Magnetic field generation and amplification in an expanding plasma

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To the origin of magnetic fields

- Magnetic field origin central problem in astrophysics (Kulsrud 2008).
- Turbulent dynamo (the standard explanation) requires a seed field to amplify
- This seed is generally attributed to the Biermann battery (Kulsrud 1992)
- Biermann battery:
  - generated by gradients $\nabla n \times \nabla T \neq 0$
  - should follow a $B \sim d_i/L$ scaling of magnetic field (Haines 1997)
  - often leads to small fields compared to pressure (β^{-2})
  - also found in laser-solid plasma experiments

What is the Biermann battery?

- Initial state:
  No magnetic fields
- Ingredients:
  - Density gradient: ∇n
  - Temperature gradient: ∇T
  - Perpendicular gradients: $\nabla n \times \nabla T \neq 0$
- Results:
  Magnetic field generated

Where do magnetic fields come from?

$$\frac{d\mathbf{B}}{dt} = -c\nabla \times \mathbf{E}$$

- All magnetic fields start as a curl of **E**
- We need an electric field, **E**
- We need the curl to be nonzero

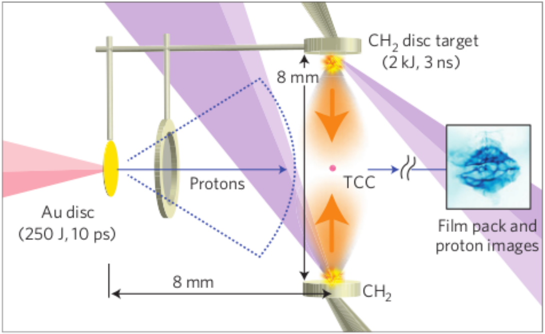
Well then where do electric fields come from

$$\mathbf{E} = -\mathbf{v_i} \times \mathbf{B}/c - \mathbf{J} \times \mathbf{B}/cne - \nabla(nT)/ne - \eta\mathbf{J} - m_e\frac{d\mathbf{J}}{dt}/ne^2$$

$$\mathbf{J} = c\nabla \times \mathbf{B}/4\pi$$

- All other terms have magnetic fields
- If $\nabla n \times \nabla T = 0$
  $\nabla \times \mathbf{E} = 0$
- $m_i/m_e > 1$, so electrons respond to the pressure gradients quicker
- A voltage drop appears, and an **E** is generated

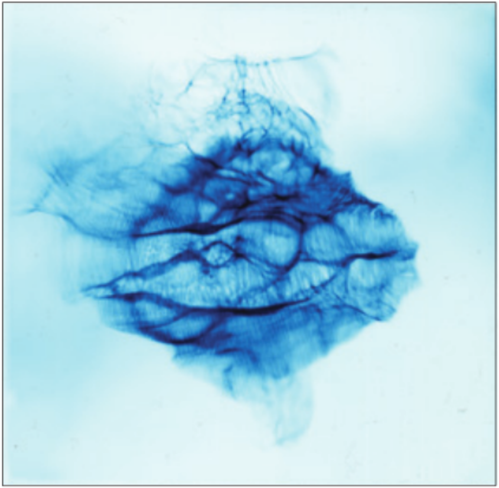
Lasers can cause Biermann



(Kugland et al. 2012)

- Two polyethylene disc targets $340\mu m \times 100\mu m$
- Ionized by 351 nm lasers, $3 \times 10^{15} Wcm^{-2}$
- ∇T perpendicular to the beam
- ∇n towards the target

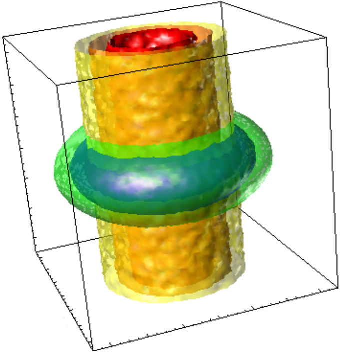
Magnetic fields are measured



(Kugland et al. 2012)

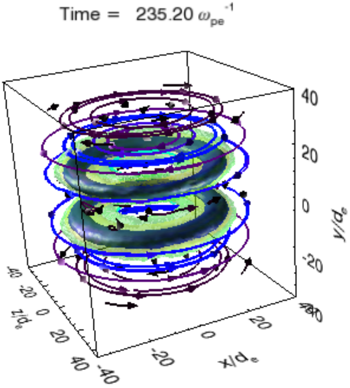
- Magnetic field measured by Thompson scattering
- Long lasting in time
- Varied length scales

The computational setup



- Using the 3D PIC code OSIRIS
  - No initial magnetic fields
  - Spheroid density profile
  - Cylindrical temperature profile
- Let it expand
- ... Magnetic fields will be generated

Self-consistent 3D kinetic Biermann battery simulated

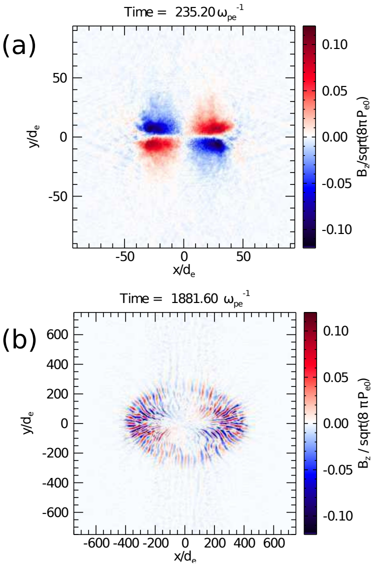


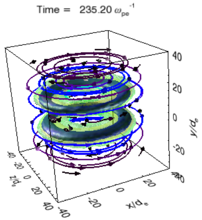
- 3D simulation performed
- Magnetic fields generated
- $L/d_e = 50$
- Simulation parameters:

$m_i/m_e = 25$, $ppg = 64$,
16 $\text{gridpoints}/d_e$, 0.625 $\text{gridpoints}/\lambda_{debye}$

- Mass ratio study shows no significant difference up to $m_i/m_e = 2000$

Let's try 2D





- Due to azimuthal symmetry 2D is sufficient
- $a)L/d_e = 50$ based on 3D (Pure Biermann)
- $b)L/d_e = 400$ (Weibel)

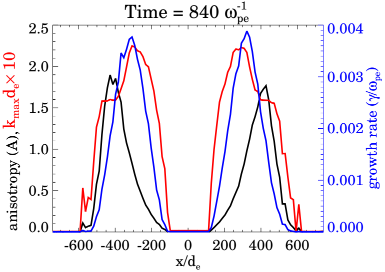
When do we get Weibel?

- the Weibel instability
  - in collisionless systems

$$k^2c^2 - \omega^2 - \sum_{\alpha} \omega_{p\alpha}^2 A_\alpha - \sum_{\alpha} \omega_{p\alpha}^2 \left(A_\alpha + 1\right) \xi_\alpha Z\left(\xi_\alpha\right) = 0$$

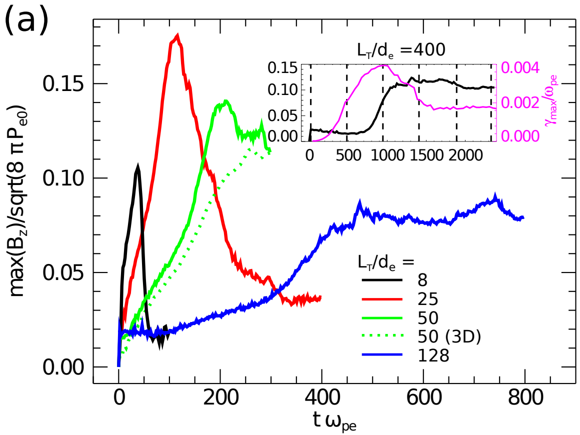
$$A \equiv T_{hot} / T_{cold} - 1$$

  - generated by pressure anisotropies, A, (found in our system)



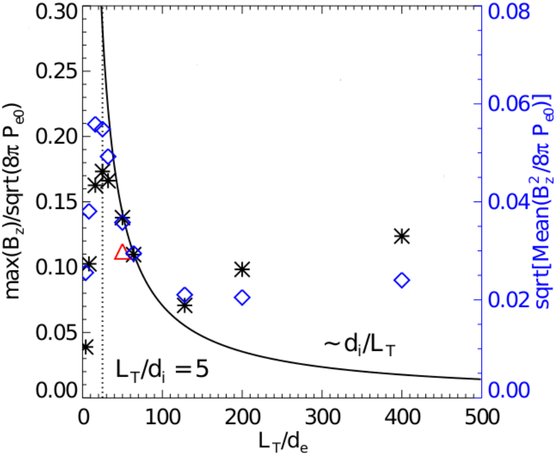
  - rapidly amplifies Biermann seed field
  - provides a new seed for dynamo

The magnetic field saturates



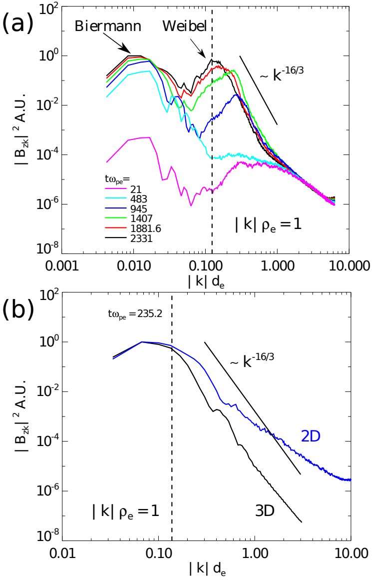
- The fields grow to a peak, and saturate for various L_T/d_e.
- The field grows when the linear Weibel growth rate is a maximum.

Haines scaling and beyond



- Normalized **B** $= \beta^{-1/2}$ follows $1/L$ scaling as expected ... (Haines 1997)
- then remains finite at large L (Weibel regime)

You can see it in the spectra



- a) Spectrum with $L/d_e = 400$
- First, Biermann peak appears
- Next, the higher k Weibel fields grow
- -16/3 spectra below ρ_e: Electron entropy cascade? (Schekochihin 2009)
- b) Spectrum with $L/d_e = 50$ (3D vs. 2D)

Summary

- Biermann battery generated by perpendicular temperature and density gradients
- We simulate these conditions in the PIC (particle-in-cell) code OSIRIS **(First self-consistent kinetic 3D model)**
- Results can be applied to
  - laser experiments
    B is **proportional to** d_i/L **confirming the Haines scaling**
  - astrophysical turbulent dynamo
    For large L/d_i the **Weibel instability generates (seed) magnetic fields independent of** L/d_i
  - turbulent collisionless plasmas
    Schekochihin $-16/3$ **sub-**ρ_e **power law observed**

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Find out more at: http://arxiv.org/abs/1308.3421