Recalling Diamagnetic Cavities: Experiments, Theory, Simulations

Dan Winske
Los Alamos

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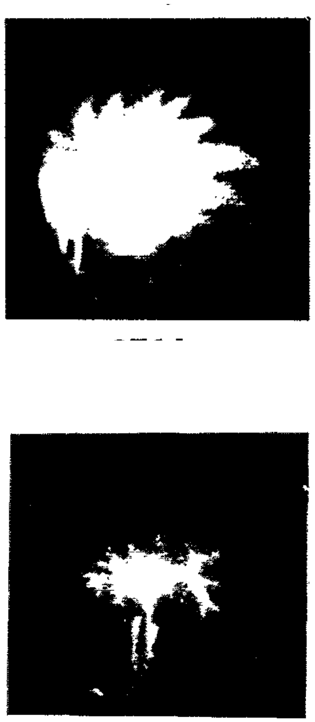
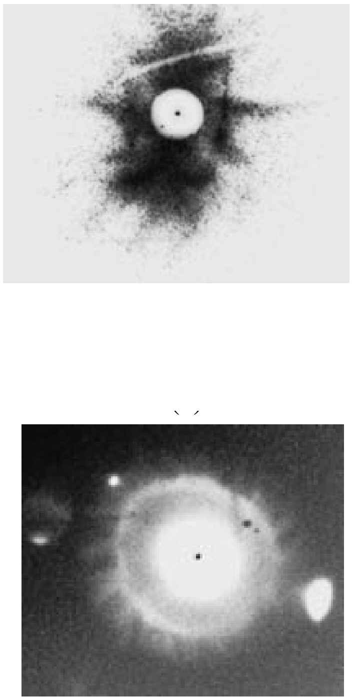
Outline

- Experiments – Diamagnetic cavities and flute modes
- Linear theory – local and nonlocal
- Simulations – full particle, hybrid, fluid
- Conclusions – where we were in 1992
- Unresolved issues – suggestions for new work

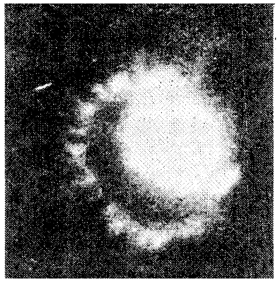
Many Experiments Produced Diamagnetic Cavities With Surface Flute Modes



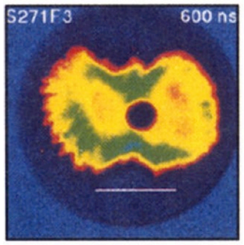
Ripin…



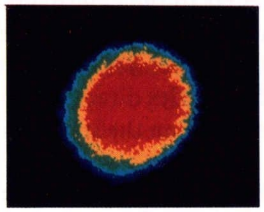
Zakharov….



Okada…



Dimonte…



Bernhardt…

Basic Physics of Cavity Formation

- Energetic ions expand ($M_A < 1$)* into low density magnetized plasma:

$$E_o = \frac{1}{2} M V_i(t)^2 + \frac{B^2}{8\pi}\frac{4\pi R(t)^3}{3} \quad \rightarrow \quad t=0, V_i = V_d, R=0 \Rightarrow V_i = 0, R = R_B = (6E_o/B^2)^{1/3}$$

- Ions compress into thin shell as they expand and slow—stopped by B field:

$$g(t) = -\frac{dV_i(t)}{dt} = \frac{B^2}{2M} R(t)^2$$

- In 2-D:

$$V_i(t) = V_d \cos(V_d t/R_B), \quad R(t) = R_B \sin(V_d t/R_B)$$

and reaches maximum size at

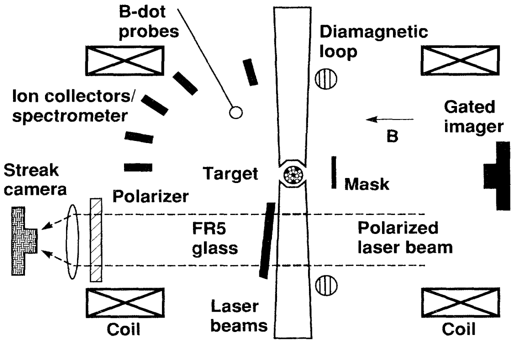
$$V_d t/R_B = \pi/2 \quad \Rightarrow \omega_{ci}\, t = \frac{\pi}{2}\frac{R_B}{\rho_i}$$

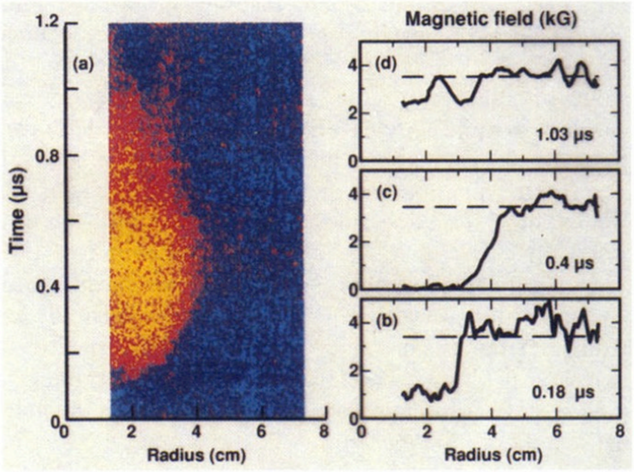
so $\rho_i / R_B > 1 \quad \Rightarrow$ ions are unmagnetized.

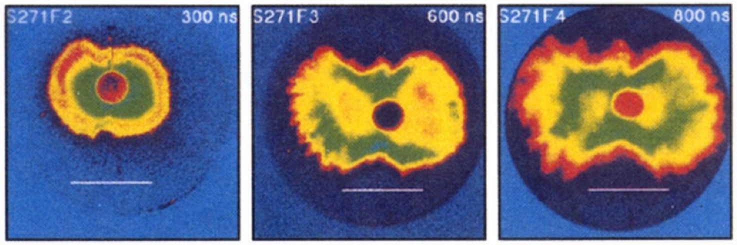
* For $M_A > 1$, physics is *much* different [Chris Niemann's talk!]

Example – Experiments of Dimonte & Wiley (1991)

- Well-developed cavities
- Well-formed flute modes on surface

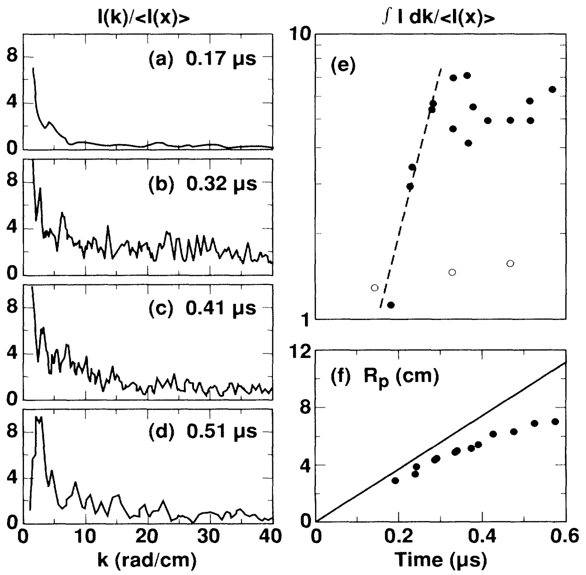


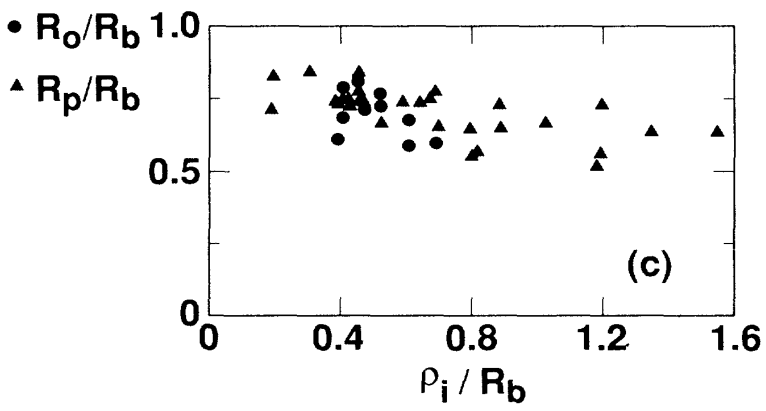




Experiments of Dimonte & Wiley (cont'd)

- Initially short wave-length modes, λ ~ L_n, λ increases in time
- Cavity size decreases with ρ_i/R_B, larger flutes





Linear Theory Predicts Excitation of Short Wavelength (~ Lower Hybrid) Flute Modes

- Experiments show expanding plasma compresses into a thin shell – use local slab model
  - Unmagnetized ions; cold, magnetized electrons
  - Work in ion frame – electrons E×B drift relative to ions

$$eE_r = -m_i g - T_i / L_n \quad [L_n = -n_i/(dn_i/dx)]$$

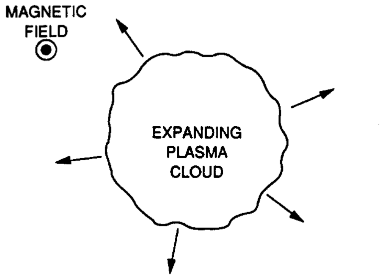
$$V_E = -cE_r/B_o = V_g + V_n$$

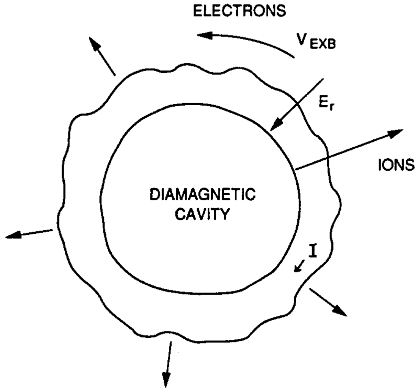
- Can also include finite T_e, finite β_e, collisions, etc.

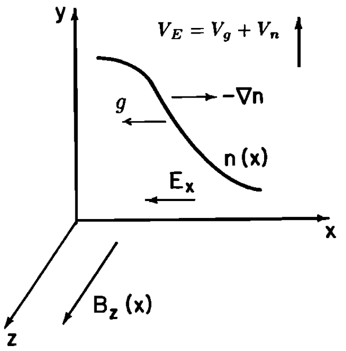
- Other ways to derive the instability: Hall –MHD (Hassam & Huba), better equilibrium (Gary & Thomsen) and compare with usual Rayleigh-Taylor instability:

$$\gamma_{kin} = k(gL_n)^{1/2} \quad \Leftrightarrow \quad \gamma_{MHD} = (g/L_n)^{1/2}$$

- “Unmagnetized ion Rayleigh-Taylor instability”, “Generalized lower-hybrid-drift instability”, “Kinetic interchange instability”







Local, Linear Theory (cont'd) – Example (1988)

- Example of linear theory results -- parameters:

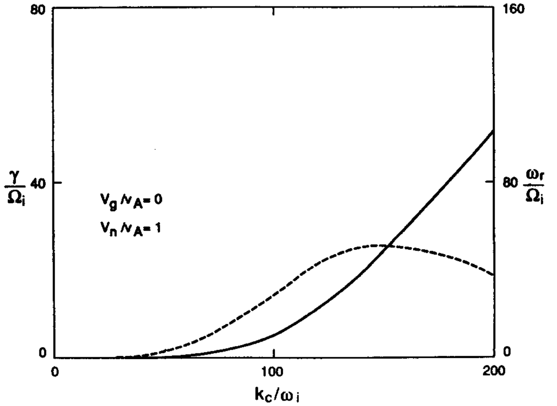
$$\beta_i = 0.2,\ m_i/m_e = 1836,\ c/v_A = 200,\ L_n = 0.1\, c/\omega_{pi}$$

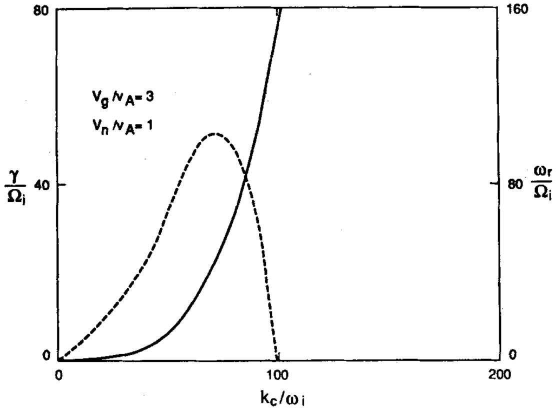
$$\Rightarrow v_i = 0.45 v_A,\quad \omega_{LH} = 43\omega_{ci},\quad kv_i/\omega_{LH} = 0.01(kc/\omega_{pi})$$

- Addition of V_g increases γ and decreases k:

$$\gamma \sim \omega_r \sim \omega_{LH} \sim kV_E$$

- But theoretical wavelengths corresponding to maximum growth are too short compared with experiments:
  - e.g., AMPTE $(\lambda_{obs} \sim 40\, km,\ \lambda_{lin} \sim 2\, km)$

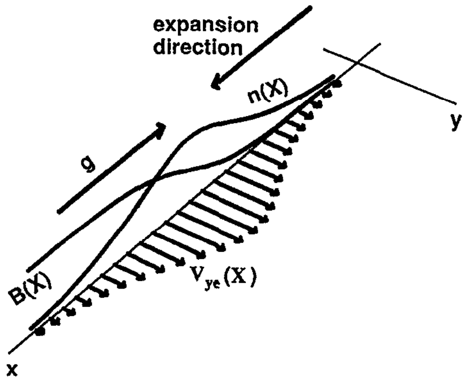


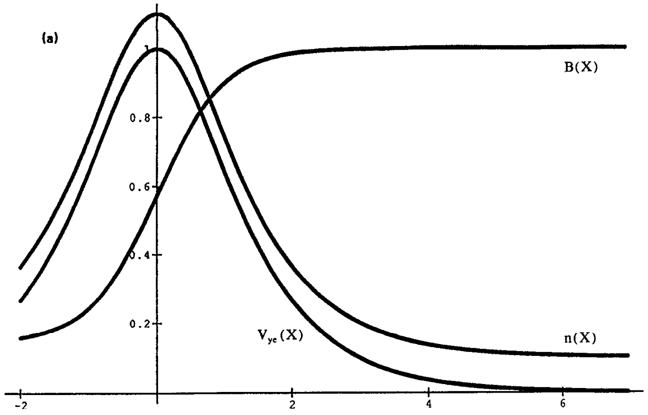


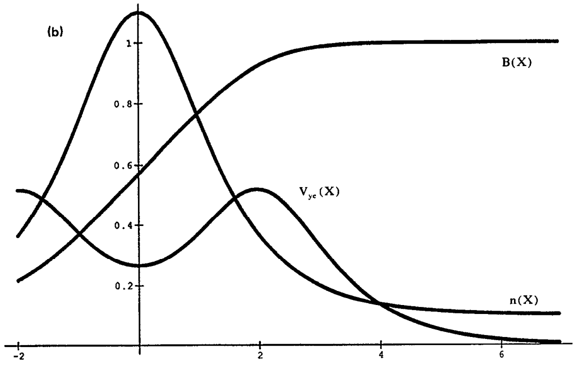
Nonlocal Linear Theory – Gladd & Brecht (1991)

- Choose different velocity profiles for $V_E(x)$:
  - But recall: $V_E(x) = V_n(x)+V_g(x)$ –> n(x) gives V_n (x), but what is g(x)?

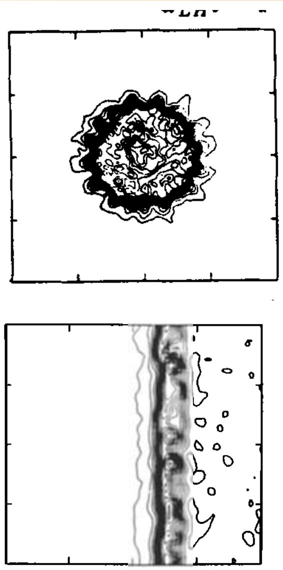
- But most rapidly growing modes still grow at very short wavelengths, $\omega_r \sim \omega_{LH} \sim kV_E$





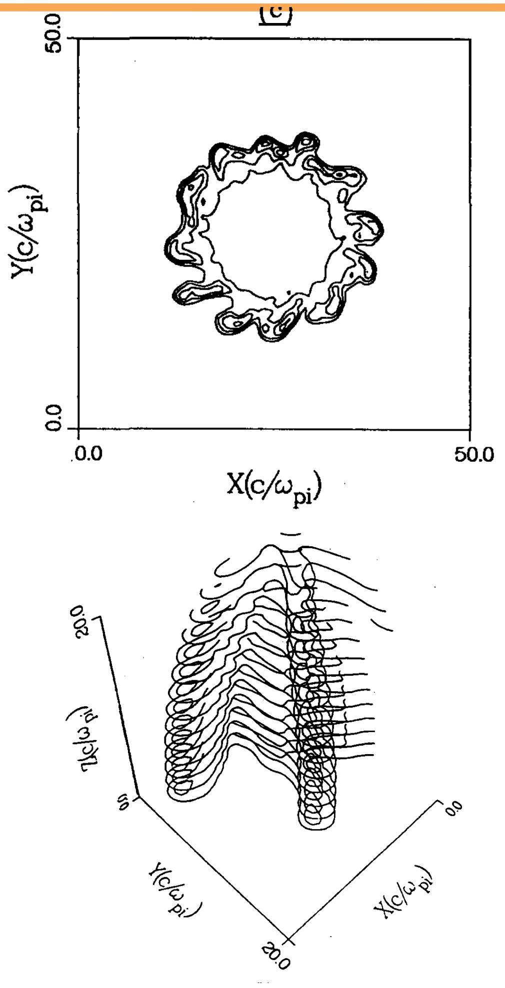


Many Different Simulations Were Done to Model the Experiments

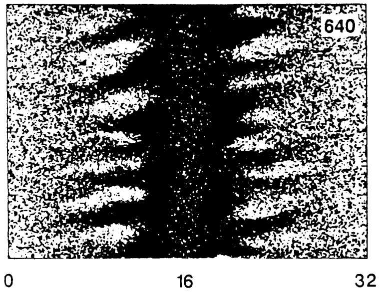


Winske

Huba…



Brecht…



Sgro…

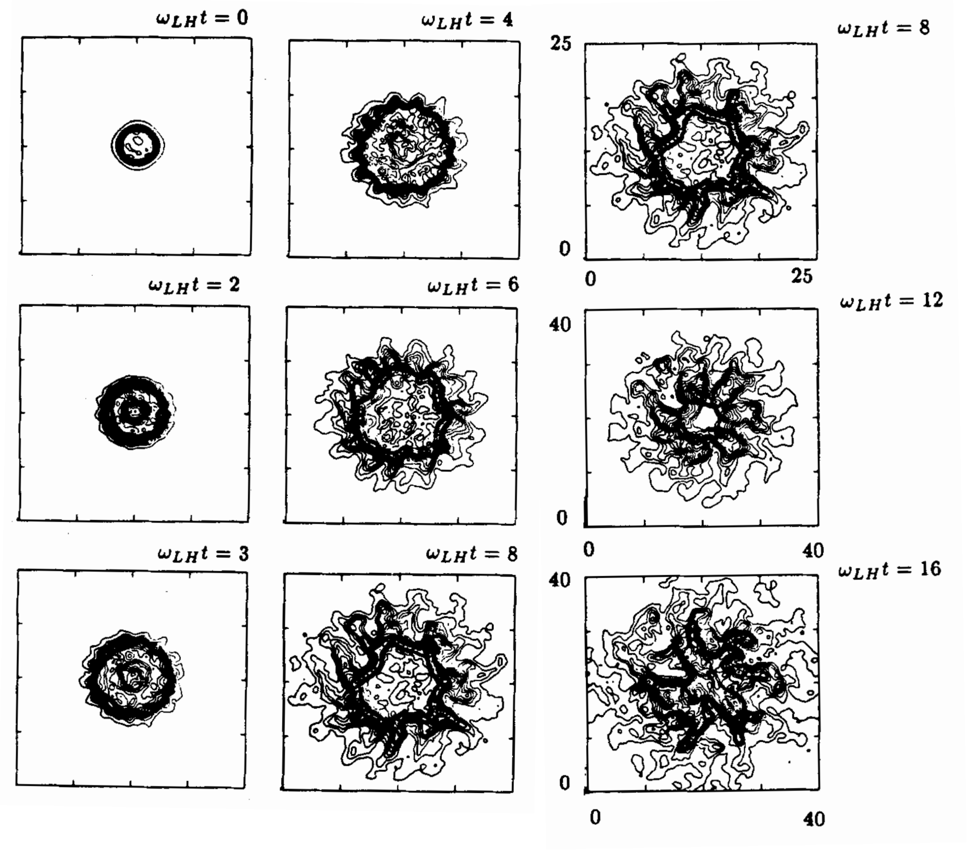
Full Particle Simulations (1988-1989)

- Parameters:

  $25\times25\ c/\omega_{pe}$, $250\times250\ cells$,

  $200{,}00\ ions\&\ electrons$

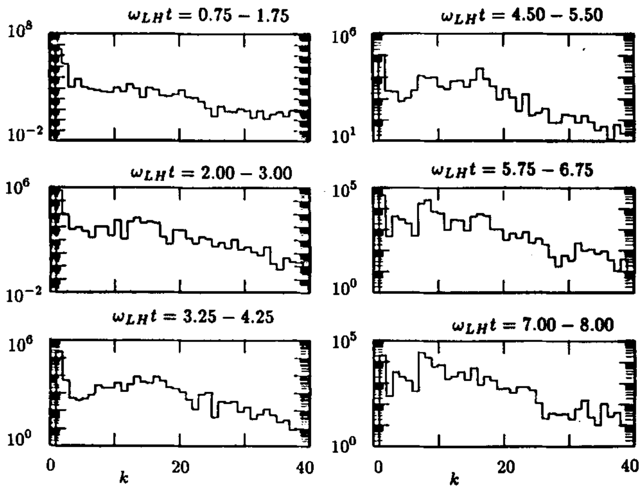
- Instability develops early, evolves to longer wavelengths, flutes continue to evolve as cavity collapses.
- Issues:
  - Fastest growing modes resolved?
  - Instability onset?

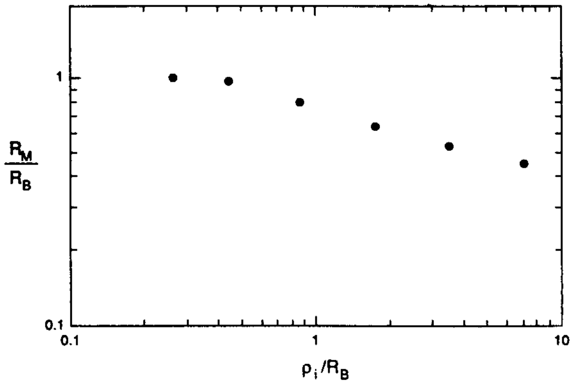


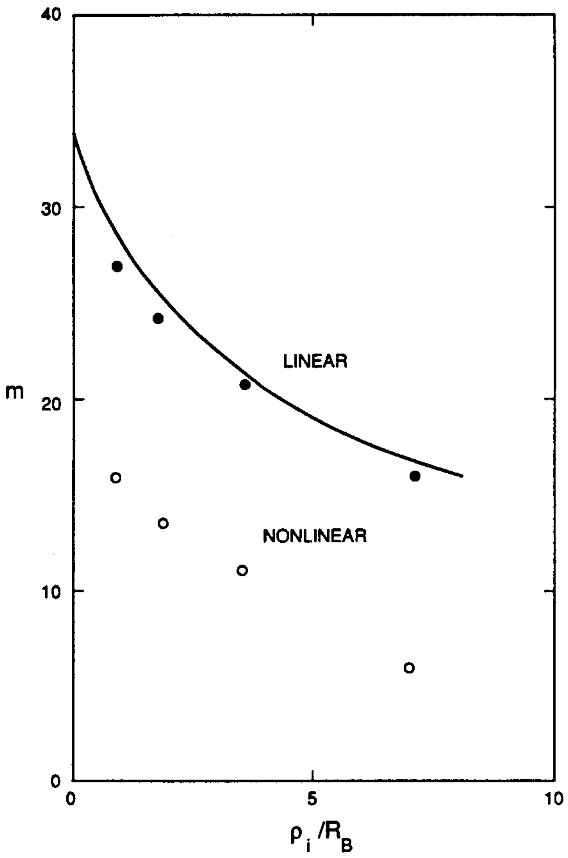
Full Particle Simulations (cont'd)

- Wavelengths in nonlinear regime are ~ 2-3 longer
- Cavity size decreases with ρ_i/R_B
- High wave saturation levels (driven system)

$$E^2_{sat-sim} >> E^2_{wave-bnd} > E^2_{ion-trap}$$





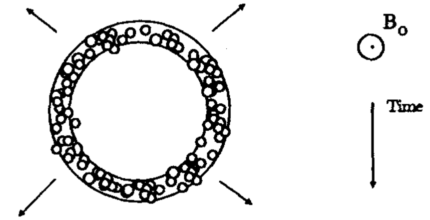


Where We Were in 1992

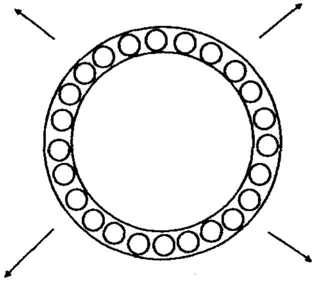
- Many experiments were done: 1980-1995
  - $M_A < 1$ expansions → cavities and flute modes,
  - Basic scaling with ρ_i/R_B .

- Extensive linear theory
  - Usually slab geometry and local, some nonlocal calculations,
  - Basic instability mechanism understood,
  - Predicted wavelengths too short compared to experiments (~ 3-15).

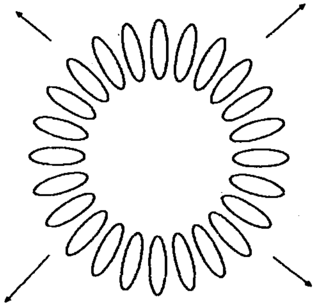
- Many, mostly 2-D simulations
  - Gave basic agreement w/ experiments, linear theory,
  - Resolution at early times?
  - Linear vs nonlinear effects?
  - 2D vs 3D .



Linear Regime: Small Scale Structure



Nonlinear Regime: Large Scale Structure

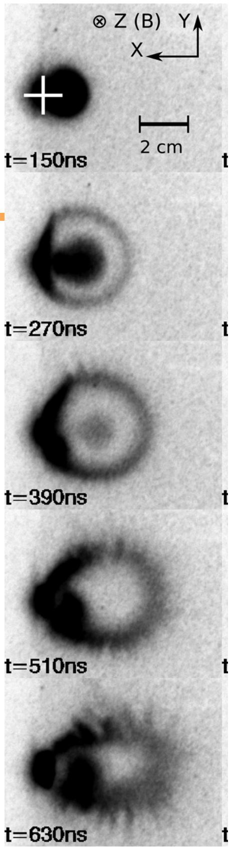


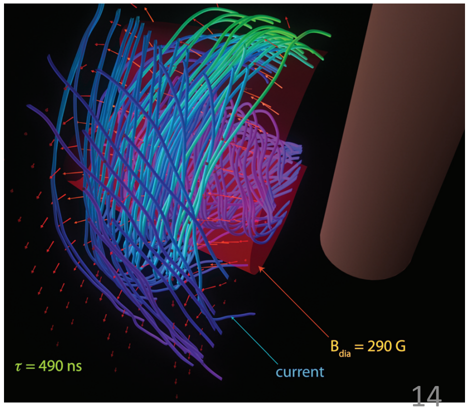
Huba … 1990

Going Forward…

- New laboratory experiments:
  - Better plasmas, lasers
  - Much better diagnostics

- New simulations (3-D PIC):
  - 3-D gives more realistic g(t)
  - When do waves first appear (better resolution)?
  - How do waves evolve (coalescence, wave-wave…)?
  - Wave amplitudes, other nonlinear processes?
  - Long-time evolution.





Collette & Gekelman, 2011

Abstract

From the mid 80's to mid 90's there was considerable interest in the generation of diamagnetic cavities produced by the sub-Alfvenic expansion of heavy ions. Examples included the AMPTE and CRRES barium releases in the magnetotail and magnetosphere as well as laser experiments at NRL. In all of these experiments field-aligned striations and other structures were produced as the cavities formed. Local and nonlocal linear theory as well as full particle, hybrid and Hall-MHD simulations (mostly 2-D) were developed and used to understand at least qualitatively the features of these experiments. A brief review of the theoretical and computational work will be given and then will be discussed in the context of present-day interest in magnetic cavities.

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