The collective effects on focusing of intense ion beams in neutralized drift compression

I. D. Kaganovich, M. A. Dorf,
E. A. Startsev, R. C. Davidson,
A. B. Sefkow, B. C. Lyons, J. S. Pennington

Princeton Plasma Physics Laboratory, USA

Outline

- **Short overview of collective focusing**
  - **Gabor lens**
  - **Collective (Robertson) lens**
  - **Passive plasma lenses**
- **Collective effects on focusing an intense ion beam ion beams in neutralized drift compression.**
  - **Self- electric fields without applied magnetic field**
  - **Generation of large radial electric fields in presence of magnetic field.**

---

50 years of collective focusing and acceleration ideas: acceleration (1/2)

v<c

- **Acceleration by a wave in medium**

V.I. Veksler, Ya.B. Fainberg, Proceedings of CERN Symposium on High-Energy Physics, Geneva 1956
the wave velocity is less than speed of light (PLIA), in particularly space charge waves.

- **Laser wake field accelerator,**

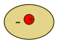
Tajima and Dawson PRL 43 267 (1979).

- **Plasma wake field accelerator**

P. Chen et al, PRL 54 693 (1985).

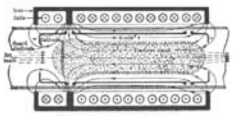
- **Collective ion acceleration by electron beams**

A.A. Plyutto, Sov. Phys. JEPT (1960)
J.R. Uglum and S. Graybill J. Appl. Phys. 41 236 (1970).
Ions trapped in an electron bunch $v_i = v_e$ energy $Mv_i^2 / m\, v_e^2$ times



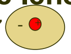
---

50 years of collective focusing and acceleration ideas: focusing (2/2)



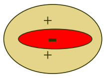
- **A space-charge lens**

D. Gabor, Nature 1947



- **Under dense plasma lens**

P. Chen, Part. Accel. 20 171 (1987).
the strong electric field created by the space charge of the electron beam ejects the plasma electrons from the beam region entirely, leaving a uniform ion column.



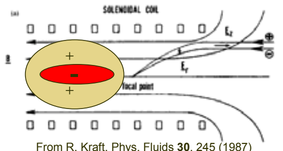
- **Over dense plasma lens**

Electric field is neutralized, Self Magnetic field is not neutralized

---

Collective Focusing Concept

(S. Robertson 1982, R. Kraft 1987)



From R. Kraft, Phys. Fluids **30**, 245 (1987)

Traversing the region of magnetic fringe fields from B=0 to $B=B_0$ electrons and ions acquire angular frequency of

$$\omega_{e,i} = \pm\Omega_{e,i}/2 \quad \left(\Omega_{e,i} = eB_0/m_{e,i}c\right)$$

$ev_\varphi B/c$ tends to focus electrons and huge ambipolar radial electric field develops, which focuses ions.

$$\begin{cases} \ddot{r}_e + \frac{1}{4} r_e \Omega_e^2 + \frac{e}{m_e} E_r = 0 \\ \ddot{r}_i + \frac{1}{4} r_i \Omega_i^2 - \frac{e}{m_i} E_r = 0 \end{cases}$$

Quasineutrality $r_e = r_i$ ⇨

$$\begin{cases} eE_r = \frac{m_e}{4} r\Omega_e^2 \\ \ddot{r} = \frac{e}{m_i}\frac{m_e}{4} r\Omega_e^2 = \frac{e}{4} r\Omega_e\Omega_i \end{cases}$$

For a given focal length the magnetic field required for a neutralized beam is smaller by a factor of $(m_e/m_i)^{1/2}$

NDCX-I: $m_i/m_e=71175$ ⇨ **8 T Solenoid can be replaced with 300 G**

Review of Collective Focusing Experiments

S. Robertson, PRL, **48**, 149 (1982)
Thin collective lens

R. Kraft, Phys. Fluids, **30**, 245 (1987)
Thick collective lens

- E_b~149 keV, r_b~15 cm, j_b~0.5 A/cm^2,

E_b~360 keV, r_b~2 cm, n_b~$1.5\cdot10^{11}$cm^{-3}

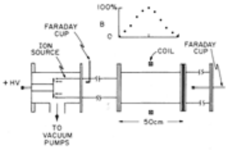


FIG. 1. Schematic diagram of the experimental apparatus.

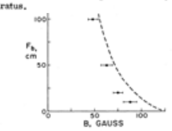


FIG. 4. The experimentally determined focal length as a function of magnetic field (points) and the calculated focal length (dotted line). The error bars give only the statistical uncertainty.

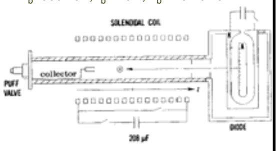


FIG. 1. Experimental apparatus.

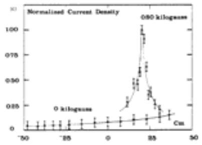


FIG. 8. Focused ion current. (a) Ion current density versus time (B = 0, 1.5 kG). (b) Peak ion current density versus axial position (B = 0, 1.5 kG). (c) Peak ion current density versus axial position (B = 0, 1.5 kG).

Conditions for Collective Focusing

○ $\omega_{pe} \geq \Omega_e/\sqrt{2}$ to maintain quasi-neutrality

$$\begin{cases} E_r = -\dfrac{r}{2e} m_e \omega_{pe}^2 \dfrac{(n_i - n)}{n_e} & \text{(Poisson's Eq.)} \\ E_r = -\dfrac{r}{4e} m_e \Omega_e^2 \end{cases}$$

○ $r_b \leq 2c/\omega_{pe}$ to assure small magnetic field perturbations (due to the beam)

$$\begin{cases} j_\theta = e n_e \Omega_e r/2 \\ \dfrac{\Delta B_z}{B_0} = \dfrac{4\pi}{c} \dfrac{e n_e \Omega_e r_b^2}{4B_0} = \dfrac{\omega_{pe}^2 r_b^2}{4c^2} \end{cases}$$

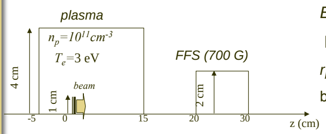
● Neutralizing electrons have to be dragged through the magnetic field fall-off region to acquire necessary rotation ($\omega_e = \Omega_e/2$)

↓

● Plasma (or secondary electrons) should not be present inside the FFS, otherwise non-rotating plasma (secondary) electrons will replace rotating electrons (moving with the beam) and enhanced electrostatic focusing will be lost → FCAPS must be turned off

Experimentally verified (R. Kraft 1987)

PIC Simulations of Collective Focusing Lens Can be Used for NDCX Beam Final Focus



Beam injection parameters

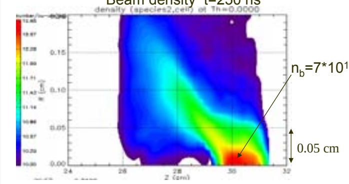
K^+ @ 320keV, $n_b = 10^{10} cm^3$

r_b=1 cm, T_b=0.2 eV

beam pulse=40ns (5 cm)

$\omega_{pe}(n_e = n_b) = 0.46\omega_{ce}$

Beam density t=250 ns



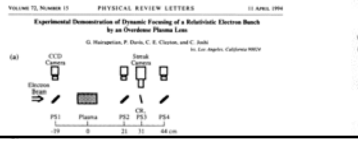
Passive plasma lenses

- **Over dense plasma lens, $n_p > n_b$**

Electric field is neutralized, Self Magnetic field is not neutralized, $ev_z B_\varphi /c$ force focuses beam particles.

Condition: $r_b < 0.5c/\omega_p$ $n_p = 2.5\ 10^{11} cm^{-3}$ r_b<5mm

Experiments: 3.8MeV, 25 ps electron beam focused by a $n_p = 2.5\ 10^{11}\ cm^{-3}$ RF plasma



VOLUME 72, NUMBER 15 PHYSICAL REVIEW LETTERS 11 APRIL 1994

Experimental Demonstration of Dynamic Focusing of a Relativistic Electron Bunch by an Overdense Plasma Lens

G. Hairapetian, P. Davis, C. E. Clayton, and C. Joshi

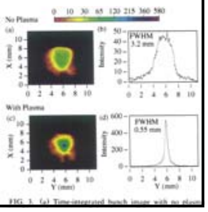
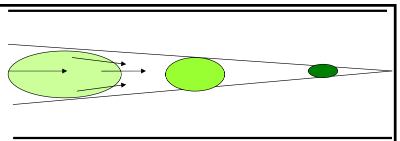


FIG. 1. (a) Time-integrated bunch image with no plasm

Outline

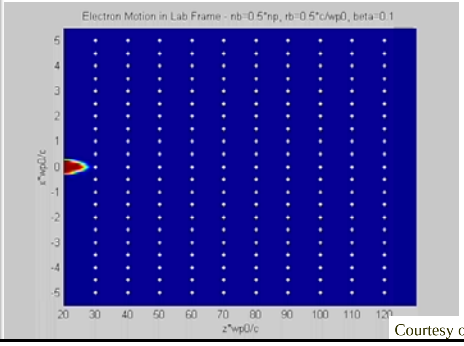


- Short ove
  - Gabor lens
  - Collective (Robertson) lens
  - Passive plasma lenses

Long neutralized transport in plasma (1-2 m) long => focusing effects in plasma are important

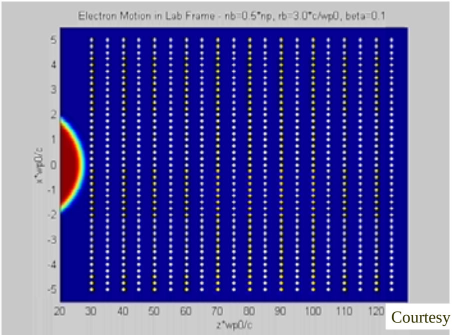
- **Collective effects on focusing an intense ion beam ion beams in neutralized drift compression.**
  - **Self- electric fields without applied magnetic field**
  - **Generation of large radial electric fields in presence of magnetic field.**

Visualization of Electron Response on an Ion Beam Pulse (thin beam)



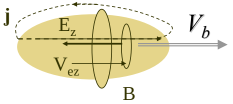
Courtesy of B. C. Lyons

Visualization of Electron Response on an Ion Beam Pulse (thick beam)



Courtesy of B. C. Lyons

Current Neutralization



$$\frac{\partial\int Bds}{\partial t} => E_z$$

Alternating magnetic flux generates inductive electric field, which accelerates electrons along the beam propagation*.
For long beams canonical momentum is conserved** $mV_{ez}=\frac{e}{c}A_z$

$$\nabla\times\mathbf{B}=\frac{4\pi\mathbf{j}}{c}\qquad -\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}V_{ez}=\frac{4\pi e}{mc^2}\left(Z_b n_b V_{bz}-n_e V_{ez}\right).$$

$$r_b^2>\frac{c^2}{4\pi e^2 n_p/m}\qquad r_b>\delta_p\qquad n_p=2.5\times10^{11}cm^{-3};\delta_p=1cm$$

* K. Hahn, and E. PJ. Lee, Fusion Engineering and Design **32-33**, 417 (1996)

** I. D. Kaganovich, et al, Laser Particle Beams **20**, 497 (2002).

Self-Electric Field of the Beam Pulse Propagating Through Plasma

$$eE_r=\frac{1}{c}V_{ez}B_\theta=-mV_{ez}\frac{\partial V_{ez}}{\partial r}\qquad \phi=mV_{ez}^{\ 2}/2e$$

$$V_{ez}\sim V_b n_b/n_p$$

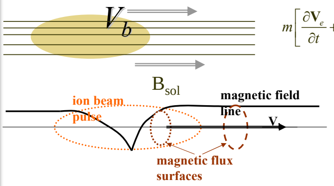
$$\phi_{vp}=\frac{1}{2}mV_b^{\ 2}\left(\frac{n_b}{n_p}\right)^2$$

NDCX I K$^+$ 400keV beam $\frac{1}{2}mV_b^{\ 2}=3eV$

NDCX II Li$^+$ 1MeV beam $\frac{1}{2}mV_b^{\ 2}=30eV$

Having $n_b \ll n_p$ strongly increases the neutralization degree.

Influence of magnetic field on beam neutralization by a background plasma



$$m\left[\frac{\partial\mathbf{V}_e}{\partial t}+(\mathbf{V}_e\bullet\nabla)\mathbf{V}_e\right]=-e(\mathbf{E}+\frac{1}{c}\mathbf{V}_e\times\mathbf{B})$$

Small radial electron displacement generates fast poloidal rotation according to conservation of azimuthal canonical momentum:

$$V_\phi=\frac{e}{mc}(A_\phi+B_{sol}\delta r)$$

$$E_r\sim\frac{1}{c}V_{e\phi}B_{sol}$$

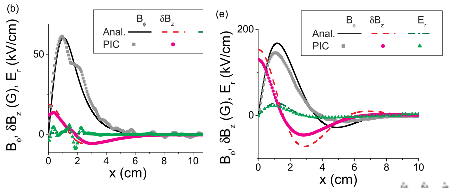
The poloidal rotation twists the magnetic field and generates the poloidal magnetic field and large radial electric field.

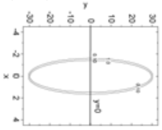
$$B_{e\varphi}=B_{ez}\frac{V_{e\varphi}}{V_{bz}}$$

I. Kaganovich, et al, PRL **99**, 235002 (2007); PoP (2008).

Applied magnetic field affects self-electromagnetic fields when $\omega_{ce}/\omega_{pe}>V_b/c$

Note increase of fields with B_{z0}





The self-magnetic field; perturbation in the solenoidal magnetic field; and the radial electric field in a perpendicular slice of the beam pulse. The beam parameters are (a) $n_{b0}=n_p/2=1.2\times10^{11}cm^{-3}$; $V_b=0.33c$, the beam density profile is gaussian. The values of the applied solenoidal magnetic field, B_{z0} are: (b) 300*G;* and (e) 900*G* corresponds to $c\omega_{ce}/V_b\omega_{pe}$ = (b) 0.57 ; and (e) 1.7.

Equations for Vector Potential in the Slice Approximation.

$$-\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial}{\partial r}A_z=\frac{4\pi}{c}j_{bz}-\frac{\omega_{pe}^2}{c^2}A_z-\frac{\omega_{ce}}{V_b}\frac{1}{r}\frac{\partial}{\partial r}(rA_\phi).$$

$$-\left(1+\frac{\omega_{ce}^2}{\omega_{pe}^2}\right)\frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(rA_\phi)\right]=\frac{4\pi}{c}j_{b\phi}-\frac{\omega_{pe}^2}{c^2}A_\phi-\frac{\omega_{ce}}{V_b}\frac{\partial}{\partial r}A_z.$$

The electron return current

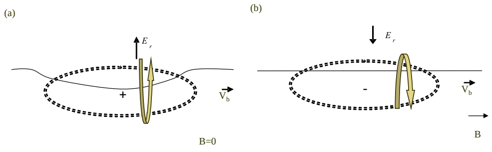
New term accounting for departure from quasi-neutrality.

Magnetic dynamo

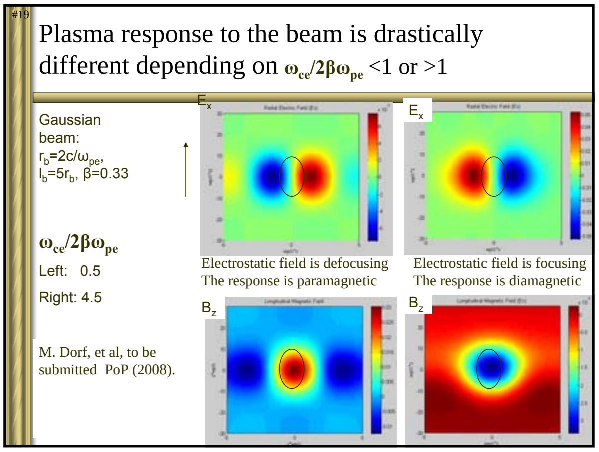
Electron rotation due to radial displacement

$\omega_{ce}=\frac{eB_z}{mc}$ I. Kaganovich, et al, PRL **99**, 235002 (2007); PoP (2008).

Plasma response to the beam is drastically different depending on **$\omega_{ce}/2\beta\omega_{pe}$** <1 or >1



Schematic of an electron motion for the two possible steady-state solutions. (a) . Radial self-electric field is defocusing for ion beam, rotation paramagnetic; (b) Radial self-electric field is focusing for ion beam; rotation diamagnetic.



Plasma response to the beam is drastically different depending on $\omega_{ce}/2\beta\omega_{pe}$ <1 or >1

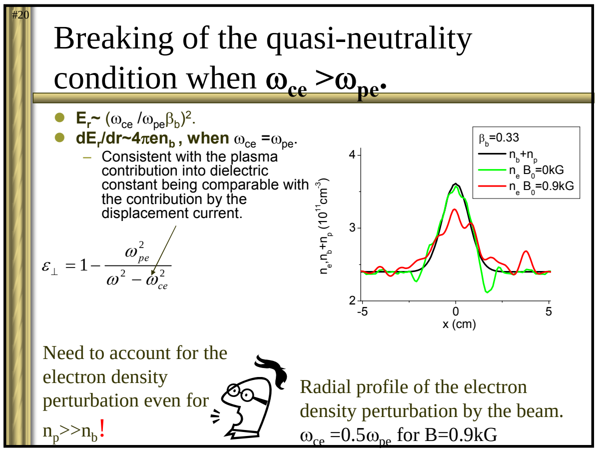
Gaussian beam:
$r_b=2c/\omega_{pe}$,
$l_b=5r_b$, $\beta=0.33$

$\omega_{ce}/2\beta\omega_{pe}$
Left: 0.5
Right: 4.5

M. Dorf, et al, to be submitted PoP (2008).

Electrostatic field is defocusing
The response is paramagnetic

Electrostatic field is focusing
The response is diamagnetic



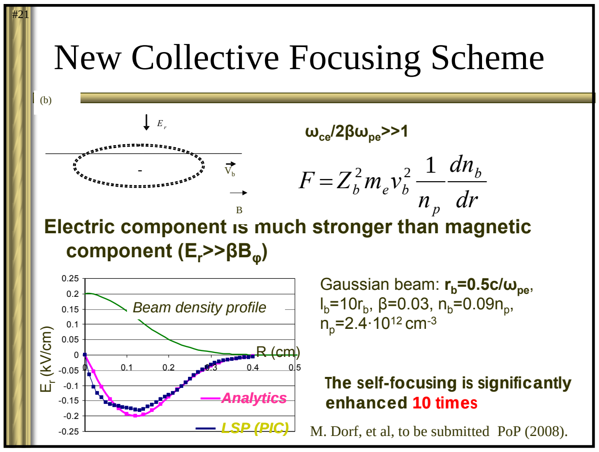
Breaking of the quasi-neutrality condition when $\omega_{ce} > \omega_{pe}$.

- **E_r~** $(\omega_{ce}/\omega_{pe}\beta_b)^2$.
- **$dE_r/dr \sim 4\pi e n_b$, when** $\omega_{ce} = \omega_{pe}$.
  - Consistent with the plasma contribution into dielectric constant being comparable with the contribution by the displacement current.

$$\varepsilon_\perp = 1 - \frac{\omega_{pe}^2}{\omega^2 - \omega_{ce}^2}$$

Need to account for the electron density perturbation even for $n_p >> n_b$!

Radial profile of the electron density perturbation by the beam. $\omega_{ce} = 0.5\omega_{pe}$ for B=0.9kG



New Collective Focusing Scheme

$\omega_{ce}/2\beta\omega_{pe}$>>1

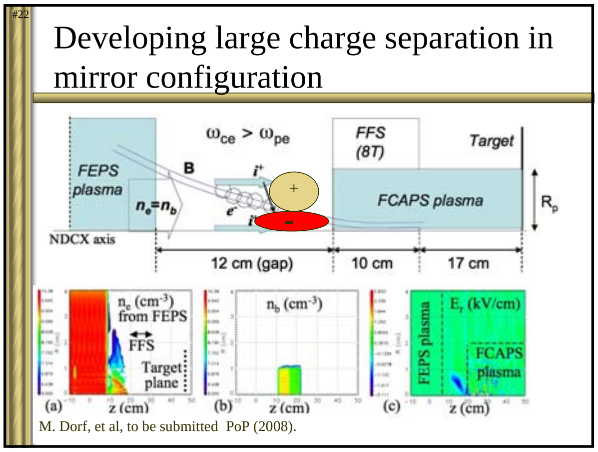
$$F = Z_b^2 m_e v_b^2 \frac{1}{n_p}\frac{dn_b}{dr}$$

Electric component is much stronger than magnetic component ($E_r >> \beta B_\varphi$)

Gaussian beam: $\mathbf{r_b=0.5c/\omega_{pe}}$, $l_b=10r_b$, $\beta=0.03$, $n_b=0.09n_p$, $n_p=2.4 \cdot 10^{12}$ cm^{-3}

The self-focusing is significantly enhanced 10 times

M. Dorf, et al, to be submitted PoP (2008).

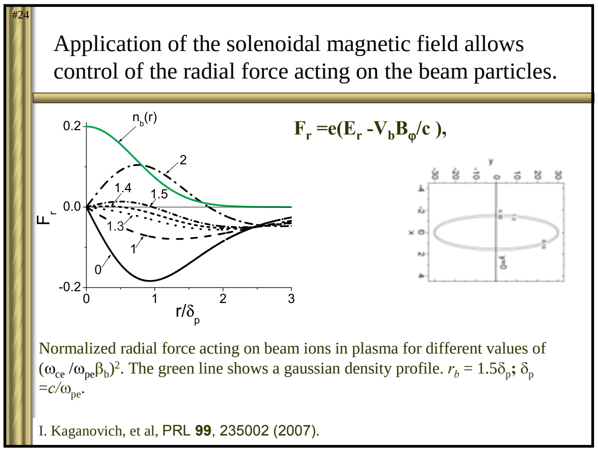


Developing large charge separation in mirror configuration

M. Dorf, et al, to be submitted PoP (2008).

Conclusions

- Application of a weak solenoidal magnetic field can be used for active control of beam transport through a background plasma.
- Application of an external solenoidal magnetic field clearly makes the collective processes of ion beam-plasma interactions rich in physics content.
  - Many results of the PIC simulations remain to be explained by analytical theory.
  - Theory predicts that there is a sizable enhancement of the self-electric field due in presence of solenoidal magnetic field $\omega_{ce} > \beta\omega_{pe}$.
  - Electromagnetic waves are strongly generated oblique to the direction of the beam propagation when $\omega_{ce} \sim \beta\omega_{pe}$.



Application of the solenoidal magnetic field allows control of the radial force acting on the beam particles.

$$F_r = e(E_r - V_b B_\varphi / c),$$

Normalized radial force acting on beam ions in plasma for different values of $(\omega_{ce}/\omega_{pe}\beta_b)^2$. The green line shows a gaussian density profile. $r_b = 1.5\delta_p$; $\delta_p = c/\omega_{pe}$.

I. Kaganovich, et al, PRL **99**, 235002 (2007).