# PHYSICS DESIGN OF LINEAR ACCELERATORS FOR INTENSE ION BEAMS*

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## Abstract

Advances in the physics and technology of linear accelerators for intense ion beams are leading to new methods for the design of such machines. The physical effects that limit beam current and brightness are better understood and provide the criteria for choosing the rf frequency and for determining optimum focusing configurations to control longitudinal and transverse emittances. During the past decade, the use of developments such as the radio-frequency quadrupole, multiple beams, funneling, ramped-field linac tanks, and self-matching linac tanks is leading to greater design flexibility and improved performance capabilities.

## Introduction

Many advances in the technology of high-current rf linear ion accelerators have occurred over the past decade. Potentially, these advances can produce brighter beams and reduced particle losses, thereby allowing the high currents required for many new applications.

The design of high-intensity linacs is strongly influenced by the requirement to provide sufficient beam focusing (confinement) to balance the effects of space-charge forces. Transverse focusing is provided by electric or magnetic lenses, which can be arranged in a quasi-periodic array. Quadrupole focusing, where the polarity is alternated to produce an overall linear focusing force, is most common. Longitudinal focusing is obtained on the rising rf accelerating field, where nonsynchronous particles receive a restoring force.

At present, the conventional high-current rf ion-linac configuration (Fig. 1) begins with a dc injector and is followed by the radio-frequency-quadrupole (RFQ)[1,2] linac, used to bunch and accelerate the beam from 100 keV or below to a few MeV for protons. The RFQ uses the rf electric-quadrupole fields of the cavity to provide strong transverse focusing for low-velocity particles. To maintain the acceleration efficiency and tranverse focusing at higher energies, the drift-tube linac (DTL) with magnetic quadrupole lenses within the drift tubes becomes a better choice. The development of high-gradient permanent-magnet quadrupoles[3] has resulted in even stronger transverse focusing in the DTL. The RFQ-to-DTL transition can occur at a few MeV for a proton beam. At much higher energies, the rf-power efficiency of the DTL decreases below that of a class of accelerating structures called coupled-cavity linacs (CCL).[4] The transition from DTL to CCL becomes attractive by about 100 MeV for a proton linac. Because the beam-physics issues are not fundamentally different for the CCL than for the DTL, the discussion in this paper will concentrate on the DTL.

The self-field forces between beam particles in high-current linear accelerators produce two undesirable effects: (1) defocusing and (2) rms emittance growth.[5-7] These effects impose limits for both the peak and the average beam current.[8] The peak current is limited by several effects[9,10] including (a) collective instability[11] driven by periodic focusing lenses, (b) attainable external focusing fields, and (c) higher multipoles and other nonlinear aberations at large beam radii. In addition, the average beam current may be limited in practice by particle losses that are caused by emittance growth and formation of an outer beam halo. These particle losses can produce an increased heat load, vacuum degradation, peak surface field reduction, and radioactivation of the structure that would make routine maintenance very difficult.[12]

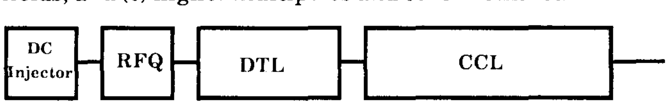


Fig. 1. Block diagram of an ion-linac configuration for high beam-current applications.

The emittances[13] (2-D phase-space areas occupied by the beam) are important beam properties that must be controlled in the design of a high-intensity linear accelerator. Generally, small emittances are desirable for two reasons: (1) for fixed focusing strength, smaller emittance implies a reduction in the beam size, and at fixed aperture, a larger beam-current capacity, and (2) some applications place constraints on the output beam optics that require a high-current beam with a small emittance. But even when Liouville's theorem is satisfied in 6-D phase space (when a collisionless system exhibits continuity of flow in phase space and dissipative forces are absent), nonlinear forces and coupling can cause increases in the effective emittances. A useful measure of effective emittance is the rms emittance,[14,15] which can be defined in terms of the second moments of the particle distribution. Generally, most transverse emittance growth occurs at low velocities,[8] where focusing is weaker and the injected dc beam becomes bunched. However, longitudinal emittance growth can persist up to high energies[16] unless the longitudinal focusing strength is maintained at high values.

The beam dynamics design is carried out with the aid of computer codes like PARMILA[17] and PARMTEQ[18] to simulate the performance, including the space-charge effects. However, a linac designer cannot afford to rely completely on such codes for several reasons. First, the code can provide little a priori guidance for choosing the many parameters that characterize the complete accelerator. Second, uncertainties always exist because of various physics approximations, and because a practical simulation involves no more than $10^5$ computer particles to represent perhaps $10^9$ particles in a linac bunch. Therefore, additional information derived from both experimental and theoretical studies is necessary to identify general design criteria and to confirm the validity of the codes.

For applications where the demand for total beam current, or for beam current within a given emittance, exceeds the capacity of either the ion source or a practical single-channel linac, a multiple-beam linac[19] system is required. The new technique of beam funneling[20] can be used to combine pairs of bunched rf-linac beams and reduce the complexity of the linac system by restricting the multiple-beam solution to only the lowest energies.

The combination of improved single-channel linac design procedures, together with the parallel development of multiple-beams and funneling, provides the linac designer with new guidelines and tools, as will be described further in this paper.

## Physics Issues

In a smooth approximation, periodic focusing produces an equivalent continuous focusing force, upon which is superimposed the local effect of the individual lenses. When space-charge forces can be ignored, the smoothed transverse oscillation frequency $\omega_{t0}$ is given by $\omega_{t0}^2 = \omega_f^2 - \omega_{\ell 0}^2/2$, where $\omega_f^2$ is the lens focusing term and $\omega_{\ell 0}^2/2$ represents the linear defocusing term from the transverse rf fields. The quantity $\omega_{\ell 0}$ is the zero-current longitudinal-oscillation frequency to be discussed later.

A simple formula for $\omega_f^2$ is obtained by assuming a hard-edged strength profile in a periodic lens array and approximating the profile function by the first term of the Fourier series. The single particle equation of motion can

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then be approximated by the Mathieu equation, for which the smooth-approximation solution can be written, and the frequency $\omega_f$ can be obtained.[10] The squared frequencies are proportional to an effective average focusing force, and results for both electric and magnetic quadrupole lenses, based on the assumption that every drift tube contains a lens, are given in Table I. The quantities in Table I are

TABLE I

SQUARED OSCILLATION FREQUENCIES, $\omega_f^2$

| Lens Type | $\omega_f^2$ |
|---|---|
| Electric quadrupoles | $\frac{1}{8\pi^2}\left(\frac{q\lambda G_E X}{\gamma mc}\right)^2$ |
| Magnetic quadrupoles | $\frac{1}{8\pi^2}\left(\frac{q\beta\lambda G_M X}{\gamma m}\right)^2$ |

defined as follows: q and m are the beam-particle charge and mass, $G_E$ and $G_M$ are the electric and magnetic gradients, $\beta c$ is the beam velocity, $\lambda$ is the rf wavelength, and $\gamma$ is the relativistic mass factor. The sequence of focusing (F) and defocusing (D) lenses is identified by a focusing lattice index N. The quantity N is the ratio of the focusing period to the rf period; therefore, for a conventional DTL, N = 2 corresponds to an FD lattice, N = 4 corresponds to FFDD, and so forth. The filling factor of the lens within a cell is $\Lambda = \ell/\beta\lambda$, where $\ell$ is the effective length of the lens. The quantity X is a quadrupole focusing efficiency, which depends on N and $\Lambda$, as shown in Table II for values up to N = 6.

TABLE II

DTL QUADRUPOLE FOCUSING EFFICIENCY VERSUS LATTICE INDEX

| N | DTL Lattice | X |
|---|---|---|
| 2 | FD | $(8/\pi)\sin\pi\Lambda/2$ |
| 4 | FFDD | $(16\sqrt{2}/\pi)\sin\pi\Lambda/4$ |
| 6 | FFFDDD | $(48/\pi)\sin\pi\Lambda/6$ |

For the RFQ, the value of $\omega_f^2$ is given by the electric quadrupole expression in Table I using N = 1; however, the RFQ does not focus with discrete quadrupoles, so X is not obtained from Table II, but is determined by the RFQ vane geometry.[2] For the DTL with quadrupole focusing, there is considerable flexibility in varying the effective focusing force, even for fixed quadrupole gradient and length, because X increases with N. The value of N can be increased up to a limit determined by the envelope instability, which can occur when the zero-current transverse phase advance per focusing period $\sigma_{t0}$ exceeds 90°, where $\sigma_{t0} = \omega_{t0} N\lambda/c$. When $\sigma_{t0}$ is fixed and the quadrupole length and gradient are not at their maximum values, larger $\omega_f^2$ values are obtained by increasing G or $\ell$ and, simultaneously, decreasing N. The approximate nonrelativistic scaling of $\omega_f^2$ with respect to $\beta$ can be seen by inspection of the formulae in Table I. For a constant filling factor $\Lambda$, $\omega_f^2$ is independent of $\beta$ for electric quadrupoles and proportional to $\beta^2$ for magnetic quadrupoles. For constant length lenses, $\omega_f^2$ decreases with $\beta$ for electric quadrupoles. For magnetic quadrupoles, $\omega_f^2$ still increases with respect to $\beta$ for constant length and constant gradient lenses, becoming independent of $\beta$ as $\Lambda$ approaches zero, according to the formulae.

The longitudinal focusing from the sinusoidal rf field is nonlinear, but for particles near the synchronous particle, it is approximately linear and produces phase oscillations about the synchronous particle with a frequency given by $\omega_{\ell 0}^2 = 2\pi q E_0 T(-\sin\phi_S)/m\gamma^3\beta\lambda$, where $E_0$ is the axial accelerating field, averaged spatially over a cell, T is the transit time factor, and $\phi_S$ is the synchronous phase ($-90° \le \phi_S \le 0°$ for phase-stable acceleration). In conventional designs of drift-tube linacs, $E_0$ and $\phi_S$ are often constant throughout the linac, while the variation of T with respect to $\beta$ is weak and usually tends to decrease at high energies. Consequently, $\omega_{\ell 0}^2$ tends to decrease with respect to $\beta$, which results in a slow longitudinal expansion of the bunch. This expansion reduces the transverse space-charge force but may have undesirable consequences for control of longitudinal emittance, as discussed later in the paper.

The necessary focusing strengths depend upon the requirements for peak current capacity and for control of emittance. The peak current is limited by the focusing available to confine a space-charge defocused beam with finite emittance to within the given radial aperture R. Approximate current limit formulas have been derived using a uniform-ellipsoid model to calculate the space-charge force. The transverse and longitudinal current limits, $I_t$ and $I_\ell$, are given by[10,21]

$$I_t = \frac{4\varepsilon_0 c\gamma^3 m}{3[1-f(p)]e\psi_f}\,\beta|\phi_S|R^2\omega_{t0}^2[1-\varepsilon_t^2/\varepsilon_{t0}^2]\,, \tag{1}$$

and

$$I_\ell = (2\varepsilon_0 c/\psi_f^{\frac{1}{2}})\,\beta E_0 T R \phi_S^2 |\sin\phi_S|\,[1-\varepsilon_\ell^2/\varepsilon_{\ell 0}^2]\,. \tag{2}$$

where $\varepsilon_0$ is the permittivity of free space, $\psi_f$ is a flutter factor, and f(p) is an ellipsoid form factor. Other quantities in Eqs. (1) and (2) include the transverse emittance $\varepsilon_t$, longitudinal emittance $\varepsilon_\ell$, and zero-current acceptances $\varepsilon_{t0}$ and $\varepsilon_{\ell 0}$ for the transverse and longitudinal degrees of freedom. Approximate formulas for the normalized acceptances are $\varepsilon_{t0} = \gamma\omega_{t0}R^2/c\psi_f$, and $\varepsilon_{\ell 0} = \gamma\omega_{\ell 0}(\beta\lambda\phi_s)^2/4\pi^2 c$. The decrease of current limits with increasing emittance reflects a competition between the space-charge and emittance terms within the available aperture. These current limits show an increase with $\beta$ because of the assumption that the maximum bunch length is proportional to $\beta\lambda$. Additional strong $\beta$ dependence associated with the magnetic focusing force may enter the transverse current limit through the quantity $\omega_{t0}$.

A deterioration of the beam quality as a result of rms emittance growth has been observed both in numerical simulation studies and in experimental measurements.[22] Two important emittance-growth mechanisms have been identified for high-current/low-emittance rms matched beams with linear external focusing:[6,7] (1) charge redistribution toward a quasi-uniform density, which occurs in about one-quarter of a plasma period and results in a transfer of space-charge field energy to particle kinetic energy and (2) kinetic-energy exchange toward equipartitioning. These mechanisms are sometimes described as internal mismatch. The results in published literature are consistent with the conclusion that the envelope instability in periodic focusing systems can be avoided by restricting the quantity $\sigma_{t0}$ to values below 90°.[7]

Design procedures for RFQ linacs have generally been effective in controlling transverse emittance growth. For an RFQ, this emittance growth occurs (while many parameters—energy, accelerating field, and synchronous phase—are changing) while nonlinear external forces act, especially in longitudinal space, and while the beam is being bunched. The nonlinear field-energy theory has yielded a useful semiempirical formula[7] for transverse emittance growth in the RFQ, given as

$$\varepsilon_f^2 = a_1\varepsilon_i^2 + a_2\,\frac{\lambda^2}{\sigma_{t0}^{2/3}}\left(\frac{q\hat{I}}{mc^2}\right)^{4/3}, \tag{3}$$

where $\varepsilon_i$ and $\varepsilon_f$ are the initial and final normalized emittances, $\hat{I}$ is the current limit, and $a_1$ and $a_2$ depend on the design procedure, which affects the bunching of the beam. Equation (2) implies that high frequency and strong focusing are important to minimize transverse emittance growth in an RFQ.

To formulate some useful design procedures for a high-current DTL, we refer to the nonlinear field-energy theory to provide some guidance. For the transport of rms-matched spherical bunches in a linear continuous-focusing channel and in an extreme space-charge limit, the final rms-normalized emittance $\varepsilon_f$ from the charge-redistribution mechanism can be written nonrelativistically as[23]

$$\varepsilon_f^2 = \varepsilon_i^2 + \left(\frac{a^2\omega_p}{3c}\right)^2 U_{ni}\ , \tag{4}$$

where $\varepsilon_i$ is the initial rms-normalized emittance, $a$ is the rms beam radius, $\omega_p = \sqrt{nq^2/\varepsilon_0 m}$ is the plasma frequency of the equivalent uniform density bunch that has the same rms beam radius, and $U_{ni}$ is the initial nonlinear field-energy parameter of the beam. The equivalent beam density is given by $n = 3N_b/20\sqrt{5}\,\pi a^3$, where $N_b$ is the number of particles per bunch, related to the average beam current $I$ by $N_b = I\lambda/qc$. When these relationships are substituted into Eq. (4), we obtain

$$\varepsilon_f^2 = \varepsilon_i^2 + q I \lambda a U_{ni}/60\sqrt{5}\,\pi\varepsilon_0 mc^3\ . \tag{5}$$

Equation (5) shows that for the same beam current, initial emittance, and particle distribution (through $U_{ni}$), emittance growth does not increase with beam density, but that large beams have a greater space-charge-induced emittance growth from charge redistribution than do small beams. Thus, to control emittance growth, one must provide strong focusing to keep the beam small. Furthermore, Eq. (5) shows that the emittance increase at a given beam size is less at high frequencies, a result that appears because a high-frequency linac has less charge per bunch for a given (average) current. This suggests that high-current, low-emittance linacs may require high-frequency multiple-beam channels to achieve the desired total current, a result suggested earlier by Maschke.[24]

What is the physical reason for an advantage of small beams for control of emittance growth? An examination of energy balance for the spherical-bunch charge-redistribution mechanism [Eqs. (4) and (5)] shows that, while the initial field energy available for emittance growth is inversely proportional to bunch radius, the kinetic energy at fixed emittance is inversely proportional to bunch radius squared. Therefore, smaller beams are better because they store more kinetic energy for a given emittance and are less affected by field-energy transfer.

In our numerical simulations, we observe that space-charge-induced emittance growth is the result of a loss of phase coherence in the collective oscillations that can be excited whenever the beam properties change. A loss of phase coherence should occur because all particles do not have exactly the same oscillation frequency in the presence of nonlinear space-charge forces. This leads to a velocity spread and a corresponding emittance increase. Although a smaller beam has a higher density and greater space-charge force, the amplitudes of the oscillations and the resulting velocity spread are less in a small beam. Also, because emittance is a measure of phase-space area, a given velocity-spread increase across the beam produces a smaller emittance increase in a smaller beam.

To control emittance growth after injection into the linac, one could try to keep all rms beam dimensions small and constant during acceleration. To hold the matched beam dimensions constant at nonrelativistic energies, it is sufficient to hold $\omega_f$ and $\omega_{\ell 0}$ constant. Constant $\omega_f$ and $\omega_{\ell 0}$ values correspond to a constant value of $\omega_{t0}$, and, if the rms dimensions are constant, the space-charge-force components of the equivalent uniform beam are also constant. As discussed earlier, there is a great deal of flexibility for achieving strong focusing in a DTL when using quadrupole focusing, and generally it should not be difficult to ensure that $\omega_f^2$ is nearly constant as $\beta$ increases. As a first approximation, the use of constant length and constant gradient quadrupoles produces a constant $\omega_f^2$ value as $\beta$ increases. For a constant value of $\omega_{\ell 0}$, it is necessary to require that $E_0 T \sin\phi_S/\beta\lambda = \text{constant}$. Also, because the longitudinal force is inherently nonlinear, the variation of $\phi_S$ with respect to $\beta$ should be chosen so that the separatrix in longitudinal phase space does not shrink relative to the beam bunch, which would expose the outer beam particles to nonlinear forces, emittance growth, and particle losses. There is no unique prescription for $\phi_S$, but a useful parameterization that results in a constant or decreasing value of $|\phi_S|$, consistent with efficient acceleration, is $\psi = \psi_i[1 + \rho(\beta_i/\beta - 1)]$, where $\psi$ is the zero-current total phase width of the separatrix at velocity $\beta$, $\psi_i$ is the corresponding width at some initial or reference velocity $\beta_i$, and $\rho$ is a parameter that can be chosen within the range $0 \le \rho \le 1$. At zero current, $\psi$ and $\phi_S$ are related by $\tan\phi_S = (\sin\psi - \psi)/(1 - \cos\psi)$, which reduces to $\phi_S = -\psi/3$ for small angles. When $\rho = 1$, we obtain $\psi \propto 1/\beta$ and approximately $E_0 T \propto 1/\beta^2$, which also corresponds to the gentle bunching prescription for the RFQ.[25] When $\rho = 0$, $\psi$ and $\phi_S$ are constant, and $E_0 T \propto 1/\beta$. At constant frequency, $E_0 T$ must be ramped upwards as the energy increases to maintain a constant bunch length. The ability to ramp the accelerating field upwards as $\beta$ increases should provide a capability for the control of longitudinal emittance growth, but peak surface field limitations will ultimately restrict this procedure. We emphasize that the longitudinal dynamics may be especially important for the control of particle losses in high-duty-factor linacs. If a longitudinal halo exists relative to the core of the beam, most losses will probably occur during the first longitudinal oscillation of the beam in an error-free linac. But losses can continue at high energies as a result of field and amplitude errors in the DTL tanks.[16] Therefore, field ramping may be an important technique for control of particle losses in high-duty linacs.

In addition to the emittance growth from charge redistribution described above, one must consider emittance growth associated with a transfer of kinetic energy between planes (kinetic energy exchange). Although much work remains to be done on this topic, previous 2-D studies have led to useful and practical conclusions.[26-28] Kinetic energy exchange does not occur when the initial beam is equipartitioned (same mean kinetic energy in all planes). If the beam is not equipartitioned, emittance will grow in one plane and decrease in another, if the beam is sufficiently space charge dominated. A nonequipartitioned beam under weaker space-charge conditions can remain stable in a nonequipartitioned state. As space charge becomes more important, some kinetic energy transfer will occur toward equipartitioning, but the beam can stabilize before a fully equipartitioned state is reached. Finally, at high space-charge conditions, a nonequipartitioned beam will equipartition with an increase in emittance in some planes. The safest guideline is to inject an equipartitioned beam into a DTL. Numerical simulations show that at typical space-charge levels, this requirement may often be relaxed without serious problems of energy transfer.[27] The use of computer simulation provides the best guidance for how much the equipartitioning requirement can be relaxed.

To illustrate these points, we have generated four DTL designs and simulated their beam performance using the PARMILA code. All linacs have been designed for 100 mA of protons with the same initial values of the normalized rms transverse and longitudinal emittances (0.02 and 0.03 cm·mrad, respectively). For each case, the beam is accelerated from 2 to 50 MeV, and the simulations were carried out using 2000 particles with an initial uniform density within a hyperellipsoid in 6-D phase space. Table III shows the rf frequency, the initial zero-current transverse and longitudinal oscillation frequencies in relative units, the invariant quantities along the linac, and the emittance growths in the transverse x-plane and longitudinal z-plane. Linac A, with weak longitudinal focusing and a constant $E_0T$ design, shows substantial emittance growth in both x- and z-planes. In linac B, the transverse focusing strength is increased as can be seen by the factor of 4 increase in $\omega_{t0}$, and the x-emittance growth shows a dramatic reduction.

The ramped-field design to keep $\omega_{\ell 0}$ constant is used in linac C and results in a large improvement in longitudinal emittance. Finally, in linac D, the frequency is doubled, which yields a further improvement in both planes.

TABLE III

PARMILA SIMULATION TESTS

| Linac | f(MHz) | $\omega_{0t}$ | $\omega_{0\ell}$ | Invariant | $\varepsilon_{x,f}/\varepsilon_{x,i}$ | $\varepsilon_{z,f}/\varepsilon_{z,i}$ |
|---|---|---|---|---|---|---|
| A | 200 | 0.38 | 1 | $E_0T$, $\omega_{0t}$ | 2.46 | 1.63 |
| B | 200 | 1.5 | 1 | $E_0T$, $\omega_{0t}$ | 1.08 | 1.70 |
| C | 200 | 1.5 | 1 | $\omega_{0\ell}$, $\omega_{0t}$ | 1.16 | 1.20 |
| D | 400 | 1.5 | 1 | $\omega_{0\ell}$, $\omega_{0t}$ | 1.09 | 1.16 |

Serious consideration must be given to alignment tolerances[29] for quadrupole magnets in the DTL, especially if the apertures are small, as they may be for a high-frequency linac. Although strong focusing is desirable for raising the current limit and reducing emittance growth, the amplitude for beam centroid oscillations produced by misaligned quadrupoles is larger for stronger quadrupoles. In terms of particle losses, this will be offset to some extent by the smaller beam size associated with stronger focusing lenses. This problem must be considered in detail for a given multitank DTL design to determine the requirements for aperture sizes, quadrupole alignment, tank lengths, and steering before injection into the next tank.

To avoid beam-envelope oscillations that produce large excursions and expose the beam to nonlinear fields, it is necessary to provide a matched beam for injection into each new tank. The lack of adjustable quadrupoles in a permanent-magnet quadrupole system makes it important to produce linac designs with intertank matching that is insensitive to variations in beam current and emittance.[30] Such intertank matching designs are possible when there are no serious discontinuities in the focusing strengths. The initial accelerating field in the DTL usually must be kept low for approximate compatibility with the final RFQ longitudinal focusing. Longitudinal matching between DTL tanks with short intertank spaces can be obtained without additional bunchers by adjusting the accelerating gap locations in the end cells of the preceding and following tanks.

## New Techniques

Perhaps the most significant development of the past decade for high-current ion-linac technology is the RFQ linear accelerator. Better than any other method, the RFQ is able to adiabatically bunch and accelerate a high-current, low-velocity dc beam. The RFQ provides strong rf-electric-quadrupole fields for transverse focusing, and the adiabatic bunching is achieved by machining the required cell structure into the four vanes or poles. The more recent development of the four-rod cavity structure[31,32] provides new flexibility for frequencies below about 200 MHz and, with low inter-rod capacitances, may be an attractive approach for efficient multiple-beam RFQ accelerators.

A DTL tank with a ramped accelerating field[33] is a useful means of providing a beam-dynamics transition between an RFQ and an efficient high-field DTL. The ramped-field tank provides the flexibility for producing an equipartitioned beam at the DTL entrance and beam-matching between the RFQ and DTL that allows for current-insensitive matches. In this paper, I have argued that for applications where the longitudinal emittance must be controlled, it is also important to use a ramped accelerating field throughout the linac to maintain strong longitudinal focusing with increasing energy. In practice, the prescribed nonlinear ramps can be approximated by piecewise linear ramps using a sequence of separate DTL tanks. Recent work has shown the feasibility of producing ramped fields in the DTL by modifying the same post couplers that stabilize the fields against tuning, fabrication, and beam-loading perturbations.[33] Ramped-field cavity designs that are more power efficient can be obtained by detuning the end cells and using the post couplers only to stabilize the field.[34]

Multiple-beam linacs will be necessary for some future high-current applications. Maschke proposed the MEQALAC in which beamlets are accelerated in common rf gaps and transported within individual channels using electrostatic quadrupoles.[35] The use of a multiple-beam array for the induction linac approach to heavy-ion fusion is being developed at the Lawrence Berkeley Laboratory, where the MBE-4 induction linac will accelerate four space-charge-dominated beams.[36]

An important multiple-beam operation in rf linacs is funneling.[19,20] Funneling combines bunched beams from two linac channels into a single colinear beam by interlacing the bunches. The funneled beam can be injected into a new rf-linac channel that operates at twice the frequency. Beams can be funneled above an energy that allows adequate longitudinal acceptance and adequate current-capacity. When a multiple-beam solution is required to achieve an adequate current capacity at low energies, funneling can greatly reduce the cost and complexity by restricting the multiple-beam solution to only the lowest energies. Furthermore, funneling permits the use of more compact and efficient high-frequency accelerating structures at high energies. Even when the current can be obtained in a single channel, if efficiency is important, it may be better to use a higher frequency multiple-beam linac with funneling rather than a lower frequency single-channel accelerator. Funneling of two beams within an RFQ-like structure[37] is an elegant solution at low energy where electric fields are needed to provide strong focusing. Discrete-element funnels use conventional discrete elements, including quadrupole lenses and buncher cavities for focusing, dipole magnets for bending, and rf-deflector cavities for combining and interlacing the two beams.

When the duty factor is large, particle losses may limit the average beam current. If the physics design procedures are not adequate for control of the beam halo, it may be necessary to introduce emittance filters[12] to clean up the beam for high-current, high-duty linacs. Such a filter might consist of a beam-transport line with collimators to remove the transverse halo, or magnetic removal of off-momentum particles to reduce a longitudinal halo. The need for such filters and the details for their design must be studied further.

## Conclusions

To control space-charge-induced emittance growth in ion linacs, we conclude that it is desirable to use high-frequency accelerating structures and to provide strong focusing to keep all beam dimensions small. For high average-current linacs, the control of both transverse and longitudinal emittance is necessary to minimize unwanted particle losses. Strong transverse focusing can be provided at low-$\beta$ in the RFQ and at higher-$\beta$ in the DTL (by use of permanent-magnet quadrupoles and by proper choice of the focusing lattice). The longitudinal focusing strength can be maintained at high values as $\beta$ increases, if the accelerating field can be ramped throughout the linac. A longitudinal field ramp that produces a constant longitudinal oscillation frequency is not a linear function of axial position but can be approximated by piecewise linear ramps in a sequence of DTL tanks. The value of the constant longitudinal oscillation frequency is determined by the requirements for matching and equipartitioning at injection to the DTL. Eventually the field levels will be limited, either by the maximum surface electric fields allowed by breakdown or by cooling requirements, or both. The ramp can be continued if the DTL frequency is doubled. If the frequency is doubled, funneling could be used to fill all available buckets of the new linac, which increases the average current without increasing the peak current in the individual bunches.

Two examples illustrate how these linac developments could be used. First, a cw multiple-beam $D^-$ RFQ accelerator can be designed for heating and current drive in a tokamak fusion reactor.[38] The RFQ is an ideal accelerator for delivering high currents in the megavolt energy range. Because the beam power required for this application is very large (tens of megawatts), a multiple-beam accelerator would be required to provide the current. At 25 MHz, an output current of about an ampere could be obtained at 2 MeV in a single channel. The beams would be independently transported to neutralizers, after which they would drift through the magnetic field of the fusion reactor into the plasma.

Second, a 1-A, 35-MeV $D^+$ accelerator can be designed for a cw accelerator-driven deuterium lithium neutron source for fusion-materials testing.[39] The total current could be obtained by four separate modules, each at a 250-mA current. Each module would consist of two dc injectors and two RFQs at 175 MHz. The 125-mA beams from the RFQs would be funneled at 3 MeV, and the output beam would be injected into a 350-MHz DTL for acceleration to 35 MeV. Because it is important to minimize radioactivation of the accelerator from particle losses, the choice of higher frequencies and the ramped-field design procedures for control of longitudinal emittance are probably desirable for this application.

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## References


1. I. M. Kapchinskij and V. A. Teplyakov, "Linear Ion Accelerator With Spatially Homogeneous Strong Focusing," Prib. Tekh. Eksp. 2 (1970), 19.
2. Richard H. Stokes and Thomas P. Wangler, "Radio-Frequency Quadrupole Accelerators and Their Applications," in *Annual Review of Nuclear and Particle Science*, Vol. 38, 1988.
3. K. Halbach, "Strong Rare Earth Cobalt Quadrupoles," IEEE Trans. Nucl. Sci. 26 (June 1979), 3882.
4. S. O. Schriber, "High-Beta Linac Structures," Proc. 10th Linear Accelerator Conf., Montauk, New York, September 10-14, 1979, Brookhaven National Laboratory report BNL-51134 (1980), 205.
5. I. Hofmann, "Emittance Growth of Beams Close to the Space Charge Limit," IEEE Trans. Nucl. Sci. 28 (3) (1981), 2399.
6. I. Hofmann, "Emittance Growth," Proc. 1986 Linear Accelerator Conf., Stanford Linear Accelerator Center report SLAC-303 (1986), 183.
7. T. P. Wangler, R. S. Mills, and K. R. Crandall, "Emittance Growth in Intense Beams," Proc. 1987 Particle Accelerator Conf., IEEE Catalog No. 87CH2387-9 (1987), 1006.
8. I. M. Kapchinskij, "Intense Linear Ion Accelerators," Sov. Phys. Usp. 23 (12) (December 1980), 835.
9. M. Reiser, "Current Limits in Linear Accelerators," J. Appl. Phys. 52 (1981), 555.
10. T. P. Wangler, "Space-Charge Limits in Linear Accelerators," Los Alamos Scientific Laboratory report LA-8388, July 1980.
11. L. Smith, L. J. Laslett, I. Hofmann, and I. Haber, "Stability of KV Distributions in Long Periodic Systems," Particle Accelerators 13 (1983), 145.
12. B. P. Murin and A. P. Fedotov, "Radiation Cleanness and Economics of Modern High-Current Linear Accelerators of Protons and Negative Hydrogen Ions," Atomnaya Energiya, 38 (3) (1975), 186.
13. J. D. Lawson, "The Physics of Charged Particle Beams," (Clarendon Press, Oxford, 1977), 197.
14. P. M. Lapostolle, "Possible Emittance Increase Through Filamentation Due to Space Charge in Continuous Beams," IEEE Trans. Nucl. Sci. 18 (3) (1971), 1101.
15. F. J. Sacherer, "RMS Envelope Equations with Space-Charge," IEEE Trans. Nucl. Sci. 18 (3) (1971), 1105.
16. M. Pabst and K. Bongardt, "Longitudinal Trapping and Particle Loss of High Intensity Bunched Beams," Proc. 1986 Linear Accelerator Conf., Stanford Linear Accelerator Center report SLAC-303 (1986), 50.
17. G. P. Boicourt, "PARMILA," Proc. Workshop on Linear Accelerator and Beam Optics Codes, San Diego, California, January 19-21, 1987, to be published.
18. T. P. Wangler and K. R. Crandall, "PARMTEQ – A Beam Dynamics Code for the RFQ Linear Accelerator," Proc. Workshop on Linear Accelerator and Beam Optics Codes, San Diego, California, January 19-21, 1987, to be published.
19. T. P. Wangler, "Summary for Working Group on Multiple Beams and Funneling," Proc. Workshop on High-Current, High-Brightness and High-Duty Factor Ion Injectors, San Diego, California, May 21-23, 1985, AIP Conf. Proc. 139 (1986), 173.
20. J. E. Stovall, F. W. Guy, R. H. Stokes, and T. P. Wangler, "Beam Funneling Studies at Los Alamos," presented at the Heavy Ion Inertial Fusion Workshop, Darmstadt, West Germany, June 28-30, 1988.
21. T. P. Wangler, "Brightness Limits in Linear Ion Accelerators," Proc. NATO ASI on High-Brightness Accelerators Conf., Pitlochry, Scotland, July 13-25, 1986, NATO ASI Series B: Physics Vol. 178, p. 411.
22. R. A. Jameson, ed., "Space Charge in Linear Accelerators Workshop," Los Alamos Scientific Laboratory report LA-7265-C, May 1978.
23. T. P. Wangler, K. R. Crandall, and R. S. Mills, "Emittance Growth from Charge Density Changes in High-Current Beams," Proc. International Symposium on Heavy Ion Fusion, Washington, D.C., AIP Conf. Proc. 152 (1986), 166.
24. A. Maschke, "Space-Charge Limits for Linear Accelerators," Brookhaven National Laboratory report BNL 51022 (1979).
25. I. M. Kapchinskij and I. M. Teplyakov, "On the Possibility of Lowering the Injection Energy and Raising the Achievable Currents in an Ion Linear Accelerator," Prib. Tekh. Eksp. 4 (1970), 17.
26. R. A. Jameson, "Equipartitioning in Linear Accelerators," Proc. 1981 Linear Accelerator Conf., Los Alamos National Laboratory report LA-9234-C (1982), 125.
27. I. Hofmann and I. Bozsik, "Computer Simulation of Longitudinal-Transverse Space-Charge Effects in Bunched Beams," Proc. 1981 Linear Accelerator Conf., Los Alamos National Laboratory report LA-9234-C (1982), 116.
28. F. W. Guy and T. P. Wangler, "Numerical Studies of Emittance Exchange in 2-D Charged Particle Beams," Proc. 1986 Linear Accelerator Conf., Stanford Linear Accelerator Center report SLAC-303 (1986), 336.
29. R. L. Gluckstern, "Nonlinear Effects," in *Linear Accelerators*, P. M. Lapostolle and A. L. Septier, Eds. (North Holland Publishing Co., Amsterdam, 1970), C.1.2d, 797.
30. R. S. Mills, K. R. Crandall, and J. A. Farrell, "Designing Self-Matching Linacs," Proc. 1984 Linear Accelerator Conf., Gesellschaft für Schwerionenforschung, Darmstadt report GSI-84-11 (1984), 112.
31. A. Schempp, H. Klein, H. Deitinghoff, P. Junior, M. Ferch, A. Gerhard, K. Longbein, and N. Zoubek, "Zero-Mode-RFQ Development in Frankfurt," Proc. 1984 Linear Accelerator Conf., Gesellschaft für Schwerionenforschung, Darmstadt report GSI-84-11 (1984), 100.
32. R. M. Hutcheon, "A Modeling Study of the Four-Rod RFQ," Proc. 1984 Linear Accelerator Conf., Gesellschaft für Schwerionenforschung, Darmstadt report GSI-84-11 (1984), 94.
33. J. H. Billen and A. H. Shapiro, 'Post-Coupler Stabilization and Tuning of a Ramped-Gradient Drift-Tube Linac," these proceedings.
34. James H. Billen, "Analysis of Measured Post-Coupler Fields in a Ramped-Gradient Drift-Tube Linac," these proceedings.
35. A. W. Maschke, "MEQALAC: A New Approach to Low Beta Acceleration," Brookhaven National Laboratory report BNL 51029 (1979).
36. A. I. Warwick, D. E. Gough, D. Keefe, and H. Meuth, "Beam Measurements for Heavy-Ion-Fusion in an Experimental Small-Scale Ion Induction Linac," these proceedings.
37. R. H. Stokes and G. N. Minerbo, "Proposed Use of the Radio-Frequency Quadrupole Structure to Funnel High-Current Ion Beams," IEEE Trans. Nucl. Sci. 32, (5) (1985), 2593.
38. R. H. Stokes, T. P. Wangler, and K. R. Crandall, "RFQ Accelerators for Heating Thermonuclear Plasmas," Proc. 1987 Particle Accelerator Conf., IEEE Catalog No. 87CH2387-9 (1987), 334.
39. G. P. Lawrence, T. P. Wangler, E. L. Kemp, M. T. Wilson, T. Bhatia, G. H. Neuschaefer, F. W. Guy, and D. D. Armstrong, "A High-Performance D-Li Neutron Source for Fusion Technology Testing: Accelerator Driver Design," presented at Eighth Topical Meeting on the Technology of Fusion Energy, Salt Lake City, Utah, October 10-13, 1988.