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Three-Dimensional EMHD Simulation Studies of Nonlinear Magnetic Structures in Magnetized Plasmas.

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Three-Dimensional EMHD Simulation Studies of Nonlinear Magnetic Structures in Magnetized Plasmas

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Outline

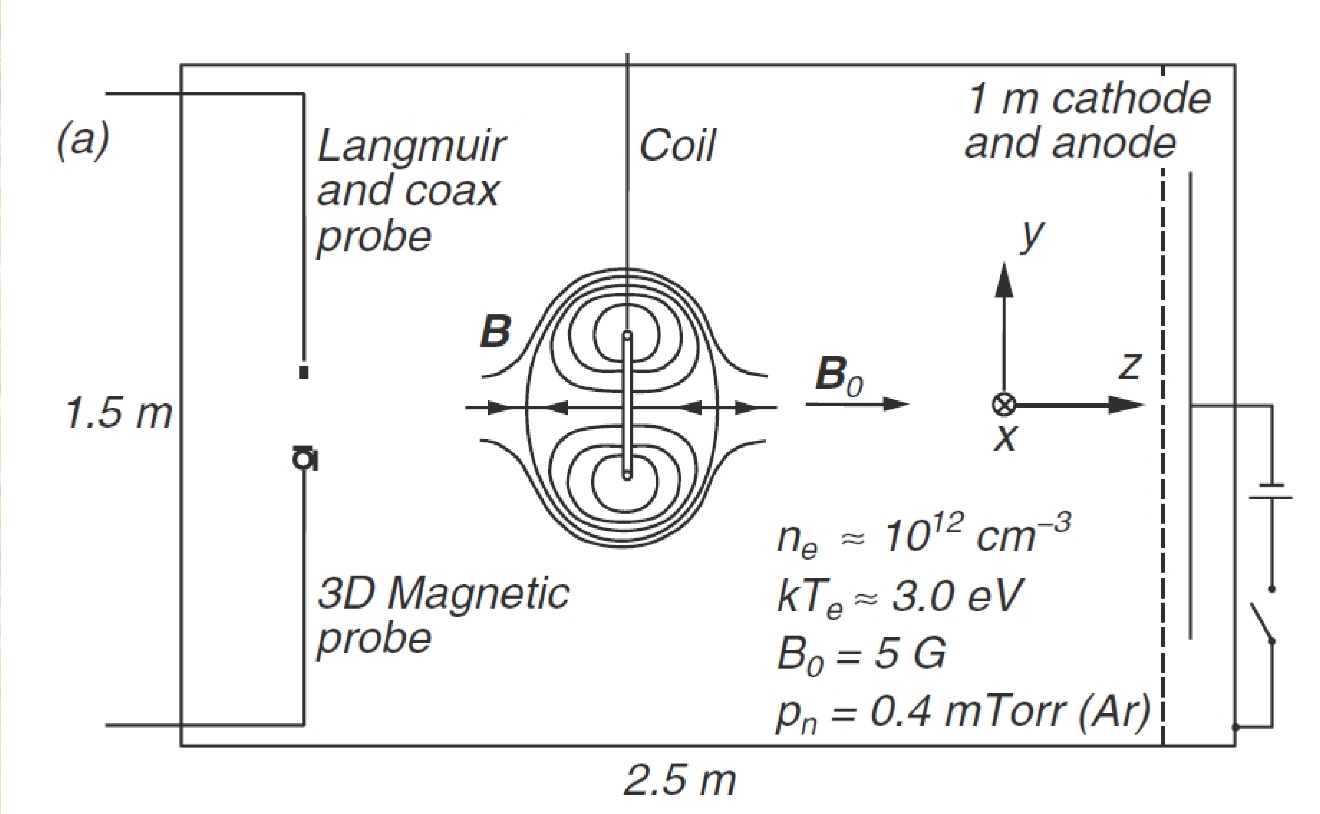
A. Observations of large-amplitude whistler spheromaks in laboratory

B. Electron magnetohydrodynamic (EMHD) model

C. Numerical results and comparison with experiments

D. Discussion

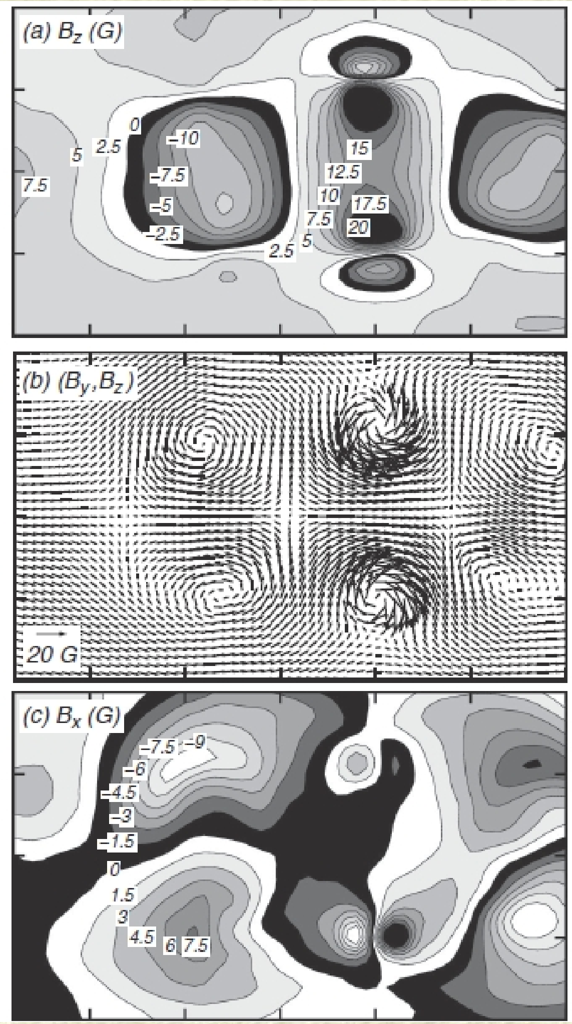
Experimental setup



$$\omega_{ce} = 10^8\,\mathrm{s}^{-1}, \quad \omega_{pe} = 10^{11}\,\mathrm{s}^{-1}, \qquad \lambda_e = c/\omega_{pe} = 5\ \text{mm}$$

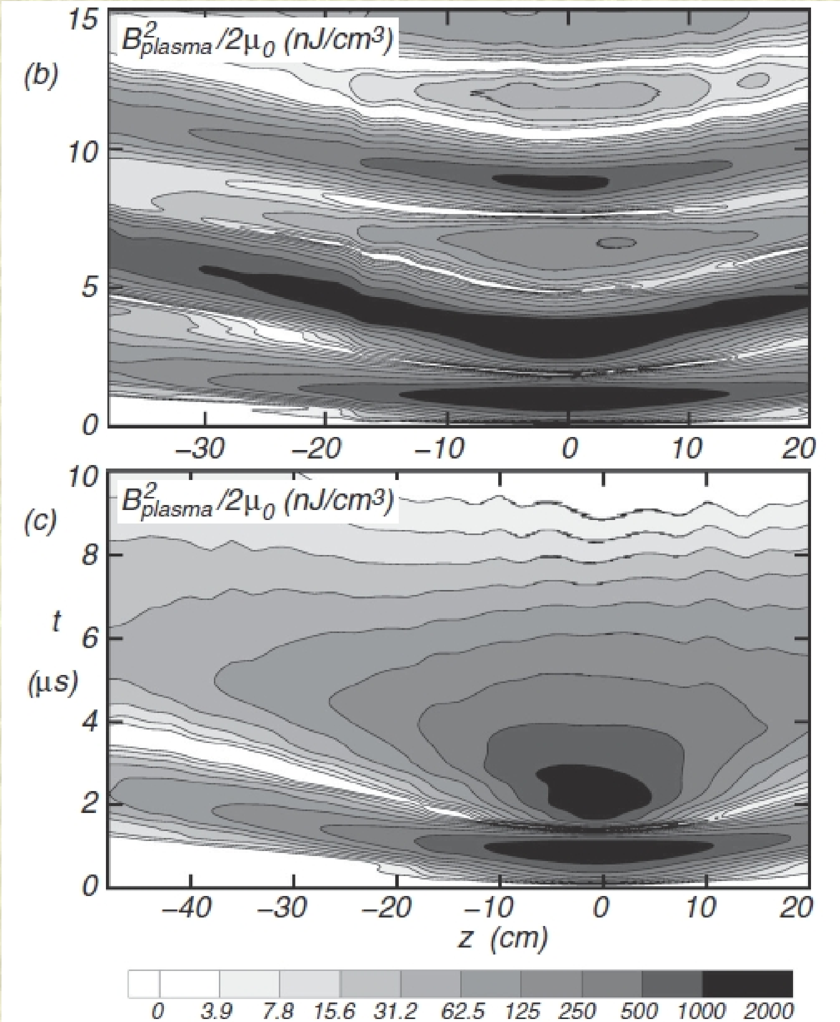
R. Stenzel *et al.*, Phys. Rev. Lett. **96**, 095004 (2006).

Experimental results: Magnetic fields



R. Stenzel *et al.*, Phys. Rev. Lett. **96**, 095004 (2006).

Experimental results: Magnetic field energy along z axis



Speed of spheromaks $\approx 10^7$ cm/s.

Mathematical model

Nonlinear EMHD equation (magnetized electrons, unmagnetized ions): Faraday's and Ampère's laws (immobile ions)

$$\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}, \tag{1}$$

and

$$\nabla \times \mathbf{B} = -\frac{4\pi e n_e \mathbf{v}_e}{c^2}. \tag{2}$$

Electron momentum equation

$$m_e\left(\frac{\partial}{\partial t} + \mathbf{v}_e \cdot \nabla\right)\mathbf{v}_e = -e(\mathbf{E} + \mathbf{v}_e \times \mathbf{B}) - \frac{\nabla p_e}{n_e}, \tag{3}$$

Eliasson & Shukla, PRL **99**, 205005 (2007)

Mathematical model

Eliminating $\mathbf{E}$ and $\mathbf{v}_e$ from Eqs. (1)–(3), and noting that $(\mathbf{v}_e \cdot \nabla)\mathbf{v}_e = -\mathbf{v}_e \times (\nabla \times \mathbf{v}_e) + \nabla v_e^2/2$, we have the nonlinear EMHD equation

$$\frac{\partial}{\partial t}(\mathbf{B} - \lambda_e^2 \nabla^2 \mathbf{B}) = \frac{c^2}{4\pi e n_0} \nabla \times [(\mathbf{B} - \lambda_e^2 \nabla^2 \mathbf{B}) \times (\nabla \times \mathbf{B})], \quad (4)$$

where we have used quasineutrality $n_e = n_i = n_0$.

Eliasson & Shukla, PRL **99**, 205005 (2007)

Initial condition

$$\mathbf{B} = B_0\widehat{\mathbf{z}} + \nabla \times \mathbf{A} + B_{\mathrm{tor}}\widehat{\varphi} \tag{5}$$

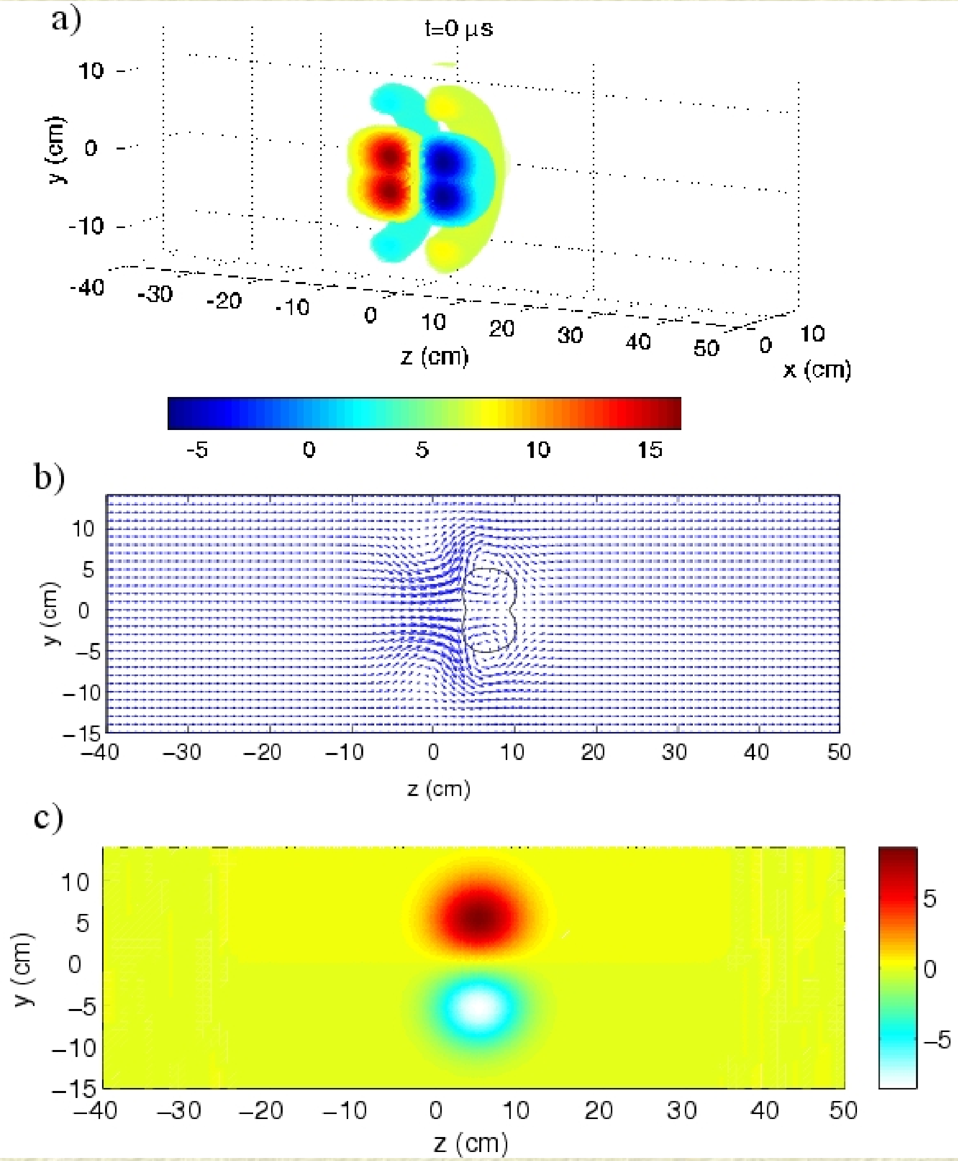
$$\mathbf{A} = [A_{\mathrm{forward}}(r,z) + A_{\mathrm{reverse}}(r,z)]\widehat{\varphi}, \tag{6}$$

$$A_{\mathrm{forward}}(r,z) = A_0\frac{r}{D}\exp\left[-\frac{(r-r_0)^2+z^2}{D^2}\right], \tag{7}$$

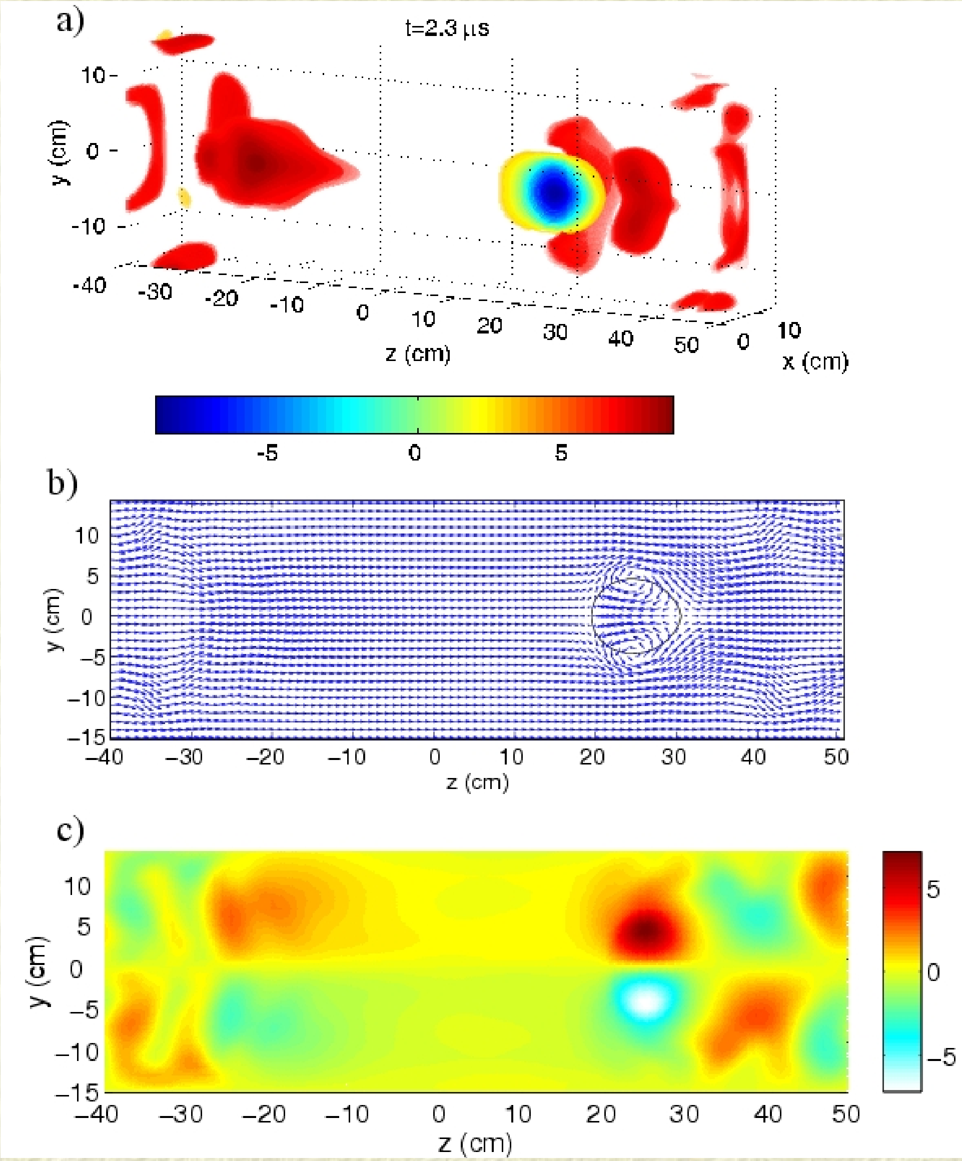
$$A_{\mathrm{reverse}}(r,z) = -A_0\frac{r}{D}\exp\left[-\frac{(r-r_0)^2+(z-5)^2}{D^2}\right], \tag{8}$$

$$B_{\mathrm{tor}}(r,z) = -B_{0,\mathrm{tor}}\frac{r}{D}\exp\left[-\frac{(r-r_0)^2+(z-5)^2}{D^2}\right]. \tag{9}$$

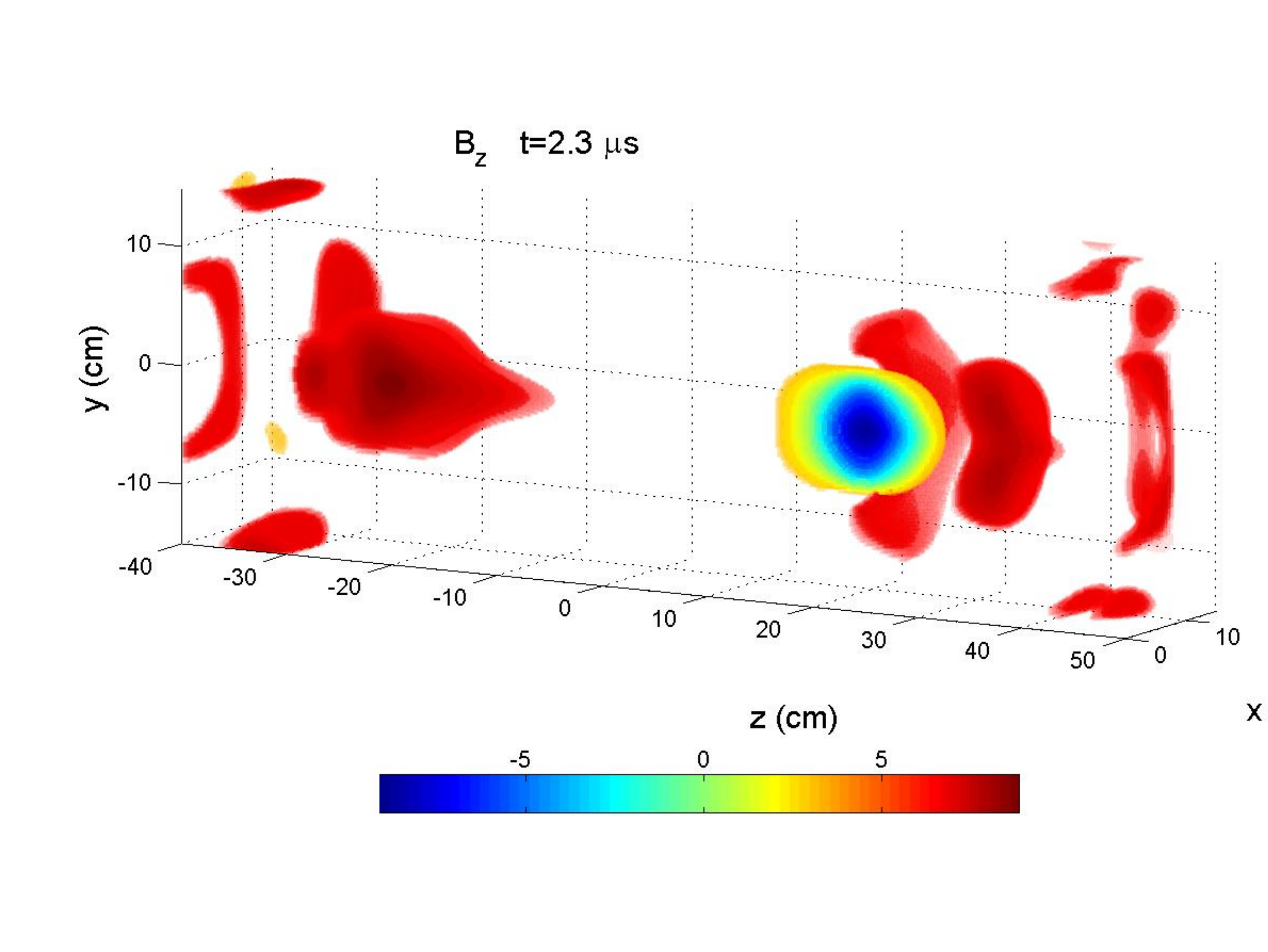
Initial fields for the simulation



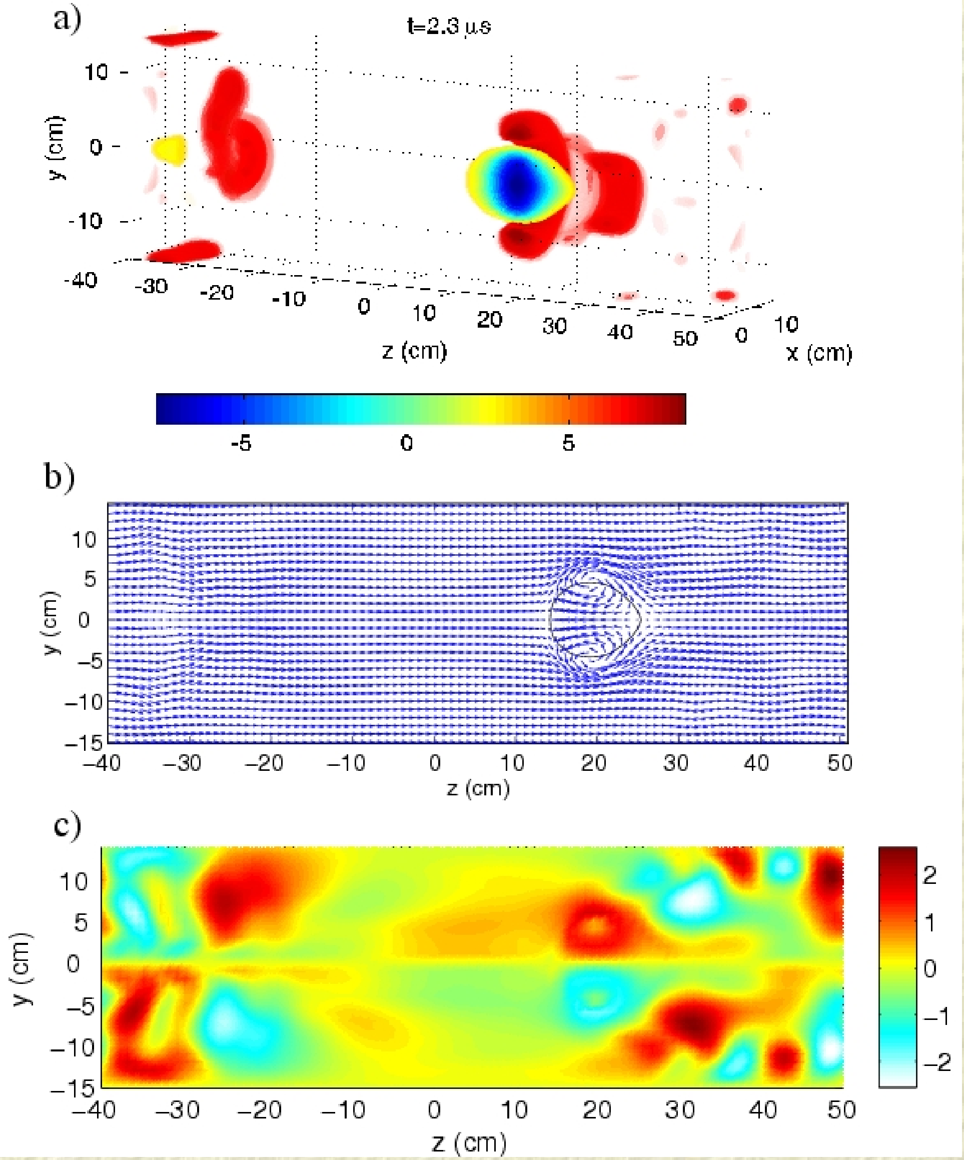
Whistler spheromak at $t = 2.3\,\mu s$



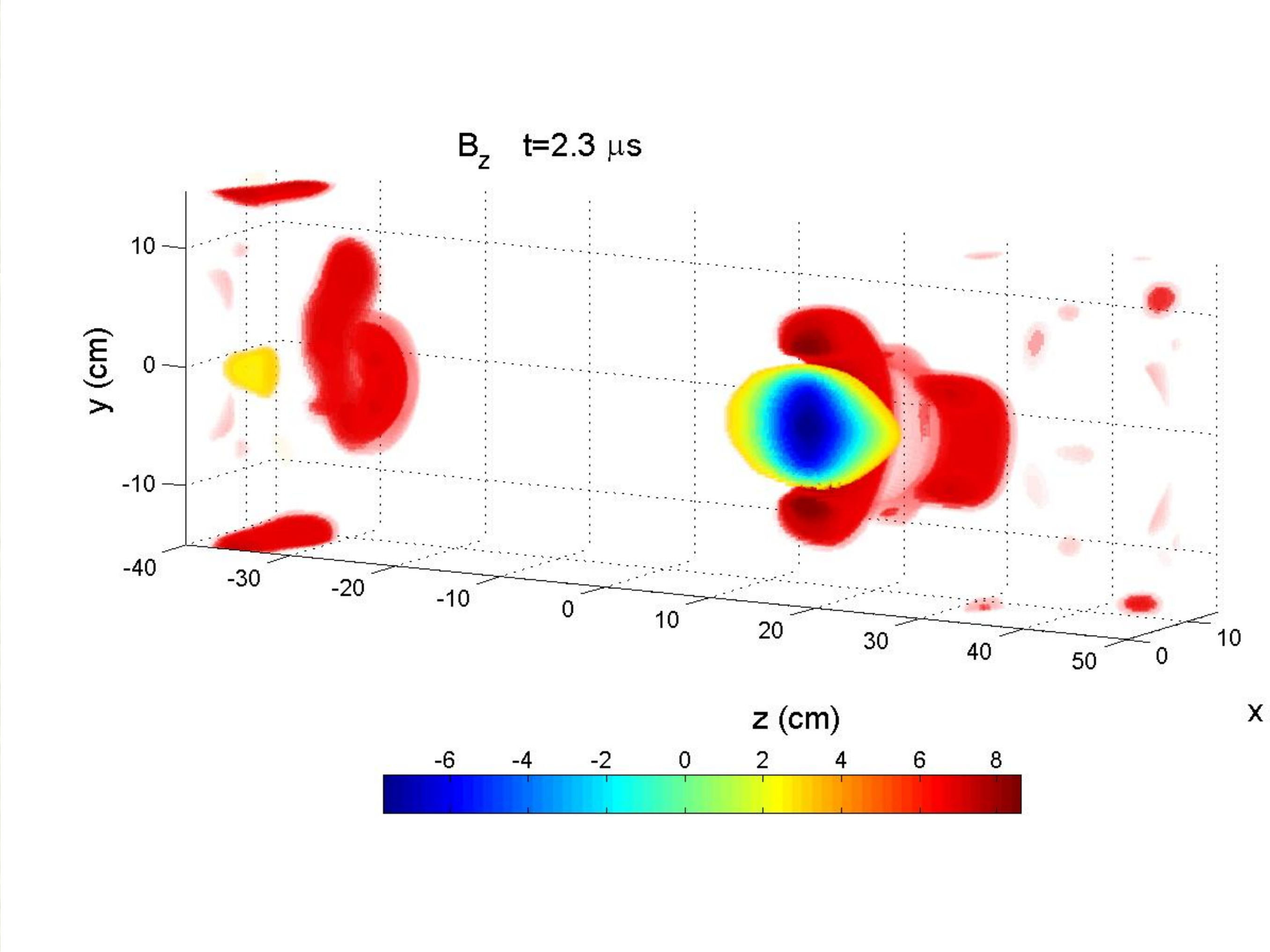
Dynamics of whistler spheromak



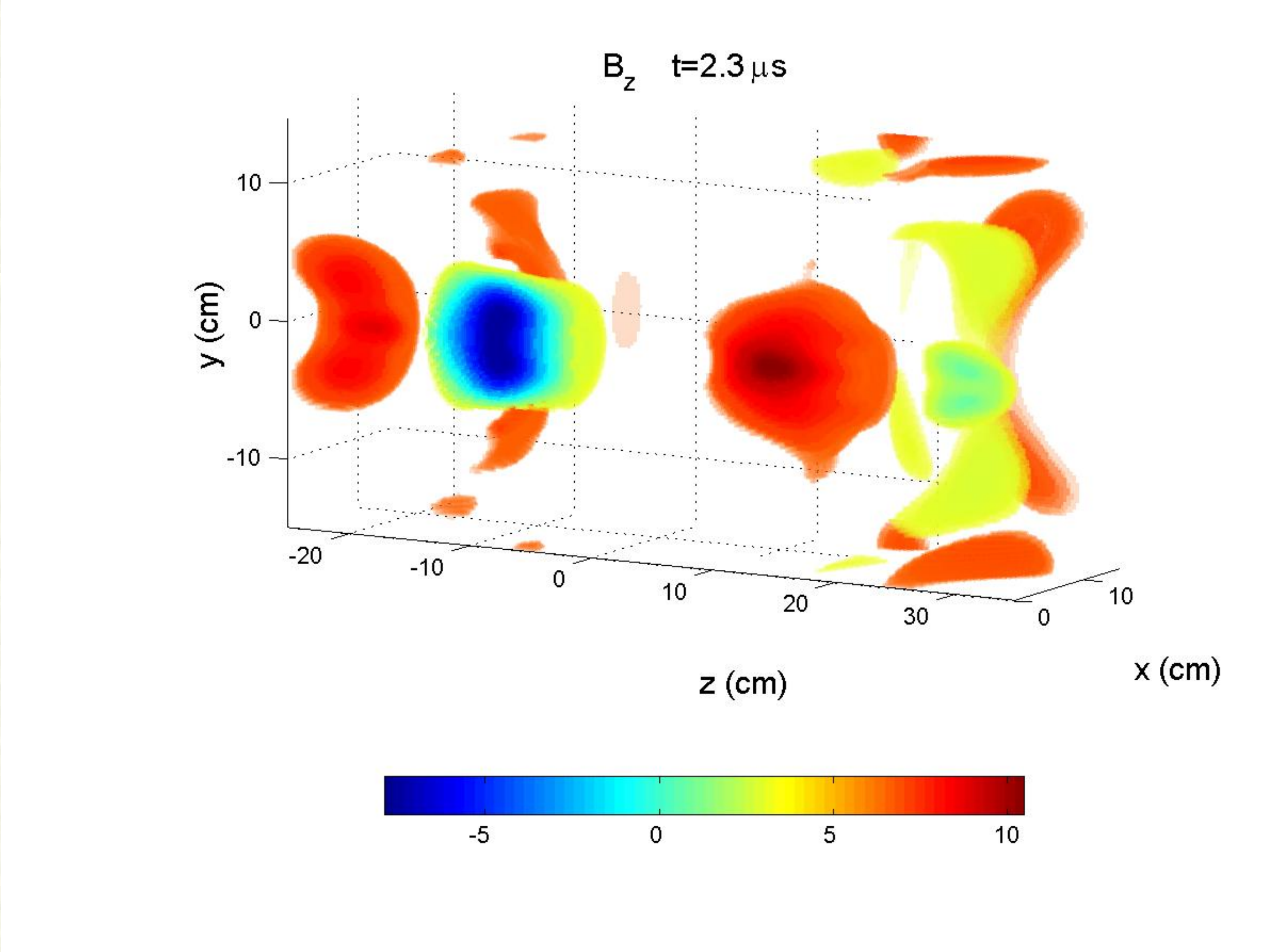
Spheromak without initial toroidal B field at $t = 2.3\,\mu s$



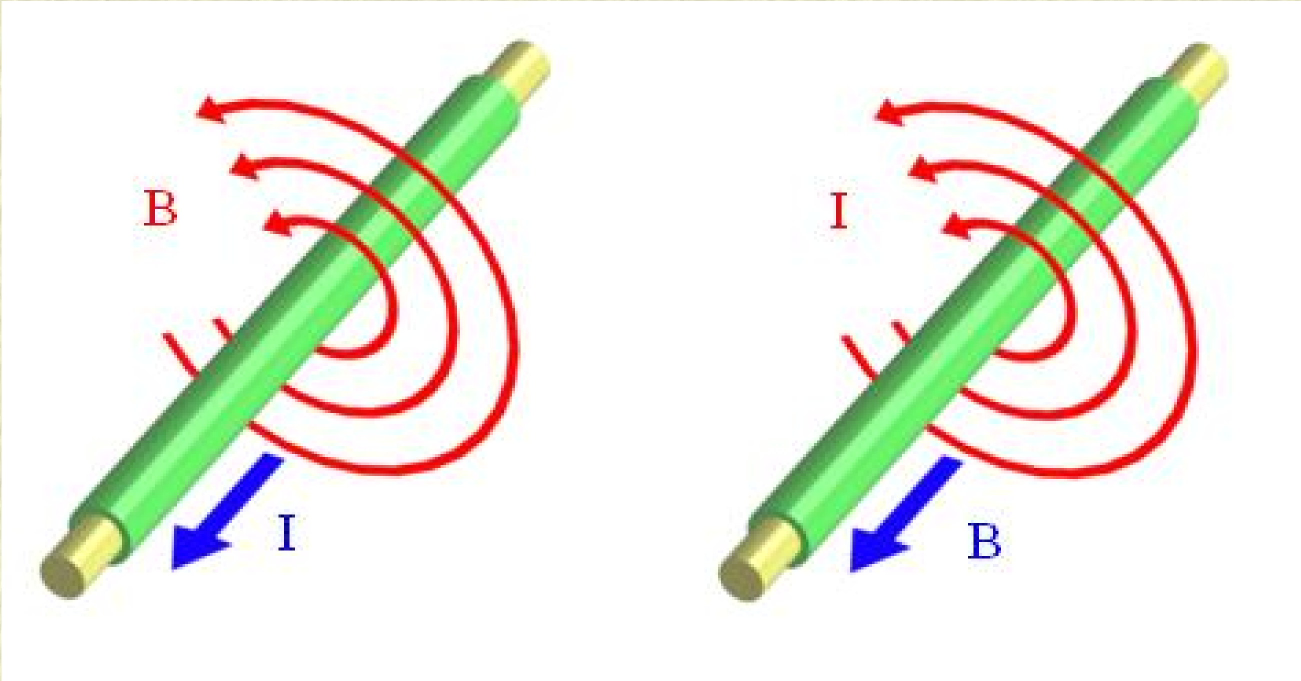
Whistler spheromak with no initial toroidal field



Whistler spheromak with reversed toroidal field

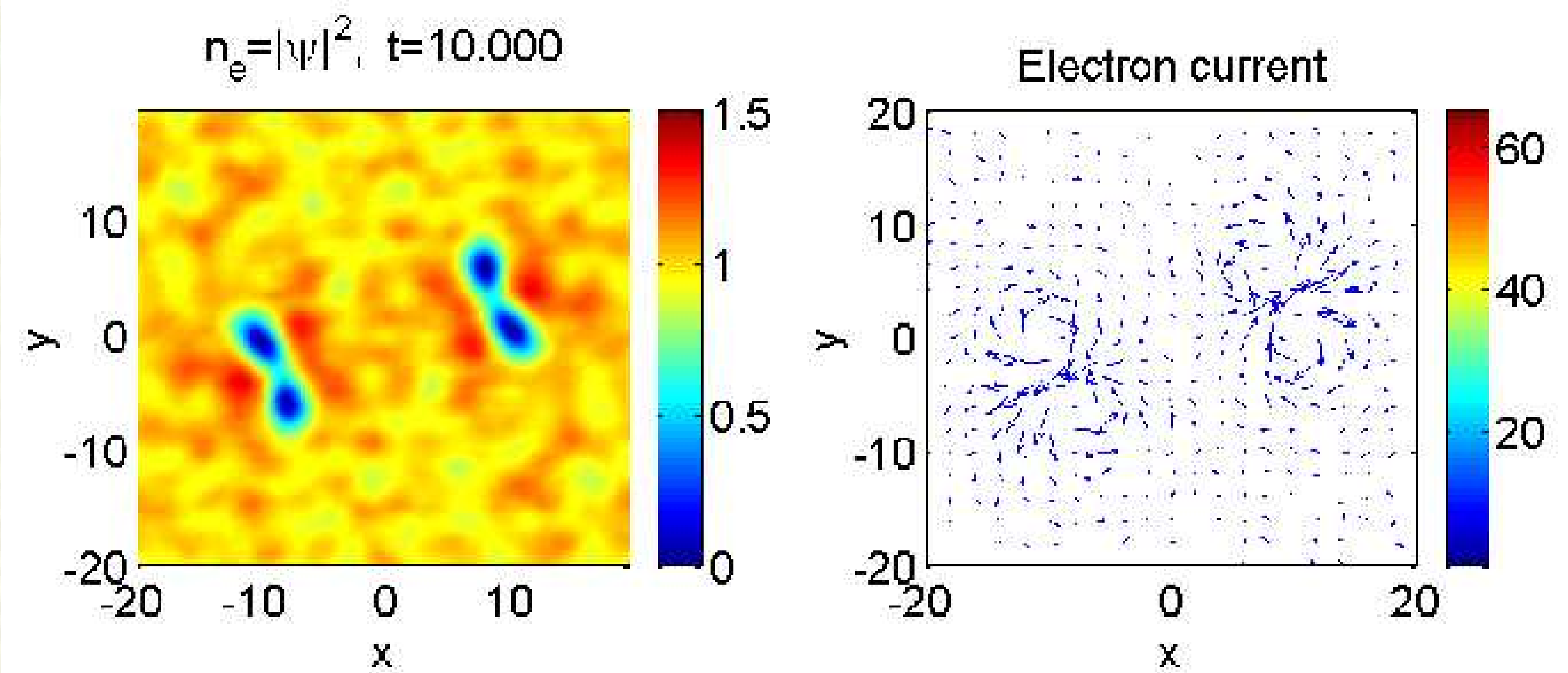


Magnetic field and currrent structures



- ❑ Toroidal current → poloidal magnetic field
- ❑ Poloidal current → toroidal magnetic field
- ❑ Poloidal current → electron fluid vortex

Dynamics of quantum electron fluid vortex pairs



Vortex pairs tend to propagate with constant speed

Shukla & Eliasson, Phys. Rev. Lett. **96**, 245001/1-4 (2006).

Summary

A. Have discussed recent experiments with localized whistler spheromaks composed of both poloidal and toroidal magnetic field.

B. Parameters: $B_z = 5$ G, reversed field ~ 7 G, toroidal & poloidal field ~ 5 G, $\lambda_e = 5$ mm, diameter of spheromak ~ 20 cm, speed of spheromak $\sim 8.5 \times 10^6$ cm/s.

B. Mathematical model: EMHD

C. Numerial results: Spheromaks are relatively stable structures. Propagation direction critically dependent on the polarity of the toroidal magnetic field. Typical speed ~ 6.5–7.5×10^6 cm/s.

D. Have neglected thermal and kinetic effects such as electron heating leading to optical emissions in the experiments.

Thank you!