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USPAS
January 19-30, 2015
Hampton, Virginia

Injectors and longitudinal physics -- II

1. Acceleration - introduction
2. Space charge of short bunches (rf)
3. Space charge of long bunches
4. Longitudinal space charge waves
5. Longitudinal rarefaction waves and bunch ends

Summary of fluid equations

$$\text{Let } n(\underline{x}, t) = \int d^3p f(\underline{x}, \underline{p}, t) \quad \text{PARTICLE DENSITY}$$

$$\underline{v}(\underline{x}, t) \equiv \frac{1}{n(\underline{x}, t)} \int d^3p \frac{\underline{p}}{\gamma m} f(\underline{x}, \underline{p}, t) \quad \text{FLUID VELOCITY}$$

$$\underline{P}(\underline{x}, t) \equiv \frac{1}{n(\underline{x}, t)} \int d^3p \underline{p} f(\underline{x}, \underline{p}, t) \quad \text{FLUID MOMENTUM}$$

$$\underline{P}(\underline{x}, t) \equiv \int d^3p (p - \underline{P}) \left(\frac{p}{\gamma m} - \underline{v} \right) f(\underline{x}, p, t) \quad \text{PRESSURE TENSOR}$$

$$\frac{d\underline{x}}{dt} = \frac{\underline{p}}{\gamma m} \quad \frac{d\underline{p}}{dt} = q(\underline{E}(\underline{x}, t) + \frac{\underline{p}}{\gamma m} \times \underline{B}(\underline{x}, t)) \quad \gamma^2 = \frac{\underline{p} \cdot \underline{p}}{(mc)^2} + 1$$

CONTINUITY EQUATION: $\frac{\partial n(\underline{x}, t)}{\partial t} + \frac{\partial}{\partial \underline{x}} \cdot n(\underline{x}, t)$

MOMENTUM EQUATION: $\frac{\partial \underline{P}}{\partial t} + \underline{v} \cdot \frac{\partial \underline{P}}{\partial \underline{x}} = q(\underline{E} + \underline{v} \times \underline{B}) - \frac{1}{n(\underline{x}, t)} \frac{\partial}{\partial \underline{x}} \cdot \underline{P}$

THE ABOVE EQUATIONS ARE RELATIVISTICALLY CORRECT.
IN THE NON-RELATIVISTIC LIMIT THE CONTINUITY EQUATION REMAINS UNCHANGED & THE MOMENTUM EQUATION MAY BE WRITTEN:

NON RELATIVISTIC $\rightarrow \frac{\partial \underline{v}}{\partial t} + \underline{v} \cdot \frac{\partial \underline{v}}{\partial \underline{x}} = \frac{q}{m} (\underline{E} + \underline{v} \times \underline{B}) - \frac{1}{m n} \frac{\partial}{\partial \underline{x}} \cdot \underline{P}$

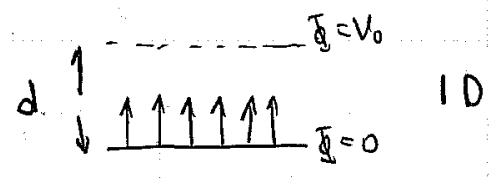
THESE EQUATIONS ARE SUPPLEMENTED WITH MAXWELL'S EQUATIONS:
for $\underline{E}(\underline{x}, t)$ & $\underline{B}(\underline{x}, t)$

$$\frac{\partial}{\partial \underline{x}} \cdot \underline{E} = \frac{q n(\underline{x}, t)}{\epsilon_0} \quad \frac{\partial}{\partial \underline{x}} \times \underline{E} = -\frac{\partial \underline{B}}{\partial t}$$

$$\frac{\partial}{\partial \underline{x}} \cdot \underline{B} = 0 \quad \frac{\partial}{\partial \underline{x}} \times \underline{B} = \mu_0 \underline{J} + \frac{1}{c^2} \frac{\partial \underline{E}}{\partial t} \quad \underline{J}(\underline{x}, t) = q n(\underline{x}, t) \underline{v}$$

NEED ADDITIONAL EQUATIONS SUCH AS $\underline{P} = 0$ OR ENERGY EQUATION TO TERMINATE SET OF EQUATIONS.

Summary of Child Langmuir Law



$\Phi = -\phi$ (ACTUAL POTENTIAL)

CONSTANT DENSITY: $J = \frac{4}{9} \epsilon_0 \left(\frac{2q}{m}\right)^{1/2} V_0^{3/2}$

$\Phi(z) = V_0 \left(\frac{z}{d}\right)^{4/3}$ - ELECTROSTATIC POTENTIAL

$E(z) = \frac{4}{3} \frac{V_0}{d} \left(\frac{z}{d}\right)^{1/3}$ ELECTRIC FIELD

$v(z) = \left(\frac{2qV_0}{m}\right)^{1/2} \left(\frac{z}{d}\right)^{2/3}$ LONGITUDINAL VELOCITY

$\rho(z) = \frac{J}{v(z)} = \left(\frac{J^2 m}{2qV_0}\right)^{1/2} \left(\frac{z}{d}\right)^{-2/3}$

IF WE MULTIPLY BY πV_b^2 (TO ACCOUNT FOR FINITE RADIUS) BEAM:

$I = \frac{4}{9} \epsilon_0 \left(\frac{2q}{m}\right)^{1/2} \left(\frac{V_b}{d}\right)^2 V_0^{3/2}$

$K \equiv$ Gun permeance $\equiv \frac{I}{V_0^{3/2}}$ [DIMENSIONAL]: $\frac{\text{CURRENT}}{\text{VOLTAGE}^{3/2}}$

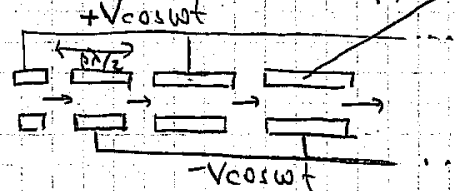
GENERALIZED PERMEANCE: $Q(z) = \frac{\lambda}{4\pi\epsilon_0 \Phi(z)} = \frac{\pi V_b^2 \rho(z)}{4\pi\epsilon_0 \Phi(z)} = \frac{1}{9} \left(\frac{V_b^2}{z^2}\right)$ (DIMENSIONLESS)

(NOTE THAT CHILD-LANGMUIR LAW ONLY VALID FOR $z \gg \lambda_D$, WHERE $\frac{1}{2} m v(z)^2 \gg kT$ & $\lambda_D = \frac{v_{th}}{\omega_p} = \frac{\sqrt{kT/m}}{\left(\frac{qV(z)}{\epsilon_0 m}\right)^{1/2}}$)

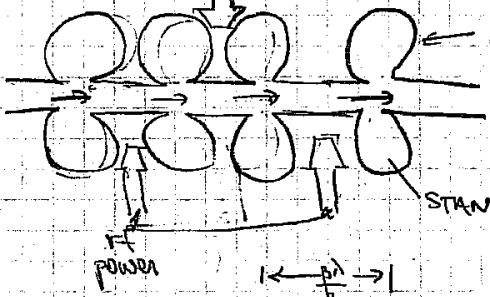
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 100 SHEETS EYE-EASE™ 8 SQUARE
 200 SHEETS EYE-EASE™ 8 SQUARE
 42,301
 42,302
 42,303
 National Brand

ACCELERATION

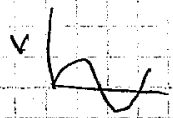
rf (radio-frequency)



TUBE SHIELDS BEAM
(WIDER GAP LINE)
LOW FREQUENCIES (< 100 MHz)



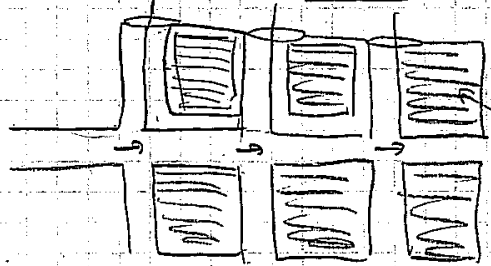
RESONANT CAVITY
(COUPLED CAVITY LINE)
 $0.4 < \beta < 1.0$
FREQUENCIES ~ 100's MHz - ~ GHz



IN EACH GAP $E = E_m \sin \omega t$

Induction acceleration

PULSED POWER

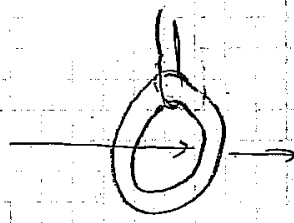


(INDUCTION LINE)

TOROIDAL
FERROMAGNETIC
CORE

$\nabla \times E = -\partial B / \partial t$

IN EACH GAP $E = \text{CONSTANT}$
(OR SOME PRESCRIBED FUNCTION)



TRANSFORMER

I STRATEGY FOR CALCULATING LONGITUDINAL EQUATIONS OF MOTION

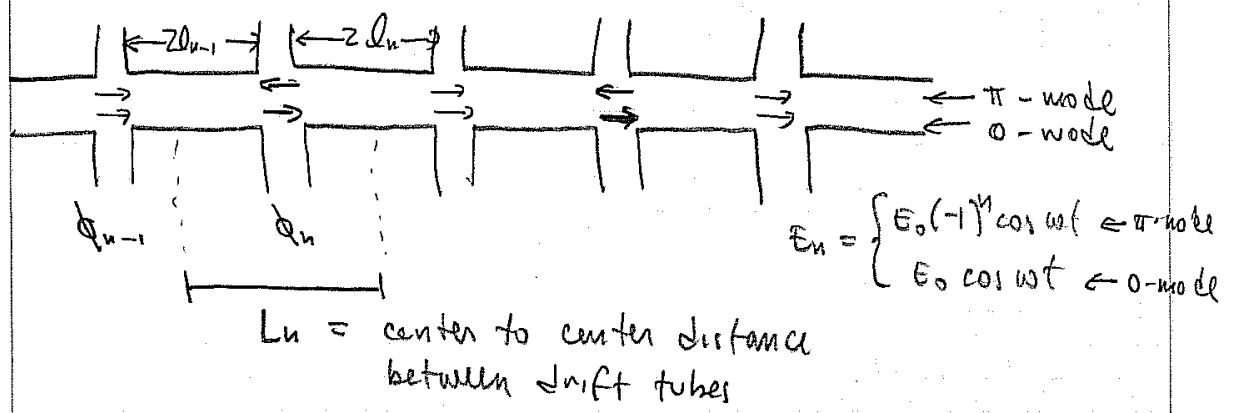
1. rf / short bunches

- EXTERNAL FIELD: ACCELERATES AND FOCUSES
 - CALCULATE CHANGE IN TIME AND ENERGY AS PARTICLE MOVES FROM ACCELERATING GAP TO ACCELERATING GAP
 - APPROXIMATE MOTION AS CONTINUOUS
- SPACE CHARGE FIELD: UNIFORM DENSITY ELLIPSOID

2. INDUCTION / LONG BUNCHES

- EXTERNAL FIELD: ACCELERATION, FOCUSING, AND COMPRESSION ACCOMPLISHED BY PRESCRIBING VOLTAGE WAVE FORM
- FOCUSING (CONFINEMENT) IS DONE AT BEAM ENDS
- SPACE CHARGE FIELD: $E_z \propto \frac{\partial \lambda}{\partial z}$

RF longitudinal equation of motion



$E_z = E_0 \cos(\phi_s)$ ← synchronous particle enters each gap at same phase

RESONANCE CONDITION ON SYNCHRONOUS PARTICLE:

$$L_{n-1} = \frac{\beta_s \lambda}{2} \begin{cases} \frac{1}{2} \\ 1 \end{cases} \begin{matrix} \pi\text{-mode} \\ 0\text{-mode} \end{matrix}$$

$\lambda = \frac{2\pi c}{\omega} =$ light travel distance in one oscillation
 $= c \Delta t = \beta \lambda$ w.f. oscillation

(IT TAKES $\frac{1}{2}$ OSCILLATION PERIOD TO TRAVEL BETWEEN GAPS).
 $\beta_s = \frac{v_s}{c} =$ velocity of synchronous particle

PARTICLE PHASE RELATIVE TO w.f. at the n^{th} gap:

$$\phi_n = \phi_{n-1} + \omega \frac{2L_{n-1}}{\beta_{n-1} c} + \begin{cases} \pi & \pi\text{-mode} \\ 0 & 0\text{-mode} \end{cases}$$

$$\Delta(\phi - \phi_s)_n = 2\pi \beta_{s,n-1} \left(\frac{1}{\beta_{n-1}} - \frac{1}{\beta_{s,n-1}} \right) \begin{cases} \frac{1}{2} \\ 1 \end{cases} \begin{matrix} \pi\text{-mode} \\ 0\text{-mode} \end{matrix}$$

$$\approx -2\pi \frac{\delta\beta}{\beta_{s,n-1}} \begin{cases} \frac{1}{2} \\ 1 \end{cases}$$

A VELOCITY DIFFERENCE LEADS TO A PHASE DIFFERENCE

$$\Delta(\phi - \phi_s)_n \approx -2\pi \frac{W_{n-1} - W_{s,n-1}}{m c^2 \gamma_{s,n-1}^3 \beta_{s,n-1}^2} \begin{cases} \frac{1}{2} \\ 1 \end{cases}$$

$$W = (\gamma - 1) m c^2$$

$$\frac{1}{\beta} - \frac{1}{\beta_s} \approx -\frac{\delta\beta}{\beta_s^2}$$

$$\delta W = \gamma_s^3 \beta_s m c^2 \delta\beta$$

SIMILARLY, A PHASE DIFFERENCE PRODUCES

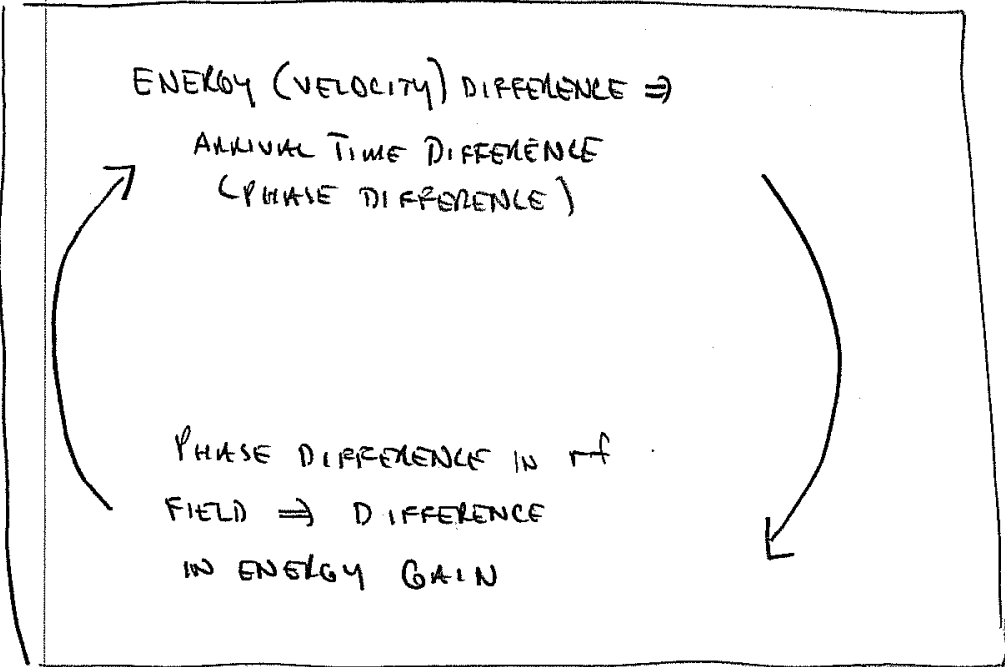
AN ENERGY CHANGE (RELATIVE TO SYNCHRONOUS PARTICLES)

$$\Delta(W - W_s)_n = q E_0 L_n (\cos \psi_n - \cos \psi_{s,n})$$

$$L_n = \frac{(\beta_{s,n-1} + \beta_{s,n}) \lambda}{2} \left\{ \begin{matrix} 1/2 \\ 1 \end{matrix} \right\} =$$

CENTER-TO-CENTER
DISTANCE
BETWEEN
DRIFT SECTIONS

$$(\Delta W_s = q E_0 L_n \cos \psi_s)$$



CONVERTING TO A CONTINUOUS VARIABLE:

$$\Delta(\phi - \phi_s) \rightarrow \frac{d\Delta\phi}{dn} \quad \Delta(W - W_s) \rightarrow \frac{d\Delta W}{dn}$$

$$\rightarrow \left[\gamma_s^3 \beta_s^3 \frac{d\Delta\phi}{ds} = -2\pi \frac{\Delta W}{mc^2 \lambda} \right] \quad \frac{dn}{ds} = \frac{1}{\beta_s \lambda} \left\{ \begin{matrix} z \\ 1 \end{matrix} \right\} = \frac{ds}{2l_{n-1}}$$

$$\frac{d\Delta W}{ds} = qE_0 (\cos \phi - \cos \phi_s)$$

$$\frac{d}{ds} \left[\gamma_s^3 \beta_s^3 \frac{d\Delta\phi}{ds} \right] = -2\pi \frac{qE_0}{mc^2 \lambda} [\cos \phi - \cos \phi_s] \quad (I)$$

NOW THE SPATIAL SEPARATION IS GIVEN BY:

$$\Delta z \equiv z - z_s = -\frac{\beta_s \lambda}{2\pi} \Delta\phi$$

$$\Rightarrow \frac{d}{ds} \text{ ALSO, LET } \cos \phi - \cos \phi_s \approx -\sin \phi_s \Delta\phi \quad \left[\text{for } \frac{2\pi \Delta z}{\beta_s \lambda} = \Delta\phi \ll 1 \right]$$

$$\Rightarrow \frac{d}{ds} \left[\gamma_s^3 \beta_s^3 \frac{d}{ds} \left(\frac{\Delta z}{\beta_s} \right) \right] \approx \frac{2\pi}{\lambda} \frac{qE_0}{mc^2} \sin \phi_s \frac{\Delta z}{\beta_s}$$

WHEN THE ACCELERATION RATE IS SMALL

$$\Rightarrow \frac{d^2}{ds^2} \Delta z \approx \frac{2\pi}{\lambda} \frac{qE_0 \sin \phi_s}{\gamma_s^3 \beta_s mc^2} \Delta z$$

$$\equiv -k_{s0}^2 \Delta z \quad (\text{synchrotron oscillations})$$

6

RETURNING TO $\Delta W - \phi$ NOTATION

Let $w = \frac{\Delta W}{mc^2}$

$A = \frac{2\pi}{\beta_s^3 \gamma_s^3 \lambda}$

$B = \frac{q E_0}{mc^2}$

$$\Rightarrow w' = B(\cos \phi - \cos \phi_s)$$

$$\phi' = -Aw$$

$$\phi'' = -AB(\cos \phi - \cos \phi_s)$$

MULTIPLYING BY ϕ' AND INTEGRATING:

$\frac{\phi'^2}{2} = -AB(\sin \phi - \phi \cos \phi_s) + \text{const}$

Using $\phi' = -Aw$ & DIVIDING BY A

$\Rightarrow \frac{Aw^2}{2} + B(\sin \phi - \phi \cos \phi_s) = \text{CONST.}$

kinetic energy

potential energy

$\frac{dW_s}{ds} \sim qE_0 \cos \phi_s$

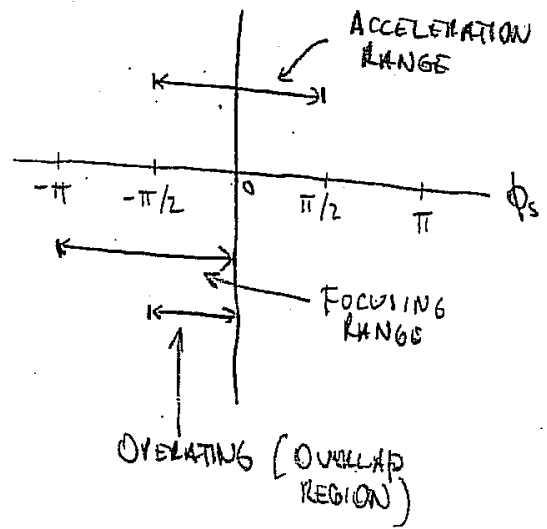
$V(\phi) = B(\sin \phi - \phi \cos \phi_s)$

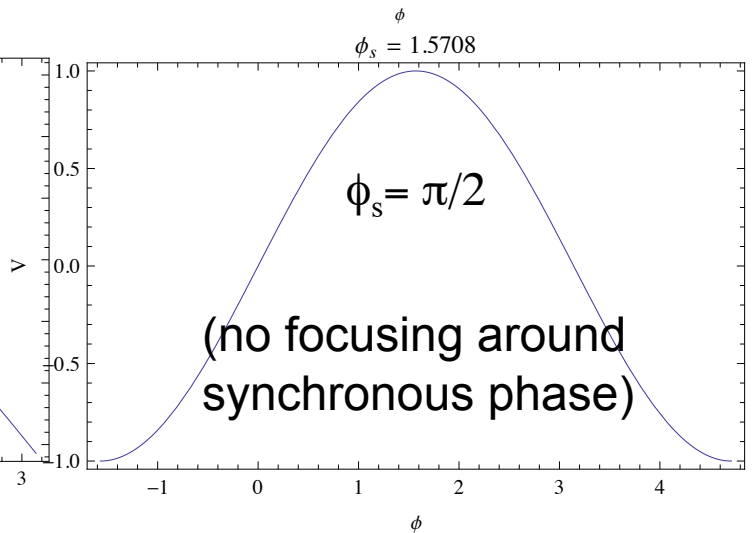
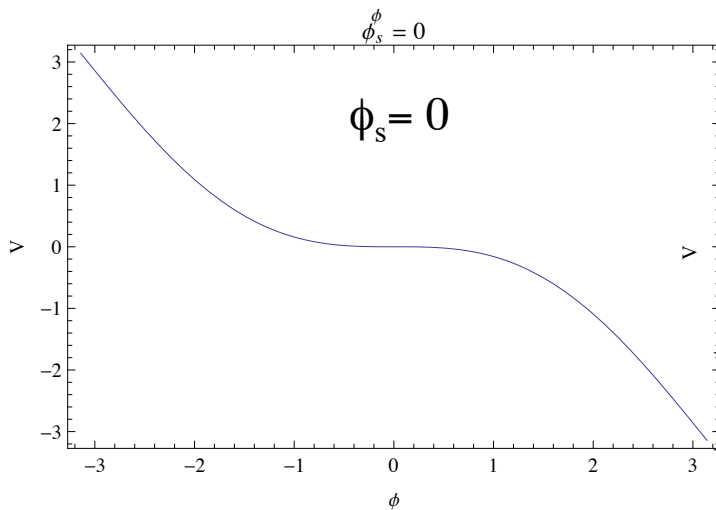
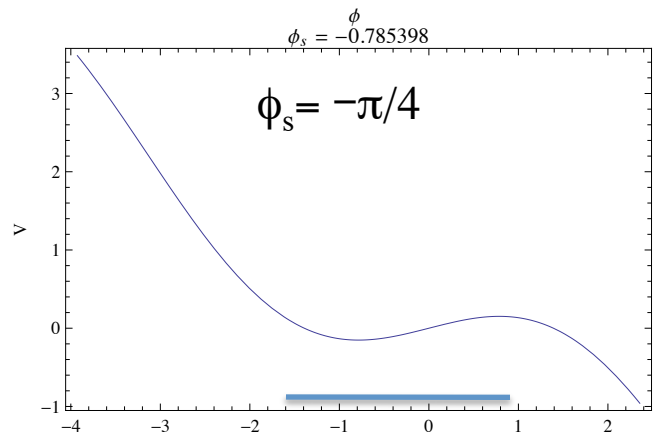
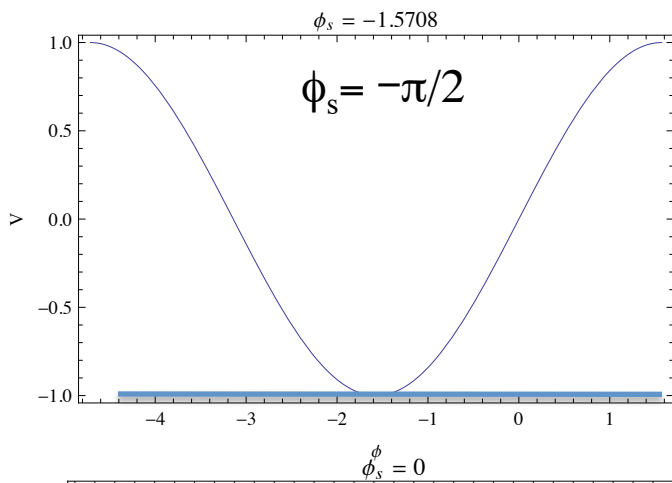
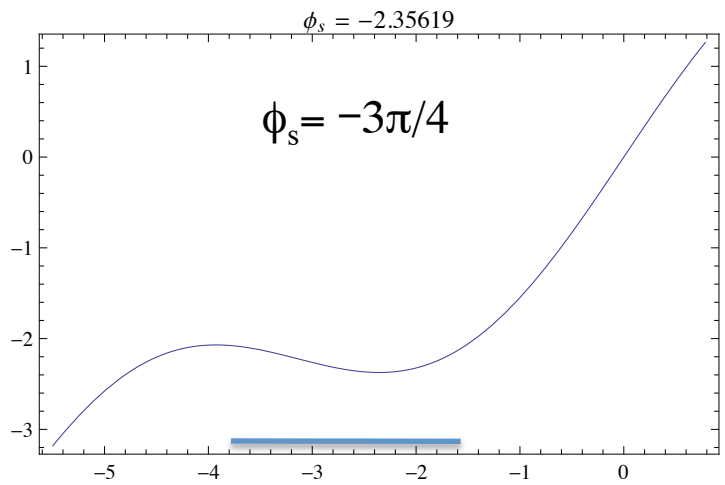
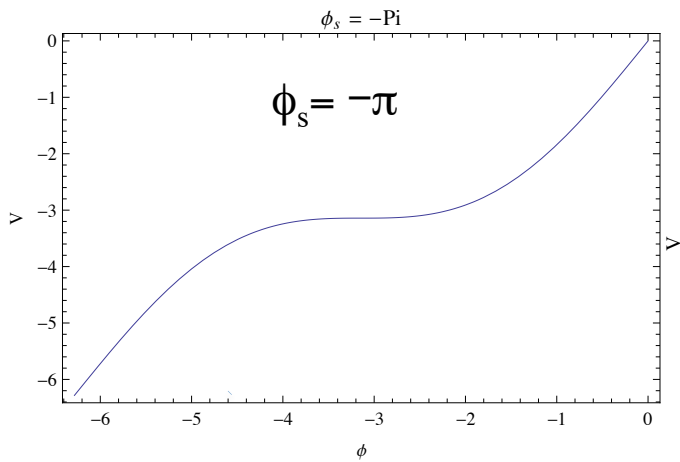
$\frac{dV}{d\phi} = B(\cos \phi - \cos \phi_s)$

$\frac{d^2V}{d\phi^2} = -B \sin \phi$

$> 0 \Rightarrow -\pi < \phi_s < 0$

FOR LONGITUDINAL FOCUSING

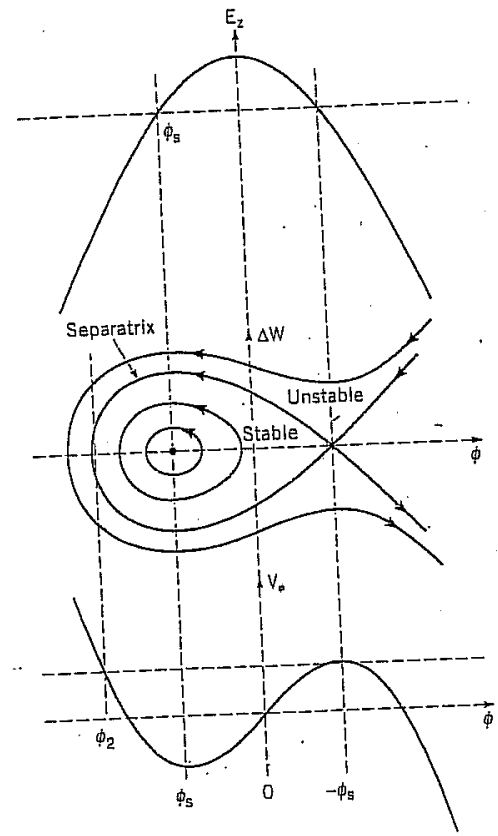




$$V(\phi) \sim B(\sin \phi - \phi \cos \phi_s)$$

For there to be a region of focusing around the synchronous phase, $-\pi < \phi_s < 0$.

simultaneous acceleration and a potential well when $-\pi/2 \leq \phi_s \leq 0$. The stable region for the phase motion extends from $\phi_2 < \phi < -\phi_s$, where the lower phase limit ϕ_2 can be obtained numerically by solving for ϕ_2 using $H_\phi(\phi_2) = H_\phi(-\phi_s)$. Figure 6.3 shows longitudinal phase space and the longitudinal potential well. At the potential maximum, where $\phi = -\phi_s$, we



from T. Waugler's "PRINCIPLES OF RF LINEAR ACCELERATORS"

← phi - delta W PHASE SPACE

Figure 6.3. At the top, the accelerating field is shown as a cosine function of the phase; the synchronous phase ϕ_s is shown as a negative number, which lies earlier than the crest where the field is rising in time. The middle plot shows some longitudinal phase-space trajectories, including the separatrix, the limiting stable trajectory, which passes through the unstable fixed point at $\Delta W = 0$, and $\phi = -\phi_s$. The stable fixed point lies at $\Delta W = 0$ and $\phi = \phi_s$, where the longitudinal potential well has its minimum, as shown in the bottom plot.

Electrostatic potential of a uniform density

ellipsoid in free space

(cf Landau & Lifshitz, Classical Theory of Fields, p. 297)

$$\frac{x^2}{v_x^2} + \frac{y^2}{v_y^2} + \frac{z^2}{v_z^2} = 1$$

It can be shown that:

$$\varphi = \frac{\rho}{4\epsilon_0} v_x v_y v_z \int_{s_{\min}}^{\infty} \left(1 - \frac{x^2}{v_x^2 + s} - \frac{y^2}{v_y^2 + s} - \frac{z^2}{v_z^2 + s} \right) \frac{ds}{R_s}$$

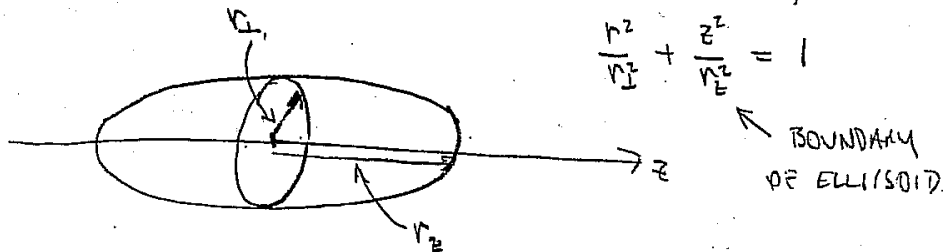
$$R_s = \sqrt{(v_x^2 + s)(v_y^2 + s)(v_z^2 + s)}$$

$$s_{\min} = \begin{cases} 0 & \text{if interior point } \left(\frac{x^2}{v_x^2} + \frac{y^2}{v_y^2} + \frac{z^2}{v_z^2} < 1 \right) \\ \xi & \text{if exterior point } \left(\frac{x^2}{v_x^2} + \frac{y^2}{v_y^2} + \frac{z^2}{v_z^2} > 1 \right) \end{cases}$$

Here ξ is the positive root of

$$\frac{x^2}{v_x^2 + \xi} + \frac{y^2}{v_y^2 + \xi} + \frac{z^2}{v_z^2 + \xi} = 1$$

AXISYMMETRIC
SPACE-CHARGE FIELD OF A BUNCHED BEAM



INTERIOR

THE POTENTIAL OF A UNIFORM DENSITY BUNCH IN FREE SPACE
(A MACLAURIN SPHEROID) IS GIVEN BY:

(cf Landau & Lifshitz, Classical Theory of ~~Fluids~~ Fluids, p 297)

$$\phi = \frac{-\rho}{4\epsilon_0} (\alpha_{\perp} r^2 + \alpha_{\parallel} z^2 - \delta)$$

where $\alpha_{\perp} = r_{\perp}^2 r_z \int_0^{\infty} \frac{ds}{(r_{\perp}^2 + s) \Delta}$

$$\alpha_{\parallel} = r_{\perp}^2 r_z \int_0^{\infty} \frac{ds}{(r_z^2 + s) \Delta}$$

$$\delta = r_{\perp}^2 r_z \int_0^{\infty} \frac{ds}{\Delta}$$

where $\Delta^2 = (r_{\perp}^2 + s)^2 (r_z^2 + s)$

FOR NON-RELATIVISTIC BEAM:

$$E_z = -\frac{\partial \phi}{\partial z} = f \frac{\rho}{\epsilon_0} z$$

$$E_r = -\frac{\partial \phi}{\partial r} = \frac{(1-f)}{2} \frac{\rho}{\epsilon_0} r$$

$$f = f(\alpha) = \begin{cases} \frac{\alpha^2}{1-\alpha^2} \left[\frac{1}{\sqrt{1-\alpha^2}} \tanh^{-1} \sqrt{1-\alpha^2} - 1 \right] & \alpha < 1 \\ \frac{1}{3} & \alpha = 1 \\ \frac{\alpha^2}{\alpha^2-1} \left[1 - \frac{1}{\sqrt{\alpha^2-1}} \tanh^{-1} \sqrt{\alpha^2-1} \right] & \alpha > 1 \end{cases} \quad \alpha \equiv \frac{r}{r_z}$$

Check: for a spherical bunch

$$\nabla \cdot \underline{E} = \frac{\rho}{\varepsilon_0} \quad \Rightarrow \quad 4\pi r^2 E_r = \frac{4\pi r^3}{3} \frac{\rho}{\varepsilon_0}$$

$$\Rightarrow E_r = \frac{\rho}{3\varepsilon_0} r$$

THE FIELD FOR ALL RADII MAY BE WRITTEN:

$$E_r = \frac{\rho}{2\epsilon_0} \left[\frac{\alpha^2}{(\alpha^2 + \chi)(1 + \chi)^{3/2}} - F(\chi, \alpha) \right] r$$

$$E_z = \frac{\rho}{\epsilon_0} [F(\chi, \alpha)] z$$

$$F(\chi, \alpha) = \begin{cases} \frac{\alpha^2}{1 - \alpha^2} \left[\frac{1}{\sqrt{1 - \alpha^2}} \tanh^{-1} \frac{\sqrt{1 - \alpha^2}}{\sqrt{1 + \chi}} - \frac{1}{\sqrt{1 + \chi}} \right] & \alpha < 1 \\ \frac{1}{3(1 + \chi)^{3/2}} & \alpha = 1 \\ \frac{\alpha^2}{\alpha^2 - 1} \left[\frac{1}{\sqrt{1 + \chi}} - \frac{1}{\sqrt{\alpha^2 - 1}} \tan^{-1} \left(\frac{\sqrt{\alpha^2 - 1}}{\sqrt{1 + \chi}} \right) \right] & \alpha > 1 \end{cases}$$

χ satisfies:

$$\frac{\alpha^2 (r^2/r_L^2)}{\alpha^2 + \chi} + \frac{(z^2/r_z^2)}{1 + \chi} = 1 \quad \text{for exterior particle}$$

$$\chi = 0 \quad \text{for interior particle}$$

$$\alpha \equiv \frac{r_L}{r_z}$$

FOR AN EXTERIOR PARTICLE AT $r \neq z \Rightarrow \chi$ CAN BE SOLVED FOR (QUADRATIC EQUATION FOR χ).

$\Rightarrow E_r$ & E_z ARE KNOWN ANALYTICALLY FOR ALL r, z .

EXAMPLE: $r = 0 \Rightarrow \chi = \frac{z^2}{r_z^2} - 1$
(and $z > r_z$)

(8.6)

RELATIVISTIC TRANSFORMATION FROM BEAM FRAME TO LAB FRAME:
(see e.g. JACKSON, CLASSICAL ELECTRODYNAMICS)

$$\underline{E} = \gamma (\underline{E}' - c\beta \times \underline{B}') - \frac{\gamma^2}{\gamma+1} \beta (\beta \cdot \underline{E}')$$

$$\underline{B} = \gamma (\underline{B}' + \frac{\beta}{c} \times \underline{E}') - \frac{\gamma^2}{\gamma+1} \beta (\beta \cdot \underline{B}')$$

$$\underline{B}' = 0$$

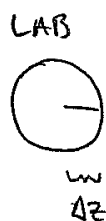
$$\Rightarrow E_z = \gamma E'_z - \frac{\gamma^2}{\gamma+1} \beta^2 E'_z = E'_z$$

$$E_r = \gamma E'_r$$

$$B_\theta = \frac{\gamma\beta}{c} E'_r$$

$$F_z = q E_z = q E'_z$$

$$F_r = q (E_r - v_z B_\theta) = \frac{1}{\gamma} q E'_r$$



$$\Delta z = \frac{1}{\gamma} \Delta z'$$

$$\underline{x}_\perp = \underline{x}'_\perp$$

$$p = \gamma p'$$

$$\underline{F}_\perp = \frac{d\underline{p}_\perp}{dt} = \gamma_s^3 m v_{zs}^2 \frac{d^2 \underline{x}_\perp}{ds^2} \quad (\text{NEGLECTING } \frac{d\gamma_s}{dt}, \frac{dv_{zs}}{dt})$$

$$\Delta F_z = \frac{dF_z}{dt} - \frac{dF'_z}{dt} = \gamma_s^3 m v_{zs}^2 \frac{d^2(z-z_s)}{ds^2}$$

$$(\text{USING } \frac{d}{ds} \gamma\beta = \gamma^3 \frac{d\beta}{ds})$$

FOR RELATIVISTIC BEAM

9
BARNARD & LUND 1997
(cf. LUND & BARNARD 1997)
PAL 97 CONF PROCEEDINGS

$$\frac{d^2 x_L}{ds^2} = \frac{F_L}{\gamma_s^3 \beta_s^2 mc^2}$$

$$F_{\perp s} = \frac{q\rho}{2\gamma_s^2 \epsilon_0} [1 - f(\alpha)] x_L$$

$$\frac{d^2 \Delta z}{ds^2} = \frac{F_z}{\gamma_s^3 \beta_s^2 mc^2}$$

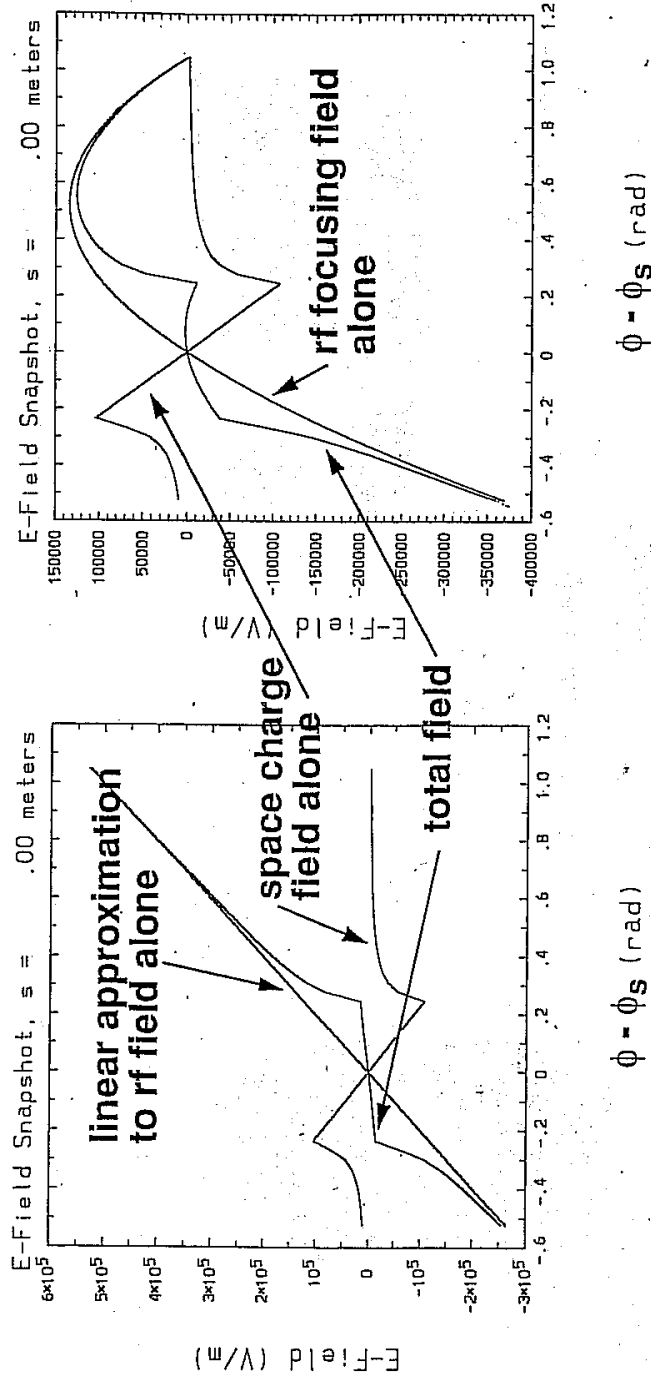
$$F_{zs} = \frac{q\rho}{\epsilon_0} f(\alpha) \Delta z$$

$$\alpha = \frac{r_L}{\gamma v_z} \quad \left[\alpha = \frac{r_L}{(r_L \text{ in comoving frame})} \right]$$

COMBINING FOCUSING + SELF FIELDS

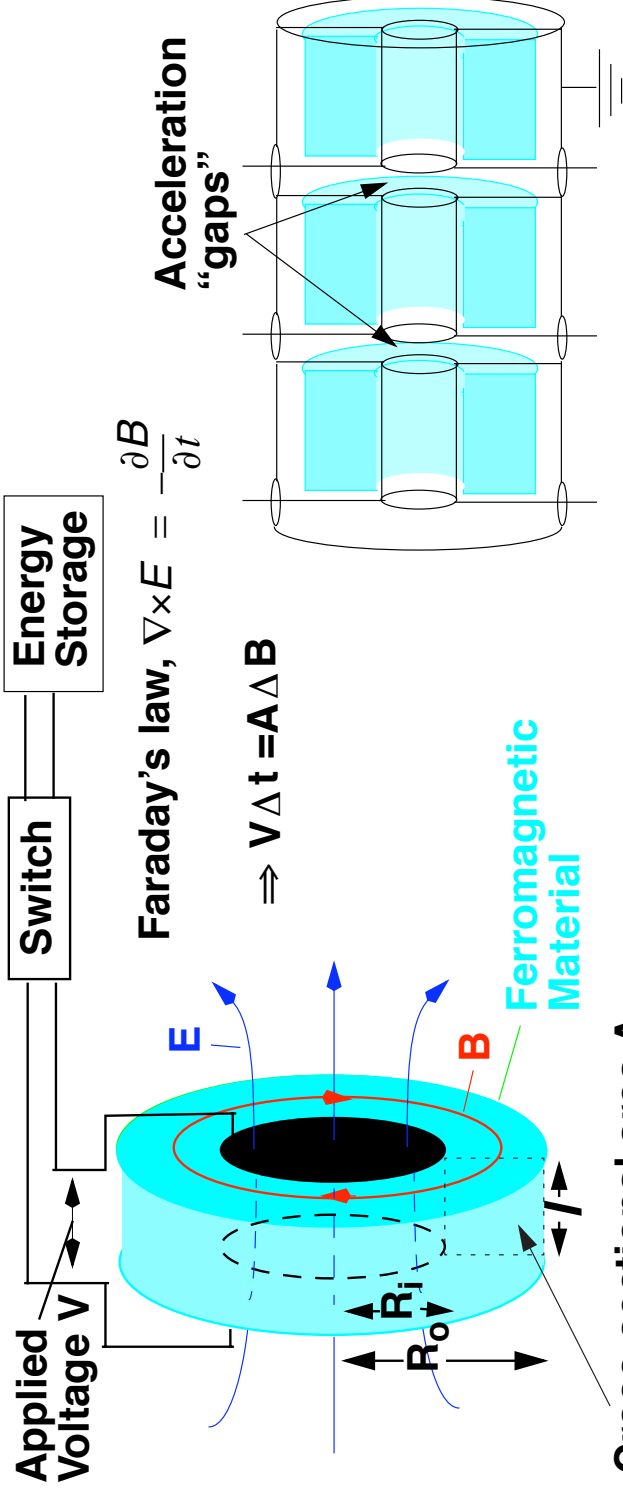
$$\frac{d^2 \Delta z}{ds^2} = -k_{s0}^2 \Delta z + \frac{q\rho f(\alpha)}{\gamma_s^3 \beta_s^2 mc^2 \epsilon_0} \Delta z \quad (\text{LINEAR rf})$$

Total field seen by particle is sum of rf and spacecharge



here $\phi - \phi_s = - (2 \pi / \beta_s \lambda) \Delta z$, where β_s is the longitudinal velocity of the synchronous particle and $\lambda = c/v$ is the rf vacuum wavelength

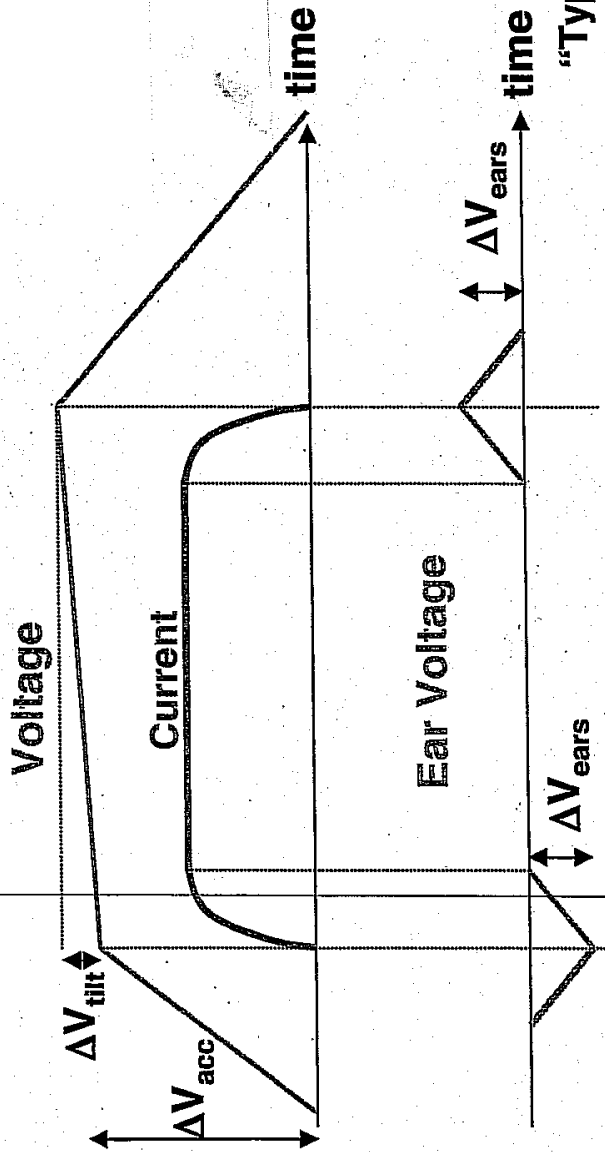
Induction acceleration: Volt-second limits



Volt-seconds per m: $(dV/dz) \Delta t = (R_o - R_i) \Delta B$ f_{radial} $f_{\text{longit.}}$
 $\sim 1 \text{ m} \sim 2.5 \text{ T} \sim 0.8 \sim 0.8$

$(dV/dz) \Delta t \ll 1.6 \text{ V-s/m}$

Several types of waveform are needed to accelerate, compress, and confine the beam



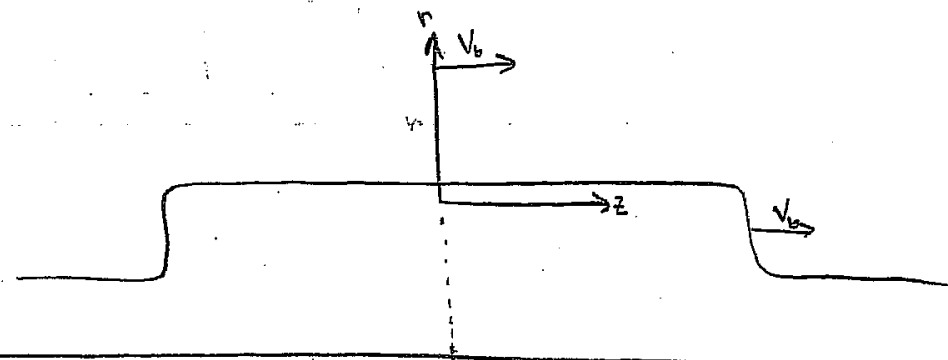
"Typical" numbers:

- $\Delta V_{tilt} \sim 1 \text{ kV}$
- $\Delta V_{ears} \sim 14 \text{ kV}$
- $\Delta V_{acc} \sim 100 \text{ kV}$



The Heavy Ion Fusion Virtual National Laboratory

COORDINATE SYSTEM



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$s=0$

$s = v_b t$ for drifting beam
= position of beam center in lab frame

$s \leftrightarrow t$ are related by βc for drifting beam

z = longitudinal coordinate in beam frame ($z=0$ = beam center)

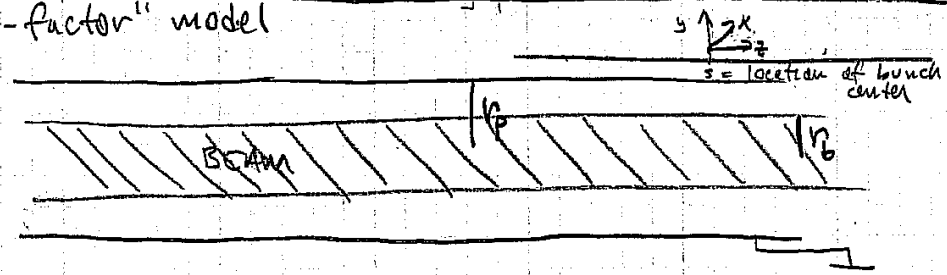
r = radial coordinate in beam frame (or lab frame).

(This class will assume non-relativistic dynamics)

These are ions with $\beta < 0.2$).

LONGITUDINAL PHYSICS OF LONG PULSES (BUNCH LENGTH $\gg r_{pipe}$)

"g-factor" model



$$\text{If } \frac{\partial^2 \phi}{\partial z^2} \ll \frac{1}{r} \left(\frac{\partial}{\partial r} r \frac{\partial \phi}{\partial r} \right) \Rightarrow \frac{\partial \phi}{\partial r} = - \frac{\lambda(r)}{2\pi\epsilon_0 r}$$

Let $\rho = \begin{cases} \rho_0 & 0 < r < r_b \\ 0 & r_b < r < r_p \end{cases} \Rightarrow \lambda = \lambda_0 \left(\frac{r}{r_b} \right)^2$

$$\phi = \int_r^{r_p} \frac{\partial \phi}{\partial r} dr = \begin{cases} \frac{\lambda}{2\pi\epsilon_0} \left[\frac{1}{2} \left(1 - \frac{r^2}{r_b^2} \right) + \ln \frac{r_p}{r_b} \right] & 0 < r < r_b \\ \frac{\lambda}{2\pi\epsilon_0} \ln \left(\frac{r_p}{r} \right) & r_b < r < r_p \end{cases}$$

$$\frac{\partial \phi}{\partial z} = \frac{1}{2\pi\epsilon_0} \left[\frac{1}{2} \left(1 - \frac{r^2}{r_b^2} \right) + \ln \frac{r_p}{r_b} \right] \frac{\partial \lambda}{\partial z} - \frac{1}{2\pi\epsilon_0} \left[1 - \frac{r^2}{r_b^2} \right] \frac{\lambda}{r_b} \frac{\partial r_b}{\partial z}$$

If $\rho = \text{const} \Rightarrow \frac{\lambda}{r_b^2} = \text{const} \Rightarrow \frac{\partial \lambda}{\partial z} = - \frac{2\lambda}{r_b} \frac{\partial r_b}{\partial z}$

$$\Rightarrow \frac{\partial \phi}{\partial z} = \frac{1}{2\pi\epsilon_0} \ln \left(\frac{r_p}{r_b} \right) \frac{\partial \lambda}{\partial z}$$

$$E_z = \frac{-g}{4\pi\epsilon_0} \frac{\partial \lambda}{\partial z}$$

where $g = 2 \ln \left(\frac{r_p}{r_b} \right)$

[SPACE-CHARGE DOMINATED BEAM]

[Example of $\rho = \text{const}$.
Magnetic Quadr focusing
 $\frac{\lambda}{4\pi\epsilon_0 Va} \approx k_{\rho 0}^2 a$
 $\Rightarrow \rho \sim V k_{\rho 0}^2 \approx \text{const}$]
(for space-charge dominated beam)

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FOR EMITTANCE DOMINATED BEAMS:

(with constant emittance and radius)

RADIUS NOT DETERMINED BY λ

$$\text{so } \frac{\partial r_b}{\partial z} \approx 0$$

$$\left\langle \frac{\partial \phi}{\partial z} \right\rangle = \frac{1}{2\pi\epsilon_0} \left[\frac{1}{2} \left(1 - \left\langle \frac{v_e}{v_b^2} \right\rangle \right) + \ln \frac{v_p}{v_b} \right] \frac{\partial \lambda}{\partial z}$$

$$\Rightarrow g = 2 \ln \left(\frac{v_p}{v_b} \right) + \frac{1}{2} \quad (\text{EMITTANCE DOMINATED BEAMS})$$

(SEE REISER, SECTION 6.3 FOR DISCUSSION ON g-FACTOR).

Vlasov - equation for a drifting beam:

$$\frac{\partial f}{\partial s} + x' \frac{\partial f}{\partial x} + x'' \frac{\partial f}{\partial x'} + y' \frac{\partial f}{\partial y} + y'' \frac{\partial f}{\partial y'} + z' \frac{\partial f}{\partial z} + z'' \frac{\partial f}{\partial z'} = 0$$

Let $\tilde{f}(z, z', s) \equiv \iiint f dx dx' dy dy'$

INTEGRATING VLASOV EQUATION:

If $z'' \neq f(x, x', y, y')$:

$$\Rightarrow \frac{\partial \tilde{f}}{\partial s} + \iiint x' \frac{\partial f}{\partial x} dx dx' dy dy' + \dots + z' \frac{\partial \tilde{f}}{\partial z} + z'' \frac{\partial \tilde{f}}{\partial z'} = 0$$

$$\Rightarrow \boxed{\frac{\partial \tilde{f}}{\partial s} + z' \frac{\partial \tilde{f}}{\partial z} + z'' \frac{\partial \tilde{f}}{\partial z'} = 0} \quad 1D \text{ Vlasov}$$

Now let $\lambda \equiv q \int \tilde{f} dz'$; $\lambda \bar{z}' = \int \tilde{f} z' dz'$; $\lambda \bar{z}'^{1/2} \equiv \int \tilde{f} z'^{1/2} dz'$

Also, let $\Delta \bar{z}'^{1/2} \equiv \bar{z}'^{1/2} - (\bar{z}')^{1/2}$

FLUID EQUATIONS

INTEGRATING 1D VLASOV OVER z' :

$$\boxed{\frac{\partial \lambda}{\partial s} + \frac{\partial (\lambda \bar{z}')}{\partial z} = 0} \quad (\text{CONTINUITY EQUATION})$$

MULTIPLYING BY z' & INTEGRATING VLASOV OVER z' :

$$\frac{\partial}{\partial s} \lambda \bar{z}' + \frac{\partial}{\partial z} \lambda \bar{z}'^2 - \lambda \bar{z}'' = 0$$

DIVIDING BY λ , USING CONTINUITY EQUATION & DEFINITION OF $\Delta \bar{z}'^{1/2}$:

$$\boxed{\underbrace{\frac{\partial \bar{z}'}{\partial s}}_{\text{INERTIAL}} + \underbrace{\bar{z}' \frac{\partial}{\partial z} \bar{z}'}_{\text{PRESSURE TERM}} + \underbrace{\frac{1}{\lambda} \frac{\partial (\lambda \Delta \bar{z}'^{1/2})}{\partial z}}_{\text{FORCE}} = \bar{z}''} \quad (\text{MOMENTUM EQUATION})$$

$$= \frac{1}{v_0^2} \frac{qE_z}{m}$$

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SOLVING WAVE EQUATION

$$\frac{\partial^2 \lambda_1}{\partial s^2} - \frac{c_s^2}{v_0^2} \frac{\partial^2 \lambda_1}{\partial z^2} = 0$$

$$\text{Let } \lambda_1 = \tilde{\lambda}_1 \exp\left[\frac{i\omega}{v_0} s \pm ikz\right]$$

$$-\frac{\omega^2}{v_0^2} + \frac{k^2 c_s^2}{v_0^2} = 0 \Rightarrow \omega = c_s k$$

\Rightarrow PHASE & GROUP VELOCITY OF WAVES = c_s
(in beam frame)

GENERAL SOLUTION

$$\lambda_1 = \lambda_0 f_+[u_+] + \lambda_0 f_-[u_-]$$

$$\text{where } u_+ = z + \frac{c_s s}{v_0} + C_0 \quad \& \quad u_- = z - \frac{c_s s}{v_0} + C_0$$

& $f_+[u_+]$ & $f_-[u_-]$ are any functions of the argument.
& C_0 is an arbitrary constant.

$$\tilde{\lambda}_1 = \frac{c_s}{v_0} [-f_+[u_+] + f_-[u_-]]$$

$s=0:$

$\lambda_1(z)$

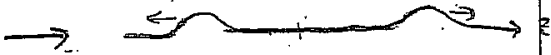


$s=s_0:$

$\lambda_1(z)$

BACKWARD WAVE

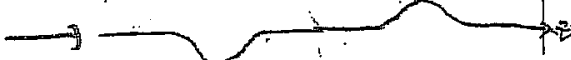
FORWARD WAVE



$\tilde{\lambda}_1(z)$



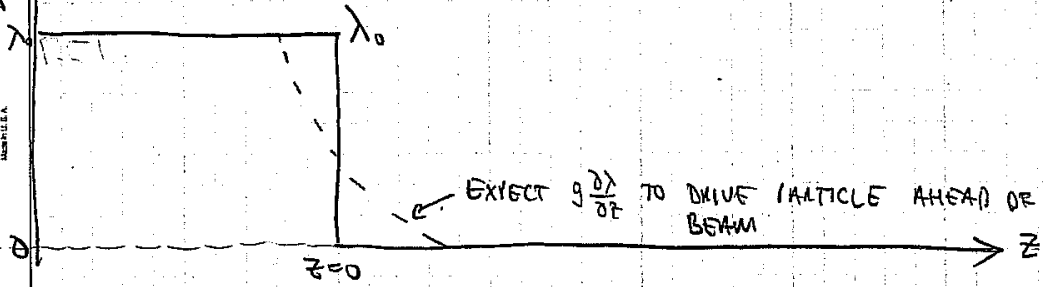
$\tilde{\lambda}_1(z)$



BEAM ENDS & RAREFACTION WAVES

(FALTINGS & LEE,
J. APPL. PHYS. 61, 5211)
(Also Landau & Lifshitz
Fluid Mechanics)

SUPPOSE YOU START WITH A PULSE THAT ENDS WITH A STEP FUNCTION IN λ . WHAT HAPPENS TO THE END?



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TO ANALYZE: RETURN TO NON-LINEAR FLUID EQUATIONS (SINCE $\delta\lambda \sim \lambda_0$) (g1):

$$\frac{\partial \lambda}{\partial t} + \lambda \frac{\partial \bar{z}'}{\partial z} + \bar{z}' \frac{\partial \lambda}{\partial z} = 0 \quad \text{(CONTINUITY)}$$

$$\frac{\partial \bar{z}'}{\partial t} + \bar{z}' \frac{\partial \bar{z}'}{\partial z} + \frac{c_s^2}{\lambda_0 v_0^2} \frac{\partial \lambda}{\partial z} = 0 \quad \text{(MOMENTUM)}$$

1st IT IS CONVENIENT TO DEFINE: $\Lambda \equiv \lambda / \lambda_0$

$$V \equiv \frac{v_0}{c_s} \bar{z}'$$

$$z \equiv \frac{v_0}{c_s} z$$

$$(c_s^2 \equiv \frac{q}{m} \frac{q \lambda_0}{4\pi \epsilon_0})$$

$$\Rightarrow \frac{\partial \Lambda}{\partial t} + \Lambda \frac{\partial V}{\partial z} + V \frac{\partial \Lambda}{\partial z} = 0 \quad \text{(CONTINUITY)}$$

$$\frac{\partial V}{\partial t} + V \frac{\partial V}{\partial z} + \frac{\partial \Lambda}{\partial z} = 0 \quad \text{(r1) (MOMENTUM)}$$

TRY A SIMILARITY SOLUTION: $\Lambda = \Lambda(x)$ & $V = V(x)$

WHERE $x = \frac{z}{s} = \left(\frac{v_0 z}{c_s s}\right)$

$\frac{\partial x}{\partial s} = -\frac{x}{s}$ $\frac{\partial x}{\partial z} = \frac{x}{z}$

$\frac{\partial \Lambda}{\partial s} = \frac{\partial \Lambda}{\partial x} \frac{\partial x}{\partial s} = -\frac{\partial \Lambda}{\partial x} \frac{x}{s}$ $\frac{\partial \Lambda}{\partial z} = \frac{\partial \Lambda}{\partial x} \frac{\partial x}{\partial z} = \frac{\partial \Lambda}{\partial x} \frac{x}{z}$ $\frac{\partial V}{\partial s} = -\frac{\partial V}{\partial x} \frac{x}{s}$ $\frac{\partial V}{\partial z} = \frac{\partial V}{\partial x} \frac{x}{z}$

$\left[-\frac{\partial \Lambda}{\partial x} \frac{x}{s} + \Lambda \frac{\partial V}{\partial x} \frac{x}{z} + V \frac{\partial \Lambda}{\partial x} \frac{x}{z} \right] = 0$ (CONTINUITY)

$\left[-\frac{\partial V}{\partial x} \frac{x}{s} + V \frac{\partial V}{\partial x} \frac{x}{z} + \frac{\partial \Lambda}{\partial x} \frac{x}{z} \right] = 0$ (MOMENTUM)

Multiply by z/s & gather terms:

$\Rightarrow \begin{bmatrix} V-x & \Lambda \\ 1 & V-x \end{bmatrix} \begin{bmatrix} \frac{\partial \Lambda}{\partial x} \\ \frac{\partial V}{\partial x} \end{bmatrix} = 0$

FOR NON-TRIVIAL SOLUTION DETERMINANT MUST VANISH:

$\Lambda = [V-x]^2$

$\Rightarrow \frac{\partial \Lambda}{\partial x} = 2[V-x] \left[\frac{\partial V}{\partial x} - 1 \right]$ & $\frac{\partial \Lambda}{\partial x} = -[V-x] \frac{\partial V}{\partial x}$

$\Rightarrow -\frac{\partial V}{\partial x} = 2 \frac{\partial V}{\partial x} - 2 \Rightarrow \frac{\partial V}{\partial x} = \frac{2}{3}$

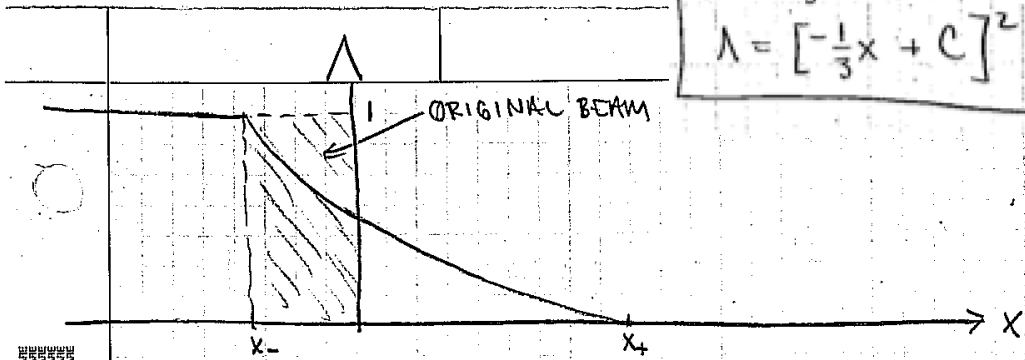
$\Rightarrow \begin{bmatrix} V = \frac{2}{3}x + C \\ \Lambda = \left[-\frac{1}{3}x + C\right]^2 \end{bmatrix}$

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$$V = \frac{2}{3}x + C$$

$$\lambda = \left[-\frac{1}{3}x + C\right]^2$$

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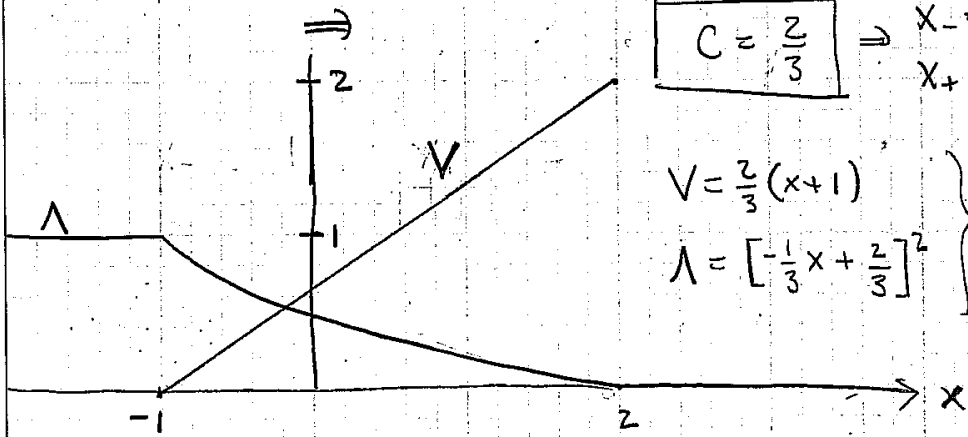


At x_+ : $\lambda = 0 \Rightarrow C = \frac{1}{3}x_+ \quad x_+ = 3C$

At x_- : $\lambda = 1 \Rightarrow C = \frac{1}{3}x_- + 1 \Rightarrow x_- = 3C - 3$

MASS CONSERVATION $\Rightarrow (x_-) - (3C - 3) = \int_{3C-3}^{3C} [C - \frac{1}{3}x]^2 dx = -3 \frac{[C - \frac{1}{3}x]^3}{3} \Big|_{3C-3}^{3C}$

$-(3C - 3) = 1$
 $C = \frac{2}{3} \Rightarrow x_- = -1$
 $x_+ = 2$



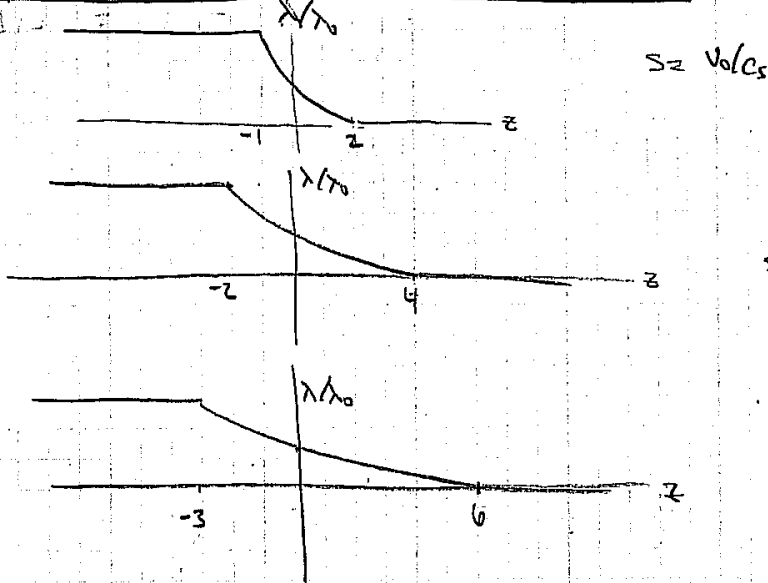
$V = \frac{2}{3}(x+1)$
 $\lambda = \left[-\frac{1}{3}x + \frac{2}{3}\right]^2 \quad \text{for } -1 < x < 2$

RECALL $x = \frac{v_0 z}{c_s s}$ so $x = 2 \Rightarrow z = 2 c_s \left(\frac{s}{v_0}\right)$
 $x = -1 \Rightarrow z = -c_s \left(\frac{s}{v_0}\right)$

SO BEAM END EXPANDS AT TWICE SPACE-CHARGE WAVE SPEED & RAREFACTION WAVE PROPAGATES INWARD AT THE SPACE-CHARGE WAVE SPEED.

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SPATIAL PROFILES OF λ/λ_0 VS z AT VARIOUS s

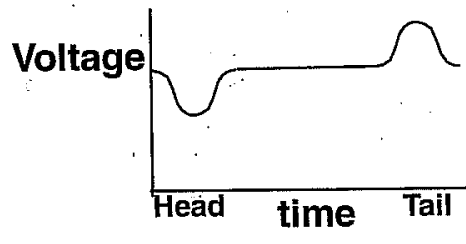
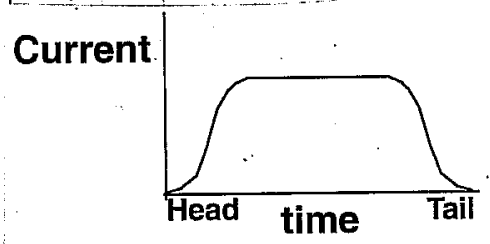


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HOW DOES ONE PREVENT "END EROSION"?

APPLY EAR PULSES AT END OF BEAM:

$$V \sim E_z = \frac{-\gamma \rho_0 \partial \lambda}{4\pi \epsilon_0 \partial z}$$



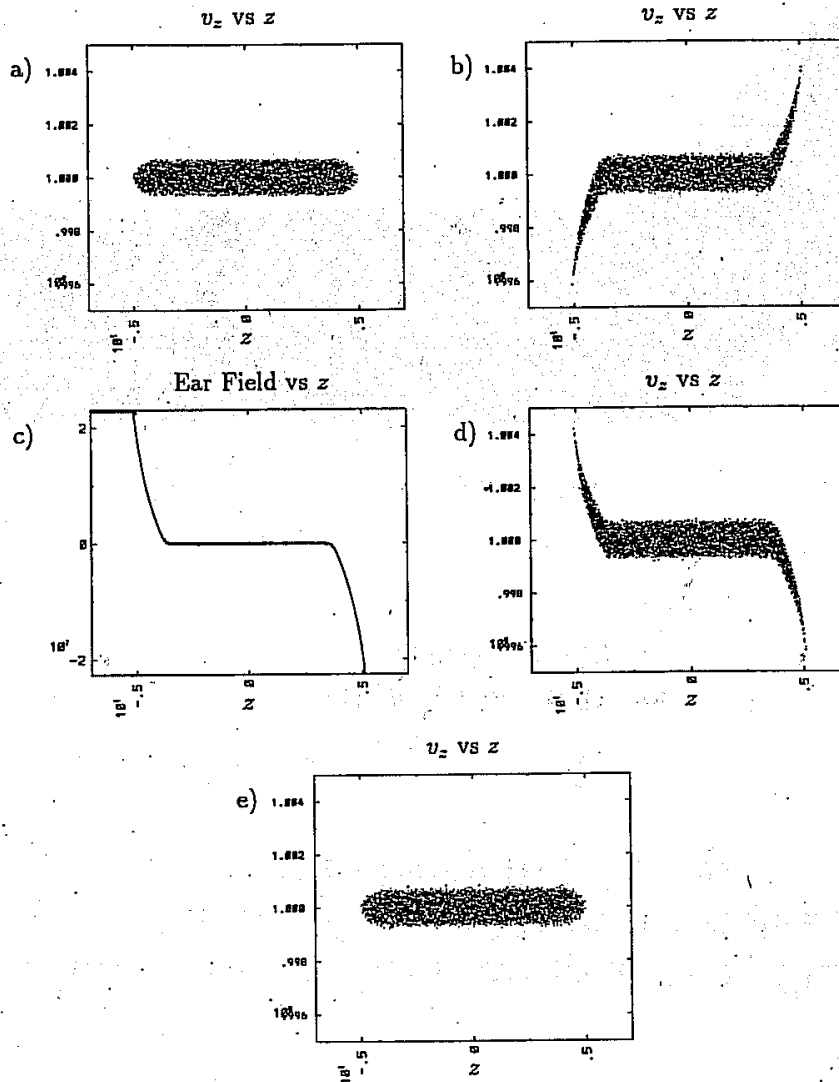


Figure 6.4: One cycle of intermittently-applied ears. (a) Initial phase space (b) Beam expands (c) Ear Field is applied (d) Beam is compressed (e) Beam expands back to its initial state

from D. Callahan Miller
PhD thesis, U.C. Davis, 1994.