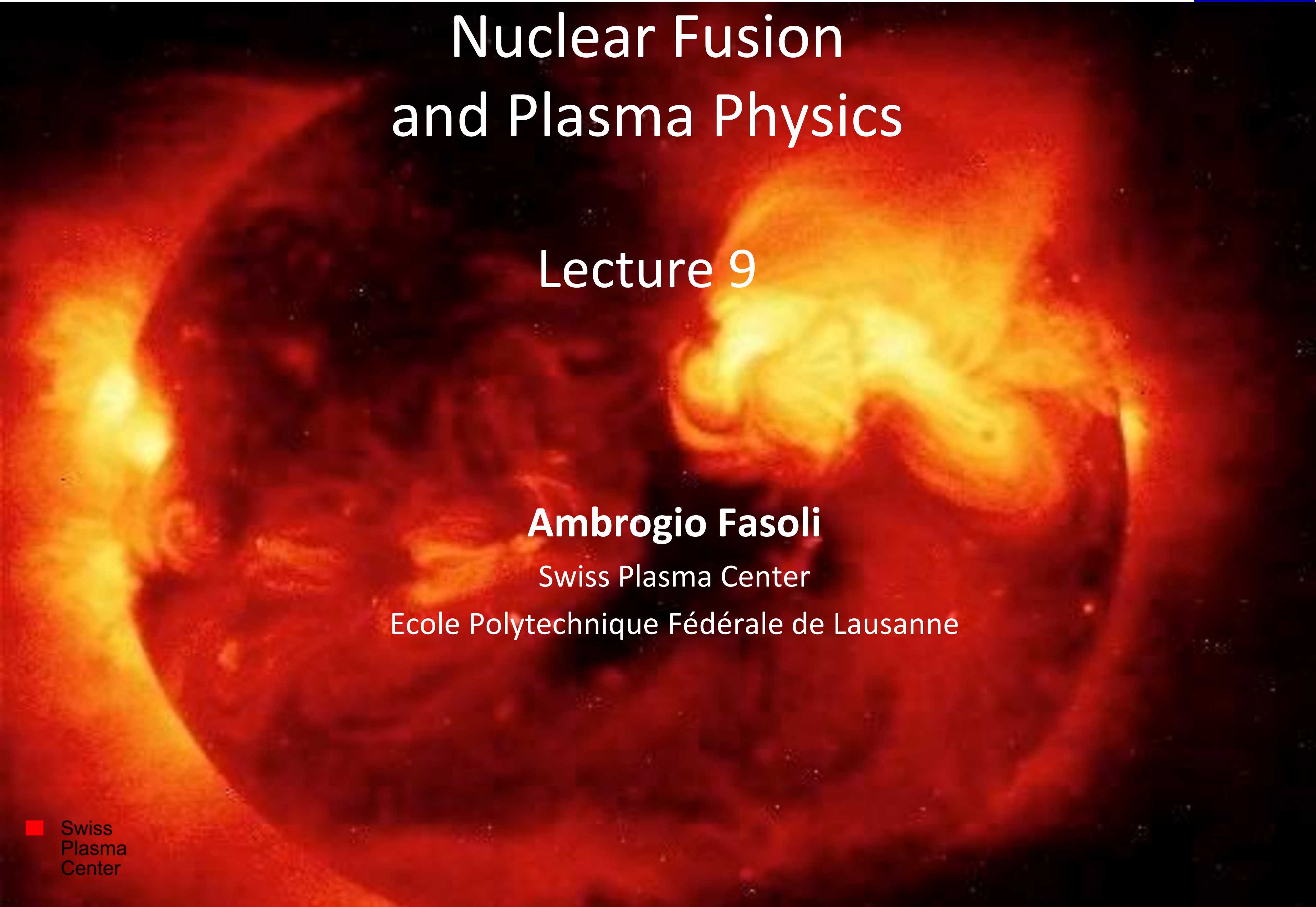


Nuclear Fusion and Plasma Physics

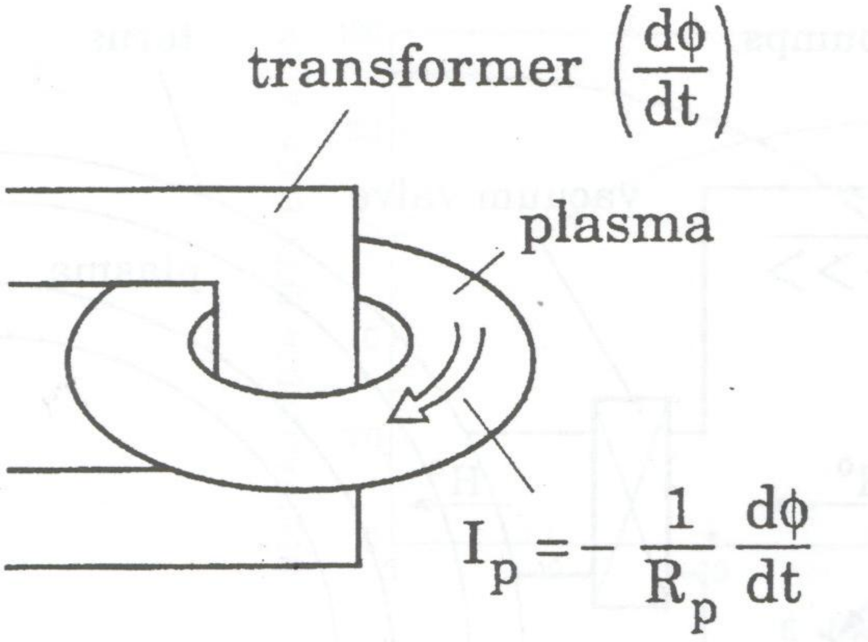
Lecture 9

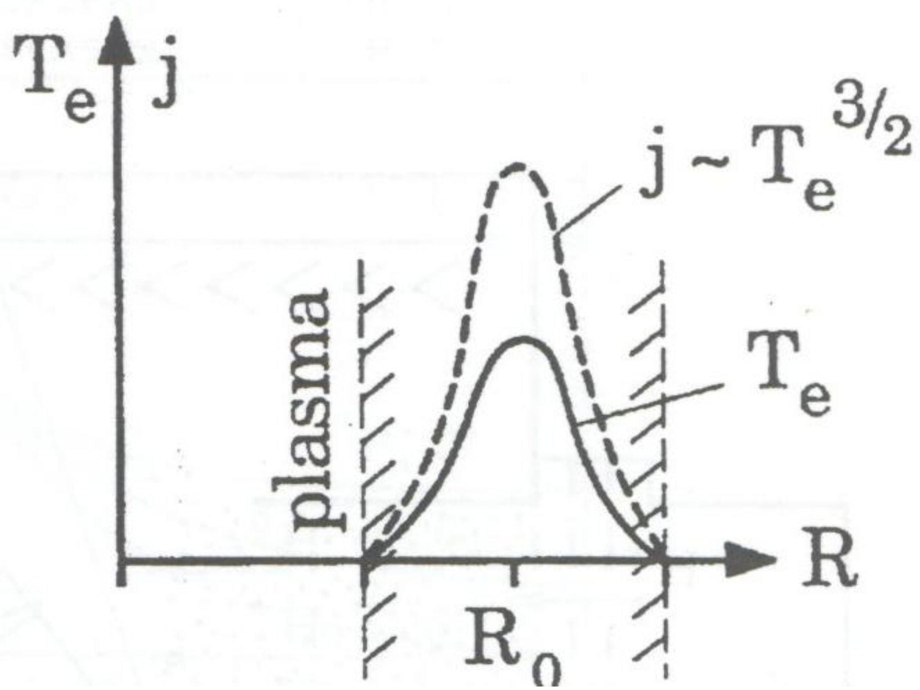
Ambrogio Fasoli
Swiss Plasma Center
Ecole Polytechnique Fédérale de Lausanne

Lay-out

- 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



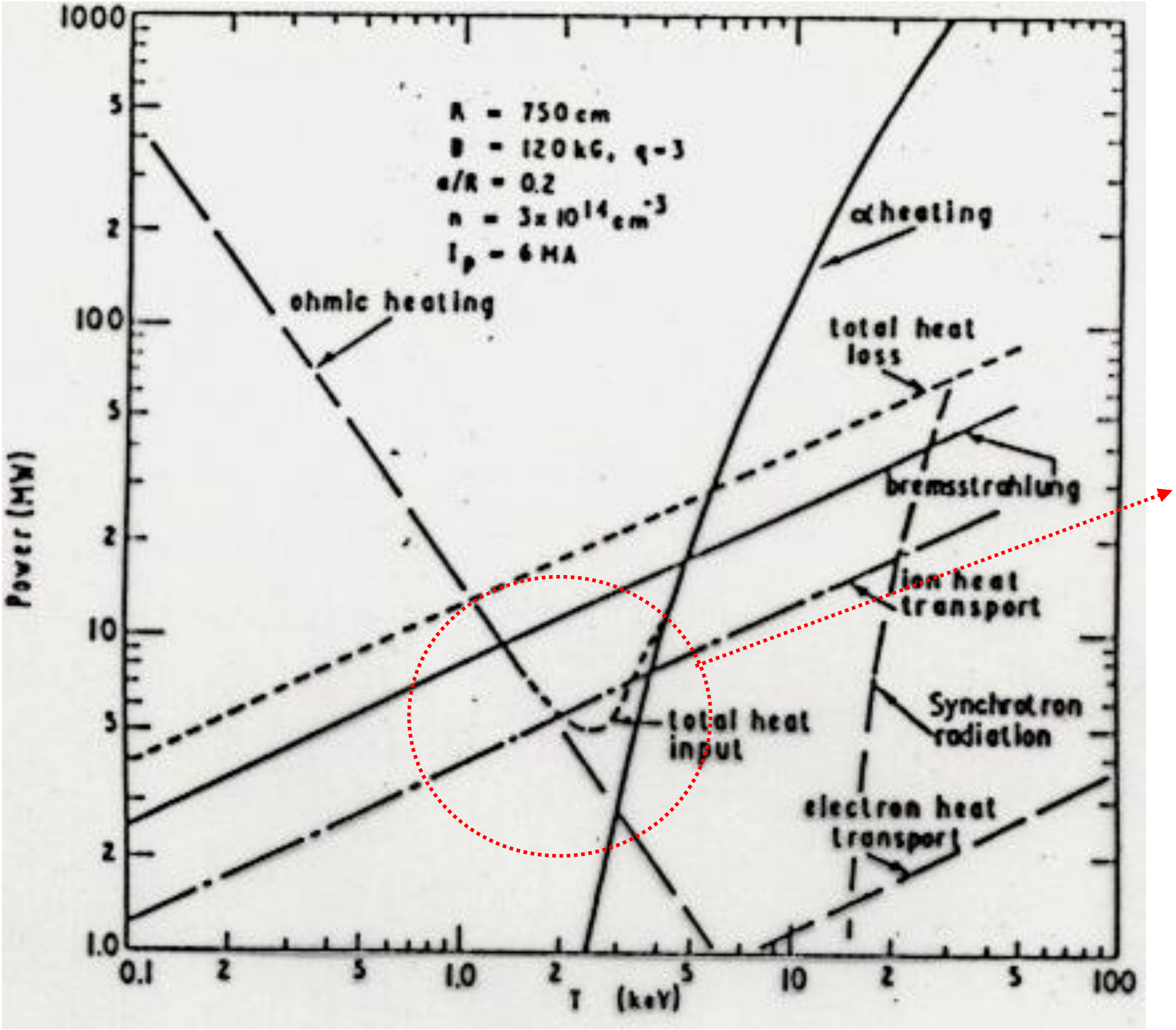


$$P_{ohmic} = V_{loop} \times I_p = R_p \times I_p^2 = \eta j^2$$

$$\eta = \frac{\sqrt{2}}{\pi^{3/2}} \frac{m_e^{1/2} Z e^2 \ln\Lambda}{12 \varepsilon_0^2 T_e^{3/2}} \propto T_e^{-3/2}$$

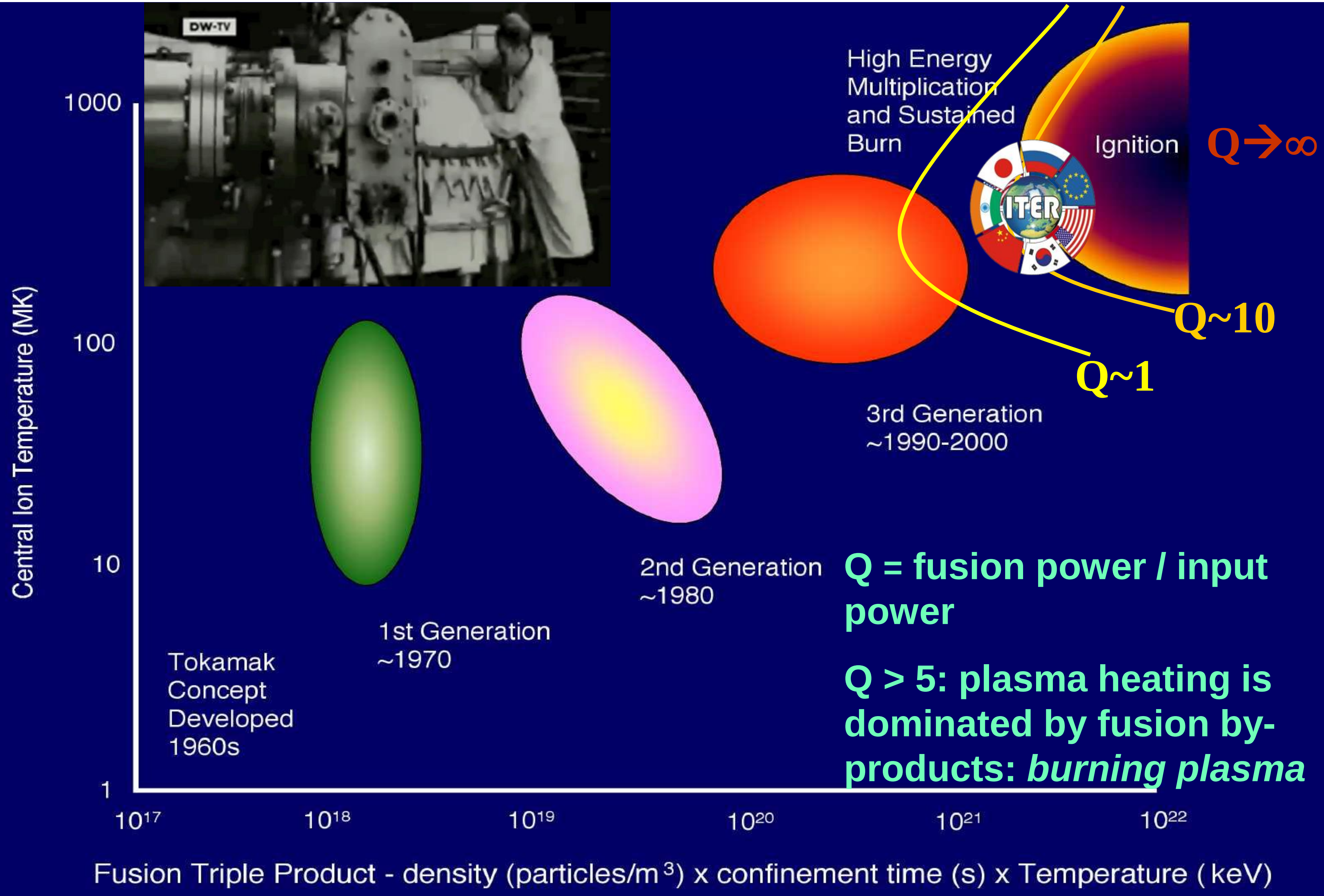
OH heating becomes less and less effective at high T_e

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



Q = fusion power / input power

Q > 5: plasma heating is dominated by fusion by-products: *burning plasma*

ITER

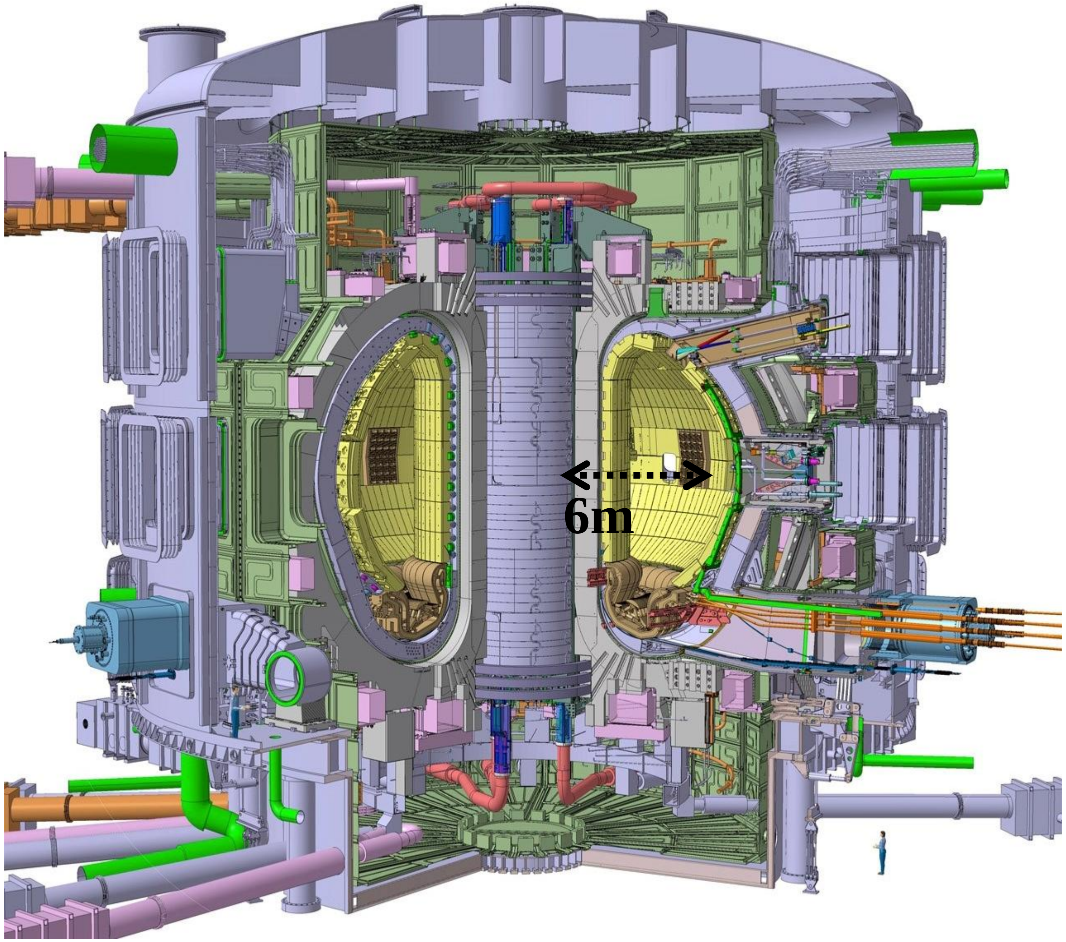
Demonstration of the scientific and technological feasibility of fusion energy for peaceful purposes

Burning plasma

$Q \geq 10$

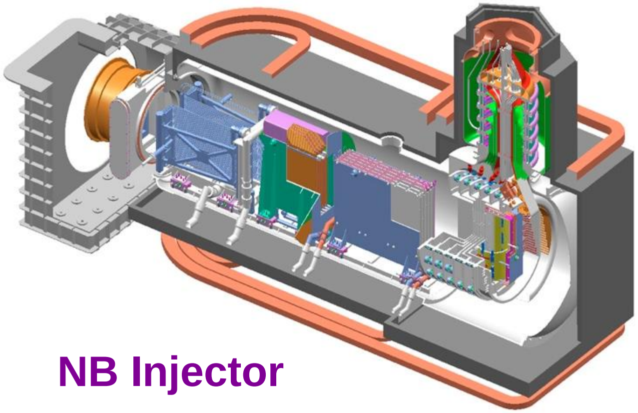
$P_{fusion} \geq$ 500MW

for ~500s

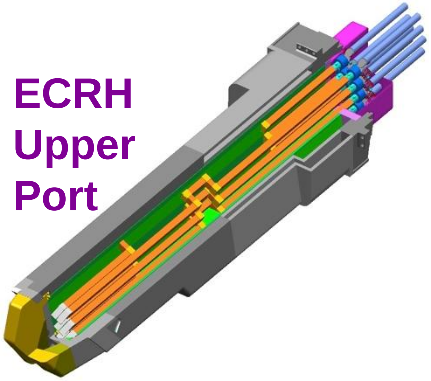


R ~ 6m; B ~ 5T; I_{plasma} ~ 15MA

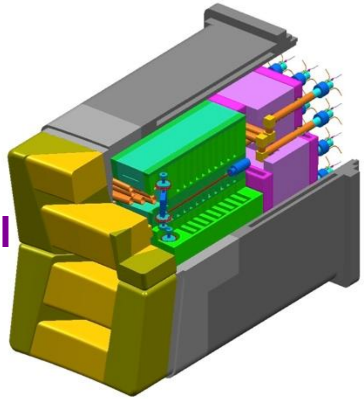
ITER Heating systems



NB Injector

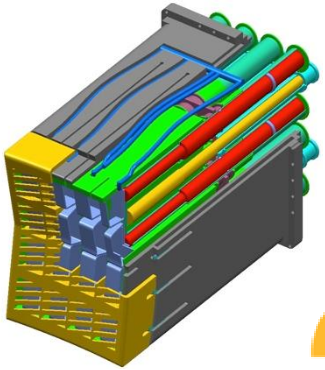


ECRH Upper Port



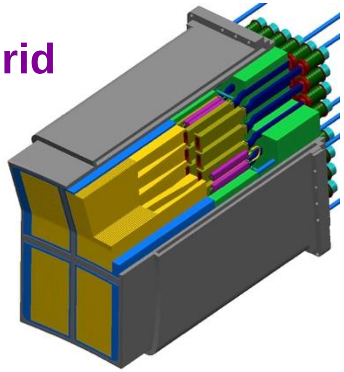
ECRH Lateral Port

System	Power [MW]	Frequency
NBI	33 MW	N/A
ICRH	20 MW	40-55 MHz
LH	*20 MW (second stage)*	*5 GHz*
ECRH	67 MW	170 GHz

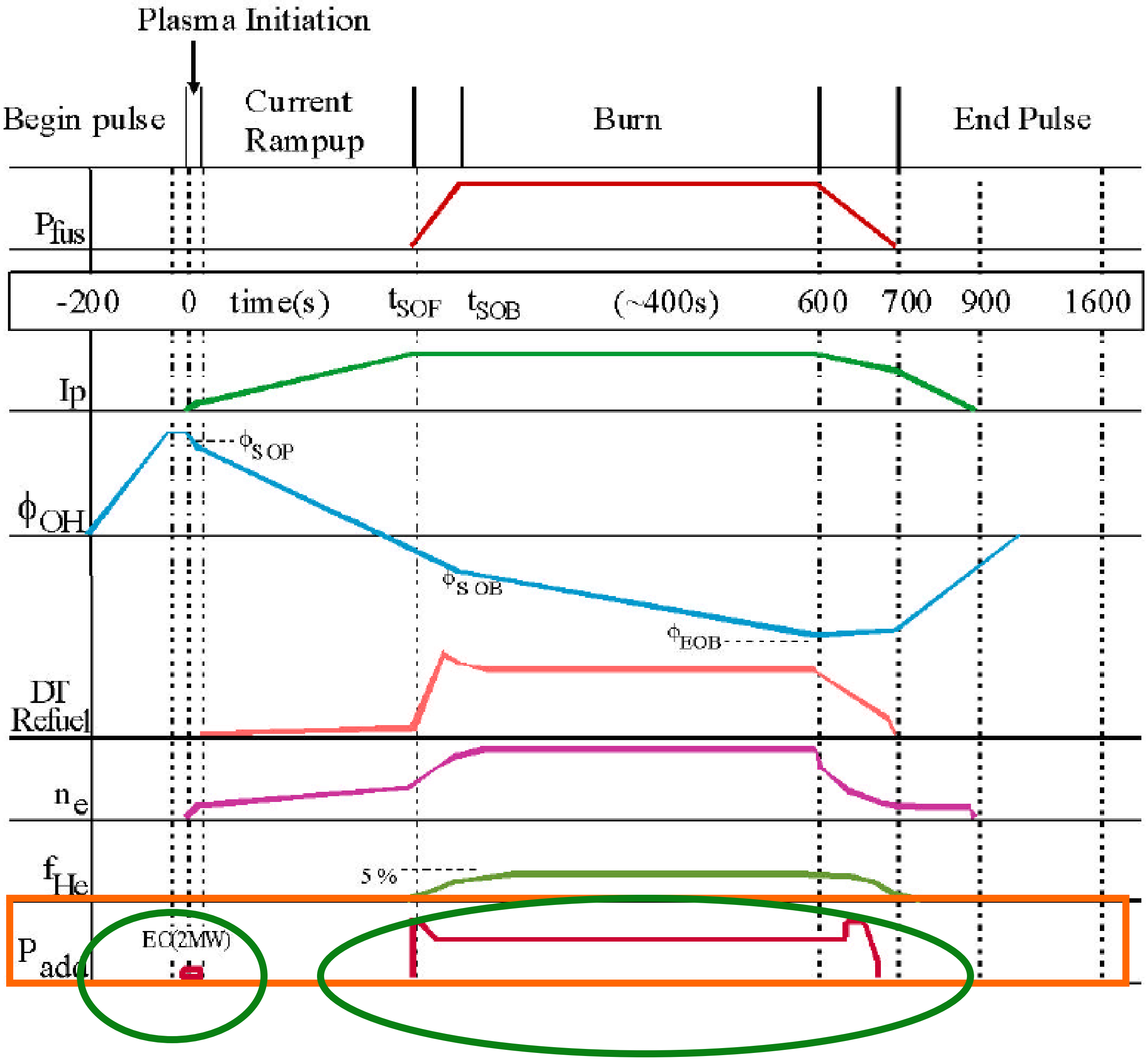


ICRH antenna

Lower Hybrid Launcher

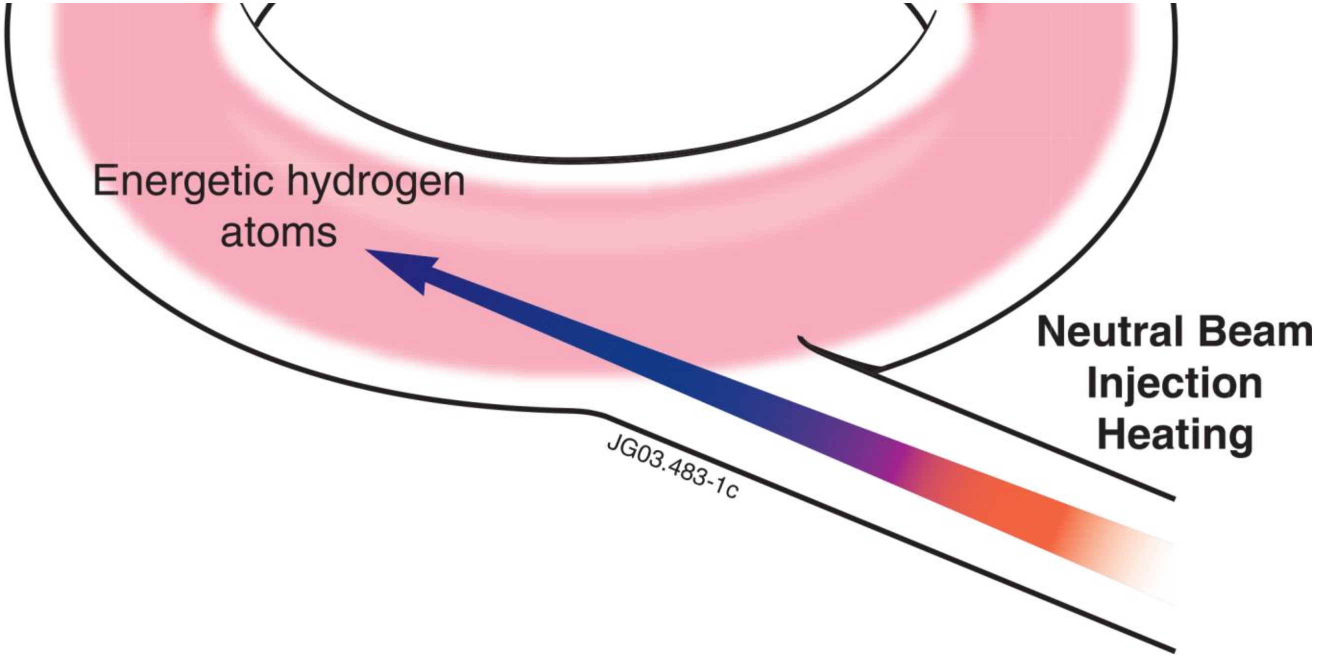


ITER plasma sequence



Heating by neutral beam injection

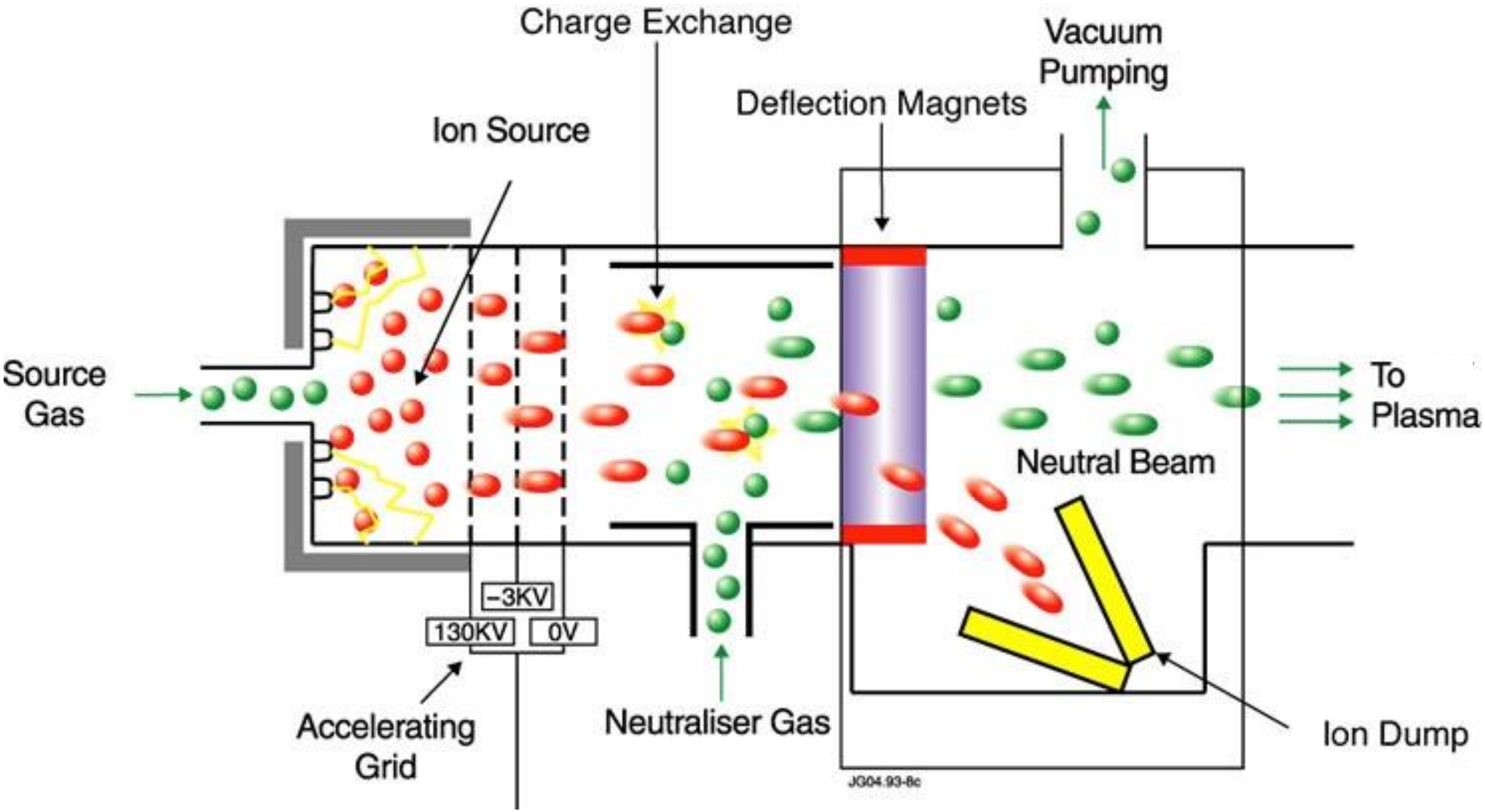
Basic idea of Neutral Beam Heating



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



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Ex. of layout of NB injector in JET

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

Charge exchange: $H_b + H_p^+ \rightarrow H_b^+ + H_p$

Ionization by ions: $H_b + H_p^+ \rightarrow H_b^+ + H_p^+ + e^-$

Ionization by electrons: $H_b + e^- \rightarrow H_b^+ + 2e^-$

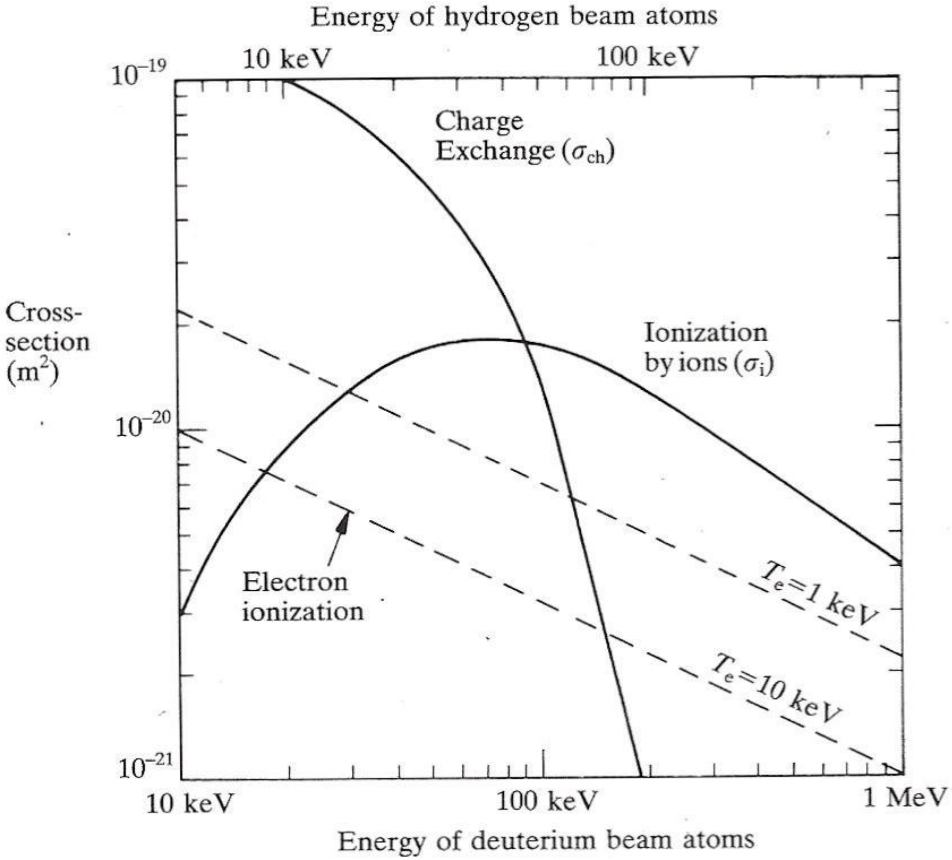
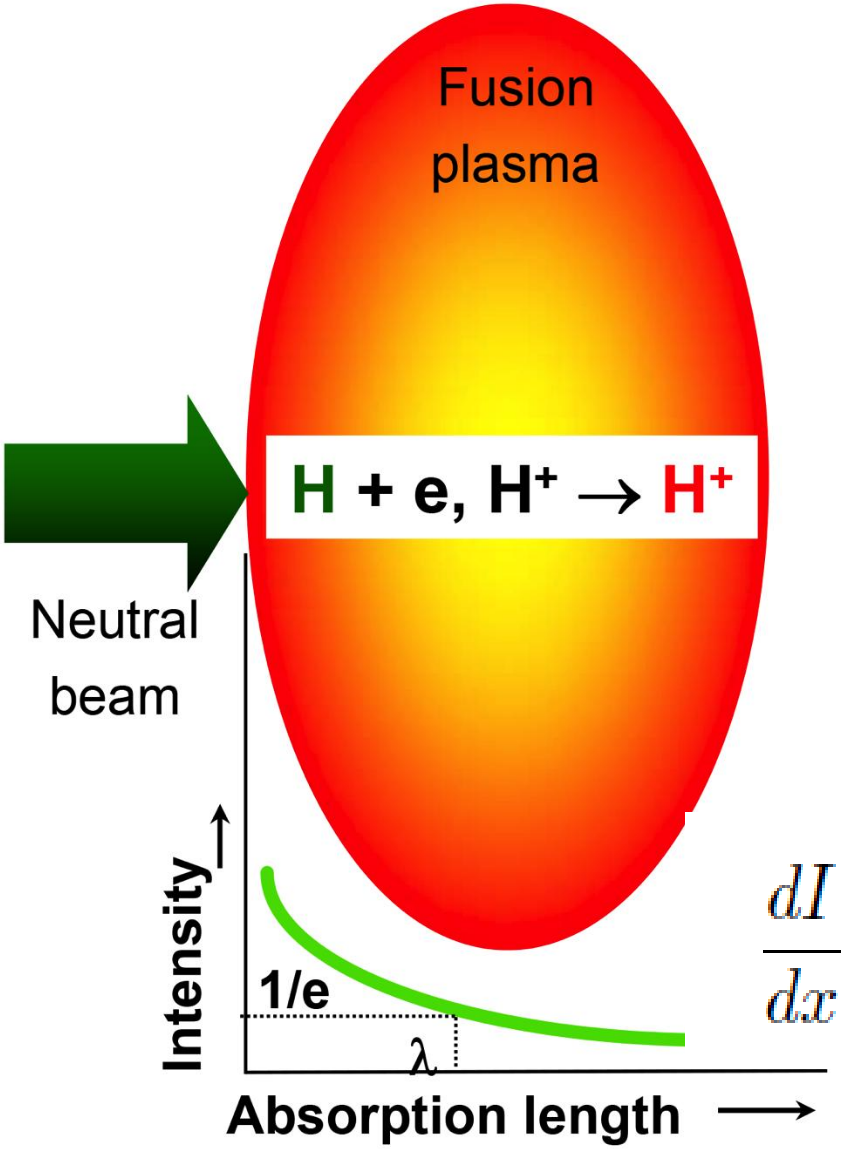


Fig. 5.3.1 Cross-sections for charge exchange and ionization by plasma ions (protons, deuterons, or tritons) and the effective cross-section $\langle \sigma_e v_e \rangle / v_b$ for ionization by electrons, as functions of the neutral beam energy. The cross-sections for a hydrogen beam are the same as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

Evolution of beam intensity



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

λ = penetration distance

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

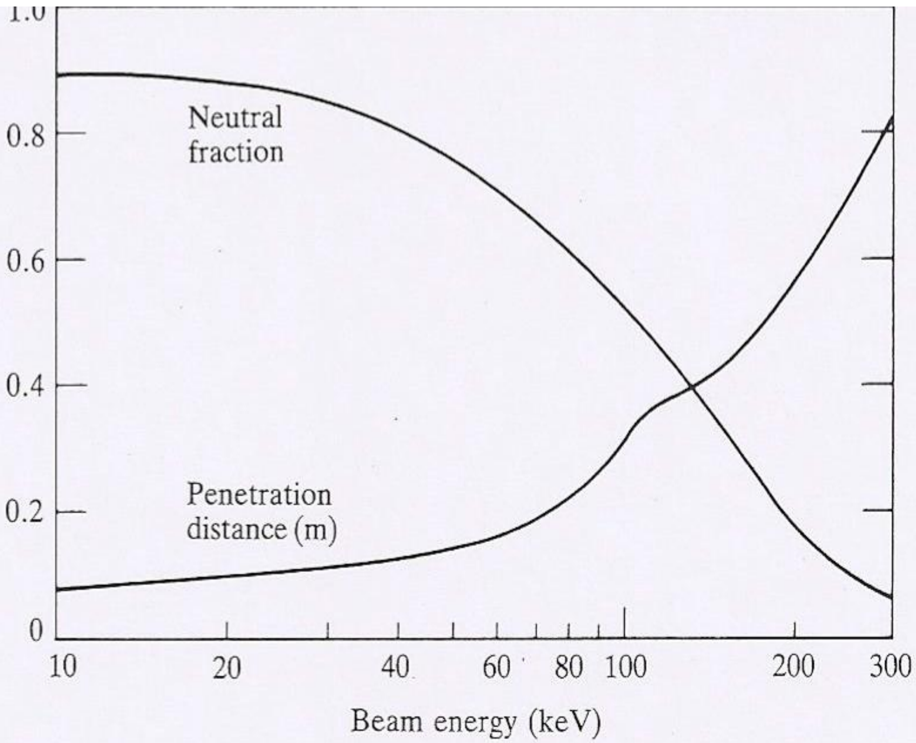
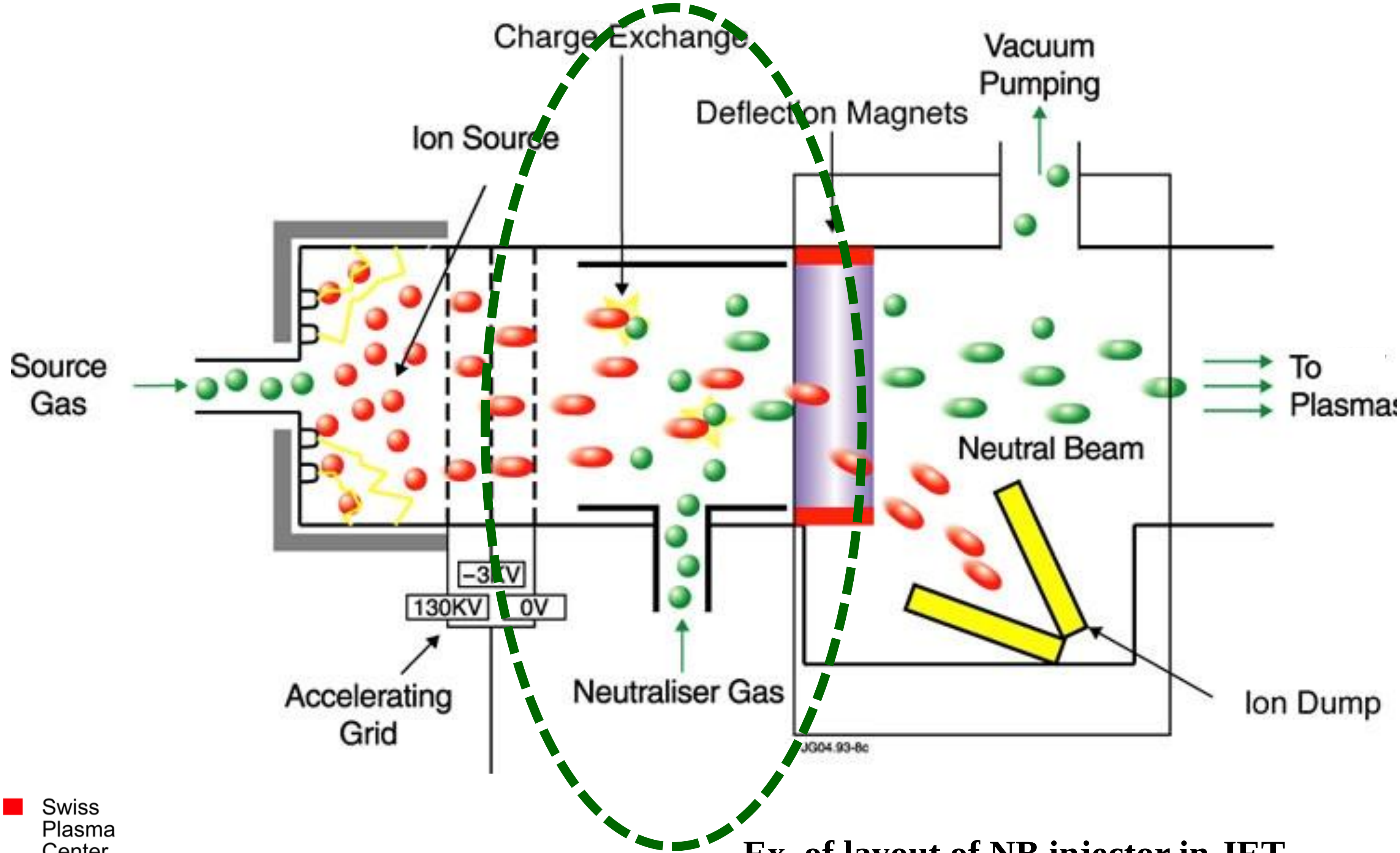


Fig. 5.5.3 Graphs showing the energy dependence of (i) the equilibrium neutral fraction in a deuterium beam and (ii) the penetration distance of the neutrals in a plasma of density $n = 10^{20}\,\mathrm{m}^{-3}$. The change of behaviour of the penetration distance at around 100 keV indicates the transition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

For large plasma (>1m) we need high beam energies (>300keV)

Neutral Beam Injector Neutralisation



Ex. of layout of NB injector in JET

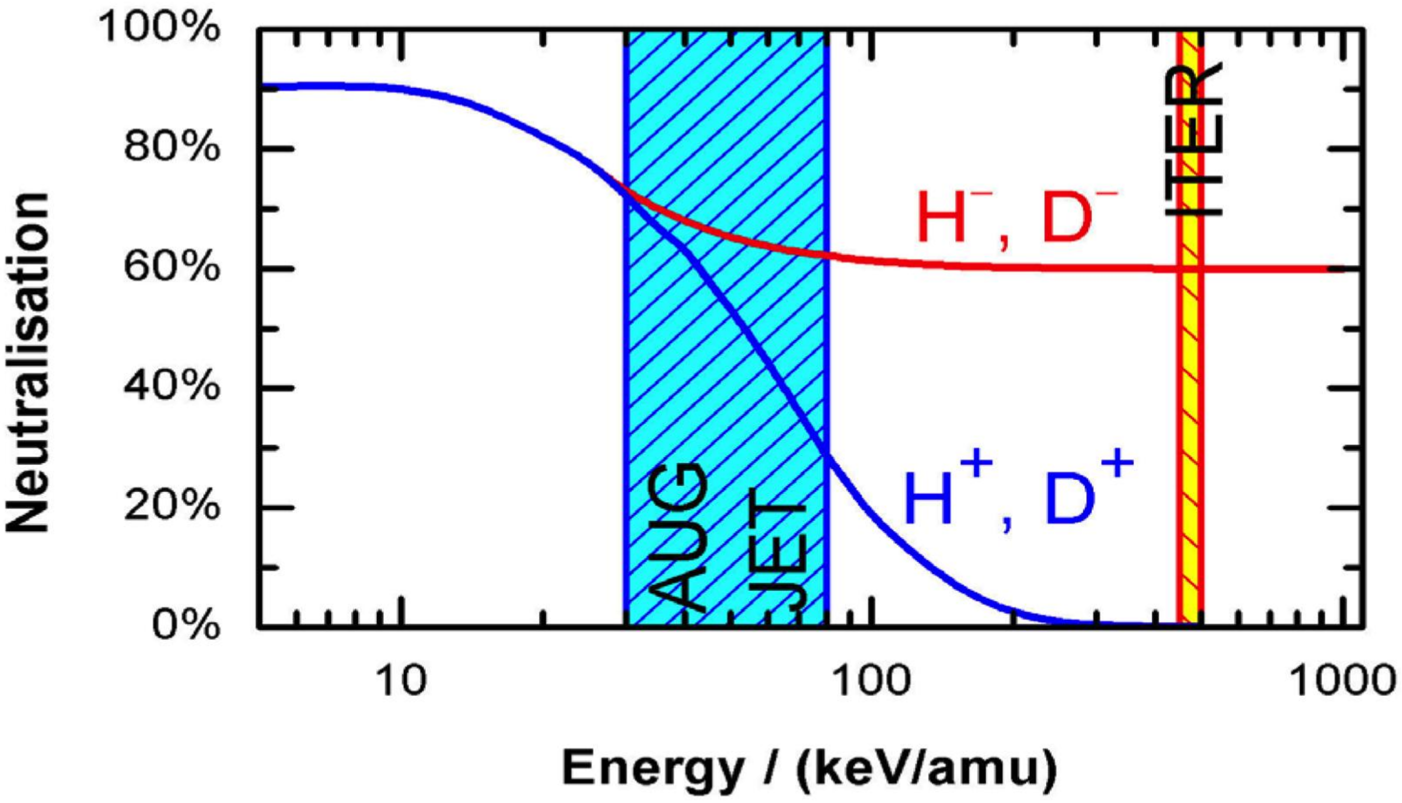
EPFL

NBI: neutralisation efficiency

Efficiency for positive ions goes down for high energies

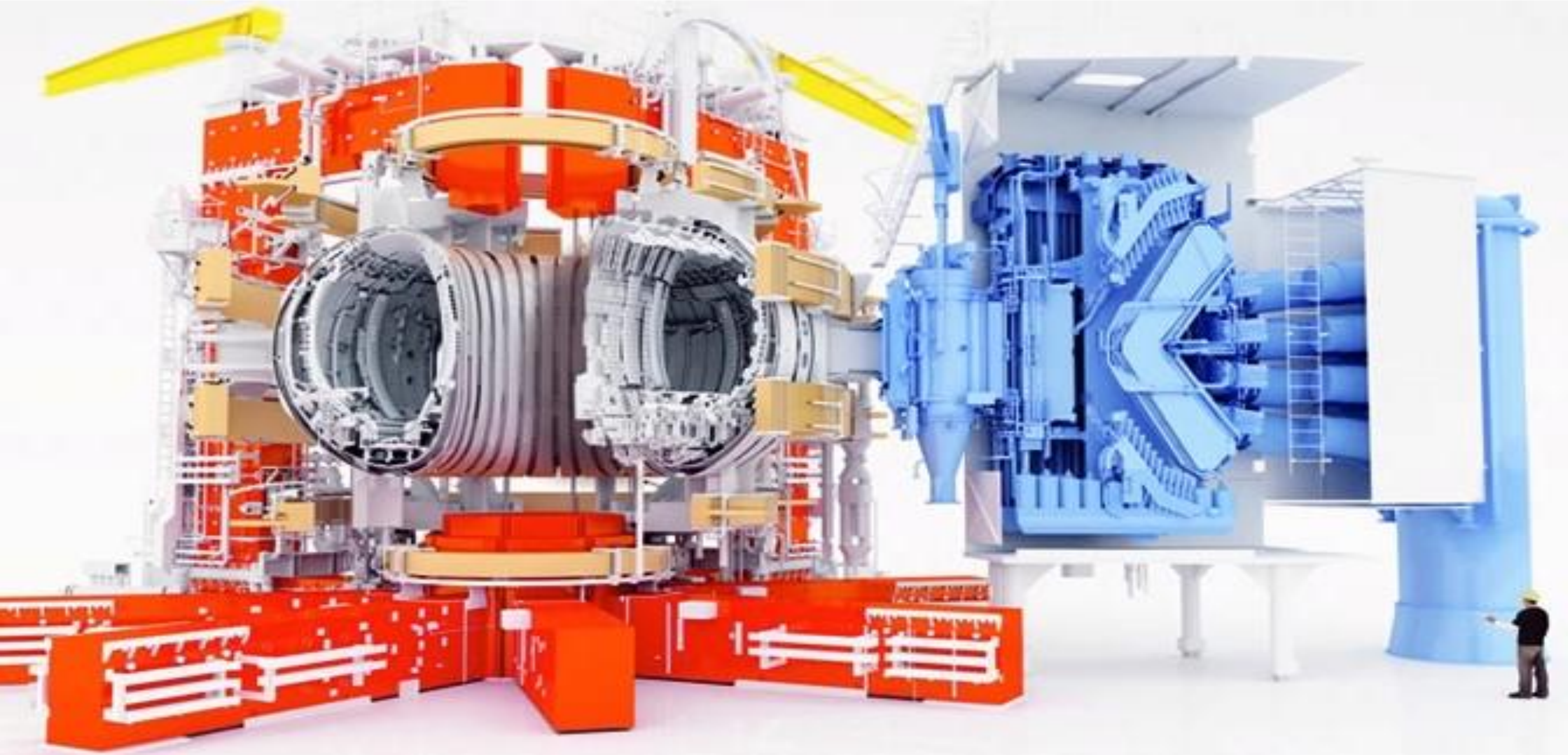
Negative ion neutralisation easier due to low affinity (0.75eV) of additional electron: $H^- + H_2 = H + H_2 + e^-$

For large, dense plasmas we need negative ion beams

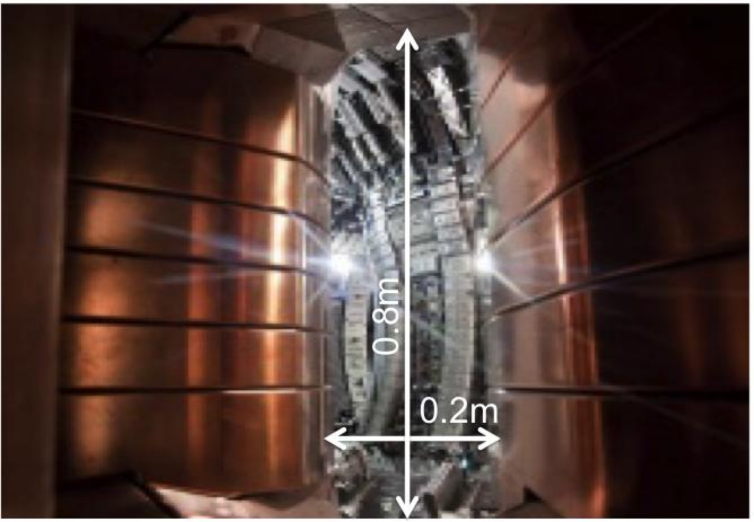


NBI in JET

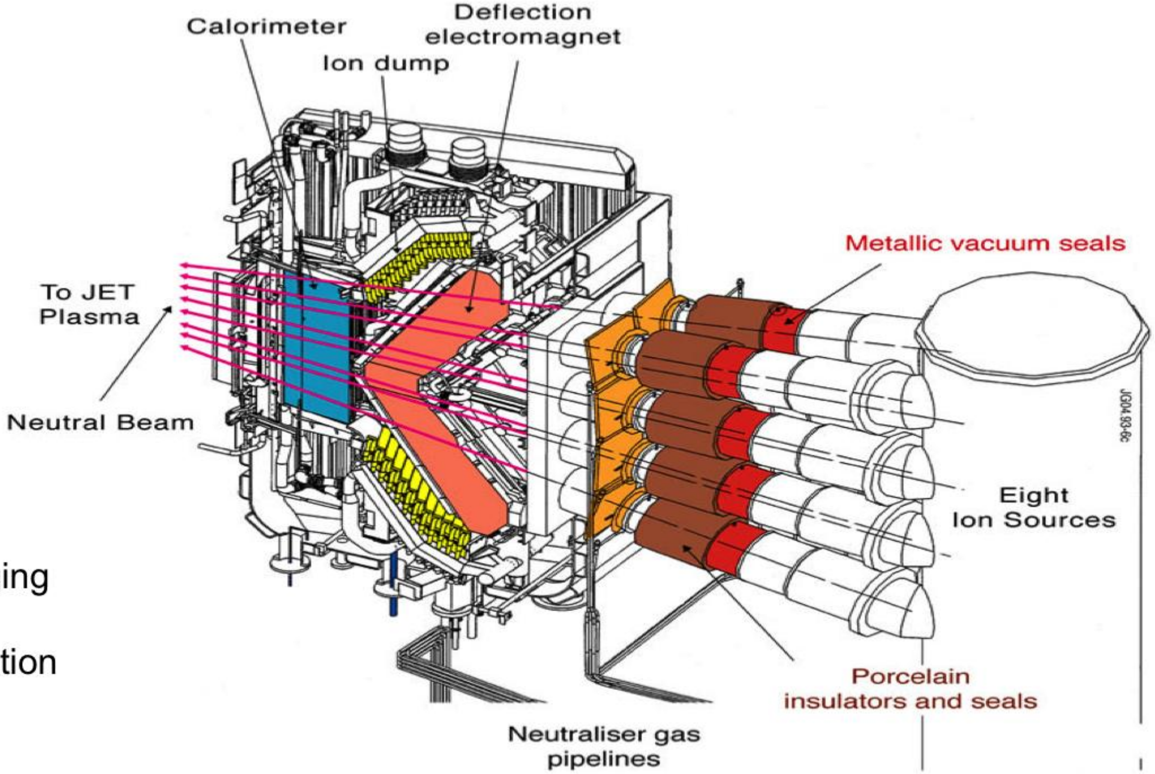
Radial and tangential injection; 2x8 injectors 80keV (H^+), 130keV (D^+) – up to 34MW



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

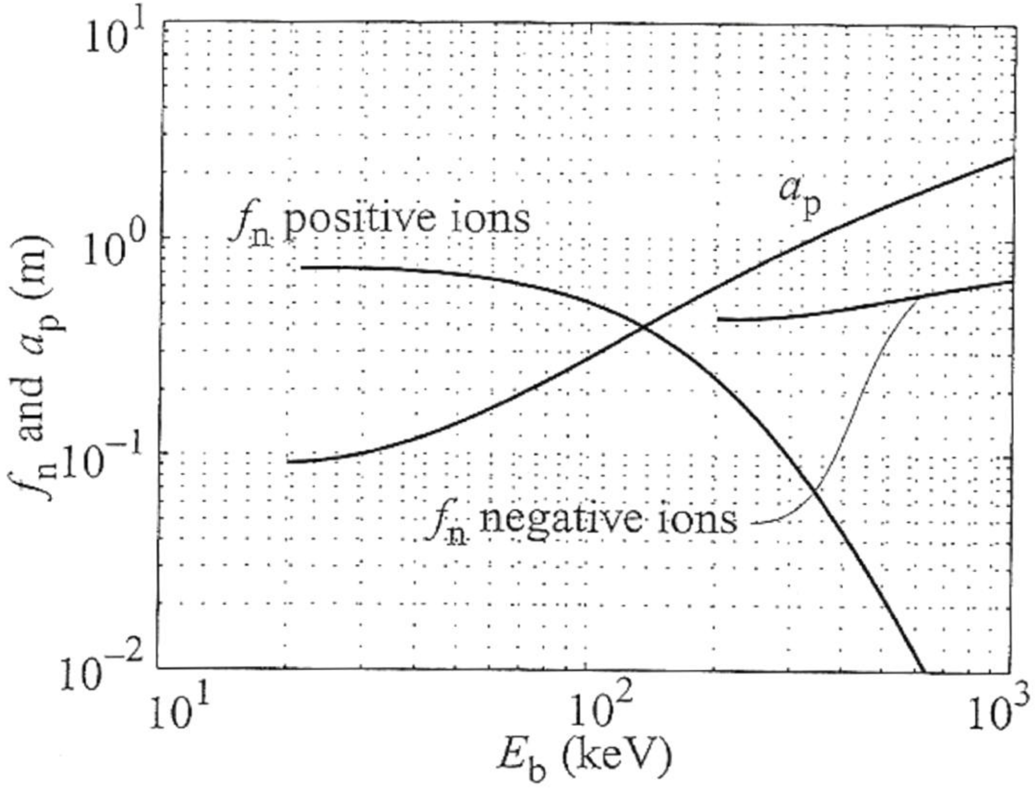


Figure 15.5 Neutralization fraction vs. beam energy for positive and negative ion beams. Also plotted is the penetration depth for $n_{20} = 1.5$. (Wesson, J. (2004). *Tokamaks*, third edition. Oxford: Clarendon Press).

Which species will be heated by the beam?

Collisional Theory: the energy transfer from fast ions (originating from a beam) to the plasma particles (electrons and ions) results in plasma heating. This process is governed by collisional interactions.

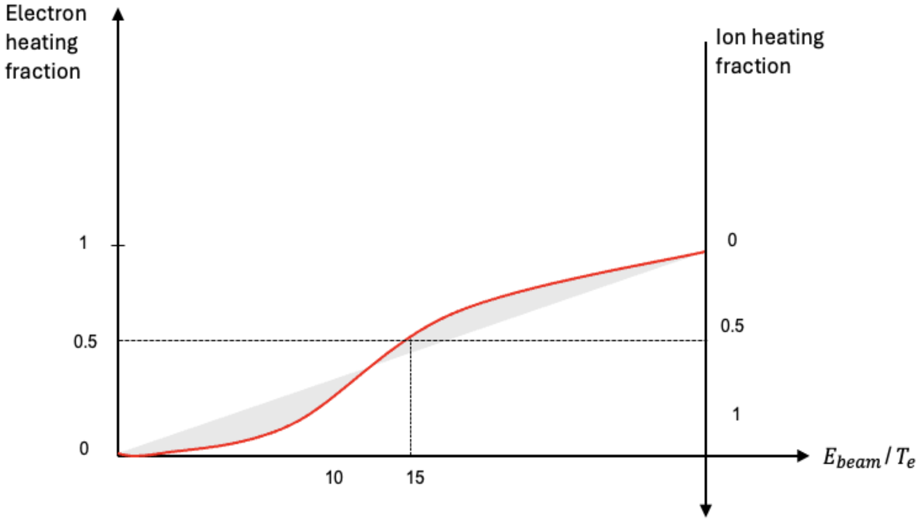
$$P = -\frac{2\,E_{\text{beam}}}{\tau_{\text{SD}}}\left[1 + \left(\frac{E_{\text{crit}}}{E_{\text{beam}}}\right)^{3/2}\right]$$

Where:

- P: Power transferred to the plasma.
- I: Current of the ion beam.
- E_{beam} : Energy of the fast ions in the beam.
- τ_{SD} : Slowing down time, the time it takes for the fast ions to lose energy through collisions.
- E_{crit} : Critical energy at which the heating of electrons and ions is balanced.

The **critical energy** $E_{\text{crit}} \approx 15\,T_e\left[\frac{M_{beam}}{m_e}\sum\frac{n\cdot Z_i^2}{n_e}\right] \approx 15\,T_e$ is the energy at which the heating of the electrons is equivalent to that of the ions.

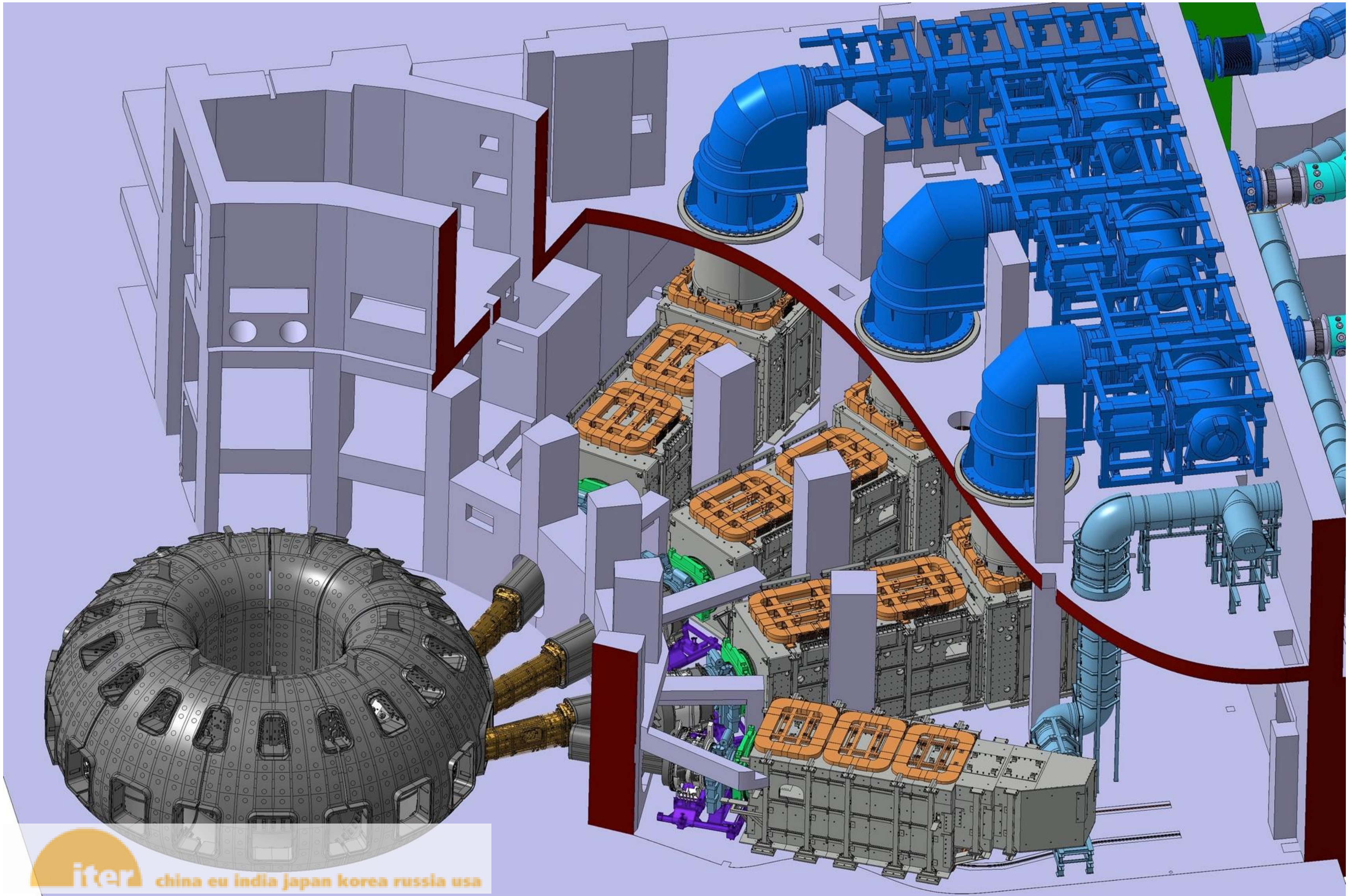
- When $E_{\text{beam}} \gg E_{\text{crit}}$: heating mainly of the **electrons** (often encountered in large devices)
- When $E_{\text{beam}} \ll E_{\text{crit}}$: heating mainly of the **ions** (current plasma devices)



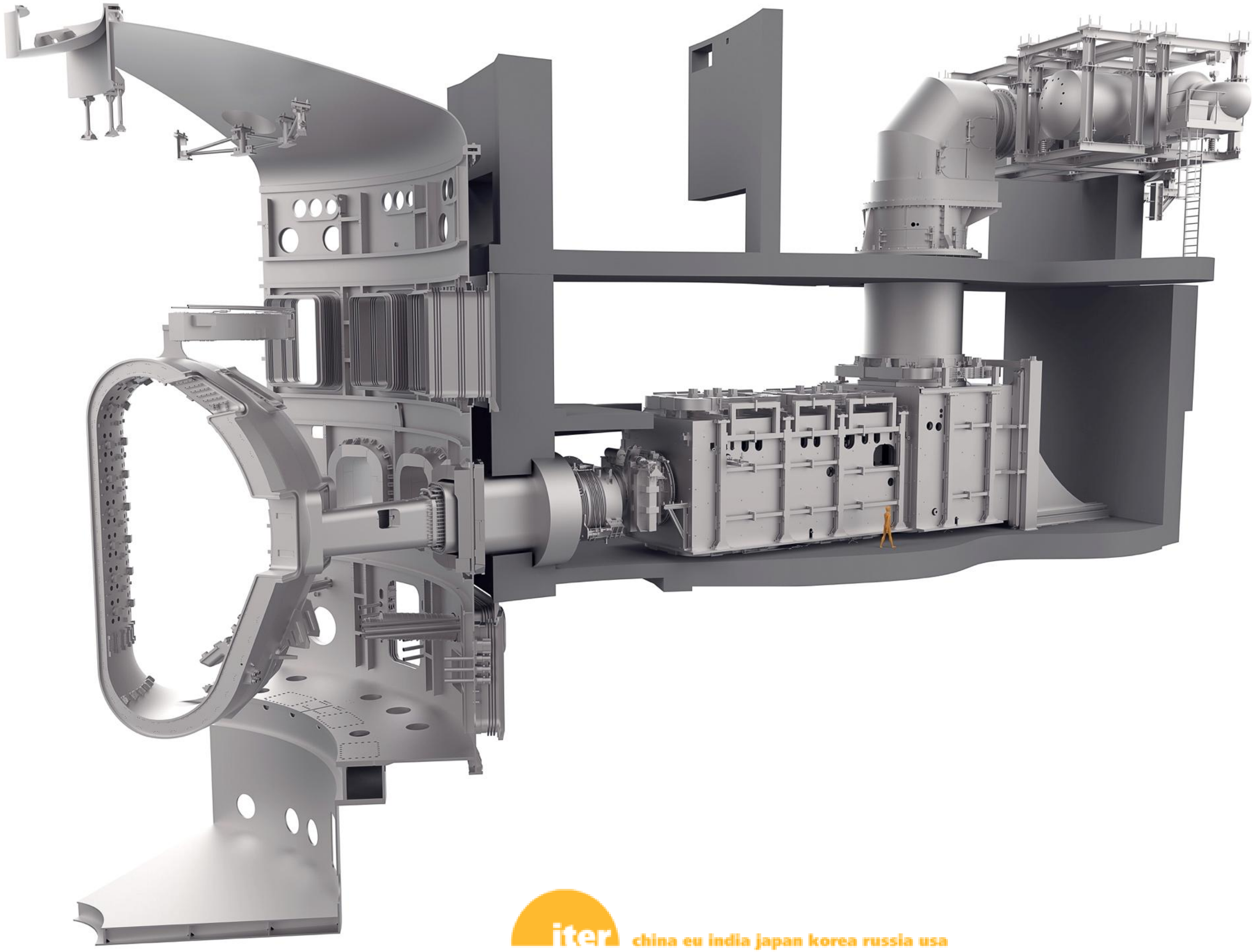
ITER neutral beams for H&CD, diagnostic

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

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



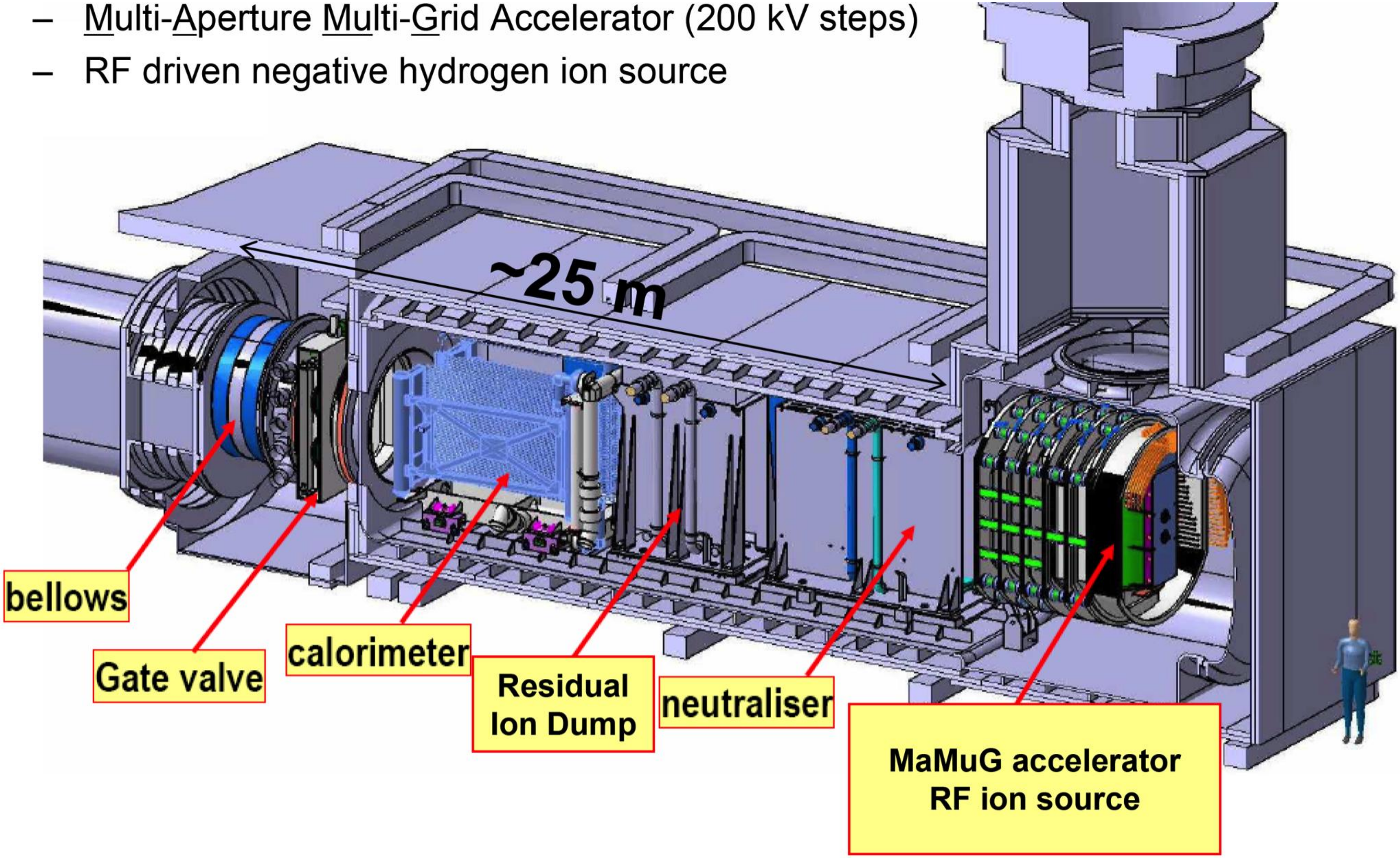
ITER neutral beams for H&CD, diagnostic



iter china eu india japan korea russia usa

ITER neutral beams for H&CD, diagnostic

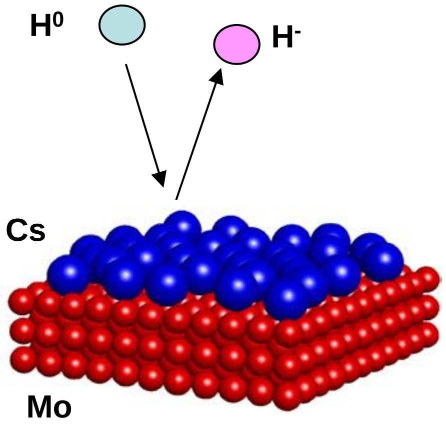
- Multi-Aperture Multi-Grid Accelerator (200 kV steps)
- RF driven negative hydrogen ion source

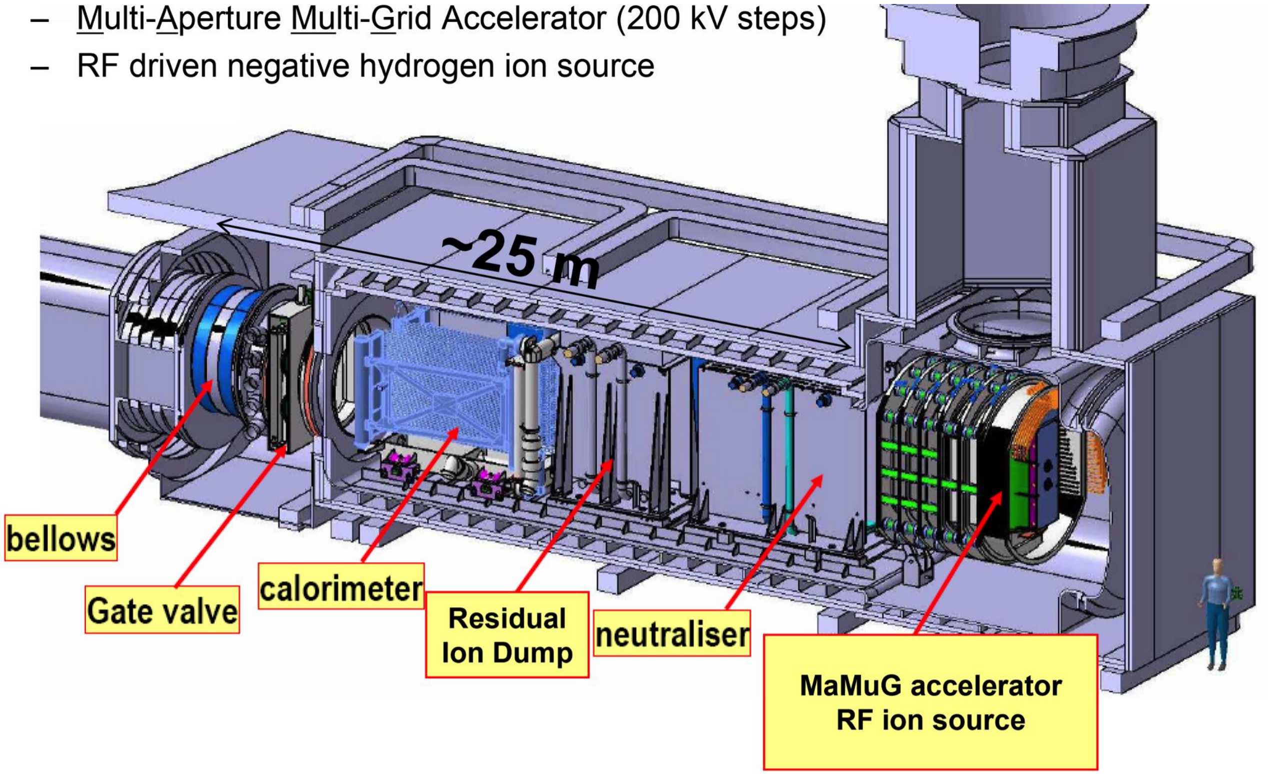


Large current density (~300A/m^2), high uniformity (±10%) over ~2m^2

ITER neutral beams for H&CD, diagnostic

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





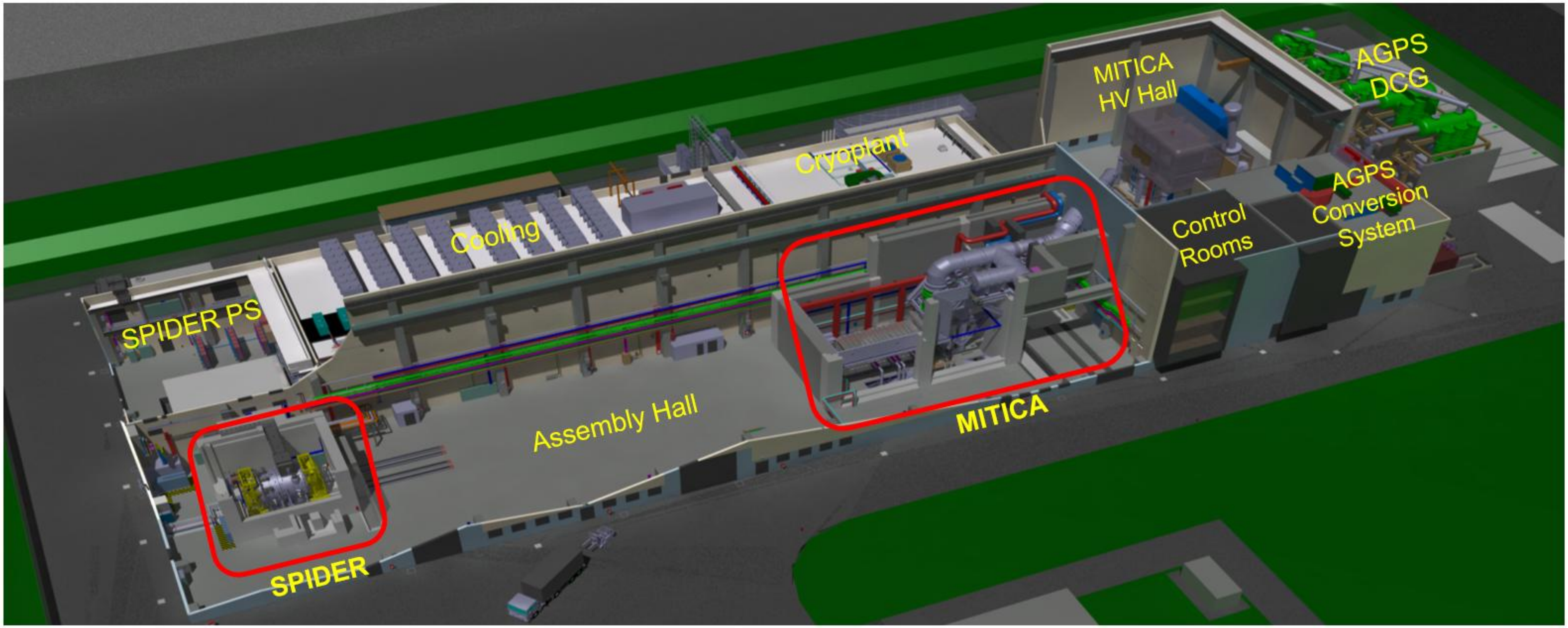
Negative ions are produced on Cs-adsorbed surfaces with low work function
Atoms and ions interact with a surface, capturing electrons to form H-

ITER neutral beams for H&CD, diagnostic

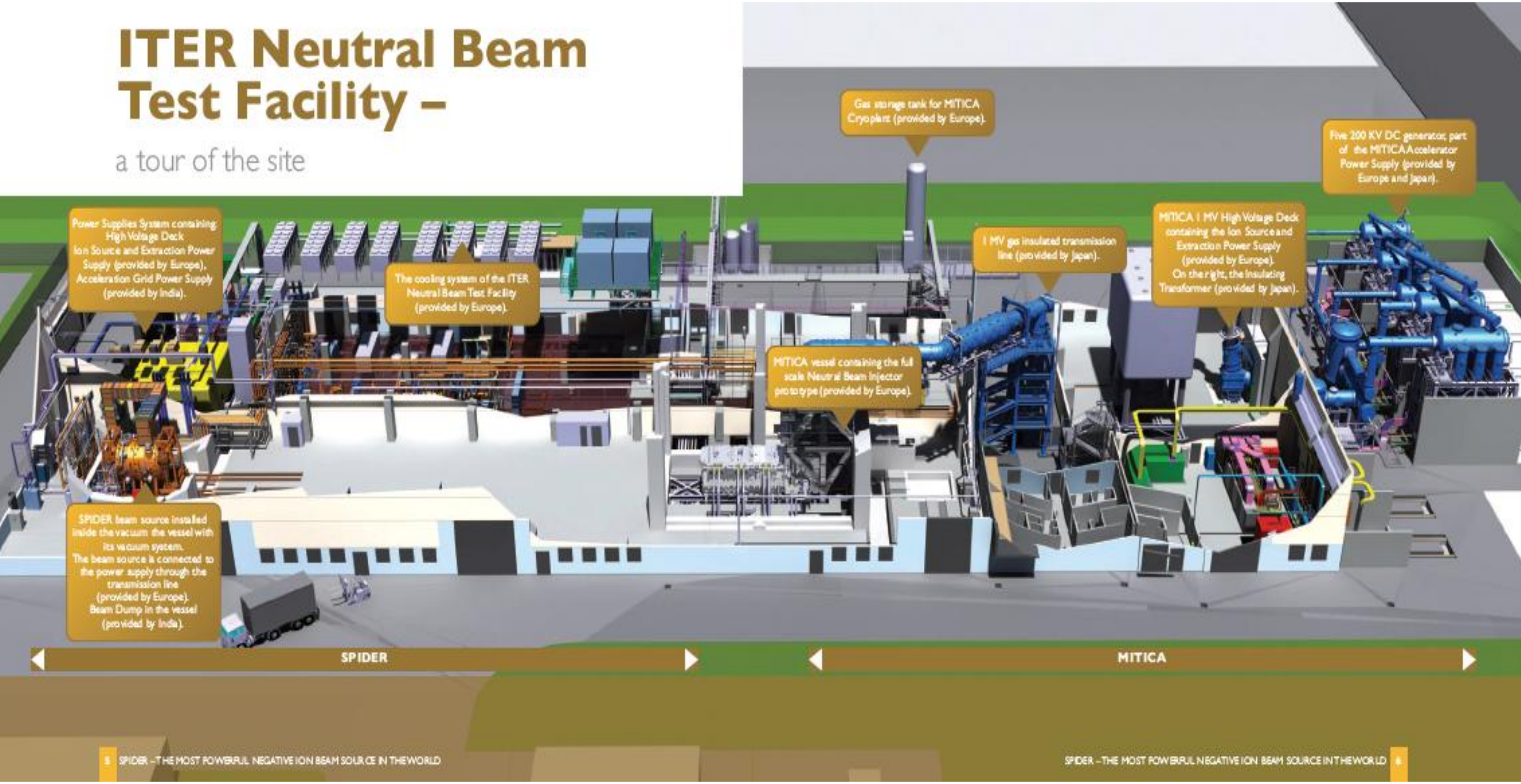
The Neutral Beam Test Facility at Padua

SPIDER – full size ITER beam source

MITICA – prototype ITER beamline



ITER neutral beams for H&CD, diagnostic



ITER Neutral Beam Test Facility –

a tour of the site

Power Supplies System containing High Voltage Deck Ion Source and Extraction Power Supply (provided by Europe), Acceleration Grid Power Supply (provided by India).

The cooling system of the ITER Neutral Beam Test Facility (provided by Europe).

Gas storage tank for MITICA Cryoplant (provided by Europe).

1 MV gas insulated transmission line (provided by Japan).

MITICA 1 MV High Voltage Deck containing the Ion Source and Extraction Power Supply (provided by Europe). On the right, the Insulating Transformer (provided by Japan).

Five 200 KV DC generator, part of the MITICA Accelerator Power Supply (provided by Europe and Japan).

MITICA vessel containing the full scale Neutral Beam Injector prototype (provided by Europe).

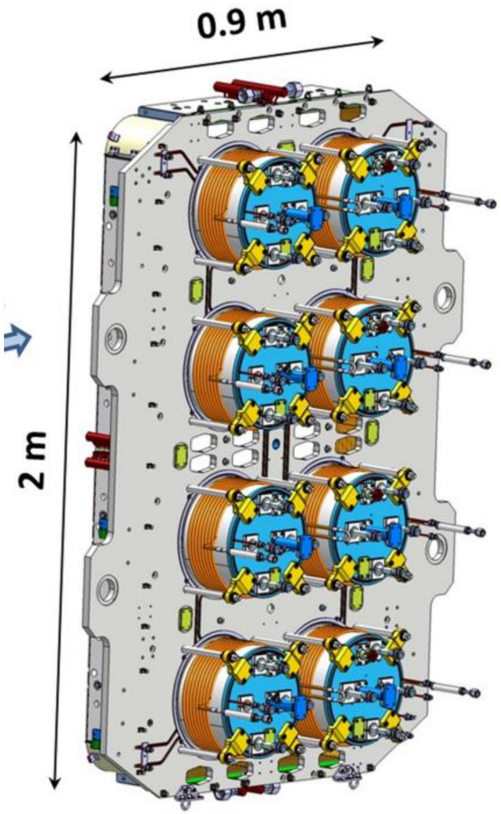
SPIDER beam source installed inside the vacuum the vessel with its vacuum system. The beam source is connected to the power supply through the transmission line (provided by Europe). Beam Dump in the vessel (provided by India).

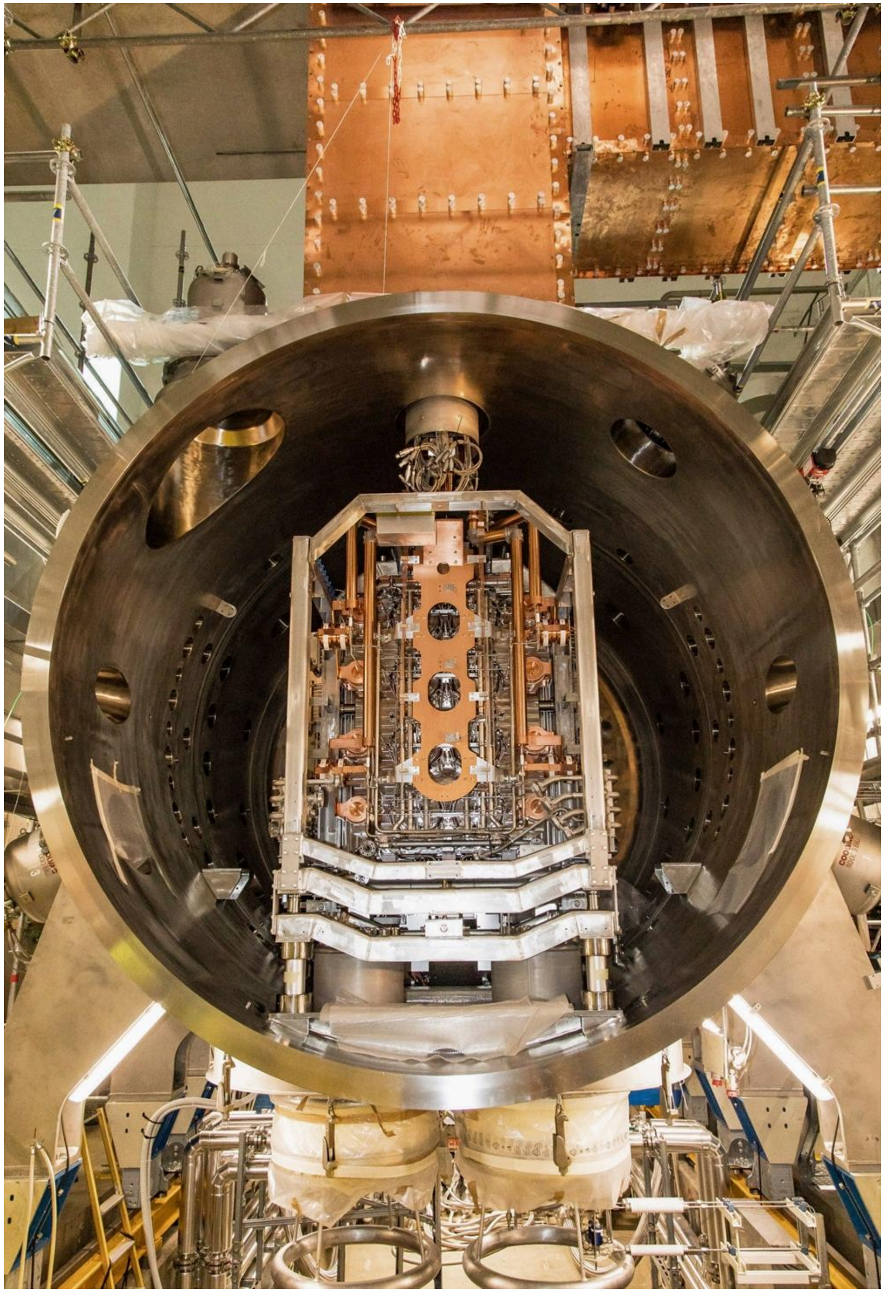
5 SPIDER – THE MOST POWERFUL NEGATIVE ION BEAM SOURCE IN THE WORLD

SPIDER – THE MOST POWERFUL NEGATIVE ION BEAM SOURCE IN THE WORLD 6

ITER neutral beams for H&CD, diagnostic

SPIDER H- beam RF-source





EUROfusion

Swiss
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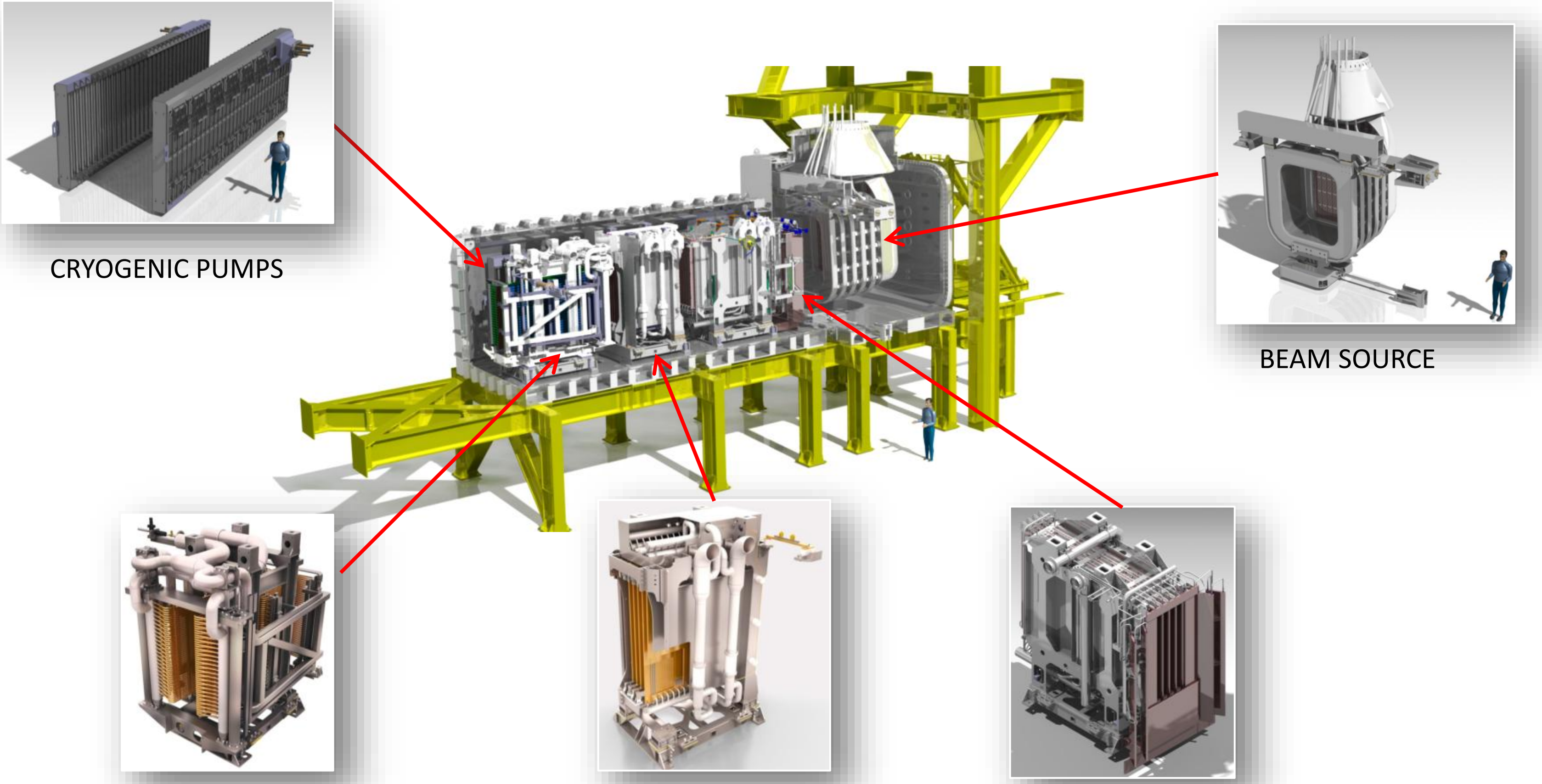
iter china eu india japan korea russia usa

ITER neutral beams for H&CD, diagnostic

MITICA



CRYOGENIC PUMPS

BEAM SOURCE

CALORIMETER

RESIDUAL ION DUMP

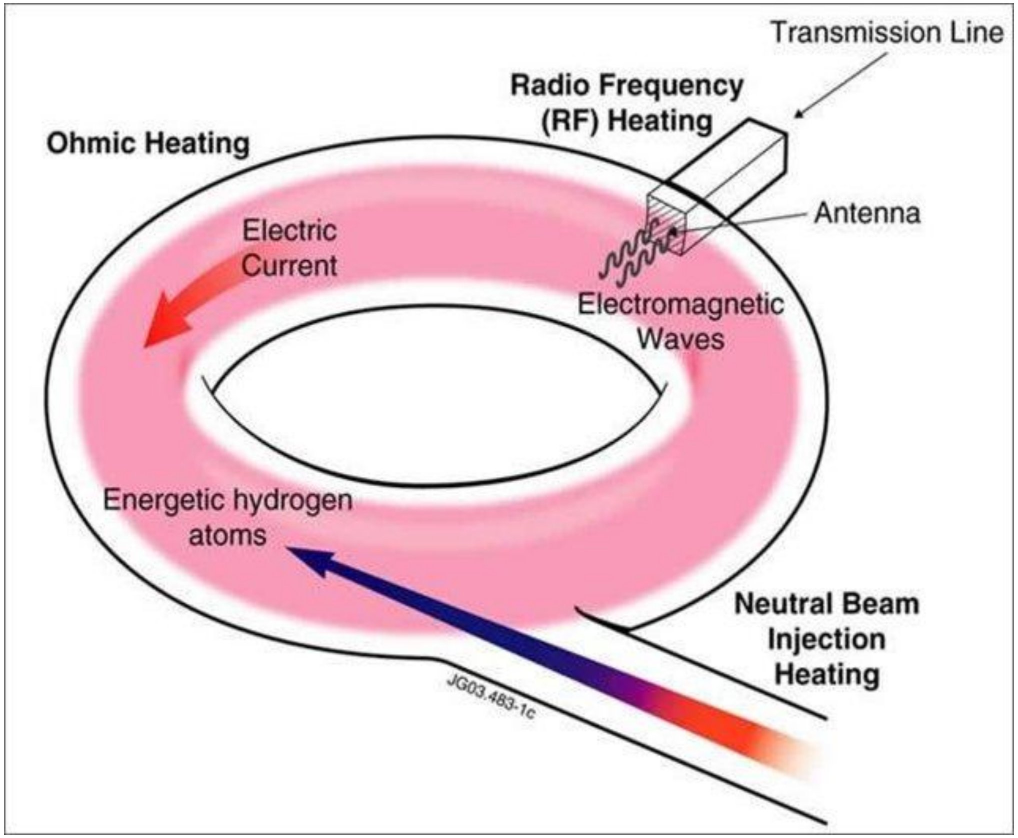
NEUTRALIZER

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 ~MeV ions, then thermalised by collisions

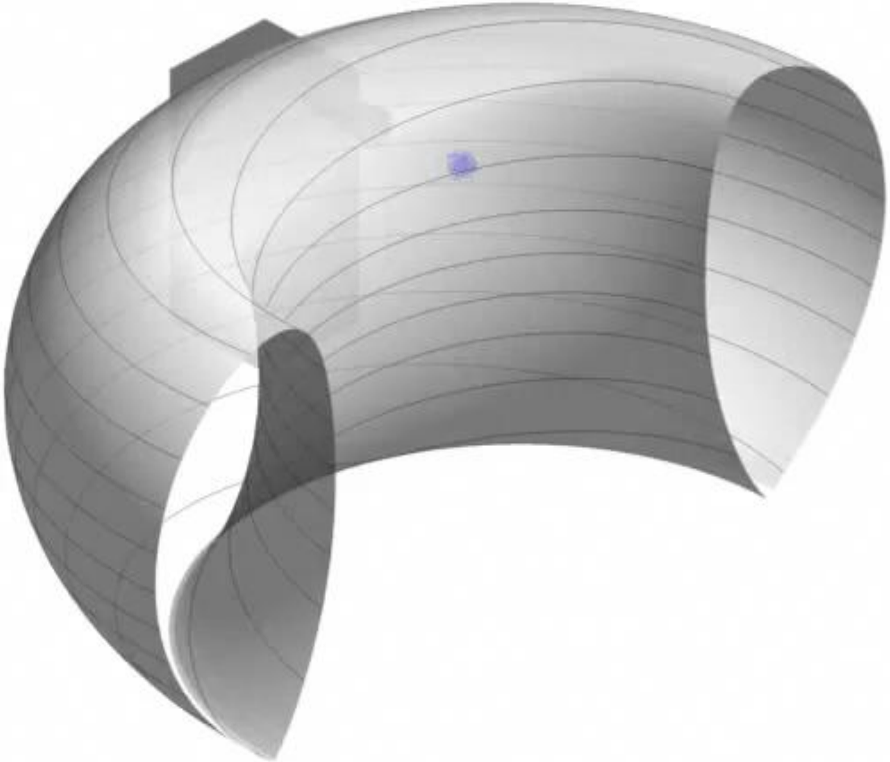


Energetic ions from Neutral Beam Injection

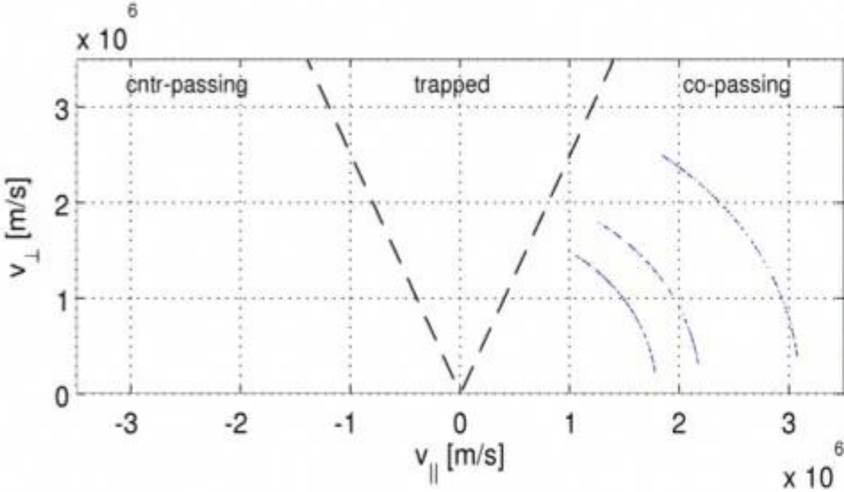
Ions at ~100keV in present devices, ~1MeV in ITER

Injection geometry determines initial orbits

- If tangential, mostly passing orbits, collisions scatter into trapped



Mattia Albergante

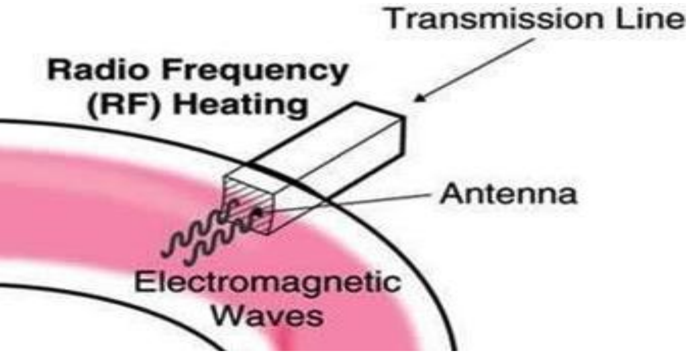


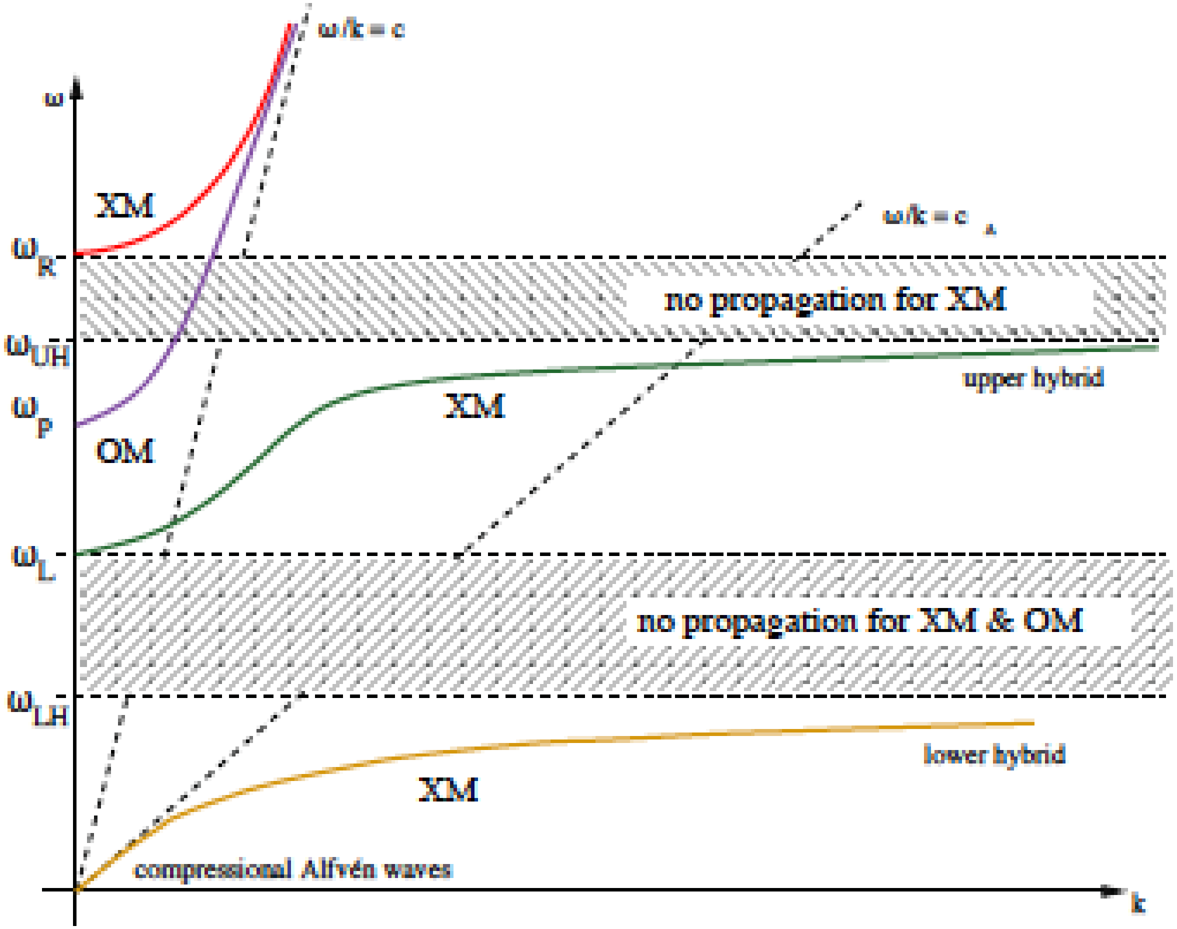
Heating by waves

Heating by waves

Reminder of waves dispersion relation (T ~ 0)

Perpendicular to $\mathbf{B_0}$





Heating by waves

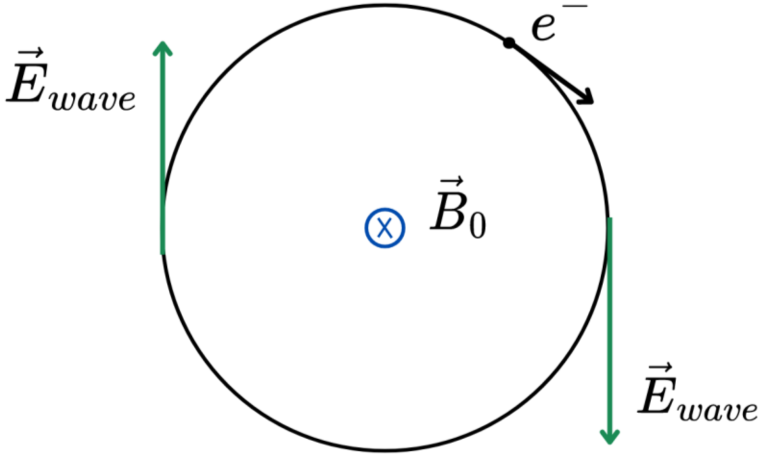
If T >> 0 (hot plasma - kinetic model needed)

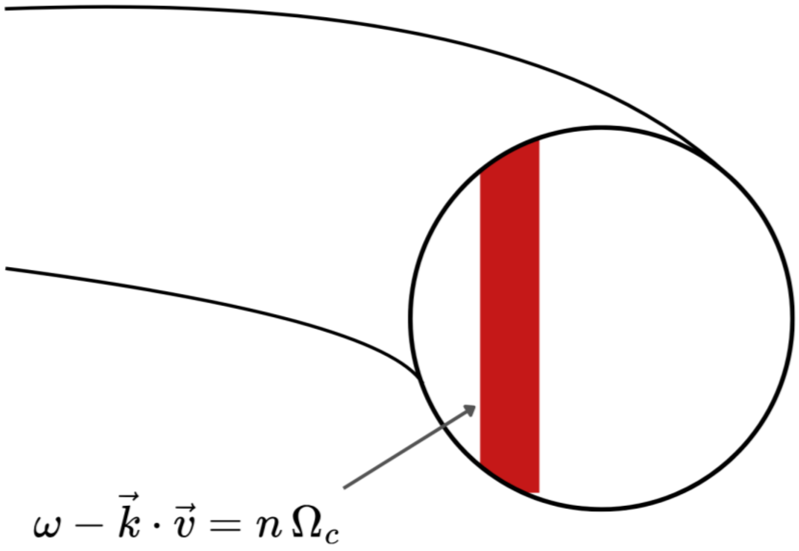
Wave-particle resonances occur at $\omega - \mathbf{k} \cdot \mathbf{v} = n\Omega_c$ (n= 0, 1, 2,…)

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 $k_{||}$ 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

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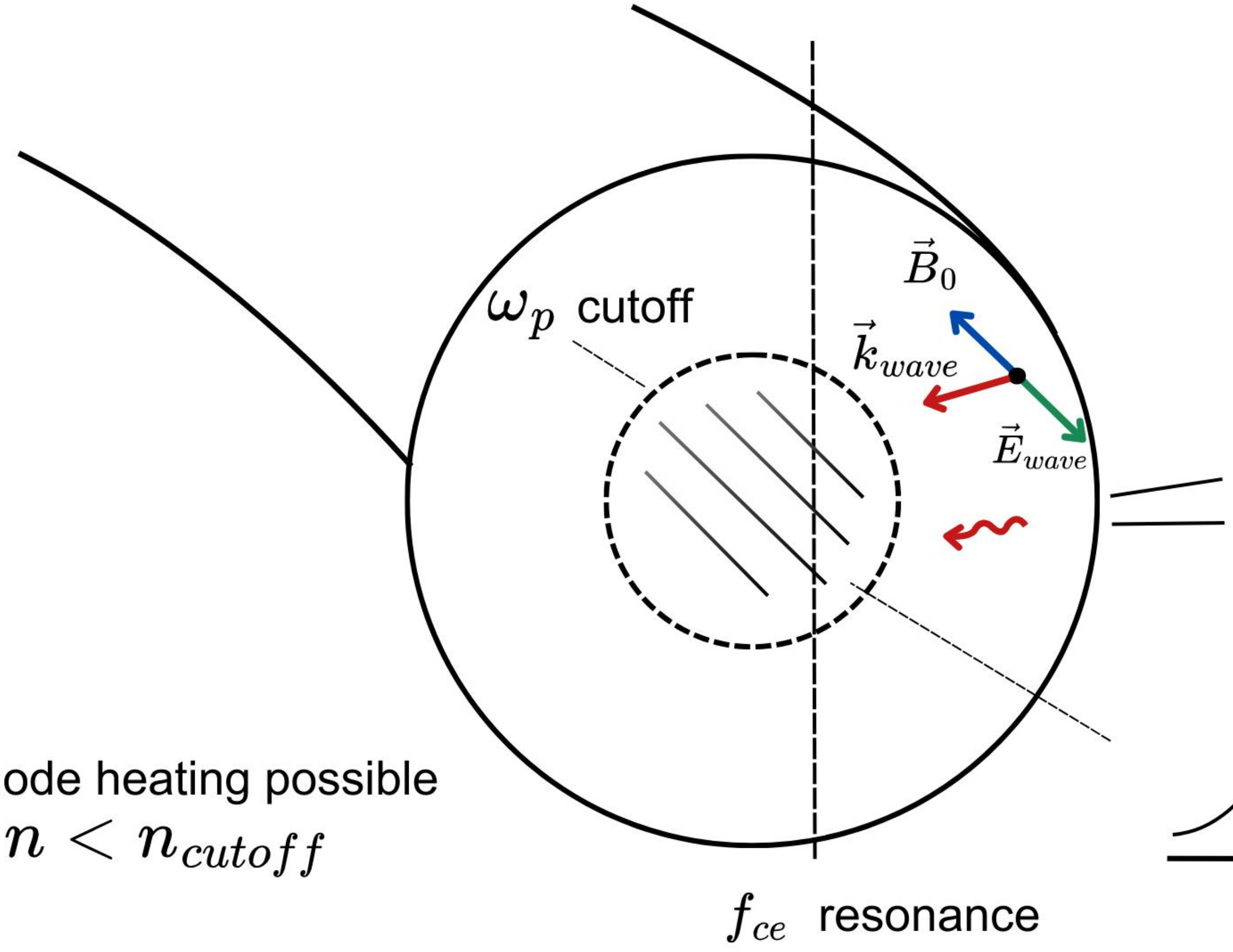
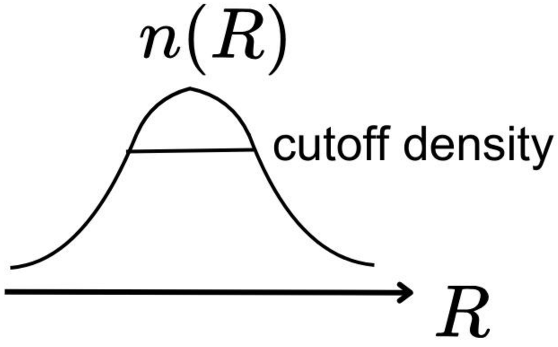
ECRH – Ordinary mode ($E \parallel B_0$)

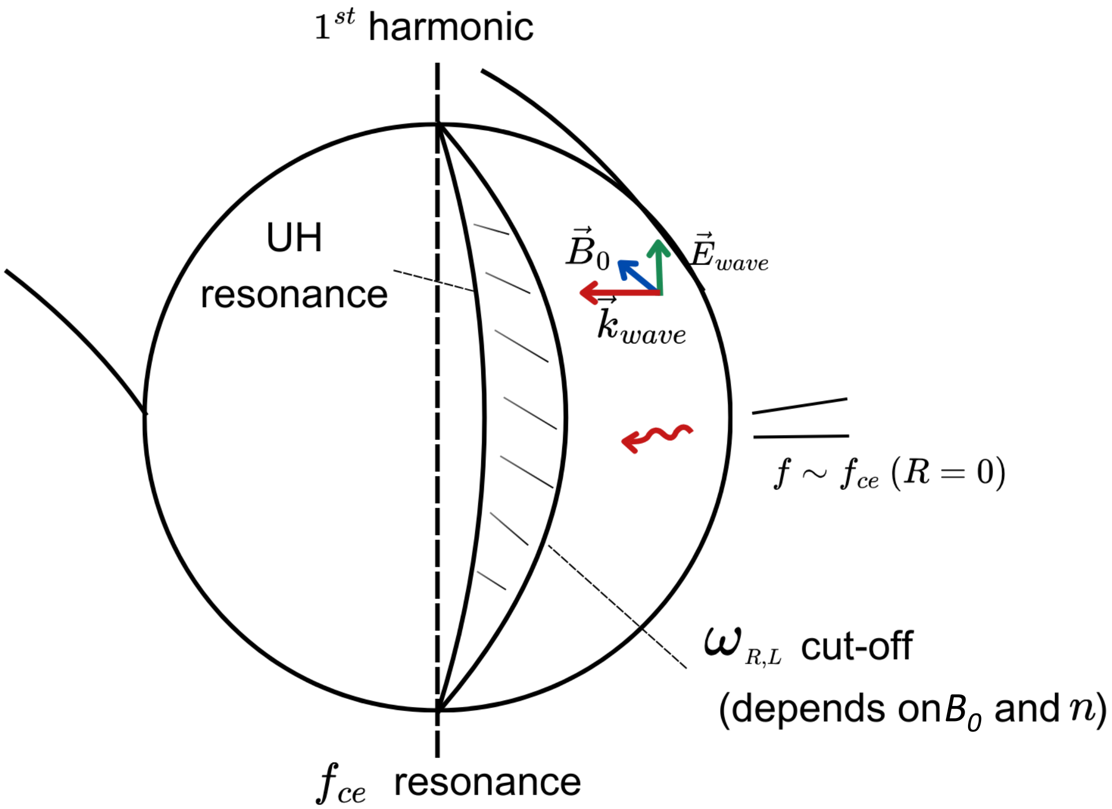




O-mode heating possible
for $n < n_{cutoff}$

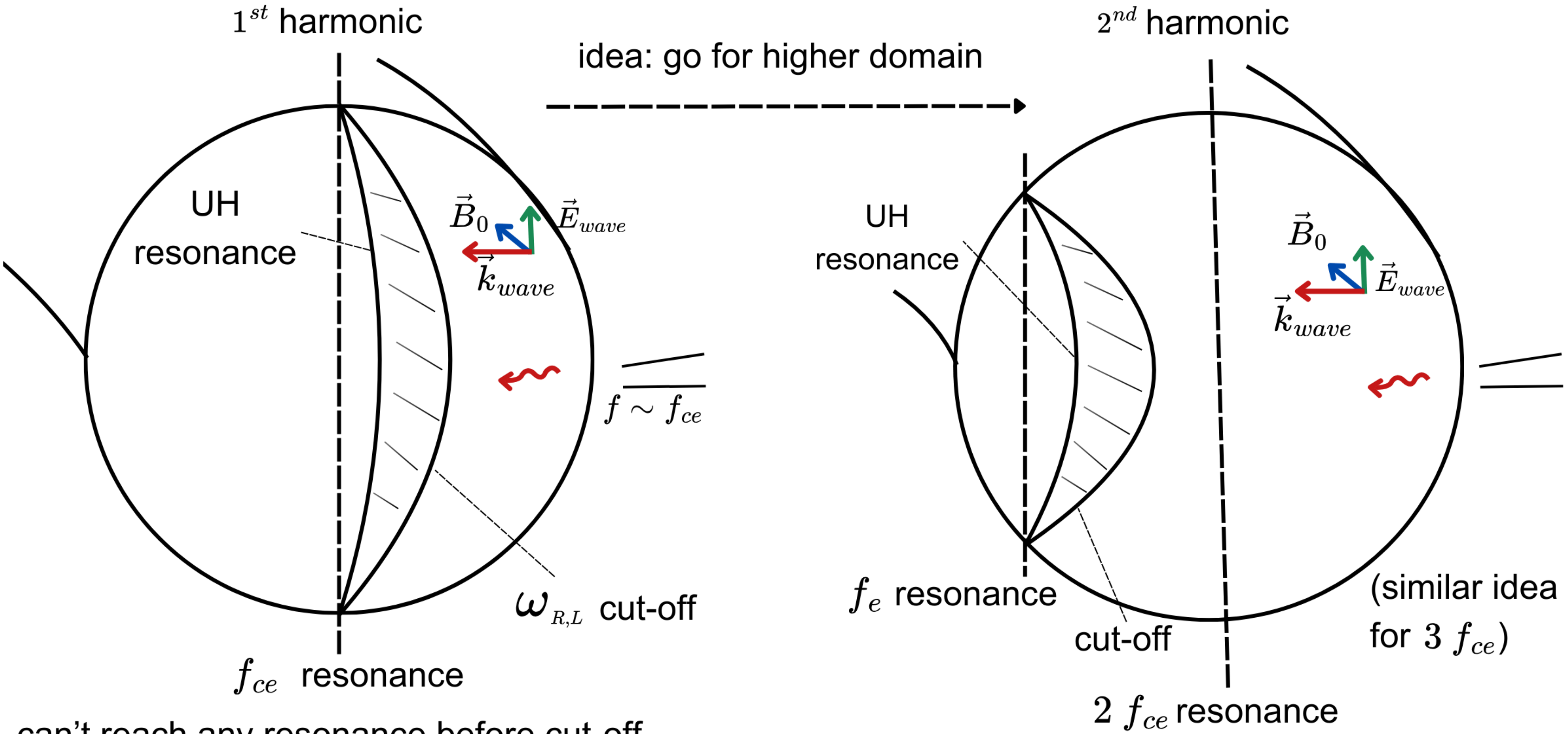
Swiss
Plasma
Center

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



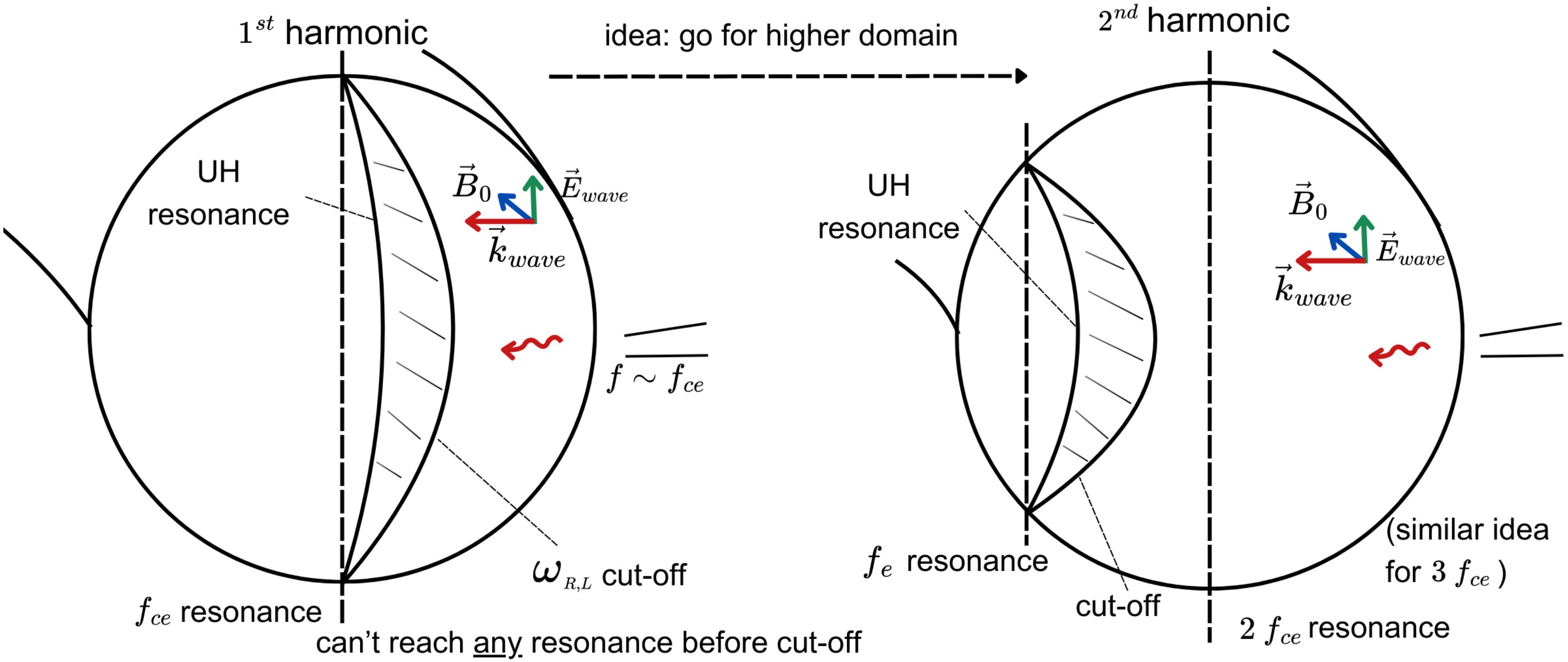
can’t reach <u>any</u> resonance before cut-off

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



can't reach <u>any</u> resonance before cut-off

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



Note: Pb with going to higher frequency 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:

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

Resonances:

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

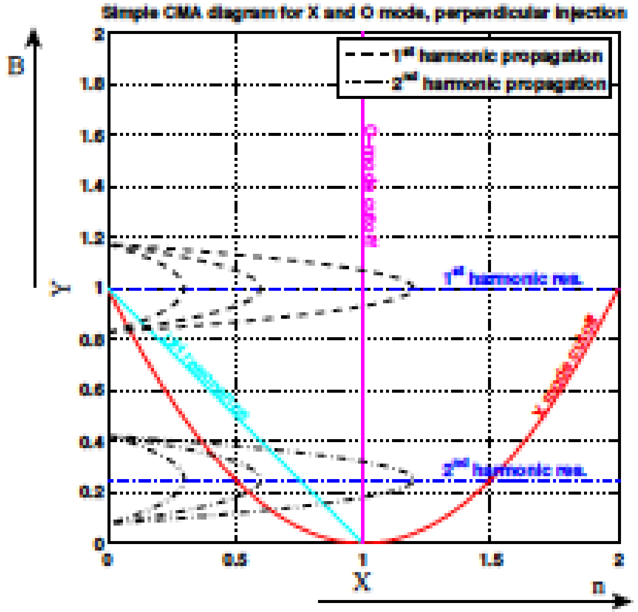
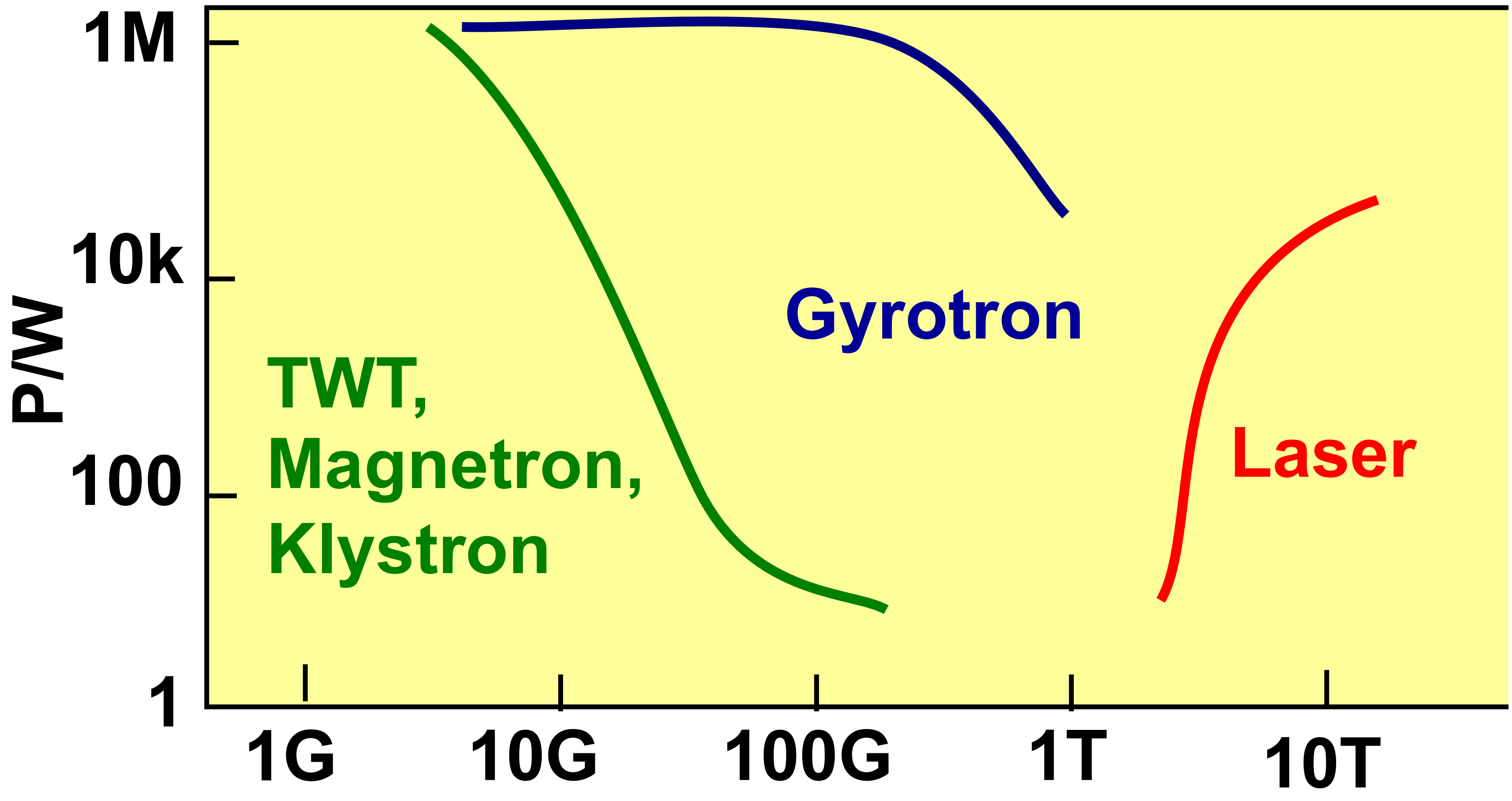


Figure 9.3: Clemmow-Mullaly-Allis diagram for X and O mode. Wave trajectories are shown for 1st and 2nd harmonic injection and for different core plasma densities. Note that for low field side X1 injection the wave first encounters a cutoff. X2 may encounter a cutoff or resonance, depending on the density.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

ECRH – Possible microwave sources



ECRH – Accessibility

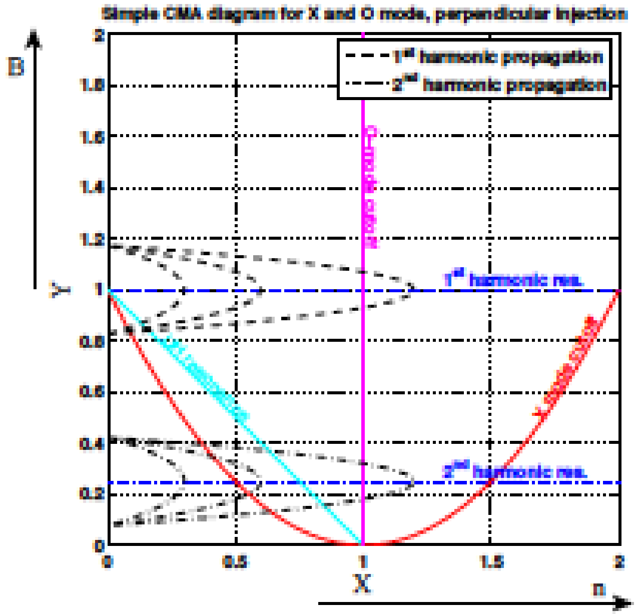
$$X = \frac{\omega_p^2}{\omega^2}(\propto n) \quad Y = \frac{\Omega_e^2}{\omega^2}(\propto B_0^2)$$

Cut-offs:

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

Resonances:

$$\omega = w_{UH} \quad Y = 1 - X$$
$$\omega = l\Omega_e \quad Y = \frac{1}{l^2}(1, 0.25, ...)$$



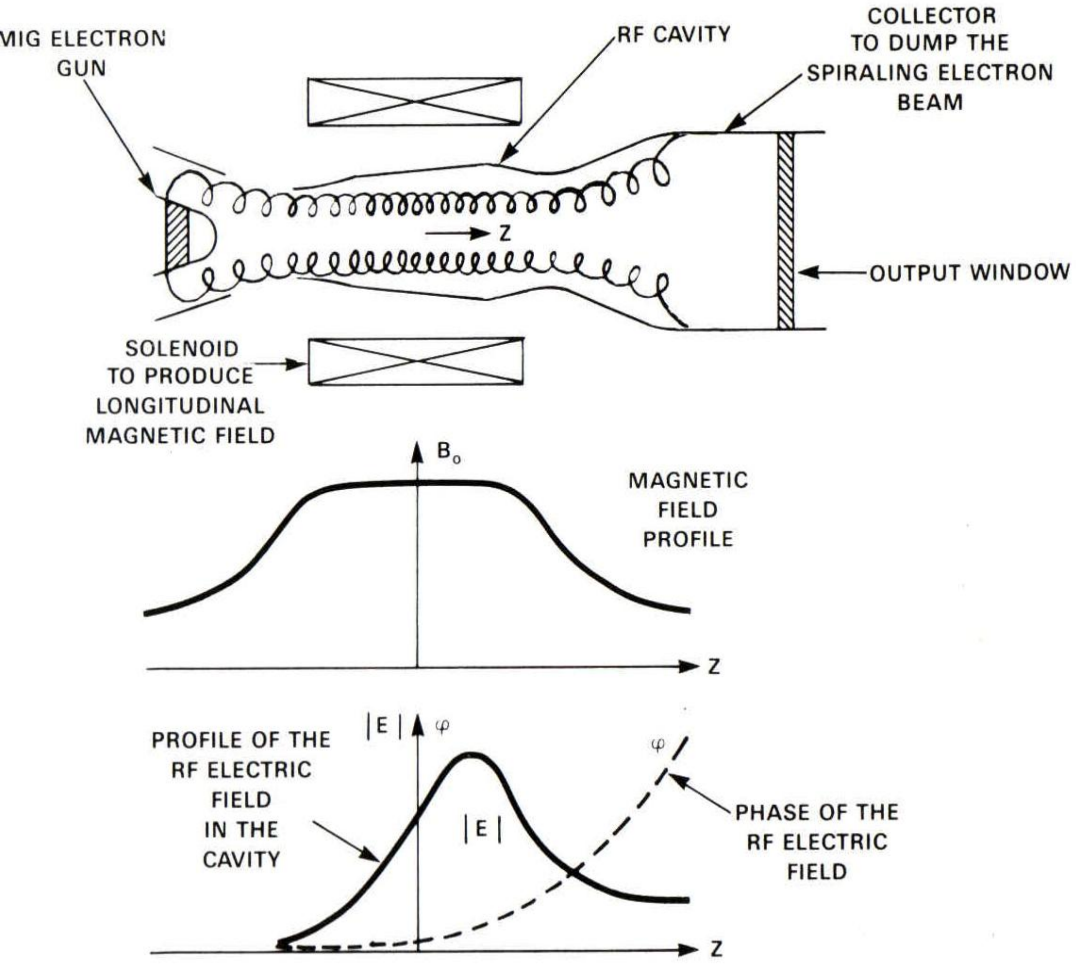
TCV (f_{ce}=41GHz)
can use n=2 or n=3
X2 (83GHz) or X3 (118GHz)

ITER (f_{ce}=170GHz)
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.

ECRH – Microwave source: gyrotron

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

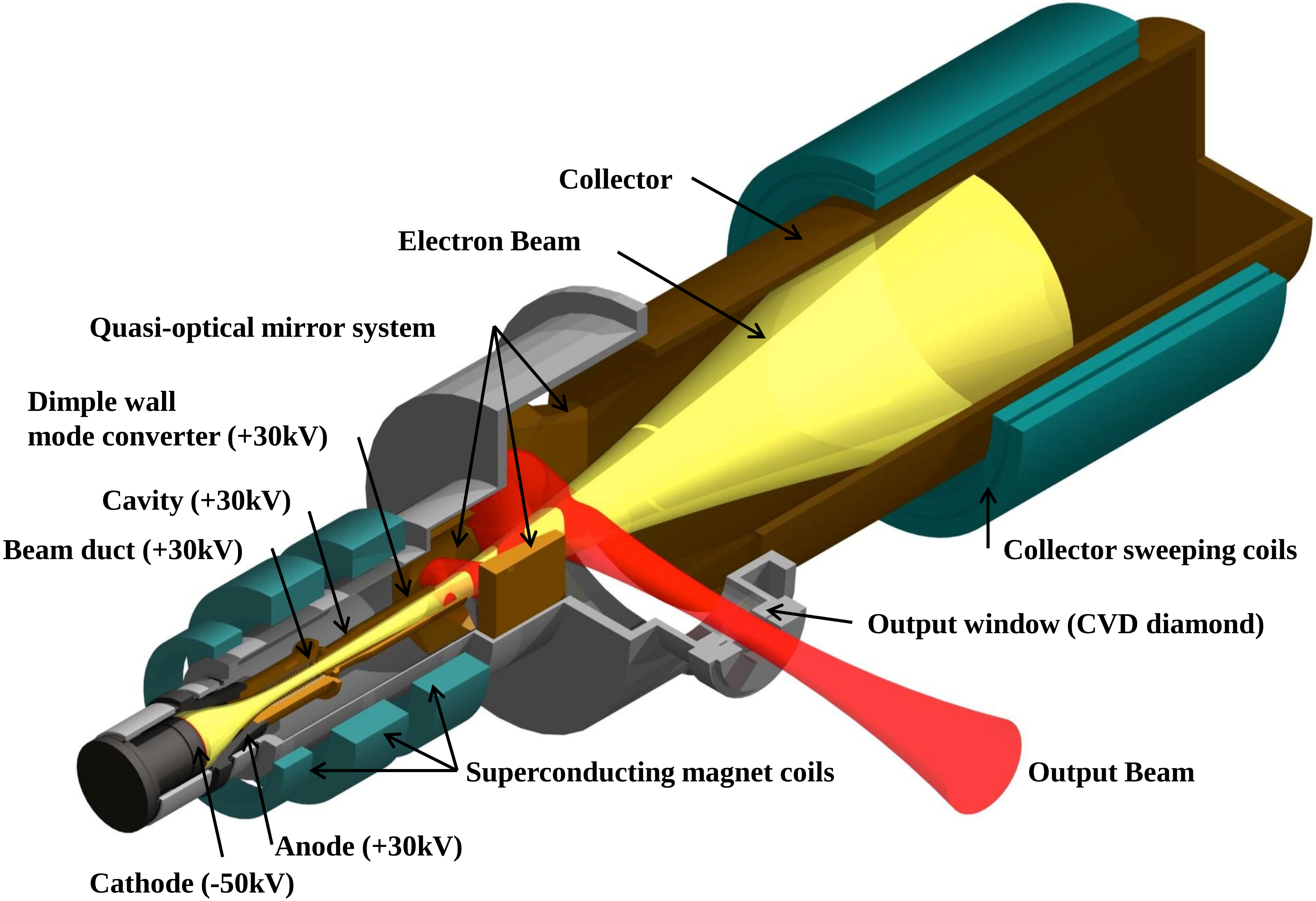
Source of free energy

Resonant cavity

Cylinder with a smoothly varying cross-section

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

The gyrotron



Collector

Electron Beam

Quasi-optical mirror system

Dimple wall
mode converter (+30kV)

Cavity (+30kV)

Beam duct (+30kV)

Collector sweeping coils

Output window (CVD diamond)

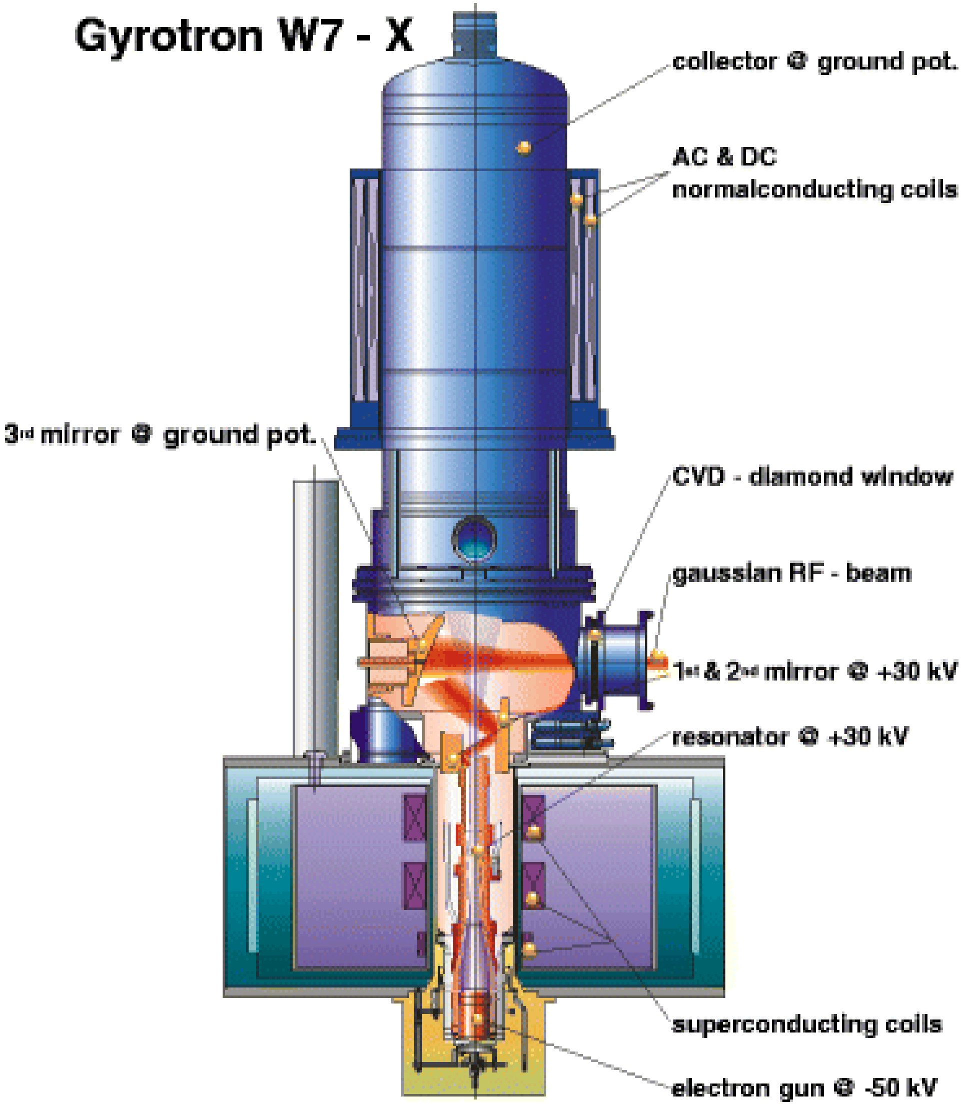
Superconducting magnet coils

Output Beam

Anode (+30kV)

Cathode (-50kV)

The gyrotron



Swiss
Plasma
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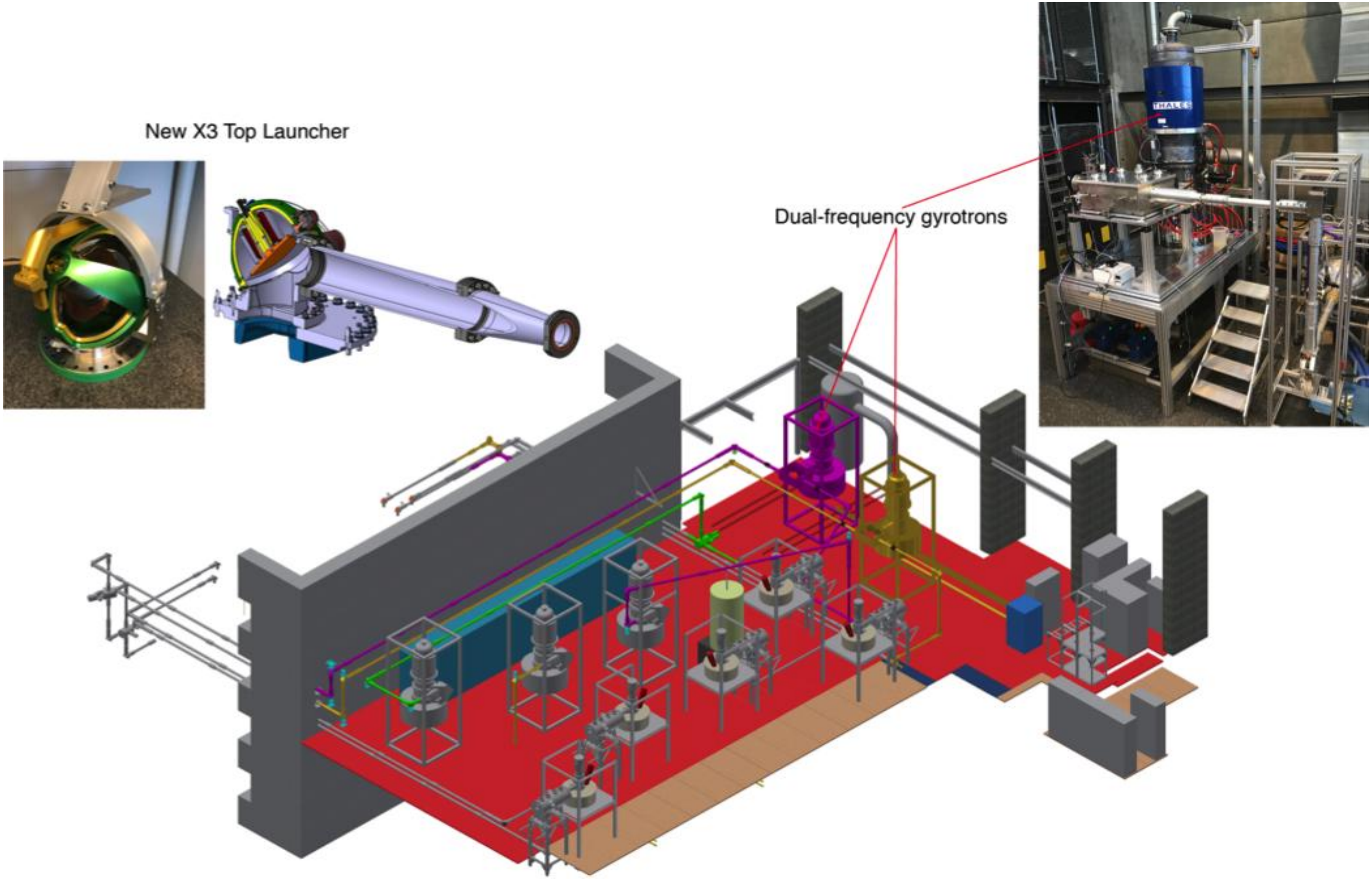
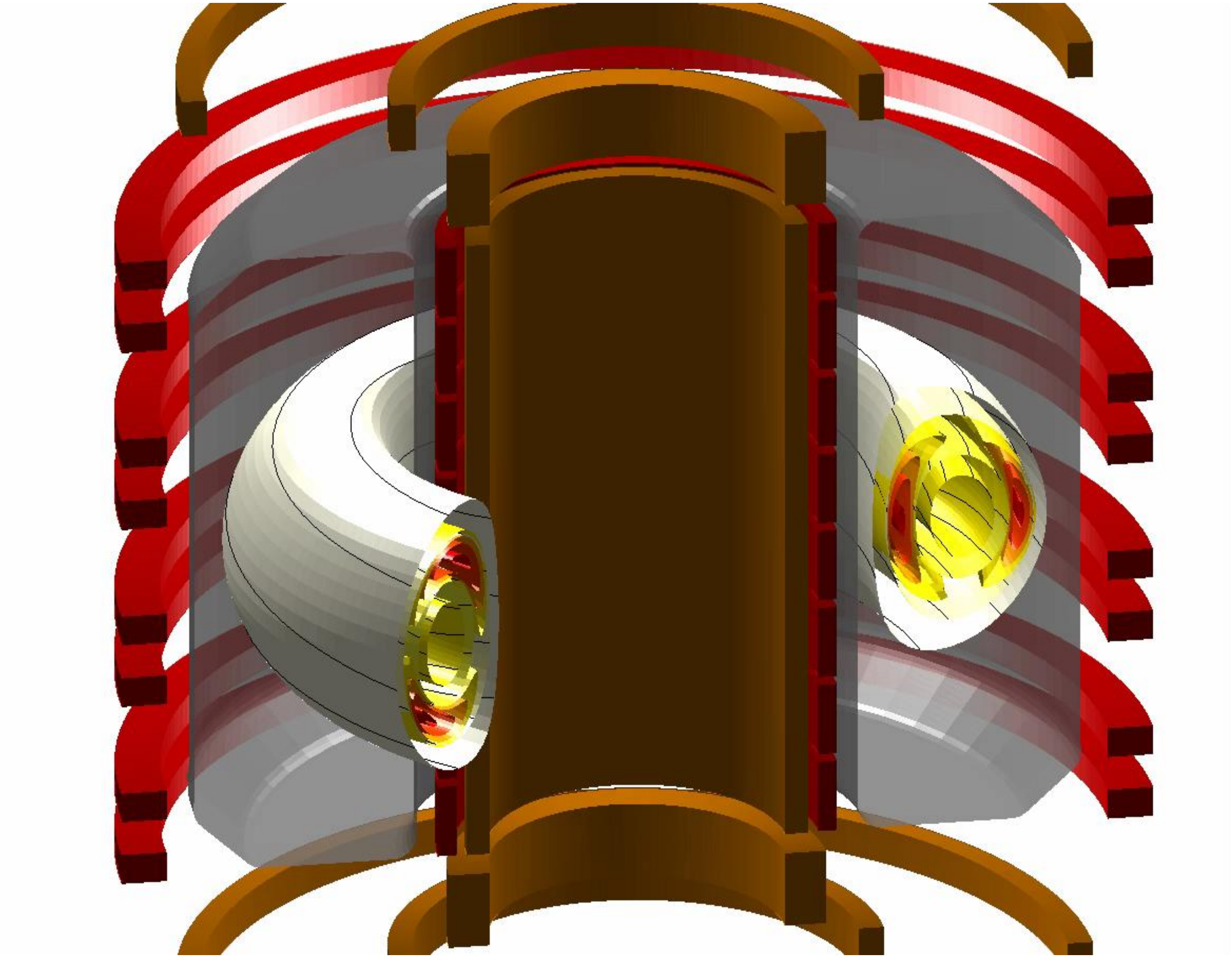
A modern ECRH system: TCV



ECRH for instability control



TCV

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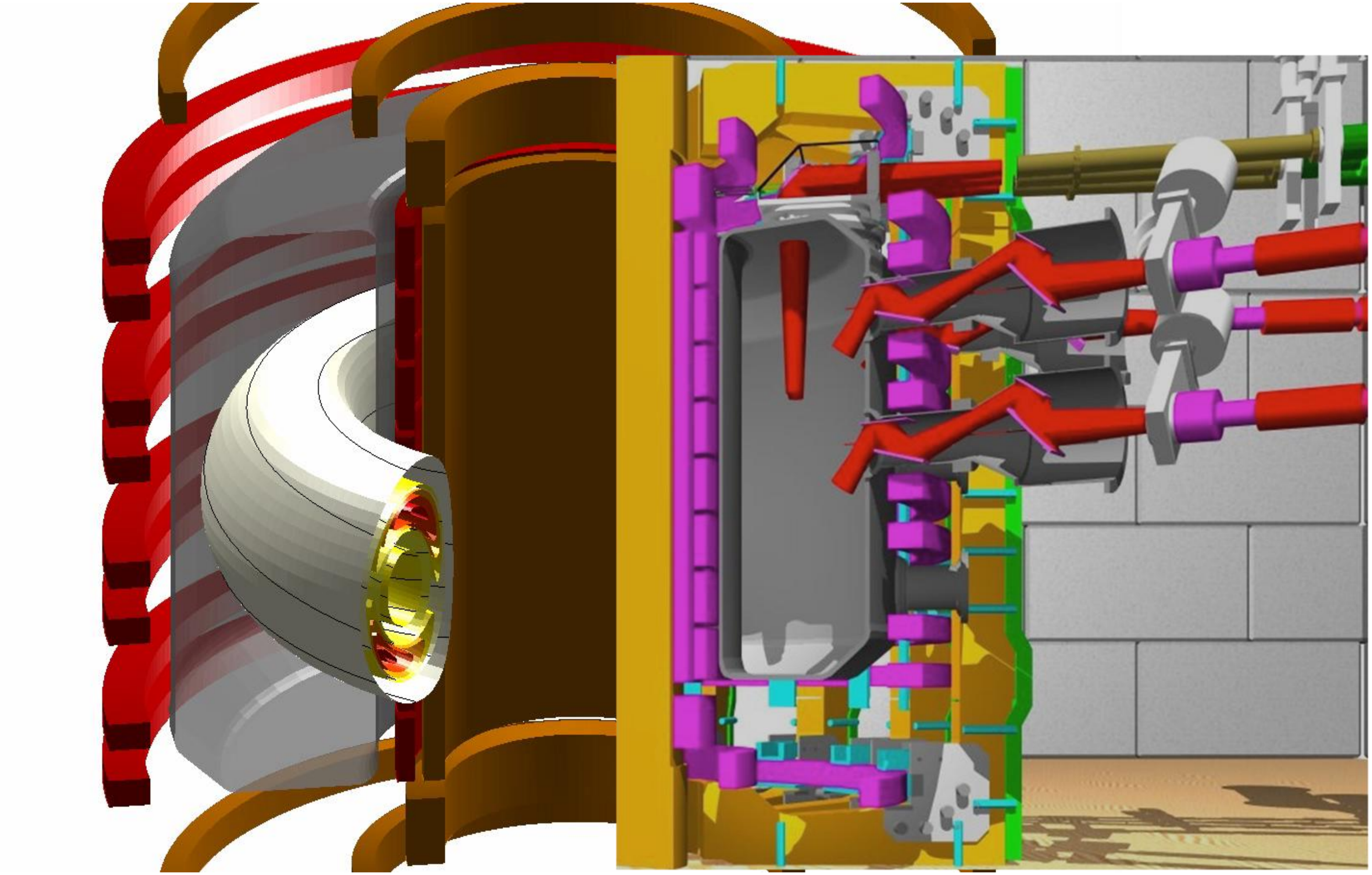
Plasma
Center

ECRH for instability control

Proof of principle on TCV



TCV

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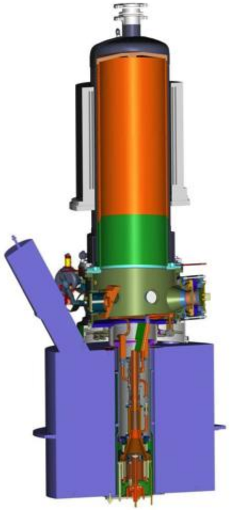
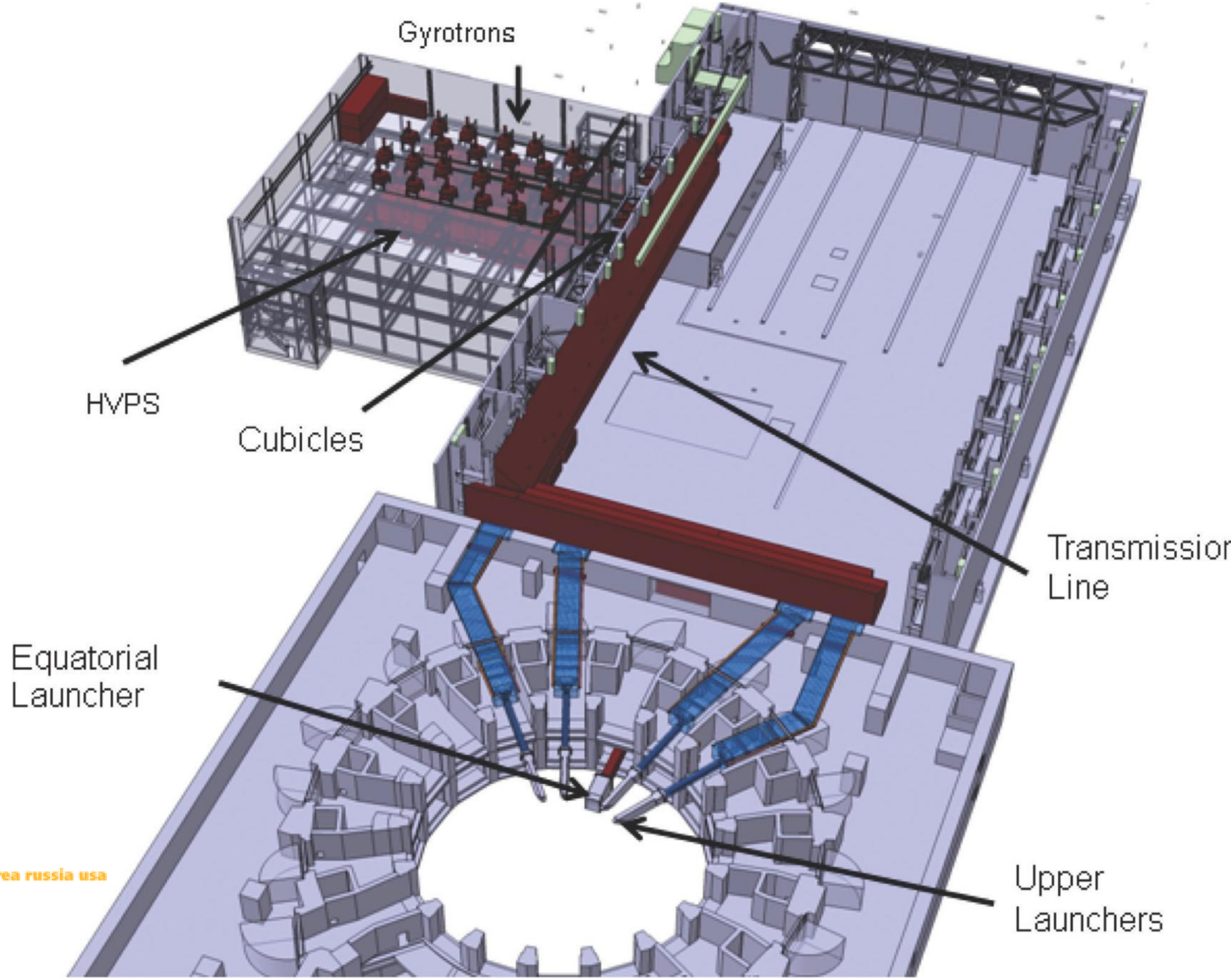
ECRH system on ITER

80 gyrotrons

1MW each

170GHz

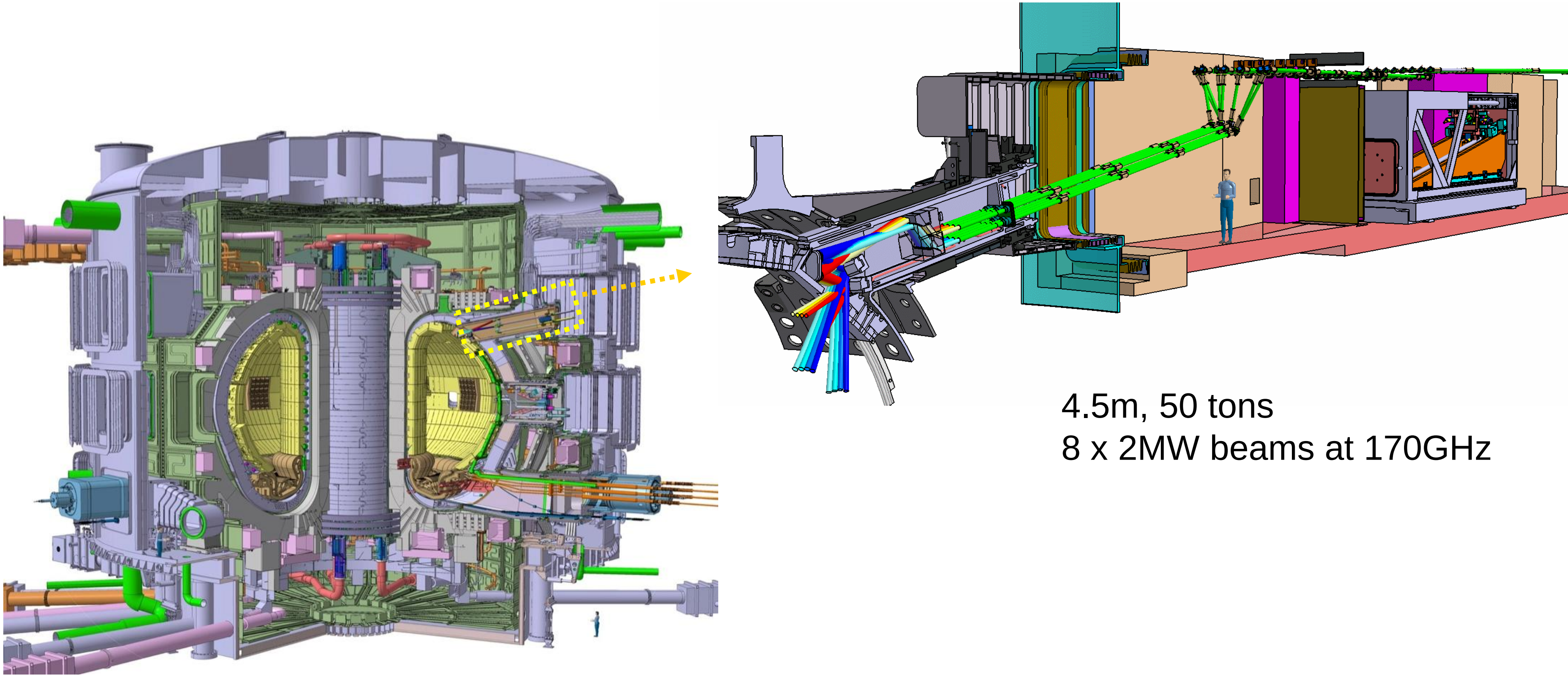




ITER upper launcher (Swiss contribution)

Front steering launcher of 170 GHz microwaves

Goal: heat locally and stabilize plasma instabilities



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

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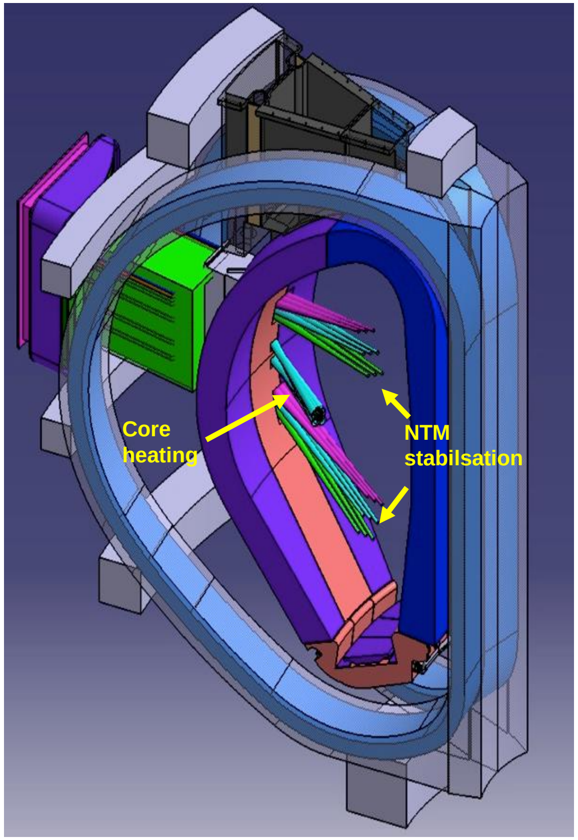
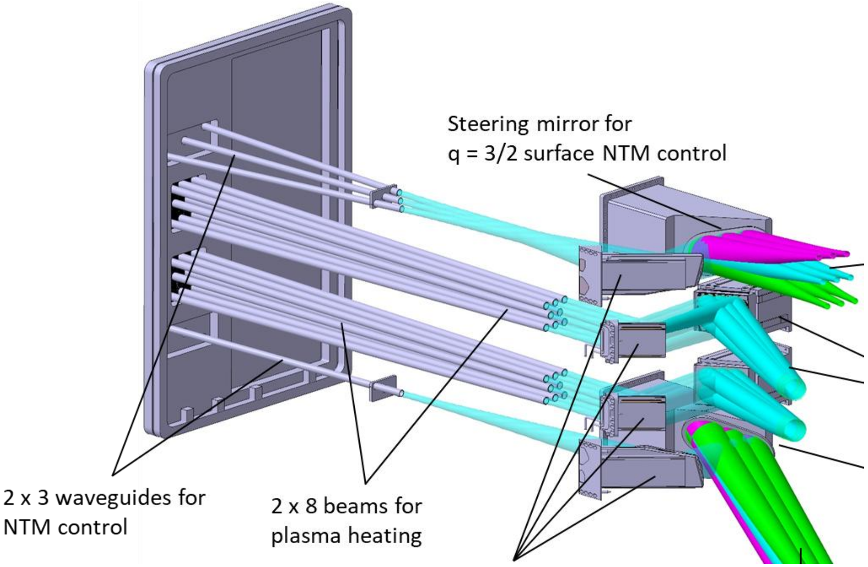
Center

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



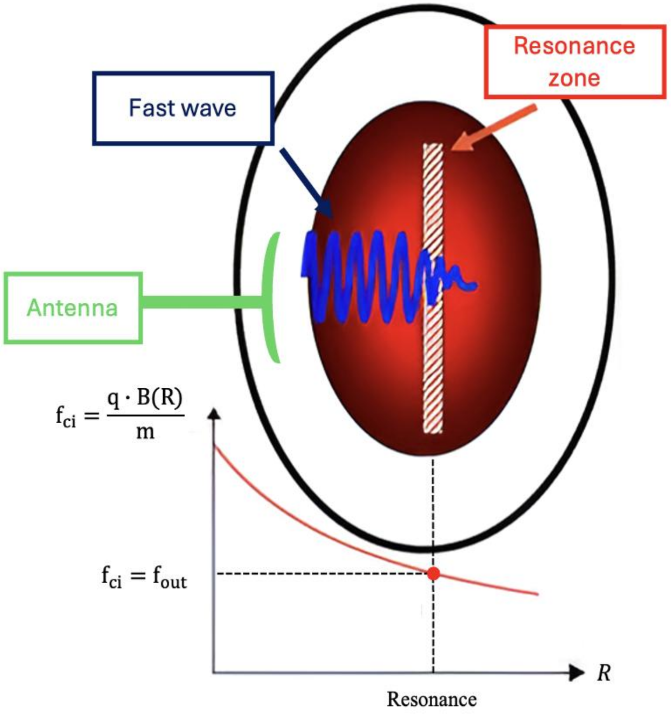


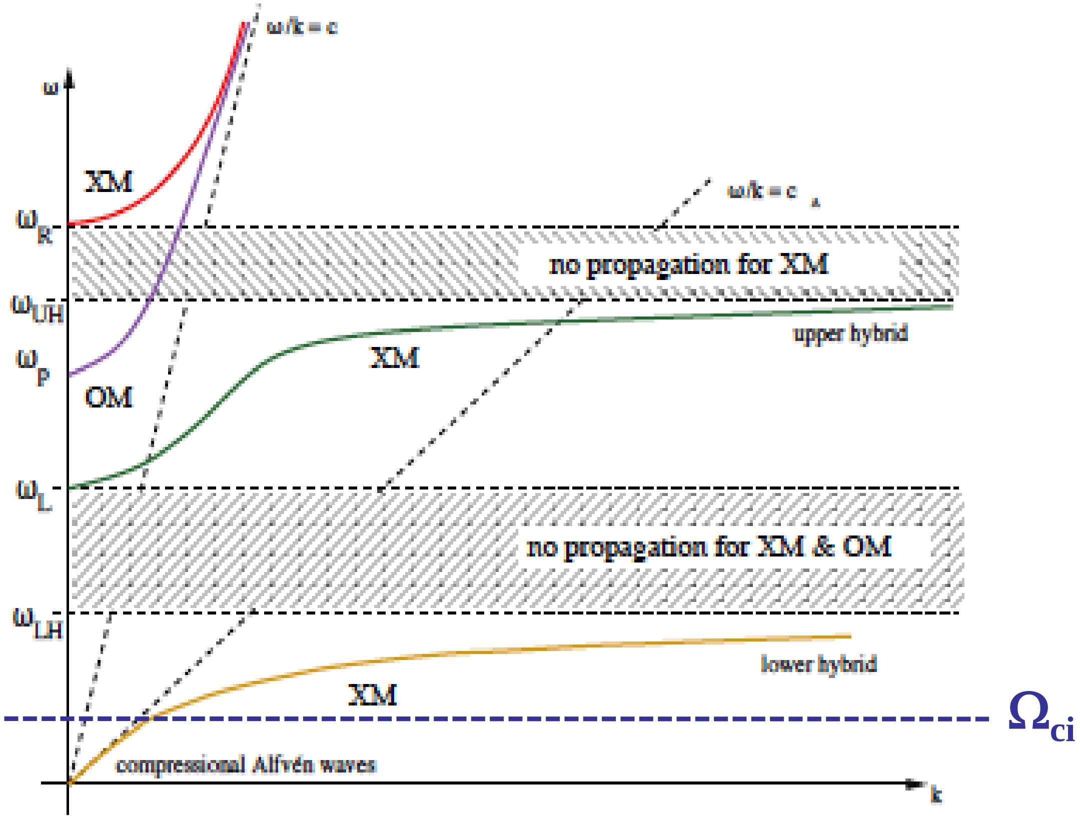
Consiglio Nazionale delle Ricerche ISTP Istituto per la Scienza e Tecnologia dei Plasmi
Politecnico di Torino
KIT Karlsruhe Institute of Technology
Εθνικό και Καποδιστριακό Πανεπιστήμιο Αθηνών National and Kapodistrian University of Athens
Università degli Studi della Tuscia
THALES Building a future we can all trust
EUROfusion

Ion Cyclotron Resonance Heating
ICRH

ICRH

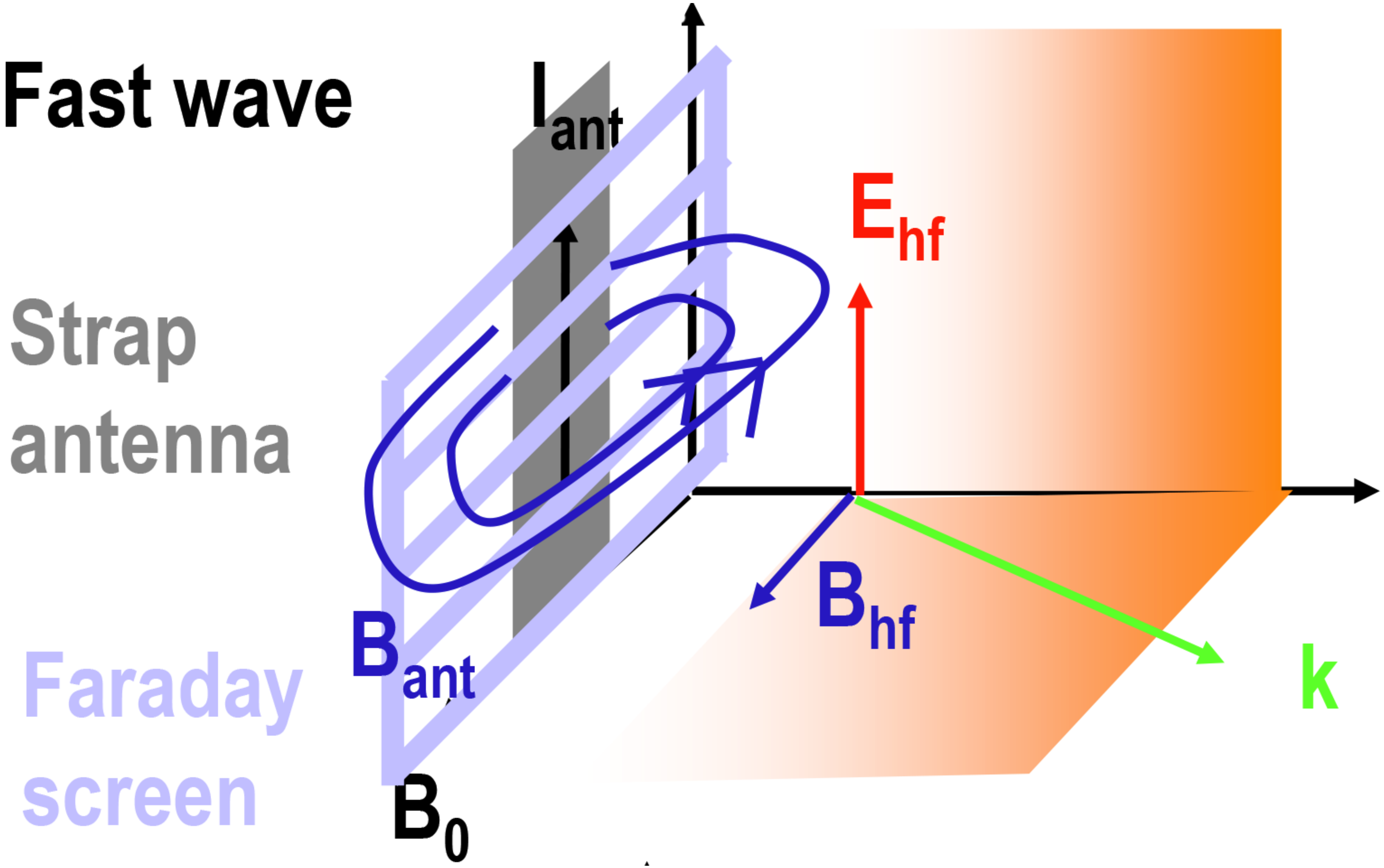
Perpendicular wave dispersion relation





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

ICRH – Antenna excitation of fast wave



ICRH - Main principles

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

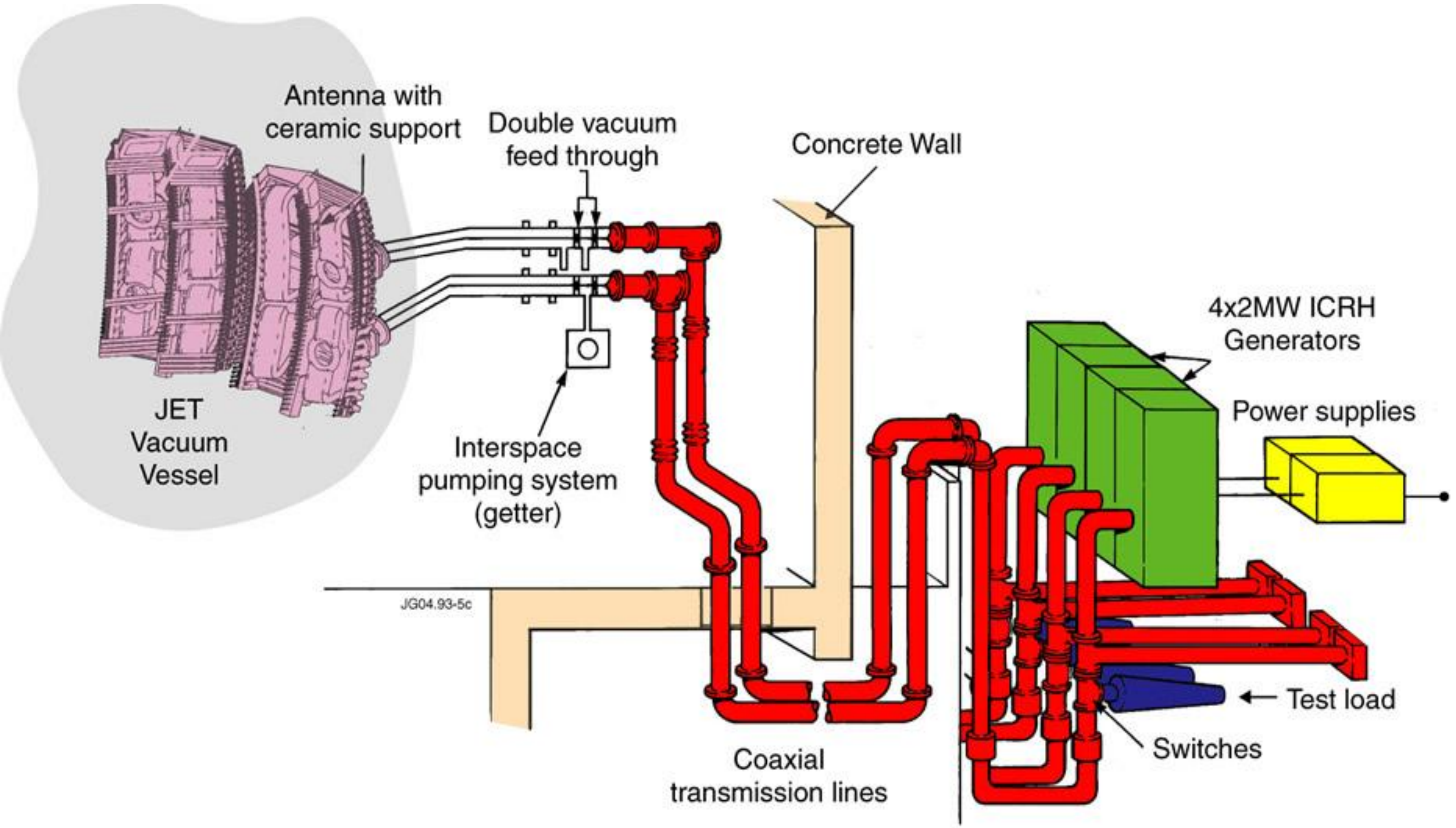
1st harmonic of a minority ion (e.g. $\omega = \Omega_{cH}$ or $\omega = \Omega_{cHe3}$)

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 $\Omega_{cT} < \omega < \Omega_{cD}$)

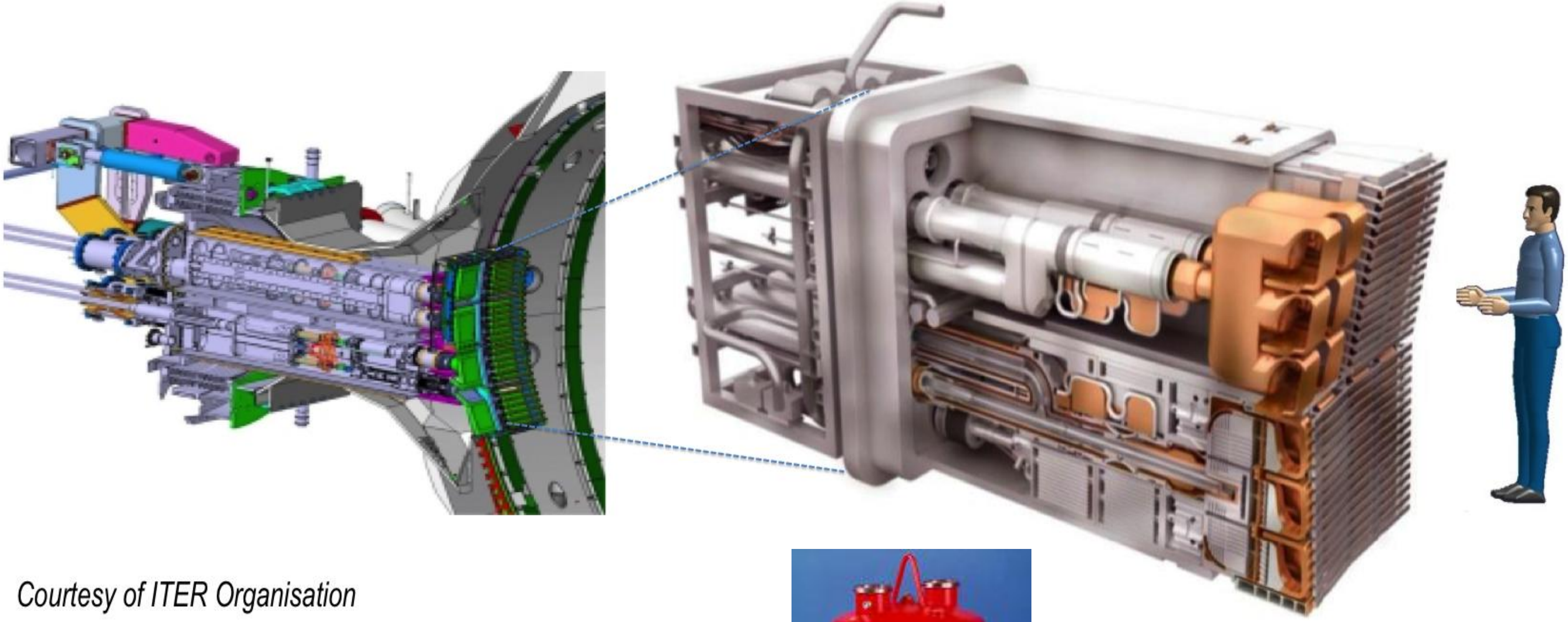
….

ICRH – JET system



ICRH – ITER antenna

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



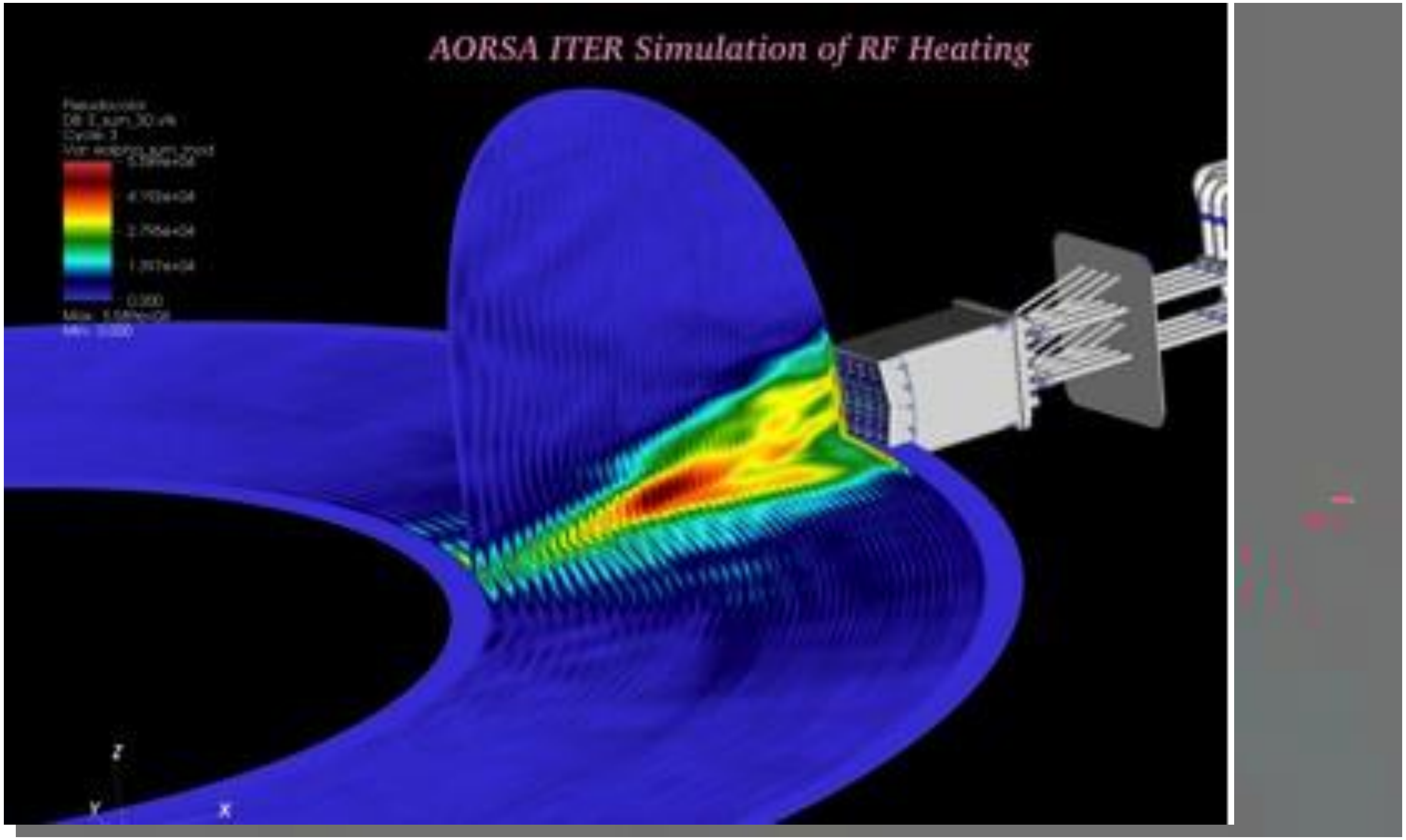
Courtesy of ITER Organisation

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)

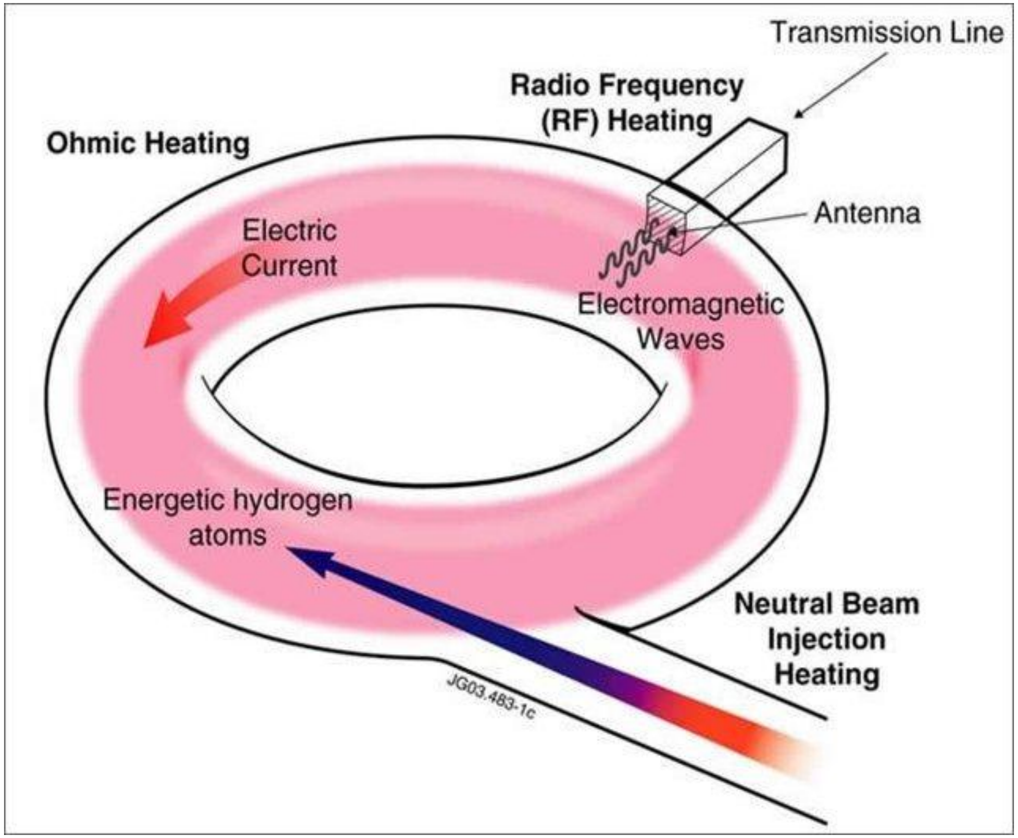


Energetic ions from additional heating

Burning plasma regime is reached using external heating and current drive

- *Electron cyclotron heating*
- Ion cyclotron heating
- Neutral beam heating

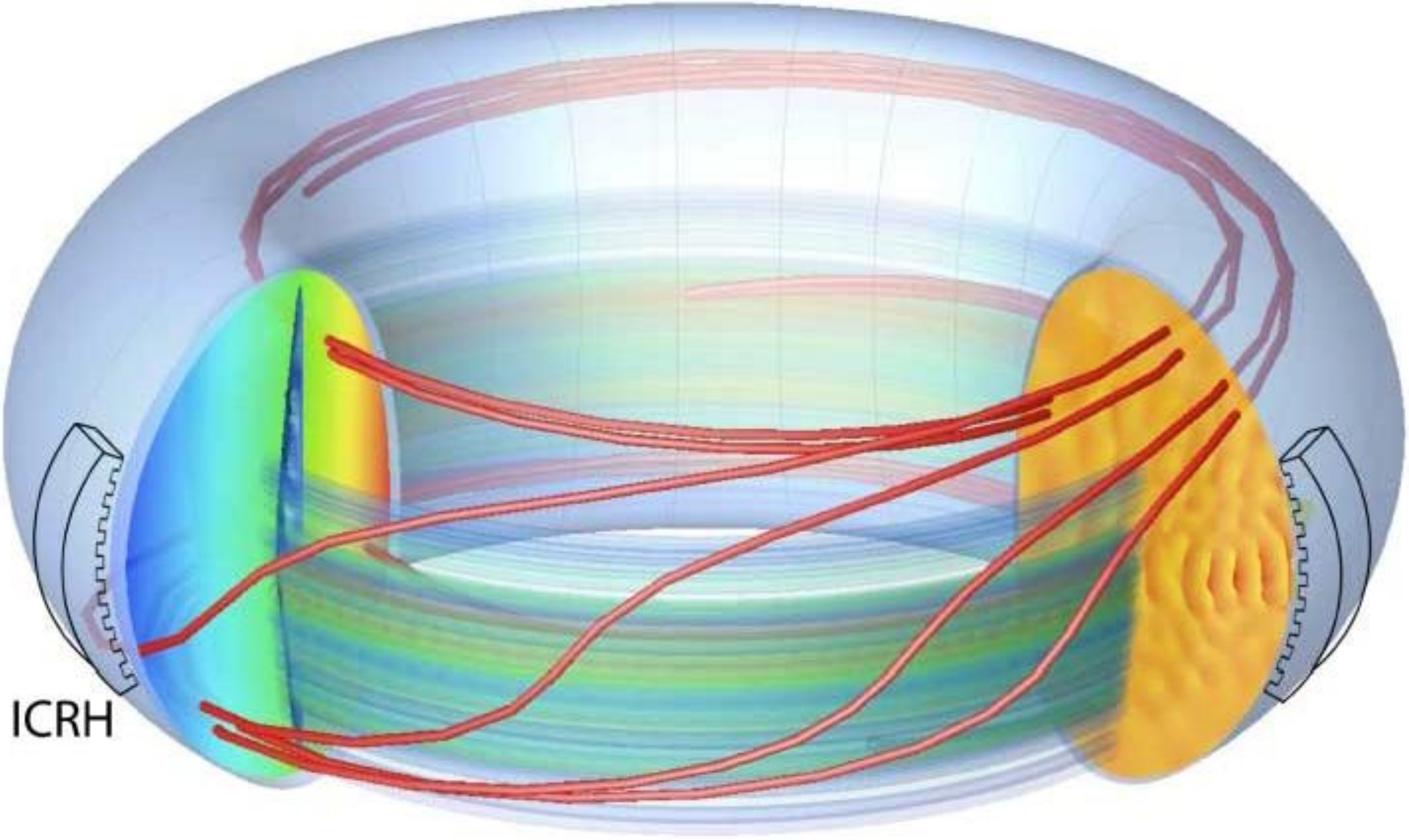
Based on creation of ~MeV ions, then thermalised by collisions



ICRH and energetic ions

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

- Strongly anisotropic distribution function: mostly trapped orbits



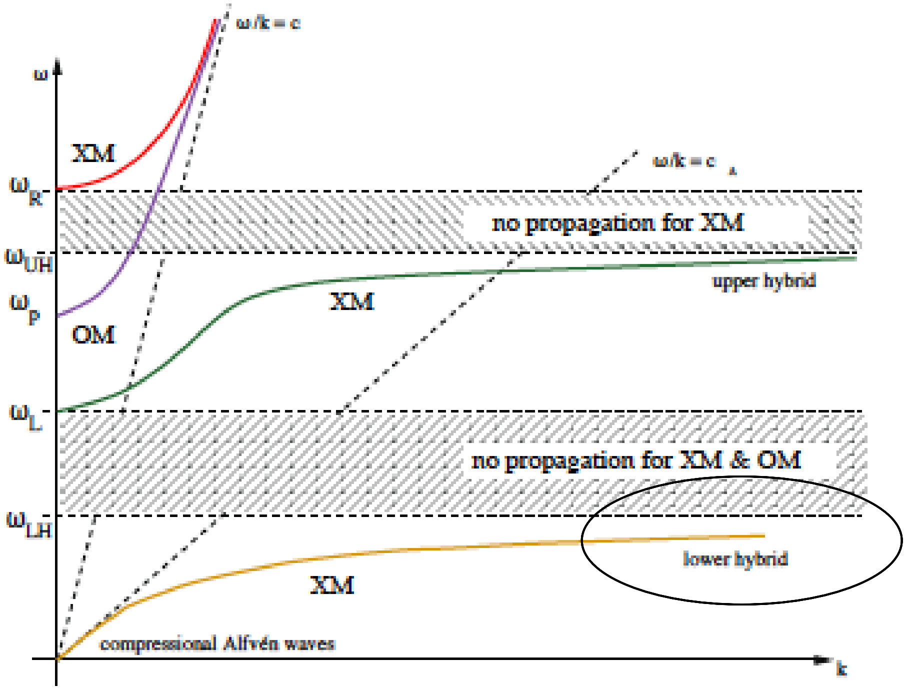
The Lower Hybrid wave – current drive

Wave-particle resonance

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

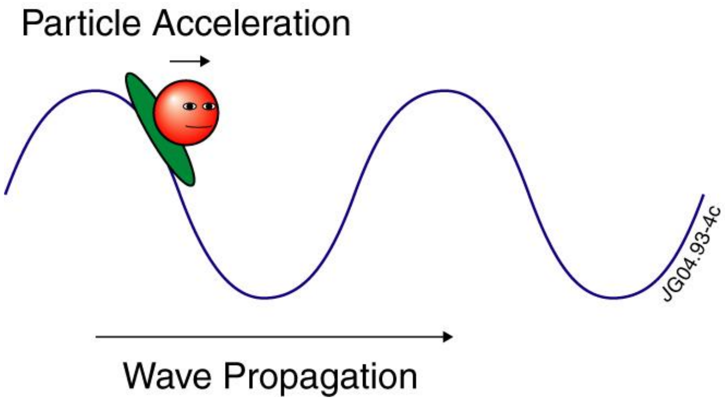
$\sim 1.3 T_e^{1/2}{}_{[keV]} / \lambda_{||\,[cm]}$ [GHz]

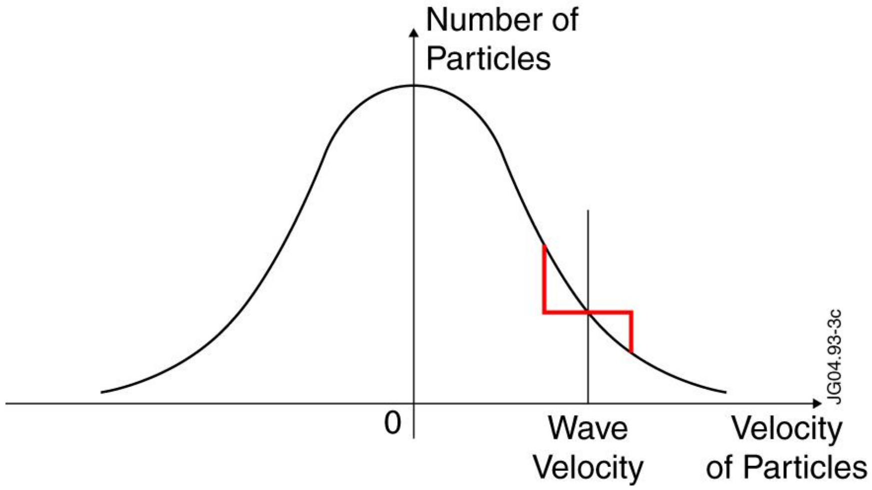
Electrostatic waves ($\delta B \sim 0$)



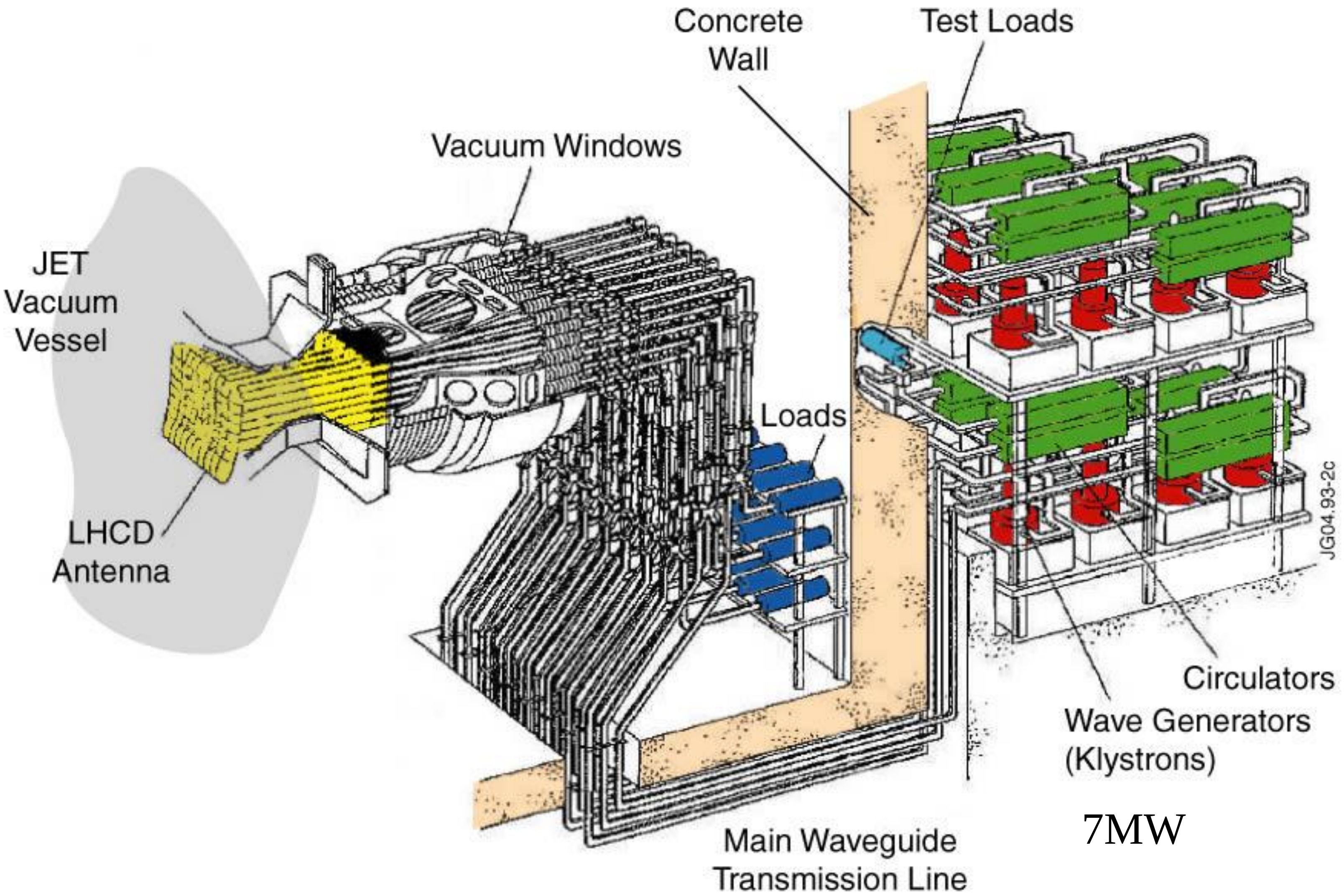
JET
$f_{LH} \sim 2.45$GHz

ITER
$f_{LH} \sim 5$GHz





The Lower Hybrid system in JET



7MW

Swiss Plasma Center

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

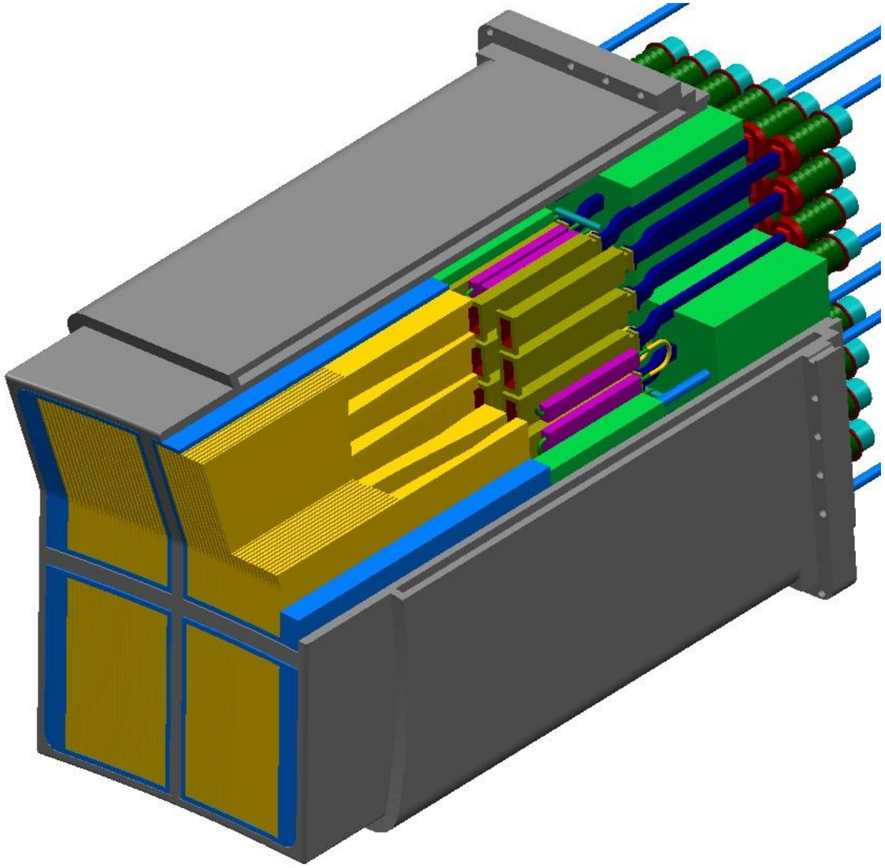
Interaction between antenna and plasma

Wave must reach core where CD is of interest

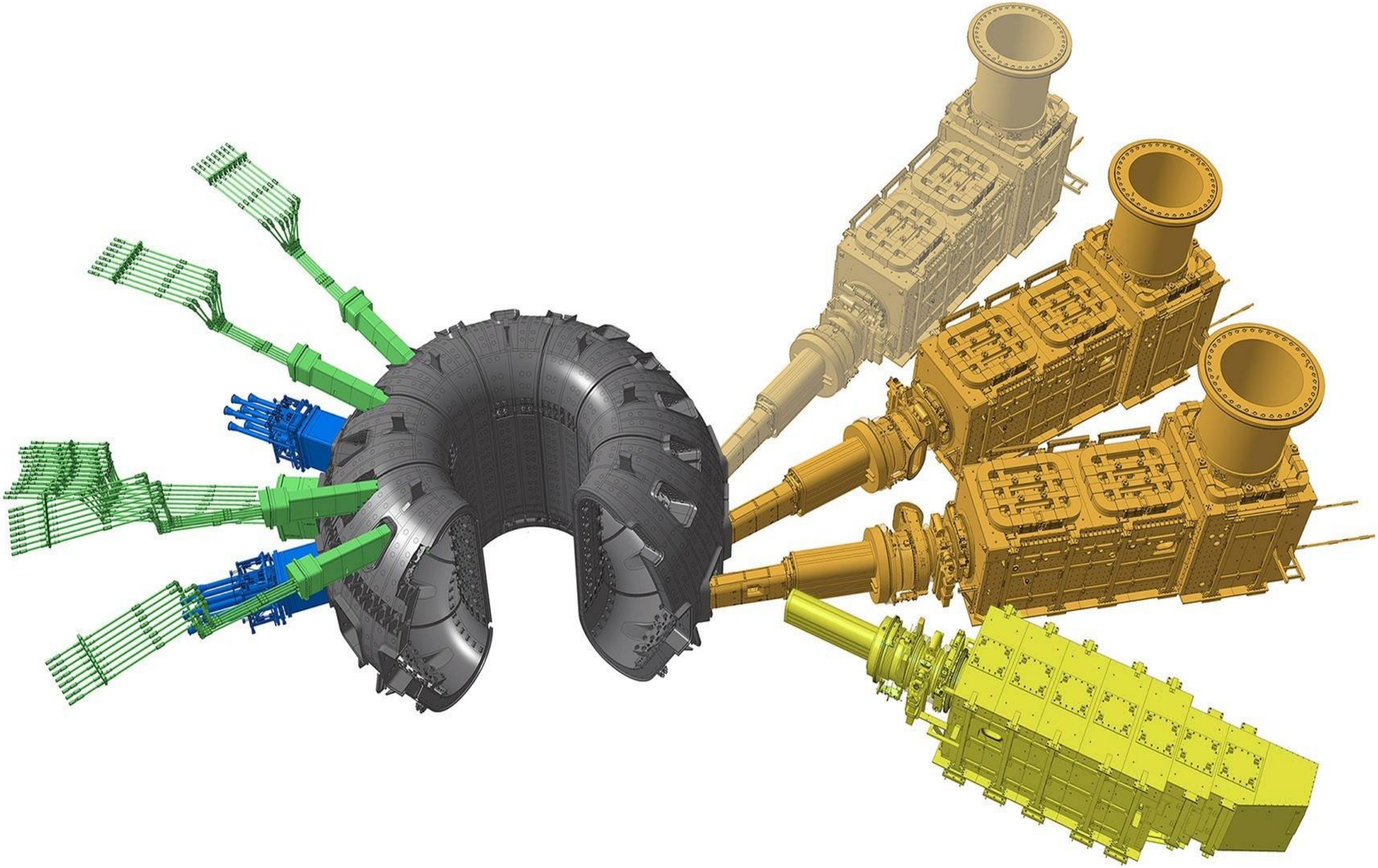
The LH system for ITER

Frequency 5GHz, 20MW will be installed for second stage of heating upgrades

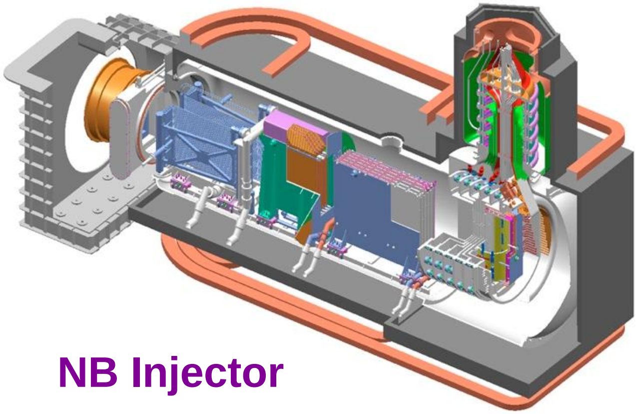
Mostly for off-axis current drive



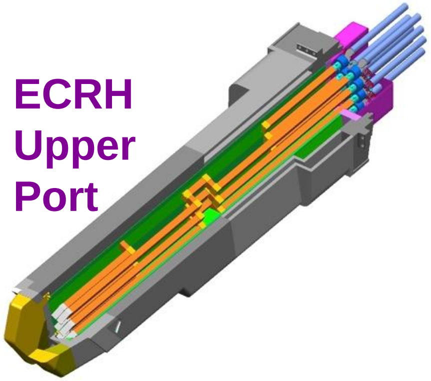
ITER Heating systems



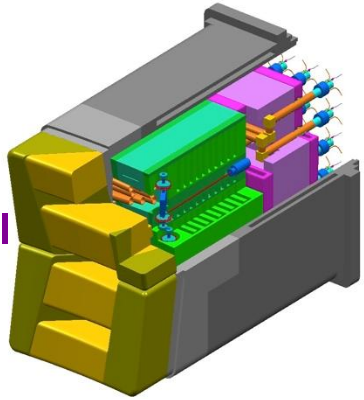
ITER Heating systems



NB Injector

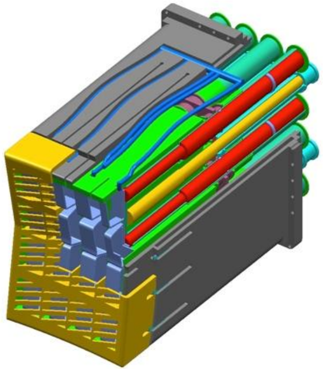


ECRH Upper Port



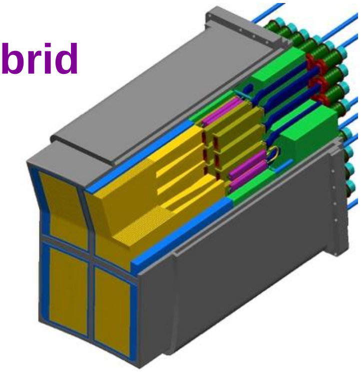
ECRH Lateral Port

System	Power [MW]	Frequency
NBI	33 MW	N/A
ICRH	20 MW	40-55 MHz
LH	*20 MW (second stage)*	*5 GHz*
ECRH	67 MW	170 GHz



ICRH antenna

Discussion: pros and cons of different methods ?



Lower Hybrid Launcher

iter china eu india japan korea russia usa