Mode-converted Electron Bernstein Waves

Francesco Volpe
currently at Dept of Applied Physics and Applied Mathematics
Columbia University, New York

Presentation prepared while at Engineering Physics Dept
University of Wisconsin, Madison
Motivation: “Someone likes it hot” and overdense
Principle of EBWs and Mode Conversions

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Summary & Conclusions
Motivation for Electron Bernstein Waves

Several MCF plasmas are too dense or have too low magnetic field for conventional Electron Cyclotron Resonant Heating (ECRH)

EBWs do not suffer from upper density limits
Electron Bernstein waves

Unmagn. plasma: plasma waves

planes of constant $n_e$

$\lambda < \lambda_D$

$\omega > \omega_p$

Magn. plasma: electrostat. EC waves, better known as EBWs

$\lambda \approx \rho$

$\omega > \omega_c$

electromag. EC waves: X-mode

O-mode
Marine waves are another example of gyrophase organization.
OXB-Scheme: special view makes modes degenerate and not evanescent

In the real space

\[ \sin^2 \phi = N_{z, \text{opt}}^2 = Y/(Y+1), \quad Y = \omega c / \omega \]

In the phase space

\[ N_{z}^2 / N_{z, \text{opt}}^2 = 1.2, 1.0, 0.8 \]
OXB-Scheme: O-X conversion

Merging of O and SX waves when their cutoffs overlap:

Angular width

FWHM = 7 ± 16 deg

Airy

even

odd
SX-B mode conversion

Finite Larmor radius $\rightarrow$

6th order correction to Booker quartic $\rightarrow$

Deflection from UHR and

Propagation at $X>1$ (overdense), until

Cyclotron damping

Conversion efficiency can be limited by:
- Collisional damping (if edge cold)
- Back-tunneling SX-FX (if barrier thin)
- Parametric decay (at high power)
FX-(SX)-B “Conversion” is a Tunnel Effect

$\theta = 32.6^\circ - \alpha = 69.8^\circ$

Unlike OXB, evanescent layer always has finite thickness.
Mode conversions are ubiquitous wave phenomena at medium interfaces. Example: seismic waves
Mode conversions are ubiquitous wave phenomena at medium interfaces. Example: seismic waves.
EBW Emission, Heating & CD in the W7-AS Stellarator

(with H.P. Laqua)
**Antenna**

- Max Transmission
- Min Doppler effects
- Pure O-mode detection

Diagram:
- corrugated horn
- plane mirror
- cyl. waveguide
- uptaper
- ellipsoidal mirror
- plasma
Oblique view → elliptic polarization → phase-shifter needed

λ/4 phase shifter

polarization rotator
Broadband phase shifter

Requirements:
Phase shift $\phi = 90^0 \pm 8^0$ (±2% intensity)
Frequency band $f = 66$-$78$GHz
Test quasi-optical components

Antenna

Polarizer

\[\phi_{\text{rot}} \text{ scan for fixed } \phi_{\text{ell}}\]

\[\phi_{\text{ell}} \text{ scan for fixed } \phi_{\text{rot}} - 2 \phi_{\text{rot}}\]
Heterodyne radiometer

24 channel ECE heterodyne radiometer, f=63-78GHz + 16 channel „Zoom“ Δf=4GHz, f_{LO} adjustable + 8 new fixed channels

After several amplifiers and Power-splitters...

Independent acquisition for 70 and 140GHz radiometer
Overlap: ECE (X2) n_e<1.2 \cdot 10^{20} \text{ m}^{-3} 
EBE (B1) n_e> 6 \cdot 10^{19} \text{ m}^{-3}
Ray tracing

5th order Runge-Kutta

\[
\frac{dx}{d\tau} = -\frac{\partial D/\partial N}{\omega \partial D/\partial \omega} \quad \frac{dN}{d\tau} = \frac{\partial D/\partial x}{\omega \partial D/\partial \omega}
\]

\[D = \text{Det}(\varepsilon_{ij} + N_i N_j - N^2 \delta_{ij}), \varepsilon = \text{hot diel. tensor}\]

OX: 1) optimization of injection angle,
2) symmetries in narrow evanescent layer

XB: Ridder’s method to correct \(N_\perp\)

Full stellarator geometry
- Poloidal component
- Off-midplane launch
- Toroidal curvature
- Broken axisymmetry

Parallel computing on 16 workstation cluster
EBE Spectrum and Profile

$n_e$ from TS and Li-Beam
B from equilibrium code TRANS

$\rightarrow$ mapping $f \leftrightarrow r$
Heat Waves: EB-diagnostic during EB-heating

Problem:

EBH

Parametric decay

Non-thermal peaks $f_{\text{pump}} \pm n f_{\text{LH}}$ (n=1,2,...)

Overlapped thermal spectrum cannot be measured at the same harmonic

Solution:

EBH 2nd harm. & EBE 1st harm.

Plasma has to be O2-overdense

(at least $n_e > 2.4 \times 10^{20}$ m$^{-3}$,
recently $n_e \approx 4 \times 10^{20}$ m$^{-3}$)
Confinement Transition

H-Mode Threshold often exceeds ECE cutoff:

EBE edge

EBE core

$H_{\alpha}$

$\frac{\langle n_e \rangle}{10^{19} \text{m}^{-3}}$

NBI 0.4 MW, density ramps

$T_{e}(H, 343-347\text{ms}) - T_{e}(L, 351-355\text{ms})$

$\Delta T_{e}(\text{eV})$

$\text{re}(\text{cm})$
Edge-localized Modes

Cross-correlation with $H_\alpha$:

- $f=64.82\text{GHz}$, $r_{\text{eff}}=13\text{cm}$
  - EBE edge
- $f=77.26\text{GHz}$, $r_{\text{eff}}=3\text{cm}$
  - EBE core
Radiative Collapse

Hysteresis?

$t = 239.750$

$t = 241.000$

$t = 242.000$

$t = 243.500$

$t = 244.250$

$t = 244.500$

$t = 244.750$

$t = 245.500$

$f_q \sim n_e n_{\text{imp}}$
Due to oblique injection, OXB heating also drives current!
Angle is fixed by OXB, but co/ctr-CD can be selected and \( N_{||} \) adjusted by varying the magnetic configuration.
EBW Emission & Heating in the MAST Spherical Tokamak

(with V. Shevchenko)
2D-steerable, multi-beam antenna allowed simultaneous EBW emission and heating
Emission in a spherical tokamak is “banded” as a consequence of low aspect ratio.

Emission in a spherical tokamak is “banded” as a consequence of low aspect ratio. The diagram shows the division into high (HCS) and low (LCS) confinement regimes, with resonances indicated by vertical lines. The vertical axis represents the major radius, while the horizontal axis shows the time in seconds.

The resonances are marked as follows:
- 2ω\text{ce}
- 3ω\text{ce}
- 4ω\text{ce}
- 5ω\text{ce}

These resonances correspond to the cutoffs in the R and L directions, with UHR Plasma Resonance indicated by a box.
EBE evidenced fast electrons at sawtooth crashes

D_α

Soft-X Rays

EBE
60.5GHz
62.5GHZ
63.5GZ
66.5GHz
2D angular scans of EBW emission indicated optimal direction for heating at MAST spherical tokamak.

f=60.5GHz, $\theta = -5.6$deg

- 2.5° FWHM

f=60.5GHz, $\phi = -7$deg

- 1.2° FWHM

Identified optimal launch direction for first OXB heating in a spherical tokamak →

In spite of non-optimal frequency (60GHz) and alignment issues.

Total Energy

ECRH Power

7 kJ (~ 0.25 MW)

60 kJ (~ 3 MW)

250 kW
2D angular scans confirmed that emission is anisotropic → New q-profile diagnostic concept

Inclination of conversion contours at various f gives
Inclination of field line at various radial positions
Special design allows tilted mirror to spin at 12,000rpm and scan EBW emission within the same discharge.

Self-balanced design spins at 12,000rpm

First measurements carried out. Analysis under way.

3.3585 tonnes

3.3585 tonnes

Talk at IAE, Kyoto University
July 30, 2012

"Mode-converted Electron Bernstein Waves"
(F. Volpe)
EBW Heating in the TCV Tokamak

(with A. Mück, L. Curchod, A. Pochelon et al.)
Angular Scan of EBW injection shows min stray (max conversion) close to calculated optimum
Stray radiation correlates with ELMy phases, consistently with reduced conversion efficiency.
SXR during pulsed EBWH was complicated by sawteeth

EBW deposition profile from BIS

EBW deposition profile from FFT

Sawteeth perturbation profile in OH

ECRH power [kW]

Soft X-ray ch 8, $\rho \sim 0.93$

Soft X-ray ch 12, $\rho \sim 0.85$

Soft X-ray ch 17, $\rho \sim 0.71$
Long, more central ($\rho \sim 0.4$) EBWH resulted in clear bigger-than-sawtooth $T_e$ increase

$T_e$ builds over $\tau_e \sim 50\text{ms}$
Modeling of EBW Current Drive in the RFX-mod RFP

(with R. Bilato and A. Köhn)
For RFX-mod values of $n_e$ and $T_e$ at EBW deposition for 28GHz, 100kW absorbed should drive ~10kA, sufficient to improve confinement.

Steady state
Localization
Position control

$$\eta_{EBCD} = R_{[m]} n_e \left[10^{20} m^{-3}\right] \frac{I_{[A]}}{P_{[W]}} \approx 0.013 \ T_e [\text{keV}]$$
Harmonics of ~11GHz are best for Current Drive at reversal layer of 1MA RFX-mod plasmas

Analytic Equilibrium:

\[ B_\varphi = B_0 \ J_0(f(x)) \]

\[ B_\theta = B_0 \ g(x) \ J_1(f(x)) \]

\[ B_0 = \mu_0 I_p / (\pi a) \]

\[ g(x) = f(x) / (2\Theta_0 \ x) \]

\[ f(x) = \int \mu(x')dx', \quad \mu(x) = 2\Theta_0 \]
Magnetic configuration of RFP has some peculiarities

1. $|B|$ almost poloidally symmetric, doesn’t scale as $1/R$

   Any launching position is Low Field Side (LFS).

   No High Field Side (HFS) schemes, e.g. no SX-B.

2. low $B \rightarrow$ low $\omega_{ce} \rightarrow$ low $\omega$ $\rightarrow$ long vacuum wavelength $\lambda \rightarrow$

   cutoffs and resonances close to each other within few $\lambda$ $\rightarrow$ tunneling
FX-B is unsuitable for RFX-mod

Equilibrium at 1MA $\rightarrow$ $f>11\text{GHz}$, e.g. $f=28\text{GHz} \rightarrow \lambda=1\text{cm}$

$L_n=2\text{cm}$

Conversion factor:

$$C = 4 \exp(-\eta_X) \left[ 1 - \exp(-\eta_X) \right]$$

with Budden parameter $\eta$:

$$\eta_X \approx 2\pi^2 \frac{L_n}{\lambda} Y \sqrt{\frac{Y}{1+Y}}$$
**Injection along a vertical port, slightly tilted, is optimal**

- **B and D:** the optimal poloidal launch cannot be achieved.
- **A:** too narrow in toroidal direction for the beam to go through.
- **C:** these are the only possible ports for O-X-B.
Further waist optimization leads to 58% efficiency

Limiting factors to higher efficiency:
- curvature mismatch (included)
- fluctuations (not included)
$n_e$ and $B$ fluctuations reduce conversion efficiency

**OXB**

$n_e$ fluctuations at O-mode cutoff →

- a) cutoff is corrugated → incidence on cutoff locally non-optimal → reduced OX conversion efficiency
- b) cutoff moves → optimal angle changes with time → mode conversion efficiency fluctuates in time

**B fluctuations at O-mode cutoff** →

- optimal angle fluctuates according to $N_{z,\text{opt}}^2 = \omega_{ce}/(\omega_{ce} + \omega)$

**FX-B**

$n_e$ and $B$ fluctuations at FX-mode cutoff and UHR → their positions and thus thickness of evanescent layer in between fluctuates

**Solutions:** f/back on direction or, easier, on $\omega$

- longer wavelength for easier tunneling
- higher frequency for deeper cutoff, in less turbulent region
"Alf's" full-wave code

(A. Köhn)

Institut für PlasmaForschung Finite Difference Mode Conversion

- Finite Difference Time-Domain code on Cartesian grid
  - spatial derivatives replaced by finite differences
  - $\vec{E}_w$, $\vec{B}_w$, and $\vec{J}$ calculated at each time step
- Plasma enters in the evolution of the plasma current $\vec{J}$

\[
\begin{align*}
\frac{\partial \vec{B}_w}{\partial t} &= -\vec{\nabla} \times \vec{E}_w \\
\frac{\partial \vec{E}_w}{\partial t} &= c^2 \vec{\nabla} \times \vec{B}_w - \frac{1}{\epsilon_0} \vec{J} \\
\frac{\partial \vec{J}}{\partial t} &= \epsilon_0 \omega_{pe}^2 \vec{E}_w - \frac{e}{m_e} \vec{J} \times \vec{B}_0
\end{align*}
\]

- Boundary conditions
  - The antenna field (amplitude and phase) at the antenna surface
  - Absorbing b.c. and perfect metal surfaces
- The conversion to EBW is taken into account by introducing the warm plasma effects in the constitutive relation.
Full-wave code reconstructs OXB conversion and follows EBWs until their wavelength can be resolved by grid.

Parameters: for 
\( \alpha = 5.1, \Theta_0 = 1.47 \), 
\( I_p = 1 \text{ MA} \), 
\( I/N = 7 \times 10^{-14} \text{ A m} \) 
\( n_0 = 2.5 \times 10^{19} \text{ m}^{-3} \) 
\( \theta = 0, w_0 = 2.8 \lambda, \) 
\( y_0 = 9 \text{ cm} \).
Multiple reflections by graphite wall re-inject some power and increase overall OXB efficiency to 67%
Summary and Conclusions

- Stellarators need EBWs
  - overdense
+ Mode-converted EBWs benefit from Stellarator environment
  - steep gradients, external control of configuration, tolerable $n_e$ and B fluctuations
  = A marriage!

- EBW heating, emission and CD all proved in W7-AS stellarator

- In spite of 60GHz being too high, EBW heating succeeded also in MAST,
  - after scenario optimization (steep gradients)
  - and guidance from EBW emission (optimal direction).

- “Spinning mirror” provided angular scans of OXB conversion efficiency every
  10ms → possible q-profile diagnostic.

- EBW heating also proved in TCV tokamak
- EBW CD at edge of RFX-mod RFP plasma might trigger transport barrier
Stellarators: compensation for undesired bootstrap current at high $\beta$.


Tokamaks: $T_e$ diagnosis of ITER divertor region? Not overdense, but Upper Hybrid resonant layer (thus, EBWs) exists.

RFPs: Improved confinement by suppressing MHD and triggering transport barriers at reversal layer.