Final Report

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Project title: Properties of the ion-ion hybrid resonator in fusion plasmas
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Executive summary:
The project developed theoretical and numerical descriptions of the properties of ion-ion hybrid Alfvén resonators that are expected to arise in the operation of a fusion reactor. The methodology and theoretical concepts were successfully compared to observations made in basic experiments in the LAPD device at UCLA. An assessment was made of the excitation of resonator modes by energetic alpha particles for burning plasma conditions expected in the ITER device. The broader impacts included the generation of basic insight useful to magnetic fusion and space science researchers, defining new avenues for exploration in basic laboratory experiments, establishing broader contacts between experimentalists and theoreticians, completion of a Ph.D. dissertation, and promotion of interest in science through community outreach events and classroom instruction.

Comparison of accomplishments with goals:
The project completed all the initial goals and generated new insights that outline exciting near term investigations. Noteworthy possibilities for follow-up projects include the study via PIC simulations of the interaction of energetic ions with hybrid resonators, basic experiments in LAPD involving a super-Alfvénic ion beam, possibility of relating the resonator modes to alpha channeling processes, and expanding RF-heating codes to incorporate the topology of trapped Alfvén waves along the magnetic field direction. The major accomplishments obtained were: first laboratory identification of an ion-ion hybrid resonator; description of the Cherenkov radiation pattern of shear Alfvén waves in plasmas with two ion species; illustration of the propagation characteristics of Alfvén waves in two ion species plasmas confined by a nonuniform magnetic field; determination of the properties of the ion-ion hybrid resonator for the burning plasmas in ITER.

Summary of project activities:
The project activities resulted in one Ph.D. dissertation (W. Farmer), 5 publications, and 7 conference presentations at major scientific meetings including international conferences: 17th International Congress on Plasma Physics (ICPP), Lisbon, Portugal, Sept. 15-19, 2014; 39th European Physical Society Conference on Plasma Physics joint with 16th International Congress on Plasma Physics (EPS/ICPP 2012), Stockholm, Sweden, July 2-6, 2012; 6th International ITER School, Ahmedabad, India, Dec. 2012. The following provides a brief summary of the major technical accomplishments.

***i)* The ion-ion hybrid Alfvén resonator in a fusion environment**
This investigation of an ion-ion hybrid Alfvén resonator for D-T burning plasma conditions expected in the ITER device was motivated by well-established experimental observations. In a large, linear magnetic confinement device, operating with plasmas having two ion species, shear Alfvén waves have been measured to reflect at the position where the wave frequency equals the

value of the ion-ion frequency [S. T. Vincena, G. J. Morales, and J. E. Maggs, Phys. Plasmas **17**, 52106 (2010).]. In the same device, but operating with a magnetic well configuration, this reflection property has been used to demonstrate the formation of resonator modes [S. T. Vincena, W. A. Farmer, J. E. Maggs, and G. J. Morales, Phys. Plasmas **20**, 012111 (2013).]. In a research tokamak [G. G. Borg and R. C. Cross, Plasma Phys. Contr. F. **29**, 681-696 (1987)], waves launched by a small antenna in a hydrogen-deuterium plasma have been observed to experience guided propagation along field lines, and to exhibit strong poloidal localization determined by the value of the ion-ion hybrid frequency. This phase of the project used analytical and modeling tools to explore how the challenging environment of burning plasmas modify the trapping properties of such modes for parameters expected in the ITER device.

A detailed study of the kinetic dispersion relation for shear Alfvén waves, including coupling to the compressional mode, has been made for the relevant burning plasma conditions. It was identified that the high ion temperatures introduce a variation of the reflection points of the resonator modes with perpendicular wave number. A one-dimensional WKB analysis based on the kinetic dispersion relation was used to determine the eigenfrequencies of trapped modes. It was found that ion cyclotron damping limits the possible resonator modes to a narrow bandwidth (on the order of 500 kHz) above the local ion-ion hybrid frequency on the outboard side of a given magnetic surface. Within this bandwidth several weakly damped resonator modes can be found. The modes experience strong poloidal localization (ranging from 10 to 50 degrees) about the midplane. The spatial amplification of resonator modes driven by energetic, fusion-born alpha particles was considered. The alpha particles were modeled using a ring distribution, which is relevant to the post-birth phase of the alpha particles before collisional relaxation occurs. It was determined that such a ring distribution can effectively couple energy into shear Alfvén modes, resulting in roughly three e-foldings of amplification in one pass through the resonator, as in Fig. 1.

In summary, it has been identified that the presence of an ion-ion hybrid Alfvén resonator has unique signatures that may be sampled in future burning plasma experiments. The results of this investigation have provided clear guidelines for comprehensive studies of related phenomena (e.g., plasma rotation, alpha channeling) that should be based on advanced computational techniques that expand on the present frontier RF codes such as AORSA and TORIC .

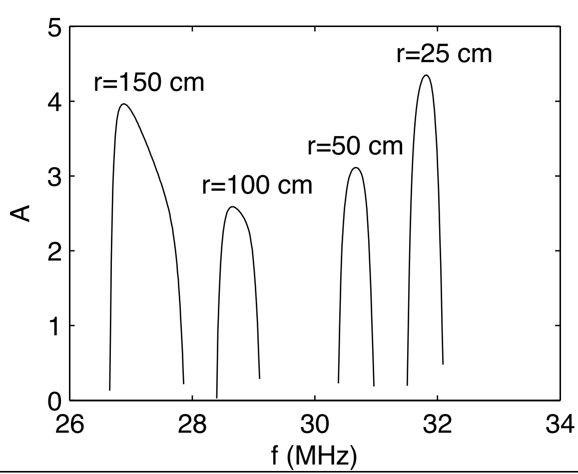

Fig.1. Amplification factors at different radii in ITER. On the horizontal axis is the frequency range of the amplified modes in MHz, and on the vertical axis, the amplification factor. The continuous decrease in the frequency band results in a spread of several MHz over which the resonator can be amplified across the plasma. The increase in A towards the magnetic axis is a geometrical effect, which lengthens the well. The increase towards the edge is due to the colder background plasma.

ii) "Propagation of shear Alfvén waves in two ion species plasmas confined by a nonuniform magnetic field"

Ray tracing calculations were performed for shear Alfvén waves in two-ion species plasmas in which the magnetic field varies with position. Three different magnetic topologies of contemporary interest were explored: a linear magnetic mirror, a pure toroidal field, and a tokamak field. The wave frequency was chosen to lie in the upper propagation band, so that reflection at the ion-ion hybrid frequency can occur for waves originally propagating along the magnetic field direction. Calculations were performed for a magnetic well configuration used in recent experiments [S. T. Vincena, *et al.*, Geophys. Res. Lett. **38**, L11101, (2011); S. T. Vincena, *et al.*, Phys. Plasmas, **20**, 012111 (2013)] in the Large Plasma Device (LAPD) which are related to the ion-ion hybrid resonator. It was found that radial spreading cannot explain the relatively low values of the resonator quality factor (Q) measured in those experiments, even when finite ion temperature is considered. This identifies that a damping mechanism is present that is at least an order of magnitude larger than dissipation due to radial energy loss. Calculations were also performed for a magnetic field with pure toroidal geometry, without a poloidal field, as in experiments being planned for the Enormous Toroidal Plasma Device (ETPD). In this case, the effects of field-line curvature cause radial reflections. A poloidal field is included to explore a tokamak geometry with plasma parameters expected in ITER. When ion temperature is ignored, it is found that the ion-ion hybrid resonator can exist and trap waves for multiple bounces, as seen in Fig. 2. The effects of finite ion temperature combine with field line curvature to cause the reflection point to move towards the tritium cyclotron frequency when electron temperature is negligible. However, for ITER parameters, it is shown that the electrons must be treated in the adiabatic limit to properly describe resonator phenomena.

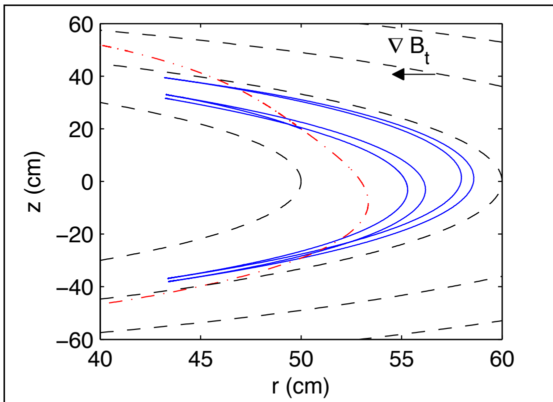

Fig. 2. Poloidal projection of ray trajectories in ITER. Vertical axis represents vertical displacement of a ray from the magnetic axis, and the horizontal axis represents the radial displacement. Black dashed lines are the flux surfaces. Blue line is from the cold plasma dispersion relation, and red line uses the hot-ion dispersion relation. Both rays have an initial perpendicular wave number that points towards the magnetic axis.

iii) "Investigation of an ion-ion hybrid Alfvén wave resonator"

A theoretical and experimental investigation was made of a wave resonator based on the concept of wave reflection along the confinement magnetic field at a spatial location where the wave frequency matches the local value of the ion-ion hybrid frequency. Such a situation can be realized by shear Alfvén waves in a magnetized plasma with two ion species because this mode has zero parallel group velocity and experiences a cut-off at the ion-ion hybrid frequency. Since the ion-ion hybrid frequency is proportional to the magnetic field, it is expected that a magnetic well configuration in a two-ion plasma can result in an Alfvén wave resonator. Such a concept has been proposed in various space plasma studies, and has relevance to mirror and tokamak fusion devices. This study demonstrated the existence of such a resonator in a controlled laboratory experiment using a H^+-He^+ mixture. The resonator response was investigated by launching monochromatic waves and sharp tone-bursts from a magnetic loop antenna. The observed frequency spectra were found to agree with predictions of a theoretical model of trapped eigenmodes, as shown in Fig.3.

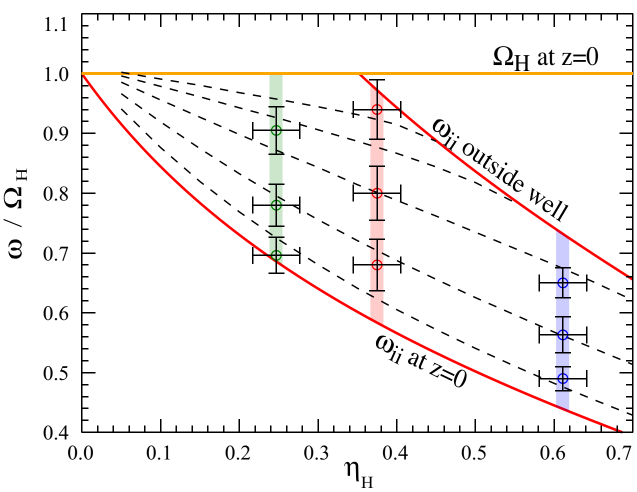

Fig. 3. Comparison of measured eigenfrequencies to theoretical predictions for three ratios of hydrogen-to-electron densities, η_H, in the helium-hydrogen resonator. Frequencies are scaled to the hydrogen cyclotron frequency at the center of the resonator (z = 0). The dashed black lines are the theoretical predictions and the data points are color-coded to the marked peaks in the measured spectra. The solid red and orange lines bound the range of possible eigenfrequencies,

iv) "Cherenkov radiation of shear Alfvén waves in plasmas with two ion species",

A calculation was made of the radiation pattern of shear Alfvén waves generated by a burst of charged particles in a charge-neutral plasma with two-ions of differing charge-to-mass ratios. The wake pattern was obtained for the inertial and kinetic regimes of wave propagation. Due to the presence of two ion-species, the Alfvén waves propagate within two different frequency bands separated by a gap. One band is restricted to frequencies below the cyclotron frequency of the heavier species and the other to frequencies between the ion-ion hybrid frequency, and the cyclotron frequency of the lighter species. The radiation pattern in the lower frequency band was found to exhibit essentially the same properties reported in a previous study [B. Van Compernolle et al., Phys. Plasmas **15**, 082101 (2008)] of a single species plasma. However, the upper frequency band differs from the lower one in that it always allows for the Cherenkov radiation condition to be met. The methodology was extended to describe the Alfvénic wake of point-charges in the inertial and adiabatic regimes. The adiabatic regime was examined for conditions applicable to fusion-born alpha particles in ITER and is illustrated in Fig. 5.

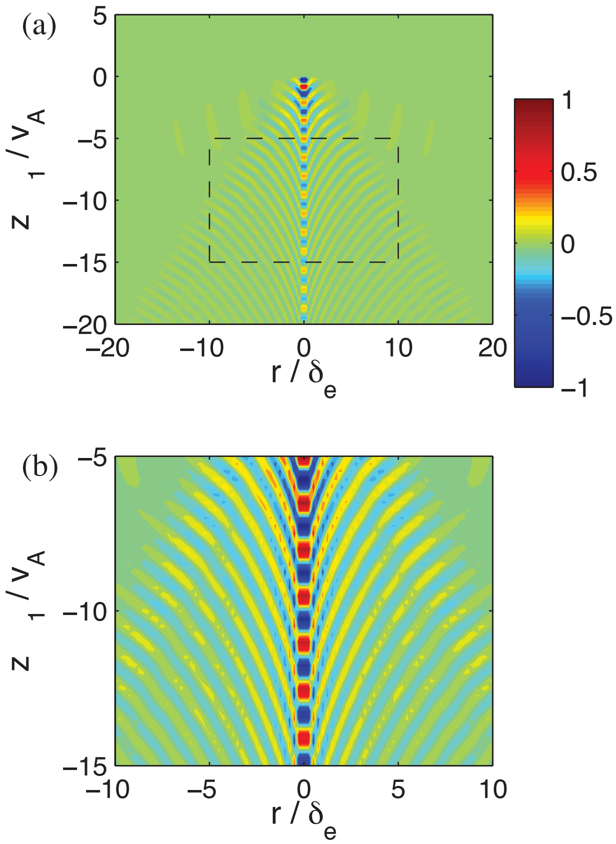

Fig 5. Wake pattern in the adiabatic regime due to a single charge traveling at 1.5 times the Alfvén speed. Background plasma consists of equal concentrations of deuterium and tritium, a situation analogous to a fusion- born alpha particle traveling parallel to the magnetic field in ITER. The parallel wave current along the field line is shown, normalized to its peak value. The bottom panel shows a magnified figure of the region inside the dashed square in the top panel. The radial direction r is scaled to the electron skin depth and the length along the field line z is scaled to the Alfvén wavelength.

Products developed:

i) Publications

1. Farmer, W. A., and Morales, G. J., " The ion-ion hybrid resonator in a fusion environment", Phys. Plasmas 21, 062507 (2014).

2. Farmer, W. A., and Morales, G. J., "Propagation of shear Alfvén waves in two ion species plasmas confined by a nonuniform magnetic field", Phys. Plasmas 20, 082132 (2013).

3. Vincena, S.T., Farmer, W. A., Maggs, J.E and Morales, "Investigation of an ion-ion hybrid Alfvén wave resonator", Phys. Plasmas 20, 012111 (2013).

4. Farmer, W. A., Morales, G. J.,Vincena, S.T., and J. E. Maggs, J. E., "The

ion-ion hybrid Alfvén resonator in a fusion environment", Proceedings of the 39th European Conference on Plasma Physics and 16th Int. Congress on Plasma Physics, Stockholm, 2012, edited by S. Ratynskaya, L. Blomberg, and A. Fasoli (European Physical Society, Stockholm, 2012), p. P.4064.

5. Farmer, W. A. , and Morales, G. J., "Cherenkov radiation of shear Alfvén waves in plasmas with two ion species", Phys. Plasmas 19, 092101 (2012).

ii) Conference presentations

1. Farmer, W. A. and Morales, G.J., "The ion-ion hybrid in a fusion environment", 21st Topical Conference on Radiofrequency Power in Plasmas, Lake Arrowhead, CA, April 27-29, 2015.

2. Farmer, W. A. and Morales, G.J., "Instability of the ion-ion hybrid Alfvén resonator in the presence of superthermal alpha-particles", 56th Meeting of the Division of Plasma Physics of the American Physical Society, New Orleans, Oct. 27-31, 2014.

3. Morales, G.J. and Farmer, W.A., "Shear Alfvén waves in ITER plasmas and the ion-ion hybrid resonator", 17th International Congress on Plasma Physics (ICPP), Lisbon, Portugal, Sept. 15-19, 2014

4. Farmer, W.A., Morales, G.J., "The ion-ion hybrid resonator in ITER", 55th Meeting of the Division of Plasma Physics of the American Physical Society, Denver, Co., Nov. 11-15, 2013, BP8.79.

5. Farmer, W.A., Morales, G.J., Vincena, S.T., and Maggs, J.E., "The ion-ion hybrid Alfvén resonator in a fusion environment", 6th International ITER School, Ahmedabad, India, Dec. 2012.

6. Farmer, W. A., and Morales, G. J., "Cherenkov radiation of shear Alfvén waves in plasmas with two ion species" 54th Meeting of the Division of Plasma Physics of the American Physical Society, Providence, Rhode Island, Oct. 29-Nov. 2, 2012, TP8.00078.

7. Morales, G.J., Farmer, W.A., Vincena, S.T., and Maggs, J.E., "The ion-ion hybrid Alfvén resonator in a fusion environment", 39th European Physical Society Conference on Plasma Physics joint with 16th International Congress on Plasma Physics (EPS/ICPP 2012), Stockholm, Sweden, July 2-6, 2012,P4.064.