Waves in Plasmas

[Part II]

Radio-Frequency Waves
Heating and Current Drive in a tokamak

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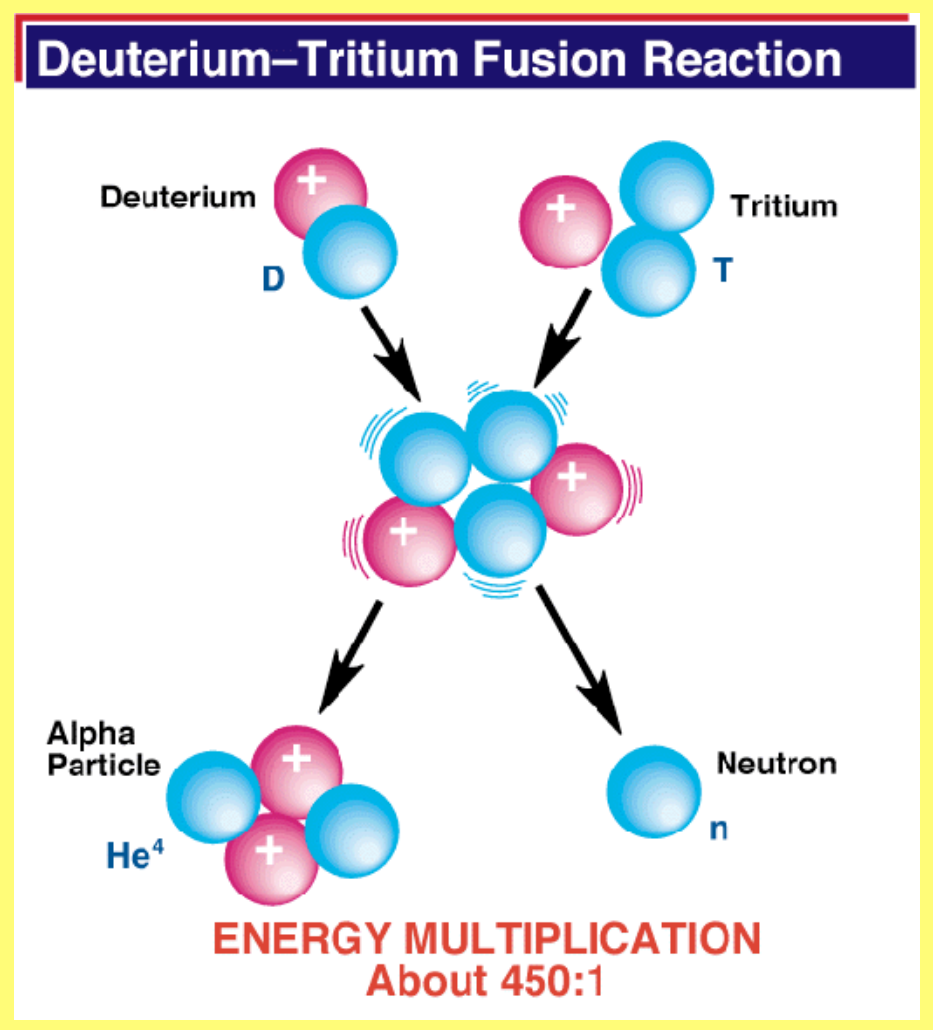
Spring school: “Hot Plasmas” - Cadarache - 03-04/2004

Introduction

Non-inductive plasma heating



[Source: PPPL]

- **Lawson criterion:**

$$n_e.T_i.\tau_E > 5.10^{21}\ \text{keV.s.m}^{-3}$$

- **D-T fusion reaction**

$$T_i \approx 5 - 30\ \text{keV}$$

→ { Ion heating
Electron heating

- **Joule effect heating**

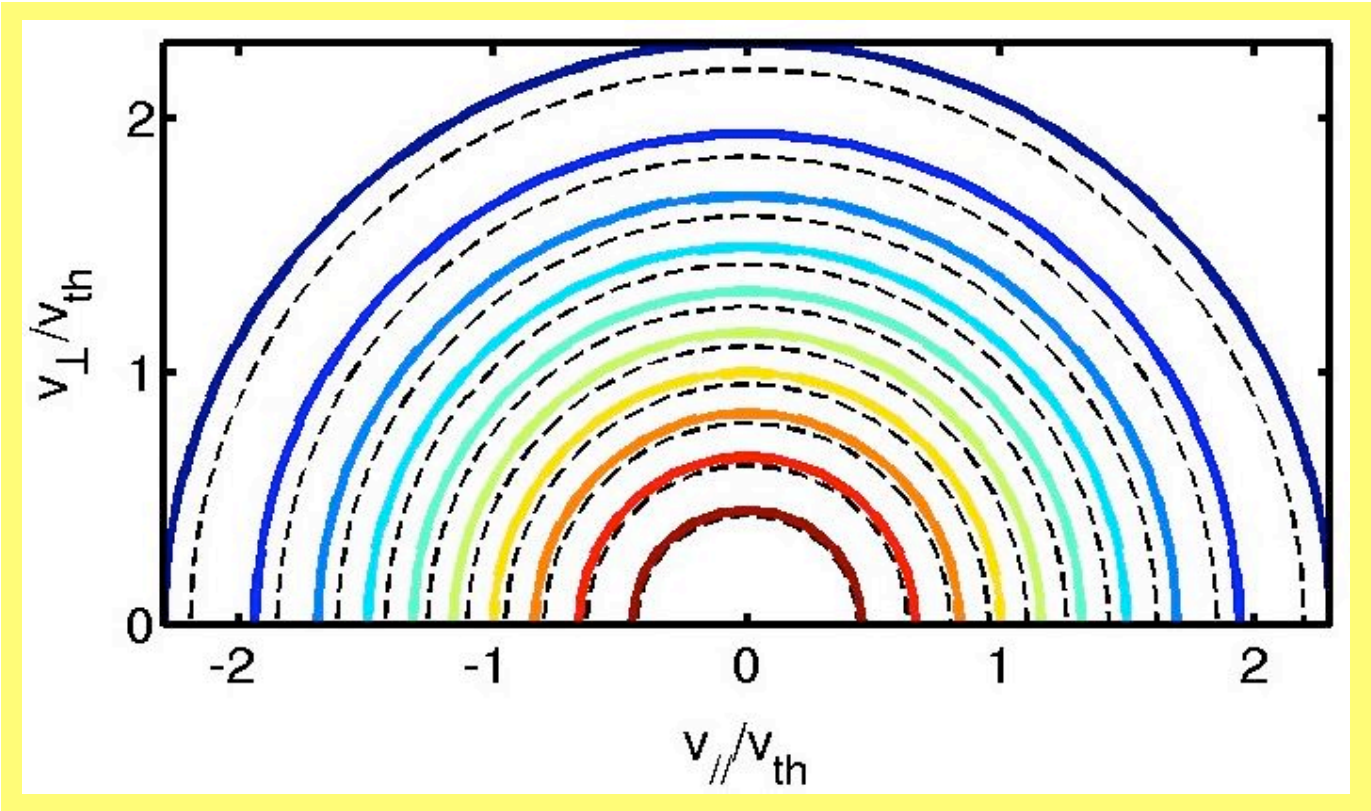
$$\begin{cases} P_h & \eta(T_e).I_p^2 \\ \eta(\eta_e) & T_e^{-3/2} \end{cases}$$

→ Limited temperature

→ **Needs for a non-inductive heating scheme.**

Plasma heating: general principle

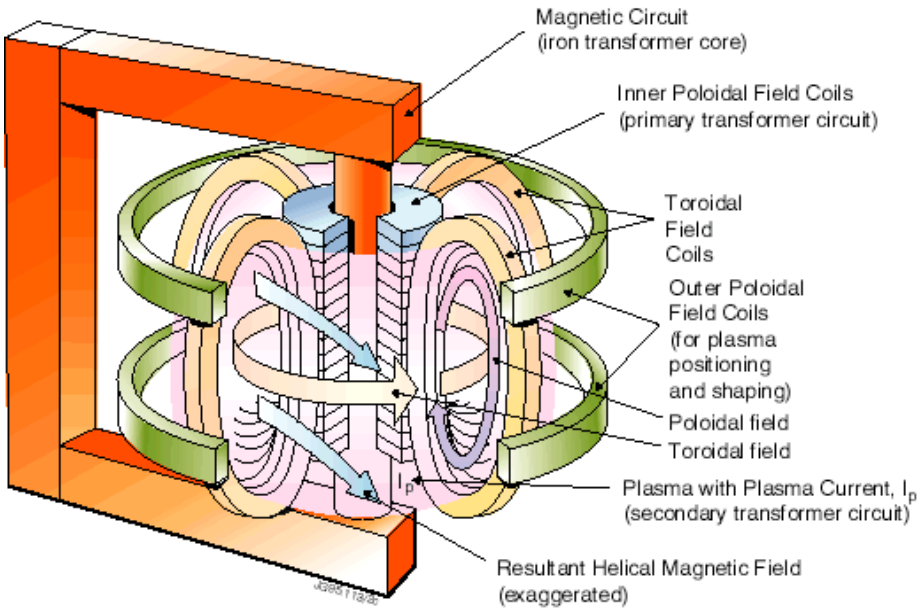
- **Distribution function contours:**



Energy density (species "s"):

$$\varepsilon_s = n_s \frac{m_s}{2} \int d^3\mathbf{v}\, v^2 f_s(\mathbf{v})$$

Toroidal current in a tokamak



- **Stable confinement:**

Toroidal magnetic field

→ Central solenoid coils

+

Poloidal magnetic field

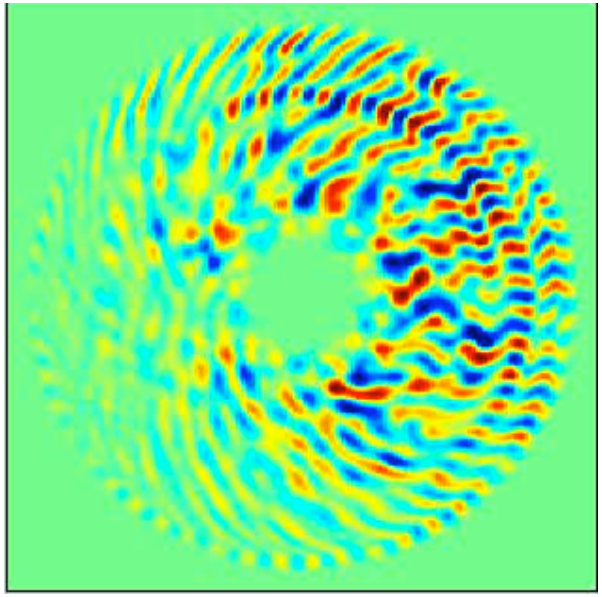
→ Toroidal current in the plasma

- **Toroidal current: 3 sources**
  - Variable current circulating in the coils
  - Self-generated current
  - External sources : beams, radiofrequency waves
- **Continuous operation:**

→ Fully non-inductive current (V_{loop}=0)

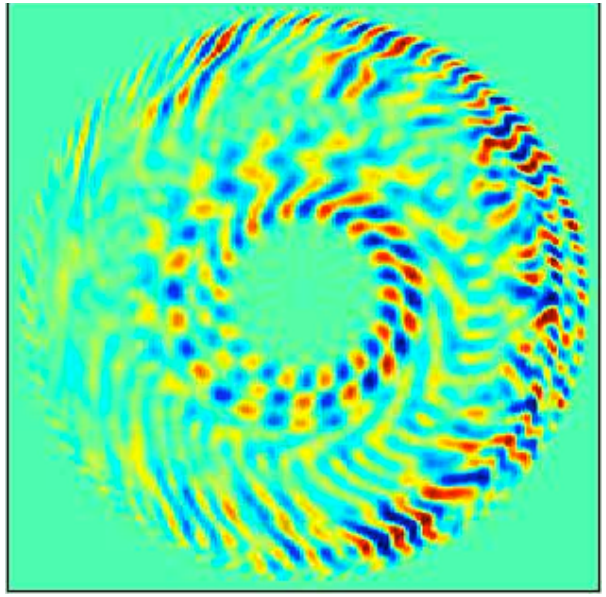
Influence of the current profile

- **Turbulence:**
  - Anomalous energy transport
  - Confinement degradation
- **Turbulence suppression (reduction):**
  - Shear of the plasma rotation velocity
  - Optimized current profile ⟶ Magnetic shear inversion



Monotonous q-profile

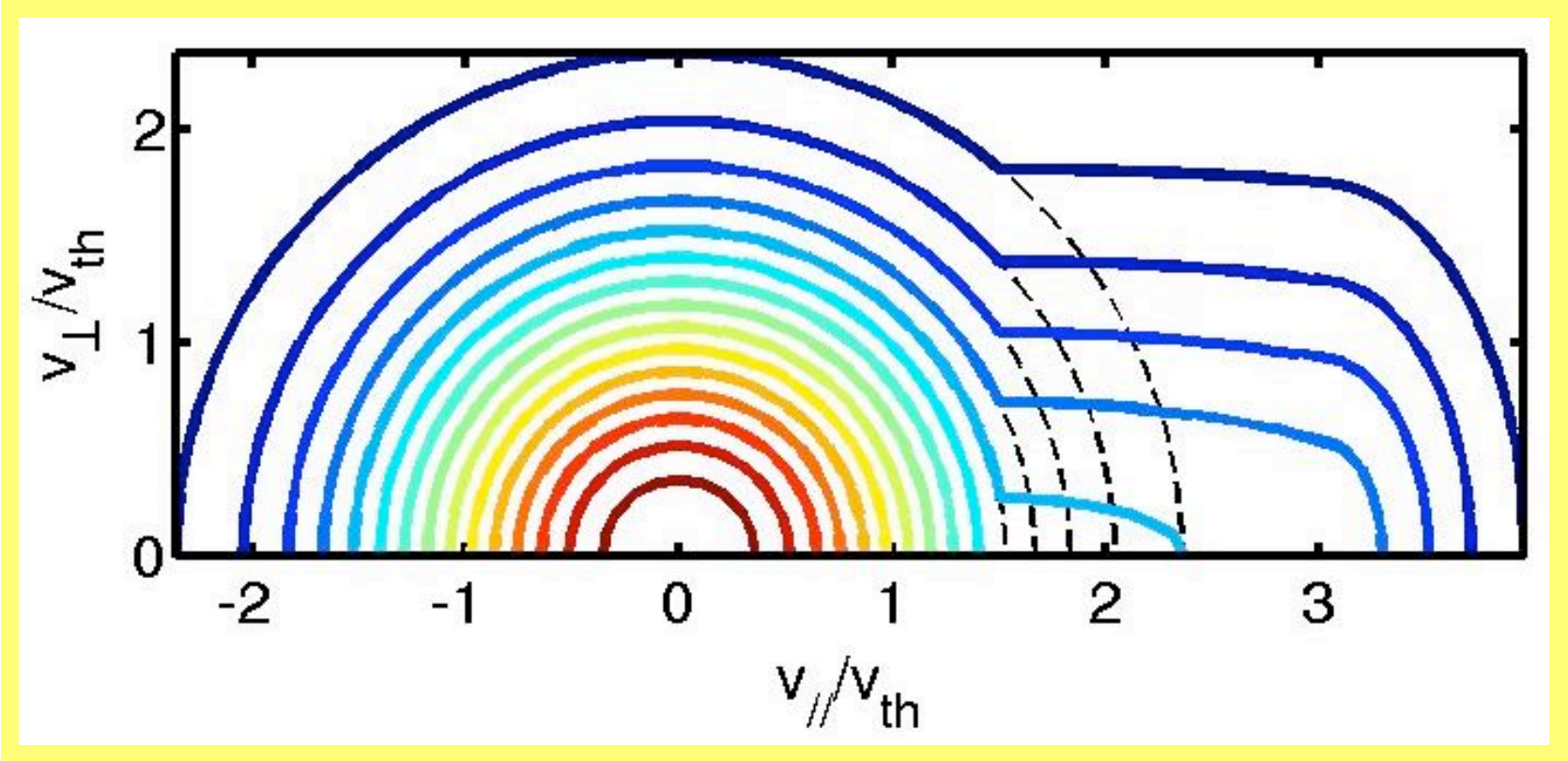
Optimized
⟶
current profile



Inverted q-profile

Current drive: general principle

- **Distribution function contours:**



Current density:

$$j = \sum_s n_s q_s \int d^3\mathbf{v}\, v_\parallel f_s(\mathbf{v}) \approx -e n_e \int d^3\mathbf{v}\, v_\parallel f_e(\mathbf{v})$$

Superthermal electrons

- **Current drive physics:**

- **Elemental current:** $\Delta j = -e\Delta v_{||}$
- **Expended power:** $p = \nu_e m_e v_{||} \Delta v_{||}$

Collision frequency

Current drive efficiency: $\eta \equiv \dfrac{|\Delta j|}{p} = \dfrac{e}{m_e v_{||} \nu_e}$

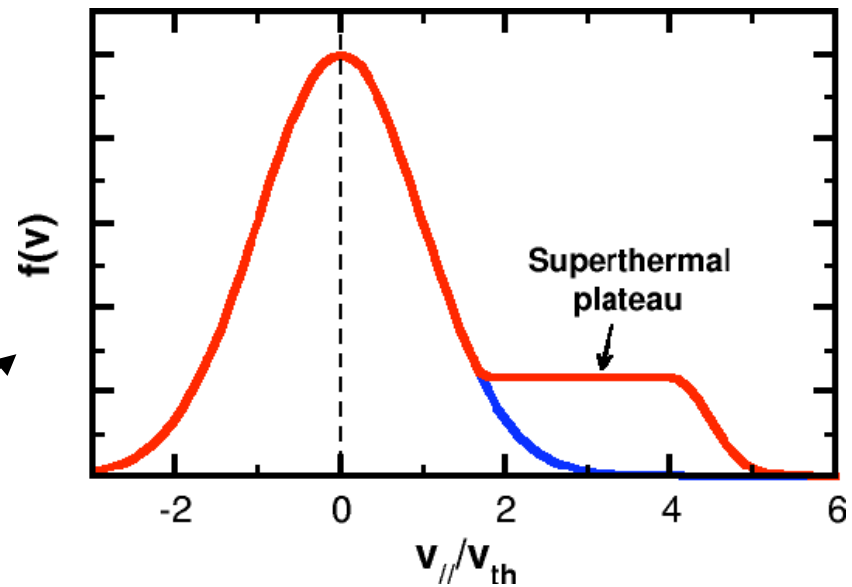
Thermal electrons:

$$\nu_e \approx \text{const.} \longrightarrow \eta \propto 1/v_{||}$$

but trapped electrons effects

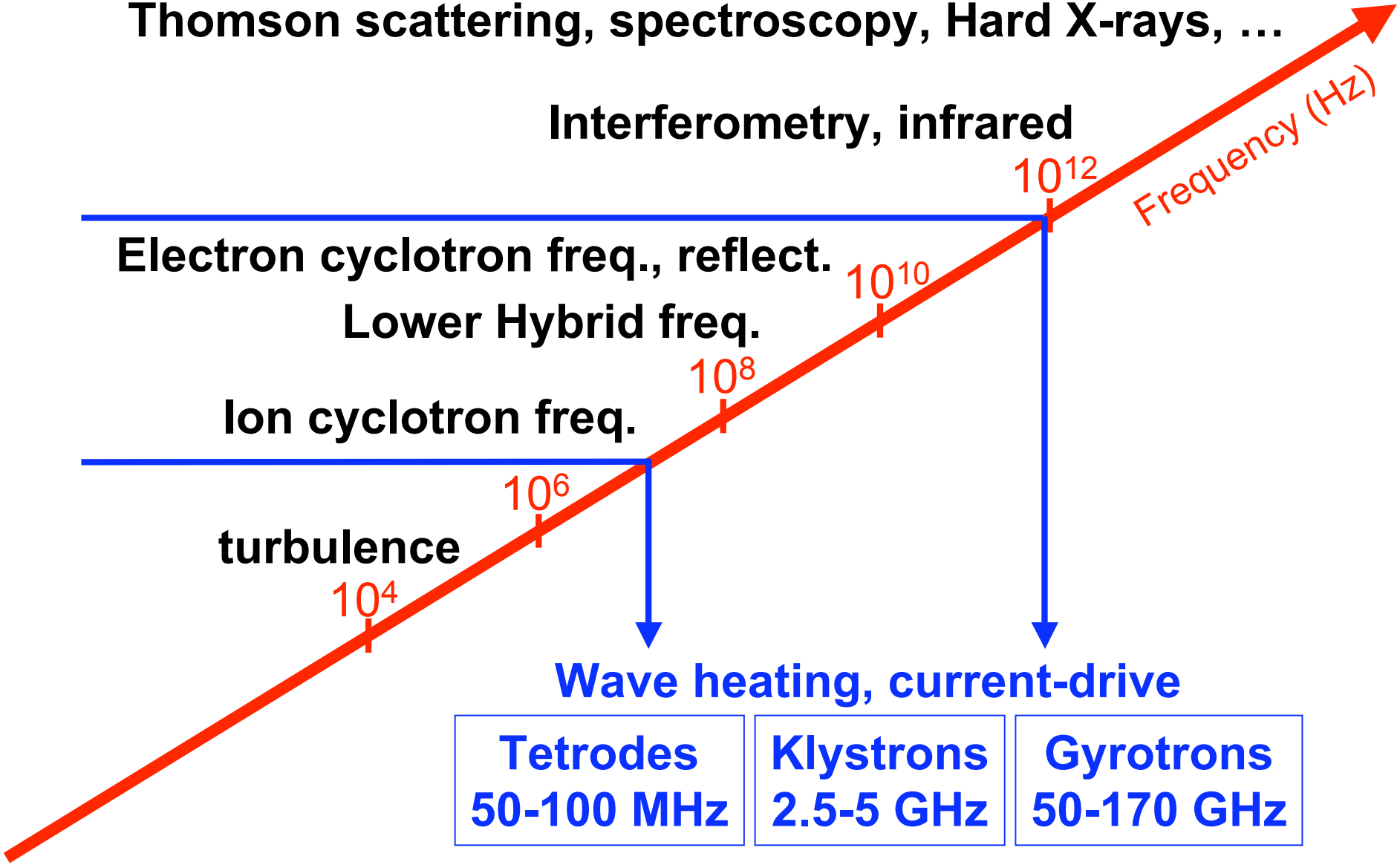
Superthermal electrons:

$$\nu_e \propto v_{||}^{-3} \longrightarrow \eta \propto v_{||}^2$$



Best efficiency obtained with fast electrons

Radiofrequency waves



The tokamak plasma

- **Geometric aspect:**
  - Anisotropic system
  - Antenna geometry
  - Confinement magnetic structure
  - Un-perturbed trajectories

- **Target plasma characteristics:**
  - Composition
  - Density profile(s)
  - Temperature profile(s)
  - Current profile

- **Kinetic effects:**
  - Hot plasma
  - Superthemmal populations
  - Trapped populations

Waves in the Ion Cyclotron frequency range (ICRF)

ICRF system

- **Frequency range:**

  40 MHz < f < 80 MHz

  $\omega \# \omega_{ci}, \omega_{pi} << \omega_{ce}, \omega_{pe}$

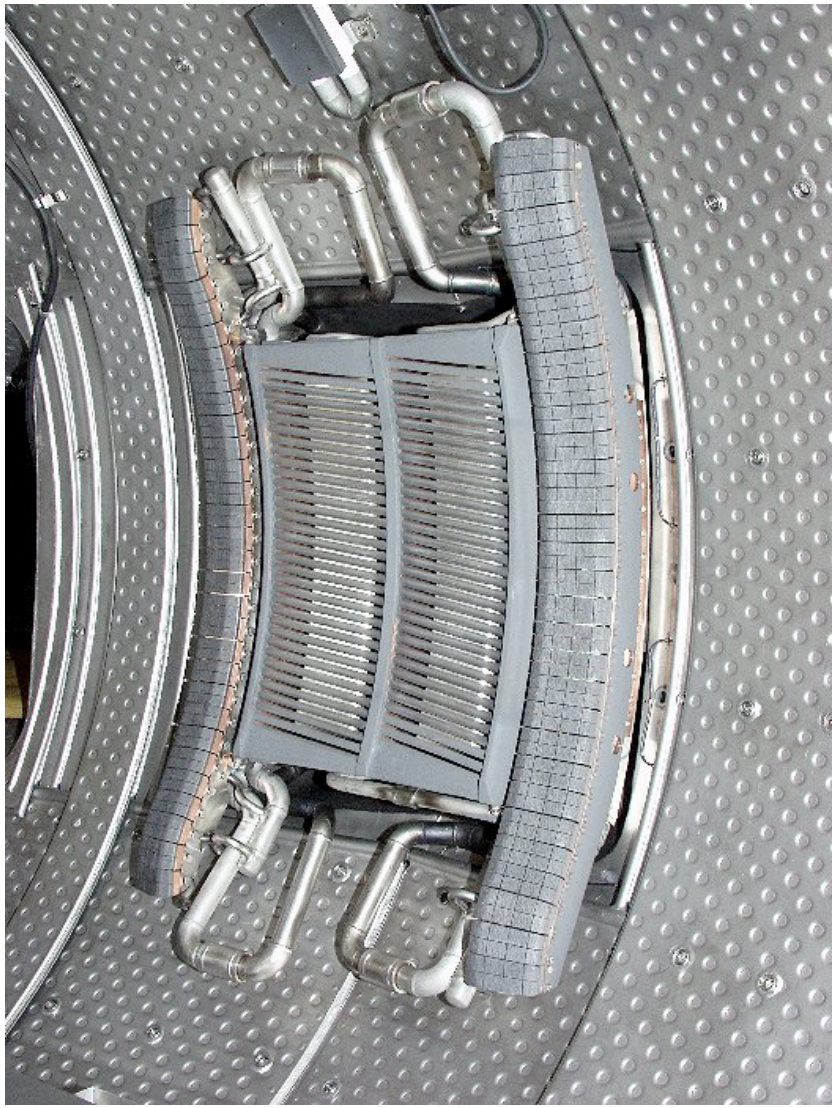
- **Generators:**

  Tetrodes

- **General principle:**

  Wave absorbed
  by **ions** (cyclotron abs.) or
  by **electrons** (ELD - TTMP)

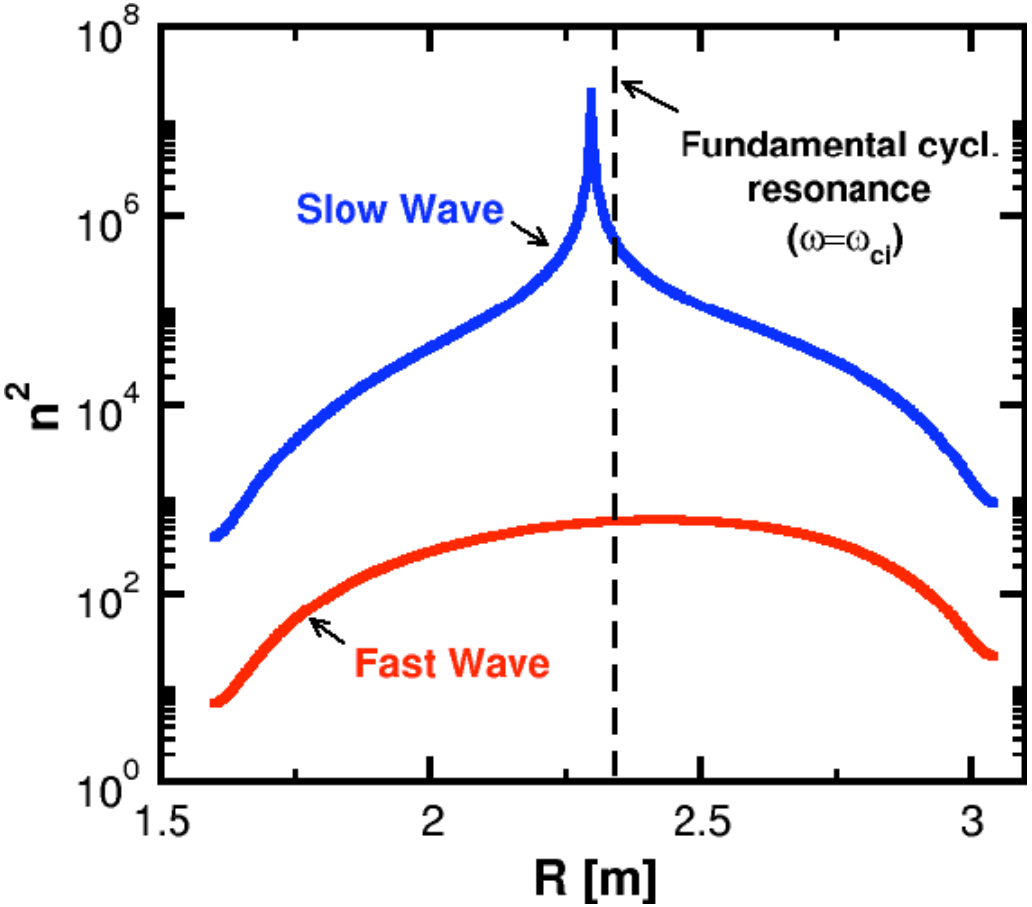
  ⟶ Heating system
  (mostly)



[Tore Supra ICRF antenna]

Fundamental cyclotron ion heating

- **Cyclotron resonance:** $\omega = \omega_{ci} + k_{//} v_{//}$
- **Dispersion relation:**



[Hydrogen plasma in Tore Supra]

1) Slow Wave (O)

- Sensitive to the fundamental cyclotron resonance
- **Excitation in toroidal geometry is unpractical**

2) Fast Wave (X)

- Excitable from plasma edge
- **Insensitive to fundamental cyclotron resonance**

Resonance ($\omega \approx \omega_{ci}$)

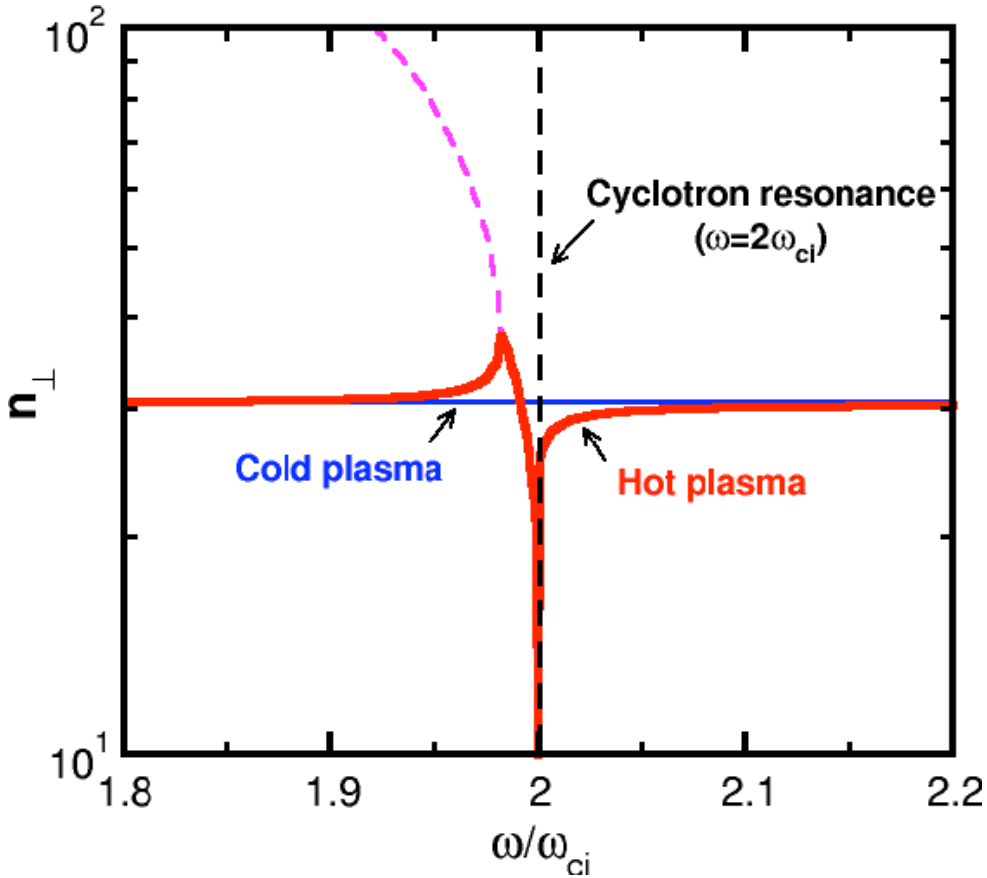
$$E_x \to -iE_y \quad (E_+ \to 0)$$

→ **Screening**

→ **No heating**

First harmonic heating

- **Dispersion relation**



[Hydrogen plasma in Tore Supra]

- **Resonance relation:**

$$\omega=2\omega_{ci}+k_{//}v_{//}$$

- **Features:**
  - No screening problem
  - Energy transfer:

$$\frac{dW_\perp}{dt} \propto \rho_L^2 \propto T_i$$

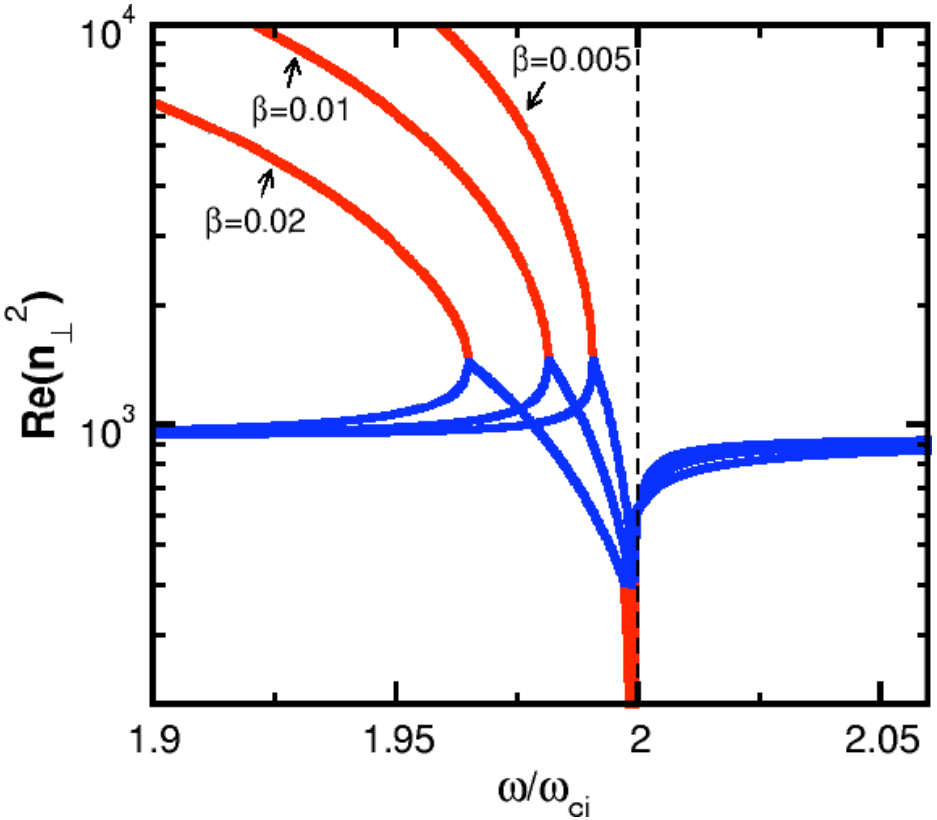
→ **Efficient in hot plasmas**

→ **Self-bootstrapping**

- Finite Larmor Radius effect
- In competition with mode conversion mechanism

Mode conversion (first harmonic)

- **Perpendicular propagation**



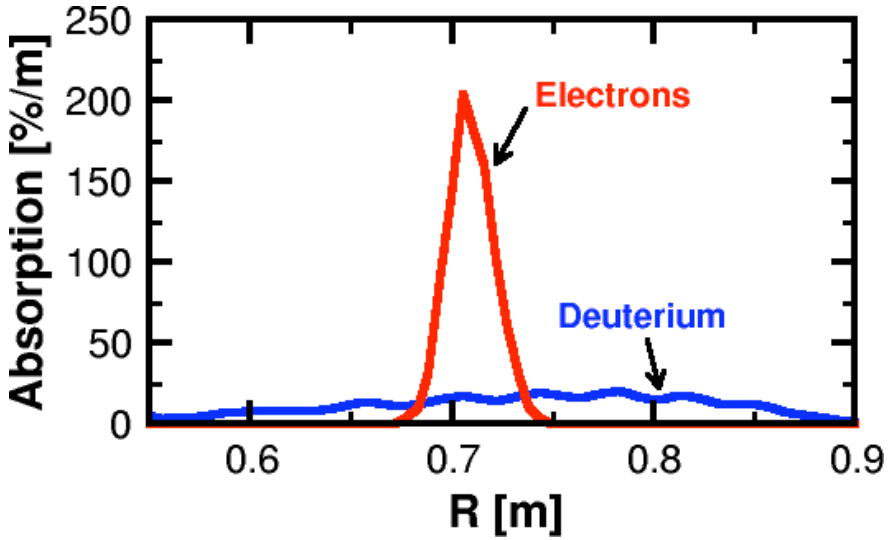
[Hydrogen plasma in Tore Supra]

- **Mode conversion**

Fast Wave Slow Wave (IBW)

- **Ion Bernstein Wave (IBW)**

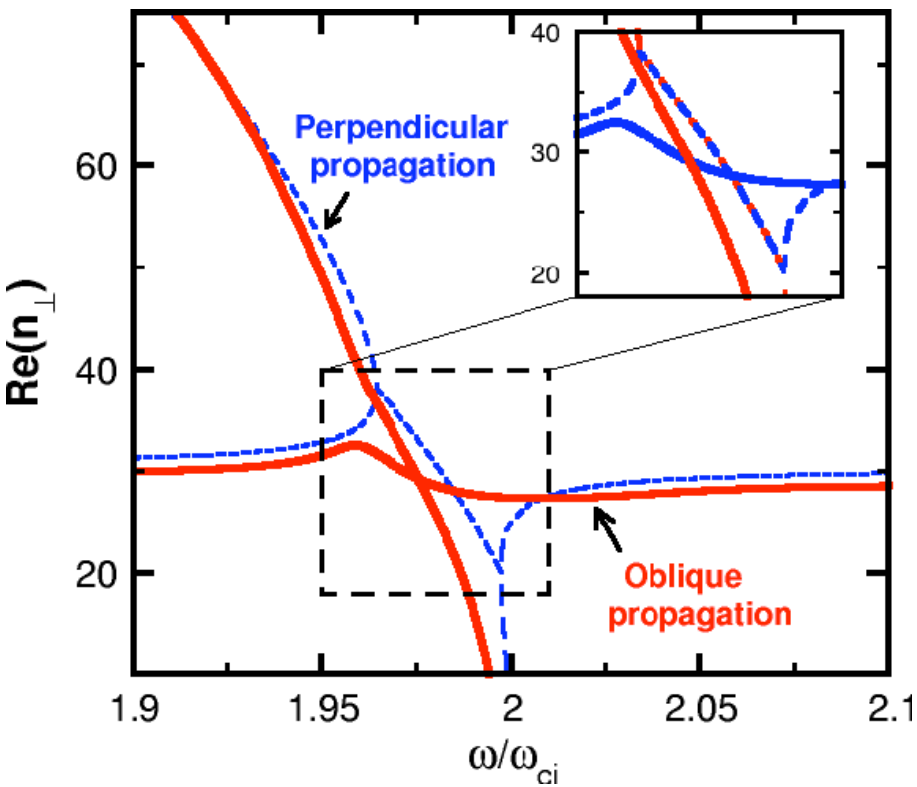
Absorbed on electrons by Landau damping

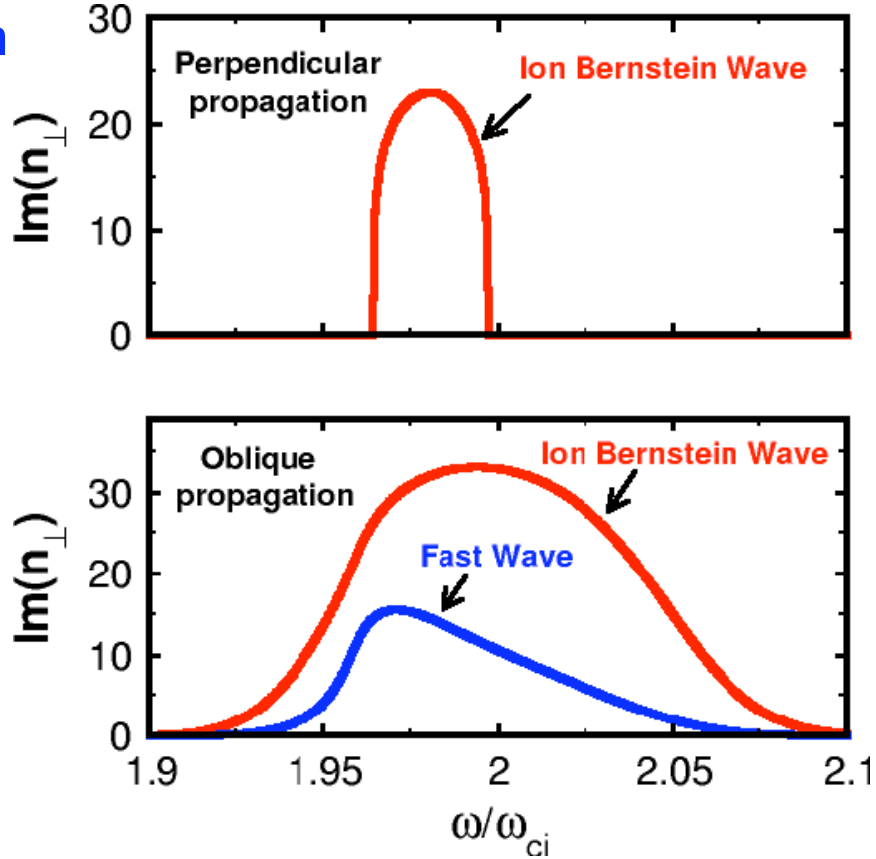


[Deuterium plasma in Alcator C-Mod]

Ion or Electron heating scheme ?

- **Perpendicular / Oblique propagation**



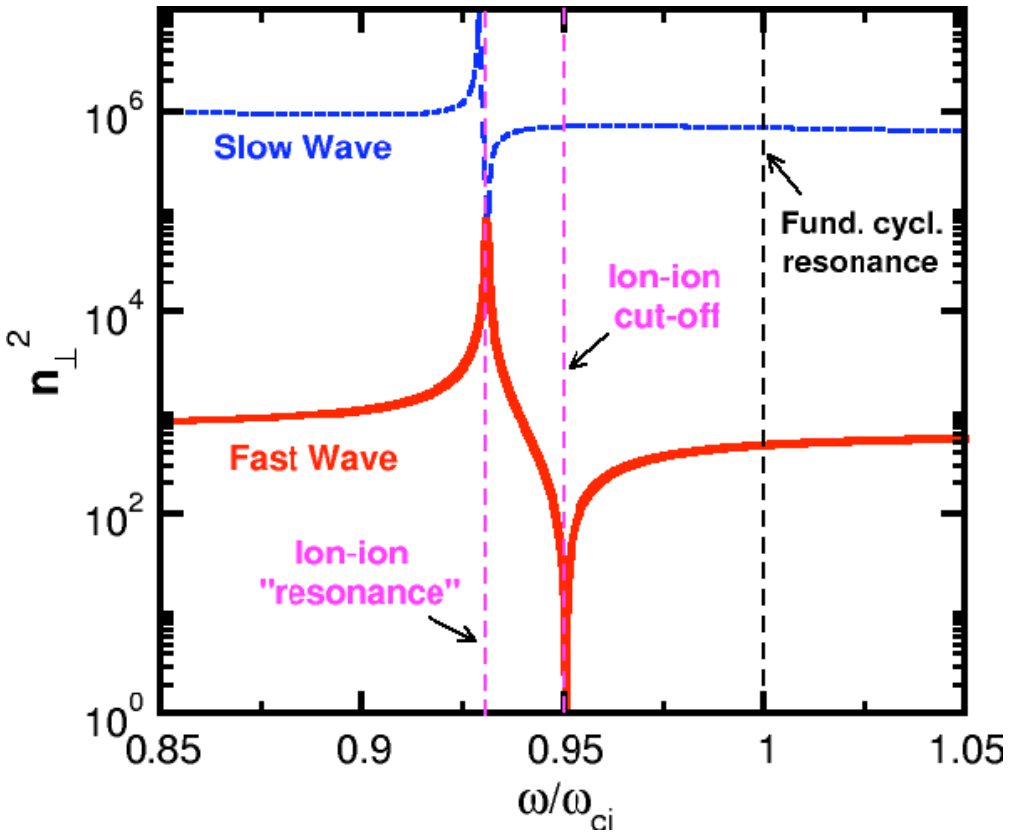


→ **Ion heating is possible for oblique propagation**

- **Gap overlap criterion:** $|n_{\|}|\frac{v_{th,i}}{c} \gtrsim 2.5 \cdot \frac{\omega_{pi}^2}{\omega_{ci}^2} \cdot \frac{v_{th,i}^2}{c^2}$

Heating in a multi-ion plasma

- **Fundamental resonance:** $\omega = \omega_{ci} + k_{//} v_{//}$



90 % Deuterium
+ 10 % Hydrogen (min.)

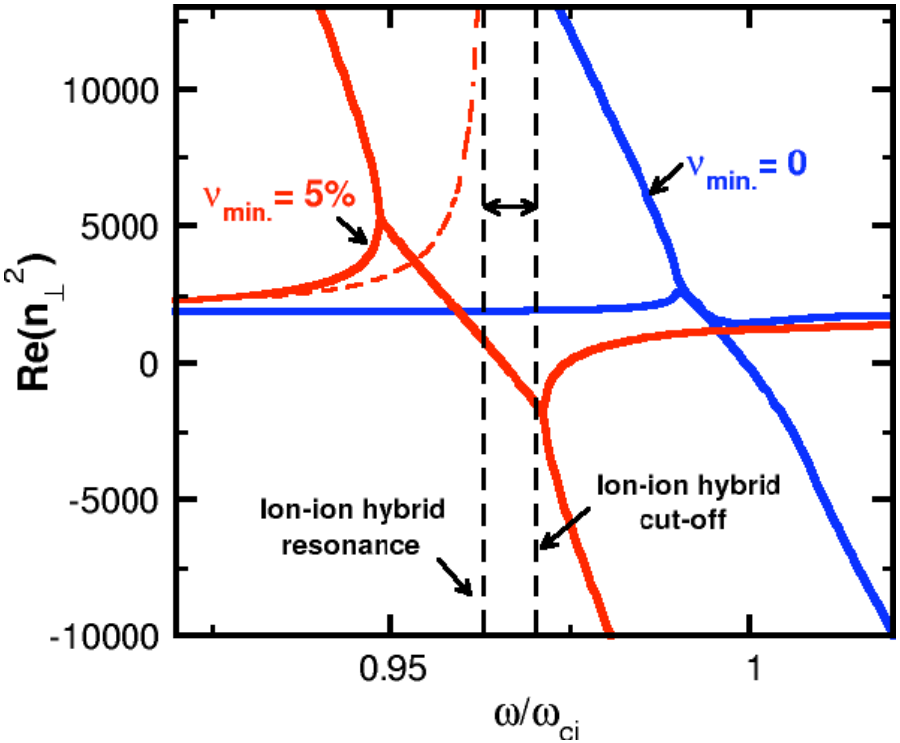
- **Single ion:**
  - No ion heating possible at fundamental resonance

- **Two ions:**
  - Appearance of a ion-ion cut-off / hybrid resonance couple
  - **Propagation** determined by majority ion
  - **Absorption** on minority ion

→ **Ion heating is possible**

Fundamental resonance heating

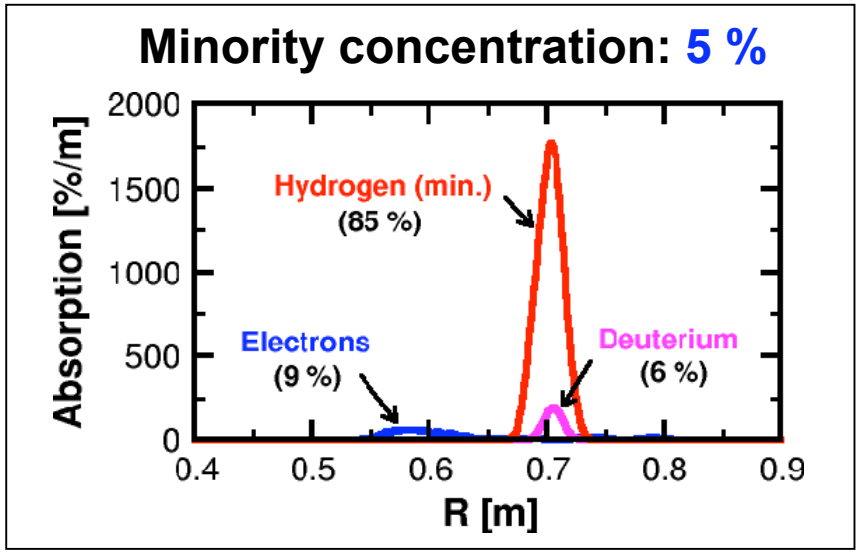
- **Minority heating scheme:**

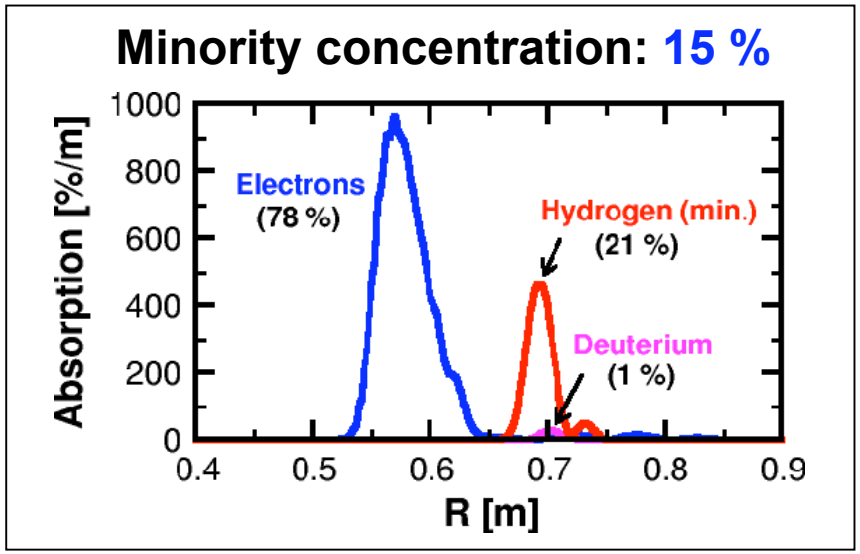


[Minority Hydrogen in a Deuterium plasma]

- **Minority heating criterion:**

$$|n_{||}| \cdot \frac{v_{th,H}}{c} \gtrsim \frac{3}{2}\nu_H + \sqrt{\frac{3}{2}\beta_D \nu_H}$$



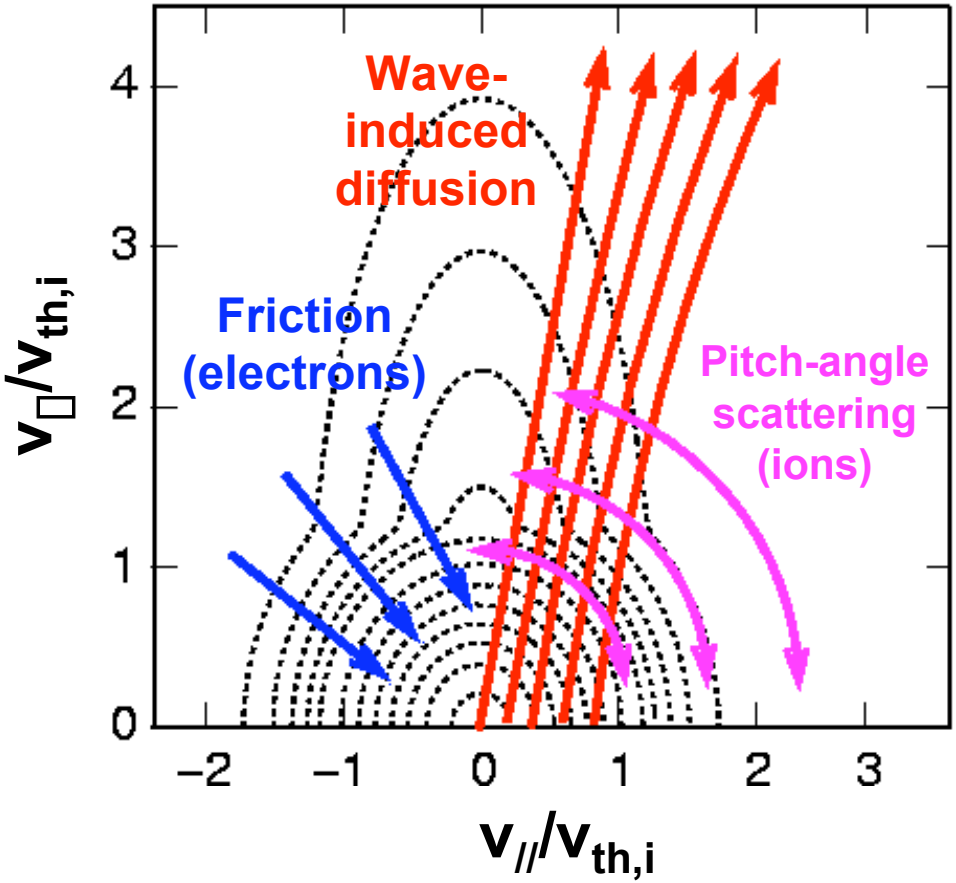


[D(H) plasma in Alcator C-Mod]

Ion heating: kinetic aspect

Quasilinear dynamics

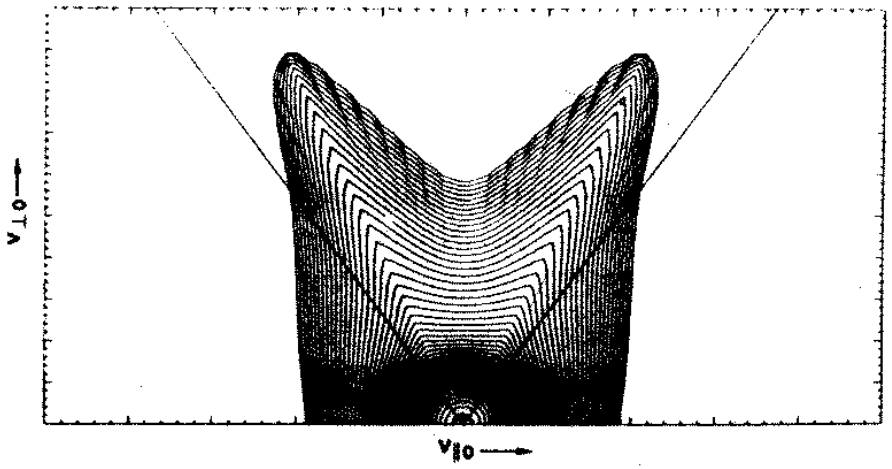
(Velocity space)



- **Antagonist phenomena**
  - Wave effect
  - Collisions effect

→ Development of a fast ion tail

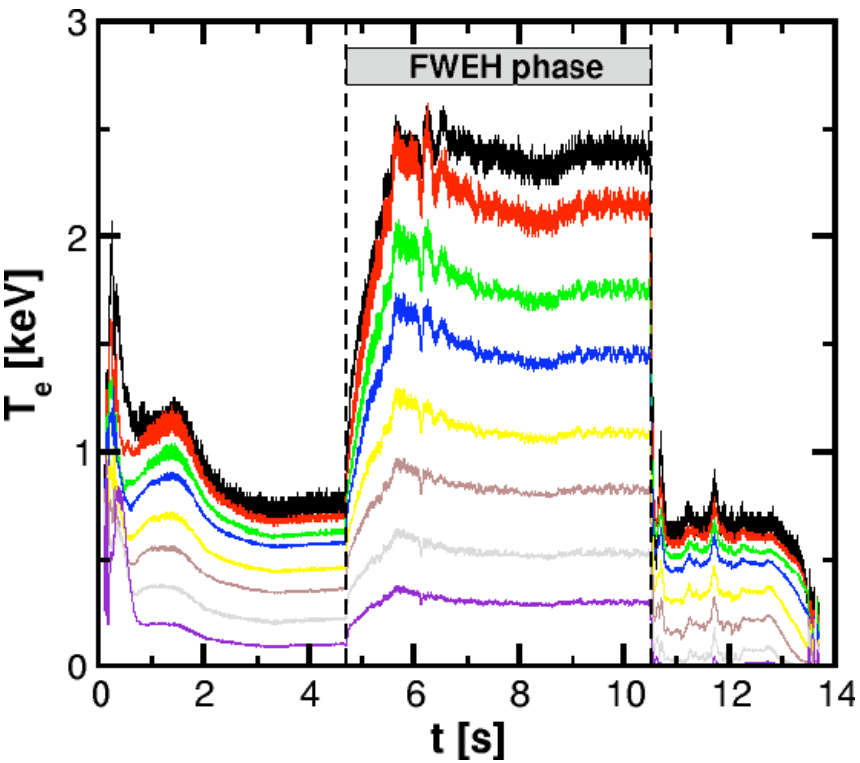
- **"Rabbit ear" distribution**

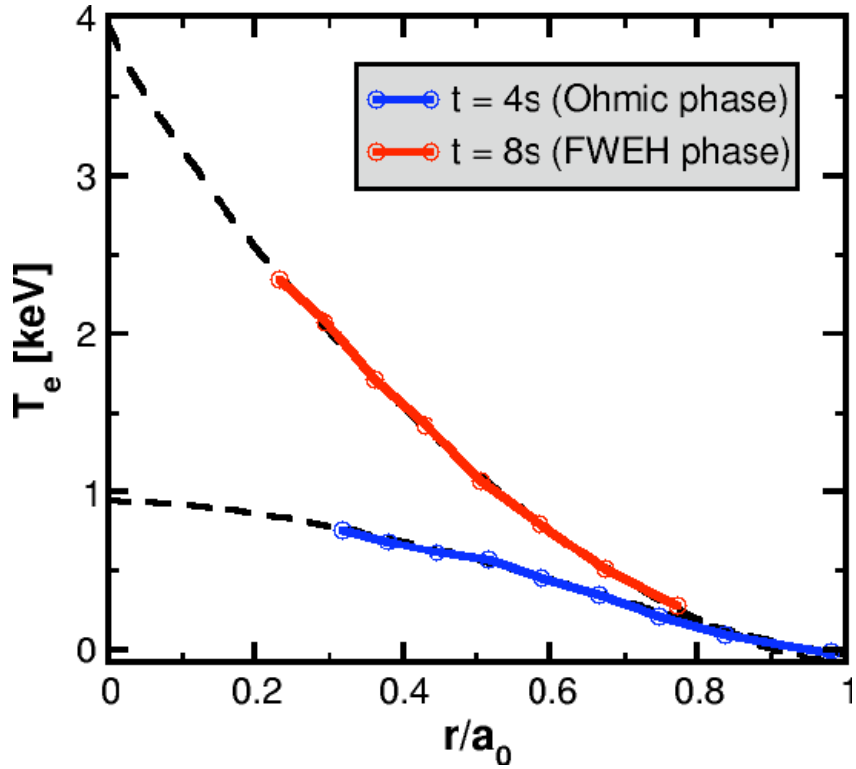


[G.D. Kennel and M.G. McCoy Phys. Fluids **28** (12) 3629]

Fast Wave Electron Heating

- **Resonance:** $\omega = k_{//} v_{//}$
- **Goal:** Avoid ion cyclotron resonances in order to heat thermal electrons (Electron Landau damping + TTMP)
- **Example:** Fast Wave (2T) experiment on Tore Supra

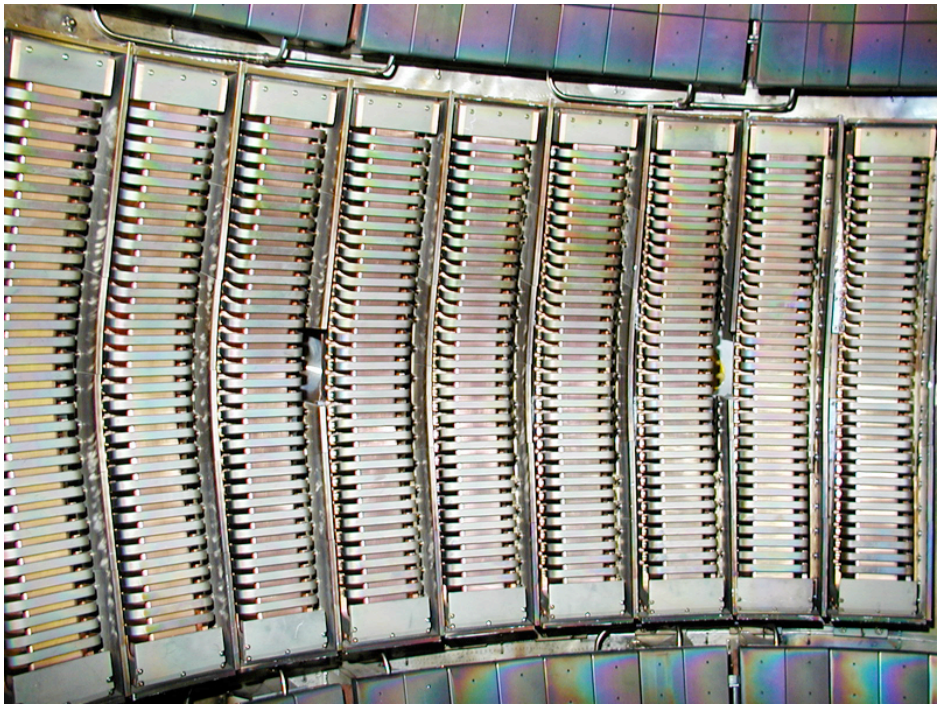




[Super-heterodyne radiometer measurements]

Particular case: HHFW on NSTX

[NSTX HHFW antenna]



[Source : PPPL]

- **Resonance:**

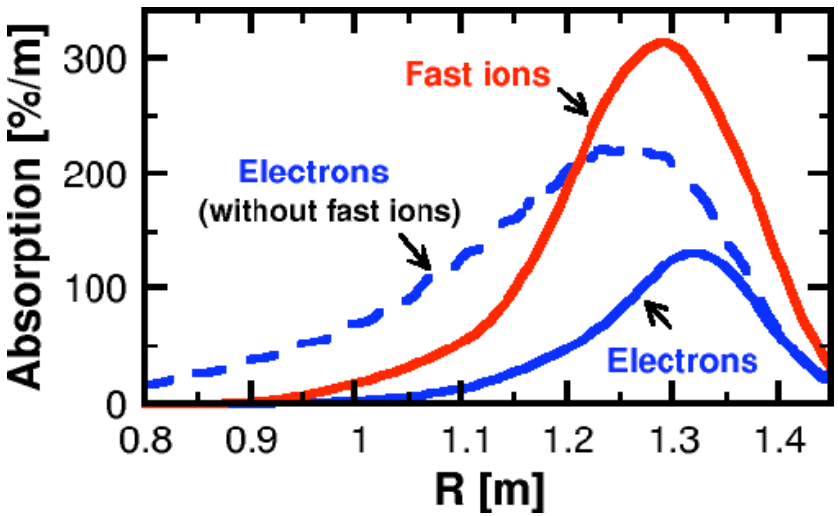
$\omega = n\Omega_{ci} + k_{//}v_{//}$, $5 < n < 15$

→ **Weak ion absorption**

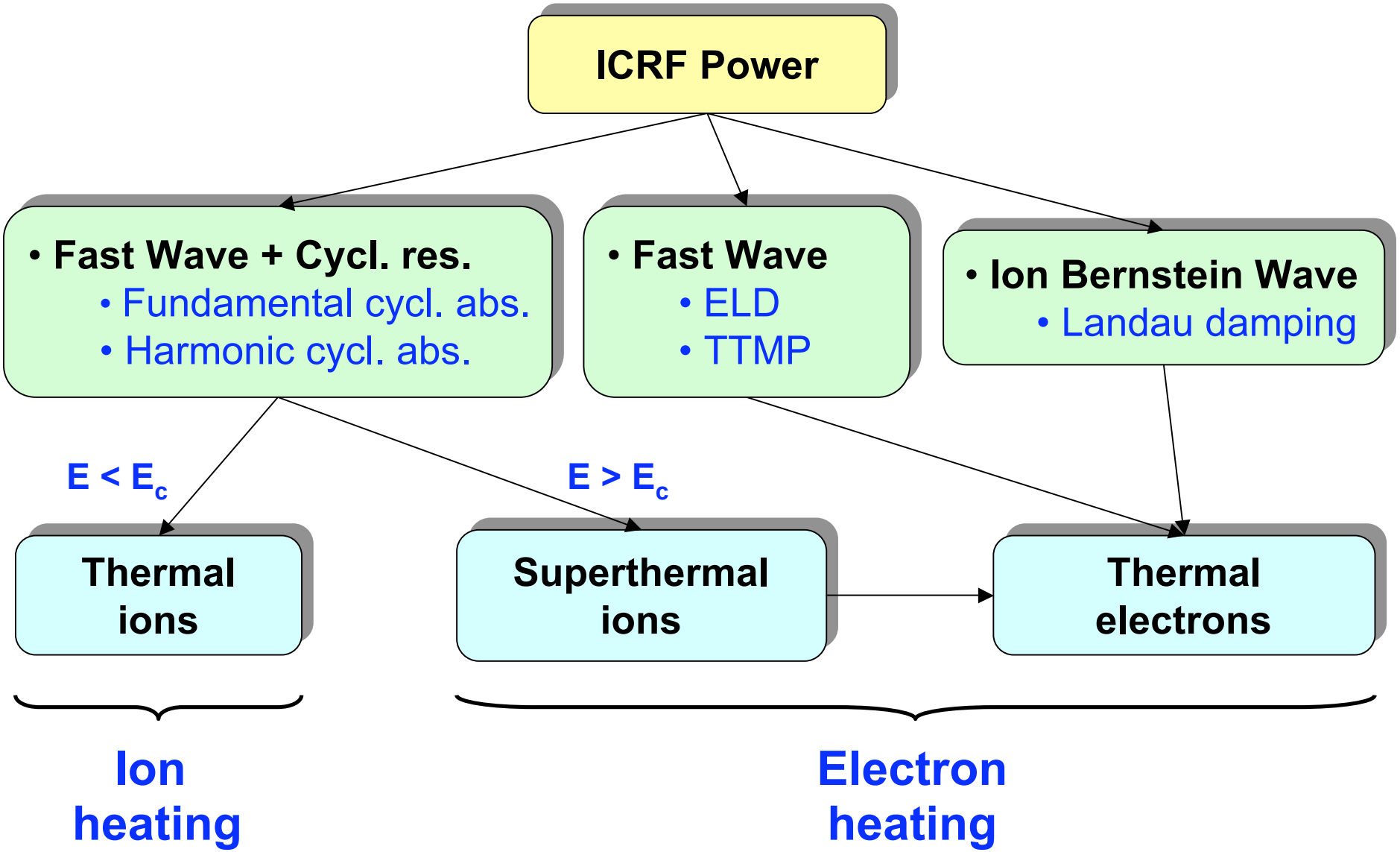
→ **Landau damping + TTMP on thermal electrons**

- **Ion absorption:**

In the presence of fast particles (NBI), the wave is partially absorbed by ions



ICRF: summary



Waves in the Lower Hybrid frequency range (LH)

LH system

- **Frequency range:**

  1 GHz < f < 8 GHz

  $\omega_{ci} << \omega << \omega_{ce}$

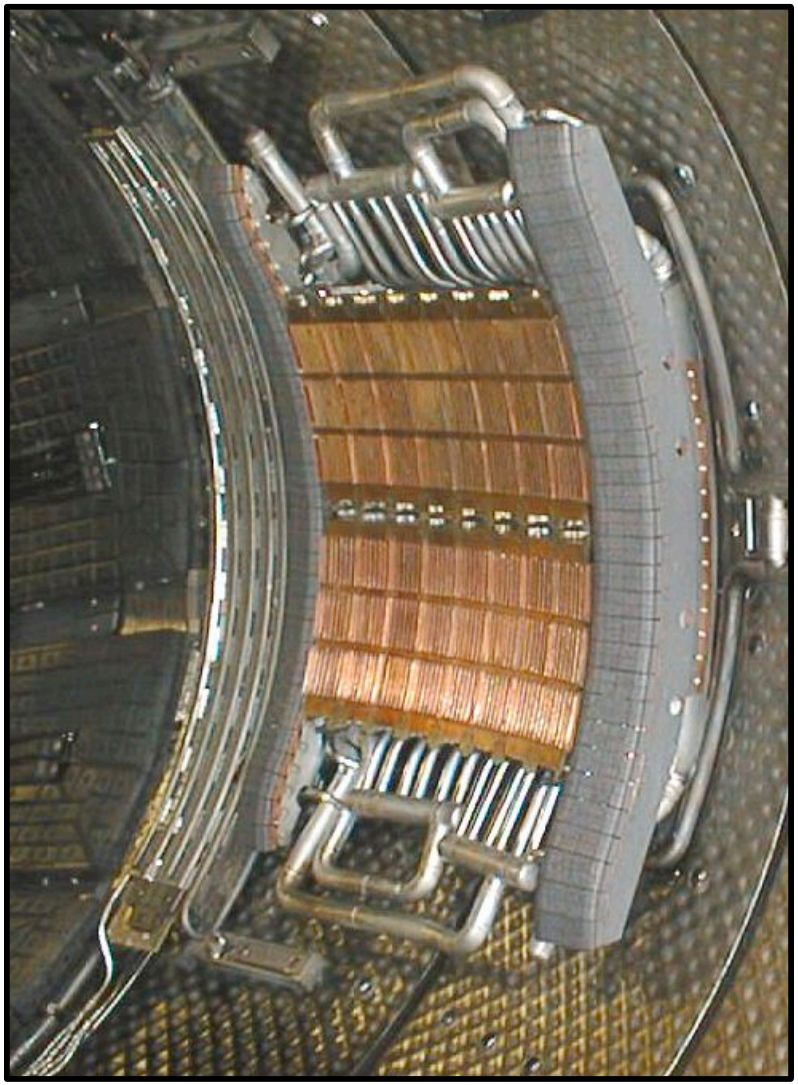
- **Generators:**

  Klystrons (or gyrotrons)

- **General principle:**

  Landau damping of the wave on superthermal electrons

  → Current Drive system

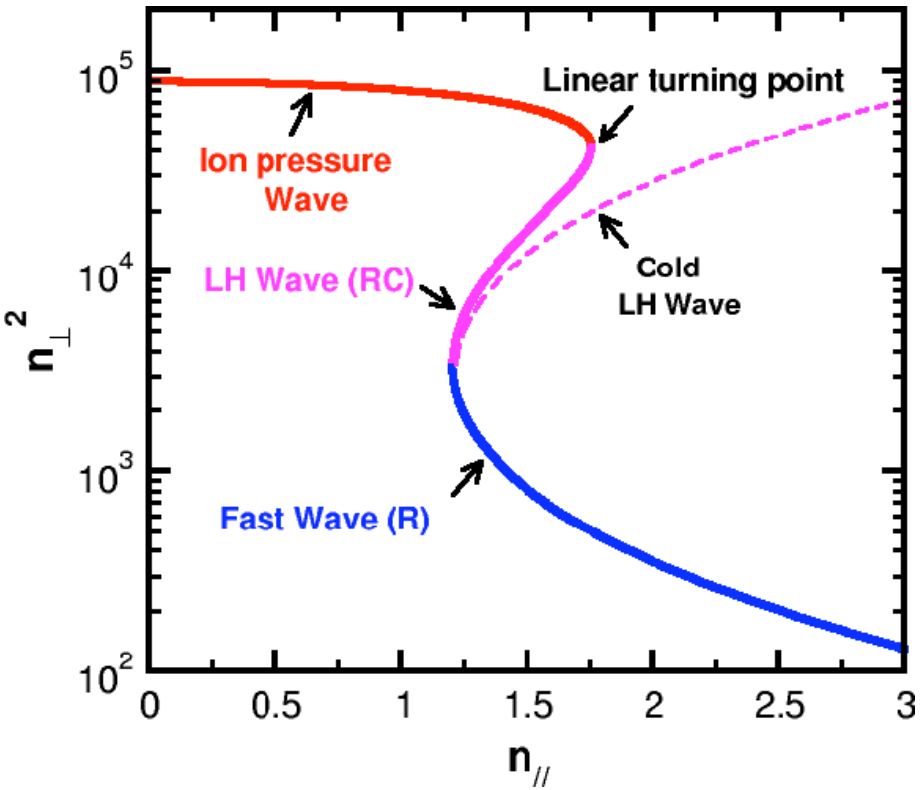


[Tore Supra LH antenna]

Lower Hybrid frequency heating

- **Original ideal:** converting the LH wave in a pressure wave

  ⟶ **Ion heating**



- **Issues:**
  - ($n_{//}$,□) range is very narrow
  - Excitation of a Resonance Cone wave (RC)

    ⟶ Non-linear effects
  - Large values of the perpendicular refraction index at conversion

    ⟶ Parametric instabilities
  - Landau damping of the wave on electrons prior to conversion

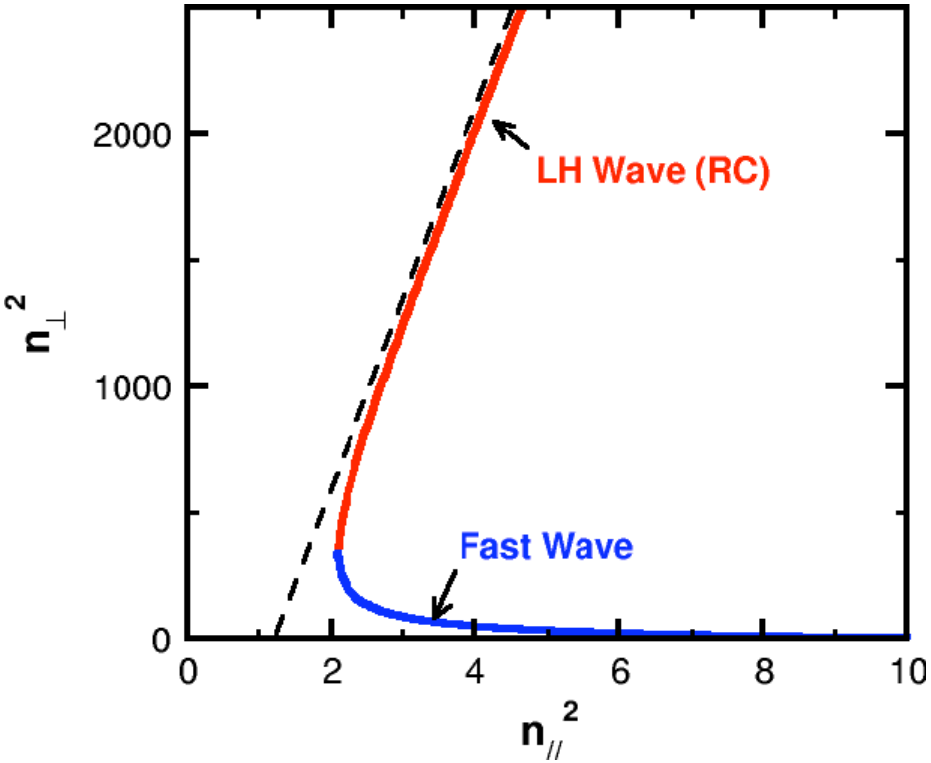
- **Modern use:** exploit the once feared Electron Landau Damping

  ⟶ **Electron heating**

Resonance Cone wave

- **Resonance cone:**

$$n_\perp^2 \approx \frac{m_i}{m_e} \cdot \frac{\omega_{lh}^2}{\omega^2 - \omega_{lh}^2} \cdot n_\parallel^2$$

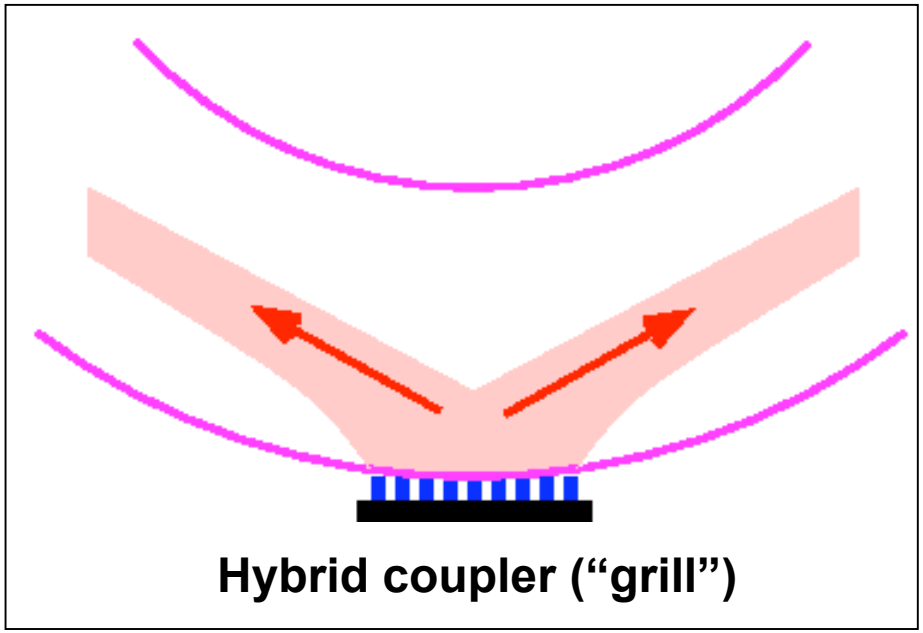


- **Polarization - group velocity:**

$$\left.\frac{E_\perp}{E_\parallel}\right|_S \approx \frac{n_\perp}{n_\parallel} \quad \rightarrow \quad \mathbf{E} \parallel \mathbf{k}$$

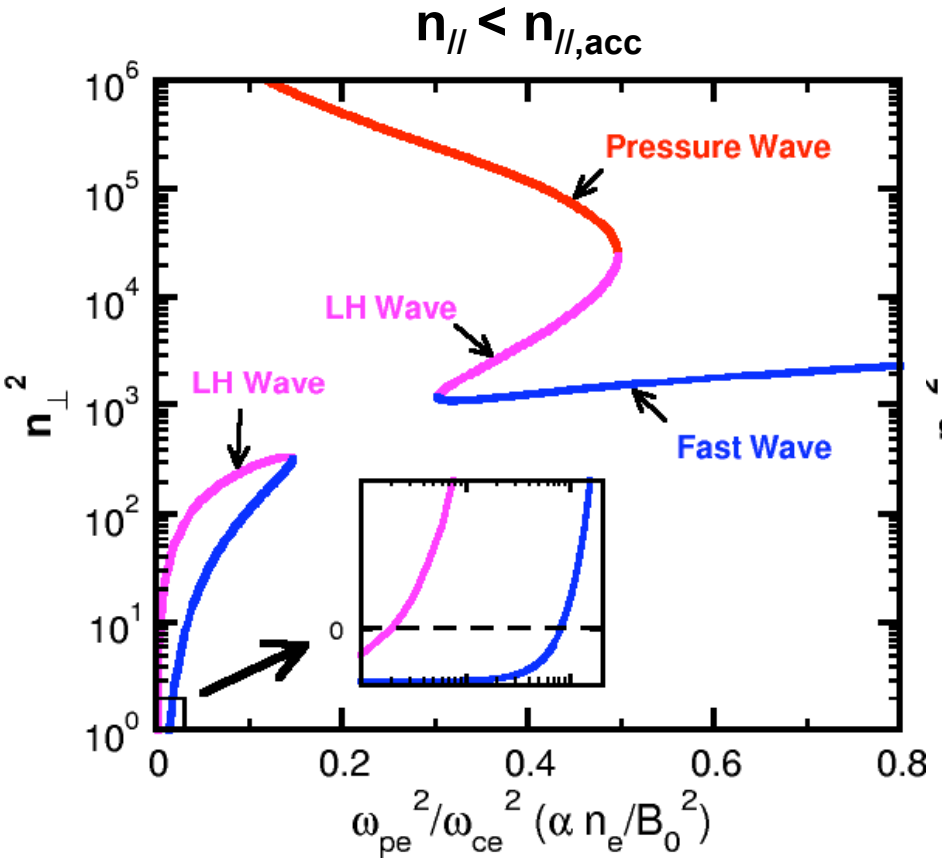
$$\left.\frac{v_{g,\perp}}{v_{g,\parallel}}\right|_S \approx -\frac{n_\parallel}{n_\perp} \quad \rightarrow \quad \mathbf{v}_g \perp \mathbf{k}$$

- **Directivity:**

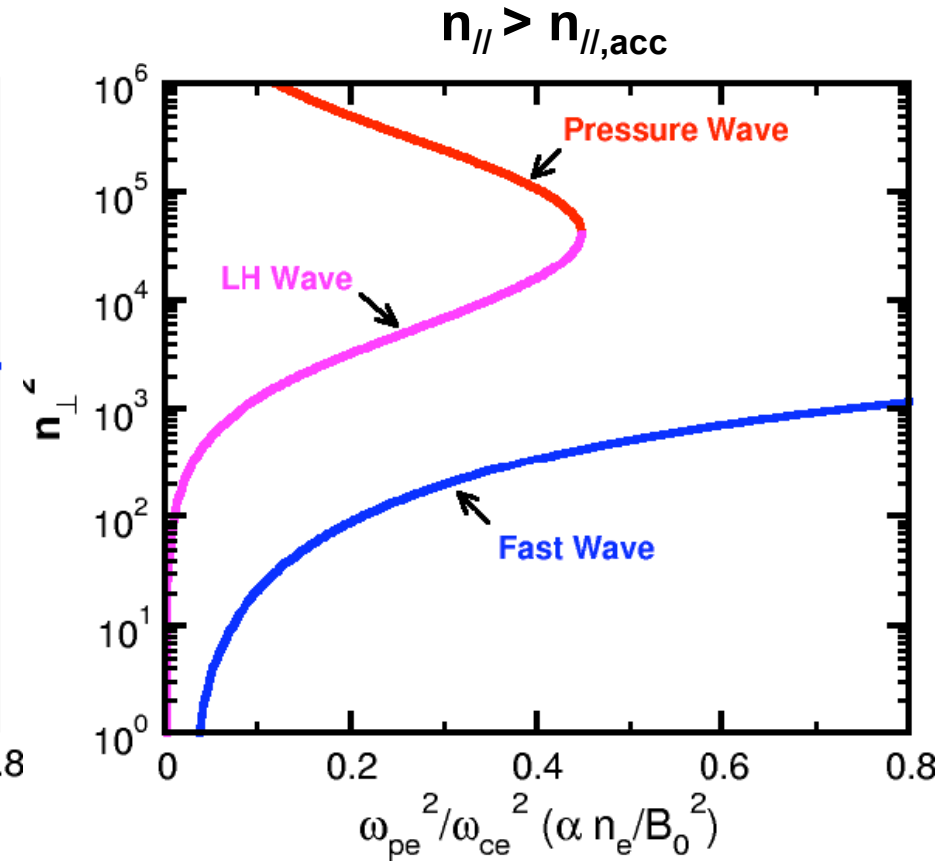


Accessibility in a tokamak

- **Coupling and propagation of the LH wave:**
  - Evanescence at the plasma edge
  - Potential confluence with the Fast Wave



Inaccessible case



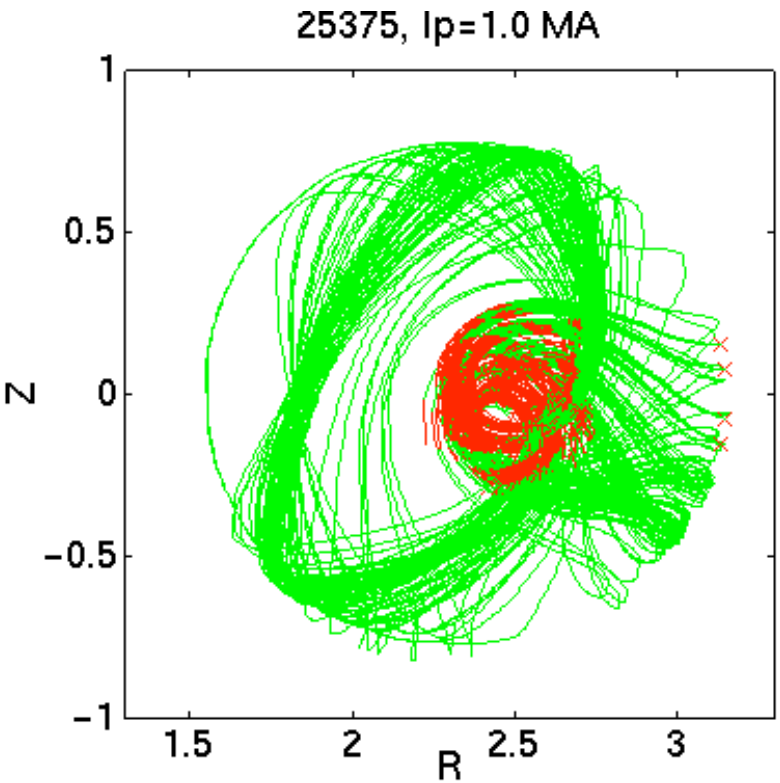
Accessible case

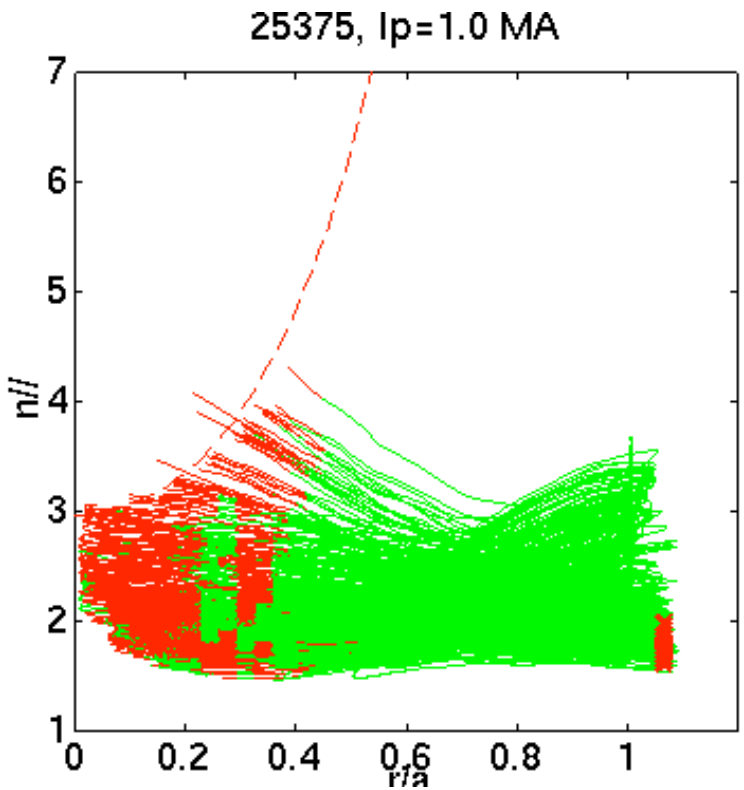
Propagation in a tokamak

- **Wavelength:** $\lambda \ll L_B$

→ **Quasi-optical propagation**

- **Ray-tracing calculations:**



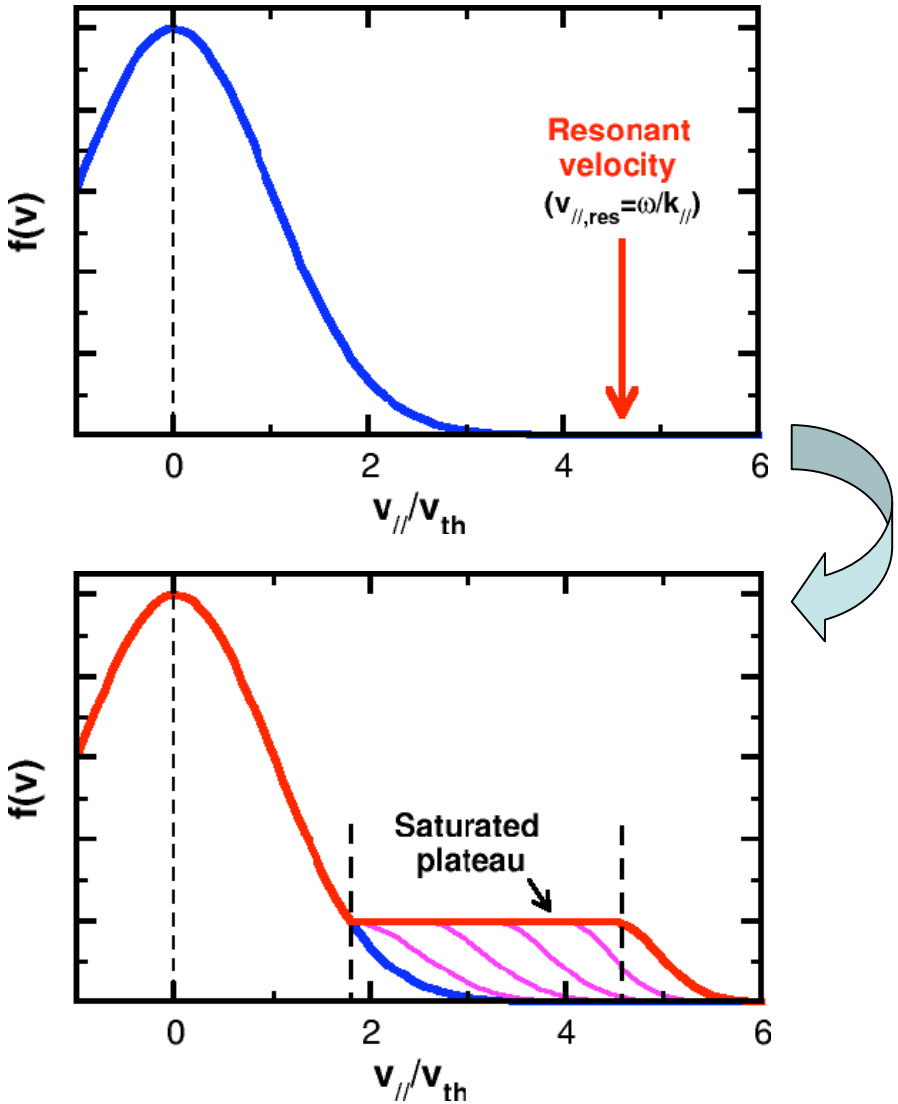


[Source : F. Imbeaux]

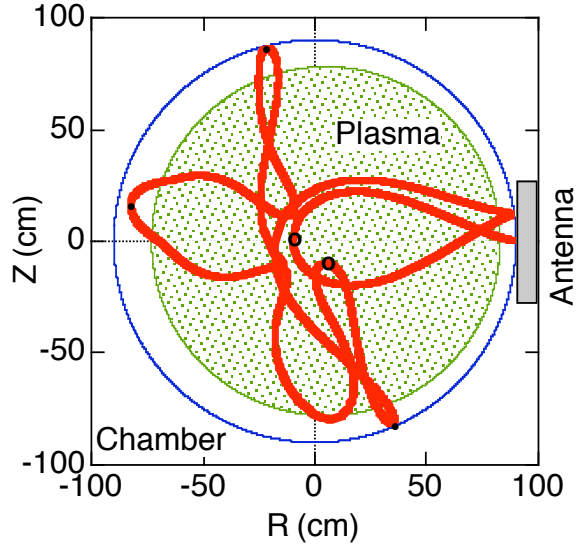
→ **Multiple reflections ("multipass" regime)**

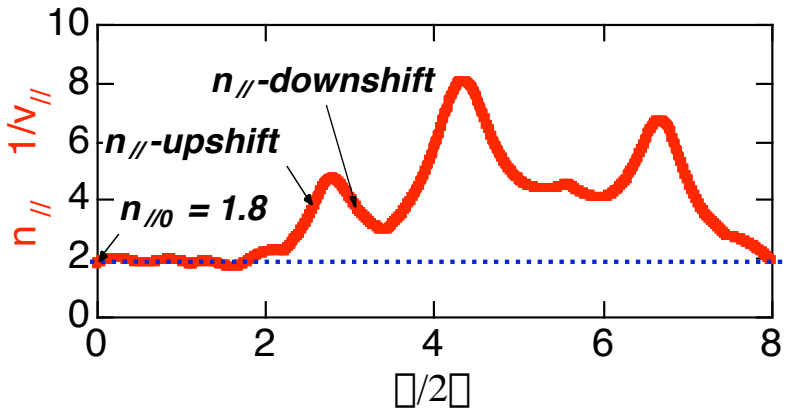
Kinetic aspect: the spectral “gap”

- **Plateau build-up:**



- **Single-ray propagation:**

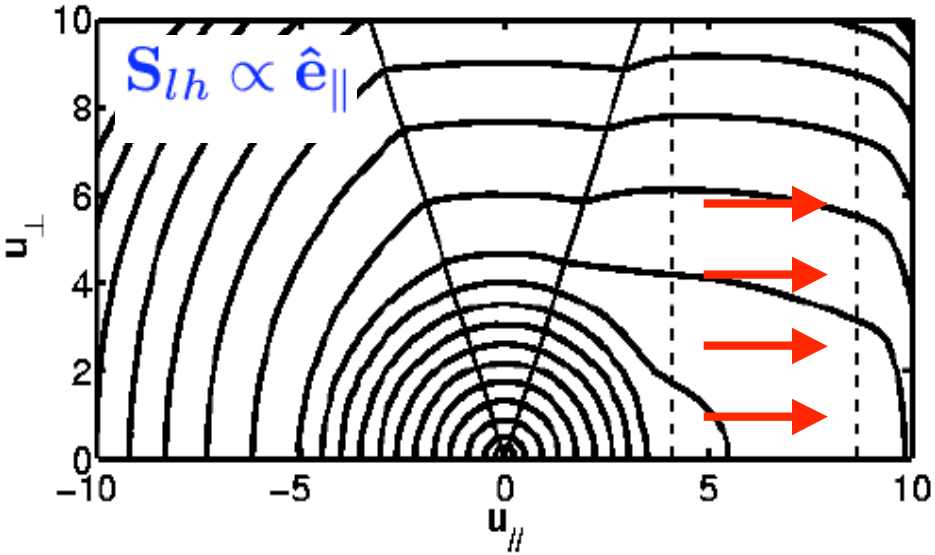




[Source : Y. Peysson]

LHCD: main features

- **Distribution function $f_e(v)$**



- **Generated current:**

$$j \approx -en_e \int d^3\mathbf{v}\, v_{\parallel} f_e(\mathbf{v})$$

Advantages:

- Excitation of very fast electrons
- Direct transfer of parallel momentum

+

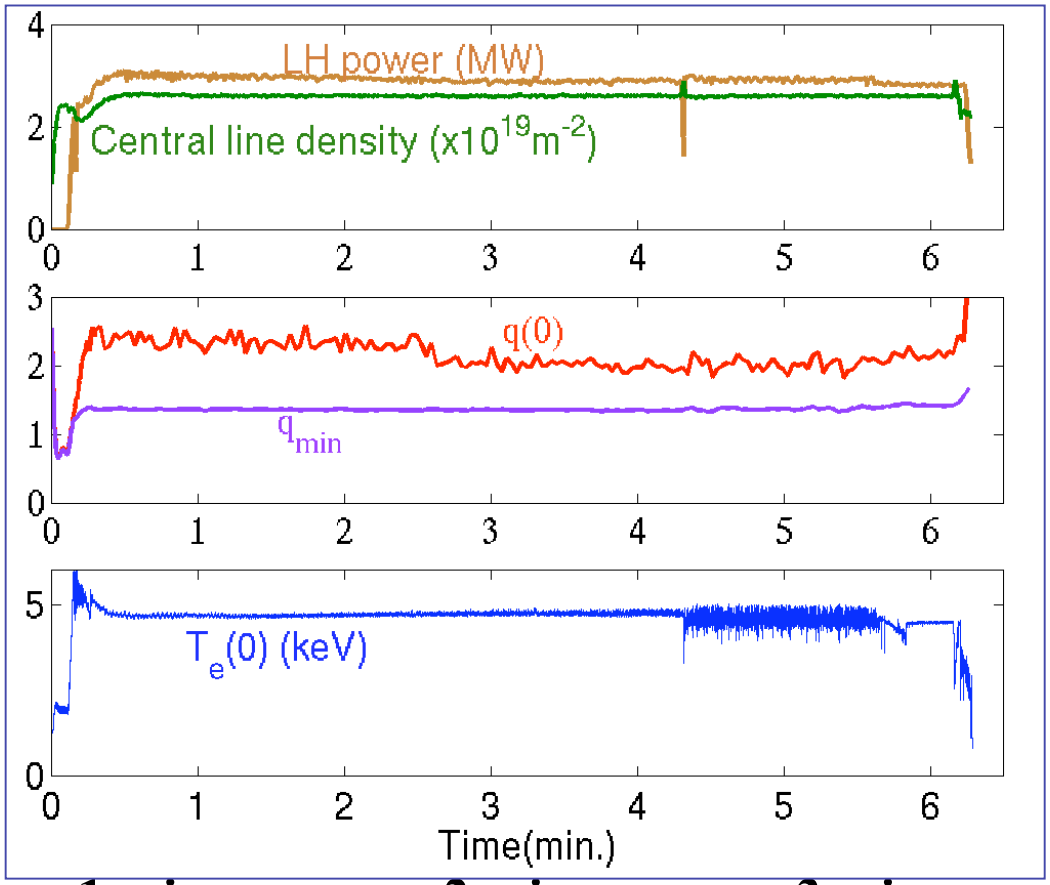
- Creation of an asymmetric resistivity
- Low sensitivity to trapped electrons

→ Very efficient scheme

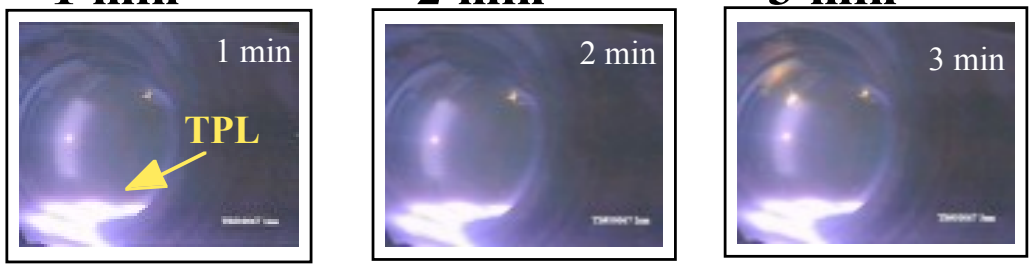
Drawbacks:

- Difficult to control
- Wide power deposition
- Sensitive to plasma edge conditions

Record shot on Tore Supra



1 min **2 min** **3 min**



GigaJoule discharge:

- Duration: **> 6 minutes.**
- Injected energy: **1.1 GJ.**
- Fully non-inductive current, **almost totally sustained by Lower Hybrid waves.**

Waves in the Electron Cyclotron frequency range (EC)

EC system

- **Frequency range:**

  110 GHz < f_{ec} < 140 GHz

  $\square$ # $\square_{ce}$

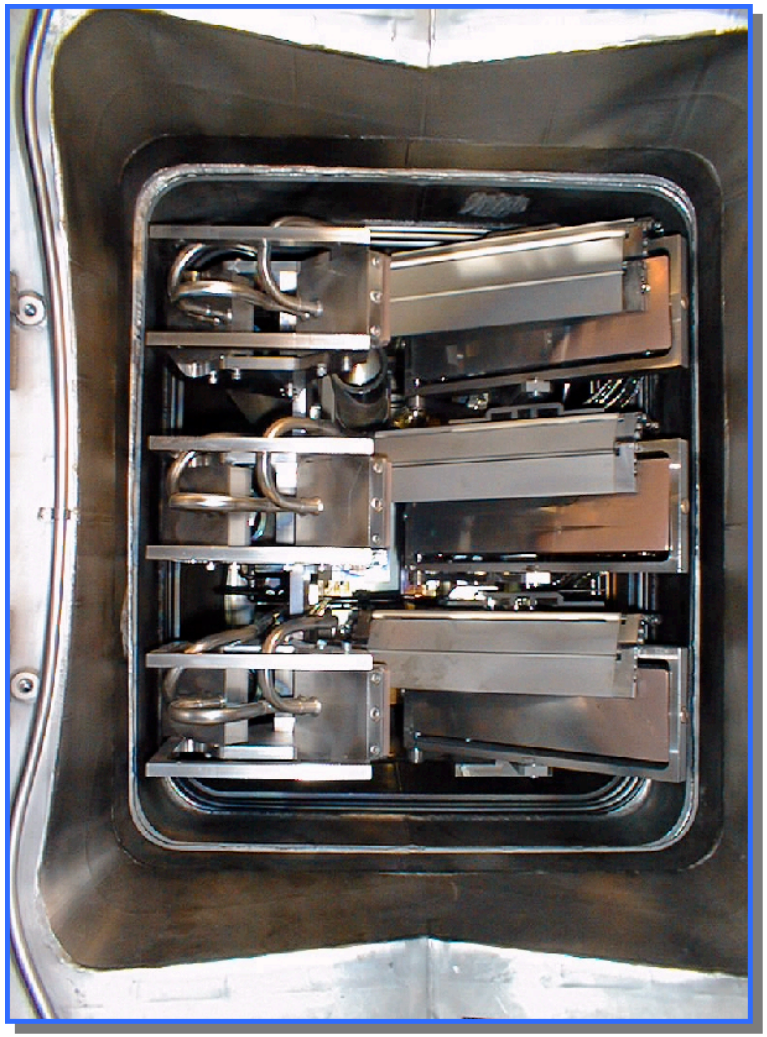
- **Generators:**

  Gyrotrons

- **General principle:**

  Cyclotron absorption of the wave on either **thermal** or **fast** electrons

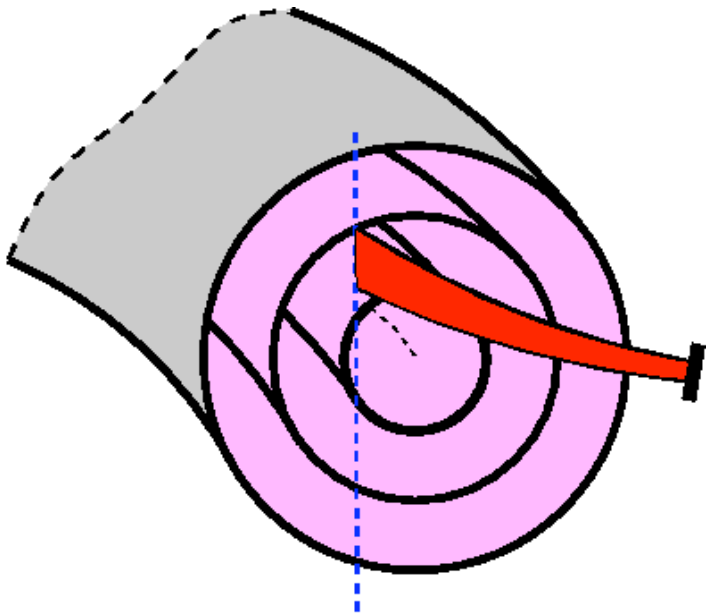
  → Heating and/or Current Drive system



[Tore Supra EC antenna]

Electron Cyclotron heating

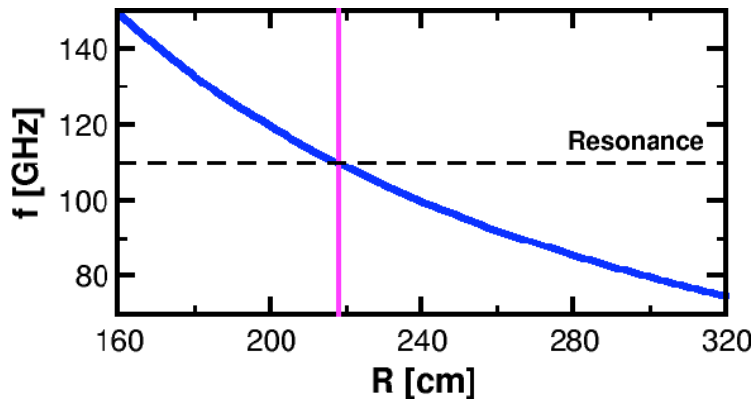
- **Injection by optical mirrors:**

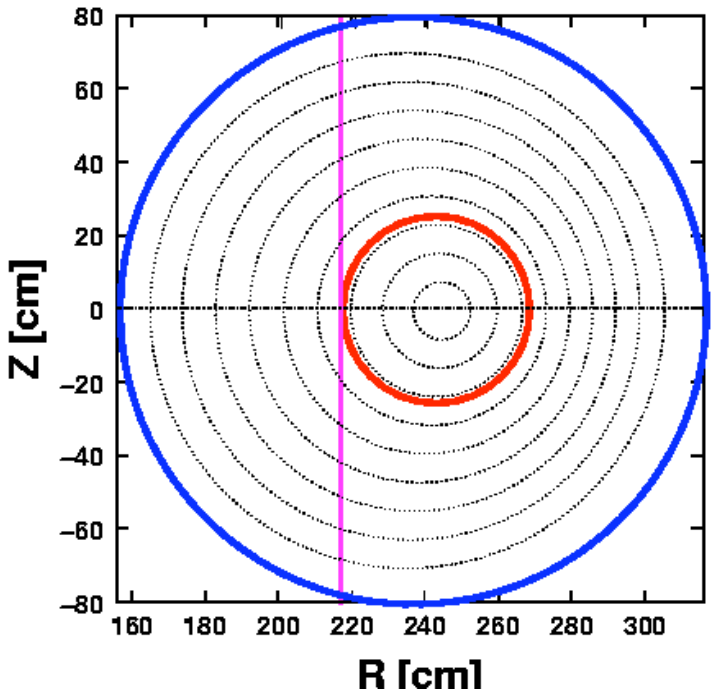


- **Relativistic resonance relation:**

$$\begin{cases} \omega = n\dfrac{\omega_{ce}}{\gamma} + k_{\|}v_{\|} \\ \dfrac{\omega_{ce}}{\gamma} = \dfrac{eB_0}{m_{e0}/\sqrt{1-v^2/c^2}} \end{cases}$$

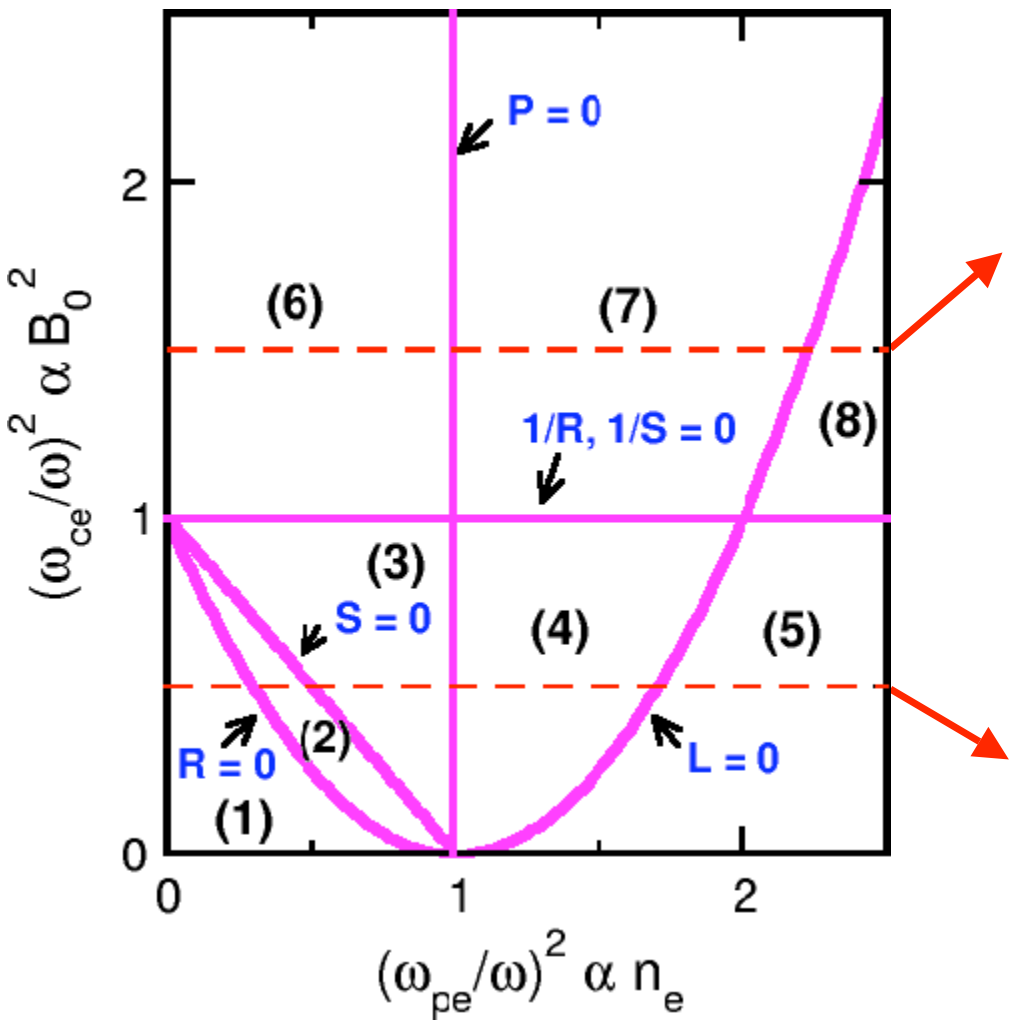
- **Resonant heating:**

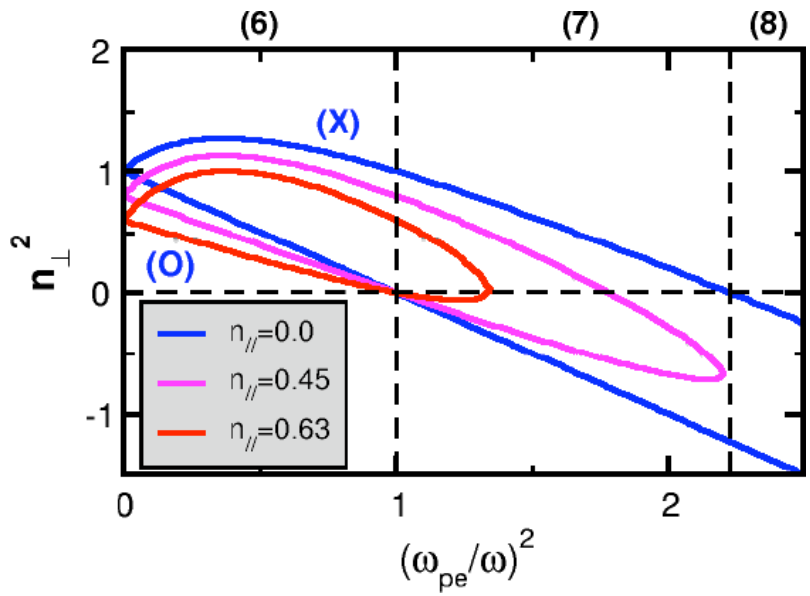


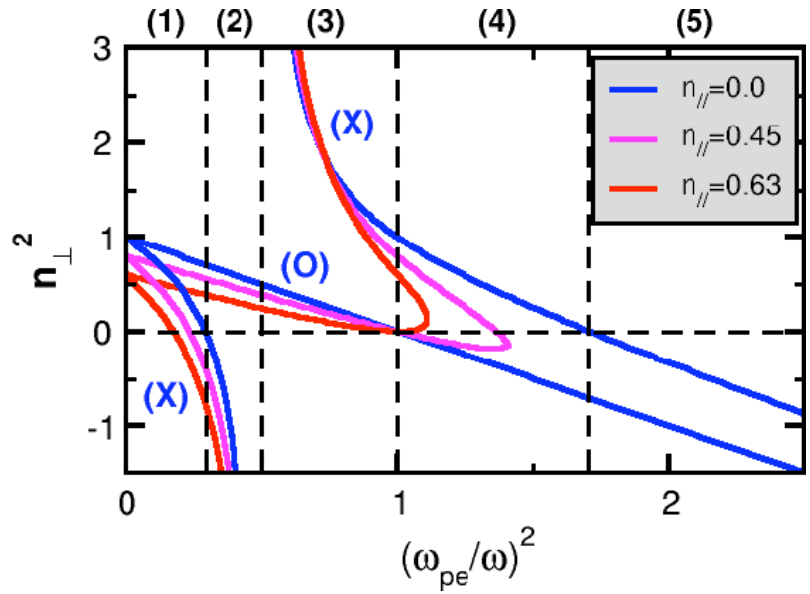


EC Waves: dispersion relation

- **CMA diagram:**

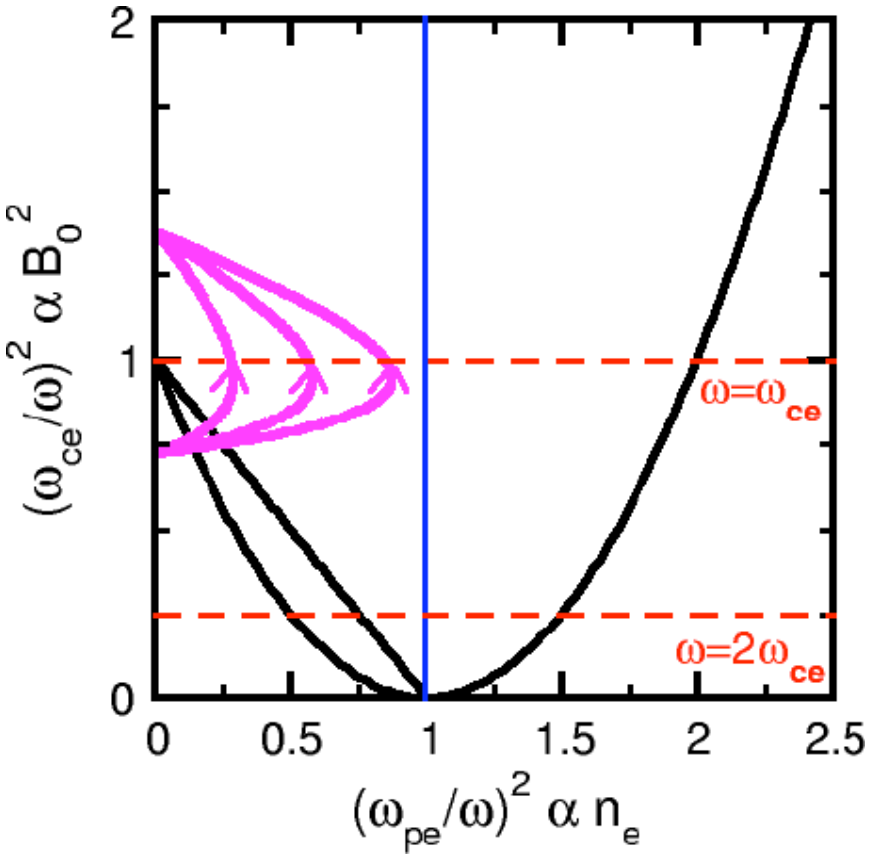


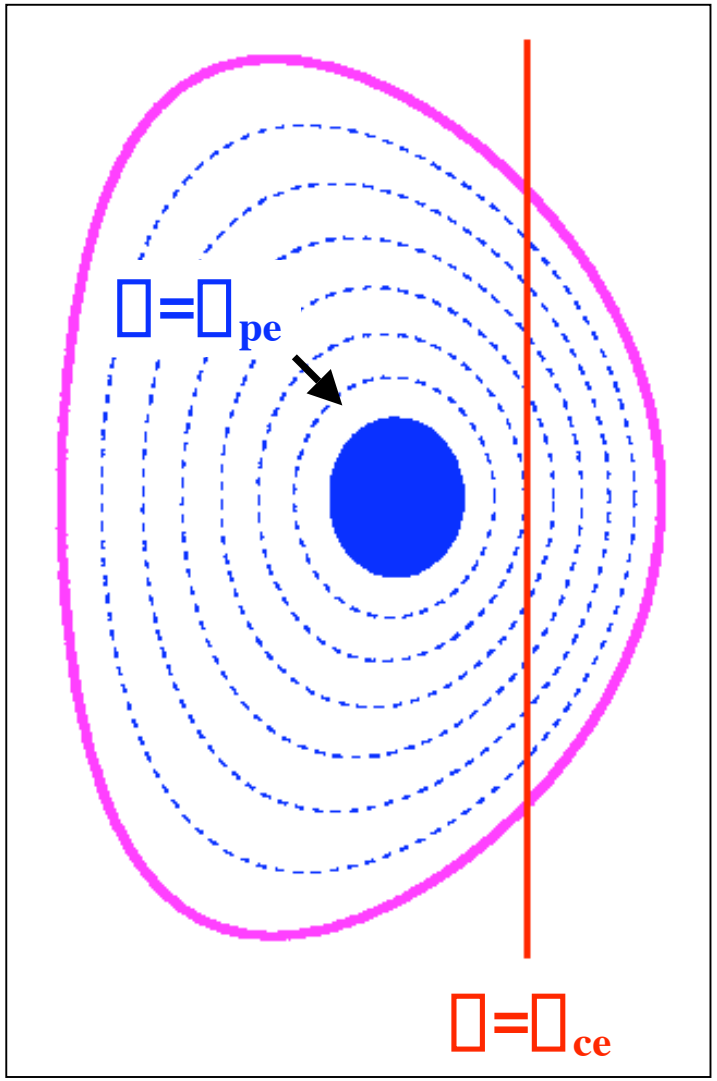




Ordinary mode in a tokamak

- **O-mode injected from Low Field side:**

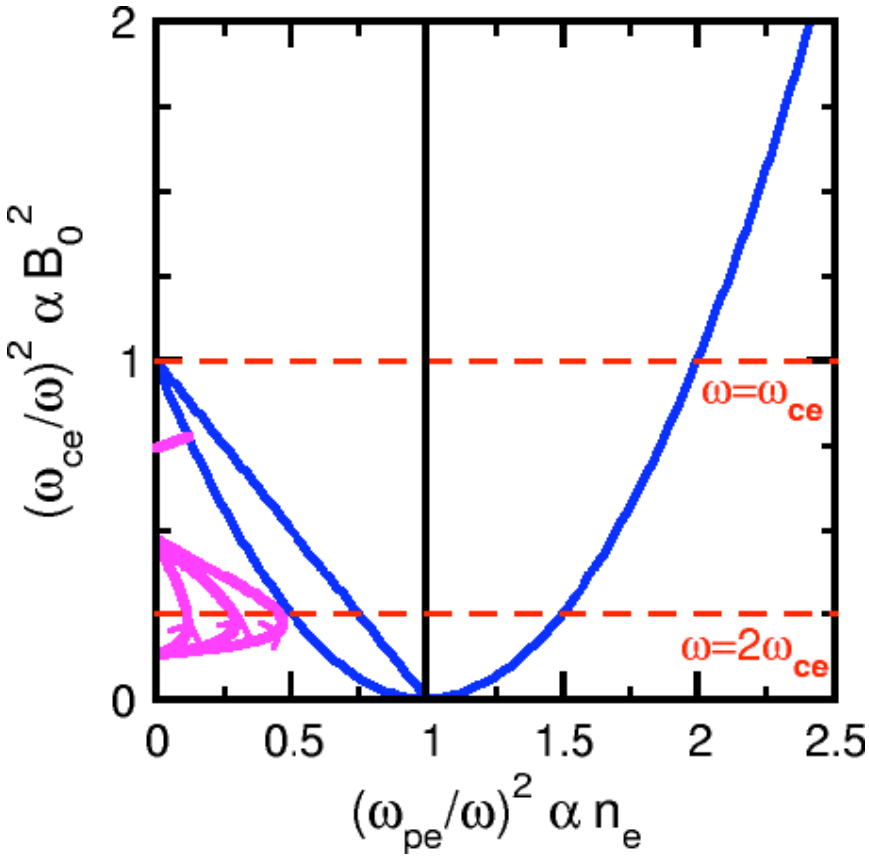


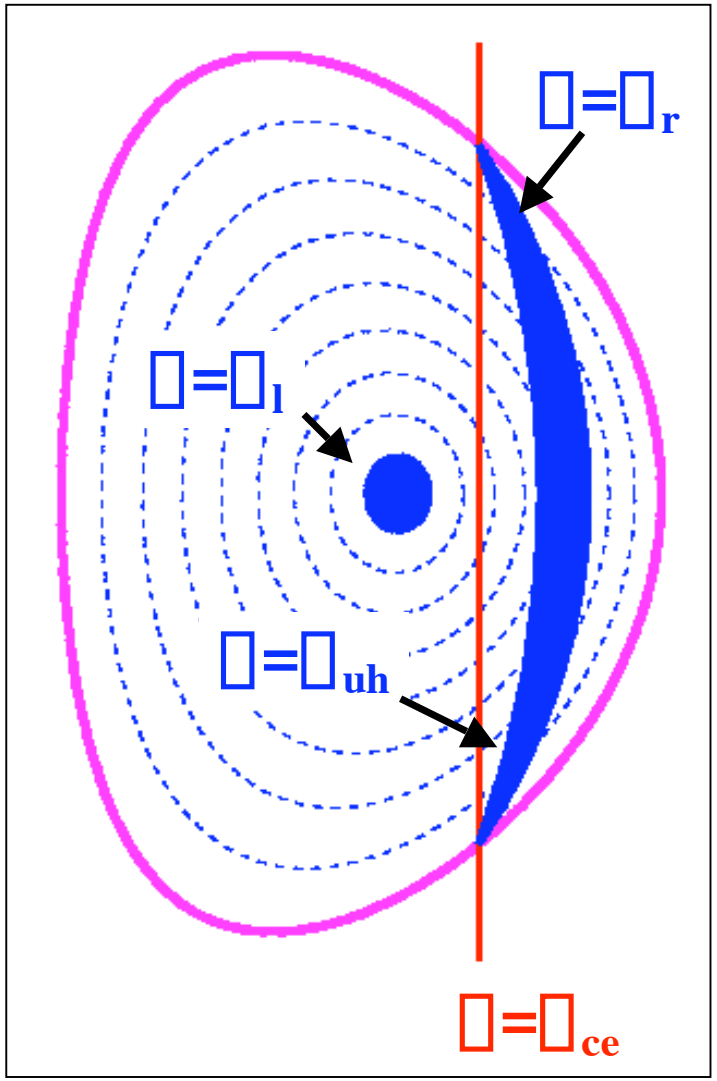


- **Fundamental O heating (O-1): possible**
- **First-harmonic O heating (O-2): possible**

Extraordinary mode in a tokamak

- **X-mode injected from Low Field side:**



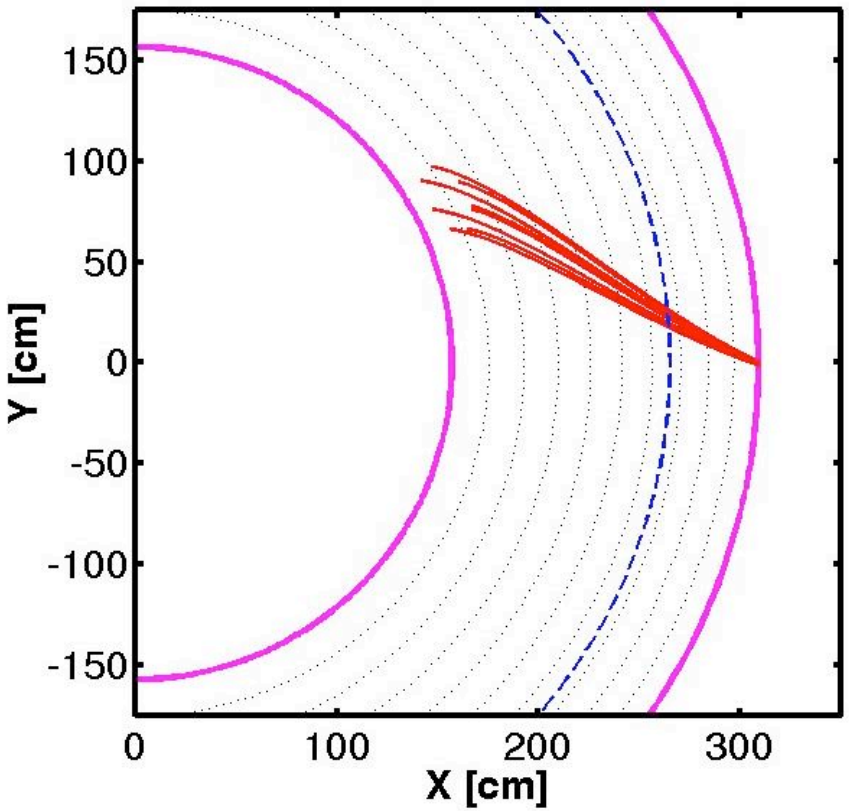


- **Fundamental X heating (X-1): impossible**
- **First-harmonic X heating (X-2): possible**

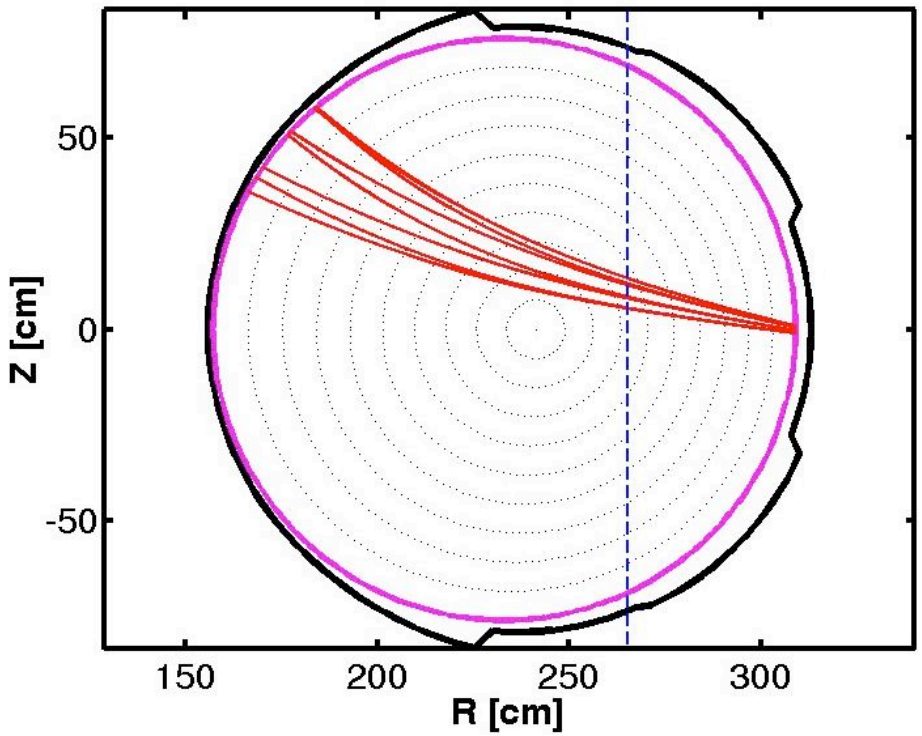
Propagation in a tokamak

- **Wavelength:** $\lambda \ll L_B$ ⟶ Quasi-optical propagation
- **Ray-tracing modelling:**

8-rays beam in Tore Supra



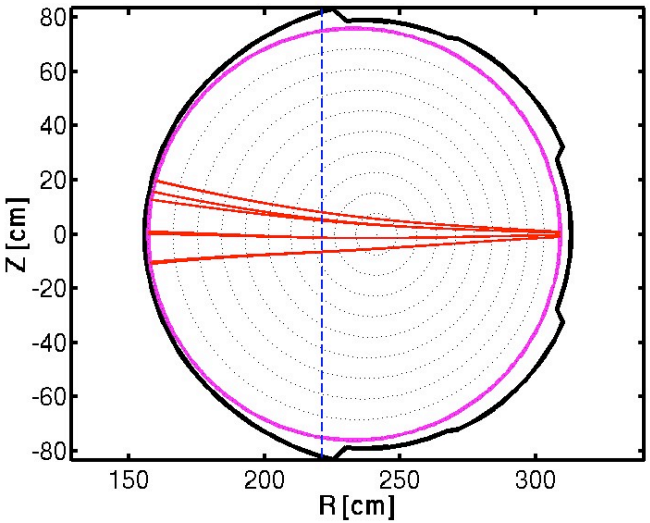
Toroidal projection



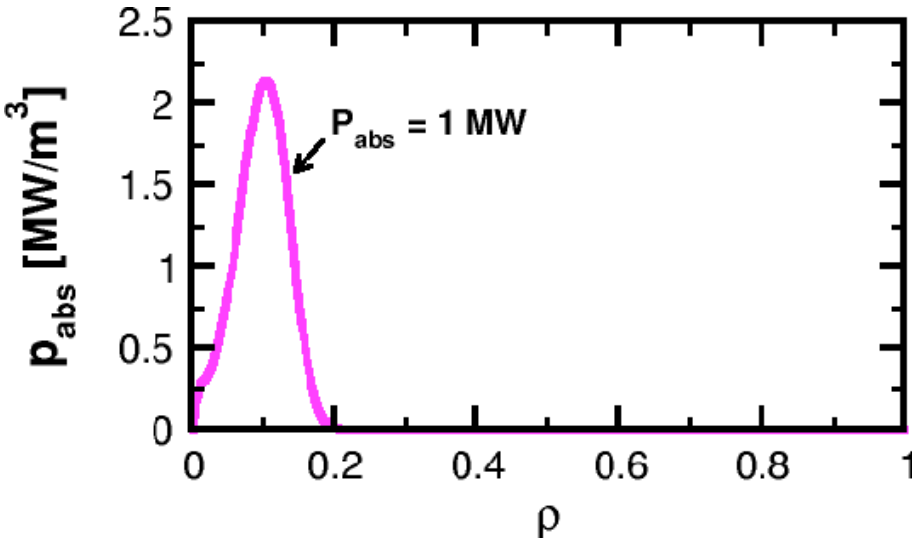
Poloidal projection

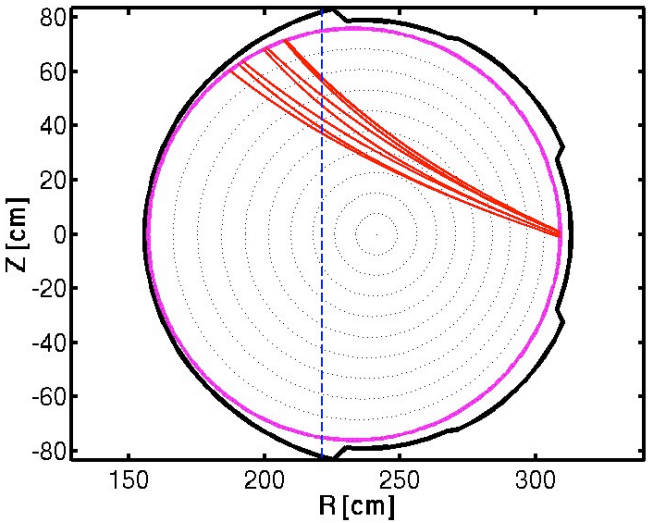
Absorption in a tokamak

- **Ex: modification of the wave injection poloidal angle**

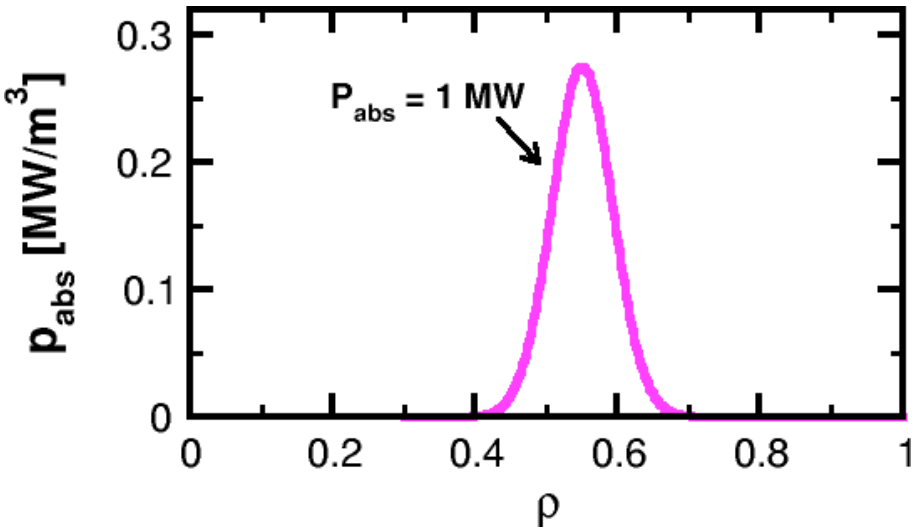


□ = 0°





□ = 20°

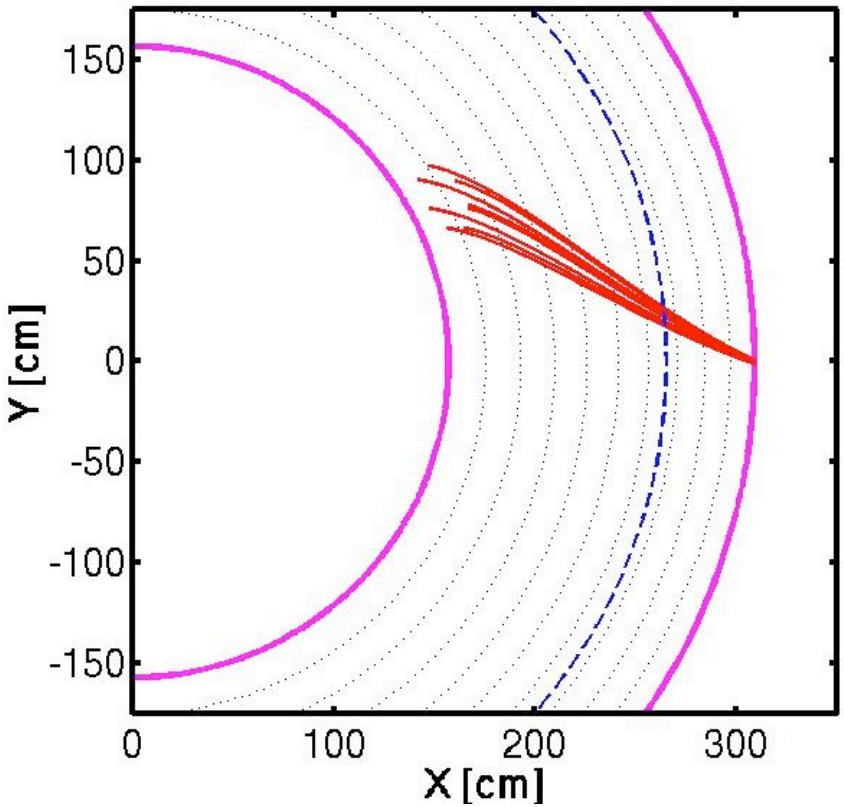


Electron Cyclotron Current Drive

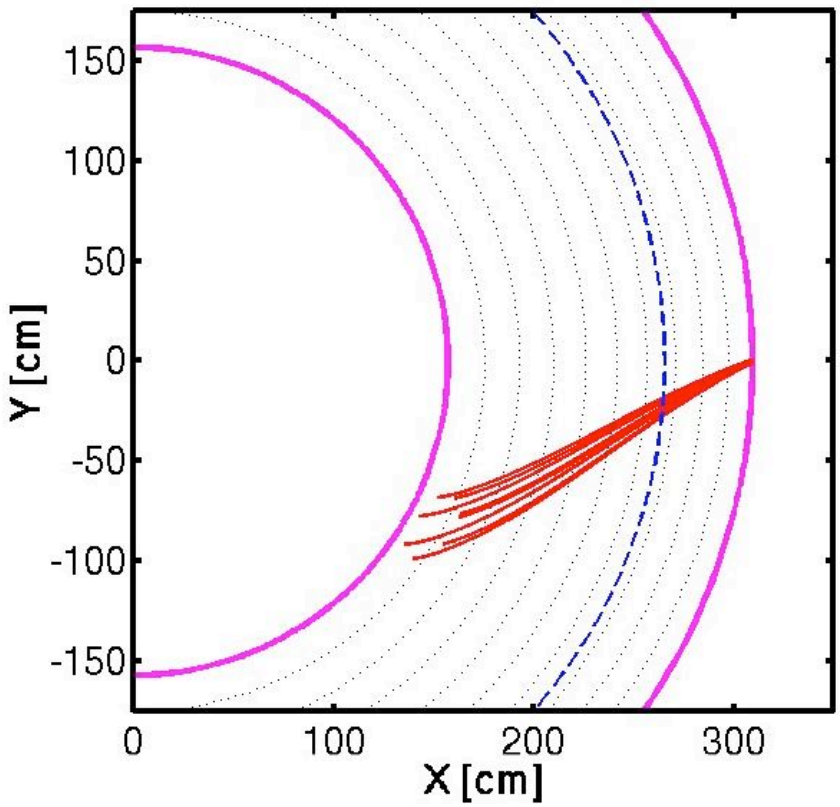
- **Modification of the wave injection toroidal angle**

  → Very localized current drive

  → Sharp control of the current profile



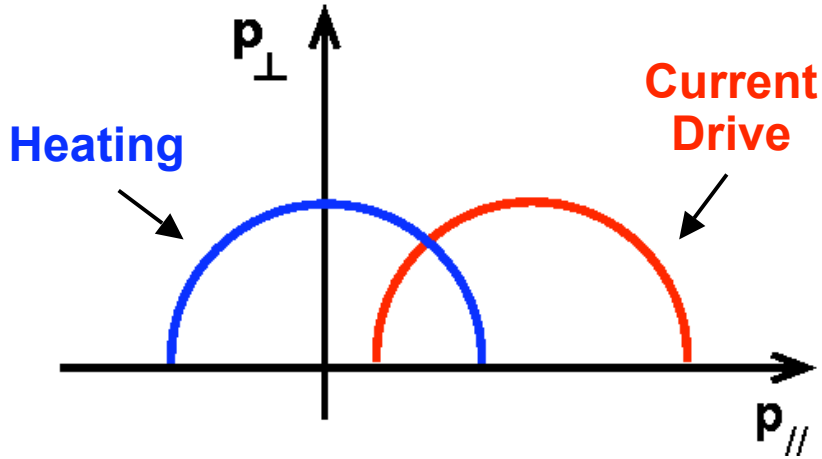
= +20°: Co-current



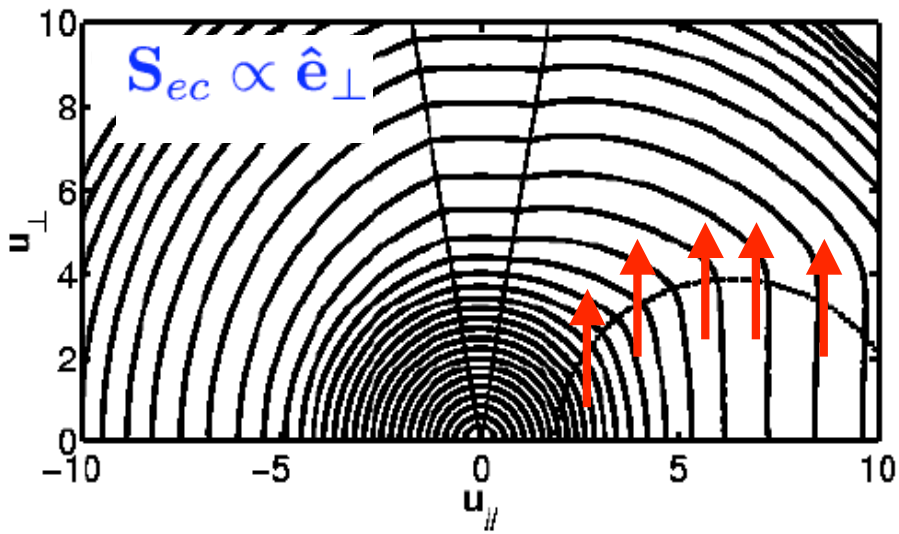
= -20°: Counter-current

ECRH - ECCD: main features

- **Resonance curves:**



- **Distribution function $f_e(v)$**



Advantages:

- Well controlled power deposition
- Narrow deposition profile
- No coupling problem
- Heating **or** Current Drive
- Possible synergy with the LH wave

→ Very flexible

Drawbacks:

- Sensitive to trapped electrons
- No transfer of parallel momentum

→ Less efficient than LH waves

A few un-discussed points

- **Ion Cyclotron frequency waves (ICRF)**
  - Current Drive schemes (FWCD and MCCD)
  - Génération de rotation du plasma
- **Lower Hybrid frequency waves (LH)**
  - LHCD in a reactor: “single-pass” absorption
  - Heating of fast ions by Landau damping
- **Electron Cyclotron frequency waves (ECRF)**
  - Current Drive at the plasma edge (Ohkawa effect)
  - Transport studies, MHD modes stabilization
- **Others:**
  - Synergies: LH-EC, LH-Bootstrap…
  - Wave coupling to the plasma (ICRF and LH)
  - Electron Bernstein Wave (EBW)
  - Wave-induced transport
  - Modelling aspects: wave codes, kinetic codes…