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Modeling Non-linear Plasma-wave Interaction at the Edge of a Tokamak Plasma

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MIT-PSFC

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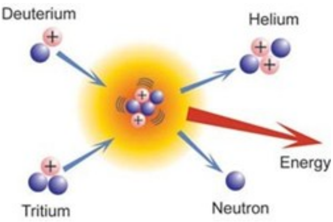
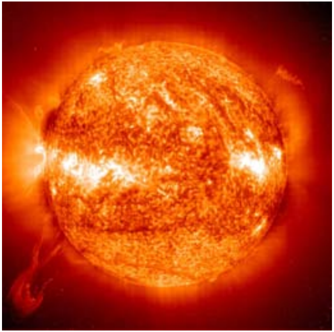
Nuclear fusion: bringing the power of the stars on earth



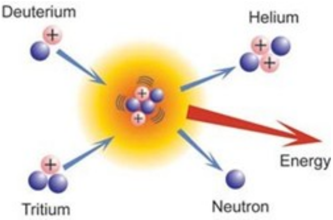


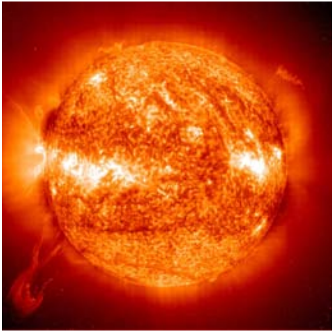
- Process by which light atomic nuclei join together to form a single heavier nucleus
- Nuclei must have a lot of energy to smash into each other (> 100 million degreees) $\rightarrow$ matter becomes a ionized gas: plasma
- Results in lower total mass $\rightarrow$ release of large quantities of energy

$$E = m\,c^2$$

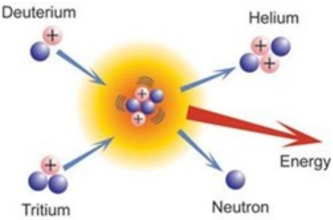
- Fusion is the process that powers active stars, experimental devices examining fusion power for electrical generation
    - A long-term energy supply: 3000 years of DT fusion, 150 billion years DD fusion
    - No high-level radioactive waste
    - Fusion fuel is not proliferation threat
    - No risk of catastrophic faliure
    - No carbon emission
    - High density, dispatchable energy source

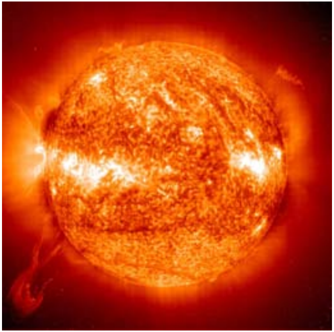
Nuclear fusion: bringing the power of the stars on earth

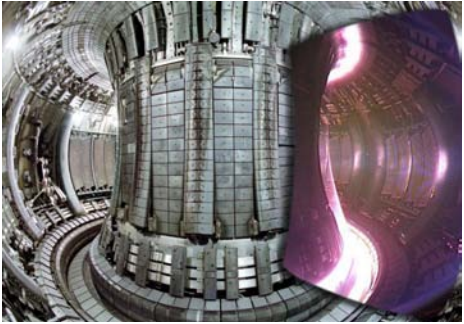


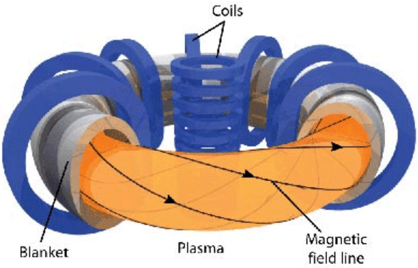


Nuclear fusion: bringing the power of the stars on earth

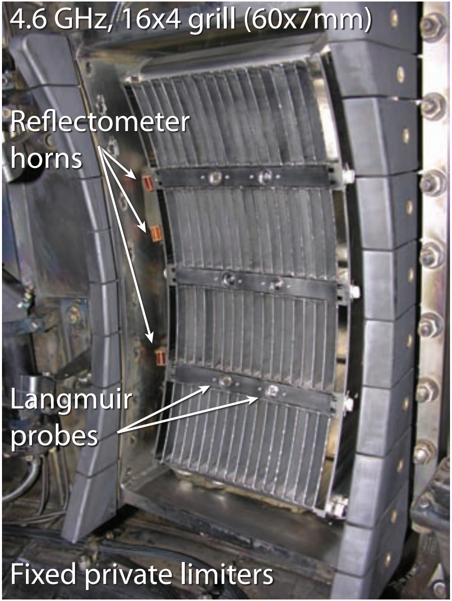


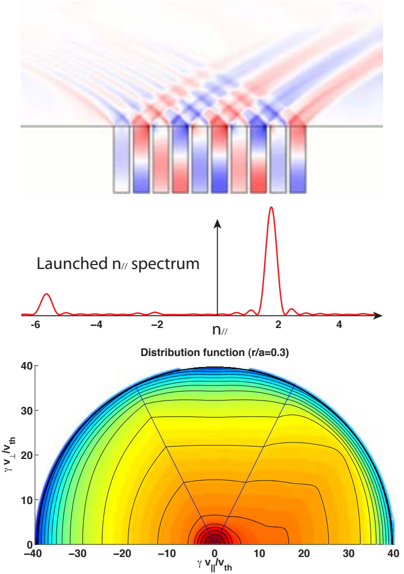




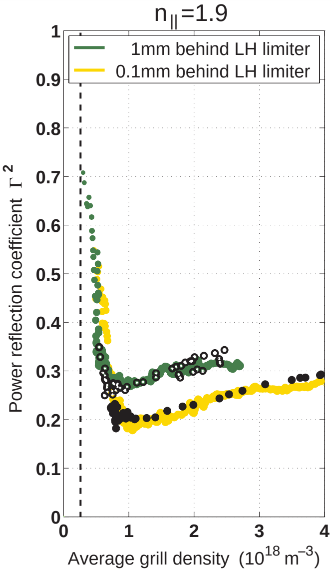


Lower Hybrid current drive (LHCD)

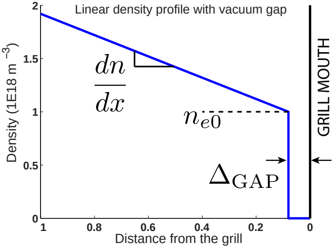




Coupling agrees with linear coupling theory, provided density profile has a millimetric vacuum gap



- Systematic study of antenna coupling
- Comparison with Brambilla code* required millimetric vacuum gap to match experiments $\Delta_{GAP} = 1 - 2 \times 10^{-2} n_{e0}/10^{18}$ [mm]



- Consistent with higher reflection coefficients for larger $n_{||}$

*Brambilla, M., *Waveguide launching of lower hybrid waves* Nuclear Fusion, **19** 1343-1357 (1979)

Effect of high power RF on SOL is a long standing problem

Millimetric vacuum gap was also invoked for WEGA, ASDEX, TdeV, PBX-M, TS, JET. Predictions for ITER done for $0 \leq \Delta_{GAP} \leq 1$ cm, with highly variable results [Belo, J. & Bibet, P., 2004].

Several theories have been proposed to explain its origin:

1. Ponderomotive forces *(most prominent theory)* [Morales, 1977; Chan, 1979; Fukuyama, 1980; Petrzilka, 1983; Ekedahl, 2009]
2. Increased cross field transport [P. Jacquet, 1996]
3. Mismatch launcher radius of curvature with plasma [Bell, 1994; Bibet, 2000]
4. Misalignment of the launcher [Bell, 1994; Frincu, 2009]

Open questions:

1. Does this evanescent layer really exist?
2. Can ponderomotive forces predict the presence of such gap?

Alcator C-Mod is in a unique position to address these issues

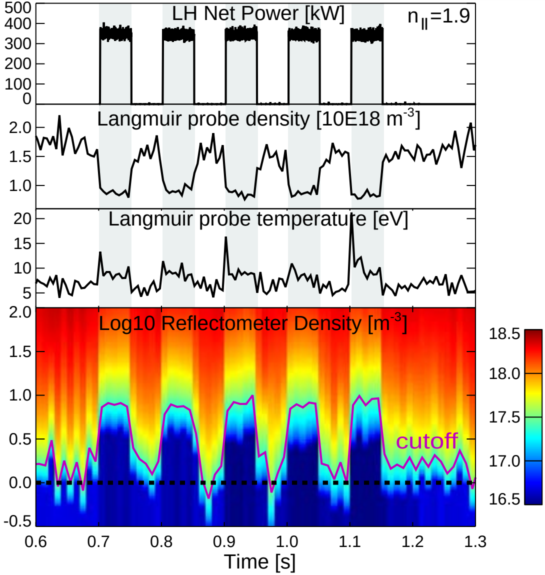
For the first time the depletion of the density profile in front of the launcher was directly measured

SOL shows clear response to LH waves at high power

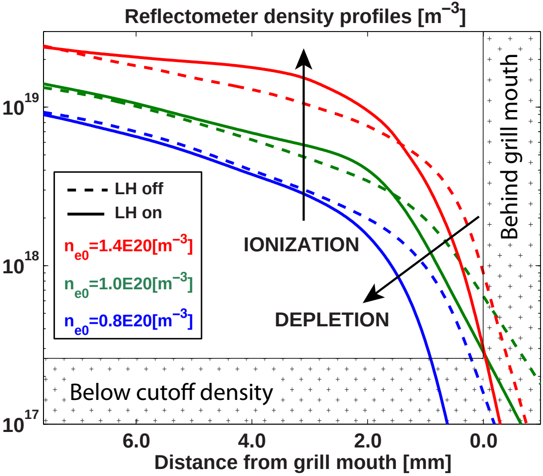
Langmuir probes constrain the reflectometer density profiles at edge

Minimizes reflectometer radial error bars to ∼mm scale and is the largest uncertainty of the measurement

Same consistent assumption for all measurements



SOL measurements allow self-consistent simulations



	0.8E20	1.0E20	1.4E20
Experiment	29%	29%	28%
Simulation	34%	27%	30%
Sim. OH phase	20%	11%	10%

2D slab coupling simulations using COMSOL Multiphysics software* agree within few % of the measured reflection coefficient.

Comparing simulations during LH and OH phases suggests that high reflection is due to:

- Evanescent layer only at lowest density
- Low edge density and steep gradient at higher densities

*Shiraiwa, S. et al., *Plasma wave simulation based on versatile FEM solver on Alcator C-mod*, AIP Conference Proceedings **1187** 363-366 (2009)

Can the evanescent layer be due to ponderomotive forces?

Force that pushes charged particles that are in an inhomogeneous oscillating electromagnetic field towards the weaker field areas

In a plasma this results in a depletion of the density where the wave fields are high. The plasma density (n) can be described as a perturbation (δn) to the density in absence of waves (n_0):

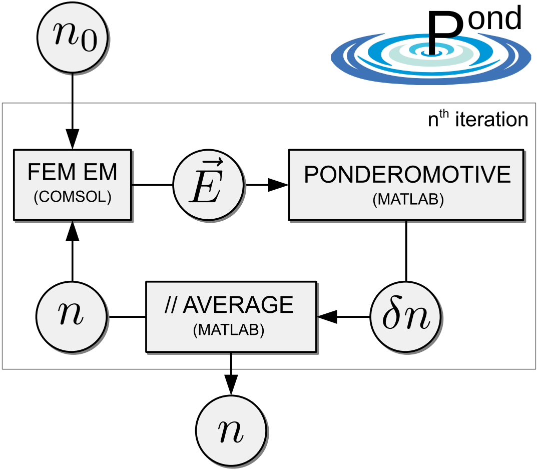
- $n \approx n_0 + \delta n$, where $\delta n = -n_0 \frac{e(\Phi_{Pe}+\Phi_{Pi})}{\kappa(T_e+T_i)}$
- Φ_P is the ponderomotive potential, which for a magnetized plasma $\mathbf{B} = B_0\hat{z}$ (derived from the Hamiltonian of the particles oscillation center in a oscillating electromagnetic field) is given by*:
  $\Phi_P = \frac{e}{m}\left[\frac{|E_z|^2}{\omega^2} + \frac{|E_x|^2+|E_y|^2}{\omega^2-\Omega^2} + \mathrm{Im}\left\{\frac{\Omega(E_y*Ex-E_x*E_y)}{\omega(\omega^2-\Omega^2)}\right\}\right]$

Density perturbation and wave propagation are **coupled** $\rightarrow$ non-linear problem

*Cary, J. R.; Kaufman, A. N., *Ponderomotive Force and Linear Susceptibility in Vlasov Plasma*, Phys. Rev. Lett., American Physical Society, **39** 402-404 (1977)

FEM + iterative procedure to solve the non-linear problem

Efficient and generic approach: electromagnetic and electrostatic waves, different frequency ranges, 1-D, 2-D, 3-D.

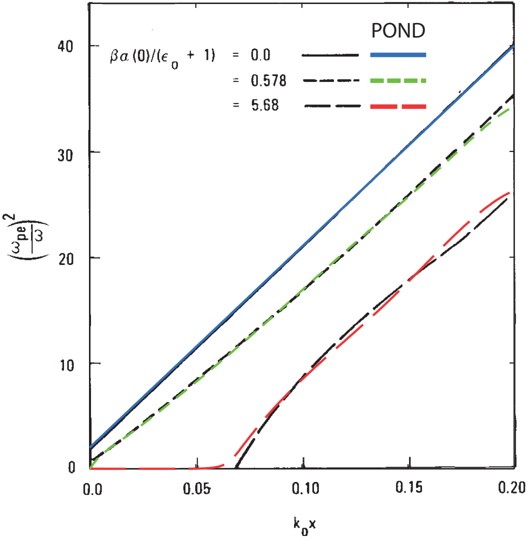


POND iteration scheme:

1. Start from density profile during OH phase
2. Calculate electric fields using FEM
3. Calculate density perturbation by ponderomotive forces
4. Assume ∞ parallel particle trasport (average density in $\hat{B}$ direction)
5. Iterate to step 2, until convergence

Comparing POND with existing work*

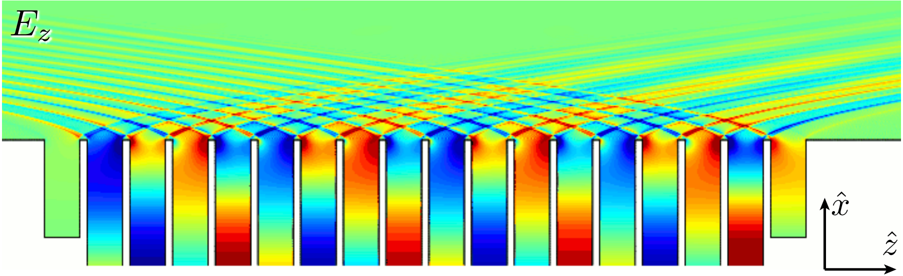
- 1D $\rightarrow f(x)$ no y or z dependence
- **B**$=B_0\hat{z}$
- $n_e(x) = n_{e0}(1 + x/\lambda_n)$
- Considering single spectral component: $n_\parallel = 10$
- Slow wave (electromagnetic + electrostatic)
- 3 power levels: 0 W, 6 kW, 60 kW
- $T_e = 10$ eV, $T_i \sim 0$

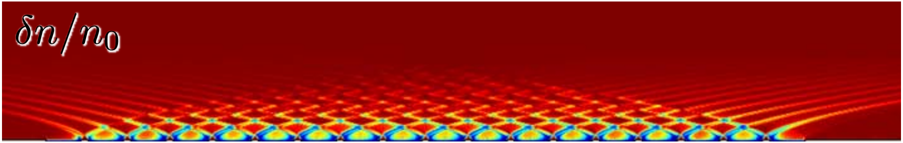


*Chan, V.; Chiu, S., *Wave-plasma coupling at the lower hybrid frequency*, Physics of Fluids, **22** 1724, (1979)

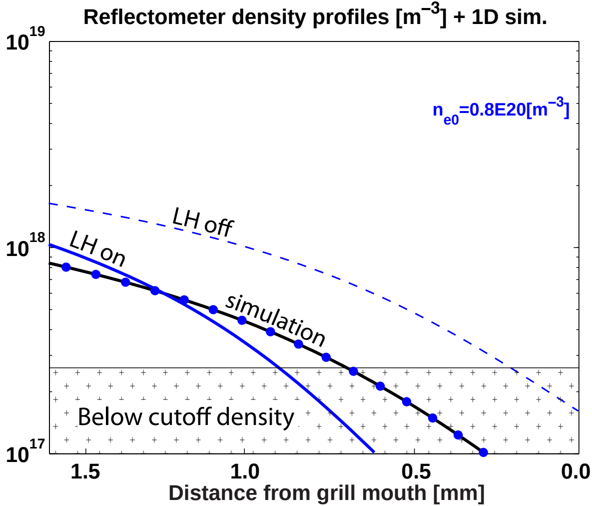
Important geometric effects can be taken into account

2D/3D geometry show enhanced density depletion caused by the standing wave pattern of resonance cones. Other effects 2D/3D which could be included, WG modes, $\vec{B}$ tilt, curvatures, poloidal/toroidal non-uniformities...





1D POND simulation of density depletion

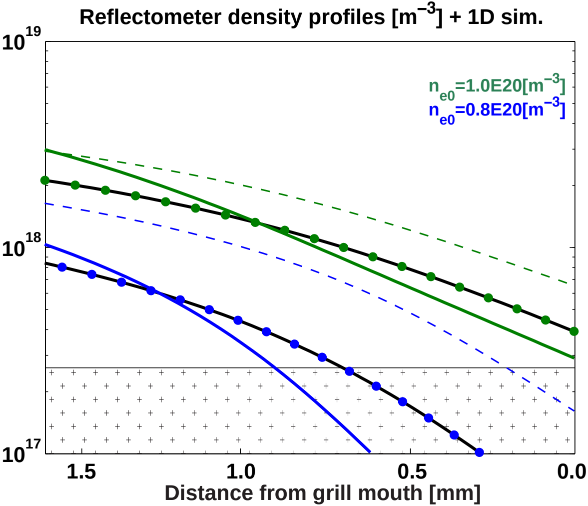


Consider only few mm in front of the launcher, since ionization is not included in the model

Temperature set to decay exponentially from 70 eV at separatrix to what measured by Langmuir probes

1. Start from reflectometer OH density profile
2. POND calculates the density perturbation by LH waves
3. "Target" is the density profile during LH phase

1D POND simulation of density depletion



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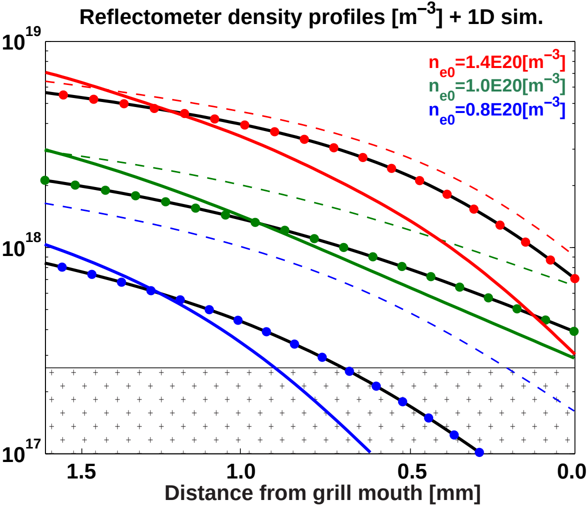

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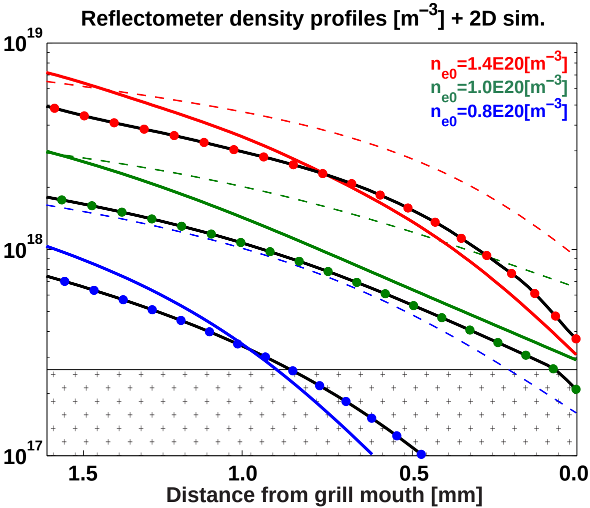
2D POND simulation of density depletion



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Temperature set to decay exponentially from 70 eV at separatrix to what measured by Langmuir probes

1. Start from reflectometer OH density profile
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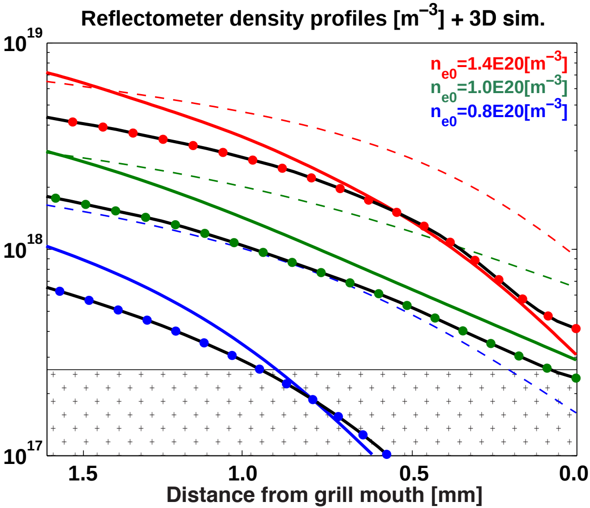
3. "Target" is the density profile during LH phase

3D POND simulation of density depletion



Consider only few mm in front of the launcher, since ionization is not included in the model

Temperature set to decay exponentially from 70 eV at separatrix to what measured by Langmuir probes

1. Start from reflectometer OH density profile
2. POND calculates the density perturbation by LH waves
3. "Target" is the density profile during LH phase

Summary: LH wave coupling in the non-linear regime

- High power coupling experiments
  - Agreement with linear coupling theory provided presence of vacuum layer
  - Reflectometer measure density depletion profiles during high power LH waves
  - Non-perturbative very low power experiment confirmed lower reflections
- A new FEM based model for ponderomotive forces was developed
  - Verified with existing code in 1D
  - 2D/3D simulations predict stronger density depletion due to overlapping of resonance cones
- Validation of ponderomotive force theory
  - Conclusions in agreement with existing work*, higher reflection coefficients are found to be caused by a density depletion in front of LH grill whose extent is compatible with ponderomotive force theory
  - The availability of SOL density depletion profiles allowed an unprecedented strong validation of the theory
- Future work
  - Account for ionization to model density profiles further inside of the plasma
  - For upcoming campaign the LH private limiter will be moving with the launcher (allowing to reach for higher density/temperature regions)

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*Morales (1977); Chan (1979); Fukuyama (1980); Petrzilka (1983, 2010); Ekedahl (2009)