BEAM BRIGHTNESS IN LOW BETA LINACS: A SENSITIVITY STUDY

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Introduction

Heavy ion drivers for inertial confinement fusion reactors depend on the ability to produce a high intensity, high quality beam with a minimum of in-machine loss. Deterioration of the beam quality, which subsequently leads also to beam loss, tends to occur in the early (low energy) stages of the acceleration process, since all nonlinear effects decrease with velocity. Accordingly, considerable effort has been invested[1-3] in studying the various mechanisms of emittance growth in low energy accelerators.

The current work does not directly address the specific causes for beam deterioration on a fundamental level. Rather, we present the results of a numerical study aimed at gaining an engineering characterization of the dependence of the accelerated beam quality and intensity on various parameters in the linac design, the initial beam configuration, and the initial current. A dramatic improvement is observed when injection energy is raised, and some tentative suggestions are offered for techniques of achieving this increase.

Wideroe Linacs

Table (1) lists the structures we have investigated and describes their pertinent features. All are single tank Wideroe accelerators, operating in the π-3π mode and configured to accelerate Xe^+ ions. They were designed using the WIDEROE linac code developed at Lawrence Berkeley Laboratory[4] in collaboration with GSI.[5] The gap voltages and transit time factors are, therefore, electrically consistent with the rf frequency and the drift tube table. The only exception to this statement involves the gap asymmetry introduced by the π-3π structure. This effect decreases the transit time factor in the gap upstream from a short drift tube and enhances it in the downstream gap. In an effort both to assess the importance of this effect and to improve comparability with other reports[6] we have deleted the asymmetry from structures 3 and 4.

Focussing was achieved with a FOFODODO scheme. Quadrupole lenses were a constant length for each linac, with the length chosen so that it would fit easily within the shortest of the long drift tubes. A physical aperture with a 5 cm diameter was included throughout.

Particle Dynamics Code

Beam behavior and emittance growth were treated using the PARMILA code[7] with slight local modifications. PARMILA is a 6-D simulation code which traces macroparticle orbits. Quadrupoles are treated as thick lenses, gaps as impulse acceleration, and defocussing thin lenses including longitudinal/transverse coupling and lowest order transverse nonlinearities. The effects of momentum spread are treated naturally. Space charge effects are calculated from a direct sum of Coulomb interactions with a linear cutoff to avoid close approach singularities. These sums are computed at the midpoint of each drift tube, the midpoint of each gap, and the beginning and end points of each quadrupole. They are applied as an impulse to the particle momenta. A cylindrical aperture is included, and particles whose radii exceed the aperture are discarded.

The emittance to be reported below are computed from the normalized rms formulae

$$\begin{aligned} \varepsilon_x &= 4\,\bar{\beta}\,\left[\overline{(x-\bar{x})^2}\;\overline{(x'-\bar{x}')^2} - \overline{(x-\bar{x})\,(x'-\bar{x}')}^{\,2}\right]^{1/2} \\ \varepsilon_y &= 4\,\bar{\beta}\,\left[\overline{(y-\bar{y})^2}\;\overline{(y'-\bar{y}')^2} - \overline{(y-\bar{y})\,(y'-\bar{y}')}^{\,2}\right]^{1/2} \end{aligned} \tag{1}$$

In Eq. (1), a bar refers to an average over the particles that are successfully accelerated. β_i is the velocity of the i'th particle divided by the speed of light, while x_i and y_i are its transverse coordinates. The transverse momenta are measured by $x_i' = \partial x_i/\partial z = (p_x)_i/(p_z)_i$ and y_i'. The factor of 4 is appropriate for a Kapchinskij-Vladimirskij (K.V.) particle distribution[8] in which the particle coordinates uniformly cover the surface of a four dimensional hyperellipsoid in transverse phase space. For the runs using a waterbag distribution - uniformly filling the interior of that ellipsoid - the computed results have been multiplied by 3/2 to permit direct comparison of the results with those using the K.V. distribution.

Linac Tuning

The importance of properly matching the input beam and the linac is well established.[3] Unfortunately, while this concept is well defined for transport lines, the situation in accelerators, especially at low energy, is considerably less clear. The presence of acceleration, which generates momentum spread and phase dependent defocussing forces in the gaps, and results in inevitable emittance growth, invalidates the simple ideas of envelope periodicity or constant particle phase advances, except as qualitative guides. The topic of optimal input beam parameters and quadrupole settings in the context of an accelerator requires substantial effort on a fundamental level.[9]

Rather than become enmeshed at this time in an extensive investigation, we have adopted an iterative, heuristic procedure, which we call tuning. The basic concept is that at approximately the center of the short drift tube separating a horizontally focussing region from a defocussing one, the beam profile (in the x-y plane) should be circular. Furthermore, the rate of divergence in one direction should match the rate of convergence in the other. For a periodic transport line, the matched beam with $\varepsilon_x = \varepsilon_y$ satisfies these criteria exactly.

Our tuning procedure, then, consists of adjusting the quadrupole strengths in equal polarity pairs so that

$$\begin{aligned} \overline{(x - \bar{x})^2} &= \overline{(y - \bar{y})^2} \\ \overline{(x' - \bar{x}')^2} &\approx \overline{(y' - \bar{y}')^2} \end{aligned} \tag{2}$$

at the center of the short drift tube following that pair. The initial beam parameters are chosen, within the constraint of yielding the given initial emittance, to minimize both the early emittance growth and the disparity in strength between the two lenses in the first few pairs.

This procedure, of course, is <u>not</u> exact in the presence of acceleration. The results obtained by following it, however: (1) clearly form a lower bound for the obtainable optimum, (2) are sufficiently good in terms of final beam brightness to indicate that they are close to that optimum, and (3) are sufficiently consistent to allow exploration of trends and sensitivity analysis.

Results

The purpose of our investigation was to elucidate the variation in the obtainable beam quality and intensity as a function of injection energy, rf frequency, bunch length, energy spread, and initial transverse emittance. The results are displayed in Table II.

The overall trends are quite clear. The most striking is the marked improvement afforded by injecting at 5 MeV rather than 2.3. There are, of course, significant difficulties connected with achieving this injection. Increasing the beam brightness by more than a factor of 2, however, can justify some trouble. The approach that seems most promising is to extend the output energy of the combination of high voltage pre-accelerator and independently-phased rf cavities beyond the 2.3 MeV that is the present goal of the Argonne HIF Accelerator Demonstration Program. The Dynamitron is a convenient power supply for voltages of 5 MV, and oscillators with adequate power to drive the beams under consideration pose no difficulty. The accelerating column for total voltages above 1.5 MV probably should be divided into separate sections to block the path of back-streaming secondary particles. By inserting focussing lenses between the sections, it should be possible to control the growth of emittance that otherwise occurs beyond the voltage where the Pierce condition must be abandoned. Making up the difference between the pre-accelerator output energy and the desired Wideroe input energy with independently-phased cavities also seems to make electrostatic quadrupoles more practical. This is because the smaller units are easier to design around the requirements of reliable voltage holding that is the larger Wideroe structure. Further modeling of both the electrical and the transport properties of such systems is under way.

The previously reported improvement associated with increasing the rf frequency[10] is verified. Two notes of caution, however, are pertinent to this result. First, to obtain focussing in the 25 MHz schemes requires advanced technology quadrupole lenses. All 12.5 MHz linacs are tuned with a maximum magnetic field gradient of 5.5 kG/cm (13.75 kG pole tip field), corresponding to more or less standard iron core magnet technology. For the 25 MHz results, maximum gradients between 9 and 13 kG/cm are required - necessitating superconducting quadrupoles. The second point pertains to the credibility of run Number 19, where the high frequency coupled with the low particle energy lead to short drift tube lengths of 1.5 cm at the linac entrance. With the drift tube length less than its aperture radius, many of the physical approximations made in PARMILA break down. Examples of these suspect approximations are:

(1) Assuming the electric fields vanish in the drift tube interior,

(2) Representing the transverse electric field in the gap by the first two terms in the power series of a single Bessel function,

(3) Modeling the acceleration by an impulse at the gap center.

The importance of this breakdown to the overall emittance growth has not been investigated.

Dependence on the other parameters investigated is much less dramatic. The theoretically predicted maximum bunch length for magnetic stability[11] of ± 18° appears to be somewhat conservative and better final beam brightness can be obtained by filling a ± 25° bucket to the same average charge density. The decrease in final intensity associated with filling a still longer bucket to the same charge density (Run 6) is probably associated with a failure in the tuning procedure as the losses become large. The small extend to which decreasing the input emittance improved the final brightness in Run 7 over that in Run 2 is consistent with Chasman's results[1] that there is a lower bound to the output emittance from a given linac. The more sizable improvement of Run 16 over Run 15 indicates that at the higher frequency and energy that limit has not yet been reached. Finally, the penalty associated with increasing the initial energy spread is of about the size that might be expected.

Conclusion

The numerical simulation code PARMILA has been used to describe and quantify the parametric variation of low energy Wideroe accelerators. All studies were performed on achievable engineering linac designs. The beam tuning procedure, applied consistently throughout, is a faithful operational analogue of actual hardware tuning. The striking increase in beam brightness achieved by increasing the injection energy motivates further efforts at developing advanced pre-injector techniques. One apparently achievable approach to such a pre-injector is a combination of high voltage, multi-section dc acceleration followed by independently-phased rf cavities. Another which has received considerable attention recently, is the RFQ[12] concept. Further modeling work on both of these suggestions is necessary to explore and compare their characteristics.

Table I. Description of Linacs Studied[a]

Linac No.	Energy Range (MeV)	Frequency (MHz)	Energy Gradient (MeV/m)	Number of Gaps	TTF Description	Quad Length (cm)
1	2.3→8.8	12.5	1.0	30	Realistic	17.0
2	5.0→10.3	12.5	1.0	20	Realistic	24.0
3	5.0→11.4	12.5	1.0	24	Smooth	17.0
4	5.0→9.0	25.0	0.8	40	Smooth	13.0
5	5.0→10.3	25.0	1.0	40	Realistic	13.0
6	2.5→4.83	25.0	0.65	40	Realistic	8.5

[a] The energy gradient, the average rate of increase in particle energy has been held approximately constant. The TTF description refers to whether the transit time factor realistically accounts for cell assymetry or artificially smooths the effect.

Table II. Description of Initial and Final Beam Attributes[a]

Run No.	Linac No.	$\Delta\phi$ (deg)	ΔE (MeV/nuc)	ε_T (cm-mrad)	Distribution	I_o (mA)	Maximum Quad Gradient (kG/cm)	I_f (mA)	ε_x (cm-mrad)	ε_y (cm-mrad)	Brightness (A/cm^2-mrad^2)
1	1	18	$5.0*10^{-4}$	.032	W.B.	25	5.5	17.7	.126	.177	.161
2	1	18	$5.0*10^{-4}$	.032	K.V.	25	5.5	18.9	.107	.113	.317
3	1	25	$3.6*10^{-4}$	.032	K.V.	25	5.5	18.9	.128	.112	.267
4	1	32	$2.81*10^{-4}$	.032	K.V.	25	5.5	16.9	.104	.112	.293
5	1	25	$3.6*10^{-4}$	.032	K.V.	34.7	5.5	22.8	.121	.110	.349
6	1	32	$2.81*10^{-4}$	.032	K.V.	44.4	5.5	17.8	.094	.112	.346
7	1	18	$5.0*10^{-4}$	.016	K.V.	25	5.5	20.0	.092	.107	.413
8	1	18	$1.5*10^{-3}$	.032	K.V.	25	5.5	13.4	.109	.099	.254
9	2	18	$5.0*10^{-4}$	.032	K.V.	25	4.1	24.0	.087	.084	.666
10	2	18	$5.0*10^{-4}$	.024	K.V.	25	4.0	24.4	.081	.081	.752
11	2	25	$3.6*10^{-4}$	.032	K.V.	25	4.2	24.3	.086	.082	.700
12	2	32	$2.81*10^{-4}$	.032	K.V.	25	4.2	23.5	.093	.085	.604
13	3	18	$2.46*10^{-4}$	.031	W.B.	25	5.5	23.7	.131	.139	.266
14	3	18	$2.46*10^{-4}$	.031	W.B.	40	5.5	31.2	.148	.140	.390
15	4	18	$2.46*10^{-4}$	.031	W.B.	25	9.4	25.0	.053	.056	1.682
16	4	18	$2.46*10^{-4}$	.016	W.B.	25	12.0	25.0	.033	.041	3.718
17	5	18	$2.46*10^{-4}$	.032	W.B.	25	10.3	25.0	.058	.063	1.388
18	5	18	$2.46*10^{-4}$	.032	W.B.	65	13.0	64.7	.080	.102	1.604
19	6	18	$3.48*10^{-4}$	.031	W.B.	25	13.0	25.0	.065	.067	1.163

[a] $\Delta\phi$ is the bunch half length in degrees (always centered on a synchronous phase of 32^o). ΔE is the energy spread in MeV/nucleon. ε_T is the initial normalized transverse emittance in cm-mrad. Under distribution, W.B. refers to an initial water-bag particle distribution, while K.V. signifies a Kapchinskij-Vladimirskij distribution. The initial and final currents are in mA. ε_x and ε_y are the normalized final transverse emittances calculated from Eq. (1). For those runs with water-bag distribution, ε_T refers to the actual size of the phase space region occupied by the beam, while the factor of 4 in Eq. (1) has been replaced by 6. The brightness is $2I/\pi^2\varepsilon_x\varepsilon_y$, given on A/cm^2 mrad^2.

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