

Nuclear Fusion and Plasma Physics

Lecture 9

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Ohmic heating

The need for auxiliary heating

ITER auxiliary heating systems

Neutral beam heating

Heating by waves

- Electron Cyclotron

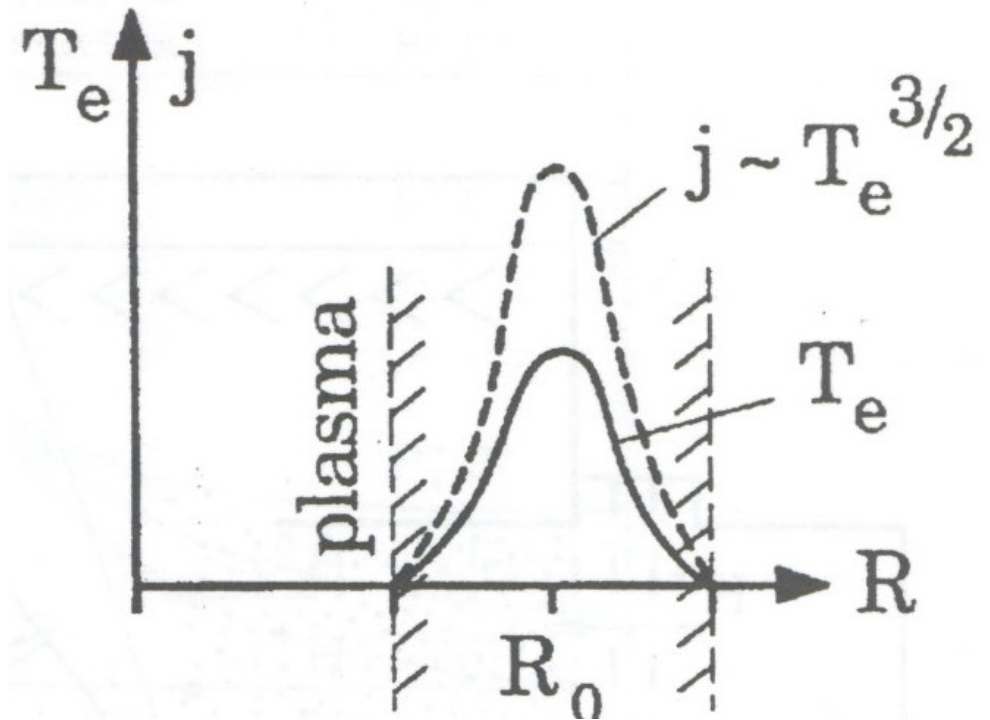
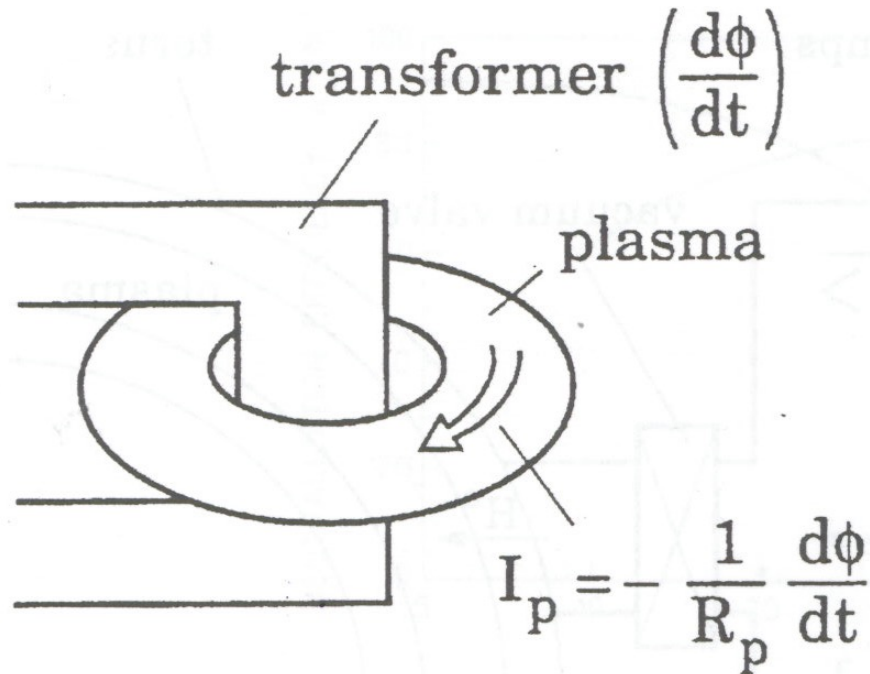
- Ion Cyclotron

- Lower Hybrid

Discussion

- Pros and cons of the different methods

Ohmic heating

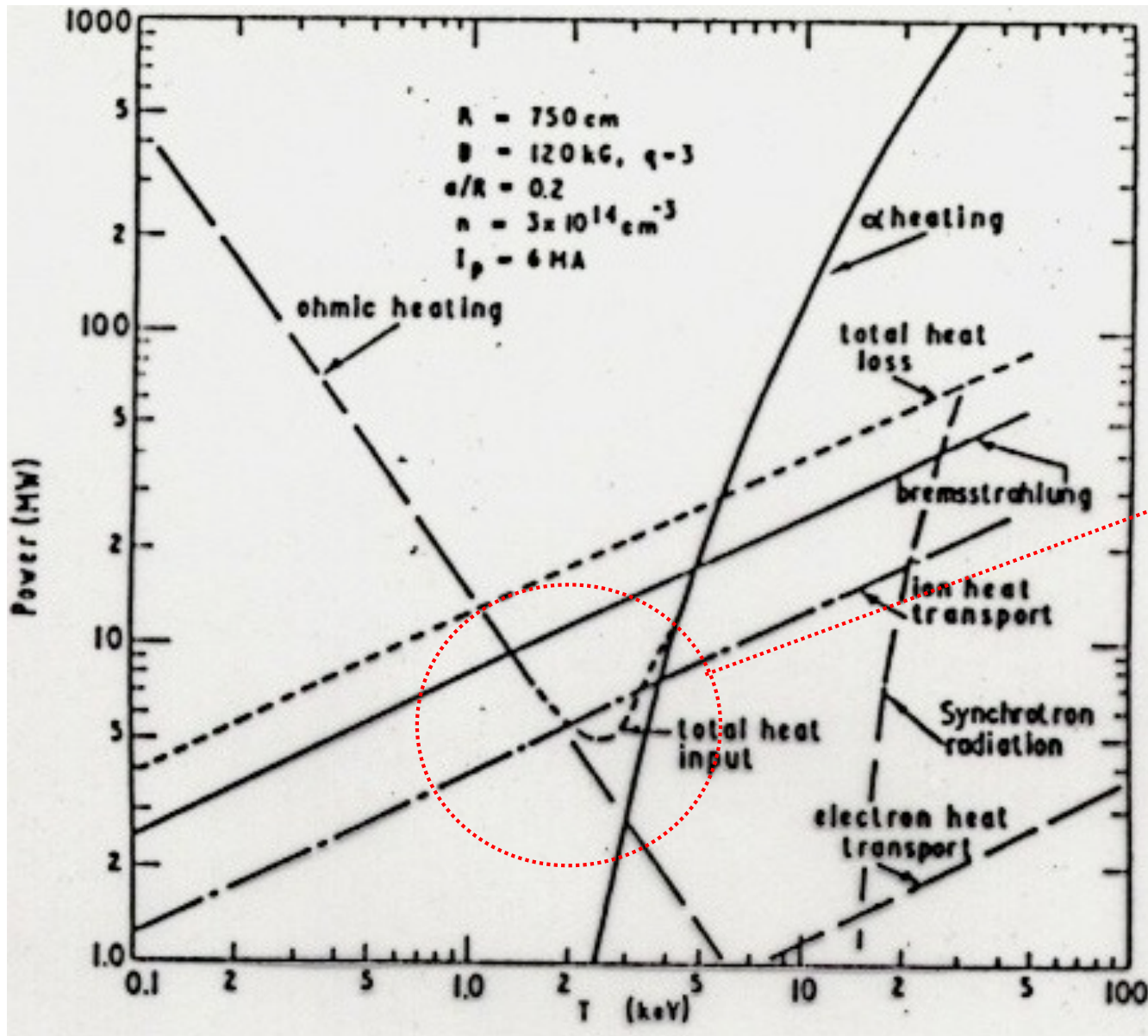


$$P_{\text{ohmic}} = V_{\text{loop}} \times I_p = R_p \times I_p^2 = \eta j^2$$

$$\eta = \frac{\sqrt{2}}{\pi^{3/2}} \frac{m_e^{1/2} Z e^2 \ln \Lambda}{12 \epsilon_0^2 T_e^{3/2}} \propto T_e^{-3/2}$$

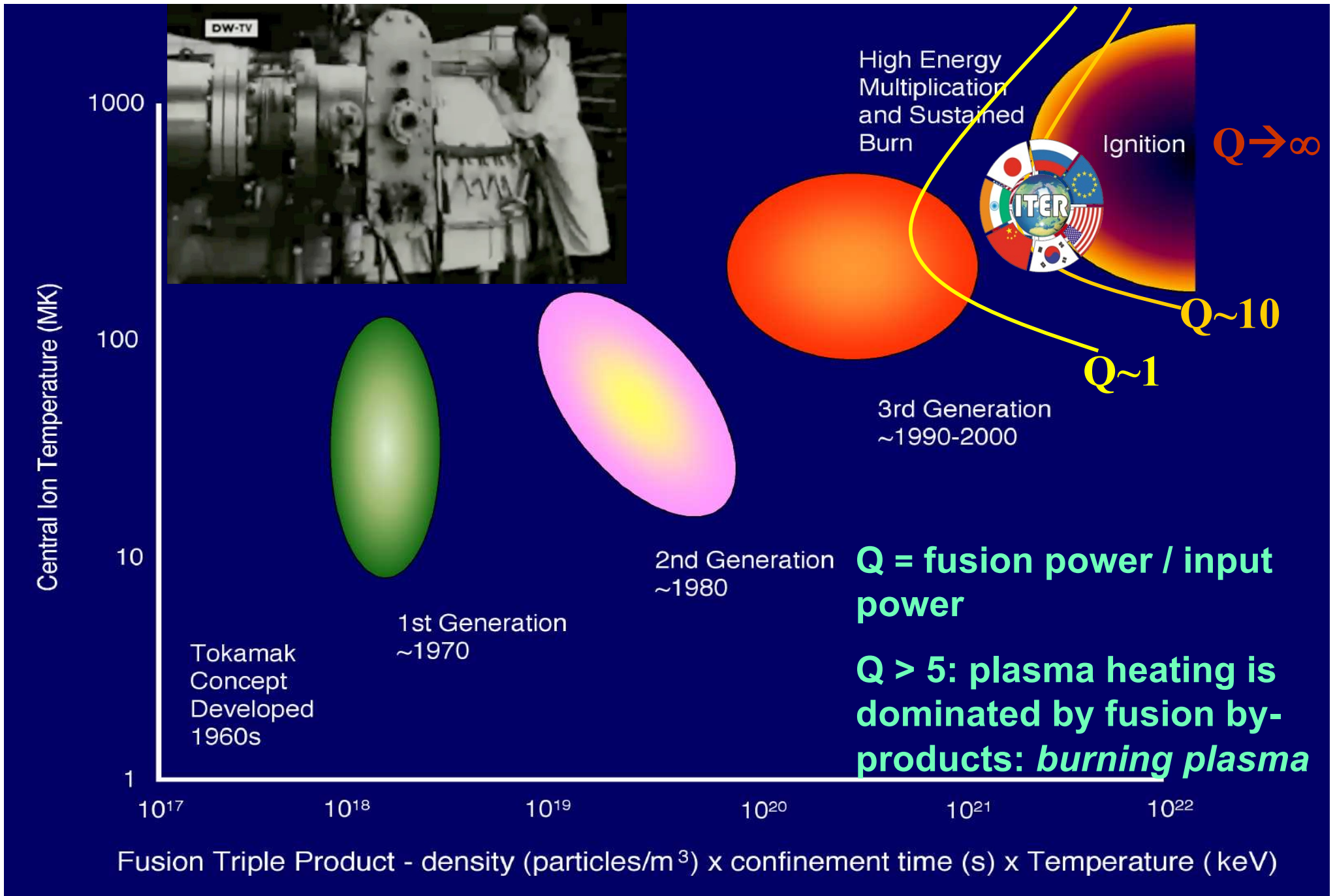
OH heating becomes less and less effective at high T_e

The need for additional plasma heating



Need to fill in 'gap' between ohmic heating region and α -heating, where losses dominate

Progress in magnetic fusion



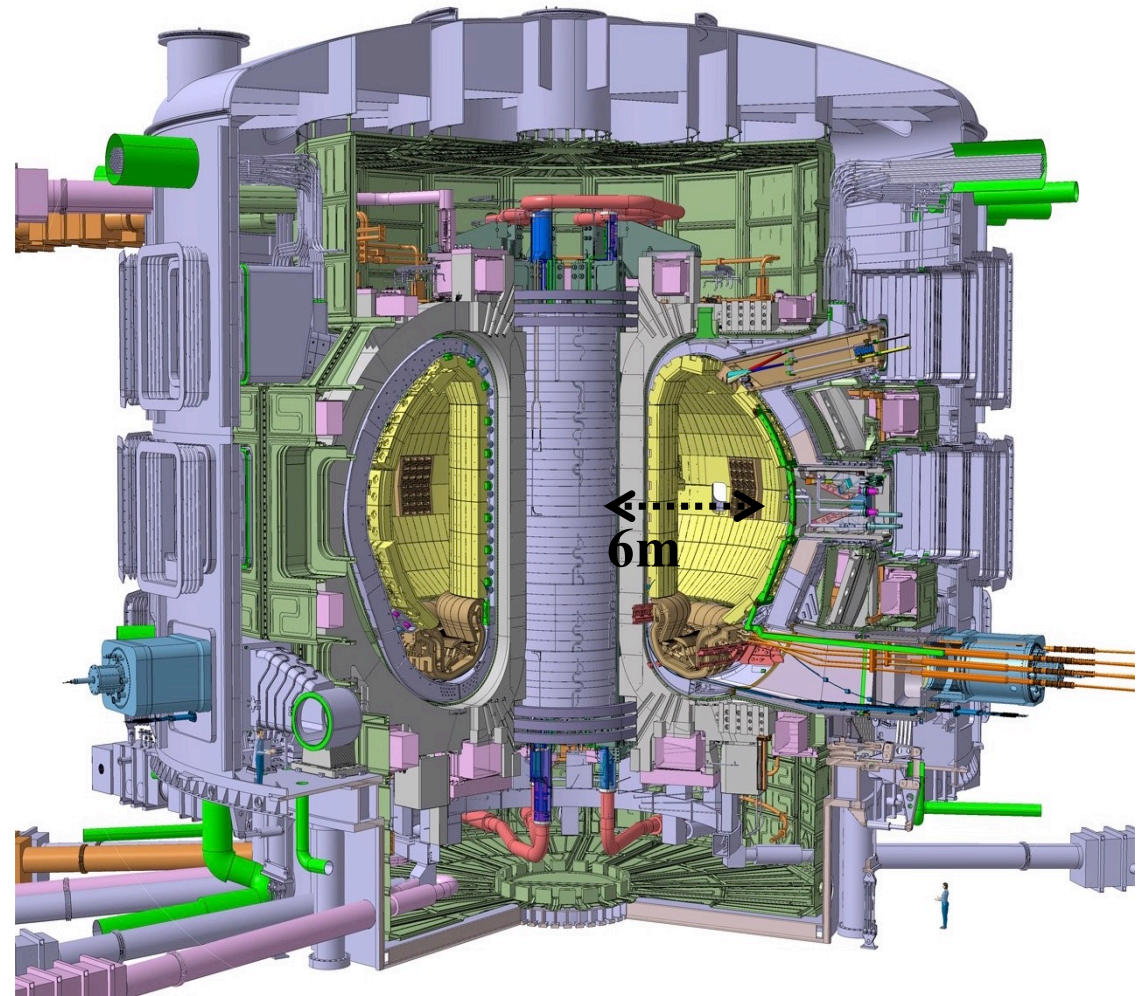
Demonstration of the scientific and technological feasibility of fusion energy for peaceful purposes

Burning plasma

$$Q \geq 10$$

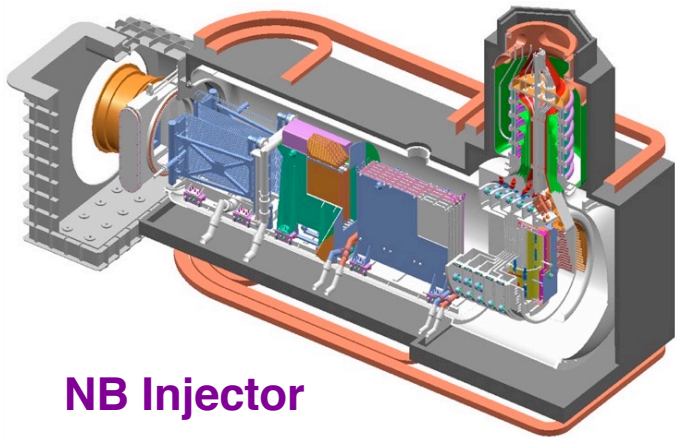
$$P_{\text{fusion}} \geq 500\text{MW}$$

for ~500s

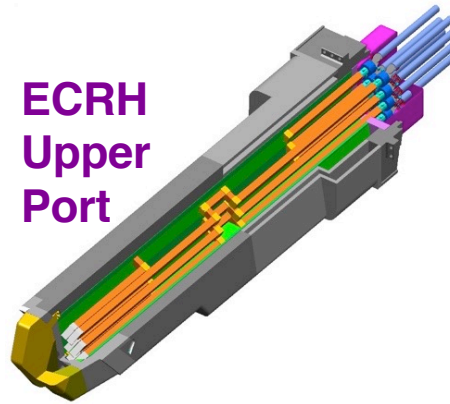


$$R \sim 6\text{m}; B \sim 5\text{T}; I_{\text{plasma}} \sim 15\text{MA}$$

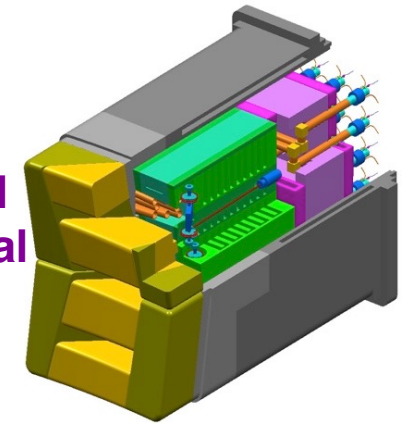
ITER Heating systems



NB Injector

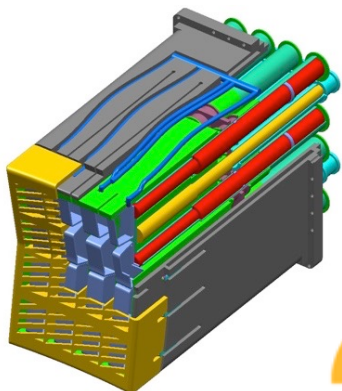


ECRH Upper Port



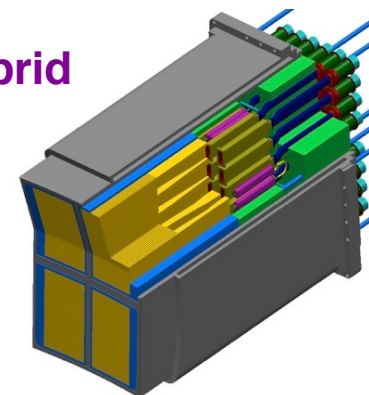
ECRH Lateral Port

System	Power [MW]	Frequency
NBI	33 MW	N/A
ICRH	20 MW	40-55 MHz
LH	20 MW (second stage)	5 GHz
ECRH	24 MW	170 GHz

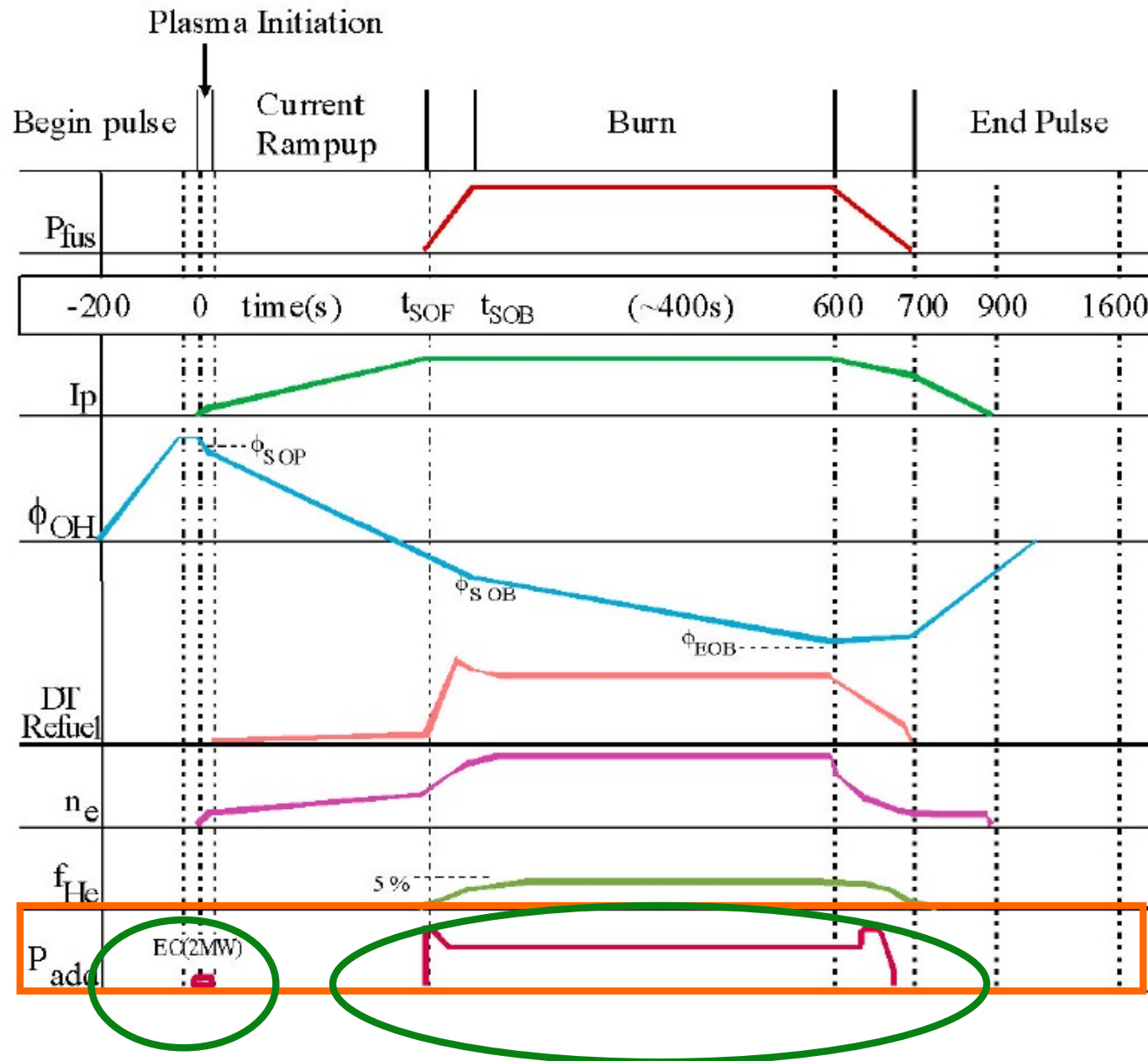


ICRH antenna

Lower Hybrid Launcher

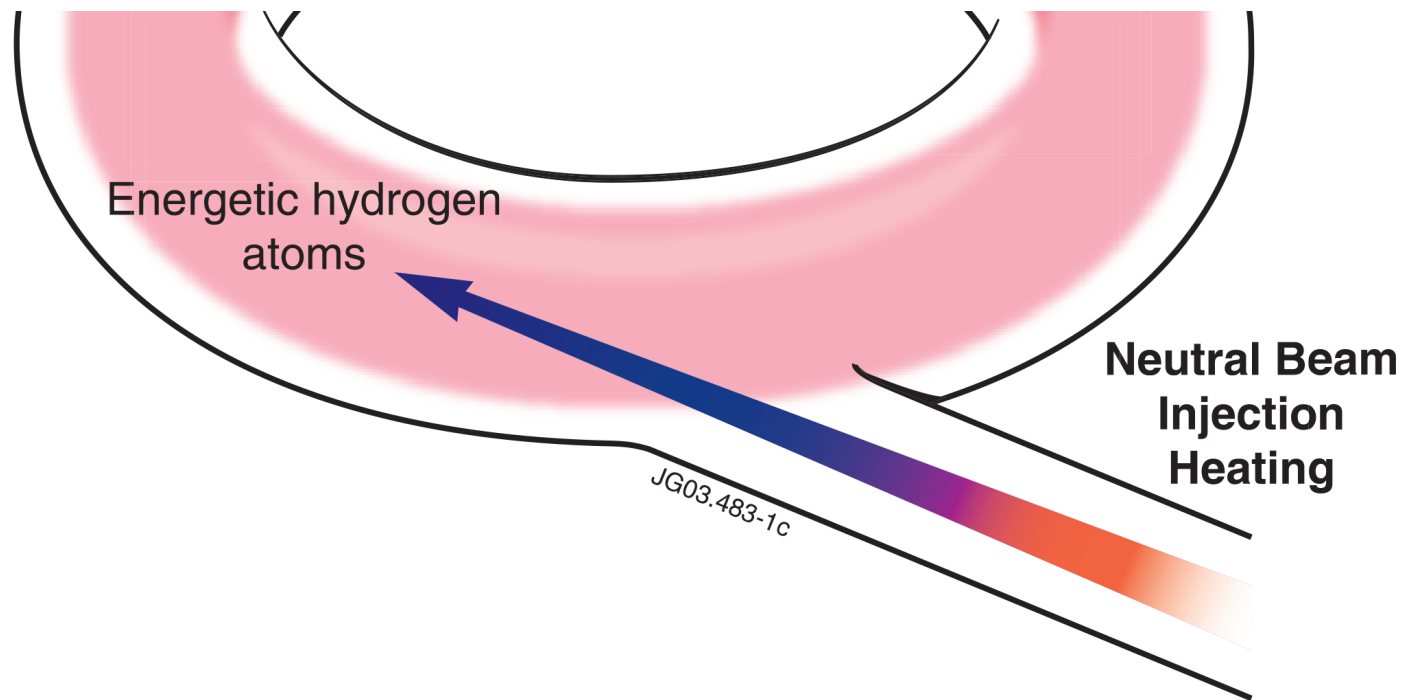


ITER plasma sequence



Heating by neutral beam injection

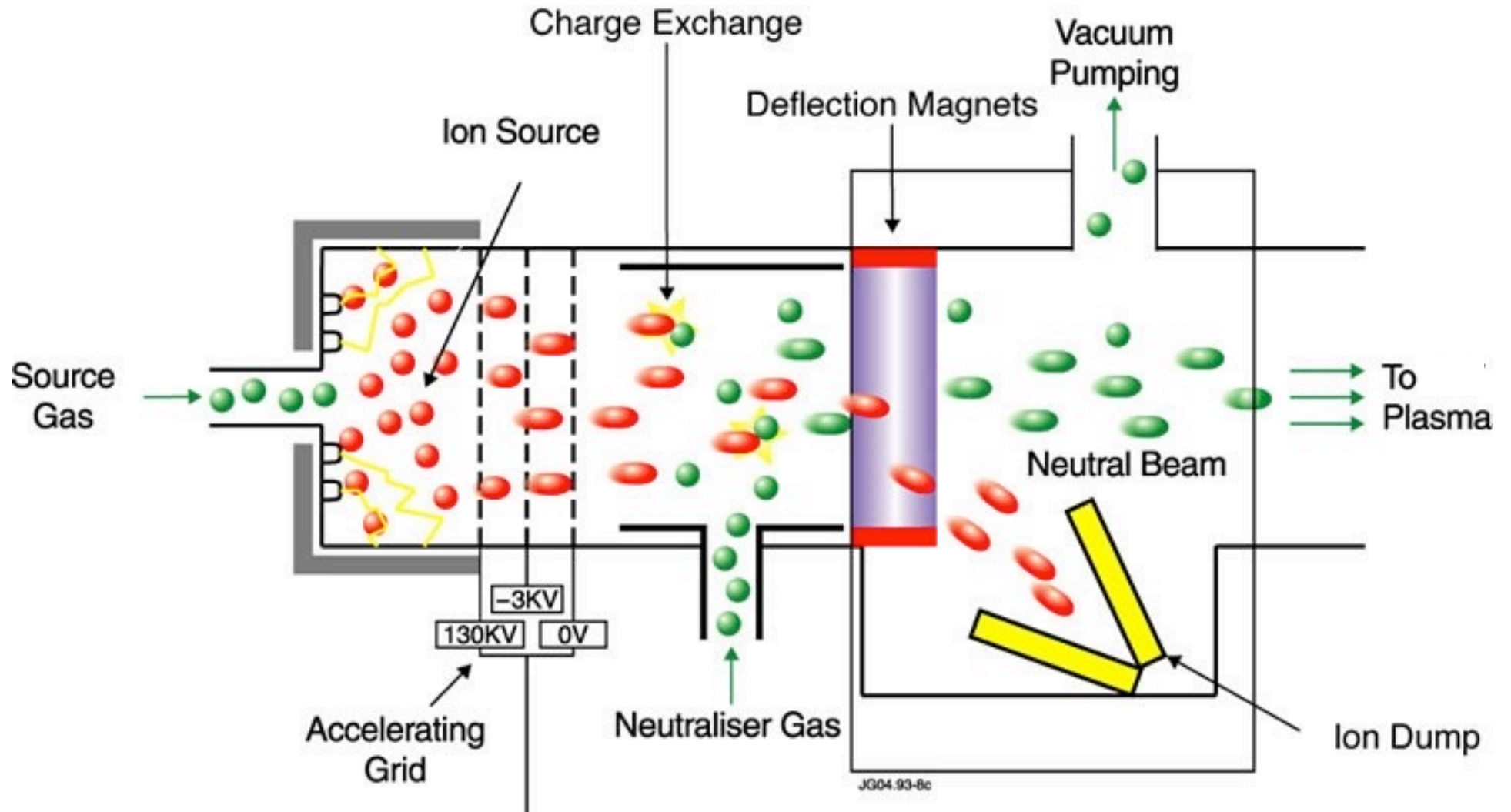
Basic idea of Neutral Beam Heating



Energetic ions could be injected into plasma, to give energy to *colder* plasma particles, but B-field would prevent energetic ions penetration

Idea: use neutral particles at high energy to get into the plasma, then let them be ionized by the plasma itself, so that they become a beam of energetic ions

Neutral Beam Injector



EPFL Physical processes occurring during beam penetration in plasma, leading to ionization

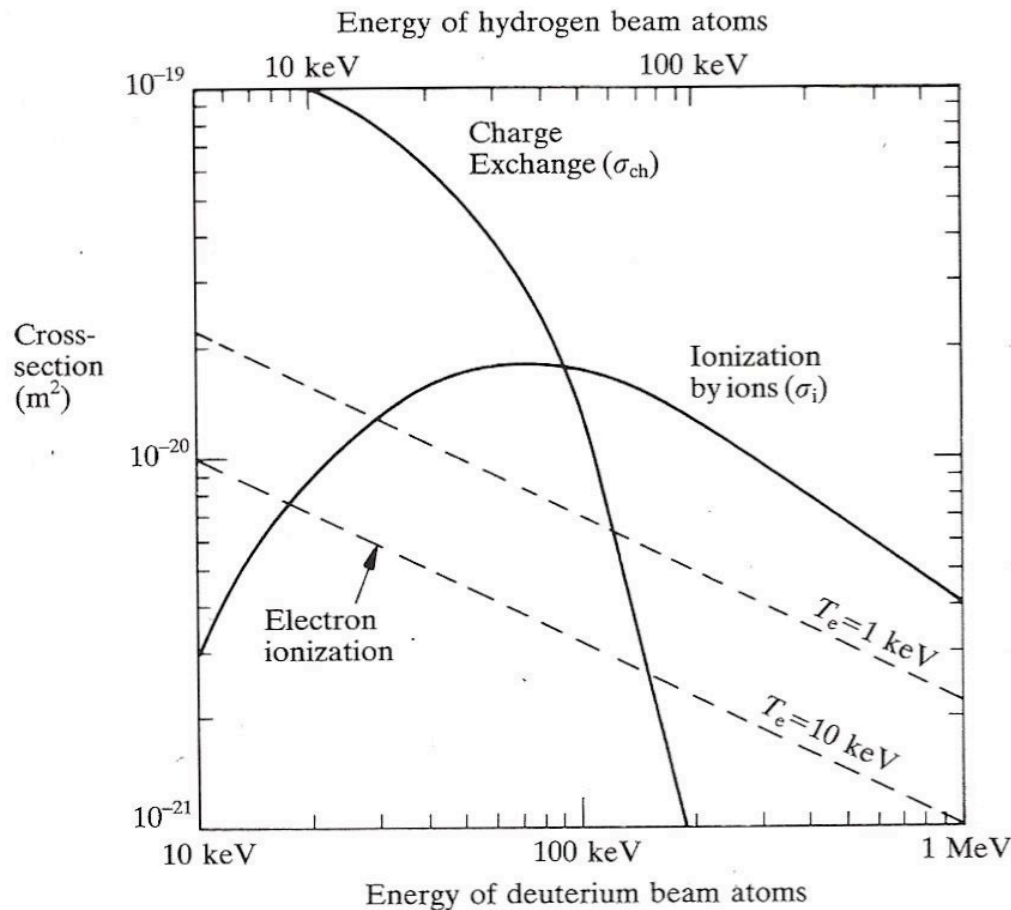
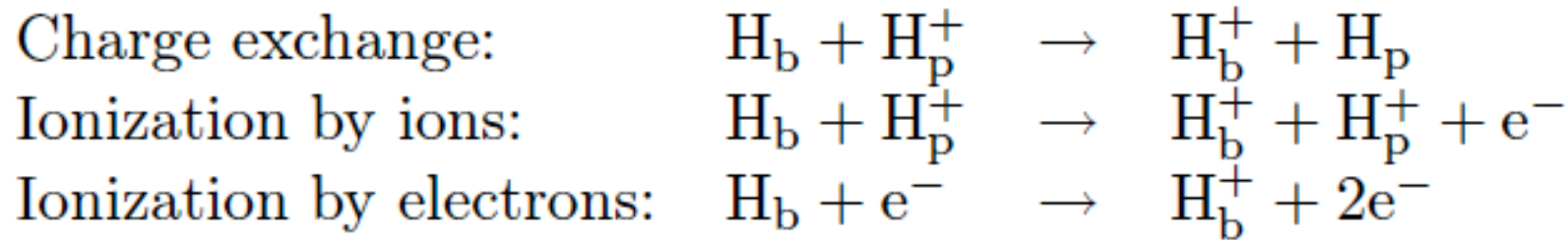
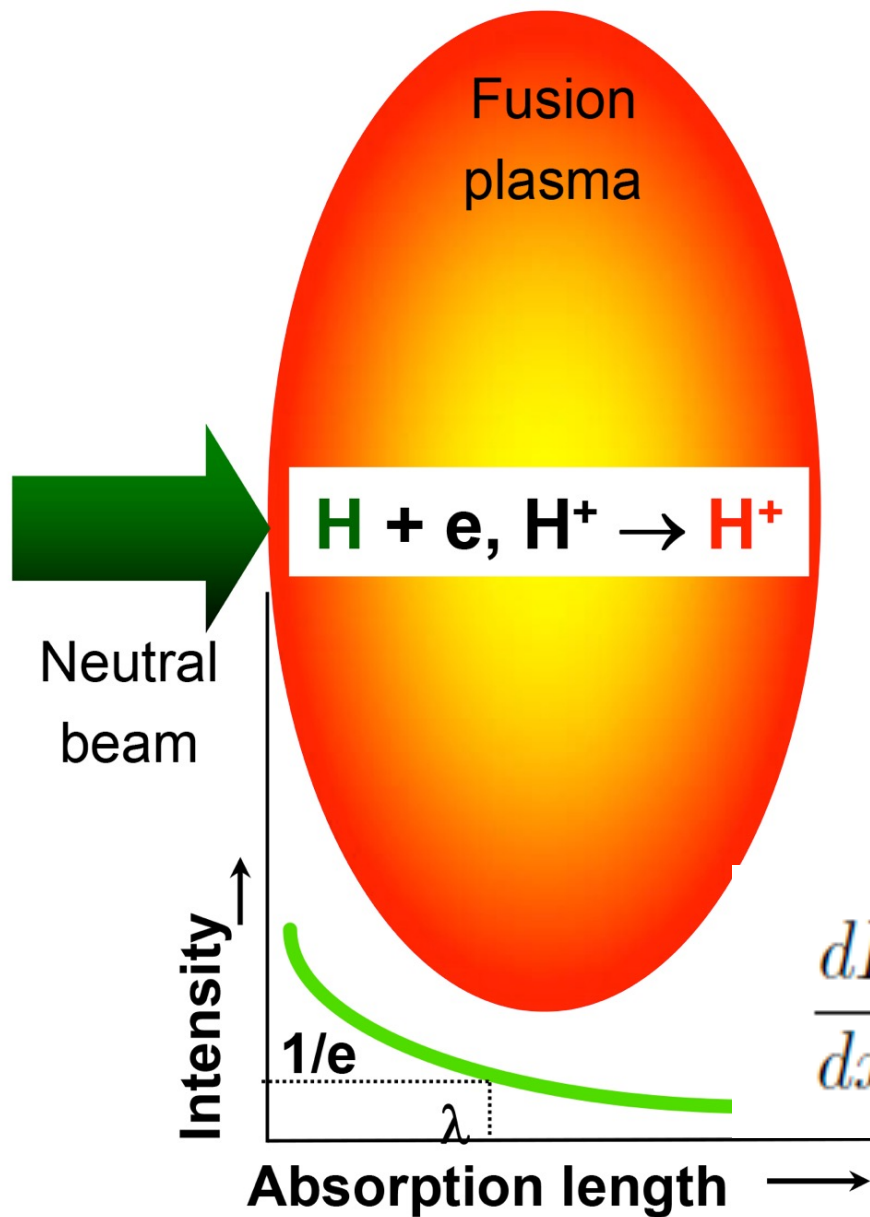


Fig. 5.3.1 Cross-sections for charge exchange and ionization by plasma ions (protons, deuterons, or tritons) and the effective cross-section $\langle \sigma_e v_e \rangle / v_b$ for ionization by electrons, as functions of the neutral beam energy. The cross-sections for a hydrogen beam are the same as those for a deuterium beam having twice the energy.

Evolution of beam intensity

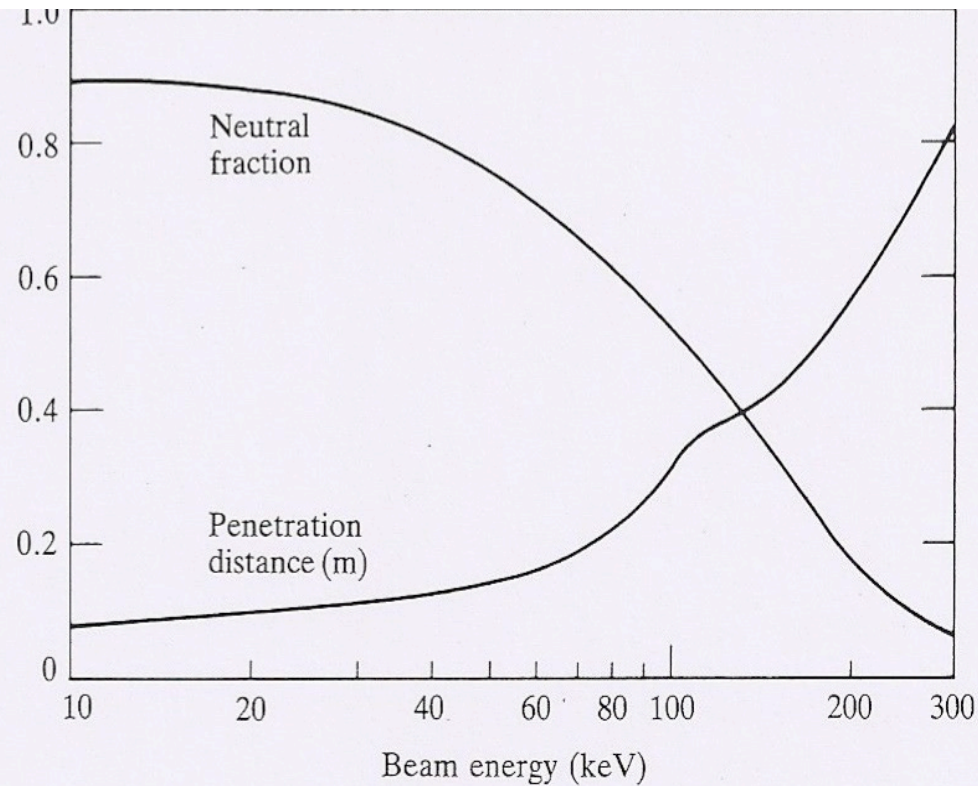


$$\frac{dI}{dx} = - n_p \left(\sigma_{ch} + \sigma_i + \frac{\langle \sigma_e v_e \rangle}{v_b} \right) I$$

λ = penetration distance

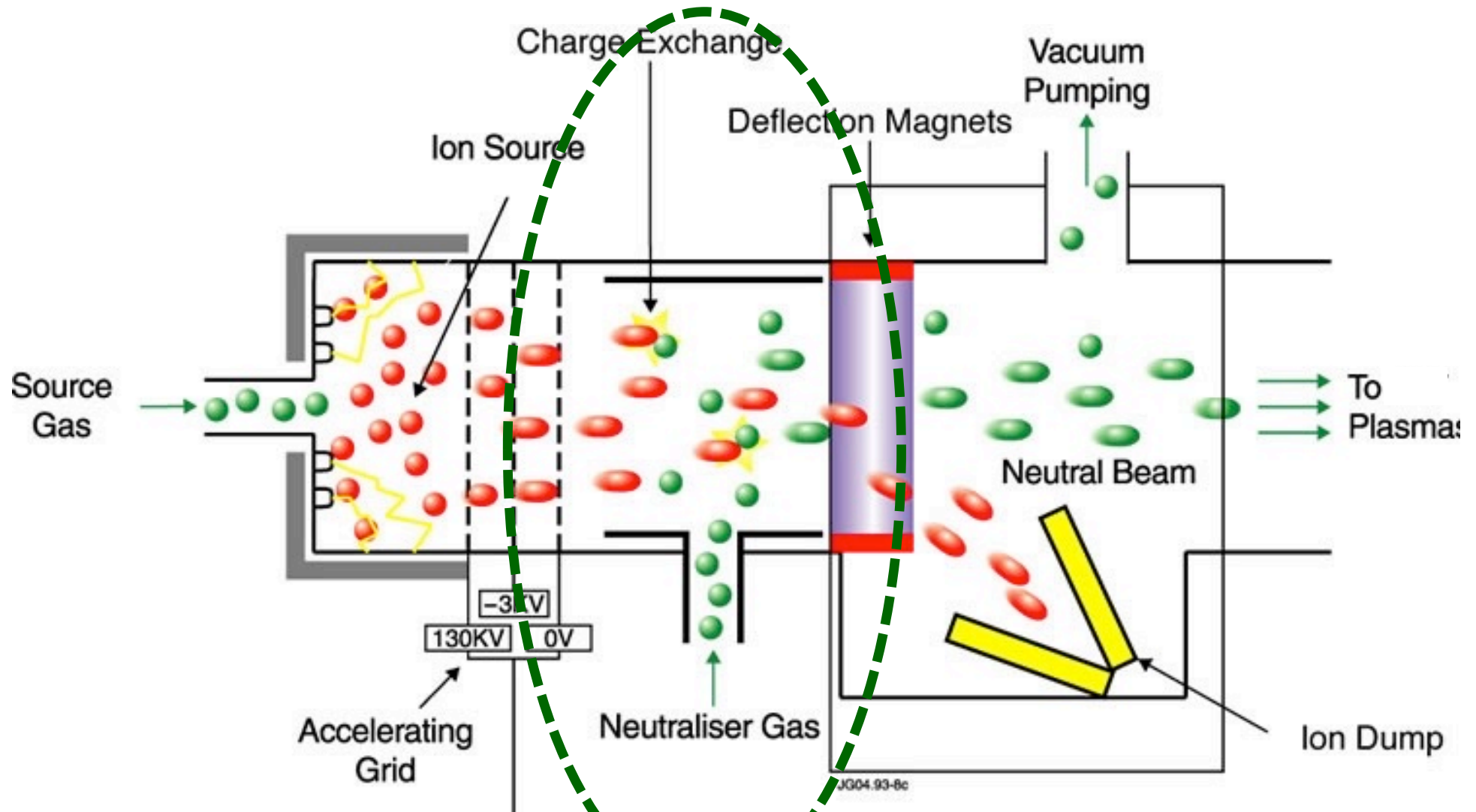
Beam penetration in a 10^{20} m^{-3} plasma

Fig. 5.5.3 Graphs showing the energy dependence of (i) the equilibrium neutral fraction in a deuterium beam and (ii) the penetration distance of the neutrals in a plasma of density $n = 10^{20} \text{ m}^{-3}$. The change of behaviour of the penetration distance at around 100 keV indicates the transition from charge exchange dominance to ionization dominance.



For large plasma ($>1\text{m}$) we need high beam energies ($>300\text{keV}$)

Neutral Beam Injector Neutralisation

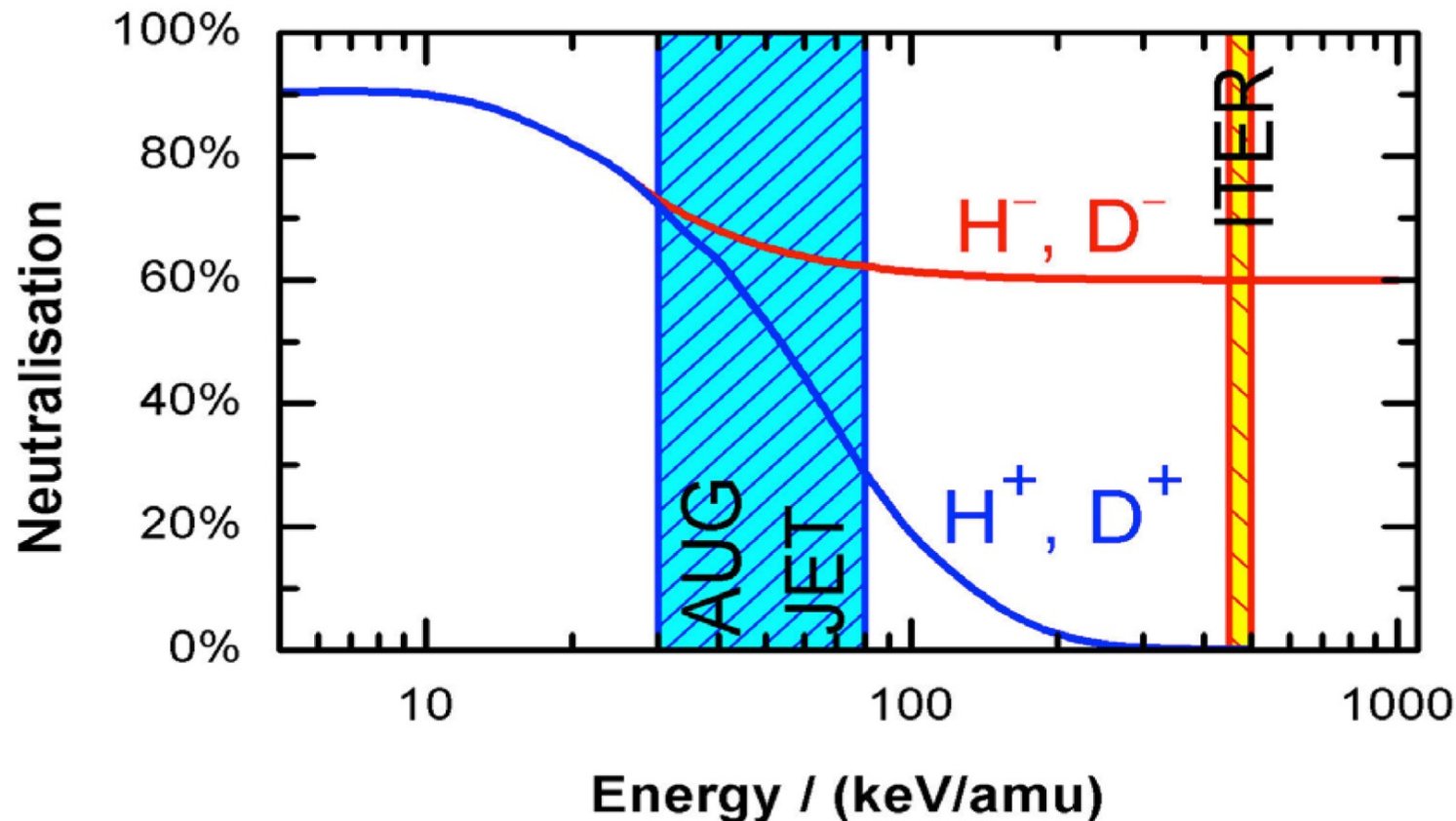


NBI: neutralisation efficiency

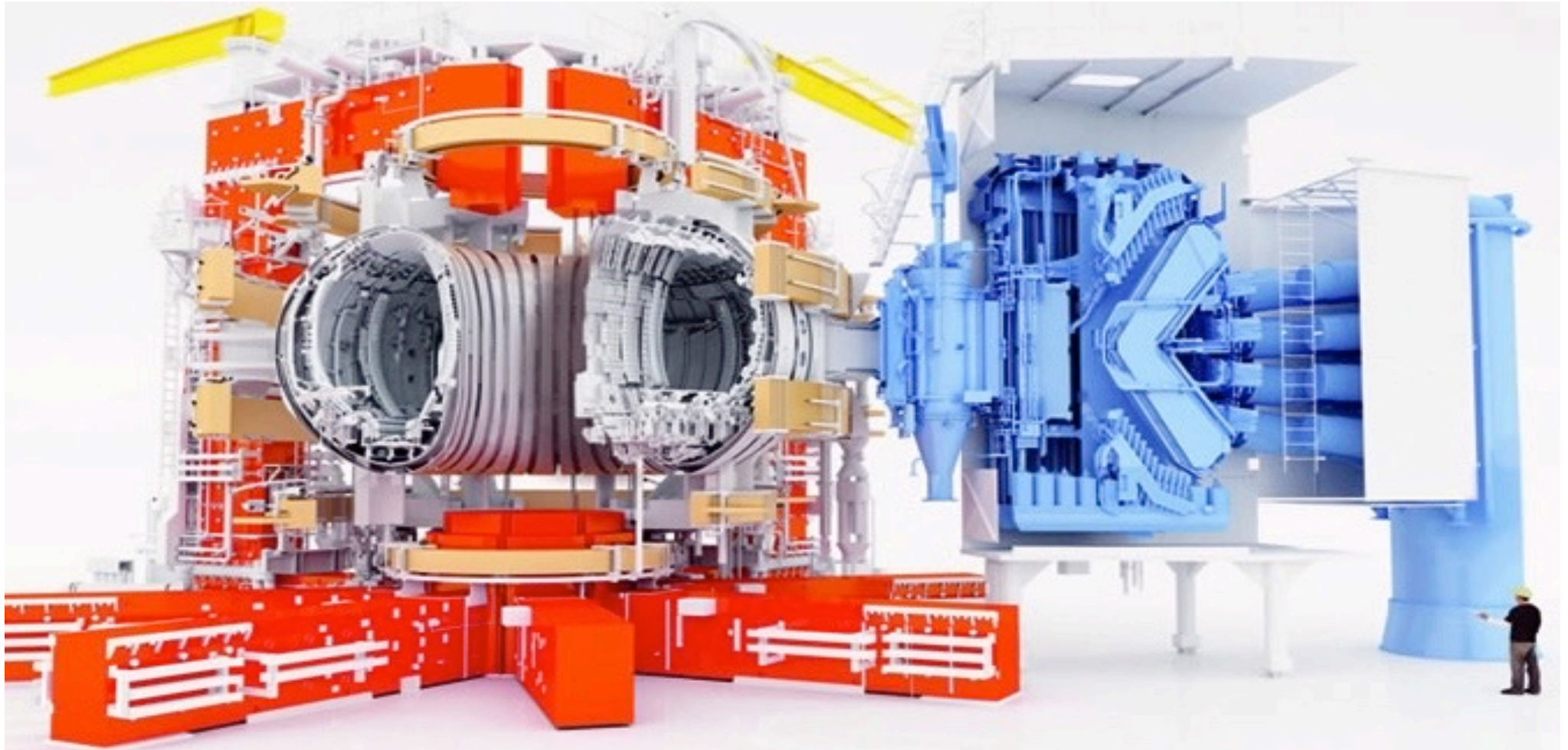
Efficiency for positive ions goes down for high energies

Negative ion neutralisation easier due to low affinity (0.75eV) of additional electron: $\text{H}^- + \text{H}_2 = \text{H} + \text{H}_2 + \text{e}^-$

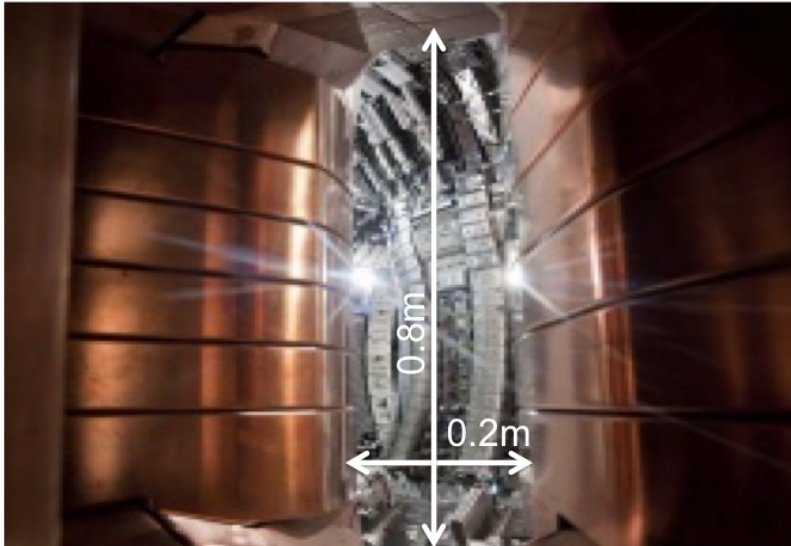
For large, dense plasmas we need negative ion beams



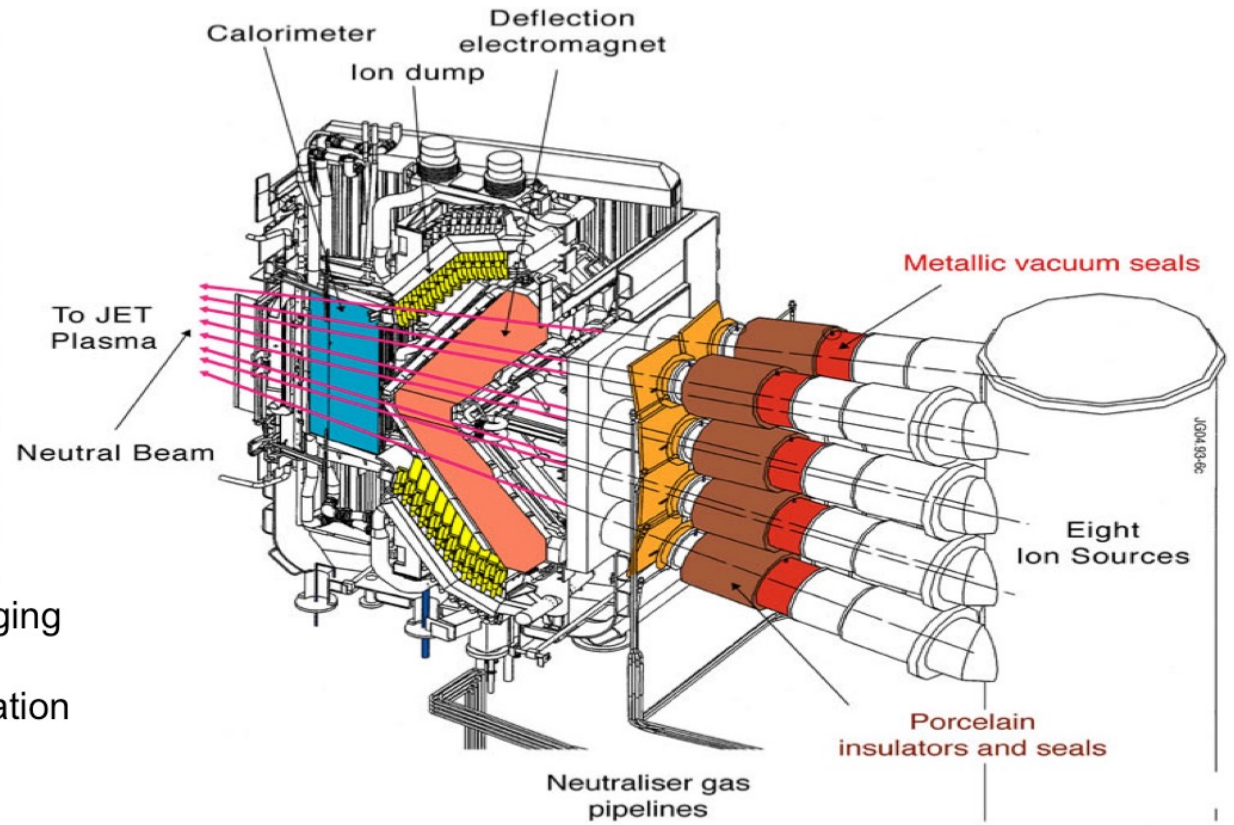
Radial and tangential injection; 2x8 injectors 80keV (H^+), 130keV (D^+) – up to 34MW



NBI in JET



Beam divergence must be low to avoid damaging beam duct and outgassing from beam-wall interactions, which would block beam propagation



For ITER we need negative ion beams

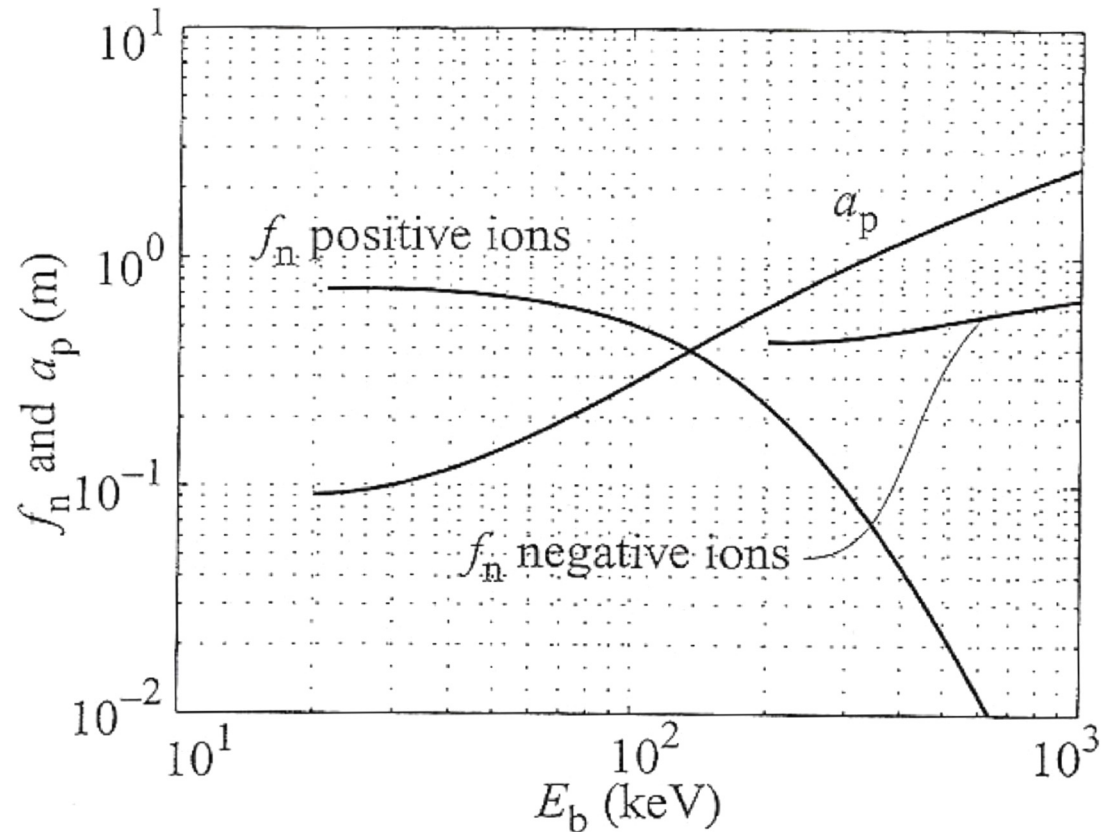


Figure 15.5 Neutralization fraction vs. beam energy for positive and negative ion beams. Also plotted is the penetration depth for $n_{20} = 1.5$. (Wesson, J. (2004). *Tokamaks*, third edition. Oxford: Clarendon Press).

EPFL Which species will be heated by the beam?

Heating ← collisions between fast ions from beam and plasma electrons / ions

Collisional theory: energy transfer to plasma \equiv plasma heating

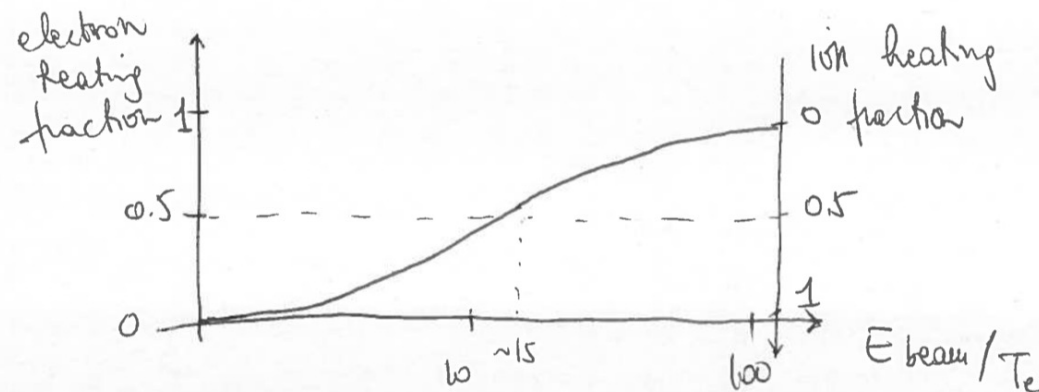
$$P = - \frac{2 E_{\text{beam}}}{\tau_{\text{SD}}} \left[1 + \left(\frac{E_{\text{crit}}}{E_{\text{beam}}} \right)^{3/2} \right]$$

slowing down time
to electrons
to ions

Critical energy $E_{\text{crit}} \approx 15 T_e \left[\frac{M_{\text{beam}}}{n_e} \sum_i \frac{n_i Z_i^2}{M_i} \right] \sim 15 T_e$ is the energy at

which the heating of electrons is equivalent to that of ions

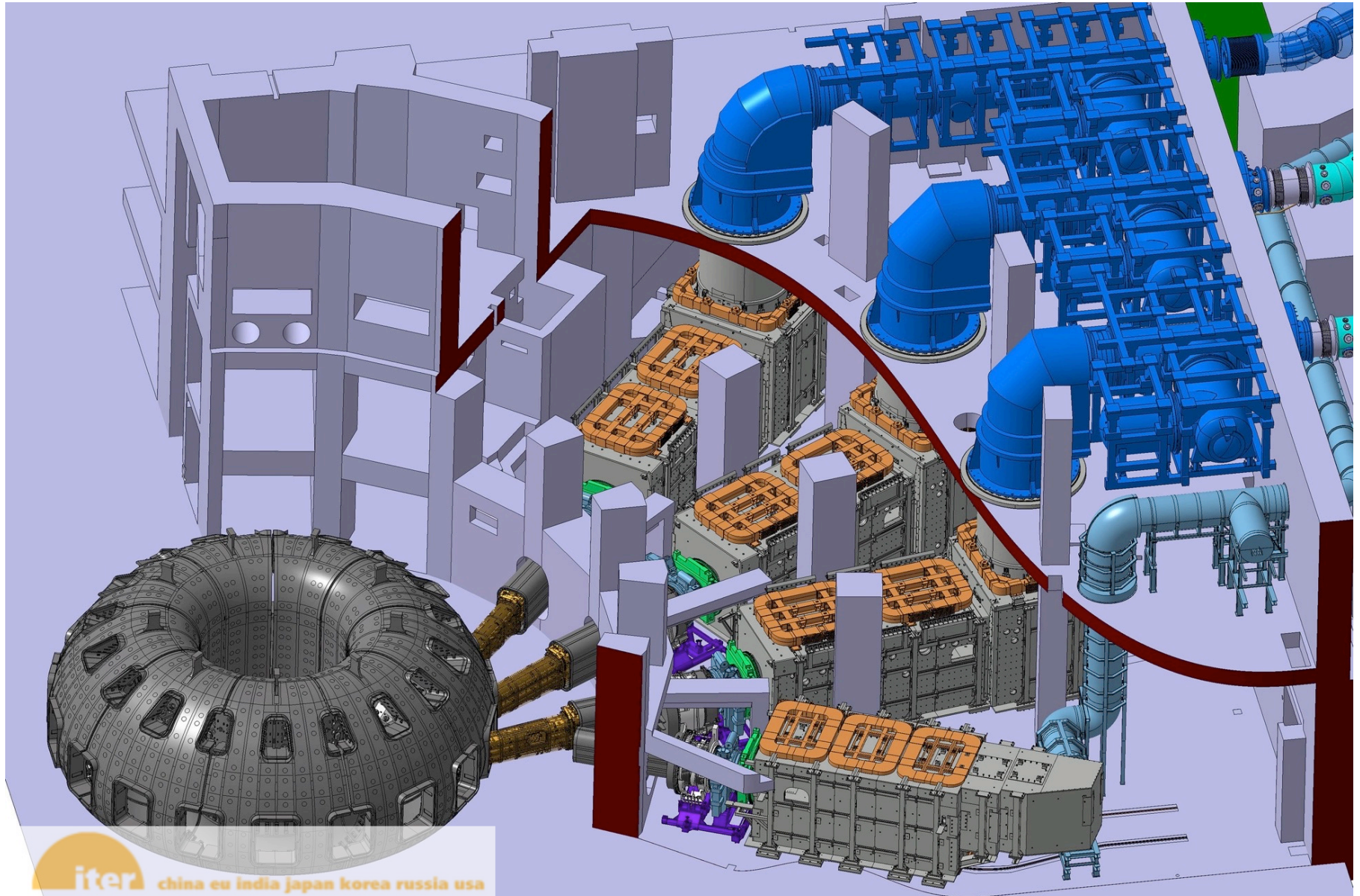
- $E_{\text{beam}} \gg E_{\text{crit}}$: heating mainly of electrons (unfortunately the case of large devices!)
- $E_{\text{beam}} \ll E_{\text{crit}}$: " " " ions (present devices)



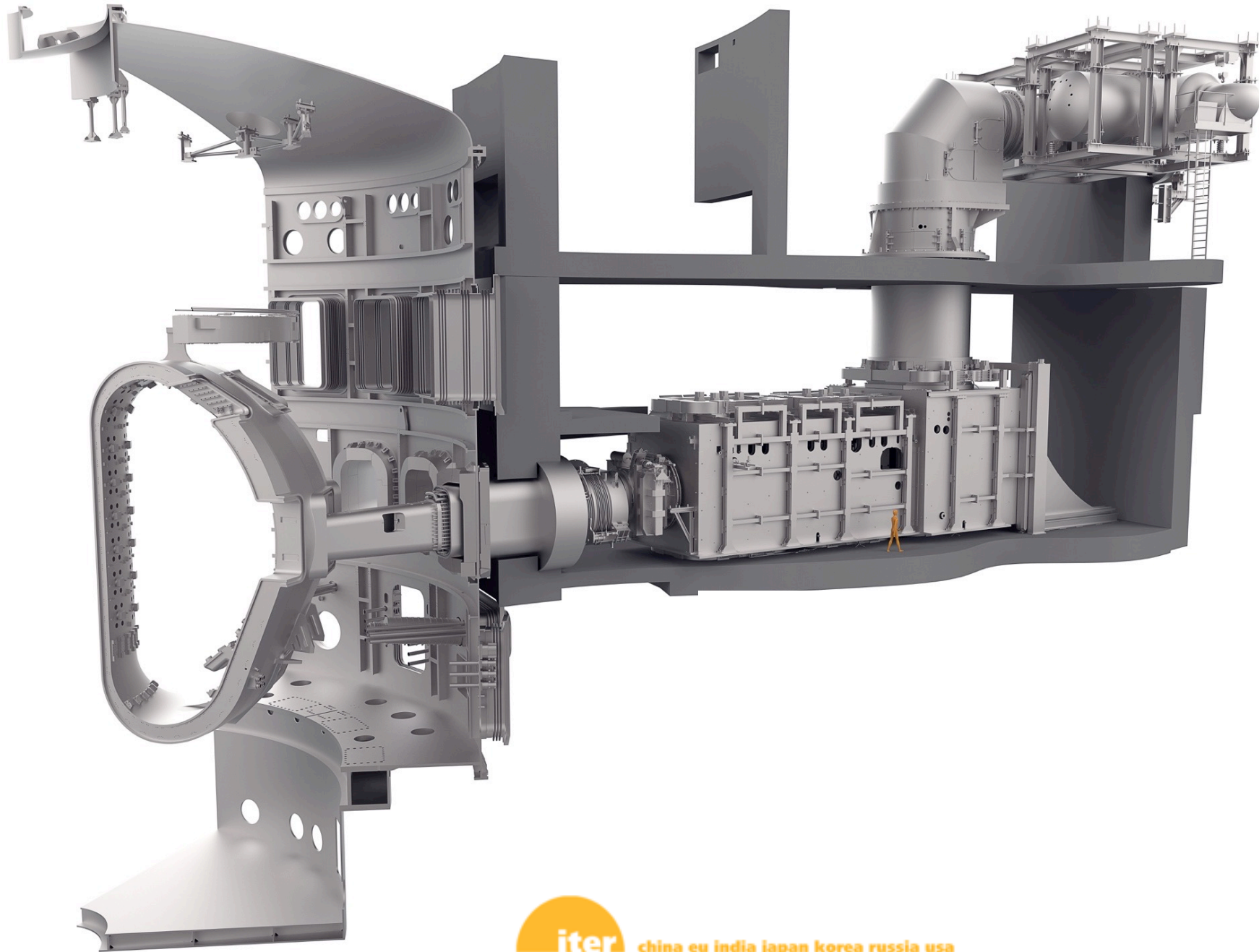
EPFL ITER neutral beams for H&CD, diagnostic

Heating and current drive: 2 tangential D⁻ (1MeV, 33MW,3600s)

Charge exchange diagnostic: 1 radial H⁻ (100keV, 3MW, 400s)

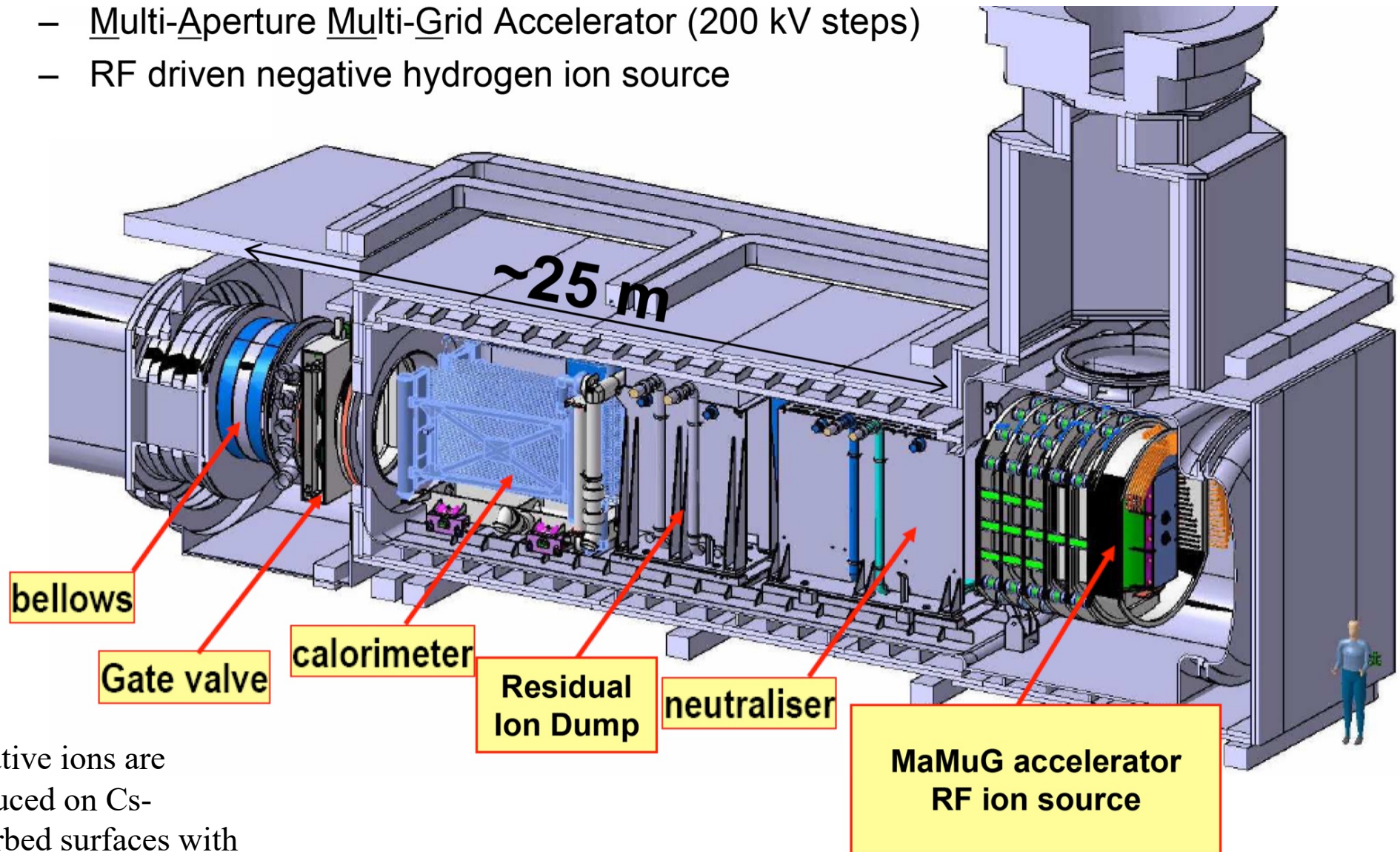


EPFL ITER neutral beams for H&CD, diagnostic



EPFL ITER neutral beams for H&CD, diagnostic

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



Negative ions are produced on Cs-adsorbed surfaces with low work function

Large current density ($\sim 300\text{A/m}^2$), high uniformity ($\pm 10\%$) over $\sim 2\text{m}^2$

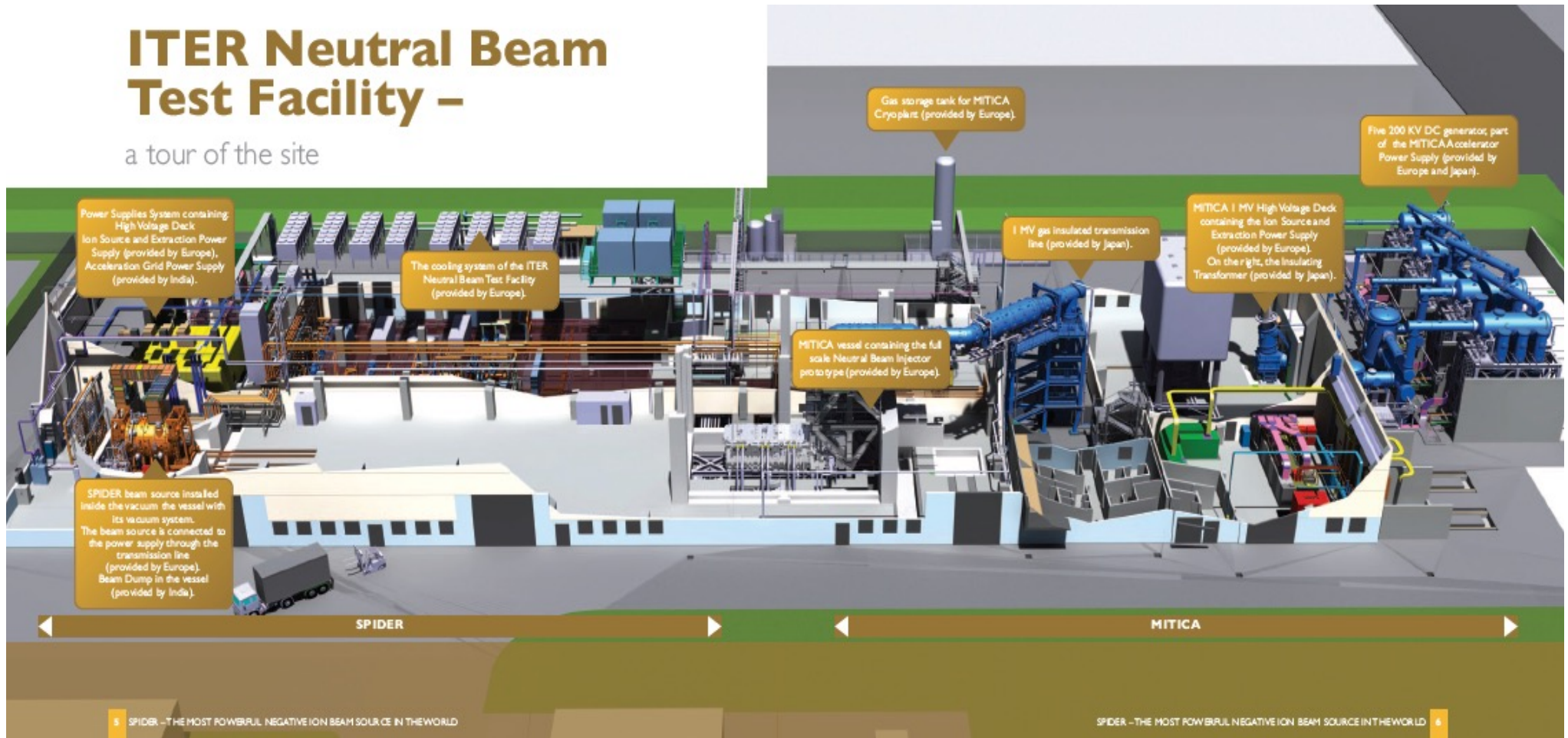
EPFL ITER neutral beams for H&CD, diagnostic

Test facility for beam source

SPIDER – Padua, Italy

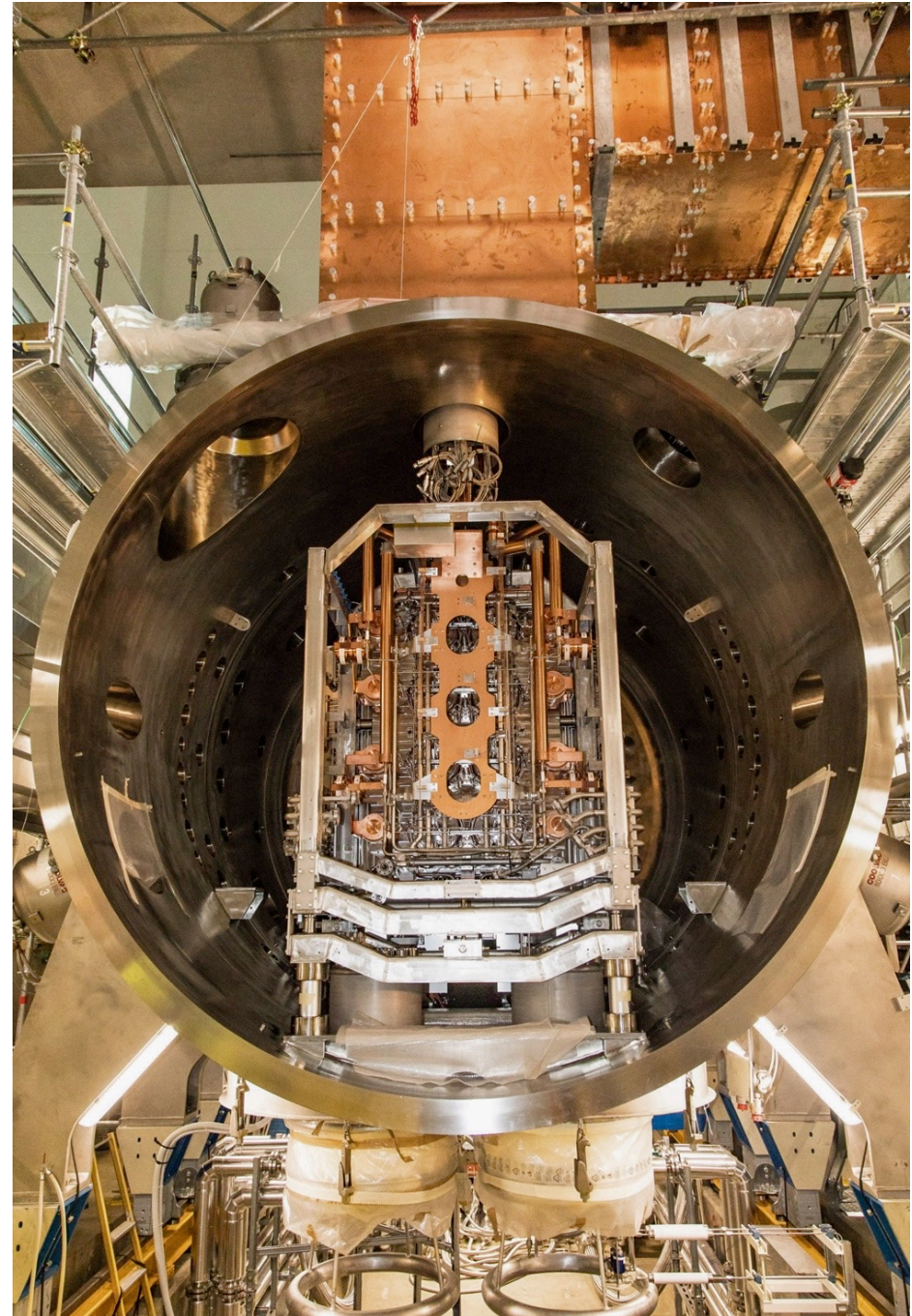
ITER Neutral Beam Test Facility –

a tour of the site



EPFL ITER neutral beams for H&CD, diagnostic

Test facility for beam source
SPIDER – Padua, Italy



Energetic ions from additional heating

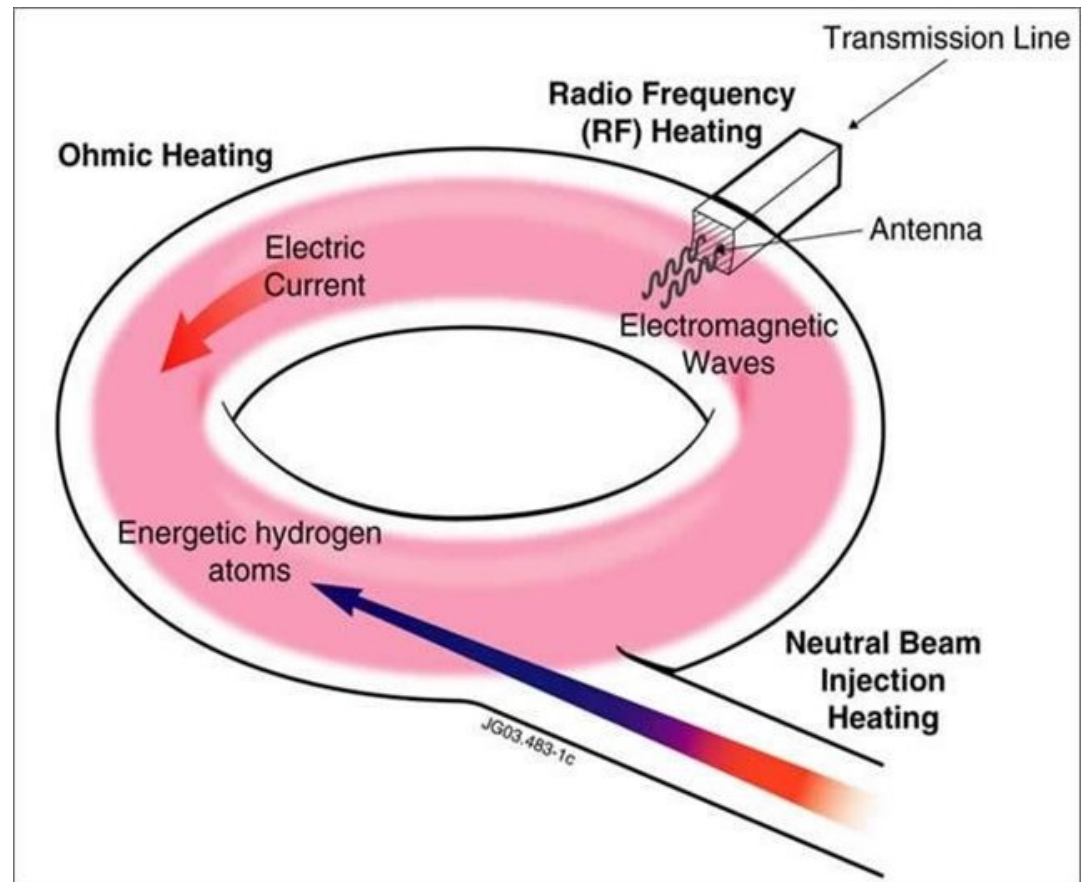
Burning plasma regime is reached using external heating and current drive

Electron cyclotron heating

Ion cyclotron heating

Neutral beam heating

Based on creation of \sim MeV ions, then thermalised by collisions

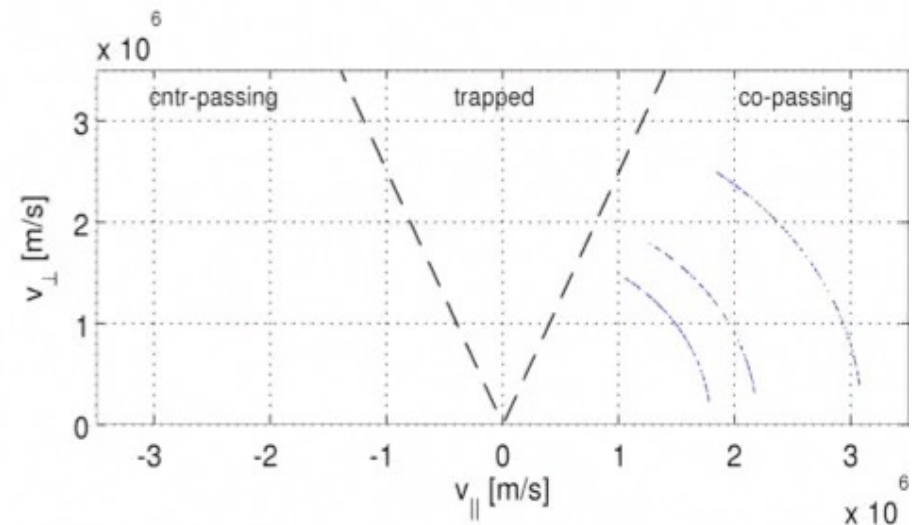
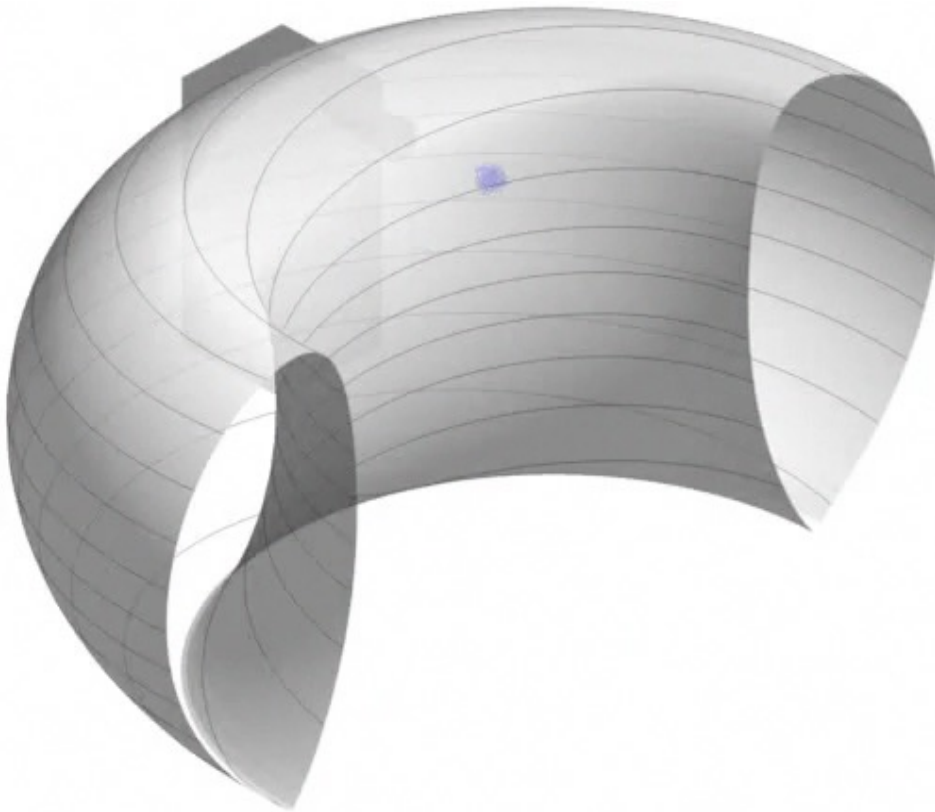


EPFL Energetic ions from Neutral Beam Injection

Ions at $\sim 100\text{keV}$ in present devices, $\sim 1\text{MeV}$ in ITER

Injection geometry determines initial orbits

If tangential, mostly passing orbits, collisions scatter into trapped



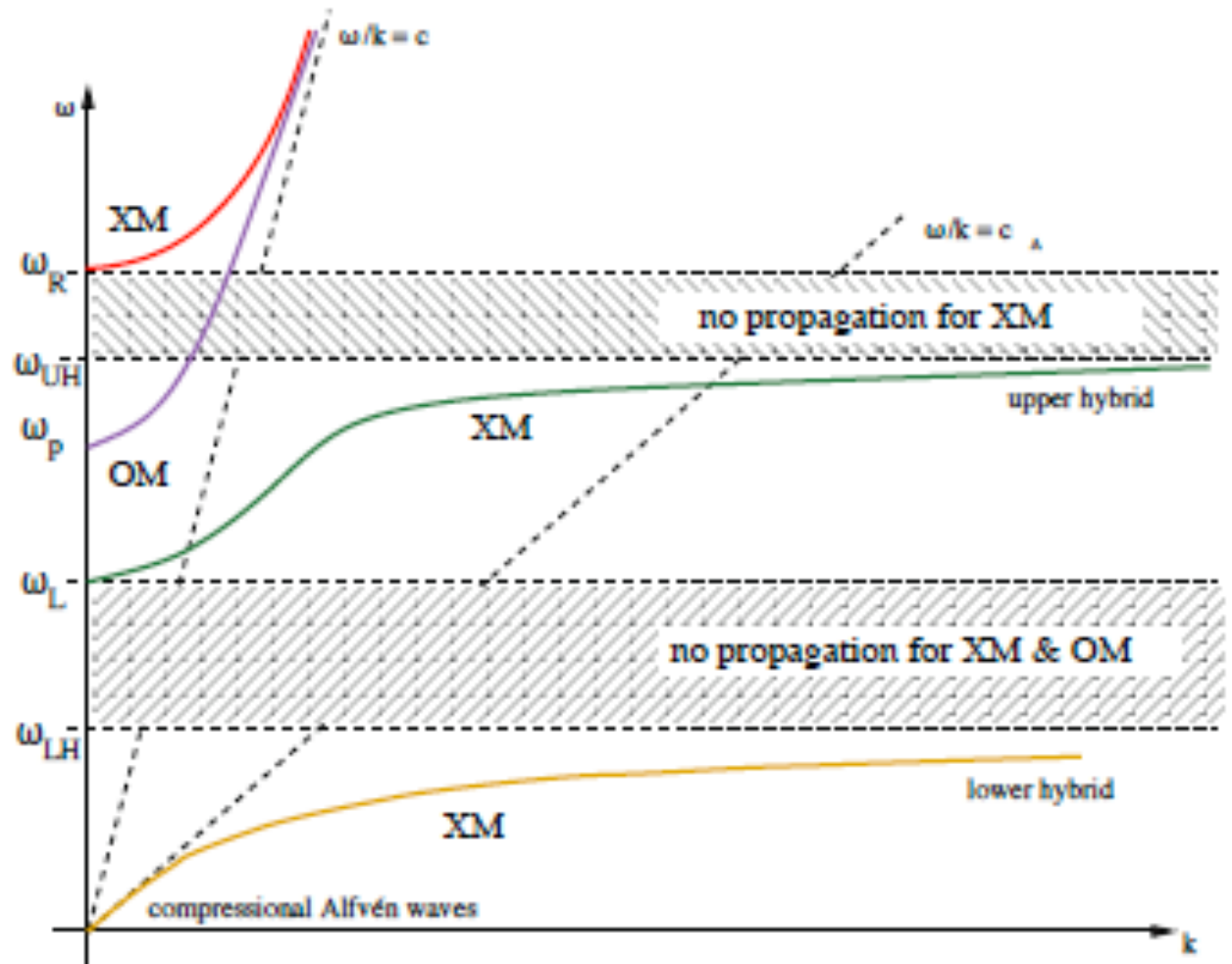
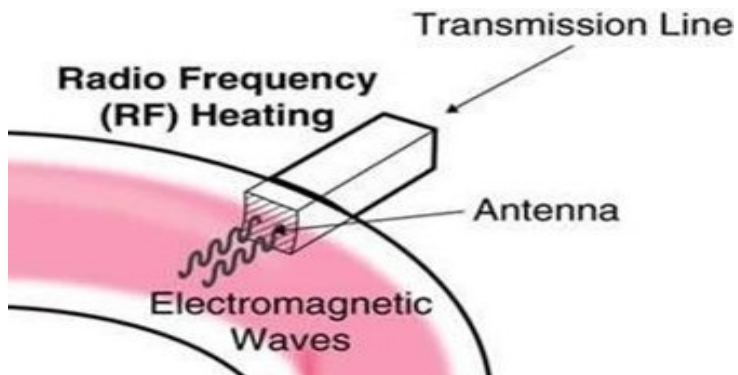
Mattia Albergante

Heating by waves

Heating by waves

Reminder of waves dispersion relation ($T \sim 0$)

Perpendicular to \mathbf{B}_0



Heating by waves

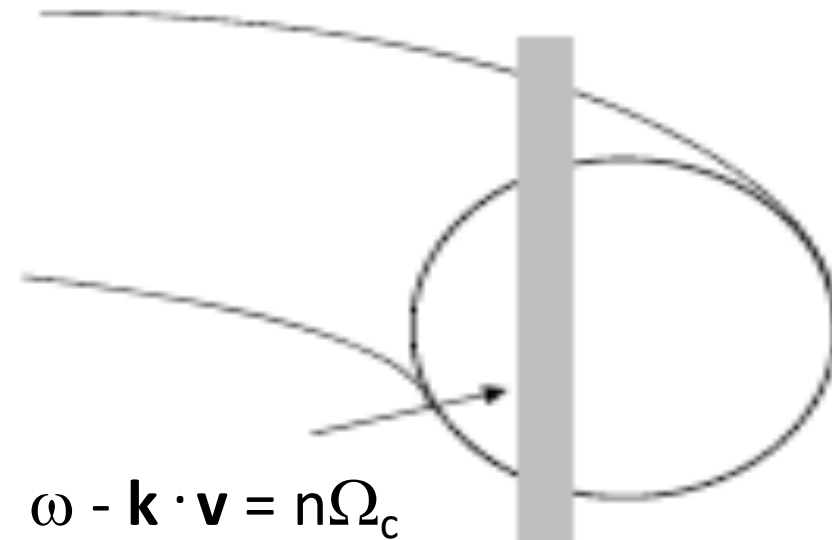
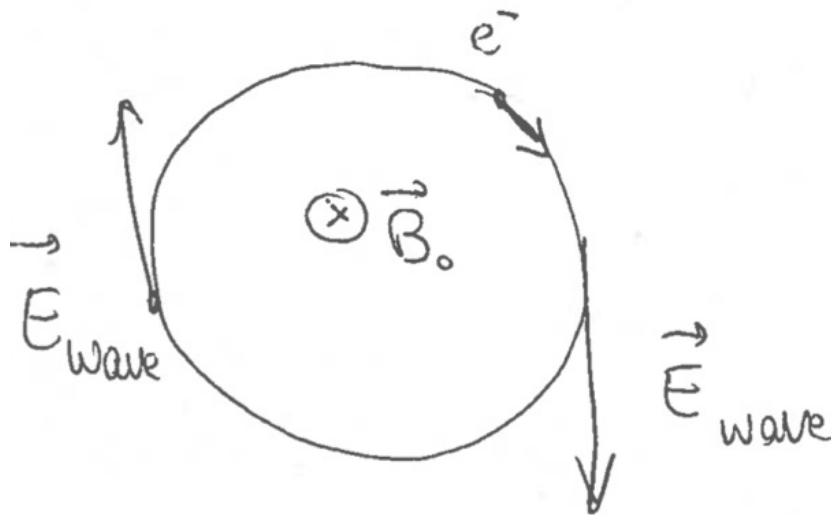
If $T \gg 0$ (hot plasma - kinetic model needed)

Wave-particle resonances occur at $\omega - \mathbf{k} \cdot \mathbf{v} = n\Omega_c$ ($n=0, 1, 2, \dots$)

Ions or electrons feel in their reference frame a constant force when the E-field is in phase with their motion

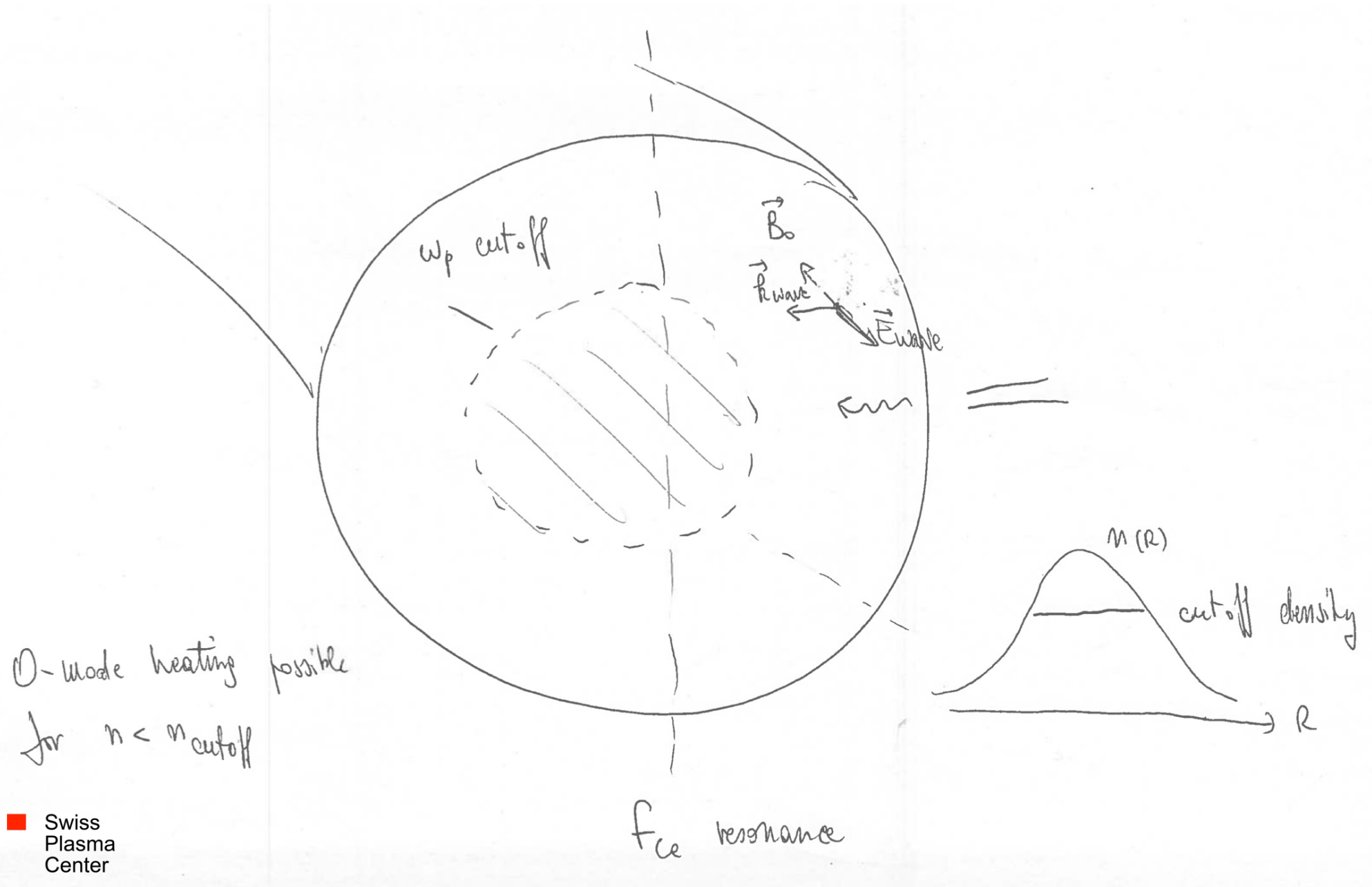
Cyclotron resonances also for waves that do not propagate along \mathbf{B}_0

Finite k_{\parallel} and relativistic effects, for electrons, $\Omega_{ce} = eB_0/m(v)$, make the resonance velocity dependent, i.e. of finite width, effective for the energy exchange between particles and waves



Electron Cyclotron Resonance Heating ECRH

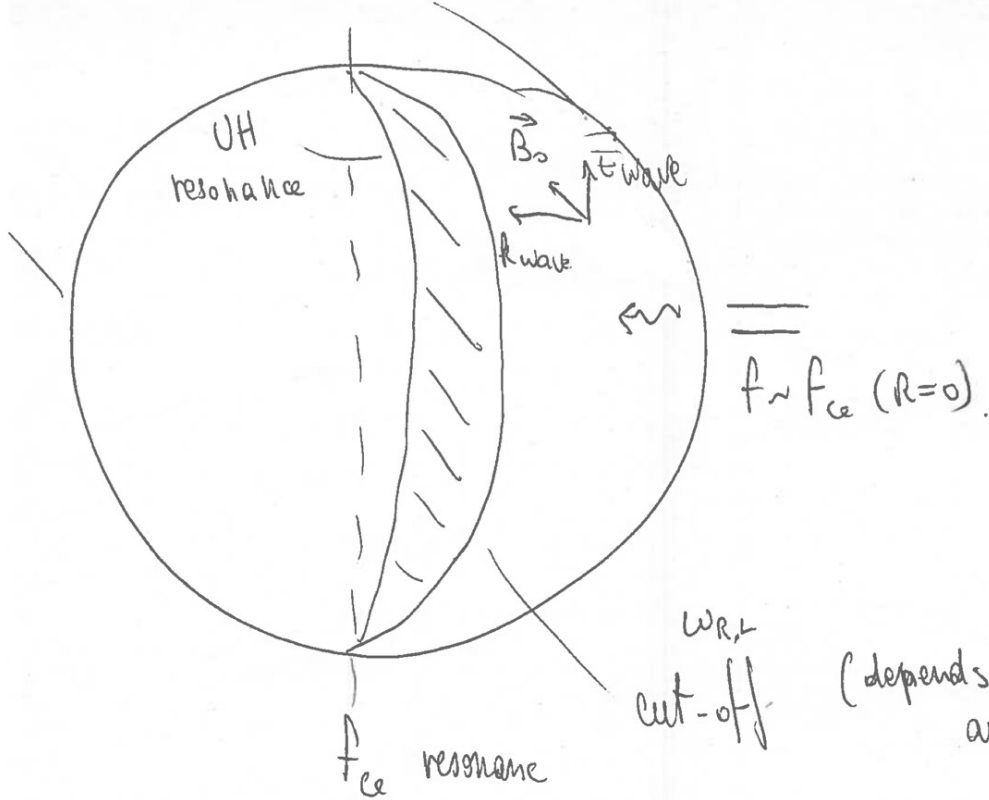
ECRH – Ordinary mode ($E \parallel B_0$)



ECRH – eXtraordinary mode ($E \perp B_0$)

idea: go to higher harmonics

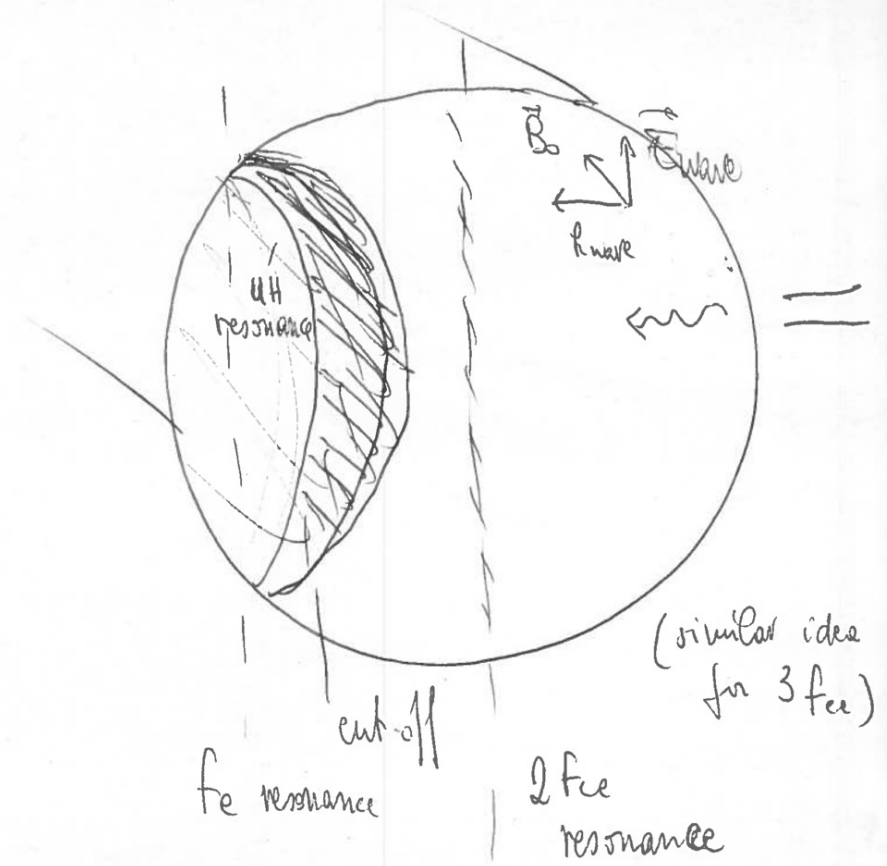
1st harmonic



W.R.L
cut-off (depends on B_0 and n)

can't reach any resonance before cut-off

2nd harmonic



(similar idea for $3 f_{ce}$)

Note: Pb. with going to higher and higher harmonics

- < reduced absorption
- < availability of high power sources

ECRH – Accessibility

$$X = \frac{\omega_p^2}{\omega^2} (\propto n) \quad Y = \frac{\Omega_e^2}{\omega^2} (\propto B_0^2)$$

Cut-offs:

$$O - \text{mode} : X = 1$$

$$X - \text{mode} : Y = (1 - X)^2$$

Resonances:

$$\omega = \omega_{UH} \quad Y = 1 - X$$

$$\omega = l\Omega_e \quad Y = \frac{1}{l^2} (1, 0.25, \dots)$$

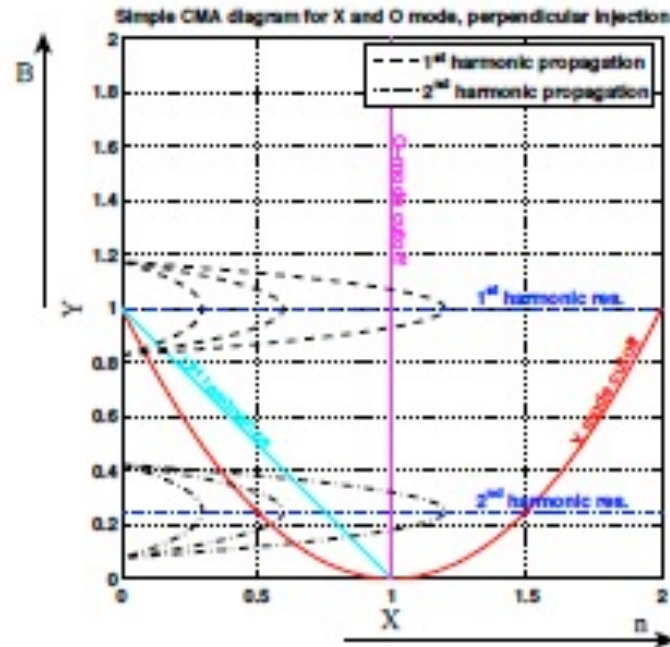
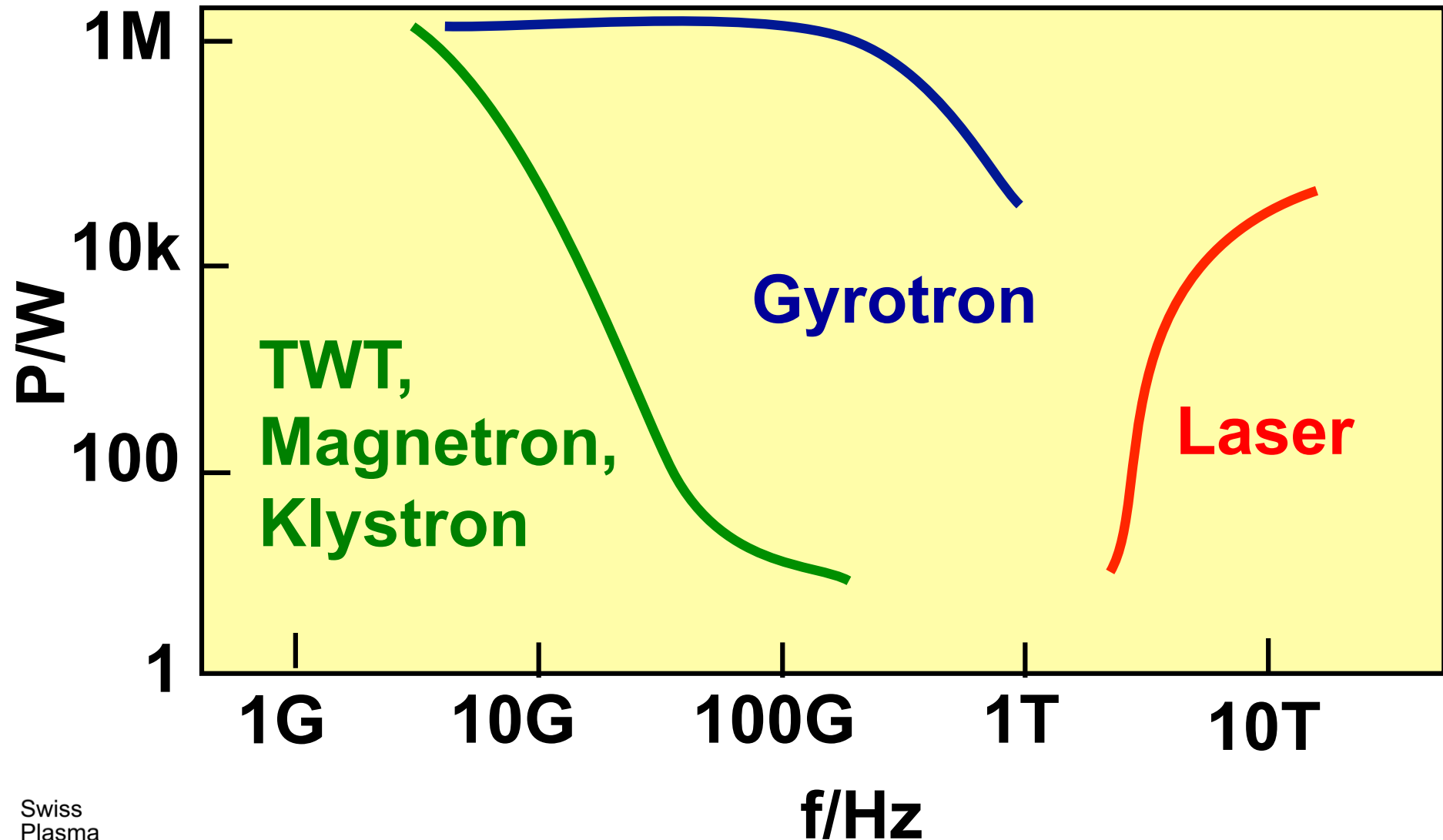


Figure 9.3: Clemmow-Mullaly-Allis diagram for X and O mode. Wave trajectories are shown for 1st and 2nd harmonic injection and for different core plasma densities. Note that for low field side X1 injection the wave first encounters a cutoff. X2 may encounter a cutoff or resonance, depending on the density. O mode has a higher density limit but will eventually be cut off at the plasma frequency.

EPFL ECRH – Possible microwave sources



ECRH – Accessibility

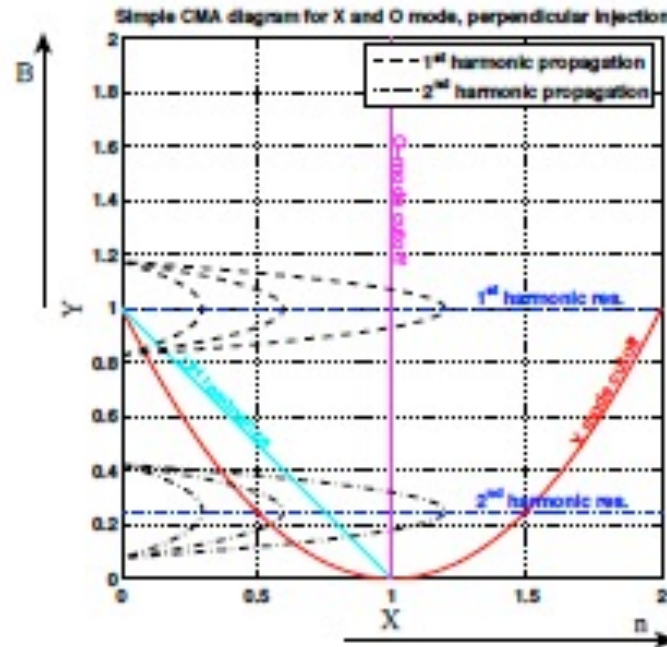
$$X = \frac{\omega_p^2}{\omega^2} (\propto n) \quad Y = \frac{\Omega_e^2}{\omega^2} (\propto B_0^2)$$

Cut-offs:

$$\begin{aligned} \text{O - mode} &: X = 1 \\ \text{X - mode} &: Y = (1 - X)^2 \end{aligned}$$

Resonances:

$$\begin{aligned} \omega = \omega_{UH} & \quad Y = 1 - X \\ \omega = l\Omega_e & \quad Y = \frac{1}{l^2} (1, 0.25, \dots) \end{aligned}$$

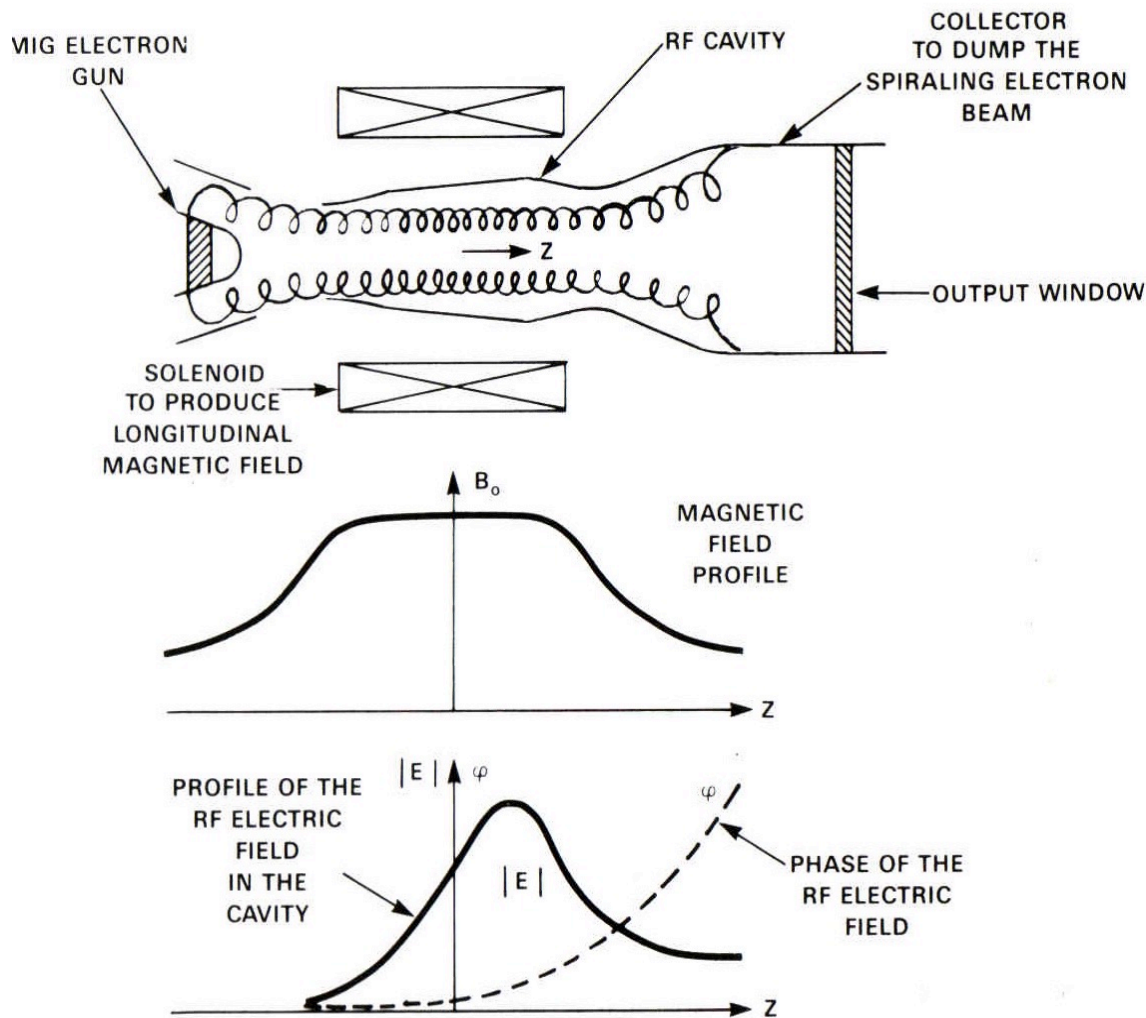


TCV ($f_{ce}=41\text{GHz}$)
 can use $n=2$ or $n=3$
 X2 (83GHz) or X3 (118GHz)

**ITER ($f_{ce}=170\text{GHz}$)
 must use $n=1$
 O1 (170 GHz)**

Figure 9.3: Clemmow-Mullaly-Allis diagram for X and O mode. Wave trajectories are shown for 1st and 2nd harmonic injection and for different core plasma densities. Note that for low field side X1 injection the wave first encounters a cutoff. X2 may encounter a cutoff or resonance, depending on the density. O mode has a higher density limit but will eventually be cut off at the plasma frequency.

Principle based on Cyclotron Resonance Maser instability



Three “ingredients”:

Magnetic field

Guides the e⁻

Determines the frequency

$$\omega \approx \frac{\Omega_0}{\gamma}$$

ω	Oscillation frequency
Ω_0	Cyclotron frequency
γ	Relativistic factor

Annular electron beam

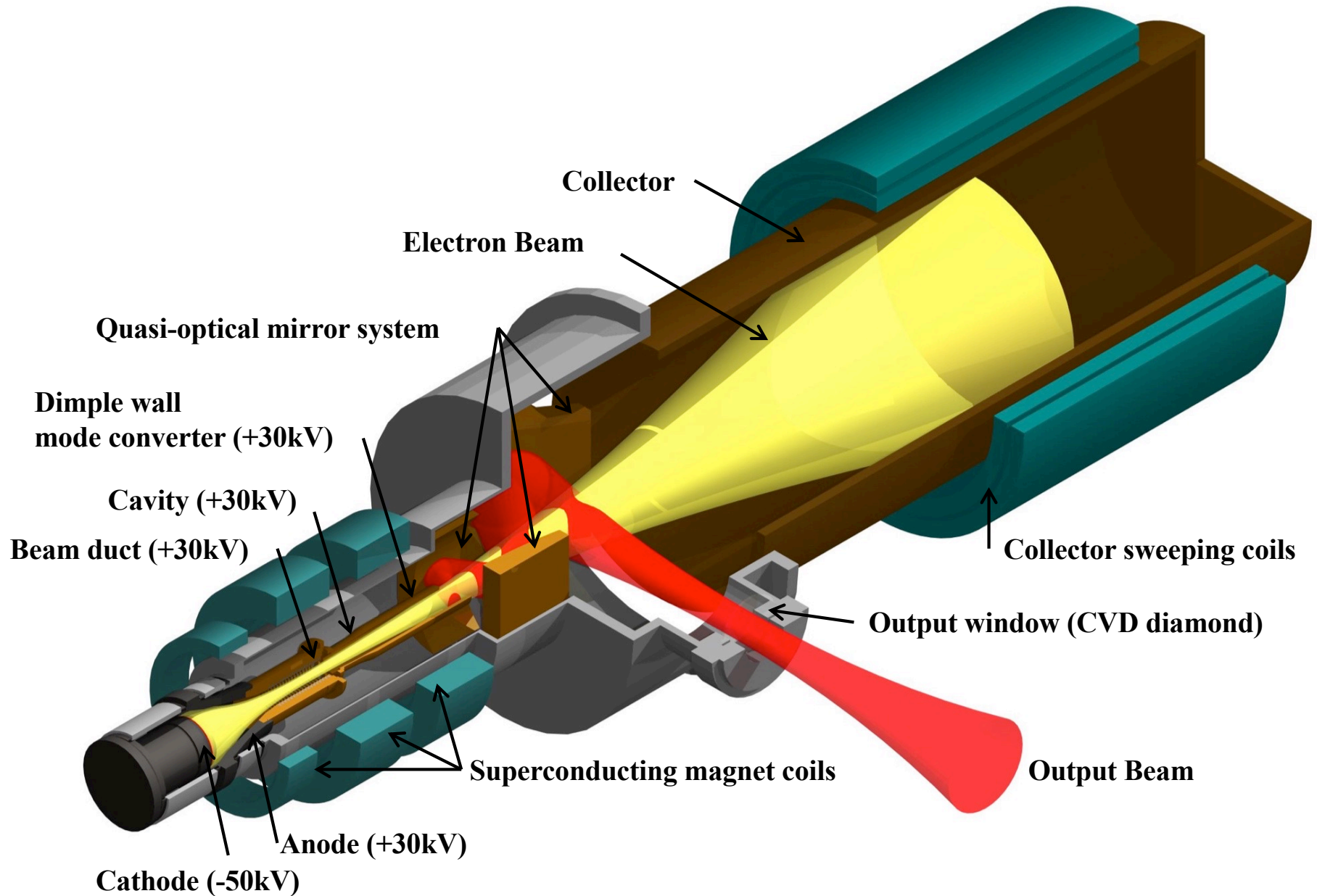
Source of free energy

Resonant cavity

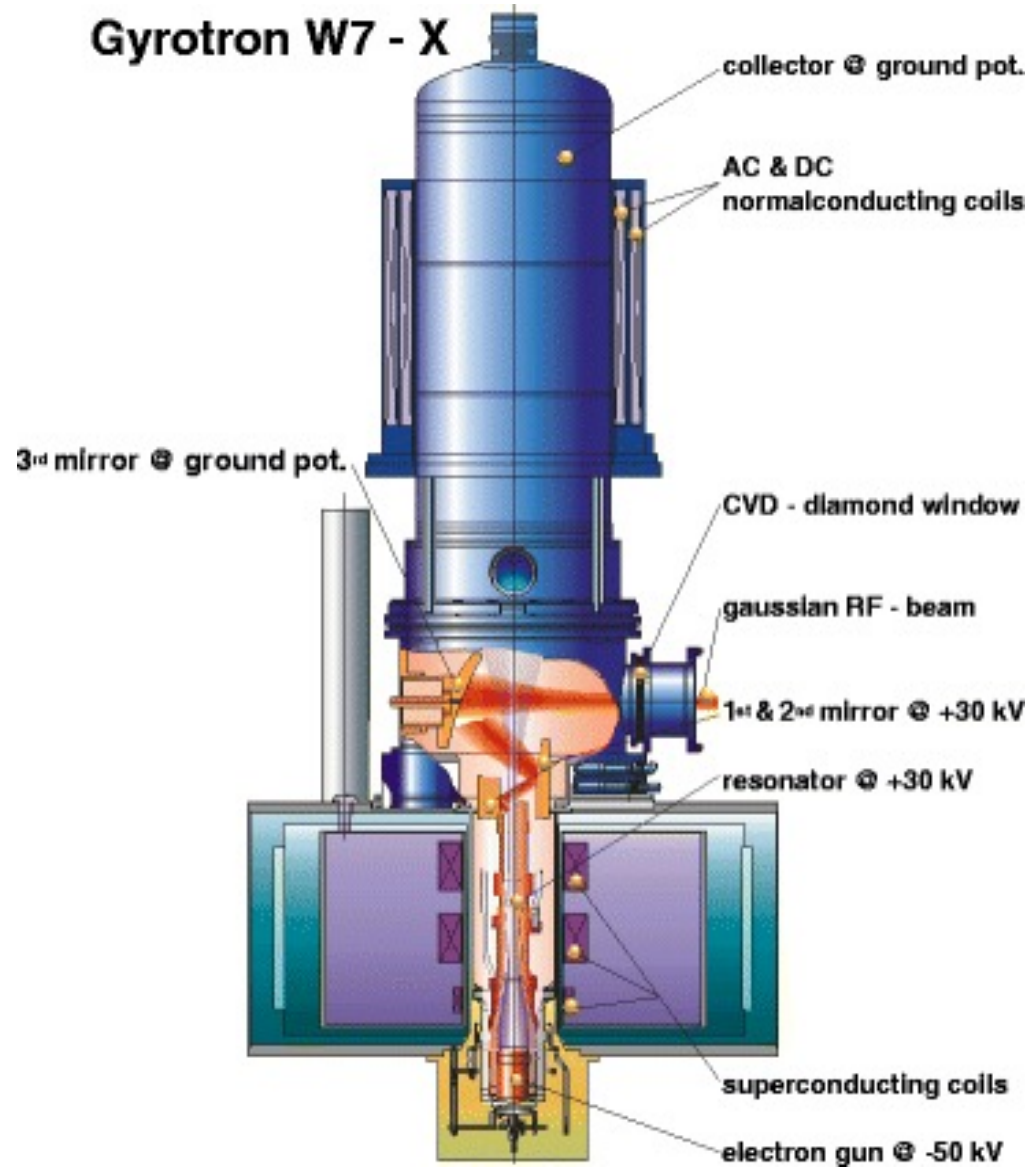
Cylinder with a smoothly varying cross-section

Resonant interaction between electrons and cavity mode (TE_{m,n})

The gyrotron

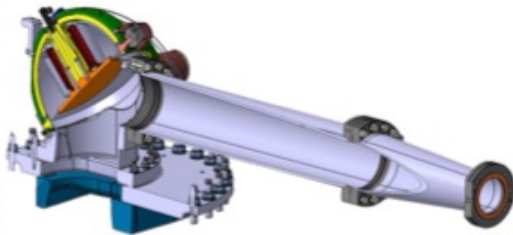


The gyrotron

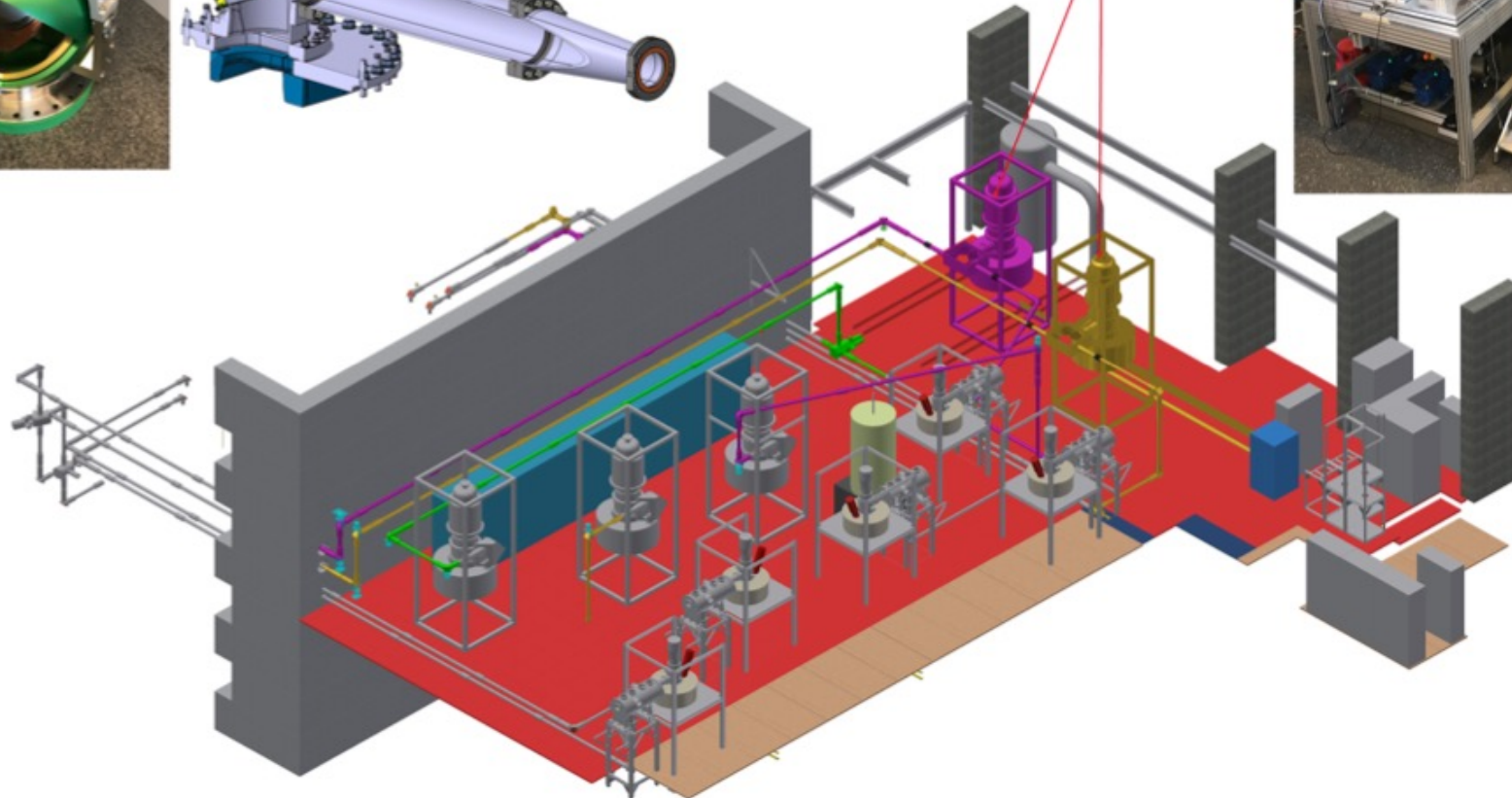


A modern ECRH system: TCV

New X3 Top Launcher



Dual-frequency gyrotrons

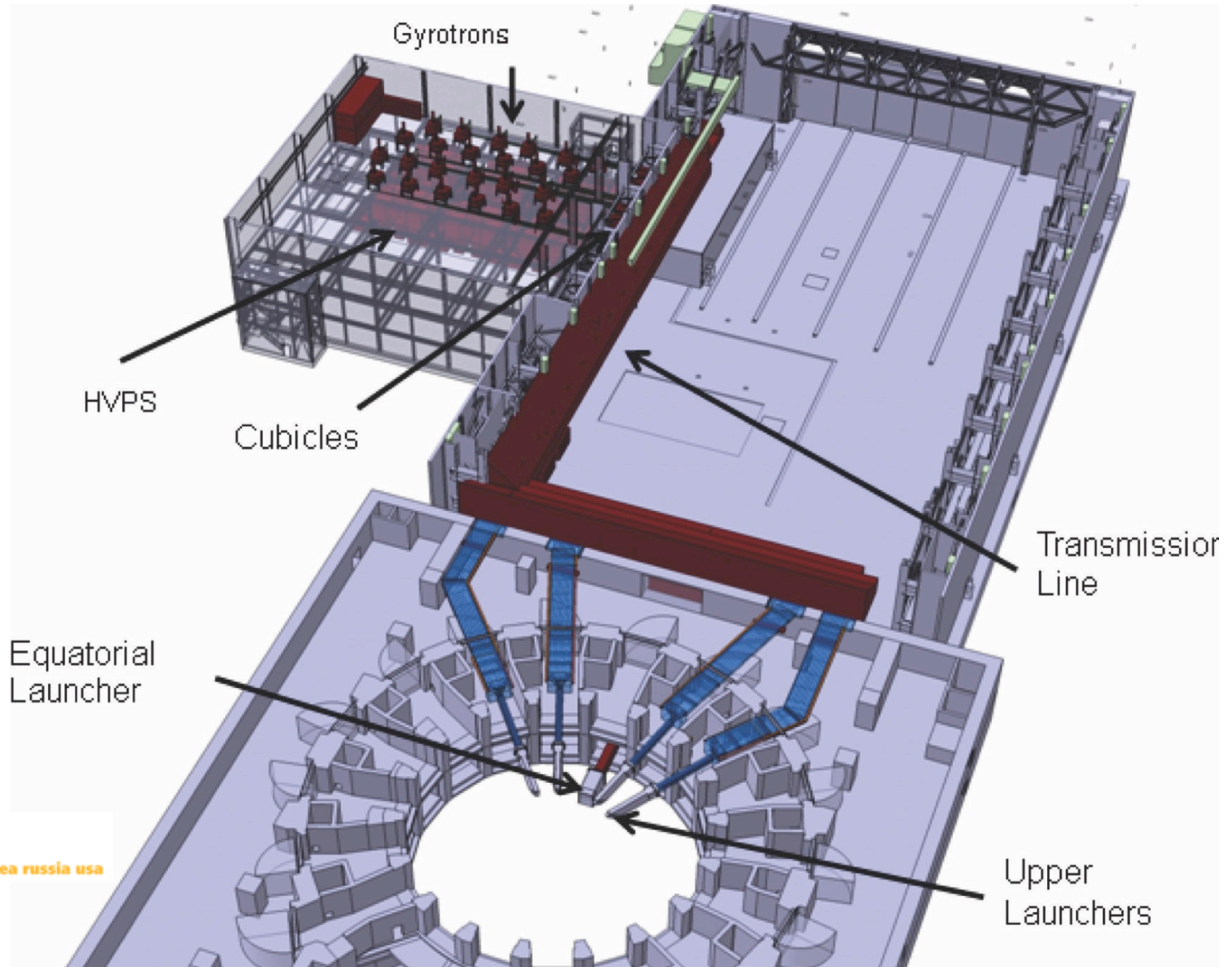
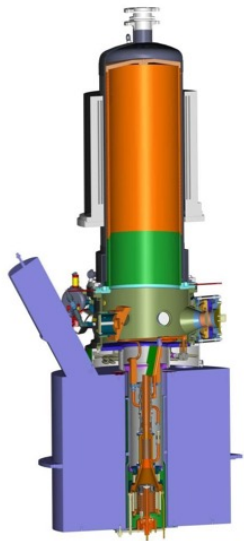


ECRH system on ITER

24 gyrotrons

1MW each

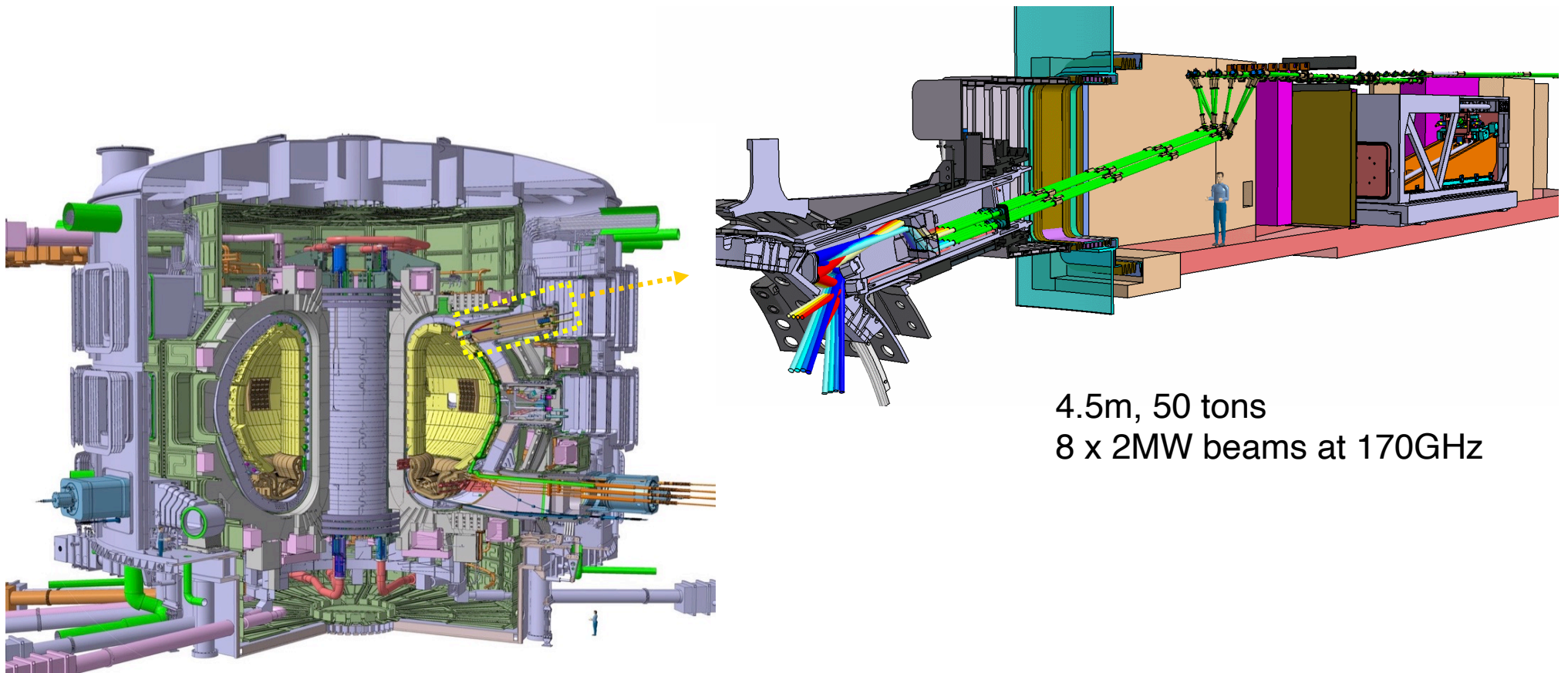
170GHz



ITER upper launcher (Swiss contribution)

Front steering launcher of 170 GHz microwaves

Goal: heat locally and stabilize plasma instabilities



4.5m, 50 tons
8 x 2MW beams at 170GHz

EPFL We already work on EC systems for DEMO

108 gyrotrons (216MW), 7200s

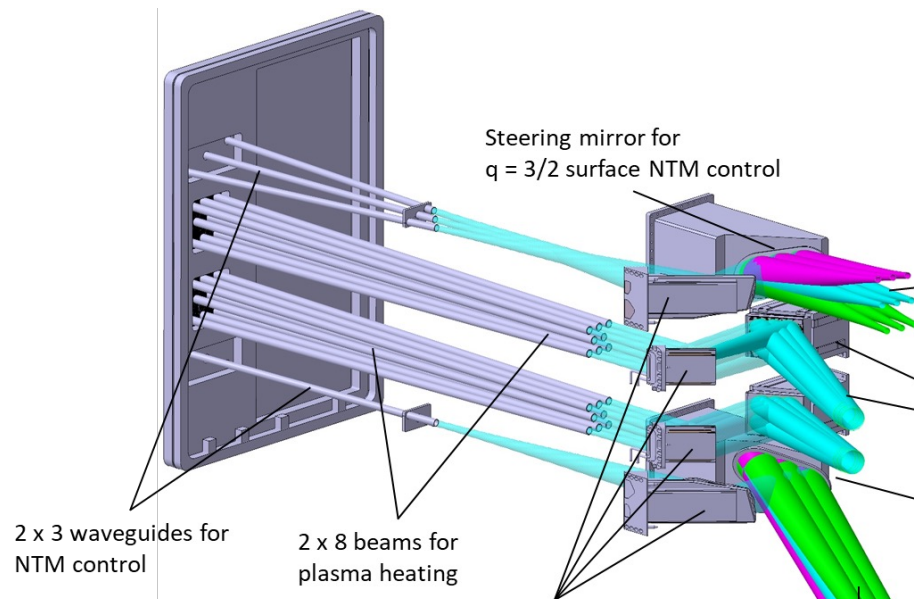
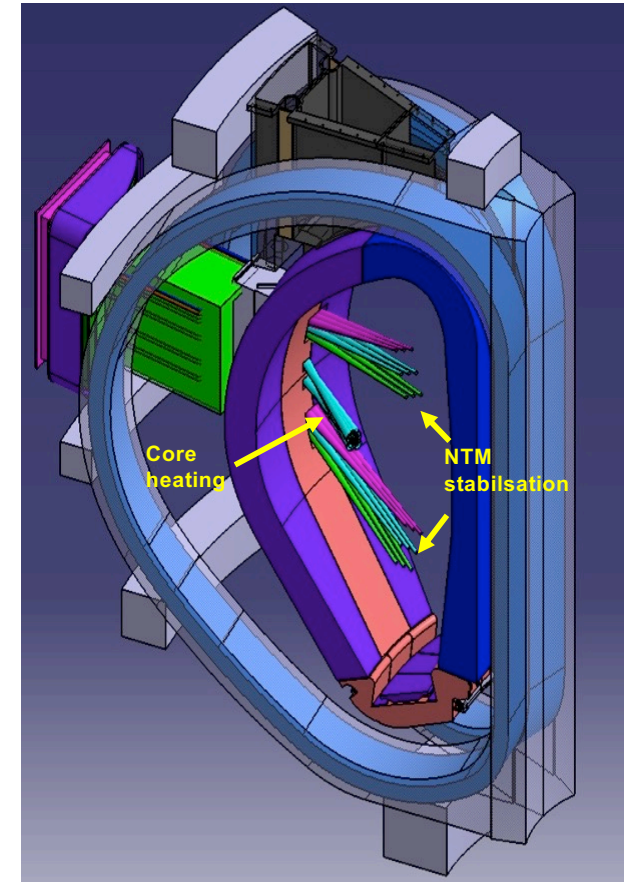
Break down and plasma ramp-up

Bulk heating and NTM control (core)

Radiative instability control (edge)

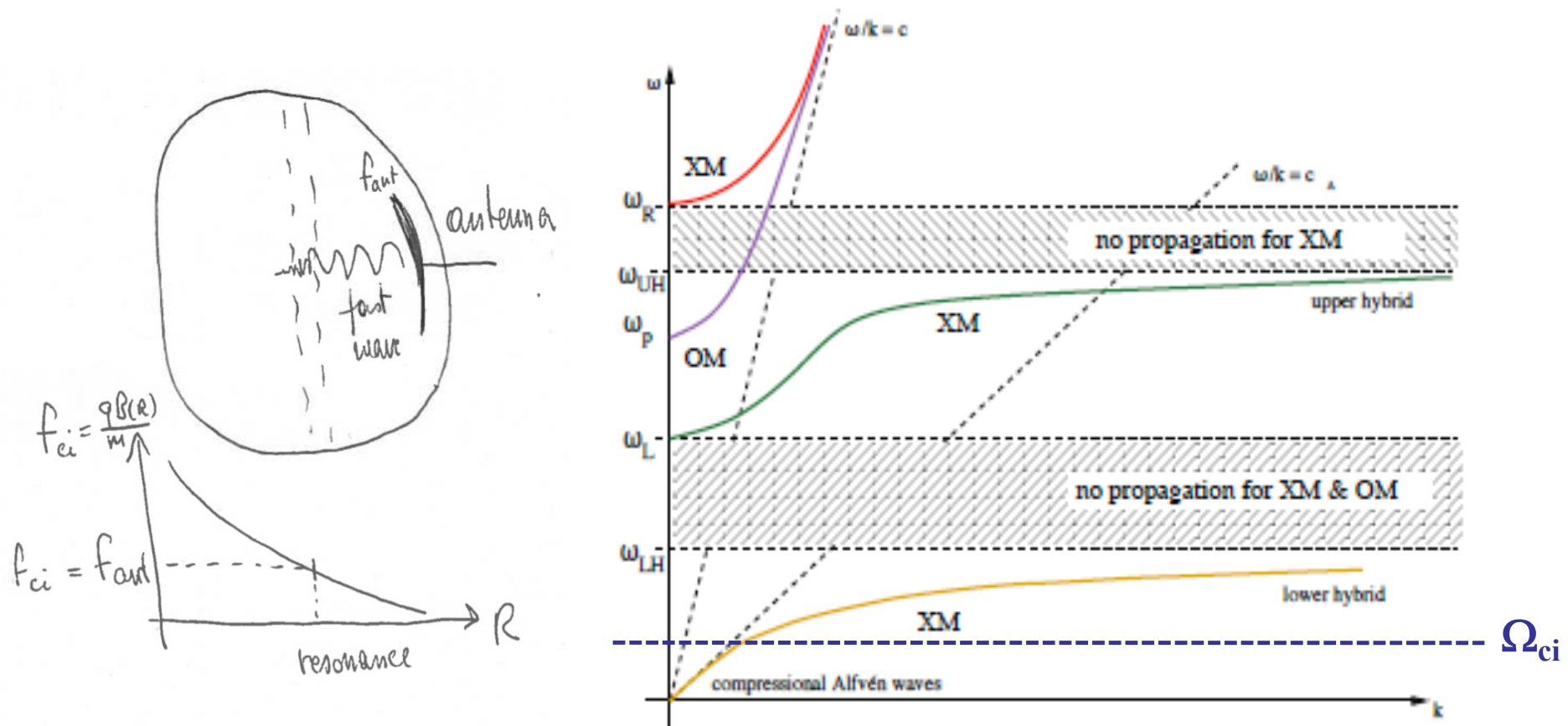
Plasma ramp-down

SPC contribution - launcher

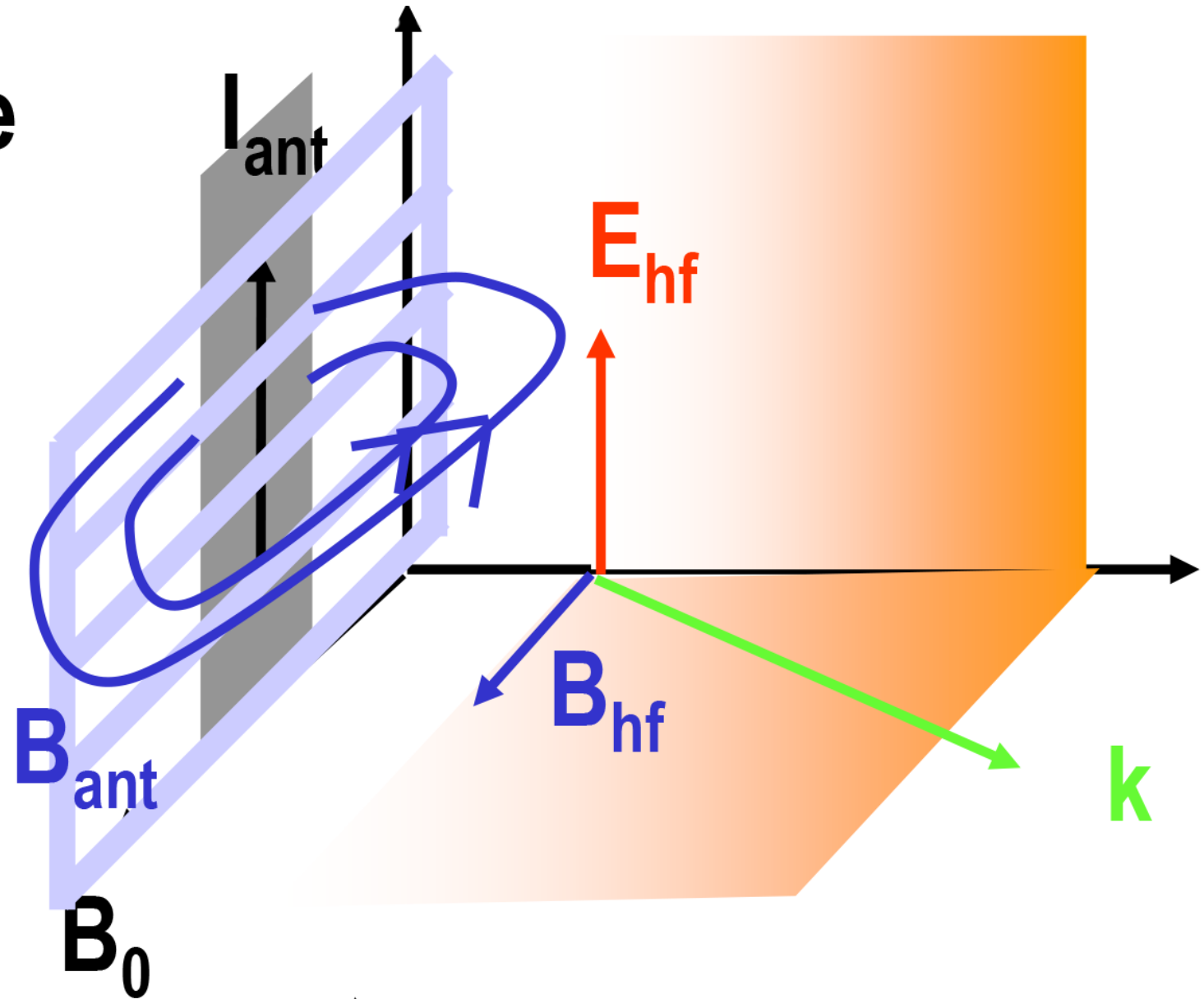


Ion Cyclotron Resonance Heating ICRH

Perpendicular wave dispersion relation



We rely on the *fast wave*, i.e. compressional Alfvén (fast magnetosonic) wave, to bring energy to antenna to plasma

Fast waveStrap
antennaFaraday
screen

ICRH - Main principles

Tokamak plasmas contain more than one ion species:
dispersion relation is more complicated and allows different
schemes for wave absorption

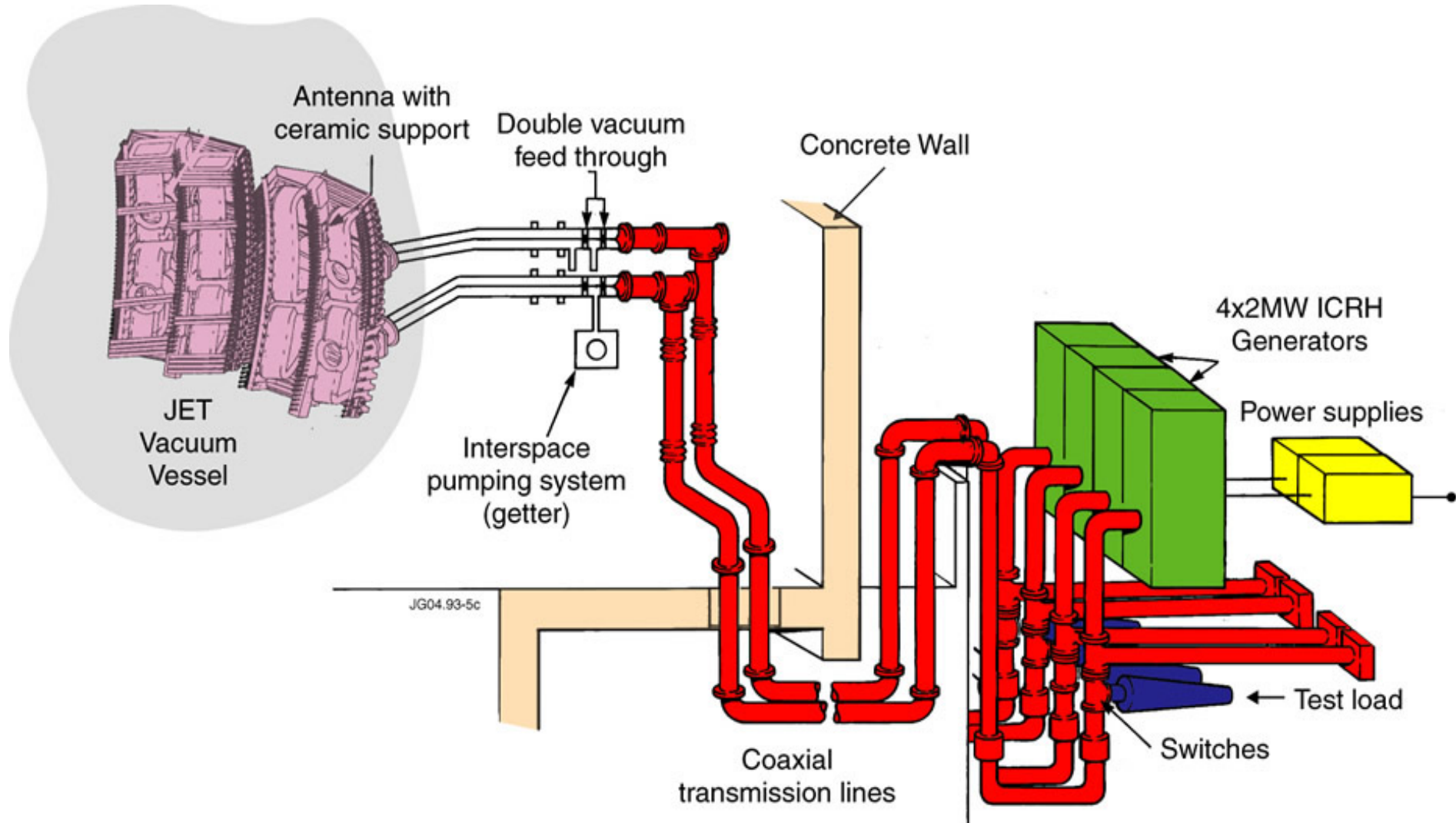
1st harmonic of a minority ion (e.g. $\omega = \Omega_{cH}$ or $\omega = \Omega_{cHe3}$)

2nd harmonic of main ion species (e.g. in 50:50 DT plasmas $\omega = 2\Omega_{cT}$)

Ion-ion hybrid resonance (e.g. in 50:50 DT plasmas $\Omega_{cT} < \omega < \Omega_{cD}$)

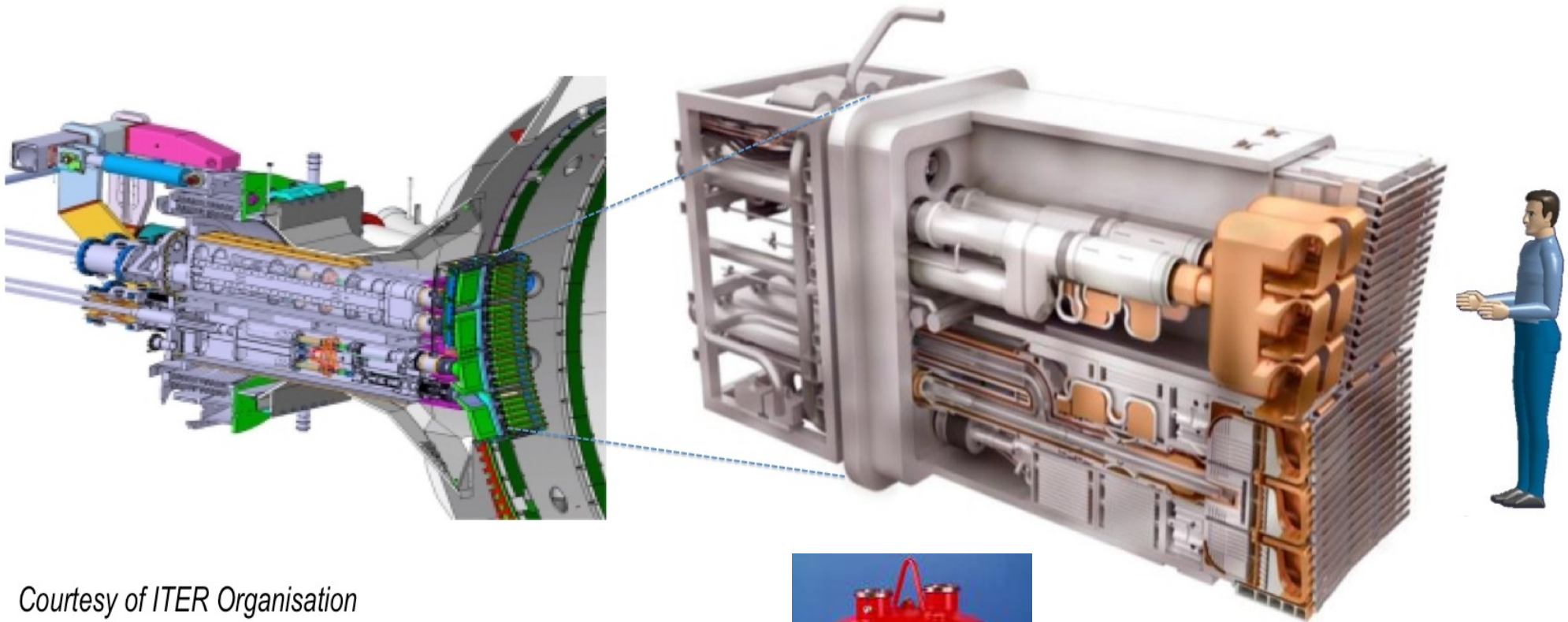
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ICRH – JET system



ICRH – ITER antenna

40 – 55MHz, 20MW, 3600s, 8 coaxial lines, antenna on port-plug



Courtesy of ITER Organisation

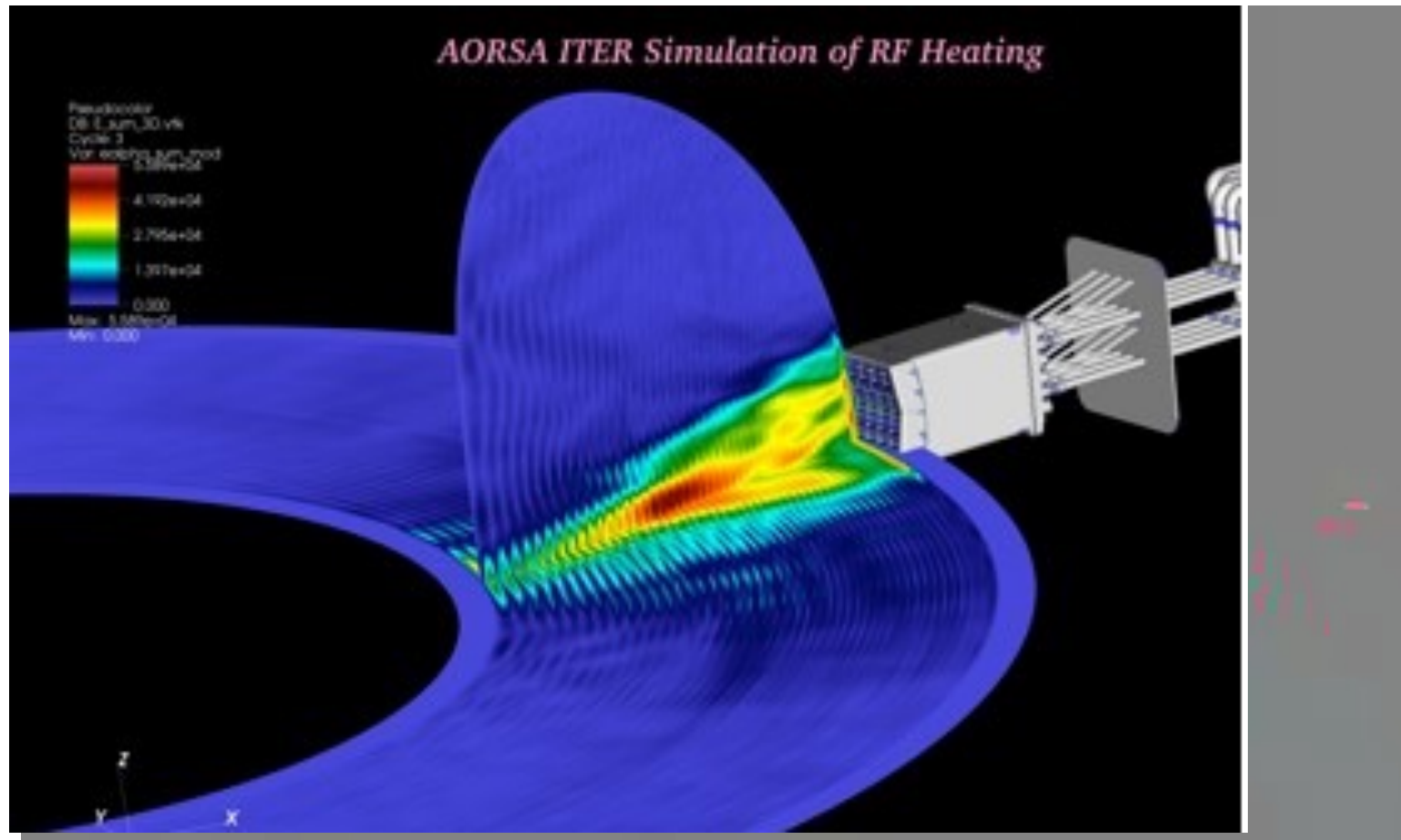


ICRH modeling

Fast wave has large vacuum λ – cannot be described in simple Fourier formalism

Ex. of wave field from full wave calculation of 2nd harmonic
T ICRH in ITER (53MHz, 20MW)

Courtesy of P.Bonoli, E.F.Jaeger et al., PoP 15, 072513 (2008)



Energetic ions from additional heating

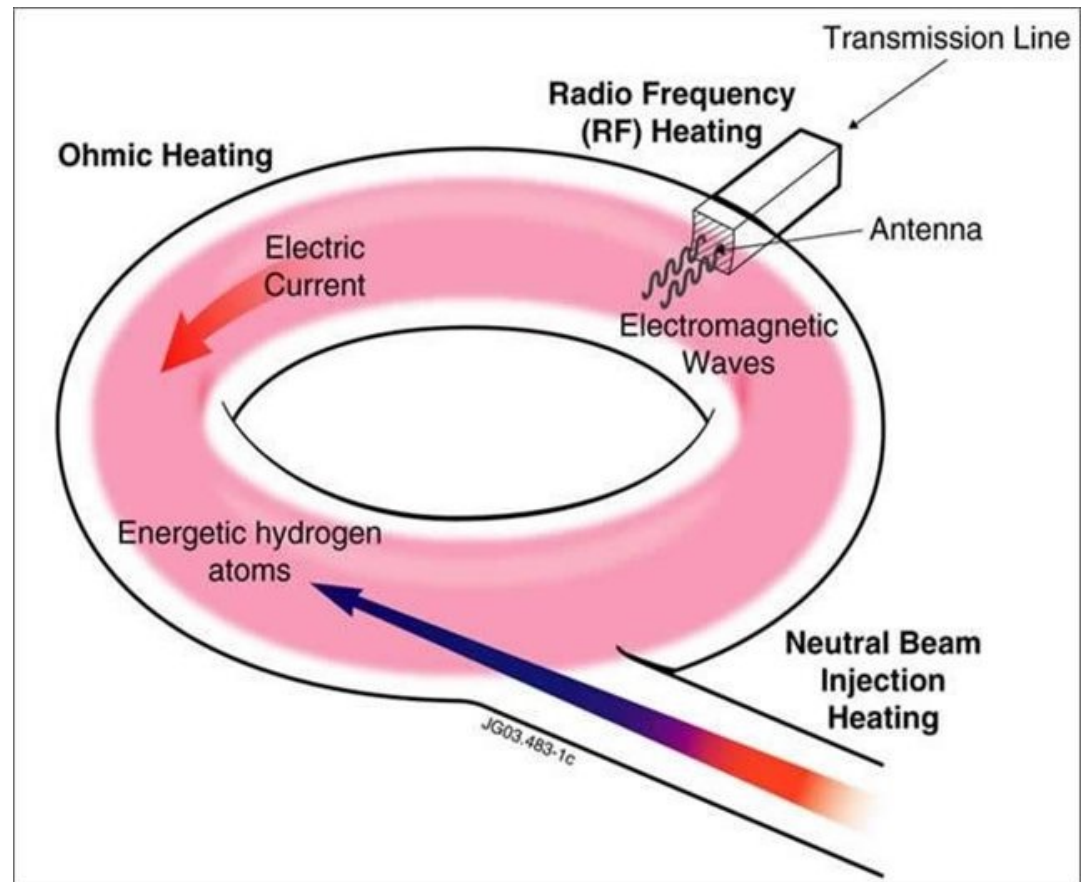
Burning plasma regime is reached using external heating and current drive

Electron cyclotron heating

Ion cyclotron heating

Neutral beam heating

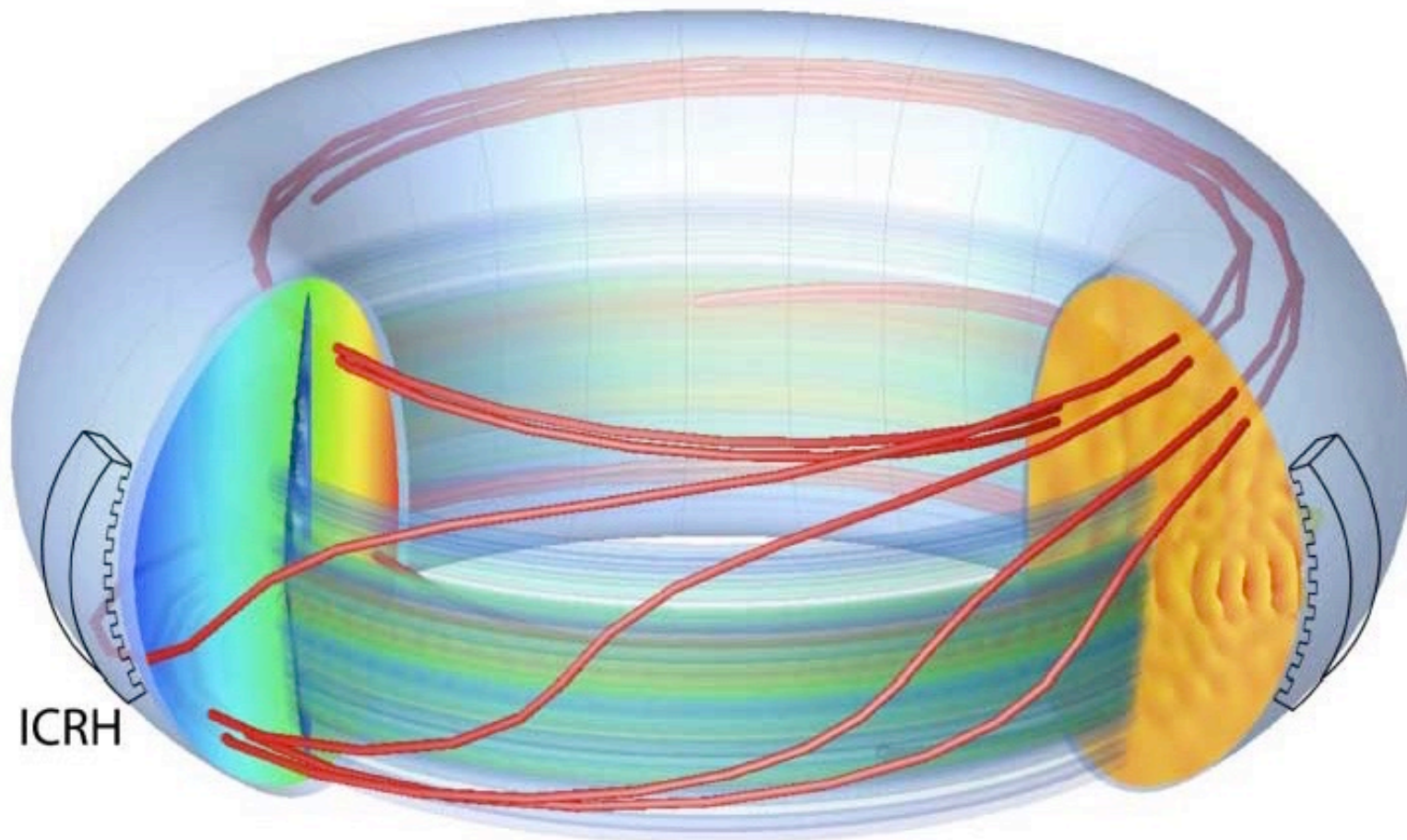
Based on creation of \sim MeV ions, then thermalised by collisions



ICRH and energetic ions

Wave fields at $\omega \sim \Omega_{ci}$ give energy to perpendicular motion of minority ions

Strongly anisotropic distribution function: mostly trapped orbits



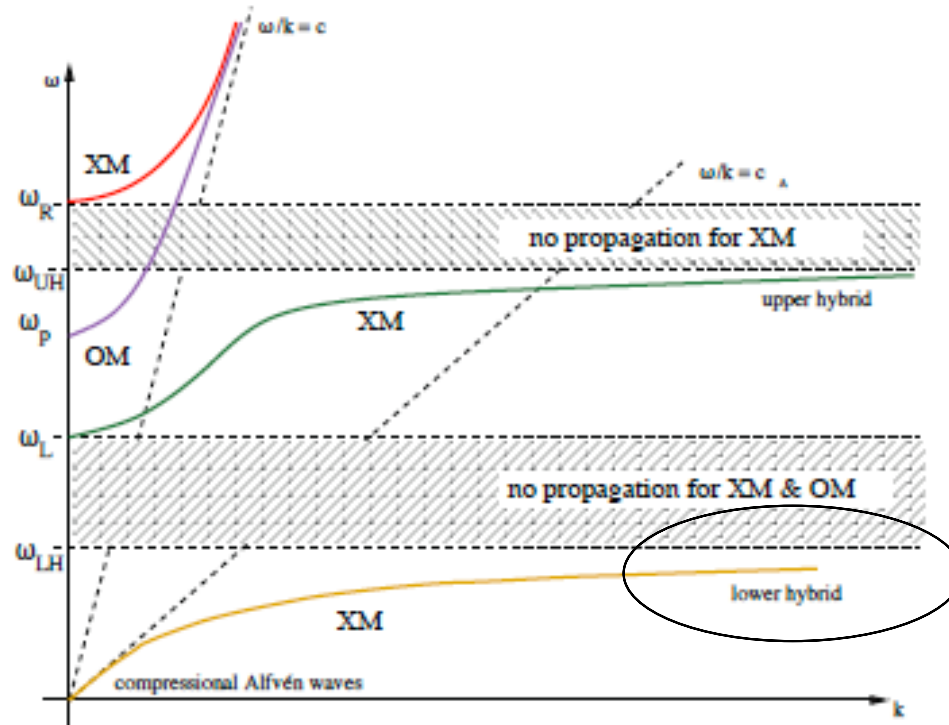
Wave-particle resonance

$$f_{LH} = k \cdot v / 2\pi$$

$$\sim 1.3 T_e^{1/2} [\text{keV}] / \lambda_{||} [\text{cm}]$$

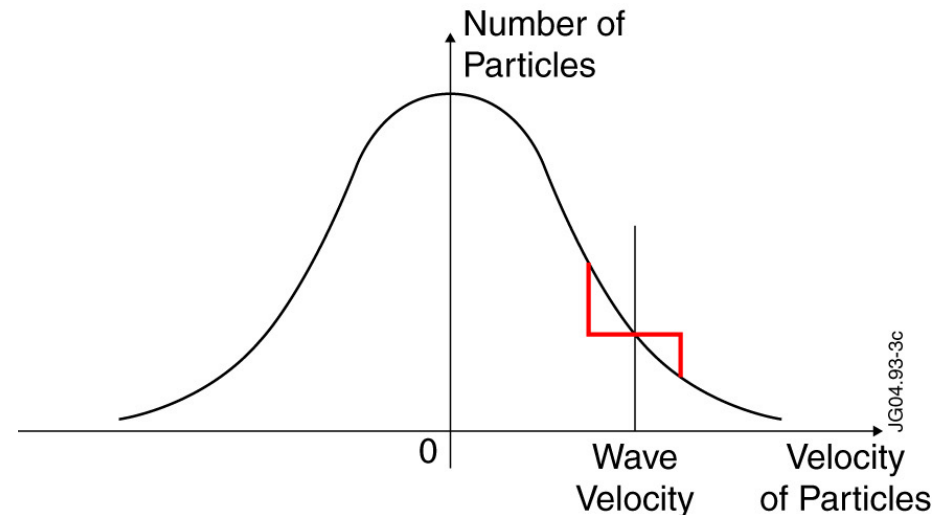
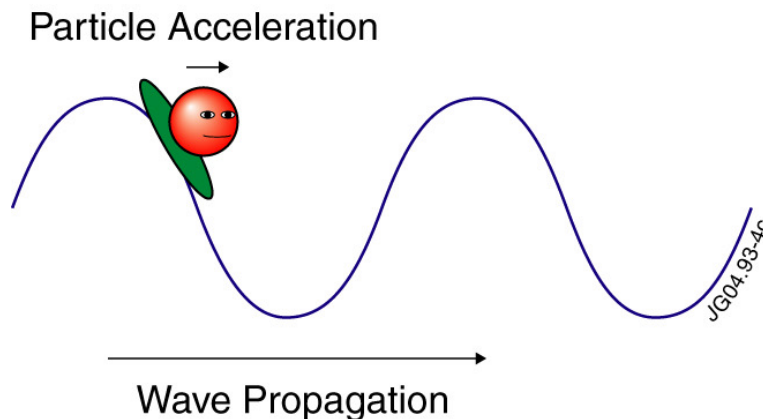
[GHz]

Electrostatic waves
($\delta B \sim 0$)

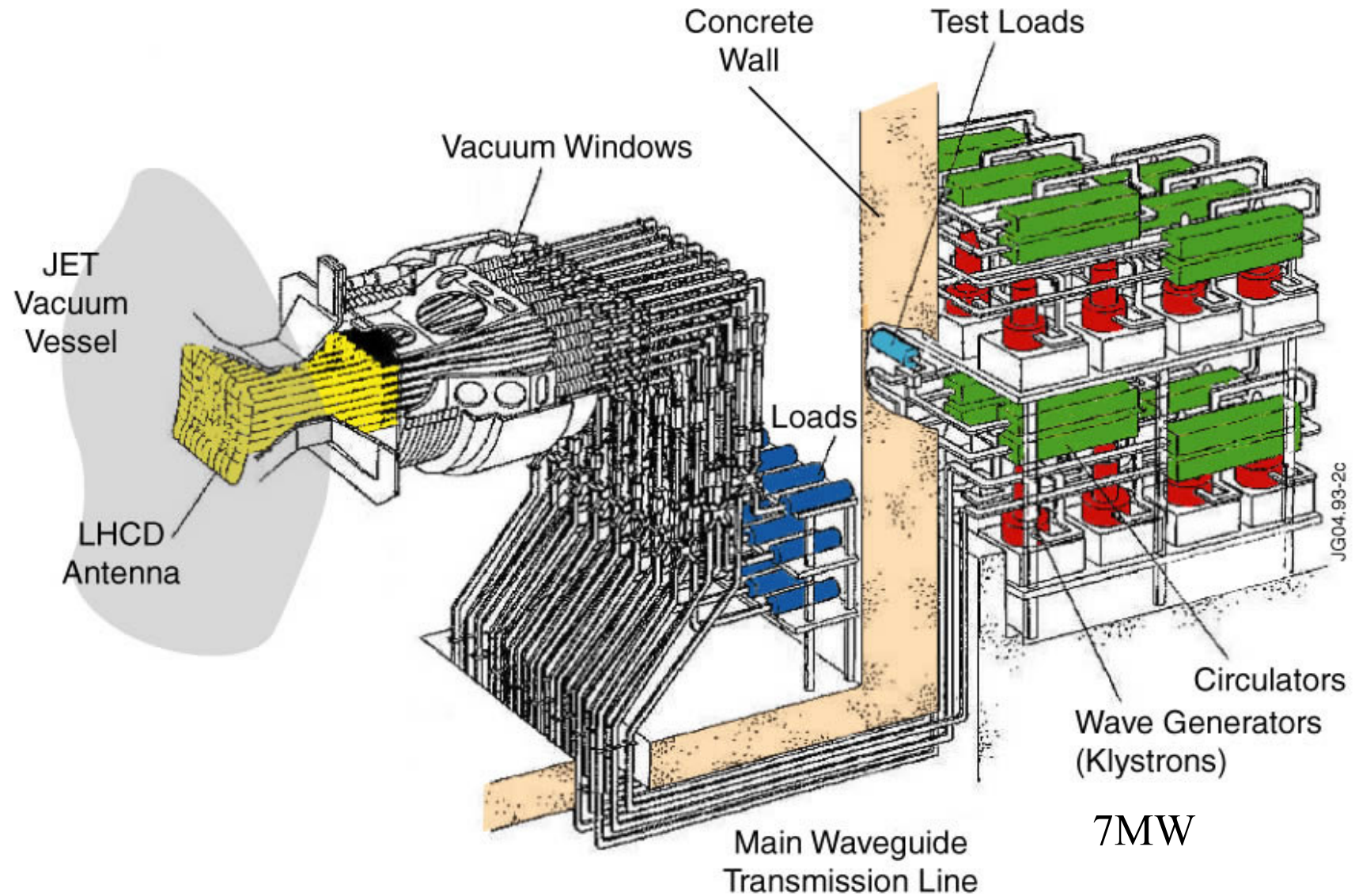


JET
 $f_{LH} \sim 2.45 \text{GHz}$

ITER
 $f_{LH} \sim 5 \text{GHz}$



The Lower Hybrid system in JET



LH waves are electrostatic: need antenna in the plasma

The Lower Hybrid antenna in JET



To launch propagating wave for CD, needs well defined spectrum → phasing of many waveguides (‘grill’)

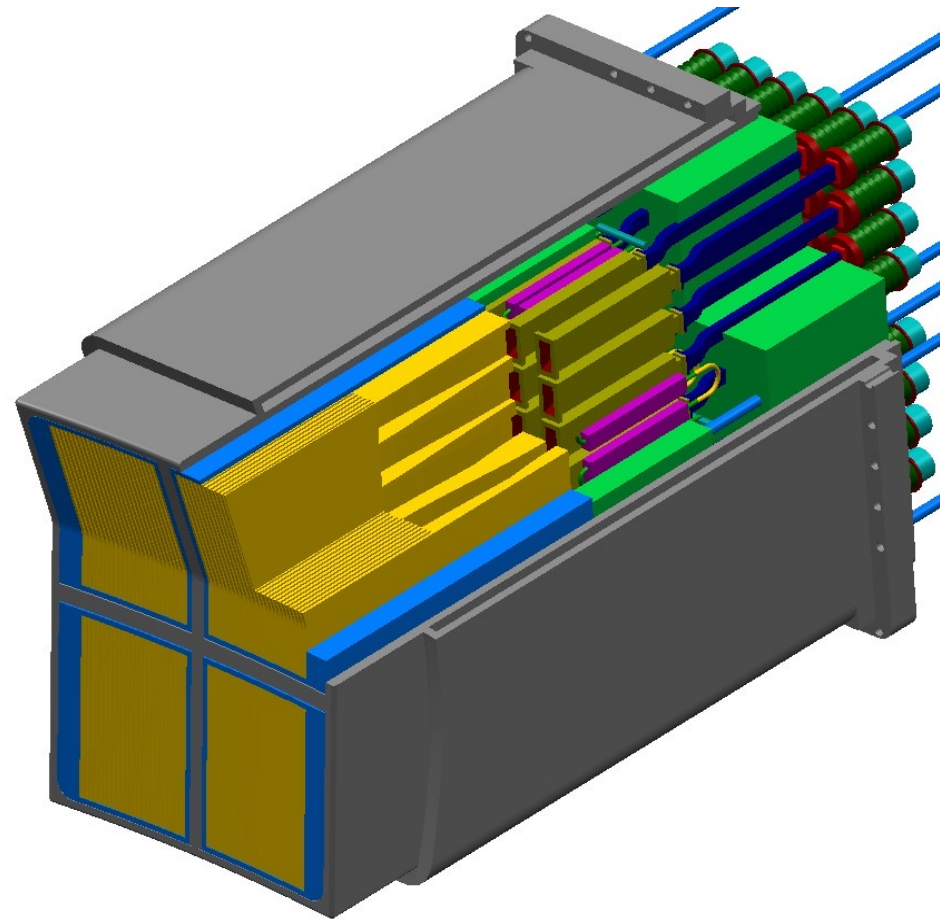
To couple to plasma needs proximity

Interaction between antenna and plasma

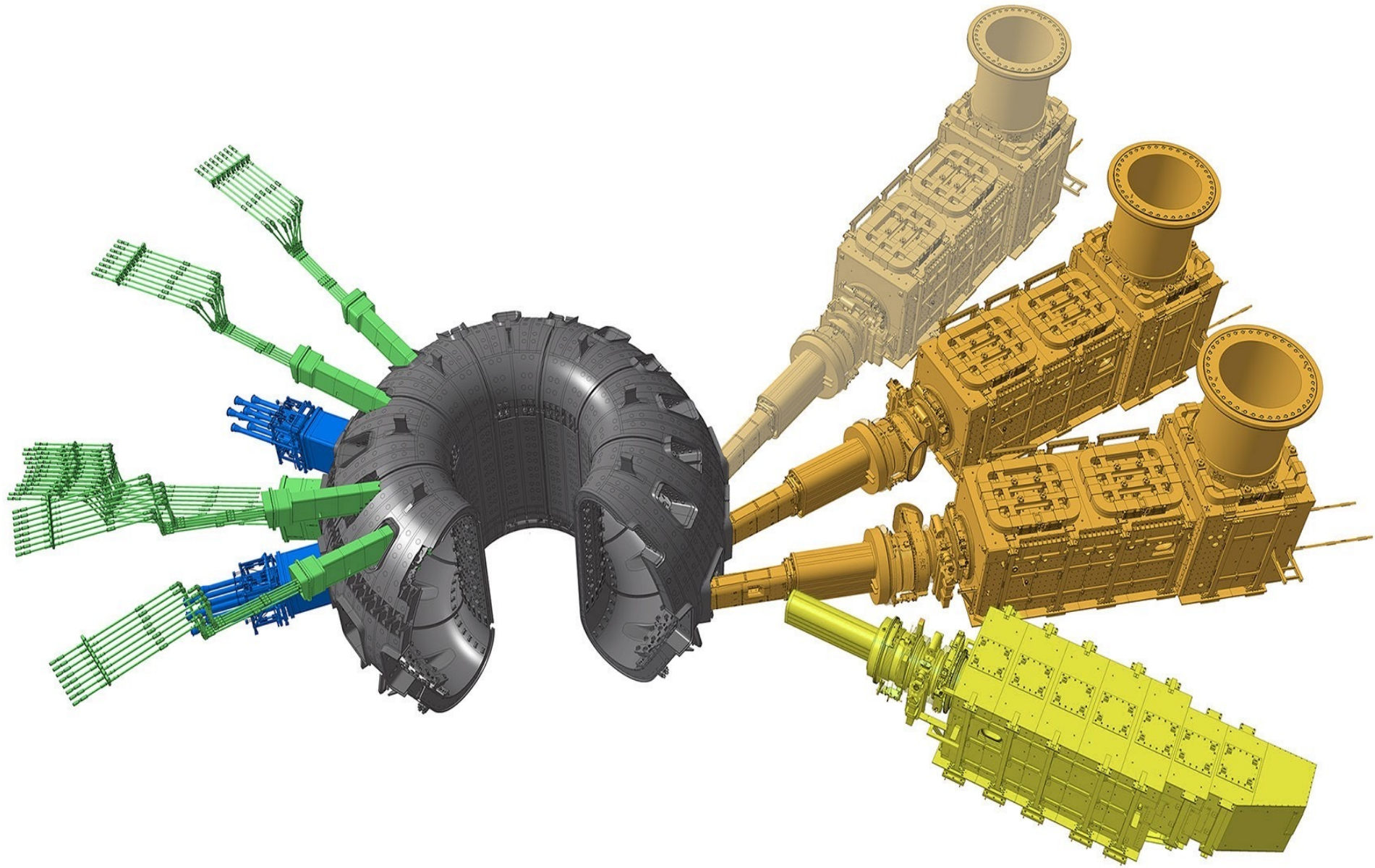
Wave must reach core where CD is of interest

The LH system for ITER

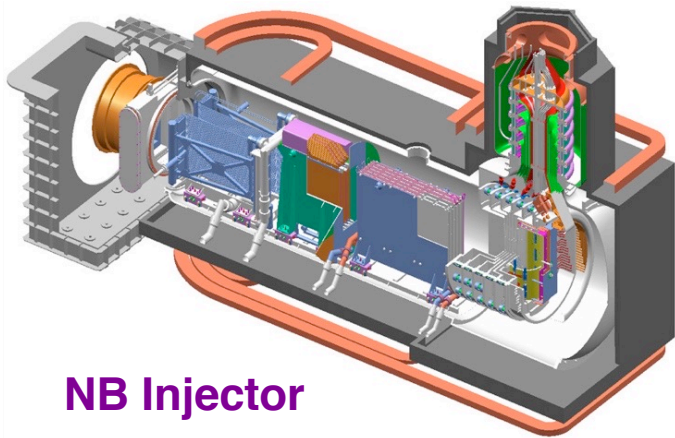
Frequency 5GHz, 20MW will be installed for
second stage of heating upgrades
Mostly for off-axis current drive



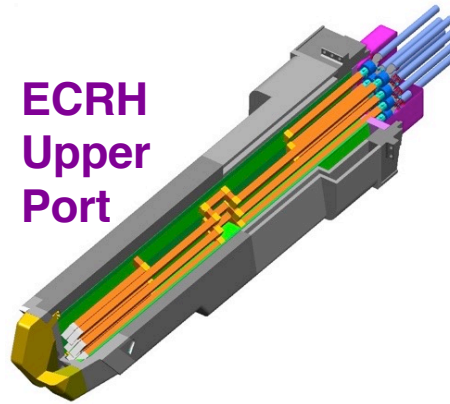
ITER Heating systems



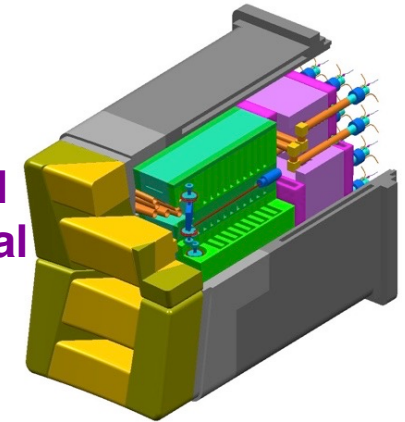
ITER Heating systems



NB Injector

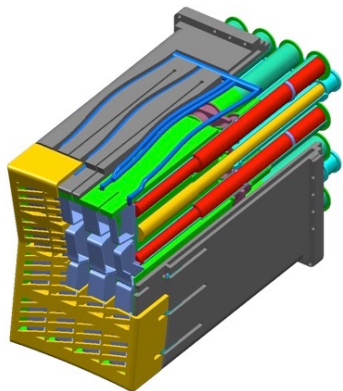


ECRH Upper Port



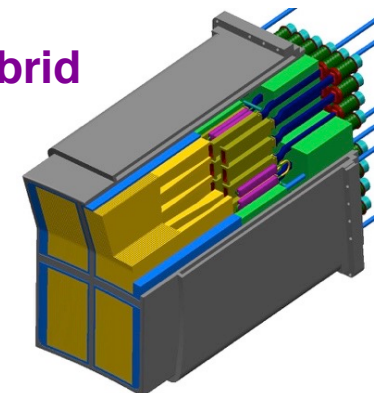
ECRH Lateral Port

System	Power [MW]	Frequency
NBI	33 MW	N/A
ICRH	20 MW	40-55 MHz
LH	20 MW (second stage)	5 GHz
ECRH	24 MW	170 GHz



ICRH antenna

Lower Hybrid Launcher



Discussion: pros and cons of different methods ?