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HOSE INSTABILITY OF A BEAM WITH THE BENNETT PROFILE*

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November 1974

ABSTRACT

The hose instability is examined for an unmodulated beam with the Bennett current profile $J(r) \propto (1 + r^2/a^2)^{-2}$. The channel conductivity $\sigma(r)$ is also assumed to be of this form. To model particle orbit effects the beam is represented as a collection of independent disks with distribution of response frequency appropriate for the Bennett equilibrium. An effective decay length for dipole currents is determined by requiring that the well-known low frequency dispersion formula be recovered. The maximum growth rate for a disturbance propagating backwards in the beam frame is found to be $\omega_i = 5.52$ in units of the inverse skin length.

*Work performed jointly under the auspices of the U.S. Atomic Energy Commission, and the Department of the Navy under the contract number NAonr 13-74

I. Model

It has been established in theory⁽¹⁾ and by experiment⁽²⁾ that a pinched relativistic beam, when scattered by gas evolves to the Bennett equilibrium. The current density profile is

$$J(r) = \frac{I}{\pi a^2} (1 + r^2/a^2)^{-2} , \quad (1)$$

where (I) is total beam current and (a) is the scale radius. The hose dispersion relation for this beam is worked out in detail here to serve as a standard in interpreting experiments and computer simulation.

None of the available analytic treatments of hose instability^(3,4,5,6,7,8) is completely satisfactory by itself*, but the essential features of each may be incorporated into a simple model. We adopt here the hose equations of reference (3):

$$\left(\frac{\partial^2 Y_i}{\partial z^2} \right)_x + k_i^2 (Y_i - D) = 0 , \quad (2)$$

$$\left(\frac{\partial D}{\partial x} \right)_z + \frac{1}{\lambda} (D - \bar{Y}) = 0 , \quad (3)$$

with $x = \beta c t - z$. Y_i is the displacement of a disk or group of particles characterized by response frequency k_i , and their mean displacement from the channel axis is $\bar{Y}$. The mean displacement of the pinch field is D , and λ is an effective decay length for induced dipole currents. Eq. (2) and (3) have previously been used to study the effect of spread relativistic particle mass with $k_i^2 \propto \gamma_i^{-1}$, here we assume they provide a valid description of the spread response frequency of a collection of particles in an anharmonic well.

*A brief discussion of these models is given in the reference list.

The Vlasov^(5,6) and rigid beam^(4,8) models of the hose motion yield a dispersion relation which is valid at low frequency; this result should be duplicated by the system (2), (3). In addition, these models provide considerable information about the response frequencies, which we incorporate in the assumed distribution function.

Let a disturbance be of the form

$$\bar{Y}, D, Y_i \propto e^{-i(\Omega z + \omega x)} \quad (4)$$

with Ω or ω having positive imaginary part. Eliminating D from eq. (2), we have

$$-\Omega^2 Y_i = -k_i^2 Y_i + k_i^2 (1 - i\omega\lambda)^{-1} \bar{Y}. \quad (5)$$

The terms on the right are respectively the monopole and dipole acceleration. A dispersion formula is found by dividing eq. (5) by $k_i^2 - \Omega^2$ and taking the average; it is found to be (after arrangement of terms)

$$-i\omega = \frac{1}{\lambda} \frac{\Omega^2}{k^2 - \Omega^2} \equiv \frac{1}{\lambda} \int dk^2 f(k^2) \frac{\Omega^2}{k^2 - \Omega^2}. \quad (6)$$

$f(k^2)$ is the distribution of squared response frequency.

Our task is to find the appropriate f , accurately evaluate λ , and tabulate the growth rate of instability.

II. Distribution Of Response Frequency

Since f is a distribution we begin by requiring

$$f \geq 0, \quad \int_0^\infty dk^2 f = 1. \quad (7)$$

The integral (6) must be finite, i.e. to gain contact with the usual low frequency limit it is necessary that as $\Omega^2 \rightarrow 0$,

$$-i\omega = \frac{\Omega^2}{\lambda} \int dk^2 \frac{f(k^2)}{k^2} . \quad (8)$$

Hence^{*}

$$f \rightarrow 0 \text{ as } k^2 \rightarrow 0 . \quad (9)$$

The highest response frequency of the beam is the betatron frequency of a particle located near the z axis. Thus

$$k^2 \leq k_m^2 = \lim_{r \rightarrow 0} \left(\frac{e}{\beta \gamma m c^2} \frac{B(r)}{r} \right) . \quad (10)$$

For the Bennett profile⁽¹⁾ the magnetic field is

$$B(r) = \frac{2I(r)}{rc} = \frac{2I}{c} \frac{r/a^2}{1 + r^2/a^2} \quad (11)$$

where $I(r)$ is the current inside radius r :

$$I(r) = \int_0^r dr' 2\pi r' J(r') = I \frac{r^2/a^2}{1 + r^2/a^2} . \quad (12)$$

Eqs. (10) - (12) give

$$k^2 \leq k_m^2 = \frac{2eI}{\beta \gamma m c^3 a^2} \quad (13)$$

The Bennett equilibrium has an isothermal distribution of velocities so only a vanishingly small fraction of particles are localized near the beam axis we let

$$f \rightarrow 0 \text{ as } k^2 \rightarrow k_m^2 . \quad (14)$$

A result of the Vlasov treatment is that the beam displaces rigidly at low frequency:

$$Y_i = \bar{Y} + O(\Omega^2) , \quad (15)$$

* If this condition is not satisfied by f a low frequency limit may exist, but $i\omega$ does not vary as Ω^2 .

this is guaranteed in our model. Since the rigid beam treatment is correct at low frequency, an appropriate average of eq. (5) should reproduce the rigid beam results. It is found to be necessary to divide eq. (5) through by k_i^2 before averaging, this makes sense if the disks are thought of as having distributed mass m_i with $k_i^2 \propto m_i^{-1}$. We have

$$-\Omega^2 \left(\frac{\bar{Y}}{k^2} \right) = -\bar{Y} + (1 - i\omega\lambda)^{-1} \bar{Y} . \quad (15)$$

Expanding eq. (15) in powers of Ω^2 yields, to first order

$$-\Omega^2 \frac{\bar{Y}}{k^2} = -\bar{Y} + (1 + i\omega\lambda) \bar{Y} . \quad (16)$$

To zeroth order the monopole and dipole terms on the right cancel leaving the low frequency dispersion formula (8). However, eq. (16) also shows that the monopole acceleration of the rigid beam model is related to the inverse mean of k^2 . We apply the results of reference (4):

$$\left(\frac{1}{k^2} \right)^{-1} = \left(\text{rigid beam response frequency} \right)^2 = \frac{4\pi^2 e}{m\gamma\beta c^3 I} \int_0^\infty dr r J^2(r) . \quad (17)$$

Expression (1) for the Bennett profile is inserted in eq. (17) to obtain

$$\left(\frac{1}{k^2} \right)^{-1} = \frac{4\pi^2 e}{m\gamma\beta c^3 I} \int_0^\infty dr r \left(\frac{1}{\pi a^2} \right)^2 \left(\frac{1}{1 + r^2/a^2} \right)^4 = \frac{4\pi^2 e}{m\gamma\beta c^3 I} \left(\frac{1}{\pi a^2} \right)^2 \frac{a^2}{2} + \frac{1}{3} = \frac{1}{3} k_m^2 . \quad (18)$$

There being no further obvious constraints* on f , we select an elementary function satisfying those given above, it is

$$f(k^2) = \frac{6}{k_m^2} \left(\frac{k}{k_m} \right)^2 \left[1 - \left(\frac{k}{k_m} \right)^2 \right] . \quad (19)$$

*It is tempting to also require $\overline{k^2}$ to equal the mean square betatron frequency in the beam, which in this case is $k_m^2/2$. No good argument has been found for this condition - the fact that it is satisfied by (19) is a coincidence.

The mean of k^2 and its standard deviation are

$$\overline{k^2} = k_m^2/2, \quad (20)$$

$$\Delta k^2 \equiv \left[\overline{k^4} - (\overline{k^2})^2 \right]^{1/2} = (k_m^4/20)^{1/2} = \overline{k^2}/\sqrt{5} \approx .447 \overline{k^2}$$

III. The Decay Length

The low frequency dispersion formula of the Vlasov and Rigid Beam models is⁽⁷⁾

$$\frac{\Omega^2}{-1\omega} = \frac{4\pi e}{m\gamma I c^4} \int_0^\infty \frac{dr}{r} I^2(r) \sigma(r). \quad (21)$$

Comparison with eq. (8) yields

$$\lambda \left(\frac{1}{k^2} \right)^{-1} = \frac{4\pi e}{m\gamma I c^4} \int_0^\infty \frac{dr}{r} I^2(r) \sigma(r). \quad (22)$$

It is necessary at this point to assume some conductivity profile $\sigma(r)$. Since the beam itself may generate the plasma channel it is natural to take $\sigma(r) \propto J(r)$ and set

$$\sigma(r) = \frac{\sigma_0}{(1 + r^2/a^2)^2} \quad (23)$$

To compare the effects of different profiles the normalization

$$(\text{given constant}) = 2\pi \int_0^\infty dr r \sigma(r) = \pi a^2 \sigma_0 \quad (24)$$

should be observed. Hence the skin length is defined (in invariant fashion) as *

$$\lambda_s \equiv \left(\frac{4\beta}{c} \right) 2\pi \int_0^\infty dr r \sigma(r) = \frac{4\pi \sigma_0 \beta a^2}{c} \quad (25)$$

* We also assume that the radial channel dimension is not much different than that of the beam.

Expression (22) is evaluated to be

$$\lambda \left(\frac{1}{k^2} \right)^{-1} = \frac{4\pi e}{m\gamma I c^4} \int_0^\infty \frac{dr}{r} \left(\frac{I r^2/a^2}{1 + r^2/a^2} \right)^2 \frac{\sigma_0}{(1 + r^2/a^2)^2}$$

$$= \frac{4\pi e}{m\gamma I c^4} \frac{I^2 \sigma_0}{2} \cdot \frac{1}{6} = \left(\frac{4\pi \sigma_0 \beta a^2}{c} \right) \left(\frac{2eI}{\beta \gamma m c^3 a^2} \right) \frac{1}{24} = \frac{k_m^2}{24} \quad (26)$$

Combining (18) and (26) gives

$$\lambda = \frac{1}{8} \lambda_s \quad (27)$$

This decay length is only moderately sensitive to the conductivity profile provided it is not spread far beyond the beam radius. For example let

$$\sigma = \begin{cases} \sigma_0 & 0 < r < a \\ 0 & r > a \end{cases} \quad (28)$$

but retain the Bennett current $J(r)$ then eq. (22) gives

$$\lambda \left(\frac{1}{k^2} \right)^{-1} = \lambda_s k_m^2 \frac{1}{4} \left[\log 2 - \frac{1}{2} \right]$$

and

$$\lambda = \frac{3}{4} \left[\log(2) - \frac{1}{2} \right] \lambda_s = \frac{\lambda_s}{6.903} \quad (29)$$

These values should also be compared with the decay length of the lowest dipole eigen mode⁽⁴⁾ of the channel (28)

$$\lambda_1^{(0)} = \frac{4\pi \sigma_0 \beta a^2}{j_0^2 c} = \frac{\lambda_s}{5.784} \quad (30)$$

where $j_0 = 2.405$ is the first zero of the Bessel function J_0 .

IV. Evaluation of Growth Rate

The distribution function (19) is now inserted in eq. (6) to get

$$\begin{aligned} -i\omega\lambda &= \int_0^{k_m^2} \frac{dk^2}{k_m^2} \frac{6k^2}{k_m^2} \left(1 - \frac{k^2}{k_m^2}\right) \frac{\Omega^2}{k^2 - \Omega^2} \\ &= 6s \int_0^1 du u (1-u) \frac{1}{u-s} \quad , \end{aligned} \quad (31)$$

where $s \equiv \Omega^2/k_m^2$. To compute the integral Ω/k_m is considered to lie in the range (0,1) with small positive imaginary part, so s has the same range. Then we find

$$-i\omega\lambda = 6s \left[\frac{1}{2} - s + (s - s^2) \left(\pi i + \ln \frac{1-s}{s} \right) \right] . \quad (32)$$

The growth rate for real Ω computed from eq. (32) is given in

Table 1 and Figure 1. Note that the range of unstable frequencies is only $0 < \Omega^2 < k_m^2/2$.

TABLE 1

$s = \Omega^2/k_m^2$	$\text{Im}(\omega\lambda)$	s	$\text{Im}(\omega\lambda)$
.00	.00000	.325	.65391
.01	.03213	.350	.61075
.02	.06675	.375	.55063
.03	.10280	.400	.47354
.04	.13969	.425	.37962
.05	.17696	.450	.26910
.06	.21427	.475	.14238
.07	.25133	.500	.00000
.08	.28788	.55	-.32890
.09	.32372	.60	-.71032
.10	.35865	.65	-1.13424
.125	.44088	.70	-1.58732
.150	.51405	.75	-2.05195
.175	.57631	.80	-2.50467
.200	.62617	.85	-2.91282
.225	.66239	.90	-3.22785
.250	.68398	.95	-3.36221
.275	.69015	1.00	-3.00000
.300	.68028		

The peak growth rate is seen to be

$$\text{Max Im}(\omega\lambda) \cong .69 \quad (33)$$

with

$$s = \frac{\Omega^2}{k_m^2} \cong .275 \quad (34)$$

The oscillatory part of ω at this frequency is

$$\text{Re}(\omega\lambda) = -6\pi(s^2 - s^3) = -1.033 \quad (35)$$

In terms of the skin length the maximum growth rate is

$$\text{Max } I_m(\omega) = \frac{.69}{\lambda} = (.69) \frac{8}{\lambda_s} = \frac{5.52}{\lambda_s} \quad (36)$$

If we allow 3 orders of magnitude growth then the maximum length of unmodulated pulse is limited to be less than

$$L_{\text{max}} = \frac{\lambda_s}{5.52} \ln(1000) = 1.25 \lambda_s \quad (37)$$

Other factors not considered above may modify this maximum pulse length- for example the further generation of conductivity within a pulse can change growth from an exponential to algebraic function of x .

It is also important to determine the complex root Ω for given real ω , giving the growth length in the laboratory frame for a beam perturbation driven at fixed z . The solution has been found numerically by James M. Leary and is given in graphical form in figure 2. The point of maximum growth is

$$\begin{aligned} \omega\lambda &\cong -.452, \\ \text{Re}(\Omega/k_m) &\cong .365, \\ I_m(\Omega/k_m) &\cong .1825. \end{aligned} \quad (38)$$

There is no growth if $|\omega\lambda| > 3\pi/4$.

V. Phase Mixing

It is interesting to directly view the phase mixing effect implied by the distribution (19). If a piece of beam is displaced rigidly in the unperturbed field and released, the Y_i oscillate at their respective response frequencies but with a single amplitude (which we set equal to unity here.)

The mean of the displacements, as a function of z is

$$\begin{aligned} \bar{Y} &= \int d(k^2) f(k^2) \cos kz \\ &= \int_0^{k_m^2} d(k^2) \frac{6k^2}{k_m^4} \left(1 - \frac{k^2}{k_m^2}\right) \cos kz = 12 \int_0^{k_m^2} du \left[\frac{u^3}{(k_m^2)^4} - \frac{u^5}{(k_m^2)^6} \right] \cos u. \end{aligned} \quad (39)$$

Setting $k_m z \rightarrow z$ we have

$$\bar{Y} = 12 \left[\cos(z) \left(-\frac{2}{z^2} + \frac{54}{z^4} - \frac{120}{z^6} \right) + \sin(z) \left(\frac{14}{z^3} - \frac{120}{z^5} \right) + \frac{6}{z^4} + \frac{120}{z^6} \right]. \quad (40)$$

The limits of small and large z are

$$\begin{aligned} \bar{Y} &\rightarrow 1 - \frac{z^2}{4} & z &\rightarrow 0, \\ \bar{Y} &\rightarrow \frac{-24 \cos z}{z^2} & z &\rightarrow \infty. \end{aligned} \quad (41)$$

A graph of $|Y(z)|$ is given in figure 3. It is seen that an order of magnitude damping occurs in $k_m z \approx 15$. This result is in fair agreement with simulation (within $\sim 20\%$ in the range $0 < k_m z < 20$.)

VI. Growth Of A Wave Packet

Previously we have only studied the behavior of a pure wave. The general disturbance may be written

$$\bar{Y}(x,z) = \int_{-\infty + i\epsilon}^{+\infty + i\epsilon} d\Omega F(\Omega) e^{-i(\Omega z + \omega x)} \quad (42)$$

with

$$\omega(\Omega) = \frac{i}{\lambda} \int \frac{dk^2 f(k^2) \Omega^2}{k^2 - \Omega^2} \quad (43)$$

The function F is dependent on initial conditions and does not strongly affect the asymptotic behavior of $\bar{Y}$, so it is not specified here.

The maximum values of ω_i and Ω_i found in section IV are used to place limits on the growth of $\bar{Y}$ as a function of x or z . First, the integration (42) may be taken along the real Ω axis, in which case the maximum contribution comes from the point ($\Omega_r = \sqrt{.275} k_m$, $\Omega_i = 0$.) From (33) the bounding growth at fixed x is thus

$$\bar{Y} < \exp(.69x/\lambda) \quad (44)$$

Similarly, the contour of integration of (42) may be deformed to follow the curve of real ω - (see figure 2), and the maximum contribution comes at ($\Omega_r = .365 k_m$, $\Omega_i = .1825 k_m$.) The growth at given z is then

$$\bar{Y} < \exp(.1825 k_m z) \quad (45)$$

We are primarily interested in the growth and decay of a perturbation on a beam of finite length (L). The behavior of a given segment (at fixed $x < l$) as it propagates in z may be followed with a saddle point evaluation. The approximate solution is

$$\bar{Y} \propto e^{-ix(\Omega_0 \frac{z}{x} + \omega(\Omega_0))} \quad (46)$$

where Ω_0 is the solution of

$$\frac{z}{x} = - \frac{d\omega(\Omega_0)}{d\Omega_0} \quad (47)$$

For a single value of z/x we have already solved (47) - this is the point of maximum growth rate with Ω real derived in section IV. The point z at which this is reached is found from the real part of (47):

$$\begin{aligned} \frac{z}{x} &= - \frac{d\omega_r(\Omega_0)}{d\Omega_0} = \frac{6\pi}{\lambda} \left[\frac{4\Omega_0^3}{k_m^4} - \frac{6\Omega_0^5}{k_m^6} \right] = \frac{6\pi}{\lambda k_m} \left[4\sqrt{.275}^3 - 6\sqrt{.275}^5 \right] \\ &= \frac{6.388}{\lambda k_m} \end{aligned} \quad (48)$$

The displacement $\bar{Y}$ at this point is just the limiting value (44).

Hence this is the point of maximum displacement for given x . Eq. (48) may thus be interpreted as defining the orbit of the wave packet of a disturbance.

A simple picture of the evolution a disturbance is as follows. The leading segment damps as shown in figure 3. Subsequent segments with x/λ large grow in amplitude until they pass the point of maximum amplitude (48), then they decay. The larger the value of x , the larger the value of z required for saturation, but the bounds (44) and (45) are always observed. Since the beam length is finite the disturbance ultimately disappears.

FIGURE CAPTIONS

Fig. 1 Growth Rate for real Ω

Fig. 2 Growth Rate for real ω

Fig. 3 Damping of the Mean Displacement

Table 1 Growth Rate for real Ω (Page 9)

FIGURE 1

FIGURE 2

FIGURE 3

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