Magnetic Fields in HED and ICF Systems

ICF Lecture

D. J. Strozzi

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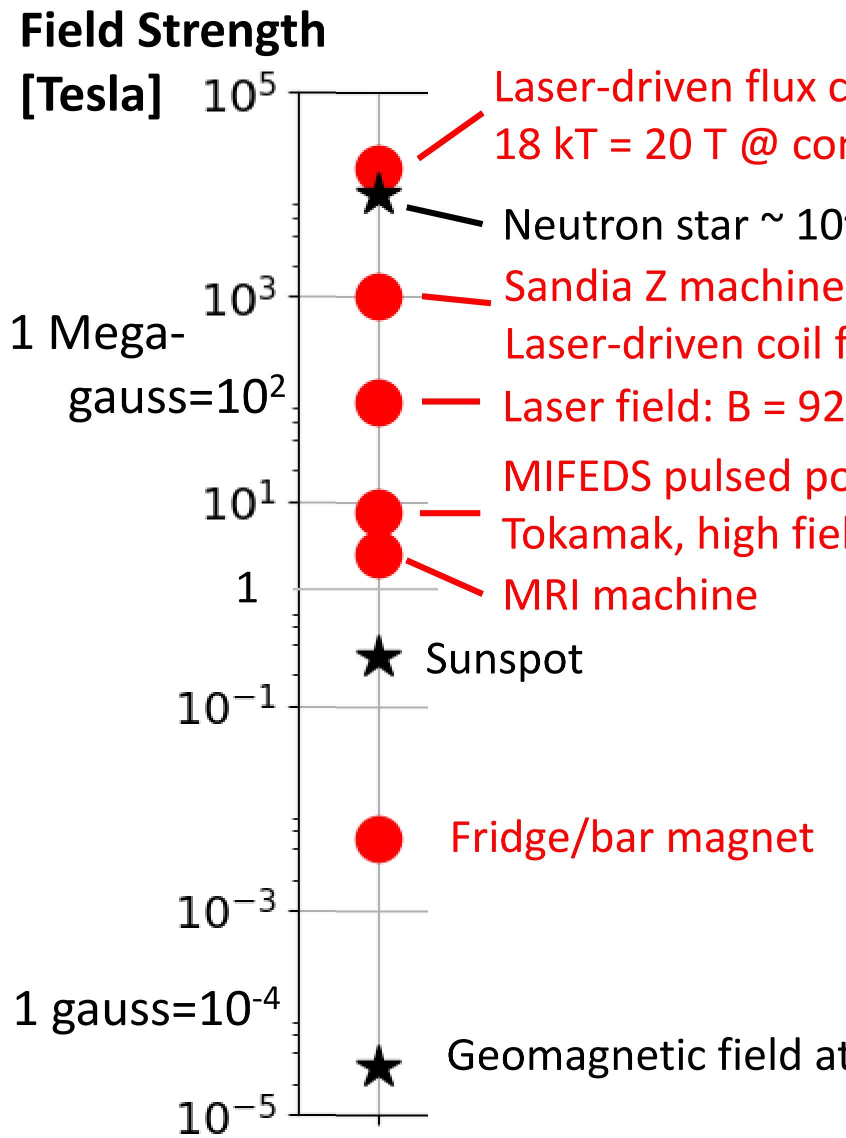
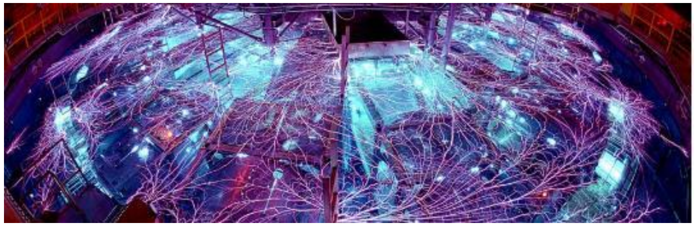
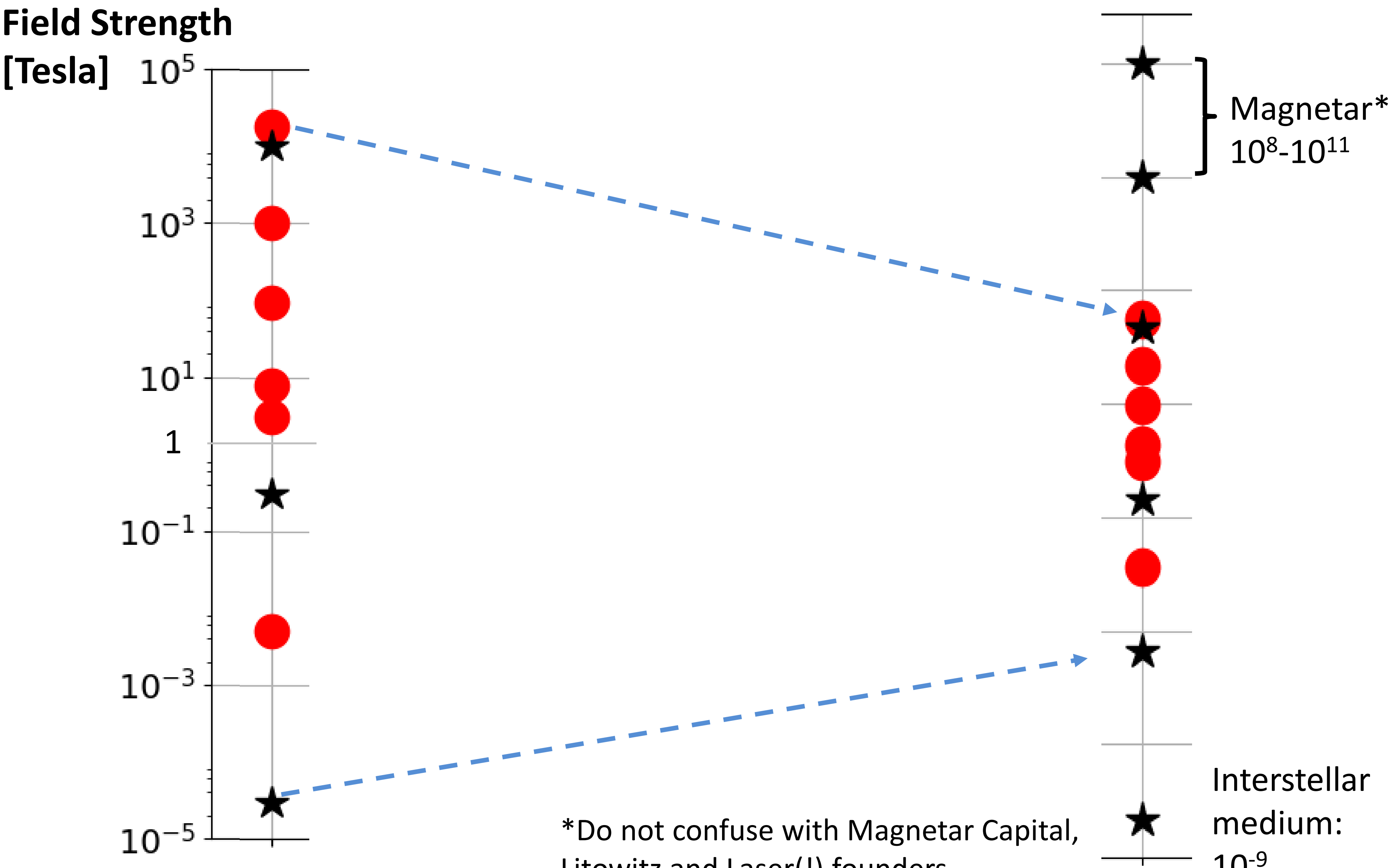
Lawrence Livermore National Laboratory

Magnetic fields are everywhere! Even ICF





Magnetic fields are everywhere! Even ICF



*Do not confuse with Magnetar Capital, Litowitz and Laser(!) founders

Outline

FUNDAMENTALS

- Particle motion, drifts, magnetic mirroring
- Waves in magnetized plasma, Faraday rotation
- MHD single-fluid model: derivation
- MHD effects
  - Magnetic pressure
  - Reduced heat flow
  - Frozen-in law
  - Biermann battery
  - Nernst, Righi-Leduc

EXPERIMENTS / APPLICATIONS

- Diagnostics
- Imposed fields – pulsed power, laser-driven coils
- Flux compression – explosives, laser driven
- Fusion
  - Magnetic vs. inertial fusion
  - Magneto-inertial fusion
  - Imposed fields in ICF
  - MagLIF
- B fields in hohlraums: self-generated, imposed

OTHER DOMAINS not covered

- Astrophysics, lab-astro
- Plasma propulsion

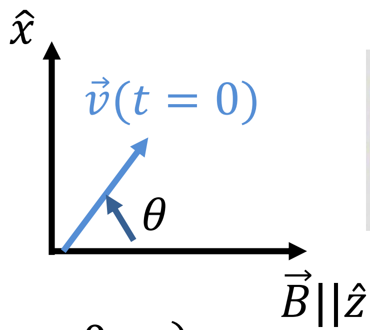
Thanks for slides, conversations, insight, codes, data, supervision …

- Will Farmer
- Clement Goyon
- Steve Haan
- Darwin Ho
- Elijah Kemp
- Joe Koning
- Dave Larson
- Grant Logan
- John Moody
- Mira Partha
- John Perkins
- Brad Pollock
- M. Rosen
- A. Sefkow
- Mark Sherlock
- Max Tabak
- Sasha Velikovich

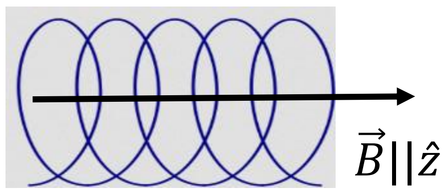
Motion in uniform B field: gyromotion

- Lorentz force: $\frac{d\vec{p}}{dt} = q\vec{v} \times \vec{B}$ $\quad \vec{p} = \gamma m \vec{v}$ $\quad \gamma \equiv (1 - v^2/c^2)^{-1/2}$
- Magnetic fields do no work: $\vec{p} \cdot \frac{d\vec{p}}{dt} = 0 \quad \rightarrow \quad$ γ=constant

$$\vec{B} = B\hat{z}, \qquad B > 0 \quad \rightarrow \quad \frac{d\vec{v}}{dt} = \omega_c \vec{v} \times \hat{z}$$



Helical orbit



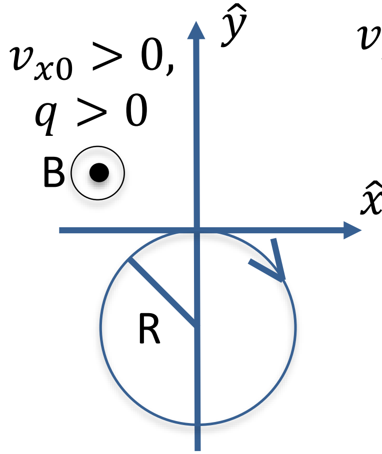
- Cyclotron frequency: $\omega_c \equiv \frac{qB}{\gamma m}$
- Initial condition: $\vec{x}(t=0) = \vec{0}, \quad \vec{v}(t=0) = (v_{x0}, 0, v_z)$

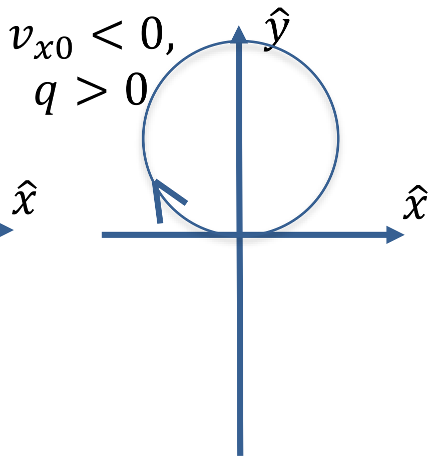
$$\vec{x} = \frac{v_{x0}}{\omega_c}(\sin \omega_c t\,, \cos \omega_c t - 1{,}0) + v_z t \hat{z}$$

- Gyroradius:

$$R \equiv \left| \frac{v_{x0}}{\omega_c} \right| = \frac{(2mW)^{\frac{1}{2}}}{qB} \sin \theta \left(1 + \frac{W}{2mc^2}\right)^{1/2}$$

relativity





Some numbers

	B [T]	Kinetic Energy	Cyclotron period [ps]	Gyroradius [um]	Example
Electron	10	1 keV	3.58	10.7	MIFEDS, MFE
Hydrogen	10	1 keV	6560	457	Same
Alphas (He4)	27,000	3.5 MeV	4.83 <~ hotspot size /	10.0 burn duration	Implosion: 30 T @ CR=30

Electrons

$$\text{cyclotron period } \tau_{ce} \equiv \frac{2\pi}{\omega_c} = 36\text{ps}\frac{\gamma}{B[\text{T}]}$$

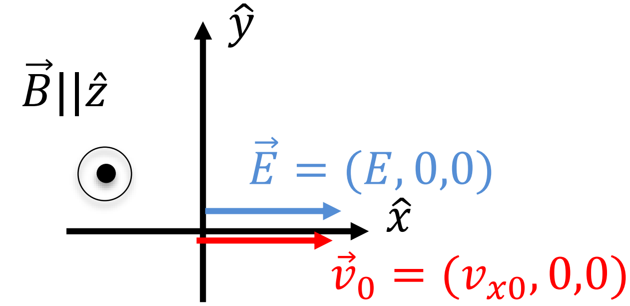
$$\text{gyroradius } R = 107\mu\text{m}\frac{(W[\text{keV}])^{\frac{1}{2}}}{B[\text{T}]}\sin\theta\left(1 + \frac{W}{1\ MeV}\right)^{1/2}$$

Particle drifts in B field: $\vec{E} \times \vec{B}$ drift

$$\frac{d}{dt}(v_x, v_y) = \left(\frac{q}{m}E + \omega_c v_y, -\omega_c v_x\right)$$

Non-relativistic

E increases v_x → v_y more negative → reduces dv_x/dt



"Guiding center" frame: E=0

$$\vec{v}_E = \frac{\vec{E} \times \vec{B}}{B^2} = -v_E\hat{y} \qquad v_E \equiv \frac{E}{B}$$

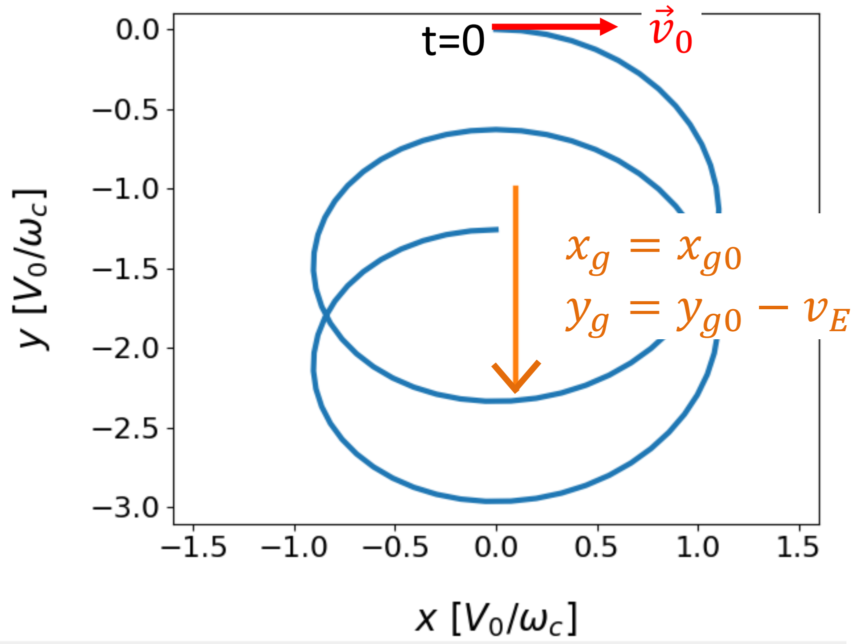
$$\vec{E}_g = \vec{E} + \vec{v}_E \times \vec{B} = 0$$

$$\vec{B}_g = \vec{B} - \vec{v}_E \times \vec{E} = \left(B - \frac{E^2}{B}\right)\hat{z}$$

GC frame: gyromotion in uniform B

$$v_{xg} = V_0 \cos(\omega_c t - \phi)$$
$$v_{yg} = -V_0 \sin(\omega_c t - \phi)$$
$$V_0^2 = v_0^2 + v_E^2$$

$$\langle v^2 \rangle_t = v_0^2 + 2v_E^2$$



Particle drifts in B field: $\nabla\overrightarrow{B}$, curvature, etc.

More on $\vec{E} \times \vec{B}$ drift

- Same for all particles – independent of mass, charge, sign of charge
- Perpendicular to both $\vec{B}$ and "driving force" - $\vec{E}$ in this case
  - Common aspect of magnetic effects, e.g. Nernst, Righi-Leduc effects

- **Zoo of other drifts**
  - Grad B
  - Curvature – important for tokamaks
  - Polarization
  - Most are perpendicular to $\vec{B}$ and a "driving force"

See Jackson or any plasma physics textbook, e.g. Krall and Trivelpiece

- Free online book: Prof. R. Fitzpatrick (UT Austin):
  farside.ph.utexas.edu/teaching/plasma/plasma.html

Motion parallel to $\overrightarrow{B}$: adiabatic invariance of magnetic moment

Action for periodic motion in q_i: $$J_i = \oint p_i \, dq_i$$ one cycle

q_i = canonical coordinate
p_i = canonical momentum

In B field: canonical momentum $\vec{p} = m\vec{v} + q\vec{A}$

Strictly periodic motion: J conserved

Nearly periodic motion: J approximately (but very well) conserved

Adiabatic invariance: parameters change slowly vs. period (and not resonant with it)

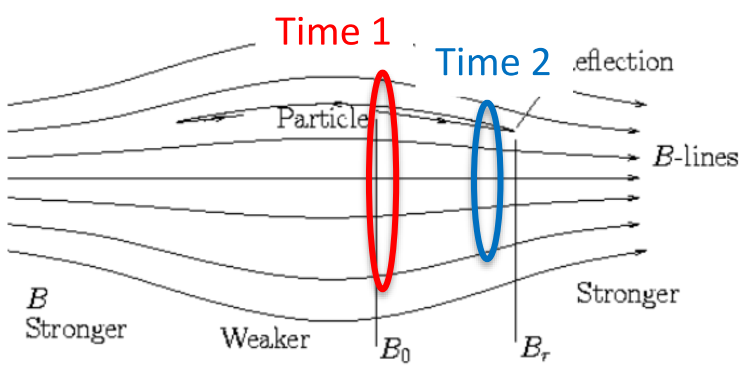
$\vec{B}$ slowly varying in space: change over one gyro-orbit small:
Transverse motion ≈ periodic →

$$J = \oint \vec{p}_\perp \cdot d\vec{l} = qB\pi R^2 \propto \frac{v_\perp^2}{B}$$

flux through gyro-orbit

∴ Magnetic moment $\mu \equiv \frac{v_\perp^2}{B}$ invariant

Non-relativistic



I. Hutchinson, MIT

Motion parallel to $\vec{B}$: magnetic mirror

Non-relativistic

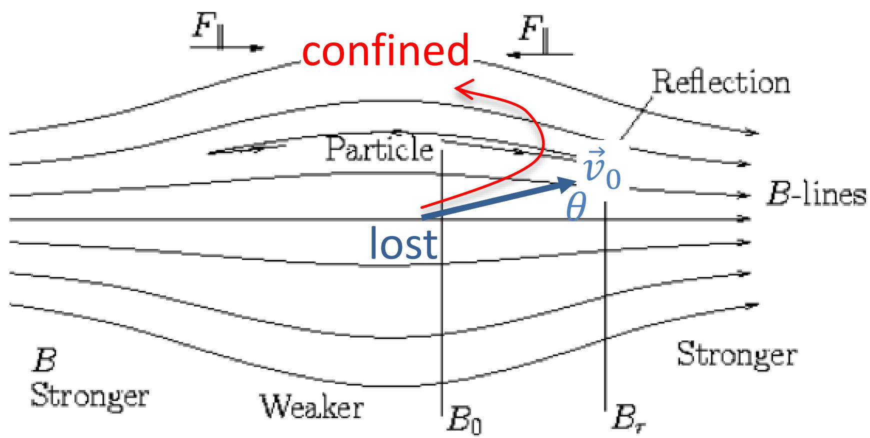
Static, non-uniform $\vec{B}$; $\vec{E}$=0

Kinetic energy conserved: $v_\perp^2 + v_{||}^2 = v_{\perp 0}^2 + v_{||0}^2$ → $v_{||}^2 = v_{||0}^2 - \left[\frac{B}{B_0} - 1\right] v_{\perp 0}^2$

Magnetic moment adiabatic invariant: $\frac{v_\perp^2}{B} = \frac{v_{\perp 0}^2}{B_0}$

Magnetic mirror: turning point: $v_{||} = 0$ → $\frac{B_{mir}}{B_0} = 1 + \frac{v_{||0}^2}{v_{\perp 0}^2}$

Loss cone in velocity: particles escape if no turning point → $\theta < \arctan\left[\left(\frac{B_{max}}{B} - 1\right)^{1/2}\right]$



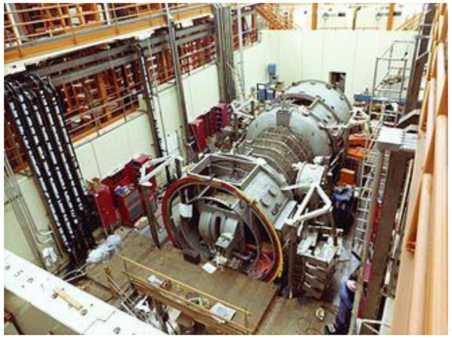
I. Hutchinson, MIT

"Magnetic mirror": MFE concept

Loss-cone hard to overcome

TMX: Tandem Mirror Experiment

LLNL: 1979-1987 TMX (near superblock)



Waves in magnetized plasmas

Waves in magnetized plasma: a zoo

- $\vec{E} = \vec{E}_{in} + \vec{E}_{ex}$ internal (plasma, "bound") + external (driven, "free") fields
- Linearize + Fourier transform { Maxwell's equations + plasma equations of motion } →
- Dispersion relation: $\overleftrightarrow{D} \cdot \vec{E}_{in} = -\overleftrightarrow{\chi} \cdot \vec{E}_{ex}$ $\overleftrightarrow{\chi}$ = susceptibility tensor

$$\overleftrightarrow{D} = \overleftrightarrow{\epsilon} + \vec{N}\vec{N} - N^2 \qquad \vec{N} \equiv c\vec{k}/\omega$$

- Normal modes: $\vec{E}_{in} \neq 0$ when $\vec{E}_{ex} = 0$: → $\overleftrightarrow{D} \cdot \vec{E}_{in} = 0$ → $\det \overleftrightarrow{D} = 0$
- Cold plasma:

$$\vec{B} = B\hat{z}$$

$$\text{dielectric } \overleftrightarrow{\epsilon} = 1 + \overleftrightarrow{\chi} = \begin{bmatrix} S & -iD & 0 \\ iD & S & 0 \\ 0 & 0 & P \end{bmatrix}$$

$$\begin{matrix} R \\ L \end{matrix} = 1 - \sum_s \frac{\omega_{ps}^2}{\omega(\omega \pm \omega_{cs})}$$

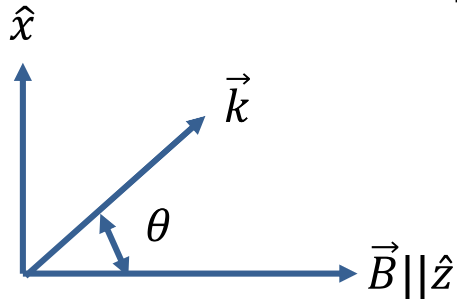
$$S = \frac{1}{2}(R + L) \qquad D = \frac{1}{2}(R - L) \qquad P = 1 - \frac{\sum_s \omega_{ps}^2}{\omega^2}$$

Classic text: T. H. Stix, *Waves in Plasmas*

Alfven waves, Bernstein waves, electrostatic ion cyclotron waves, O mode, X mode, …

Wave dispersion relation

$$\overleftrightarrow{D} = \overleftrightarrow{\epsilon} + \vec{N}\vec{N} - N^2 = \begin{bmatrix} S - N^2\cos^2\theta & -iD & N^2\cos\theta\sin\theta \\ iD & S - N^2 & 0 \\ N^2\cos\theta\sin\theta & 0 & P - N^2\sin^2\theta \end{bmatrix} \qquad \vec{N} \equiv \frac{c\vec{k}}{\omega}$$



"Principal modes:" $\theta = 0$ or $\pi/2$

Fixed ions, cold electrons, B=0 → 3 modes:

- R = L = S = P, D=0
- $\overleftrightarrow{D} = \begin{bmatrix} P - N^2\cos^2\theta & 0 & N^2\cos\theta\sin\theta \\ 0 & P - N^2 & 0 \\ N^2\cos\theta\sin\theta & 0 & P - N^2\sin^2\theta \end{bmatrix}$ $\quad\theta$ arbitrary, can set to 0
- $\det\overleftrightarrow{D} = (P - N^2)^2 P = 0$ independent of θ
- P=0: Plasma oscillation, electrostatic ($\vec{E}||\vec{k}$): $\omega = \omega_{pe}$
- P-N^2=0: Electromagnetic (light, $\vec{E} \perp \vec{k}$): 2 polarizations: $\omega^2 = \omega_{pe}^2 + c^2k^2$

$\vec{k} || \vec{B}$: $\theta = 0$ principal modes

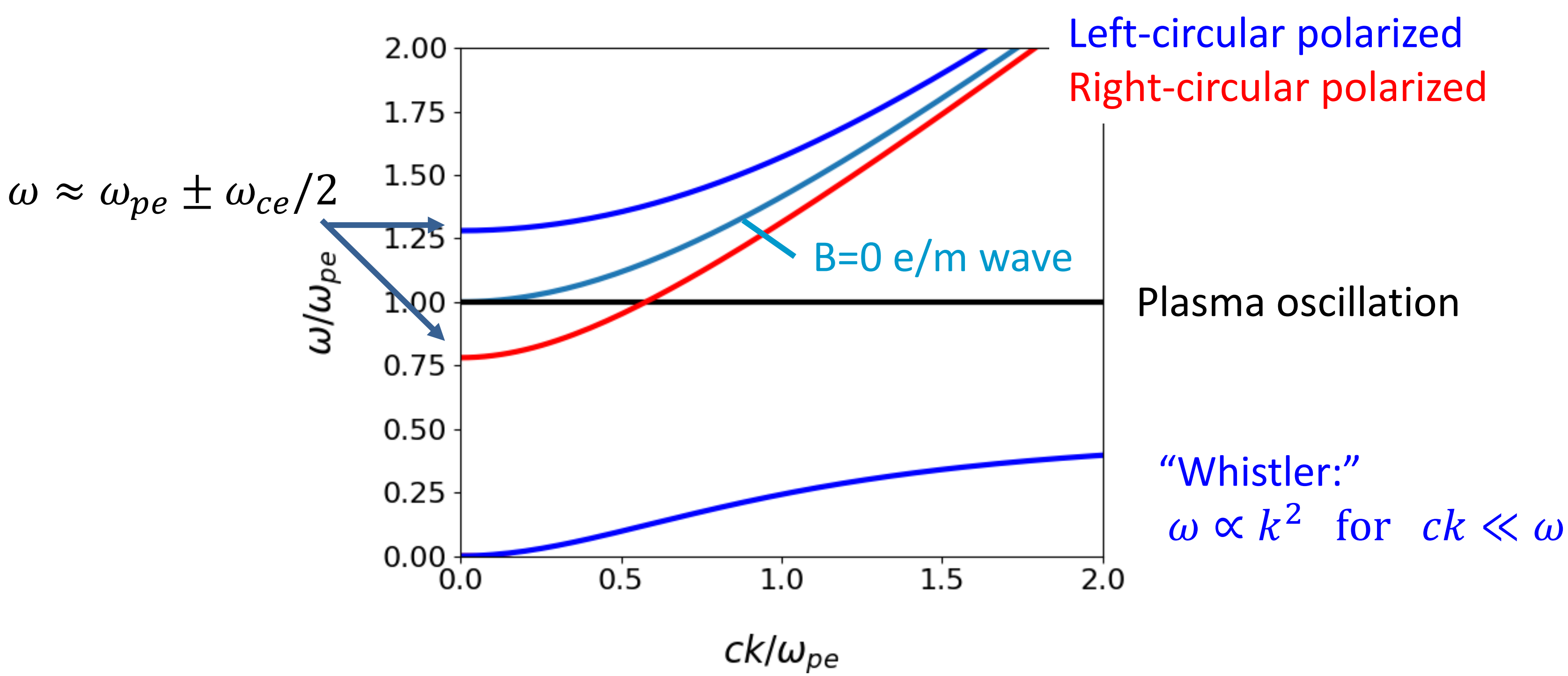
Fixed ions, cold electrons, $B \neq 0$ → 4 modes:

- Plasma oscillation ($\vec{E} || \vec{k}$): $\omega = \omega_{pe}$
- Electromagnetic ($\vec{E} \perp \vec{k}$): 3 modes:

$$\omega^3 \pm \omega_{ce}\omega^2 - \left(\omega_{pe}^2 + c^2k^2\right)\omega \mp \omega_{ce}c^2k^2 = 0$$

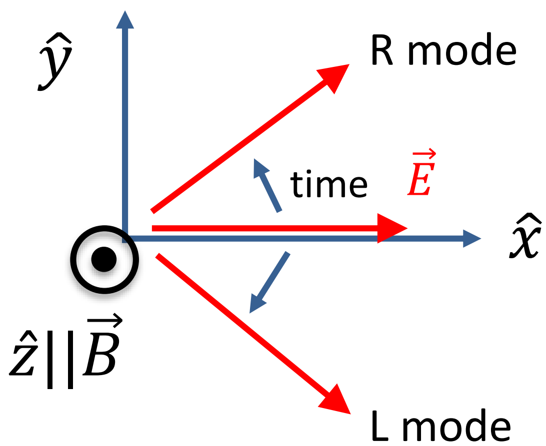
$\omega_{ce} = 0.5\omega_{pe}$

e.g. $n_e = 10^{20}$ cm^{-3}, B=1600 T

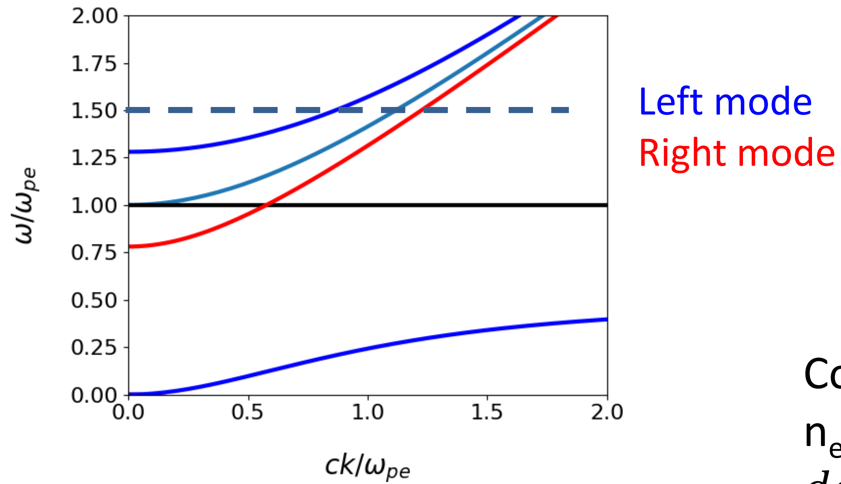


$\vec{k} \,||\, \vec{B} \,||\hat{z}$: polarization, Faraday rotation

fixed z: $\vec{E} = (\cos(\omega t)\,, \pm\sin(\omega t))$

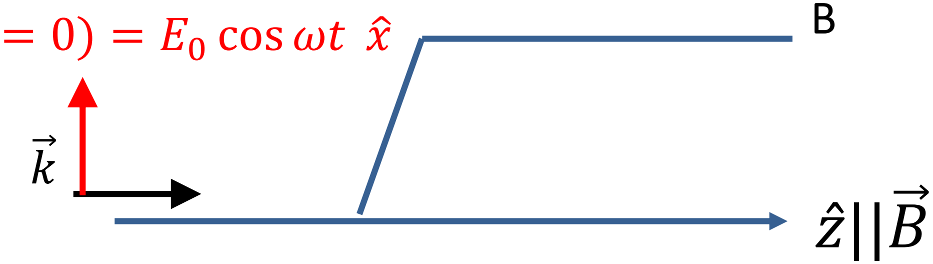


Fixed ω: L mode > R mode phase velocity



Light wave launched from vacuum

$\vec{E}(z=0) = E_0 \cos\omega t\ \hat{x}$



$$\vec{E} = E(\cos\alpha\,, \sin\alpha)$$

$$\alpha = \frac{1}{2}(k_L - k_R)z$$

$$E = \frac{E_0}{\sqrt{2}}(1 + \cos((k_L + k_R)z - 2\omega t))^{1/2}$$

$$\frac{d\alpha}{dz} \approx -\frac{\omega_{pe}^2}{2\omega^2}\left(1 - \frac{\omega_{pe}^2}{\omega^2}\right)^{-1/2}\frac{\omega_{ce}}{c} \qquad \omega_{ce} \ll \omega$$

$$\frac{d\alpha}{dz}\,[\frac{\text{deg}}{\text{mm}}] = -16.8\frac{n_e/n_{cr}}{(1 - n_e/n_{cr})^{\frac{1}{2}}}B_T$$

Could matter in MagLIF or magnetized hohlraum:
n_e/n_{cr} = 0.1, B = 10T:
$d\alpha/dz = 17.7$ deg/mm

Faraday rotation: First experimental evidence that light and electromagnetism are related

Michael Faraday[1], 1845

Faraday's diary, 1845:
"…when the contrary magnetic poles were on the same side, *there was an effect produced on the polarized ray*, and thus magnetic force and light were proved to have relation to each other."

"I have at last succeeded in illuminating a magnetic curve or line of force, and in magnetizing a ray of light."

Heavy glass (lead traces)

[1]Only two names. Declined knighthood, preferred to remain "plain Mr. Faraday to the end"

E/M waves used in magnetic and inertial fusion

Magnetic: external waves (e.g. microwaves) used to drive current and heat plasma

Inertial: we use lasers! Laser-plasma interaction should include B fields

- B. Winjum (UCLA): PIC simulations
- E. Los (LLNL summer student): analytic instability growth / gain
- N. Fisch et al.: parametric amplifiers with magnetized waves

MHD single-fluid model

MHD "single-fluid" model: equivalent to one ion, one electron fluid species

$\rho = m_i n_i + m_e n_e$ mass density

$Q = Z_i e n_i - e n_e$ charge density

$$\vec{v} = \frac{m_i n_i \vec{v}_i + m_e n_e \vec{v}_e}{\rho}$$ center – of – mass velocity

$\vec{J} = Z_i e n_i \vec{v}_i - e n_e \vec{v}_e$ current density

Single-fluid equations: plasma + Maxwell

Plasma:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \qquad \text{mass continuity}$$

$$\frac{\partial Q}{\partial t} + \nabla \cdot \vec{J} = 0 \qquad \text{charge continuity}$$

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p + Q\vec{E} + \vec{J} \times \vec{B} \qquad \text{CM momentum}$$

$$\frac{1}{\epsilon_0 \omega_{pe}^2} \frac{D\vec{J}}{Dt} = \vec{E} - \vec{E}_{eff} \qquad \text{Ohm's law} \approx \text{e}^- \text{ momentum}$$

$$\omega_{pe}^2 = \frac{n_e e^2}{\epsilon_0 m_e} \qquad \text{plasma frequency}$$

+ energy equation

Maxwell:

$$\nabla \cdot \vec{E} = \epsilon_0^{-1} Q \qquad \text{Gauss}$$

$$\nabla \cdot \vec{B} = 0$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \qquad \text{Faraday}$$

$$\nabla \times \vec{B} = \mu_0 \vec{J} + \epsilon_0 \mu_0 \frac{\partial \vec{E}}{\partial t} \qquad \text{Ampère} - \text{Maxwell}$$

Scaled variables: $X = X_0\widetilde{X}$, X_0 = "unitful" scale, $\widetilde{X}$=unitless

$t = T\tilde{t}$ $\quad \vec{x} = L\tilde{\vec{x}}$ $\quad \vec{v} = V\tilde{\vec{v}}$

Unitless scales

$n_e = N_e\widetilde{n_e}$ $\quad \rho = \frac{m_i N_e}{Z_i}\tilde{\rho}$ $\quad Q = eN_e\alpha_Q\tilde{Q}$ $\quad \vec{J} = eN_eV\alpha_J\tilde{\vec{J}}$

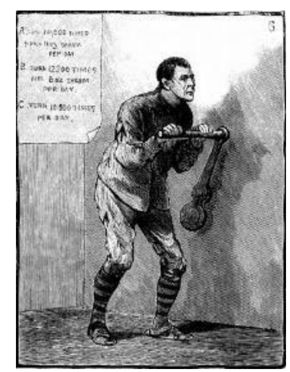
$\vec{E} = E_0\tilde{\vec{E}}$ $\quad \vec{B} = B_0\tilde{\vec{B}}$ $\quad \alpha_Q \ll 1:\ \text{quasi}-\text{neutral}$

Balance terms:

Mass continuity: $$\frac{\partial\tilde{\rho}}{\partial\tilde{t}} + \frac{VT}{L}\tilde{\nabla}\cdot\left(\tilde{\rho}\tilde{\vec{v}}\right) = 0 \quad \rightarrow \quad V = \frac{L}{T}$$

Faraday: $$\frac{\partial\tilde{\vec{B}}}{\partial\tilde{t}} = \frac{TE_0}{LB_0}\tilde{\nabla}\times\tilde{\vec{E}} \quad \rightarrow \quad B_0 = \frac{T}{L}E_0$$

Homework: Turn the crank…



Scaled single-fluid model: unitless, drop ~'s

Plasma:

$$\partial\rho/\partial t + \nabla\cdot(\rho\vec{v}) = 0$$ mass continuity

$$\alpha_Q \partial Q/\partial t + \alpha_J \nabla\cdot\vec{J} = 0$$ charge continuity

$$\mathrm{M}^2\rho\frac{D\vec{v}}{Dt} = -\nabla p + \beta_p^{-1}(\vec{J}\times\vec{B} + \beta_V^2 Q\vec{E})$$ CM momentum

$$\vec{E} = \vec{E}_{eff} + \frac{1}{(\beta_V\omega_{pe}T)^2}\frac{1}{n_e}\frac{D\vec{J}}{Dt}$$ Ohm's law

Maxwell:

$$\nabla\cdot\vec{E} = Q$$ Gauss

$$\nabla\cdot\vec{B} = 0$$

$$\partial\vec{B}/\partial t = -\nabla\times\vec{E}$$ Faraday

$$\nabla\times\vec{B} = \vec{J} + \beta_V^2\frac{\partial\vec{E}}{\partial t}$$ Ampère – Maxwell

MHD ordering:

$\beta_V = \frac{L}{cT} \ll 1$ drop red terms

$\omega_{pe}T \gg \frac{1}{\beta_V}$ drop blue term (e^- inertia)

$\rightarrow \omega_{pe}T \gg \frac{cT}{L} \gg 1$

6 Unitless parameters

α_Q, α_J

$\beta_V \equiv L/cT$

$\omega_{pe}T$

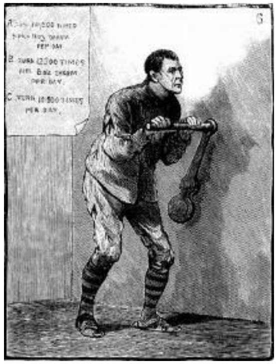
$M \equiv V/c_s$ Mach number

$c_s^2 = \frac{Z_i p_0}{m_i N_e}$ sound speed

$\beta_p \equiv \frac{\mu_0 p_0}{B_0^2}$ (1/2) plasma beta

Light and Langmuir waves eliminated: Model does not support them

Homework: what about quasi-neutrality and charge continuity?



- Turn the crank
- What is the relation between α_Q and α_J?
- How does this relate to charge continuity?
  - What “loophole” allows the MHD model to satisfy it?

Single-fluid MHD model: physical units

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

$$\rho \frac{D\vec{v}}{Dt} = -\nabla p + \vec{J} \times \vec{B}$$

Magnetic pressure:

$$\vec{J} \times \vec{B} = -\nabla \left(\frac{B^2}{2} \right) + \vec{B} \cdot \nabla \vec{B}$$

Maxwell:

$$\nabla \cdot \vec{B} = 0$$

$$\partial \vec{B} / \partial t = -\nabla \times \vec{E}$$

$$\vec{J} = \mu_0^{-1} \nabla \times \vec{B}$$

Generalized Ohm's law:

$$\vec{E} = \vec{E}_{eff} = -\vec{v} \times \vec{B} + \frac{1}{n_e e} \vec{J} \times \vec{B} - \frac{\nabla p_e}{n_e e} + \overleftrightarrow{\eta} \cdot \vec{J} - e^{-1} \overleftrightarrow{\beta} \cdot \nabla T_e$$

advection / induction term; Hall term; Biermann battery — collisionless

resistivity; thermal force* — collisional

- E field from Ohm's law: function of current plasma conditions
- B field evolves in time by Faraday's law – not function of current plasma conditions
- MHD models distinguished by terms in Ohm's law:
    - Ideal MHD: just advection
    - Resistive MHD: also resistivity
    - Hall MHD: also Hall term
- In ICF /HED, hard to say a priori which terms can be neglected – for all time and space

*thermal force collisional, but $\overleftrightarrow{\beta}(B = 0)$ independent of collisionality

Magnetic field generation: Biermann battery[1]

$$\partial \vec{B}/\partial t = -\nabla \times \vec{E}$$

$$\vec{E} = -\frac{\nabla p_e}{n_e e} - \vec{v} \times \vec{B} + \frac{1}{n_e e}\vec{J} \times \vec{B} + \overleftrightarrow{\eta} \cdot \vec{J} - e^{-1}\overleftrightarrow{\beta} \cdot \nabla T_e$$

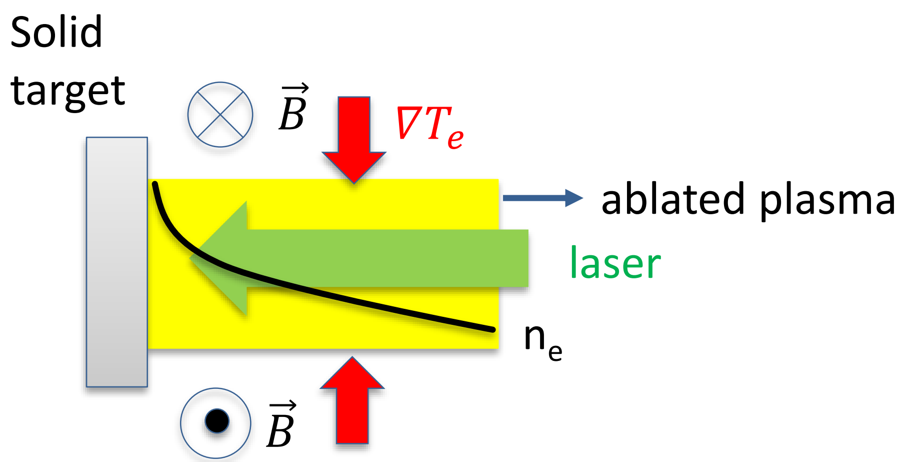
=0 when B=0 ($\vec{J} = \mu_0^{-1}\nabla \times \vec{B}$)

$\overleftrightarrow{\beta}$ constant at B=0,
So $\nabla \times \nabla T_e = 0$

Electron EOS: $p_e = n_e T_e$ neglects Fermi degeneracy

Biermann battery: magnetic fields "spontaneously" (from B=0 state) develop due to non-parallel electron density and temperature gradients

$$\frac{\partial \vec{B}}{\partial t} = -\frac{1}{n_e e}\nabla n_e \times \nabla T_e \quad \text{when} \quad B = 0$$



[1]Ludwig Franz Benedict Biermann, Zeitschrift fur Naturforschung 5: 65 (1950)

Magnetic field evolution: advection, diffusion

$$\vec{E} = -\vec{v} \times \vec{B} - \frac{\nabla p_e}{n_e e} + \eta \vec{J}$$ simplified Ohm's law

$$\vec{J} = \mu_0^{-1} \nabla \times \vec{B}$$

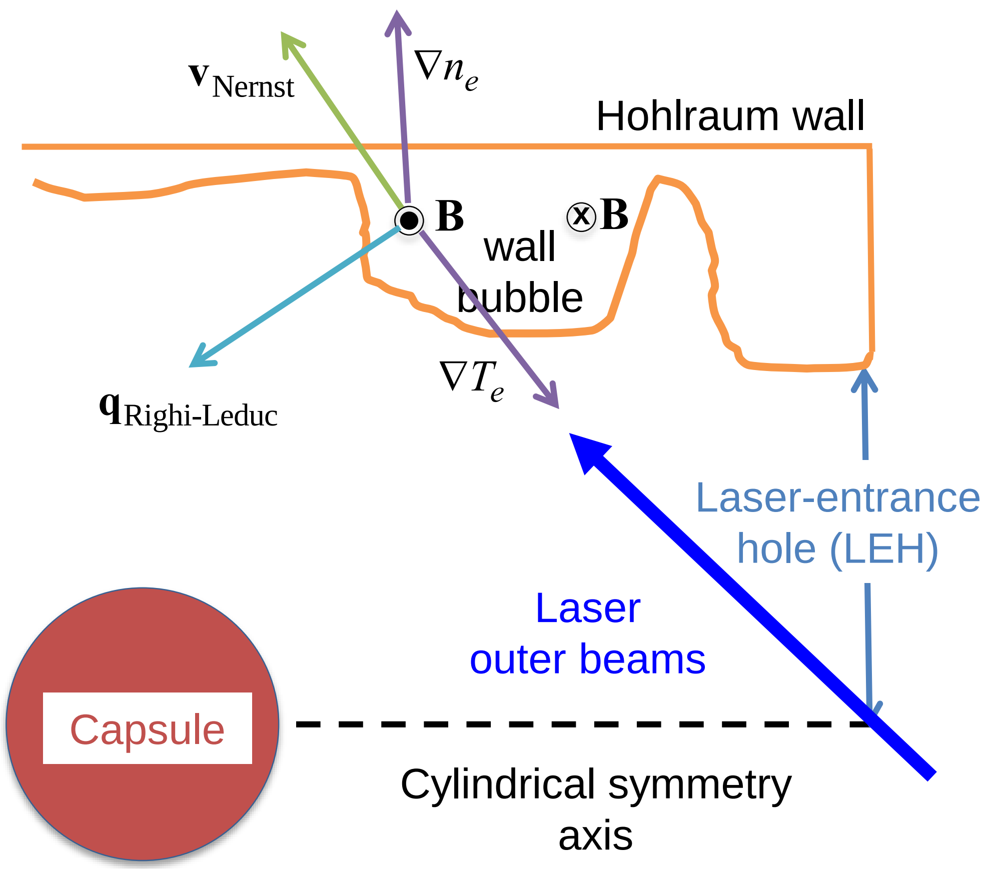
$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\overrightarrow{v \times B}) - \frac{1}{n_e e} \nabla n_e \times \nabla T_e + \mu_0^{-1} \eta \nabla^2 \vec{B} - \mu_0^{-1} \nabla \eta \times (\nabla \times \vec{B})$$

advection | Biermann battery | Resistive diffusion | Resistivity gradient

- Advection: B field advected with plasma flow, frozen-in law (2 slides below)
- Diffusion: breaks frozen-in law, dissipates magnetic energy
  - Magnetic Reynolds number: field advection vs. diffusion
  - Sets time to diffuse through good conductor, e.g. magnetizing a hohlraum with external coils
- $\nabla \eta$: useful for schemes to self-guide electron beams for e.g. fast ignition:
  - A. Robinson et al.
- Imposed B fields also considered for fast ignition:
  - D. J. Strozzi, M. Tabak, et al., Phys. Plasmas 2012: compressed in implosion
  - Osaka group: laser-driven <~ 1 kT

MHD effects in hohlraums[1]

Slide courtesy Will Farmer



$$\left(\frac{\partial \mathbf{B}}{\partial t}\right)_{\text{Biermann-Battery}} \propto \nabla T_e \times \nabla n_e$$

Biermann-Battery creates magnetic fields when temperature and density gradients are misaligned

$$\left(\frac{\partial \mathbf{B}}{\partial t}\right)_{\text{Nernst}} \propto \nabla \times \left(\mathbf{v}_{\text{Nernst}} \times \mathbf{B}\right)$$

$$\mathbf{v}_{\text{Nernst}} = -\frac{c b_\wedge \nabla T_e}{eB}$$

Nernst advects B-field opposite the electron temperature gradient

$$\mathbf{q}_{\text{Righi-Leduc}} = -k_\wedge \hat{\mathbf{b}} \times \nabla T_e$$

Righi-Leduc convects heat at right angles to temperature gradient and B-field

[1]W A Farmer, J M Koning, D J Strozzi, D E Hinkel, L F Berzak Hopkins, O S Jones, M D Rosen, Phys. Plasmas (2017)

Frozen-in law, or Alfven's theorem[1]

Ideal MHD: $\vec{E} = -\vec{v} \times \vec{B}$, magnetic flux though surface moving with plasma conserved

$$\Phi \equiv \int_S \vec{B} \cdot d\vec{a} \qquad \text{magnetic flux through surface S}$$

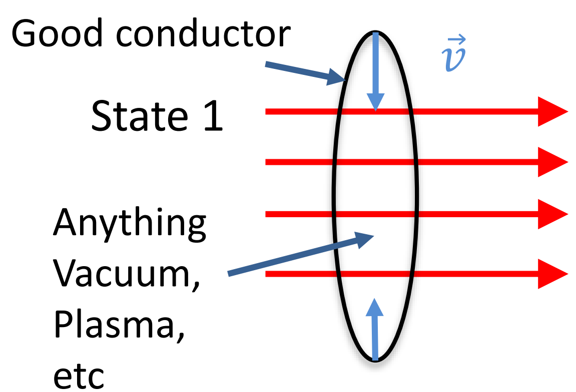
$$\frac{\partial \Phi}{\partial t} = \int_S \left(\partial_t \vec{B} + (\underbrace{\nabla \cdot \vec{B}}_{=0})\vec{v}\right) \cdot d\vec{a} - \oint_{\partial S} \vec{v} \times \vec{B} \cdot d\vec{l} \qquad \text{Leibniz's theorem}$$

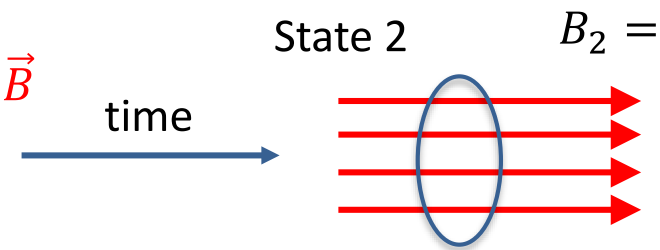
$$\frac{\partial \Phi}{\partial t} = \int_S \nabla \times (-\vec{E}) \cdot d\vec{a} - \oint_{\partial S} \vec{v} \times \vec{B} \cdot d\vec{l} \qquad \text{Faraday's law}$$

$$= \oint_{\partial S} -(\vec{E} + \vec{v} \times \vec{B}) \cdot d\vec{l} \qquad \text{Stokes' theorem}$$

← Completely general

$$= 0 \qquad \vec{E} = -\vec{v} \times \vec{B} \quad \text{on boundary}$$





$$B_2 = \left(\frac{R_1}{R_2}\right)^2 B_1$$

[1]Hannes Olof Gösta Alfvén:
"Existence of electromagnetic-hydromagnetic waves," Nature (1942)

Collisional tensors with B field: resistivity, thermal conductivity

Resistivity: $\overleftrightarrow{\eta} = \begin{bmatrix} \eta_\perp & \eta_\wedge & 0 \\ -\eta_\wedge & \eta_\perp & 0 \\ 0 & 0 & \eta_{||} \end{bmatrix}$

$\vec{B} = b\hat{z}$

$\overleftrightarrow{\beta}$ and $\overleftrightarrow{\kappa}$ same form – watch out for sign of ^ term!

"Hall effect": Electric field develops perpendicular to applied B field and current

$$\vec{J} = J\hat{y} \quad \rightarrow \quad \vec{E} = \overleftrightarrow{\eta} \cdot \vec{J} = (\eta_\wedge J, \eta_\perp J, 0) = \eta_\perp \vec{J} + \eta_\wedge \vec{J} \times \hat{b}$$

- Combines with collisionless JxB term

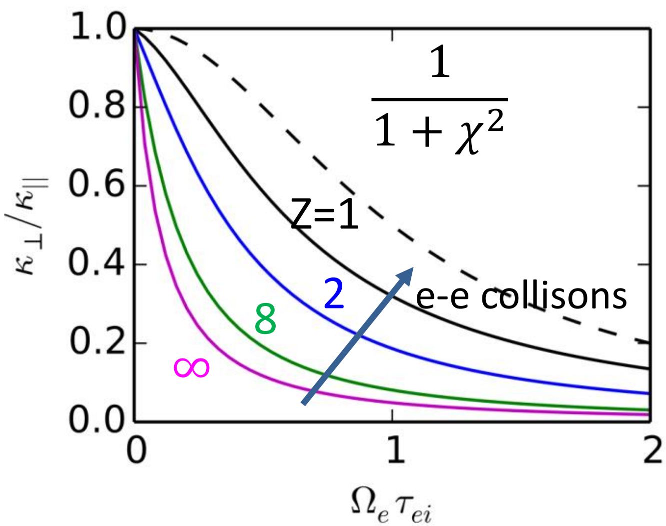
Heat flow reduced perpendicular to B

$$\vec{q} = \overleftrightarrow{\kappa} \cdot \nabla T_e$$

Hall parameter $\chi \equiv \omega_{ce}\tau_{ei}$
Characterizes magnetization of transport coeffs.

$\kappa(Z, \chi)$ found numerically,
e.g. Epperlein and Haines, Phys. Fluids 1986

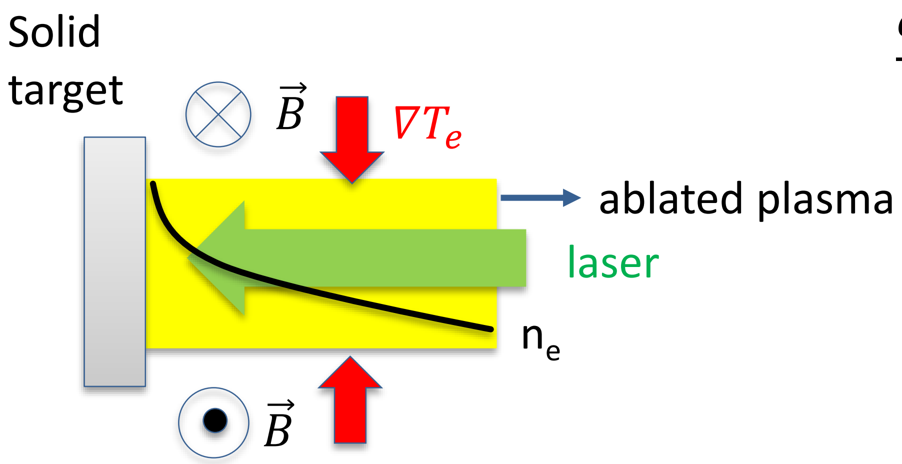
Don't forget Righi-Leduc! Heat flow along $\vec{B} \times \nabla T_e$



HED magnetic field experiments

Magnetic field measurements in laser-produced plasmas date to at least 1971

Biermann fields



$$\frac{\partial \vec{B}}{\partial t} = -\frac{1}{n_e e} \nabla n_e \times \nabla T_e \qquad (B = 0)$$

- 1971 J. A. Stamper et al., Phys. Rev. Lett.:
  0.1 T fields from B-dot probes
- 1975 J. A. Stamper, B. H. Ripin, Phys. Rev. Lett.:
  100 T fields from Faraday rotation
- 1991 J. A. Stamper, Laser and Particle Beams:
  Review article

Magnetic field diagnostics in HED

B-dot probes: workhorse in magnetic confinement devices

- Hard to use in HED / laser-plasma systems

Faraday rotation: line-integral of B*n_e

- Need path where n_e sub-critical for probe wavelength

Proton radiography:

- 1-100 MeV protons feel E and B fields, and collisions with background
- Line-integral of Lorentz force
- Hard to distinguish E and B:
  - Multiple energies, geometric inversion
- Short-pulse laser protons: TNSA, other ion acceleration schemes
  - Borghesi et al., Plasma Phys. Control. Fusion 2001, Phys. Plasmas 2002
  - MacKinnon et al., Phys. Rev. Lett. 2006
- Fusion protons (mono-energetic): D-He3 exploding pusher
  - C. K. Li, R. Petrasso – numerous paper

Spectroscopy: Zeeman splitting $\Delta E = \pm\frac{1}{2}\hbar\omega_{ce} = 0.058\ \mathrm{eV/kT}$

- Measured imposed ~ 10 T field on Janus via optical Neon lines
- B. B. Pollock, D. H. Froula, P. F. Davis et al., Rev. Sci. Sci. 2006

Proton radiography: D-He3 protons

PRL **103,** 085001 (2009) PHYSICAL REVIEW LETTERS week ending 21 AUGUST 2009

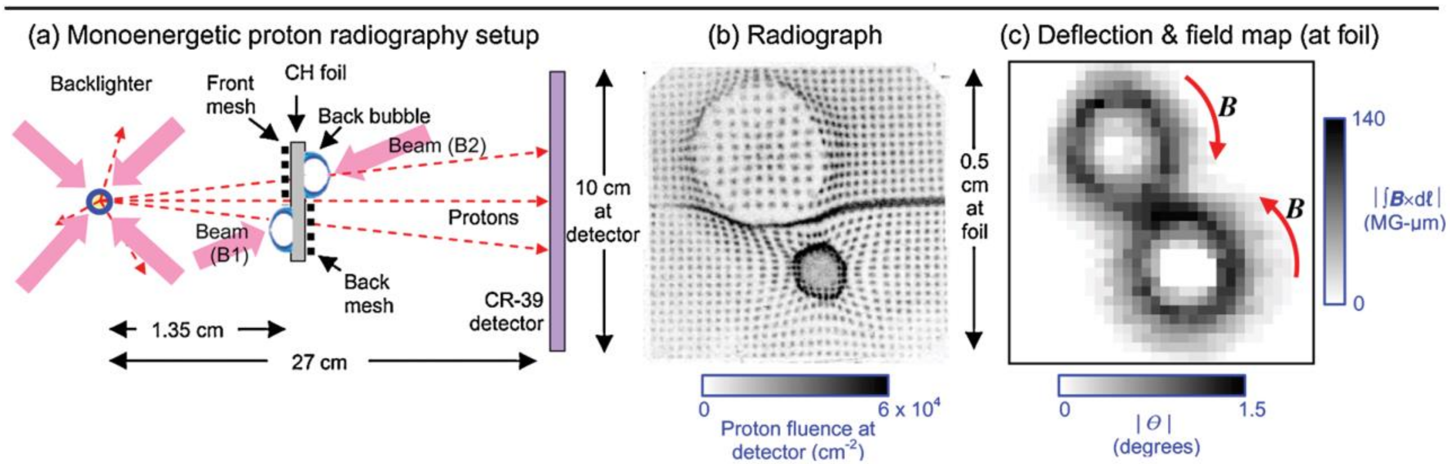
Lorentz Mapping of Magnetic Fields in Hot Dense Plasmas

R. D. Petrasso, C. K. Li, F. H. Seguin, J. R. Rygg,* and J. A. Frenje
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA

R. Betti, J. P. Knauer, and D. D. Meyerhofer
Laboratory for Laser Energetics, University of Rochester, Rochester, New York 14623, USA

P. A. Amendt, D. H. Froula, O. L. Landen, P. K. Patel, J. S. Ross, and R. P. J. Town
Lawrence Livermore National Laboratory, Livermore, California 94551, USA
(Received 12 March 2009; published 17 August 2009)

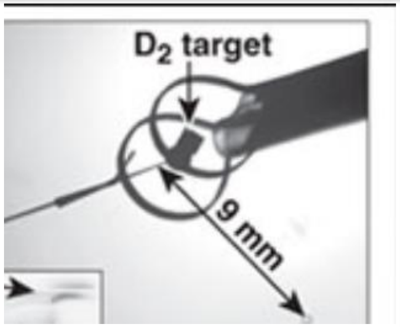
Unique detection of electromagnetic fields and identification of field type and strength as a function of position were used to determine the nature of self-generated fields in a novel experiment with laser-generated plasma bubbles on two sides of a plastic foil. Field-induced deflections of monoenergetic 15-MeV probe protons passing through the two bubbles, measured quantitatively with proton radiography, were combined with Lorentz mapping to provide separate measurements of magnetic and electric fields. The result was absolute identification and measurement of a toroidal magnetic field around each bubble and determination that any electric field component parallel to the foil was below measurement uncertainties.



Imposed fields: pulsed-power laser-driven coils

Imposed B field: pulsed power: 10 – 40 T

- B_0 = 12 T at Janus (LLNL):
  - e- heat flow reduced to Braginskii values, nonlocality for B_0 = 0 quenched
  - B. B. Pollock, D. H. Froula, P. F. Davis et al., Rev. Sci. Sci. 2006
  - D. H. Froula, J S Ross, B B Pollock et al., Phys. Rev. Lett. 2007
- MIFEDS at Omega: 2007 – present:
  - Magneto-Inertial Fusion Electrical Discharge System
  - 8-10 T, microsec. risetime, plans to upgrade
  - Cylindrical and spherical implosions, mini MagLIF
  - 2015: magnetized hohlraum: D. Montgomery et al.



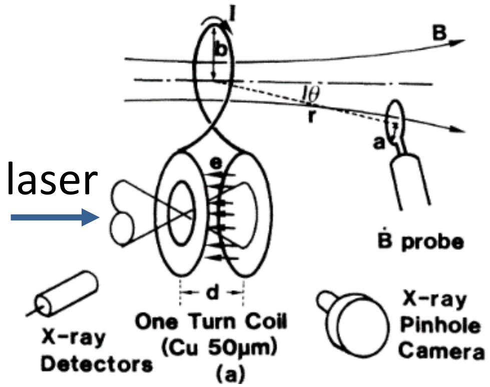
MIFEDS (LLE)

- 2013 – present: Z machine (Sandia) for MagLIF
  - Split Helmholtz coil: 10 T w/ diagnostic access, 30 T without
  - Very slow rise time vs. MIFEDS: several milliseconds, to diffuse through Be liner
- 2013: B_0 = 40 T at ELFIE laser (Ecole Polytechnique)
  - Albertazzi et al., Rev. Sci. Instrum. 2013
- 2014 – present: U. Michigan coil, used on Janus, 12.5 T
  - Used for astrophysical magnetized jets, E. Kemp mid-Z foams
  - S. R. Klein, M. J.-E. Manuel, B. B. Pollock et al., Rev. Sci. Inst. (2014)
  - M.J.-E. Manuel, C.C. Kuranz, A.M. Rasmus, High. En. Dens. Phys. (2015)

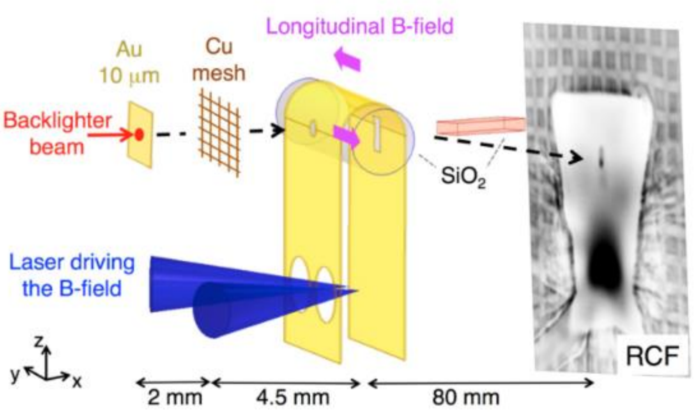
Imposed magnetic field: laser-driven coil

Laser-driven hot electrons carry current b/t 2 conductors

Daido et al., 1986



Goyon et al., 2017



1979 V V Korobkin, S L Motylev: Sov. Technical Phys. Lett.
- First paper on basic concept

1986 H Daido et al., Phys. Rev. Lett. (Osaka)
- 60 T, 10.6 um CO_2 laser

2005 C Courtois et al., J. Applied Phys. (York)
- 7 T, Nd:glass laser (1.053 um), hot electron model

2013 S Fujioka et al., Scientific Reports (Osaka)
- 1500 T (!!), 0.53 um or 1.06 um Nd:glass laser
- Subsequent analysis suggests << field

2015 J J Santos et al., New J. Phys. (LULI pico 2000)
- 800 T
- B-dot probes, Faraday rotation, proton radiography

2017 C Goyon et al., Phys. Rev. E (Omega EP)
- 210 T, 0.351 um Nd:glass laser
- Time and space dynamics, lumped circuit model

Flux compression: explosive drive laser drive

Flux compression with explosives

Pioneers of magnetic flux compression

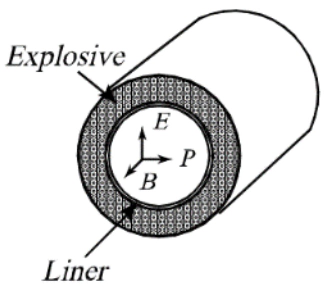
USSR VNIIEF - Sarov	USA Los Alamos
	
Andrei Sakharov 1921-1989	C. Max Fowler 1918-2006

J. L. Fowler, Los Alamos (1944, unpublished) ~ experiment, ~hundreds gauss.
Ya. P. Terletskii, Sov. Phys. JETP **32**, 301 (1957) – theory, original report dated 1952.
C. M. Fowler, W. B. Garn and R. S. Caird, J. Appl. Phys. **31**, 588 (1960) – explosive experiments, peak **15 MG**.
A. D. Sakharov *et al*., Dokl. Akad. Nauk SSSR **165**, 65 (1965); A. D. Sakharov, Usp. Fiz. Nauk **88**, 725 (1966).
Suggested in 1951, explosive experiments started in 1952, peak **25 MG**.
C.M. Fowler and L.L. Altgilbers, "Magnetic Flux Compression Generators: a Tutorial and Survey," Electromagnetic Phenomena **3**, No. 3 (11), 306 (2003).

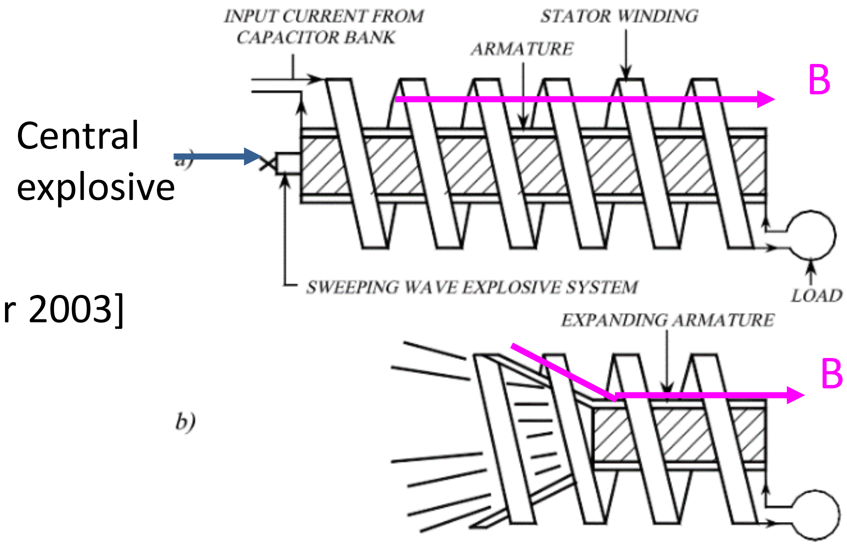
Slide courtesy A. Velikovich

Flux compression with explosives

Cylindrical implosion: compress axial field



Cylindrical explosion into helical coil



[Figs. From Fowler 2003]

Purposes

- Large B fields
- Large currents to drive other loads

Literature

1944: J. L. Fowler, unpublished – LANL

1960 LANL: C. M. Fowler, W. Garn, R. Caird, J. Applied Phys.: **1400 T**

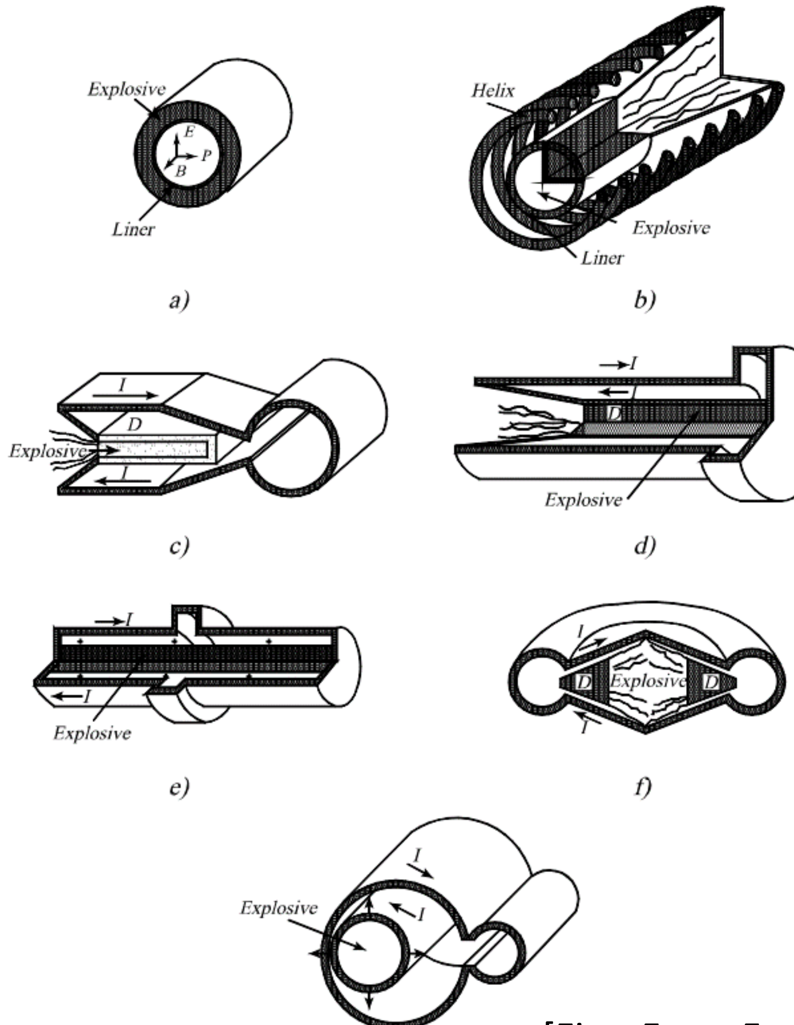
1965: A. D. Sakharov, Soviet Phys. Uspekhi
Accelerate particles to 1 TeV - nuclear explosive driven

1993: C. M. Fowler, B. L. Freeman: “The Los Alamos-Arzamas-16 High Magnetic Field Shot Series, Ancho Canyon Site, 1993”, LANL report: LA-UR-94-2802. **2800 T**

2003: C. M. Fowler, L. L. Altgilbers, Electromagnetic Phenomena (Ukraine) – review

2012: A. L. Velikovich – APS DPP tutorial talk, plus Phys. Plasmas 2015

Explosive flux compression: advanced configurations have been developed



[Figs. From Fowler 2003]

Strip generator powered railgun Ancho Canyon firing site (LANL)

Fig. 30. Strip generator powered railgun at Ancho Canyon firing site (LANL).

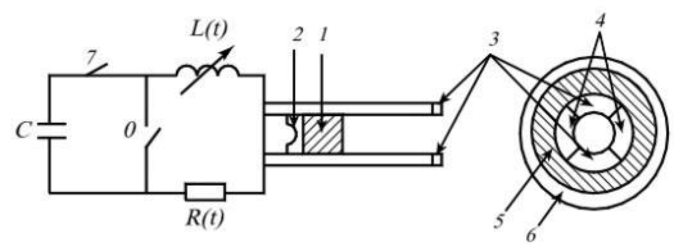
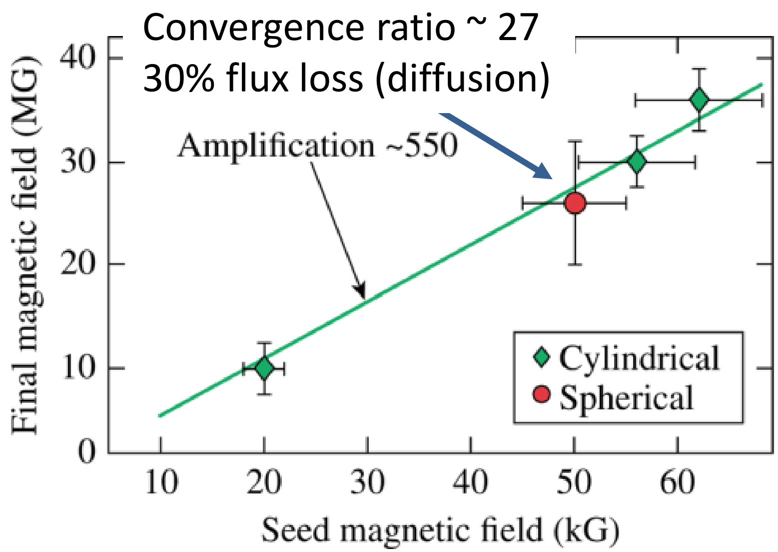


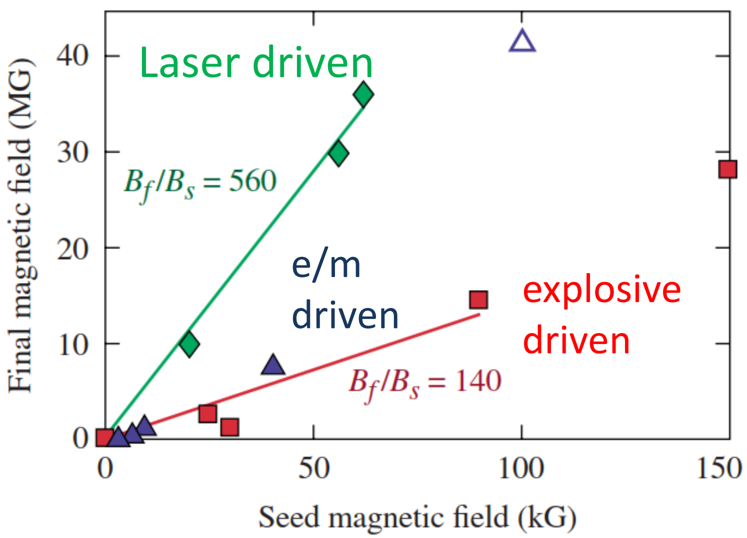
Fig. 31. FCG Driven railgun scheme proposed by Shvetsov et al. [132].

Flux compression with lasers:
Omega experiments with MIFEDS

- Cylindrical[1,2] and spherical[3,4] implosions
- CH capsule, D2 gas fill
- <= 8 T seed field
- T_{ion} up by 15%, fusion yield up by 30% (spherical)



From Hohenberger et al.



From Knauer et al.

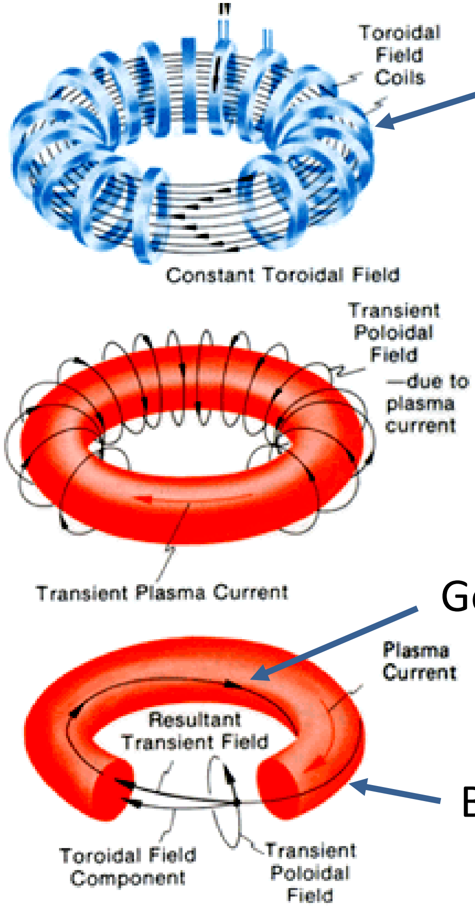
1 O. V. Gotchev et al., Phys. Rev. Lett. (2009); 2 J. P. Knauer et al., Phys. Plasmas (2010)
3 P. Y. Chang et al., Phys. Rev. Lett. (2011); 4 M. Hohenberger et al., Phys. Plasmas (2012)

Fusion: magnetic, inertial, magneto-inertial

Magnetic fusion

- T_{ion} ~ 10 keV for DT, like ICF
- Need B to confine 3.5 MeV alpha:
  - B = 10 T → R_a = 2.7 cm
  - Plus exotic orbits, e.g. bananas
  - Machine size matters!
  - → Meter scale, > $1 Billion cost
- Low beta: magnetic >> plasma pressure
  - beta < 0.1 for stability
  - B = 10 T, T = 10 keV → ρ < 4E-10 g cm^{-3}
- Steady state: Alpha heating balances losses
  - $P_\alpha + P_{aux} > P_{brem} + P_{dif}$
- Energy confinement time τ_E
  - $P_{dif} = n_e T_e / \tau_E$
  - Very complicated – turbulent transport
  - Increases with B field!
- Lawson condition: $n_{ion} T > f(T)$

tokamak



"Bad curvature:" Outward drift all way around

Good curvature

Bad curvature

Magnetic and inertial fusion scales

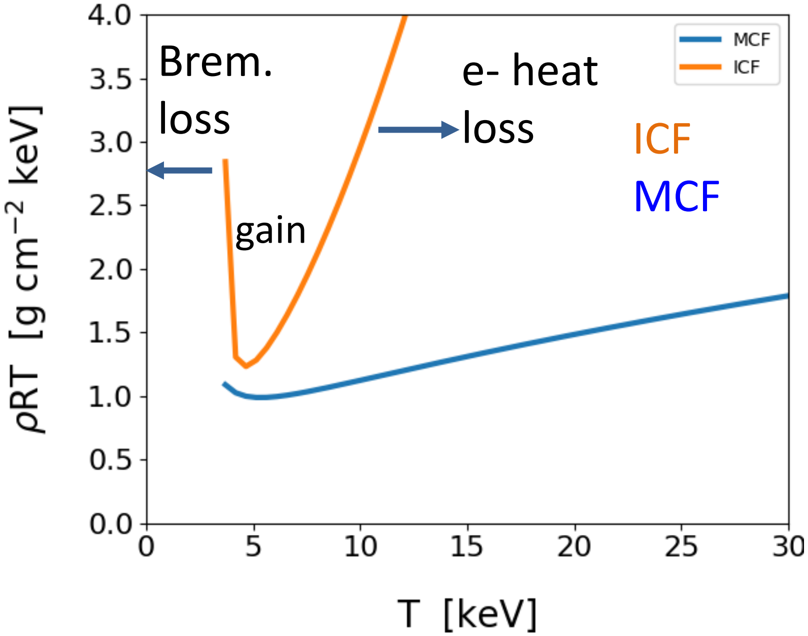
Parameter	Magnetic	Inertial (hotspot)
N_{ion} [cm^{-3}]	1E14	2E25
ρ [g cm^{-3}]	4E-10	100
T_{ion} [keV]	10	10
Pressure	1.6 bar	320 Gbar
Energy confinement time τ_E	10 sec	100 ps
System size	1 m	50 um
"Confinement length" $R_E = c_{sound}\tau_E$	1E9 cm	50 um
ρR_E [g cm^{-2}]	0.4	0.5
$\rho R_E T_{ion}$ [g cm^{-2} keV]	4	5

"Confinement length" R_E for MFE

- Convenient scale to compare with ICF
- >> system size – as well it should be! B field is doing something

Lawson condition for magnetic and inertial fusion

“Triple product” ρRT for self-heating



$$P_\alpha + P_{aux} + PpdV > P_{brem} + P_{dif}$$

$P_a = f_a\, n_a\, E_a$ = alpha deposition

MCF: $f_a = 1$; pdV = 0 (pressure balance)

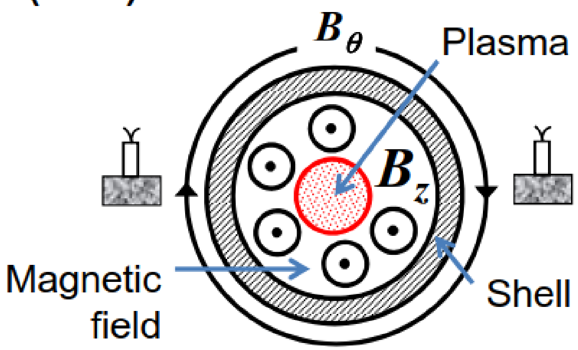
ICF: $f_a(\rho R, T) < 1$

Magneto-inertial fusion has a long history

Linhart et al., 1962

The principle is described of inertial confinement of plasma in which a cylindrical metallic shell compresses a magnetic field and plasma in a "soft-core" geometry. The shell transforms a part of its kinetic energy into the thermal energy of the compressed plasma and into the stored magnetic energy…

J. G. Linhart, H. Knoepfel and C. Gourlan, "Amplification of magnetic fields and heating of plasma by a collapsing metallic shell," Nucl. Fusion Suppl. Pt. 2, 703 **(1962).**



MIRAPI – Minimum Radius Pinch

- Outer shell either ionized dust (MIRAPI-1) or tungsten 200-wire array (MIRAPI-2)
- Inner shell hydrogen

Still relevant for Z-pinch neutron production

Looks like MagLIF!

Slide courtesy A. Velikovich

Magnetized ICF: help ignition, hurt burn?

"Magnetized ICF:" intermediate B field

- B field reduces electron conduction and alpha losses
- But magnetic pressure << plasma pressure

Lindemuth and Kirkpatrick, Nucl. Fusion 1983:

- 0D model, azimuthal B field

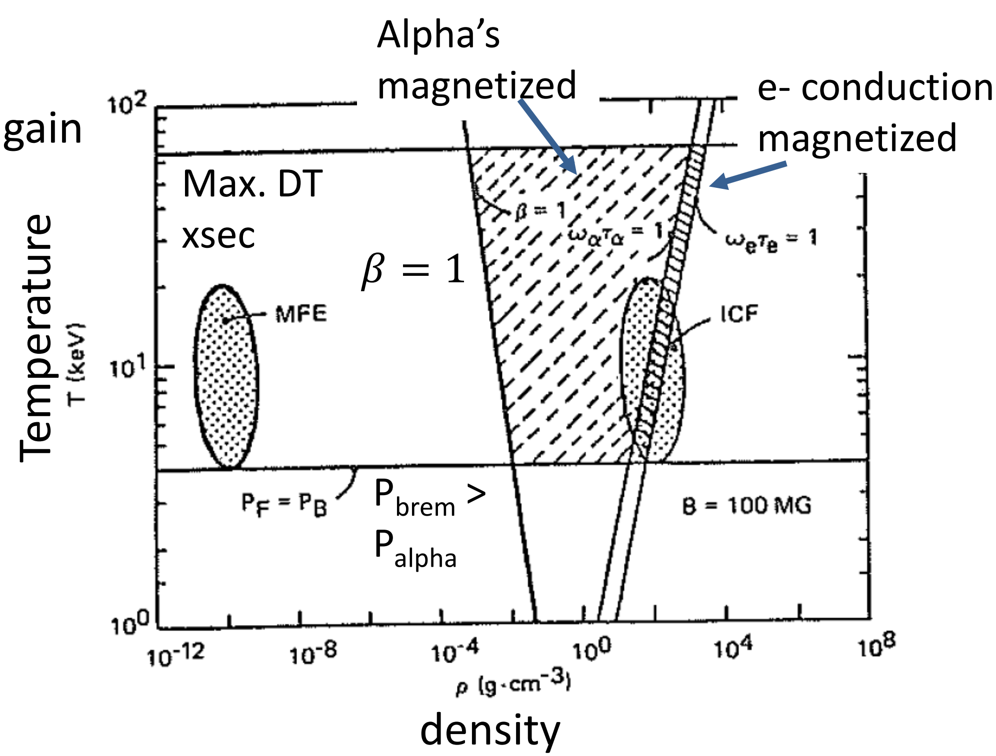
Jones and Mead, Nucl. Fusion 1986:

- 1D model, azimuthal B field
- B field can help get to ignition
- BUT can impede propagating burn, high gain

From Jones and Mead:

> Let us ask which properties would make a desirable regime in which to consider fusion with magnetized DT fuel. We would like the magnetic pressure to be negligible for a number of reasons: the magnetic field can impede the implosion, it can destroy the symmetry of the implosion, and in the $\beta = 1$ regime the usual deleterious magnetic fusion energy (MFE) instabilities can occur. Here, β is the ratio of plasma pressure to magnetic pressure. One might like the conductivity and alpha mobility to be small in order to reduce losses to a pusher.

B = 10 kT in hotspot



Magnetic field reduces electron heat conduction, increases alpha deposition

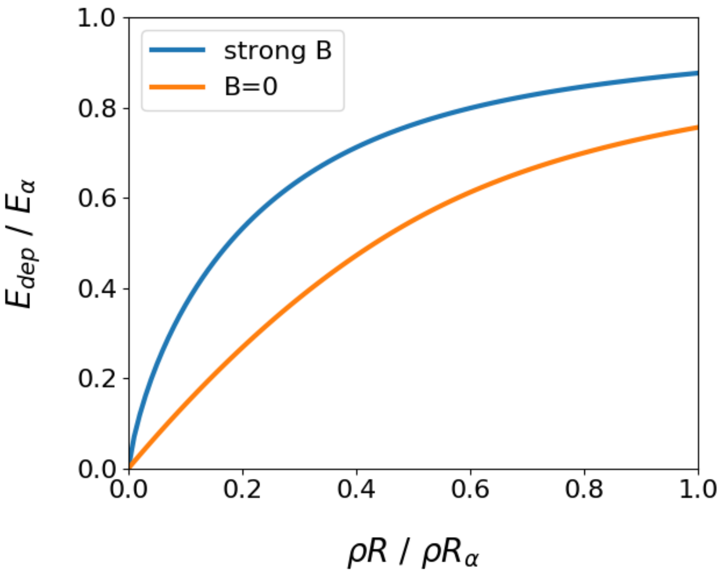
Electrons:

- Axial field, spherical geometry
- Magnetized in 2 directions
- Radial heat flux 1/3 unmagnetized value

$$\langle q_r \rangle (B) = \frac{1}{3} \langle q_r \rangle (B = 0)$$

$$\langle q_r \rangle (B = 0) = -\kappa_{||}^{e} \frac{\partial T_e}{\partial r}$$

Alphas: energy deposition in hotspot[1]



Strong B: α cyclotron freq > rate α's stop on e-'s

$$B[\mathrm{T}] = 7850 \frac{\rho[100\ \mathrm{g/cm^3}]}{T_e[10\ \mathrm{keV}]^{3/2}}$$

α range:

$$\rho R_\alpha [\mathrm{g/cm^2}] \approx 0.44\ (T_e/10\ \mathrm{keV})^{5/4}$$

Example:

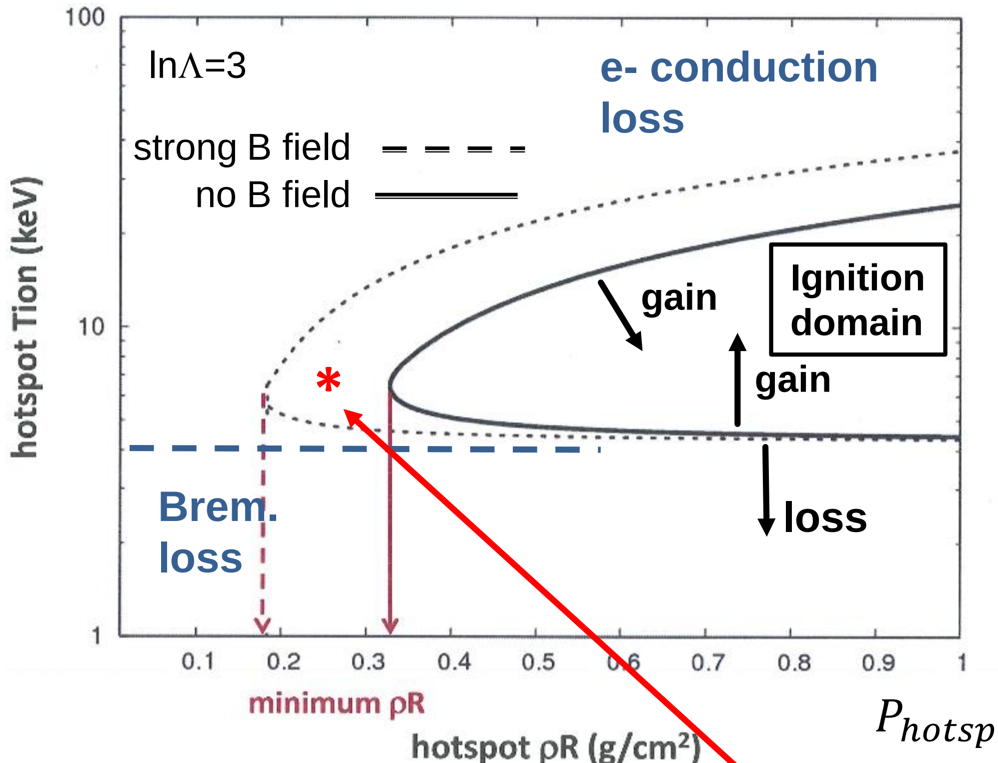
T_e = 10 keV, ρ = 100 g/cm^3

→ B = 7850 T, or B_0 = 8.7 T at conv. ratio 30

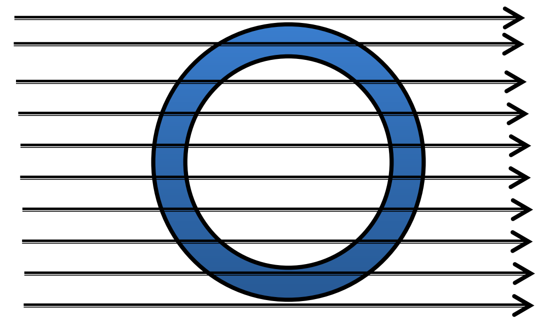
[1]S. Yu. Gus'kov, V. B. Rozanov, L. E. Trebuleva, Sov. J. Quantum Electronics 14, 1062 (1984)

Imposed magnetic field expands hotspot self-heating domain

Hotspot conditions for self-heating



Slide courtesy Darwin Ho



Significantly lower ρR for self-heating:

- Strong field: 0.18 g/cm^2
- No field: 0.32

Hotspot power balance

$$P_{hotspot} = P_{pdV} + P_{\alpha}(\rho r) + P_{rad} + P_{e-cond}$$

P_{pdV} =0 at stagnation

P_{e-cond}: $-\frac{1}{3}\kappa_{||}^{e}\frac{\partial T_e}{\partial r}$

"Ho approach":

- Take a target that doesn't ignite in 1D
- Impose B → ignition

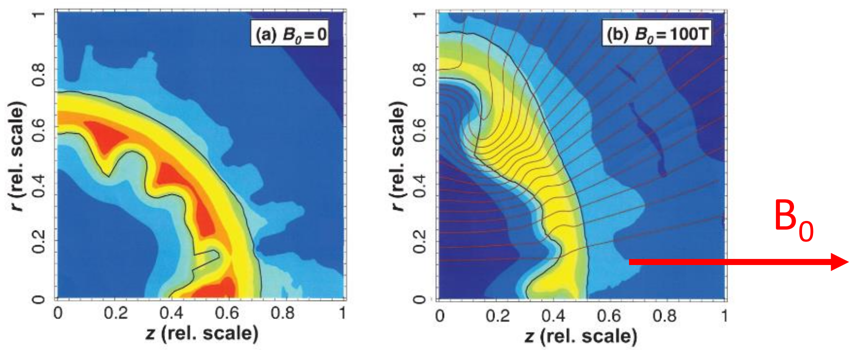
Imposed field improves capsule performance

"Perkins approach:" recovery of 1D ignition

- Target ignites in 1D
- But not in lab
- Perturb simulation to degrade yield
- Imposed B: ignites for stronger perturbation
- Does not increase 1D yield

Too much of a good thing:

B_0 = 100 T → pancaked implosion

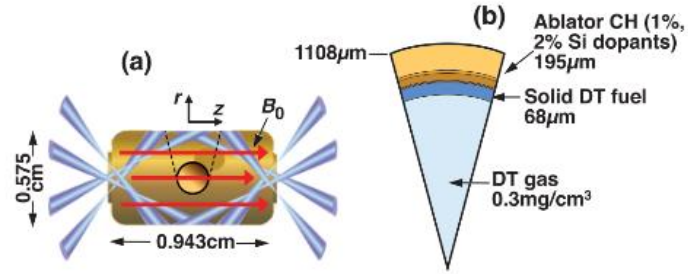


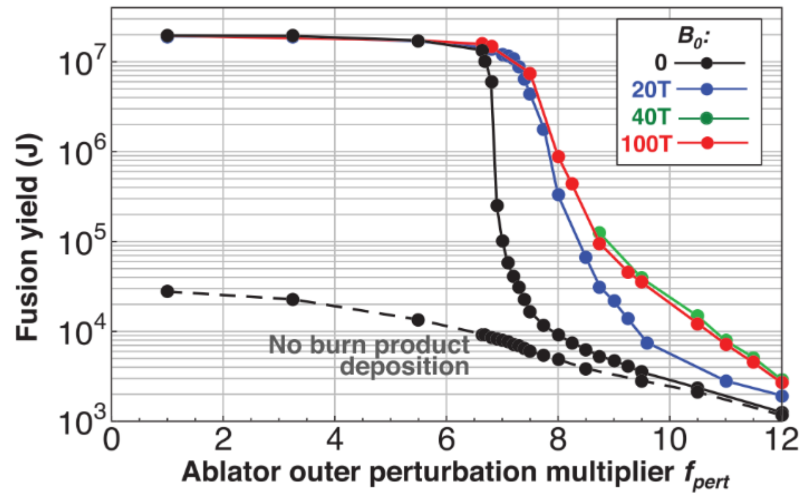
See also:

Perkins et al., Phys. Plasmas 2017

LDRD final report – contact Perkins

"Low foot" NIF design: imposed axial B





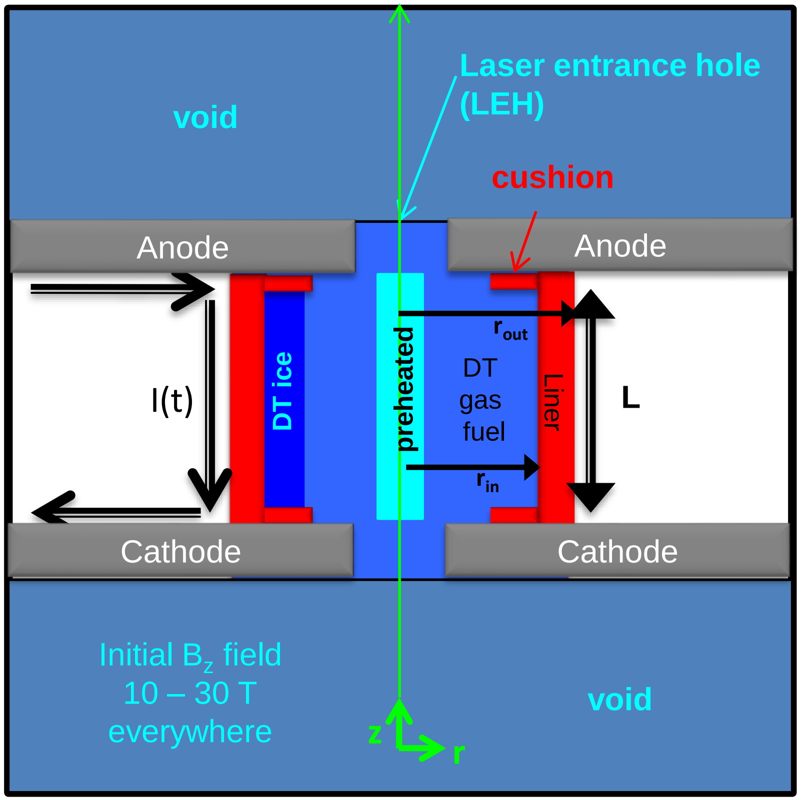
2D RZ Lasnex MHD simulations

L. J. Perkins et al., Phys. Plasmas 2013

Perkins and Ho support both approaches, just a mnemonic

MagLIF* = Magnetized Liner Inertial Fusion: fusion gain on device like Sandia's Z Machine

MagLIF schematic
S. A. Slutz, IFSA 2015 talk



*S. A. Slutz, R. A. Vesey, Phys. Rev. Lett. 2012

3 key elements
A. B. Sefkow, Phys. Plasmas 2014

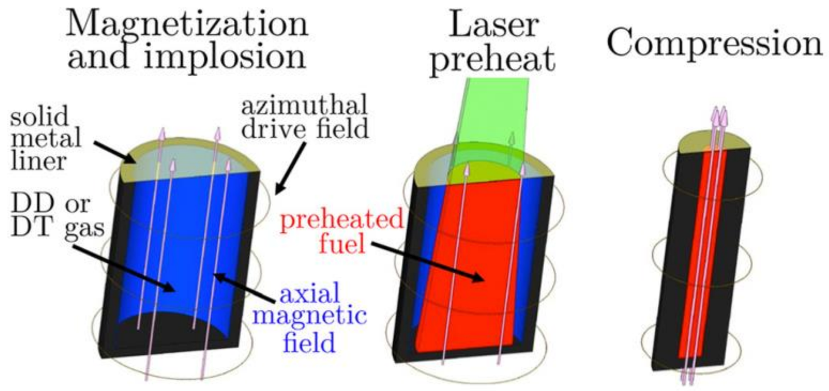


FIG. 1. Schematic of the MagLIF concept.

- Laser preheat: ~ 10 kJ, ions to ~ 500 eV
- B_{z0} ~ 30 T lower e- thermal loss, confine alphas
  - Relaxed hotspot ρR
  - Too much field impedes burn propagation
- Slow implosion: liner v_{imp} <~ 100 km/s
- Long implosion time ~ 60 ns
  - Laser preheat over ~10 ns: low power, intensity

MagLIF homework

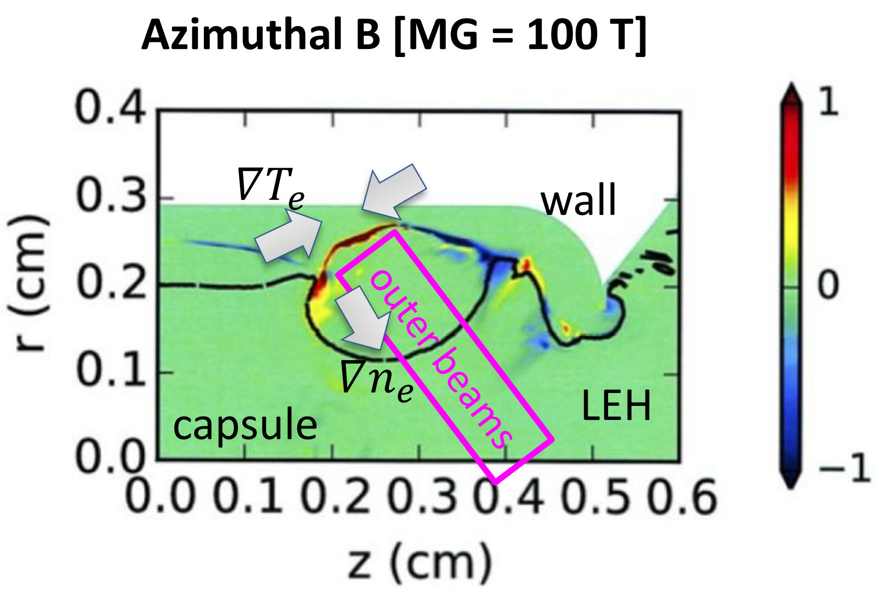
- Draw a self-heating curve for MagLIF's hotspot.
- Place it on the plot from Darwin Ho on slide 50.
- Recall that MagLIF is a cylindrical and not spherical system.

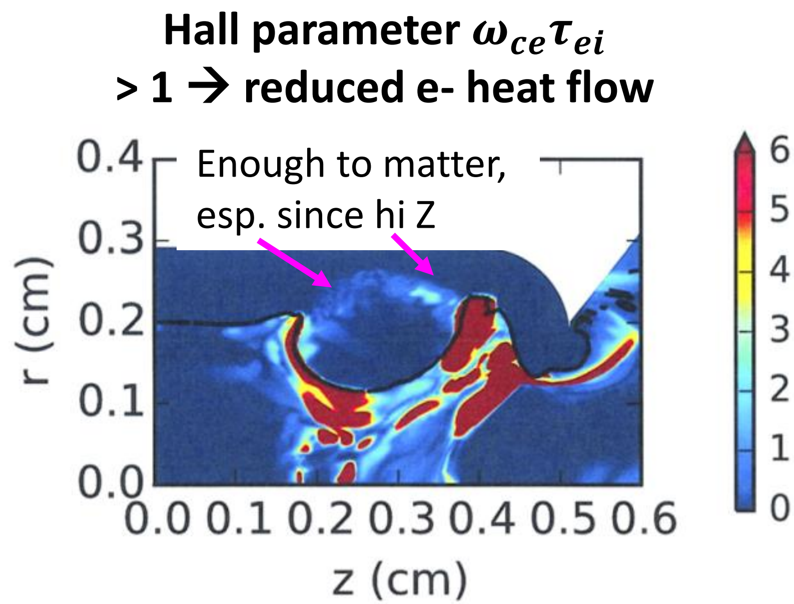
B fields in hohlraums

- Self-generated
- Imposed

Self-generated fields in hohlraums[1]: Highly localized ~ MG fields, reduced heat flow

- Main effect on plasma: reduced electron heat conduction perpendicular to B
- NIF shot N151122: HDC, 0.3 mg/cc hohlraum fill – late peak power [5 ns]





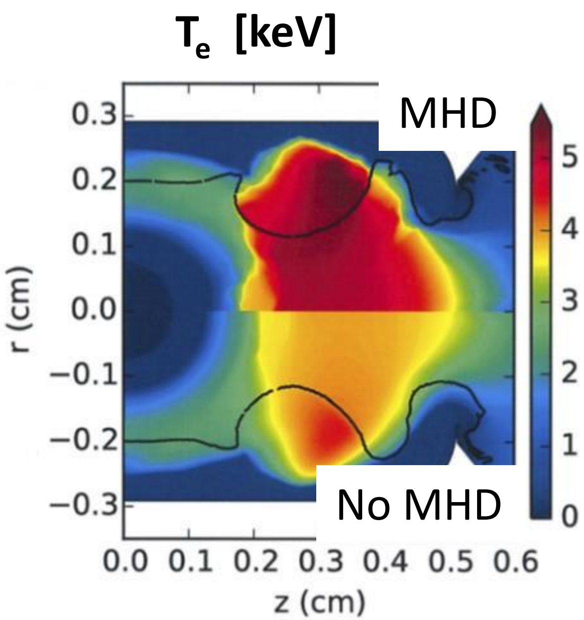
HYDRA MHD 2D R-Z simulations

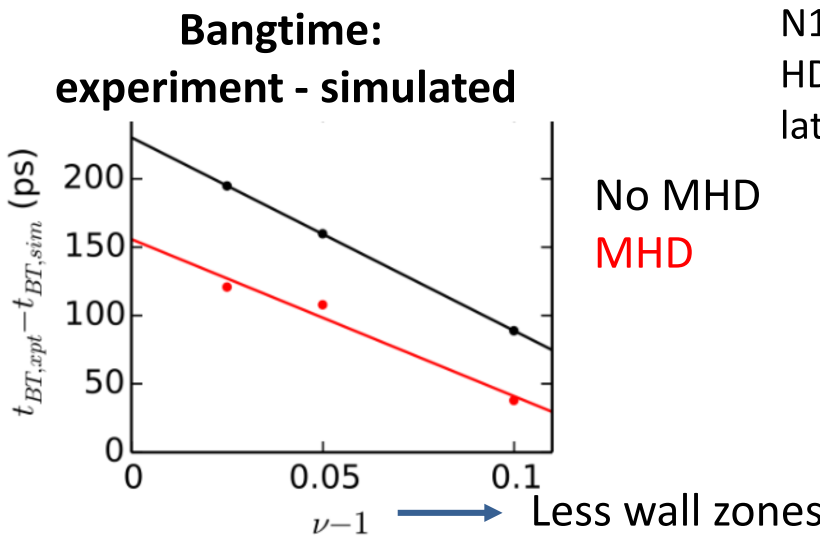
- B field advection, diffusion, Biermann battery, Nernst effect, reduced heat flow
- No Righi-Leduc effect – but now in code [J. Koning]

[1]W A Farmer, J M Koning, D J Strozzi, D E Hinkel, L F Berzak Hopkins, O S Jones, M D Rosen, Phys. Plasmas (2017)

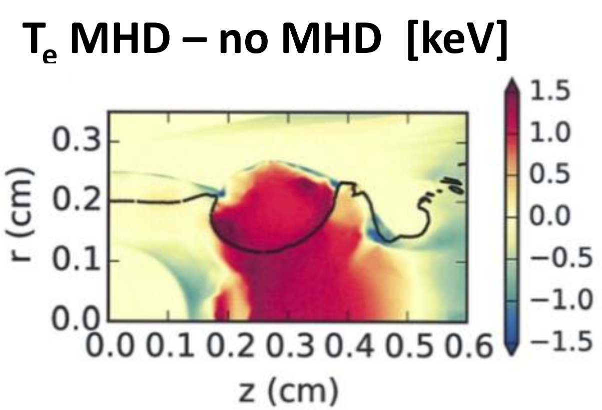
Lasnex work by M. D. Rosen: similar results, but Nernst more fully “erases” Biermann fields

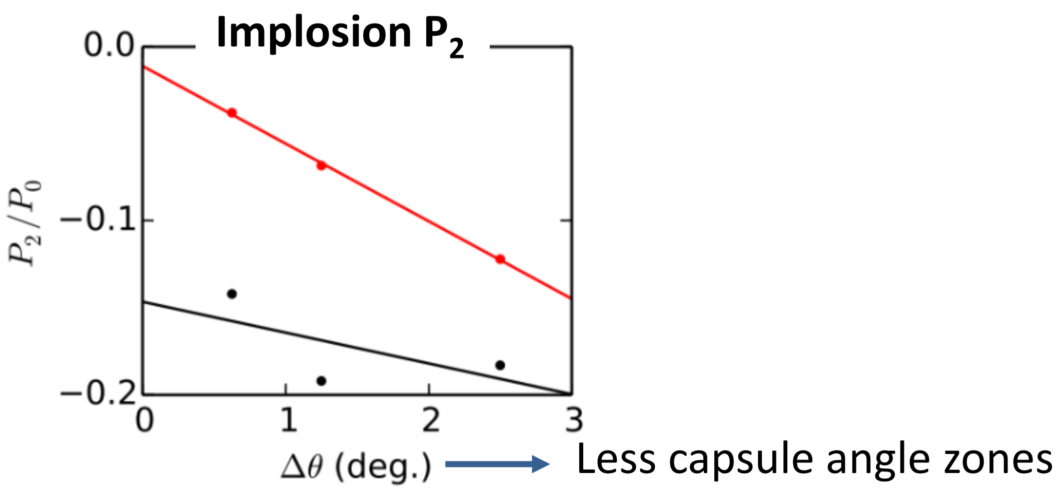
Self-generated fields in hohlraums[1]: increased T_e, later bangtime, less pancaked shape





N151122:
HDC, 0.3 mg/cc,
late peak power [5 ns]

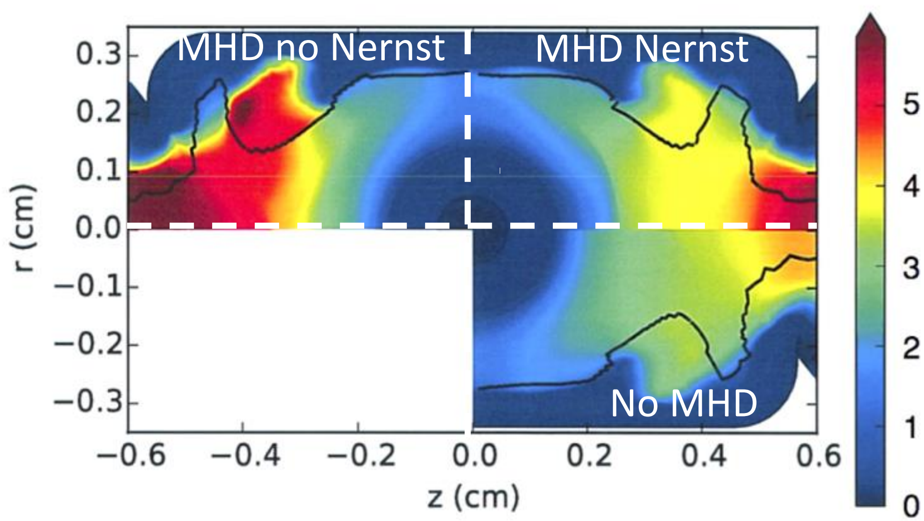


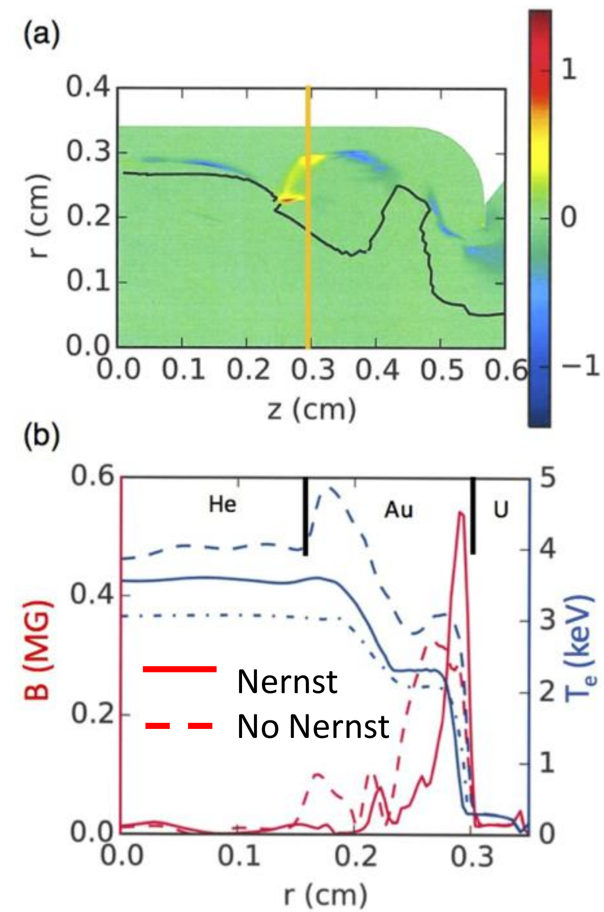


[1]W A Farmer, J M Koning, D J Strozzi, D E Hinkel, L F Berzak Hopkins, O S Jones, M D Rosen, Phys. Plasmas (2017)

Self-generated fields in hohlraums[1]: Nernst effect advects field into wall, reduces T_e

High-foot simulation, Late peak power [13 ns]





- Nernst effect: B field advected by e^- heat flow
- Reduced by things that limit heat flow:
  - Nonlocality, ion acoustic turbulence
- MHD sims with fluid Nernst: likely upper bound on effect

"What Biermann giveth, Nernst taketh away" – M. D. Rosen

[1]W A Farmer, J M Koning, D J Strozzi, D E Hinkel, L F Berzak Hopkins, O S Jones, M D Rosen, Phys. Plasmas (2017)

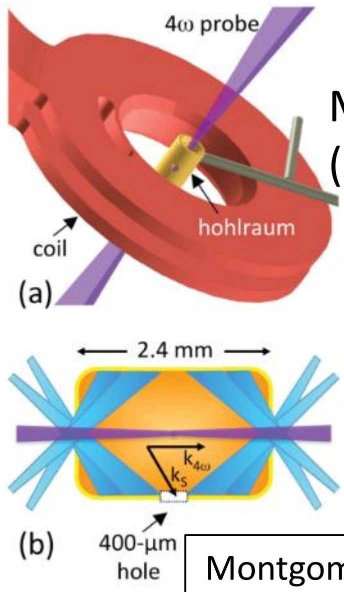
Self-generated B fields in capsule

Two recent works: effects are there but not huge:

- Walsh et al., Phys. Rev. Lett. 2017
- M. Partha (summer student), S. Haan – LLNL 2016

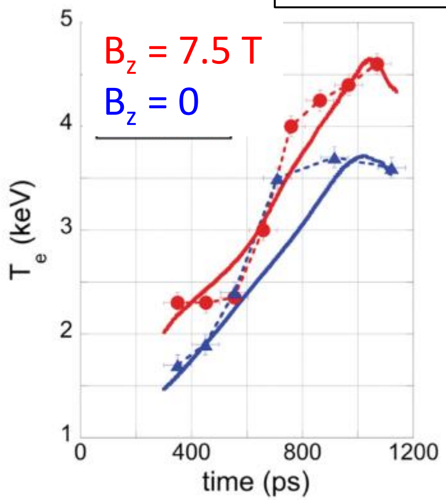
Imposed B field effects on hohlraum dynamics[1]

- Underdense hohlraum fill magnetized for B_{z0} ~ 10 T
- Raises plasma temperature
- Improves inner-beam propagation:
  - Higher T_e, lower n_e in equatorial channel → less absorption
- May reduce SRS[2]
- Hot electrons:
  - Magnetized in underdense fill
  - Could guide toward or away from capsule
  - Strongly depends on when and where sourced



MIFEDS (LLE)

Montgomery et al., PoP 2015

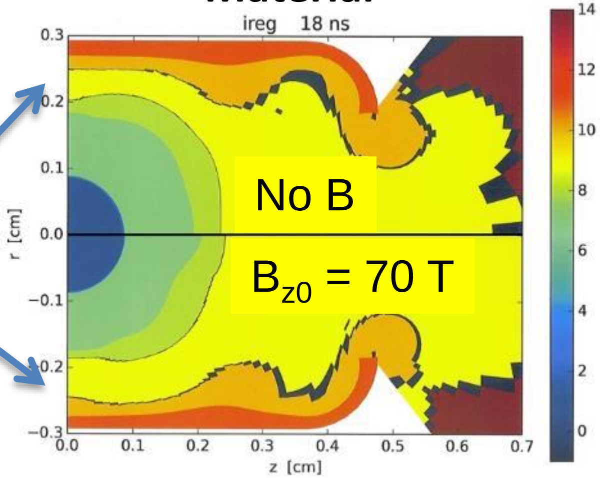


[1]D J Strozzi, L J Perkins, M M Marinak, D J Larson, J M Koning, B G Logan, *J. Plasma Phys.* (2015)
[2]D S Montgomery, B J Albright, D H Barnak, P Y Chang, J R Davies, et al., *Phys. Plasmas* (2015)

Imposed B field raises plasma temperature, improves inner-beam propagation

Low-foot shot N120321
B_{z0} = 70 T
18 ns: early peak power

Material

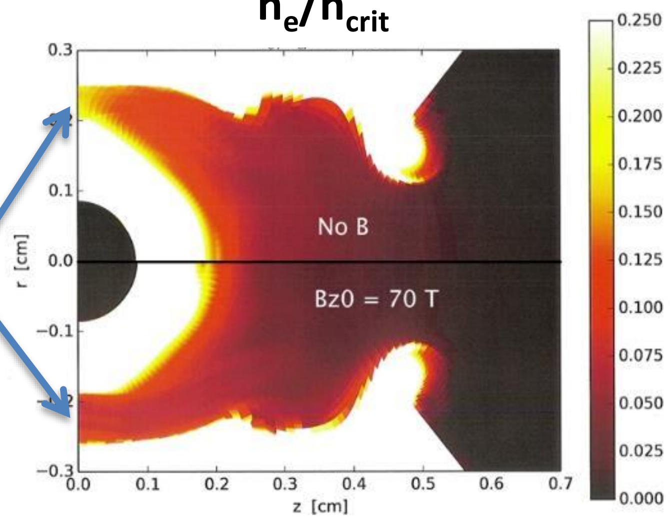


RZ HYDRA MHD

Each figure is a hohlraum quadrant with (top) and without (bottom) B field

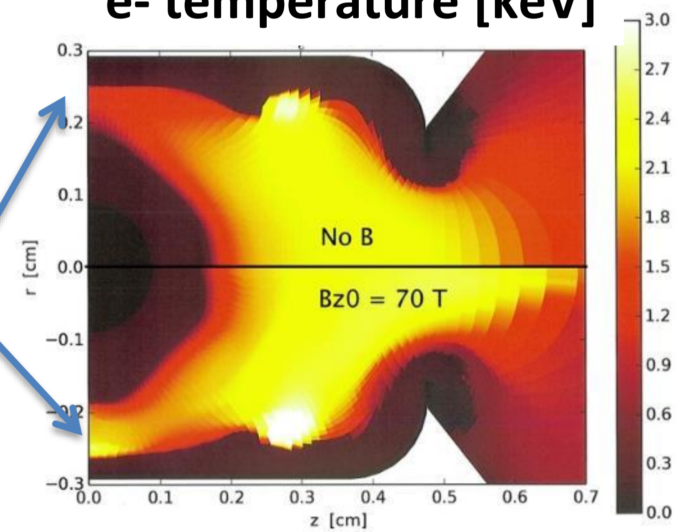
Wider equator channel with B

n_e/n_{crit}



Less n_e w/ B

e- temperature [keV]



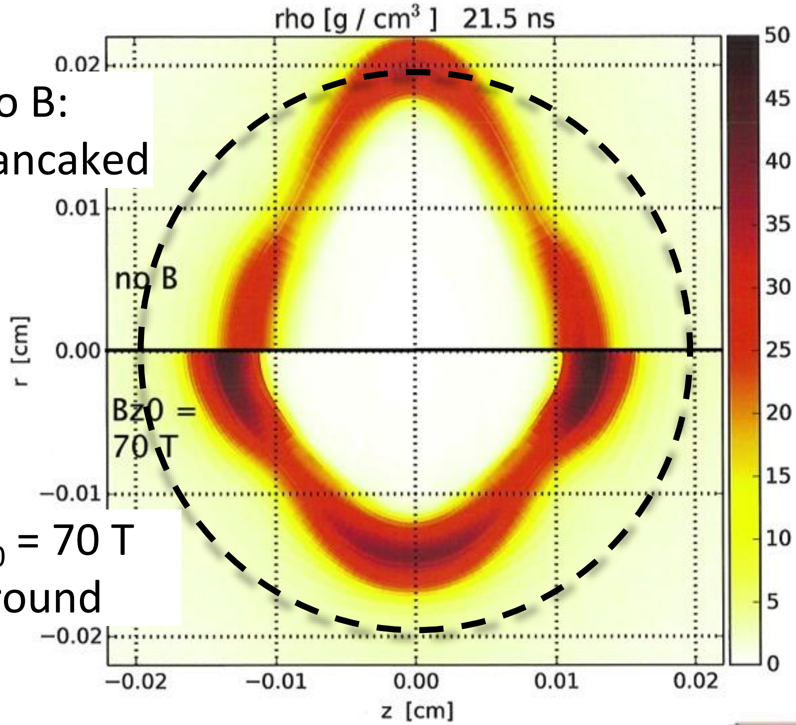
Higher T_e w/ B, esp. on equator

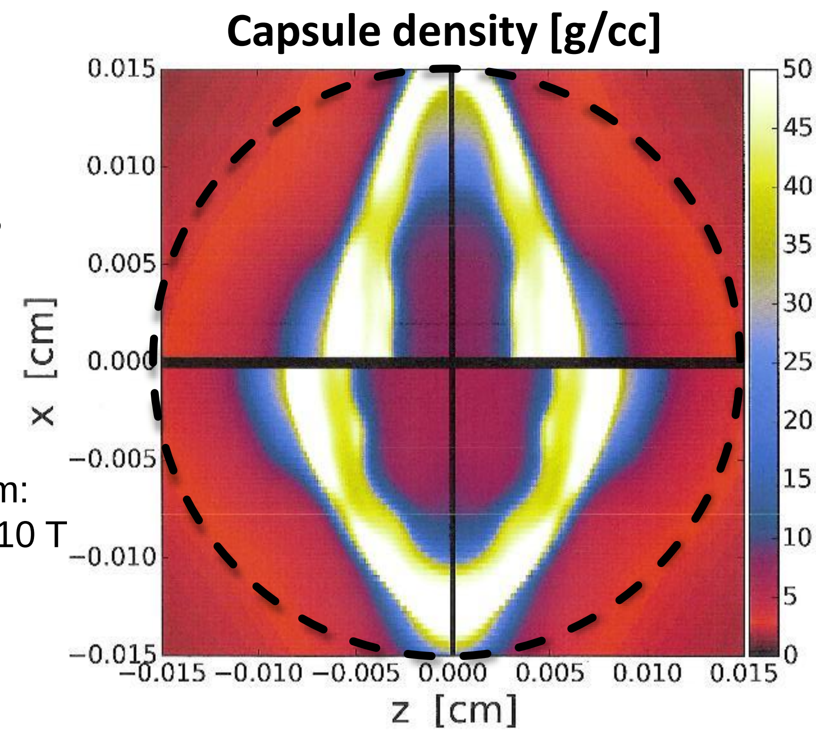
[1]D J Strozzi, L J Perkins, M M Marinak et al., *J. Plasma Phys.* (2015)

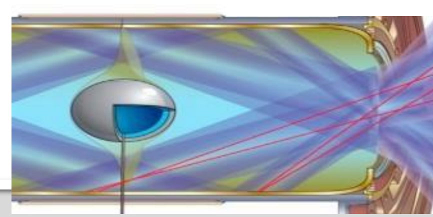
Inner beam propagation: B field reduces inner beam absorption in fill, less pancaked implosion

Low-foot shot N120321
B_{z0} = 70 T
21.5 ns: end of pulse

High-foot shot N121130[2]
B_{z0} = 10 T
15.2 ns





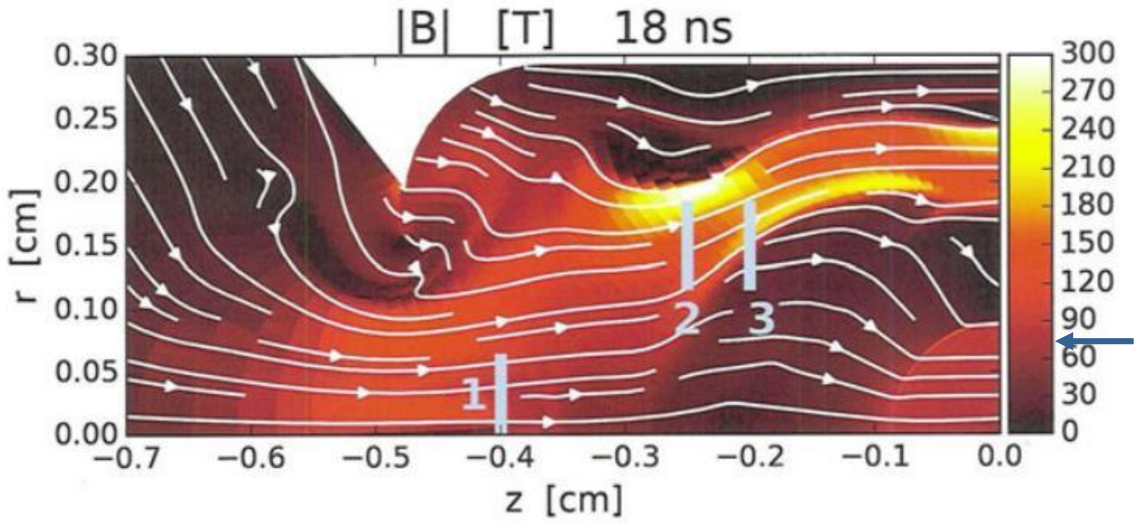


[1]D J Strozzi, L J Perkins, M M Marinak et al., *J. Plasma Phys.* (2015)

[2]L. J. Perkins et al., LDRD final report

B field follows MHD "frozen-in law:" advected with flow

Low-foot shot N120321
B_{z0} = 70 T
18 ns: early peak power



Light blue boxes are hot electron sources for next slide

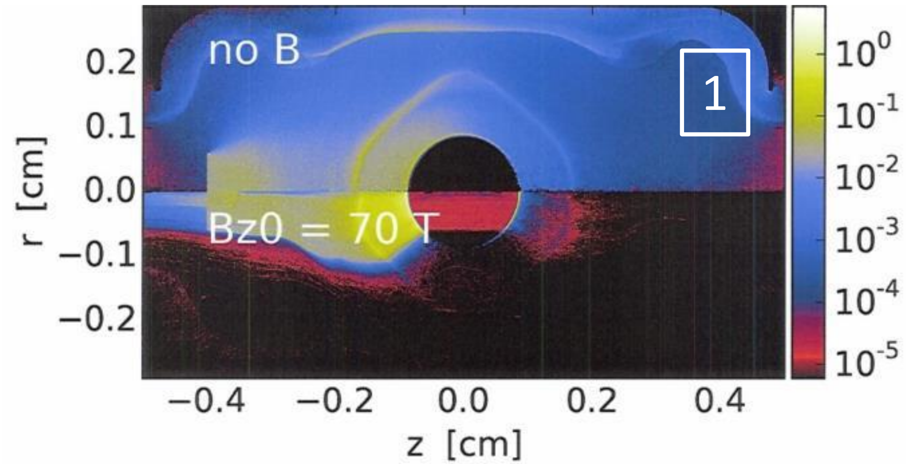
[1]D J Strozzi, L J Perkins, M M Marinak et al., *J. Plasma Phys.* (2015)

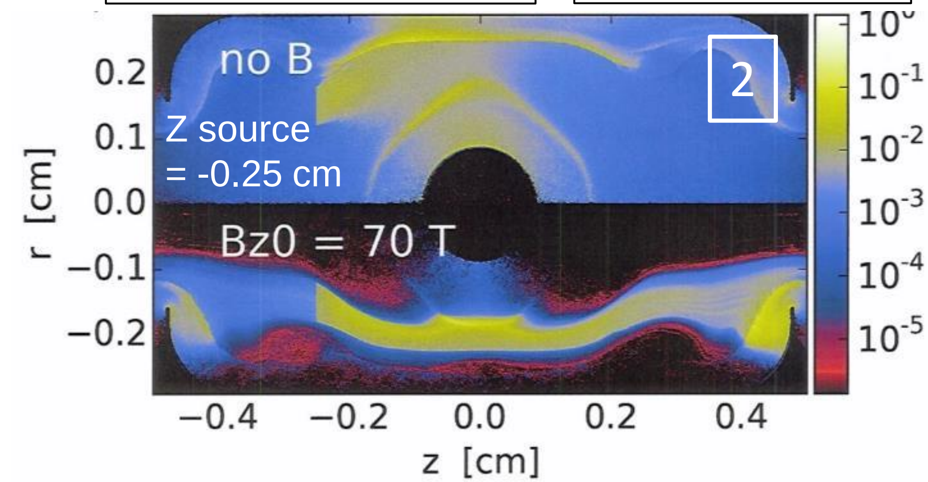
Hot electrons: coupling to DT early in peak power is very sensitive to source location

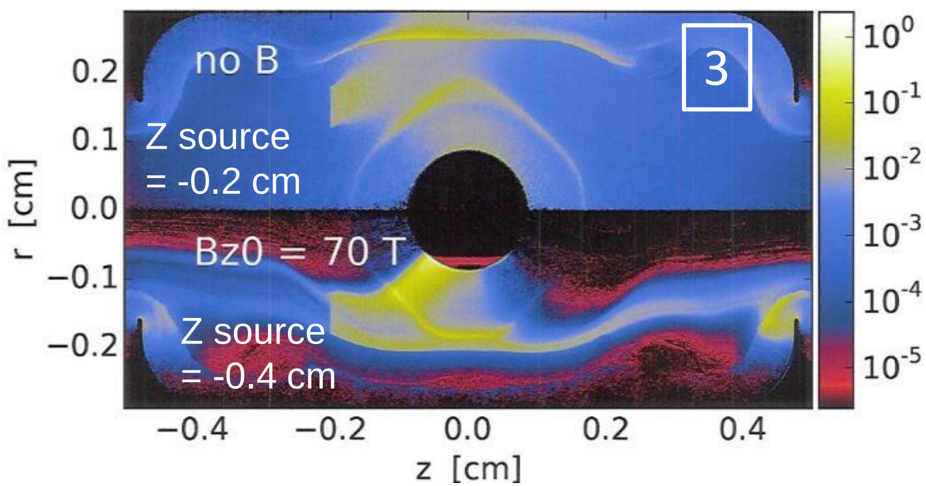
Coupled energy [J/mm^3] per injected hot e- Joule

ZUMA hybrid PIC code
D. J. Larson

Low-foot shot
B_{z0} = 70 T; 18 ns







Fraction of hot e- energy coupled to DT ice

Source	No B	B_{z0} = 70 T	B_{z0} / no B
1	1.19E-4	1.26E-3	10.6
2	1.37E-4	3.44E-6	0.025
3	3.58E-4	2.89E-3	8.07

[1]D J Strozzi, L J Perkins, M M Marinak et al., *J. Plasma Phys.* (2015)

Outline again

FUNDAMENTALS

- Particle motion, drifts, magnetic mirroring
- Waves in magnetized plasma, Faraday rotation
- MHD single-fluid model: derivation
- MHD effects
  - Magnetic pressure
  - Reduced heat flow
  - Frozen-in law
  - Biermann battery
  - Nernst, Righi-Leduc

Thank you!

EXPERIMENTS / APPLICATIONS

- Diagnostics
- Imposed fields – pulsed power, laser-driven coils
- Flux compression – explosives, laser driven
- Fusion
  - Magnetic vs. inertial fusion
  - Magneto-inertial fusion
  - Imposed fields in ICF
  - MagLIF
- B fields in hohlraums: self-generated, imposed

OTHER DOMAINS not covered

- Astrophysics, lab-astro
- Plasma propulsion

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