Variational description of low frequency waves in magnetically confined plasmas

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Outline

▶ Low frequency waves in magnetic fusion devices
  ▶ Plasma heating by ICRF waves
  ▶ MHD (Alfvén) waves
  ▶ Modelling aspects

▶ Global modelling of low frequency waves
  ▶ Wave-field calculation
  ▶ Plasma kinetic response description
  ▶ Towards a self-consistent treatment
  ▶ Variational approach

▶ The EVE-3D code
  ▶ Setup and numerical implementation
  ▶ Benchmarks
  ▶ Applications

▶ Conclusions and prospects
**Advanced scenarios require electromagnetic waves excited by external antennas**
- Ion and/or electron heating
- Non inductive current drive
- Rotation, flow drive (reduction/suppression of turbulence)
- Alpha-channelling

**Three base ingredients of modelling**
- Calculation of electromagnetic field: wave code
- Description of plasma response to the RF power: kinetic code
- Antenna / edge plasma interaction: antenna code

**Room for improvement in each of these subtopics**
**Needs to work towards self-consistent loop**
Plasma heating by ICRF waves

- **ICRH** (= Ion Cyclotron Resonance Heating)
- **General principle:**

  - A (fast magnetosonic) wave is excited on the Low Field Side of the tokamak
  - Its frequency is in the range $\omega \sim \Omega_{ci}$ ($f \approx 50$MHz)
  - Resonance relation: $\omega = p\Omega_{ci} + k_{||}v_{||}$, $p$ integer
  - In most scenarios, it is used for ion heating
  - Creation of superthermal populations (fast ions)
ICRF: Ion Cyclotron Range of Frequency ($f \sim 30 - 80$ MHz)

- Fast Wave + Cycl. Res.
  - Fundamental absor.
  - Harmonic absorption

- Fast Wave
  - ELD
  - TTMP

- Ion Bernstein Wave
  - ELD

E < $E_c$
Thermal ions

E > $E_c$
Superthermal ions

Thermal electrons

Ion heating

Electron heating
MHD waves

- Magnetically confined plasmas feature Alfvén waves (compressional / shear)
- Toroidal effects result in a coupling of these waves
- Within the frequency gaps lie global, regular, modes: **Alfvén Eigenmodes (AE)**
- These modes may be destabilized by fast ions (fusion born alphas / fast ICRF ions)

**Alfvén eigenmodes are crucial to ITER operation and performance**
MHD / Kinetic simulation of LF waves

Kinetic (Vlasov) equation

Fluid moments
- Fluid (MHD) equations (Linear / Non linear)
  - Extension to hybrid kinetic-MHD models
    - CASTOR-K, HMGC

Simplified Lagrangian
- Gyrokinetic theory (Linear / Non linear)
  - Gyrokinetic MHD
    - LIGKA

Linearization
- Dielectric tensor / Particle Lagrangian
  - Full-Wave codes
    - TORIC, EVE
Low frequency RF waves modelling: a summary

- Low frequency waves in fusion plasmas
  - Alfvén eigenmodes
  - ICRF waves

- Three basic components of RF waves modelling

- Modelling of ICRF waves propagation and absorption in ongoing and future experiments should include
  - 2D / 3D effects
  - Non-thermal particle distributions
  - Finite orbit effects
Global modelling of LF waves

- **Wave excitation**
  - Current flowing in the antenna structure (frequency $\omega$)
  - Excitation of a fast magnetosonic wave (evanescent in vacuum)
  - Coupling is determined by the radiative resistance
    \[ P_{icrf} = R_{rad} l_{ant}^2 / 2 \]

- **Propagation**
  - Driven oscillation at frequency $\omega$
  - Space / time dispersion
  - Global electromagnetic field

- **Plasma response**
  - Modification of distribution functions
  - Collisional effects
Linear calculation of wave-field

- Wave equation
  - System driven at frequency \( \omega \):
    \[
    \nabla \times \nabla \times \mathbf{E} - \frac{\omega^2}{c^2} \left( \mathbf{E} + \frac{i}{\omega \epsilon_0} \mathbf{j} \right) = i \omega \mu_0 \mathbf{j}_{\text{ant}}
    \]
  - Non-local response:
    \[
    \mathbf{j}(r, t) = \sum_s \int d^3 \mathbf{r}' \int_{-\infty}^{t} dt' \mathbf{\overline{\sigma}}_s(r, \mathbf{r}', t, t', f_{s0}) \cdot \mathbf{E}(\mathbf{r}', t')
    \]
    \[
    \text{Conductivity kernel}
    \]
- Linear conductivity kernel: \( \mathbf{\overline{\sigma}}_s \propto \delta f_s \)
  - Anisotropy
  - Time dispersion
  - Space dispersion
- Vlasov equation (collisionless)
  \[
  \frac{df_s}{dt} \equiv \frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \frac{\partial f_s}{\partial \mathbf{r}} + \frac{q_s}{m_s} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f_s}{\partial \mathbf{v}} = 0.
  \]
Unperturbed orbits

Linear response (formal solution of Vlasov equation)

\[ \delta f_s = -\frac{q_s}{m_s} \int_{-\infty}^{t} dt' \left[ \delta E(r', t) + \mathbf{v}' \times \delta \mathbf{B}(r', t) \right] \cdot \frac{\partial f_{s,0}}{\partial \mathbf{v}'} \cdot \partial f_{s,0}. \]

Characteristics of Vlasov equation

\[ \frac{dr'}{dt'} = \mathbf{v}', \quad \frac{d\mathbf{v}'}{dt'} = \frac{q_s}{m_s} (\mathbf{E}_0(r', t) + \mathbf{v}' \times \mathbf{B}_0(r', t)). \]

Unperturbed orbits

\[ \mathbf{r} = r_g(\mu, H, P_\phi) + r_c(\mu, H, P_\phi, \phi_c) \]
Fast ion orbits

Trajectory (guiding center) of a trapped ion

- Banana width:
  \[ \Delta_b \sim \frac{v_{||0}}{\omega_b} \]

- Confinement is determined by
  \[ \Delta_b / a_0 \]

- Orbit effects crucial when
  \[ \Delta_b \sim r \]

- Ex: \( \alpha \) particle, \( E = 3.5 \text{MeV} \)
  - JET: \( 2\Delta_b / a_0 \sim 0.8 \)
  - ITER: \( 2\Delta_b / a_0 \sim 0.2 \)
Wave-field calculation in a nutshell

Equilibrium fields $\mathbf{B}_0, \mathbf{E}_0$

Unperturbed orbits

Perturbed distribution function

Perturbed current $\delta \mathbf{j}$

Dielectric tensor $\varepsilon$

Wave-field $\delta \mathbf{B}, \delta \mathbf{E}$
Plasma kinetic response

- **Kinetic equation** for $f_s$:

  $$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \frac{\partial f_s}{\partial \mathbf{r}} + \frac{q_s}{m_s} (\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \frac{\partial f_s}{\partial \mathbf{v}} = \left( \frac{\partial f_s}{\partial t} \right)_{\text{coll}}$$

- **Linearization**: $f_s(\mathbf{r}, \mathbf{v}, t) \equiv f_{s,0}(\mathbf{r}, \mathbf{v}) + \delta f_s(\mathbf{r}, \mathbf{v}, t)$

- **Linear treatment** (wave-field calculation):
  - $f_{s,0}$ stationary
  - Collisions are neglected

- **Quasilinear treatment** (kinetic response calculation):
  - $f_{s,0}$ varies slowly compared to $2\pi/\omega$ (secular effects)

  $$\langle \delta f_s(t) \rangle = 0 \quad \rightarrow \quad \langle f_s(t) \rangle = f_{s,0}(t)$$

  where $\langle \cdot \rangle$ means averaging over fast time scale
  - Collisions need to be included
Averaged kinetic equation

\[ \left\langle \frac{df_s}{dt} \right\rangle = \frac{df_{s,0}}{dt} \equiv \frac{\partial f_{s,0}}{\partial t} + v \cdot \frac{\partial f_{s,0}}{\partial r} + \frac{q_s}{m_s} (E_0 + v \times B_0) \cdot \frac{\partial f_{s,0}}{\partial v} = \hat{C}(f_{s,0}) + \hat{Q}(f_{s,0}) \]

\[ \hat{C}(f_{s,0}) : \text{Collision operator (Fokker-Planck)} \]

\[ \hat{Q}(f_{s,0}) : \text{Quasilinear operator} \]

\[ \hat{Q}(f_{s,0}) = - \frac{q_s}{m_s} \left\langle (\delta E + v \times \delta B) \cdot \frac{\partial \delta f_s}{\partial v} \right\rangle. \]
RF waves have a strong impact on the fast ion orbits.

The unperturbed trajectories are modified.
Kinetic response calculation in a nutshell

Wave-field
- Intrinsic chaos
  - Wave
  - QL diff. coefficient

Collisions
- Extrinsic chaos
  - Collisional
  - QL diff. coefficient

F.P. Equation

Distribution function $f_{s,0}$

Heating
- Current Drive
- Instabilities
Waves in a plasma: the whole story (almost)

Challenges:

1. Unperturbed orbits
2. Consistency of wave and kinetic calculations
3. Phase decorrelation processes
Waves in a plasma: the whole story (almost)

- Challenges:
  1. Unperturbed orbits
  2. Consistency of wave and kinetic calculations
  3. Phase decorrelation processes
Wave-field calculation: variational approach

- Electrical current / charge conservation

\[
\begin{aligned}
j_{\text{ant}} + j_{\text{part}} &= \frac{1}{\mu_0} \nabla \times \nabla \times A + \varepsilon_0 \partial_t (\partial_t A + \nabla \varphi) \equiv j_{\text{maxw}}, \\
\rho_{\text{ant}} + \rho_{\text{part}} &= -\varepsilon_0 \nabla \cdot (\partial_t A + \nabla \varphi) \equiv \rho_{\text{maxw}}
\end{aligned}
\]

- Three gauge-invariant functionals
  - Antenna functional
    \[
    \mathcal{L}_{\text{ant}} \equiv \mu_0 \int d^3r \left\{ j_{\text{ant}} \cdot A^* - \rho_{\text{ant}} \varphi^* \right\}
    \]
  - Maxwellian functional
    \[
    \mathcal{L}_{\text{maxw}} \equiv \mu_0 \int d^3r \left\{ j_{\text{maxw}}(A, \varphi) \cdot A^* - \rho_{\text{maxw}}(A, \varphi) \varphi^* \right\}
    \]
  - Plasma functional
    \[
    \mathcal{L}_{\text{part}} \equiv \mu_0 \int d^3r \left\{ j_{\text{part}}(A, \varphi) \cdot A^* - \rho_{\text{part}}(A, \varphi) \varphi^* \right\}
    \]
Wave-field calculation

- Variational statement \(\equiv\) extremalization of

\[
\mathcal{L}_{\text{part}}(\mathbf{A}, \varphi, \mathbf{A}^*, \varphi^*) + \mathcal{L}_{\text{maxw}}(\mathbf{A}, \varphi, \mathbf{A}^*, \varphi^*) + \mathcal{L}_{\text{ant}}(\mathbf{A}^*, \varphi^*)
\]

- Decomposition of electromagnetic potential: \((\mathbf{A}, \varphi) \equiv \sum_i \alpha_i (\mathbf{a}_i, \phi_i)\)

- Decomposition of functionals:

\[
\mathcal{L}(\mathbf{A}, \varphi, \mathbf{A}^*, \varphi^*) \equiv \mathcal{L}_{\text{part}} + \mathcal{L}_{\text{maxw}} = \sum_{ij} L_{ij} \alpha_i \alpha_j^*, \quad \mathcal{L}_{\text{ant}}(\mathbf{A}^*, \varphi^*) = \sum_j K_j \alpha_j^*,
\]

with

\[
L_{ij} \equiv \mathcal{L}(\mathbf{a}_i, \phi_i, \mathbf{a}_j^*, \phi_j^*), \quad K_j \equiv \mathcal{L}_{\text{ant}}(\mathbf{a}_j^*, \phi_j^*)
\]

- Electromagnetic field calculation

\[
\delta \left\{ \left[ (L_{ij,\text{part}} + L_{ij,\text{maxw}}) \alpha_i + K_j \right] \alpha_j^* \right\} = 0
\]

\[
\frac{\delta \alpha_j^*}{\delta \alpha_i^*} \rightarrow (\mathbf{A}, \varphi) \text{ is obtained by solving } (L_{ij,\text{part}} + L_{ij,\text{maxw}}) \alpha_i = -K_j.
\]
Energy balance and functionals

- Global energy balance
  - Power coupled by the antenna
    \[
    \dot{W}_{\text{ant}} \equiv \left\langle \int d^3 \mathbf{r} \mathbf{E} \cdot \mathbf{j}_{\text{ant}} \right\rangle = \frac{\omega}{2\mu_0} \Im(\mathcal{L}_{\text{ant}})
    \]
  - Power transferred to plasma species
    \[
    \dot{W}_{\text{part}} \equiv \left\langle \int d^3 \mathbf{r} \mathbf{E} \cdot \mathbf{j}_{\text{part}} \right\rangle = \frac{\omega}{2\mu_0} \Im(\mathcal{L}_{\text{part}})
    \]
  - Maxwellian functional
    \[
    \mathcal{L}_{\text{maxw}} = -2\mu_0 \int d^3 \mathbf{r} \left( \frac{\epsilon_0 |\mathbf{E}|^2}{2} - \frac{|\mathbf{B}|^2}{2\mu_0} \right)
    \]
    is a real quantity,
    \[
    \dot{W}_{\text{ant}} + \dot{W}_{\text{part}} = \frac{\omega}{2\mu_0} \Im(\mathcal{L}_{\text{ant}} + \mathcal{L}_{\text{part}}) = 0
    \]

- Local energy balance (Poynting theorem)
  \[
  -i\omega \mathcal{W}_{\text{field}} + \mathcal{S}_{\text{poynting}} - \dot{W}_{\text{ant}} - \dot{W}_{\text{part}} = \frac{i\omega}{2\mu_0} \{ \mathcal{L}_{\text{maxw}}(s) + \mathcal{L}_{\text{ant}}(s) + \mathcal{L}_{\text{part}}(s) \} 
  \]
Integration with kinetic calculation

▶ Wave calculation
  ▶ Variational approach

\[ \sum_s \mathcal{L}_{part,s} + \mathcal{L}_{Maxw.} + \mathcal{L}_{ant} = 0, \]

▶ Resonant plasma functional

\[ \mathcal{L}^{(res)}_{part,s} = \mu_0 \sum_{N_1=p,N_2,N_3=N} (2\pi)^3 \int d^3J \frac{\omega}{\omega - N_i \Omega_i} \frac{\partial f_{s,0}}{\partial J_i} |\delta h_{p,N_2,N}|^2 \]

▶ Kinetic response calculation
  ▶ Fokker-Planck equation

\[ \frac{\partial f_{s,0}}{\partial t} = \hat{C} f_{s,0} + \frac{\partial}{\partial J_i} D^{(QL)}_{ij} \frac{\partial f_{s,0}}{\partial J_j} \]

▶ Wave quasilinear diffusion coefficient

\[ D^{(QL)}_{ij} = 2\pi \sum_{N_1=p,N_2,N_3=N} N_i N_j |\delta h_{p,N_2,N}|^2 \delta(\omega - N_i \Omega_i) \]
The **EVE** code

- **Physics features**
  - Wave equation formulated in terms of potentials
  - 2nd order Larmor radius code + Order Reduction Algorithm
  - Resolution of 2 ($E_\parallel = 0$) or 4 variables ($E_\parallel \neq 0$)
  - Uses quasi-local plasma functional

- **Numerical features**
  - 3D version functional (no coupling of toroidal modes)
  - Radial direction: finite elements (cubic + quadratic)
  - Fourier expansion in the toroidal and poloidal directions
  - Uses code generator for some parts
  - Core in Fortran 90 - Post-processing in Python

- **Objectives**
  - Main element of a wave + kinetic package
  - ICRF module for integrated modelling
  - Detailed physics studies of wave-particle interactions
Geometric setup

- Vacuum chamber
  - Perfect conductor
  - Arbitrary shape
  - $\psi = \text{const. surface}$

- Antenna
  - Must coincide with a virtual flux surface
  - Current flowing in 3 directions
  - No feedback of the plasma

- Plasma
  - Cold / hot (FLR 2$^{nd}$) / hot (ORA) plasma
  - Analytical / numerical (HELENA) equilibrium
  - Analytical / numerical profiles
Numerical implementation

- Spectral decomposition of state vector for periodic directions

\[ u_k(s, \theta, \phi) \equiv \sum_{mn} u_{k,mn}(s) e^{i(m \theta + n \phi)} \]

- Finite elements in radial direction

\[ u_{k,mn}(s) \equiv \sum_{jp} \alpha_{j,mn}^{k,p} h_p(s - s_j) \]

2\textsuperscript{nd} order FLR kinetic equations only involve $\partial_s u$ and $\partial_{ss}^2 u$

$\rightarrow (h_p)$ are quadratic / cubic Hermite finite elements
Variational principle yields directly Garlekin weak form

\[ \mathcal{L}_{\text{part}} + \mathcal{L}_{\text{Maxw.}} = \mu_0 \int d^3r \left\{ J(A, \varphi) \cdot A^* - \rho(A, \varphi) \varphi^* \right\} \]

\[ = \mu_0 \int ds d\theta d\phi J L_{\text{eq}}^{k\bar{k}} \times u_k u_k^* \]

\[ = \mu_0 \delta_{n,\bar{n}} \int ds \left\{ J L_{\text{eq}}^{k\bar{k}} \right\} m - m h_{pj} h_{\bar{p}j} \times \alpha_{jmn}^{kp} (\alpha_{jmn}^{k\bar{p}})^* \]

Provide stiffness matrix elements

Toroidal modes (n) are decoupled (in axisymmetric devices)

Poloidal modes (m) are coupled by equilibrium geometry and wave/particle interaction
Numerical implementation (3)

- **Antenna functional**

\[
\mathcal{L}_{ant} = \mu_0 \int d^3 r \{ j_{ant} \cdot A^* - \rho_{ant} \psi^* \}
\]

\[
= \mu_0 \int ds d\theta d\phi J_{ant}^k \bar{k} \times u_k^*
\]

\[
= \mu_0 \int ds \{ J_{ant}^k \bar{k} \} \bar{m},\bar{n} h_{\bar{p}j} \times (\alpha_{j m \bar{n}}^k \bar{p})^*
\]

- Provides source vector (RHS)
- Antenna current is decomposed in toroidal harmonics:

\[
j_{ant} = \sum_n j_{ant,n} e^{in\phi}
\]

- Separate computation for each \( n \)
- 3D solution is constructed afterwards
Numerical implementation (4)

- Electromagnetic field calculation
  - Linear system solution (block matrix)

\[
x = \begin{bmatrix}
  1 \\
  2 \\
  3 \\
  4 \\
  5 \end{bmatrix}
\]

- Matrix elements calculation:
  - Fast Fourier Transforms (FFTW)
  - Radial integrals (Gauss quadrature)

- Code is partially generated by symbolic manipulation software
- Boundary conditions and unicity directly applied to stiffness matrix
- Parallel matrix inversion (ScalAPACK)
Benchmarks in reference cases

K. Appert and J. Vaclavick


- Homogeneous plasma column
  - Hydrogen plasma
  - $n_e = 0.52 \times 10^{19} \text{m}^{-3}$
  - $B_0 = 1 \text{T}$
  - No eq. plasma current

- Linearized MHD model

\[
\begin{aligned}
\rho \partial_t \delta \mathbf{v} &= \delta \mathbf{j} \times \mathbf{B}_0 \\
\delta \mathbf{E} + \delta \mathbf{v} \times \mathbf{B}_0 &= m_i (\delta \mathbf{j} \times \mathbf{B}_0)/(e\rho) \\
\nabla \times \delta \mathbf{B} &= \mu_0 \delta \mathbf{j} \\
\nabla \times \delta \mathbf{E} &= -\partial_t \delta \mathbf{B}
\end{aligned}
\]

- Perturbed quantities $\propto \exp(i(k_z z + m\theta - \omega t))$
  \[\rightarrow\] Dispersion relation $\mathcal{D}_{m, a_p, a_v}(\omega/\omega_{ci}, k_z) = 0$
EVE benchmarks: MHD waves

- **Alfvén frequencies**: $\omega < \omega_{cH}$
  - Divergence free helix antenna
    - Single poloidal mode ($m = -1$)
    - $k_\parallel = 15m^{-1}$

Peaks in the antenna loading are obtained at the Alfvén wave eigenfrequencies
EVE benchmarks: MHD waves

- Fast wave frequencies: $\omega > \omega_{cH}$
  - Divergence free helix antenna
    - Single poloidal mode ($m = -1$)
    - $k_\parallel = 15 \text{m}^{-1}$

Peaks in the antenna loading are obtained at the fast magnetosonic wave eigenfrequencies
Example: minority heating in JET

- **D(H) minority heating scenario**
  - $R_0 = 3\text{m}$, $a_0 = 0.8\text{m}$, $B_0 = 3.1\text{T}$
  - $n_{e0} = 5 \times 10^{19}\text{m}^{-3}$
  - $n_{H,b}/n_e = 4.75\%$, $n_{H,f}/n_e = 0.25\%$
  - $T_{e0} = T_{D0} = T_{H,b0} = 5\text{keV}$, $T_{H,f0} = 10\text{keV}$

- **Strap antenna**
  - $f_{FW} = 46\text{MHz}$
  - $N_{tor} = 15$, $k_{||,ant} \approx 4\text{m}^{-1}$
  - Current perp. to $B_0$

- **Computation grid**
  - $N_s = 250 + 50$, $N_\theta = 128$
  - 49 poloidal modes
  - 1 toroidal mode

\( \Re(E_-) \) contours
**Ion Bernstein wave:**
- excited by mode conversion
- small wavelength
- damps on thermal electrons
- backward wave

**Fast Magnetosonic wave:**
- direct excitation by the antenna
- large wavelength
- damps on ions / electrons
- forward wave
Artificial IBW damping

Electric field (equatorial plane)

- Real part
- Imaginary part

Artificial damping of the IBW

- Eases the convergence
- Does not affect the power split (for these parameters)
He-3 mode conversion heating

- He-3 minority heating
  - $R_0 = 2.96\,\text{m}$, $a_0 = 0.9\,\text{m}$, $B_0 = 3.6\,\text{T}$
  - $n_{e0} = 3.5 \times 10^{19}\,\text{m}^{-3}$
  - Helium-3 in Deuterium
  - $n_{He-3}/n_e$ between 2% to 30%
  - $T_{e0} = T_{D0} = T_{H, b0} = 5\,\text{keV}$

- Strap antenna
  - $f_{FW} = 37\,\text{MHz}$
  - $N_{tor} = 26$ (dipole phasing)
He-3 mode conversion heating

4% Helium-3

20% Helium-3

IBW on the HFS, damped by ELD
He-3 mode conversion heating

**Antenna loading**

- **Loading resistance [Ω]**
  - Plot showing the loading resistance as a function of $n_{\text{He-3}}/n_e$.

- **Electron power deposition**
  - **Single-pass absorption [%]**
  - Plot showing the single-pass absorption for different $n_{\text{He-3}}/n_e$.

**Power / species**

- **Electrons**
- **Deuterium**
- **Helium-3**
  - Plot comparing power deposition across species.

Increasing $\text{He}_3$ concentration:
- Minority $\rightarrow$ electron heating
- Poorer absorption for $n_{\text{He-3}}/n_e \gtrsim 15\%$
Fast wave
▶ “Cold”-like propagation
▶ Same branch as the compressional Alfvén wave

Fast Wave Electron Heating
▶ Electron absorption by ELD + TTMP
▶ Damping is highly sensitive to $\beta_e$

FWEH scenario in JET
▶ 50% Hydrogen - 50% Deuterium
▶ $B_0 = 1.34\,\text{T}, \, n_{e0} = 2.5 \times 10^{19}\,\text{m}^{-3}$
▶ Wave frequency: $f_{FW} = 48\,\text{MHz}$
▶ Parallel wavenumber:
  $k_{||,\text{ant}} \approx 8\,\text{m}^{-1}$
▶ H-2 cyclotron layer on the HFS
**Power deposition profiles**

- **Electrons**
  - $T_H(0) = 4\text{keV}$
  - $T_H(0) = 30\text{keV}$

- **Hydrogen**

**Power split / species**

- **Electrons**
- **Hydrogen**

- **Electron vs ion damping**
  - Increase of ion damping with $T_{\perp,H}$
  - Bootstrapping process
  - Self-consistent wave + kinetic simulation required
ICRF antennas are comprised of metallic straps

Tore Supra: 2 straps / antenna
ITER: 4 straps / antenna

Oscillating current flowing in straps with relative phase shifts

\[ I_0 \propto \exp\left(i(kz_0 - \omega t)\right) \]
\[ I_1 \propto \exp\left(i(k(z_0 + \Delta z) - \omega t + \varphi_1)\right) \]

Antenna current is decomposed in toroidal harmonics

\[ j_{ant}(\phi) = \sum_n j_{ant,n} e^{in\phi} \]
3D effects: antenna phasing

Adjustable phase shifts yield flexible antenna phasing
3D reconstruction: dipole phasing
Antenna spectrum effects

Antenna phasing determines the 3D field structure
Magnetic fusion plasmas feature low frequency electromagnetic waves
- ICRF waves are used for plasma heating / current drive
- Alfvén eigenmodes develop and impact plasma performance

A variational approach is adapted to simulate the wave-field and plasma kinetic response self-consistently

EVE-3D is a full-wave code built on a Hamiltonian formalism
- Describes ICRF scenarios and linear MHD waves
- Extensively benchmarked vs analytical models and other codes

Ongoing and foreseen developments include
- Full integration to ITM framework
- Kinetic response module (based on the same formalism)
- Coupling of toroidal modes (non-axisymmetric plasmas)