cea irfm

IC principles
Physics Overview

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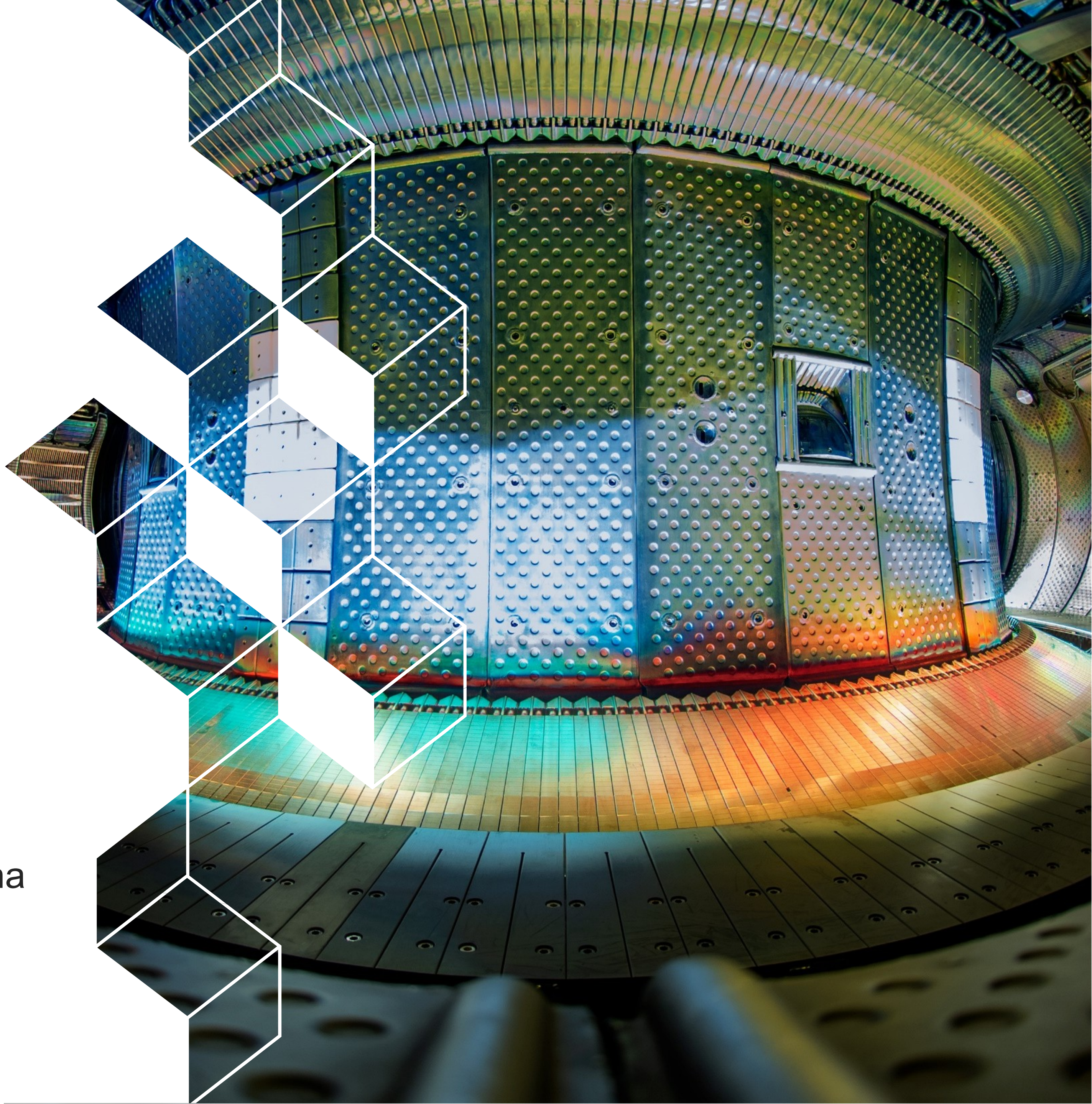
15th ITER International School – Leshan, China

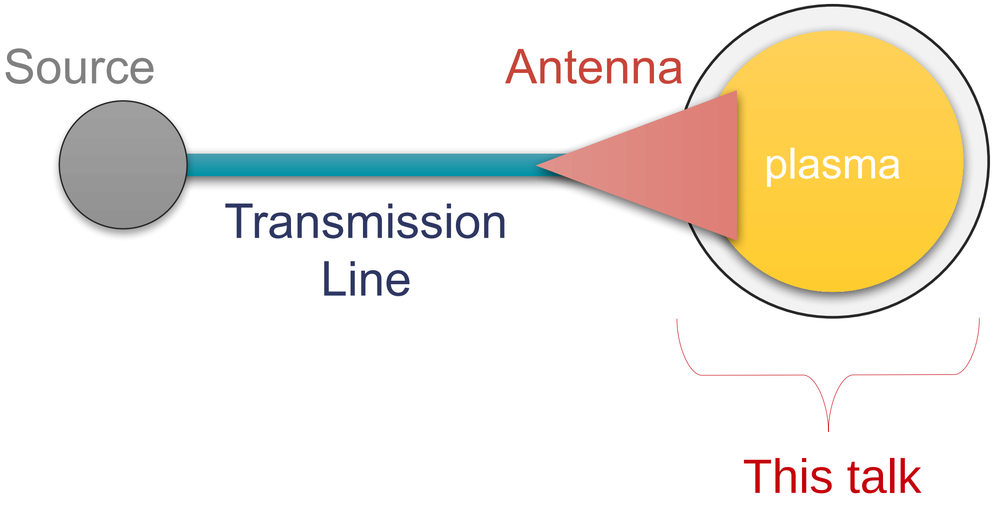
July 2026

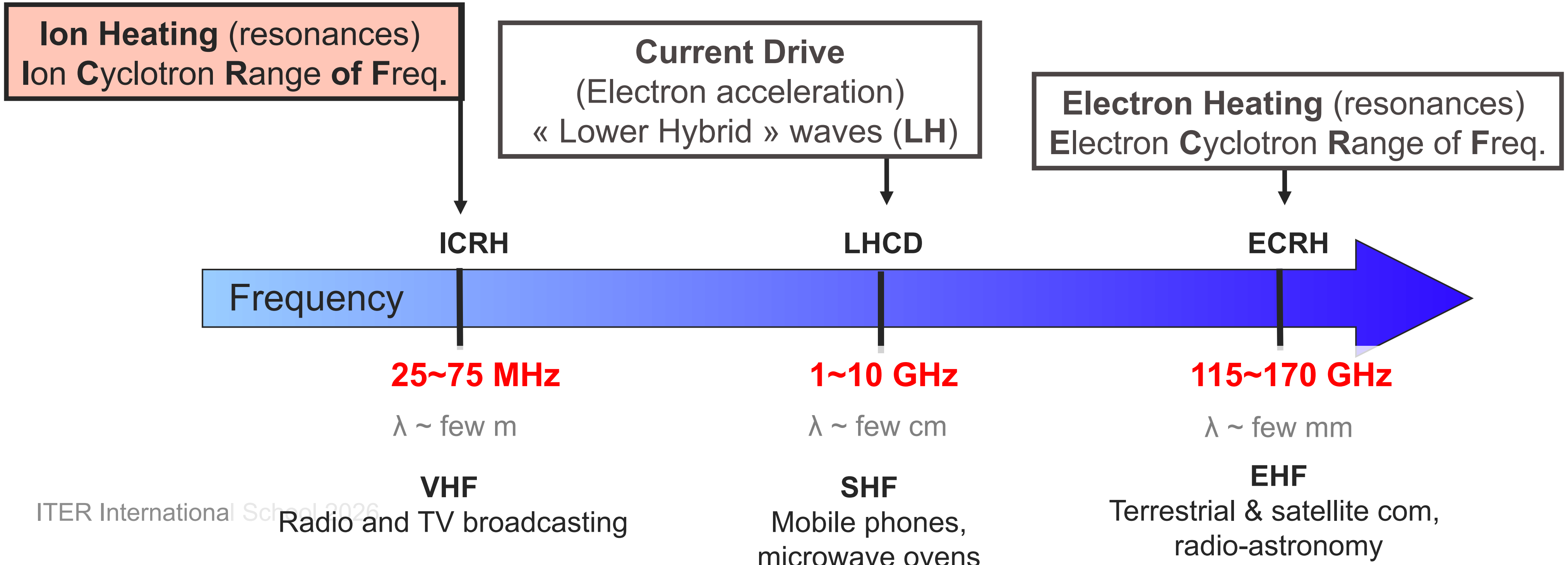


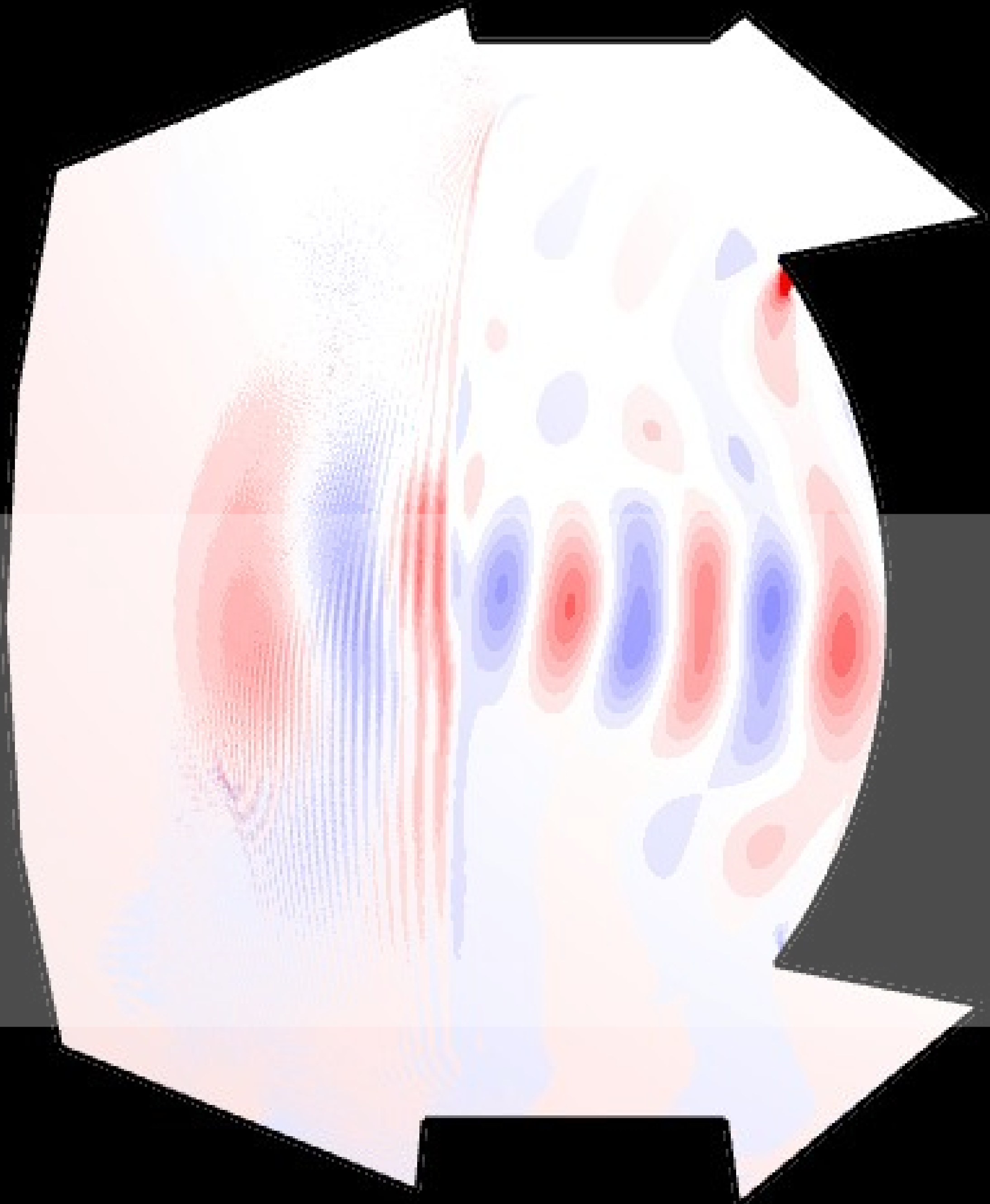
High Power RF/Microwave Systems in Fusion Devices

For all RF High Power RF system:

1. RF power source(s)
2. Transmission line(s)
3. Antenna(s)







Ion Cyclotron Range of Frequency

General Overview

WEST ICRH Minority Heating 55MHz 5% D(H) – [V.Maquet]

Ion Cyclotron Range of Frequency: what for?

Robust core plasma heating

- Wave energy transfer to ions and electrons at the ion cyclotron frequency (or its harmonics)
- Heat-up ions directly (do not rely on thermal equilibration from the electrons)
- No accessibility problem to plasma core and high densities
- Suitable heating scheme in high magnetic field (hence high plasma densities)

But also

Real-time Sawtooth stabilization and control

- ICRH-driven fast ions stabilization mechanism

Plasma rotation effects and current drive

- Using toroidally directed ICRF waves

Wall conditioning

- Fast RF-accelerated atoms hit the wall

Assisted breakdown

- Improve the plasma preionization during start-up

ICRF Absorptions Mechanisms

- **Ion Cyclotron damping**

Wave and ions resonate when RF frequency matches the cyclotron motion (or its harmonics)

- Efficient energy transfer from the wave to the particles
- Resonance position perturbed by the Doppler shift $k_\parallel v_\parallel$
- Wave damping region has a finite width (*cyclotron resonance layer*) due to distribution of parallel velocities

wave (angular) transmitter frequency

$$\omega = n\,\Omega_{c,s} \pm k_\parallel v_{\parallel,s}$$

Particle's velocity parallel component

$$\Omega_{c,s} = \frac{q_s B}{m_s}$$

Harmonic number

Cyclotron (angular) frequency (gyrofrequency)

Wave wavenumber parallel component

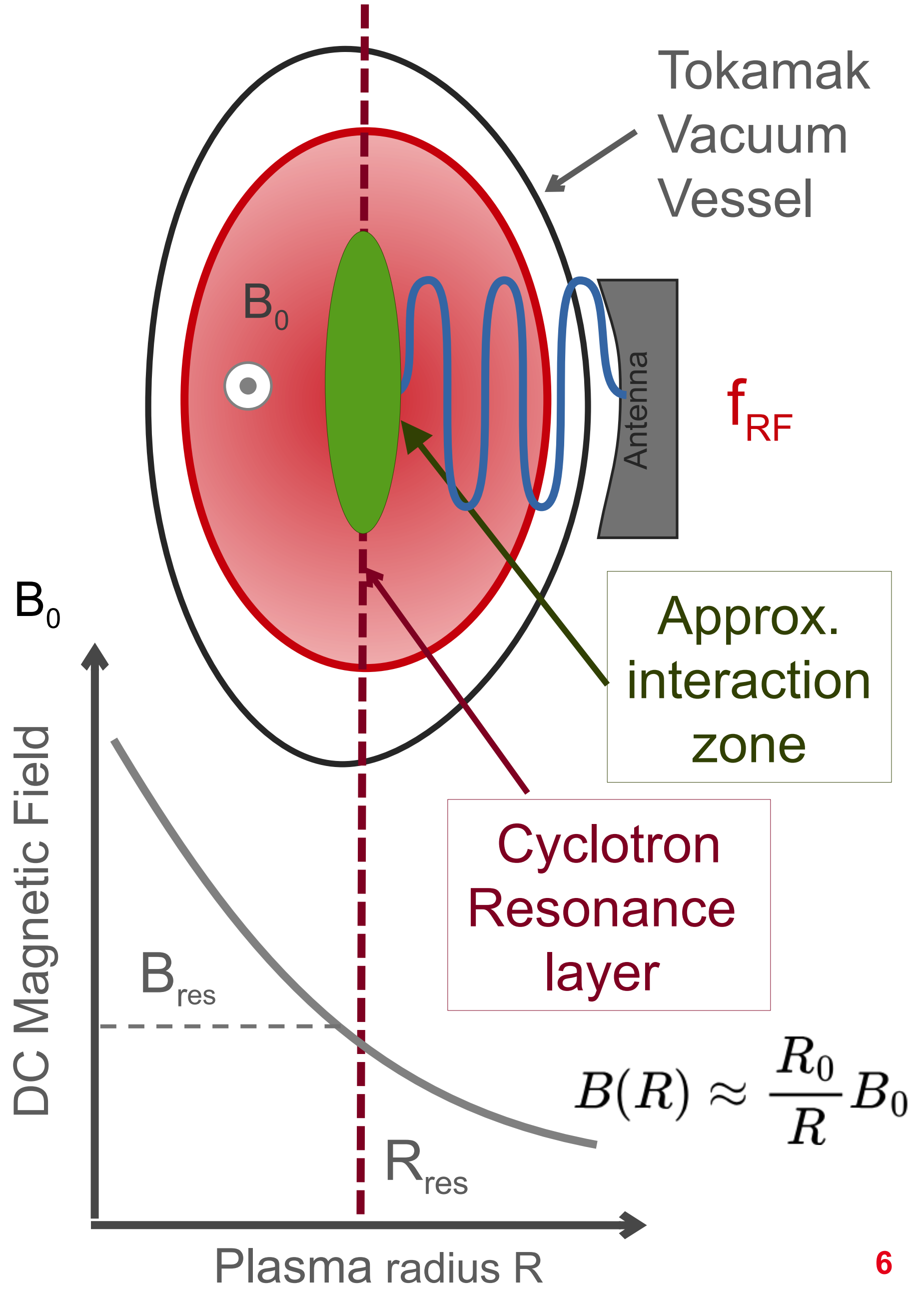
- A significant fraction of the wave energy is also absorbed by electrons (not localized) through:
  - **Electron Landau damping**
  - **Transit-Time Magnetic Pumping (TTMP)**
  - **Mode Conversion to Ion Bernstein Waves**

ICRF is a flexible actuator

In Tokamaks: Magnetic field decreases as 1/R

- Wave-Ions resonance are localized
- Possible to control the resonance layer location by tuning the RF frequency f_{RF}
  - Ex: center of the plasma (central heating)
  - Rule of thumb for Hydrogen: ~ 15 MHz/T
  - Resonance layer location:

$$R_{\mathrm{res}}\Big|_{\omega=n\Omega_{ci}} \approx R_0 \frac{nZ_i}{A_i}\frac{15.25 B_0}{f_{[MHz]}}$$



ICRF Orders of Magnitude

Frequency range: 30 MHz - 120 MHz (λ_{vacuum} ~ 10 m)

Current antennas

- RF Power: ~ 2 – 4 MW
- RF Voltage: ~ 10 – 50 kV
- RF Current : ~ 1 kA
- Radiating element (strap) dimensions: ~ 0.2 m x 0.5 – 1 m
- Distance to the confined plasma: 3 – 20 cm
- Flexible parallel wavenumber range: $k_{//}$ ~ 0 (monopole) – 40 m^{-1}

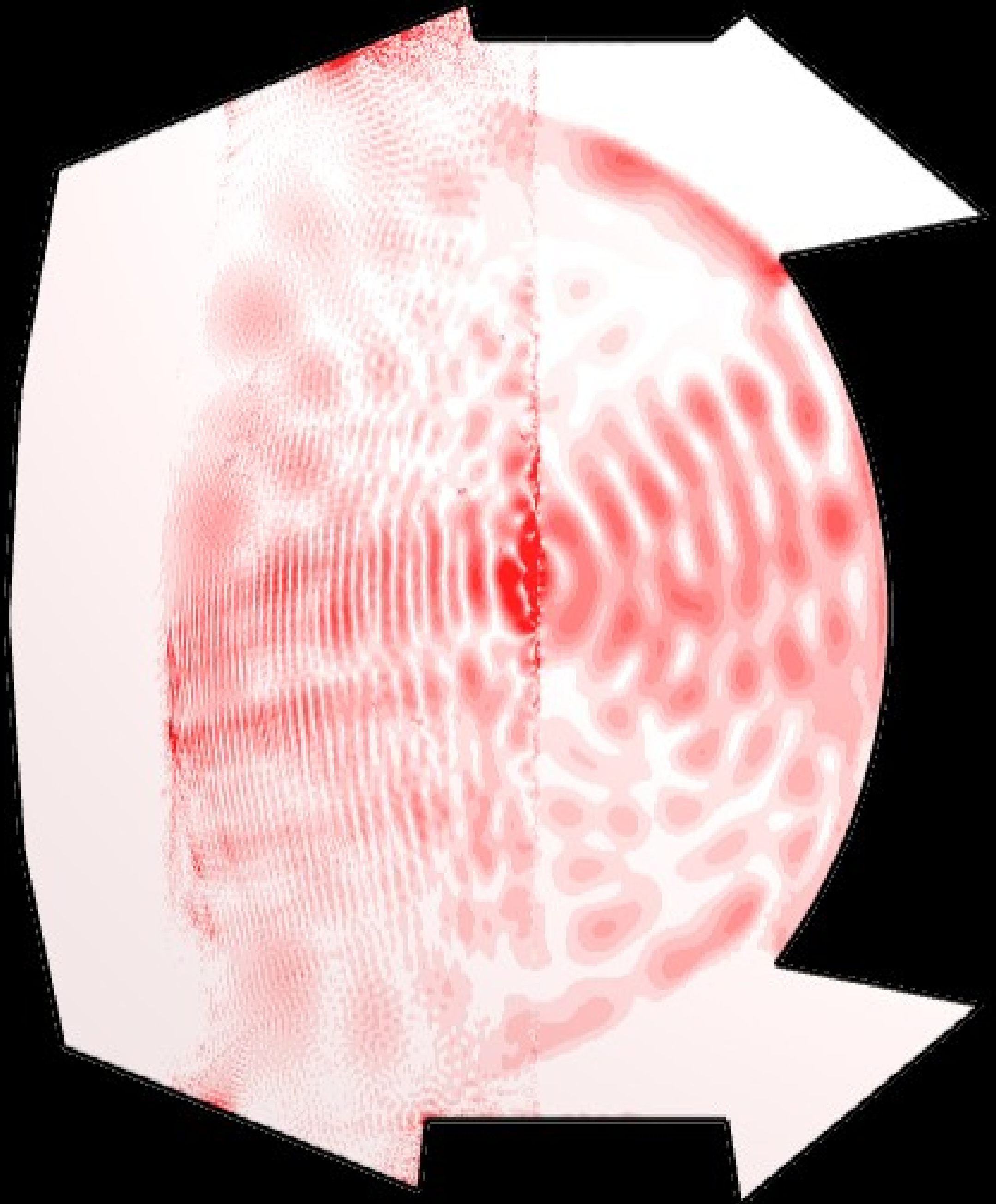
Ratio V/I & power coupling capability is determined by antenna geometry and plasma edge properties.

Electromagnetic field in the plasma

- RF B-field magnitude: ~10^{-3} T << ~3 T (B_0)
- RF E-field magnitude: ~20 kV/m << ~1.5 MV/m (v_{Ti} x B_0)

RF field can only causes small perturbations on particle trajectory → use of perturbation theory

R. Koch, Fusion Technology 1998



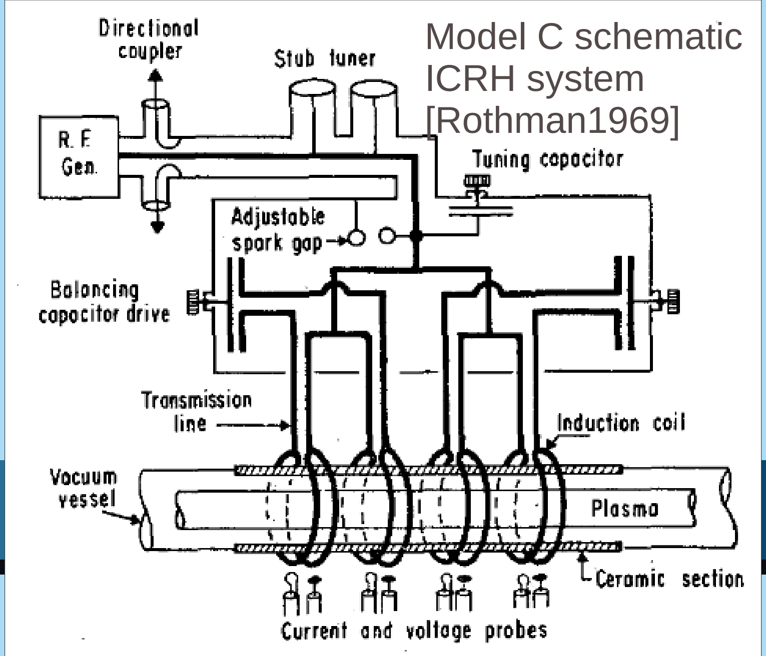
Second harmonic heating H in WEST modelling (|E-|) [V.Maquet]

Ion Cyclotron Range of Frequency

Physics Overview

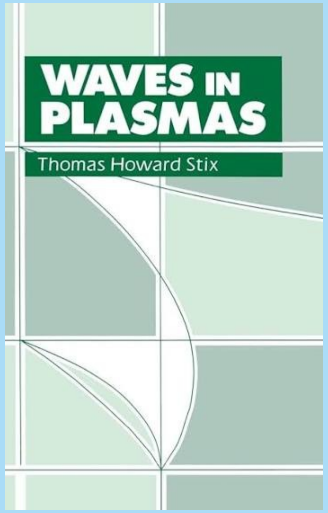
ICRF (brief) Timeline

1970 1980 1990



Model C schematic ICRH system [Rothman1969]

1960's: 1st experimental wave absorption
1960 : wave absorption in B-65 stellarator
1962 : Stix's plasma wave theory
1969 : 1st use of ICRF in Model C stellarator



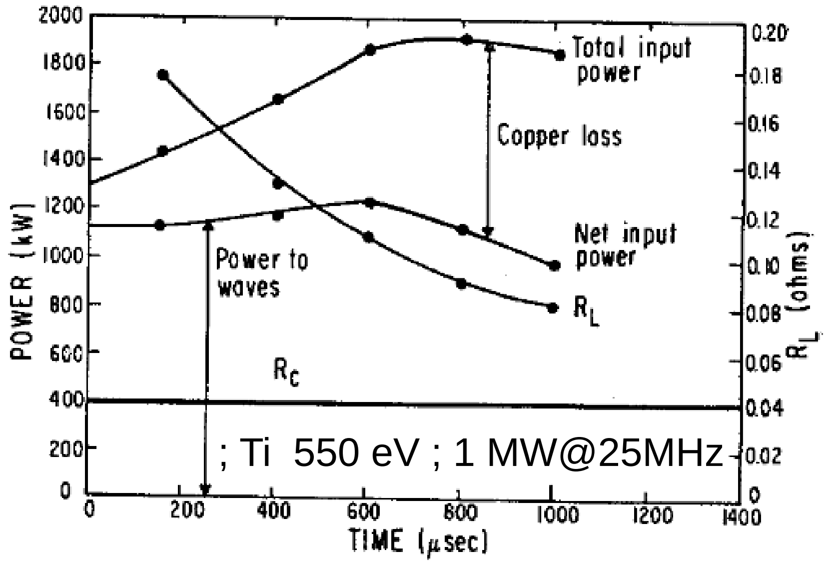


FIG. 14. Power and load resistance versus time during the heating pulse of Fig. 13.

J.M.Noterdaeme, AIP Conf. Proc. 2020

Waves in magnetized plasma (1/3)

The wave equation

- Propagation and dissipation of electromagnetics waves are governed by the **wave equation**
  - In time-harmonic regime (-iωt)

$$\nabla \times (\nabla \times \mathbf{E}) - \frac{\omega^2}{c^2}\mathbf{E} = i\omega\mu_0 (\mathbf{J}_{ind} + \mathbf{J}_{ext})$$

Induced currents = free charges + polarization + magnetization

External excitation (=antenna)

  - In a (fully) ionized plasma, one can't distinguish the different induced currents: they all contribute to the polarization of the medium
  - Look simple, but non-linear : $\mathbf{J}_{ind}$ depends on **E**, generally in a complex way
  - Assuming $\mathbf{J}_{ind}(\mathbf{E}) = \boldsymbol{\sigma}\mathbf{E}$ (**σ** being an operator), leads to :

$$\nabla \times (\nabla \times \mathbf{E}) - \frac{\omega^2}{c^2}\mathbf{K}\mathbf{E} = i\omega\mu_0\mathbf{J}_{ext}$$

$$\mathbf{K} = \mathbf{1} + \frac{i}{\omega\varepsilon_0}\sigma$$

conductivity operator

Dielectric operator

Susceptibility operator

  - Integro-differential equation: challenging to solve !

T. Stix, *Waves in Plasmas*, 1992
M. Brambilla, *Kinetic Theory of Plasma Waves*, 1998
D. Swanson, *Plasma Waves*. 2003
R. Dumont, *Waves in plasma lecture*, 2017

Waves in magnetized plasma (2/3)

The wave equation in the frequency-spectral domain

- In magnetized plasma
  - Anisotropy: response is different depending on the direction of the excitation → tensor relationships
- In a low collisionality plasma (ie. long mean free path):
  - Particle's **v**(**r**,t) depends on the cumulative acceleration along its entire orbit
  - The plasma's response to an incident wave inherently **non-local** in time and space

Time dispersion — Space dispersion — Anisotropy — Conductivity kernel

Constitutive relation

$$\mathbf{j}(\mathbf{r},t) = \int_{-\infty}^{t} dt' \int d^3\mathbf{r}' \,\bar{\bar{\boldsymbol{\sigma}}}(\mathbf{r},\mathbf{r}',t,t') \cdot \mathbf{E}(\mathbf{r}',t').$$

- For stationary and homogeneous plasmas
  - Fourier representation (spectral domain) leads to simplifications
  - Dispersion effects differ depending on direction parallel or perpendicular to magnetic field (**σ** depends on **k**)

$$\mathbf{j}_{\mathbf{k},\omega} = \bar{\bar{\boldsymbol{\sigma}}}_{\mathbf{k},\omega} \cdot \mathbf{E}_{\mathbf{k},\omega}, \qquad \mathbf{k} \times \mathbf{k} \times \mathbf{E}_{\mathbf{k},\omega} + \frac{\omega^2}{c^2} \bar{\bar{\mathbf{K}}}_{\mathbf{k},\omega} \cdot \mathbf{E}_{\mathbf{k},\omega} = i\omega\mu_0 \left(\mathbf{j}_{ext}\right)_{\mathbf{k},\omega},$$

- However, tokamak plasmas are inhomogeneous (n_s, T_s, B…)
  - If quantities vary little over a wavelength, plasma is said *quasi-homogeneous* and the approximation can still hold

T. Stix, *Waves in Plasmas*, 1992
M. Brambilla, *Kinetic Theory of Plasma Waves*, 1998
D. Swanson, *Plasma Waves*. 2003
R. Dumont, *Waves in plasma lecture*, 2017

Waves in magnetized plasma (3/3)

The dispersion relation

- From the Fourier (space) - Laplace (time) wave equation in *homogeneous* & *steady-state* without source:

$$\mathbf{k} \times \mathbf{k} \times \mathbf{E} + \frac{\omega^2}{c^2} \overline{\overline{\mathbf{K}}} \cdot \mathbf{E} = 0$$

Rewriting as a matrix operator **M**(**k**,ω):

$$\overline{\overline{\mathbf{M}}}_{\mathrm{k},\omega} \cdot \mathbf{E}_{\mathrm{k},\omega} = 0 \qquad \left(\overline{\overline{\mathbf{M}}}_{\mathbf{k},\omega}\right)_{ij} = k_i k_j - k^2 \delta_{ij} + \frac{\omega^2}{c^2} (\overline{\overline{\mathbf{K}}})_{ij}$$

- The non-trivial solution of det(M(**k**,ω))=0 leads to the **dispersion relation k=k**(ω)
  - Using **n** = **k** c/ω with n is the refraction index, the dispersion relation has the generic form:

$$\det\left(n_i n_j - n^2 \delta_{ij} + (\overline{\overline{\mathbf{K}}})_{ij}\right) = 0$$

The possible modes existing (k_{perp}) in the plasma are the solutions of the dispersion relation

T. Stix, *Waves in Plasmas*, 1992
M. Brambilla, *Kinetic Theory of Plasma Waves*, 1998
D. Swanson, *Plasma Waves*. 2003
R. Dumont, *Waves in plasma lecture*, 2017

Plasma Model Approximations

Cold plasma

- Plasma treated as a cold fluid with an effective relative permittivity
- Gives only 2 modes

Warm plasma

- Fluid approach with additional pressure terms
- Brings out additional modes
- Regularizes the singular behavior observed at cold resonances

(Cold plasma and warm plasma: Fluid description)

Hot plasma

- Kinetic approach based on Boltzmann/Vlasov equation
- Brings out wave-particle resonances and wave damping

(Hot plasma: Kinetic description)

T. Stix, *Waves in Plasmas*, 1992
M. Brambilla, *Kinetic Theory of Plasma Waves*, 1998
D. Swanson, *Plasma Waves*. 2003
R. Dumont, *Waves in plasma lecture*, 2017

Waves in cold magnetized plasma

In a cold magnetized ($B_0=B_0z$) plasma, the dielectric tensor reads

$$\overline{\overline{K}}_\omega = \begin{pmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{pmatrix}$$

With S (Sum), D (Difference) and P (Plasma) terms are

$$S \equiv \frac{1}{2}(R+L) \qquad D \equiv \frac{1}{2}(R-L)$$

$$P \equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega^2} \qquad \omega_{ps}^2 = \frac{n_s q_s^2}{m_s \varepsilon_0}$$

Plasma (gyro)frequency

- And L(eft) and R(ight) terms defined by:

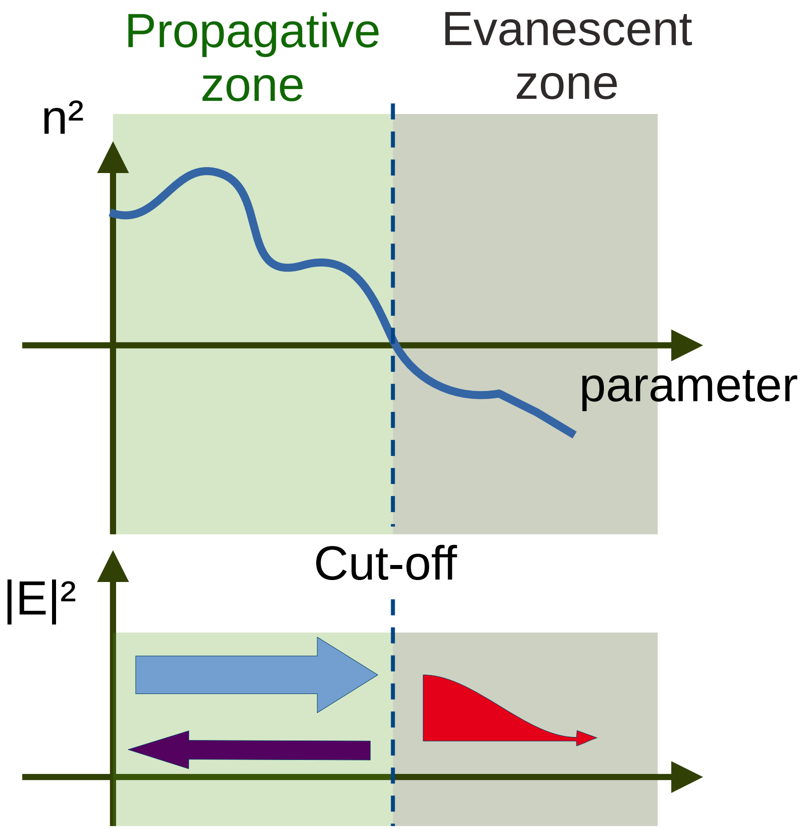
$$L \equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega - \omega_{cs})} \quad R \equiv 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega + \omega_{cs})}$$

- **K** independent of wavenumber **k** (or **n**): *no spatial dispersion*
  - Dispersion relation is then a simple quadratic equation for n^2 : $An^4 + Bn^2 + C = 0$
  - which gives at most *two waves* propagating in the plasma (usually called the *slow* & *fast* waves)
- After obtaining solution for a mode $n_i(k,\omega)$
  - injecting this solution in the wave equation give the solutions for $\mathbf{E}_i$ (Actually the ratio of its components, i.e. its *mode polarization*)

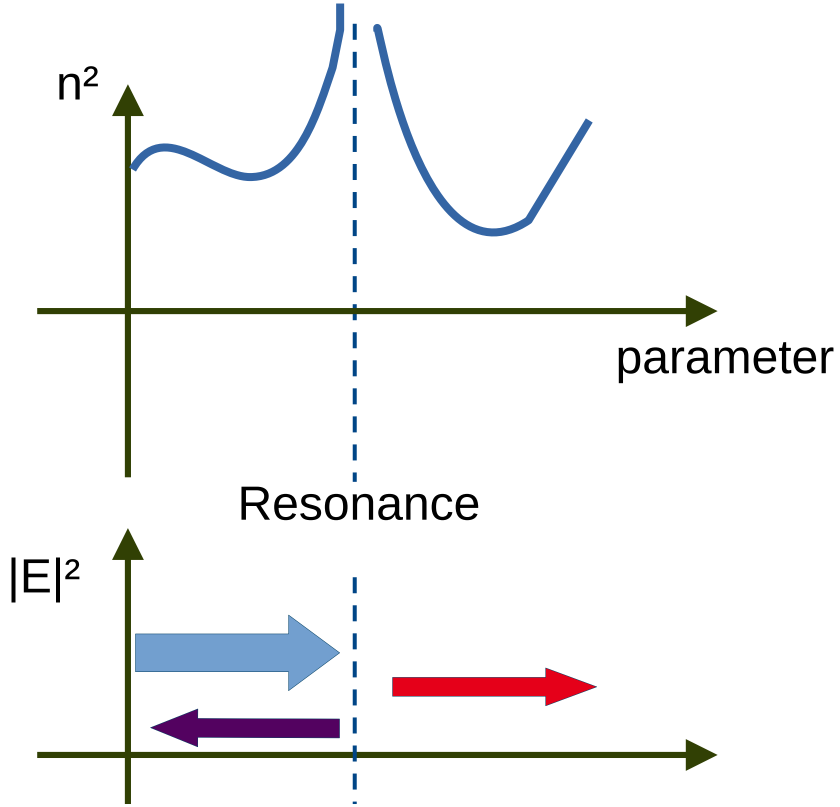
T. Stix, *Waves in Plasmas*, 1992
M. Brambilla, *Kinetic Theory of Plasma Waves*, 1998
D. Swanson, *Plasma Waves*. 2003
R. Dumont, *Waves in plasma lecture*, 2017

Fundamental waves features: cut-off and resonances

- **Cut-off**: occurs when n = 0
  - Wave is propagative if $n^2 > 0$
  - And evanescent if $n^2 < 0$



- **Resonances:** occurs when $n \rightarrow \infty$



Dispersion relation solutions in cold magnetized plasma

- The dispersion relation can be solved for $\mathbf{n}(n_x,n_y,n_z)$
- In magnetized experiments
  - Antennas excites a *spectrum* of parallel (to $\mathbf{B_0}$) wavenumbers $k_{//}=n_{//}\ \omega/c$
  - convenient to solve for $\mathbf{n}(n_\perp,n_y,n_{//}) \rightarrow n_\perp^2=n_\perp^2(n_{//},\omega, n_e, n_i, B_0, \ldots)$

In a cold homogeneous magnetized plasma in the ICRF

Fast wave

$$n^2_{\perp,FW} \approx S - n^2_{\parallel} - \frac{D^2}{S - n^2_{\parallel}}$$

Propagative in confined plasma region

Slow wave

$$n^2_{\perp,SW} \approx \frac{P(S - n^2_{\parallel})}{S},$$

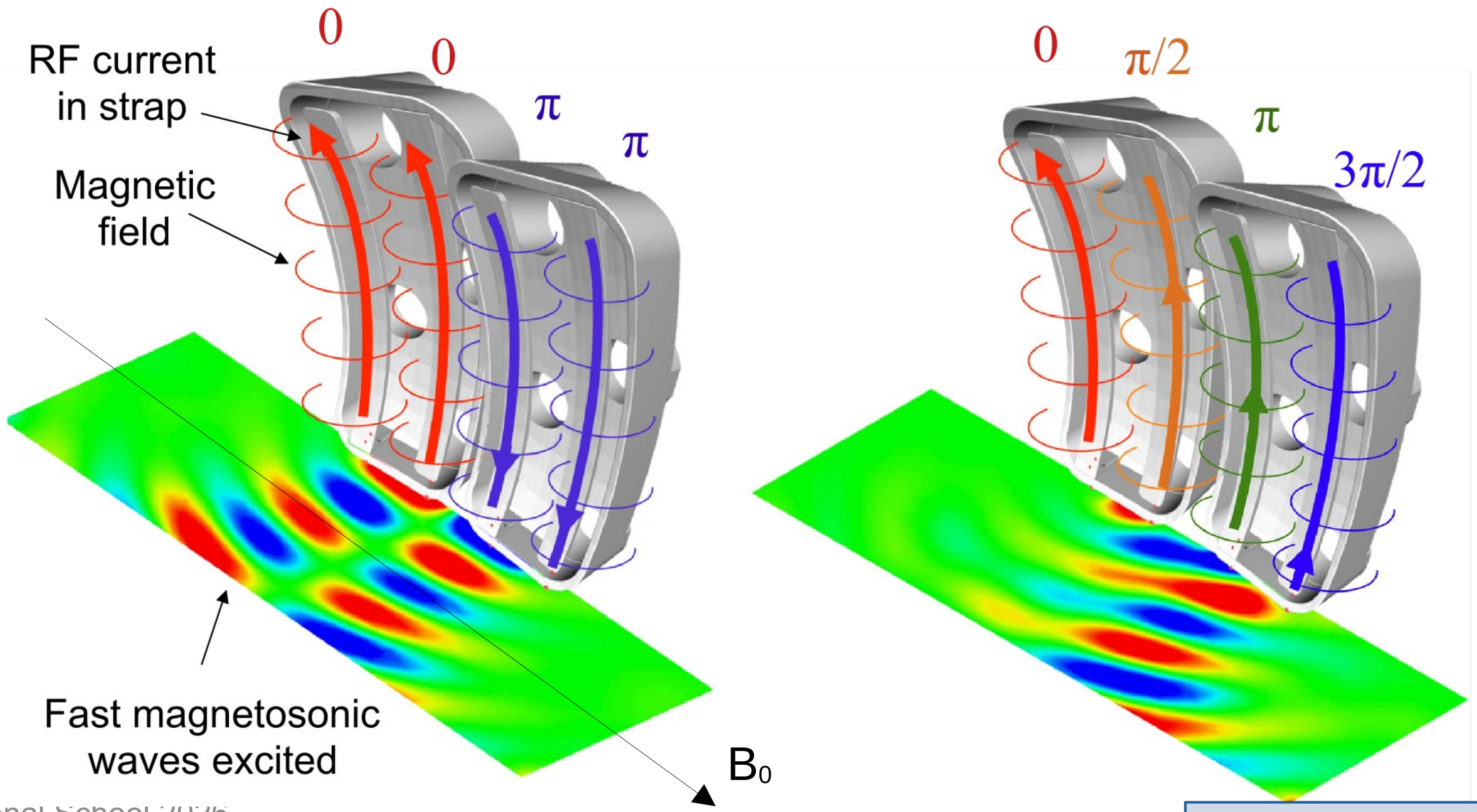
Evanescent in confined plasma region

T. Stix, *Waves in Plasmas*, 1992
M. Brambilla, *Kinetic Theory of Plasma Waves*, 1998
D. Swanson, *Plasma Waves*. 2003
R. Dumont, *Waves in plasma lecture*, 2017

$k_{//}$ spectrum is fixed by the antenna design and power/phase excitation

- ICRF antennas uses several metal *straps* oriented in the poloidal direction (or perpendicular to $\mathbf{B_0}$)
- RF currents generate an RF magnetic field that excite (mostly) fast waves
  - Which eventually propagate towards the bulk plasma

Symmetric wave propagation | **Asymmetric** wave propagation

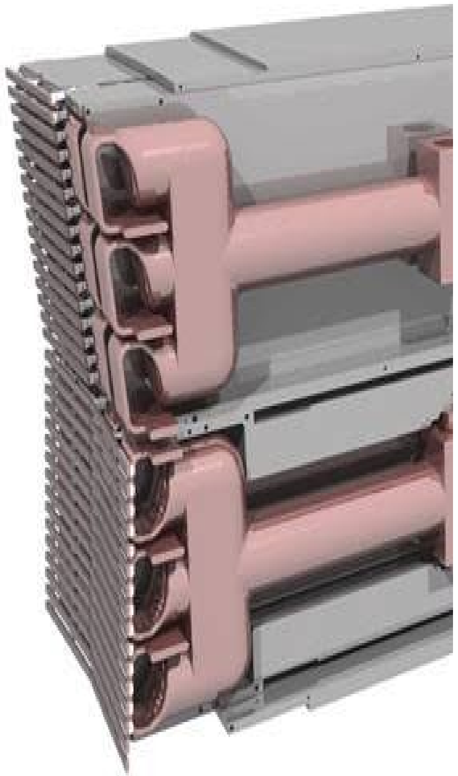


J Ongena et al 2017 Plasma Phys. Control. Fusion 59 054002

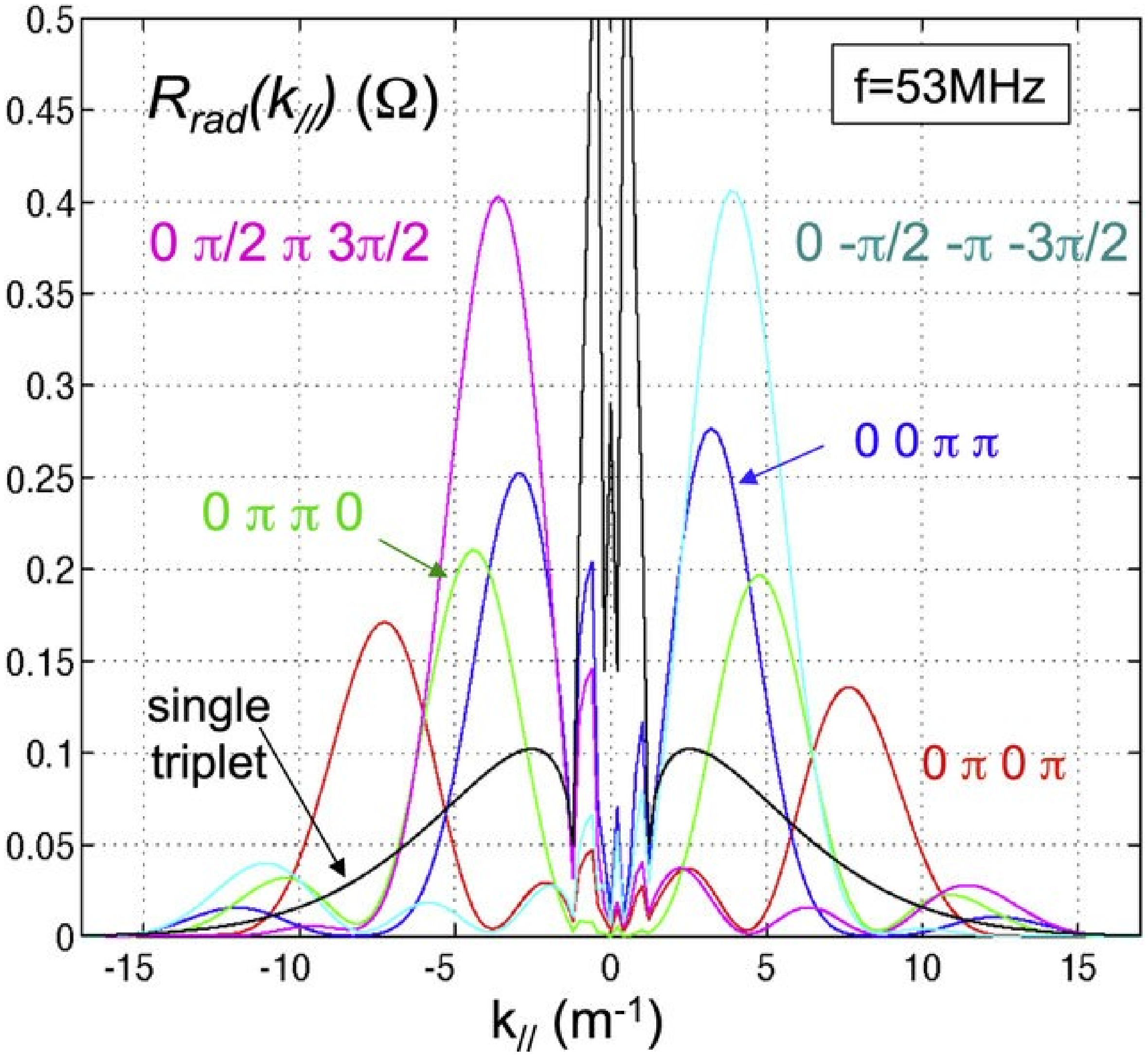
Example : ITER antenna $k_{//}$ spectra

Antenna $k_{//}$ spectrum can adjusted

- by varying the relative toroidal phasing between straps



ITER antenna front face [IO]



ITER antenna $k_{//}$ spectrum for different phase excitations [J.Ongena 2017]

A Messiaen et al 2021 Plasma Phys. Control. Fusion 63 045021
J Ongena et al 2017 Plasma Phys. Control. Fusion 59 054002
E. Lerche et al., EPJ Web Conf., vol. 346, p. 02017, 2026

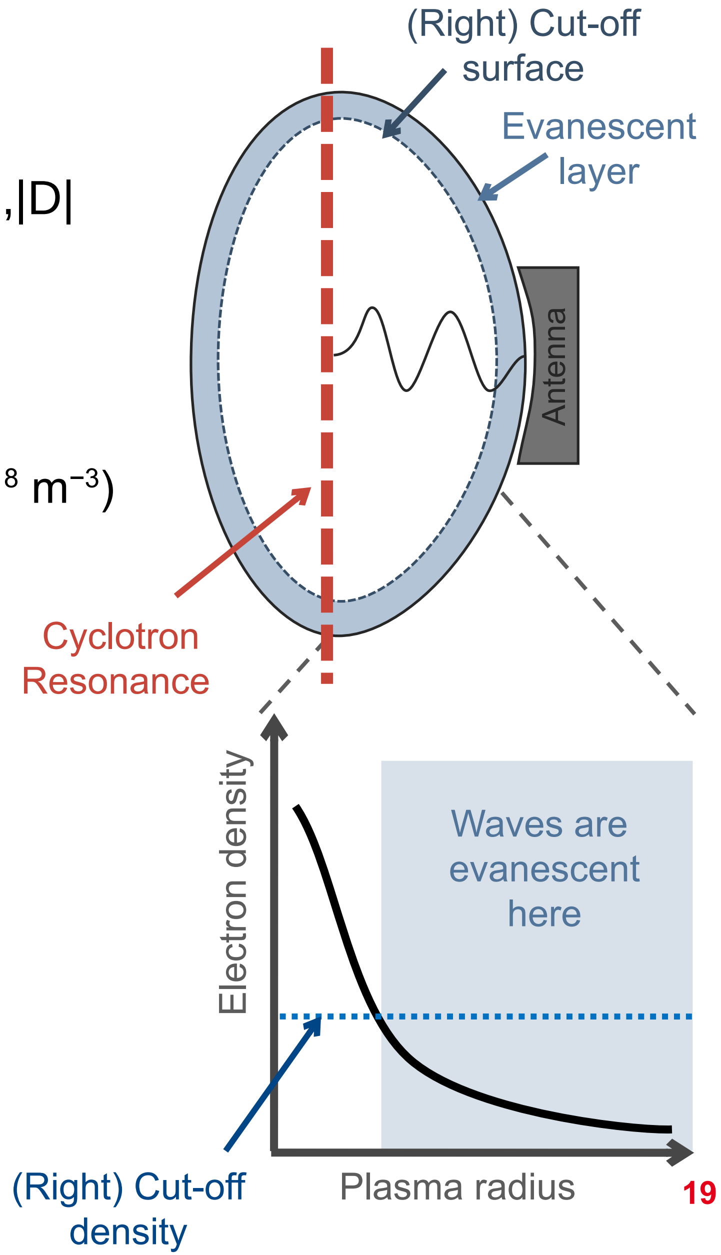
Fast Wave Properties the ICRF in cold plasma

The fast wave dispersion relation for a cold plasma in the ICRF is given by:

$$n_{\perp,FW}^2 \approx S - n_\parallel^2 - \frac{D^2}{S - n_\parallel^2}$$

ICRF : |P|>>|S|,|D|

- The fast wave exhibits 2 cut-offs:
  - the right cut-off: $n_{//}^2 = R$
  - the left cut-off : $n_{//}^2 = L$
- Right cut-off: fast wave does not propagate below a finite density ($n_{e,cut\text{-}off} \sim 1.10^{18}$ m^{-3})
  - Located significantly inside the plasma SOL
    → fast wave is evanescent near the plasma edge
  - Distance btw antenna and cut-off increases with $n_{//}$
    → plasma filters out high $n_{//}$ components
  - A significant fraction of the power can tunnel through the evanescence layer to reach the right cut-off, and propagate onward to the plasma core.
- Left cut-off: located well inside the plasma core (not an issue).
- Elliptically polarized: **E** = **E+** (left-hand) + **E-** (right-hand)
- Once coupled to the plasma
  - Fast wave is able to propagate between these two cut-offs
  - It remains trapped until dissipation mechanisms damp the power.



A Messiaen et al 2021 Plasma Phys. Control. Fusion 63 045021
R.Dumont - Encyclopedia of Nuclear Energy, 2021

ICRF (brief) Timeline

FAST WAVE HEATING OF TWO-ION PLASMAS IN THE PRINCETON LARGE TORUS THROUGH MINORITY CYCLOTRON RESONANCE DAMPING

J. Hosea, S. Bernabei, P. Colestock, S. L. Davis, P. Efthimion, R. J. Goldston, D. Hwang, S. S. Medley, D. Mueller, J. Strachan, H. Thompson
Plasma Physics Laboratory, Princeton University
Princeton, NJ 08544 USA

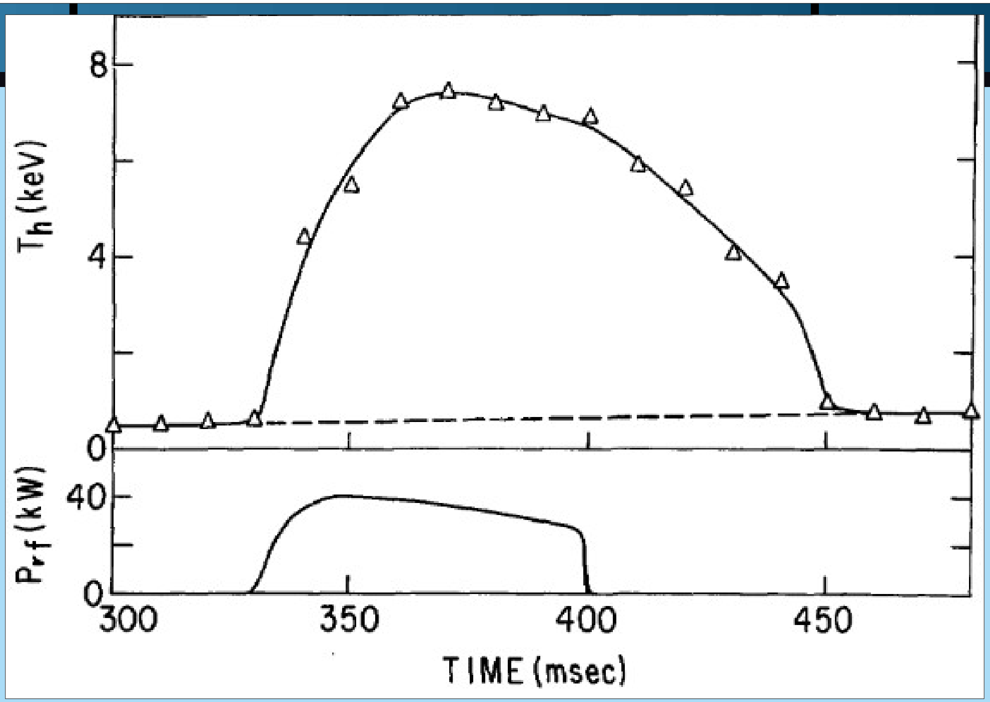
1970

1980

1960's: 1st experimental wave absorption
1960 : wave absorption in B-65 stellarator
1962 : Stix's plasma wave theory
1969 : 1st use of ICRF in Model C stellarator

1970's: Heating Scenarios Development

- Theoretical basis of heating scenarios:
  - 2nd harmonic, mode conversion and minority heating
  - Basis of ICRF antenna design
- Availability of high power sources (broadcasting)



Central minority heating (~3%H in D plasma) in PLT [Hosea1979]

J.M.Noterdaeme, AIP Conf. Proc. 2020

Electron (e^-)

Ion $(+1e)$

Charged particles have periodical motion

- Ions and electrons rotation direction is opposed
- Ions gyrate in a **left-hand** sense with respect to the magnetic field.

Cyclotron frequency depends on charge to mass ratio (Z/A)

Cyclotron gyro-frequency

$$\Omega_{c,s} = \frac{q_s}{m_s} B_0$$

(Larmor) gyro-radius

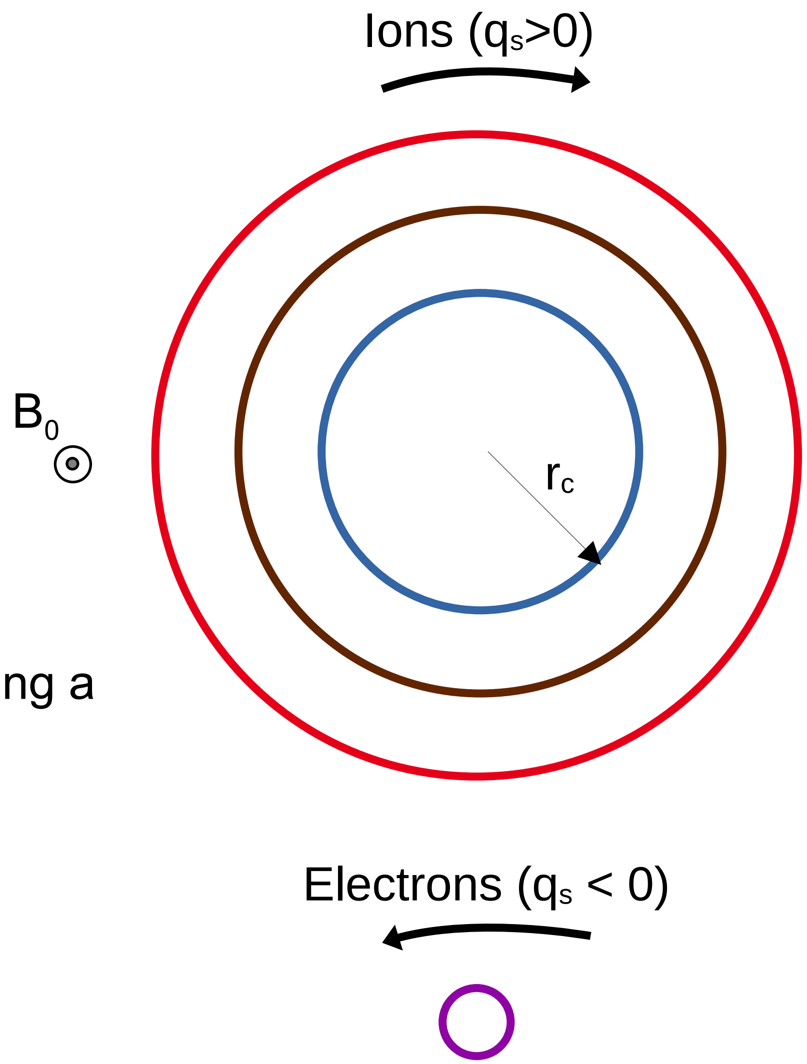
$$r_{c,s} = \frac{m_s}{|q_s|} \frac{v_\perp}{B_0}$$

Examples

- Hydrogen ions (A = 1, Z = 1)
- Deuterium ions (A = 2, Z = 1)
- Tritium ions (A = 3, Z = 1)

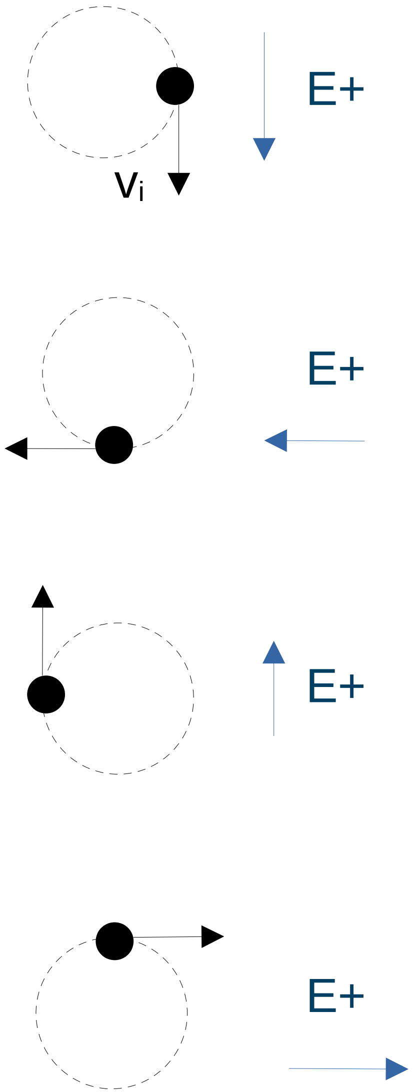
Some order of magnitude

- Cyclotron gyration time
  - 10ps for an electron
  - 40ns for an ion
- Toroidal distance travelled during a single gyration
  - Electron ~ 0.4mm
  - Ion ~ 2cm
- Gyroradii
  - Electron ~ 0.05mm
  - Ion ~ 3mm



Ion Cyclotron Resonance Damping
Simple picture

n = 1
(« first » harmonic)



Power absorbed by the ions when passing through a cyclotron resonance

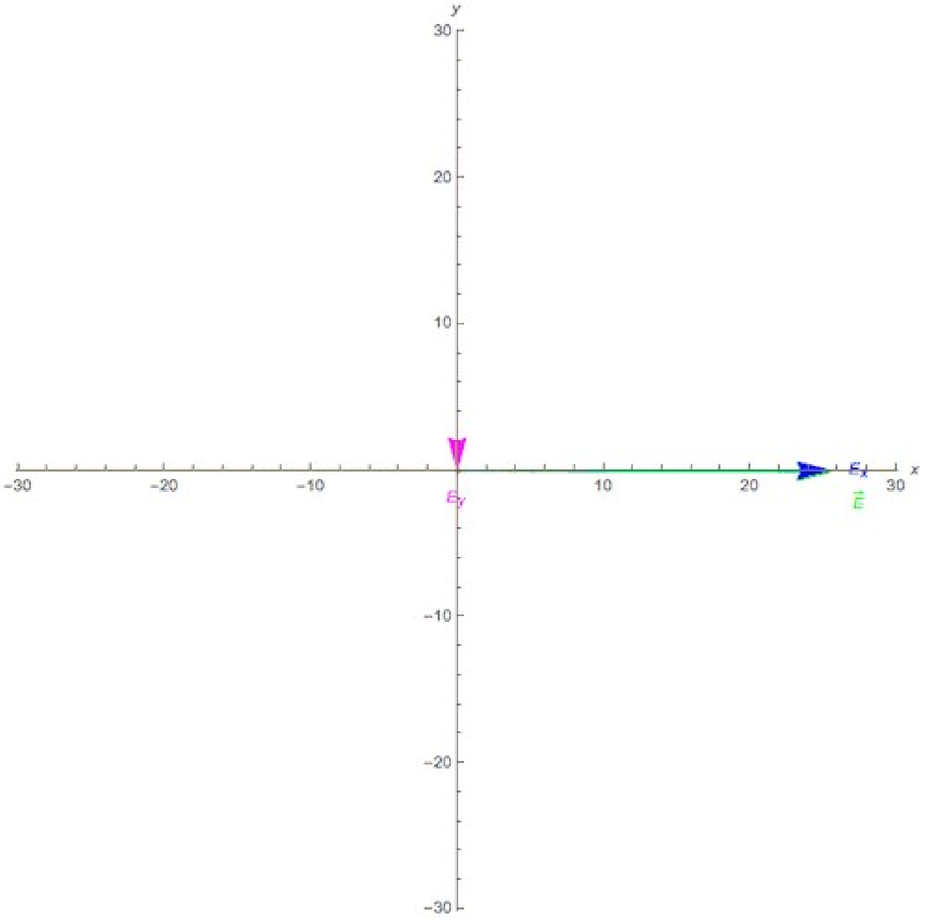
$$P_{\mathrm{abs}} \propto \left|E_+ J_{n-1}(k_\perp \rho_L) + E_- J_{n+1}(k_\perp \rho_L)\right|^2 \longrightarrow |E+|^2$$

Cold plasma:
$k\rho_L \ll 1$
n=1

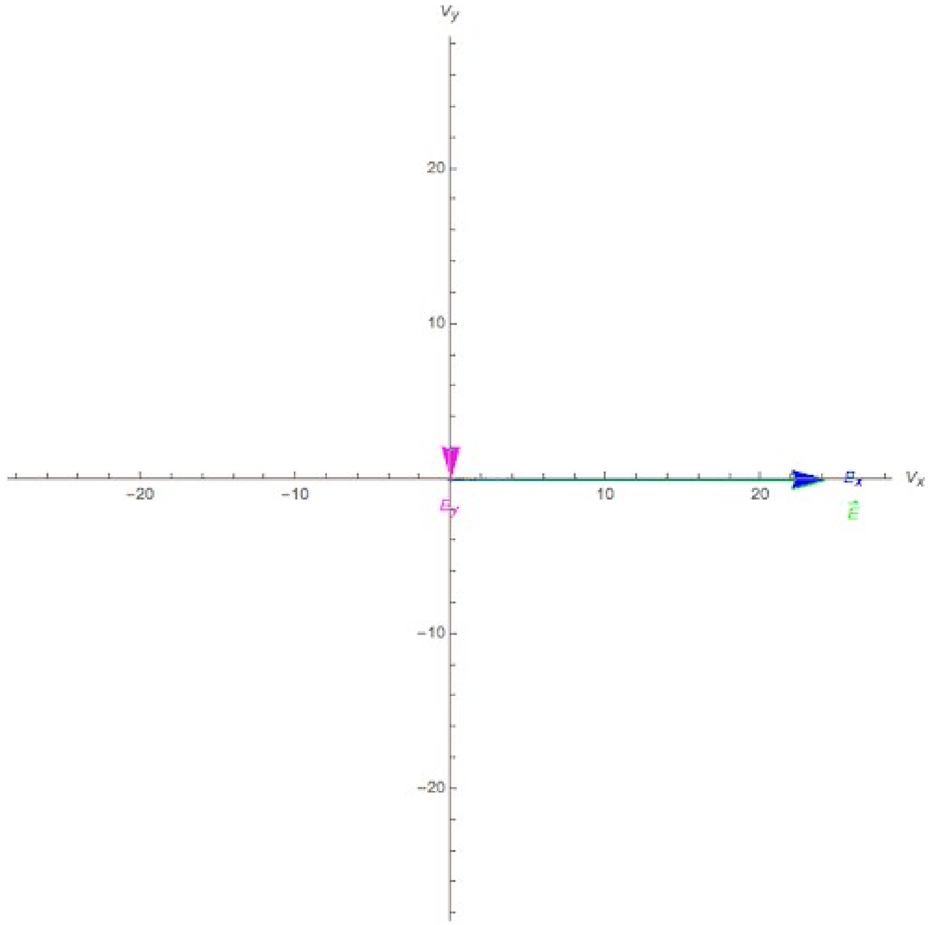
- E_+: Left-handed circular polarization
- J: Bessel function 1st kind
- $k_\perp$: Perpendicular (to B_0) wavenumber
- ρ_L: Larmor radius
- E_-: Right-handed circular polarization

Stix T, Waves in Plasmas, 1992

Ion Cyclotron Resonance Damping
Simple picture



position vs. time



velocity vs. time

https://commons.wikimedia.org/wiki/File:Cyclotron-Resonance-Motion_Circularly-Pol-Fields_Freq-1.0_Efield-1.0_fps-20_Image-Res-100_Image-Size-610x610.gif

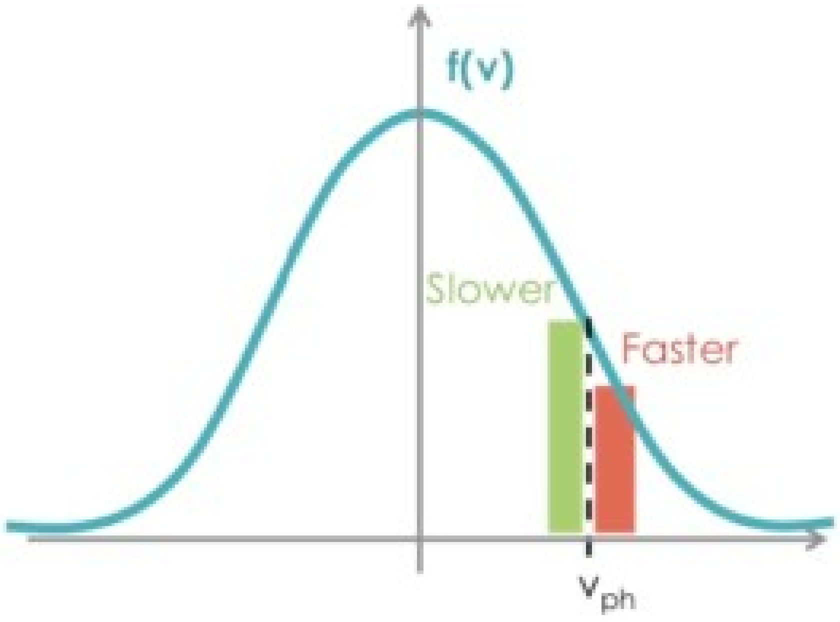
Ion Cyclotron Resonance Damping
Real picture

Particles have periodical motion

- Resonance occurs at multiple times as the particle travels in plasma
- Wave field rotates at same period than Larmor orbit
- But not necessarily “in phase” vs v_{perp}
- Increasing or decreasing v_{perp} depends on phase (diffusive damping in v_{perp})

- Net effect is heating is $df/dv_{perp} < 0$
  - usually the case for Maxwellian distribution

- NB : for Landau damping, diffusion in $v_{//}$

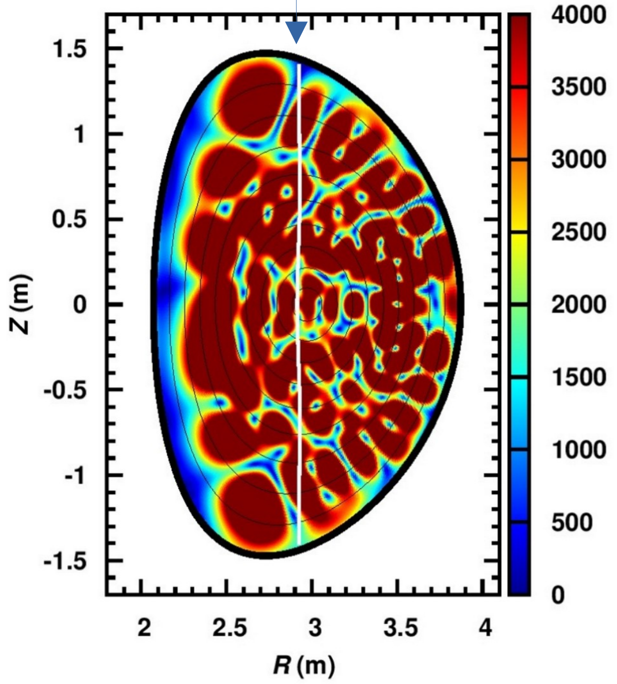


But: Single ion plasma fundamental heating is impossible

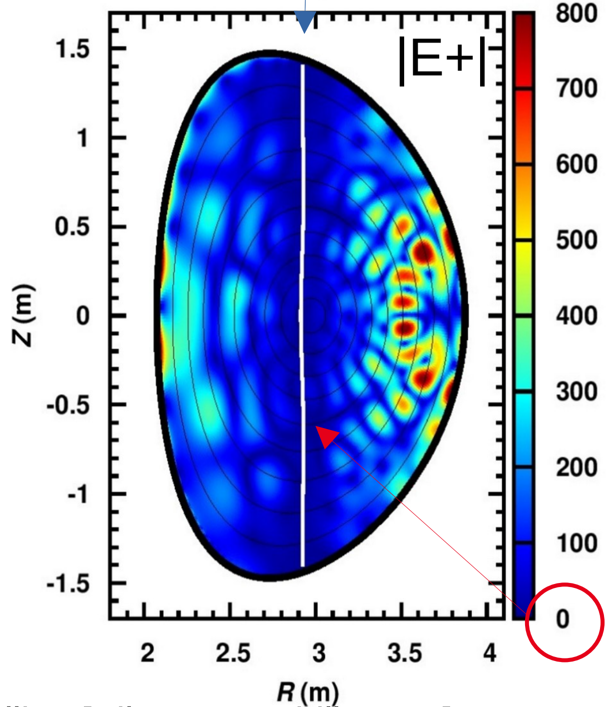
Electric field polarization components depends on plasma composition

- E+ and E- vary locally and mainly determined by plasma composition:
  - number of ion species with different Z/A, relative concentrations, n_i/n_e
- In single-ion plasmas
  - E+ (same wave circular polarization direction than ions gyration) vanishes at $\omega \sim \Omega_{ci}$ → no damping!

$\omega = \Omega_c$



$\omega = \Omega_c$



$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\omega - \omega_{ci}}{\omega + \omega_{ci}}\right| \xrightarrow{\omega \to \omega_{ci}} 0$$

$P_{abs} \to 0$

Images : Y.Kazakov : TORIC modelling [Bilato, Brambilla, IPP]

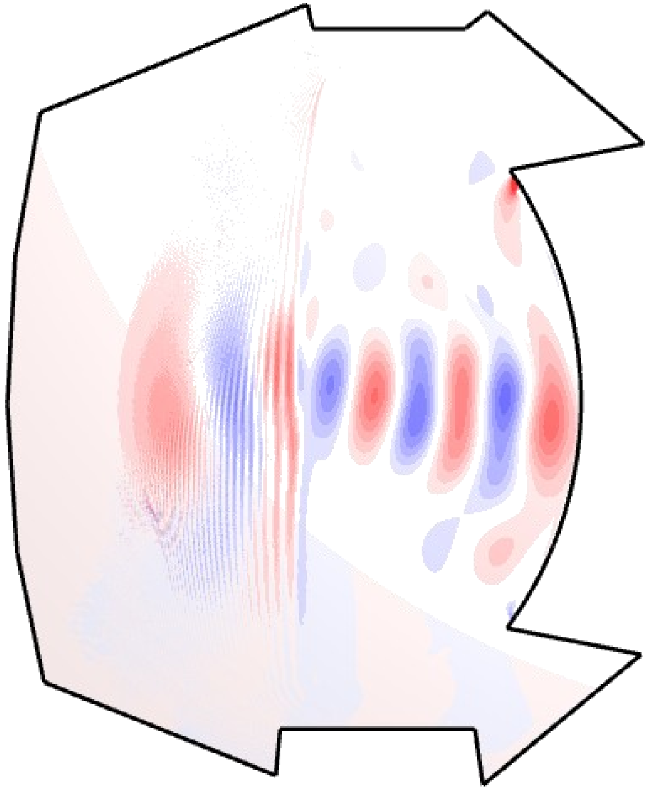
Minority Heating: adding a small concentration of a second ion species

Minority Heating

- n=1 ICRH of the majority ions does not work
  - However, adding a *minority* (ie. small concentration fraction) ions $(Z/A)_{min} > (Z/A)_{maj}$ will absorb wave power when using fundamental heating schemes (H or ^{3}He in D, T or DT)
  - RF heated minority then transfer their energy through Coulomb collisions to other plasma particles (bulk ions and electrons)
  - Heating efficiency depends on minority concentration (ion → e)
- Explained by the *ion-ion hybrid* resonance Ω_{IIH} for 2 species plasma:
  - Ω_{IIH} is bounded between the 2 ion species cyclotron frequencies Ω_{ci}

$$\min(\Omega_{c1}, \Omega_{c2}) < \Omega_{IIH} < \max(\Omega_{c1}, \Omega_{c2})$$

  - If minority ions concentration is much less than majority ions → $\Omega_{IIH} \approx \Omega_{ci,minority}$
- Also works: *inverted* scenarios $(Z/A)_{min} < (Z/A)_{maj}$ → useful in non-activated phase of ITER, ex: ^{3}He or ^{4}He in H



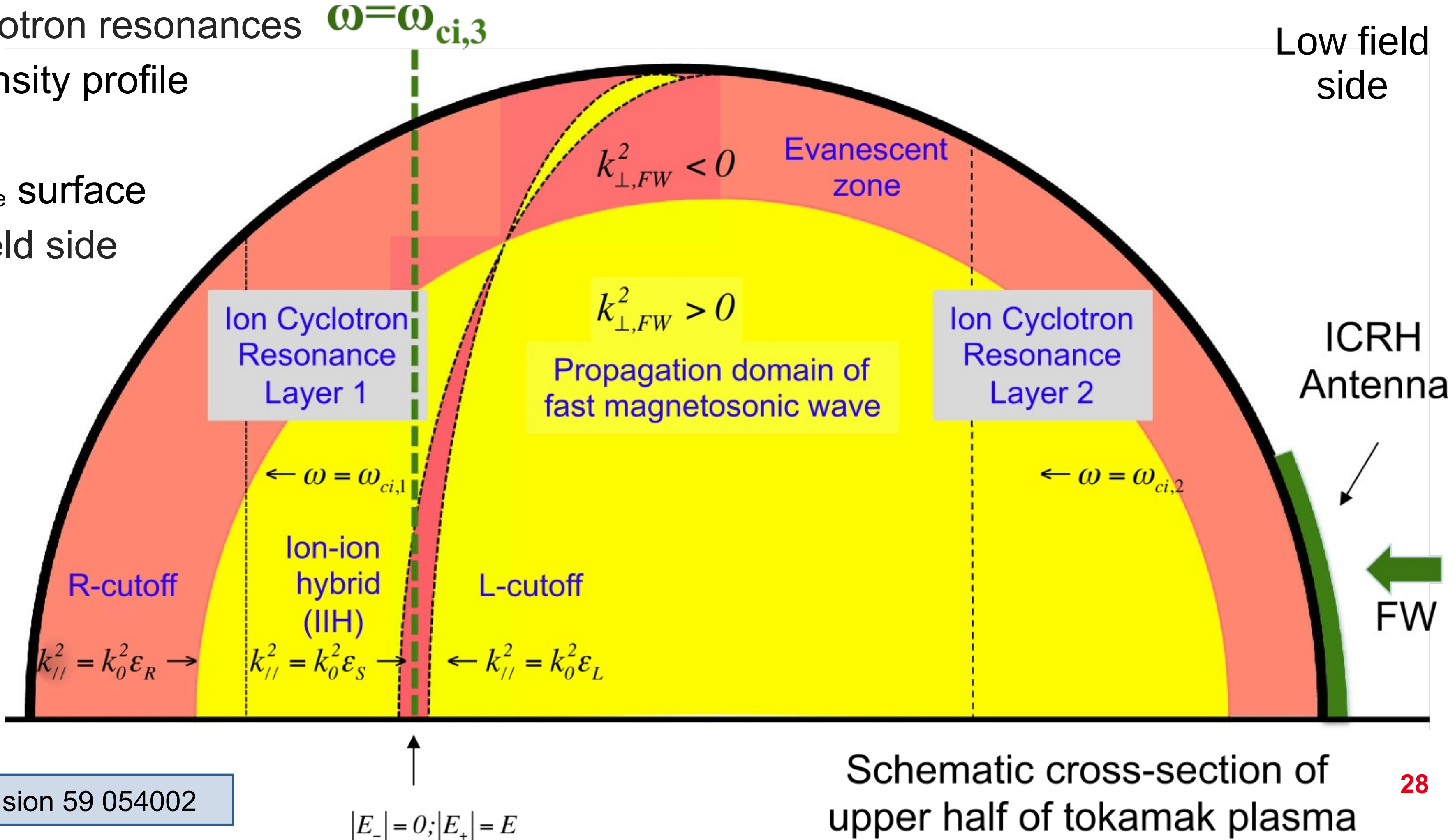
Minority heating in WEST at 55MHz 5% D(H) [V.Maquet]

F.W. Perkins 1977 Nucl. Fusion 17 1197
D.Van Eester, EPJ Web of Conferences 157, 03061 (2017)

Summary schematic of waves propagation regions in ICRF

In tokamak with a parabolic density profile and 2 ion species

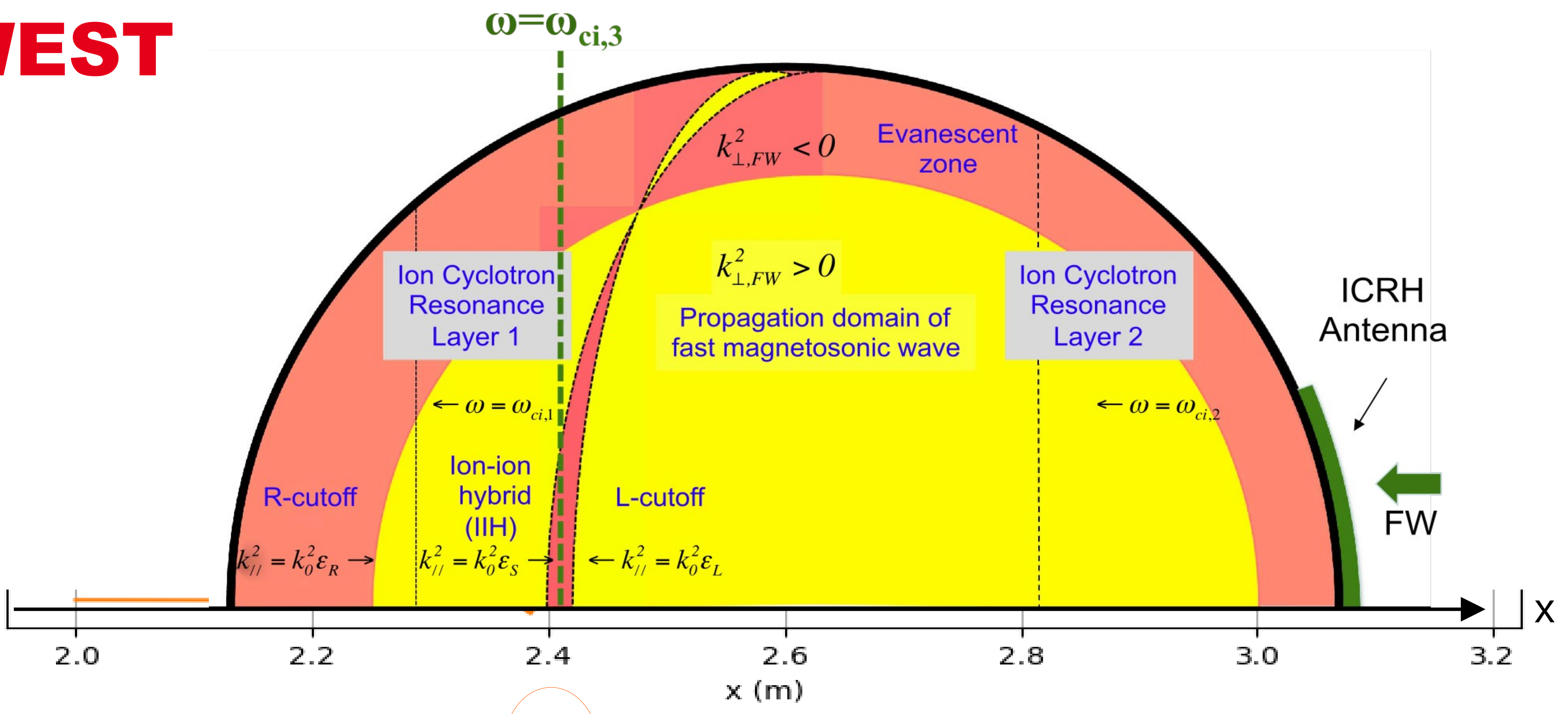
- FW propagates in a large fraction of the bulk plasma
- Mode conversion layer ($k_{perp,SW}=k_{perp,FW}$) at Ion-Ion Hybrid res.
  - located in btw these 2 cyclotron resonances
- IIH resonance bent due to density profile
  - So as L cut-off
- R-cutoff close to a constant-n_e surface
  - So also present on high field side

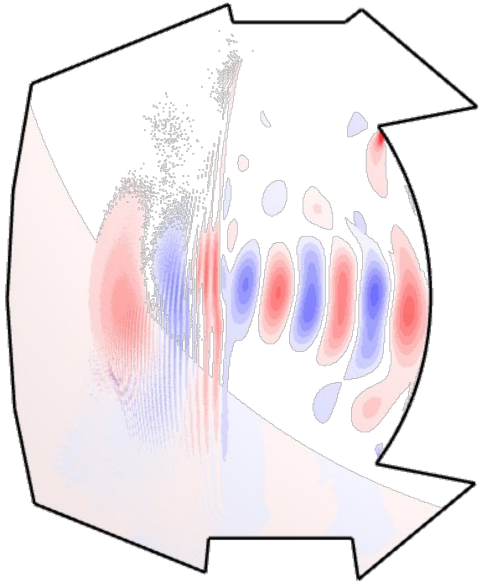


Schematic cross-section of upper half of tokamak plasma

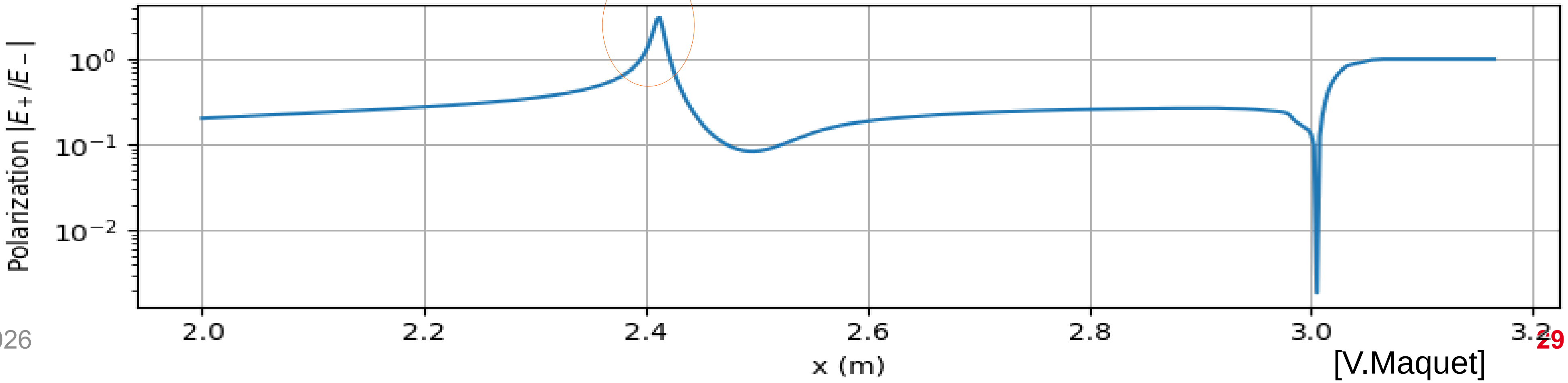
J Ongena et al 2017 Plasma Phys. Control. Fusion 59 054002

Cold Plasma Dispersion relation in the ICRF: example on WEST





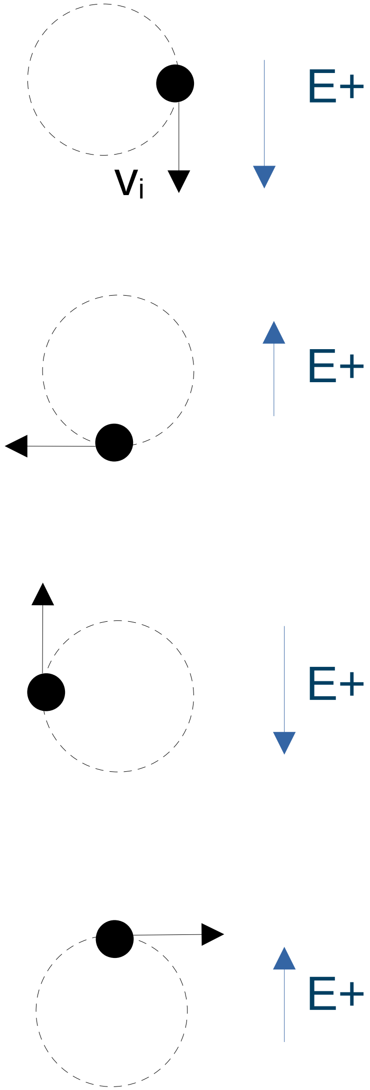
Minority heating in WEST at 55MHz 5% D(H) [V.Maquet]



[V.Maquet]

Second Harmonic Heating

Intuitive view:

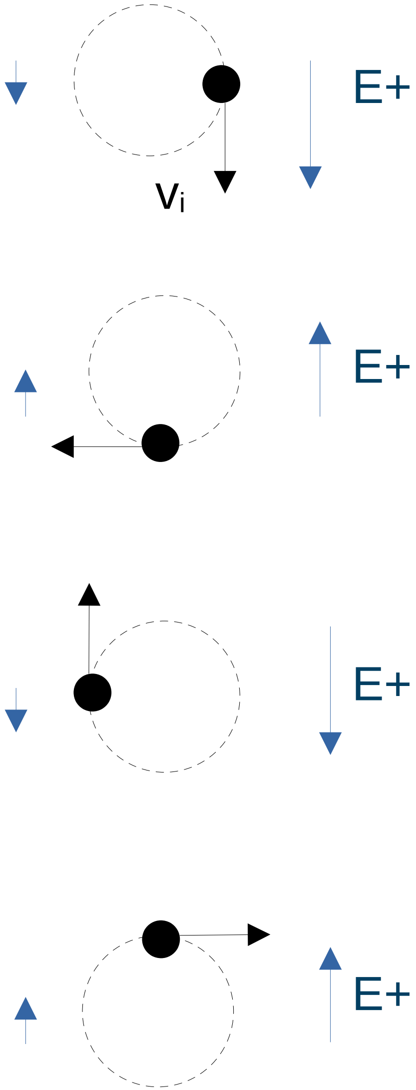


n = 2
(« second » harmonic)

Not net acceleration !

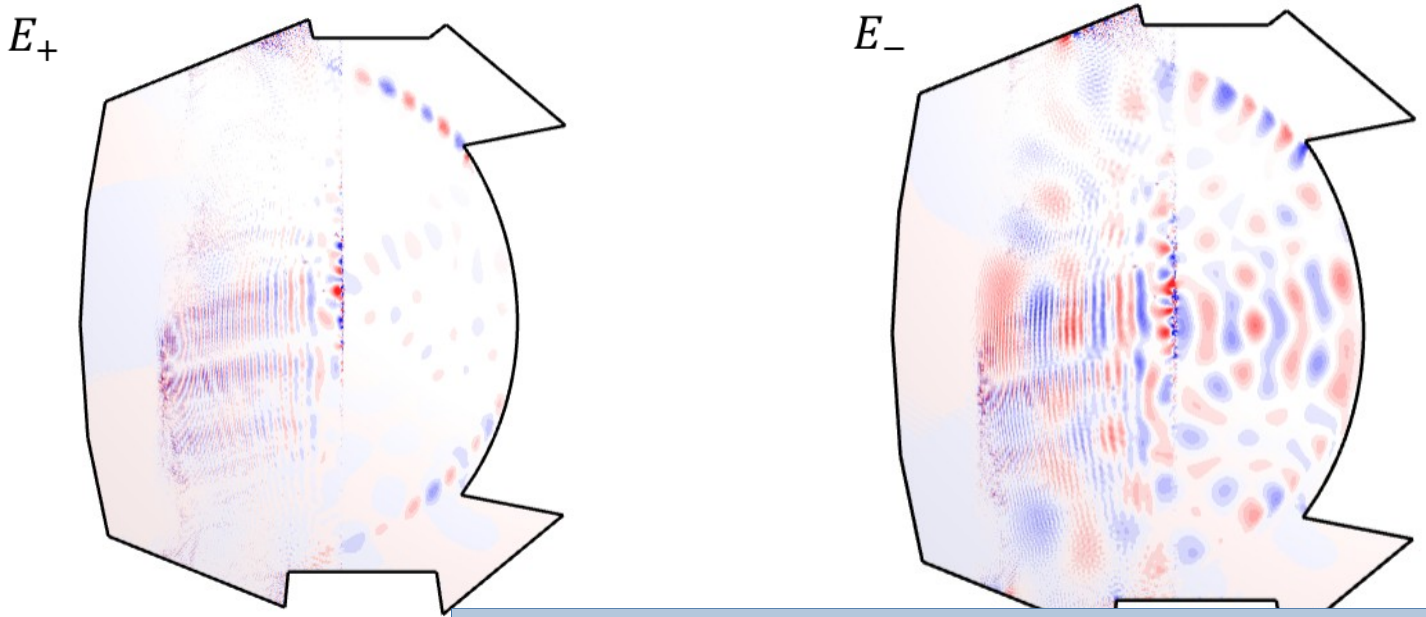
However, in practice

- there is a gradient of the E-field along the orbit ($k_{perp}\rho_L$ effects)
- Net effect!



Second Harmonic Heating

- n=2 heating (majority or minority) also works
- Requires high energies and E-field gradient (Finite Larmor radius effect)
- Can furnish larger ion temperature than H-minority
  - n=2 T heating is one of the scenarios envisaged for DT in ITER at 53 MHz/5.3 T
- Can be used in combination of ^{3}He-minority heating
  - Relevant when not yet hot enough for efficient bulk ion heating by second harmonic



Second harmonic heating H in WEST [V.Maquet]

T. Hellsten etal 1985 Nucl.Fusion 25 99
Koch, R. (2012). Fusion Science and Technology, 61(2T), 296–303J.
Mantsinen et al., Nucl. Fusion, vol. 63, no. 11, 2023

Fast Wave Ion Cyclotron Current Drive

Relies on direct heating of electrons

- When electron parallel velocity matches the parallel phase velocity of the fast wave
  - Via electron Landau damping and transit time magnetic pumping
  - But presence of the ion cyclotron layers parasitic, in particular with large plasmas

Fast wave current drive obtained by exciting a toroidally asymmetric antenna spectrum.

- Challenging scenario due to
  - Low absorptivity of the fast wave electron damping
  - Parasitic damping on ions
  - Efficiency increase linearly with the central electron temperature
- Fast waves at frequencies >> cyclotron frequency (*helicons* or *whistlers*) for off-axis CD
- In ITER and large plasma
  - FWCD could generate an interesting moderate level of central non-inductive current
  - Can be improved with addition of ^3He to increase single-pass absorption rate

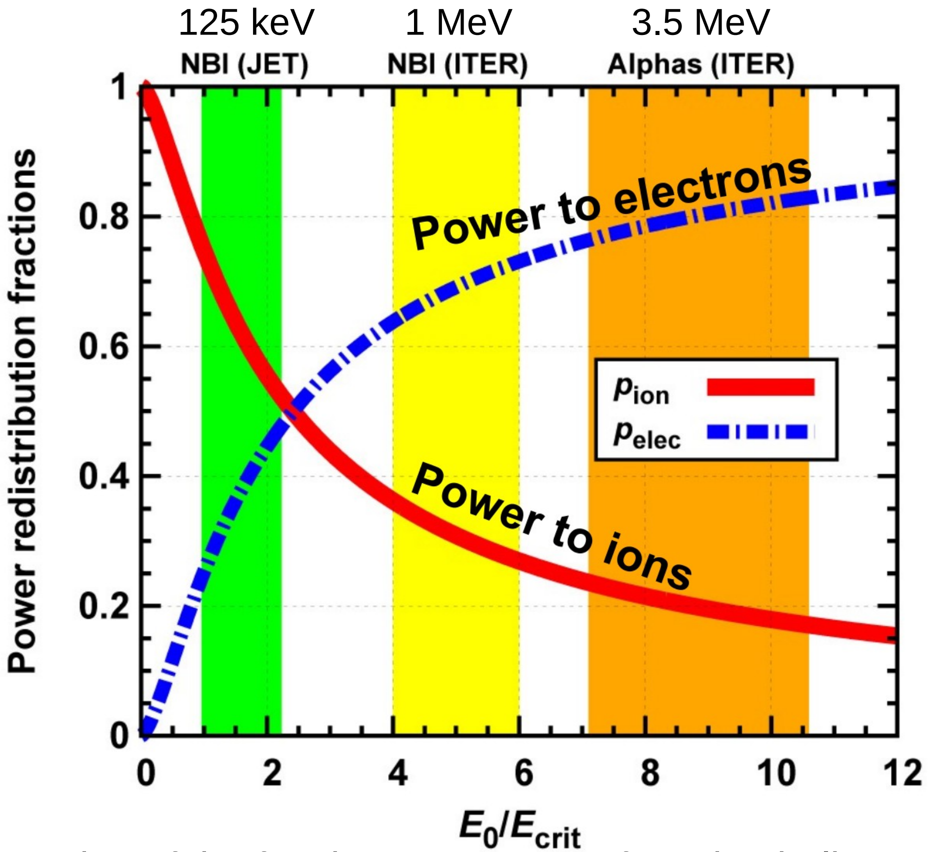
T.Hellsten, AIP Conf. Proc. 787, 273–278 (2005)
R.J. Dumont and D. Zarzoso 2013 Nucl. Fusion 53 013002
Y. O. Kazakov, Plasma Phys. Control. Fusion, vol. 57, no. 2, 2015
D.Van Eester, AIP Conf. Proc. 2984, 030004 (2023)

The amount of bulk ion and electron heating depends on fast ion energy

- Depends on fast-ion energy versus the critial energy:
  - $E_{fast} >> E_{crit} \rightarrow$ electron heating
  - $E_{fast} << E_{crit} \rightarrow$ bulk ion heating
- Fast ions with ~MeV energy mainly heat electrons
  - Alpha particles will generate dominant electron heating
  - High energy negative NBI too
- However, still possible to get dominant heating of bulk ions
  - by selecting resonant ions with higher A_{fast} to increase E_{crit}

atomic mass of the energetic ions

$$E_{\mathrm{crit}} = 14.8\, T_e\, A_{\mathrm{fast}} \left(\sum_i \frac{(n_i/n_e) Z_i^2}{A_i} \right)^{2/3}$$

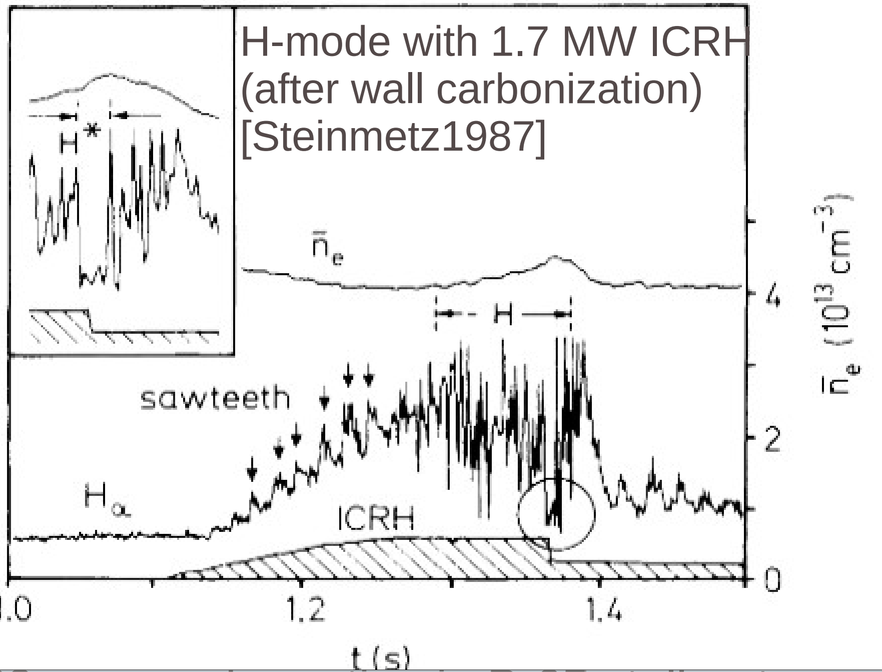


Fraction of the fast ion energy transferred to bulk ions and to electrons as a function of E_0/E_{crit} [Y.Kazakov 2015. FZJ-2016-01957]

T.H. Stix, Plasma Phys. 14, 367 (1972)

Y. Kazakov, 2025. doi: 10.7910/DVN/TXTIBZ

ICRF (brief) Timeline



H-mode with 1.7 MW ICRH (after wall carbonization) [Steinmetz1987]

power to half the initial value. The duration of these H^* phases has been found to be mainly limited by the continuously increasing central radiation due to a strong high-Z impurity accumulation which is directly related to the good particle confinement. Unfortunately, the

This conceptual picture immediately suggests three classes of improvements for ICRF antenna design: (1) Alignment of Faraday screen elements along the magnetic field. (2) Orientation of surfaces where sputtering occurs so that impurities are directed away from the plasma. (3) Coating of the Faraday screen elements with low-Z material so that the sputtered material does not radiate severely at high temperatures. Step (3) is already realized in present ICRF antennas [14].

[Perkins1989]

1990

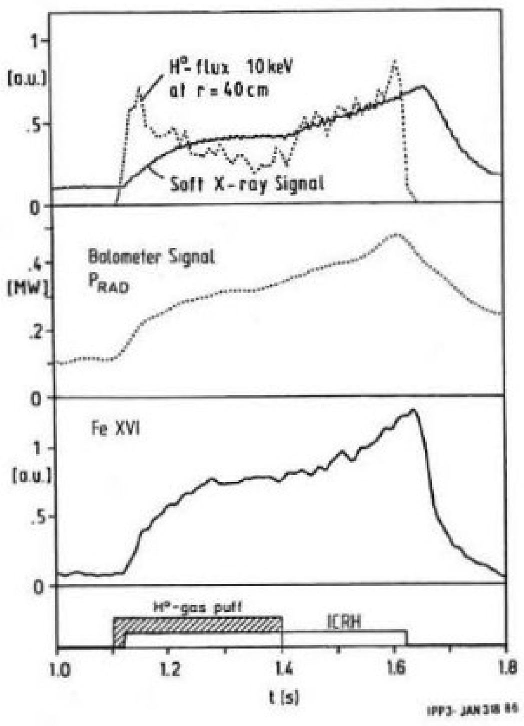
1980's: MW power experiments

1982: H-mode discovery (1987 with IC)

- Plasma core heating
- Sawtooth stabilization
- Coupling challenge (H-mode)
- impurity issues (link to RF sheaths)

1970's: Heating Scenarios Development

- Theoretical basis of heating scenarios:
  - 2nd harmonic, mode conversion and minority heating
  - Basis of ICRF antenna design
- Availability of high power sources (broadcasting)



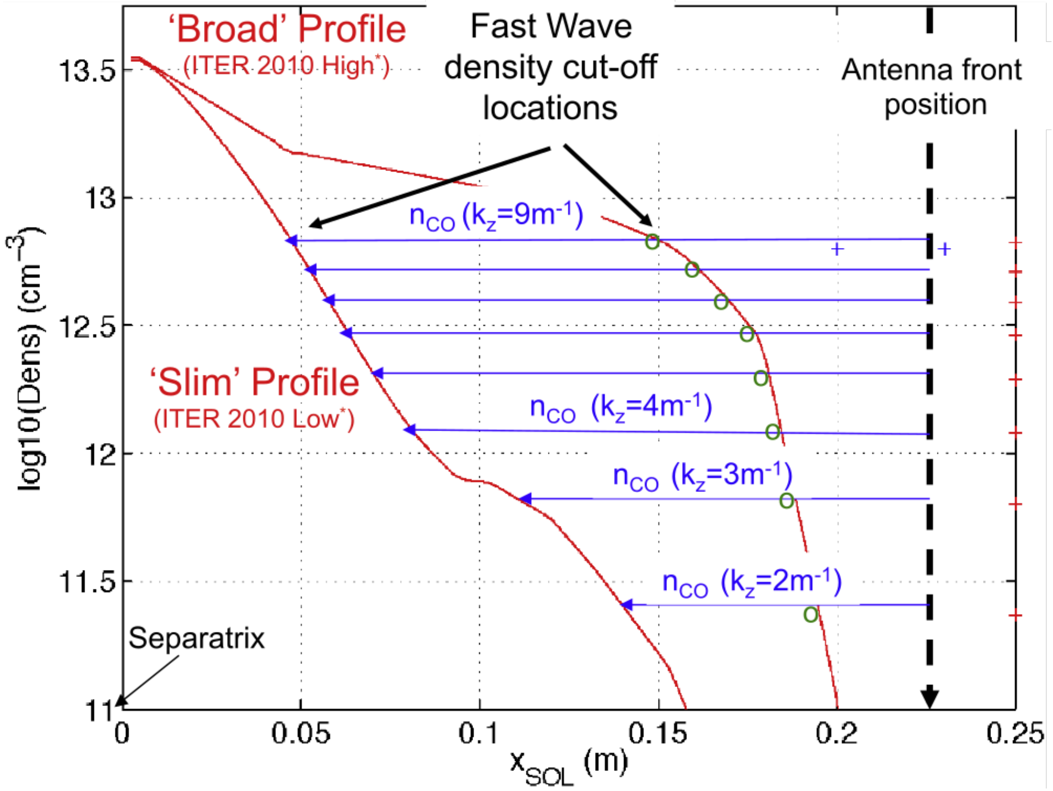
[Janeschitz1986]

J.M.Noterdaeme, AIP Conf. Proc. 2020

ICRF Antenna Coupling Challenges

Long distance plasma coupling

- A plasma tends to reflect waves whose frequency is much lower than plasma electron frequency
- Wave launched by the antenna requires a minimum plasma density to propagate (cut-off density n_{CO}): ~10^{18} particles/m^3
  - Value not reached before a few cm
  - Value depends on $k_{//}$ (antenna design)
- The wave has to travel an evanescent layer, where the wave amplitude decreases exponentially
- The larger this layer is:
  - the higher the power reflected back on the antenna
  - … and the lower the coupling



Radial positions of the fast wave cut-off densities n_{CO} for two electron density profiles in ITER [J.Ongena 2017]

ELMS (Edge Localized Modes)

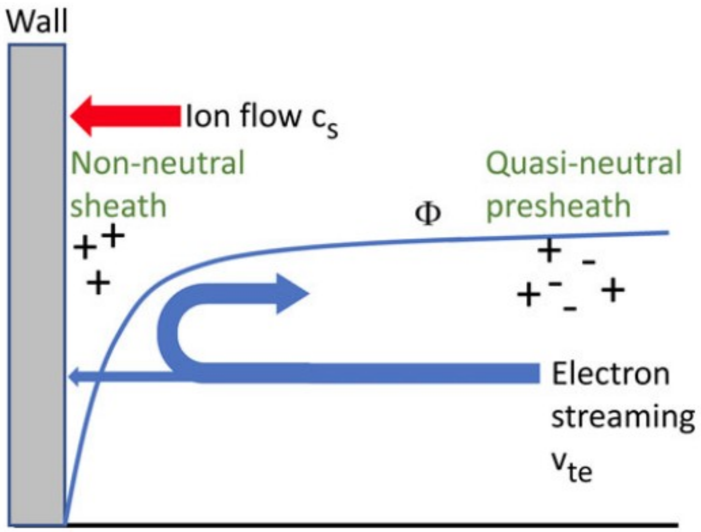
- Repetitive, plasma eruptions that occur in high performance tokamak plasmas.
- In addition to damage wall components by ablating them away due to their extremely high energy transfer rate (GW/m²), also rapidly increase the ICRF antennas loading

  → *load resilient* schemes

J Ongena et al 2017 Plasma Phys. Control. Fusion 59 054002

X.Zhang's lecture, this school

RF Sheaths



[Myra 2021]

Thermal sheaths

- In contact to conductor, neutral plasma looses electrons faster than ions
  - Because of larger v_{Te}
  - Create charges imbalance: positively charged plasma w.r.t the surface
  - Plasma *sheath*: region created where potential drop takes place (1-100µm)
- Plasma is non-neutral in the sheath region
  - Nearly free of electrons (repelled)
  - Ions are accelerated toward the surface → can create desorption and sputtering/erosion

RF Sheaths

- If RF fields are excited by the ICRH antenna around the surface
  - An RF component will induce an additional (*rectified*) DC voltage
  - Which further increases ion acceleration and the release of impurities by sputtering from surfaces
  - Also induces parasitic power loss (wave not efficiently reaching the core)

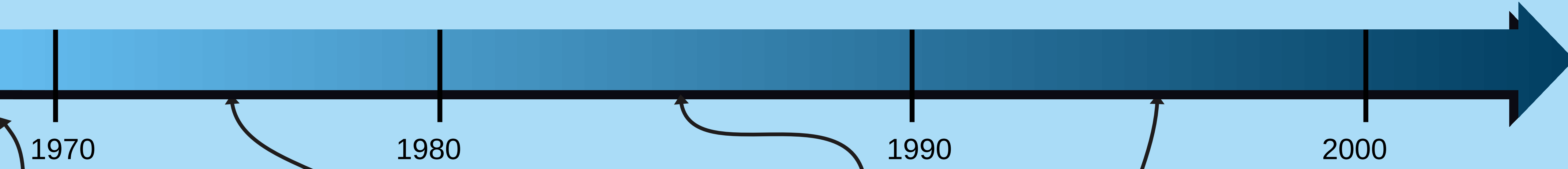
NB: intense Plasma-Wall Interaction is found for high local density, with or without ICRF waves

- Both sputtering and local heat loads are proportional to the local particle fluxes
- In ITER, ICRF-induced increment of gross W production is at worse 22% of the W source expected from thermal sheaths
  - Moderate expected global increase: questions ability to detect ICRF-specific W contamination of the plasma

J. R. Myra, J. Plasma Phys., vol. 87, no. 5, p. 905870504, Oct. 2021
L. Colas et al., Nucl. Fusion, vol. 62, no. 1, p. 016014, Dec. 2021
L. Colas et al., Nuclear Materials and Energy, vol. 42, p. 101831, Mar. 2025

X.Zhang's lecture, this school

ICRF (brief) Timeline



1960's: 1st experimental wave absorption
1960 : wave absorption in B-65 stellarator
1962 : Stix's plasma wave theory
1969 : 1st use of ICRF in Model C stellarator

1970's: Heating Scenarios Development
- Theoretical basis of heating scenarios:
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- Availability of high power sources (broadcasting)

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1982: H-mode discovery (1987 with IC)
- Plasma core heating
- Sawtooth stabilization
- Coupling and impurity issues (RF sheaths)

1990's: Performance improvements
- ICRF on D-T plasmas (TFTR, JET)
- Load/ELMs resilience systems
- Long pulses

J.M.Noterdaeme, AIP Conf. Proc. 2020

D-T Plasmas ICRH Scenarios in ITER

f = 40-55MHz

$B_0(R_0 = 6.2m) = 5.45T$

Non-active operation phase of ITER will be done in H and ^{4}He plasmas at half nominal field (2.65 T)

- Fundamental ICRH of majority H plasmas at f ≈ 40MHz → poor ion absorption
- Second harmonic (N = 2) ^{3}He ICRH in H plasmas at f ≈ 53MHz → poor ion absorption
- Fundamental minority H heating in ^{4}He plasmas at f ≈ 40MHz.

ITER Fusion Power Operation (FPO): 2 main scenarios at ~53 MHz

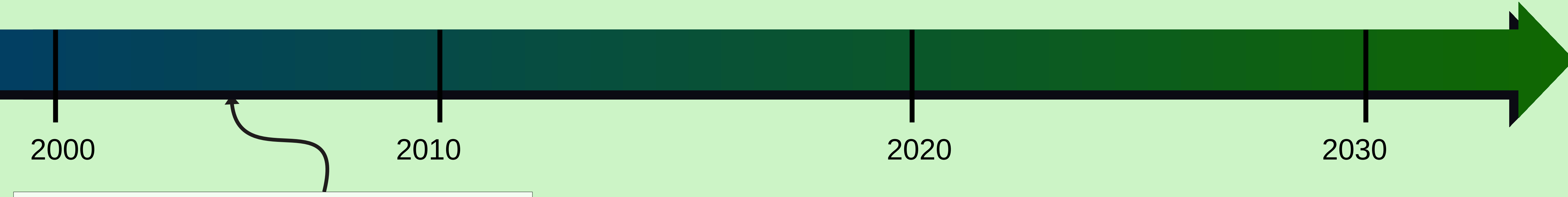
- ^{3}He minority — efficient at low temperature
- Second harmonic T — efficient at intermediate ion energies

} Injection ^{3}He for a limited time, until 2nd harmonic T becomes efficient enough

- 3-ion schemes [see next slides]
  - ~~T – (^{9}Be) - D~~
  - T - (fast-D) – D

ITER Research Plan, 2024
D. Van Eester et al 2002 Nucl. Fusion 42 310
V. Bergeaud et al 2000 Nucl. Fusion 40 35

ICRF (brief) Timeline



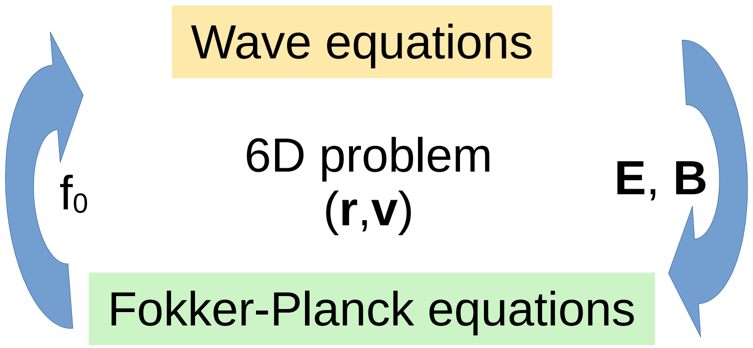
2000's: Towards ITER
- ITER-like antennas
- Very long pulses (45min LHCD)
- Quantitative modeling (core, edge)
- IC-induced Fast Particle

J.M.Noterdaeme, AIP Conf. Proc. 2020

Core Modelling

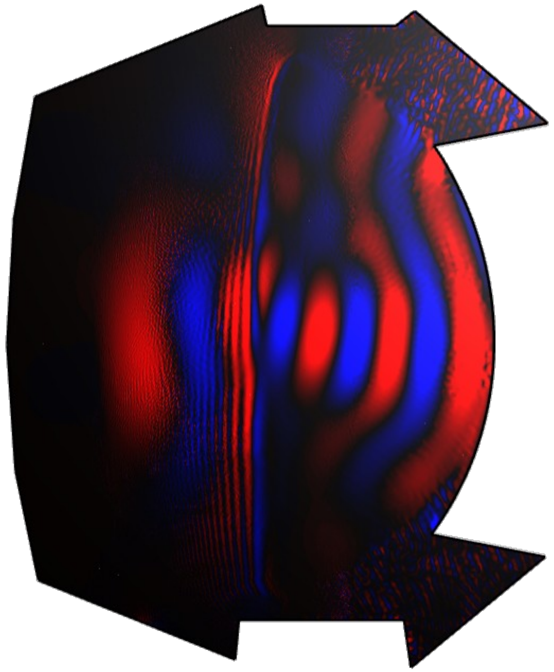
Plasma heating modelling

- Wave point of view: solve for which particles and where the wave energy is lost
  - Results from wave equation with full hot relativistic tensor
- Particle point of view: being accelerate or deccelerate by an E-field
  - Result from Fokker-Planck equation
- Because of complexity, often solved separately
- Most current codes give very good agreements between them



Numerical challenges

- **Magnetized fusion plasmas are spatially dispersive**
  - Plasma response permittivity tensor depends on the wavelength (wavevector)
    - Each plane wave experience a different epsilon
  - Formulation in frequency/spectral domain
    - Fourier decomposition of the wave equation leads to dense matrices that are time consuming to invert
- **Local effects**
  - Inhomogeneity of the plasma induces a spatial localization of the resonance.
  - Important effects due to gyromotion of the particles (wavelength comparable to natural length scales)
  - Mode conversion, as well as upshift of k|| and finite Larmor radius effects are difficult to model.



WEST / Minority heating [V.Maquet]

Brambilla, 1998
Bilato AIP Conf. Proc. 1580, 291–294 (2014)

ICRF Edge Modelling

Progresses toward high-fidelity modelling

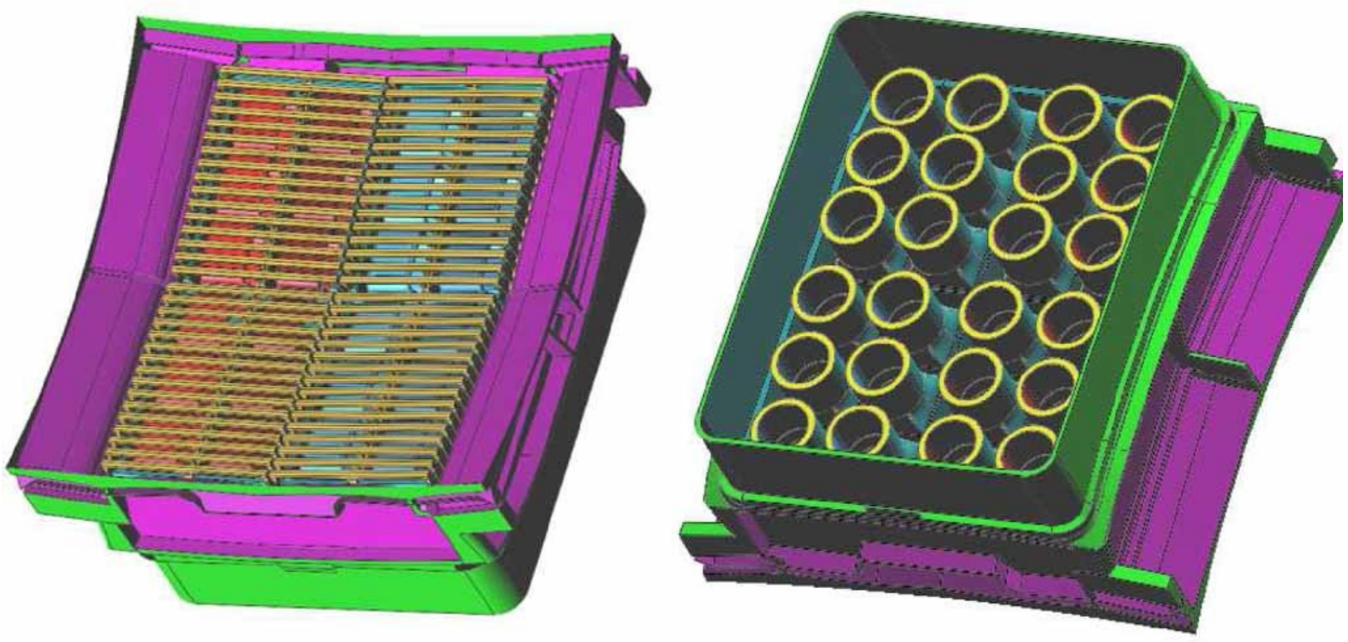
- Realistic 3D antenna geometry
- Realistic 2D/3D plasma profiles (cold or hot)
- Realistic plasma equilibrium
- Link with electric model (matching, etc)

Numerical methods

- Integral-equation formulation (TOPICA)
- Finite Element Methods (COMSOL, HFSS, open-source codes, etc.)

Results

- Good agreements of the coupling calculations with experiments confirmed on several machines (Tore Supra, DIII-D, Alcator C-Mod, AUG, WEST, EAST, etc).
- Robust predictions
  - when the plasma density profile is known !



Front and back view of the ITER ICRF launcher TOPICA model [Milanesio 2023]

D. Milanesio et al 2023 Nucl. Fusion 63 046010

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- IC-induced Fast Particle

2010's: The return of metallic walls
- High Z impurities issues
- Field aligned and 3-straps antennas
- RF sheath modeling progresses
- 3-ions scheme

J.M.Noterdaeme, AIP Conf. Proc. 2020

(The return of) High Z Impurities Issues

- Heavy impurities (high Z) radiate away the energy from the plasma and cause fuel dilution
  - A small concentration of W (<0.01%) can lead to excessive central radiation and temperature collapse

Initial tokamak experiments were performed with metallic walls

- Impurity release during RF operation found in early experiments
- But Low Z material coatings (ex: C) of the antenna front face element reduced impurity to tolerable levels

In the 2010's, tokamaks transited from Carbon-wall to Metallic-wall (W)

- High power operation resulted in high levels of high Z-impurities (again)
- Development of new antennas designs to minimize spurious E-field and impurity production
  - Field-aligned antennas
  - 3-straps antennas

  → substantial progresses, but still a hot research topic (ex: far field impurity generation)

F.W. Perkins 1989 Nucl. Fusion 29 583
R. Diab et al., Nucl. Fusion, vol. 65, no. 7, p. 076038, Jun. 2025
R. Diab et al 2026 Nucl. Fusion 66 066011

3-ions scenarios

A new promising approach showed high heating efficiency

- Plasma mixtures of hydrogen and helium isotopes: D-T, H-D, H-^{4}He, and D-^{3}He
- By adding a 3rd ion population, resonant wave-particle condition is satisfied near an ion-ion hybrid layer
  - Where left-hand RF field component is greatly amplified in this region
- The method can use the intrinsic and extrinsic impurities (^{9}Be, Ne, Ar)

$$Y_2\text{-}(Y_3)\text{-}Y_1$$

Non-resonant species
Ordered to their Z/A value
$\Omega_{c2} < \Omega_{c1}$

Resonant ion

2 choices available for resonant absorber

- Use an ion population with a charge-to-mass ratio Z/A *sandwiched* between the two non-resonant ions
  - $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$
  - Absorption by resonant ions at extremely low concentrations (< 1%)
- Use *same* charge-to-mass ratio Z/A as one of the main plasma ions
  - The 3rd ion population must have sufficiently large parallel velocities to resonate (large Doppler shift)
  - Fast ions injected by neutral beam injection (NBI) are a natural choice
    → synergetic effects between NBI and ICRH

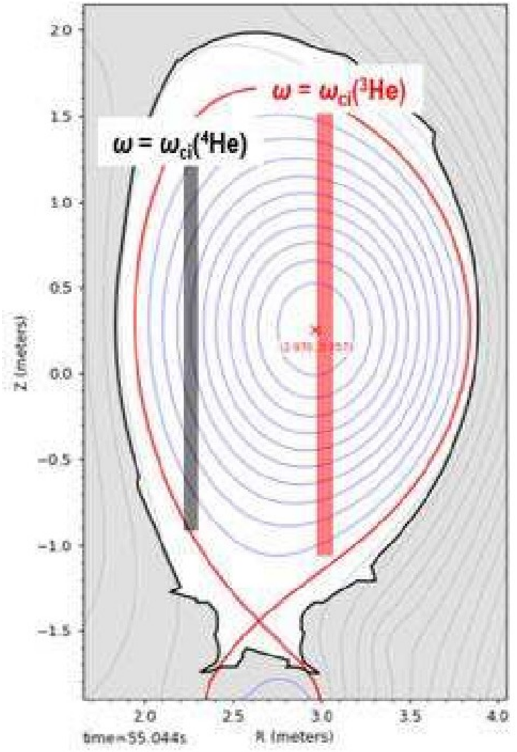
Y. Kazakov, 2025. doi: 10.7910/DVN/TXTIBZ

Example: 3-ions scenarios (1/2)

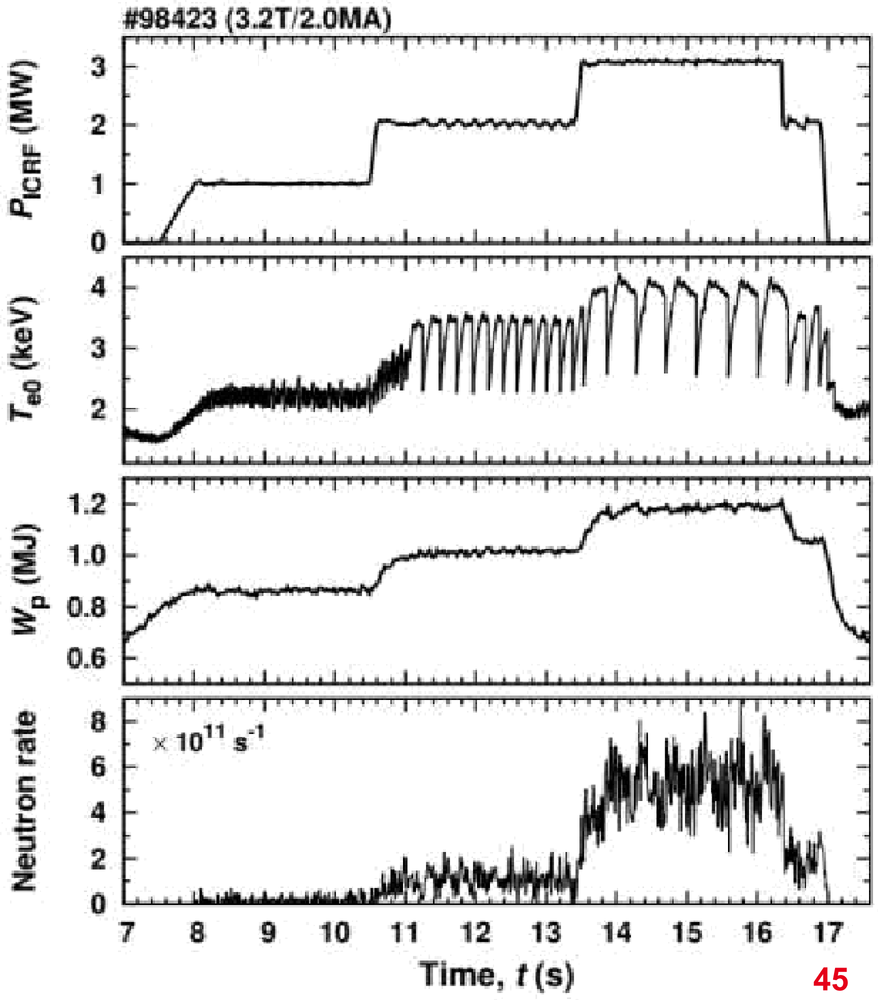
^{4}He-(^{3}He)-H ICRF or D-(^{3}He)-H scenarios

- ITER Relevant for plasma heating in non-active H & ~10% ^{4}He
- Efficient plasma heating with low ^{3}He concentration (<1%) and large range of ^{4}He (5-15 %)
  - ^{3}He accelerated to MeV → dominant electron heating

Overview of JET pulses #98423
3.2T/2MA, n_{e0}~4 10^{19} m^{-3}
f=33.0 MHz
$n(^4He)/n_e$ ~ 13 %
$n(^3He)/n_e$ ~ 0.2 %



^{4}He-(^{3}He)-H ICRF scenario in JET experiments (B_0=3.2T, f=30 MHz)

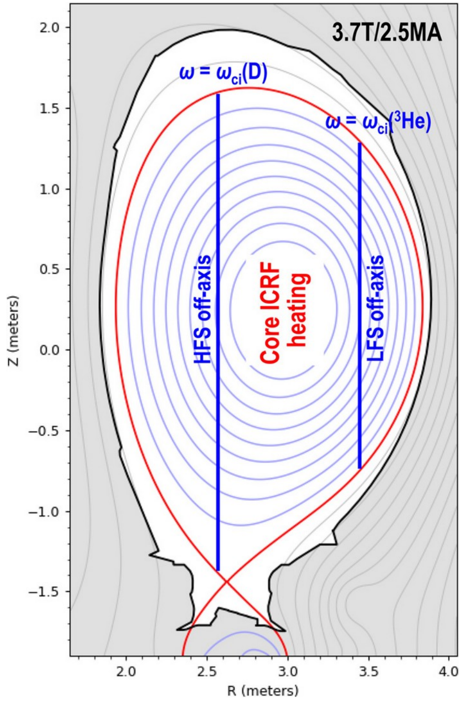


Y. Kazakov, 2025. doi: 10.7910/DVN/TXTIBZ

Example: 3-ions scenarios (2/2)

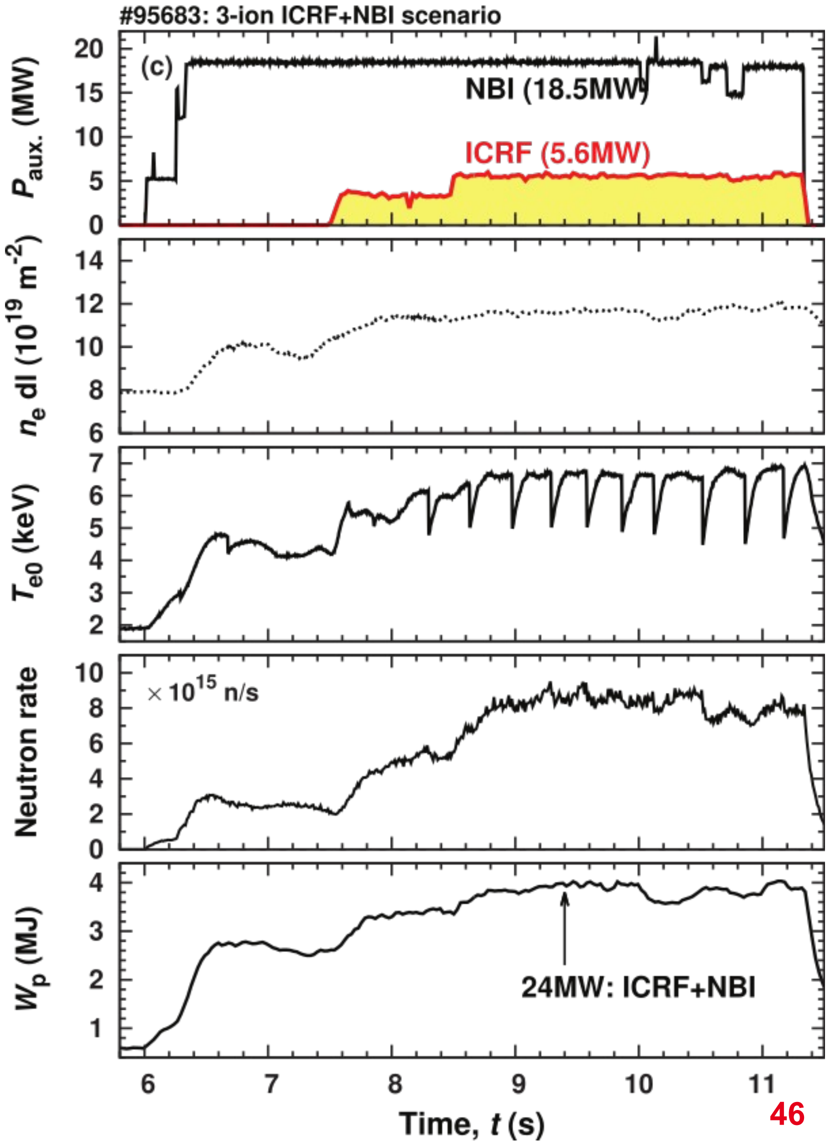
D–(D_{NBI})–^{3}He scenario in D–^{3}He

- Tangential 100 keV used to provide resonant absorbers at the ion-ion-hybrid layer to absorb RF power
  - Accelerated Deuterons from the NBI
  - Further accelerated to higher energies with ICRF in the plasma core → generation of alpha from D-^{3}He fusion



JET cross-section with thermal D and ^{3}He ions resonance locations in D-^{3}He plasmas (3.7 T/2.5 MA, n_{e0} ~ 6 10^{19} m^{-3}, f=32.2–33.0 MHz)

JET pulse #95683 in mixed D-^{3}He plasma



Ye.O. Kazakov et al., Phys. Plasmas 28, 020501 (2021)

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- 3-ions scheme

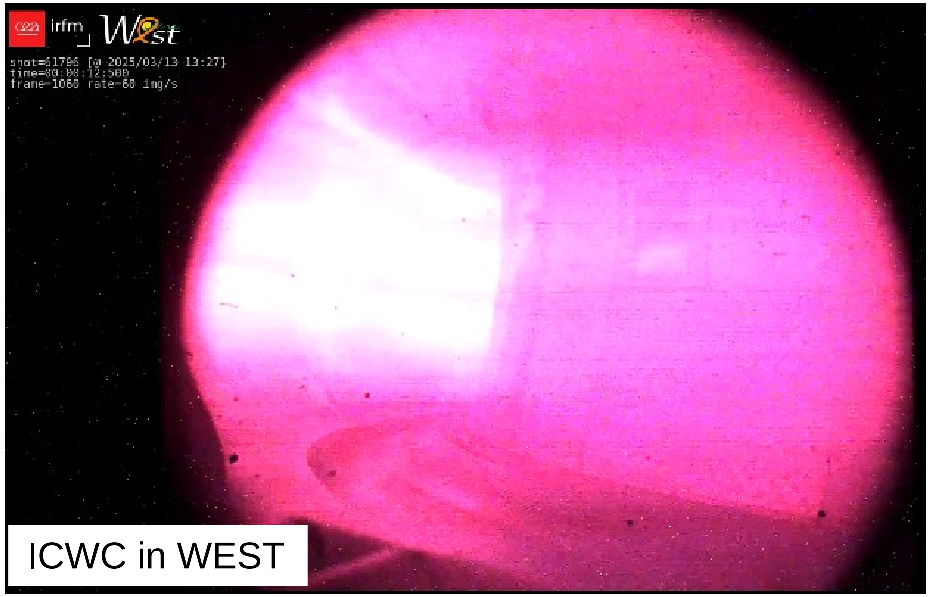
2020’s: ITER and beyond
- High B-field heating
- Non-heating ICRF applications
- Traveling Wave Array antenna

J.M.Noterdaeme, AIP Conf. Proc. 2020

Ion Cyclotron Wall Conditioning (ICWC)

Rationales

- Continuous presence of toroidal magnetic field limits the execution of DC glow discharges (GDC)
  - Only outside operational periods
- RF fields in front of the antenna can create a plasma in presence of toroidal field (+eventually vertical field)
  - When plasma density high enough, plasma waves start propagating, enhanced further ionization
  - Plasma (T_e ~ eV, $n_e < 10^{18}$ m^{-3}) fills the whole vacuum vessel (eventually stronger near resonance layer)
  - Accelerated charged particles falling on surfaces release adsorbents (physical or chemical processes)
- Can be employed in the presence of the toroidal field
  - Ex: between pulses



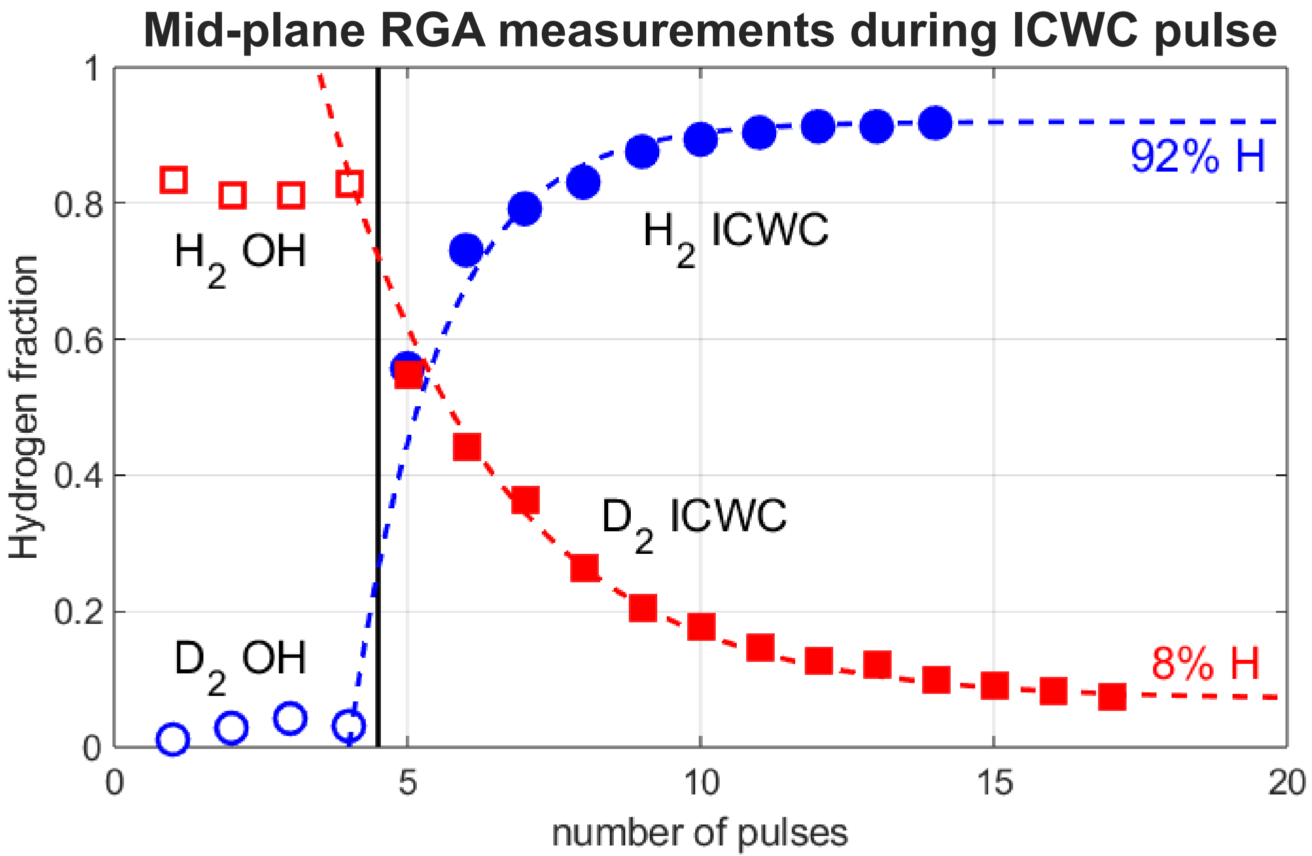
ICWC in WEST

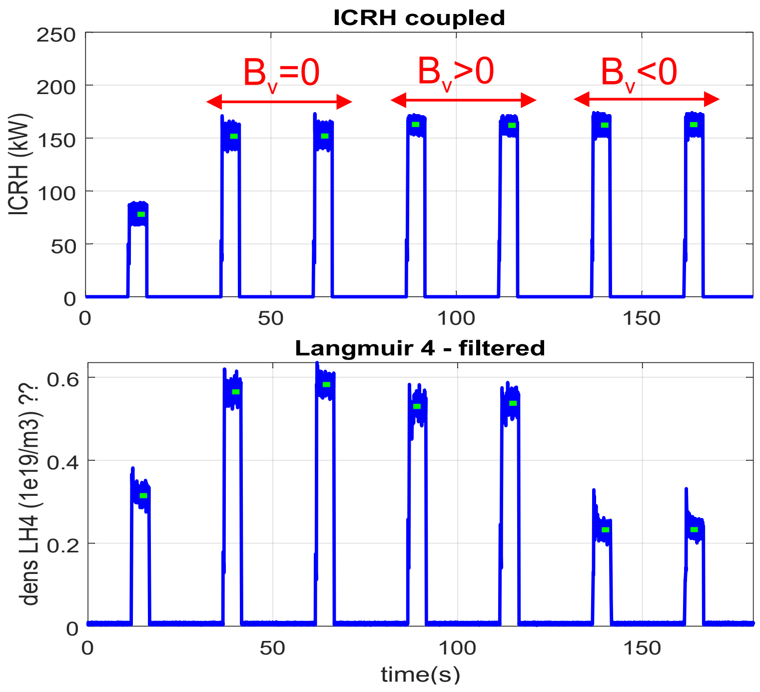
Example: ICWC Missions in ITER

- Remove Low-Z impurities (Ne, N, e.g. after DMS activation)
- Control T-inventory
- After unmitigated disruptions, conditioning pulses might be required to help recovering from PFC degradation

M.K. Paul et al. Fusion Eng. Design 2012
T.Wauters et al., Journal Nucl. Mat. 2015

Example: ICWC wall changeover in WEST





5s ICWC 'slugs' with different vertical fields

- Efficient D_2 → H_2 → D_2 wall changeover with ICWC achieved in WEST (160kW, 2 antennas)
- It takes longer for H_2 → D_2 changeover than for D_2 → H_2 (Is H_2 implanted deeper in the wall?)

E Pawelec et al Plasma Phys. Control. Fusion 2026

[E.Lerche et al., to be published]

RF-assisted boronization

Full-W PFCs face several challenges

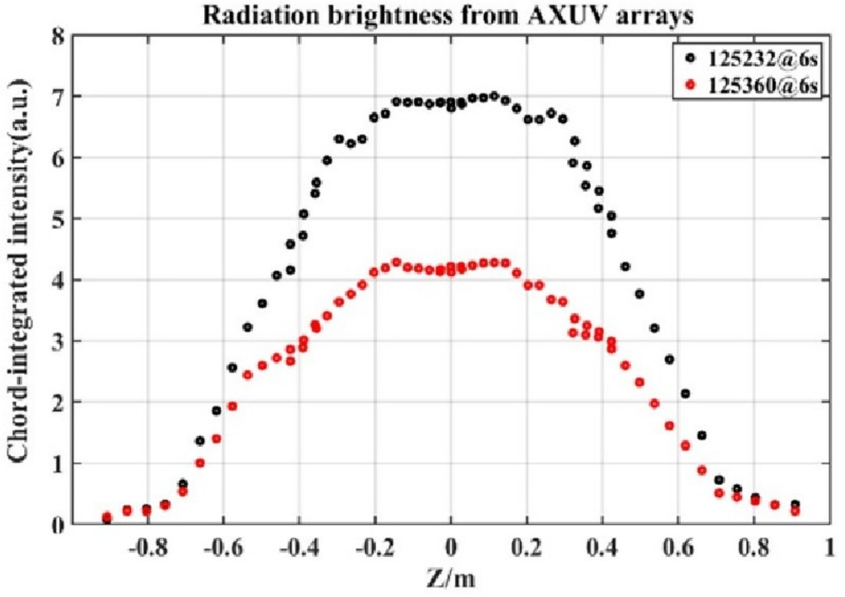
- W melting, cracking and sputtering
- W impurities generate line-radiation by penetrating deeply in plasma, lowering the plasma temperature

Boron is extensively used for wall conditioning to improve plasma performance

- Helps condition PFCs, reduce fuel particle recycling and reduce line-radiation in plasma core
- However, duration of the Boron film on PFC is relatively short (~1000 MJ) and depends of heating methods

Boronization usually made using Glow-Discharge (GDC)

- But not compatible with continuous presence of toroidal magnetic field
  → RF assisted boronization



Evolution of the radiation intensity from the AXUV (impurities radiation) before (#125232) and after (#125360) boronization in EAST [Y.H.Guan]

J.Li et al. Nucl.Fusion 1999
Y. H. Guan et al., Nucl. Fusion 2025

Ion Cyclotron RF Assisted Breakdown

$$\frac{L_c}{\lambda_i} \gg 1 \quad \text{with} \quad \lambda_i = \left(\frac{a}{p}\right) e^{b \frac{p}{E_{\text{loop}}}}$$

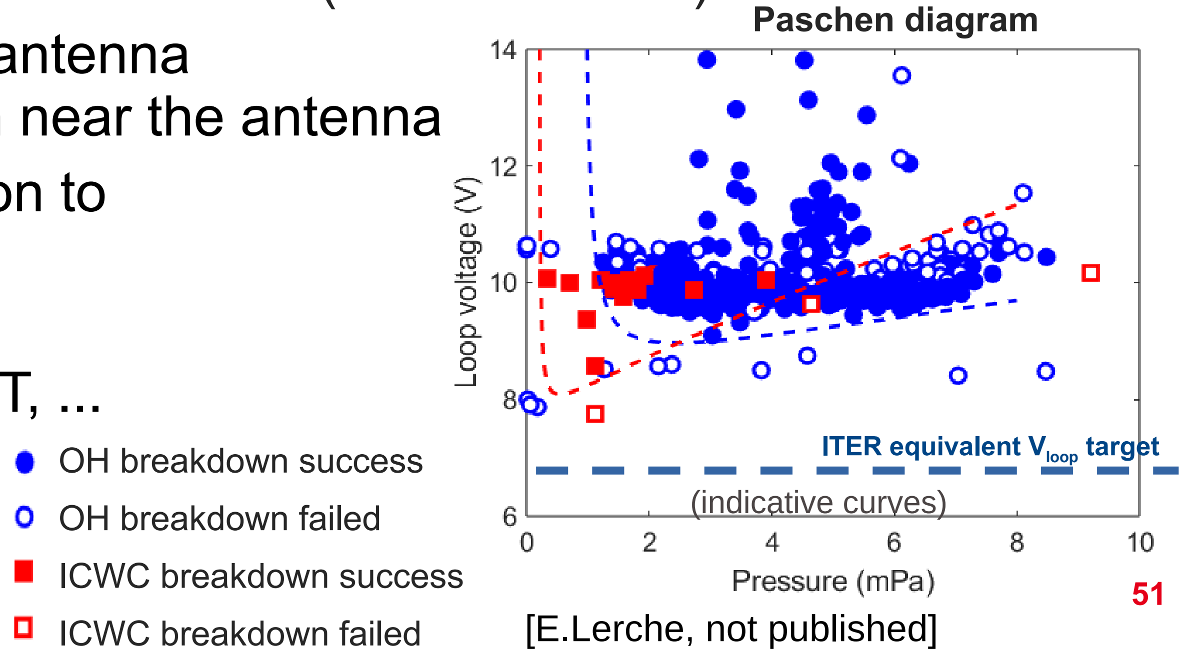
To obtain a successful breakdown

- Townsend avalanche criteria:
  ratio connection length (L_c)/ionization length (λ_i) much larger than 1

In ITER

- Max toroidal electric field E_{loop} will be ~0.33 V/m (1 V/m in JET) → long ionization length
- Challenge for purely Ohmic plasma initiation in ITER (in part. in rich H-background press.)
  - 170 GHz ECH assisted breakdown not effective at 1.8 T (3rd harmonics)
- ICRF-generated toroidal electric field induced antenna initiates working gas breakdown and ionization near the antenna
- ICRF assisted breakdown can expand operation to lower pressure and E_{loop}
  → would reduce risk of failed plasma initiation
- Studies conducted and on-going on JET, WEST, ...

H J Sun et al Plasma Phys. Control. Fusion 2023

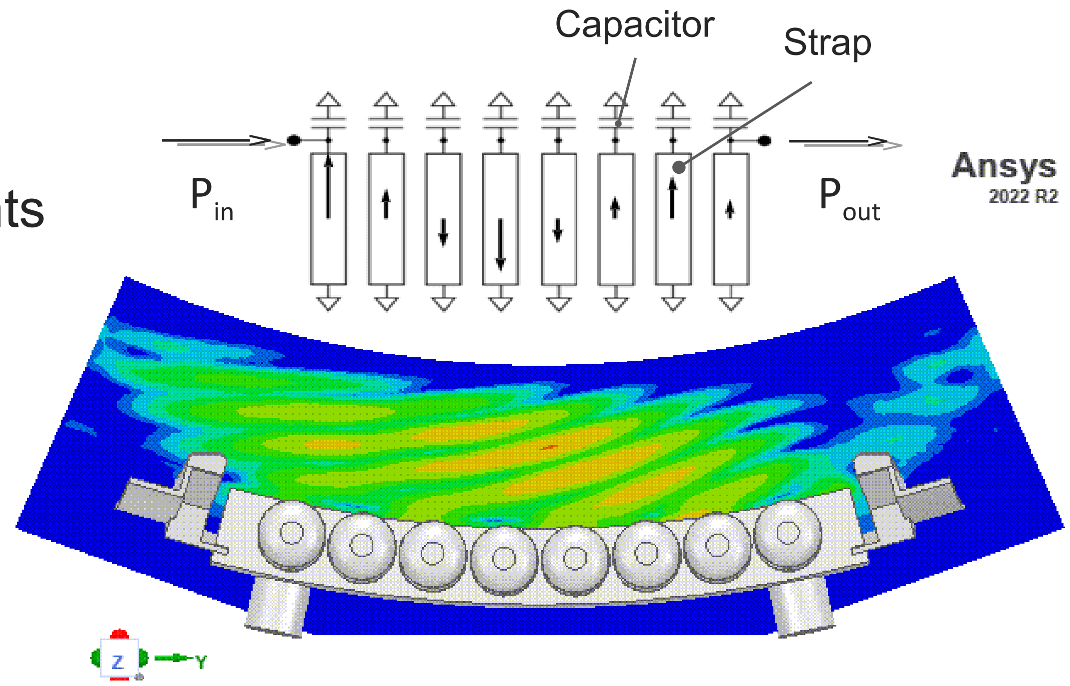


[E.Lerche, not published]

Travelling Wave Array (TWA) launcher for ICRF

An innovative launcher concept for the ICRF

- Array of tuned straps
- RF current is induced by mutual coupling between elements
- No ceramic in the capacitors (parallel-plate like)
- No direct feeding of each element
- Higher coupling
- Higher $k_{//}$ spectrum selectivity
- Reduced Electric field



High-power mock-up successfully tested in 2021 in Vacuum

- 2 MW / 3s, 1.75 MW / 5s and 500 kW / 60s
  - Limited by RF generator only
- No pressure increase during long pulses
- Thermal & electrical responses as expected by modelling

[Chiu 1984 Nucl. Fus. 24]
[Moeller 1994 AIP Conf. Proc 289]
[Ragona 2016 Nucl. Fus. 56]

Ragona 2022 *Nucl. Fus* 62
J.Hillairet et al., EPJ Web of Conferences, 2026

Next step: demonstrating ICRF TWA on WEST plasmas

Expected advantages of TWA launchers in a W-environment

- Increased RF coupling ($k_{//}$ spectrum narrower and of lower value)
  → Plasma can be located further away from the launchers
- Lower electric field
  → Reduced RF sheaths and lower risk of arcs
- Enhanced directivity
  → Reduced parasitic coaxial mode excitation (reduced parasitic uncoupled power/far sheaths)
- Provides operational simplicity (no tuning elements in vacuum)
  → Load-resilient launchers, low reflected power to RF sources
- Fusion power plant compatibility
  → Materials (stainless-steel), reliability, efficiency, reduced radial volume
- Large bandwidth launchers: allows to change RF frequency (power deposition) in real-time
  → Open new operational scenarios!

Reduced impurity production

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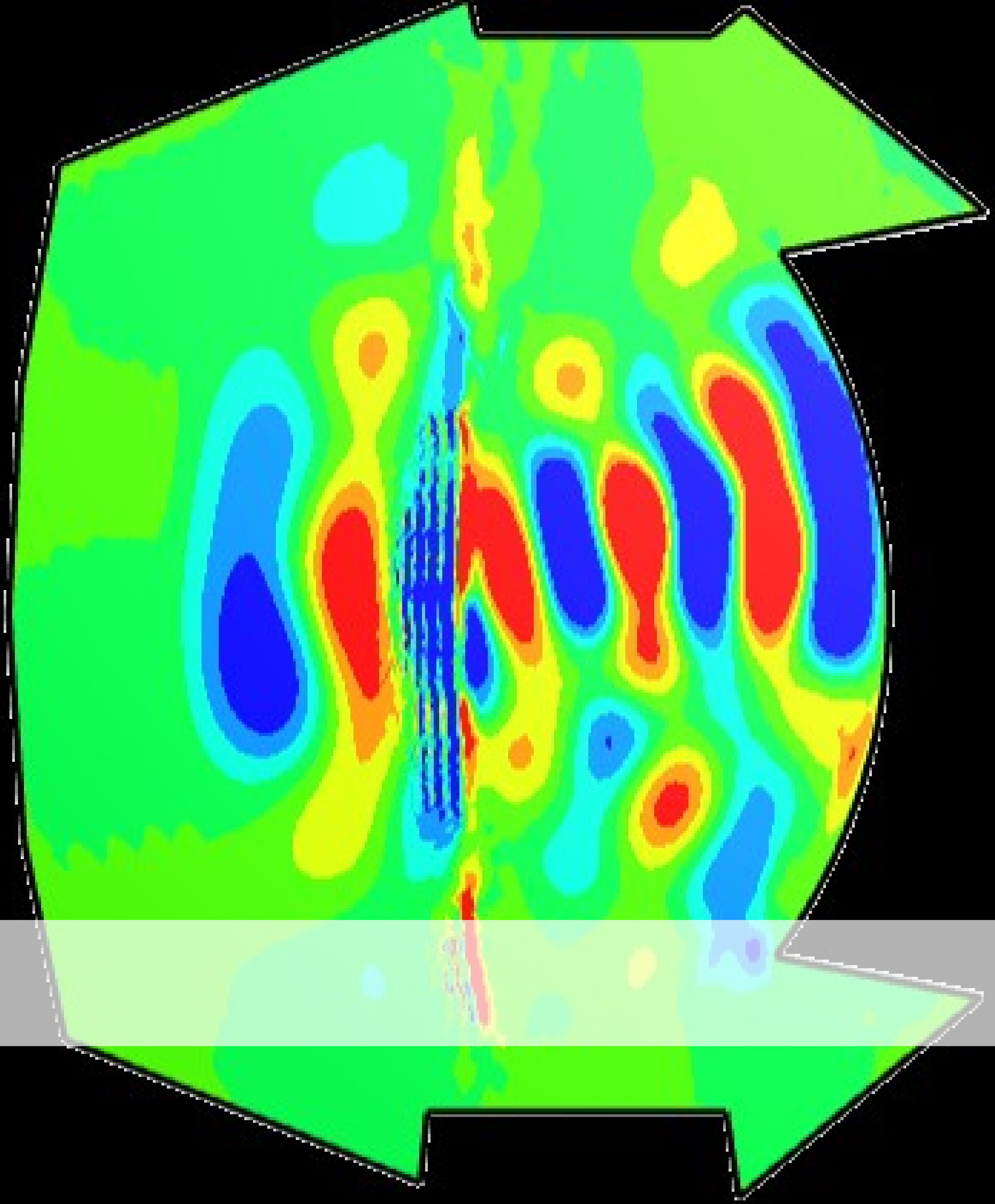

Summary

Minority heating modelling in WEST [V.Maquet]

Ion Cyclotron Range of Frequency - Summary

A successful and proven plasma heating method

- RadioFrequency heating method in range of ~10-120 MHz
- Only method which heats directly ions in future fusion plants
  - Robust and tested heating schemes
  - Recent 3-ions heating schemes can have higher critical energy (more power to ions)
- Can also used for other applications: wall conditioning, startup assistance, etc.

J Ongena et al 2017 Plasma Phys. Control. Fusion 59 054002

Challenges and future work for fusion plants

- Coupling the RF Power into the plasma
  - Wave is evanescent in the low density and temperature scrape-off layer (SOL)
  - Must tunnel through this region before it starts propagating inside the plasma

T.H.Stix, Nuclear Fusion 1975
A Messiaen and R Weynants, Plasma Phys. Control. Fusion 2011

- RF Sheaths Rectification can produce heavy impurities in the plasma
  - Responsible for enhanced impurity generation and antenna heat loads
  - Can be minimized with careful antenna design and increased distance to the plasma

L. Colas et al Nucl. Fusion 2022
R. Diab et al Nucl. Fusion 2025

Additional References

Books

- Fundamentals of Magnetic Fusion Technology, IAEA, https://www.iaea.org/publications/14898/fundamentals-of-magnetic-fusion-technology (free)
- Fusion Physics, IAEA https://www.iaea.org/publications/8879/fusion-physics (free)
- J Freidberg, *Plasma Physics and Fusion Energy*, Cambridge University Press (2007), *Chapter 15: Heating and current drive*
- J Wesson, *Tokamaks* (third edition), Clarendon Press (2004), Chapter 5
- T. Stix, Waves in Plasmas, 1992
- M. Brambilla, Kinetic Theory of Plasma Waves, 1998
- D. Swanson, Plasma Waves. 2003

ITER physics

- *The new ITER baseline, research plan and open R&D issues, Plasma Phys. Control. Fusion 67 (2025) 065023*
- *Progress in the ITER physics basis*, Nucl. Fusion **47**, No. 6 (2007) S285, *Chapter 6: Steady state operation*
- *ITER physics basis*, Nucl. Fusion **39**, No. 12 (1999) 2495, *Chapter 6: Plasma auxiliary heating and current drive*

Join the ICRF Network!

WEST ICRF launcher, energized inside a vacuum test bed (CEA/IRFM) cea irfm

Join the ICRF Network!