

PHY 564

Advanced Accelerator Physics

Lecture 22

Collective Effects II: Examples of Collective Instabilities

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Outline

- Transverse beam breakup instability (BBU) in linear accelerator
 - Two particle model
 - BNS damping
- Longitudinal microwave instability
 - Dispersion relation
 - Cold beam
 - Warm beam (Keil-Schnell criteria for stability)

Single pass BBU (Two particle model)

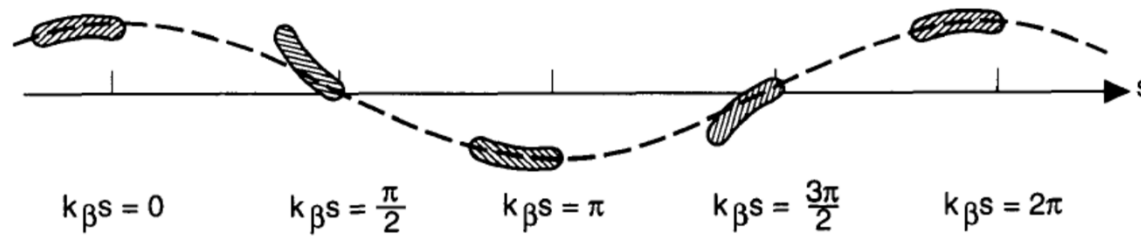
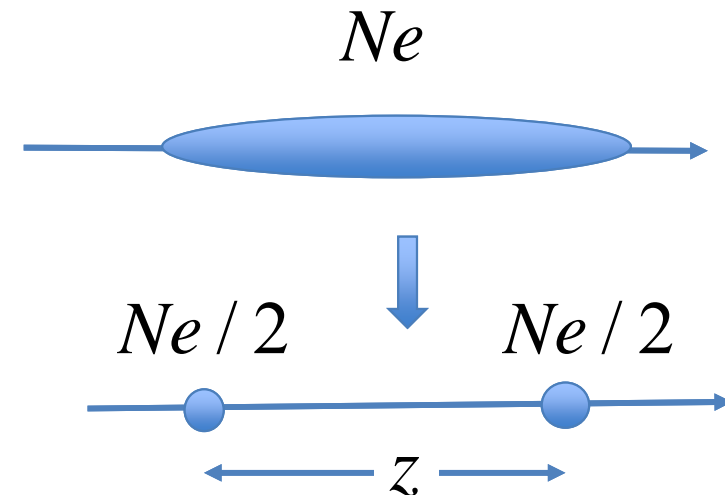


Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π . The dashed curves indicate the trajectory of the bunch head.

Leading particles $y_1(s) = \hat{y} \cos(k_\beta s)$

Trailing particles $y_2(s)'' + k_\beta^2 y_2(s) = \frac{Ne^2 W_1(z)}{2EL} y_1(s)$

$$r_0 = \frac{1}{4\pi\epsilon_0} \frac{e^2}{mc^2} = 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{2\gamma L} \hat{y} \cos(k_\beta s)$$



*Note: our definition of the transverse wake function follow G. Stupakov's note and has a sign difference from that defined in A. Chao's book, i.e. W_1 here is $-W_1$ in Chao's book.

Driving term for particle 2

$$\vec{w}_t(x, y, s) = \frac{c}{qe} \Delta \vec{p}_\perp \quad q = \frac{Ne}{2}$$

$$m = 1 \quad \vec{w}_t(r', r, \theta, s) = W_1(s) r' [\cos(\theta) \hat{r} - \sin(\theta) \hat{\theta}]$$

$$\Delta p_y = \frac{W_1(s) y_1 e Ne}{c} \frac{Ne}{2} \quad \leftarrow \text{Transverse momentum change of particle 2 due to wakefield while it goes through the structure}$$

$$\Delta y' = \frac{\Delta p_y}{p_z} \approx \frac{c \Delta p_y}{E} = \frac{W_1(s) y_1 Ne^2}{2E} \quad \leftarrow \text{Transverse angle change of particle 2 due to wakefield}$$

$$\frac{\Delta y'}{L} = \frac{W_1(s) y_1 Ne^2}{2EL} \quad \leftarrow \text{Transverse angle changing rate of particle 2 due to wakefield, driving term}$$

Single pass BBU (Two particle model)

For a linear inhomogenous 2nd order differential equation

$$\frac{d^2 x}{dt^2} + a(t) \frac{dx}{dt} + b(t) x = f(t)$$

its solution is given by

$$W(t) = \begin{vmatrix} \phi_1(t) & \phi_2(t) \\ \phi_1'(t) & \phi_2'(t) \end{vmatrix}$$

$$x(t) = c_1 \phi_1(t) + c_2 \phi_2(t) + \int_{t_0}^t \frac{\phi_1(\xi) \phi_2(t) - \phi_2(\xi) \phi_1(t)}{W(\xi)} f(\xi) d\xi$$

$$y_{2,inh}(s) = 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{2\gamma L k_\beta} \hat{y} \int_0^s \sin(k_\beta s - k_\beta \xi) \cos(k_\beta \xi) d\xi$$

$$\phi_2 = \sin(k_\beta s) \quad \phi_1 = \cos(k_\beta s)$$

$$= 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{2\gamma L k_\beta} \hat{y} \frac{1}{2} \left[s \sin(k_\beta s) - \int_{-s/2}^{s/2} \sin(2k_\beta \tilde{\xi}) d\tilde{\xi} \right]$$

$$W(t) = \begin{vmatrix} \cos(k_\beta s) & \sin(k_\beta s) \\ -k_\beta \sin(k_\beta s) & k_\beta \cos(k_\beta s) \end{vmatrix} = k_\beta$$

$$= 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{4\gamma L k_\beta} \hat{y} s \sin(k_\beta s)$$

Single pass BBU (Two particle model)

$$y_2(s) = c_1 \cos(k_\beta s) + c_2 \sin(k_\beta s) + 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{4\gamma L k_\beta} \hat{y} s \sin(k_\beta s)$$

Noticing that before going through the structure, particle 2 has the same trajectory as that of Particle 1, i.e.

$$y_2(0) = y_1(0) = \hat{y} \cos(0) = \hat{y}$$

$$y_2'(0) = y_1'(0) = -\hat{y} k_\beta \sin(0) = 0$$

We obtain $c_1 = \hat{y}$ and $c_2 = 0$. Thus the solution for particle 2 is

$$y_2(s) = \hat{y} \left[\cos(k_\beta s) + 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{4k_\beta \gamma L} s \sin(k_\beta s) \right]$$

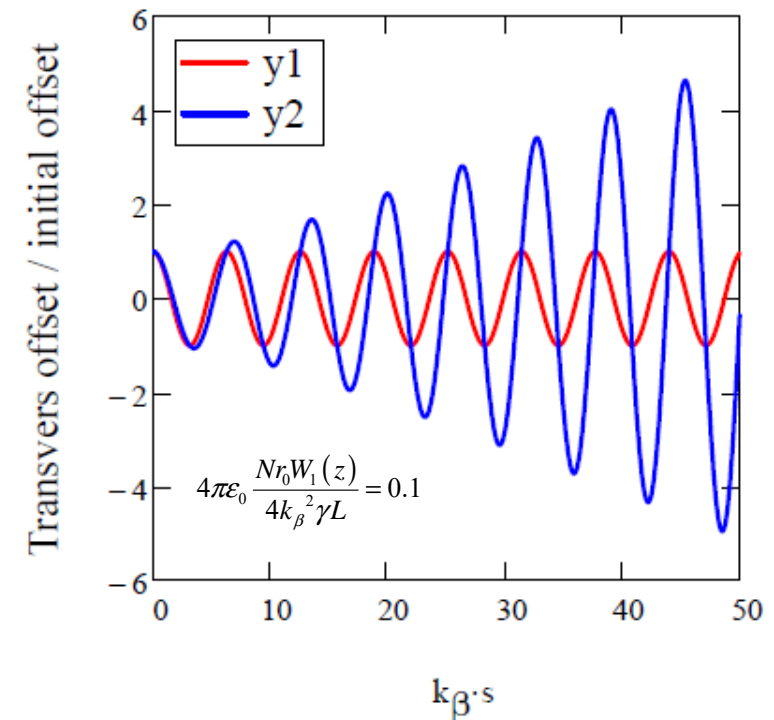
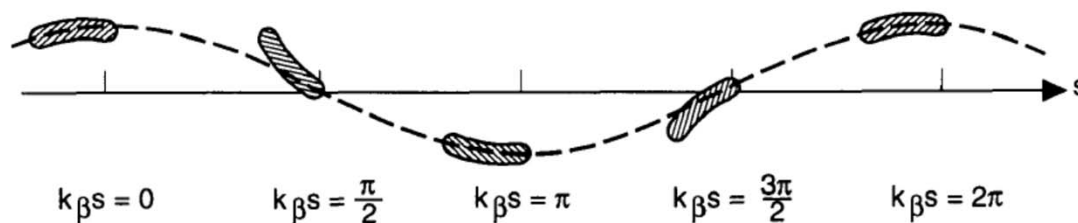


Figure 3.3. Sequence of snapshots of a beam undergoing dipole beam breakup instability in a linac. Values of $k_\beta s$ indicated are modulo 2π . The dashed curves indicate the trajectory of the bunch head.

Single pass BBU II

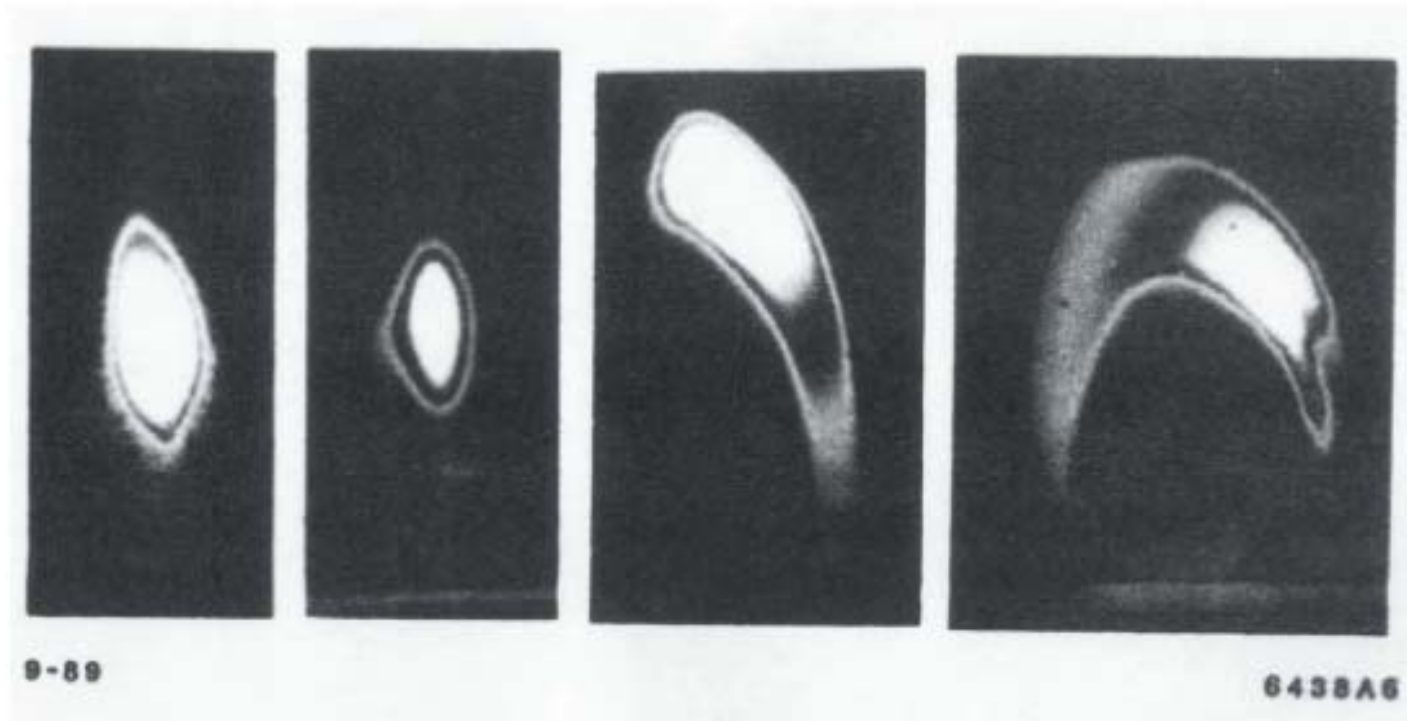


Figure 4.4: Four transverse beam profiles observed at the end of the SLAC linac are shown when the beam was carefully injected, and injected with 0.2, 0.5, and 1 mm offsets. The beam sizes σ_x and σ_y are about $120 \mu\text{m}$. (Courtesy John Seeman, 1991)

One possible cure: BNS damping

Balakin, Novokhatsky, and Smirnov

Introduce focusing variation along the bunch, i.e. head and tail have different focusing strength

$$y_2'' + (k_\beta + \Delta k_\beta)^2 y_2 = 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{2\gamma L} \hat{y} \cos(k_\beta s) \quad \tilde{k}_\beta \equiv k_\beta + \Delta k_\beta$$

$$\phi_2 = \sin(\tilde{k}_\beta s) \quad \phi_1 = \cos(\tilde{k}_\beta s)$$

$$y_{2,inh}(s) = 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{2\gamma L \tilde{k}_\beta} \hat{y} \int_0^s \sin(\tilde{k}_\beta s - \tilde{k}_\beta \xi) \cos(k_\beta \xi) d\xi$$

$$W(t) = \tilde{k}_\beta$$

$$= -4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{2\gamma L \tilde{k}_\beta} \hat{y} \frac{1}{2} \left[\int_0^s \sin\left(\Delta k_\beta \left(\xi - \frac{\tilde{k}_\beta}{\Delta k_\beta} s\right)\right) d\xi + \int_0^s \sin\left((\tilde{k}_\beta + k_\beta) \left(\xi - \frac{\tilde{k}_\beta}{\tilde{k}_\beta + k_\beta} s\right)\right) d\xi \right]$$

$$= 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{2\gamma L \tilde{k}_\beta} \hat{y} \frac{1}{2} \left[\frac{1}{\Delta k_\beta} + \frac{1}{\tilde{k}_\beta + k_\beta} \right] [\cos(k_\beta s) - \cos(\tilde{k}_\beta s)]$$

$$\approx -4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{4\gamma L k_\beta \Delta k_\beta} \hat{y} [\cos(\tilde{k}_\beta s) - \cos(k_\beta s)] \quad \leftarrow \text{assume } \Delta k_\beta / k_\beta \ll 1$$

$$y_2(s) = \hat{y} \cos((k_\beta + \Delta k_\beta)s) - 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{4\gamma L k_\beta \Delta k_\beta} \hat{y} [\cos(\tilde{k}_\beta s) - \cos(k_\beta s)]$$

Condition for complete compensation:

$$4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{4\gamma L k_\beta \Delta k_\beta} = 1 \Rightarrow \Delta k_\beta = 4\pi\epsilon_0 \frac{Nr_0 W_1(z)}{4\gamma L k_\beta} \Rightarrow \boxed{y_2(s) = \hat{y} \cos(k_\beta s)}$$

Longitudinal Microwave Instability

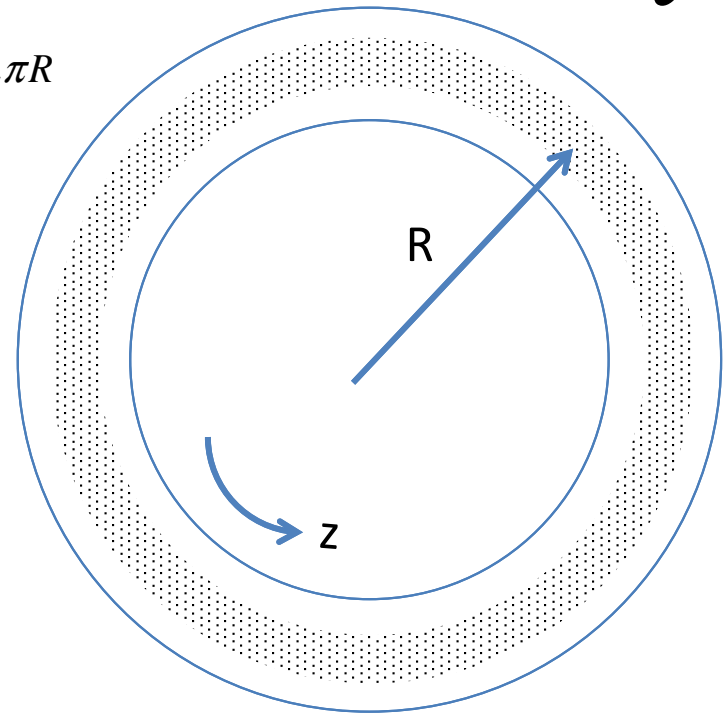
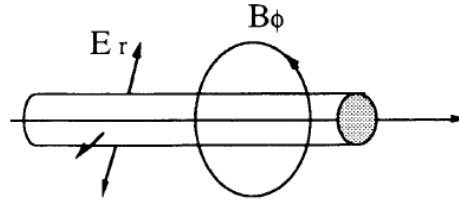
Unperturbed phase space density:

$$\psi_0(z, \Delta E) = \psi_0(\Delta E) = \frac{N}{C_0} f_0(\Delta E) \quad \rho_0(z) = \rho_0 = \frac{N}{C_0}$$

$$C_0 = 2\pi R$$

DC current does not excite wake

$$V_{//}(z_0) = \int_{z_0}^{\infty} \lambda(z_1) w_{//}(z_1 - z_0) dz_1$$

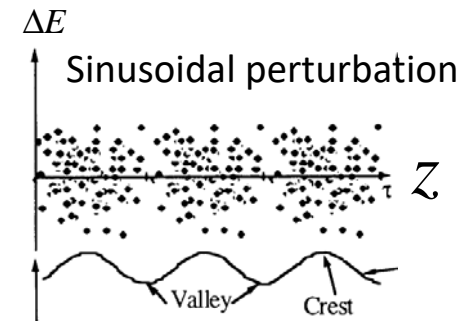
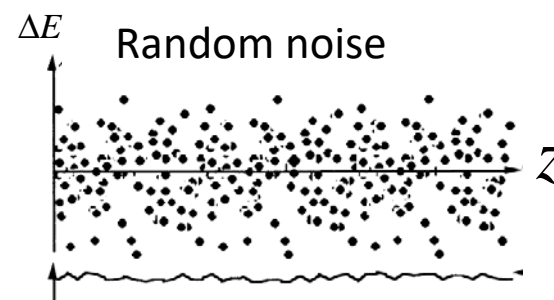


$$= \rho_0 \int_{z_0}^{\infty} W_0'(z_1 - z_0) dz_1 = -\rho_0 W_0(0) = 0$$

Consider perturbation in phase space density: n-th azimuthal mode

$$\psi_1(z, \Delta E, 0) = \hat{\psi}_1(\Delta E) e^{inz/R}$$

Ansatz: $\psi_1(z, \Delta E, t) = \hat{\psi}_1(\Delta E) e^{inz/R - i\Omega t}$



*Note that if a perturbation is static,

$$\psi_1^*(z, \Delta E, t) = \hat{\psi}_1^*(\Delta E) e^{in(z-v_0 t)/R} = \hat{\psi}_1^*(\Delta E) e^{inz/R - i\Omega^* t} \Rightarrow \Omega^* = nv_0 / R = n2\pi v_0 / C = n\omega_0$$

Longitudinal Microwave Instability

But the system is not likely to be static and we need to solve Vlasov equation self-consistently to know the answer for Ω and hence $\psi_1(s, \Delta E, t)$

$$\frac{\partial}{\partial t} \psi_1(z, \Delta E, t) + \frac{dz}{dt} \cdot \frac{\partial}{\partial z} \psi_1(z, \Delta E, t) + \frac{d\Delta E}{dt} \cdot \frac{\partial}{\partial \Delta E} \psi_0(\Delta E) = 0$$

where
$$\frac{dz}{dt} = v(\Delta E) \quad (1)$$

and $\frac{d\Delta E}{dt}$ is obtained by calculating the longitudinal wake potential $\frac{d\Delta E(z, t)}{dt} = -\frac{c\Delta p_z(z, t)}{T_0}$

$$c\Delta p_z(z, t) = -eQ_e V_{//}(z, t) = -e^2 v_0 \int_{-\infty}^t \rho_1(z, t_1) w_{//}(t - t_1) dt_1 = -e^2 v_0 \int_0^{\infty} \rho_1(z, t - \tau) w_{//}(\tau) d\tau$$

$\rho_1 v_0 dt$ gives particle number in the slice $(t, t+dt)$.

Longitudinal Microwave Instability

Hence, we obtain

$$\frac{d\Delta E(z,t)}{dt} = -\frac{c\Delta p_z(z,t)}{T_0} = -\frac{e^2 v}{T_0} \int_0^\infty \rho_1(z, t-\tau) w_{//}(\tau) d\tau$$

where $T_0 = \frac{C_0}{v_0}$ is the revolution period. Using the test solution

$$\psi_1(z, \Delta E, t) = \hat{\psi}_1(\Delta E) e^{inz/R - i\Omega t}$$

and the following relations

$$w_{//}(\tau) = \frac{1}{2\pi} \int_{-\infty}^{\infty} Z_{//}(\omega) e^{-i\omega\tau} d\omega$$

$$\rho_1(z, t) = \int_{-\infty}^{\infty} \psi_1(z, \Delta E, t) d\Delta E = \hat{\rho}_1 e^{inz/R - i\Omega t} \quad \hat{\rho}_1 \equiv \int_{-\infty}^{\infty} \hat{\psi}_1(\Delta E) d\Delta E$$

we can write the energy kick in term of longitudinal impedance

$$\frac{d\Delta E(z,t)}{dt} = -\hat{\rho}_1 \frac{e^2 v_0}{2\pi T_0} e^{inz/R - i\Omega t} \int_{-\infty}^{\infty} d\omega Z_{//}(\omega) \int_{-\infty}^{\infty} e^{i(\Omega-\omega)\tau} d\tau = -\hat{\rho}_1 \frac{e^2 v_0}{T_0} e^{inz/R - i\Omega t} Z_{//}(\Omega) \quad (2)$$

Longitudinal Microwave Instability

Inserting eq. (1) and (2) into Vlasov equation, we obtain

$$-i\Omega\psi_1(z, \Delta E, t) + v(\Delta E) \cdot \frac{in}{R}\psi_1(z, \Delta E, t) - \hat{\rho}_1 \frac{e^2 v_0}{T_0} e^{inz/R - i\Omega t} Z_{//}(\Omega) \cdot \frac{\partial}{\partial \Delta E} \psi_0(\Delta E) = 0$$

, which can be rewritten as

$$\psi_1(z, \Delta E, t) = \frac{ie^2 v_0 Z_{//}(\Omega)}{T_0} \frac{\hat{\rho}_1 e^{inz/R - i\Omega t}}{\Omega - \omega(\Delta E)n} \frac{d\psi_0(\Delta E)}{d\Delta E} \quad \omega(\Delta E) = \frac{v(\Delta E)}{R}$$

Integrating above equation over energy, i.e. $\int_{-\infty}^{\infty} d\Delta E \rightarrow$, yields

Dispersion relation:

$$1 = \frac{ieI_0 Z_{//}(\Omega)}{T_0} \int_{-\infty}^{\infty} \frac{f_0'(\Delta E)}{\Omega - \omega(\Delta E)n} d\Delta E$$

$$\psi_0(\Delta E) = \frac{N}{C_0} f_0(\Delta E)$$

$$I_0 = eN/T_0$$

Longitudinal Microwave Instability

$$1 = \frac{ieI_0 Z_{//}(\Omega)}{T_0} \int_{-\infty}^{\infty} \frac{f_0'(\Delta E)}{\Omega - \omega(\Delta E)n} d\Delta E$$

*Phase slip factor:

$$\eta = \frac{1}{\gamma_t^2} - \frac{1}{\gamma^2}$$

$$\omega(\Delta E) = \omega_0 + \Delta\omega(\Delta E) = \omega_0 - \eta\omega_0 \frac{\Delta p_z}{p_{0,z}} = \omega_0 - \frac{\eta\omega_0}{\beta^2} \frac{\Delta E}{E_0}$$

*Imaginary part of Ω tell us whether the system is stable

$$\psi_1(z, \Delta E, t) = \hat{\psi}_1(\Delta E) e^{inz/R - i\Omega t}$$

Cold Beam: $f_0(\Delta E) = \delta(\Delta E)$

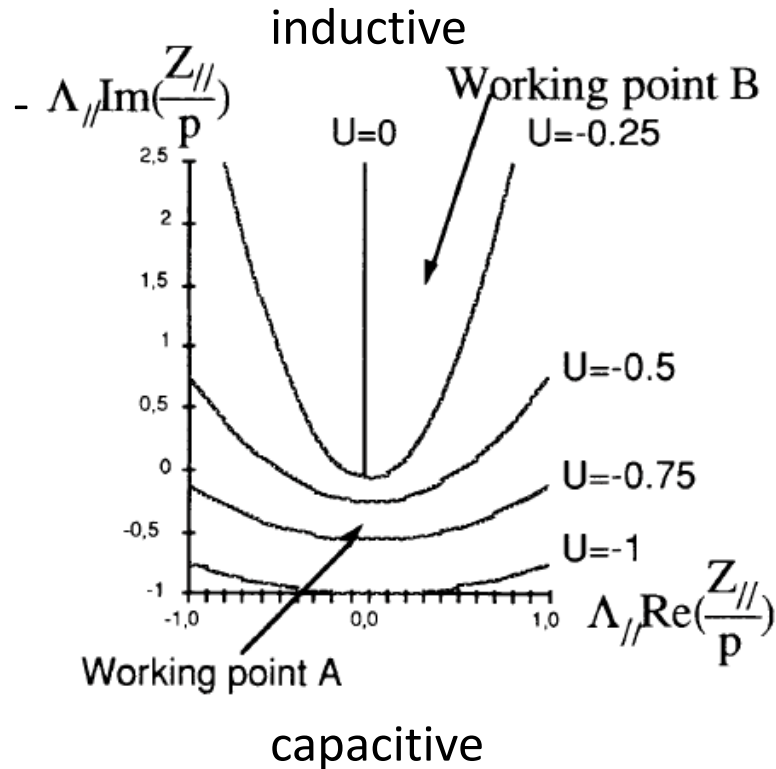
$$1 = \frac{ieI_0 Z_{//}(\Omega)}{T_0} \frac{\eta n \omega_0}{E_0 \beta^2} \int_{-\infty}^{\infty} \frac{f_0(\Delta E)}{\left(\Omega - n\omega_0 + \frac{\eta n \omega_0}{E_0 \beta^2} \Delta E \right)^2} d\Delta E$$

$$\Rightarrow \Omega = n\omega_0 \pm \omega_0 \sqrt{\frac{ieI_0 \eta n Z_{//}(\Omega)}{2\pi E_0 \beta^2}} \approx n\omega_0 \pm \omega_0 \sqrt{\frac{ieI_0 \eta n Z_{//}(n\omega_0)}{2\pi E_0 \beta^2}}$$

Perturbative approach assuming $\frac{|\Omega - n\omega_0|}{n\omega_0} \ll 1$

Longitudinal Microwave Instabilities

Cold beam continued:
(assuming $\eta > 0$)



$$\Omega \approx n\omega_0 \pm \omega_0 \sqrt{\frac{ieI_0 \eta n Z_{//} (n\omega_0)}{2\pi E_0 \beta^2}}$$

For cold beam, the only case for stable beam is the machine impedance is pure inductive, i.e. $\text{Im}(Z_{//}) < 0$, for $\eta > 0$ and capacitive, i.e. $\text{Im}(Z_{//}) > 0$ for $\eta < 0$.

Taken from 'Accelerator Physics' by S.Y. Lee

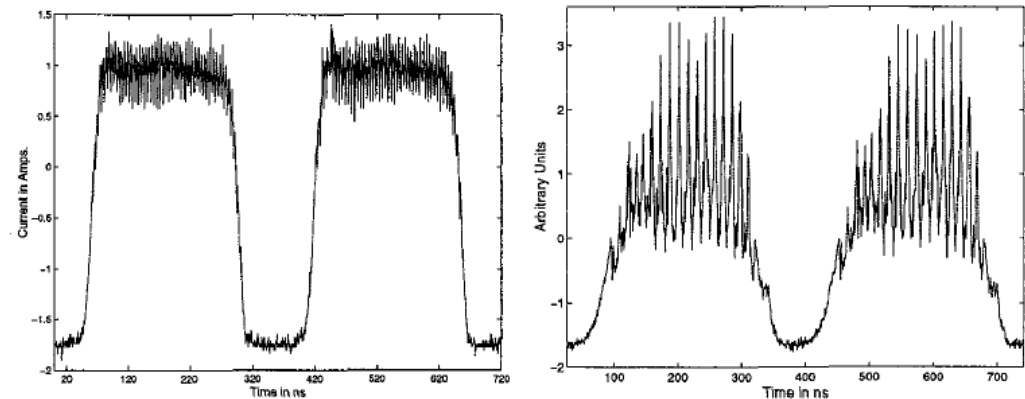


Figure 3.36: The longitudinal beam profiles observed at PSR the bunched coasting beam in the presence of inductive inserts, where three 1-m long ferrite ring cavities were installed in the PSR ring. [Courtesy of R. Macek, LANL]

Longitudinal Microwave Instabilities

Warm Beam: $f_0(\Delta E) = \frac{1}{\sqrt{2\pi}\sigma_E} \exp\left(-\frac{\Delta E^2}{2\sigma_E^2}\right)$

Dispersion relation for warm beam

$$1 = \frac{ieI_0 Z_{//}(n\omega_0)}{T_0} \frac{1}{\sqrt{2\pi}\sigma_E^2} \int_{-\infty}^{\infty} \frac{-\frac{\Delta E}{\sigma_E} \exp\left(-\frac{\Delta E^2}{2\sigma_E^2}\right)}{\Omega - \omega(\Delta E)n} d\Delta E = i \frac{1}{2} \left\{ \frac{eI_0 [Z_{//}(n\omega_0)/n] E_0 \beta^2}{2\pi\eta\sigma_E^2} \right\} J_G(\tilde{\Omega})$$

$$= i \frac{2\ln(2)}{\pi} \left\{ \frac{eI_0 [Z_{//}(n\omega_0)/n] E_0 \beta^2}{\eta\sigma_{E,FWHM}^2} \right\} J_G(\tilde{\Omega})$$

$$J_G(\tilde{\Omega}) = \sqrt{\frac{2}{\pi}} \int_{-\infty}^{\infty} \frac{-x \exp\left(-\frac{x^2}{2}\right)}{\left[\tilde{\Omega} \frac{E_0 \beta^2}{\eta n \omega_0 \sigma_E} + x \right]} dx$$

$$U' - iV' \equiv \frac{eI_0 [Z_{//}(n\omega_0)/n] E_0 \beta^2}{\eta\sigma_{E,FWHM}^2}$$

$$U' \sim \text{Re}(Z_{//}(n\omega_0))$$

$$V' \sim -\text{Im}(Z_{//}(n\omega_0))$$

$$\tilde{\Omega} = \text{Re}(\tilde{\Omega}) + i\text{Im}(\tilde{\Omega}) \equiv \Omega - \omega_0 n$$

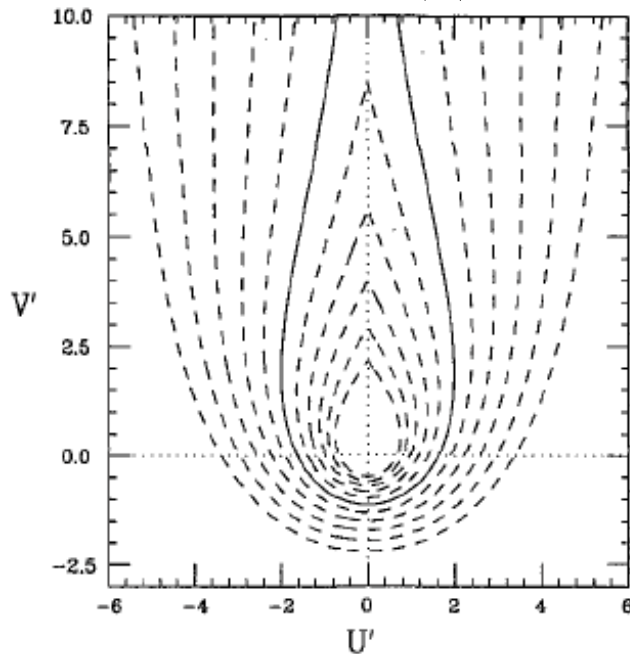
$$U' - iV' = \frac{-i\pi}{2\ln(2) J_G(\text{Re}\tilde{\Omega} + i\text{Im}\tilde{\Omega})}$$

- The dispersion relation is solved by numerical plotting the contours for various $\text{Im}\tilde{\Omega}$ in the complex impedance plane.

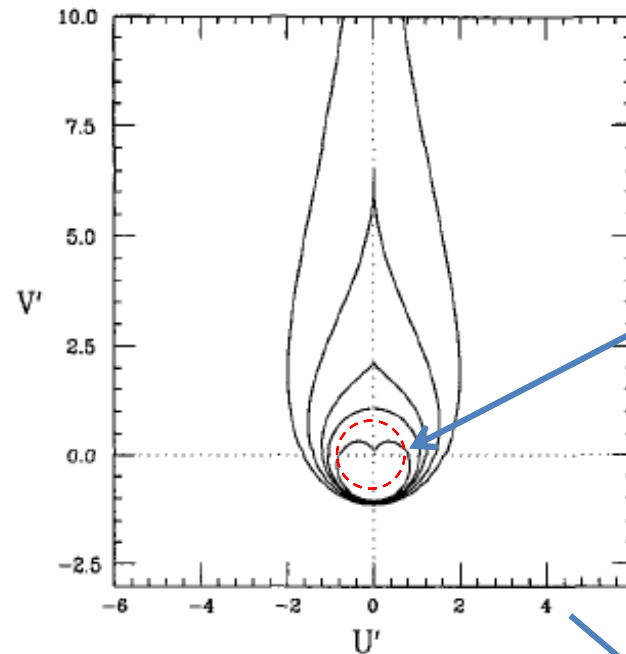
$$\psi_1(z, \Delta E, t) = \hat{\psi}_1(\Delta E) e^{inz/R - i\Omega t}$$

Longitudinal Microwave instability

Gaussian with various growth rate, $\text{Im}(\tilde{\Omega})$



Contours with $\text{Im}(\tilde{\Omega})=0$ for various energy distribution



Simplified estimation for stability condition:
Keil-Schnell criterion

$$\left| Z_{\parallel}(n\omega_0) / n \right| \leq \frac{2\pi |\eta| \sigma_E^2}{E_0 \beta^2 e I_0} F$$

F depends on distribution and for Gaussian energy distribution, it is 1.

Figure 3.34: Left: The solid line shows the parameters V' vs U' for a Gaussian beam distribution at a zero growth rate. Dashed lines inside the threshold curve are stable. They correspond to $-\text{Im} \Omega / (\sqrt{2 \ln 2} \omega_0 \eta \sigma_\delta) = -0.1, -0.2, -0.3, -0.4,$ and -0.5 . Dashed lines outside the threshold curve have growth rates $-\text{Im} \Omega / (\sqrt{2 \ln 2} \omega_0 \eta \sigma_\delta) = 0.1, 0.2, 0.3, 0.4,$ and 0.5 respectively. Right: The threshold V' vs U' parameters for various beam distributions.

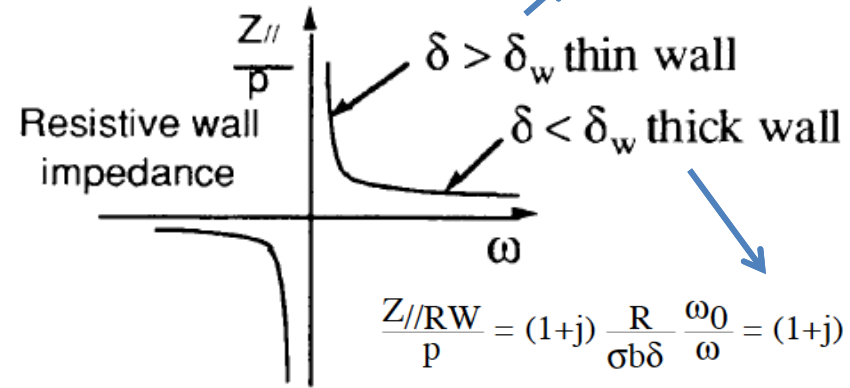
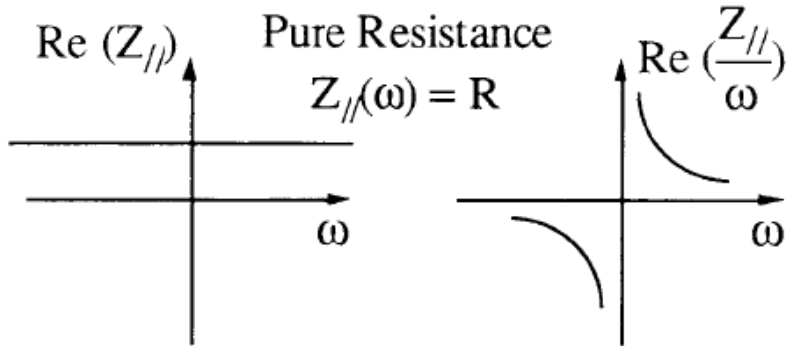
from inside outward, for the normalized distribution functions $\Psi_0(x) = 3(1-x^2)/4,$ $8(1-x^2)^{3/2}/3\pi,$ $15(1-x^2)^2/16,$ $315(1-x^2)^4/32,$ and $(1/\sqrt{2\pi}) \exp(-x^2/2)$. All dis-

Typical Longitudinal Impedance

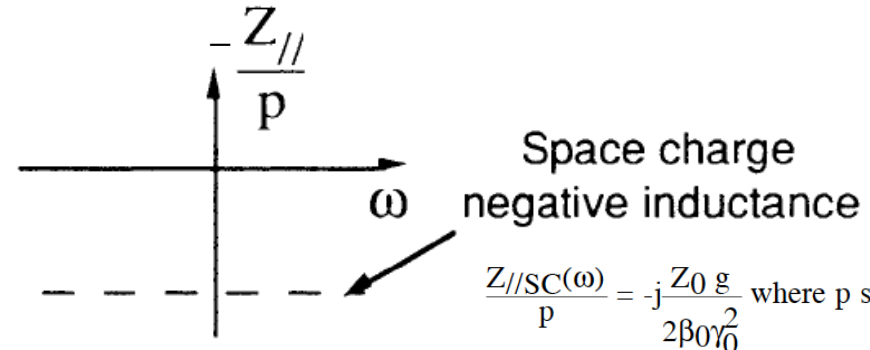
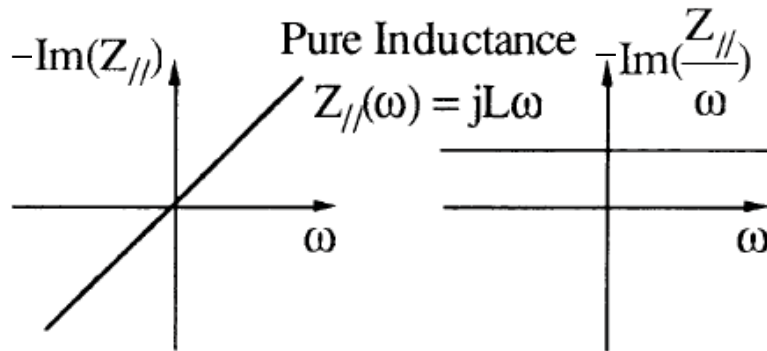
$$j = -i$$

Taken from 'Coasting beam longitudinal coherent instabilities' by J.L. Laclare

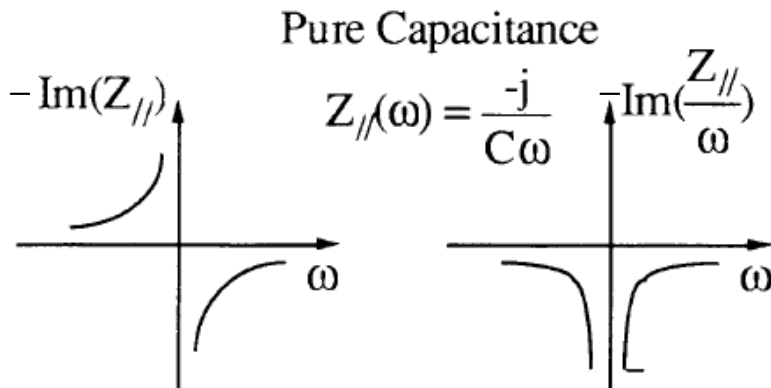
$$\frac{Z_{//RW}}{p} = \frac{R}{\sigma b \delta_w} \frac{1}{p}$$



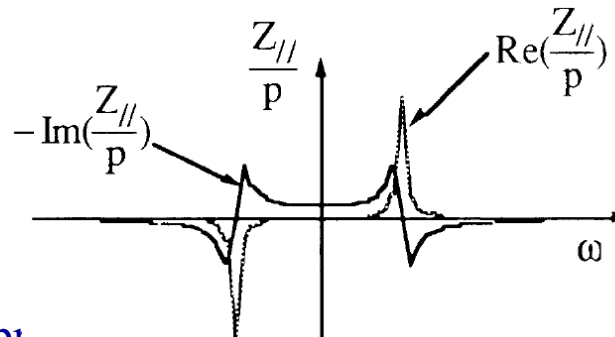
$$\frac{Z_{//RW}}{p} = (1+j) \frac{R}{\sigma b \delta} \frac{\omega_0}{\omega} = (1+j) \frac{Z_0 \beta_0 \delta_0}{2b} \frac{1}{\sqrt{p}}$$



$$\frac{Z_{//SC}(\omega)}{p} = -j \frac{Z_0 g}{2\beta_0 \gamma_0^2} \text{ where } p \text{ stands for } \frac{\omega}{\omega_0}$$



Resonator model (cavities)



$$Z_{//} = \frac{R_s}{1 + jQ\left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega}\right)}$$

Many pictures and derivations used in the slides are taken from the following references:

[1] ‘Accelerator Physics’ by S.Y. Lee;

[2] ‘Physics of Collective Beam Instabilities in High Energy Accelerators’ by A. Chao;

[3] ‘Coasting beam longitudinal coherent instabilities’ by J.L. Laclare

What we learned today

- In linear accelerator, **single bunch transverse beam break up instability** can develop if the bunches are not carefully injected and machine transverse wake function / impedance is large. Such a instability can be compensated by introducing focusing variation along the bunch, i.e. **BNS damping**.
- We also derived the dispersion relation for longitudinal microwave instability in a coasting beam. For **cold beam**, the beam is always unstable unless the impedances is pure inductive above transition or pure capacitive below transition. For **warm beam**, **Landau damping** make beam stable if the beam energy spread is sufficiently large. The stability condition can be estimated from **Keil-Schnell criteria**.