Two ion species studies in LAPD*
Ion-ion Hybrid Alfvén Wave Resonator

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Experiments performed at the Basic Plasma Science Facility (BaPSF)

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***S. T. Vincena, G. J. Morales and J. E. Maggs, Physics of Plasmas 17, 052106 (2010)**

Motivation

•Shear Alfvén waves in two-ion species plasmas
(a.k.a. ion cyclotron waves, EMIC,
ion-hybrid waves etc..) interact strongly with ions

•Altitude-sensitive noise detected by spacecraft in H^+-He^+ geoplasma

5. M. Temerin and R.L. Lysak, J. Geophys. Res. 89, 2849 (1984).

•Ion acceleration in solar corona

6. K. G. McClements and L. Fletcher, Astrophys. J. 693, 1494 (2009).

•Possible wave resonators in equatorial region of planetary magnetospheres----RESONANCE MISSION

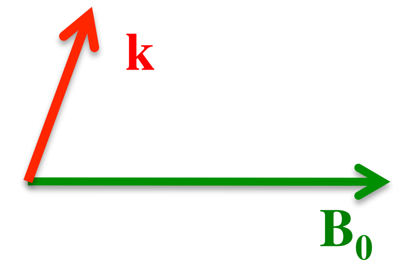
7. A.V. Gigliemi, A.S. Potapov, and C.T. Russell, Pis'ma v ZhETF 72, 432 (2000).
8. A. G. Demekhov, V. Y. Trakhtengerts, M. M. Mogilevsky, and L. M. Zelenyi Adv. Space Res. 32, 355 (2003).

Essential Physics--I

For small transverse scales the compressional mode is evanescent

Shear Alfvén wave dispersion relation is well approximated by

$$k_{II}^2 = \left(\frac{\omega}{c}\right)^2 \varepsilon_\perp \left[1 - \left(\frac{k_\perp c}{\omega}\right)^2 \frac{1}{\varepsilon_{II}}\right]$$



For two cold ion species

$$\varepsilon_\perp \approx \frac{\omega_{p1}^2}{\Omega_1^2 - \omega^2} + \frac{\omega_{p2}^2}{\Omega_2^2 - \omega^2}$$

Perpendicular dielectric vanishes at

$$\omega_{ii} = \sqrt{\frac{\omega_{p1}^2 \Omega_2^2 + \omega_{p2}^2 \Omega_1^2}{\omega_{p1}^2 + \omega_{p2}^2}}$$

and singular at $\omega = \Omega_1$ **and** $\omega = \Omega_2$

Essential Physics--II

Frequency ω and $k_\perp$ are set by source

Axial cut-off occurs when $\varepsilon_\perp = 0$

For cold ions at $\omega = \sqrt{\dfrac{\omega_{p1}^2 \Omega_2^2 + \omega_{p2}^2 \Omega_1^2}{\omega_{p1}^2 + \omega_{p2}^2}} \equiv \Omega_{ii}$

But when $k_\perp \rho_i$ is not negligible

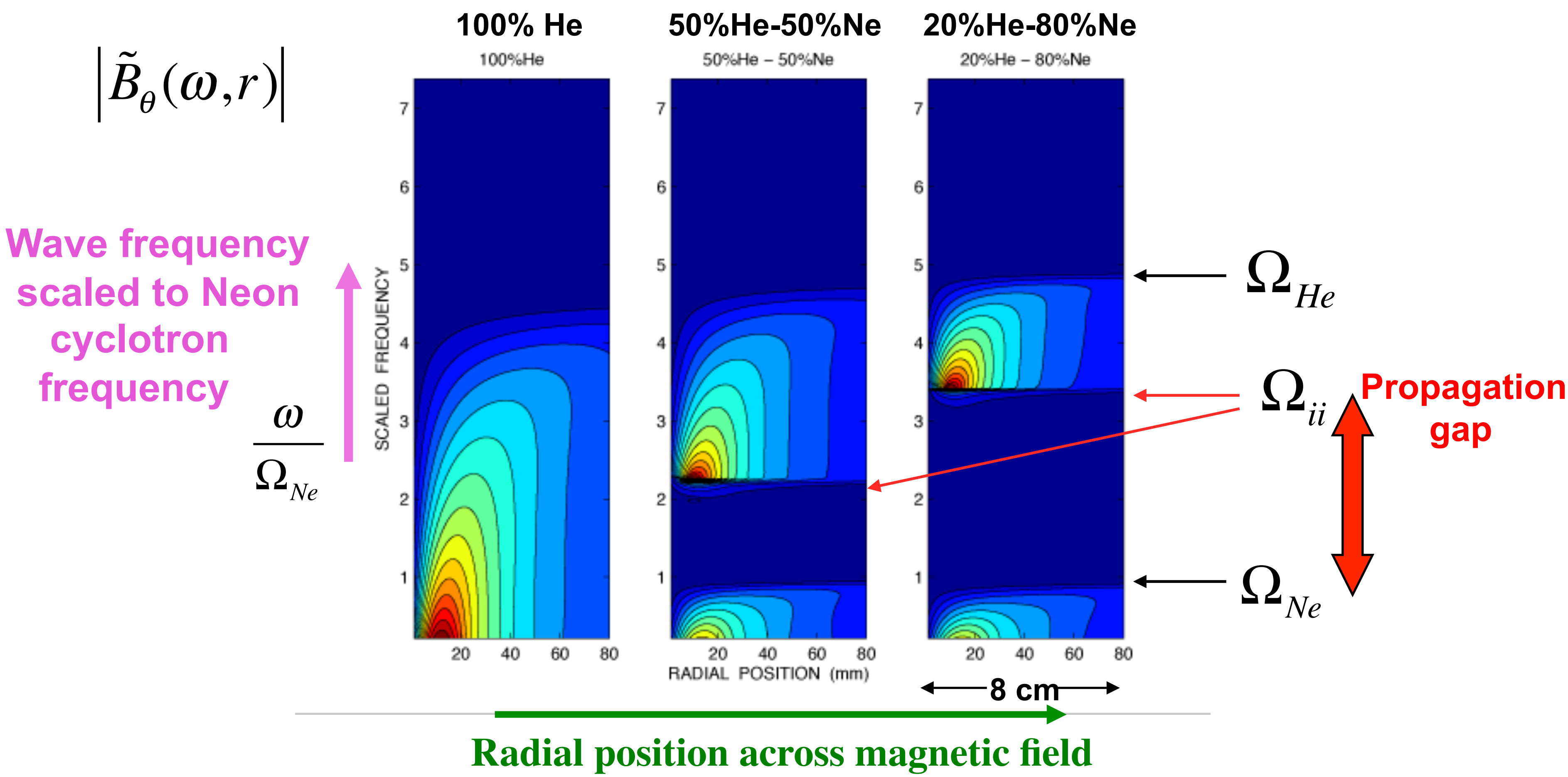
$$\varepsilon_\perp = 1 + \left(\frac{\omega_{pe}}{\Omega_e}\right)^2 - 2\sum_s \left(\frac{\omega_{ps}}{k_\perp \rho_s}\right)^2 \sum_{l=1}^{\infty} \frac{e^{-(k_\perp \rho_s)^2} I_l\left(k_\perp^2 \rho_s^2\right)}{\omega^2 - \left(l\Omega_s\right)^2}$$

Vanishes at frequencies corresponding to "pure" IBW

<u>Consequence:</u> shear Alfvén wave experiences multiple propagation bands between the lower and the higher cyclotron frequencies that become more pronounced at large ion temperatures or small transverse scales

Effect of Species (He/Ne) Concentration for Cold Ions

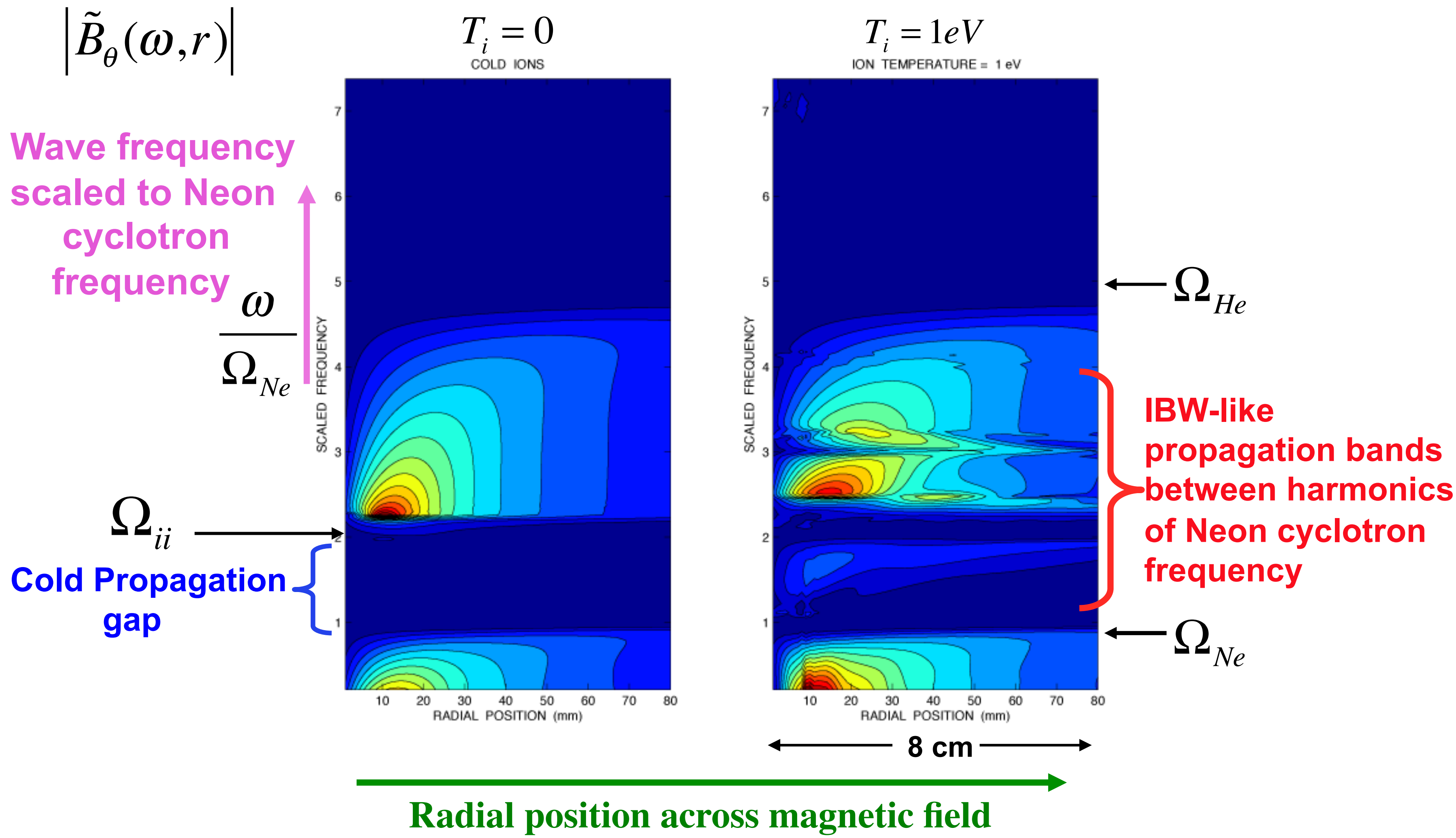
Contour in "frequency-radial position space" at fixed axial location z = 4 m



Typical LAPD parameters N_e=10^{12} cm^{-3} ; B_0 = 750G ; T_e = 5 eV; T_i = 0; a = 1 cm

Modification of Cold Propagation Gap by Ion Temperature

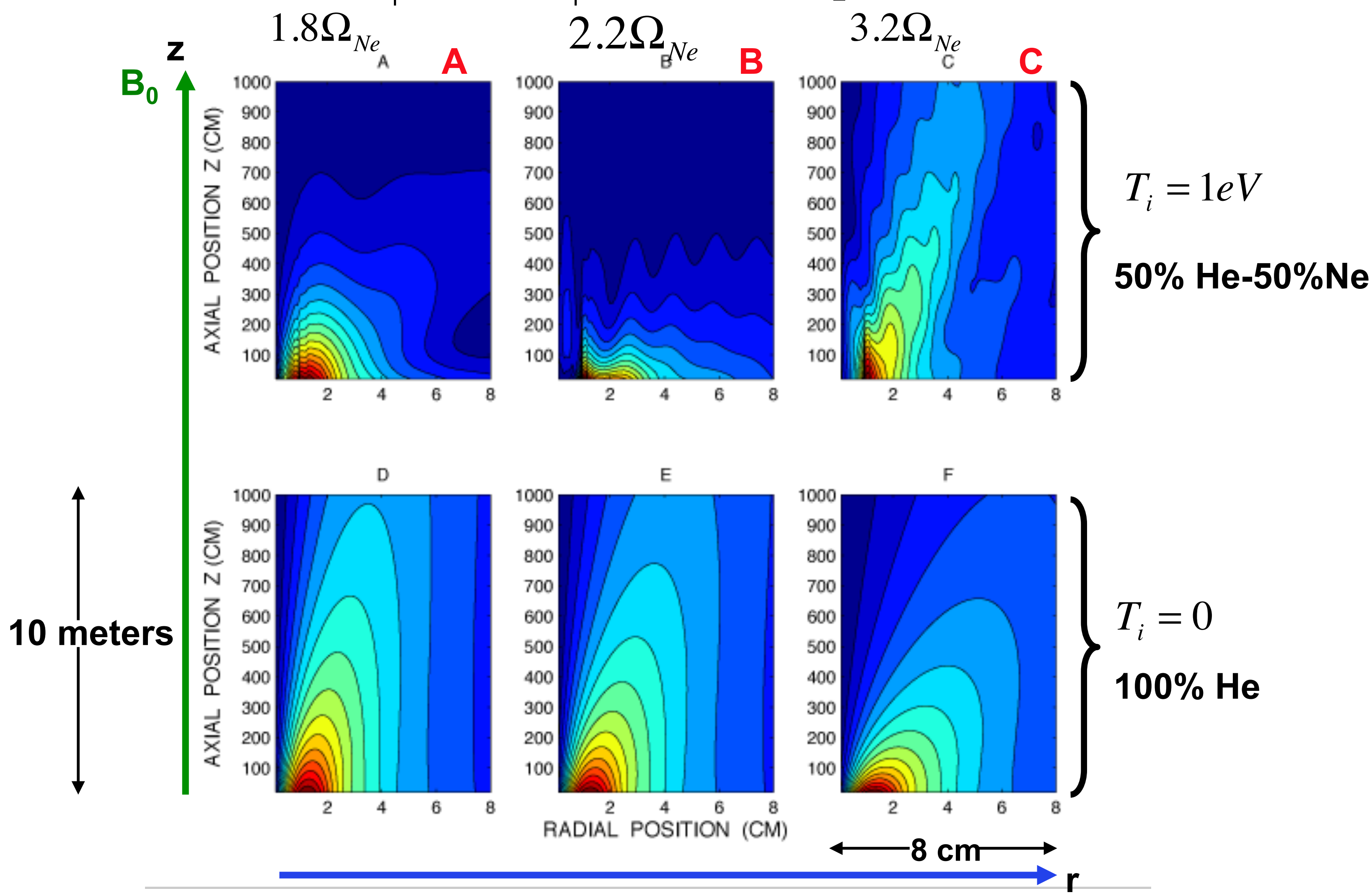
Contour in "frequency-radial position space" at fixed axial location z = 4 m



Typical LAPD parameters $N_e = 10^{12}$ cm^{-3} ; B_0 = 750G ; T_e = 5 eV; 50%He-50%Ne; a = 1 cm

Comparison of Spatial Pattern (z, r) for Different Frequencies

Contour of $\left|\tilde{B}_\theta(\omega, z, r)\right|$ for fixed frequencies

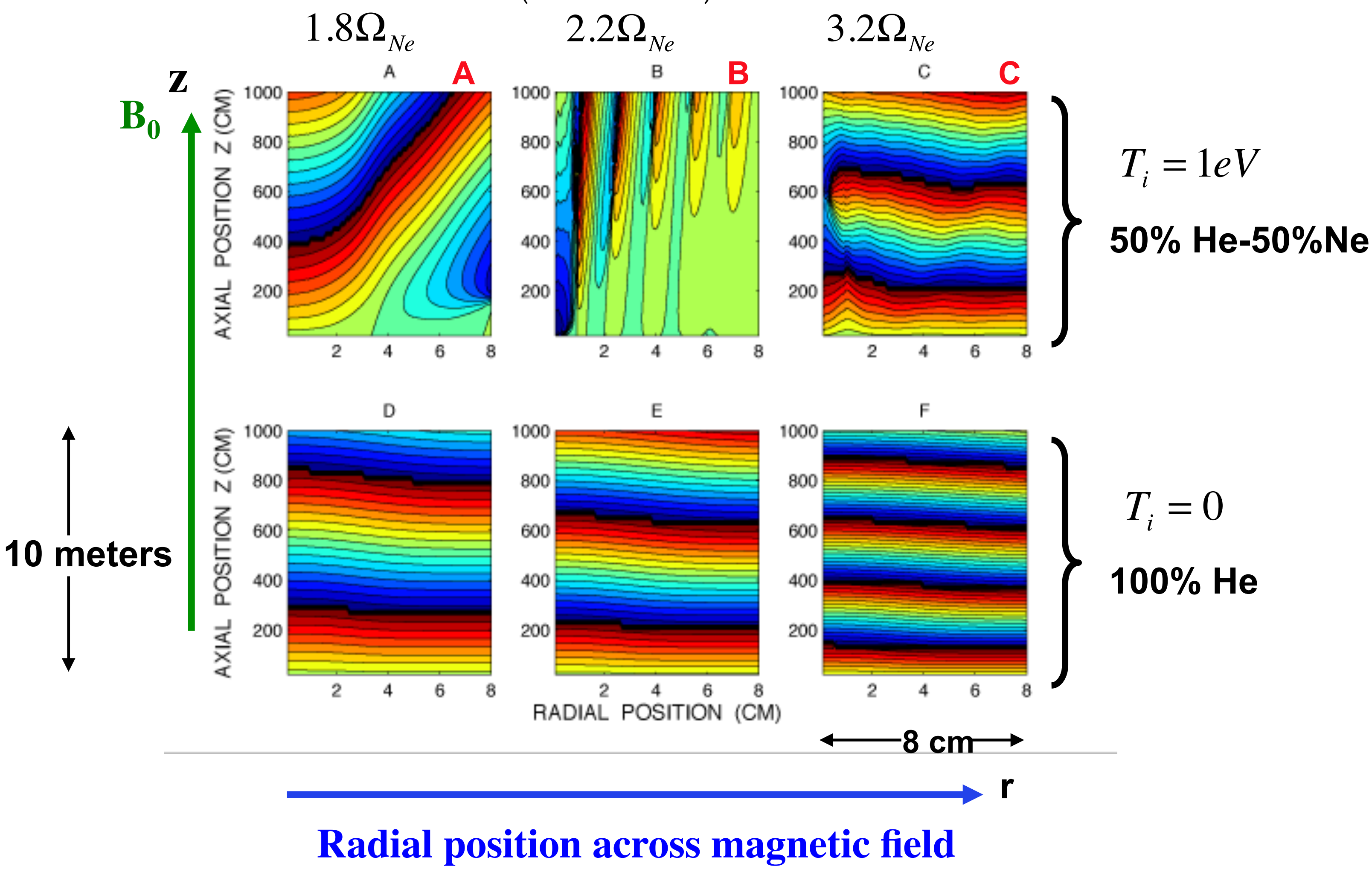


Radial position across magnetic field

Typical LAPD parameters $N_e = 10^{12}$ cm^{-3} ; B_0 = 750G ; T_e = 5 eV; a = 1 cm

Comparison of Spatial Phase-Pattern (z, r) for Different Frequencies

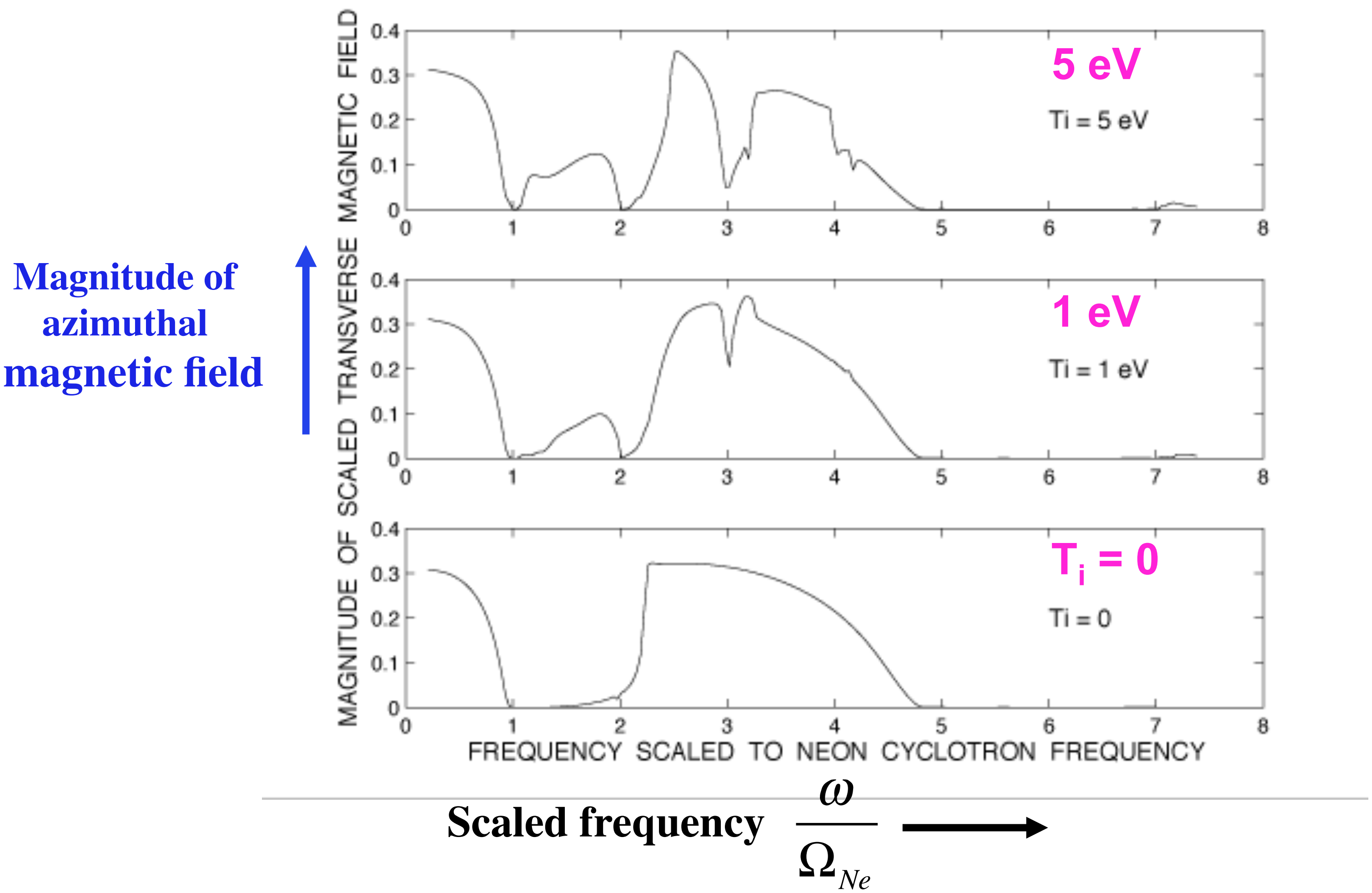
Contour of $\arg\left(\tilde{B}_\theta(\omega,z,r)\right)$ **for fixed frequencies**



Typical LAPD parameters N_e=10^{12} cm^{-3} ; B_0 = 750G ; T_e = 5 eV; a = 1 cm

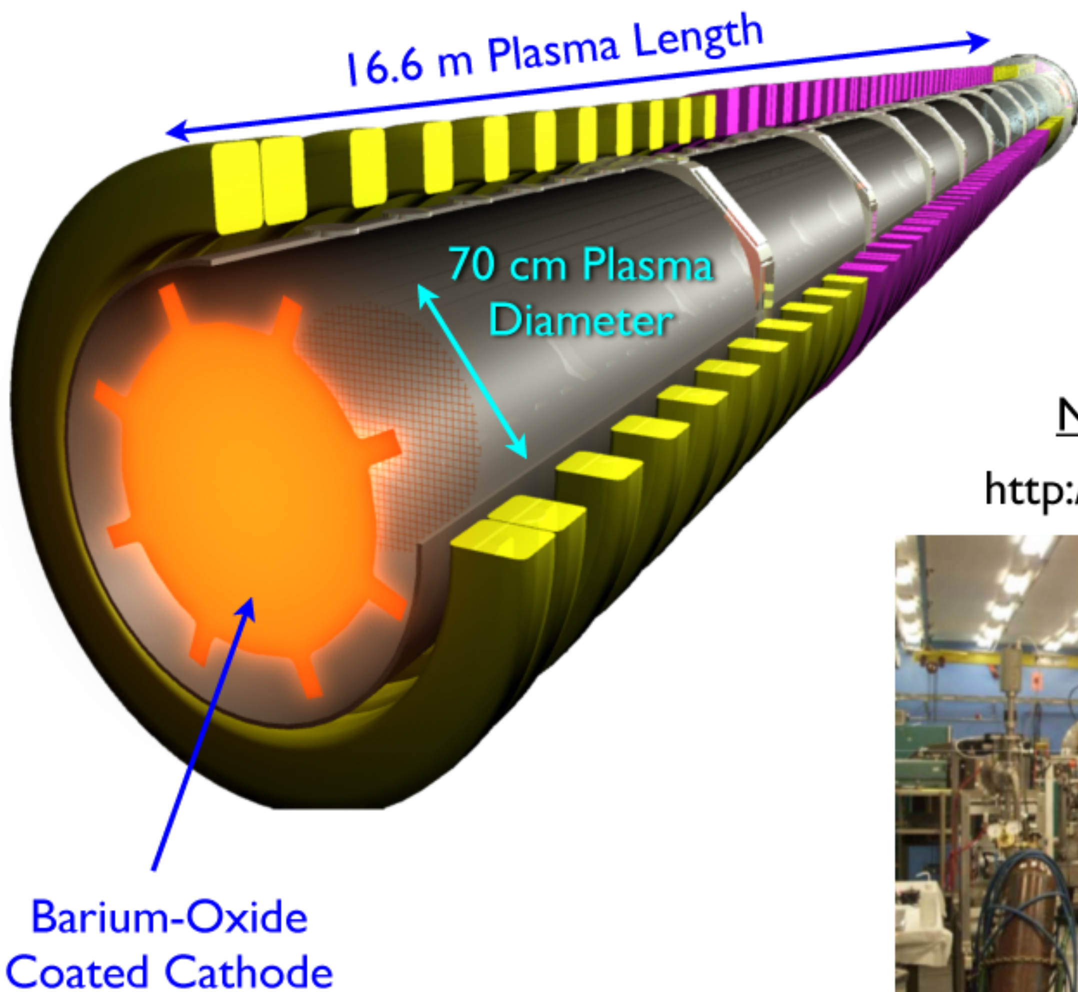
Effect of Increasing Ion temperature

Frequency dependence of $\left|\tilde{B}_\theta(\omega, r, z)\right|$ at a fixed position
z = 4 meters, r = 3 cm



Typical LAPD parameters $N_e = 10^{12}$ cm^{-3} ; B_0 = 750G ; T_e = 5 eV; a = 1 cm; 50%He-50%Ne

Large Plasma Device (LAPD)



Typical Parameters

T_e = 5 ev n_e = 1-3 x 10^{12} cm^{-3}

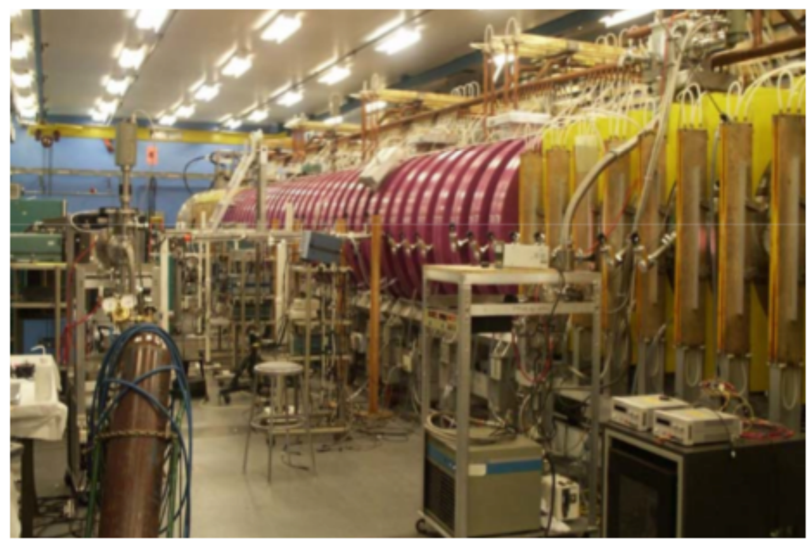
T_i = 1 ev t_{pulse} = 10 - 12 ms

Rep. Rate = 1 Hz

B_o = 500 - 2500 G

National User Facility

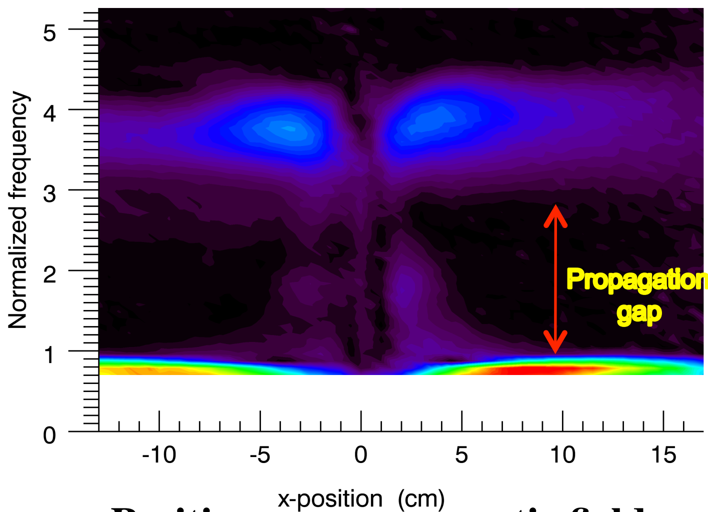
http://plasma.physics.ucla.edu



4

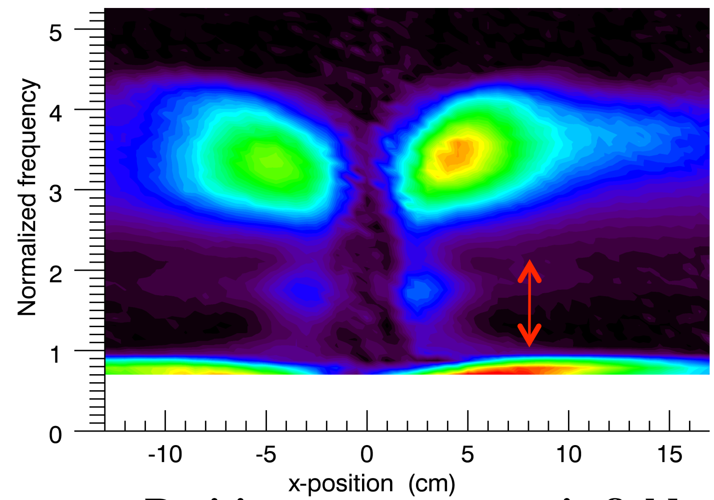
Changing concentration ratio – Helium/Neon mix

30% Helium – 70% Neon



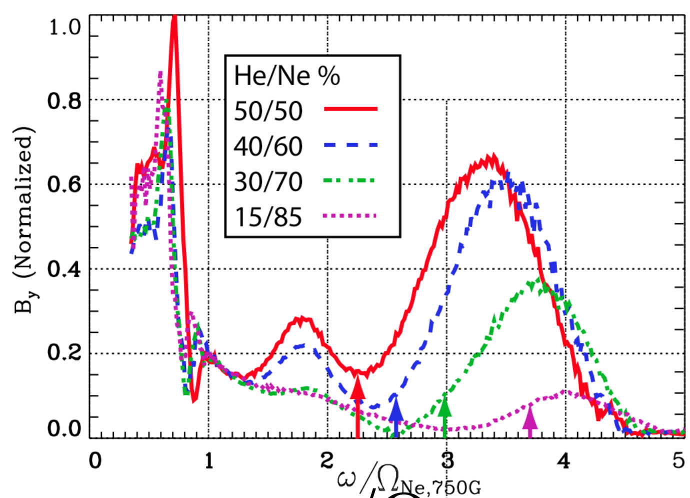
Position across magnetic field

50% Helium – 50% Neon



Position across magnetic field

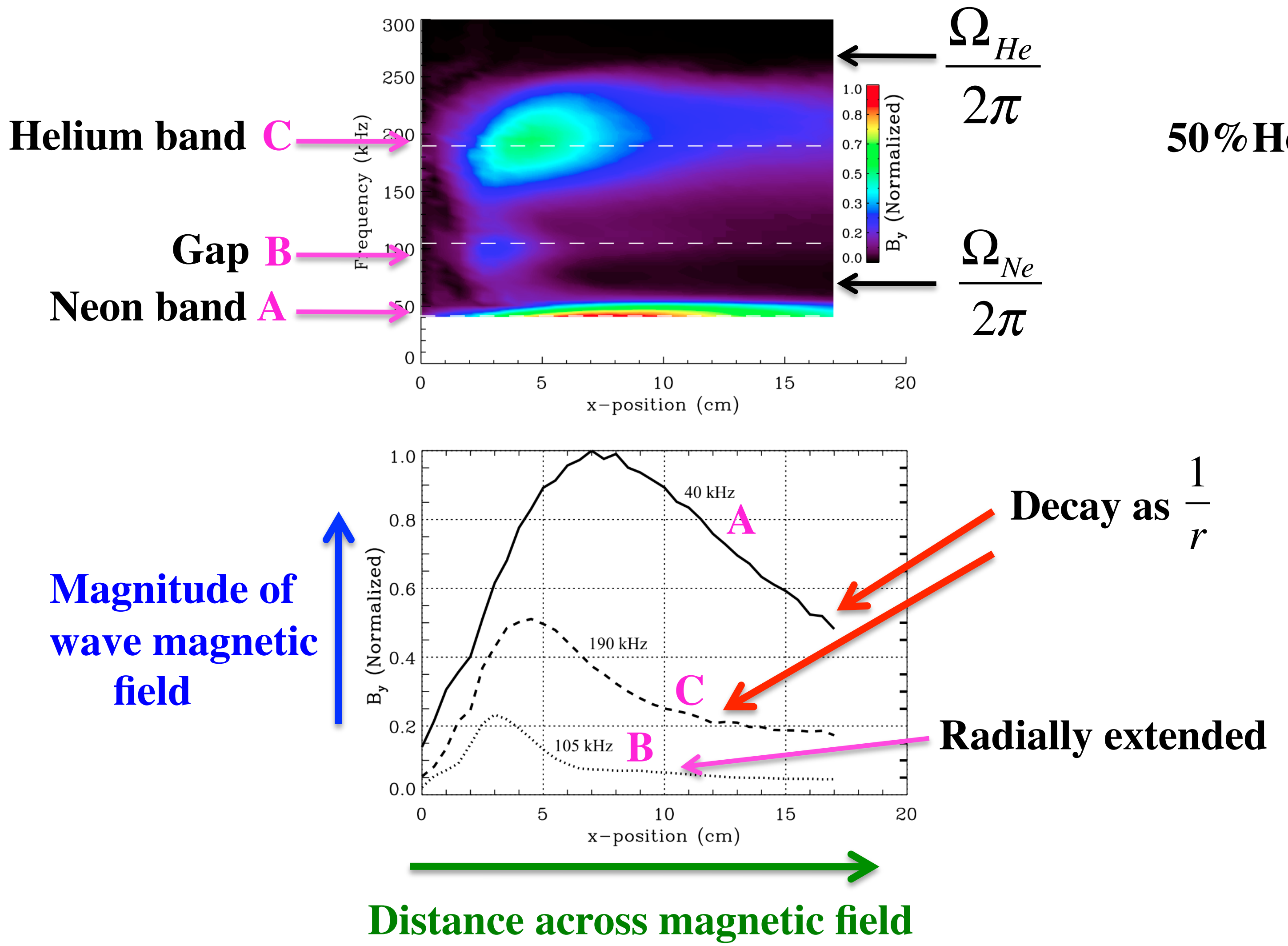
Fig. 9



ω/Ω_{Ne}

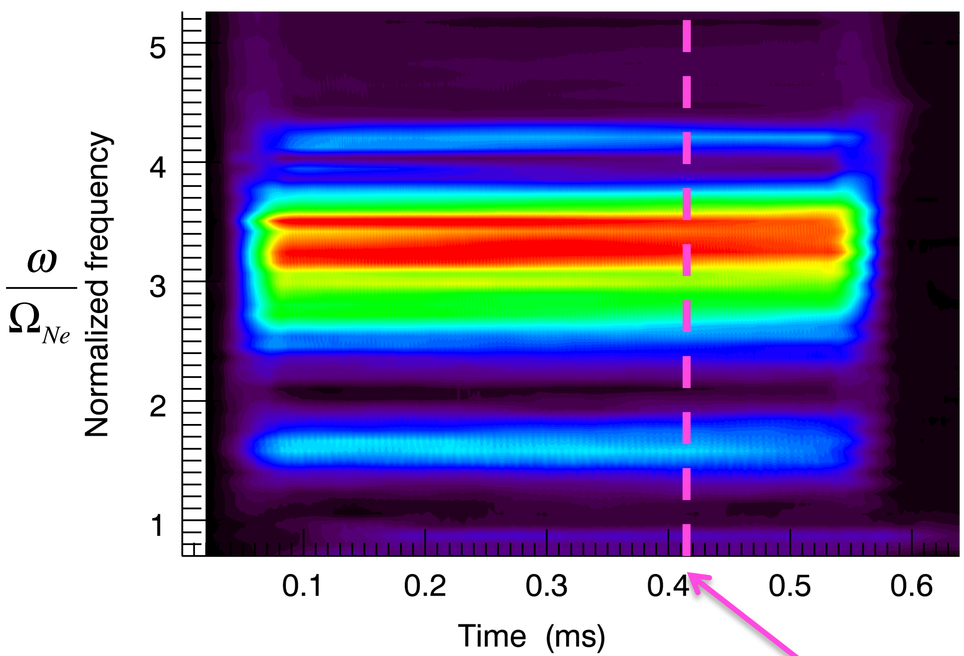
Frequency dependence of magnetic field at z = 4.8 m and r= 2 cm

Measured frequency-radial dependence at fixed z = 4.8 m of wave magnetic field



50%He-50%Ne

Evidence of IBW-like features

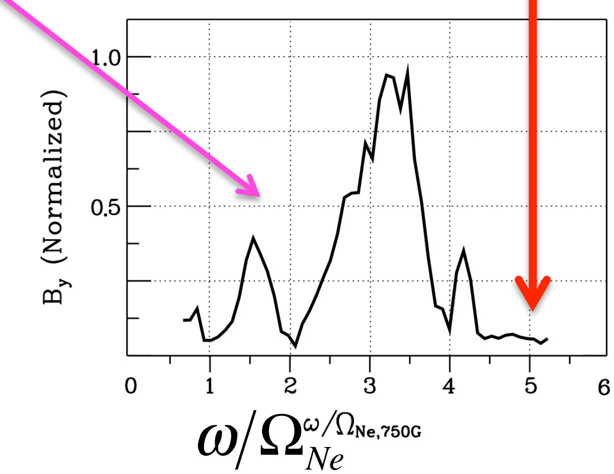


Spectral evolution

(ω, t)

of wave magnetic field at fixed position

$\Omega_{He} = 5\Omega_{Ne}$



50%He-50%Ne

Essential Physics--III

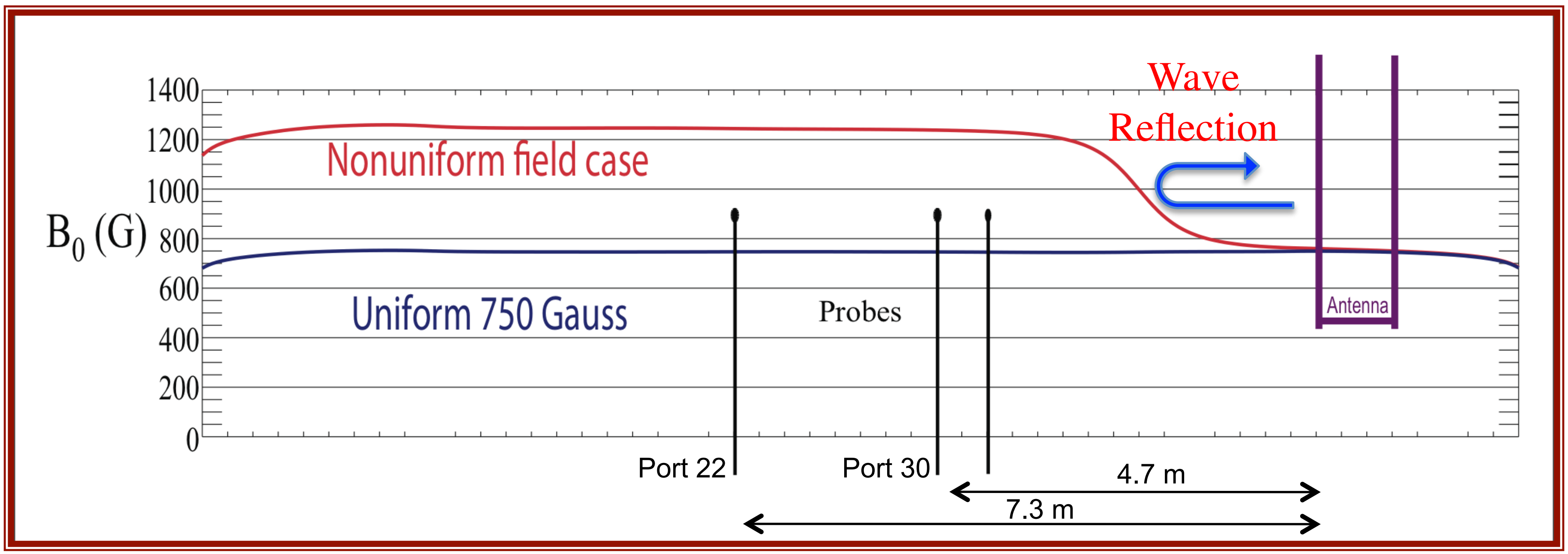
Frequency ω and $k_\perp$ are set by source

Axial cut-off occurs when $\varepsilon_\perp = 0$

For cold ions at $\omega = \sqrt{\dfrac{\omega_{p1}^2 \Omega_2^2 + \omega_{p2}^2 \Omega_1^2}{\omega_{p1}^2 + \omega_{p2}^2}} = \omega_{ii}$

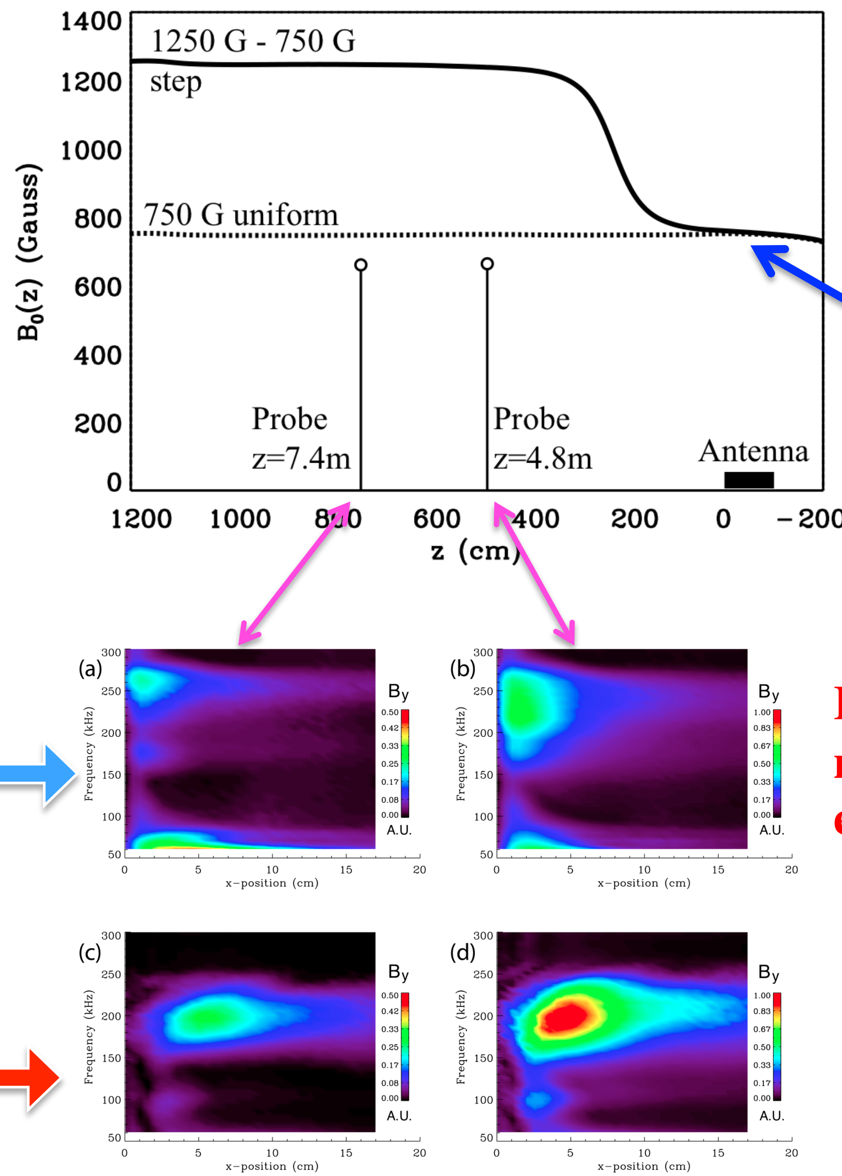
Since $\omega_{ii} \propto B_0(z)$

Waves can be reflected from a magnetic –field ramp



Effect of a magnetic step in a two ion plasma

Experimental configuration



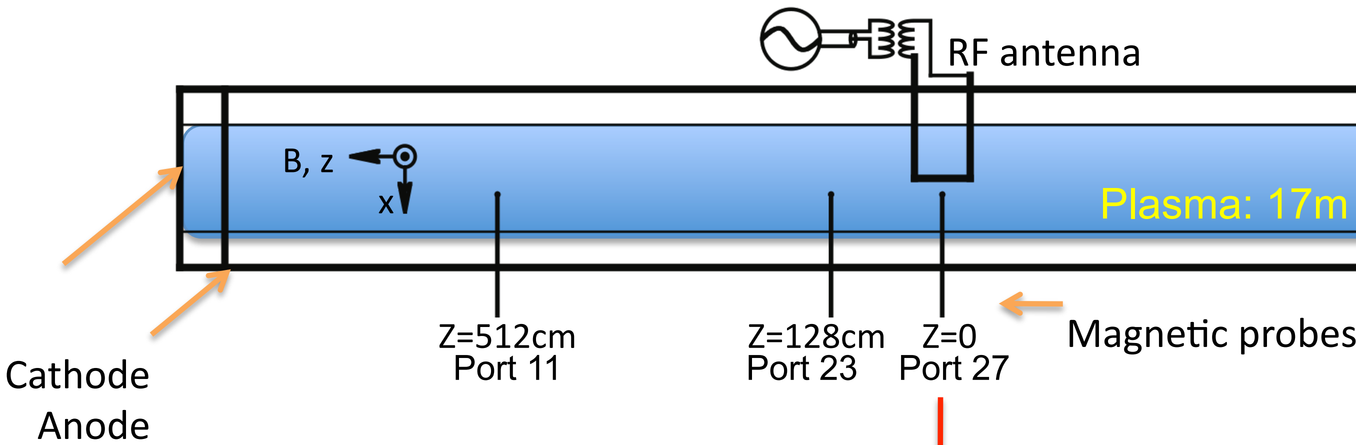
Wave is launched in low field side

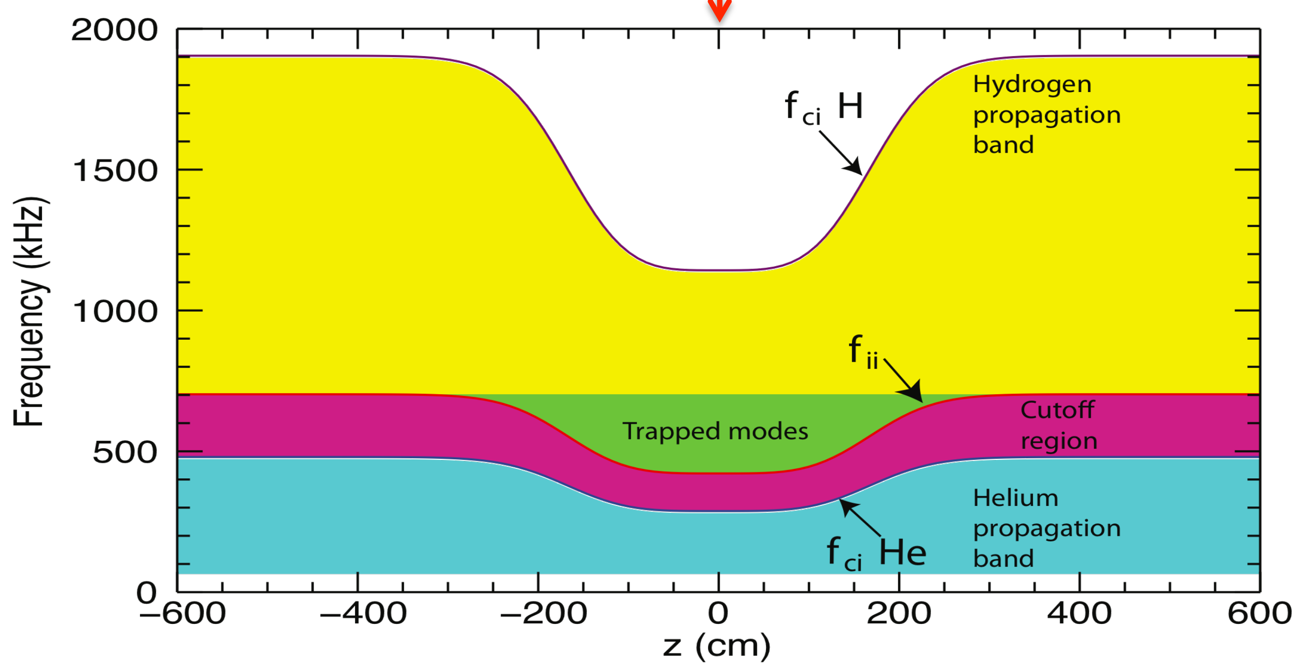
With magnetic step

Lower amplitude and no spreading due to evanescence

Uniform field at 750 G

A resonator can be achieved in a magnetic well





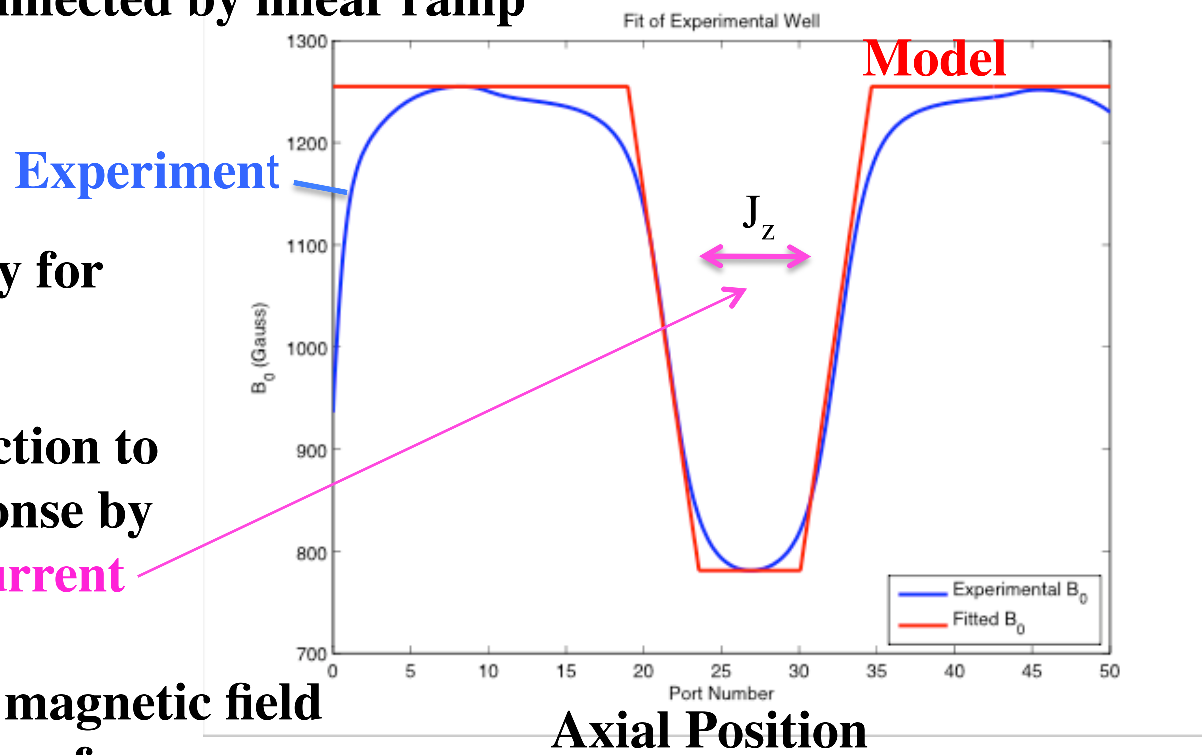
H-He plasma

Theoretical Model

1) Approximate experimental magnetic well by two uniform regions connected by linear ramp

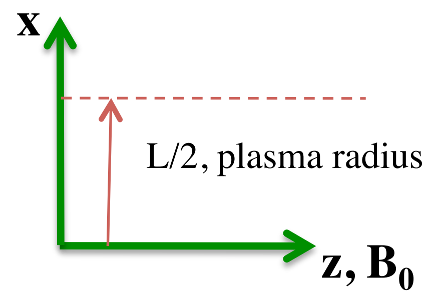
2) Solve analytically for Green's function

3) Use Green's function to obtain driven response by straight antenna current



4) Calculate driven magnetic field as a function of driver frequency

Basic equations in cylindrical geometry (r, z)



$$\frac{\partial^2 E_r}{\partial z^2} - \frac{\varepsilon_\perp}{\varepsilon_\parallel}\left(k_\perp^2 - k_0^2\varepsilon_\parallel\right)E_r = -\frac{k_\perp}{k_0^2\varepsilon_\parallel}\frac{\partial S_z}{\partial z}$$

$$E_z = \frac{1}{k_\perp^2 - k_0^2\varepsilon_\parallel}\left(S_z - k_\perp \frac{\partial E_r}{\partial z}\right)$$

$$B_\varphi = -\frac{ik_\perp}{k_0(k_\perp^2 - k_0^2\varepsilon_\parallel)}S_z + \frac{ik_0\varepsilon_\parallel}{k_\perp^2 - k_0^2\varepsilon_\parallel}\frac{\partial E_r}{\partial z}$$

$$k_0 \equiv \frac{\omega}{c}$$

$$\mathbf{S} \equiv \frac{4\pi}{c} ik_0\mathbf{j}$$

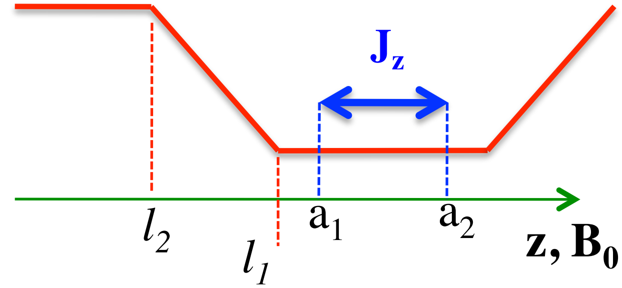
$$\varepsilon_\parallel = 1 - \frac{\omega_{pe}^2}{\omega(\omega + i\nu_e)}$$

Approximate antenna by a line current source at frequency ω

$$j_z(r,z,t) = \begin{cases} j_0\left(\Theta(z-a_1) - \Theta(z-a_2)\right)e^{-i\omega t} & x < R \\ 0 & otherwise \end{cases}$$

$$\tilde{j}_z(k_\perp,z,t) = \frac{Rj_0}{k_\perp}J_1\left(k_\perp R\right)e^{-i\omega t}\left(\Theta(z-a_1) - \Theta(z-a_2)\right)$$

$$\frac{\partial S_z}{\partial z} \propto \delta(z-a_1) - \delta(z-a_2)$$



Matching piecewise analytic solutions at 6 axial boundaries

Solution for Fourier component of electric field $\tilde{E}_x(k_\perp, z)$

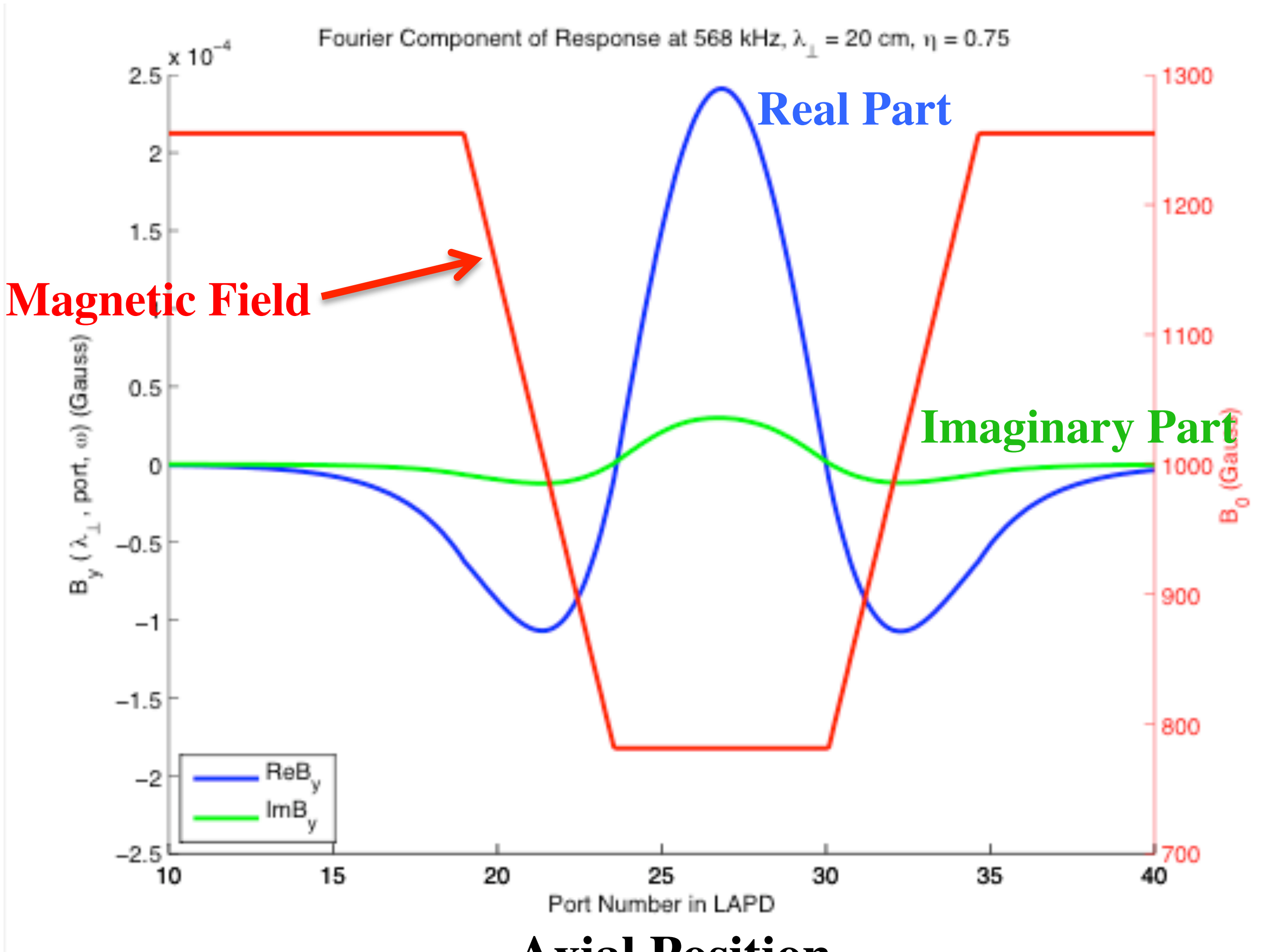
$$\begin{array}{r} \text{Outside well} \\ \text{Reflection layer} \\ \text{Left antenna} \\ \tilde{E}_x(k_\perp, z) = \\ \text{Right antenna} \\ \text{Reflection layer} \\ \text{Outside well} \end{array} \begin{cases} C_1 e^{k_2(z+l_2)} & z < -l_2 \\ C_2 \mathrm{Ai}\left(-\alpha(z+z_0)\right) + C_3 \mathrm{Bi}\left(-\alpha(z+z_0)\right) & -l_2 < z < -l_1 \\ C_4 e^{ik_1(z-a)} + C_5 e^{-ik_1(z-a)} & -l_1 < z < a \\ C_6 e^{ik_1(z-a)} + C_7 e^{-ik_1(z-a)} & a < z < l_1 \\ C_2 \mathrm{Ai}\left(\alpha(z-z_0)\right) + C_3 \mathrm{Bi}\left(\alpha(z-z_0)\right) & l_1 < z < l_2 \\ C_{10} e^{-k_2(z-l_2)} & z > l_2 \end{cases}$$

- **Relate B_{φ} to E_r through Faraday's Law, and invert the Hankel transform using antenna spectrum**

$$B_\varphi(r,z,\omega) = \int_0^\infty \frac{Rj_0}{k_\perp} J_1(k_\perp R) \tilde{B}_\varphi(k_\perp, z) J_1(k_\perp r) k_\perp dk_\perp$$

Eigenfunction of Lowest-Frequency Trapped Mode at 568 kHz

Theory



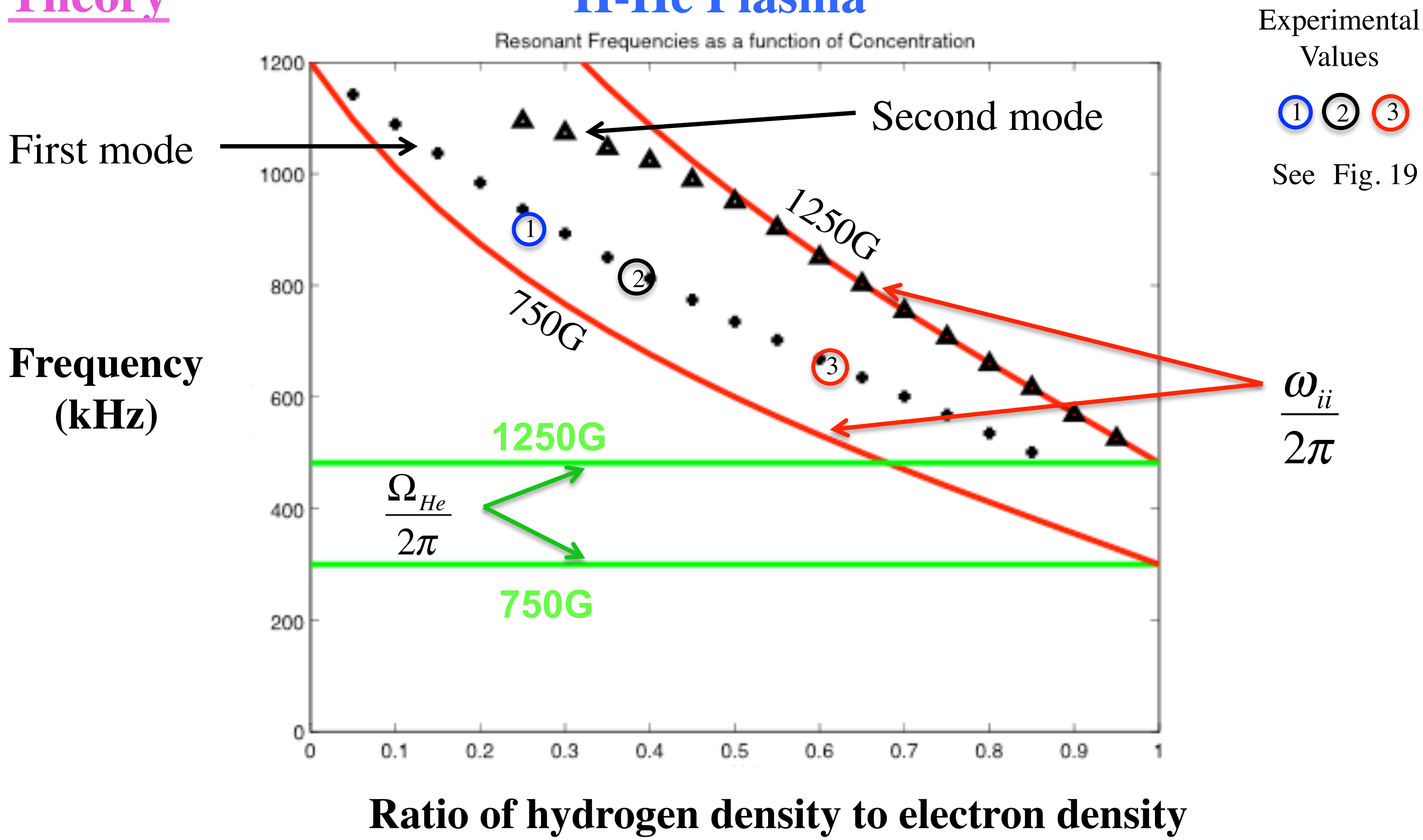
H-He plasma

Axial Position

Dependence of trapped mode frequency on concentration ratio

Theory

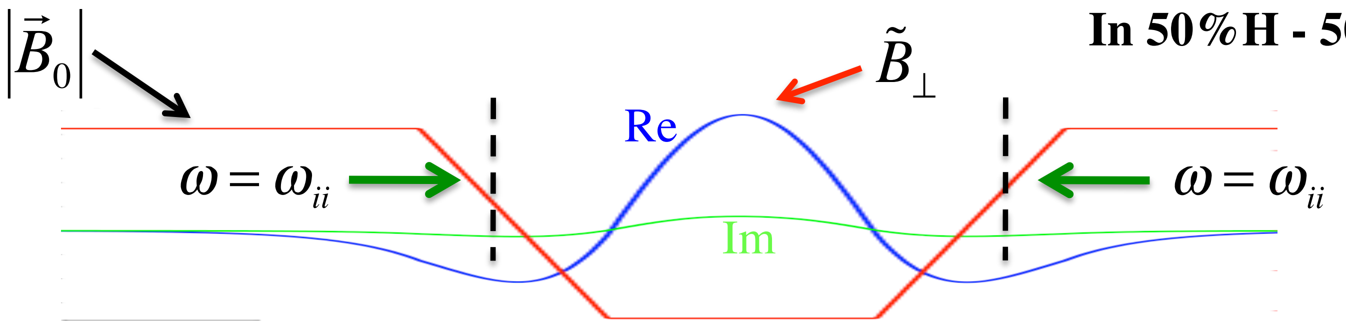
H-He Plasma



Resonator eigenmodes excited by a current pulse in a magnetic well

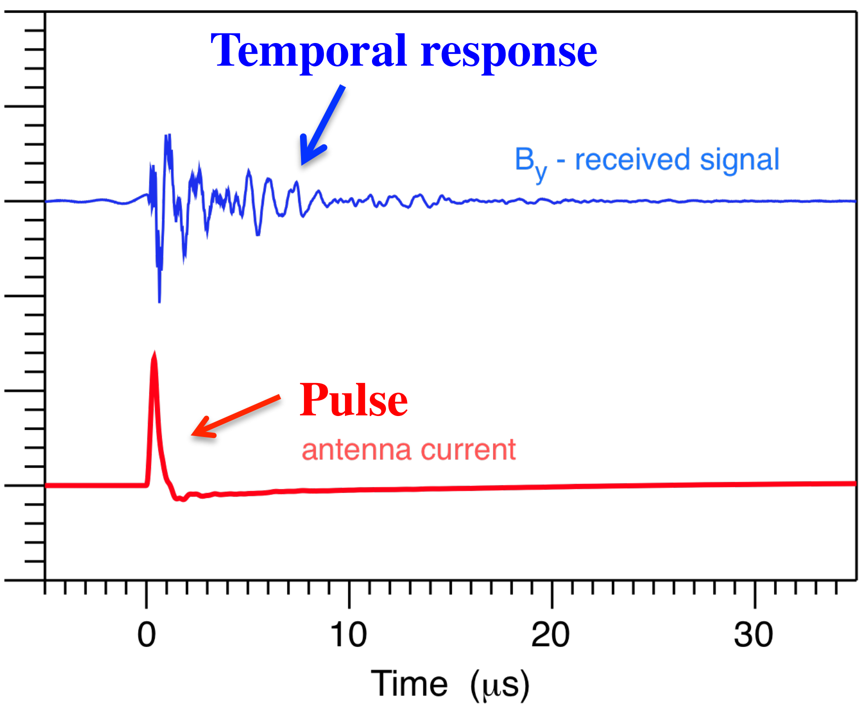
Wave trapping occurs by reflection at ion-ion hybrid resonance

In 50%H - 50%He plasma

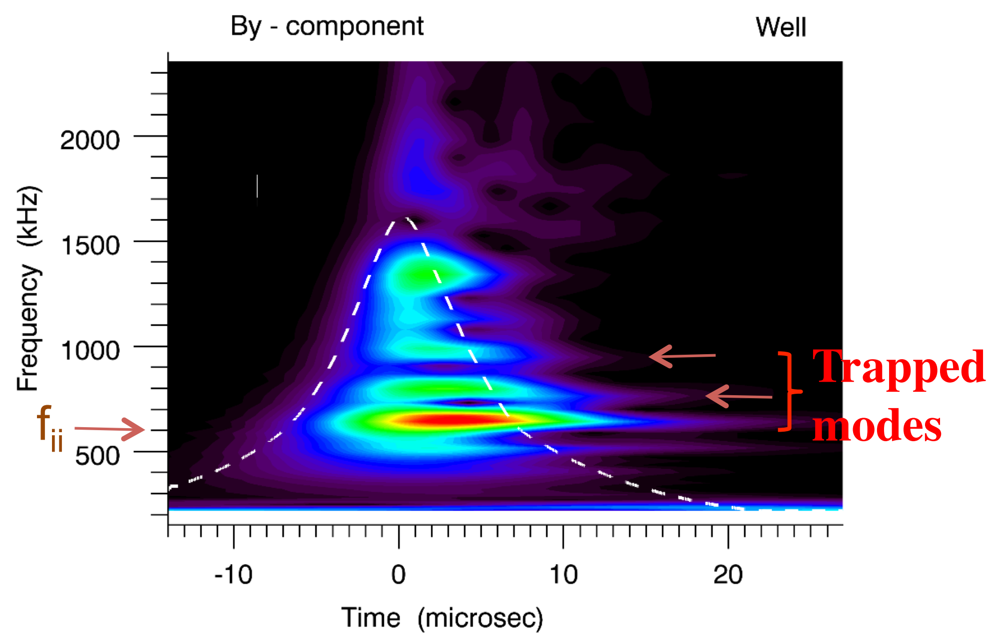


Well (750G - 1250G) - Pulse

r = 10 cm



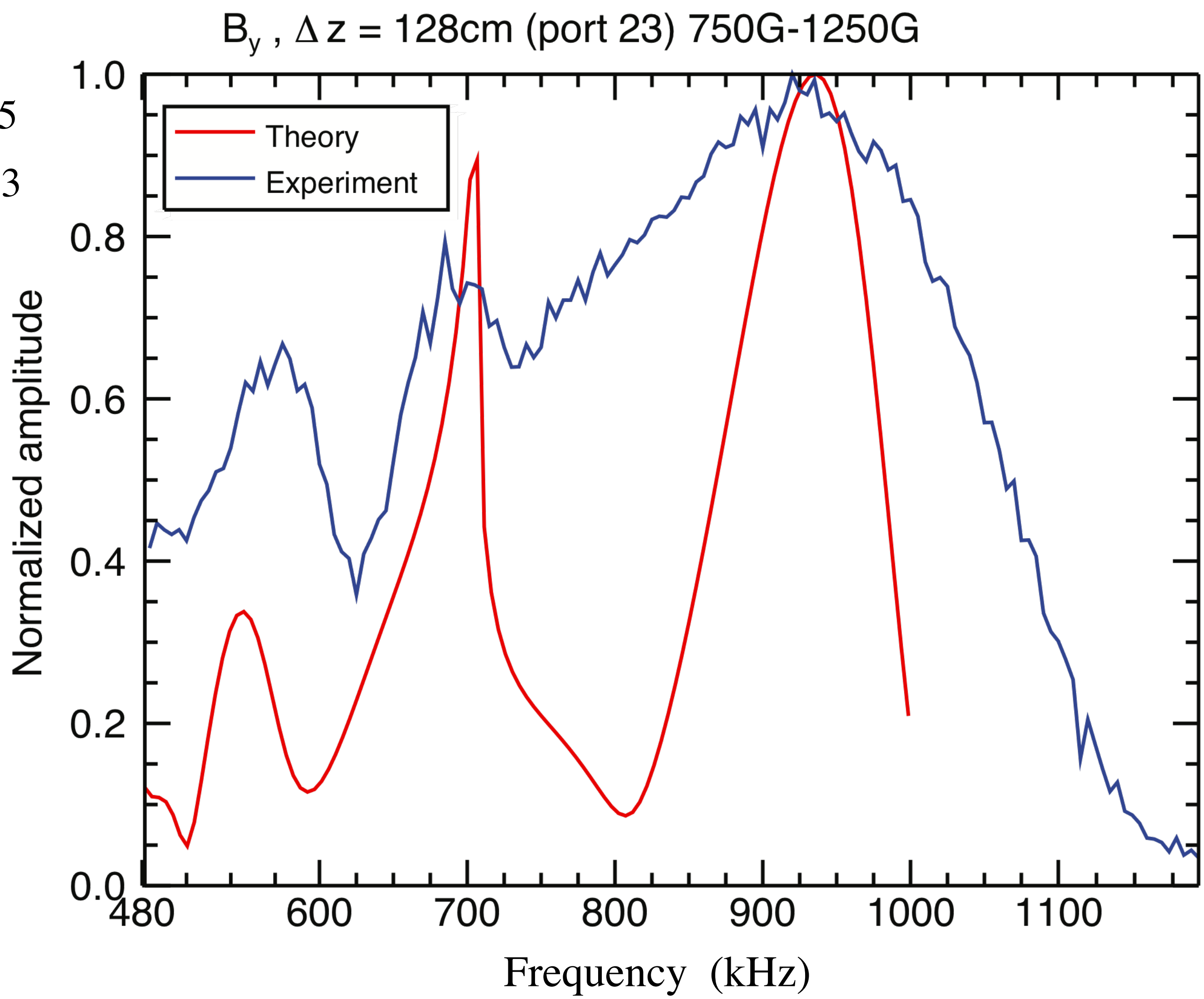
Wavelet analysis



Magnetic field spectra measured inside the magnetic well

$\eta_H = 0.75$

$\mu = -0.3$



Magnetic field spectra measured outside the magnetic well

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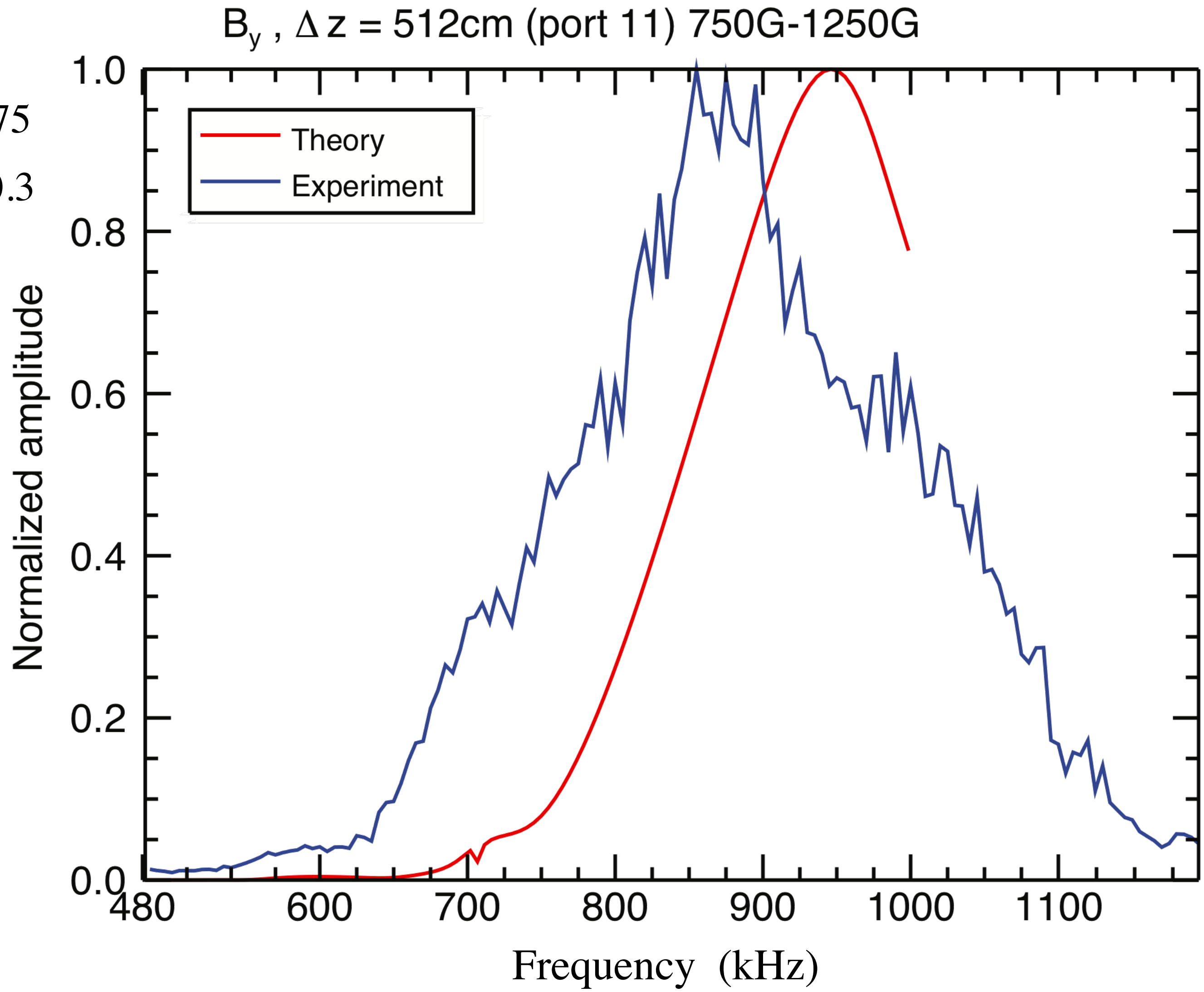
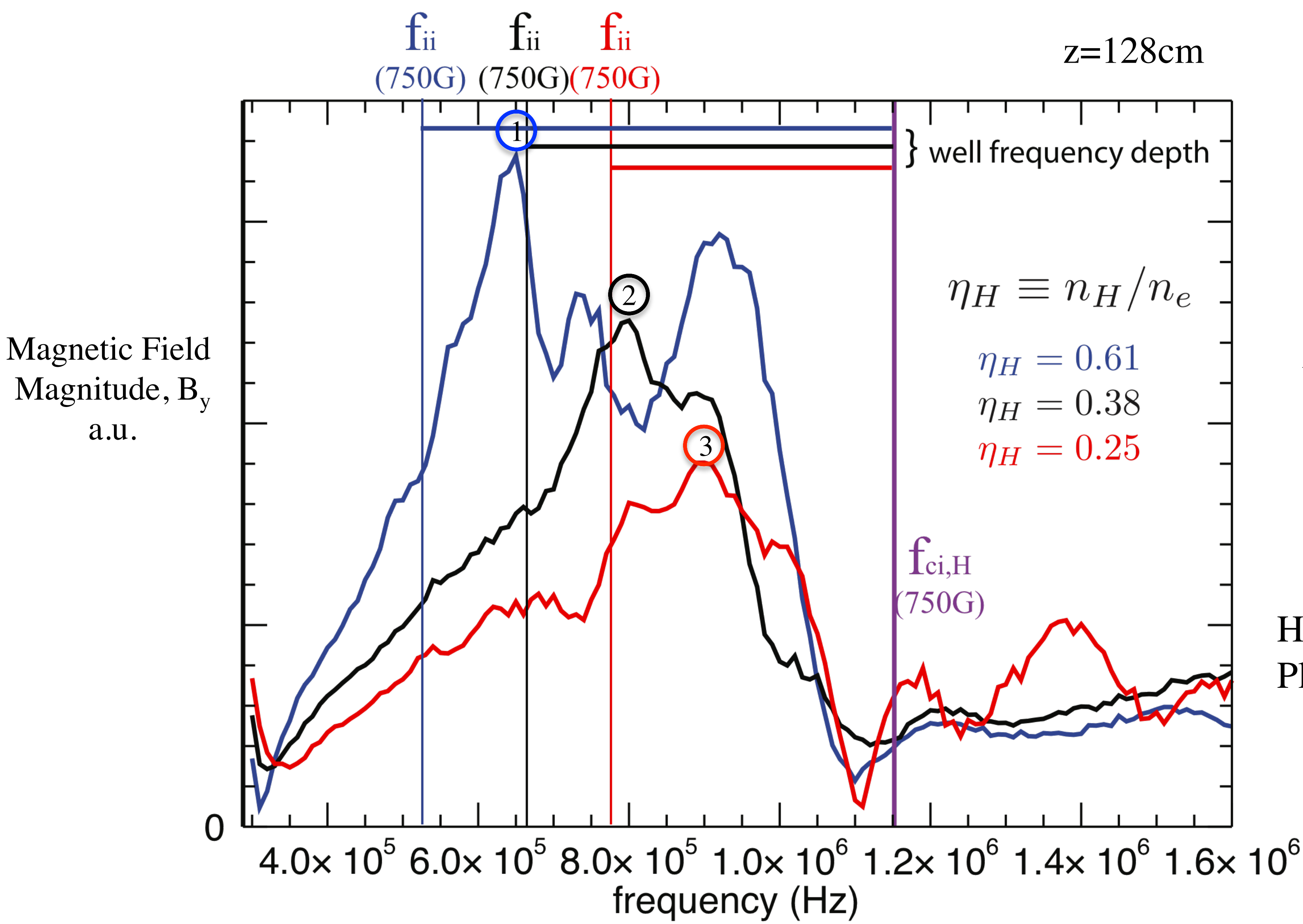


Effect of decreasing hydrogen density (at fixed electron density) on magnetic field spectra inside the magnetic well



1 Denotes Resonant Frequency value shown In Fig. 15.

Perspective on ion-ion hybrid Alfvén wave resonator

- **Experimentally have demonstrated that a magnetic step prevents wave penetration into high-field side --a necessary condition**

- **Pulsed excitation in a magnetic well shows formation of trapped eigenmodes with low "Q" values**

Key issues:

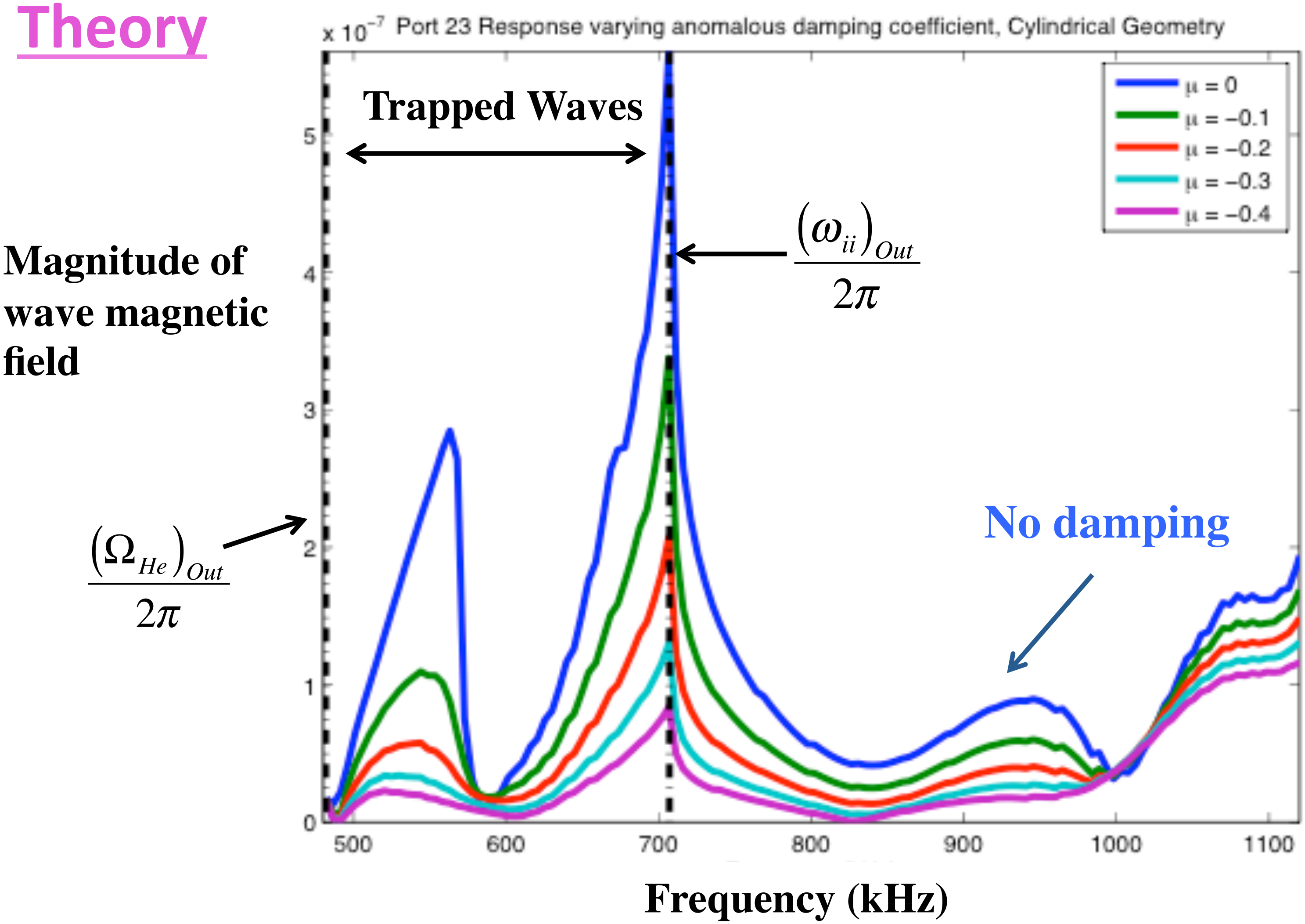
- **How large is the dissipation near the ion-ion hybrid reflection layer ?**
- **Can an ion beam or a plasma current trigger maser behavior?**
- **Nonlinear interaction with ions and electrons**

Extra Slides

Effect of anomalous damping at reflection layer on spectrum

an effective imaginary part is added to $\varepsilon_\perp$ near reflection point

Theory



H-He plasma