CRITICAL PROBLEMS IN PLASMA HEATING/CD IN LARGE FUSION DEVICES AND ITER

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Outline

• Motivation

• ICRF
  scenarios and advanced antennae for large machines
  TWA Proposal for ITER
  New far off axis Fast Wave CD scenario in non active ITER

• ECRF
  3D full wave updated STELEC code modelling at fundamental harmonic.
  Outstanding role of EB waves
  second harmonic modelling for middle-size tokamaks and ITER

• NBI
  benefits, sinergism with ICRF, problems and HFFW back up
  for NBI in ITER

• LHH
  coupling and modelling problems in large machines,
  old/new problems with electron energetic tails
ICRF and ECRF modelling tools
PSTELION and STELION full wave 3D codes
ANTRES3, ANPORT in multi port 3D antenna codes

• Motivation

Mainly ICRF and ECRF heating
  - scenarios development
  - optimised antennae

• Features
  - Configuration: 3D, 2D (tokamaks included)
  - Hot plasma model: Ion and Electron Bernstein and Kinetic Alfven Waves, FLR effects – through second order expansion

• Numerical method:
  - Finite differences, Modes expansion

• Magnetic flux coordinates

• Plasma equilibrium – VMEC (ORNL) code
JET Plasma parameters

- Central deuterium temperature: 4.5-6.5 keV
- Central NBI effective deuterium slow down temperature: 52 keV
- Central hydrogen temperature: 4.5-6.5 keV
- Central electron temperature: 5.50 keV
- Separatrix temperatures: 0.25 keV
- Temperatures exponent, $\alpha_T$: 2.0
- Central electron density: $2.5-4.0 \times 10^{19} \text{ m}^{-3}$
- Central hydrogen/Be/Ar temperatures: 4.5-6.5 keV
- Impurity fractions: $f_H, f_{NB_D}, f_B, f_{Ar}$: 0.05, 0.05, 0.001, 0.005
- Effective Z: 1.71
- NBI D power (80 & 130 kV): 5 MW
- RF frequency: 25 MHz
- RF power: 2 MW
JET radial power deposition profiles at $F=25$ MHz, $N=27$, $B_0=3.6$ T, 0.5% Ar, 5% 130 keV D beam.
Fundamental ICRF harmonic at JET interaction with NBI ions and D-D reactivity 45% rise with $P_{RF} < 1.5$ MW

Power deposition to 130 keV NBI slow down deuterons at $F=25$ MHz, $N=27$, $B_0=3.6$ T
Power deposition to electrons in JET at $F=25$ MHz, $N=27$, $B_0=3.6$ T
JET “ITER-like” 0-pi antenna
Loops Cross coupling through a plasma

F. Durodie & JET EP ICRH
PROJECT TEAM 2001-7
Layout of the front part of the ITER-EM ICRH antenna plug (from the CATIA reference)
Large Scale Fast Waves and Slow waves at $B = 3.3 T$ in ITER-like JET Advanced 20\%He-3+50\%H scenario, $f = 50 \text{ MHz}$.

Re($E_z$) contours

He-3/H hybrid
Far inside MC CD scenario in JET
H/He3 ITER D-T like scenario
at F=50 MHz, N=27, B₀=3.3 T, 20%He-3/H plasma
JET ICRF far inside current driven profiles
F=50 MHz, N=27, \( B_0 = 3.3 \) T

20\% He-3/H plasma, \( \gamma = 2.3 \times 10^{-2} \) A/W/M
However, there are severe Problems for individually phased loop array antennae

- Each loop with capacitance or coaxial peace is a resonant contour
- Inter loop inductive coupling mismatches these resonant circuits and requires installation of individual conducting boxes
- Thus total antenna has decreased coupling/power capability
- More, in Current Drive mode loops inter coupling through a plasma is unavoidable one due to weak FW attenuation, even in a reactor, and mismatches an antenna
- Thus qualitatively new antenna approach is needed one
Problem resolution is use of Advanced frequency broad band TWA antenna (C. Moeller 1992, Vdovin 1993) toroidal loop array supported by ridged waveguide.

Vdovin ITER concept-1995,
theory in EPS_1998
ITER-like TWA supported by ridge waveguide (lumped capacitances are not need ones)

Frequency band 40 – 90 MHz, only TWO coaxes
TWA recirculator and matching with RF generator
(similar to DIII-D recirculator, Phelps et al., 1997, with our updates)
ICRF screen less “O-mode” antenna
very non efficiently excites Fast Waves
and Faraday screen looks not to be needed
ITER F=53 MHz D-T scenario

X-mode (FW) antenna

Sreen less antenna on AUG was demonstrated: J-M Noterdaeme 1996

O-mode (SW) antenna
ICRF support for ITER start up

- $F = 80$ MHz,
- $N_e(0) = 4.27 \times 10^{16}$ m$^{-3}$,
- $T(0) = 25$ eV, $B_0 = 5.3$ T,
- $I_p = 80$ kA

- Slow Wave excitation with FW antenna, on axis power deposition

- In T-15 e.m. WG opening eigen mode is at 107 MHz
ICRF support for ITER start up

- F = 300 MHz
- Ne(0) = 4.27 × 10¹⁶ m⁻³
- T(0) = 25 eV, B₀ = 5.3 T,
- Iᵢ = 80 kA

Slow Wave excitation with FW waveguide antenna, off axis power deposition to the electrons – preheating for Oh current rise

![Graph showing power density vs. ρ₀](image)
New far off axis Fast Wave CD scenario in non active ITER (ctd)

- The proposed (and natural) so called “heavy” minority scheme H(He-4) (minority ions - in brackets) keeps the cyclotron and i-i resonances behind of a cut off layer (being practically vertical one) – at the Low Field Side (LFS). Fast Waves, propagating from an antenna, partly will be reflected from the cut off, partly will tunnel through the evanescent region and will be absorbed at the IC He-4 minority ions resonance.

- The reflected FW will be remarkably trapped between the cut off layer and vacuum chamber, at the LHS. The amount of the wave power penetrated to the cyclotron resonance (to the HFS) depends on the minority ions amount and on antenna’s toroidal number.
The 2D wave power deposition in non active $H(2.5\text{He}-4\%)$

ITER Plasma at 38 MHz, $N=27$
The radial wave power deposition to the electron and ions and driven current in the $H(2.5\%\text{He-4})$ ITER plasma at the frequency 38 MHz, $N=27$.
ECH full wave modelling in NSTX

All relevant ECH wave induced

Plasma currents are included
Fundamental harmonic

O-mode quasi perpendicular

2 MW outside launch in NSTX L-mode plasma:

| $E_{\text{minus}}$ |

$N_e(0) = 0.037$, $f = 7.65 \, \text{GHz}$,

$T_e(0) = 4.95 \, \text{kV}$, $B_0 = 0.2856 \, \text{T}$

$I_p = 200 \, \text{kA}$, $q(0) = 1.5$, $q(95) = 15.5$

$\Omega = \omega$

Cut off UHR

EBW

N (0) =
Fundamental harmonic O-mode quasi perpendicular launch in NSTX, 2D power deposition to electrons. Main power absorption is at right resonance zone wing.
Fundamental harmonic O-mode launch in NSTX, radial power deposition to electrons

EBW wave activity is crucial one
Role of density gradients
DIII-D H-mode Second harmonic X-mode upper port launch at \( f = 60 \, \text{GHz} \) Coupling X-mode and O-mode, 2 diffraction lobs: \(|\text{real}(E_{\text{eps}})|, |\text{Im}(E_z)|\)

\( N = 160 \) (\( N(0) = 0.075 \)), \( T_e = 6.55 \, \text{kV} \) \( N_e(0) = 1.0 \times 10^{19} \, \text{m}^{-3} \) \( I_p = 360 \, \text{kA} \)
Second harmonic X-mode launch in DIII-D H-mode plasma:

Radial power deposition to electrons, two diffraction lobs

\[ N = 160 \quad (N(0) = 0.075) \quad F = 60\text{GHz} \quad N_e(0) = 0.5 \times 10^{19} \text{ m}^{-3} \quad I_p = 360 \text{ kA} \]
Weaker coupling X-mode and O-mode, 2 diffraction lobs
Second harmonic X-mode upper port launch at
$F = 60 \text{ GHz}$ in DIII-D L-mode: $|\text{real}(E_{\epsilon})|$, $|\text{Im}(E_z)|$

$N = 160 \ (N_0 = 0.075), \ T_e^0 = 6.55 \text{ kV} \ Ne_0 = 0.5 \times 10^{19} \text{ m}^{-3} \ I_p = 360 \text{ kA}$
Second harmonic X-mode launch in DIII-D L-mode
more rare and smooth plasma:
Radial power deposition to electrons, two diffraction lobs

\[ N=160 \quad (N(0) = 0.075) \quad F=60\text{GHz} \quad N_e(0)=0.5 \times 10^{19} \text{ m}^{-3} \quad I_p = 360 \text{ kA} \]
• Outside quasi perpendicular O-mode ECH launch STELEC full wave well resolved modelling shows:
  - strong coupling to X-mode with respective mode conversion to small scale EBW
  - Large amplitude EB waves and strong modification of $K_{\text{parallel}}$ spectrum provide power absorption on right side of resonant zone (contrary to usual analytic and ray tracing approach)
  - This effect must be accounted in analysis of ECRF power deposition in large fusion machines and predictive ITER ECH/CD modelling
  - Huge EBW amplitudes can create sheared flows, important for ITB creation and turbulence control
  - Probe fundamental physics of nonlinear waves and flows
ECH similarity laws check for non active ITER at B

\[ B_0 = 2.65 \, \text{T} \]

X-mode second harmonic for \( F = 20.2 \, \text{GHz} \) and \( 10.1 \, \text{GHz} \)

NTM scenario upper port launch with gaussian beam divergence \( \pm 0.71^\circ \) and \( N_\parallel = 0.09 \) (STELEC code)
O-mode and X-mode are coupled (weakly) in toroidal plasma even at second harmonic. Non active ITER $|ImE_z|$ contours
ECH power deposition in non active ITER at X-mode second harmonic for $F=20.2 \text{ GHz}$ and $10.1 \text{ GHz}$
HFFW CD in large machines and ITER

- JT-60U reported NNB CD experiments (Einj~400 keV) in conditions modelling the ITER ($V_{\text{beam}} \sim V_{\text{alfven}}$) with very bad results: instabilities (waited from theory) have appeared and expelled energetic ions before their slow down (Sorrento 2000 IAEA Conf)

- This information became even more worse with recent off-axis ASDEX NB CD experiments (Hobirk's paper at EPS30, St-Petersburg, July 2003 [7]) which demonstrated NO any change in driven current PROFILE (JT-60U previously also reported similar results) thus manifesting on ions and current profile decoupling

- In such situation HFFW CD may substitute NB in ITER creating driven current at HALF of plasma minor radius (goal of NNB).
Plasma parameters of representative ITER scenario #4

- Central deuterium temperature $T_{D0}$ 25.2 keV
- Central tritium temperature $T_{T0}$ 25.2 keV
- Central electron temperature $T_{e0}$ 24.4 keV
- Volume averaged electron temperature $< T_e >$ 10.5 keV
- Central electron density $n_{e0}$ $7.27 \times 10^{19}$ m$^{-3}$
- Volume averaged density $< n_e >$ $6.74\times 10^{19}$ m$^{-3}$
- Impurity fractions $f_{He}$, $f_{Be9}$, $f_{Ar}$ 0.039, 0.02, 0.0035
- Effective $Z_{eff}$ 2.17
- RF power 20 MW
HFFW CD in ITER scenario #4

Power deposition to the electrons and driven current profiles at frequency 300 MHz, N = 50 (PSTELION)

CD efficiency is 0.55 A/W/m²
**SS-active ITER - HFFW, 300 MHz**

12 loops, $5\pi/8$ phasing ($N_{||\text{max}} = 3$)

**full antenna spectrum**

Toroidal antenna spectrum

Poloidal antenna spectrum

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**Toroidal spectrum of antenna** ($A^T_N$)

- $N = 156$ ($N = 3.03$)
- $N = -343$

**Poloidal spectrum of antenna** ($A^P_n$)
Power deposition profiles and the profile of driven current at $N_{\text{max}} = 3$ in ITER scenario #4, $\gamma = 0.32$ A/W/M$^2$ (for $Z_{\text{eff}} = 1.4$). MRAYS code, 990 rays.
SS-ACTIVE ITER - HFFW flexible CD profile
300 MHz 12 loops, $5\pi/8$ phasing ($N_{||\text{max}} = 2$)
\(\gamma = 0.18 \text{ A/W/M}^2\)
Waveguide slightly oversized narrow frequency band electrically strengthen Travelling Wave Antenna
HFFW power source and antenna

- CW sources 1 MW/tube at 200 MHz are available ones (EU accelerator Thales developments [6])
- Compact narrow frequency band Travelling Wave Antenna
  - toroidal array of poloidal loops/holes supported by slightly oversized waveguide with large electrical strength
Difficulties of Antenna-plasma coupling for LH waves

- The e.m. wave decays from an antenna mouth as

  \[ E \sim \exp(-\sqrt{|k_{\parallel}^2 - k_0^2|} \, x), \]

  \( x \) - antenna-plasma distance, \( k_0 = \omega/c \)
  
  For \( k_{\parallel} = 2 \, k_0 \)

  \[ E \sim \exp(-1.71 \, k_0 \, x) \]

  LH waves a frequency \( \sim 100 \) FW ICRF frequency

  This means that e.m. field of the

  **LH Wave practically does not touch the plasma**

  and wave attempts to be much easy reflected back to the RF generator –
  in compare with ICRF waves case.

  Thus for the LH waves the tokamak’s or ITER’s (with its SOL distance 20-30 cm) **plasma must be very close** to the antenna mouth
LH waves spectrum at **main plasma surface** must be properly modelled and calculated – to be meaningfully predictive for ITER modelling.
Conclusions

A. ICRF

1) Advanced ICRF Travelling Wave Antenna, based on Multi loop array supported by ridge waveguide, was proposed and may be a back up to designed now. This is electrically strong, frequency broad band antenna: 38-80 MHz

2) Antenna due to small frequency sweep keeps constant power coupling to ELMy plasma. It has only two coaxes and there are no lumped capacitances at all.

3) Power recirculator, located outside machine, is an essential element of proper antenna operation

4) New FW far off axis CD scenario for non active ITER was proposed to support hybrid scenario

5) Proposed action: expand ICRF system frequency band to 38-80 MHz
Conclusions (ctd)

B. ECRH

1) 3D Full wave ECH STELEC code numerically well resolved modelling for NSTX and FT-2 tokamaks (EC-15) supported our previous finding: O-mode and X-mode coupling in toroidal plasmas at fundamental EC harmonic

1) Electron Bernstein wave play crucial role at O-mode antenna polarization (contrary to ray tracing) and lead to broader EC power deposition profiles. Last ones are located in another space positions in compare with usual ray tracing predictions

3) This new role of huge amplitudes mode converted EB waves provides a possibility of sheared flow generation (~$E^2$), important for ITB creation and turbulence control.

The poloidal magnetic field plays an essential role in allowing strong damping of the EB wave on electrons, which is optimal for flow drive.
Conclusions (ctd)

C. NBI back up HFFW scheme

1) To fulfil NBI role – CD creation in middle of minor ITER radius – we propose for ITER new/old HFFW CD scheme (Kurchatov 1960 – PPPL 2007 activity) operating at 200 – 300 MHz

1) 3D antenna - plasma modelling revealed RF current generation peaked in middle of plasma minor radius

2) CD efficiency is about 0.3 A/W/m-2

3) Wave guide type Travelling Wave antenna, surviving ELMy plasma activity with constant coupling, was proposed.

4) CW power sources at 200 MHz are commercially available
Conclusions (ctd)

D. LH waves

Projection for ITER must overcome several problems

1) - coupling with main plasma through broad SOL region in ITER
   - “Plasma arm” appearing at plasma mouth must be properly modelled to predict correct toroidal LH wave spectrum near boundary of bulk plasma needed for integrated modelling

1) Viability of delicate grill antenna at severe ITER conditions
2) Relativistic electron tail generation, played dangerous role in ASDEX, Alcator-C, JT-60 etc: divertor plates damage, carbon/Be bloom due interaction with chamber wall.