ROUNDTABLE ON PERFORMANCE OF NEW LINACS

Moderator: G. W. Wheeler (BNL)

Participants: K. Batchelor (BNL)
R. L. Gluckstern (U. of Mass.)
J. M. Lefebvre (CEN-Saclay)
P. V. Livdahl (NAL)
D. A. Swenson (LASL)
C. S. Taylor (CERN)

(Summary by F. T. Cole)

The moderator, G. W. Wheeler, opened by stating that the Program Committee had viewed this roundtable as an opportunity to compare the performance of the new linacs with the theoretical calculations and predictions. He pointed out that, because of the extensive use of digital computation, it was possible to design these new linacs more carefully and to measure fields and beam properties better and quickly.

R. L. Gluckstern opened the discussion with some remarks about the comparison between theory and equipment:

(i) The computations assume four- or six-dimensional phase-space configurations, which are determined from two-dimensional emittance measurements. There can be correlations that require four- or six-dimensional information. The measurements of emittance are at an early stage and we need more in the way of multi-dimensional measurements in order to make predictions that are directly comparable.

(ii) There is no universal way of describing emittances. Some use contours at the 90% level, some at the 80% level, while others discuss rms emittance. Care must be taken in comparisons.

(iii) The greatest attention in recent years has been toward understanding and minimizing the increase in transverse emittance in a projected plane, say (x, x'). There appear to be many possible sources of this increase. The first is variations and fluctuations in rf level in the tanks. The advances in rf measurements have made this factor quite unimportant in the present linacs. There are also nonlinear effects in particle dynamics, particularly couplings between dimensions. Unless one assumes that a bunch is a three-dimensional ellipsoidal configuration of constant charge density (which one does not have in practice), there will be coupling between the two transverse dimensions. Thus, fluctuations in charge density can give rise to coupling.

The phenomena of coupling have some of the aspects of the thermodynamic model proposed some time ago by Lapostolle, in which the increase in emittance of the initially smaller dimension is described as arising from thermal contact with the initially larger-emittance dimension. Gluckstern had not seen any large number of predictions of this model and was not sure how far it could be pushed quantitatively.

The conclusion of theoretical studies is that, in order to minimize the growth of emittance, one should have matching conditions in each dimension at injection and have areas in the longitudinal phase plane and in the two transverse planes that are all within a factor two or so of one another. These initial conditions should limit the growth of emittance to approximately a factor two.

With the limited information now available, it appears that the computations are in good agreement with the observations. The fact that BNL has a somewhat larger emittance than planned indicates that the space-charge parameter is somewhat lower than the design value. Statements made about agreement may therefore apply only in lower space-charge regimes.

Gluckstern summed up by enumerating some theoretical problems, now being considered, with the hope that the measurements would provide information toward their solution:

(i) To what extent is there agreement between calculations and measurements?

(ii) What particle distributions are stable? Is the Kapchinsky-Vladimirski distribution the most stable in all ranges of space charge? A more stable distribution will undergo a smaller increase in emittance.

(iii) What are the effects of alternating-gradient behavior? Most calculations have been done assuming smooth focusing. There is concern, particularly with the thermodynamic model, that the rapid pulsation in an alternating-gradient system may cause some problems. This concern is not shared by all.

(iv) How can emittance be specified in a way that will be general enough for a beam that does not have uniform density? The rms emittance discussed by Emigh yesterday has the interesting property that it obeys the Kapchinsky-Vladimirski equation, which was derived for a uniform distribution, if one also takes the rms radius.

(v) Another problem about which we do not have full understanding is the behavior inside an ion source. Perhaps there is some correlation in four-dimension phase space arising inside the ion source that is preserved through acceleration and might be used to reduce the final emittance.

J. M. Lefebvre discussed the Saclay linac. The major original feature planned in the project has been the pressurized injector, which has been a success in practice. From the results described yesterday, it seems reasonable to hope for a 1.5-MV injection energy, which would help both the sparking and space-charge problems at the front end of a linac.

A non-uniform radial-density distribution has been observed from the preinjector. There are resulting strong aberrations at the output end of the linac, plus poor beam transmission (approximately 50%). Improvement has been hampered by lack of current- and emittance-measuring gear at the entrance to the linac. In addition, there has not been time for a systematic exploration of phase acceptance.

The pulse to be injected into the synchrotron is very long and there have been problems with rf stability. The beam energy spread depends very critically on the rf field level.

The double-harmonic buncher has not given the predicted 20% increase in transmission through the linac, but has given a more constant density of beam across the energy-spread spectrum, which is important for multi-turn injection into the synchrotron.

C. S. Taylor discussed the 3-MeV experimental cavity at CERN. It is a copper-clad structure with 18 drift tubes, which has produced 120 milliamps at 3 MeV. It is in use for beam-diagnostic instrumentation studies and for calibrating reflectometers, as well as for experimental work to measure emittances at low and at high intensities. Numerical work suggests that the transverse phase space is not sensitive to the distribution of the input, but experimental work on the CERN 50-MeV linac suggests that there may be some memory of input density distribution. It is this kind of phenomenon that will be investigated on the 3-MeV cavity, together with development of numerical experiments.

An attempt is being made at CERN to study the evolution of proton density from the ion source to the ISR, to find out whether the ISR interaction rate can be increased by putting in a high-energy preinjector. One concern has been the energy-spread growth from space charge at booster injection (50 MeV). Use of a double-harmonic buncher made it possible to keep the energy spread of the debunched beam in the booster to within 150 keV, the limit of the booster rf system.

With 100 to 120 milliamps of current, the booster requirements are fulfilled. It should be noted that the pulse length required is 100 microseconds, and it is difficult to keep the emittance and energy spread constant over this long pulse. There is apparently no present need for a higher-energy preinjector and its construction has been postponed.

There are difficulties in the 3-MeV cavity arising from the injection beam-transport system. The preinjector has a single gap. The divergence at 500 keV is therefore large, which in turn requires large excitation of the last triplet. As a consequence, the aberrations are large and the beam waist at the buncher is larger than the aperture. There is anomalous beam loading and poor transmission as a result. Some consideration is being given to using a Pierce structure and calculations by Davis will be reported later in the meeting.

Taylor also expressed skepticism about the correspondence between calculations and measurement. In his view, the numerical experiments and the beam measurements need to be designed together to get results that are directly comparable.

K. Batchelor had discussed some of the BNL results in his talk the previous day. Here he discussed some of the difficulties with their measurements.

Although they have made systematic measurements, the operation of the ion scurce is not fully understood. Nearly all the emittance data show a double beam, which they have not found a way to eliminate.

With a single buncher, transmission of approximately 65% is achieved. With a second buncher (at the same frequency), the transmission is increased to 72%. But it is necessary to readjust the quadrupole in the transport system to achieve this improvement. Apparently, this is necessary to match six-dimensionsl phase space at the linac input.

Batchelor gave a comparison between experimental data and the computations of Chasman. At the output of the 750-keV transport line, the computed emittance area is in agreement with the measured area, but their orientation is slightly different. At the third drift-tube gap, a definite mismatch is evident. There is a better match in the y-y' plane than in the x-x', but the growth is larger in the y-y' plane. The growth factor at 10 MeV from the computations was slightly more than 2 in x-x' and slightly less than 2 in y-y', whereas the measured data gave growth factors of 2 in x-x' and 2.5 in y-y'.

Batchelor also commented that they had attempted to use a sieve for beam dilution for measurements, but the sieve burned up in approximately 10 seconds.

D. A. Swenson commented on the LASL emittance measurements. Horizontal and vertical emittances can be measured just beyond the accelerating column and at the input and output ends of the linac. Just beyond the accelerating column, the beam has a normalized horizontal emittance of 1.3×10^{-6} mrad. It is parallel horizontally and about the right width. They would like the beam to be parallel in the vertical also, but have so far always had a beam that is converging vertically. All quadrupole currents between the source and this point were reversed as a test, with the result that the horizontal and vertical patterns were interchanged, which indicates that the plasma boundary is cylindrically symmetrical. With reference to Regenstreif's comment, no beam loss is seen in this system, so it is believed that these are indeed measurements of the beam emittance, not the transport admittance.

Measurements at the entrance to the linac show no evidence of emittance increase in the transport system in either the horizontal or vertical. There is apparently some mismatch of the beam to the linac, which is reflected in emittance growth in the linac.

Orbit calculations have been carried out for the low-current case; there is as yet no detailed comparison between computations and measurements.

Experiments have been carried out with a sieve, a 1-mil tungsten screen with a 1-mil mesh and about 30% transmission. This had adequate lifetime at low current and there is no plan to use it at full current.

P. V. Livdahl began by commenting that, in terms of the status of the measurements, the conference might be considered to be a little premature. The NAL results, for example, are the results of only a few minutes of operation. Some of the NAL results, even though not thoroughly analyzed, may perhaps give some clues about how to match in longitudinal phase space. This phase space can be investigated by measuring the current through an (n + 1)st tank as a function of its rf phase relative to the earlier n tanks. The current will be level through the region in which the occupied "ellipse" from the nth tank lies completely within the acceptance of the (n + 1)st, falling off as the ellipse goes beyond the acceptance. This acceptance can also be changed by varying the rf level in the (n + 1)st tank. If, for example, the rf level is lowered far enough that the acceptance is smaller than the ellipse, the current in the level part of the curve will decrease. One can deduce the phase width of the beam from these measurements.

There is a shoulder on one side of the falloff of some of the curves from Tank 1. It does not show up in Tank 2. It is suspected that this arises from the S-shaped part of the rf phase "ellipse" (the tail of the "fish"). More work is required to understand this shoulder.

At this point, the formal presentations were complete and a general discussion among the panelists followed.

R. L. Gluckstern commented to Livdahl that the shoulder seen on the NAL curves might also be a consequence of mismatch between tanks, which could generate a coherent phase oscillation. He also remarked that the NAL observations are the first indication that there may be no growth after 10 MeV. This lack of growth, if confirmed, would be very important for the design of the entire accelerator and experimental-area systems downstream of a linac.

Gluckstern also discussed the envelope equations. He sketched a derivation from the Kapchinsky-Vladimirski equations of an equation for the rms emittance. This equation holds for distributions having circular symmetry and was first suggested by Lapostolle. Gluckstern pointed out that Liouville's theorem does not apply to this rms emittance.

Batchelor then commented on Livdahl's talk. First, the precision of the edges (fall-off parts of the curves) can be greatly improved by using an energy-degrading foil to intercept the lower-energy particles that are not being stably accelerated. Second, the acceptance diagram is less well defined for later tanks because the phase-oscillation wavelength becomes long compared with a cavity length. At BNL, they plan to make detailed momentum analyses to set cavity field levels in later tanks.

Livdahl stated that foils were used in the NAL measurements of 35-MeV thickness in the Tank 2 case (37 MeV) and 64 MeV in the Tank 3 case (66 MeV).

Taylor commented that there appears to him to be some measure of agreement between theory and experiments at low intensity, but he is more doubtful about measurements at high intensity. He described some theoretical work Sacherer is doing at CERN in which he puts space-charge forces into both a four-dimensional program (a modified SLAC transport) and a six-dimensional program. The results are similar with the two programs, but the six-dimensional program does give a 10 to 15% dilution of phase space. It was not clear to Taylor that there is a true stationary state in an alternating-gradient structure.

Batchelor felt that the overriding problem in making these comparisons is in having correct information on initial parameters, both in the computations and in the measurements. It is premature to discuss agreement until it is clearer that the programs are calculating from the input conditions of the measurements. Finally, he emphasized that at BNL it is felt that a brighter source would greatly enhance the possibility of making detailed studies of space-charge effects and BNL therefore is working to improve its source.

The floor was opened to questions and comments from the heretofore spellbound audience.

Wilson (SLAC): Are present-day proton linacs good enough to do their job as injectors? Are there significant improvements possible in current, emittance, and energy spread that will lead to improvements in synchrotron output?

K. Batchelor (BNL): We feel there is work to be done in matching the linac beam to the AGS. Claus will discuss the theoretical work we have done in a paper at this conference.

R. L. Gluckstern (U. of Mass.): If one could get substantially higher current through a linac, one could have a higher intensity in a circular accelerator.

C. S. Taylor (CERN): Is it thought that the intensity limitations of Serpukhov, the AGS, and the CERN PS are now understood?

G. W. Wheeler (BNL): We certainly don't think the AGS understands it at this point.

M. Promé (Saclay): To answer a question raised by Gluckstern about the thermodynamic model, I point out that the six-dimensional computations show that, if the transverse emittance is larger than the longitudinal, there is a cooling of the transverse motion.

Gluckstern: Is the cooling such that the total energy in the two is constant, as one might expect from a simple thermodynamic theory?

Promé: We do not yet know. It is rather difficult to define the total energy in this case.

C. D. Curtis (NAL): Is the BNL emittance at 10 MeV that for one beam or two?

Batchelor: The second beam is almost all scraped off in the machine, but the total emittances quoted do include whatever there is of the second beam. Some of the measurements, for example, one showed by Witkover yesterday, do definitely exhibit the second proton beam at the output. In most cases, in a 90 to 95% emittance percentage, we do not see the second beam at either the input or output ends.

T. J. M. Sluyters (BNL): The preinjector emittances we quote are now a little higher than previously, because we are now working with 350-400 mA rather than 200.

At BNL, we do not get the hollow beams that some people speak of. This may be because the NAL and LASL cups are much larger than the BNL cup.

We had been concerned about emittance variation during the pulse, but we do not see any important increase, even for pulse lengths of 100 microseconds.

Many people have spoken of Pierce construction in preinjectors. It seems to me that at high intensity it is very unlikely that one can get the uniform density distribution in the cup that is the starting point of a proper Pierce column.

Taylor closed by commenting that Lapostolle had not come to the conference because he is working hard on computer runs to test emittance growth, using the Tanguy programs developed by Regenstreif's group. Lapostolle sends his greetings and wishes for success.