DESIGN OF LONG INDUCTION LINACS*

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Abstract

A self-consistent design strategy for induction linacs is presented which addresses the issues of brightness preservation against space charge induced emittance growth, minimization of the beam breakup instability and the suppression of beam centroid motion due to chromatic effects (corkscrew) and misaligned focusing elements. A simple steering algorithm is described that widens the effective energy bandwidth of the transport system.

Introduction

In this paper we will discuss the various requirements imposed on the output beam of electron induction accelerators and the principal known mechanisms which make it difficult to satisfy these requirements. This will lead us to a self-consistent design strategy which overcomes these mechanisms and should make it possible to simultaneously achieve all the requirments discussed.

Output Beam Requirements

Electron induction linacs can be used for many purposes such as drivers for FEL's and relativistic klystrons, flash x-ray radiography and for propagation experiments in various gases. Most of these applications require a high beam brightness, especially the FEL. In addition, all the applications require a "quiet" output beam in the sense that the transverse motion of the beam's centroid should be small compared to its radius. Lastly, most applications require the energy variation over the usable portion of the pulse to be on the order of one percent to avoid violating the resonance condition in an FEL, or to avoid chromatic effects in the final focusing lens, etc.

Obstacles to Achieving Beam Requirements

Space Charge Induced Emittance Growth

For intense beams the most serious threat to beam brightness is from the effects of nonlinear space charge forces[1]. By now it is well known that "excess" non-linear field energy can be interchanged with transverse thermal kinetic energy causing emittance to vary in a beam which is propagating at its matched radius in a focusing channel. Profile oscillations of the beam can lead to oscillations in the emittance and a finite growth in the emittance which depends on the difference in non-linear field energy between the initial and asymptotic states of the beam spatial profile. This can be seen by integrating the equation for growth of the normalized rms emittance.

$$\frac{\partial E_n^2}{\partial z} = -\frac{2IR^2}{\gamma\beta I_o}\frac{\partial \Omega}{\partial z} \quad . \tag{1}$$

Here R is the rms radius, $I_0 \cong 17$ kA and Ω is a dimensionless quantity that characterizes the field energy in the beam and is dependent upon the spatial profile[1]. Integration of this equation for constant R and γ yields

$$E_n^2(\infty) = E_n^2(0) + \frac{2IR^2}{\gamma\beta I_o}\left[\Omega(0) - \Omega(\infty)\right] \quad . \tag{2}$$

However, it is also possible to have additional emittance growth if a beam is mismatched in a focusing channel where a portion of the kinetic energy associated with the beam's envelope motion can be converted into transverse themal kinetic energy. Consider an oscillation of the beam rms radius so that $R=R_0+\Delta R \cos kz$. Profile oscillations will usually be associated with the envelope oscillations. It can be shown that the frequency of the profile oscillations is twice that of the envelope oscillations so that we may put $\Omega=\Omega_0+\Delta\Omega\cos(2kz+\theta)$ where θ is an unknown phase angle. If we substitute these forms for R and Ω into equation (1), average over an oscillation period and retain only lowest order terms we obtain

$$\overline{\frac{\partial E_n^2}{\partial z}} = \frac{I}{\gamma\beta I_o}(\Delta R)^2\, k\, \Delta\Omega \sin\theta \tag{3}$$

where a horizontal bar denotes a time average over an oscillation period. This result admits a growing emittance for a proper value of the phase angle. The rate of emittance growth is proportional to the beam current, the focusing strength and to the square of the radial mismatch. At present there is no first principles' calculation that can describe the evolution of this angle so that we must rely on simulations for insight into this mechanism.

Beam Breakup Instability (BBU)

This instability dominates the design of the focusing system for the induction linac. The accelerating cells have dipole cavity modes which are driven by any beam transverse displacements. Usually one mode dominates the process. The magnetic field of the dipole mode interacts with the beam impressing a modulated transverse momentum on the beam at the frequency of the dominant mode and so exicites that mode in downstream cells to even greater amplitude. The evolution of the instability may be described by two model equations which govern the excitation of the mode by the beam and the response of the beam to the cavity fields[2]:

$$\left(\frac{\partial^2}{\partial\tau^2} + \frac{\omega_0}{Q}\frac{\partial}{\partial\tau} + \omega_0^2\right)\Delta = \frac{\omega_0^3}{L_g}\frac{Z_\perp I\,\xi}{Q\gamma I_o} \tag{4}$$

$$\frac{\partial^2\xi}{\partial z^2} + \frac{1}{\gamma}\frac{\partial\gamma}{\partial z}\frac{\partial\xi}{\partial z} + k_\beta^2\,\xi = \Delta \quad . \tag{5}$$

Here ω_0, Q and $Z_\perp/Q$ are respectively the angular frequency, quality factor and transverse shunt impedance of the cavity mode and L_g is the average distance between cells. ξ represents either the phasor x+iy for solenoidal guiding (with $k_\beta=k_c/2$) or x or y for alternating gradient quadrupole focusing. Under worst case conditions for "strong" focusing we have

$$\xi \sim \xi_0 \exp\left\{\frac{\omega_0\left(\frac{Z_\perp}{Q}\right)Q\,I}{2L_g I_0}\int_0^z \frac{dz'}{\gamma k_\beta}\right\} . \qquad (6)$$

The quantity $\omega_0(Z_\perp/Q)Q$ appears in the exponent and may be shown to scale as[2]

$$\omega_0\left(\frac{Z_\perp}{Q}\right)Q = \frac{4\,w}{b^2}\,\eta \qquad (7)$$

where w is the axial width of the accelerating gap, b is the beam pipe radius and η is a dimensionless quantity that describes how well the cavity modes are damped. Typical values for η range from 1 to 3. It is currently thought that the minimum possible value for η is about 0.7[2].

"Corkscrew" (Chromatic Aberration)

This mechanism leads to the development of a time varying displacement of the beam centroid. The apparent frequency of the motion increases as the beam propagates further along the machine. Any focusing system that provides an energy dependent betatron wavelength will be subject to this difficulty since all beams have some variation of energy across the pulse[3,4,5]. The mechanism is illustrated in figure 1 where the motion of three beam "slices" labelled A, B and C, initially offset from the center line of the accelerator are followed through a focusing system. At each accelerating gap the particles receive a slightly different energy. Since the betatron wavelengths of the particles depend on their energies the particles will eventually fall out of step with one another and will lead to a displacement which varies with time across the pulse. The apparent local frequency of the time varying displacement or "corkscrew" is roughly given by

$$\omega \approx \frac{1}{\gamma}\frac{\partial\gamma}{\partial\tau}\int_0^z k_\beta\, dz' . \qquad (8)$$

For a system with solenoidal focusing k_β should be replaced by k_c in equation (8). It is clear from the above expression that the frequency of this motion will upshift as the beam propagates down the accelerator. Note that increasing the focusing causes the frequency to increase. It is important that the frequency of this motion be sufficiently small that the differential phase or integral of the frequency over time across the desired portion of the pulse be small compared to 1. The amplitude of the corkscrew is proportional to the orbit amplitude of a reference particle (say in the middle of the pulse). If the differential phase across the pulse is very large then the corkscrew amplitude will be on the order of the orbit amplitude of the reference partilcle. However, if the differential phase is small then the corkscrew amplitude is of order the orbit amplitude of the reference particle multiplied by the sine of the differential phase. Thus in this regime it is important to keep the differential phase as small as possible.

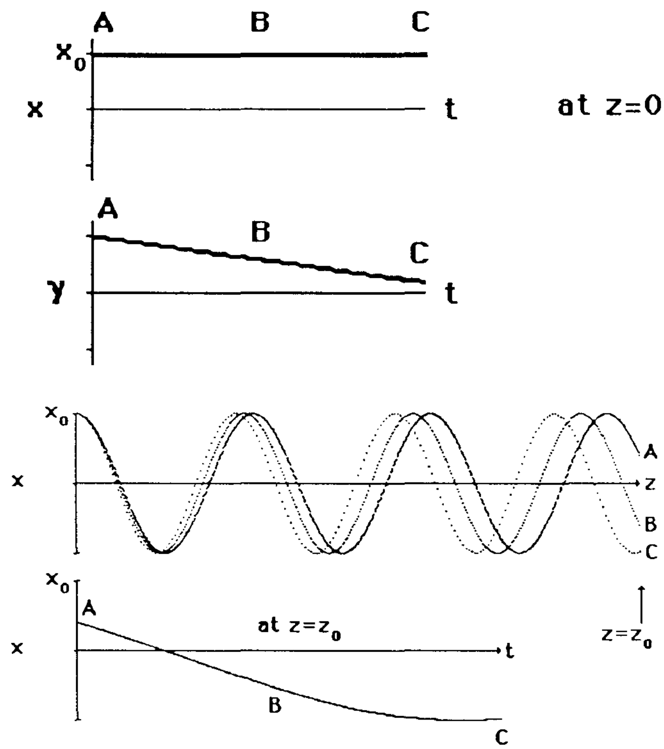

Fig. 1. Illustration of the corkscrew mechanism.

Sources of Energy Variation Across the Pulse

Figure 2 shows a circuit model of an accelerating gap. The pulse power unit is represented by the voltage source and the transmission line to the cell by the resistor Z_0. R_c is a compensation load resistor, C_g represents the capacitance of the cell, the current source represents the beam current and Z_c represents the ferromagnetic or ferrimagnetic core impedance.

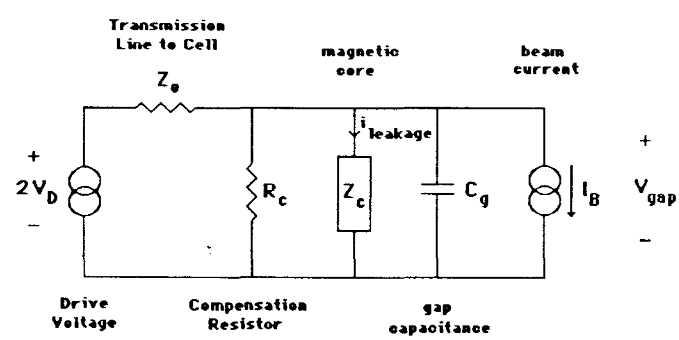

Fig. 2. Cell equivalent circuit model.

Considerable effort is usually expended to insure that the drive voltage waveform delivered to the cell is flat. Likewise a relatively constant voltage on the anode of the injector usually produces a current pulse with a flat top. Practically speaking there will be variations of both of these quantities on the order of several percent even in a well designed system. A feature which can cause an even larger variation in the cell voltage is the fact that the leakage current which flows around the core of the cell is time dependent. In accelerators which are designed for high electrical efficiency this leakage current may be on the order of 50% of the beam current and so exerts a significant nfluence on the cell voltage.

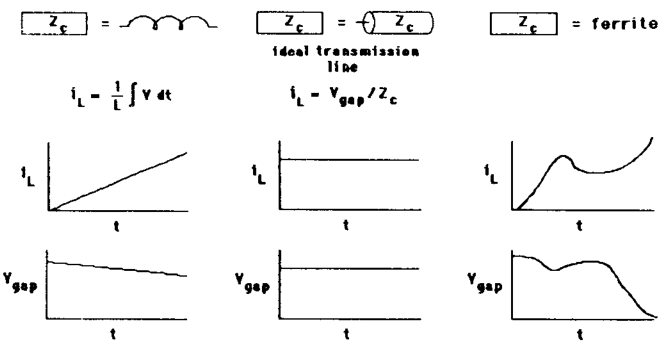

Fig. 3. Accelerator core models.

Various simplified models have been used to calculate the time dependence of the leakage current of ferrite cores and these are illustrated in figure 3. The actual behavior of the leakage current in a realistic core is much more complicated than any of the simple models and is only now beginning to be understood[6].

Another problem which occurs especially for highly efficient accelerators is the variation of cell voltage due to timing jitter of the injected current. Several cases are illustrated in figure 4. In the case of nominal timing a relatively flat voltage across the bulk of the pulse can be achieved. However if the beam current arrives earlier than expected at the cell it will load the voltage down too early and the duration of the "flat top" will be reduced. Likewise if the current arrives too late the cell voltage will overshoot and then decay also reducing the flat top. The voltage errors are proportional to the jitter time and decay with an exponential time constant on the order of Z_0C_g which may be roughly 10 nsecs. for an efficient accelerator. High efficiency generally translates into a high value of Z_0 thus making beam loading very important and causing the time constant to be increased.

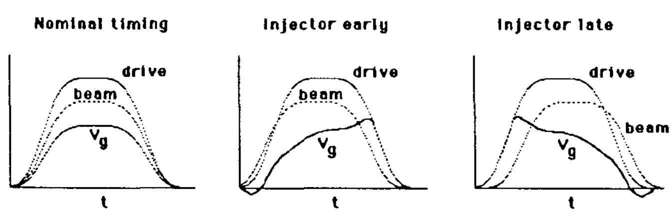

Fig. 4. Effects of current timing jitter.

Specific Solutions

Reduction of Emittance Growth by Rapid Acceleration

Simulations and equations (2) and (3) suggest that the scale length over which emittance grows due to envelope oscillations is inversely proportional to the focusing strength. In addition equation (1) suggests that if γ is increased rapidly enough the emittance growth can be quenched. By reducing the focusing field and increasing the average accelerating gradient significant reductions in emittance growth can be seen in simulations. Figure 5 shows the results of a simulation in which a high brightness beam is accelerated through a structure with an average gradient of 1.0 MV/meter with virtually no increase in rms normalized emittance. Figure 6 shows the change in the square of the normalized emittance for the same problem as a function of the accelerating gradient. This result suggests we seek a transport strategy that minimizes focusing and maximizes accelerating gradient as a way to preserve brightness against space charge induced emittance growth.

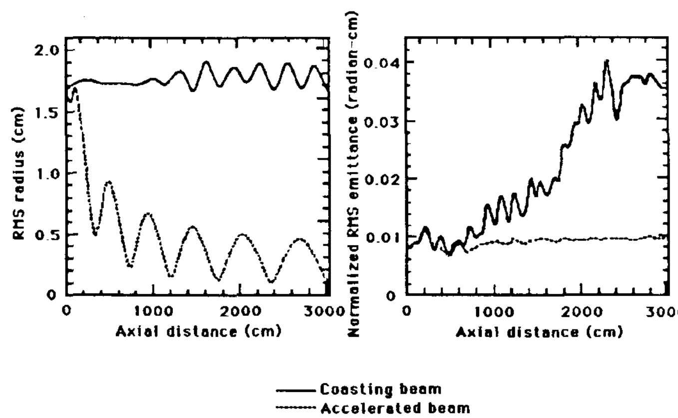

Fig. 5. Effects of acceleration on emittance.

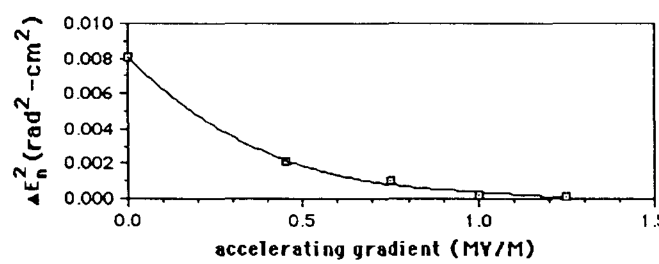

Fig. 6. Emittance growth vs. gradient.

Optimization of BBU and Corkscrew

We have considered two mechanisms which cause transverse beam motion, BBU and corkscrew. From equation (6) we see that BBU growth is reduced by increased focusing yet we see from equation (8) that the corkscrew amplitude is reduced by minimizing the phase advance. These two conditions can be used to find an optimum tune or focusing strategy for the accelerator. Specifically if we define Γ as the log of the BBU gain and ϕ_β as the betatron phase advance:

$$\Gamma = \frac{\omega_0 Z_\perp}{2L_g}\frac{I}{I_0}\int_0^z \frac{dz'}{\gamma k_\beta} \tag{9}$$

$$\phi_\beta = \int_0^z k_\beta\, dz' \tag{10}$$

then if we minimize the phase advance with a fixed BBU gain we find that

$$k_\beta = \frac{\omega_0 Z_\perp}{L_g \lambda} \frac{I}{I_0} \frac{\left(\sqrt{\gamma_\infty} - \sqrt{\gamma_0}\right)}{\Gamma \sqrt{\gamma}} \quad . \tag{11}$$

We find that k_β is proportional to $1/\sqrt{\gamma}$ so that the focusing field varies as $\sqrt{\gamma}$. Using this result we may define a figure of merit for an accelerator transport system[7]:

$$\Gamma \phi_\beta = \frac{2\,\omega_0 Z_\perp}{L_g \lambda^2} \frac{I}{I_0} \left(\sqrt{\gamma_\infty} - \sqrt{\gamma_0}\right)^2 \quad . \tag{12}$$

Here λ is the gradient of the accelerator ($\gamma=\gamma_0+\lambda z$). Reasonable numbers for a high performance design are $\Gamma=3$ and $\phi_\beta=100$ radians.

Techniques to Improve Focusing Field Alignment

The present discussion will be confined to the case of solenoidal focusing. Magnetic field errors can arise from several sources. First there may be undesirable components of fields due to the design. Current flowing in the coil leads for example may lead to residual transverse fields on axis. Even if the design is such as to generate no error fields there will be some error in laying down the windings which may cause significant error fields. Finally, even if the coil is perfectly designed and constructed there will be some error in its placement in the accelerator; the coil may be tilted or displaced with respect to the machine axis.

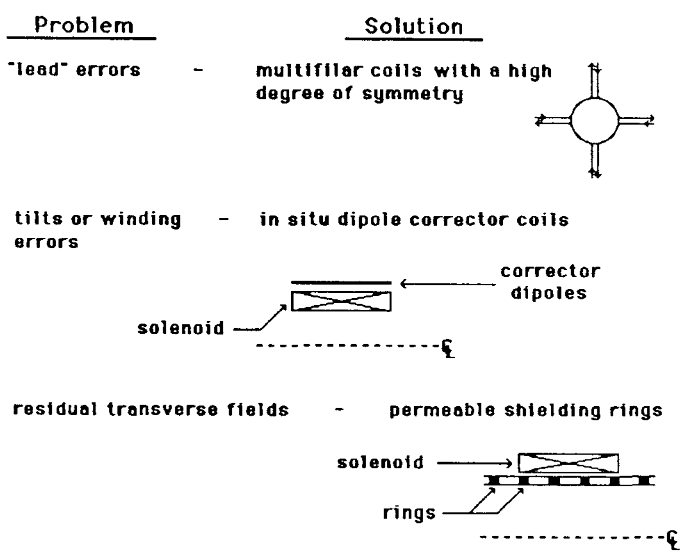

Fig. 7. Magnetic field alignment techniques.

A variety of approaches have evolved to treat the various types of errors. Providing a coil with a high degree of symmetry in the windings is a way to eliminate the transverse fields associated with the leads. Using multifilar coils such as a quadrufilar coil with eight leads packed in bundles of two spaced at 90 degrees around the coil reduces transverse fields on the axis[8]. Tilts and displacements may be minimized by taking care in the placement and alignment of coils within the accelerator cells. To correct for any residual dipole fields on axis a thin, flexible printed circuit set of dipoles may be wrapped around each solenoid for later adjustment. Such an arrangement is in use on several of the accelerators at LLNL[9].

Finally, to reduce any residual transverse fields magnetically permeable rings may be installed inside the coil assemblies. These rings present a low reluctance to any transverse fields and effectively "short" them out while the reluctance in the axial direction is only slightly affected[10]. Figure 7 illustrates these approaches. A pair of accelerators incorporating all of these measures simultaneously is planned for construction at LANL[11].

Delayed Feedback Steering

Even if well designed magnets are precisely installed in the accelerator there will still be residual transverse fields. These fields may be sufficient to cause large transverse beam motion in a long linac (for example if the requirement on transverse beam motion is 200 microns then a beam motion of 1 mm is "large"). In that case some additonal measures must be taken to correct the transverse motion of the beam.

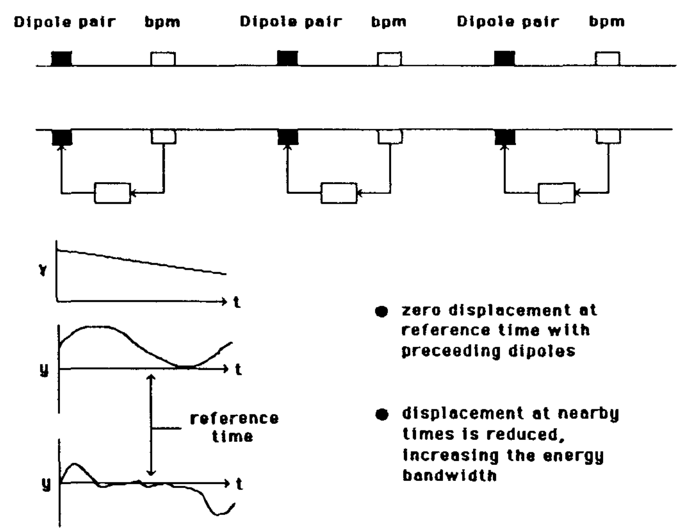

Fig. 8. Delayed feedback steering scheme.

A simple solution in moderate to high repetition rate machines is the use of a delayed feedback steering system. *The accelerator pulses must be sufficiently repeatable in order for this technique to work.* Beam position monitors (bpm's) are placed along the beamline so that there is less than 180 degrees of cyclotron phase advance between them. A point on the pulse (at the middle for example) is chosen as a reference point. A dipole corrector pair upstream of a bpm is then used to zero out the displacement of the reference point at that bpm. The correction is made after observing some number of pulses in order to determine an average correction. One then proceeds to the next bpm downstream and makes similar corrections. A resident computer system could make the corrections very rapidly. The bpm's have some resolution limit and accuracy and these will determine the minimum beam displacement that can be attained for the reference point if the monitors are sufficiently close together (i.e. on the order of 1 radian betatron phase advance between monitors).

An interesting effect occurs as a result of using delayed feedback steering of the reference point. Parts of the beam adjacent to the reference point are also corrected to a high degree if the their energy does not vary too much from that of the reference point. *This leads to a widening of the effective energy bandwidth of the transport system and a dramatic reduction in the corkscrew amplitude.* This is illustrated in figures 8 and 9. There is a 5% energy variation from 20-65 ns. in figure 9.

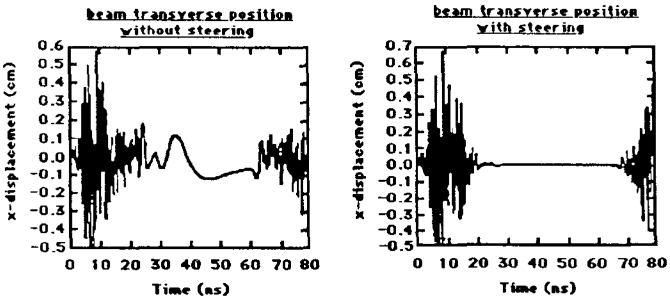

Fig. 9.Steering dramatically improves bandwidth.

Delayed Feedback Energy Regulation

A similar technique can be used to correct the final energy of the beam across the "flat top". The system for accomplishing this is shown in figure 10. An on-line energy analyzer is used to measure the pulse energy as a function of time throughout the pulse over subsequent pulses.

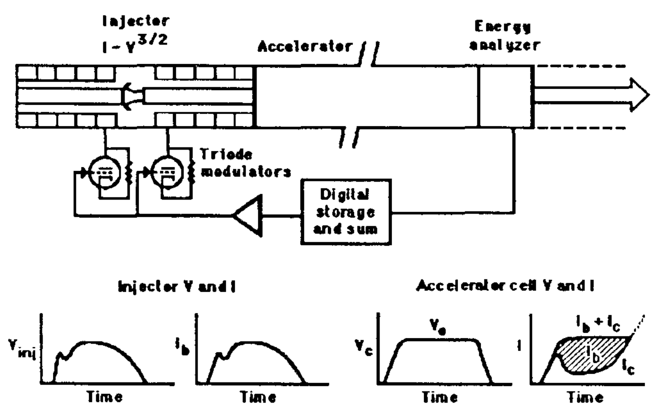

Fig.10. Delayed feedback current control .

This information is used to drive modulators which can apply time varying voltage corrections to the anode of the injector causing the current to vary in a prescribed manner as a function of time through the pulse. The modified beam current will cause cell voltage changes through beam loading and will result in a change in the final energy of the pulse. If the pulses are sufficiently repeatable the feedback system will cause the final energy to be flat limited only by the resolution of the energy analyzer and by the pulse to pulse variations in the final energy[12].

Design Strategy

All of the elements are now in place to formulate a self-consistent design strategy that addresses all the obstacles discussed thus far. The steps in the design are as follows. First determine Γ , the allowable BBU gain, from the output beam requirements. Next set the pipe radius to the maximum practical value and the accelerating gap width to the lowest practical value for the gap voltage and pulse width chosen. Design the cell with a code such as AMOS[13] to obtain a low value of η. Use the highest energy injector possible to minimize the phase advance required in the accelerator and to preserve brightness. These values will then specify the phase advance ϕ_β through equation (12). Use multifilar coils with corrector dipoles and/or permeable rings to provide a relatively error free guide field. Space bpm's at approximately 1 radian betatron phase advance apart for use in delayed feedback steering (if the requirements are not too stringent or the accelerator too long one may be able to dispense with delayed feedback steering and operate the accelerator "open loop"). Use delayed feedback current control to regulate the final beam energy if required.

Conclusions

A number of problems have been discussed which limit the performance of induction linacs. These problems can be overcome by the use of a strategy which incorporates a low phase advance, and high accelerating gradient along with a focusing field that is ramped up proportional to $\sqrt{\gamma}$. The transport line should have the largest bore practical to reduce the BBU growth and thus permit reduction of the focusing field. This should facilitate brightness preservation and result in acceptable BBU gain. The corkscrew problem is then further reduced for a long linac by using delayed feedback to control the energy variations over the pulse and delayed feedback steering to correct the orbit of a reference point on the beam.

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