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BEAM-INTENSITY LIMITATIONS IN LINEAR ACCELERATORS*

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Summary

Recent demand for high-intensity beams of various particles has renewed interest in the investigation of beam current and beam quality limits in linear RF and induction accelerators and beam-transport channels. Previous theoretical work is reviewed, and new work on beam matching and stability is outlined. There is a real need for extending the theory to handle the time evolution of beam emittance; some present work toward this goal is described. The role of physical constraints in channel intensity limitation is emphasized. Work on optimizing channel performance, particularly at low particle velocities, has resulted in major technological advances. The opportunities for combining such channels into arrays are discussed.

Introduction

Beam intensity in a linac is not uniquely limited. "Performance limitations" would be a better title; these depend on the problem definition and the specific constraints under which the problem must be solved. Either quantity (current) or quality (emittance) of the beam, or a combination of both, can determine the channel or output limitation, which may be reached for physics or engineering reasons. The subject is thus very broad--the view chosen here will concentrate on some of the efforts being made to understand in general how beams behave dynamically in straight channels. The influence of this work on specific machine development programs will be indicated, again in general. Further, although the development and use of analytic and simulation tools form the major theme, detailed formulas are not presented. It would be rather easy to get lost in the intricacies of how a "limit" varies with some parameter. A general discussion that outlines major topics, highlights advances, and refers to specific literature for details is in order here. The approach will be to trace chronologically and interweave a few perspectives through the past three years or so, from background, through evolution, to new work.

Background

At the end of 1977, our knowledge of linear accelerator performance limits was summarized at a Los Alamos workshop[1] and in a lengthy bibliography.[2] We will pick up four threads: matched, or equilibrium distributions; the use of envelope equations; the added constraint of stability requirements; and practical methods for approaching the performance limits.

Matched or Equilibrium Distributions

The shape and density of a completely matched beam particle distribution will repeat exactly after each period of a channel. Maximum performance would be achieved with such a beam; but mismatch, instabilities, random errors, or the effect of constraints can degrade actual performance. Lysenko,[3] after carefully considering the plasma properties of linac beams and the theoretical and simulation techniques used in plasma physics, elected to extend the one-degree-of-freedom Hamiltonian approach of Gluckstern to study how the beam's self-forces, from space-charge, interact with the external channel forces to affect the particle distribution.[4] The idea was to start with distributions known to be initially in equilibrium with, or matched to, their surroundings; in this case, time independent, smooth focusing. Then we would systematically make changes to the focusing system (for example, couplings, nonlinearities, time dependence) and study the effects to see if equilibria for these more realistic cases could be developed.

Distributions satisfying $f(x,p) = F(H) \sim n(H_0-H)^{n-1}$ are stationary, or in equilibrium, where H is the single particle Hamiltonian,

$$H = \frac{p^2}{2m} + \frac{k_r\, r^2}{2} + \frac{k_z\, z^2}{2} + e\phi(r,z) \quad , \tag{1}$$

with k_r and k_z representing the external focusing forces and ϕ the space-charge potential. Stable equilibria result if the distributions are monotonically decreasing functions of H. These distributions have the same average kinetic energy in the transverse and longitudinal directions. The distribution parameters can be normalized to three variables: the distribution order n (n=2 is quite realistic); the ratio of longitudinal to transverse-force constants, describing the accelerator; and μ, a weighted ratio of r and z space-charge defocusing to external focusing forces. Specifying the number of particles and the length scale for external forces relates the distribution to a real machine, current, and phase advance per focusing period σ (with current), or σ_0 (without current). Current-limit formulas can then be written, from which we found that if maximum current is the goal (disregarding emittance), then higher injection energy and lower operating frequencies are favored; but if high brightness is the goal, the maximum current achievable for a fixed transverse emittance favors higher frequency linacs, and depends weakly on injection energy. This result confirmed numerical experiments,[5] and was considered very surprising at the time. Lysenko's paper also shows how the same parametric behaviors are derived from simpler, uniformly charged sphere models. The results were applied to the LAMPF and agreed reasonably well with experimental data; predictions that a higher brightness source would improve operation were later proven true. Lysenko proceeded to write particle-tracing codes in which to study other systems, using these distributions as input.

Envelope Equations

Another approach to limits in periodic channels uses the famous KV model,[6] from which a linearized and self-consistent envelope equation can be derived for a beam with uniform particle density. Sacherer[7] showed that more general rms envelope equations can be derived for bunched or continuous ellipsoidal beams with arbitrary charge distribution, with the major restriction being that the time dependence of the rms emittance ϵ is constant or known. For linacs, equations for both transverse and longitudinal motion are needed, of the form:

$$\ddot{a} + (\sigma_0^t)^2\,(1-\mu_t)a = (N\beta\lambda)^2\,\epsilon_t^{\,2}/a^3 \quad ,$$

$$\ddot{b} + (\sigma_0^\ell)^2\,(1-\mu_\ell)b = (N\beta\lambda)^2\,\epsilon_\ell^{\,2}/b^3 \quad , \tag{2}$$

where $(\sigma_0)^2(1-\mu) = \sigma^2$, and the μ's are functions of the beam current, the dimensions a and b, and other parameters. For present purposes, we assume a, b, and ϵ are rms quantities; they can be related to total values for known distributions. For matched beams, $\ddot{a} = \ddot{b} = 0$. Design equations, readily derived from the envelope equations, were being used to make parameter choices,[8-10] and as the basic design approach for the new CERN linac.[11] In the early discussions of heavy

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ion fusion[9] (HIF), debate had arisen because there seemed to be different "scaling laws" having opposite dependencies on some parameters.

Stability considerations

The envelope equations are also incomplete in that they do not include instabilities from nonlinear effects. At LBL, studies on the KV beam, ignoring acceleration, found many regions of instability.[12] A parametric envelope resonance with an alternating-gradient focusing-channel's period occurred when $\sigma_0 > 90°$ and $\sigma \sim 90°$. For $\sigma_0 < 90°$, the quadratic disturbing potential case was stable. Higher order perturbations showed isolated stability regions for lower currents, and finally, a continuously unstable regime as the current was raised. A remarkable feature--discovered empirically and still not understood (see remark below) showed that the instability continuum at each order set in at almost exactly the same tune depression (near 0.4). This occurred without dependence on σ_0, whether the system was continuous or interrupted solenoid or quadrupole.

Practical developments

Manca[4] discussed a Soviet[13] structure that seemed to have very high-capture efficiency for low-velocity dc beams and to produce bunched beams with little emittance growth. We became excited about the idea that this new circuit, the radio-frequency quadrupole (RFQ), would allow gentle manipulation of a beam from continuous to bunched-and-accelerated, while at the same time the particle distribution remained nearly matched to, or in equilibrium with, the structure. Similar "near-adiabatic" beam handling was being considered for induction linacs.[12]

Evolution

In January 1978, Mittag[14] published a very useful compendium unifying the analytical beam-dynamics design of linacs. In a key paper later in the year, Reiser[15] clearly showed why different scaling laws had been derived. He rigorously derived general formulas for the transportable current in a periodic channel, using the smooth approximation, showing:

$$I = \frac{I_0}{2} \beta^3 \gamma^3 \frac{\sigma_0}{S} \alpha \left[1 - \left(\frac{\varepsilon}{\alpha}\right)^2 \right] ; \left(\frac{\varepsilon}{\alpha}\right)^2 = \left(\frac{\sigma}{\sigma_0}\right)^2 = 1 - \mu , \quad (3)$$

where α is the channel acceptance, $I_0 = 1.7 \times 10^4$ A for electrons and 3.1×10^7 A/Z for ions. The lattice period is S. He applied this result in detail to quadrupole and solenoidal channels. In discussing the theory's validity, and the scaling laws, he stated that:

- Except for the continuous solenoid, there is no simple, generally valid scaling law explicitly relating beam current to all experimental parameters.
- The form of the scaling law depends on σ_0 and the constraints imposed by the designer. For example, he discussed the scaling law resulting from holding σ_0 constant, and with a lower limit on σ/σ_0, which might be necessary from stability considerations. If technical constraints such as bore size, achievable voltage or field are included, the equations have different forms. This can be extremely confusing if the assumptions are not stated explicitly.

Late in 1978, we had the opportunity to compare experimental results from the new CERN linac first tank to predictions and were able to bracket the observed emittance growths by including input mismatch and off-axis central trajectories in the simulations.[16] Different characteristic patterns in curves of emittance vs percentage of beam result from each type of error. The importance of careful matching and steering, and the difficulties of doing this in practice, were emphasized by this work and by experience at LAMPF. Unfortunately, complete and conclusive sets of experiments have not been possible at either facility, because of operational demands.

At the 1979 PAC, a number of important results were presented. In work that included acceleration, Lysenko (in a particle-tracing code), subjected his initial Hamiltonian distributions to slowly varying parameters, with uncoupled, linear, harmonic oscillator, external restoring forces in all three directions, allowing coupling and nonlinearities only through the space charge.[17] Even near the space-charge limit ($\mu > 0.95$), the beams were well behaved. Although the emittance of mismatched beams did not grow, the increase in spatial dimensions indicated that effective emittance growth from filamentation would occur when external nonlinearities were added. He then localized the longitudinal forces to gaps, making the longitudinal focusing discrete and the effective potential nonlinear. Phase damping was the same as before, a small increase in transverse emittance was observed, and the longitudinal emittance increased from filamentation. The input beam had been matched to the harmonic smooth case. He prepared to study matching procedures that took the nonlinearities and external couplings into account.

An LBL/NRL/NBS collaboration[18-20] found isolated instabilities for the KV transport beams and proved that computer simulation codes gave the growth rates predicted by the theory. Hofmann[21] reported initial results from his fluid model analyses. A new "conservative design window" for transport-channel design evolved: set σ_0 no higher than 60°, to avoid a KV body mode, and keep $\sigma/\sigma_0 > 0.4$, to avoid the unstable continuum observed for KV beams. Their work turned to consideration of more realistic distributions, whose behavior appeared to be less pathologic (both from many computer simulations and on fundamental plasma-physics grounds).

We noted[22] the distortion of transverse emittance caused by longitudinal-to-transverse RF gap coupling when space charge is present, and used the envelope equations to discuss a possible lower bound on output emittance. Another thread also was woven in: how neutralization might play a part in raising the current limits in both transport and accelerator design.[23-25]

At the 1979 Linac Conference, Weiss[26] discussed the CERN design philosophy. Also, the rapidly evolving analytical modeling and particle-code simulations for the RFQ were discussed in detail.[27] A remarkable property of the RFQ bunching scheme was becoming clear: the current limit does not occur at the dc injection energy, as is usual in a drift-tube linac having a simple conventional buncher. Instead, it occurs at the end of the bunching process, where the energy has increased about ten times, with correspondingly higher current limits. Wangler has used the analytic formulas to write very accurate design programs for RFQ's; his later report,[28] rederives the basic space-charge limit equations and delineates many useful relations for all types of linac channels.

Accelerator design strategy has to consider the transverse and longitudinal limits and matching simultaneously, and the coupled envelope equations are a good guide. For example, in the RFQ, where the electrostatic field is the source of both focusing and acceleration, Wangler shows (Fig. 1) these two limits and excellent agreement with simulation results. As indicated in Eq. (3), the input emittance must be smaller than the channel acceptance. The analytical limit is set

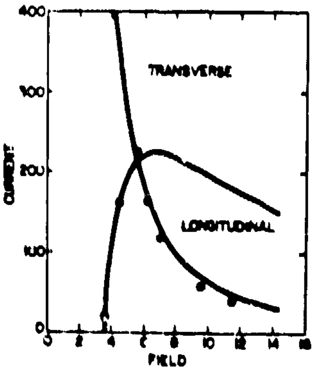

Fig. 1. Typical RFQ current-limit diagram.

by $\varepsilon/\alpha = \sigma/\sigma_0 = 0.4$. The simulation limit is the saturated output current that results when the input current is increased, holding the input emittance constant, but rematching. At the limit, more than half the input current is lost along the channel. Simulations also showed that the limiting transverse emittance under these conditions (for Wideröe and Alvarez, as well as RFQ channels) is determined by the channel acceptance and agrees with the value computed from envelope equations with $\sigma/\sigma_0 \sim 0.4$ at the appropriate bottleneck. At the 1979 HIF workshop,[29] we emphasized that care must be taken to distinguish between current-limit estimates, where particle loss is allowed in the channel, and estimates where no loss is allowed.

I also discussed preliminary numerical investigations of emittance growth in short accelerator sections using σ and σ_0 as the parameters, and included effects of mismatch and steering errors.[30] Using least-squares techniques, I can compute the actual phase advance and matched ellipse parameters in a full PARMILA simulation for any particle distribution, and adjust the focusing parameters to achieve a desired focusing law along the machine. The presence of envelope instabilities* at σ_0 above 90° was verified for accelerators.

At BNL, Maschke's insight into the scaling relationships, and his knowledge that high-voltage gradients can be applied across small gaps, led him to consider very small aperture channels arranged in arrays for high-brightness ion beams.[31] These intriguing circuits, called MEQALAC's, are being tested at BNL, and progress will be reported by others at this conference. Arrays are a natural way to beat the current limit in one channel, where performance probably can't be improved above $\mu = 0.9$, say, without exhorbitant effort. The problem becomes one of circuit design, and arrays of Wideröes, RFQs, or electrostatic channels for HIF induction linacs are now actively under consideration.[32] In the present LBL HIF thinking, the channels may be separated through the entire machine to 10 GeV. In the RF linac approach to HIF, channels would be combined by funneling into channels operating at twice the preceding frequency, as soon as the space-charge limit permits. Detailed work on this process has yet to be done, but it is believed it would be possible without significant brightness dilution.

Continuing with results of the past year, Particle Accelerators contains a number of important papers, including consideration of the current limits in recirculating electron linacs, where completely different problems from transverse cavity modes occur.[33] Even here, however, the thread of detailed matching persists in specific selection of beam-orbit optics to enhance perperformance. Hofmann[34] discusses emittance growth as collective instabilities caused by nonmonotonic distribution functions, anisotropy between degrees of freedom, or nonlinear resonances. He predicts that anisotropy affects rms emittance above a threshold, which agrees with my numerical observations on drift-tube linacs (Fig. 2). Plasma oscillations play a dominant role, explained in terms of + and - energy oscillations, which release free energy, finally saturating nonlinearly. Most growth goes into velocity spread, rather than into the physical dimensions of the beam.

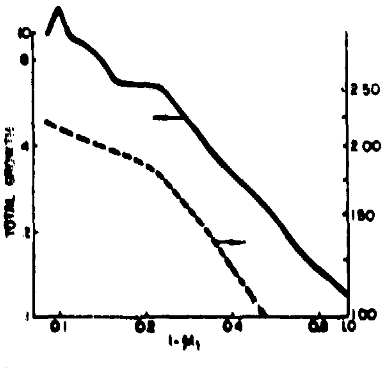

Fig. 2. Emittance growth in 72-cell, constant $\sigma_0^t = 60°$, constant E_0 drift-tube linac; $(\varepsilon_\ell/\varepsilon_t)$initial = 5.65.

Some New Results

Transport System Limits

Hofmann and Haber[35] have found cases where $\sigma_0 = 60°$ quadrupole or solenoid transport systems (with no external nonlinearities or couplings) show no rms emittance growth for KV or non-KV distributions even for 0.1 tune depressions. The KV quickly changes to a monotonic distribution. Total effective emittance does grow. Lapostolle's argument[36,12] for potential well flattening from plasma shielding is confirmed in these simulations and by Lysenko's recent works.

Envelope Equations Plus Equipartitioning

I have recently extended drift-tube linac simulations, with different σ_0^t, σ^t, or μ^t focusing laws, out to several betatron wavelengths. The envelope equations are useful predictors, but need to be augmented to handle changing emittances. We now have a little more insight into how this might be done. Reserving the question[30] of how to properly balance emittance between planes, I, along with most previous authors, had used injected beam phase spreads nearly equaling the synchronous phase, because narrow spreads are hard to achieve with conventional bunchers. Properly matched to the correct energy spread, the resulting longitudinal emittance is usually larger than the achievable transverse emittance. My simulations clearly show balancing of the rms anisotropy (Fig. 3).

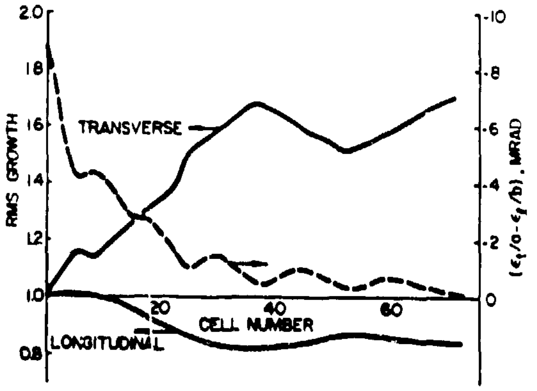

Fig. 3. Rms emittance growth and $(\varepsilon_t/a-\varepsilon_\ell/b)$ in constant E_0 linac. Initial $\mu^t \sim 0.75$, $\mu^\ell \sim 0.55$, $\varepsilon_\ell/\varepsilon_t = 5.65$.

Using simple energy-balance arguments, we showed the requirement

$$\varepsilon_t/\varepsilon_\ell = \sigma^\ell/\sigma^t = a/b \tag{4}$$

Matching using Eq. (2) requires $\varepsilon_t/\varepsilon_\ell = a\sigma^t/b\sigma^\ell$. A full linac with constant $\mu_t \sim 0.9$ was generated, using an input beam satisfying these conditions simultaneously. The required $\varepsilon_t/\varepsilon_\ell$ for the parameters chosen was 0.96, and the remarkably small emittance growth shown in Fig. 4 resulted. An $\varepsilon_t/\varepsilon_\ell = 1/1.5$ using only the matching equations, Eq. (2), resulted in transverse rms emittance growth and longitudinal decrease, whereas an $\varepsilon_t/\varepsilon_\ell = 1.5$ showed the opposite effect. We suspect that a simple exponential model

$$\varepsilon_t' = -\sigma\left(\frac{\varepsilon_t}{a} - \frac{\varepsilon_\ell}{b}\right) + \kappa\,(\varepsilon_t + \varepsilon_\ell)\ ,$$

$$\varepsilon_\ell' = \sigma\left(\frac{\varepsilon_t}{a} - \frac{\varepsilon_\ell}{b}\right) + \kappa\,(\varepsilon_t + \varepsilon_\ell)\ , \tag{5}$$

might account for much of the effect, where the first term models the equipartitioning and the second covers residual growth from other nonlinear resonance or dispersion effects. Gluckstern has derived a model[37] based on coupled motion near a resonance

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*Not Rayleigh-Taylor, mistakenly blamed at the time.

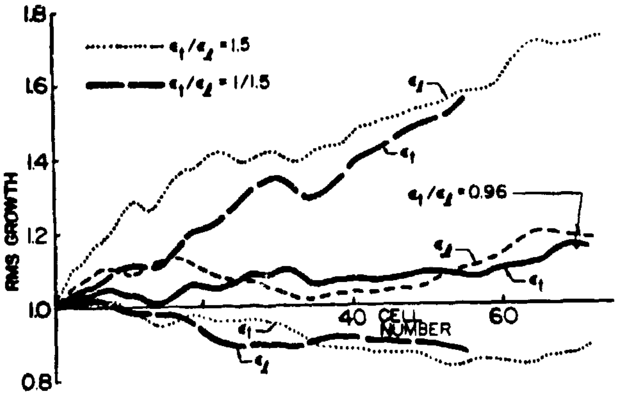

Fig. 4. Rms emittance growth in 72-cell, constant $\mu^t = 0.9$, constant E_0 linac. Initial $\mu^\ell \sim 0.8$.

that has this form on the average, with an "inverse mean time" to approach equilibrium given by

$$\sigma_{ep} = C_1 \sigma_0^t \sigma_0^\ell \, (\mu_t \mu_\ell / \sigma^t \sigma^\ell)^{1/2} \quad , \qquad (6)$$

where C_1 depends on the form of the particle distribution and the mode number. Numerical integration of Eqs. (2) and (5), given initial conditions and the σ_0 laws, models the exponential character quite well. We are considering the addition to Eq. (5) of coupling terms oscillating at the plasma frequency, because residual mismatch energy release thorough plasma oscillation has a strong effect during the first betatron period or so.

Matched Distributions

Our equipartitioning argument requires equal velocity spreads in all directions, also implicit in Lysenko's Hamiltonian initial distributions. In his paper at this conference,[38] he numerically transforms a matched initial distribution, without space charge, through a system that starts with smooth focusing and ends with full alternating-gradient transverse focusing and gap acceleration. Particular external nonlinearities and nonlinear couplings are included. The resulting distribution is matched; that is, it is periodic with the period of the continued structure. The projected emittances are nearly constant, and the sum of the projections is very nearly constant. This latter conservation law is interesting, because it could not be predicted for more than one degree of freedom. The result is important, because the formulation makes it clear that the addition of space charge, if done in full 3-D, will not change the answer. It may be hard to thread through the resonances, but we should be able to see for the first time what a beam fully matched in 6-D really looks like. Adiabatic formation of distributions has been studied also by Haber,[19] who raised the current in a cylindrical beam through an instability threshold, allowed the growth to saturate, ramped the current back down, and found the resulting distribution behaved better when reinserted. Most important, we believe we are using all these ideas practically, in the RFQ for example, and can now envision that understanding of this approach can be so applied.

3-D Simulations

How to do 3-D space-charge computations? It turns out that we have a good lead for the two geometries of interest--round pipes and RFQ's. At this conference[39] Lysenko will describe algorithms, which appear to be both accurate and computer efficient, although large machines are still obviously required. These subroutines will be embedded in Lysenko's particle-tracing codes and in PARMILA. The method also handles image forces for off-axis beams, another possible problem area in terms of current limits, which are difficult to treat analytically. This progress is truly exciting, for we did not believe six months ago that we might be able to begin true 3-D work so soon.

Other Aspects

Breakthroughs also have been made recently on the stability analysis of long beam bunches in ion induction linacs;[40] density waves in finite length bunches appear to be only weakly unstable. Although envelope equations (confined to induction linac practical constraints) are useful, much work remains to be done to understand their limitations. The LBL team is pursuing both analytical and simulation development.

We alluded to neutralization as a method for raising the current limit far beyond the usual space-charge limit. Humphries' Pulselac[41] deserves close attention; he has accelerated 3 kA of carbon ions, perhaps 10^4 times the unneutralized limit, through 5 gaps to 600 keV; and is now building a 16-gap machine designed to take 5 kA of ions, in 50-ns pulses, from 100 keV to 4 MeV.

Another area we haven't touched, although it is related to "adiabatic formation" of distributions, is the transient case. The RFQ buncher never reaches any kind of steady state. As an example of maximum performance from a short linac, Stokes has described[42] a 2.4-A deuteron RFQ (per channel) from 0.2-1.0 MeV for fusion heating.

Many experimental programs now are aimed at testing the latest ideas and technical constraints. An electron beam-transport experiment at U. Md.,[43] and a Cs^+ beam-transport line at LBL[44] are being set up to study a wide range of σ_0 and σ in transport systems. High-brightness and high-current/low-loss accelerator prototypes are being built at Los Alamos.[45] ANL will test current limits in Wideröe structures,[46] and BNL in MEQALAC's.[31] A particularly important constraint is the attainable electric field; at Los Alamos we are pushing our designs toward twice the Kilpatrick limit.[14]

Will we ever understand the "limits?" Probably, in the sense that each new machine will press the art; but probably not in detail. We will require complicated techniques of nonlinear dynamics,[47] plasma physics, and turbulence theory[48] to help us understand, especially in the problem of beam-loss prediction. At Los Alamos, P. Channell has developed a lengthy and elegant functional theory of emittance growth from mismatches, using the techniques of nonlinear dynamics. The theory starts by describing the matched solution over a structure period. The match is perturbed and the time-evolution of the mismatch is developed to the scale of the plasma period. A result shows that the 3-D and time-dependent parts of the problem wind up in the driving term of a linear fast-term, partial differential equation, which may be worthy of study. The appropriateness of the cold-fluid model on this time scale is shown, and it is seen that coherent plasma oscillations will disappear, with time, in a system of finite resolution; but that the energy from them appears in coarse-grained rms velocity growth. He then expands the fluid-model solution to explore times out to one betatron period, and we can see how the betatron motion damps the plasma oscillations. The introduction of emittance projections seriously complicates the theory, but he succeeds in making some asymptotic predictions. It has been pointed out[49] that extension of this theory to the next order--a hard job--might justify the smooth approximation and show why the onset of the KV instability continuum is the same for different systems. This theory is formidable. The insights it gives are valuable in themselves; it is too early to know if we will succeed in making useful numbers from it, but it is exciting to try.

Another semiphenomenological model has been proposed at LLL[50] for emittance growth in intense beams launched near self-pinch equilibrium or for cold beams launched in near-ballistic condition. Suitably modified for beam transport or accelerator systems, this approach might also be a valuable design tool.

Conclusion

- Useful equations have been developed and specialized to various machines. Clear papers outlining their use are available (esp. 14,15,28). Use them carefully, for they are not the whole answer. Your problem may have different requirements or different constraints. The limits are not very useful in considering beam losses, except in a frame-work of safety factors.
- New options need to be explored that use varying parameters along the channel or "transient" sections. Integration of the coupled[50] envelope and equipartitioning equations, or of the LLL model may prove useful in exploring these cases. The current limits will be a moving target.
- After you know what you want the channel to do, design the circuit to provide the fields. It may be an RFQ, an electrostatically focused channel, Alvarez, Wideröe, or something new. You may need an array.
- Watch the new developments. Successful use of neutralization or a successful collective-effect accelerator will change everything.

Acknowledgment

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