Exploring Enhanced Neutron Rate through Simulation

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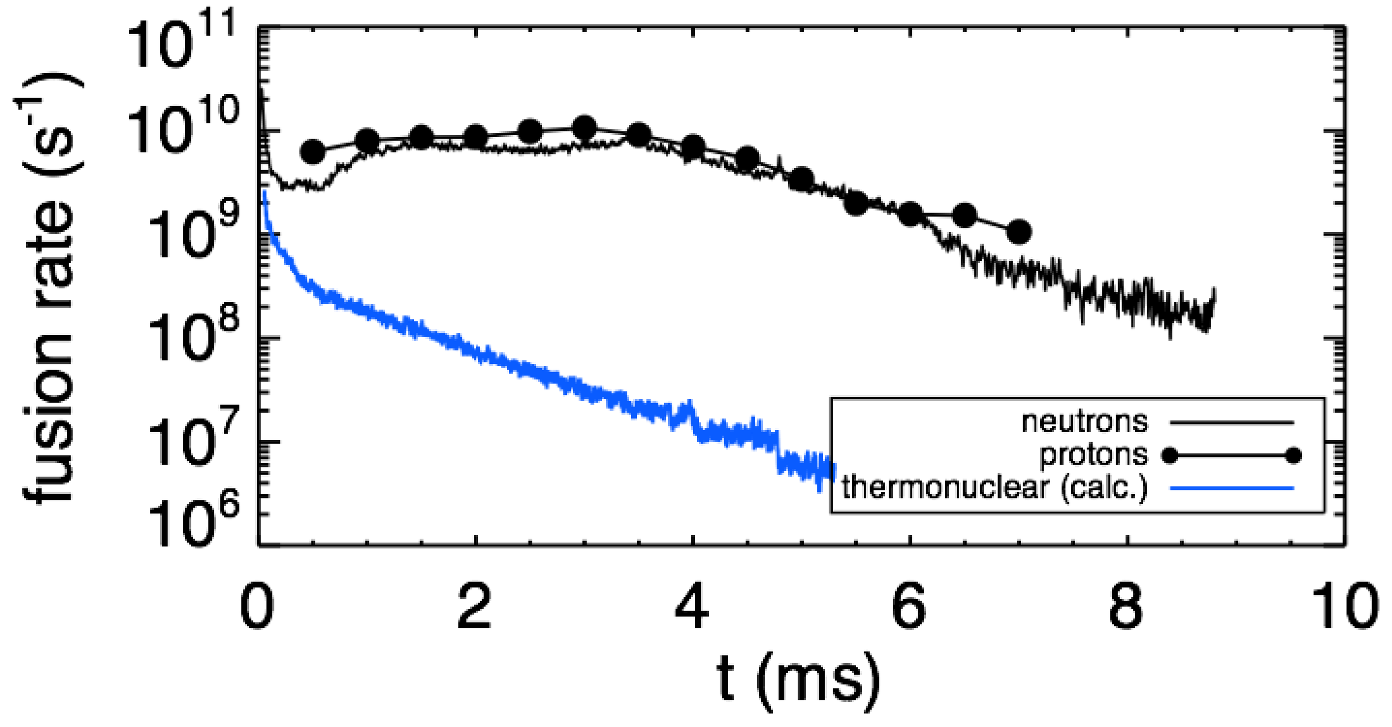
1. Experimental Motivation

- Neutron rate measurements on C2-U experiment consistently show anomalously high values, $\sim 10^2$ higher than theoretical thermonuclear calculation, indicating a fast-ion tail for background deuterium.
- Other measurements (FIR) suggest a beam-driven ion-cyclotron mode is cause of fast-ion tail and is most active at FRC radius of 45 cm. Mode is high-phase velocity and non-destructive, similar to wakefield phenomenon.
- 1D implicit PIC simulations reproduce fast-ion tail.
- Mode onset can be catalyzed by RF-maintained modulation ("bunching") of beam density[1].



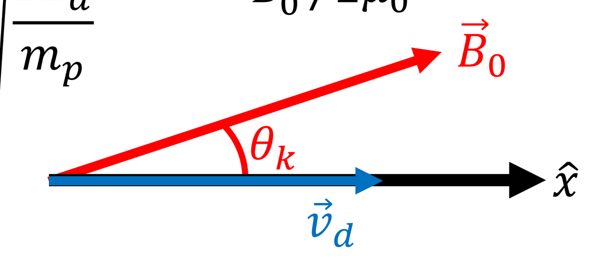
2. Simulation Setup

- Implicit PIC code LSP—allows high-beta plasmas to be simulated very fast
- Uniform background magnetic field $\vec{B}_0$
- Background uniform plasma of deuterons and heavy electrons ($m = 20m_e$)
- Plasma parameters mimic 45 cm in C2-U FRC
- 1D domain near-parallel to B_0 (also wave propagation angle)
- Hydrogen ion beam initialized with drift parallel to B_0

Plasma Parameters

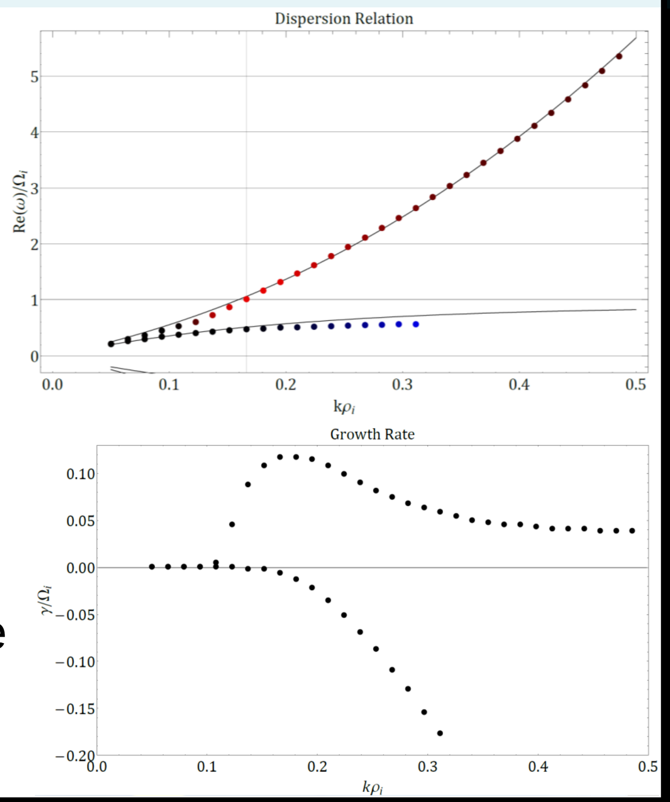
B_0	$T_{i,e}$	T_b	θ_k
0.075 T	200 eV	500 eV	10°
E_d	n_e	n_b	β_i
15 keV	7E18 m^{-3}	$0.1n_e$	10%

$$v_d = \sqrt{\frac{2E_d}{m_p}} \qquad \beta_i = \frac{n_e T_i}{B_0^2/2\mu_0}$$



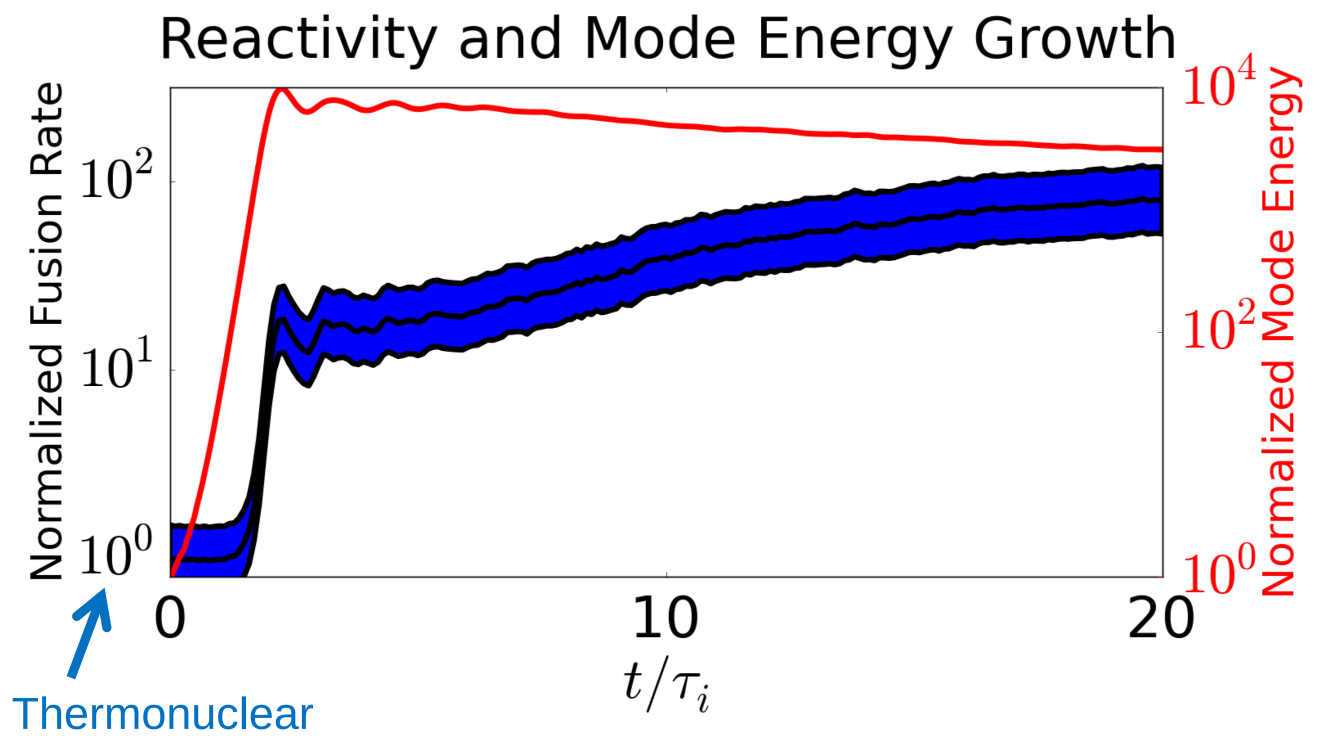
3. Theory

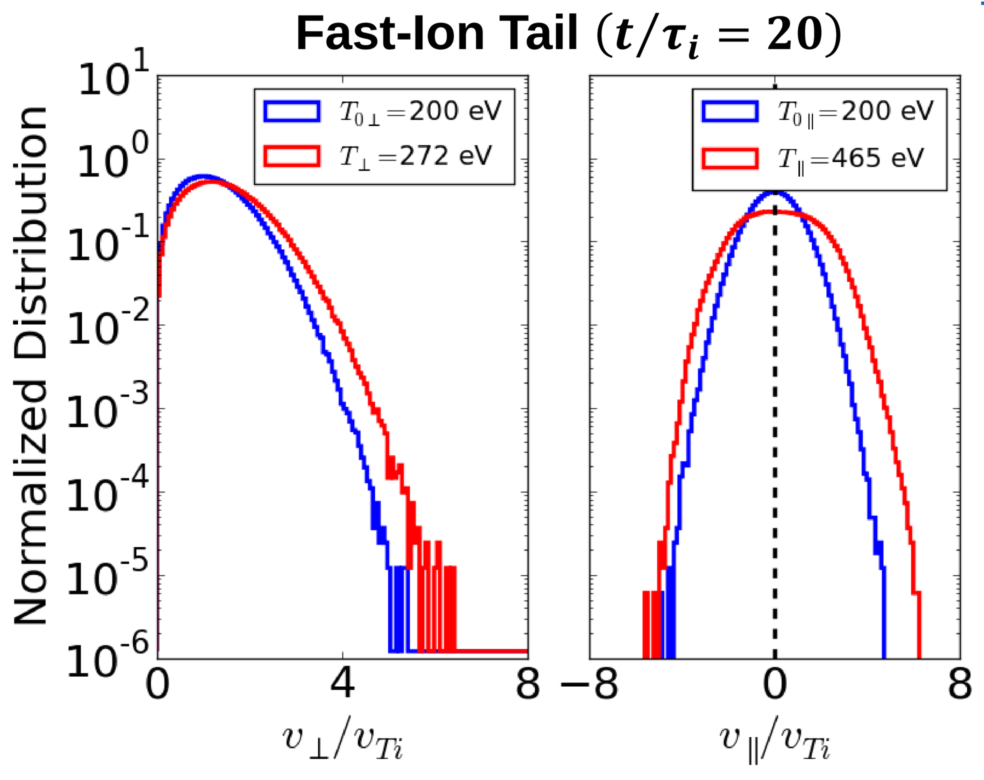
- Semi-analytical solver of linear dispersion tensor.
- For 45 cm parameters, right-hand resonant mode[2] is fastest-growing on deuteron cyclotron frequency.
- Mode derives from right-handed beam resonance condition
- Mode generates fast-ion tail in nonlinear interaction via cyclotron acceleration.
- Robust fast-ion generation despite weak coupling between right-handed wave and ions.

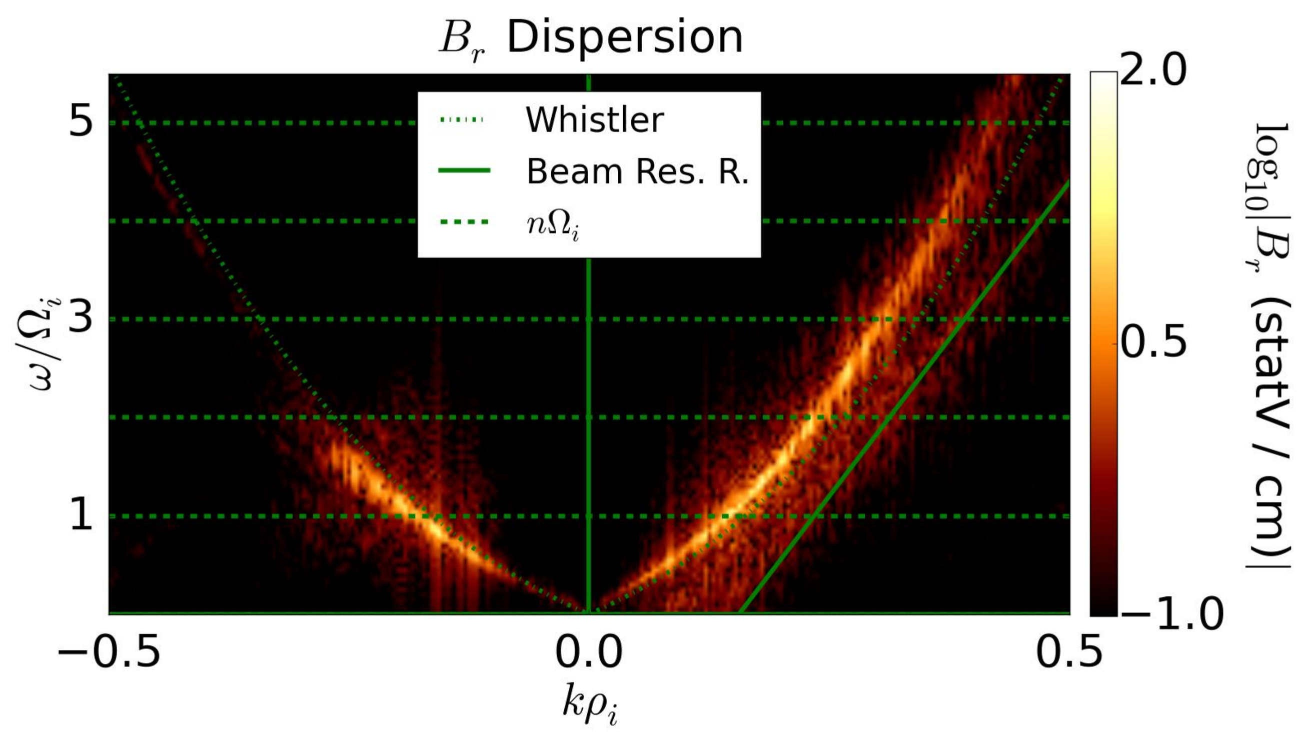


4. Simulation

- Robust mode growth followed by development of fast-ion tail after delay
- Reactivity grows by $\sim 10^2$
- Mode activates extended portion of right-handed Alfven mode (whistler), but is dominant at deuteron cyclotron fundamental.
- Sub-dominant backwards-propagating mode present as well. This mode may be related to left-handed beam resonance condition.







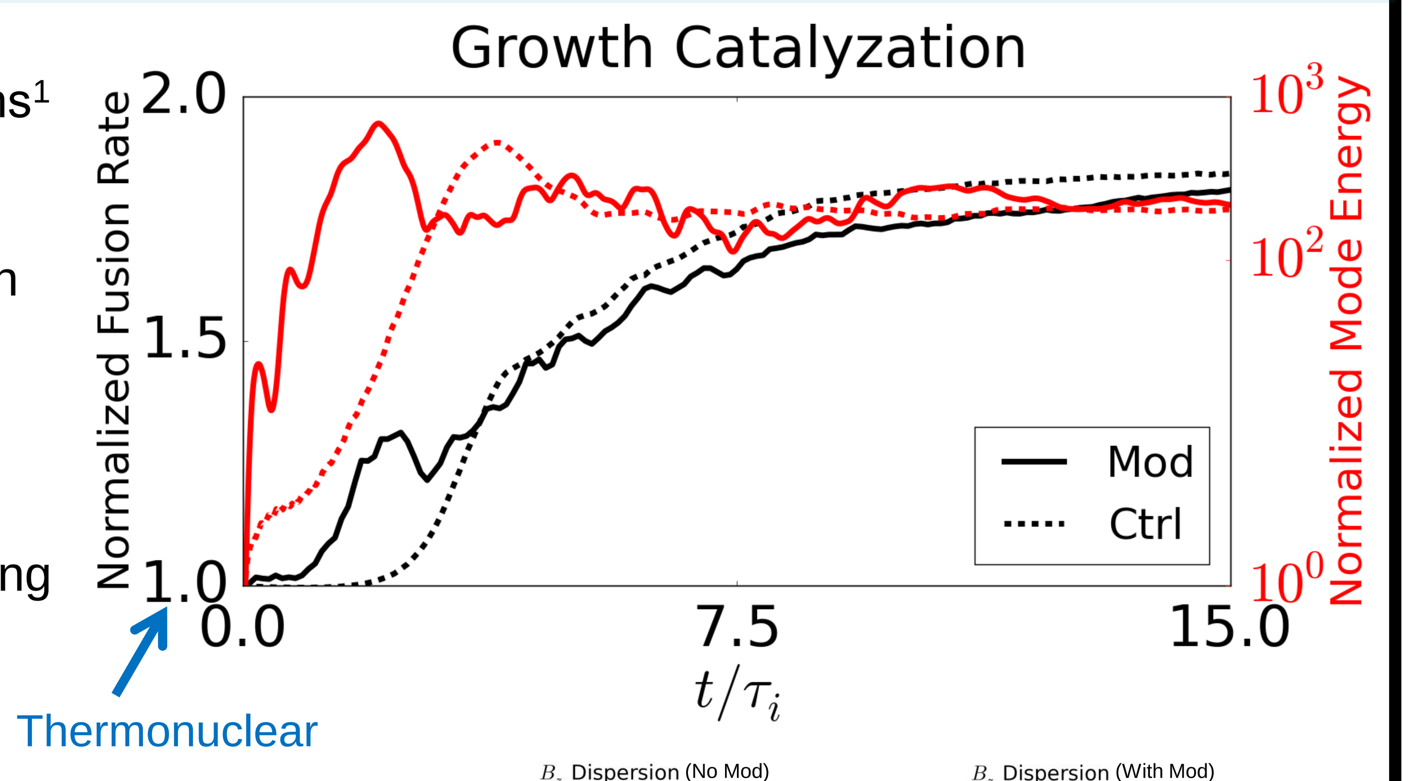
5. Simulation in B. Richter Vision

Setup

- Original idea of Burton Richter to use "bunched" beams[1]
- Beam density given sinusoidal spatial modulation according to formula in plot (right)
- n_b^0 is base beam density, n_b^1 is amplitude of modulation
- k_m is wave-vector of fastest-growing mode

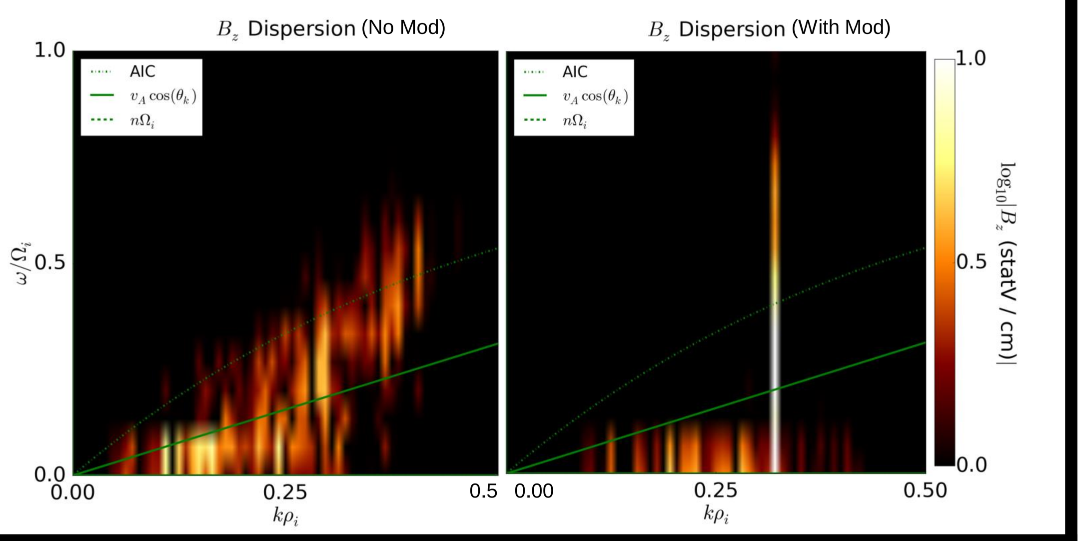
Discussion

- Mode grows substantially more quickly than in un-modulated case, but saturation level is unchanged
- Wakefield and RF could sustain modulation, maintaining plasma in non-equilibrium Higgs' state.
- Most applicable to narrow resonances in k; mode that form large respond weakly to single modulation k



Plasma Parameters

B_0	$T_{i,e}$	T_b	θ_k	θ_b
0.04 T	500 eV	500 eV	70°	70°
E_d	n_e	n_b^0	n_b^1	β_i
15 keV	5E18 m^{-3}	$0.1n_e$	0.5	63%



6. Summary and Future Work

- 1D PIC simulations can reproduce fast-ion tails—and therefore increased neutron rate—through beam-driven modes and others.
- By seeding the beam with a spatial density modulation at a particular wavenumber k, the onset of a particular mode can be catalyzed significantly, though most successfully for modes with narrow k range.
- RF techniques could be used in experiment to form and maintain ion beam modulation and wakefield, sustaining the high-energy Higgs' plasma state.
- More constraining data is obtained from experiment will clarify the theoretical picture of enhanced neutron production and narrow the possible modes.
- For future work, 2D, and possibly even 3D, PIC simulations can give a more physically accurate picture of beam-driven modes.

References

1. B. Richter, (1966). Design Considerations for High Energy Electron -- Positron Storage Rings. United States.
2. S. Peter Gary, *et al.*, The Physics of Fluids **27**, 1852 (1984)