BASIS FOR LOW BEAM LOSS IN THE HIGH-CURRENT APT LINAC

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Abstract
The APT linac has been designed for very low beam loss. This important aspect of the design is supported by three main bases: 1) an understanding of the performance of the 800-MeV LANSCE proton linac at Los Alamos using measurements and simulations, 2) a theoretical understanding of the dominant halo-forming mechanism in the APT accelerator from physics models and multiparticle simulations, and 3) a conservative design approach for APT aimed at maximizing beam quality at low energies and providing large apertures at high energies to reduce beam loss to a very low value.

1 BEAM LOSS AND ACTIVATION

The APT accelerator [1] is a cw medium-energy proton linac with a design beam current of 100 mA, a number of particles per bunch equal to 1.8×10^9, and a final energy of 1030 MeV or higher, depending on the desired tritium production rate. It has been designed to operate with extremely low beam losses to avoid radioactivation of the machine components. It is important to achieve hands-on maintenance capability along the machine in order to meet overall plant availability requirements, although remote maintenance techniques could be employed at a few high-beam-loss locations without major impact.

The maintenance criterion limits post-shutdown activation levels to a few mrem/hr at the beamline. The corresponding beam loss rate that can be tolerated, as a function of beam energy, has been estimated in Ref. [2]. Expressed in beam power, the loss above 100 MeV is limited to a few tenths watt per meter, a value that is consistent with experience at the LANSCE linac, which operates with hands-on maintenance. LANSCE is the highest power operating proton linac in the world. It is a pulsed machine with multiple beam operation that includes a 6%-duty-factor 1-mA average current 800-MeV output beam. For LANSCE the average fractional H^+ loss rate above 100 MeV is about 10^{-6}/m. Excluding two hot spots at focusing transitions lowers this value to about a few times 10^{-7}/m. The number of particles per bunch in APT is only about 3.4 times greater than for LANSCE, and the beam focusing strength in the APT design is greater so that the beam-physics regimes of the two linacs are nearly the same. The APT peak beam current of 100 mA is by no means a record for proton linear accelerators; the Brookhaven and Fermilab injector linacs have operated with H^+ beams at peak proton currents near 300 mA. Nevertheless, the challenge for the APT linac is to deliver an average current 100 times higher than LANSCE in the same energy range, while achieving a beam-loss rate that is no larger in absolute terms. This scales for APT to an acceptable average fractional loss rate of about 10^{-8}/meter, or a total of about 10^{-5} fractional beam loss above 100 MeV. The design objective for APT is a factor of 10 smaller than these numbers.

2 APT BEAM-LOSS THREAT

Our evaluation of the beam-loss threat in APT and its impact on the linac design are based on a combination of operational experience, and theory plus simulation. The approach we have used has several aspects and components:

- Use of measurements of beam performance and activation levels in the LANSCE linac combined with computer simulations to determine the causes of beam loss in that accelerator.
- Choice of the APT linac design architecture and parameters to avoid the halo-generating and loss-mechanisms seen in LANSCE.
- Use of analytic modeling and computer simulation to understand the remaining physical mechanisms responsible for generating halo, and the amplitudes of particles projected into the halo.
- Confirmation of the predicted beam performance (at low energies) by measurements on the Low Energy Demonstration Accelerator (LEDA) now being built at Los Alamos. In the present schedule, initial data should be available in late FY99.

3 BEAM LOSS AT LANSCE

LANSCE routinely achieves hands-on maintenance at all locations in the accelerator and beam transport. Typical H^+ loss rates after the major focusing transitions in the linac are very low; the integrated fractional loss along the high-energy linac is normally less than 5×10^{-4} and never more than 10^{-3}. Simulations of the LANSCE linac [3] have shown several causes of beam loss. The main cause is the incomplete bunching action of the 2-cavity 201.25-MHz bunching system in the low-energy beam transport. This system, which pre-dates the development of the RFQ, produces a beam with an extended tail in longitudinal phase space, leading to poor longitudinal capture. A significant beam loss occurs downstream from the frequency jump at 100 MeV, where the 201.25-MHz drift-tube linac (DTL) transitions to the 805-MHz coupled-cavity linac (CCL); here both the transverse and the longitudinal acceptance decrease substantially, and the beam is also poorly matched longitudinally. Near 200 MeV, there is a sudden reduction in the transverse focusing strength, which leads to additional losses downstream.

Several other effects are believed to contribute to beam loss in LANSCE. First, the dual beam (H^+ and H^- accelerated together) operation of the accelerator limits the effectiveness of beam steering and other corrections.

In practice, beam steering is restricted to the low-energy beam transport and the transition region between the DTL and CCL, where the two beams are separated. Second, LANSCE is a pulsed linac, and as much as 40% of the beam loss occurs during the beam-turn-on transients. This loss can be caused by several factors, including beam-neutralization variations in the low-energy transport, and the beam-induced transient in accelerating-cavity fields, uncorrected by feedforward signals. Finally, the aperture radii in the LANSCE focusing elements and accelerating structures are relatively small, 1.6 to 1.9 cm in the high-energy linac, and the transverse focusing is relatively weak, because of the large spacing of quadrupole magnets. These two factors taken together result in a small "aperture ratio" (the ratio of physical aperture radius to rms beam radius), which varies from about 4 to 7 in the high-energy linac.

4 LANSCE LINAC AND APT DESIGN

How are the beam-loss mechanisms identified in LANSCE addressed in the APT linac design? First, the dominant loss mechanism in LANSCE, longitudinal tails caused by incomplete bunching, is almost completely eliminated in APT by the use of the RFQ, the modern replacement for the LANSCE injection and bunching architecture. Second, only one charge species, H^+, is accelerated in the APT linac, allowing uncompromised beam steering and matching. Third, APT is a cw linac with no pulse structure during normal operation, so there are minimal losses due to beam-turn-on transients; these should be managed to a greater degree than in LANSCE by the rf control loops planned for this system with feedback and feedforward. Fourth, APT is designed with much larger apertures than in LANSCE and with stronger transverse focusing. In the APT high-energy linac, the aperture radius is 8 cm. Combined with the stronger focusing in APT, the resulting aperture ratio ranges from 13 at 100 MeV to about 50 at 1030 MeV, compared with those given above for LANSCE. The very much larger aperture ratios in APT mean that beam halo is much more easily contained within the aperture. The large aperture ratios at high energies, where the activation threat is greatest, are a major benefit of using superconducting cavities for the high energy linac. Finally, improved longitudinal phase-space margin for APT is provided by conservative choice of the accelerating gradient in the superconducting linac. A 10% field increase above the design value is possible in most of the linac, which produces a 27% increase in bucket phase width and a 14% reduction in longitudinal beam size.

Improved matching is also addressed in the APT linac design. Beam-current-independent matching is obtained by maintaining the same transverse and longitudinal focusing strength across accelerating structure transitions, and focusing-strength changes are made adiabatically wherever possible. Operational setting errors that would lead to mismatch are reduced by providing adjustable focusing and appropriate beam diagnostics.

5 BEAM HALO IN APT

Given that the LANSCE beam-loss mechanisms have been addressed in the APT design, what remains as the main potential cause of APT beam loss? The beam spends only a short time transiting the linac (a few microseconds) and effects common in circular machines, such as intrabeam scattering from single Coulomb collisions have insufficient time to develop. Far more important are collective space-charge forces due to the beam as a whole. Numerical-simulation studies predict that the most important potential cause of beam loss is that associated with space-charge-induced halo caused by beam-optics mismatches [4]. These mismatches produce density oscillations of the beam core that can resonantly drive particles to larger radial amplitudes. Theoretical and numerical studies of halo formation show particle amplitudes resulting from single mismatches that extend well beyond the Debye tail of a matched beam, but not growing without limit.

Particle-core models of mismatched beams such as those in Refs.[5-14] have been constructed to provide quantitative estimates of the characteristics of halo-particle amplitudes caused by a single mismatch. In these models, the space-charge field from the oscillating beam core in a uniform linear-focusing channel is obtained from an oscillating density distribution. The amplitude of the core oscillation is directly related to the magnitude of the rms mismatch of the beam. The behavior of halo particles is studied by representing them with test particles that oscillate through the core and interact with it. A parametric resonance occurs [6] when the particle oscillation frequency is half the core frequency. The amplitude growth for the resonant particles is self limiting, because outside the core the space-charge force falls off and the net restoring force increases nonlinearly with radius, producing a dependence of frequency on the particle amplitude such that the particles drop out of resonance as their amplitudes grow. A simple scaling formula has been derived [11] from the transverse halo models that shows how the maximum amplitude for an rms mismatched beam decreases with increased focusing strength. Halo formation from the particle-core model has also been studied in 3D bunches with self consistent stationary distributions [14] with bunch parameters close to the APT case. Results for the transverse halo are similar to those from 2D models; the relative extent of the longitudinal halo has been found to be smaller than that of the transverse halo. The halo models have provided a basic understanding of the underlying physics of the most important beam-loss mechanism expected in the APT linac.

6 NUMERICAL-SIMULATION STUDIES

Numerical simulation studies are an important tool for the analysis of the beam behavior in APT. Simulations using several codes have been carried out to support the basic design of the linac. The forces acting on the particles in the simulations include the external focusing fields and the direct space-charge fields; nonlinear force terms are included. Two-dimensional cylindrical-beam simulations with a single beam mismatch, initiating a breathing-mode core oscillation, were carried out for comparison with the particle-core halo models; these have shown remarkably good agreement in terms of maximum radial amplitude as a function of mismatch[11, 13].

End-to-end (from injector to linac output) simulation studies of the LANSCE accelerator have also been carried out for comparison with beam measurements [3] and loss estimates. The simulations agreed with measured rms quantities to within 10% to 15%. The major loss locations in the high-energy linac were correctly indicated by the simulations, but the loss magnitudes were overpredicted by about an order of magnitude. This discrepancy was not unexpected because of the sensitivity of the beam losses to the details of the particle distribution in the beam tails formed during the LANSCE bunching process, and the lack of longitudinal phase-space measurements, which are very difficult to make.

Both 2D(r-z) and 3D particle-in-cell space-charge routines have been compared and are in excellent agreement for APT, which suggests that 3D effects that account for x-y differences are not important. Nevertheless, precise calculation of the details of the particle distribution at the edges of the beam may be beyond our capabilities. Even assuming that the simulation code contains all the correct beam physics, and if sufficient numbers of particles could be run to eliminate artificial statistical fluctuations, as a practical matter the exact configuration of the machine errors can not be precisely known, nor can the initial phase-space distribution of the particles in the beam be precisely known. Because of these uncertainties, the numerical simulation studies can only make probabilistic predictions and at best have statistically validity. Given the expected statistical distributions of the errors, many computer runs are needed to predict statistical distributions of the beam parameters.

Supercomputers using massively-parallel processing are now being applied to these simulations. Some preliminary simulations looking at beam halo using up to 10^7 particles per run have already been done, and have shown the potential of applying increased computing power to the halo problem. Unlike the LANSCE simulations, the APT simulations for a linac with realistic errors produce zero beam loss above 100 MeV when using 10^7 particles per calculation. If the total fractional loss above 100 MeV was equal to 10^{-5} (an acceptable loss level), these simulations would yield an integrated loss of about 100 particles along the high energy APT linac. The absence of particle loss above 100 MeV is an encouraging result, and is positive evidence for a successful design.

At present, no direct measurements of beam-halo amplitude distributions are available for comparison with the codes, although such measurements will be carried out on LEDA. Such measurements are not trivial, and to be definitive must be carried out with careful characterization of the input beam in all six phase-space dimensions, and using precision beam diagnostics capable of taking measurements over a large intensity range.

7 BEAM-LOSS CONTROL

We believe that the practical approach to achieving very-low beam loss in the APT linac is to produce a strongly-focused well-matched high-quality beam in the low-energy normal-conducting linac, including an RFQ, and inject this beam into the large-aperture high-energy superconducting linac. Throughout the linac, rf phase and amplitude (feedback) control loops must keep the beam well centered within the longitudinal bucket, and beam steering must be provided to keep the beam well centered in the aperture. The beam halo observed in simulations with realistic errors does not extend radially beyond 5σ for a well-matched beam, or beyond about 10 σ for a beam with mismatches; the maximum particle amplitudes are well within the apertures of the high-energy linac.

8 ACKNOWLEDGMENTS

The authors acknowledge support from the U.S. Department of Energy, and wish to thank Robert Gluckstern for useful discussions.

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