SUMMARY OF LOW-β LINAC WORKING GROUP

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Requirements

The linac is required to deliver a certain current within a prescribed 6-D phase space volume to the storage ring(s). Ion sources exist with brightness greater than can be handled by linacs. Adequate brightness for the storage rings can be preserved through the linacs if the current is shared by multiple linacs at the low-β end, with funneling to a single linac as beta increases.

Assumptions

Quite adequate safety margins can be insured, perhaps at the expense of a few extra low-β linac branches, (1) by requiring that the ratio of space charge to restoring force be $\leqslant 0.5$ in transverse and longitudinal phase space, implying a tune shift $\sigma/\sigma_0 \geqslant 0.7$; (2) by keeping the beam loading on the rf system $\leqslant 50\%$ (probably over-restrictive); and (3) by realizing that beam scraping can be tolerated to any degree in the low-β linac, since no radioactivity is induced.

Scaling Laws

Scaling laws for current limits work very well within the range of the assumptions. At the Workshop some scalings pertinent to phase-space density and emittance growth under various conditions were compared to simulation and experimental results. Further work in this area would be useful to clarify design issues and relative merits of various structures.

Problem Areas

There appear to be no fundamental problem areas in meeting the low-β linac requirements.

Emittance dilution must be controlled. The assumptions above essentially assure this, at the expense of a linac tree to split up the current at the low-β end. Two modes of operation were proposed by the various participants: one where the emittance always remains smaller than the machine acceptance even if growth occurs, and another where the acceptance is filled and some particles are lost. Further work is needed to clarify the trade-offs involved.

Combining the branches of the linac tree can be done in a variety of ways by stacking, funneling and interlacing the beams transversely and/or longitudinally. Schemes are possible which keep the emittance within the requirements. Nominal allowances for growth should be made for some tuning error during operation. Rf deflectors would be required for longitudinal interlacing; detailed design and simulation work is needed, particularly at the final highest-β combination sections.

A detailed simulation combining all elements of a linac tree has not been done - this is easily within the capability of existing codes and would quickly answer questions about emittance dilution for proposed designs.

Some further experimental work in determining voltage breakdown limits at various frequencies with actual beams would be most helpful in eventual performance optimization.

Wall effects, structure impedance interactions, beam loading and coherent effects do not appear to be problems within the range of the assumptions - at least for conventional structures. New types such as the RFQ require scrutiny. The induction linac is a rather independent line of approach and much more experimental evidence is needed to arrive at level of confidence similar to rf linacs.

Machine Studies

Test programs under way at ANL (Dynamitron + independently-phased-cavities + Wideröes), LBL (long drift-tubes), BNL (multiple-beam-electrostatic-focusing linac (MEQALAC)), and LASL (radio-frequency-quadrupole (RFQ) structure) seem adequate to provide beam to subsequent stages where the problems are harder, and provide options for eventual optimization.

Studies on the low-β accelerators will be very useful in pushing the performance to the ultimate levels and understanding effects in detail.

Computer Simulation

As stated above, detailed simulation of complete systems should resolve most remaining questions for conservative designs where the assumptions are applied. Existing codes have good accuracy and have been experimentally verified in terms of what happens to the main 95% or so of the beam.

Simulations can help develop guidelines or formulas for predicting emittance growth.

We used simulation tools at the Workshop to partially test a new code against the PARMILA standard, and to simulate the ANL Wideröe and the BNL MEQALAC to check scaling.

Design of the low-β sections will benefit from code development (e.g. 3-D space-charge) when it becomes necessary to optimize system efficiency and performance.

Finally, comparison of simulations with experiments on the linacs will push hardest the development of the *experimental* techniques.

Further Remarks

We expand the summary above, prepared immediately after the Workshop, with the following remarks.

Requirements and Assumptions

The assumptions above are very conservative. Even though the economic impact of the low-beta section is small in terms of total facility cost, there has been and will be interest in optimizing this section. This would involve operating with tune shifts $\leqslant 0.7$, closer to (or even near) the space-charge limit. *It must be strongly emphasized*, however, *that the HIF requirement is on six-dimensional brightness*, and the requirement is reasonably stringent. Few of the designs presented so far have adequately considered the overall brightness requirement. Little is known about emittance behavior, except at the limits of zero or saturated current. Also, "current limits" mean different things to different authors, and the definition being used in a particular case is often not stated.

Saturated vs. Unsaturated Operation

Two asymptotic regions are commonly used in discussions of linac operation: a low-current region where things are essentially linear and a high-current region where the linac is saturated. We must carefully separate these two extrema from each other and also from the region where we usually operate a linac, which usually turns out to be in neither asymptotic region. The scaling laws for each of these regions are very different from each other, a point that needs to be emphasized.

Direct comparison between designs running in these two very different operating modes, and "scaling" inferences drawn from these comparisons are rather too common in the HIF literature to date.* We argue with this method of inferring general properties and deciding "best approaches," rather than with the results of the particular cases. In other words, such comparisons should not be called "scaling."

In the low-current region, single-particle dynamics essentially holds, the particle loss is low or zero, and the tune depression is small. Since the particle loss is negligible, it is meaningful to talk about a ratio of exit to entrance emittance (dilution factor). The brightness of the output beam is linear with input current if the input emittance is constant, or conversely, if the input brightness is constant, so is the output brightness if the machine always operates in the very-low-current mode. Few real linacs operate in this region (but the SuperHILAC may be one of them).

In the intermediate region, tune shift is significant and emittance blow-up is not negligible. Scaling equations which account for emittance behavior do not exist yet, but particular cases can be investigated quite well with computer simulation codes. It is essential that emittance as well as current be considered in system designs.

Scaling Laws

"Scaling laws" presented without proper explanation can be confusing, if not outright misleading.

Using linearized equations of motion and assuming ellipsoidal beam bunches with uniform charge distribution and no emittance growth, general equations result for the transverse and longitudinal beam envelope behavior

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*Including these proceedings. Let the reader beware.

in periodic focusing systems with acceleration. These equations, written in terms of the forces acting on the particles, are the same for all rf linacs.

The equations may then be rewritten in forms specific to a particular type of linac. For example, the rf-quadrupole linac has continuous focusing and may be formulated in that manner, or may be represented by an equivalent hard-edged quad system. The number of $\beta\lambda$'s per focusing period has a particularly strong influence.

Certain criteria may then be placed on the linac performance, for example on the phase advance per period at zero current, σ_0, or on the phase advance with current, σ, or on both σ_0 and σ.

Further, physical constraints appropriate to a particular type of structure or focusing method (e.g. electrostatic or electromagnetic) may then be added. Cost constraints, for instance from rf power requirements, can also be folded in.

The resulting equations, and numbers from them, can be extremely confusing to someone else, unless the derivation is made very clear. That is why we want to emphasize that the basic equations are the same, but <u>performance and physical constraints can change the effect of a parameter drastically</u>. <u>Further, direct comparisons of examples using two different sets of assumptions are likely to be misleading</u>. A particularly good elucidation of this point is given by Reiser[1] for transport systems. For application to linacs, the longitudinal properties must be taken into account simultaneously, but the concepts are the same.

It was very apparent at the Workshop that a consistent comparison of various low-beta linac types has not been made. By systematically deriving relations for different sets of constraints, in the manner of Reiser, rather than imposing the constraints a priori and instantly jumping to conclusions and specific designs, we would at least clarify the issues and might even find more attractive systems.

We did check various specific designs currently under consideration, and found that the calculated current limits agreed well with computer code simulations in which the input current was raised until the output current saturated. We also found that the envelope equations, used with a tune shift $\sigma/\sigma_0 = 0.4$, give a value for the saturated transverse output emittance which agrees very well with computer simulations. The limit formulas must be applied on the basis of experience gained from the simulations as to the point in the machine where the "bottleneck" occurs. For example, in the LASL RFQ, the current limit bottleneck occurs at the end of the gentle buncher, where the bunches are well-formed and the rapid acceleration begins. In machines where bunched beams are injected, the current is limited at the injection end.

Having gained this confidence in the agreement between computer codes and the formulae at the current limit, we could, and should, now proceed as suggested above to refine our estimates of performance bounds, including saturated emittance and current loss.

The scaling relationships also are quite accurate and useful at lower currents, except that they do not account for emittance growth. Some systematic numerical experiments have been done[2] which provide some insight into emittance growth, but there are no useful formulas yet. However, meaningful system comparisons could be made by assuming reasonable growth factors. In this regime we must also be aware of the ion source brightness and how it varies as the current is changed, either by changing the ion source parameters or by various types of scraping.

Funneling

Some of the important requirements on funneling schemes were reemphasized at the Workshop, in particular the desirability of filling every accelerating bucket in each stage. The geometries of the RFQ and Wideröe structures are particularly suited to accomplishing this,[3] while other multi-channel configurations may not be.

Computer simulation work is needed on the funneling regions to design suitable transport lines and deflectors and look at possible emittance growth. With proper design, it is expected that the funneling sections will not degrade the emittance significantly. Accelerator arrays having close-packed beam channels and intrinsic longitudinal phasing (thus avoiding flight-path differences in the funneling transport) are clearly preferable.

At the lowest energy end of the system, there may be some advantage in running in a current-saturated mode, with the consequent beam loss and geometry defined emittance. This might, for example, avoid another level in the tree while not compromising the emittance required downstream by an excessive amount. At the funneling points in the tree, the degree to which the space charge limit is approached can easily be controlled by choosing the appropriate velocity for the transition point. Consideration of longitudinal matching will also be important in the funneling region.

Computer Simulation

We wish to reemphasize our belief that existing rf linac simulation codes are quite adequate to proceed with more detailed designs and system comparisons. Simulation of induction linacs is less advanced; the problem is complicated by the extreme aspect ratio of the beam bunch.

Experiment vs. Simulation

It was mentioned in the initial summary above that existing codes for rf linacs have been experimentally verified for the main part of the beam. It must be said that a spectrum of opinion could be found on this point. The above statement is considered reasonable *if* the modeling is done with extreme care, and *if* physics clearly not in the present simulations, like neutralization effects, is also clearly not a factor in the experiment. The main particle-tracing codes for rf linacs are six-dimensional and include non-linear effects; thus there is general confidence in the physical description for the bulk of the beam. A whole host of detailed considerations come into any discussion of the entire beam, including fringe particles. The main point is there is not a wide body of experimental verification, and research accelerators will be very helpful. Development of diagnostic techniques is necessary, and the work involved in an overall verification program is far from trivial. An area which will be particularly hard to measure experimentally, and to simulate properly, is the initial injection and beam bunching region, where neutralization and longitudinal-transverse coupling effects will complicate the situation.

Acknowledgment

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References

1. M. Reiser, Particle Accel. 8, 167 (1978).
2. R. A. Jameson, contributed paper to this working group.
3. D. Swenson, contributed paper to this working group.

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