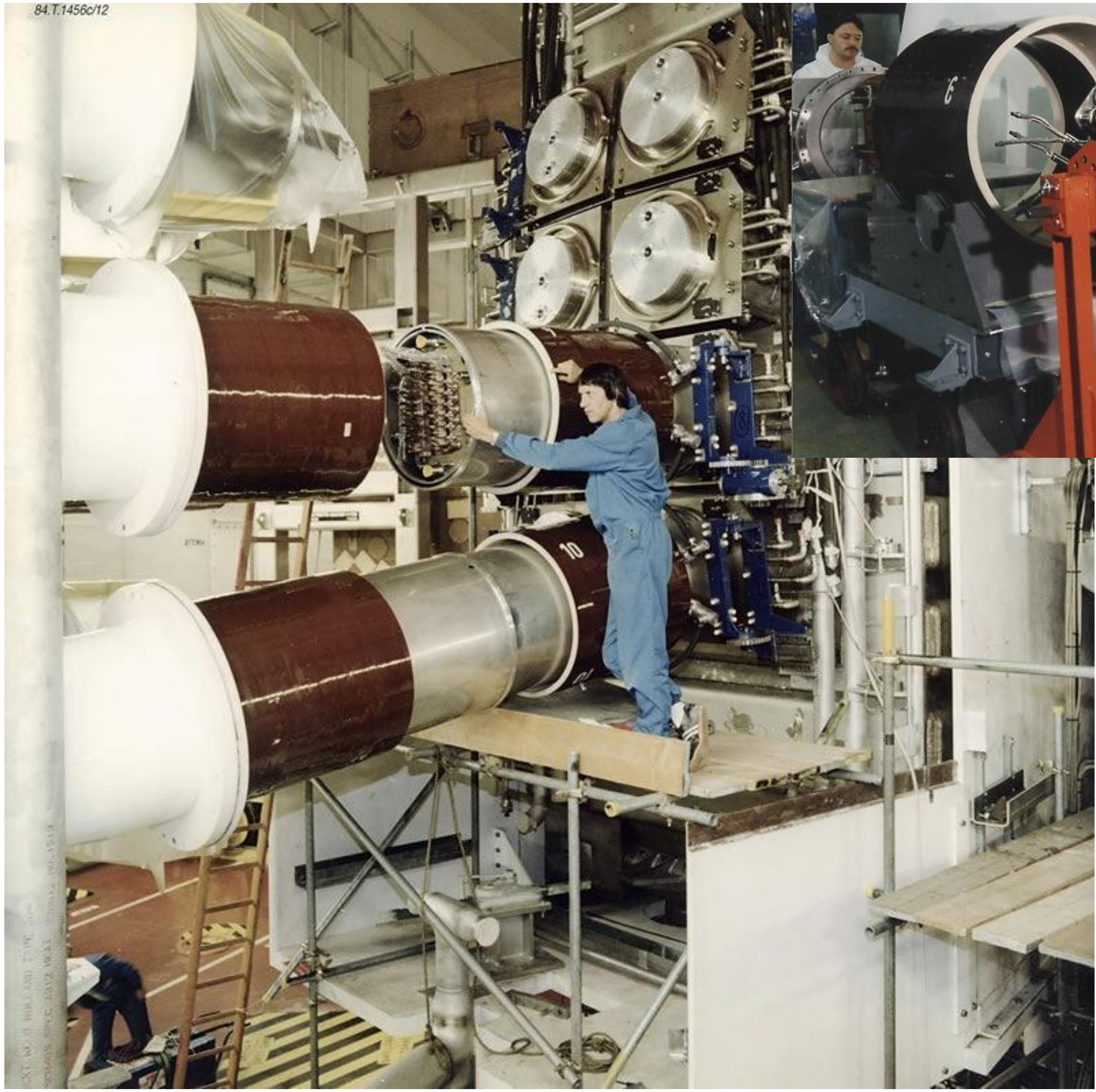
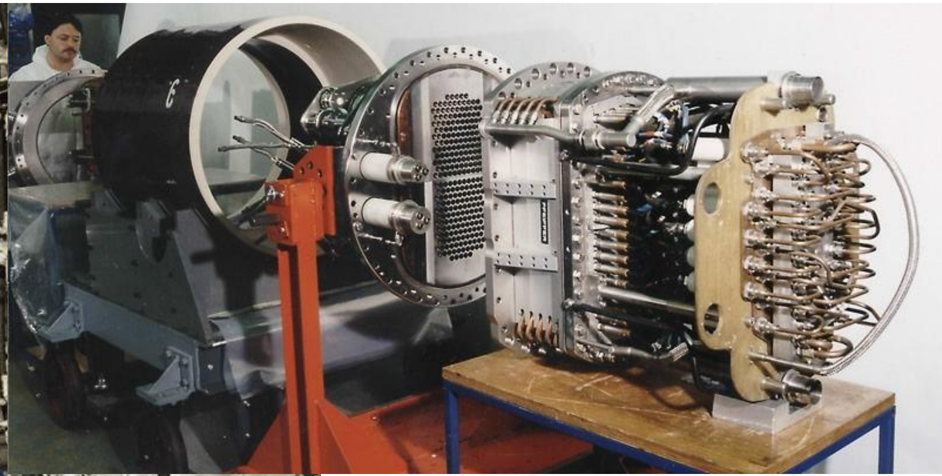


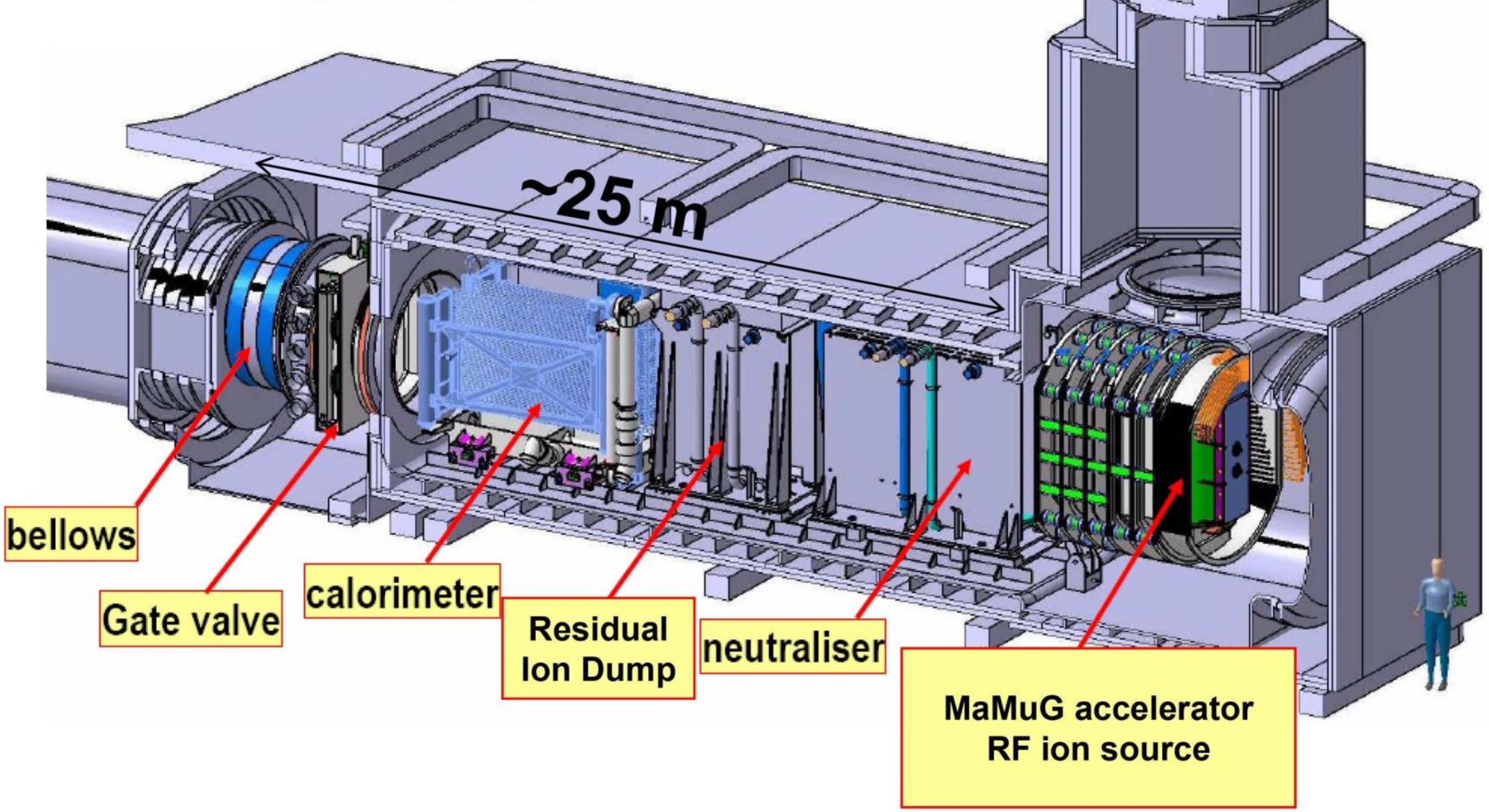


The JET neutral beam (drift) ducts have a height and width of about 0.8 m x 0.2 m

The ITER neutral beam system is based on negative hydrogen ions (1 MeV, 40 A, 33 MW)

Heating Beam

- Multi-Aperture Multi-Grid Accelerator (200 kV steps)
- RF driven negative hydrogen ion source



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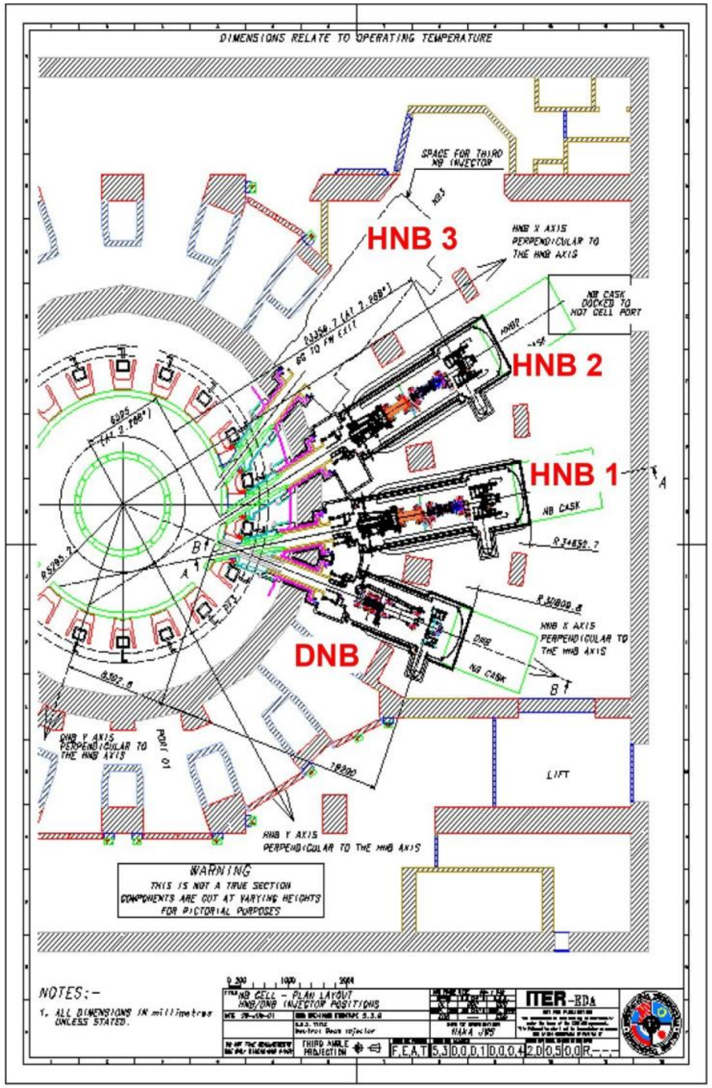
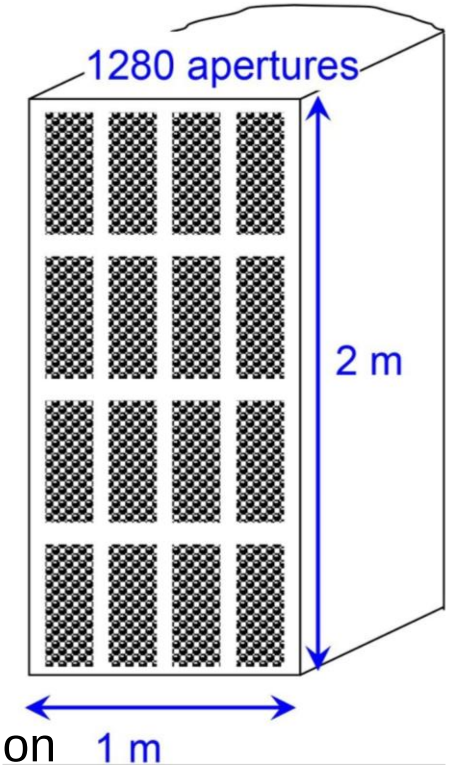


Heating beams (EU, JA)

- 33 MW injected power
- 2 injectors, tangential
- 3600 s pulse
- 1 MeV Deuterium

Ion source

- 0.3 Pa
- $H^- + H_2 \rightarrow H + H_2 + e$
- Stripping losses



- I = 40 A (D^-)
- $j_{D^-} = 200 \frac{A}{m^2} = 20 \frac{mA}{cm^2}$
- 0.2 m^2 extraction area
- $\frac{j_e}{j_{D^-}} < 1$ (co-extracted e$^-$)

Diagnostic beam (IN)

- $I = 60\ A\ (H^-)$
- $j_{H^-} = 300 \frac{A}{m^2}, \frac{j_e}{j_{H^-}} < 0.5$
- 3 MW, 100 kW acceleration

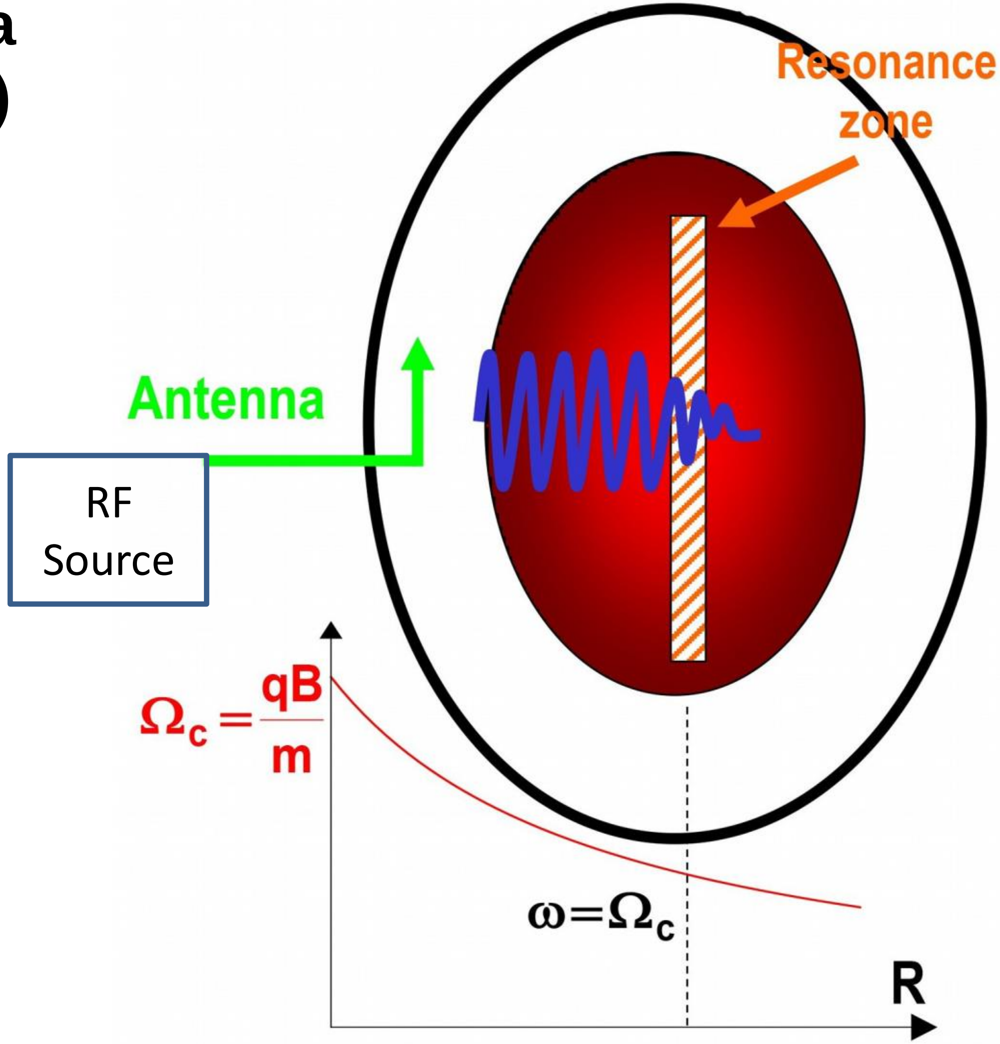
Presemo quiz #1

https://presemo.aalto.fi/fet/

Radio Frequency Heating

RF heating: energy in electromagnetic waves is converted into kinetic energy of resonant particles

- **Excitation of plasma waves (frequency ω)**
- **Transport of wave power into plasma**
- **Absorption near resonance layer $(\omega \approx \Omega_c) \Rightarrow$ electrons and ions**
- **Resonant particles subsequently thermalize with bulk plasma**



There are three primary classes of resonances with efficient wave power absorption

Resonant condition:

$$\omega = k_{\|} v_{\|} + l\omega_c$$

$l = 1,2,3, \ldots$

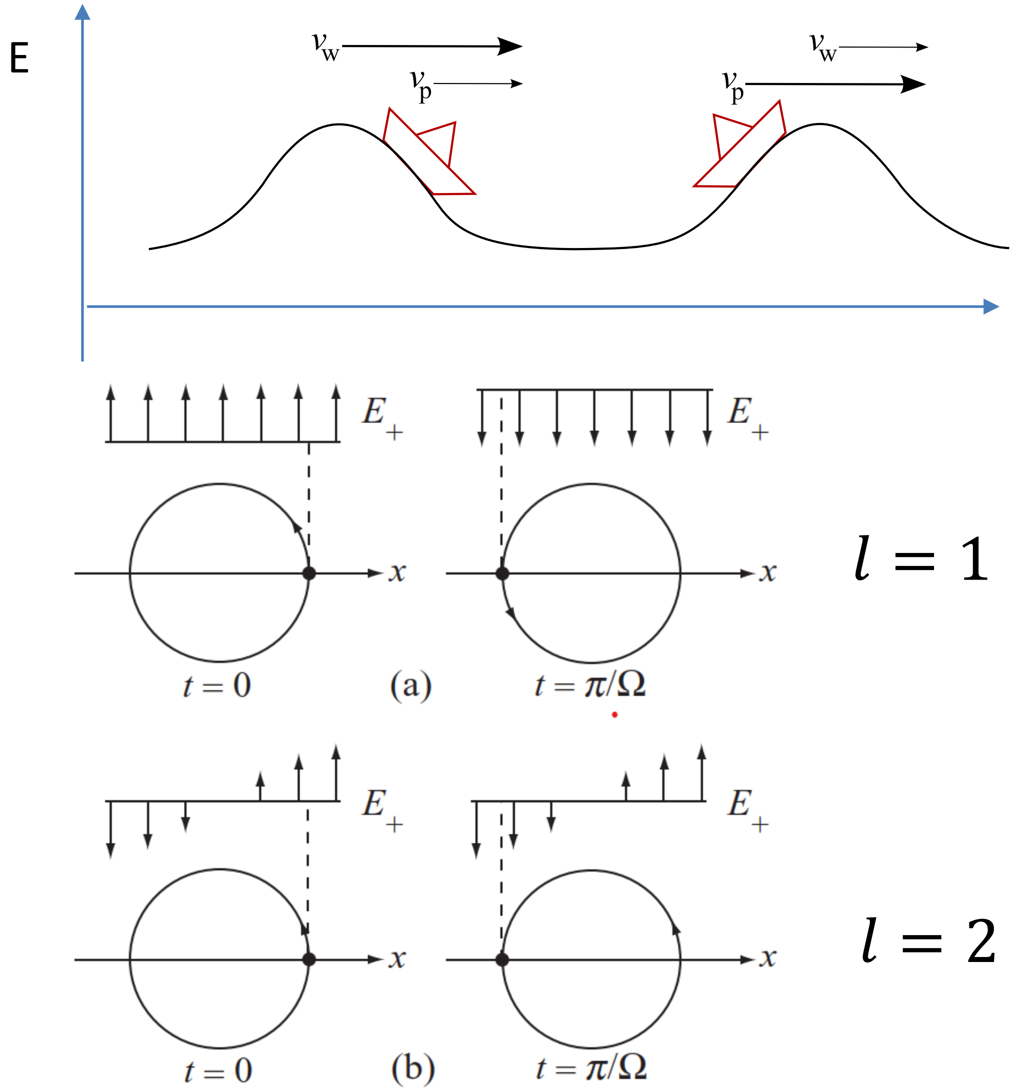
- **Electrons: $\mathbf{28\ GHz\ /B\ [T]}$ ⇒Electron Cyclotron Resonance Heating (ECRH)**

- **Hydrogen ions: $\mathbf{15\ MHz\ /B\ [T]}$ ⇒ Ion Cyclotron Resonance Heating (ICRH)**

$l = 0$

- **Landau resonance at electron thermal speed:**
$\mathbf{1.3\ GHz} \sqrt{\mathbf{T_e[keV]}}\ /\boldsymbol{\lambda}_{\|}\mathbf{[cm]}$ Lower Hybrid Heating (LH)

Physical picture of Landau damping and cyclotron resonance



$l = 1$

$l = 2$

- **Wave energy damping when there are more slower than faster particles**

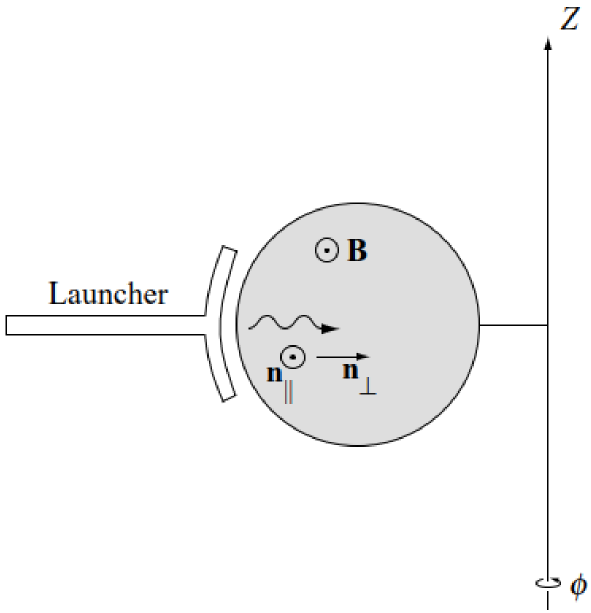
- **If $\boldsymbol{E} \perp \boldsymbol{B}_{\parallel}$, X-mode resonance with $\boldsymbol{E}_{wave}$**

- **If $\boldsymbol{E} \parallel \boldsymbol{B}_{\parallel}$, O-mode resonance with $\boldsymbol{E} = \boldsymbol{v}_{\parallel} \times \boldsymbol{B}_{\text{wave},\perp}$ -**

RF heating analysis: accessibility of waves in plasmas → cut-off and resonance

Dispersion relation:

$$D(\omega, \mathbf{k}, x) = D_r(\omega, \mathbf{k}, x) + iD_i(\omega, \mathbf{k}, x) \quad \Rightarrow \quad \mathbf{k} = k_\perp \mathbf{e}_x + k_\parallel \mathbf{e}_z$$



$D_r(\omega, \mathbf{k}, x) = 0$ **to obtain:**

$$k_\perp = k_\perp(\omega, k_\parallel, x)$$

- $\omega, k_\parallel$ → **det. by source and antenna**
- x → **dependence on n and B**

- **propagation of wave:** $k_\perp^2 > 0$
- $k_\perp^2 \rightarrow 0$ → **cut-off**
- $k_\perp^2 \rightarrow \infty$ → **resonance**

RF heating analysis: accessibility of waves in plasmas → cut-off and resonance

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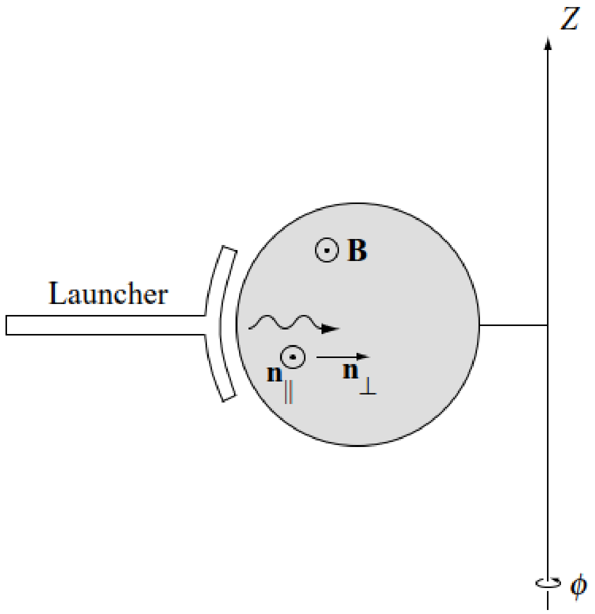

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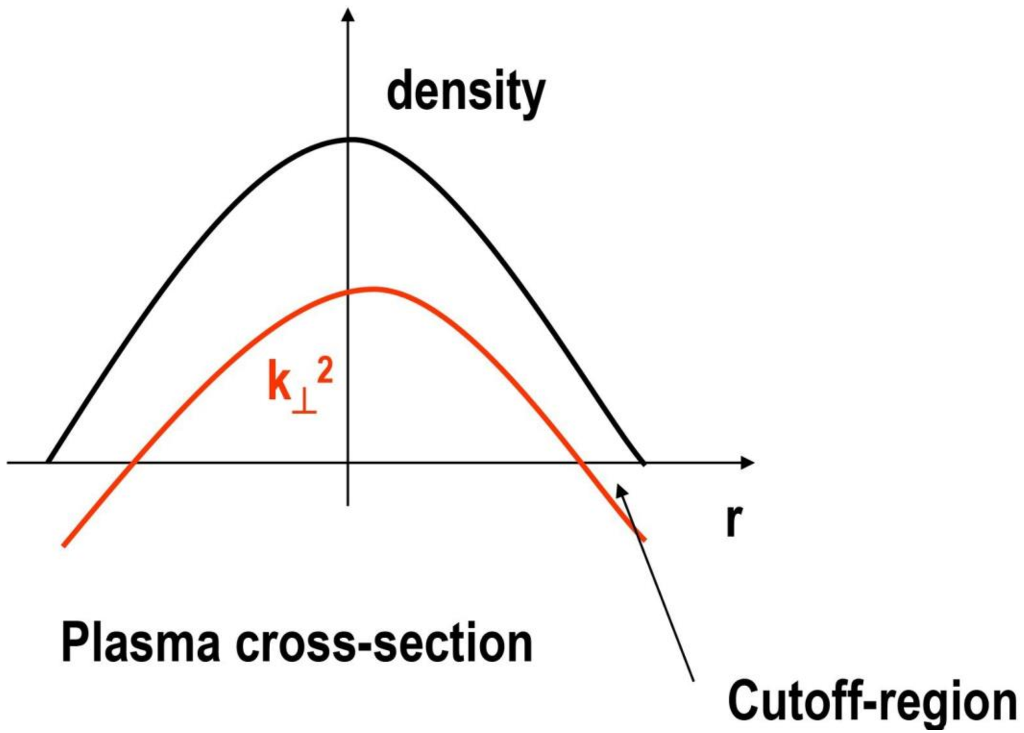
Full derivation of accessibility and wave damping:
Freidberg, *Plasma Physics and Fusion Energy*. Chap. 15

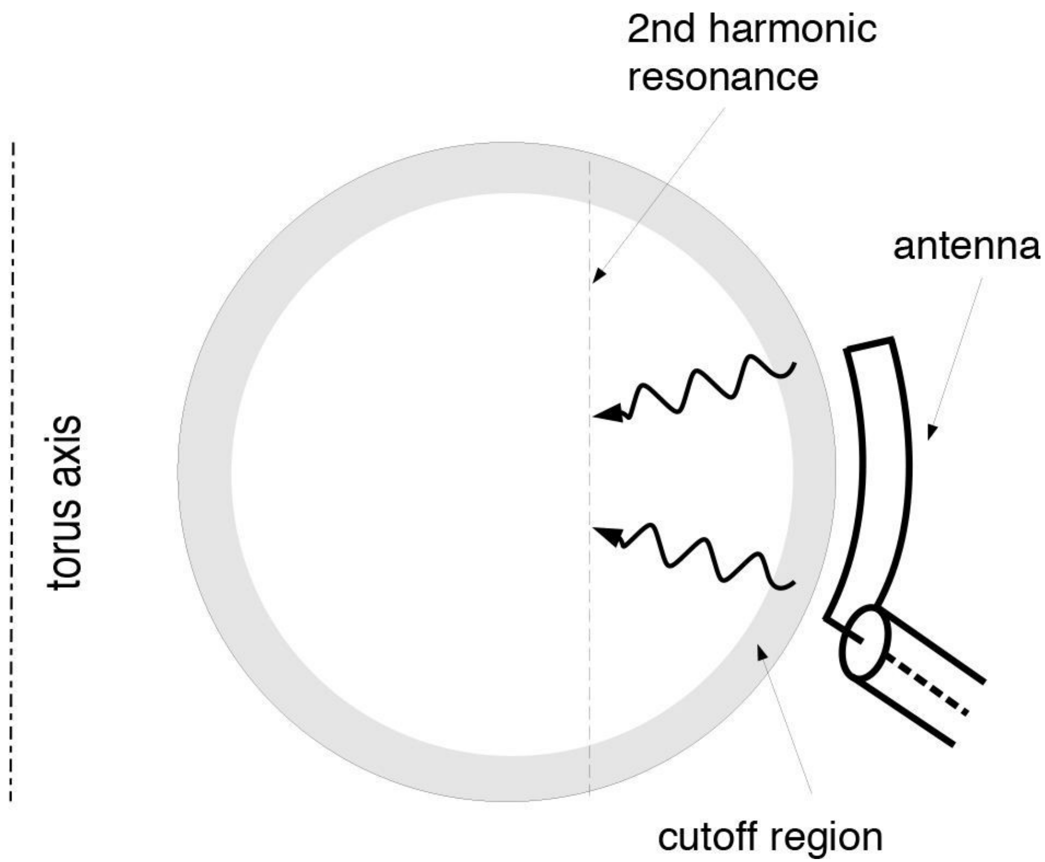
The dispersion relation for ICRH has two solution for fast and slow waves



- **Fast wave heating ($\mathbf{E} \perp \mathbf{B_0}$, X-mode) with lower density limit (2×10^{19} m^{-3}) ⇒ fast wave needs to tunnel through edge cutoff region**

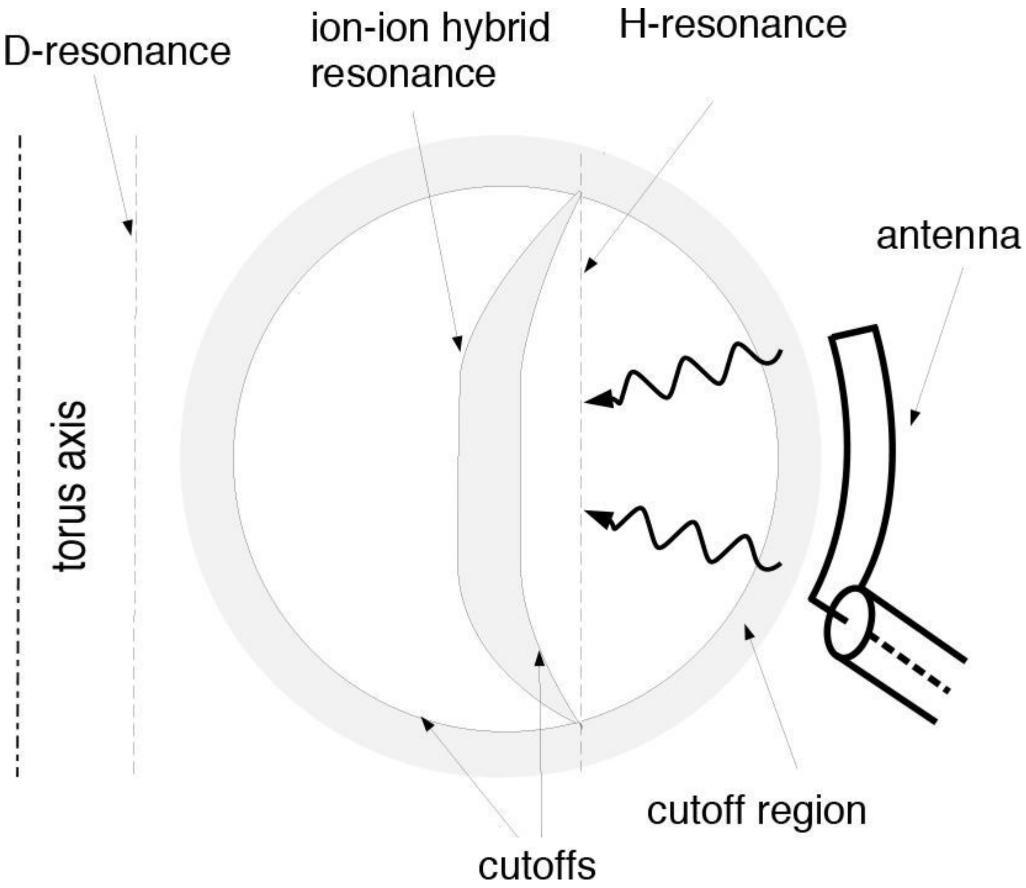
- **Slow wave heating ($\mathbf{E} \parallel \mathbf{B_0}$, O-mode) has an upper density limit (1×10^{19} m^{-3}) → not considered for reactor heating**

One of best absorption is achieved at the second harmonic resonance (due to polarization)



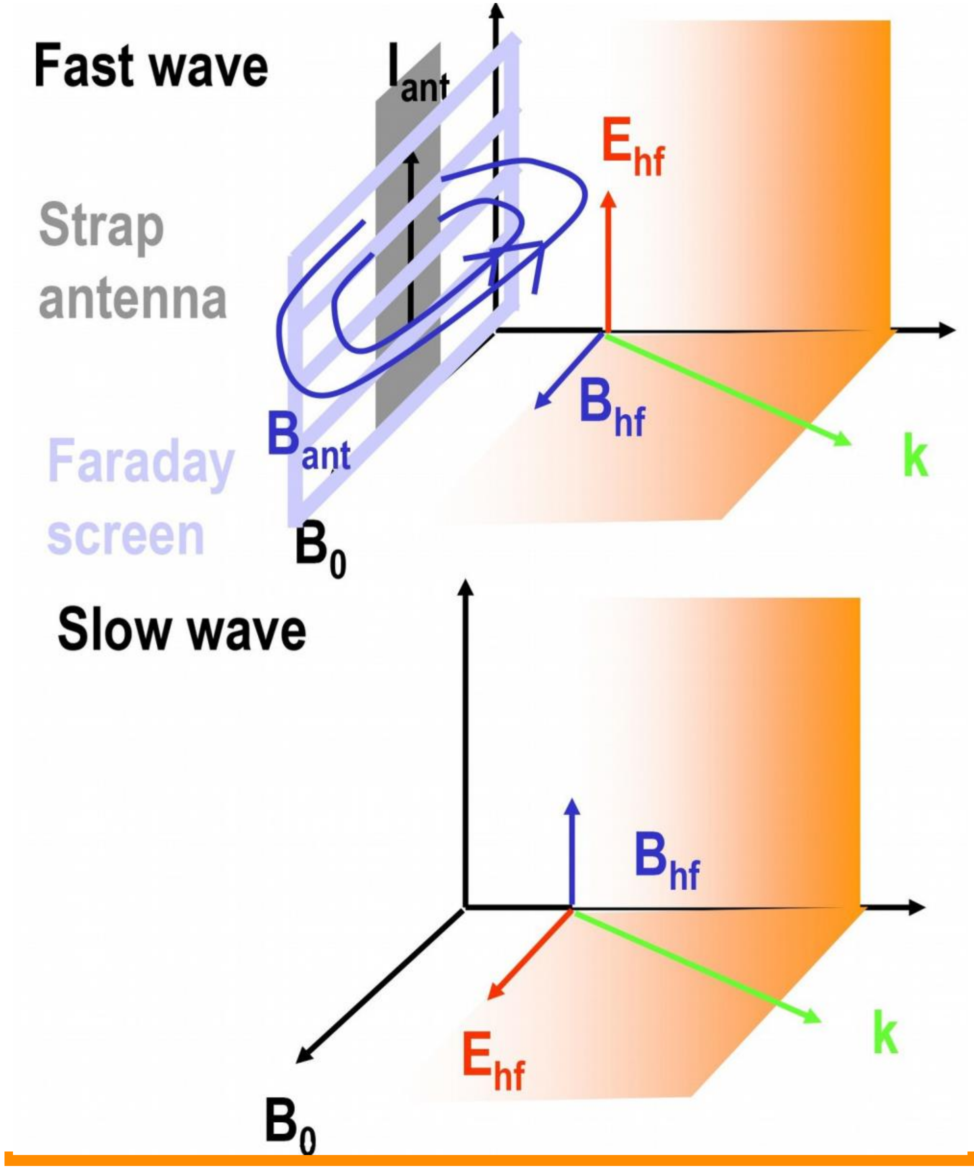
- **Applied to single ion species, with tail of fast particles**
- **Magnetic field dependence allows focusing of wave power in large plasmas**
- **Requires high density and high temperature plasmas**

Wave absorption on plasma minority species is also very efficient



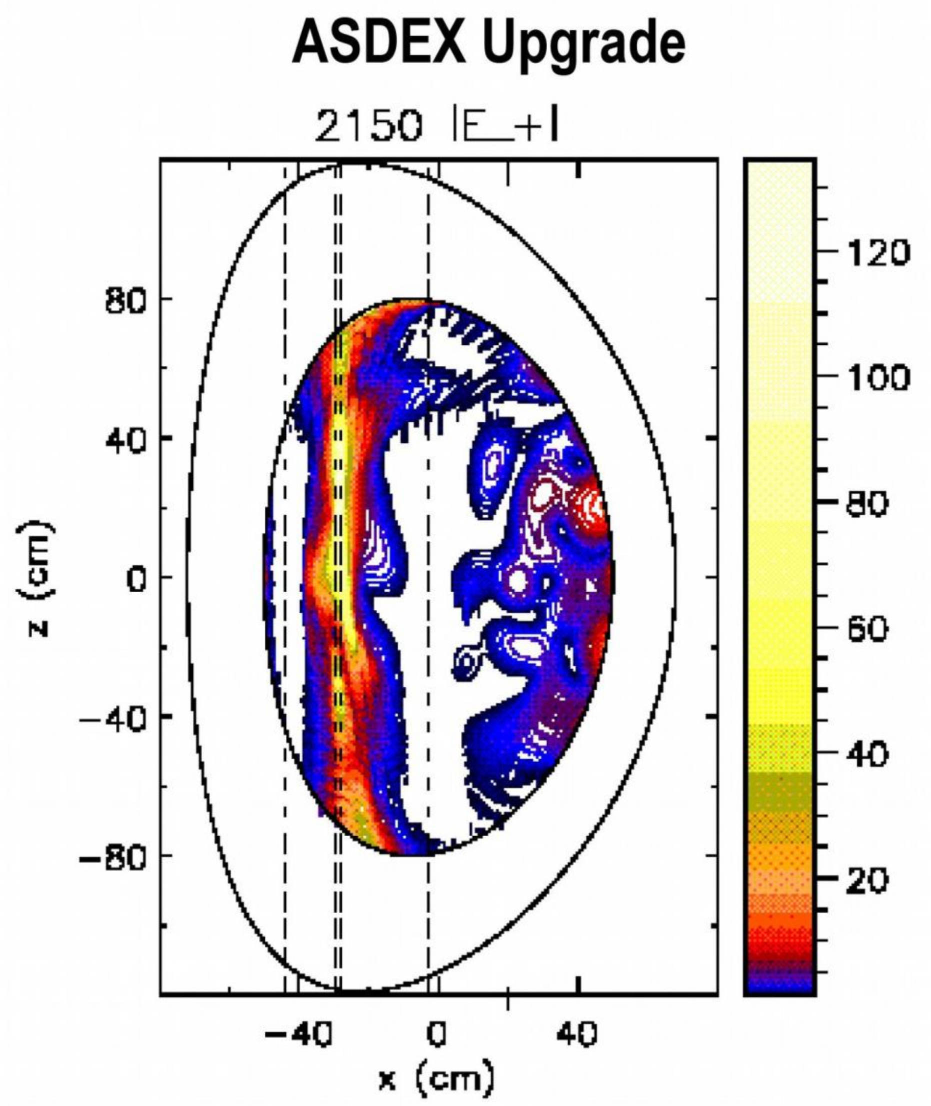
- **Low (< 10%) of hydrogen in deuterium plasmas**
- **Landau cyclotron damping on H (favorable polarization wrt. to wave polarization) ⇒ power absorbed in H with strong tail in distribution function**

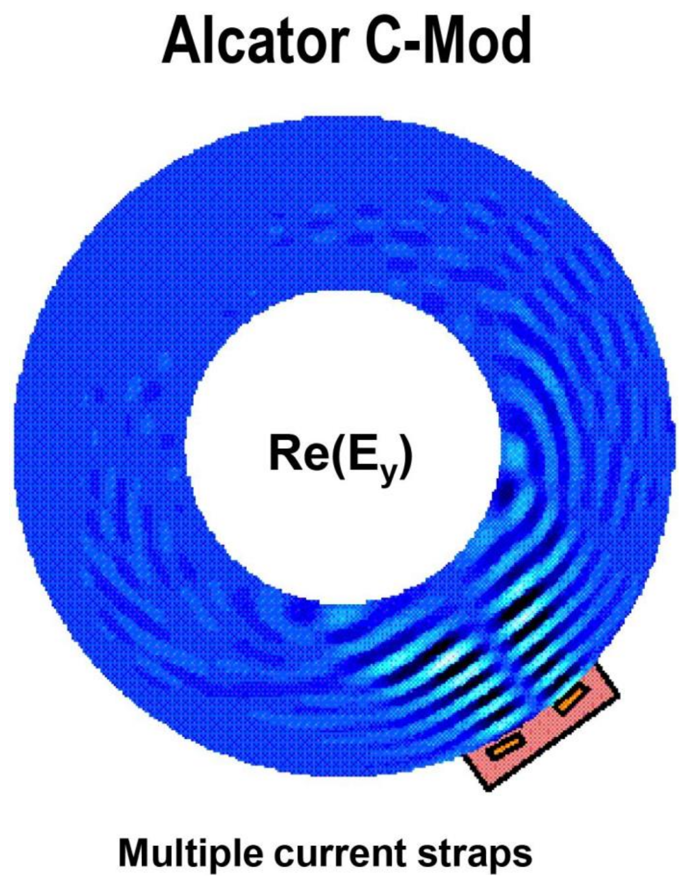
Fast waves near the plasma edge are excited by currents in poloidal conductors (straps)



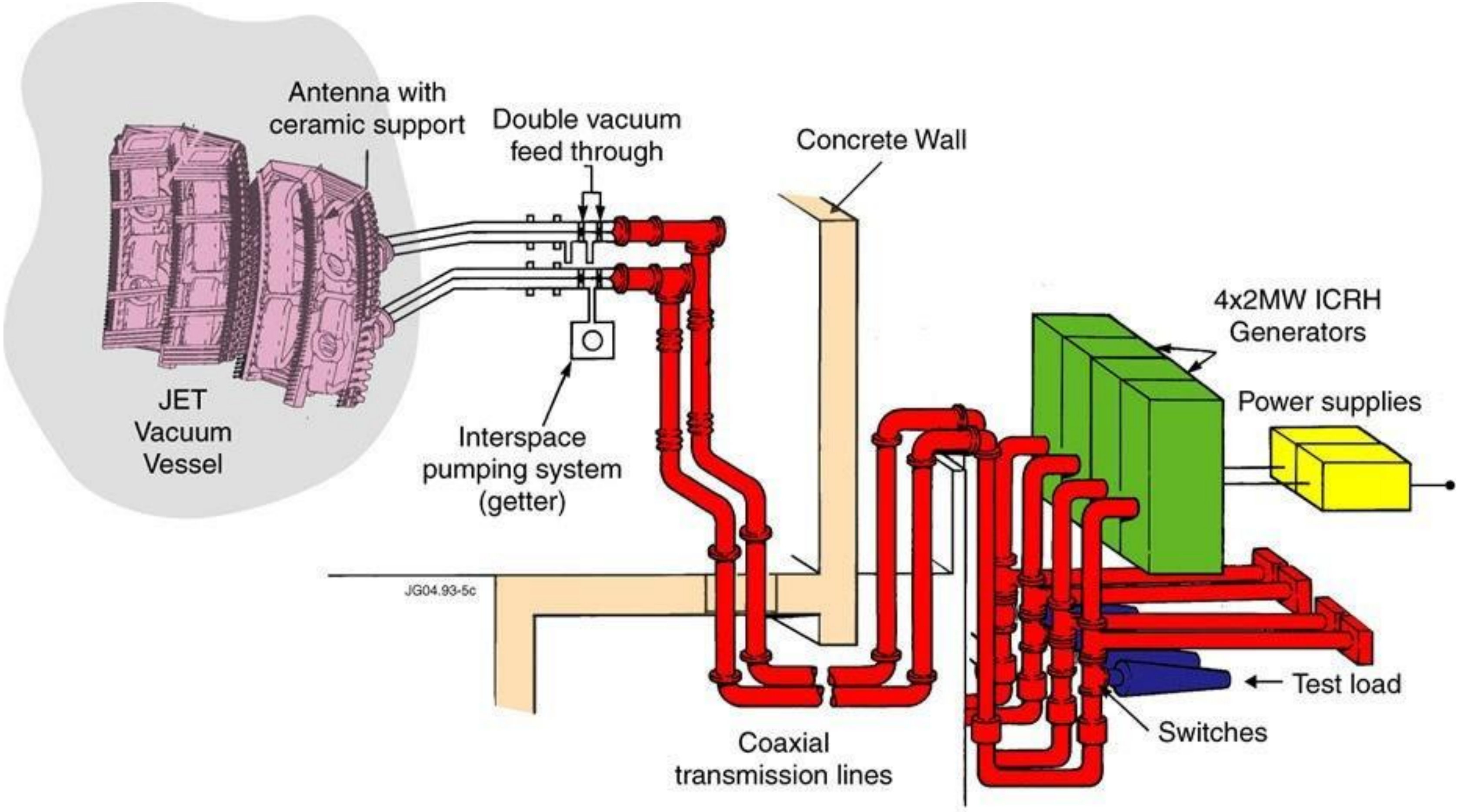
- **Launch frequency (ω) given by radio-frequency generator**
- **Fast waves travel almost ⊥ to magnetic field lines**
- **Slow-wave heating E and B fields are rotated by 90°**

Wave propagation and absorption are calculated in full (magnetic) 3-D geometry using antenna design



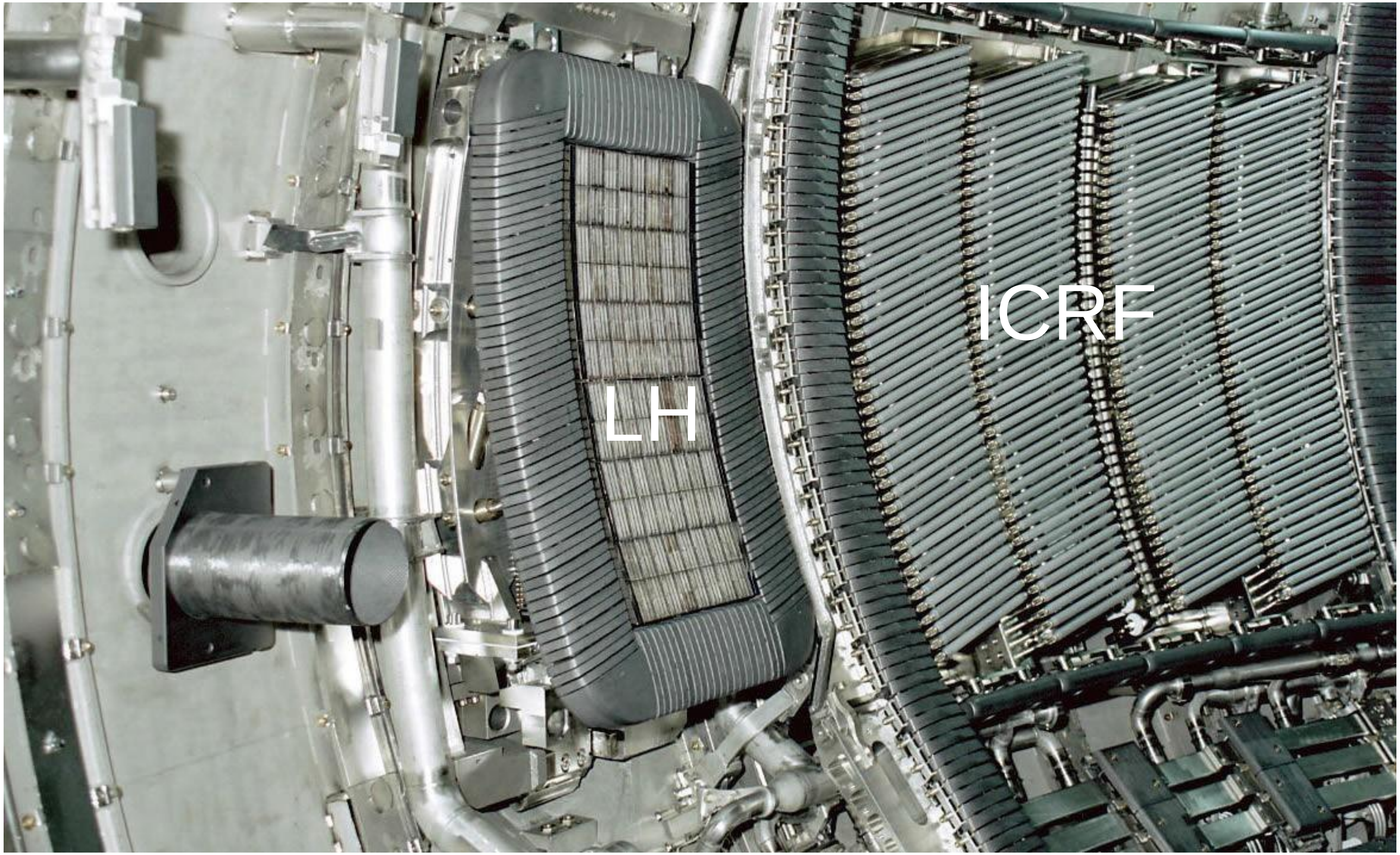


At JET, the power from the ICRH generators (4x2 MW) is transmitted to arrays of in-vessel antennas



- **For practical reasons, antennas installed at low-field side $\Rightarrow$low-loss coaxial transmission lines to tokamak**

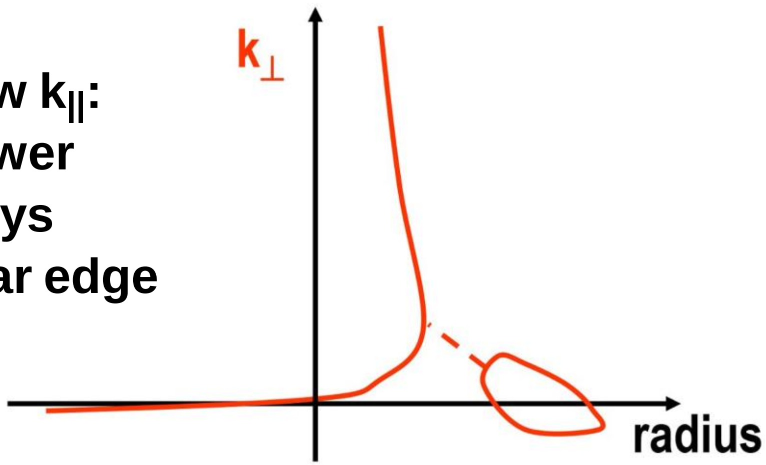
JET Lower Hybrid and Ion Cyclotron Resonance Heating antenna

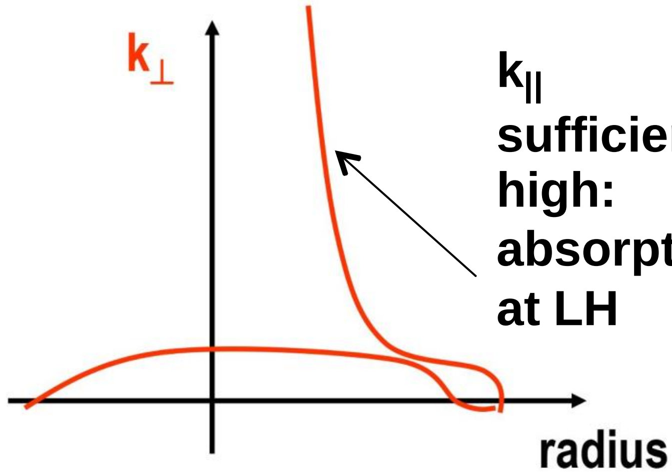


Lower hybrid typically drives off-axis current, but also heats the plasma

- **Lower hybrid frequency resides between ion and electron resonance frequencies: $\Omega_i \ll \omega_{LH} \ll \Omega_e$**
- **Dispersion relation has two solutions: slow and fast waves**
- **Minimum density required to launch wave into plasma ($10^{17}\,\mathrm{m}^{-3}$), minimum $k_{||}$ for propagation into center**

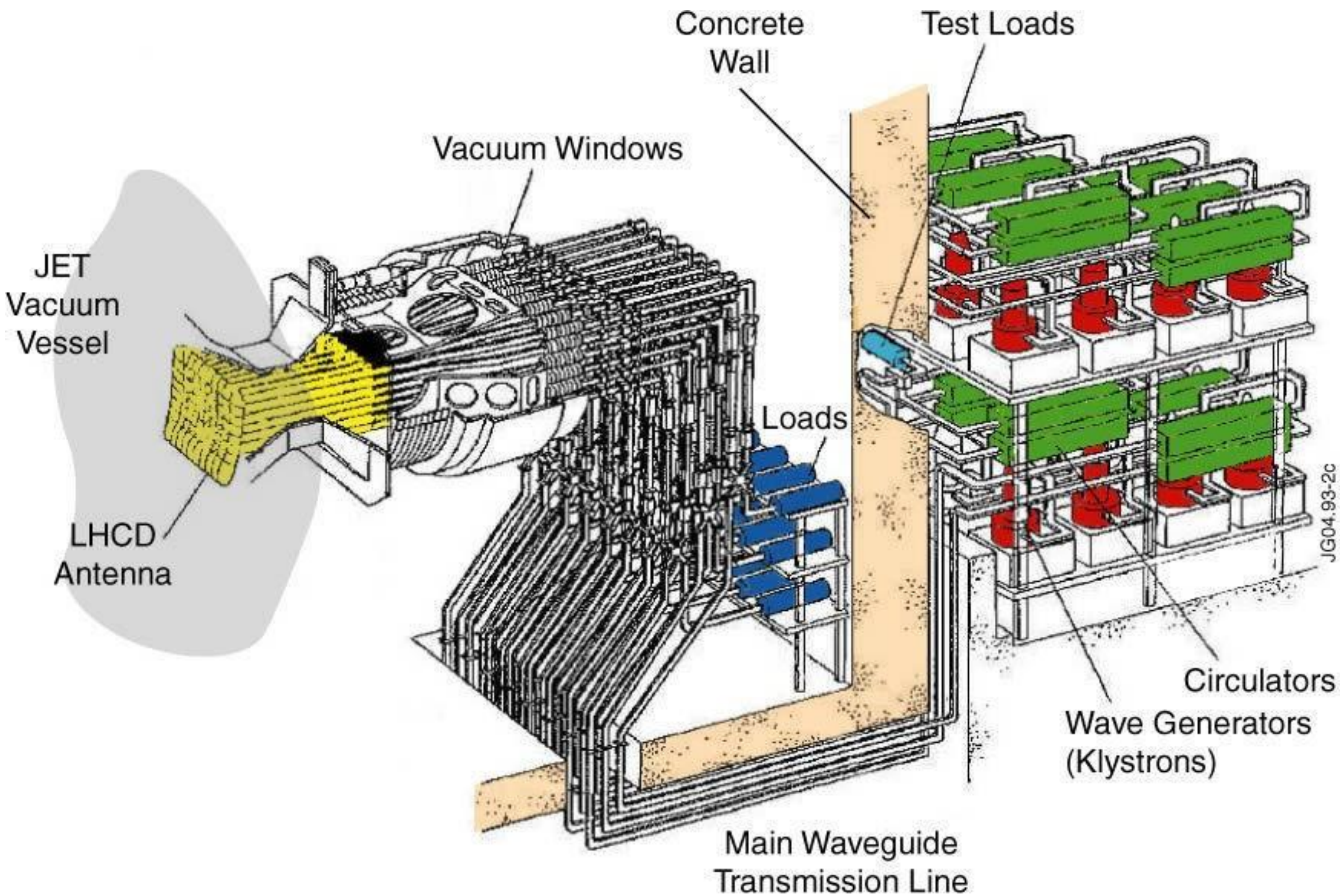
Low $k_{||}$: power stays near edge



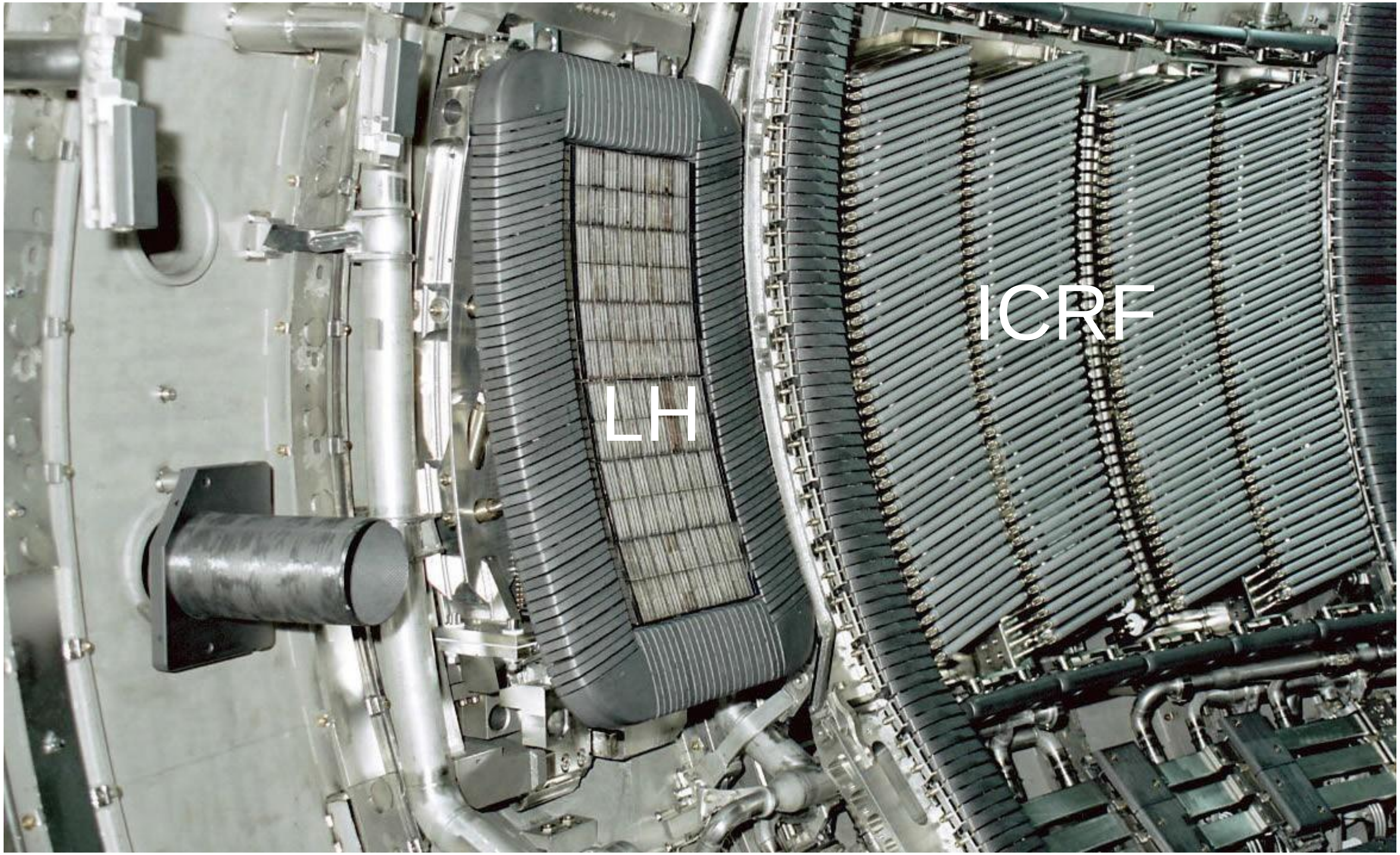


$k_{||}$ sufficiently high: absorption at LH

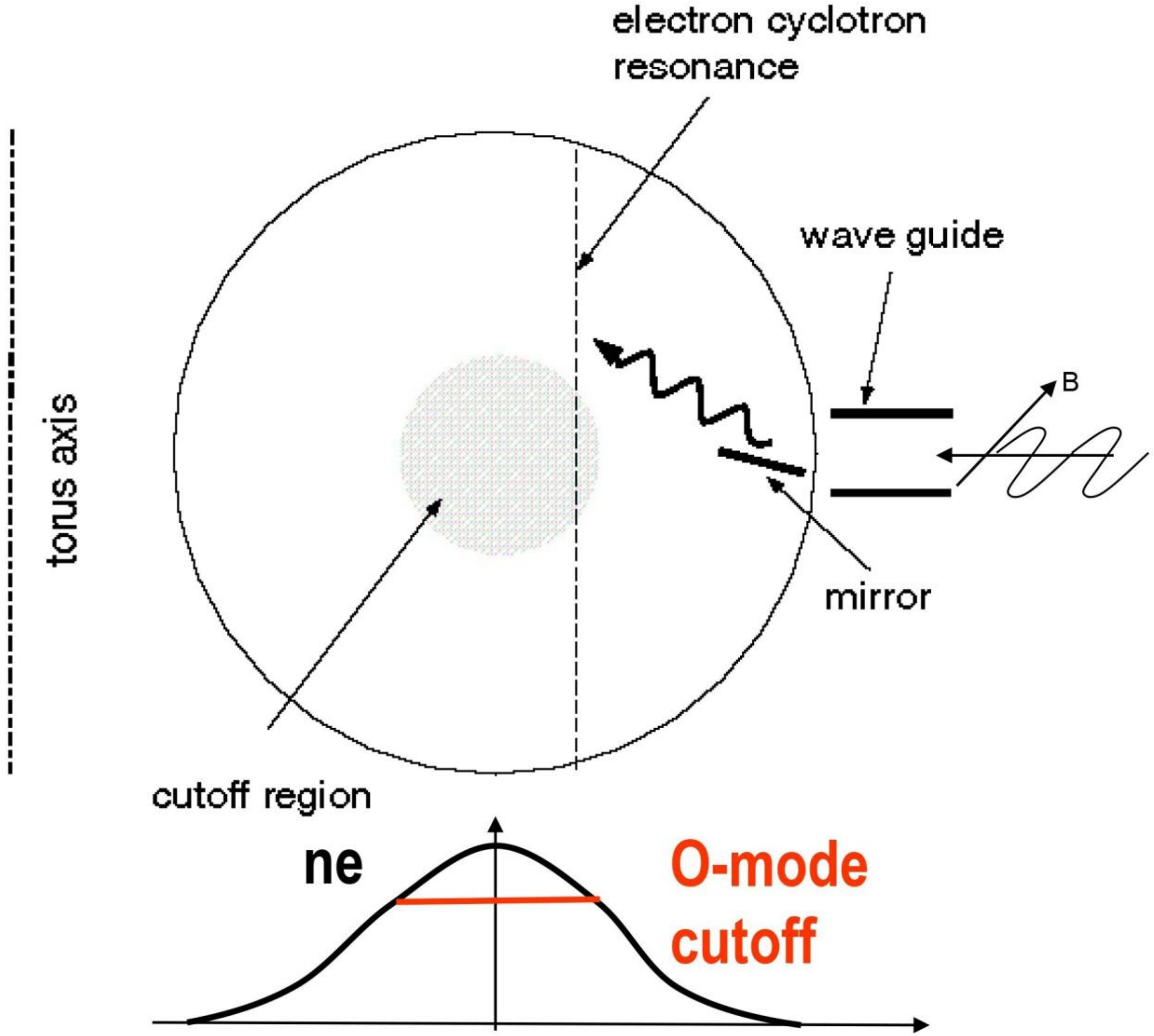
Lower hybrid waves are generated in klystrons and transmitted to antenna via transmission lines



JET Lower Hybrid and Ion Cyclotron Resonance Heating antenna

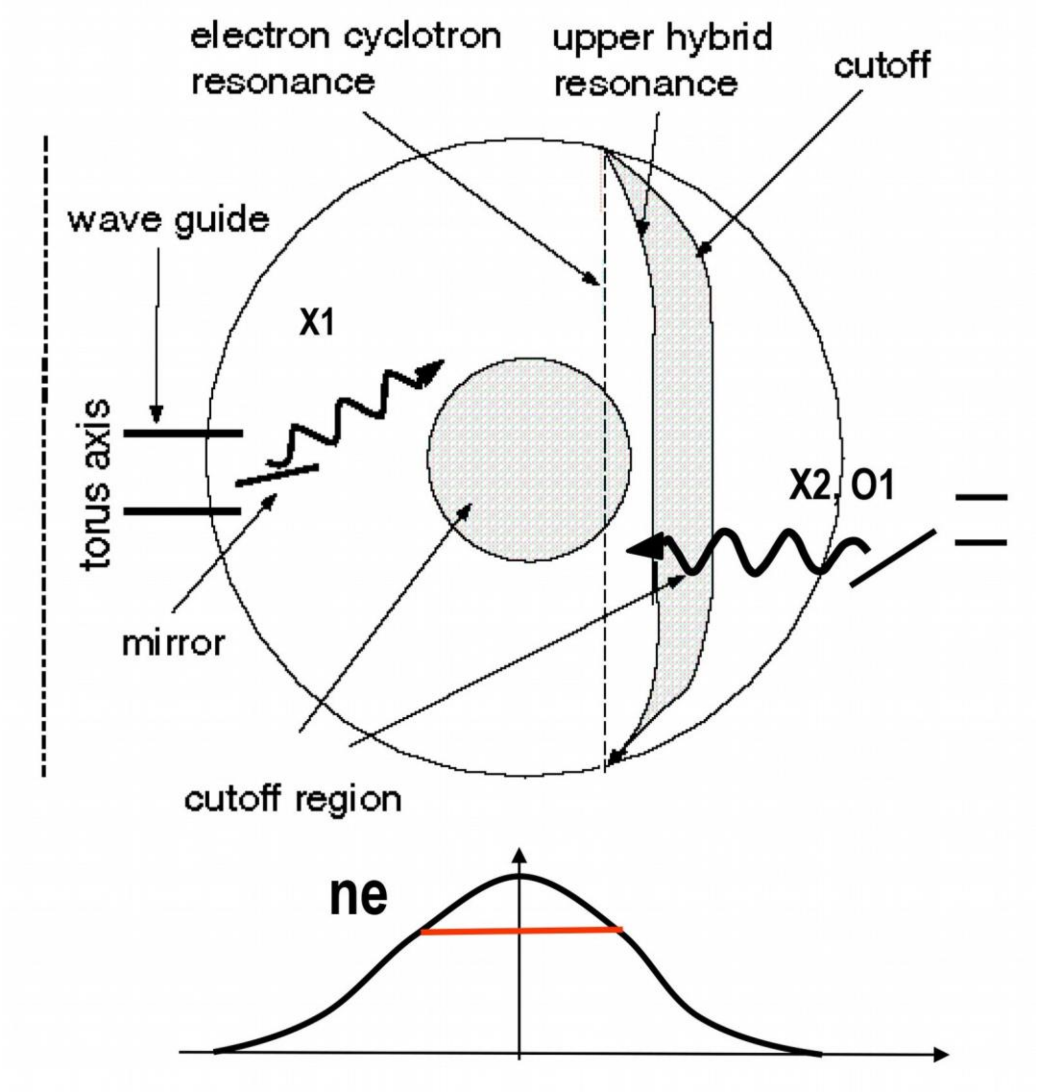


Electron cyclotron heating can be accomplished in ordinary ($E \parallel B_0$) or extraordinary mode ($E \perp B_0$)



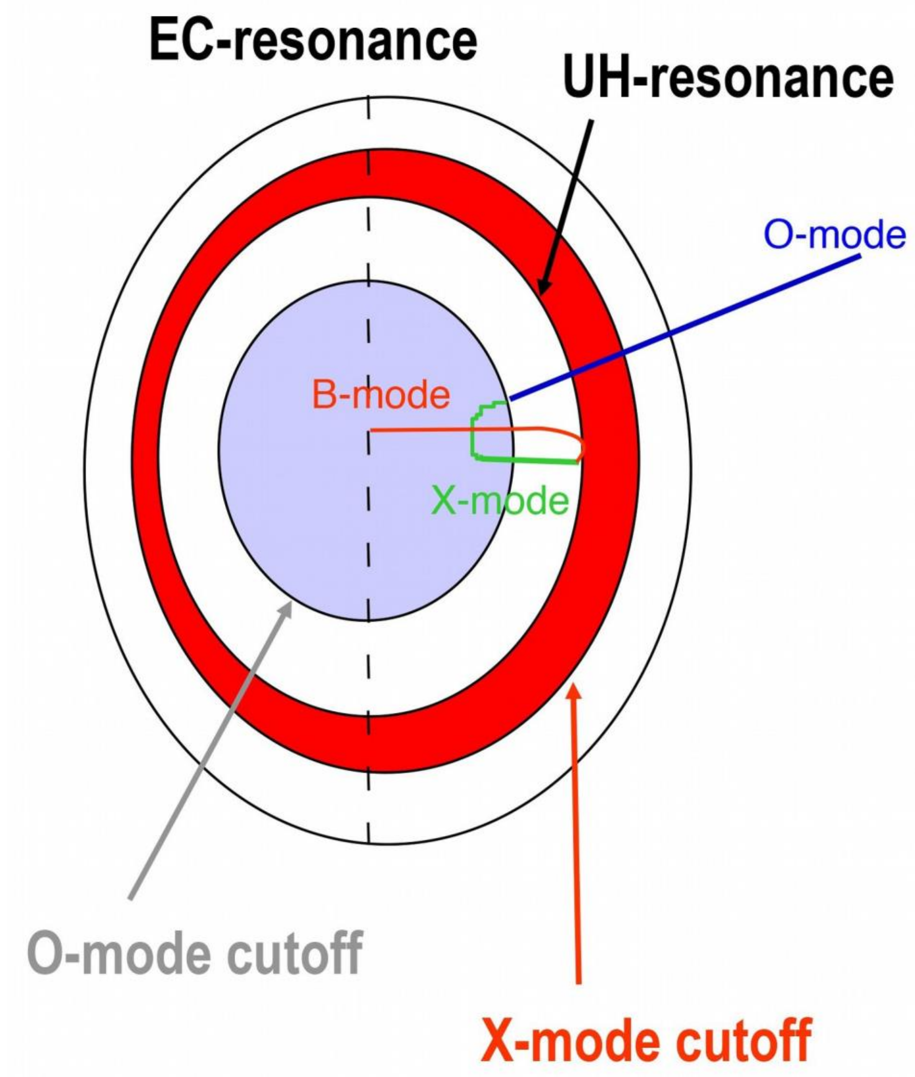
- **High-density cutoff, but no low-density cutoff**
- **Localized heating scheme!**
- **Acceleration of electrons $\Rightarrow$ energy transfer to plasma**

Electron cyclotron heating can be accomplished in ordinary ($E \parallel B_0$) or extraordinary mode ($E \perp B_0$)



- **X-mode heating from high-field side (second harmonic also from low-field side)**
- **High-density cutoff**

For certain plasma densities and launch angles, OXB mode conversion takes place



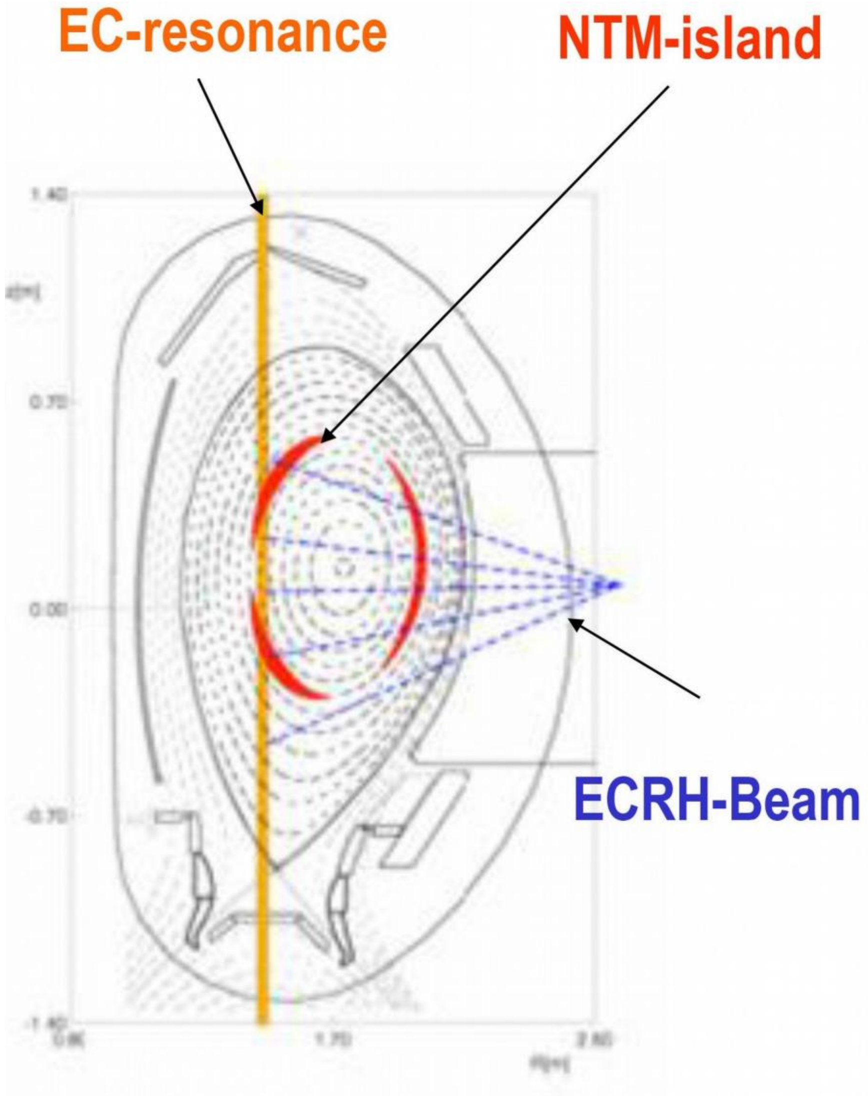
- **O-mode → X-mode at X-mode cutoff**

⇒ X-mode converts into electrostatic electron wave (Bernstein waves)

⇒ Bernstein waves absorbed by electron cyclotron damping

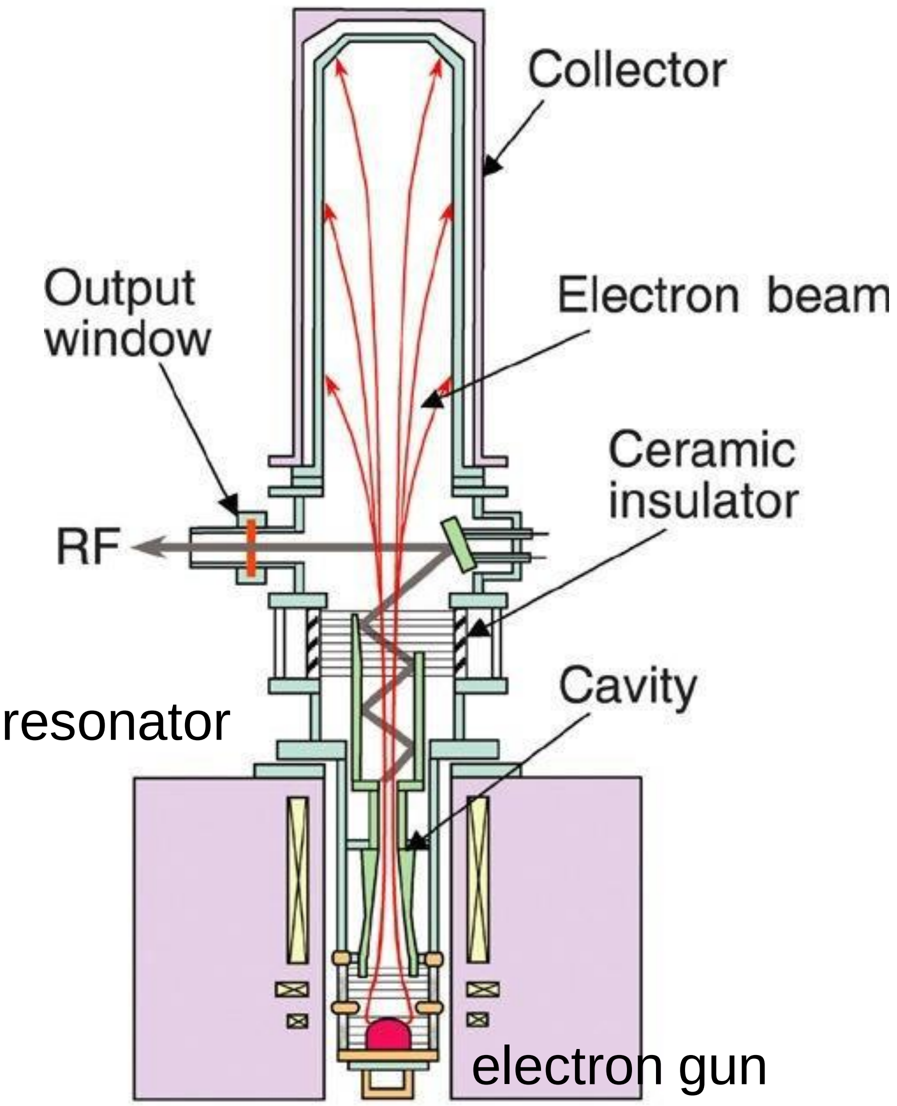
- **Scheme has no upper density limit**

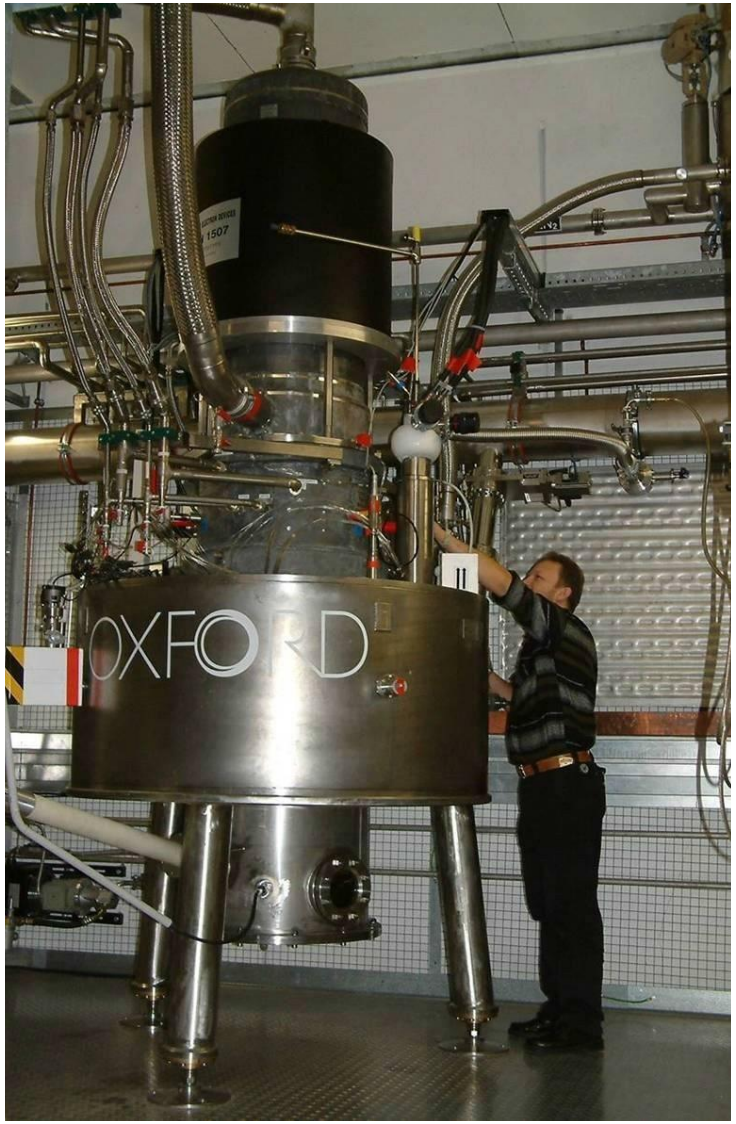
EC waves also drive (highly local) currents used for general current drive and mode suppression



- **Steerable mirrors to 'catch and subdue's neo-classical tearing modes**
- **Modular system and fast power modulation**

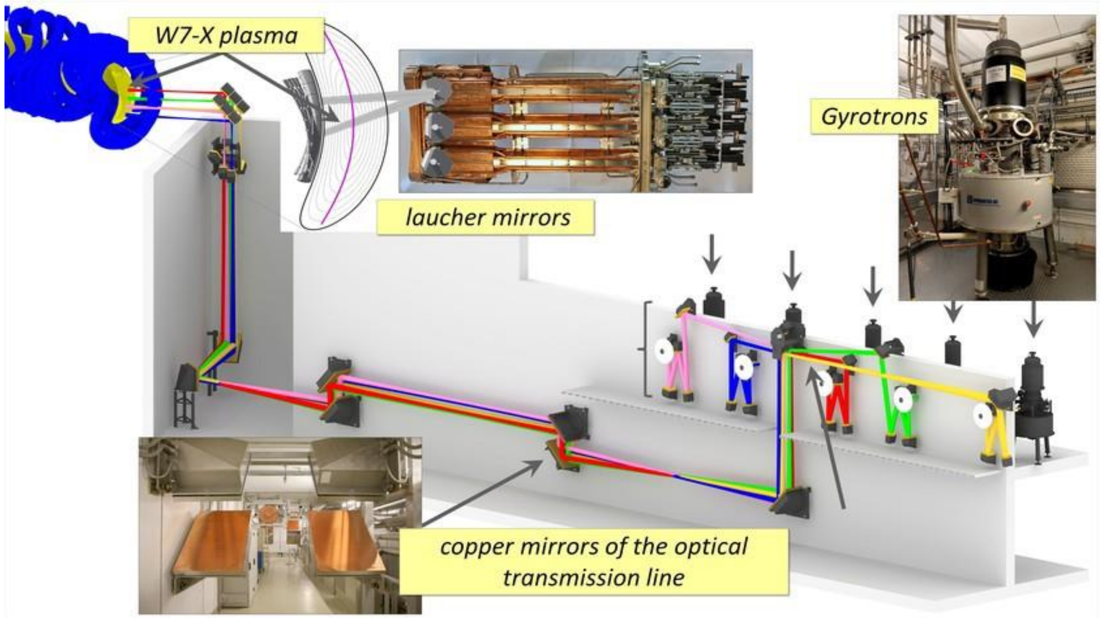
Electron cyclotron waves are generated in gyrotrons (110-170 GHz, 1-2 MW per tube)



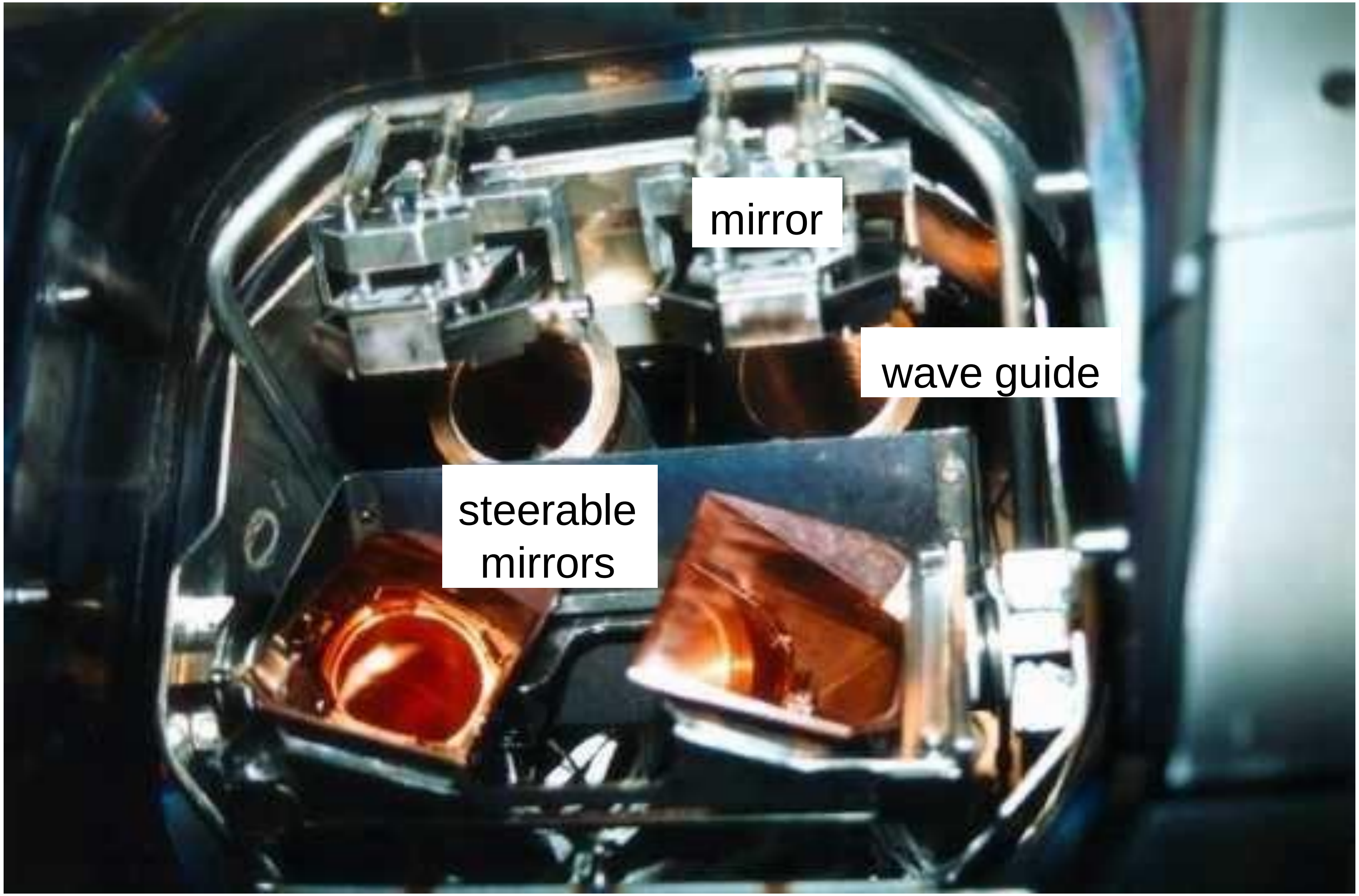


ECRH in W7-X

- **Main heating system and the only system which is already capable operating continuously. B=2.5 requires 140GHz.**
- **Each gyrotron is capable to provide nearly 1 MW heating power (1.5MW planned) over 30 minutes.**
- **A total power of up to 15 MW with 12 gyrotrons planned (in last campaign 7.5 MW / 10 gyrotrons)**



Waveguide and steerable mirrors in the DIII-D tokamak

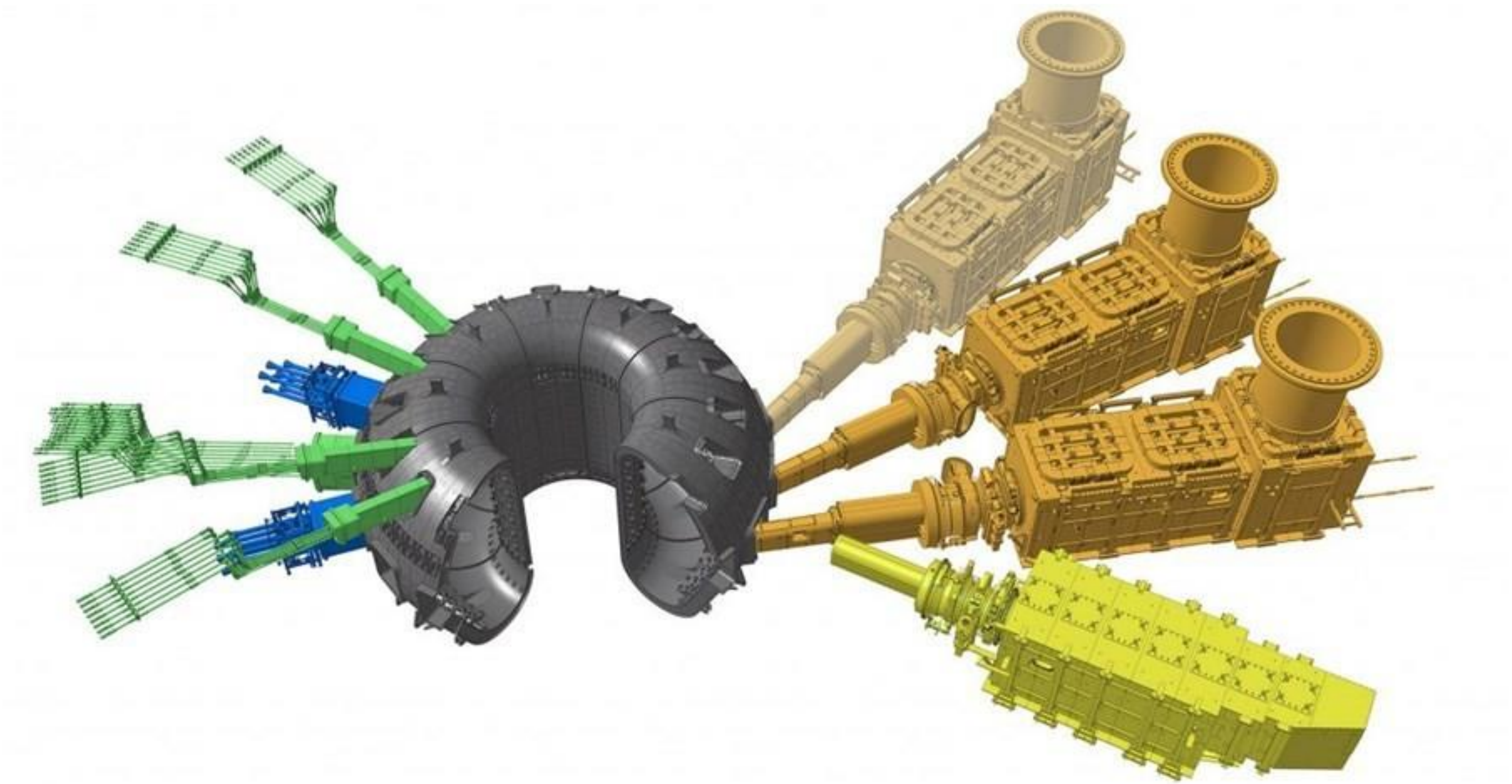


ITER plans for 24 gyrotrons at 170 GHz, up to 2 MW per tube = 25-45 MW (cost ≈ 150 M Euros)

- **Each of ITER's 24 gyrotrons will generate a microwave beam over a thousand times more powerful than a traditional microwave oven. [www.iter.org.](http://www.iter.org)**

X 1000

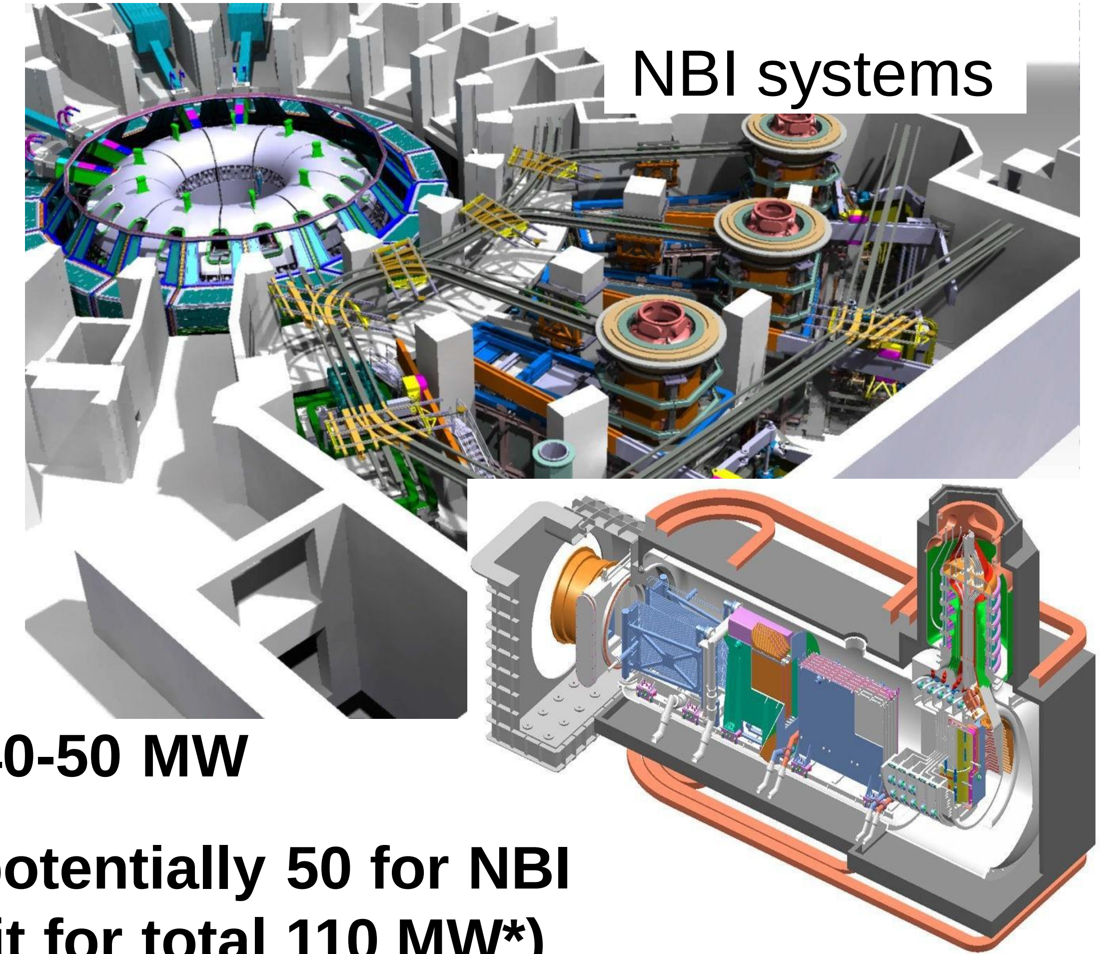
Also ITER has combination of ECRH, NBI and ICRH



- **Neutral beam injection (right) and two sources of high-frequency electromagnetic waves— ion and electron cyclotron heating (left, blue and green launchers). [www.iter.org.](http://www.iter.org)**

Auxiliary power by means of neutral beams and radio frequency heating of 50 MW is foreseen

System	Power
NBI –ve ion, 1 MeV	33 MW
ECH & CD 170 GHz	20 MW
ICRH & CD 40 – 55 MHz	20 MW



- **P_{aux} for Q_{DT} = 10 about 40-50 MW**
- **Modular for upgrades (potentially 50 for NBI and 40 for EC/IC but limit for total 110 MW*)**
- **No provision for LH**

*Singh PPCF2017

Recommended tutorial video about heating

Tutorial video "How do you heat a fusion machine?" (26 min) which roughly covers the topics of this lecture. Recommended especially for those who missed the lecture:

https://www.youtube.com/watch?v=xYxuh3w0IEI

Presemo quiz #2

https://presemo.aalto.fi/fet/

Summary

Scheme	Advantages	Limitations
Ohmic heating	Efficient	Cannot reach ignition conditions, not suitable for stellarator
Neutral beam injection	Reliable	Close to torus, large ports, negative ions necessary
Ion cyclotron resonance	Central heating	Antenna close to plasma, coupling efficiency
Electron cyclotron resonance	Reliable, flexible, localized heating + current drive	Cutoffs, electron heating ⇒ needs strong coupling to ions
Lower hybrid	Efficient current drive	Antenna close to plasma, off-axis heating only

- **All medium and large-size tokamaks and stellarators have a mix of these heating systems; also ITER**